Slide Presentations for the 2018 Westinghouse Fuel Performance Update Meeting (Non-Proprietary)

July 2018

(217 pages attached)

Westinghouse Electric Company
1000 Westinghouse Drive
Cranberry Township, PA 16066

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Westinghouse PWR Fuel Performance Update

July 18, 2018
Jeremy King
Director, Product Engineering

OUR VISION AND VALUES

Westinghouse will be the global nuclear energy industry's **first choice** for safe and efficient solutions as the world seeks clean, safe, environmentally sustainable energy programs now, and into the future.

We enhance our delivery of that vision by living our strong value system every day:

- Safety & Quality First
- Valuing Ethics, Integrity & Diversity
- Passion for Serving Our Customers Globally
- Dedication to Each Other Through Servant Leadership
- Creating Value for Shareholders, Customers and Employees
- Consistently Delivering On Our Commitments

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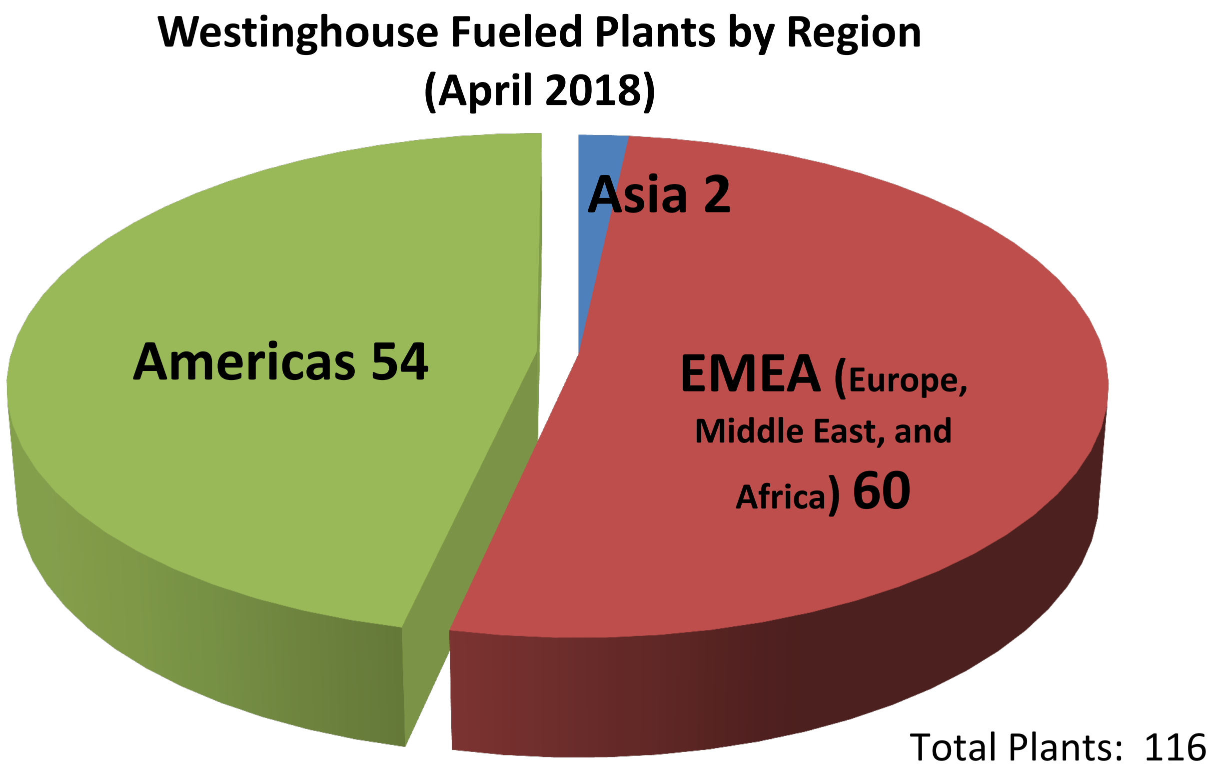
Agenda

- **Fuel performance update**
- Fuel reliability improvement process
- New inspection tooling for assembly visuals
- Summary

Westinghouse Fueled Plants by Region



Global Fuel Reliability Process Required to Achieve and Maintain 100% Leak-Free, Issue-Free Fuel

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Nuclear Fuel Reliability Progress – April 2018

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U.S. Nuclear Fuel Reliability Progress – April 2018

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Westinghouse leads the U.S. industry due to our continuous improvement fuel reliability process and strong industry partnerships

EMEA Nuclear Fuel Reliability Progress – April 2018

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Overall Westinghouse leads the EMEA industry but there are some challenges for BWR plants and some PWR plants

Historical Performance of Westinghouse Fueled Plants

[ ]a,c

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Leaking Plants, April 2018

[ ]a,c

[ ]a,c

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Historical Performance of Plants Currently Leaking April 2018

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Driving to Flawless Fuel Through Design – Current Status (April 2018)

[ ]a,c

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Driving to Flawless Fuel Through Design – Challenges: PIEs/RCAs conducted in 2016/2017/2018

[ ]a,c

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Driving to Flawless Fuel Through Design – Challenges: PIEs/RCAs conducted in 2016/2017/2018

[ ]a,c

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Recent Debris Leaker RCA Results (2016-2018)

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Driving to Flawless Fuel Through Design – [ ]a,c

[ ]a,c

Agenda

- Fuel performance update
- **Fuel reliability improvement process**
- New inspection tooling for assembly visuals
- Summary

Fuel Reliability Improvement Process - Achieving Positive Results for Our Customers

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Fuel Reliability Improvement Process

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Fuel Reliability Improvement Process

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Fuel Reliability Improvement Process

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Key topics in Westinghouse Fuel Reliability Improvement Process

[ ] a,c

Fuel Reliability Improvement Process – [ ]a,c

[ ]a,c

Fuel Reliability Improvement Process – [ ]a,c

[ ]a,c

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Fuel Reliability Improvement Process – [ ]a,c

[ ]a,c

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Fuel Reliability Improvement Process – Other Activities

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Agenda

- Fuel performance update
- Fuel reliability improvement process
- **New inspection tooling for assembly visuals**
- Summary

New Inspection Tooling for Assembly Visuals

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New Inspection Tooling for Assembly Visuals

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New Inspection Tooling for Assembly Visuals

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New Inspection Tooling for Assembly Visuals

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[ ]

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New Inspection Tooling for Assembly Visuals

[ ]a,c

[ ]a,c

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Field Services, Nuclear Services – [[redacted]]a,c

[ ]a,c

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Field Services, Nuclear Services: [ ]a,c

[ ]a,c

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Field Services, Nuclear Services: [ ]a,c

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Field Services, Nuclear Services: [[redacted]]a,c

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Summary

[ ]a,c

Questions?

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Westinghouse AXIOM™ Fuel Rod Cladding Material

July 18, 2018
Andrew Atwood and Jeremy King
Product Engineering

Introduction

- AXIOM cladding: Next generation of robust alloy targeting very high fuel duties
  - Building on the successes of **Optimized ZIRLO™** cladding
  - Designed to exhibit improved corrosion resistance, lower hydrogen pick-up, and lower creep and growth
  - Further reduction of tin, a partially recrystallized (PRXA) final microstructure as well as additional alloying elements to improve specific properties

Background and History

- The development of AXIOM alloys started in 2000, with four major variants
- Extensive out-reactor characterization program has been conducted.
- Lead Test Rod campaigns to inform final alloy selection were initiated in 2005
- AXIOM alloy has been irradiated in a variety of reactors worldwide including:
  - Five power reactors
  - Two test reactors
  - Max burnup 75 GWD/MTU
- Creep and Growth Behavior has been validated by four 18-month cycle operating experience and measurements from Vogtle Creep and Growth program

Background and History (cont.)

