Innovations in BWR Fuel Assembly Materials:

ULTRAFLOW Shield & Optimized Zry-2

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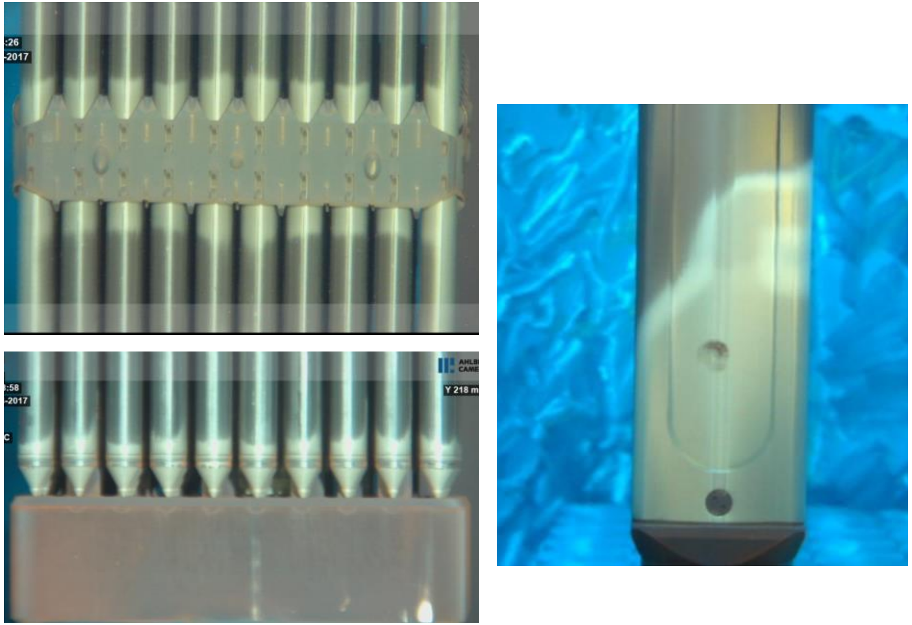
1. Introduction

What is shadow corrosion?



Examples of BWR Shadow Corrosion

- Accelerated corrosion of a metal in close proximity to a more noble metal
- No direct contact needed
- Requirements:
  - Susceptible material
  - BWR environment
- Manifests on Zircaloy components near stainless steel or nickel-based components
  - Fuel rods at the spacer positions
  - Fuel rod end caps near tie plates
  - Fuel channels at the spacer positions
  - Fuel channels exposed to the control blade

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How does shadow corrosion impact the industry?

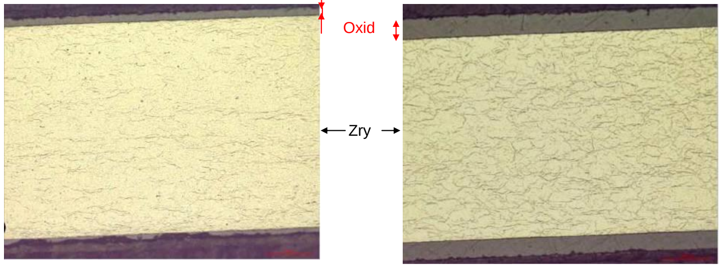
- Occurs in all commercial BWRs
- Enhanced corrosion events have led to fuel failures in the past
  - Framatome and competitor fuel have been affected
  - Contributing factors: All Ni-alloy spacer grid design and demanding plant conditions
- Shadow corrosion is currently well within satisfactory operability limits
- Current industry initiatives, such as AFM, may place increased demands on fuel
  - Power uprates
  - Increased average residence times
  - Increased cycle lengths
  - Increased operational demands

» **Increased corrosion margins are desired to ensure a robust fuel design across the full spectrum of BWR operating conditions**

Framatome's experience with shadow corrosion

- Shadow corrosion has been addressed by Framatome for more than two decades
  - Main objectives: Understand the phenomenon and reduce shadow corrosion on Zry-2 cladding
- CrN coating exhibited good behavior in an in-pile material test program
  - Outcome: ULTRAFLOW-S coated spacer grids
- First ATRIUM 10XP lead program launched in 2013
- PIE inspections of ULTRAFLOW-S LFAs revealed:
  - Coating provided protection over the first 1-2 cycles
  - Coating not durable through end of life

Material test program:
Inspection after 3 annual cycles



Zry-2 at coated spring interface

Zry-2 Reference

Significant reduction in Zry-2 oxide levels due to coating

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2. ULTRAFLOW Shield Development

