TOPFUEL | 2025
Nuclear Reactor Fuel Performance Conference

TRITON11® Fuel Performance Evaluation

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Introduction

- **TRITON11**® fuel is Westinghouse's advanced 11×11 BWR fuel product
  - Improved thermal, reactivity, stability, and pellet-cladding interaction (PCI) margins
  - Maintained low neutron parasitic absorption
  - Increased uranium weight
  - Robust mechanical design with three water rods as load bearing components
  - Improved debris fretting failure resistance with **StrongHold**® Additively Manufactured (AM) debris filter
- Proven reliable materials offering high burnup capability
  - **HiFi**™ liner cladding with lower hydrogen pick-up
  - **ADOPT**™ fuel with higher density
  - **Low Tin ZIRLO**™ channel and water rods with higher dimensional stability
  - X-750+ spacers with enhanced corrosion resistance

TRITON11 fuel is optimized for a wide range of reactor designs and operating conditions

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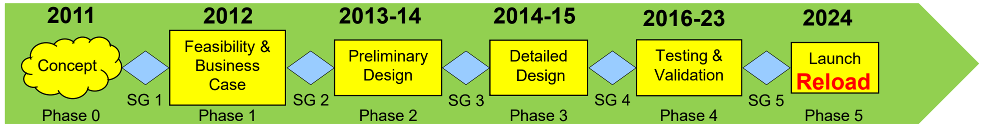
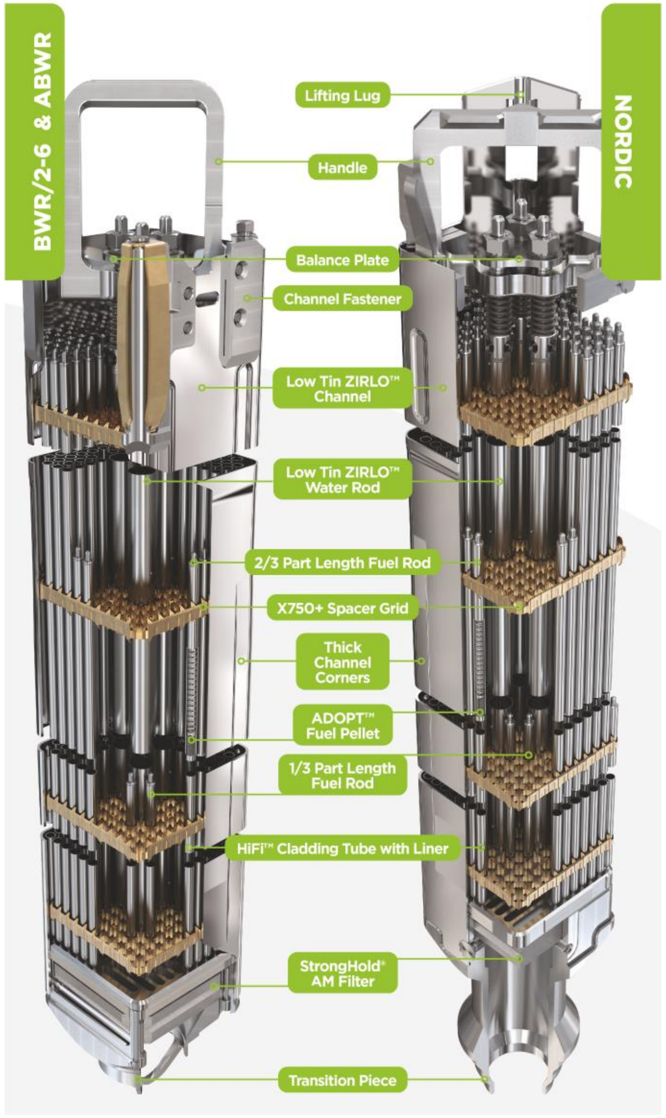
TRITON11 Introduction Status



TRITON11 product for BWR/2-6 and ABWR plants

- Preliminary design adaptations developed around 2015
- Final design completed in 2023
- Lead Use Assemblies (LUAs) shipped in Aug 2025 and being inserted in US-BWR
- Additional LUA programs underway in the U.S. and Switzerland
- Licensing Topical Reports submitted to U.S. NRC
- Reload deliveries in the U.S. expected from 2029, manufactured out of Columbia



TRITON11 product for Nordic plants

- Developed during 2013-2018
- Inserted as Lead Test Assemblies (LTAs) in two plants in 2019
- LTAs reached end-of-life (EOL) after 5 annual cycles in April 2024
- Fully licensed in Sweden and Finland
- Full reloads being delivered since 2024

It takes 10 years from Concept to Reload to ensure the success of a new 11×11 design

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TRITON11 Fuel Verification Program

- 10+8 LTAs inserted in 2019
  - Completed 5th and **final** annual cycle in April 2024, reaching **54 MWd/kgU** bundle average burnup (~60 MWd/kgU rod average)
- Poolside inspections of LTAs performed in both plants **after each cycle**
  - Visual inspection of the entire fuel assembly, including spacers and fuel rods from central positions
  - Length measurements of channels, fuel rods and water rods
  - F-SECT measurements of oxide and remaining wall thickness on channels, extracted fuel rods and extracted water rod
  - Diameter measurements on fuel rods
  - Channel bow and bulge measurements
- Hotcell examinations of water rod ongoing with preliminary results. HiFi rods to be shipped to hotcell.
- Channel (Low Tin ZIRLO), cladding (HiFi) and fuel (ADOPT) materials have all been verified to **>70 MWd/kgU** rod average burnup in previous fuel products

