framatome

Framatome’s Fuel Rod and Fuel Assembly Structural Materials for PWR and VVER Reactors

R. Borrossi, F. Bourlier, C. Forot, P. Guillermier

Nessebar – September 16, 2025

Introduction

- For PWR and VVER reactors, Framatome mainly proposes its two flagship zirconium materials for fuel assembly design: $M5_{Framatome}$ for fuel rod claddings and Q12 for structural components.

- Both $M5_{Framatome}$ and Q12 excellent performance in PWR have been demonstrated up to high burnups (above 75 GWd/tU fuel rod average burnup)

- For VVER reactors, in 2020, Framatome launched long-term corrosion testing programs to support the licensing of Framatome's VVER fuel assembly design.

- This presentation will describe the two alloys, their in-pile behavior up to very high burnups, their worldwide experience feedback and qualification extension in VVER conditions

Content

1. $M5_{Framatome}$: Framatome alloy for cladding tubes
2. Q12: Framatome alloy for structural components
3. Take Away

1

$M5_{Framatome}$: Framatome alloy for cladding tubes

$M5_{Framatome}$: Zr1Nb alloy without Sn

In-Pile Behavior of $M5_{Framatome}$

$M5_{Framatome}$ Worldwide Irradiation Experience

$M5_{Framatome}$ Qualification Extension in VVER conditions

$M5_{Framatome}$

- Developed and industrialized in the 1990s by Framatome, $M5_{Framatome}$ is:
  - a fully recrystallized Zr alloy
  - with 1 wt.% of Nb and controlled contents of Oxide, Iron and Sulfur.
- The absence of Tin in the nominal composition and low temperature heat treatments during pilgering process gives to $M5_{Framatome}$ a very good resistance against corrosion and limits the hydriding in service.

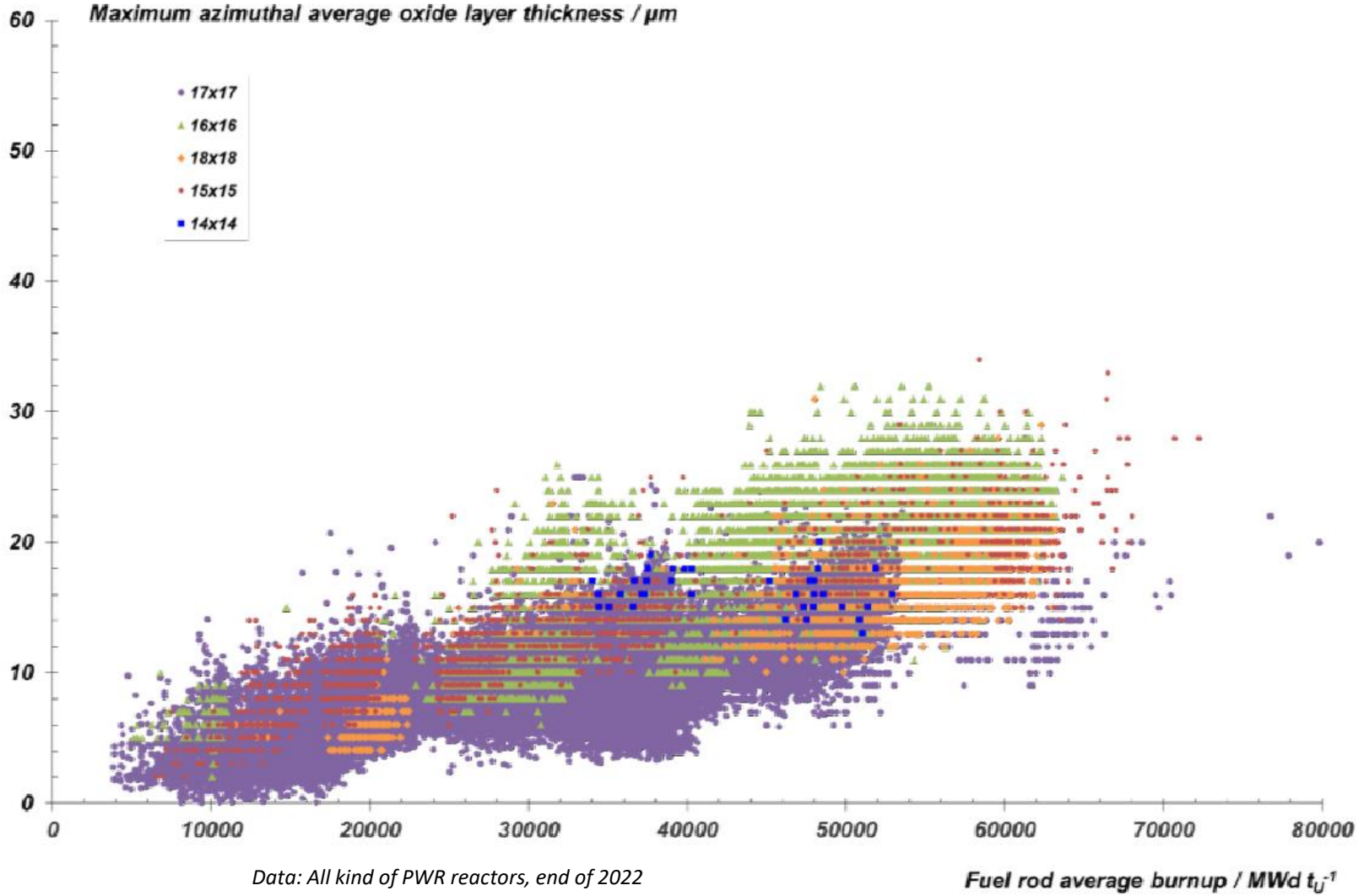
Alloy	Nb	Sn	Fe	O	S	Zr
$M5_{Framatome}$	1.0	< 0.01	0.05	0.15	0.002	Balance