- An extensive post irradiation exam (PIE) database of poolside and hot-cell results has been developed, including
  - Poolside and hot-cell oxide measurements
  - Poolside and hot-cell length measurements
  - Poolside and hot-cell profilometry measurements
  - Hot-cell mechanical testing at burnups over 70 GWD/MTU
  - Metallography, Scanning Electron Microscopy, and Transmission Electron Microscopy evaluation of irradiated microstructure and Second Phase Particle composition
  - High precision creep and growth measurements
  - Hydrogen content measurements

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Current Status of AXIOM Alloy Development

- Westinghouse has selected AXIOM Composition [ ]^{a,c} as the final material for the program
- AXIOM material selection was based on multiple variables that included:
  - Corrosion and hydrogen
  - Creep and growth behavior
  - Compatibility with fuel rod design criteria
  - Tolerance for coolant chemistry variability
  - Strength properties
  - Anticipated compliance with 10 CFR 50.46c requirements
  - Manufacturability
  - Microstructure stability at high burnup

Alloy selection based on best overall performance to ensure that all operating requirements were considered

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Alloy Composition and Performance

- Cladding Material Nominal Composition (wt-%)

Alloy	Micro-structure	Nb	Sn	Fe	Cu	V	Zr
AXIOM™	pRXA	0.7	0.35	0.1	0.12	0.25	Bal.
ZIRLO®	Stress Relief Annealed	1	1	0.1			Bal.
Optimized ZIRLO™	pRXA	1	0.67	0.1			Bal.

- Selected performance of the chosen AXIOM cladding will be presented in the following slides

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AXIOM LTA Programs Summary

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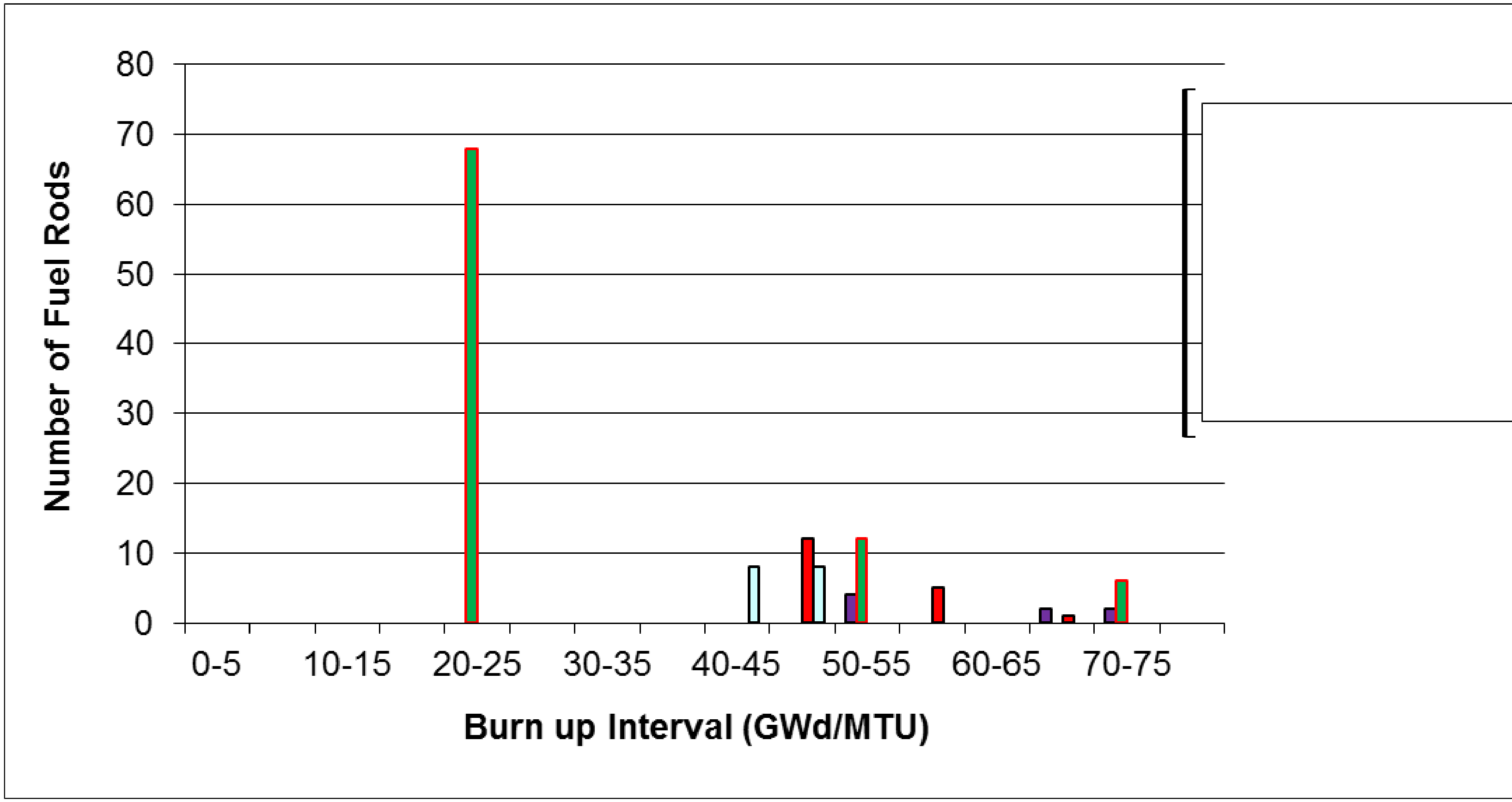
AXIOM Lead Test Rods Irradiation Experience



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In-Reactor Corrosion

[ ]a,c [ ]a,c

- **Significant advantage of AXIOM and *Optimized ZIRLO* at higher burnups;**
- **Less than [ ]a,c of oxide thickness for AXIOM alloys with MFDI up to 1000 and burnup of about 70 GWd/MTU.**

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Irradiation Growth and Creep

[ ]a,c

- **No accelerated rod growth for high burnups**
- **The general growth trend for AXIOM rods is relatively flat.**
- **Significantly less steady-state creep rate for AXIOM rods.**

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Hydrogen Pickup

[ ]a,c

- ***Optimized ZIRLO* Cladding:**
  - **lower overall hydrogen contents, with similar hydrogen pickup fraction and lower oxide thickness**
- **AXIOM Cladding:**
  - **Significantly lower overall hydrogen contents, with both lower hydrogen pickup fraction and lower oxide thickness**

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Mechanical Properties

Axial tensile tests of representative **Optimized ZIRLO** and AXIOM samples, about 3 m elevation tested at room temperature (RT) or 385°C (HT).

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AXIOM Alloy Implementation and Licensing

- Full AXIOM LTAs demonstrations
  - Continue to demonstrate the performance benefits of AXIOM clad materials in representative operating conditions
  - Gather additional operating experience and poolside data to supplement the existing PIE database for AXIOM alloy to provide additional support for licensing and commercial introduction of AXIOM alloy as a new cladding material.
- Eight (8) full AXIOM LTAs started irradiation in [ ]a,c reactor in Fall 2017.
  - Full production size ingot
  - Full range of AXIOM fuel fabrication qualification completed.
  - Comprehensive characterization conducted
  - Exemption request approved in about one year
  - 10 CFR 50.59 evaluation inputs completed.
- AXIOM lead tests rods inserted for 1 cycle irradiation experience in EDF plant in 2017 to obtain creep data

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AXIOM Cladding Development Program Timeline

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Summary

- AXIOM cladding was developed based on the successes of **Optimized ZIRLO** cladding to target increasingly challenging fuel management practices
- After about 16 years of development, Westinghouse has selected the final AXIOM cladding composition, based on the extensive PIE database of poolside and hot-cell results from various irradiation programs as well as out-of-reactor testing.
- The AXIOM alloy has demonstrated significant performance improvement including in-reactor corrosion, hydrogen pick-up, dimensional stability as well as post irradiation ductility, compared to ZIRLO and **Optimized ZIRLO**, especially in high duty operating environments.
- Full AXIOM LTA demonstrations are currently ongoing to provide additional support for licensing and commercial introduction of AXIOM alloy
- AXIOM topical report submittal is planned in 2020 and first reload is planned for 2023.