Nordic LTAs combined with previous operating experience and PIE will support licensing of TRITON11 fuel Worldwide

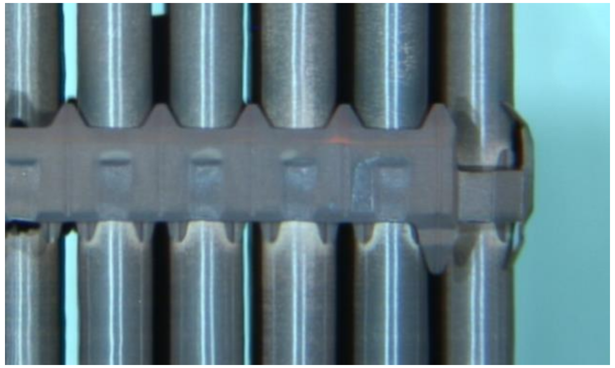
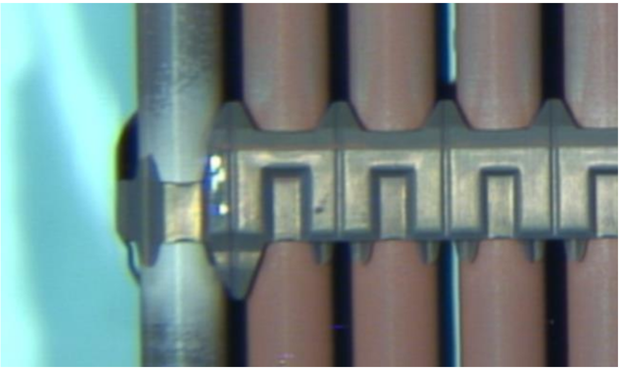
Plant	Number of LTAs	Average Power Density [MW/FA]	Cycle Length [months]	Water Chemistry
A	10	5.6	12	NWC
B	8	5.0	12	NWC

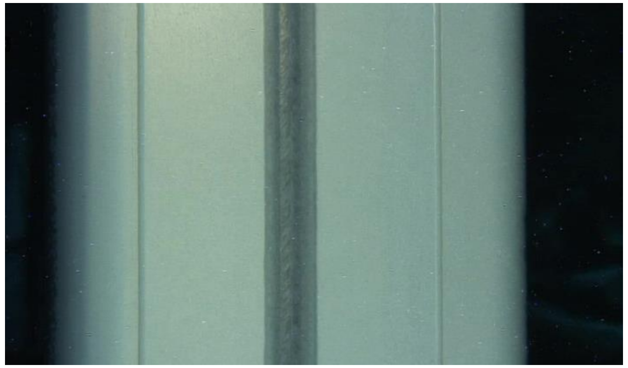
Visual Inspections

- Equal growth of water rods
- Normal levels of crud and shadow corrosion underneath spacer grids
- No extensive localized corrosion of spacers
- Normal corrosion of channels
  - Speckled oxide on sides not facing control rod (left picture)
  - Thicker white oxide from shadow corrosion on sides facing control rod (right picture)

