Operational Experience Feedback

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CONTENT

1. Operational Experience

Framatome's HTP and ATRIUM 11 Fuel Assembly design

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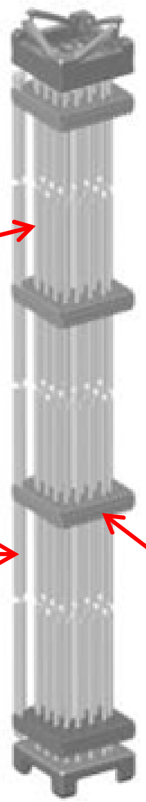
HTP Fuel Assembly Design and main components made from Zirconium base Alloys



- All deployed zirconium materials are tailored to the function of the respective components during power operation and beyond
- Base material properties are essentially featuring the performance of the designed components
- Material and alloy development programs resulting in performance improvements bearing increase of operational margins

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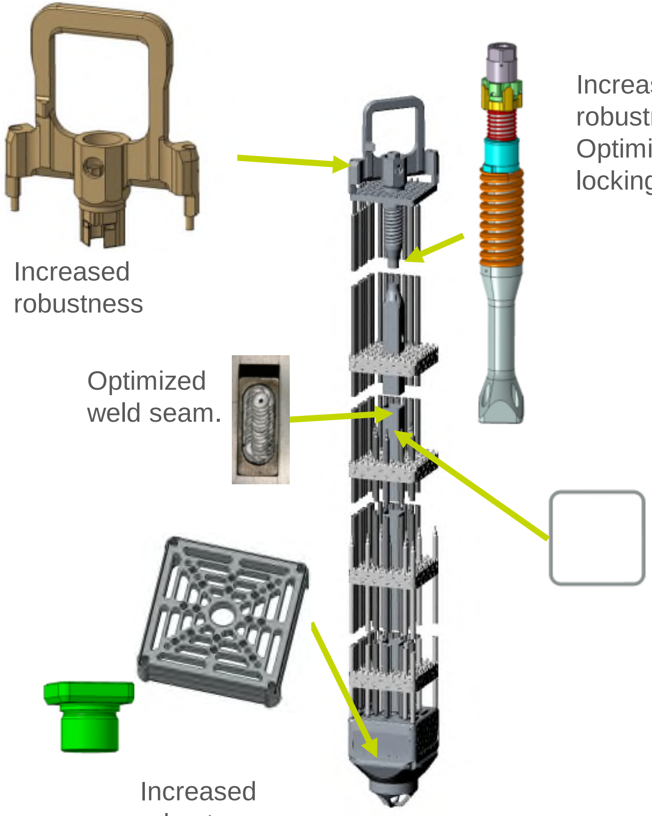
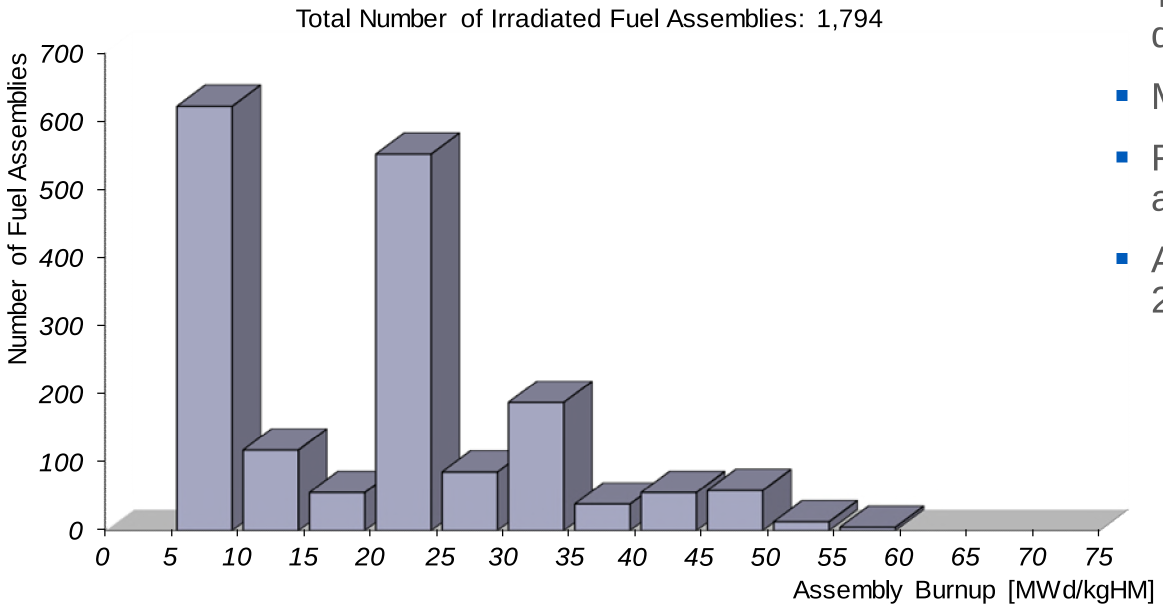
Recent ATRIUM 11 Design Evolution



