Challenges to LWR Burnup Extensions

Aylin Kucuk
Program Manager, Nuclear Fuels, EPRI

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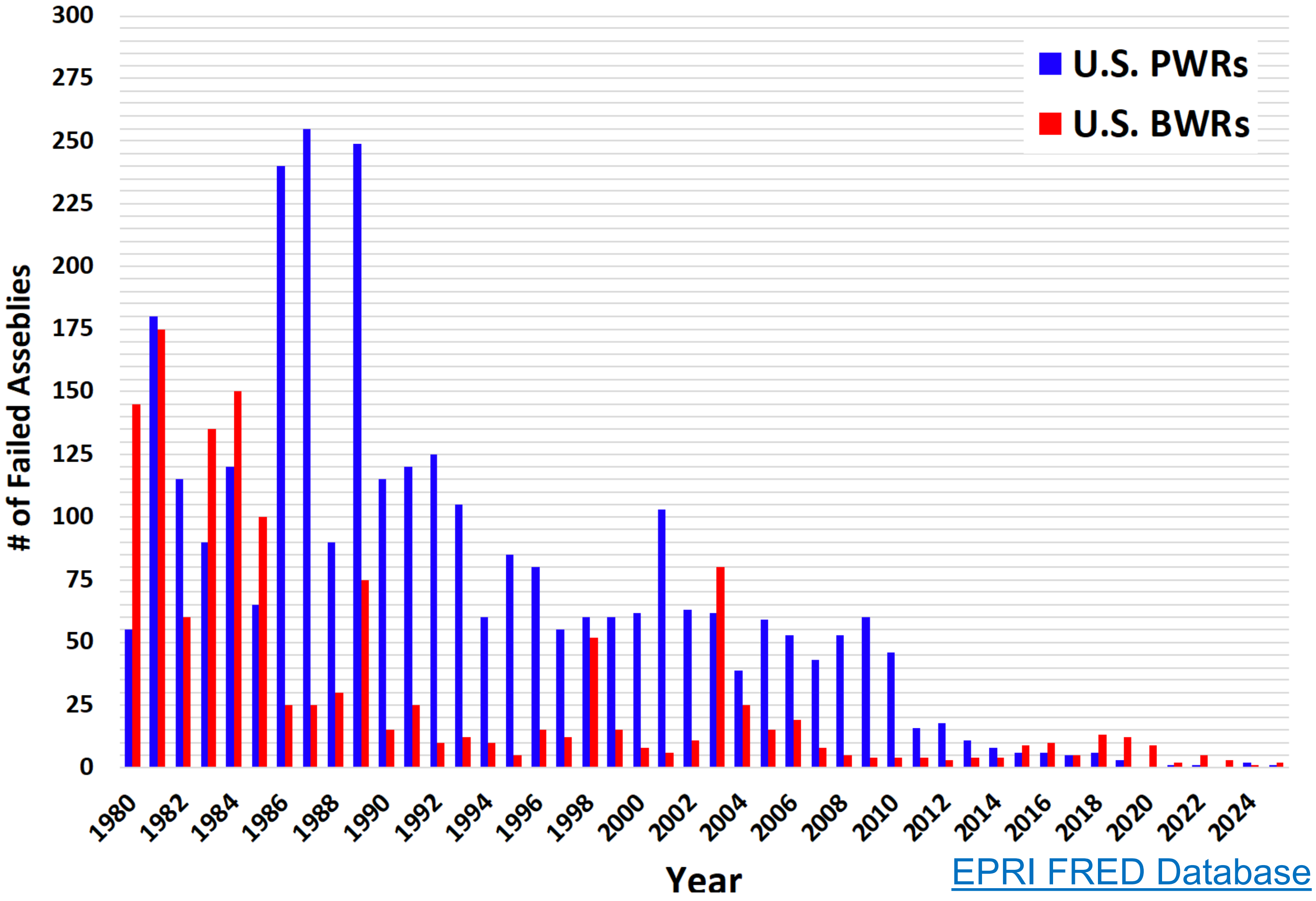
Historical Perspective

Historical Fuel Failure Trends in U.S.



EPRI FRED Database

Significant number of fuel failures in 80s and 90s

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Major Operational Changes

- Power Uprates
- Higher Burnup
- Longer Fuel Cycles
- Newer fuel designs aimed at improving mechanical and neutronic designs
- Water chemistry changes to improve system performance (PWSCC* and dose reduction)

*PWSCC: Primary Water Stress Corrosion Cracking

Resulted in increased fuel duty and eroded fuel performance margins

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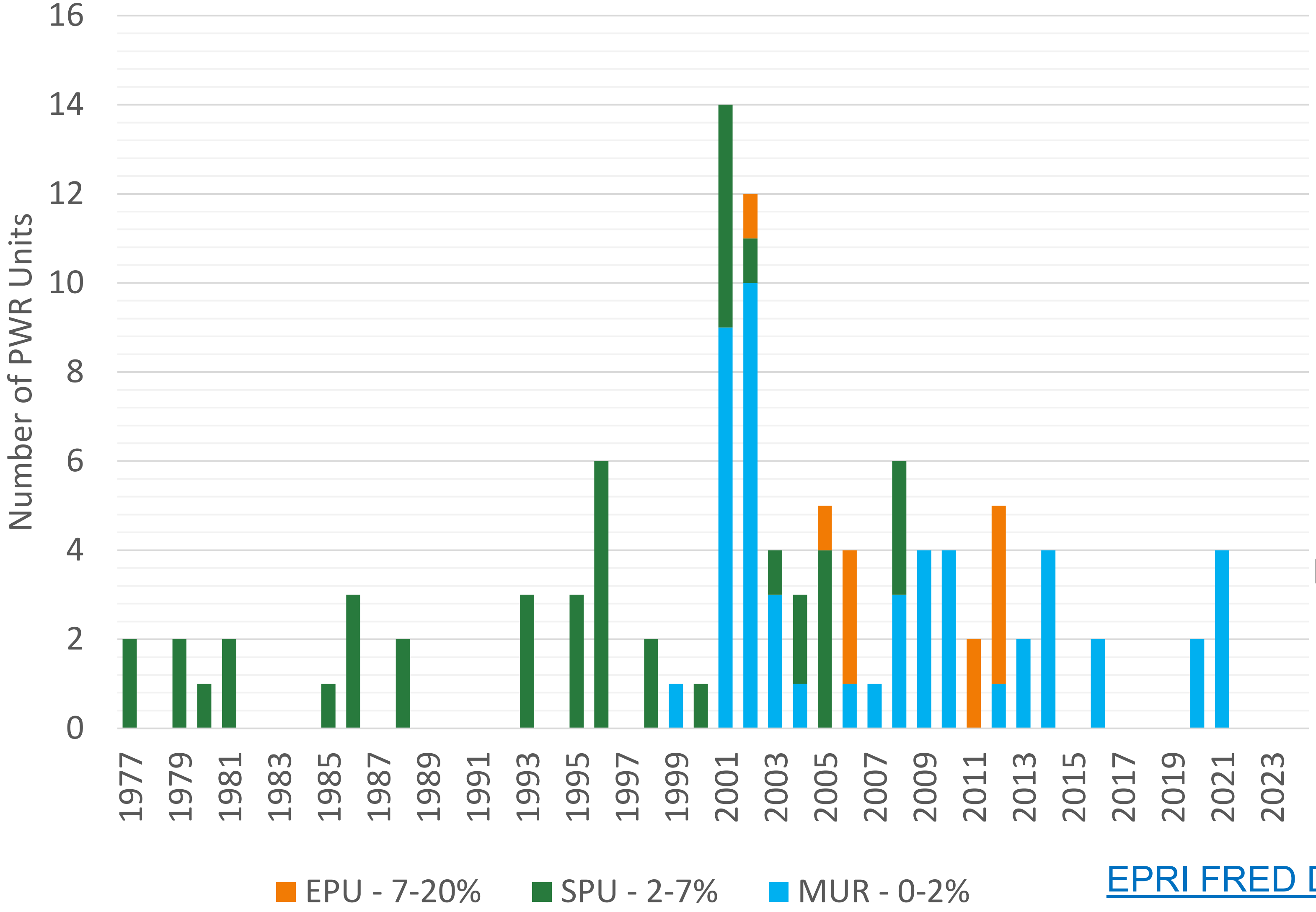
Power Uprates in U.S.



