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Performance of $M5_{Framatome}$ cladding during Loss-of-Coolant Accident

Borrossi Romain, Chosson Raphaël, Haller Xavier

Nessebar, Bulgaria & 14-19/09/2025

LOCA regulatory context

Historical requirements in 1970 s:

- Empirical limit based on ring compression tests and the Baker-Just (BJ) correlation for total oxidation
- PCT < 1204 °C and Equivalent Cladding Reacted (ECR) < 17 %

Experimental programs have shown the detrimental effect of hydrogen content on the post-oxidation mechanical behavior. Different H sources:

- In-service H pickup
- Breakaway oxidation phenomenon
- Secondary hydriding phenomenon

Limits changed to be dependent on H

- US NRC 10 CFR 50.46c, via draft regulatory guide DG-1263 (in discussion since circa 2010)
  - PCT and CP-ECR limit dependent on H
  - Experimental basis: post-quench ductility assessed by ring compression tests (RCT)
  - Additional focus on breakaway oxidation

- French GP Critère 2014 (A. Cabrera and N. Waeckel, 2015):
  - PCT remains 1204 °C but BJ-ECR limit dependent on H
  - Experimental basis (similar to Japan's): semi-integral LOCA tests with axial loading during the final quench

Content

1. In-service corrosion and H pickup

2. High temperature oxidation behavior

3. Post-oxidation mechanical behavior

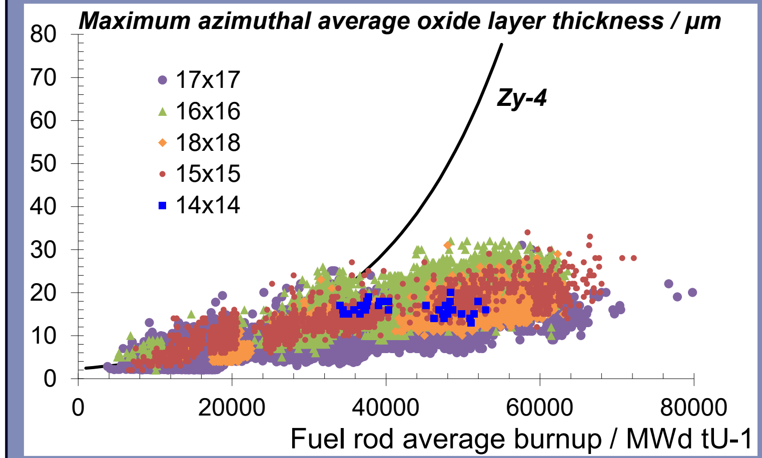
In-service corrosion and H uptake – PWR and VVER

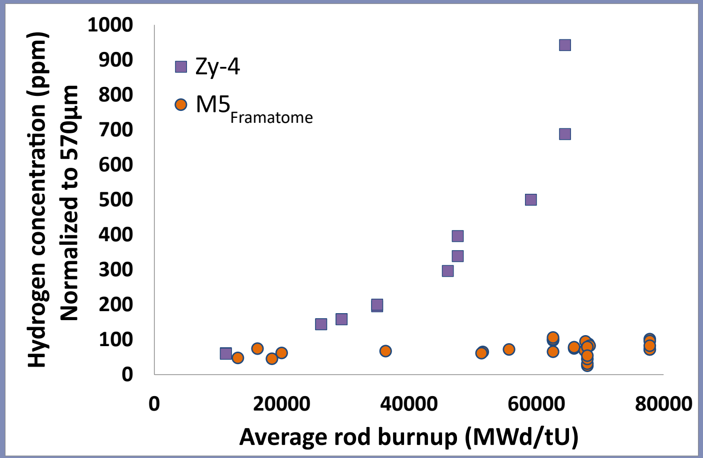
M5$_{Framatome}$* cladding: fully recrystallized Zr-1%Nb-O alloy with controlled Fe and S content

Absence of Sn results in a very low corrosion rate and H pickup pickup

PWR OPEX:

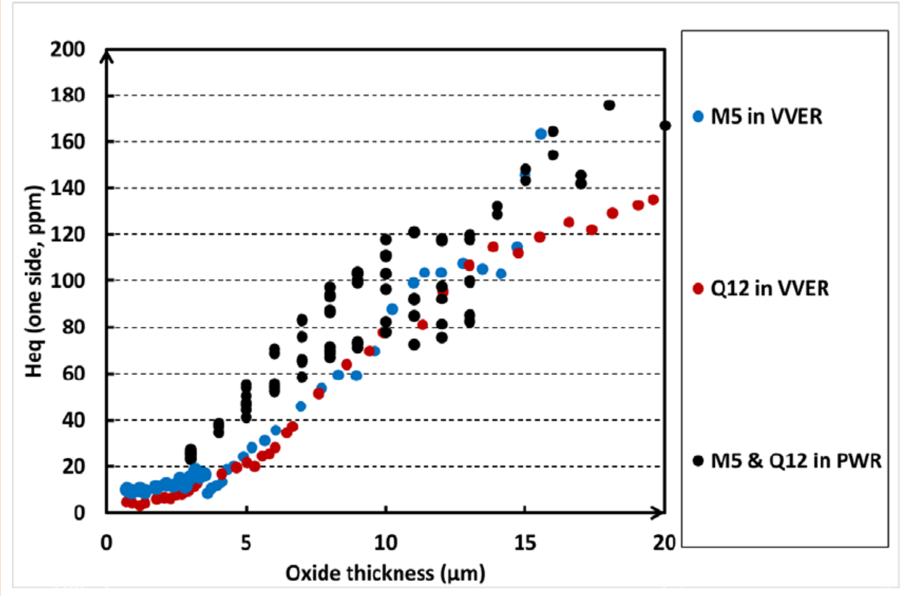
- Slow corrosion kinetics compared to Zy-4
- End-of-life max. H content around 100 wppm





Autoclave testing:

Similar corrosion and H pickup rates between VVER1000 and PWR conditions



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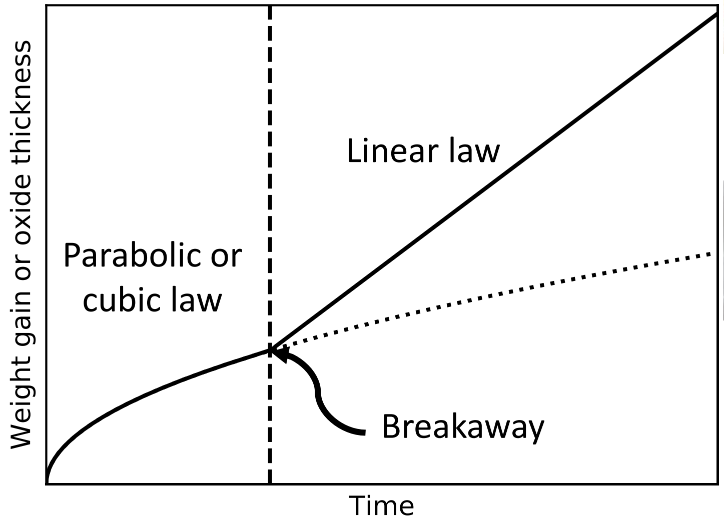
*M5$_{Framatome}$ is a registered trademark of Framatome or its affiliates, in the USA or other countries.