Normal visual appearances of fuel components at end of life



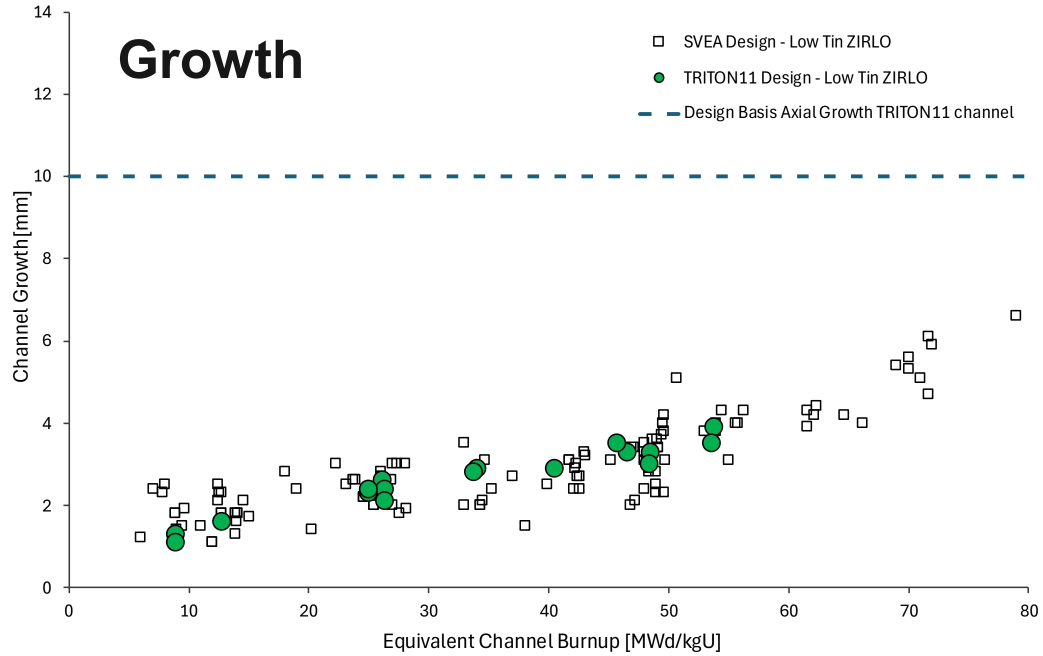



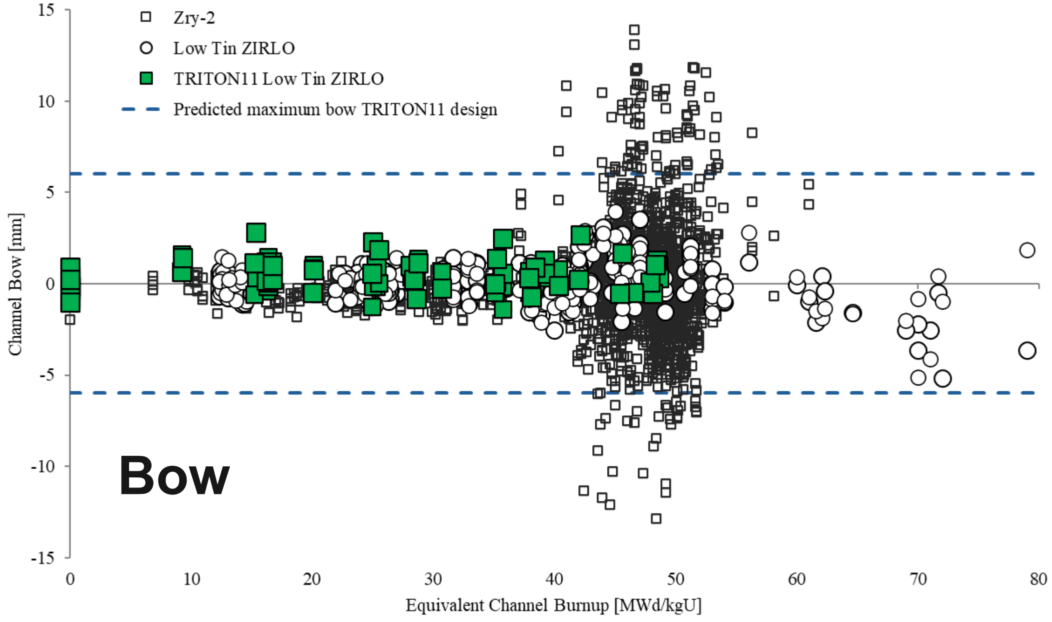


Channel Growth / Bow

- Advanced thick-thin design
- Low Tin ZIRLO material very resistant against irradiation growth and hydrogen pick-up
  - Low differential growth → Low Bow
- TRITON11 channel growth and bow are similar to previous SVEA Low Tin ZIRLO channels and well below design basis
  - No acceleration at higher burnup

High dimensional stability





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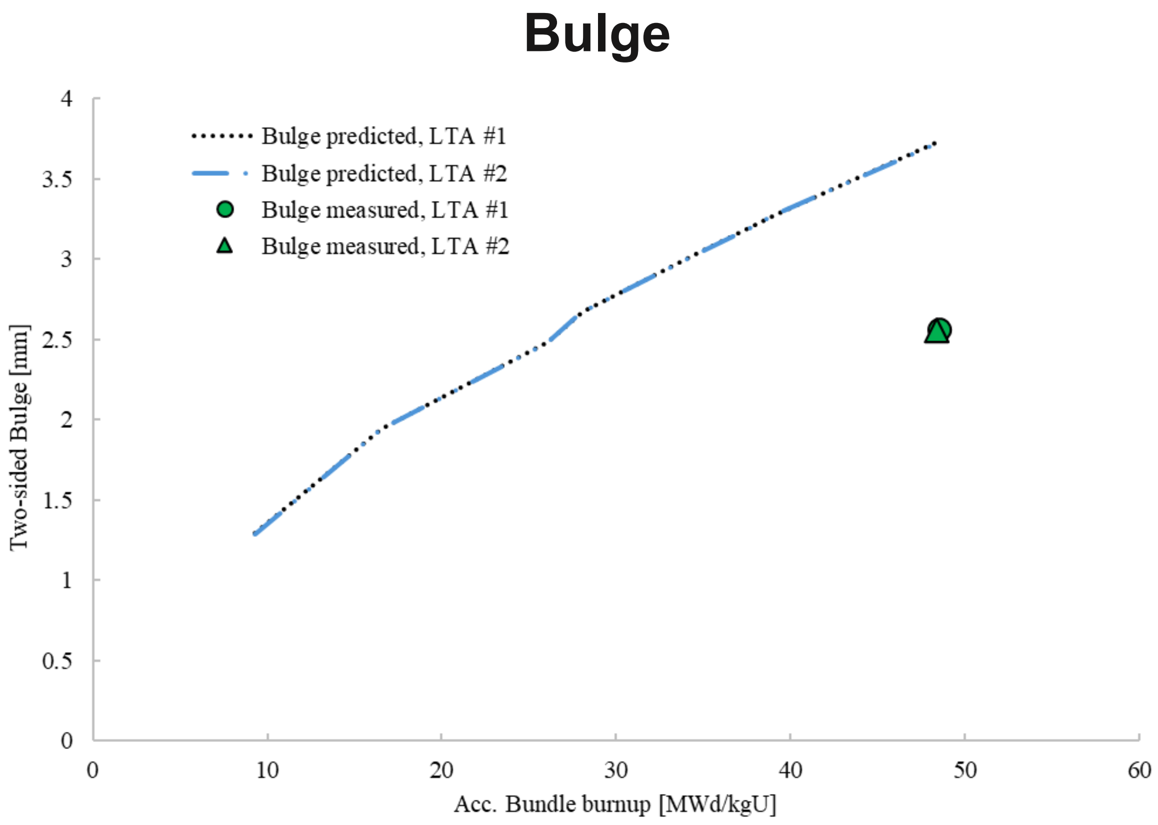
Channel Bulge