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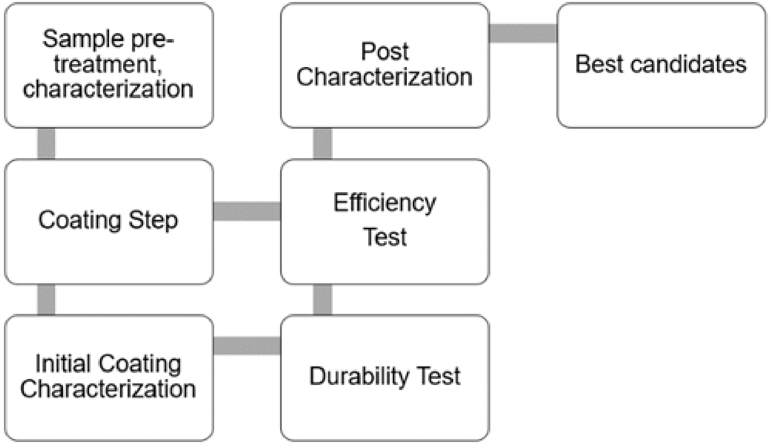
A comprehensive development approach

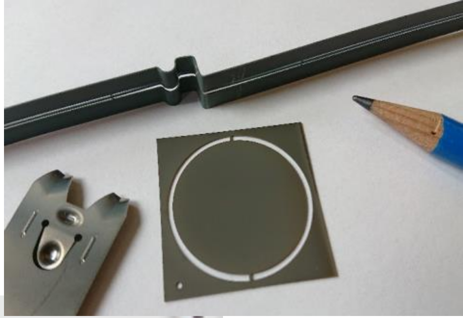


- Objective
  - Develop an <u>efficient</u> and <u>durable</u> coating
- Challenge
  - Create methodology capable of simulating shadow corrosion out-of-pile
  - Reduce cost- and time-expensive commercial irradiation programs
- Solution
  - Autoclave testing to assure durability
  - In-pile-like testing to verify coating efficiency

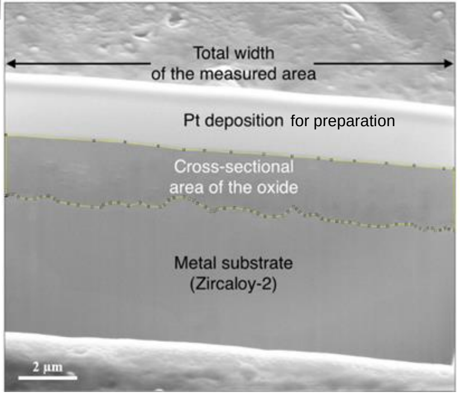
In-situ proton irradiation testing

Coating durability testing

- Durability testing in normal water chemistry (NWC) autoclave conditions
- A variety of geometries coated and tested
- Optimized coatings exhibited strong adhesion after 1+ year of autoclave exposure
- Significant post-test characterizations performed