High-temperature oxidation phenomena

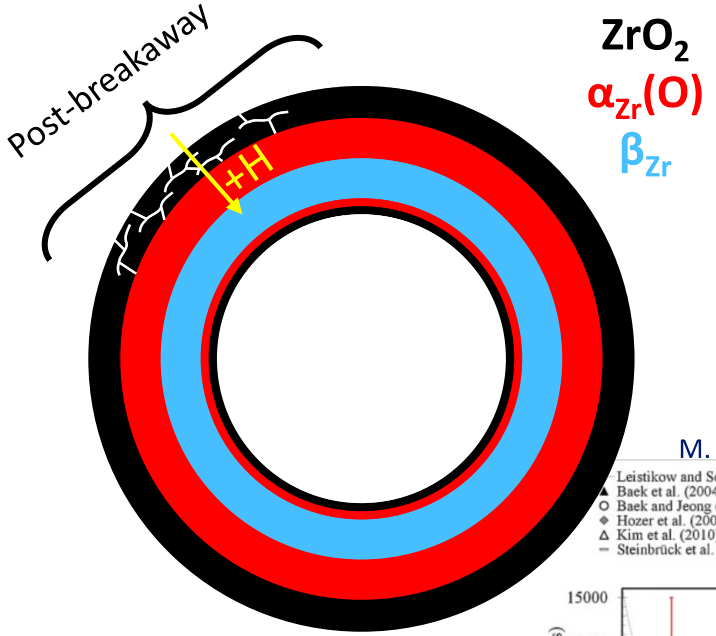
Oxidation kinetics



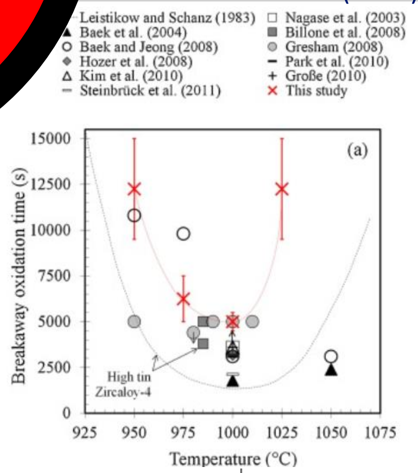
Rough dull black or discolored aspect with spallation

Smooth lustrous black aspect

Cladding cross-section



M. Le Saux et al. (2020)



Breakaway:

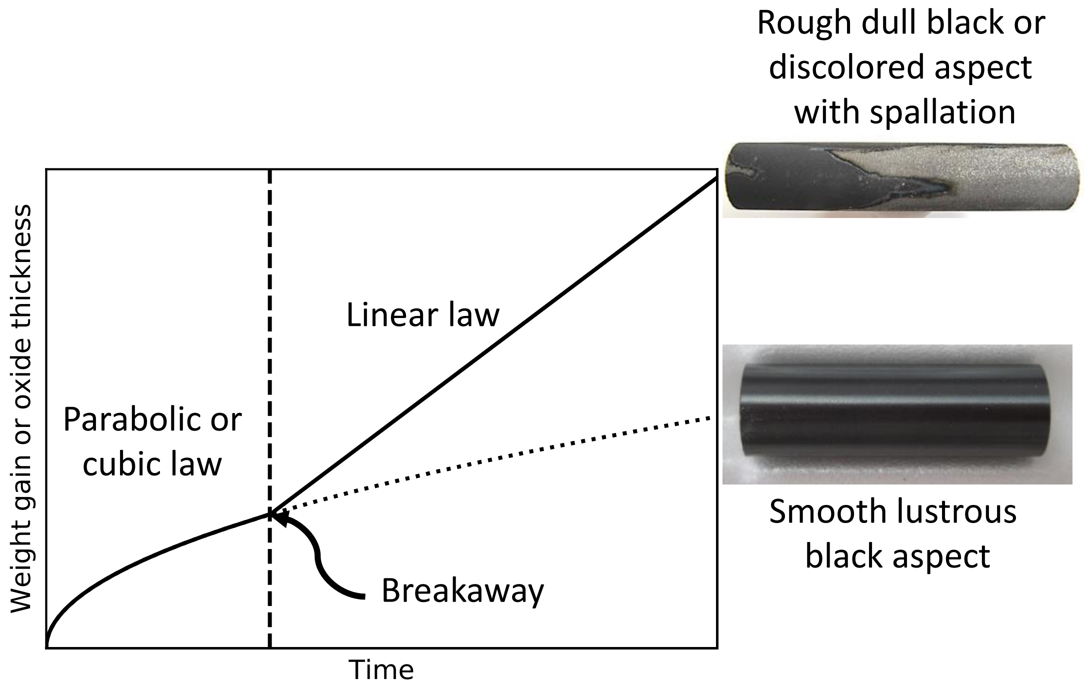
H uptake in the range of hundreds of wppm