Nominal composition (wt.%)

- The other properties (mechanical behavior, creep…) are fully compatible with a reliable use for cladding tubes in PWR

- The excellent behavior of $M5_{Framatome}$ alloy under Accidental Conditions (LOCA and RIA) are described in two other presentations during the Conference

In-Pile Corrosion Behavior of $M5_{Framatome}$



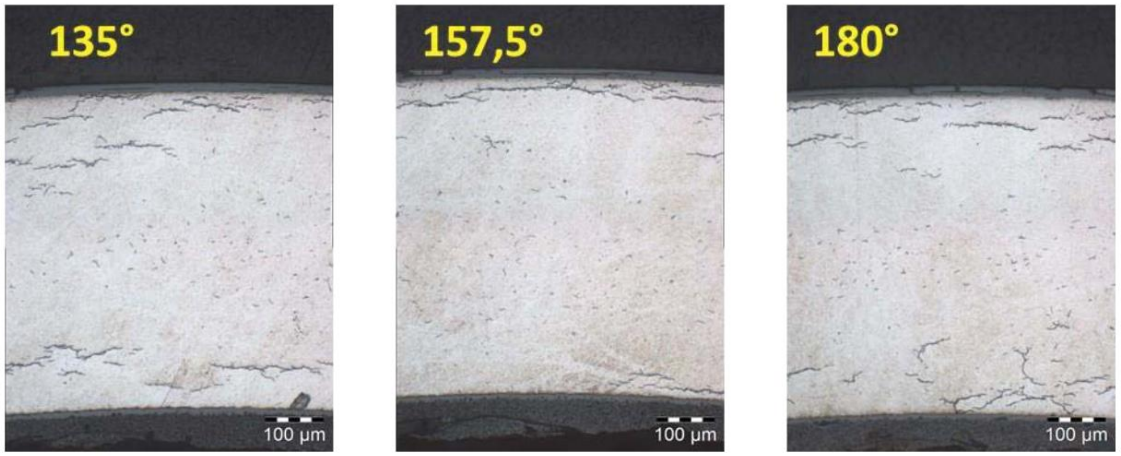
Data: All kind of PWR reactors, end of 2022

- Outer oxide layer at the hottest localization of the rod
  - Around 125,000 Eddy current measurements
  - In 37 PWRs
  - Up to rod burnups of 80 GWd/t

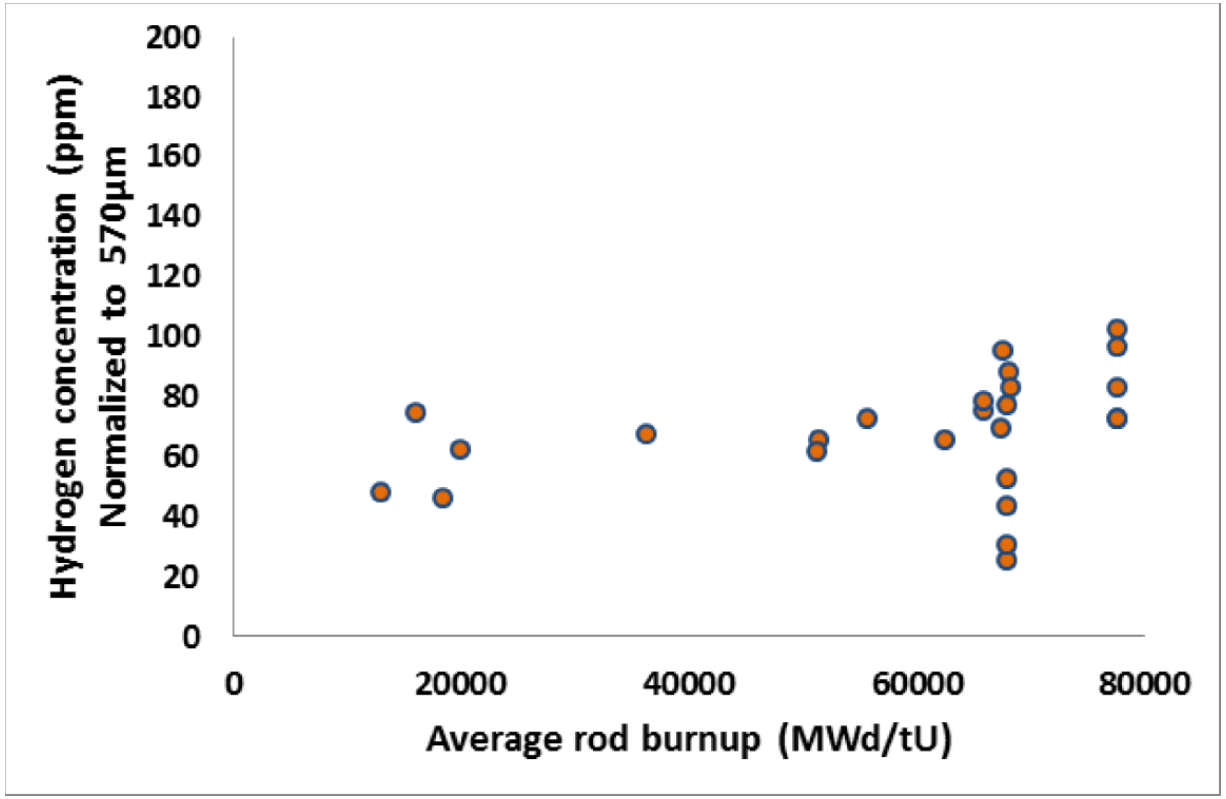
Thanks to its chemical composition and its manufacturing route, $M5_{Framatome}$ alloy shows an excellent corrosion resistance, even at high Burnup