Oxygen ingress impeded by the coating in the as-manufactured and corroded states

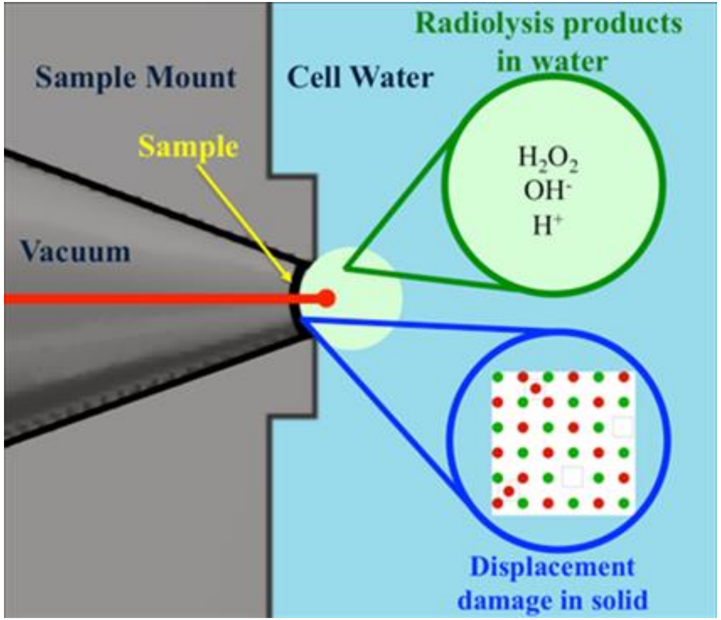


Leads to**:**

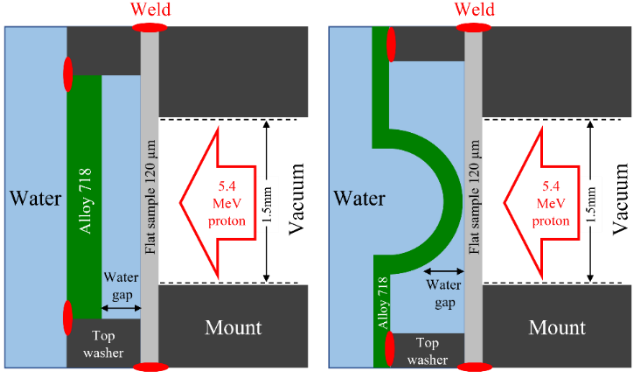
- » Efficient shadow corrosion reduction
- » Significant reduction of activated corrosion product release from Alloy 718 grid expected

3. Efficiency Testing

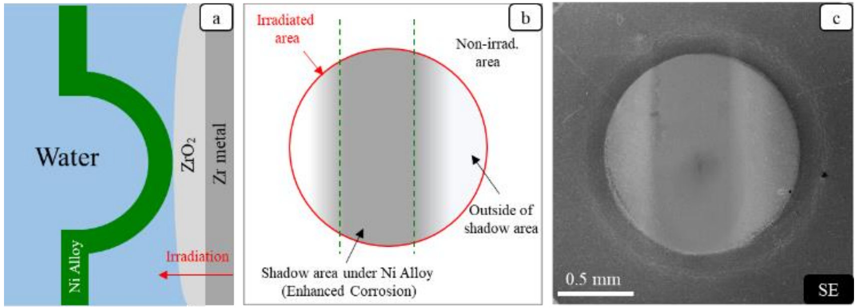
Experimental setup



Proton beam interactions



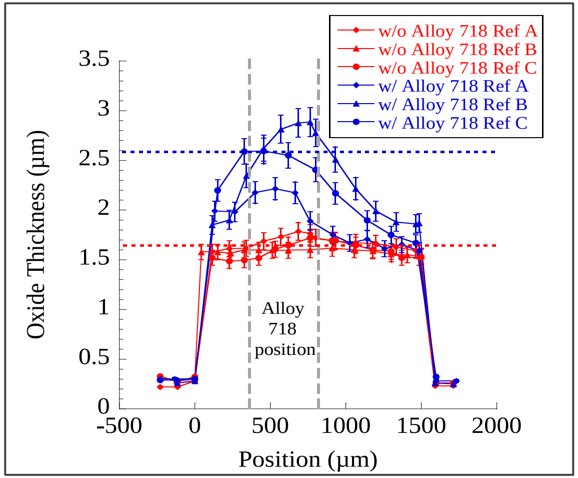
Non-contact and contact modes



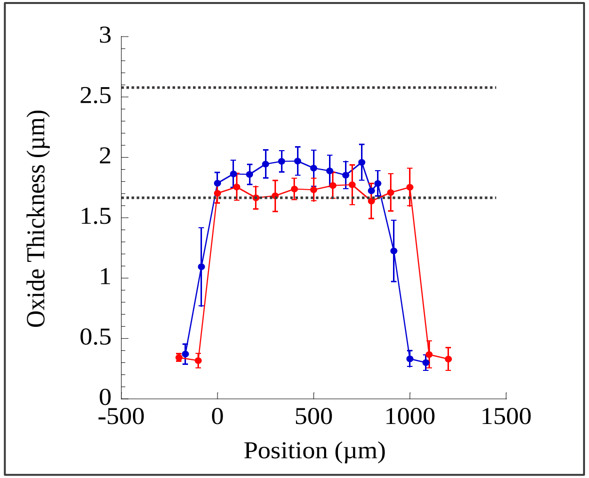
Shadow corrosion under in-situ proton irradiation