Onset time temperature dependent and affected by surface damage

Shortest onset time typically occurs for T ~1000°C

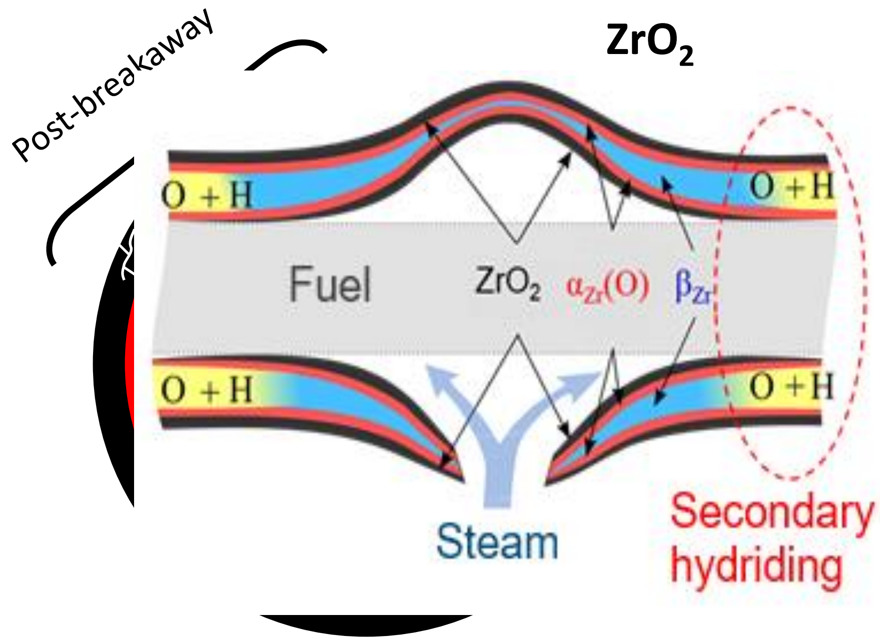
High-temperature oxidation phenomena

Oxidation kinetics



Cladding cross-section

Secondary hydriding



Breakaway:

H uptake in the range of hundreds of wppm

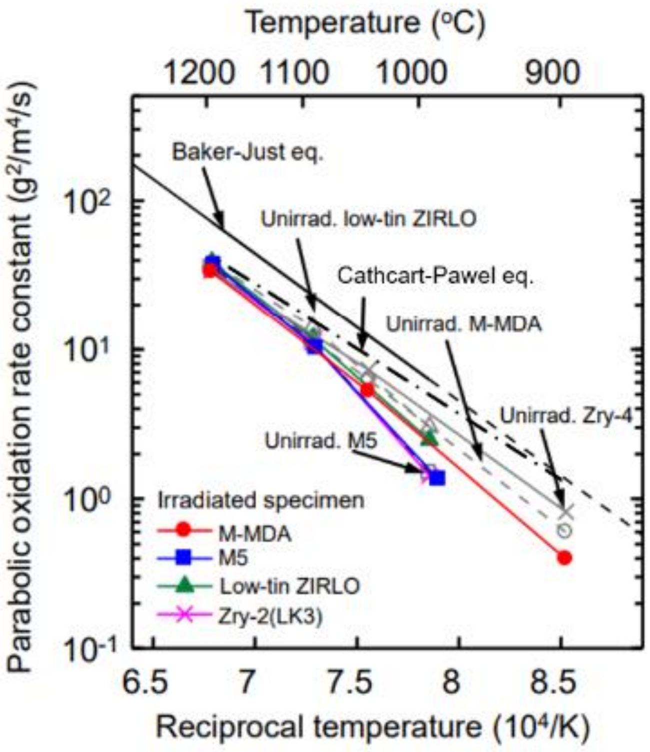
Onset time temperature dependent and affected by surface damage