EPU: Extended Power Uprates (7-20%)
SPU: Stretch (2-7%)
MUR: Measurement Uncertainty Recovery (0-2%)

	MUR	SPU	EPU	Total (MWth)
BWRs	21	21	23	13,336
PWRs	52	44	11	10,810

EPRI FRED Database

8 GWe was put in the grid through power uprates

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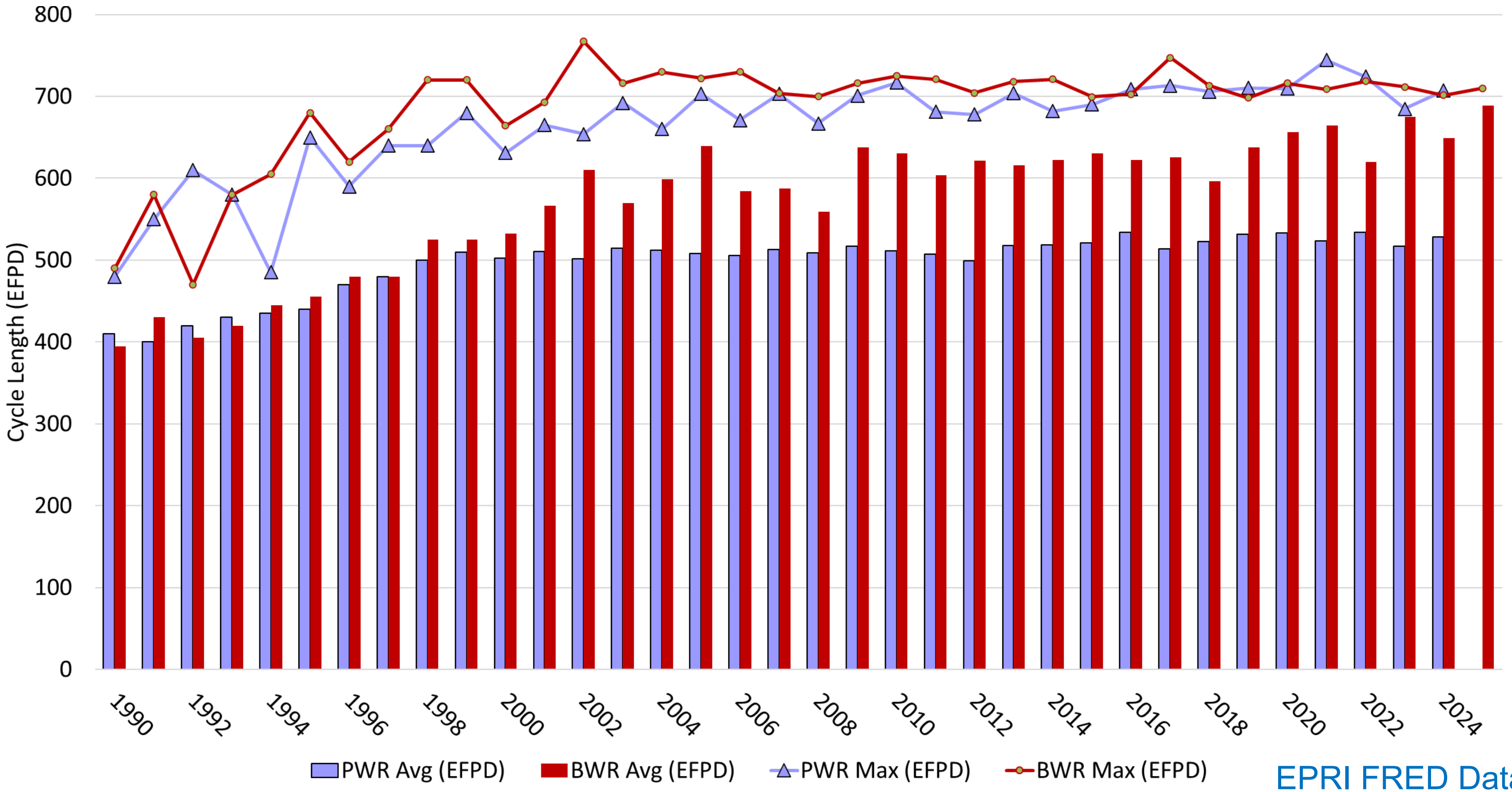
EPRI

Cycle Length Extensions



EPRI FRED Database

Fuel cycles have been extended in 1990s

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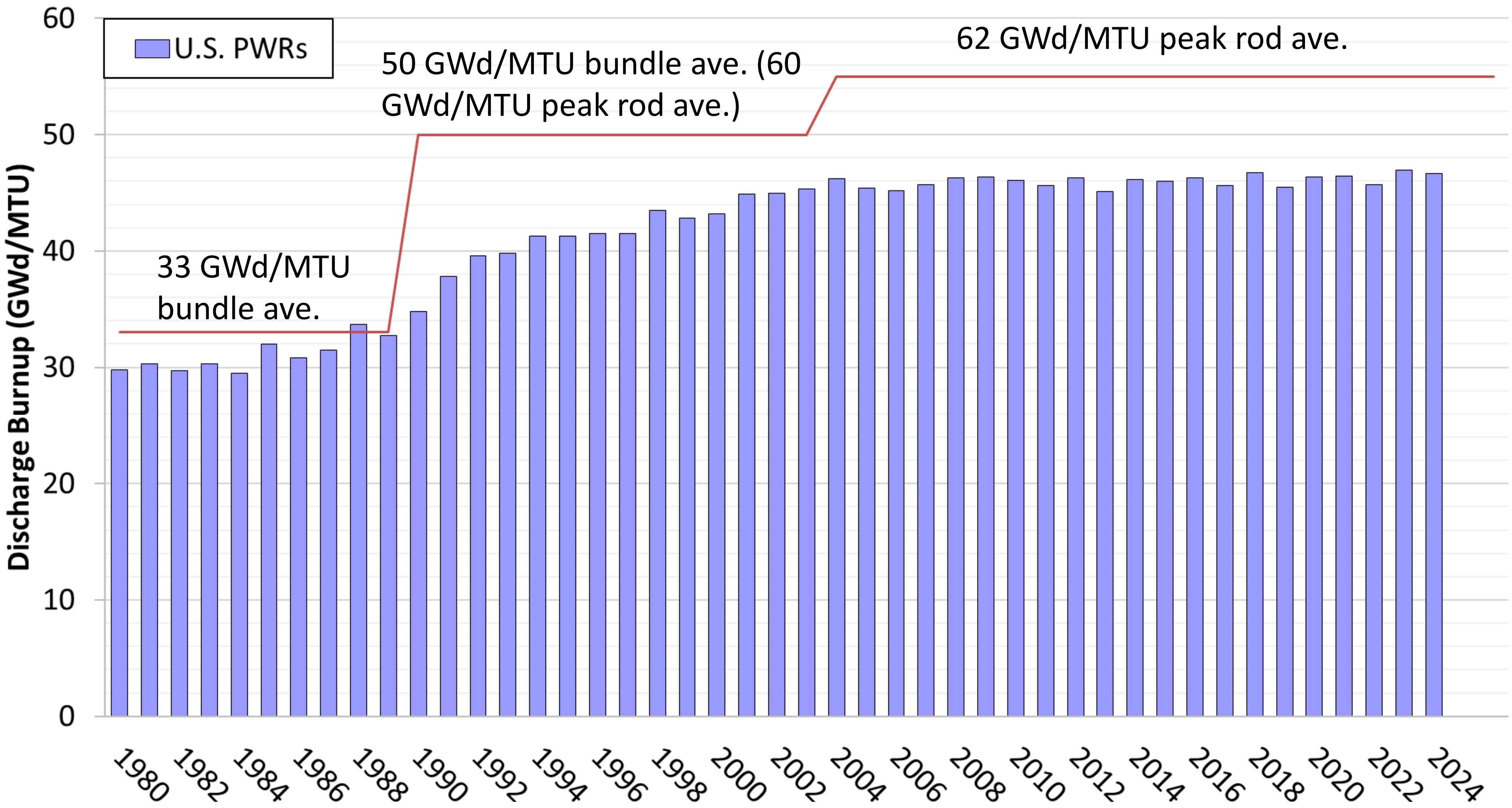
Discharge Burnup Trends and Regulatory Limits in U.S.