In-Pile Hydrogen Pickup of $M5_{Framatome}$

- Hot cell measurements on fuel rods with $M5_{Framatome}$ cladding
- irradiated 1 to 7 cycles
- in 8 reactors

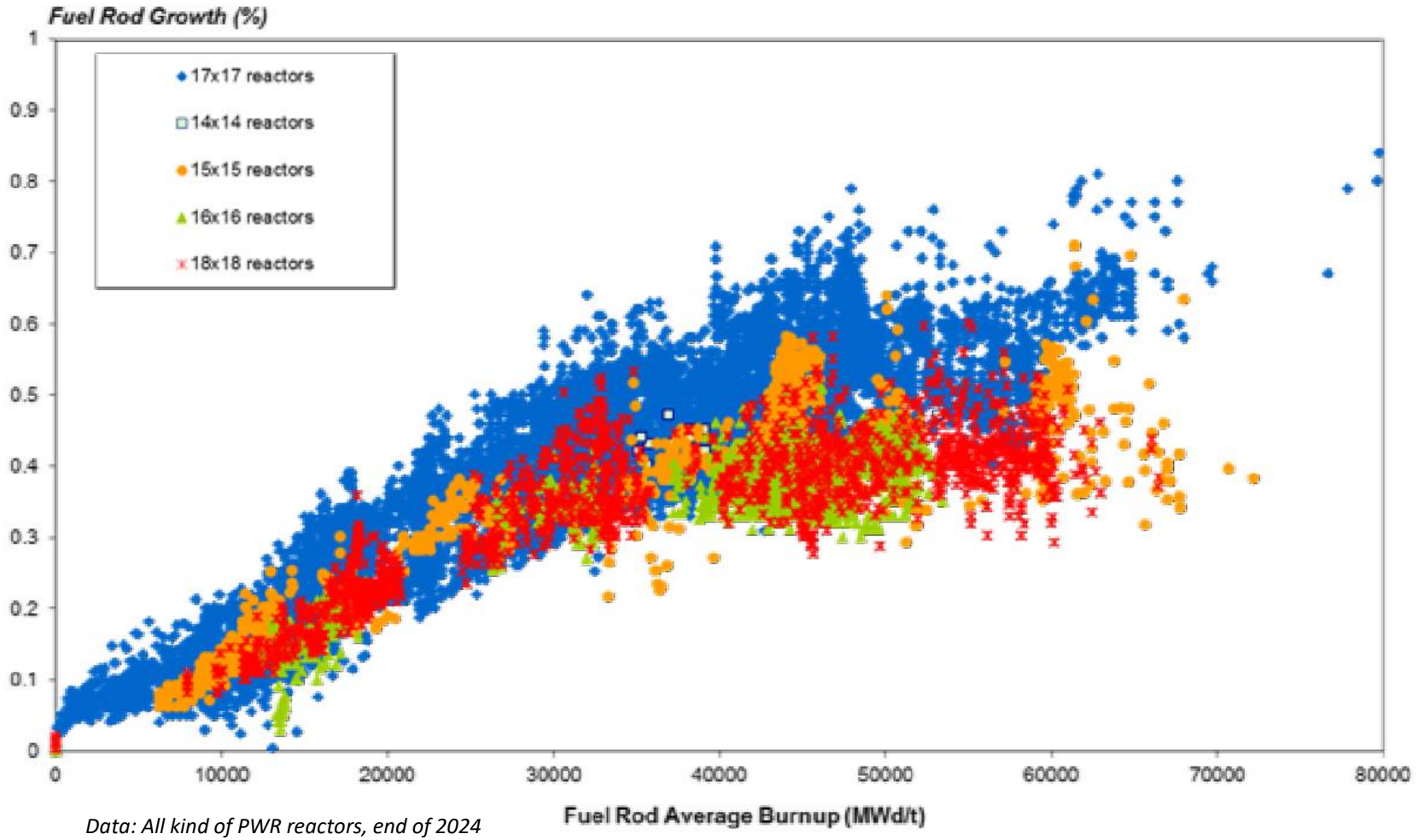


$M5_{Framatome}$, irradiated 4 cycles in PWR, mean rod BU 63.7 GWd/t, span 8 (hottest localization)