Shortest onset time typically occurs for T ~1000°C

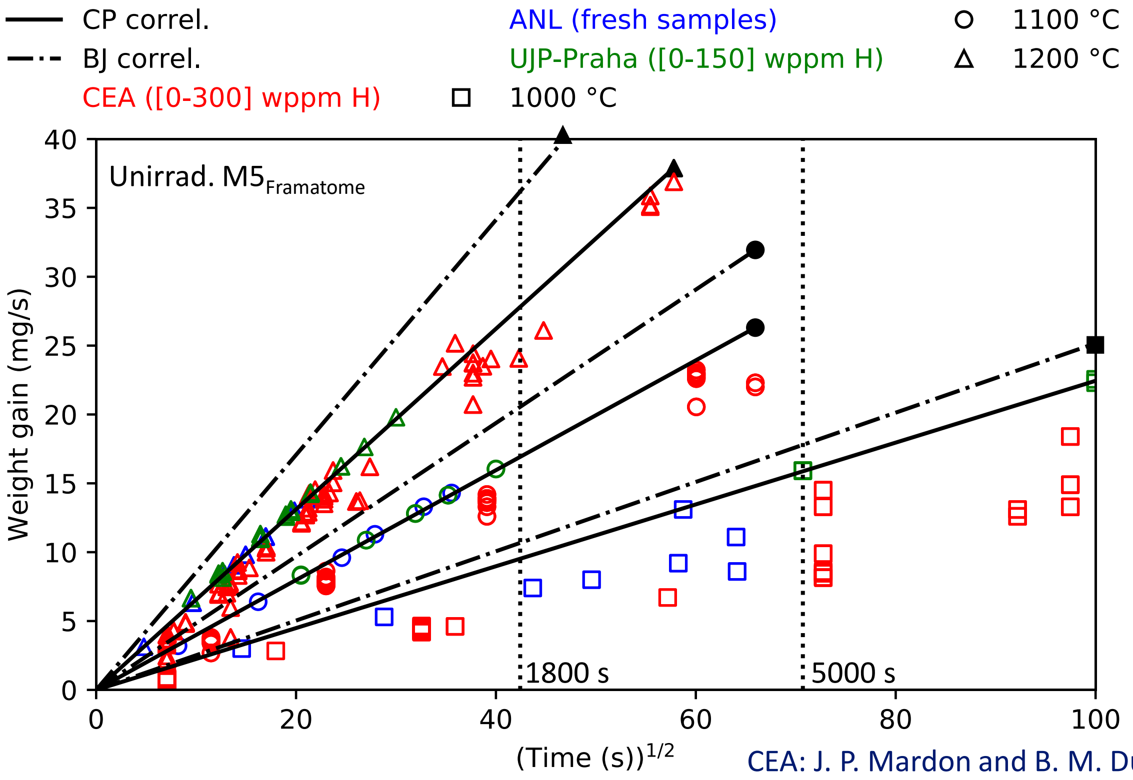
Secondary hydriding causes H uptake up to 3000-4000 wppm a few millimiters away from the burst opening

High-temperature oxidation kinetics

- No impact of irradiation on oxidation kinetic
- Cathcart-Pawel and Baker-Just correlations can be used up to 1204 °C



Adapted from figure 7 of M. Amaya et al. 2018



CEA: J. P. Mardon and B. M. Dunn (2007)
ANL: U.S. NRC NUREG/CR-6967 (2008)

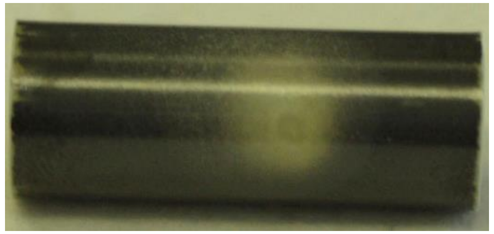
Susceptibility to the breakaway oxidation phenomenon

- High resistance of M5$_{Framatome}$ to breakaway oxidation, up to 15000 s at 1000 °C as already been demonstrated by CEA (M. Le Saux et al. 2020)
- Tests were performed at Framatome's Paimboeuf facility (V. Garat et al. 2016) on artificially scratched samples (S) (~50 µm depth and ~100 µm width)