Efficiency testing results

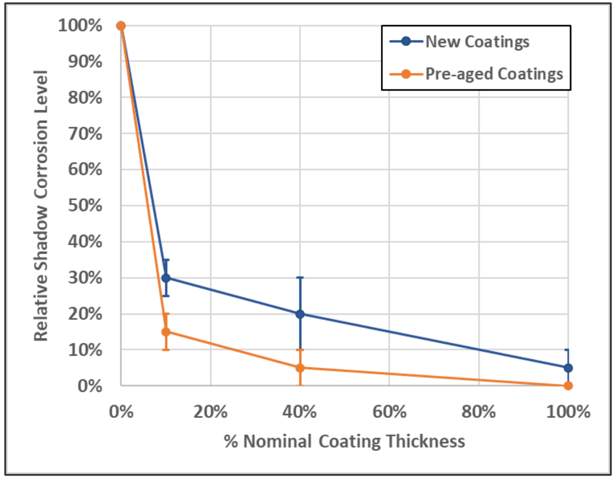
-- 40% nominal thickness new coating
-- 40% nominal thickness pre-aged coating



Reference samples



Coated samples



Relative Zry-2 Shadow Corrosion

» **First out-of-pile recreation of shadow corrosion and demonstration of coating efficiency**

4. Predicting ULTRAFLOW Shield Performance

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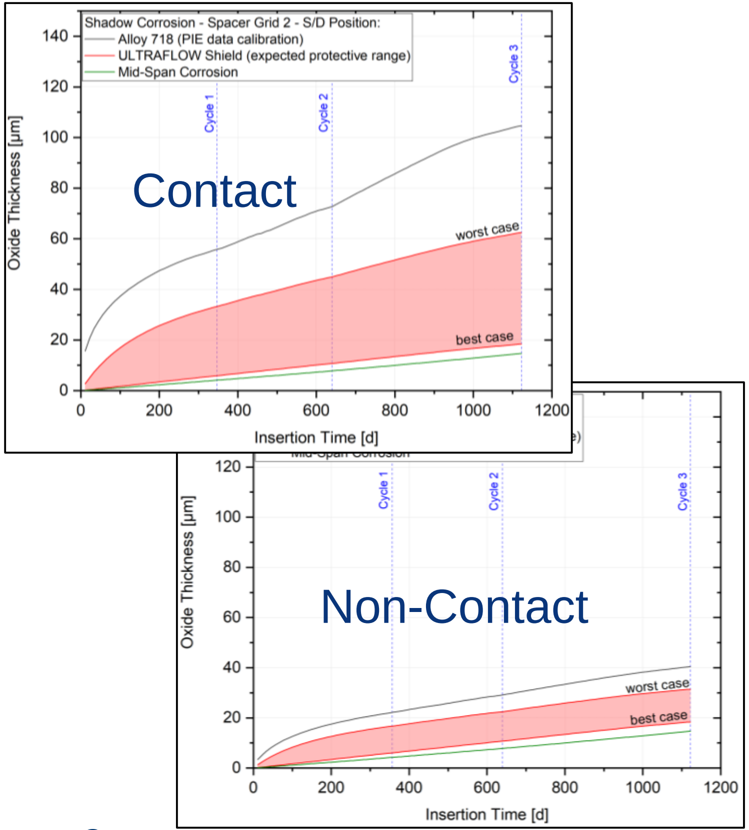
Prediction of ULTRAFLOW Shield performance



- MESSIAH: Framatome-developed model to predict cladding corrosion
- Calibrated against European plant data
- Simulates limiting shadow corrosion regions
  - Mid-core elevations for contact (S/D) positions
  - Lower elevations for non-contact (45°) positions
- Input data for modeling coating performance
  - Electrochemical measurements
  - In-situ proton irradiation tests
- Objective: Identify a range of coating performance regarding
  - As-manufactured vs pre-aged
  - Coating thickness: 10% to 100%

» **≥50% reduction in shadow corrosion predicted**

5. Z4B and Optimized Zry-2

Material Improvements for BWR applications

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Fuel Channel and Cladding Tube Material

Fuel Channel Material

- Z4B is the material for all ATRIUM 11 fuel channels.
- The channel sheets are beta-quenched which improves the fuel channel straightness.

Cladding Tube Material

- Zry-2 is the standard cladding tube material.
- « Optimized Zry-2 » is an alloys within the composition limits of Zry-2 but with optimized Cr and Ni content.
- The benefits are:
  - Reduced hydrogen pickup of the cladding.
  - Increased margin for accidental conditions.
- In-pile demonstration program was launched in a commercial BWR .