$M5_{Framatome}$ alloy shows low hydrogen pickup, even at high Burnup

In-Pile Fuel Rod Growth of $M5_{Framatome}$

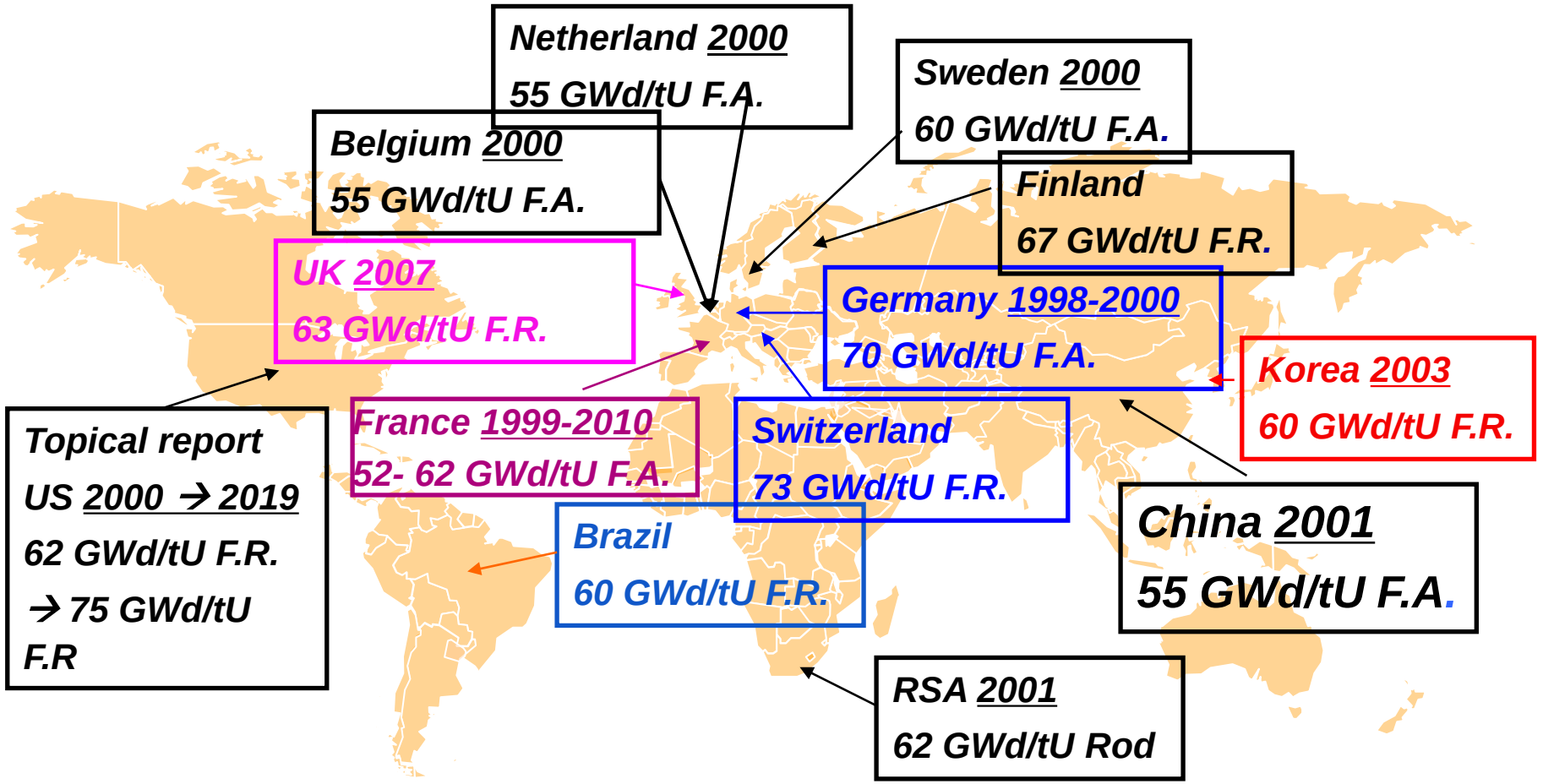


Data: All kind of PWR reactors, end of 2024

- More than 17 000 on-site dimensional measurements
- In 27 PWRs
- Up to rod burnups of 80 GWd/t

Thanks to its chemical composition and its recrystallized state, $M5_{Framatome}$ allows a limited fuel rod growth, until high burn-up

Licensing Status of M5Framatome



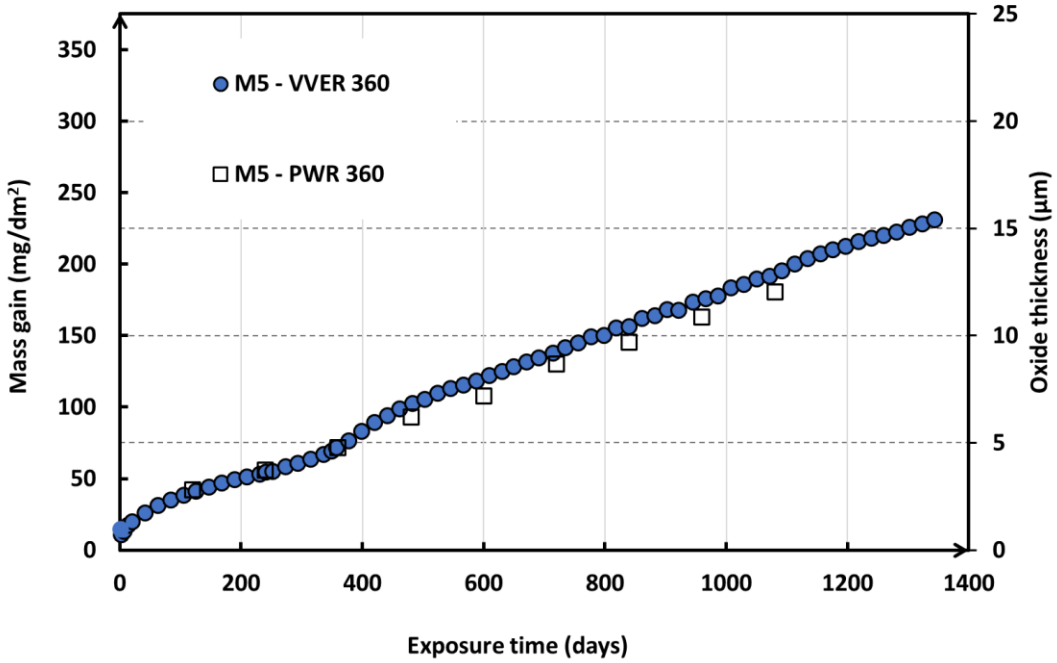
- About 10,785,000 fuel rods with M5Framatome cladding are under irradiation or discharged
- in 112 PWRs worldwide,
- for an amount of about 44,000 FAs.
- The irradiation in reactors covers a wide range of different operating conditions, with different fuel duties and maximum fuel rod burn-up of ~80 GWd/tU (7 annual cycles).