[US Energy Information Administration and EPRI FRED Database]

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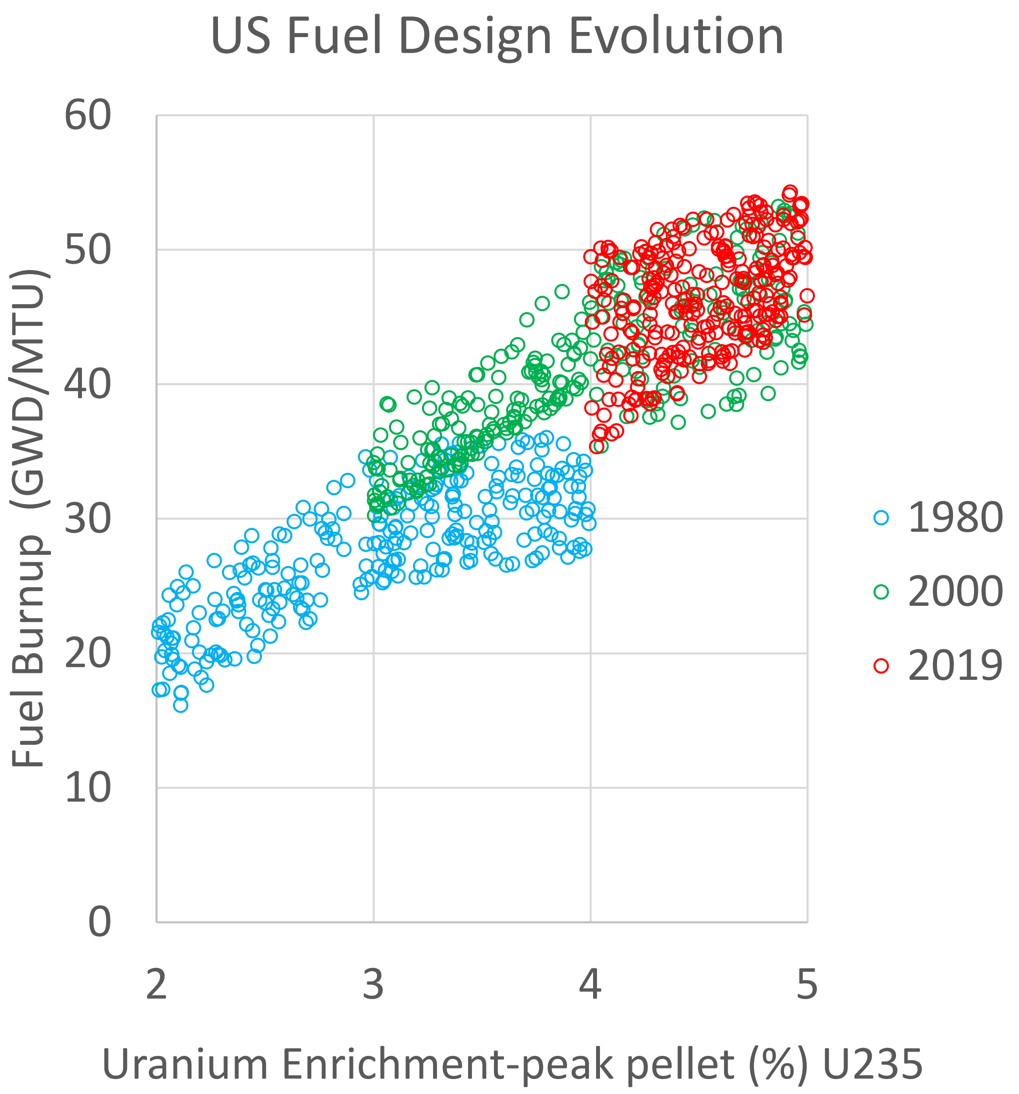
Fuel and Core Design Evolution

- Power uprates and cycle length extensions were achieved by increasing burnup and enrichment close to the limits
- Improved fuel cycle utilization and fuel cycle cost
  - Fuel mechanical and neutronic designs evolved
  - Burnable absorber designs
    - IFBA
    - Gd
    - BPRA



New operational changes need burnup and enrichment limits to be extended

IFBA: Integral fuel burnable absorber

BPRA: Burnable poison rod assembly

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Evolution of EPRI Fuel Programs

NFIR – Nuclear Fuel Industry Research
RFP – Robust Fuel Program
FRP – Fuel Reliability Program

NFIR - formed in early 80s

RFP formed in 98 – focused on high burnup

RFP to FRP – shifted focus to reliability

INPO SOERs – 1996 and 2003

FRP guidelines, handbooks, codes, training and assessments

INPO Zero-by-Ten Initiative (2006-2010)

ATF, HBU, LEU+

Fukushima accident (2011)

Delivering the Nuclear Promise (2018)

Power Uprates, Cycle Length Extension

Increased power demand

INPO – Institute of Nuclear Power Operation
SOER – Significant Operating Experience Report

Nuclear fuels continues to play a crucial role for the industry

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U.S. Industry Timeline for Licensing and Implementation of Higher Burnup and Increased Enrichment

2025

Facility Development

Fuel supplier facilities are being licensed

2027

Power Uprates

Utility license amendments

HBU and LEU+ Licensing Completion

2029

24-month cycles in high duty PWRs

2030

Power Uprates

MUR, Stretch, and some Extended Power Uprates

2034

Power Uprates

Extended Power Uprates

Higher burnup (HBU) means 62-75 GWd/MTU rod average
Increased enrichment (LEU+) is 5-8 wt.%