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Thank You

Questions / Comments

Westinghouse **EnCore**®
Accident Tolerant Fuel (ATF) Program

July 18, 2018

David Mitchell – Fellow Engineer

Westinghouse

Outline

- Westinghouse ATF development program
  - Products and benefits
  - Status
- Licensing actions for ATF
  - LTRs/LTAs
  - PIRT process
  - Topical reports
- Summary

LTR: Lead Test Rod
LTA: Lead Test Assembly
PIRT: Phenomena Identification and Ranking Table

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Westinghouse's EnCore® ATF Program

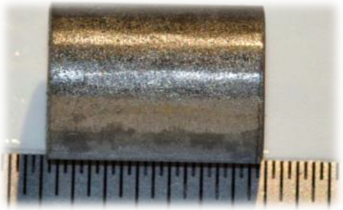
- Advanced Cladding
  - Cr-coated zirconium: increases maximum temperature by up to [ ]^{b,d}
  - Silicon Carbide: increases maximum temperature by up to [ ]^{b,d}
- Advanced Fuel
  - ADOPT™ doped UO_2 fuel: increases density and reduces pellet-cladding interactions
  - U_3Si_2 fuel: increases density and thermal conductivity

Chromium-Coated Zr Cladding

Silicon Carbide (SiC) Composite Cladding

ADOPT Pellets

Uranium Silicide (U_3Si_2) Pellets



Courtesy of Idaho National Laboratory

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Westinghouse approach has intermediate ATF products to enable full region licensing in an incremental fashion

Safety and Economic Benefits

- Comparison of benefits of ATF concepts

Benefit	Current Zr/UO_2	Cr-Coated CZR/UO_2 - Adopt	Cr-Coated CZR/U_3Si_2	SiC/U_3Si_2
Pellet U Loading			17%	17%
Fuel Utilization				
Grid to Rod Fretting/ Debris Resistance				
Load Follow/Flexibility				
LOCA/DBA Margin				
DNB Margin				
Hydrogen (10CFR50.44 Margin)				
Beyond Design Basis Accident (BDBA) Margin/Operator Response Times				

Reference/No benefit
Some/Potential Benefit
Large Benefit

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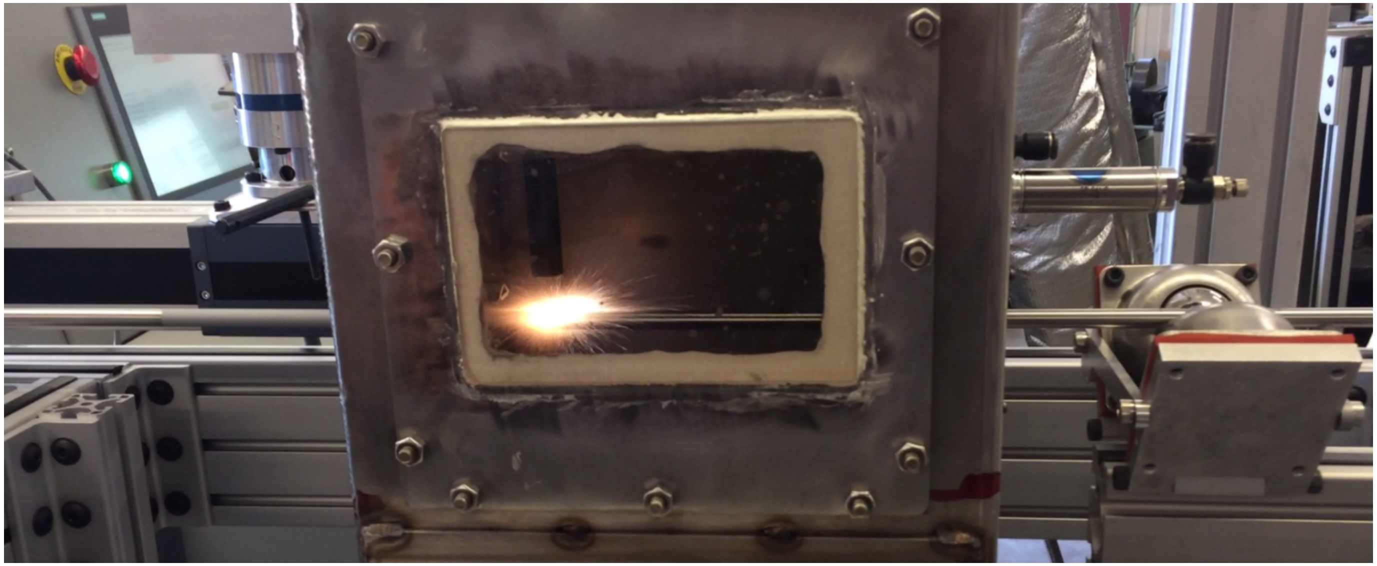
Status - Chromium-coated Zirconium Cladding

- Cold spray of chromium on standard cladding
- Coating of full length tubes achieved
- Ongoing tests and qualifications for LTRs



Cold Spray of Full Length Cladding Tubes

Coated Tube

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ARL VRC METAL SYSTEMS

Status - Chromium-coated Zirconium Cladding

- Design review process for Byron LTRs ongoing
  - Characterization, testing and engineering analysis

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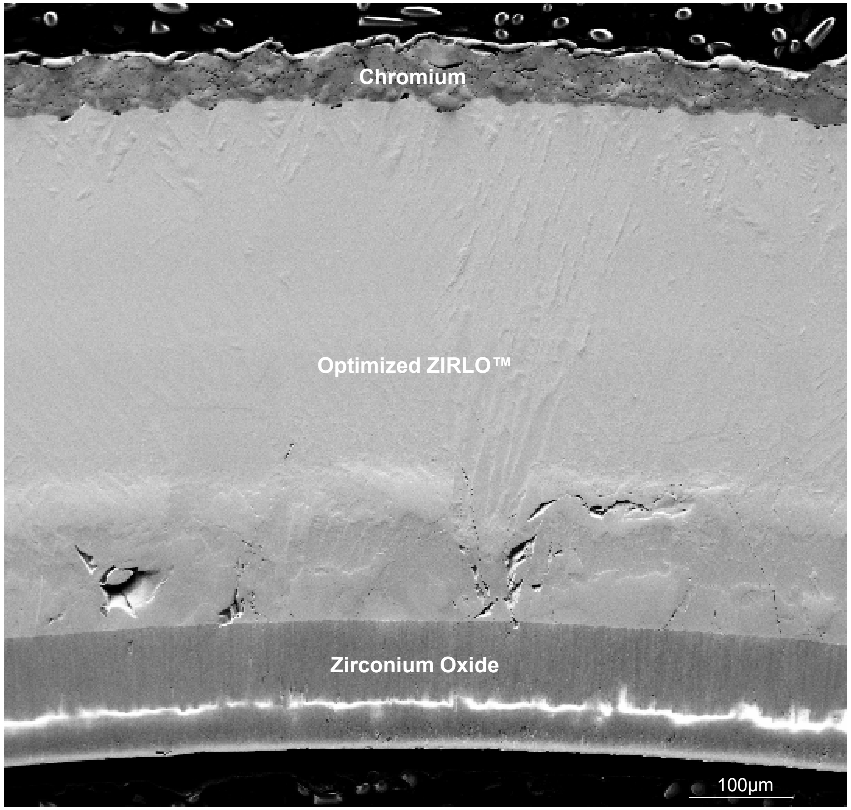
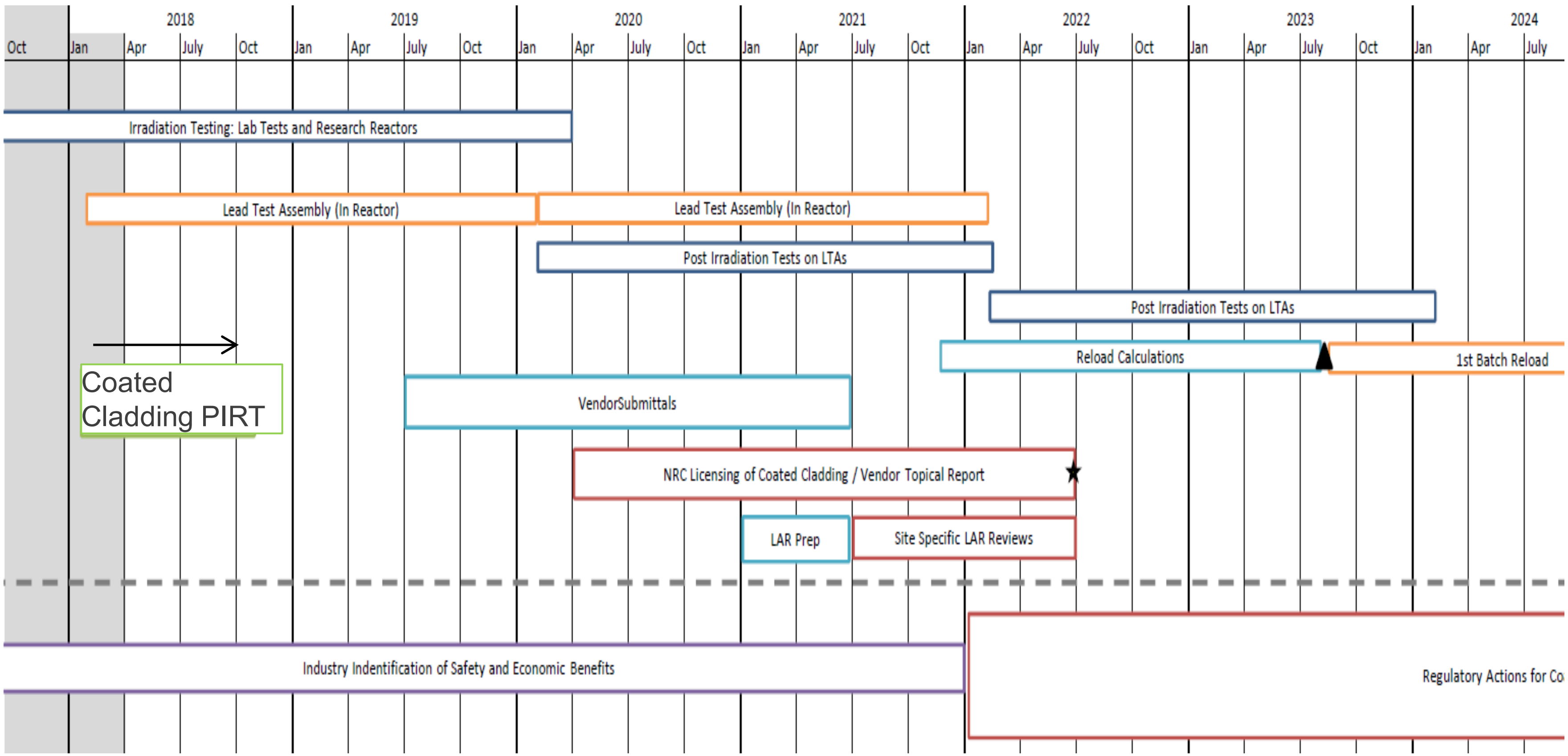