Data at end of December 2024

Out-of-pile $M5_{Framatome}$ Qualification Extension in VVER conditions

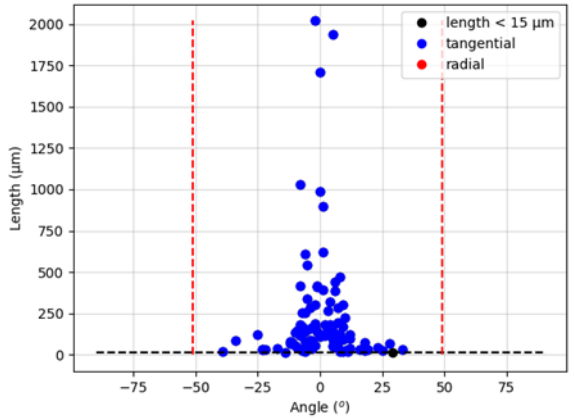
Corrosion kinetics

- Uniform oxide approximately 15 µm after more than 1300 days of exposure
- Corrosion kinetics of $M5_{Framatome}$ cladding in VVER conditions is equivalent to PWR



Hydrogen pick-up

- Hydrogen pick-up of $M5_{Framatome}$ in VVER is comparable to PWR – 15% after 1300 days
- Hydrides are mainly circumferentially orientated



In VVER conditions:

- $M5_{Framatome}$ shown excellent corrosion results
- $M5_{Framatome}$ behavior is comparable to PWR operating experience

2

Q12: Framatome alloy for structural components

Q12: a Quaternary Alloy Derived from $M5_{Framatome}$

In-Pile Corrosion Behavior of Q12

Dimensional evolution of Q12

Fuel Assembly Growth

Q12 Worldwide Irradiation Experience

Q12: a Quaternary Alloy Derived from $M5_{Framatome}$

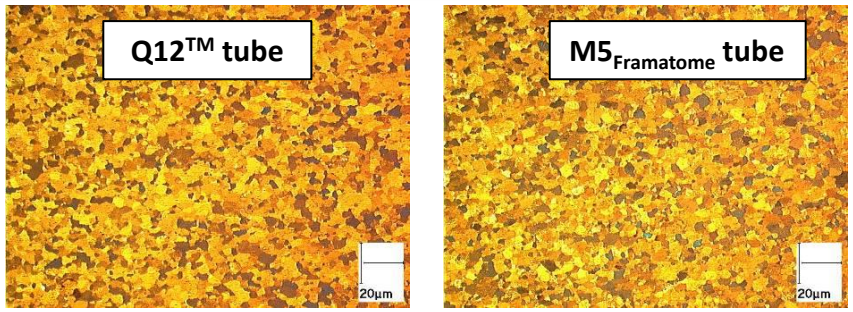
- Q12 is derived from $M5_{Framatome}$ alloy

Alloy	Nb	Sn	Fe	O	S	Zr
$M5_{Framatome}$	1.0	< 0.01	0.05	0.15	0.002	Balance
Q12	1.0	0.5	0.1	0.15	0.002	Balance

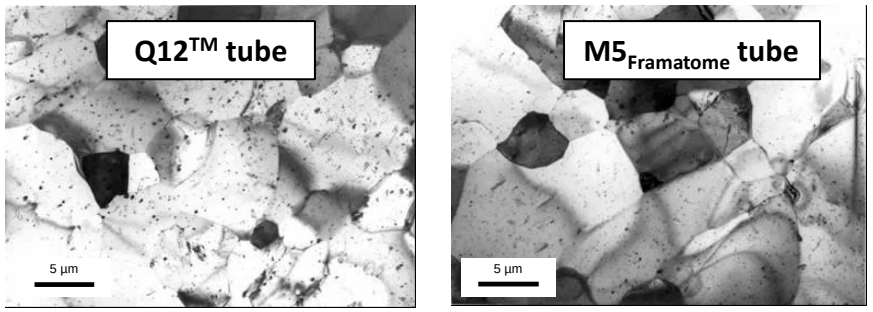
Nominal composition (wt.%)

- The manufacturing process is the same as for material $M5_{Framatome}$ leading to fully recrystallized products with fine grains and uniformly distributed precipitates and similar texture

Microstructure (optical) of Q12 and $M5_{Framatome}$ tubes



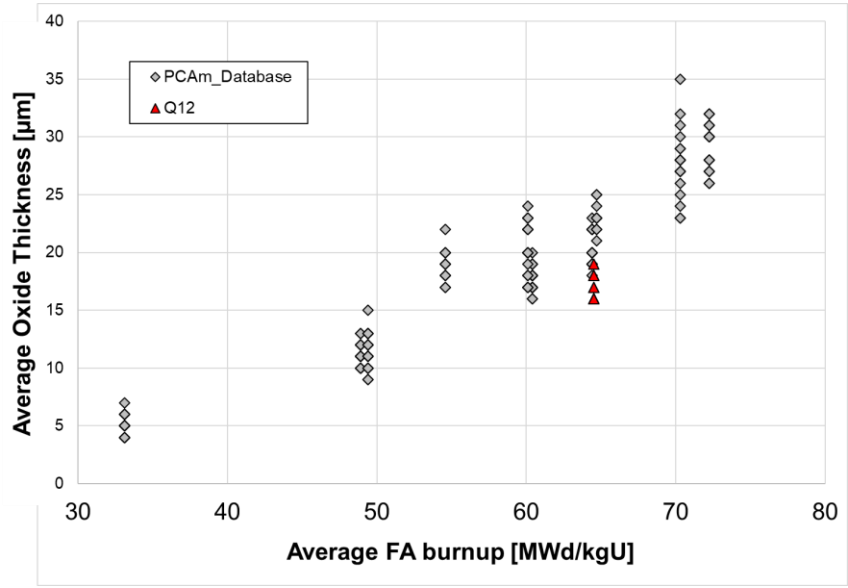
Microstructure (TEM) of Q12 and $M5_{Framatome}$ tubes