- Various modifications were made in the last years
- All parts are industrialized (e.g., top end piece grid, spacer and 3RD Generation FUELGUARD filter).
- The load chain is reinforced. The handle, the cage assembly, the lower tie plate frame and the locking parts are improved

Framatome ATRIUM 11 Fuel Assemblies



- Transition from lead programs to reload quantities visible in histogram
- Maximum FA burnup 59 MWd/kgHM
- FAs in three plants reached a BU of above 50 MWd/kgHM
- Approx. 1/3 reached a BU above 25 MWd/KkgHM

ATRIUM 11 Deliveries around the globe

- ATRIUM 11 fuel assemblies were delivered to 10 different reactors.
- First time delivery to two US reactors in 2022 and two more in 2023.

Reactor	Type	FA´s	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
			ATRIUM 11 Deliveries (Leads and Reloads)									
EU-1	KWU	56										
EU-2	BWR-6	8										
EU-3	ASEA-A.	218										
EU-4	ASEA-A.	4										
EU-5	BWR-6	12										
EU-6	ASEA-A.	228										
US-1	BWR-4	8										
US-2	BWR-4	228										
US-3	BWR-4	226										
US-4	BWR-4	300										
		1288										

Leads
Operation

Different reactors and conditions are covered by operating experience.

# of fresh fuel assemblies loaded into cores worldwide in 2022	
ATRIUM 11	684
ATRIUM 10XM	1240
Total	**1924**

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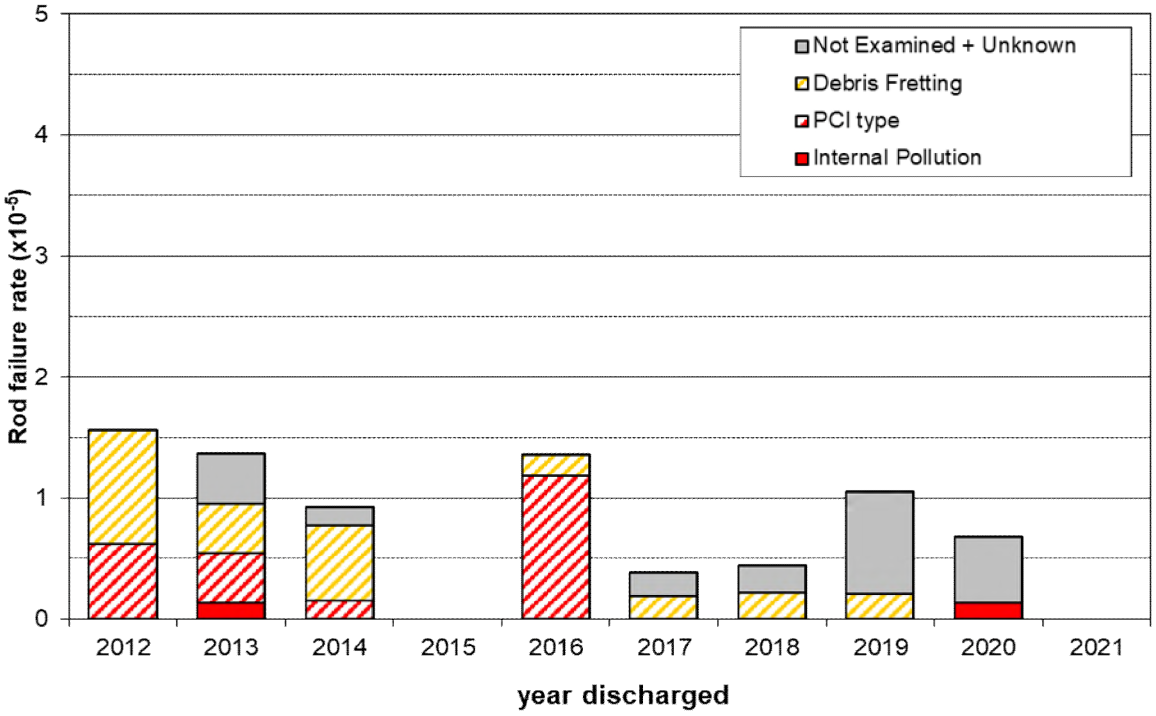
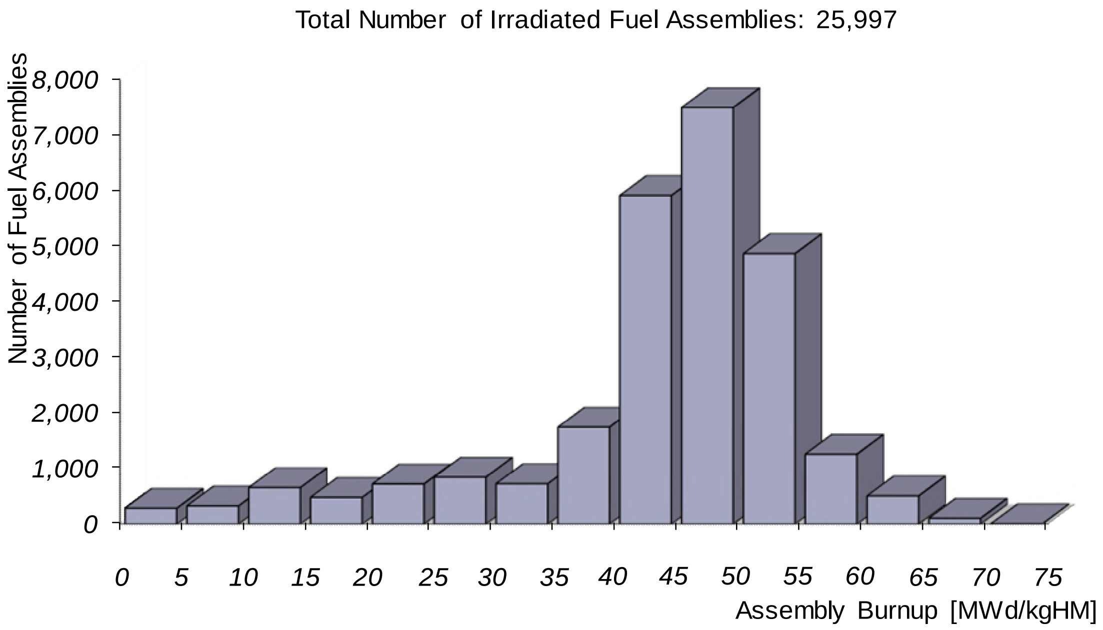
Framatome BWR Reliability (2012-2021)



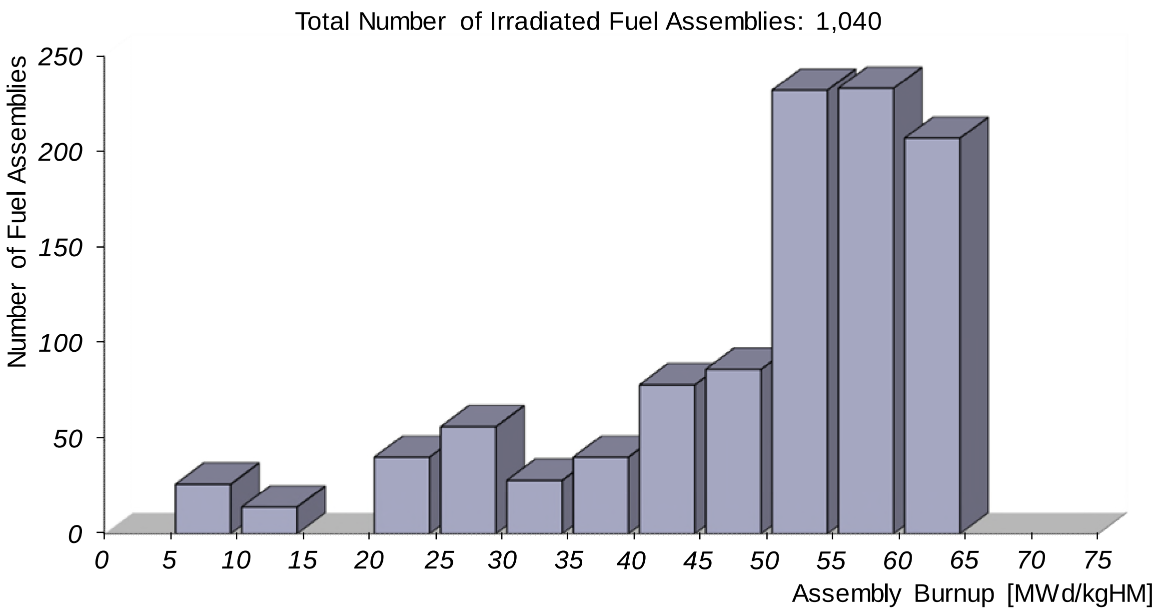
- Low defect rate for BWR fuel rods worldwide
- No defective BWR rods in Switzerland since 2013