U.S. industry is prepared to implement higher burnup and increased enrichment

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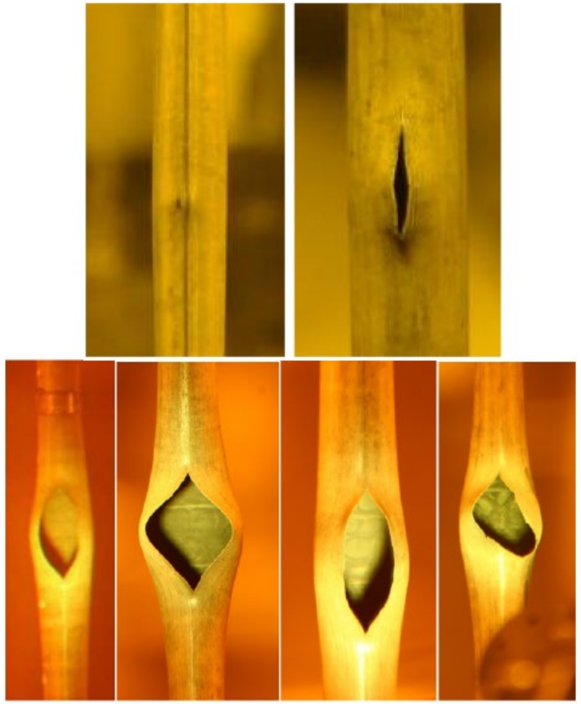
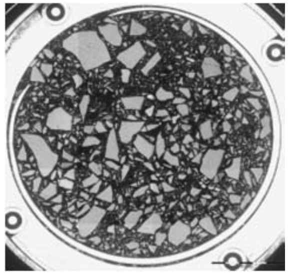
Challenges to Higher Burnup

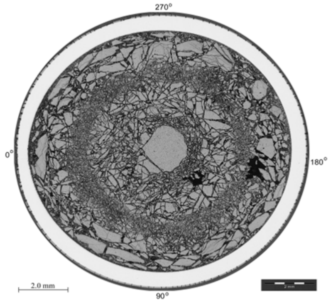
Higher Burnup - Fuel Fragmentation, Relocation, and Dispersal (FFRD)

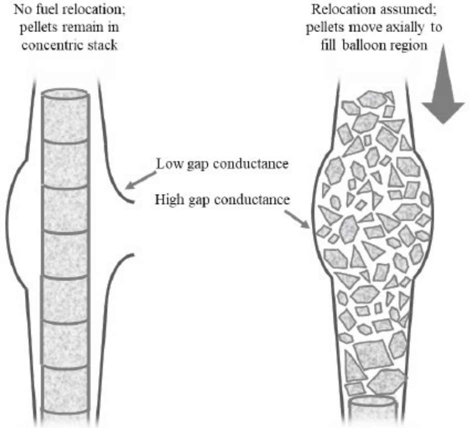
- At high burnup, experiments have shown that fuel can fragment during LOCA
- Differences in pressure across the cladding can lead to cladding ballooning and burst
- The fragmented fuel can relocate axially into the ballooning region of the fuel rod and if burst occurs, disperse into the RCS

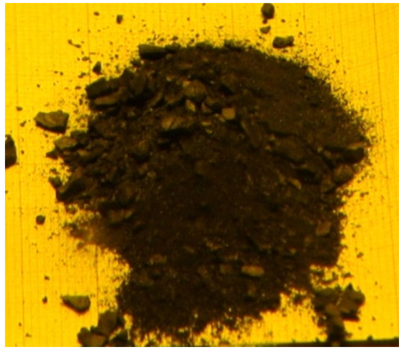


Burst openings from Studsvik LOCA tests (NUREG-2121)









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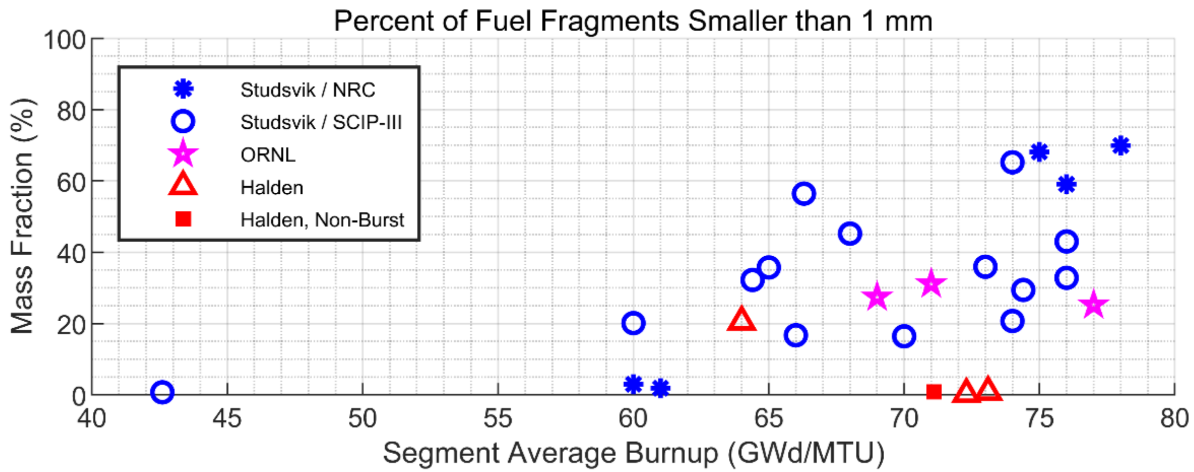
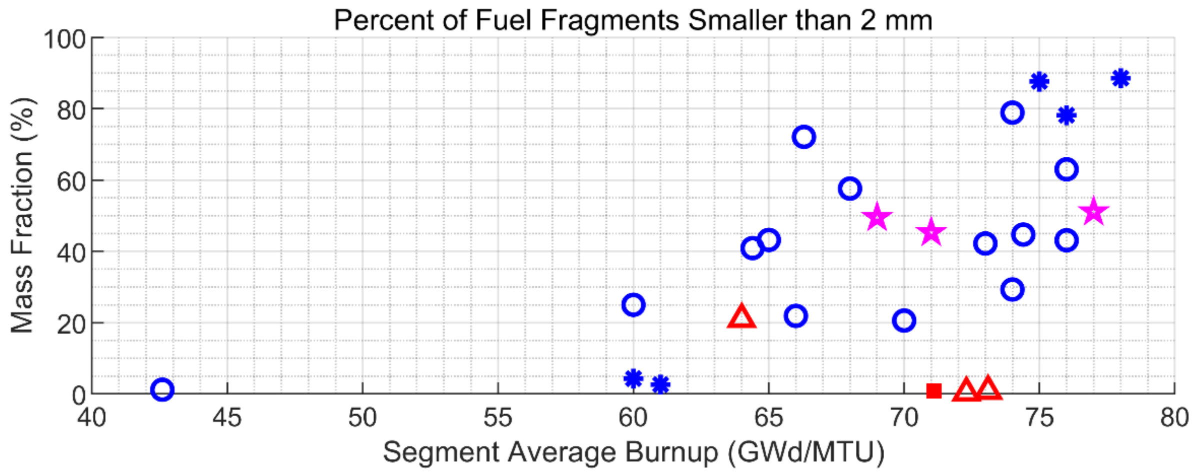
Cont'd Higher Burnup - Fuel Fragmentation, Relocation, and Dispersal

- Test data indicates that fuel dispersal increases with burnup
- Large scatter on the dispersal amount