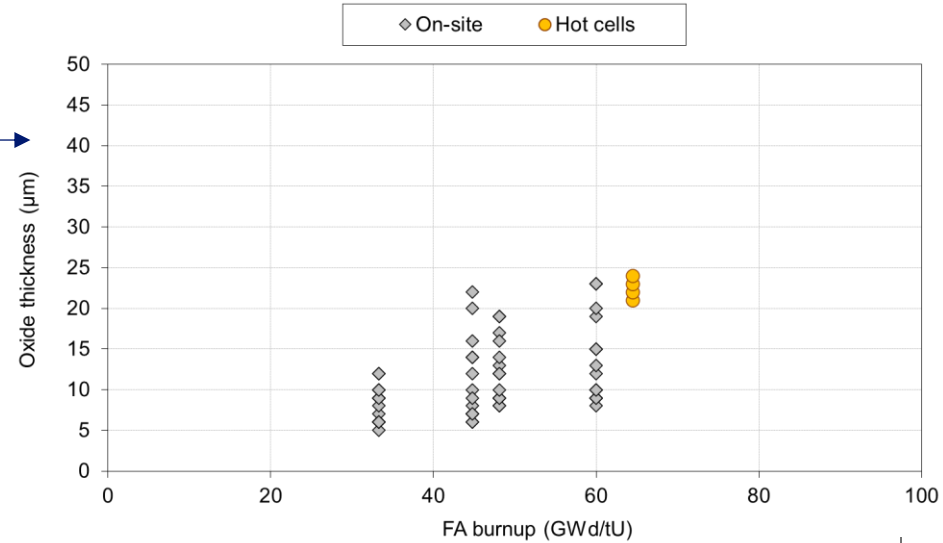


In-Pile Corrosion Behavior of Q12

- Guide tubes
  - Eddy current measurements of GT inner oxide layer at EOL (5 annual cycles)
  - Averaged oxide thickness of Q12 GT at the lower bound in comparison to Zircaloy-4 derived PCAm as reference material
- Spacers
  - Oxide layer thickness on Q12 spacers in good agreement with values determined for guide tubes
  - Maximum oxide thickness below 25 µm up to burnups of >65 MWd/kgU

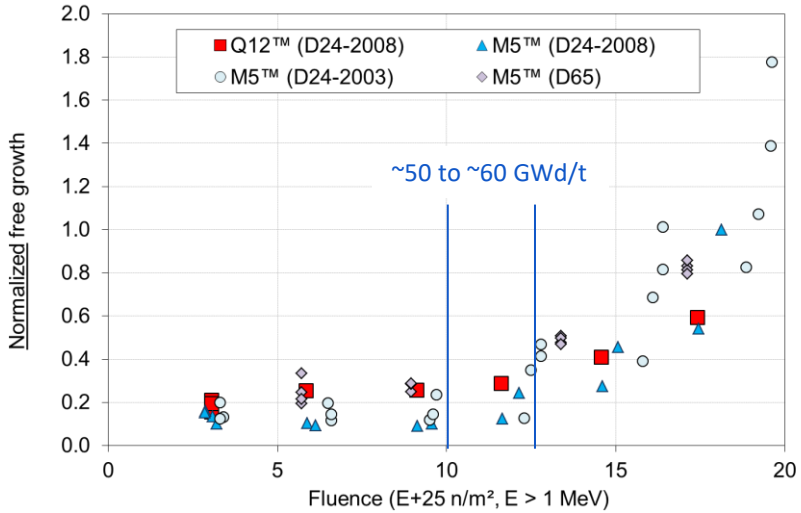
Q12 alloy shows good corrosion resistance for structural components' application

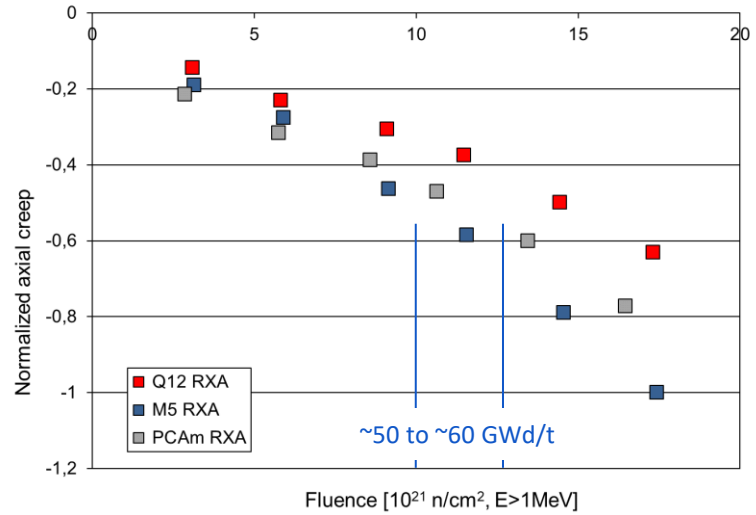




Dimensional evolution of Q12

- Free growth
  - Empty test tubes, with double side corrosion, inserted in guide tubes of host FAs
- In-pile Creep behavior
  - Length measurement of axially compressed tube samples irradiated in guide tubes
  - Assessment of creep behavior by correcting for free growth