After Steam Oxidation for 20 minutes @1200°C

Status - Coated Cladding Timeline



Coated Cladding Timeline from NEI Regulatory Taskforce, April 2018

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Status – ADOPT Pellets

- ADOPT pellet is a commercial product for European market with extensive operating experience and superior performance
  - 10 years of reload scale deliveries
  - 15 reloads delivered
  - 8 fuel assemblies above 50 MWd/KgU
- ADOPT pellets for Byron LTRs already fabricated

Status - Uranium Silicide (U_3Si_2) Fuel Pellets

- U_3Si_2 fuel pellets included in Byron LTR
  - Small quantities in short fuel rod segments
- Fabrication of pellets for LTR by Idaho National Laboratory
- Development, testing and data collection regarding corrosion resistance ongoing

Status – Silicon Carbide Cladding

- Currently testing out-of-pile
  - Corrosion testing
  - Permeability
  - Mechanical testing
  - Pellet-cladding interaction
  - Joining techniques
  - Surface finishing
- Irradiation testing ongoing
- Preparation for insertion of LTRs in 2022

In-pile Testing – Overall Status

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Reactor Campaign	Insertion Discharge	Specimens	Discharge Irradiation	Status	Data and Comments

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Licensing Actions

LTRs/LTAs
PIRT Process
Topical Reports

LTRs/LTAs

- LAR for first LTR introduction in February 2019 was accepted for review by the NRC in April 2018
  - LAR was supplemented with revised scope
- Planning to follow NRC guidance for future LTRs/LTAs
  - Letter "CLARIFICATION OF REGULATORY PATHS FOR LEAD TEST ASSEMBLIES" from the NRC
  - Full use of the 10 CFR 50.59 process

PIRT Process

- Westinghouse participating in the discussion regarding PIRT process for near-term technologies
  - Coated cladding and doped pellets
  - Preparing to contribute if PIRT is required
- Westinghouse planning to perform separate PIRT for SiC cladding and advanced fuel pellets
  - Technologies are being developed only by Westinghouse
  - Experts will be drawn from Westinghouse, industry partners and selected research organizations
    - Based on technical capabilities and access to proprietary data.
  - PIRT for SiC targeted for 2019, based on availability of upcoming data.

Topical Reports

- Forecast for submittal of topical reports includes ATF
  - LTR-NRC-18-26
- Submittals planned for 3rd quarter of 2020
  - **EnCore** Fuel Coated Cladding
  - ADOPT Fuel for PWR
- Submittals for U_3Si_2 fuel and SiC will occur at a later date
  - Number of topical reports needed to be determined
  - Planning to enhance the value of test data by augmenting validation data with advanced (including atomistic) modeling and online data collection technology

Submittal of topical reports for coated cladding and ADOPT fuel in 2020

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Summary

Summary

- Westinghouse **EnCore**® Fuel products
  - Chromium-coated zirconium cladding
  - U_3Si_2 fuel pellets
  - SiC cladding
- Promising capabilities to achieve full safety benefits
- Ongoing testing program in preparation for LTRs/LTAs
- Licensing actions ongoing
  - LAR for Byron Unit 2 LTAs
  - Preparations for PIRT process ongoing
  - Including active engagement with the NRC

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EnCore® Fuel

We're changing nuclear energy … again

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NSAL-14-5 Critical Heat Flux Data Testing - ODEN 12 Update & Future Testing Plans

July 18, 2018

Mike Conner, Fellow Engineer
PWR Fuel Technology

Westinghouse

Outline

- Background: Need for Additional CHF* Testing
  - * *Critical Heat Flux. Also a referred to as DNB (Departure from Nucleate Boiling)*
- Planned CHF Testing for 17x17 OFA/IFM
- ODEN 12 Testing – April 2018
- Plan for ODEN 12.1
- Summary

Background: DNB Issue Described in NSAL-14-5

- Lower than expected CHF results were found during data analysis from new RFA test data
  - Non-conservatism observed for WRB-1, WRB-2, WRB-2M and WNG-1 DNB correlations
  - Almost all existing plant analyses were impacted but were unaffected due to analyses not reaching high quality conditions

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Discovery of Need for Additional Testing

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Safety/Operability Significance
(same position presented in 2017)

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Planned CHF Testing for 17x17 OFA/IFM

Overview of Planned Tests

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ODEN 12 Summary

April 2018

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ODEN CHF Test Facility

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- History
  - 2003 Previous facility closed after 52 yrs (Heat Transfer Research Facility, HTRF)
  - 2006 ODEN constructed (Västerås, Sweden)
  - 2010 Qualification tests completed
  - 2011 Production testing begun

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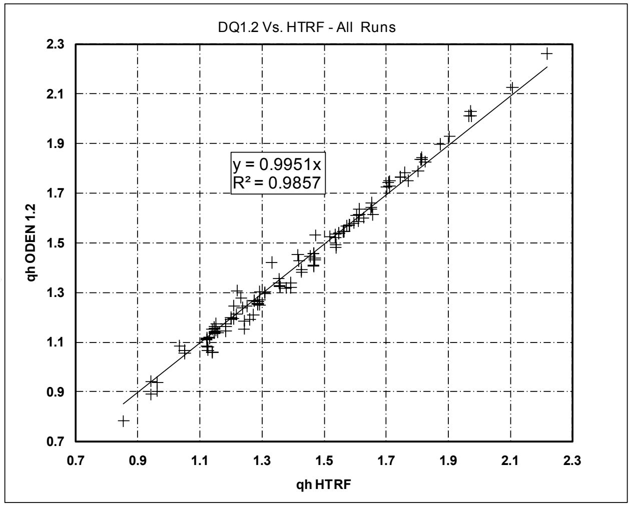
- Similar Capability to HTRF
  - Excellent ODEN to HTRF Repeatability



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ODEN CHF Test Facility: NRC tour 4/14/18 - Loop configuration (pressure vessel)

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ODEN 12 Test Section:
17x17 OFA/IFM Thimble Cell Geometry

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Plan Forward

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Summary

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Incremental High Burnup Extension

July 18, 2018

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Agenda

- Industry Motivation
- Industry Trends for High Burnup
- Outline of Proposed Incremental Burnup Extension
  - Scope of Incremental Burnup Extension
  - Fuel Rod Design Considerations
  - LOCA Analysis Considerations
  - Non-LOCA Considerations
  - Structural Considerations
- Licensing Approaches
- Summary