FFRD is the main technical challenge for higher burnup

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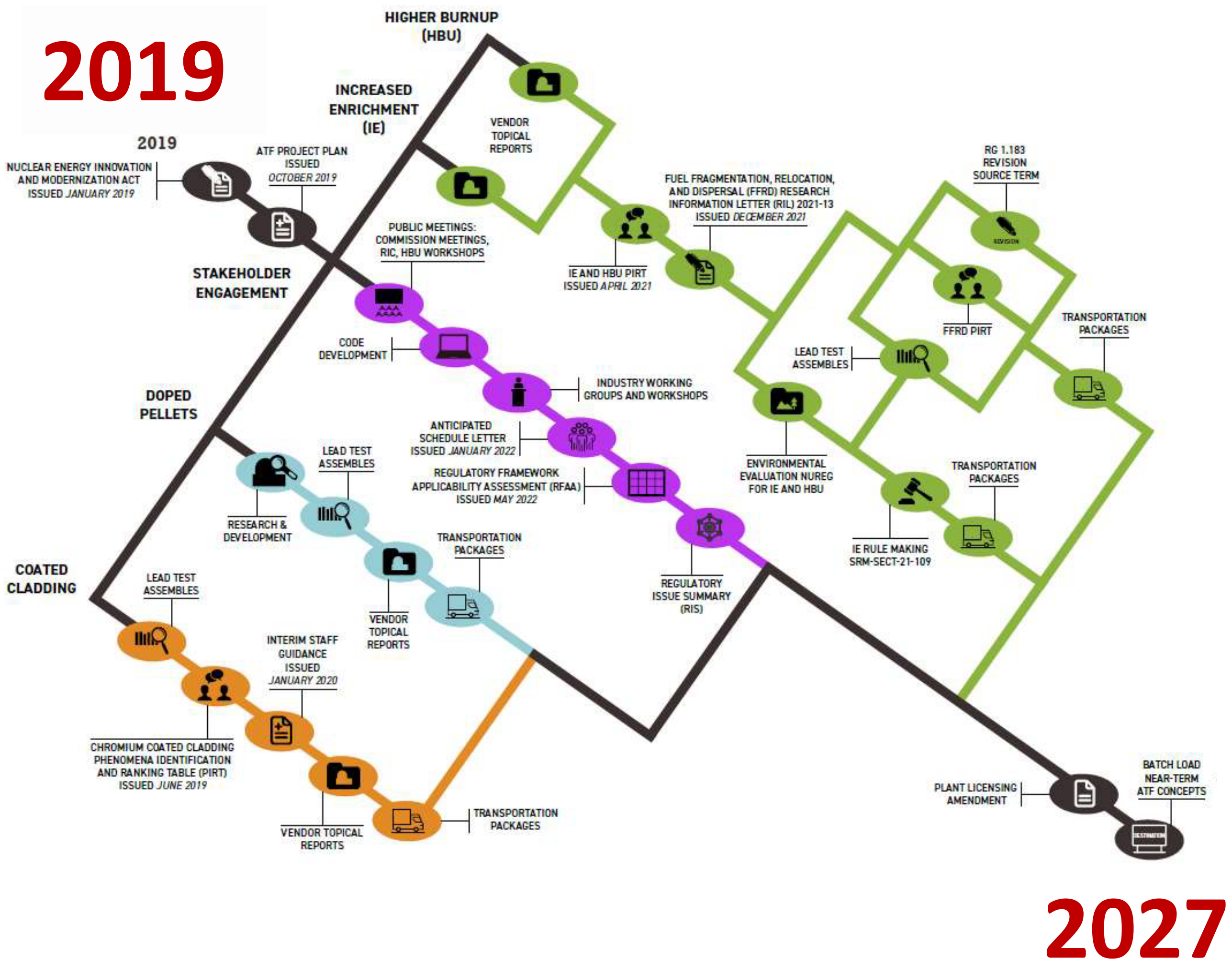
Current Status and Plans Forward for Higher Burnup Fuel

- Westinghouse recently obtained approval for a rod average limit of 68 GWd/MTU
  - Contingent on no high burnup rod burst in loss-of-coolant accident (LOCA) due to fuel fragmentation concerns
  - High burnup fuel could only be placed at low power core periphery locations
- Framatome submitted a high burnup topical report in 2024, ANP-10358P
- Some European countries may have higher limit
  - e.g. Switzerland has no fixed set limit and have irradiated fuel to much higher burnup
- Industry wide effort in the U.S. to increase burnup limit to 75 GWd/MTU rod average burnup



U.S. NRC Roadmap for Licensing HBU, IE, and ATF

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Regulatory Options to address FFRD in Higher Burnup Fuel

Options to address FFRD

Risk-informed LOCA
Develop a risk-informed transition break size methodology

ALS
A regulatory framework to address large break LOCA-induced FFRD using fracture mechanics and leak before break (LBB)

Dispersal
Develop a risk-informed method to address FFRD consequences when fuel dispersal occurs

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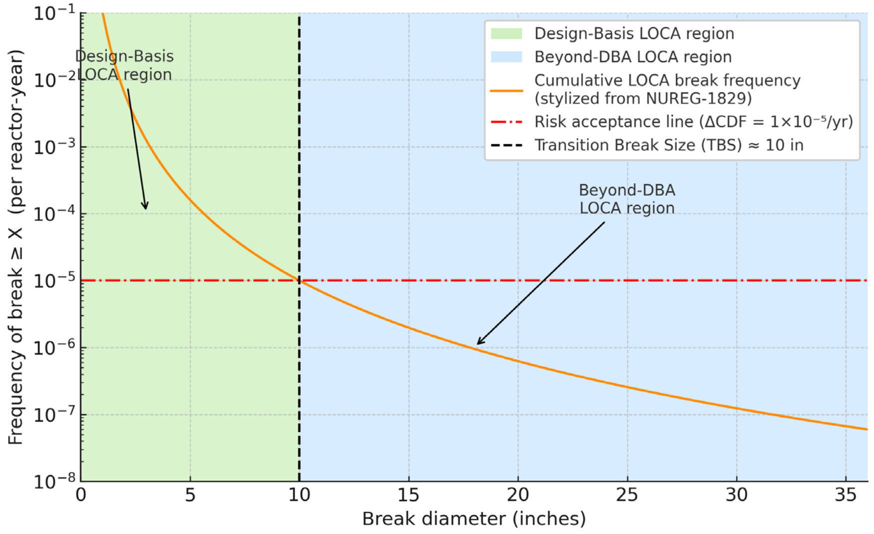
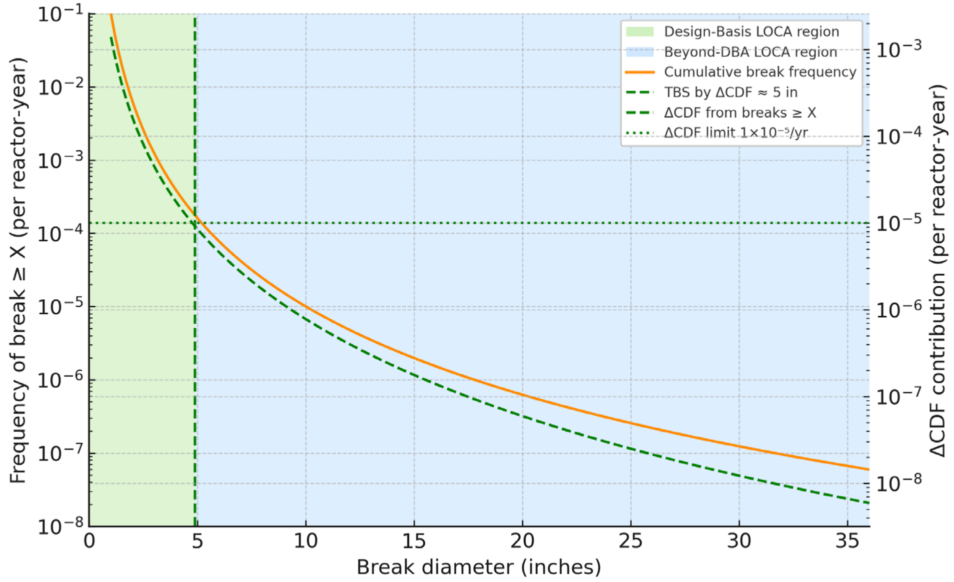
Risk-Informed LOCA