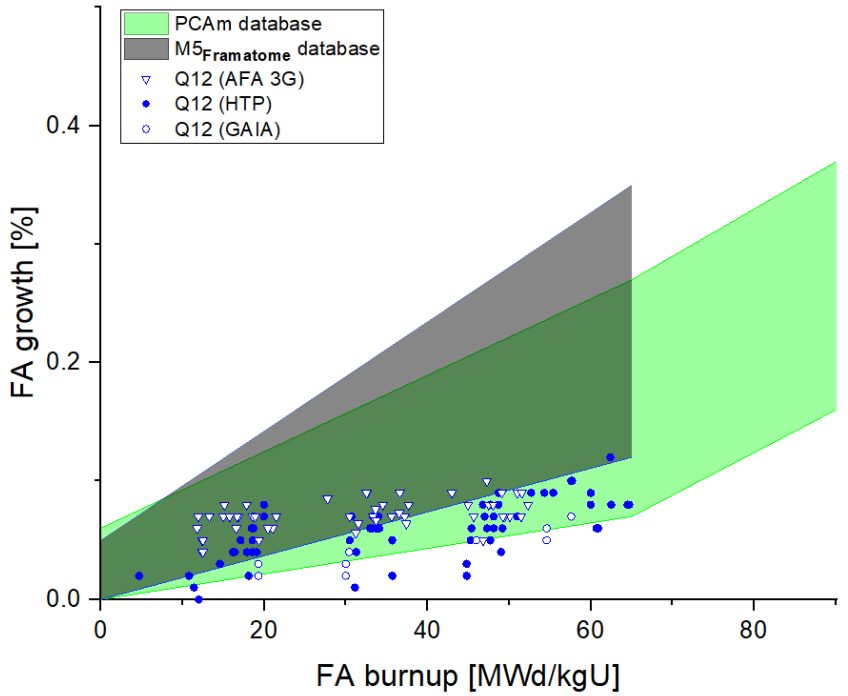


Q12 shows low and stable free growth till high fluences

Highest creep resistance for Q12 compared to $M5_{Framatome}$ and PCAm

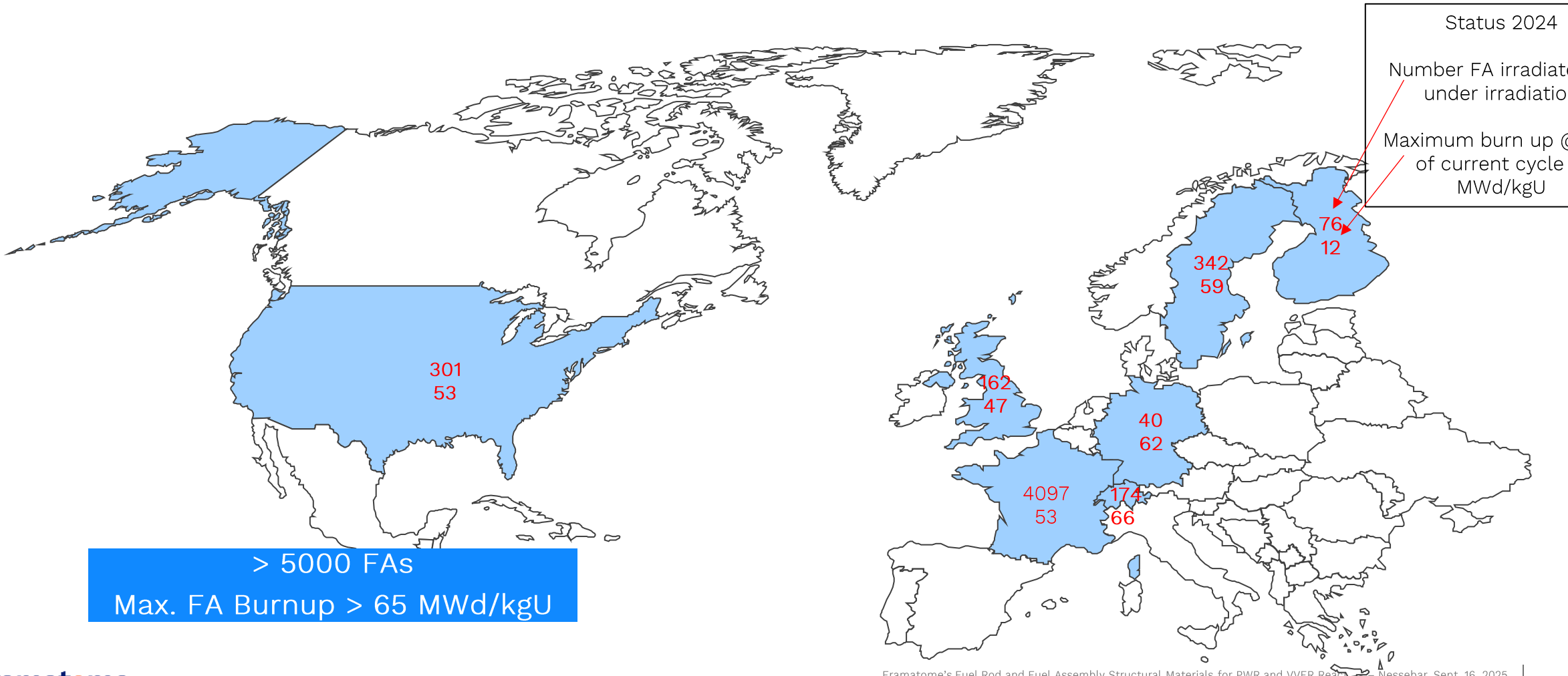
Fuel Assembly Growth

- The FAs equipped with Q12 GT show low and stable length change up to high BU as expected considering free growth and creep behavior
- Significant reduction of FA growth especially for higher BU > 55 MWd/kgU compared to reference materials