- Bulge from creep deformation is dominant in lower thick-thin part of channel
  - Max 2.6 mm two-sided (1.3 mm one-sided)
  - Well within prediction model based on Zry-2 material
- Conclusion: Low Tin ZIRLO material creeps ~35% less than Zry-2
- Will be followed up by additional measurements on reload fuel

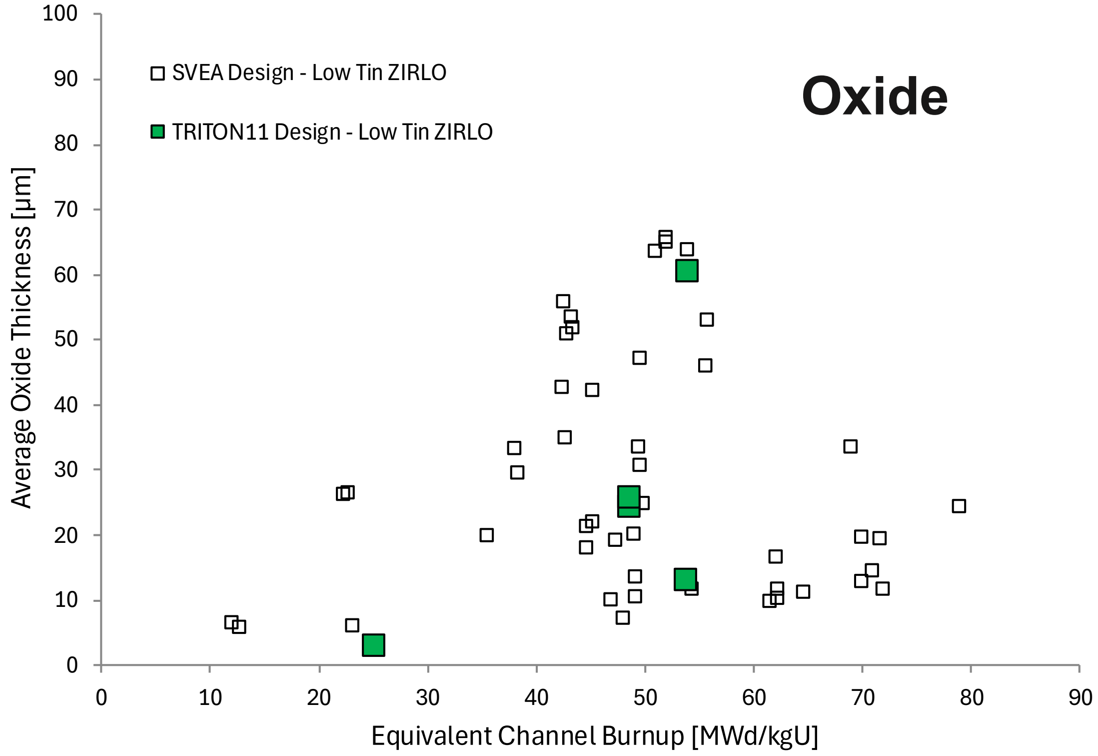
High dimensional stability

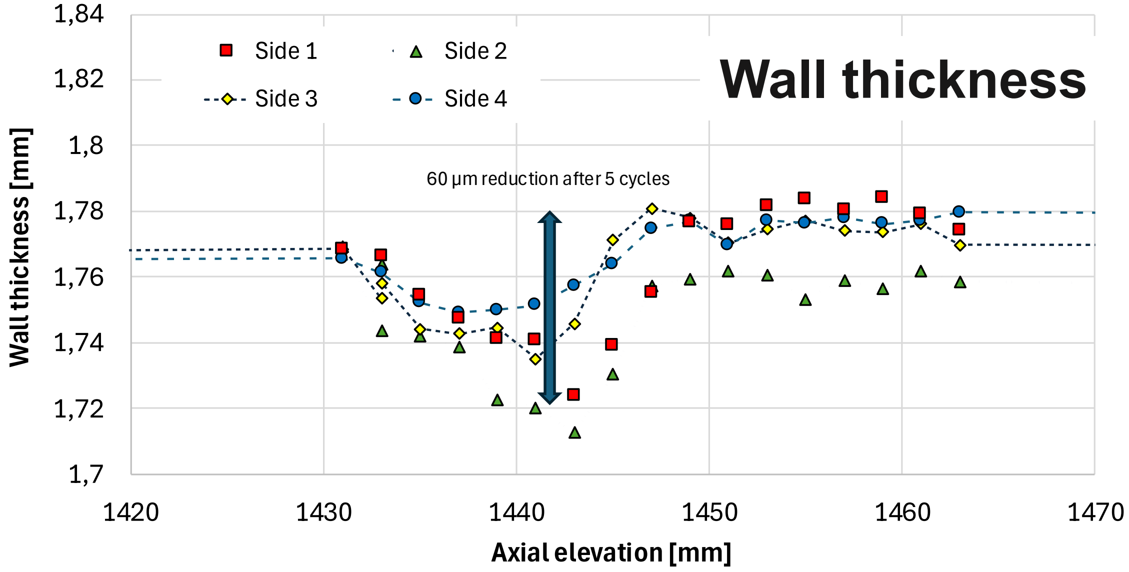


Channel Oxide

- Low uniform channel corrosion, similar to SVEA Low Tin ZIRLO channels
- Inside shadow corrosion from spacer grids determined with F-SECT by measuring remaining wall thickness
  - 60-80 µm wall thickness reduction after 5 cycles
  - Similar after 3 and 5 cycles, i.e., shadow corrosion saturates and does not result in any significant oxide spalling