Framatome HTP Fuel Assemblies worldwide



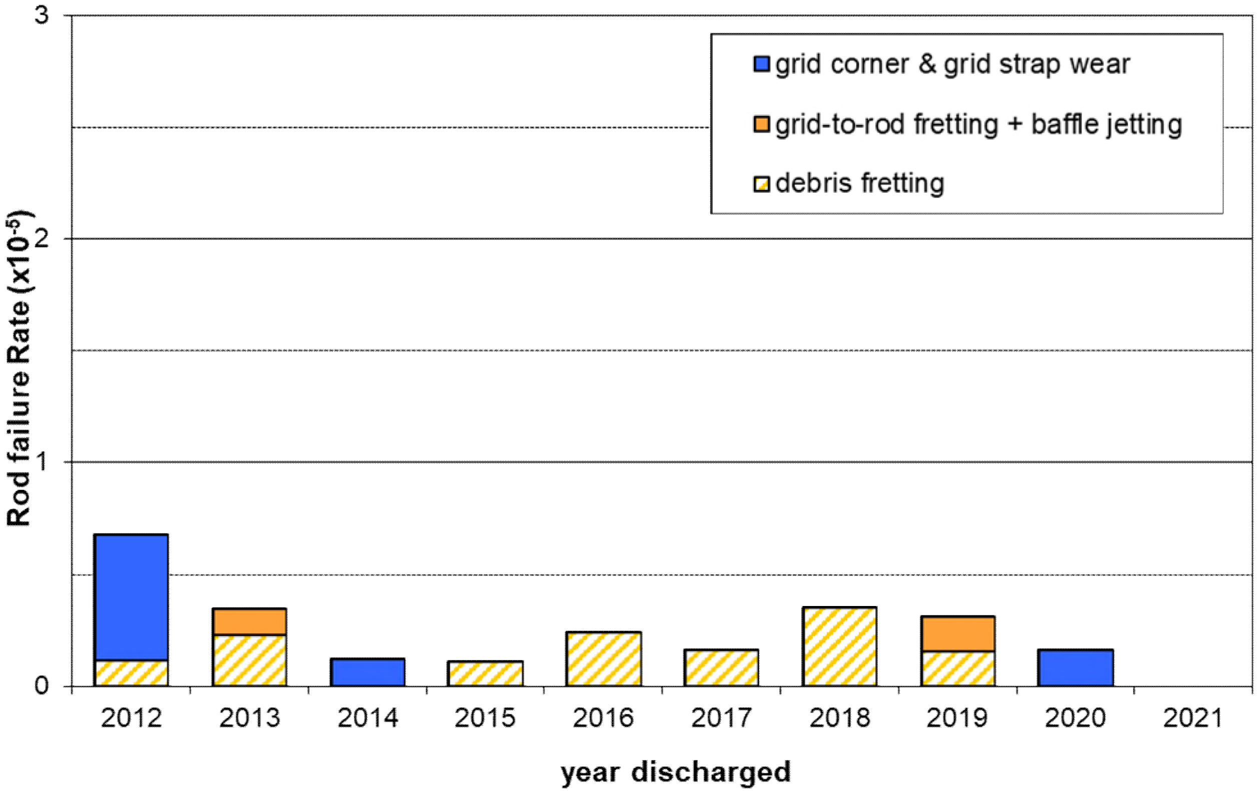
- 9 NPPs worldwide utilize the HTP fuel design
- Maximum FA burnup 70 MWd/kgHM
- FAs in all plants reached a BU of at least 53 MWd/kgHM