Q12 structural material: A solution for reliable operation until high burn-up

Q12 Worldwide Irradiation Experience



> 5000 FAs

Max. FA Burnup > 65 MWd/kgU

Out-of-pile Q12 Qualification in VVER conditions

Corrosion kinetics

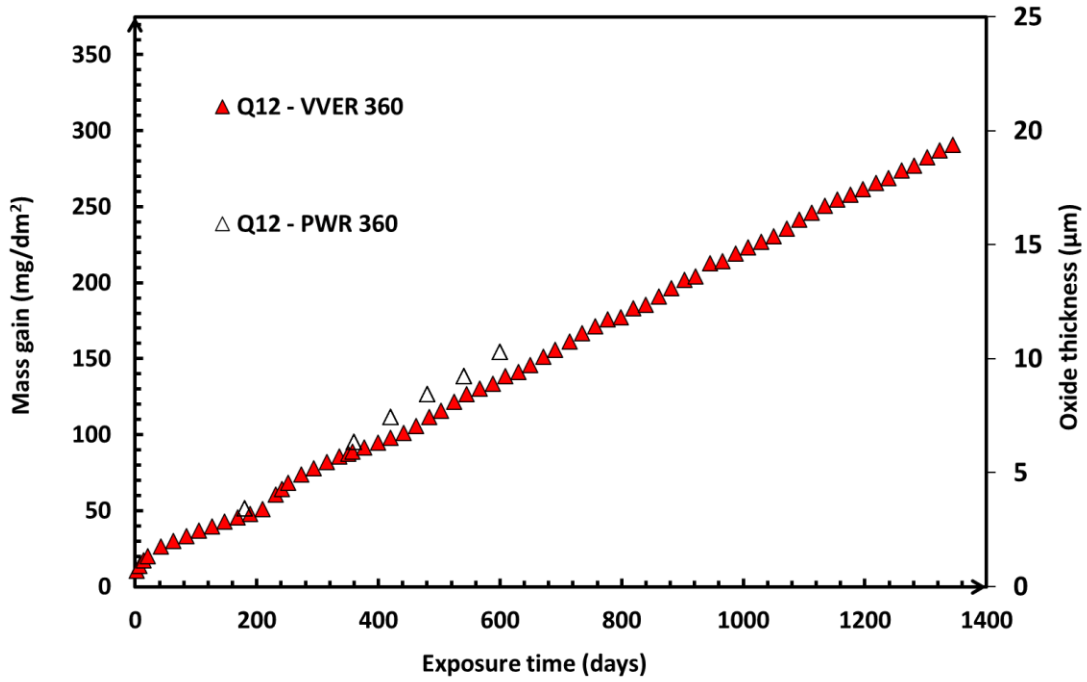
- Uniform oxide approximately 19 µm after more than 1300 days of exposure
- Corrosion kinetics of Q12 material in VVER conditions is equivalent to PWR

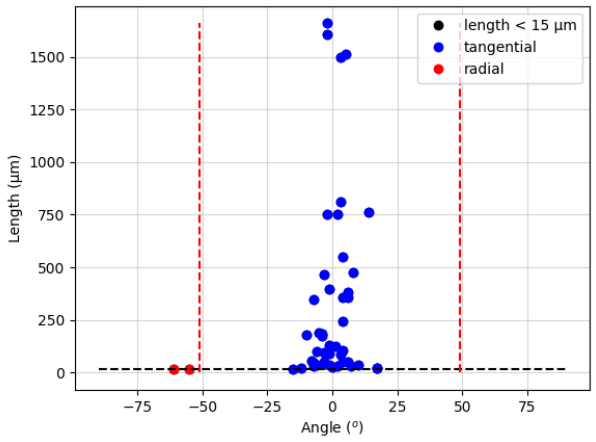
Hydrogen pick-up

- Hydrogen pick-up of Q12 in VVER is comparable to framatome feedback for HPU in PWR – 15% after 1300 days
- Hydrides are mainly circumferentially orientated

In VVER conditions:

- ➢ Q12 shown excellent corrosion results
- ➢ Q12 behavior is comparable to PWR operating experience





3

Take Away

Take Away

- $M5_{Framatome}$ is the reference alloy used as cladding tube material for Framatome PWR designs since decades.
- $M5_{Framatome}$ exhibits low oxidation kinetics and hydriding as well as a high dimensional stability up to very high burnups of 80 GWd/tU. This low hydrogen content ensures high safety margins. $M5_{Framatome}$ claddings show strong competitive advantage on fuel market, making it a reliable choice for fuel performance at high burnup and in high duty reactors.

- Q12, a Framatome PWR structural material introduced in 2010, has reached burnups of 66 MWd/kgU with excellent irradiation performance results. Since 2013, Q12 has been widely used in reload quantities, providing substantial operational feedback.
- Q12 exhibits low oxidation kinetics and higher creep strength, contributing to its durability under reactor conditions. FAs with Q12 structural components show enhanced geometrical stability, making it a reliable choice for fuel performance at higher burnups beyond 65 MWd/kgU and for longer cycles (24 months).

- For VVER reactors, in 2020, Framatome launched long-term corrosion testing programs to support the licensing of Framatome's VVER fuel assembly design. The long-term corrosion testing of $M5_{Framatome}$ and Q12 materials with VVER water chemistry demonstrates the similar excellent performance of Framatome's alloys in PWR and VVER conditions.

framatome

Thank you