Nominal optimized Zry-2 chemical composition:

Material / Element	Sn [wt.-%]	Fe [wt.-%]	Cr [wt.-%]	Ni [wt.-%]
ASTM-Zircaloy-2	1.20-1.70	0.07-0.20	0.05-0.15	0.03-0.08
Zircaloy-2 LTP	1.5	0.17	0.10	0.07
Optimized Zircaloy-2	1.5	0.17	close to upper spec. limit	close to lower spec. limit

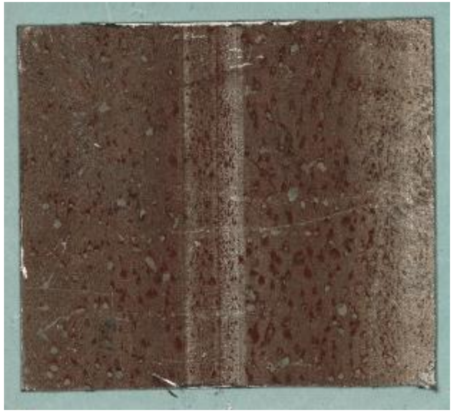
Beta-quenched Z4B is the standard fuel channel material. Positive reactor experience exist.
Optimized Zry-2 is optionally available as cladding tube material which further optimizes the alloy.

Operational Experience

- Fuel Assemblies with **Z4B** fuel channels were irradiated for up to 8 cycles in a German BWR
- Sample material was cut on-site for subsequent hot cell investigation
- HC investigation not completely finished yet
- First results show
  - an oxidation behavior at the upper bound of Zry-2 and at the lower bound of Zry-4
  - H uptake similar to Zry-4 → more margin wrt. oxidation and total H

Z4B fuel channel samples after 8 cycles of irradiation

outer surface



inner surface

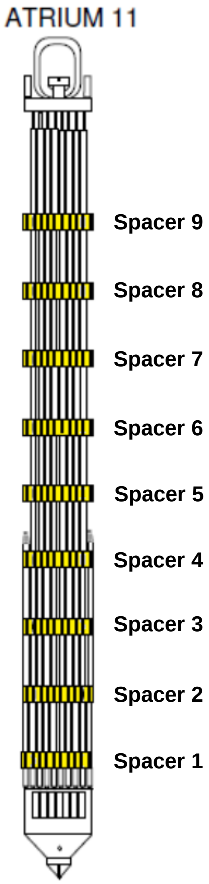
- «**Optimized Zry-2**» as a cladding material was inserted in an Scandinavian reactor by middle of 2022 (144 fuel assemblies)
- On-site visual PIE results expected 2024
- Hot Cell PIE planned for EOL

ULTRAFLOW Shield & Optimized-Zry-2 Demonstration program

- 4 ATRIUM 11 demonstration assemblies
  - All 9 spacers equipped with ULTRAFLOW Shield
  - Majority of rods made of Optimized Zry-2
- Inserted in Scandinavian BWR in 2022
  - Annual cycles
  - NWC, No additives
- Two distinct optimized designs of ULTRAFLOW Shield
  - Coating 1: Optimized for durability
  - Coating 2: Optimized for efficiency
- Inspections planned after 1st cycle and at EOL

Year	2022	2023	2024	2025	2026	2027	2028	2029
Cycle	37	38	39	40	41	42	43	

1cy (inspection after cycle 37) — EOL (inspection after cycle 42)



6. Summary and Conclusions

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Summary and conclusions

- Framatome has developed an **innovative spacer grid coating**, ULTRAFLOW Shield, to mitigate shadow corrosion
- Current industry initiatives, such as AFM, may place increased demands on fuel
  - Power uprates
  - Increased average residence times
  - Increased cycle lengths
  - Increased operational demands
- **First in industry** to use the innovative in-situ proton irradiation testing method to reproduce shadow corrosion out of pile accelerating its development
- ULTRAFLOW Shield is predicted to increase cladding wall thickness margins against shadow corrosion and mitigate corrosion product release from the spacer grid
  - ≥ **50% corrosion reduction** in the spacer grid area predicted

Summary and conclusions

- **Z4B** in beta-quenched condition is the new standard material for Atrium 11 fuel channel applications
- Irradiation **experience till EOL** (8 cycles) now exists and shows an expected performance
- Fuel channels made of Z4B offers advantaged in **fuel assembly bow** behavior
- **Improved oxidation behavior** in comparison to Zry-4 leads to **lower EOL Hydrogen** content

- **Optimized Zry-2** was introduced to **improve oxidation/hydrogen pickup** in comparison to Zry-2 cladding material
- Irradiation of **Optimized Zry-2** cladding material was launched in 2022 with the goal to demonstrate improved H uptake properties