Framatome German Platform HTP-I Fuel Assemblies



- HTP-I is a subset of HTP utilized only in the German sales region
- HTP-I design includes features to increase FA stiffness (e.g. improved GT welding, stepped hold-down springs, and/or incr. GT wall thickness)
- 6 NPPs use fuel assemblies of the HTP-I design
- Maximum FA burnup 65 MWd/kgHM
- FAs in all plants reached a BU of above 53 MWd/kgHM

Framatome HTP Reliability (2012-2021)



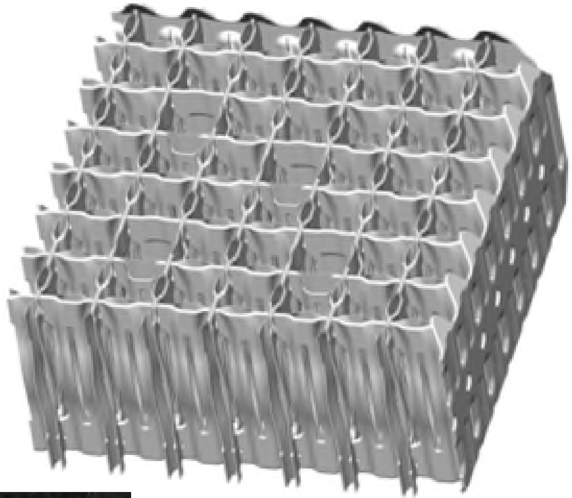
- Very low defect rate for PWR fuel rods in the German sales region
- No defective PWR rods in Switzerland since 2010
- No case of debris fretting in the German sales region since 2016
- No defective fuel rods in the German sales region from 2016 to 2019

2. Evolution of Components

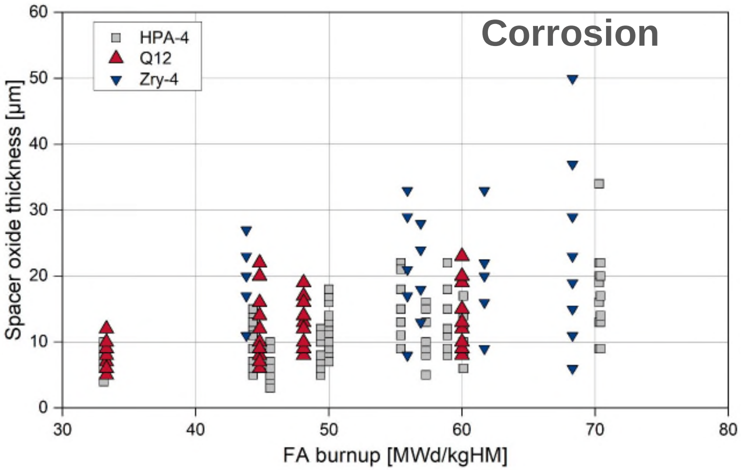
Impact of Material Improvements

Spacer Materials

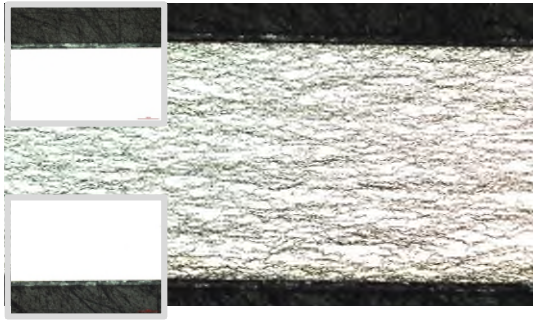
Guard for Reliable Rod Support and Dimensional Compatibility



- Operational corrosion (C) and hydrogen uptake (H)
  - Step change to reduce C and H: Zy4 → HPA-4
  - Maintain optimized level: HPA4 → Q12
  - Stabilizing impact on dimensional behavior: grid width