- Risk-informed framework for defining transition break size (TBS)
  - TBS delineates LOCAs which transition from design basis to beyond design basis events
- Realistic treatment of LOCA assumptions above TBS
- Relaxation of some LOCA assumptions below TBS
- More realistic treatment is expected to preclude fuel cladding rupture and fuel dispersal in most plants





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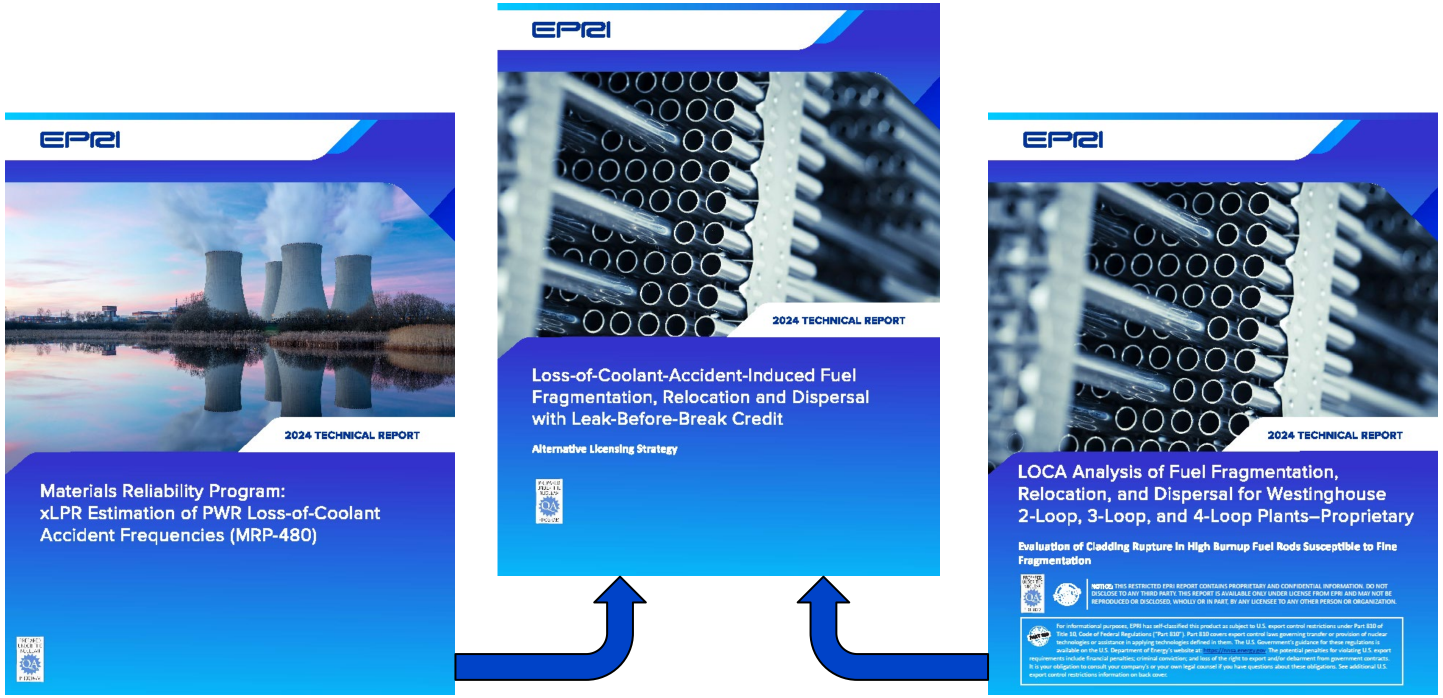
Alternative Licensing Strategy (ALS)

- Credits leak rate detection to shutdown the reactor well in advanced of the large piping rupture
- Applies conventional LOCA analysis to small and intermediate breaks
- Precludes cladding rupture and dispersal of fine fuel fragments



Under NRC Review – Final approval is expected in 2026

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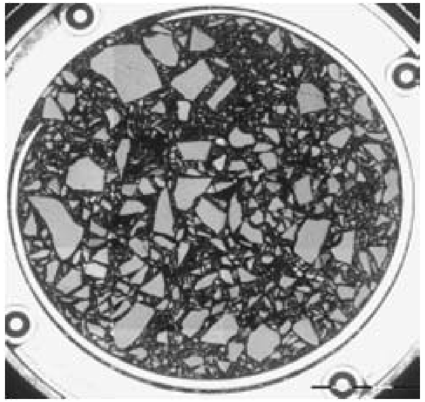
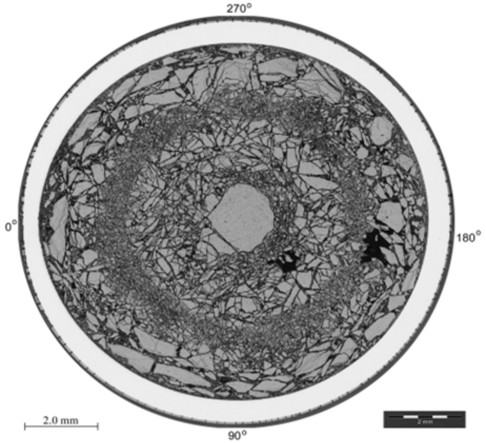
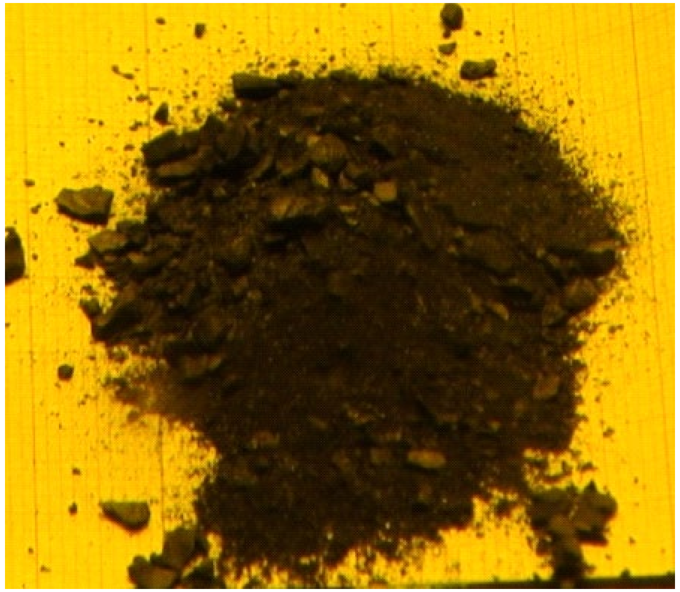
Dispersal

- Address the expected consequences of fuel dispersal
- Coolable geometry with fine fragments trapped between fuel grids
- Potential for re-criticality in the vessel or in the containment
- Radiological consequences of the fuel particle release