- **No discernible impact of scratches on M5$_{Framatome}$ up to 10000 s at 1000 °C**

ZIRLO

U.S. NRC NUREG/CR-6967 (2008)



Standard ZIRLO, 985 °C 3600 s
270±165 wppm H

Scratched ZIRLO, 985 °C 3400 s
155±98 wppm H

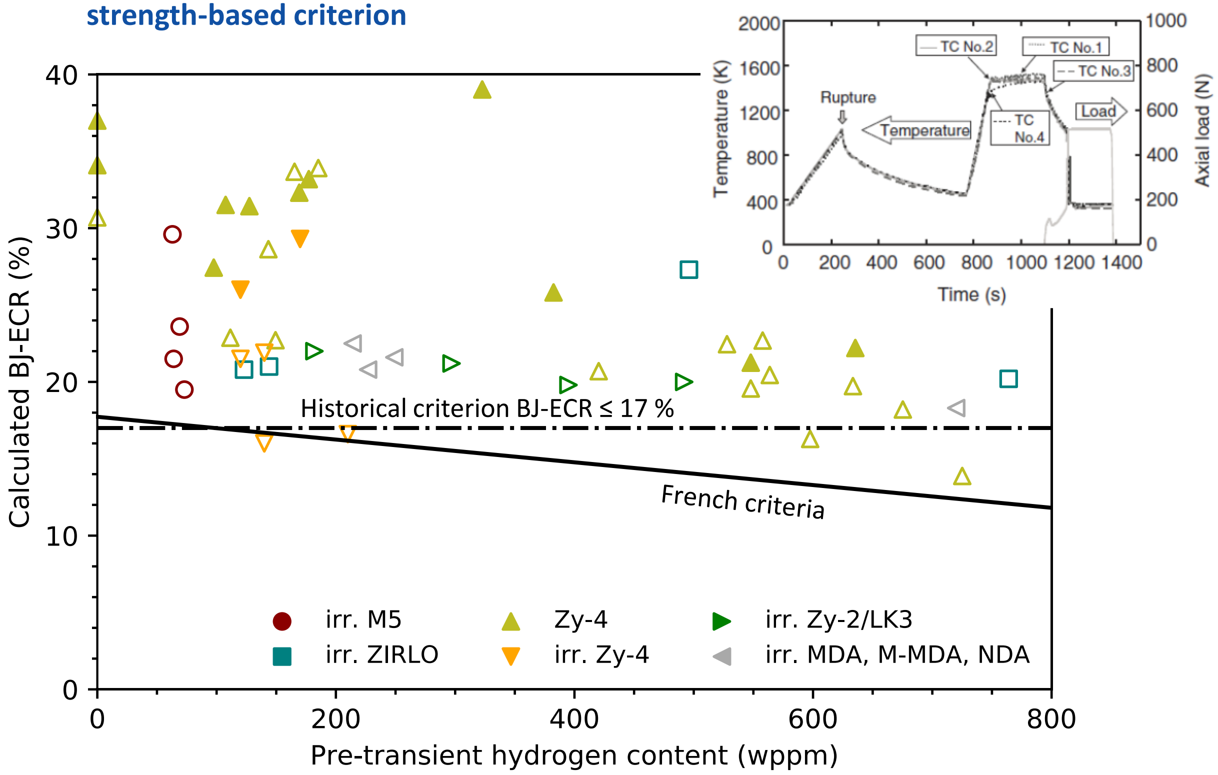
M5$_{Framatome}$

	1000 °C 5000 s	**1000 °C 10000 s**
	19 wppm H	**36 wppm H**
Standard		
Scratched		
	14 wppm H	**13 wppm H**