Hydrogen uptake



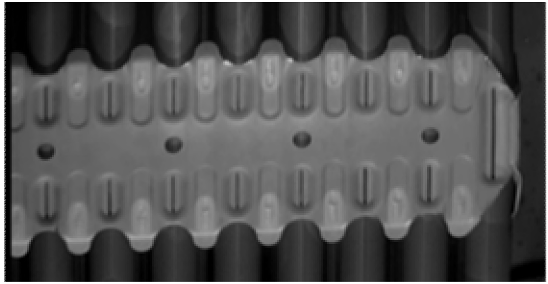
- Q12 Spacer sample at EOL etched for hydrides
- 400 ppm H from hot vacuum extraction
- Oxide thickness 20 – 25 µm

→ HPA-4 and Q12 featuring good corrosion and hydriding behavior

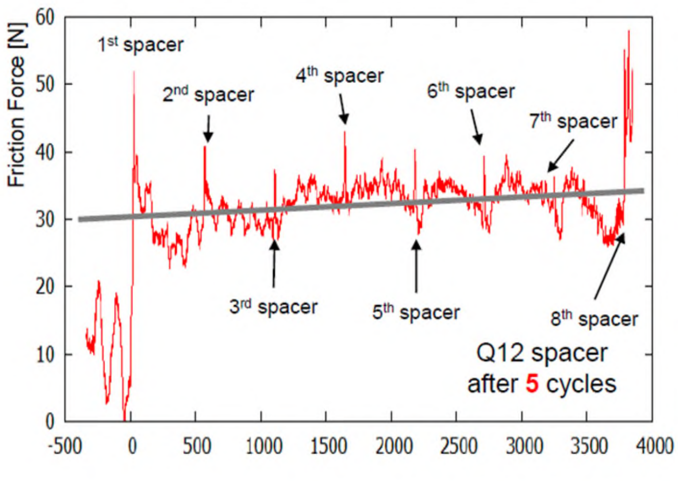
Spacer Materials

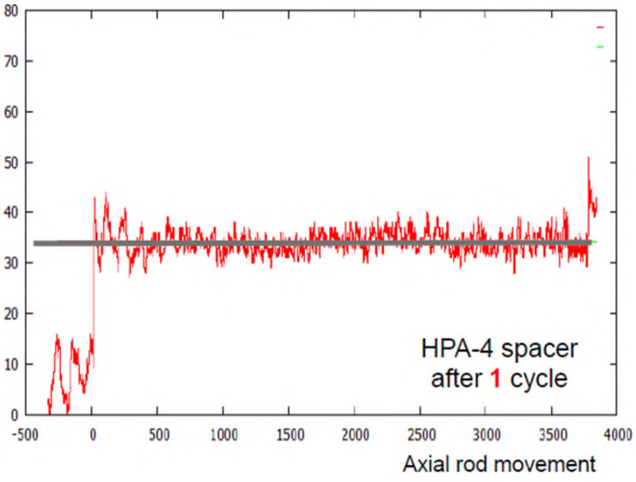
Guard for Reliable Rod Support and Dimensional Compatibility

- Mechanical Properties
  - Strength + ductility allow for component design / manufacturability
  - Important operational characteristic: creep (thermal/irradiation)
  - Q12 is clearly superior then HPA4 due to the tin alloying
  - For HTP design: better creep resistance = longer rod support