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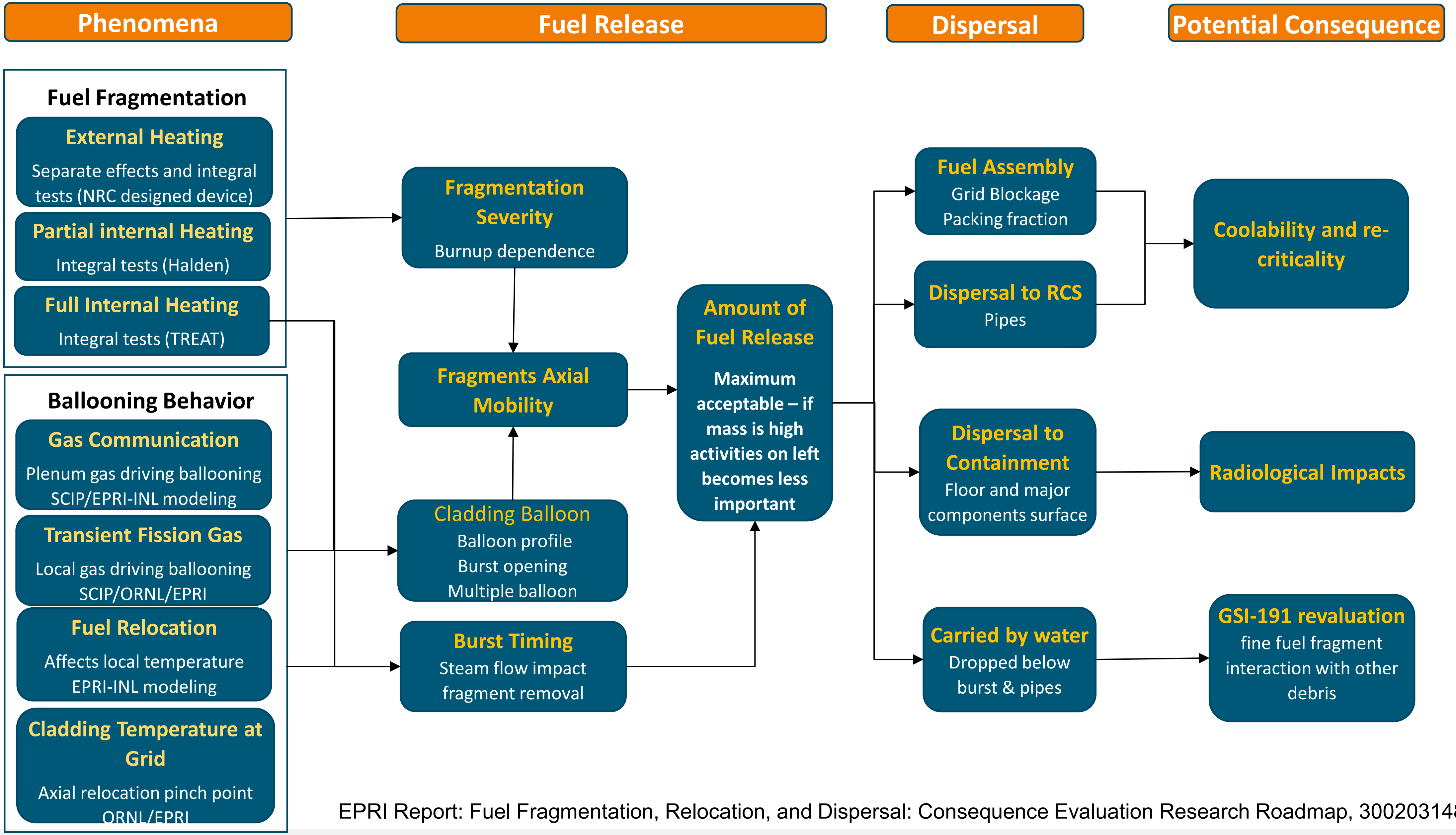
Roadmap for FFRD and Potential Consequences



EPRI Report: Fuel Fragmentation, Relocation, and Dispersal: Consequence Evaluation Research Roadmap, 3002031480

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Fuel Performance Methods for High Burnup

- Fuel suppliers need to license their fuel performance methods to higher burnup
- Potential issues related to high burnup fuel
  - Fuel cladding corrosion and hydrogen pickup
  - Fuel cladding mechanical properties
  - Fuel and cladding microstructure
  - Fission gas release
  - Fuel rod growth
  - Fuel assembly structural component growth (i.e. spacer grids)
- Combination of poolside and hot cell PIE

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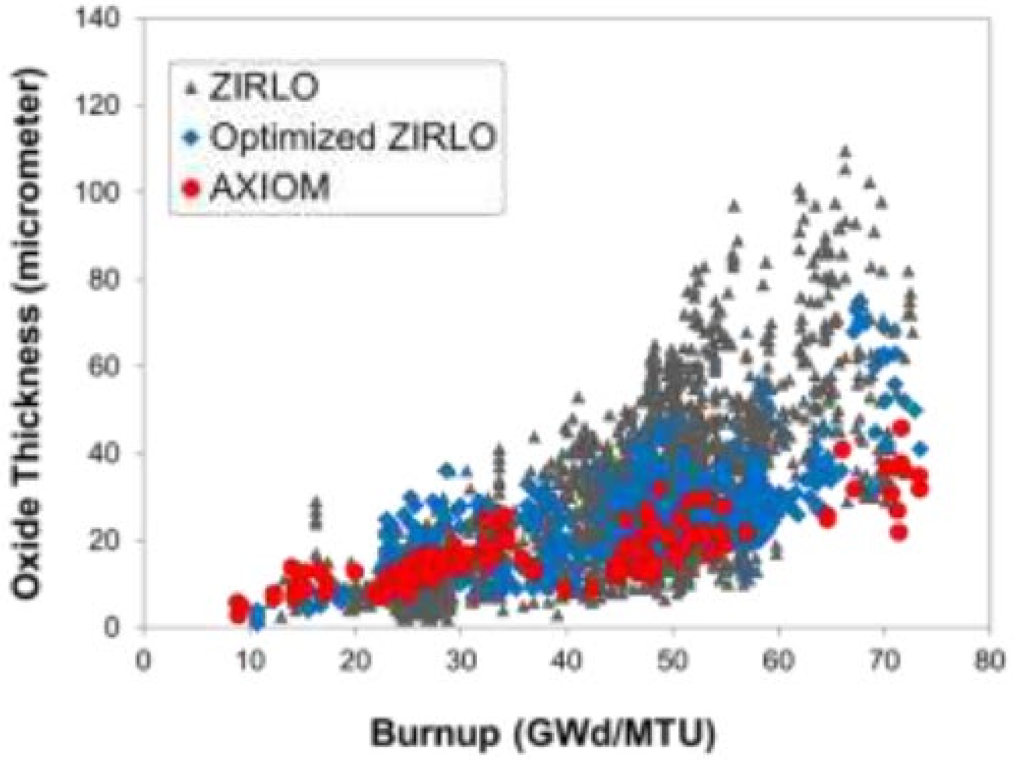
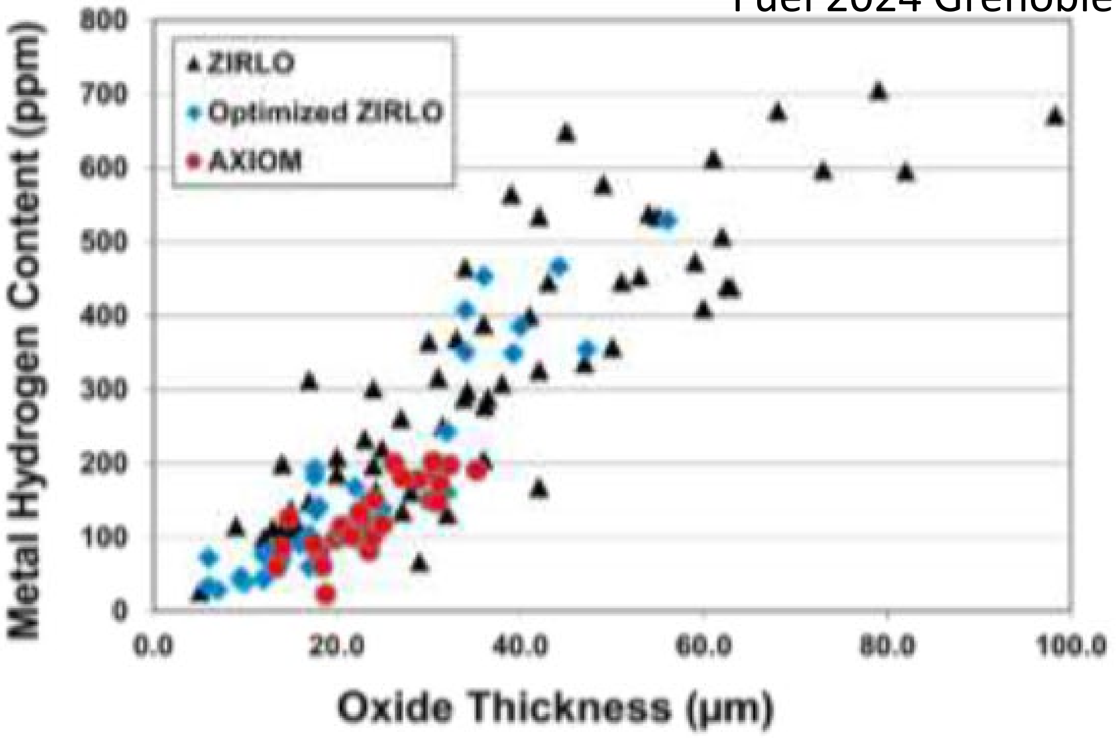
Fuel Cladding Development