Acronyms

- AOR Analysis of Record
- ATF Accident Tolerant Fuel
- BOL Beginning of Life
- EOL End of Life
- FA Fuel Assembly
- FFRD Fuel Fragmentation Relocation and Dispersal
- FGR Fission Gas Release
- HFP Hot Full Power
- HZP Hot Zero Power
- LOCA Loss-of-Coolant Accident
- RCCA Rod Cluster Control Assembly
- RIA Reactivity Insertion Accident
- RIP Rod Internal Pressure
- RSAC Reload Safety Analysis Checklist
- TCD Thermal Conductivity Degradation
- TFUEL Fuel Pellet Average Temperature

Industry Motivation

- Industry core designs are frequently constrained by the lead rod burnup limit so an increase in limit is expected to decrease reload batch size and result in more efficient fuel utilization
  - 18 and 24 month cycle designs could be made more efficient if lead rod burnup limit was increased

- EPRI received positive industry feedback at the February 2018 Reg-tac meeting on an incremental burnup extension

Improved fuel cycle economics help support continuing plant viability

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Industry Trends for High Burnup

- Various extensions are being considered as part of Accident Tolerant Fuel (ATF)
  - Extension of maximum fuel rod average burnup limit to [ ][a,c] GWd/MTU or beyond
  - Increase in maximum fuel enrichment

- Purpose of this program is a small extension in the current burnup limit for existing fuel designs under certain conditions
  - Demonstration application to VANTAGE5 fuel assembly design will be included

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Scope of Incremental Burnup Extension

- Increase maximum fuel rod average burnup limit of Westinghouse fuel designs to [ ]a,c GWd/MTU
  - Demonstrate fuel rods in high burnup assemblies do not rupture under LOCA conditions
    - Generically or via plant-specific simulations
  - Demonstrate high burnup rods do not violate the acceptance criteria for Rod Ejection Event
  - Address impact on radiological analyses
- Applicable to ZIRLO® and **Optimized ZIRLO**™ cladding

Prerequisites for Incremental Burnup Extension

- Use of best-estimate LOCA codes relative to rupture calculation under LOCA conditions
  - If plant-specific simulations are required
  - This would be a "one-off" calculation from the LOCA AOR

- Full not-LOCA PAD5 implementation
  - Transient Analysis
  - Fuel Rod Design

Fuel Rod Design - Expanded PAD5 Database

- Halden Project experiments provide measured fuel temperatures for UO_2 and Gd_2O_3-UO_2 fuel to high burnup [ ]^{a,c}
- Commercial irradiation programs provide measured fission gas release and rod growth data up to [ ]^{a,c} rod average burnup
- Joint International test programs provide data on high burnup [ ]^{a,c} fuel power ramp behavior

PAD5 added many high burnup and high duty data points

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Fuel Rod Design – PAD5 High Burnup Models

[ ]a,c

Technical bases for rod average burnup of [ ]a,c GWd/MTU are provided in PAD5 topical

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LOCA - Calculation of Cladding Rupture

- Basic methods for evaluating the conditions necessary for cladding rupture were previously established by Westinghouse, and are recognized in NUREG-2121 (“Fuel Fragmentation, Relocation, and Dispersal During the Loss-of-Coolant Accident”)
- Analytical methods can be used for more robust prediction of cladding rupture
  - Westinghouse realistic LOCA methods (ASTRUM, **FULL SPECTRUM**™ LOCA methodology) account for rupture and fuel relocation into the burst region, when burst is predicted to occur
  - Two different codes are used within the best-estimate methods (WCOBRA/TRAC and HOTSPOT vs. WCOBRA/TRAC-TF2), but important models are similar

LOCA - Important Considerations

- Important parameters and uncertainties to be considered
  - Uncertainty in fuel performance data (TFUEL and RIP)
  - Burst temperature
  - Decay heat uncertainty
  - Initial conditions
    - Linear heat rate
    - Axial power distribution

- Expect to use a conservative / bounding approach for some key parameters

LOCA simulation to demonstrate no rupture will account for these items plus others

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LOCA - Preliminary LOCA Scoping Studies

- Several preliminary simulations were executed for representative Westinghouse 3-loop and 4-loop PWRs

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LOCA Analysis Considerations for High Burnup Preliminary Studies, 3-Loop PWR

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LOCA Analysis Considerations for High Burnup Preliminary Studies, 4-Loop PWR

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Non-LOCA

- Burnup dependency is part of the current rod ejection analysis
- RSAC burnup limits currently exist for BOL & EOL conditions for both HZP & HFP cases
- 3x3 region (ejection location and adjacent assemblies) are looked at to confirm the RSAC burnup limits
- New RIA criteria
  - Include several burnup dependent limits
  - Require burnup dependent analysis, including effects of thermal conductivity degradation, melting, and radial pellet power distribution
- 3DRE method addresses burnup dependent requirements of the new RIA analysis
- Incremental increase in burnup to [ ][a,c] GWd/MTU can be accommodated in either method

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Material Considerations

- Fuel Rod
  - Oxide thickness vs burnup
  - Fuel rod growth vs burnup
- Structural
  - Material thinning vs burnup
  - Structural growth vs burnup
  - FA bow vs burnup
  - RCCA drag vs burnup
  - Spacer grid growth vs burnup

Burnup extension requested within database and material behavior demonstrates operational capability

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Fuel rod peak oxide thickness as a function of burn-up

[ ]a,c

Sufficiently well behaved oxide data at high burnup is available

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Fuel rod growth as a function of fast fluence

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Sufficiently well behaved fuel rod growth data at high burnup is available

Westinghouse

Fuel Assembly Growth as a function of burnup

[ ]a,c

Sufficiently well behaved fuel assembly growth data at high burnup is available

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Licensing Impacts

- Extend approved burnup limits for fuel designs
  - Westinghouse fuel designs are approved to 62 GWd/MTU
  - CE fuel designs are approved to 60 GWd/MTU

- Extend allowable burnup for methods
  - PAD5 (technical bases supported burnup to [ ]^{a,c} GWd/MTU)
  - Best Estimate LOCA methods

- Evaluate impact to radiological consequence analyses of record for increased burnup

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Licensing Approaches

- Licensing submittal will
  - Define methodology to demonstrate no burst for rods that exceed 62 GWd/MTU and all other LOCA criteria are acceptable
  - Justify applicability of PAD5 and disposition RIA concerns
  - Provide summary of material performance

- Two options for submittal
  - Generic topical report: broad applicability to Westinghouse fuel
  - Plant-specific license amendment request: focused scope for efficient NRC review

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Summary

- Incremental extension of maximum fuel rod average burnup limit planned for current fuel designs with ZIRLO and **Optimized ZIRLO** cladding in advance of any later extensions planned with ATF
- PAD5 database and models support extension beyond [ ]^{a,c} GWd/MTU
- FFRD issues are addressed by limiting fuel rod power at burnups > 62 GWd/MTU and precluding burst under LOCA conditions
- No changes in current structural materials
- Prepare and submit licensing document [ ]^{a,c}

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Westinghouse BWR Fuel Performance Update

July 19, 2018

Jeremy King

Director, Product Engineering

Westinghouse

Agenda

- **BWR Fuel Performance Update**
- **TRITON11™** Fuel
  - Debris Failure Elimination Initiative
- **HiFi™** Cladding
- POLCA-T
- SLMCPR