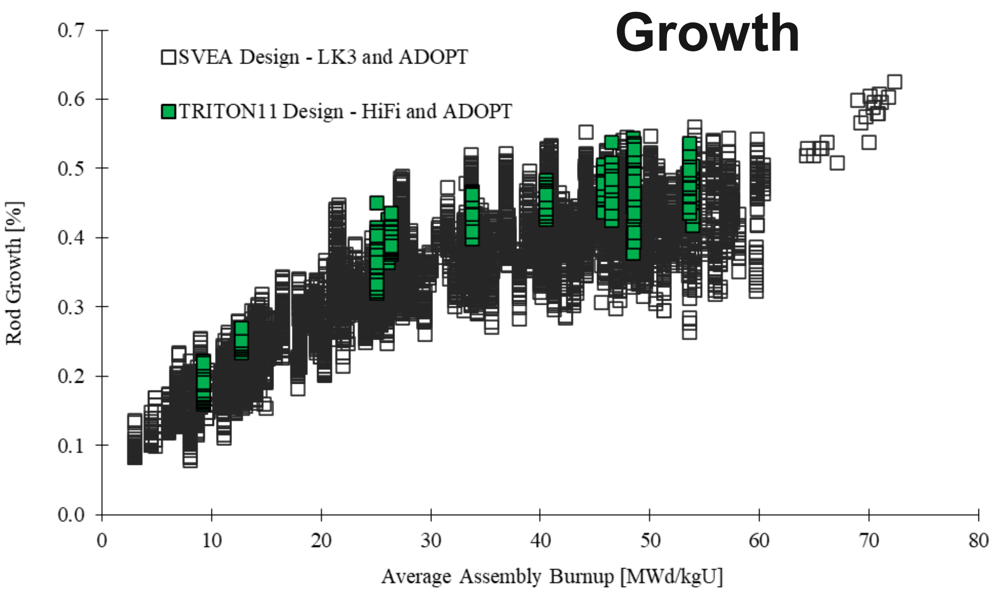
No significant material loss from corrosion

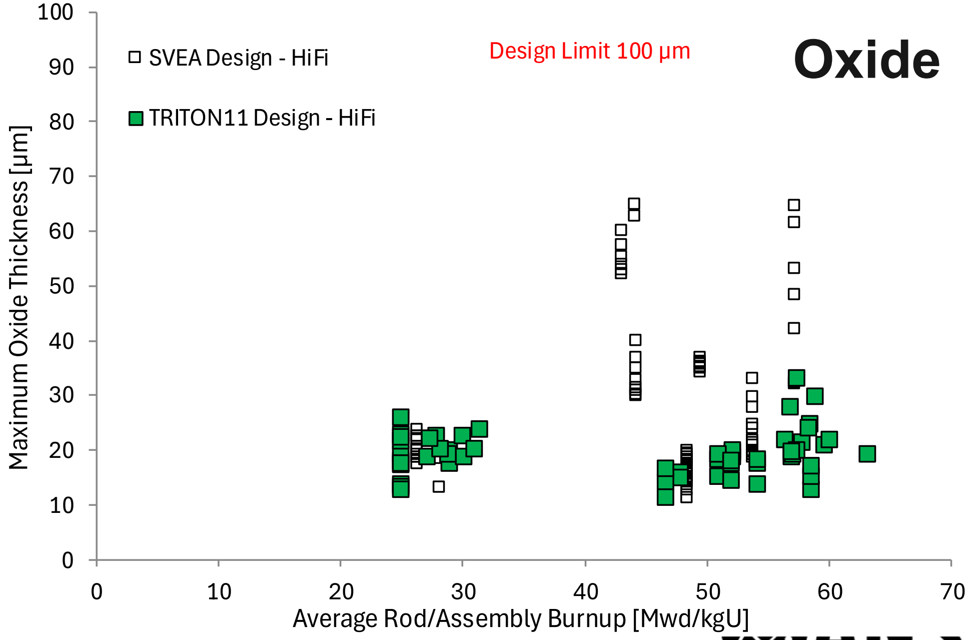




Fuel Rod Growth, Oxide and Diameter

- TRITON11 fuel rod growth with HiFi cladding is similar to SVEA fuel with LK3 cladding (both with ADOPT fuel)
  - Max growth of 0.54% at EOL is well within design limit of 0.86%
- Lift-off measurements on HiFi cladding show low oxide levels in both plants, including at high burnup
  - Well below design limit of 100 μm
- Rod diameter measured on 7 HiFi rods extracted at EOL
  - Agrees well with predicted diameter





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Water Rod Visual Inspections

- Extracted after 5 cycles
- Thin uniform oxide layer
- Very minor spalling in spacer regions