Visual appearance of the upper-most Q12 spacer by EOL / 5 annual cycles



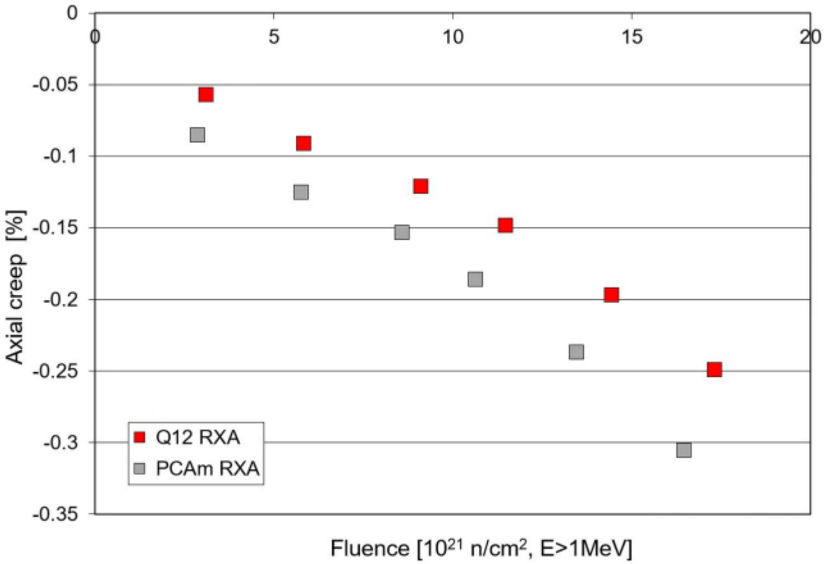


→ **Q12 is featuring improved creep resistance relative to HPA-4**

Guide / Instrumentation Tube Materials

Structural Tubing is the FA's Backbone

- FA load bearing and RCCA free insertability rely on material strength and dimensional stability
- Dimensional behavior in operation depends material properties: Creep and growth performance
- Q12 Alloy development with the intent of increased creep resistance - successfully proven:



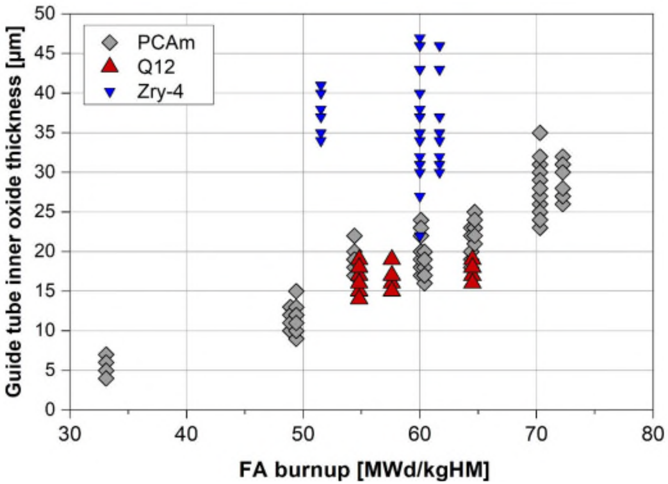
- Axial creep samples operated inside GTs and measured after each cycle
- Samples are irradiated under component prototypical conditions beyond EOL to obtain enveloping data
- Q12 consistently reveals higher dimensional stability

→ **Irradiation of samples demonstrated clearly Q12`s improved creep resistance as confirmed in the FAs' operational behavior**

Guide / Instrumentation Tube Materials

Structural Tubing to Maintain Favorable Corrosion and Hydriding Properties

- Corrosion and associated hydrogen uptake have to remain in the positive experience range – as for spacer material
- Desired creep growth performance must not be traded for corrosion/hydriding performance to maintain ductility and predictable growth
- Q12 Guide tube corrosion performance is monitored in irradiation programs:



- Directly on the component inner surface as accessible to the oxide probe
- Corrosion performance of Q12 is close and slightly improved relative to alloy PCAm
- Presented measurement results on FAs are consistent to previous irradiation programs using characterized samples including low hydrogen uptake

→ **Irradiation feedback gained from Q12 guide tubes confirms expected high corrosion resistance**

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Cladding Tube Materials

* D. Kaczorowski, J. P. Mardon, P. Barberis, P.-B. Hoffmann and J. Stevens, « Impact of Iron in M5 », in *Zirconium in the Nuclear Industry: 17th International Symposium*, 2014, vol. STP 1543, p. 159-183.

Evolutionary Change in $M5_{Framatome}$ to Prevent Enhanced Corrosion

- Role of iron in the alloy:
  - Iron is dissolved in Zr on high temperature and precipitated as secondary phase $Zr(Nb,Fe,Cr)_2$ “Laves phase” in low temperature condition including operation
  - Modest increase of iron ~300 → 700ppm: increase the quantity of the laves phase and decrease density of coexisting ß-Nb precipitates, no changes in material properties* → typical thermal in-pile corrosion remains as is and resistance to enhanced corrosion is increased
- Increase of iron has been verified in irradiation programs. In an LTA program, fuel rods with 700ppm iron were operated for five cycles – inspections and measurements confirm good performance
- Introduction of the iron increase in careful steps by specification:
  - Limit the variability towards low content by introducing minimum value 300ppm: generic since 2017
  - Increase of the previous impurity upper limit to 700ppm: ☑ since 2020
  - Center the specification around ~570ppm by applying new minimum 450ppm: : ☑ since 2021