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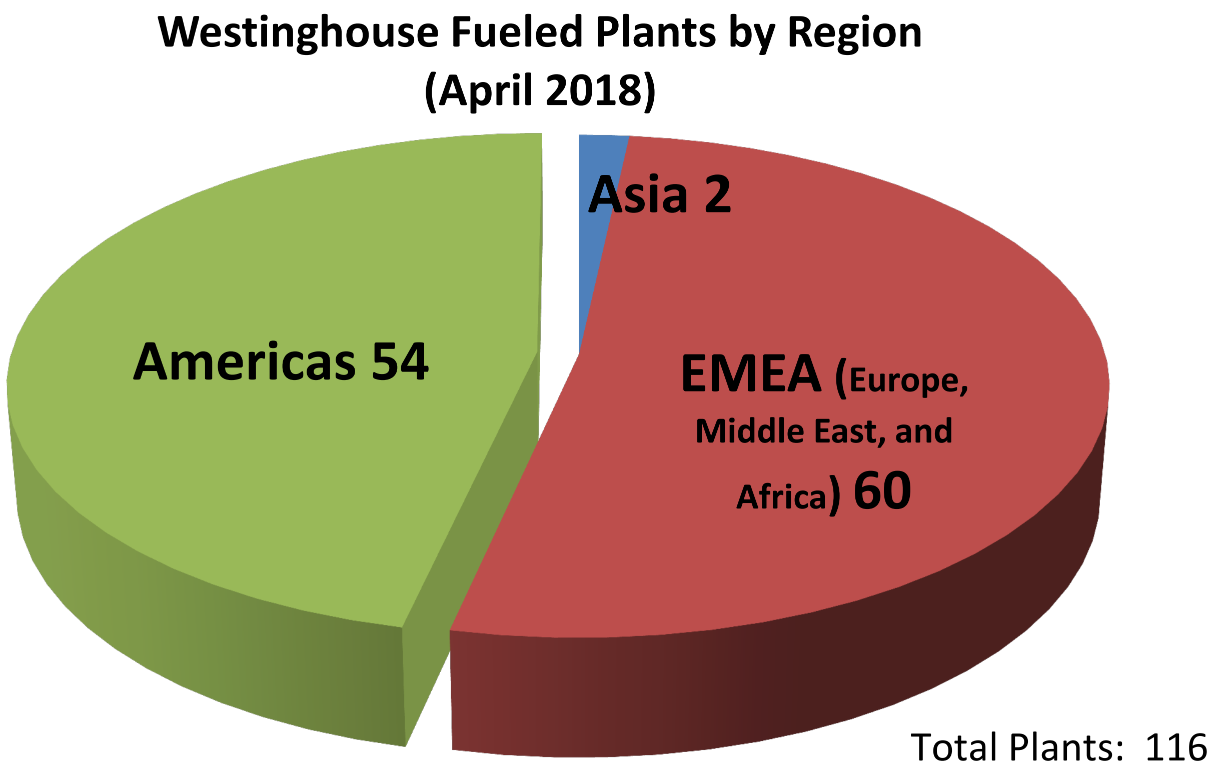
Westinghouse Fueled Plants by Region



<u>Global</u> Fuel Reliability Process Required to Achieve and Maintain 100% Leak-Free, Issue-Free Fuel

BWR Primary Failure Statistics 10X10 Fuel Designs Using Liner Cladding

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BWR Global Nuclear Fuel Reliability Progress – April 2018

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BWR EMEA Nuclear Fuel Reliability Progress – April 2018

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Westinghouse EMEA BWR Leaker Performance

a,c

Westinghouse EMEA BWR Leaker Performance

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Recent Westinghouse BWR Leakers

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Westinghouse BWR leaker causes

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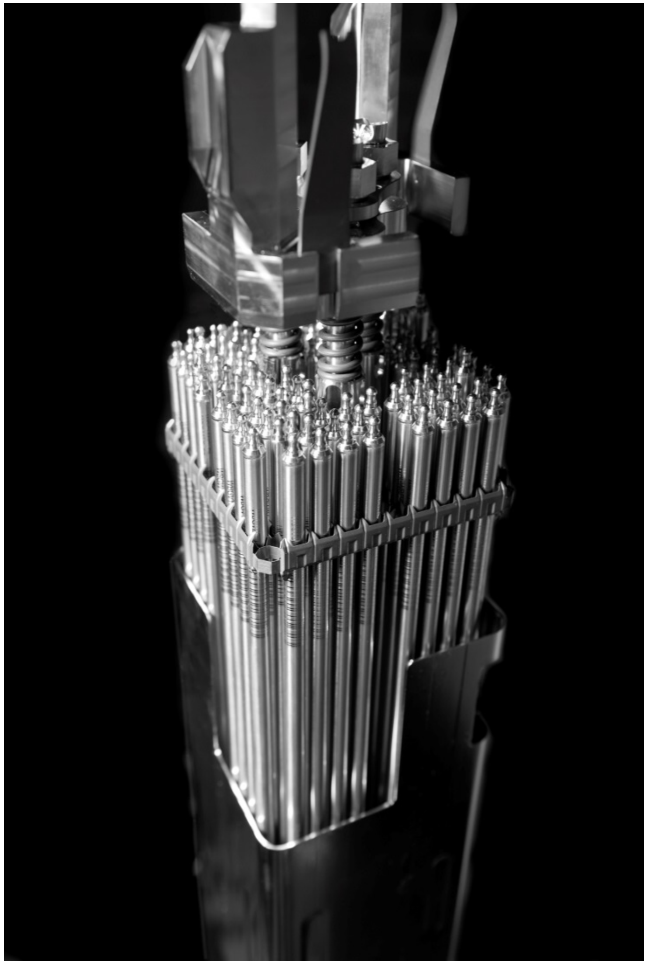
Agenda

- BWR Fuel Performance Update
- **TRITON11™ Fuel**
  - Debris Failure Elimination Initiative
- **HiFi™** Cladding
- POLCA-T
- SLMCPR

TRITON11™ Westinghouse 11x11 BWR Fuel Design



- *Next Generation BWR Fuel with;*
- ***Superior Fuel Economy***
- ***Robust Mechanical Design***
- ***Uncompromised Reliability***
- ***High-Performing Materials***

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TRITON11 Superior Fuel Economy

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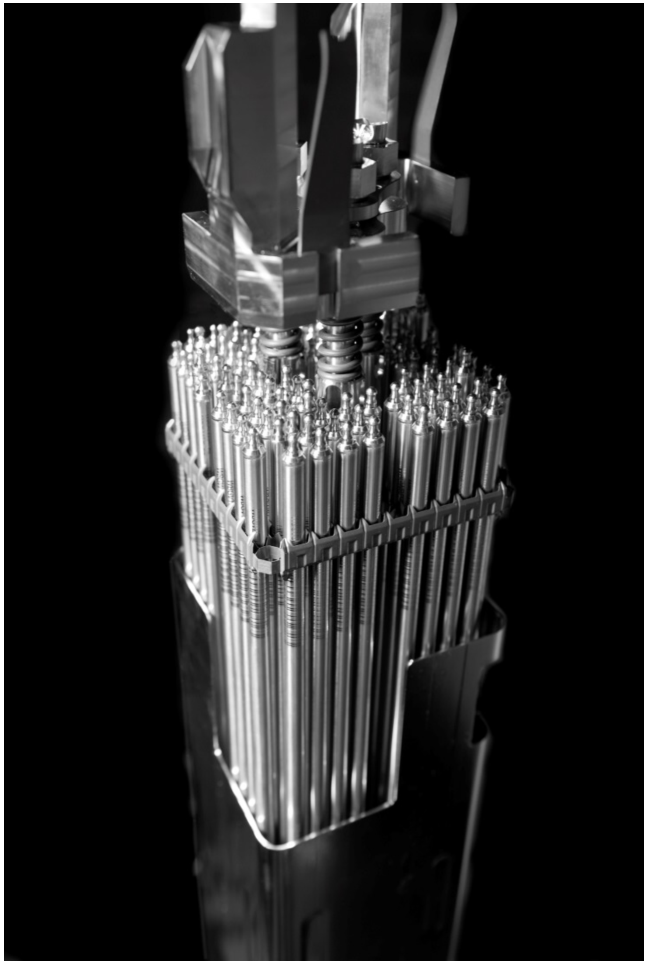

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TRITON11 – Robust Mechanical Design

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TRITON11 Innovation Overview

The greatest W-BWR fuel development leap since early 1980's

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TRITON11 Nordic Design - Project Status

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FRIGG Short Circuit in Final Top Peaked Test December 12, 2017

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Mechanical Verification

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Mechanical Verification - Example Handling Load and Tensile Tests

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Mechanical Verification - Example Functional Compatibility Tests

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Mechanical Verification - Example Spacer Capture Test

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Summary

- TRITON11 innovation project started in 2012
- TRITON11 design was selected among many conceptual designs and was optimized to current market conditions without constraints
- TRITON11 fuel provides superior fuel economy with uncompromised reliability
- TRITON11 has been received with strong customer interest in both Europe and US
- TRITON11 design builds upon proven components, mechanical design solutions and materials with known reliability benefits
- Manufacturing preparations are well under way and manufacturing of components to first LTAs have started

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Agenda

- BWR Fuel Performance Update
- **TRITON11**™ Fuel
  - **Debris Failure Elimination Initiative**
- **HiFi**™ Cladding
- POLCA-T
- SLMCPR

Remaining Challenge for W BWR Fuel: Eliminate Debris Fretting Failures

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Debris Failure Elimination Project

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Summary

- Significant effort made in Optima3 spacer design to mitigate debris fretting failures
- Potential lies in further development of debris filter and debris resistant coated cladding

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Agenda

- BWR Fuel Performance Update
- **TRITON11™** Fuel
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- **HiFi™ Cladding**
- POLCA-T
- SLMCPR

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HiFi Introduction Schedule

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HiFi Highlights from Past Year

- Start of **HiFi** irradiation in TVO mid 2017.
- Acceptance for review of NRC Topical Report "**HiFi** cladding for use in BWR fuel" in Sept 2017.
  - Planned issue of RAIs Oct 2019. Draft Safety Evaluation Feb 2020.