M. L. Boone et al. Top Fuel 2024 Grenoble





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Potential Fuel Performance Challenges

PWRs with Power Uprates, Cycle Length Extension, and Higher Burnup/Increased Enrichment

- PWR CIPS/CILC*
- Margin challenges for other performance areas such as PCI and assembly structural

BWRs with Power Uprates

- Debris-induced fuel failures
- Margin challenges for other performance areas such as water chemistry

- Potential risks need to be understood, managed, and accommodated in the new fuel designs
- Fuel inspections will be needed to confirm the performance
  - Coordinated inspection plan will reduce the burden on utilities

Targeted fuel inspections coordinated within the industry needed

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Summary

- System and operational changes affect fuel performance and may reduce fuel reliability margins
  - Fuel failures are costly and can negatively impact public perception
  - Fuel inspections and R&D are required to improve and ensure continued good fuel performance

- Industry-wide interest in increased enrichment, higher burnup, increased fuel cycle length, and power uprates
  - Improved economics, improved operational flexibility, and reduced risk
  - Programs are in place to reach the targets around 2030-2034

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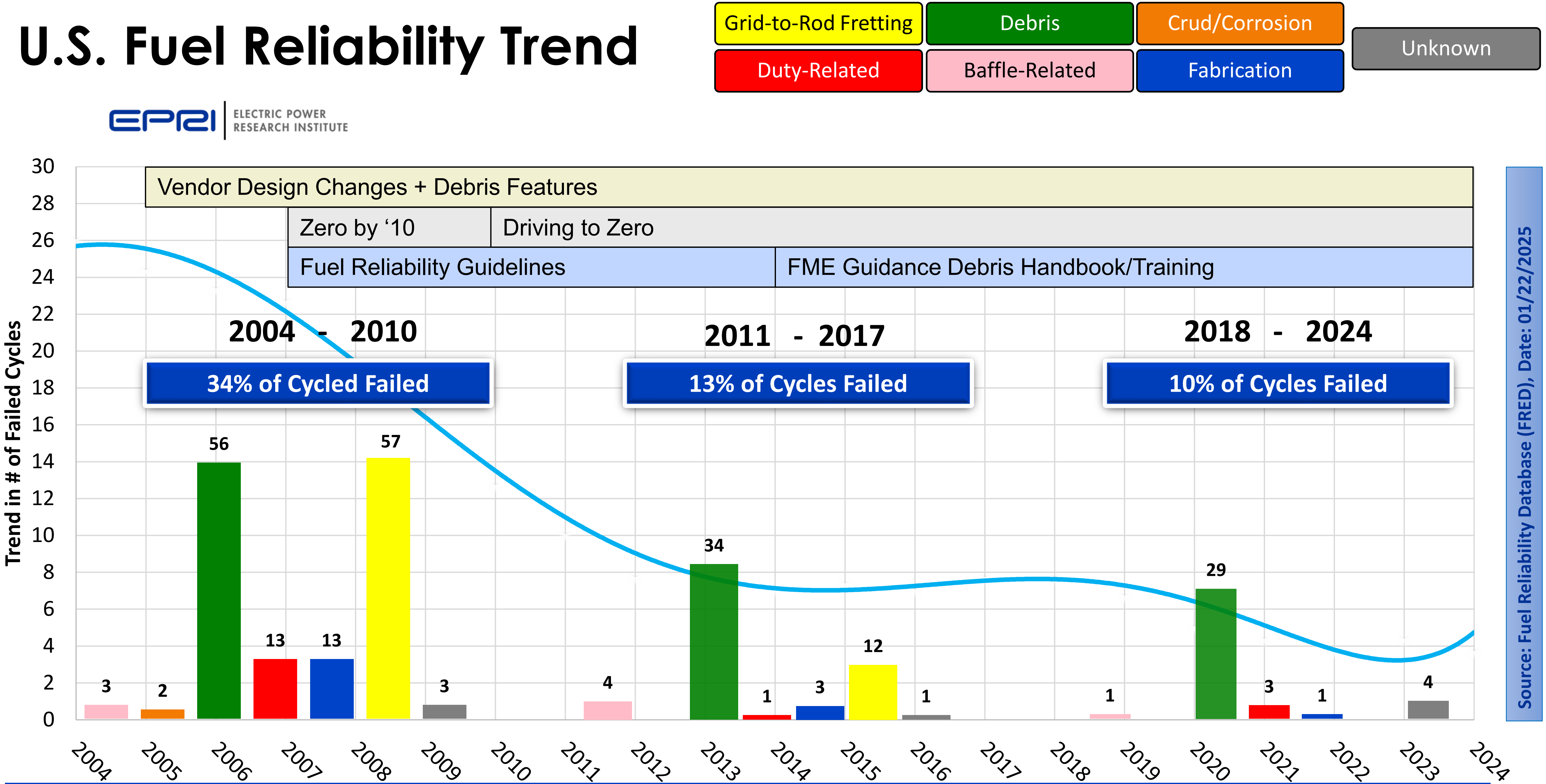
U.S. Fuel Reliability Trend



Debris appears the major cause of failure over the past ~ 15 years

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