→ **Introduction of the updated $M5_{Framatome}$ specification featuring improved resistance against enhanced corrosion is well on track for man PWRs worldwide**

Summary

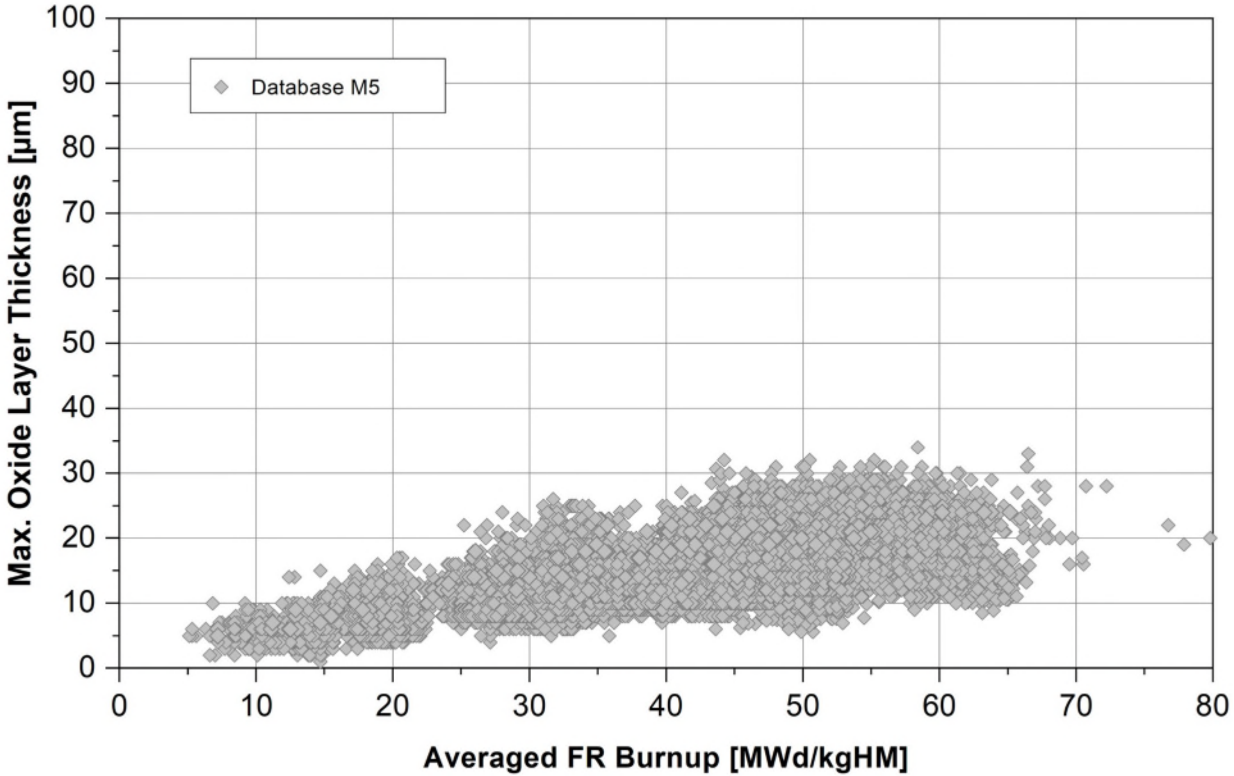
Recent Zirconium Material Implementation are a Story of Success

- In the long history of Framatome fuel supply: materials have been carefully updated to cope with increasing demand and guided by operating experience feedback.
- Structural parts and fuel rod cladding materials evolved from traditional ASTM grade alloys to advanced materials, each tailored to its function under the given demanding needs.
- For structural components superior operational behavior of the quaternary alloy Q12 is demonstrated relative to traditional Zr-Sn based alloys.
- Fuel rod cladding material $M5_{Framatome}$ featuring excellent operational experience since decades has been updated recently by introducing a modest increase of the iron content which increases the robustness against enhanced corrosion events observed in a few cases in other PWRs
- Fuel rods with the proven DX D4 cladding material continue to show a good performance in PWR application

→ Framatome materials are ready for high burnup service

Focus on BWR in the afternoon session

Backup



Data base FR oxide layer thickness