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Autoclave Results from **HiFi** Ingot 1

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Agenda

- BWR Fuel Performance Update
- **TRITON11™** Fuel
  - Debris Failure Elimination Initiative
- **HiFi™** Cladding
- **POLCA-T**
- SLMCPR

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CRDA and Stability Application

POLCA-T: System Analysis Code with Three-Dimensional Core Model

- General Parts describing the models,
- Appendix A: Control Rod Drop Accident Analysis (CRDA)
- Appendix B: Application for Stability Analysis

Approved by the NRC in 2010.

Accepted for use by the Nordic countries' Regulators.

Approved by the NRC in 2010

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Transients and ATWS analysis Application

- Appendix C: Application for AOO Transient Analysis
- Appendix D: Application for Anticipated Transients without SCRAM
- Submitted to NRC for NRO and NRR review in 2010, but review was paused until recently. Only review by NRR is pursued. An audit was held on June 11-13, 2018. Draft SER expected August 2019.
- Accepted for use by the Nordic countries' Regulators.
- Under licensing by Switzerland's Regulator.

NRC NRR draft SER expected by August 2019

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Agenda

- BWR Fuel Performance Update
- **TRITON11**™ Fuel
  - Debris Failure Elimination Initiative
- **HiFi**™ Cladding
- POLCA-T
- **SLMCPR**

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Westinghouse SLMCPR Activities

Recently Westinghouse has been involved in two separate BWR Safety Limit Minimum Critical Power Ratio activities.

1. WCAP-18032 is a supplement to the existing “Reference Safety Report for Boiling Water Reactor Reload Fuel” (CENPD-300-P-A). This supplement describes:
   - an improved mixed-core SLMCPR calculation method
   - methods for developing legacy fuel CPR correlations
2. Westinghouse also supported the BWROG initiative TSTF-564, which describes a revision to the technical specification SLMCPR definition to reduce cycle-to-cycle TS revisions.

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NRC RAI responses are being processed in both cases.

WCAP-18032

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- Creates an improved treatment of CPR for mixed-core conditions
  - More consistent application of the SLMCPR methodology between mixed-core and uniform core conditions
  - Better documentation of mixed-core approach
  - More conservative mixed-core SLMCPR
    - Conservatism eliminates the need for an adder to mixed core operating limit CPR (Limitation #7 of CENPD-300)

Submittal is NOT to change the basic SLMCPR methodology nor reduce overall conservatism. The change will improve CPR calculation and reduce licensing burden in transitions.

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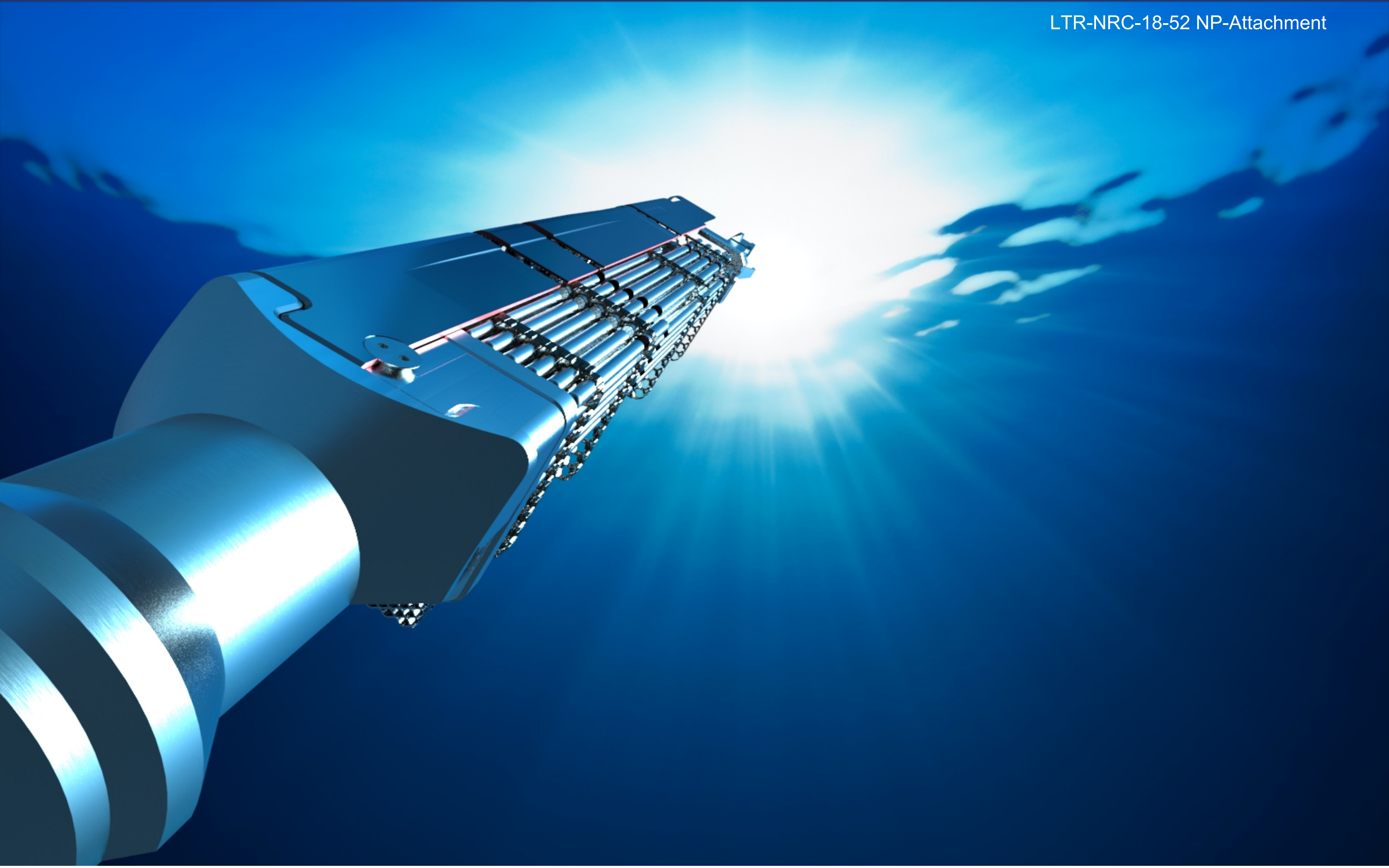
TSTF-564

- Effort supported by BWROG, Westinghouse, and GNF.
- The concept is to move the current cycle-specific SLMCPR in the Tech Specs into the Core Operating Limits Report to reduce frequent cycle-specific TS revision.
- The TS SLMCPR would be redefined to a 95% probability and 95% confidence value that would be tied to fuel product and therefore become cycle-independent.
- This approach will also be more consistent with PWR DNB limit definitions.



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July 19, 2018

Jeremy King

Director, Product Engineering

Westinghouse

Agenda

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Introduction

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Next steps

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Summary

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Additive Manufacturing (AM) Update

July 19, 2018
David Huegel
Fuel Product Engineer

Westinghouse

Additive Manufacturing (AM): Overview

- Westinghouse AM Objective
- Additive Manufacturing Process Benefits
- Examples of Westinghouse Prototypes
- Westinghouse AM Material Testing Performed to Date
- Westinghouse AM Thimble Plugging Device
- Schedule for AM Thimble Plugging Device
- Summary

AM: Objective

- Westinghouse is focused on using the AM process in order to produce high quality / high performance fuel products for use in commercial nuclear reactors.
- Westinghouse has performed significant testing, designing, prototype building, verifying design characteristics, validating material properties, etc. to ensure that the AM process is fully understood and thus can be safely used for producing high quality / high performance fuel components for use in commercial reactors.