Excellent appearance of water rod at EOL

Top end plug

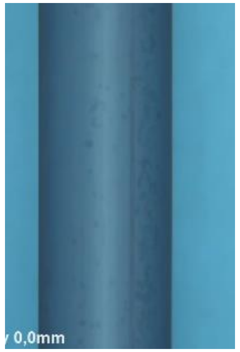

Spacer 7

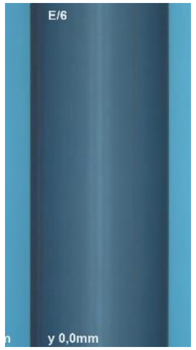

Spacer 4


Spacer 2


Spacer 10


Midspan 7

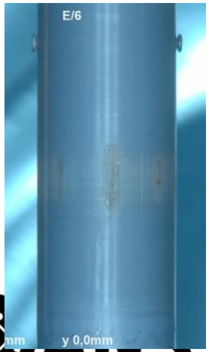

Midspan 4


Midspan 2


Midspan 8

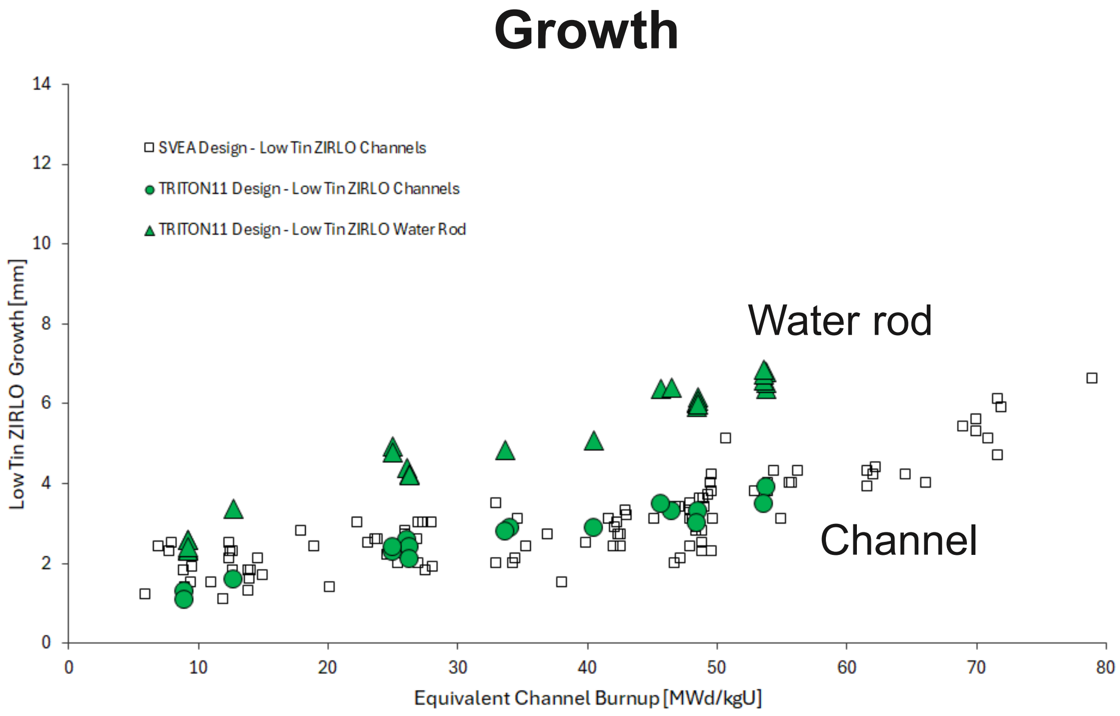

Spacer 5


Spacer 3


Spacer 1


Water Rod Growth

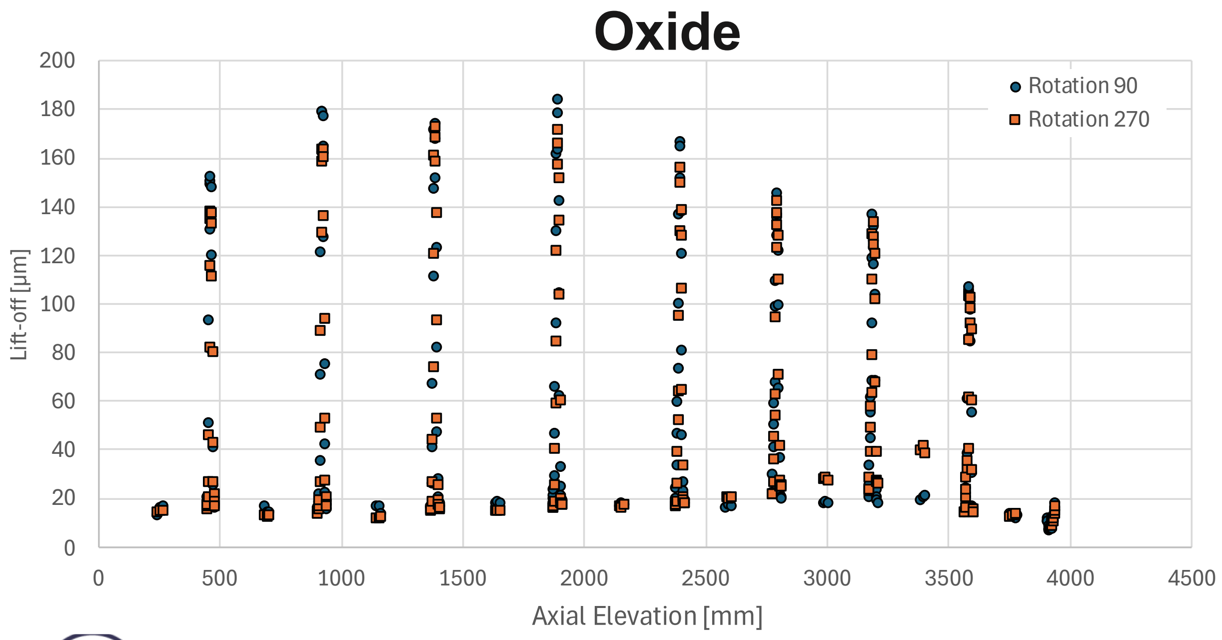
- Linear growth, no acceleration at high burnup
  - Benefit of Low Tin ZIRLO material
  - Consistent with preliminary hotcell data for extracted water rod showing low hydrogen content around 160 ppm
- Small variation within the same assembly
  - Also verified by visual inspections
- Somewhat higher initial growth compared to Low Tin ZIRLO channels
  - Likely due to differences in thickness and manufacturing process (texture)
- Large margin to design limit of 12 mm at EOL