Post-oxidation mechanical behavior

Embrittlement determined by axial loading during quench

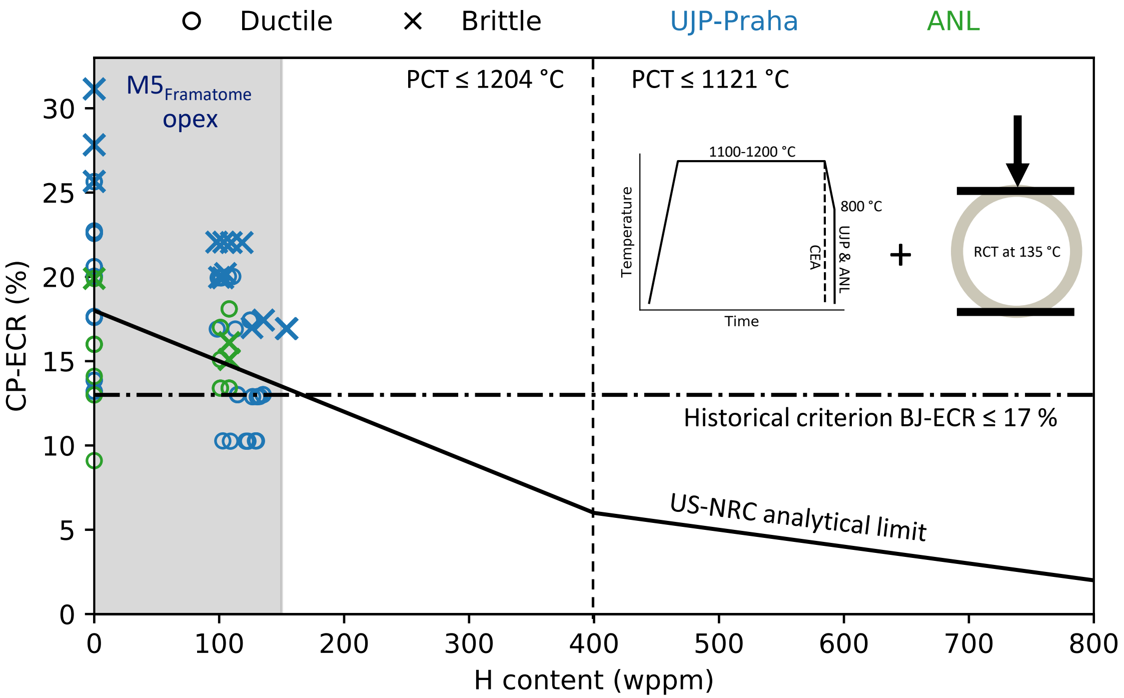
- LOCA semi-integral testing performed by JAEA on fresh, pre-hydrided and irradiated (66-84 GWd/t) claddings*
- Axial loading ranged from 0 to 540 N
- **M5$_{Framatome}$ maintains a high degree of margin with respect to the French strength-based criterion**



*F. Nagase et al. (2005), F. Nagase et al. (2006), F. Nagase et al. (2009) and T. Narukawa et al. (2020)

Post-quench ductility determined by RCT

- ANL (U.S. NRC NUREG/CR-6967 and DG-1262) and UJP-Praha: two-sided oxidation and quench from 800 °C
- **M5$_{Framatome}$ maintains a high degree of margin with respect to the analytical limit proposed in draft DG-1263**



Conclusion

- LOCA regulatory framework has evolved as experimental data has allowed better understanding of the impacts of corrosion on safety margin and the role that the pre-transient hydrogen plays in coolability

- Extensive experimental testing on $M5_{Framatome}$ cladding has demonstrated:
  - Low H uptake in nominal conditions, for both typical PWR and VVER environments
  - High-temperature oxidation kinetics well predicted by the CP and BJ correlations
  - Sufficient mechanical properties remain after high-temperature oxidation to retain a coolable geometry
  - $M5_{Framatome}$ resistance to breakaway oxidation, even with scratches, assures it will not occur during a LOCA

- In conclusion, **$M5_{Framatome}$ maintains a high degree of margin with respect to both the US and French H-dependent analytical limits for LOCA**

Acknowledgment:

Framatome thanks JAEA, CEA and UJP-Praha for their experimental work involving $M5_{Framatome}$ cladding.

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Thank you