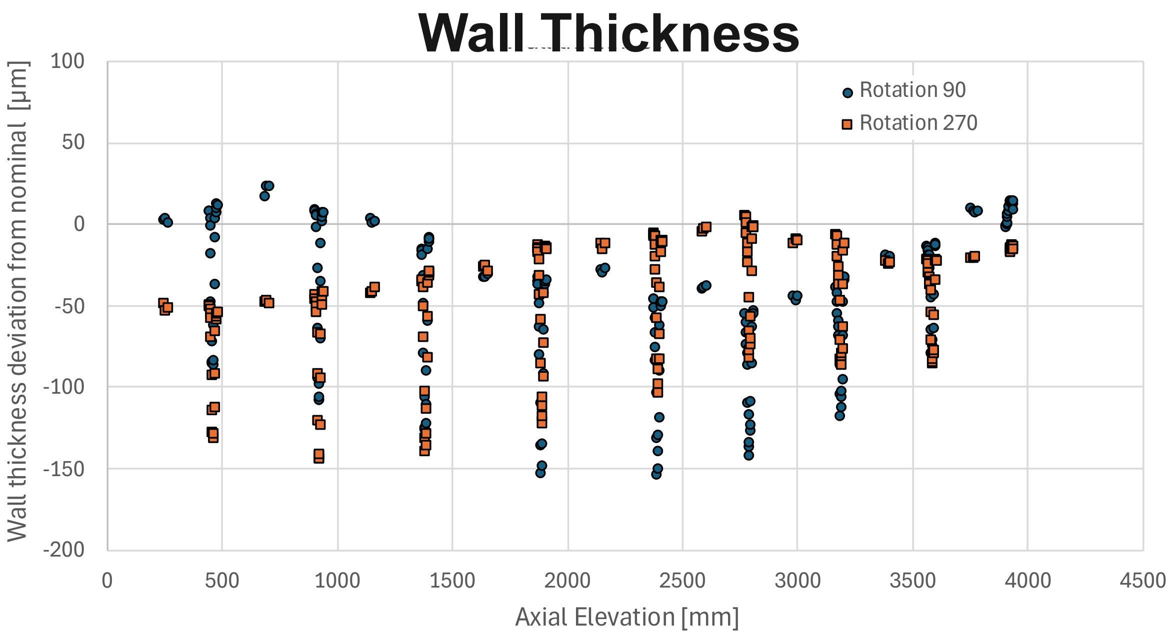


High dimensional stability

Water Rod Oxide

- Oxide (lift-off) and wall thickness measurements performed on one TRITON11 water rod after 5 cycles and 48 MWd/kgU assembly burnup
  - Two rotations along the entire water rod
- Results very similar to Low Tin ZIRLO channels with respect to uniform and shadow corrosion behaviors
  - Low uniform corrosion with a measured lift-off of around 20 µm
  - Wall thickness reductions in the spacer region agree with the measured lift-off





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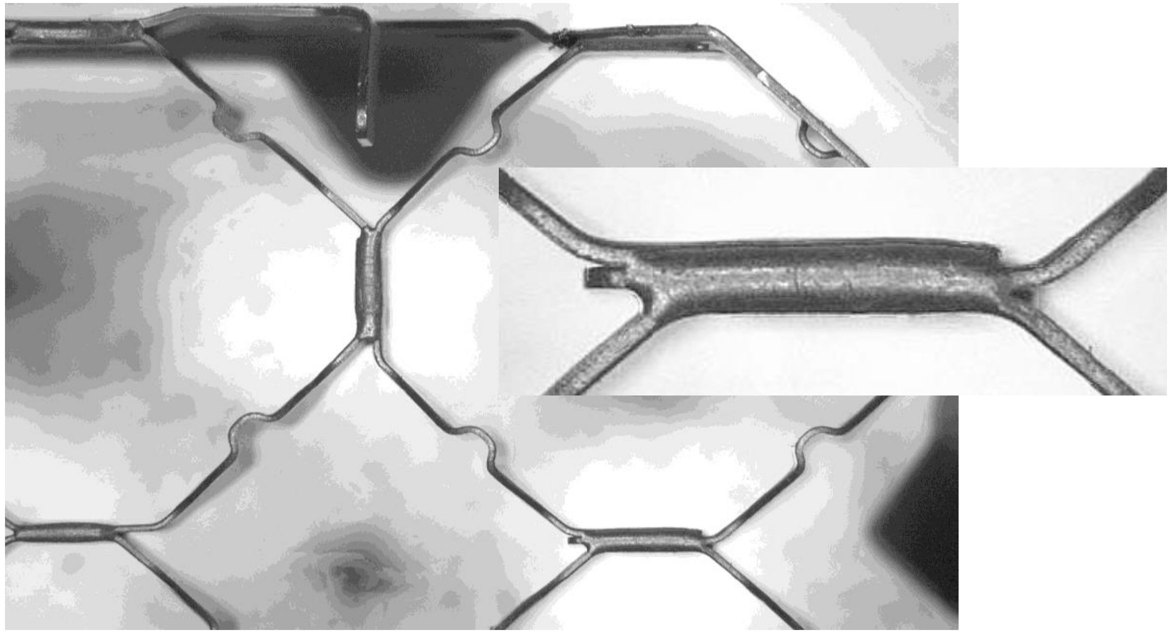
Spacer Corrosion

- Alloy X-750+ (with higher iron content) was introduced as standard spacer material in TRITON11 fuel to counteract localized corrosion seen with X-750 in certain plants with high power / high flow conditions
- Alloy X-750+ has been verified in previous SVEA-96 **Optima3**™ fuel
  - Hotcell data show clear improvement in corrosion performance compared to X-750
- TRITON11 spacer design is similar to SVEA-96 Optima3
  - Scale-up from 5x5 to 11x11 rod pattern

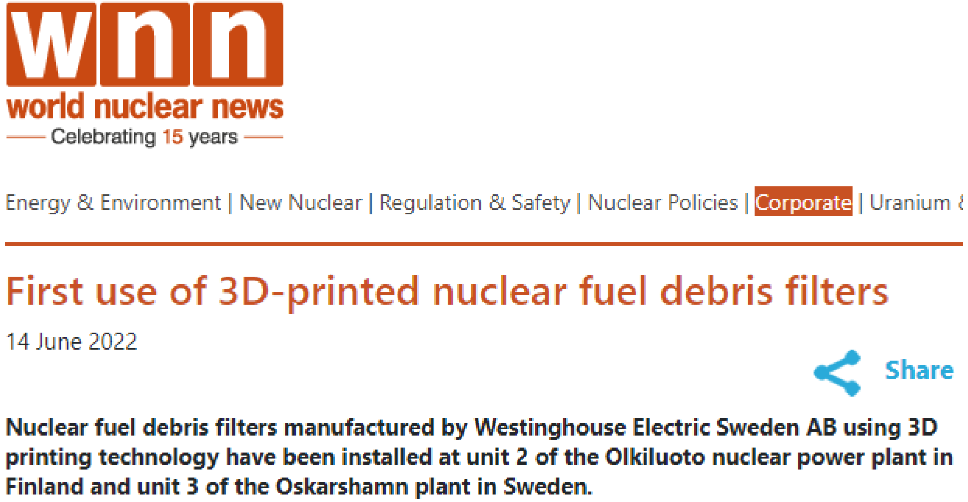


Hotcell inspection of SVEA-96 Optima3 spacer (level 10) in X-750+ material after irradiation for 7 cycles to 53 MWd/kgU burnup in demanding plant

Excellent corrosion resistance of Alloy X-750+ spacer material demonstrated with hotcell data

StrongHold AM Filter Visual Inspections

- In May 2022, lead test filters of StrongHold AM design were installed in 2+2 fuel assemblies in two Nordic reactors
- Lead test filters are visually inspected during each annual outage and detailed hotcell examination will be performed at EOL (2027)
  - Inspections after 1st , 2nd and 3rd cycles showed excellent behavior
- StrongHold AM filter will soon be a standard component in all TRITON11 fuel delivered Worldwide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First use of 3D-printed nuclear fuel debris filters

14 June 2022

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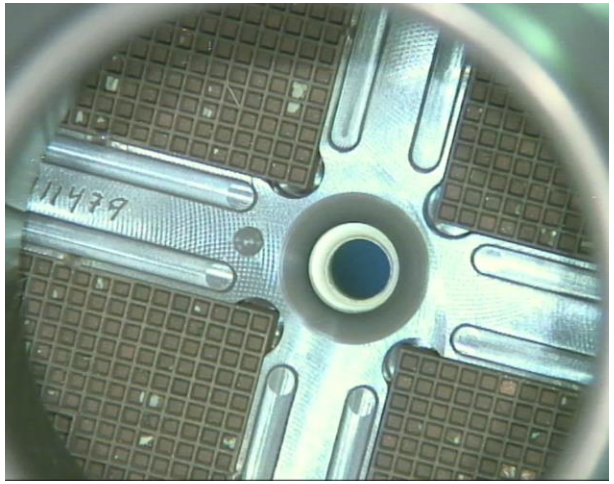
Nuclear fuel debris filters manufactured by Westinghouse Electric Sweden AB using 3D printing technology have been installed at unit 2 of the Olkiluoto nuclear power plant in Finland and unit 3 of the Oskarshamn plant in Sweden.



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Summary

- The TRITON11 fuel design was carefully developed and optimized to meet the future needs of the global BWR market, including extended power uprates (EPU), higher burnup, flexible power operation, new rulemaking, etc.
  - Balanced performance without any weaknesses was ensured through many design iterations with feedback from testing
- Followed by a comprehensive LTA program in two Nordic EPU plants with TRITON11 assemblies placed in demanding/leading core locations and irradiated to EOL
- Extensive post irradiation examinations (PIE) performed after each cycle in both plants showed excellent behavior of all TRITON11 components
  - TRITON11 fuel meets all design criteria set out during its development

TRITON11 fuel product is fully verified

Reload quantities are being delivered since 2024