AM: Benefits

AM process is being developed within Westinghouse to improve products and to enhance product performance.

1. AM provides design freedom allowing complex geometries to support existing and next generation plant component designs not easily produced with existing technologies.
2. Allows for advanced designs to improve fuel and reactor performance.
3. Allows for fast prototyping, mockups, fixtures, tooling, etc. to support advanced design development as well as manufacturing processes.

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AM: Benefits (continued)

AM process is being developed within Westinghouse to improve products and to enhance product performance.

4. Help minimize defects by reducing/eliminating multiple processes as components are manufactured in a single build.
5. Improved material lead-time and properties (custom chemistry, isotropic mechanical properties, improved machinability, improved inspectability, etc.).

Advanced Designs Obtainable

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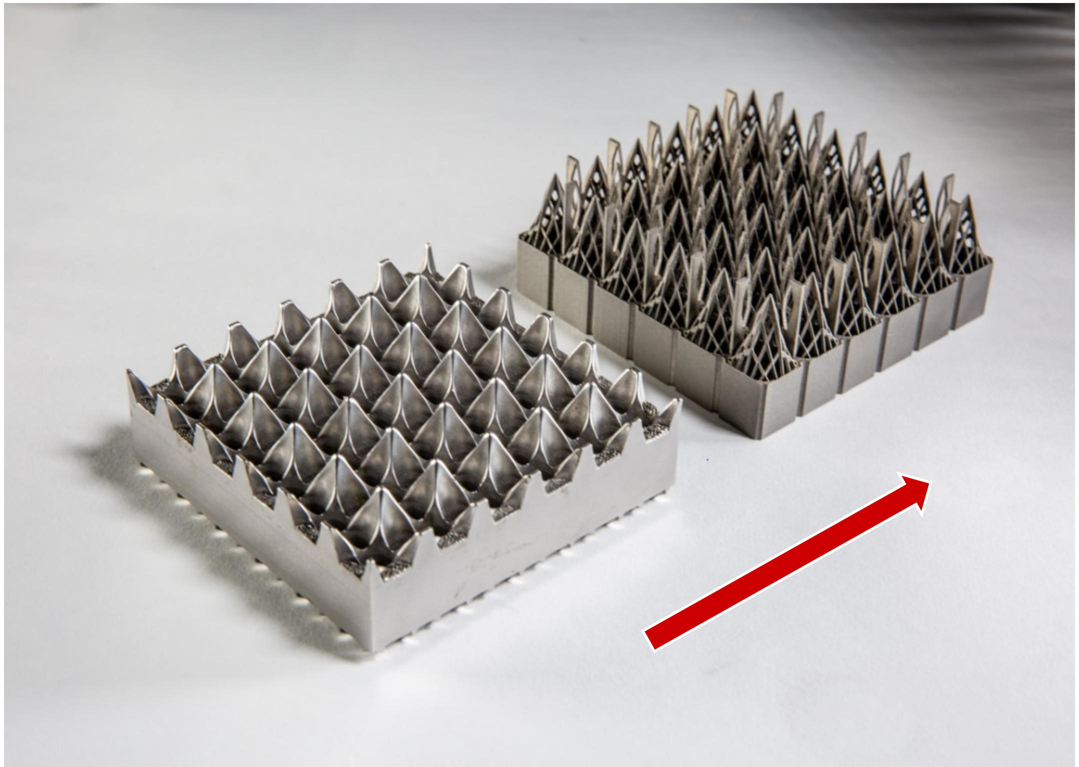
AM: Conceptual Models

Numerous Conceptual Models have been developed (and created and tested) by Westinghouse

- Advanced debris filtering bottom nozzle (early prototypes to advanced designs)



Optimize performance

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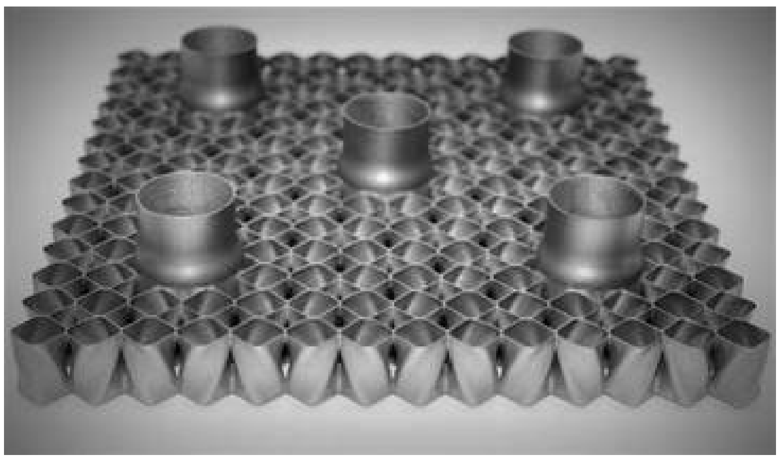
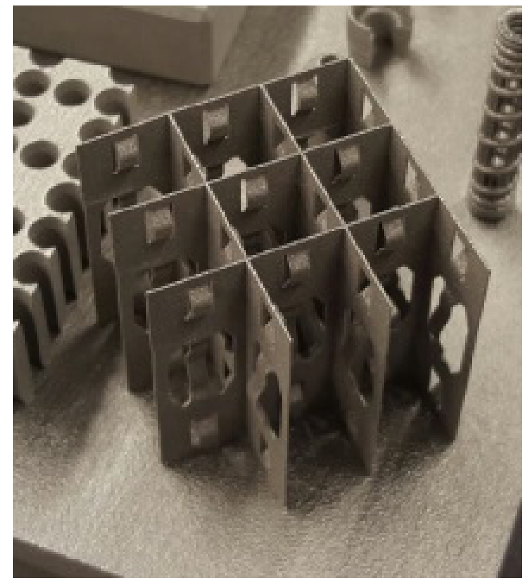
AM: Conceptual Models

Numerous Conceptual Models have been developed (and created and tested) by Westinghouse

- Advanced spacer grids





Prototyping to improve results and shorten development cycle time

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AM: Westinghouse AM Material Testing

Westinghouse has spent significant time and resources over the last 6+ years developing AM technology for the placement of a fuel component in a commercial reactor:

Evaluation of Material Mechanical Properties:
Tensile specimens were created for the purposes of testing the mechanical properties of the AM material such as:

- Ultimate Tensile Strength (UTS)
- Yield Strength (YS)
- Young's Modulus
- Ductility

AM mechanical properties validated to be the consistent with conventional Stainless Steel (SS)

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AM: Westinghouse AM Material Testing (continued)

Irradiation of AM produced tensile specimens:

- Miniature AM produced tensile specimens were irradiated in the MIT test reactor with conditions (temperatures, pressures, boron concentrations, etc.) comparable to that of a commercial Pressurizer Water Reactor (PWR) reactor.
- Testing of un-irradiated and irradiated tensile specimens have demonstrated that the AM material behaves similarly to wrought / cast materials.
- Westinghouse paper "Hot Cell Testing of Neutron Irradiated Additively Manufactured Type 316L Stainless Steel" presented at the 18th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, August 13-17, 2017, Portland, Oregon, USA

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AM: Westinghouse AM Material Testing (continued)

Autoclave Testing of AM Austenitic Stainless Steel, Type 316L:

- Corrosion testing was performed on AM austenitic stainless steel, Type 316L and also Nickel Alloy 718 for 30 days in a flowing water autoclave at simulated pressurized water reactor primary temperature, pressure and chemistry conditions.
- The morphology and thickness of the resulting oxide was characterized using a Focused Ion Beam and Scanning Electron Microscopy.
- It was concluded that the relative corrosion rates of conventional and AM alloys are similar. The base material manufacturing method (AM or conventional) did not influence the corrosion rates.

AM: Thimble Plugging Device

The first Westinghouse AM Fuel Assembly component will be a Thimble Plugging Device (TPD)

- Final design of the AM TPD is a combination of wrought 304 SS (used on existing TPD) and AM 316L SS.
- AM TPD is considered "low" risk as the AM TPD is contained in Guide Thimble Tubes at the top of fuel assembly.
- AM TPD is equivalent in Form, Fit and Function as existing TPD.
- Two TPDs have been manufactured this past Spring and will be delivered with the fuel to a Westinghouse fuel customer late this summer.

AM Thimble Plugging Device is a "Low" Risk Component

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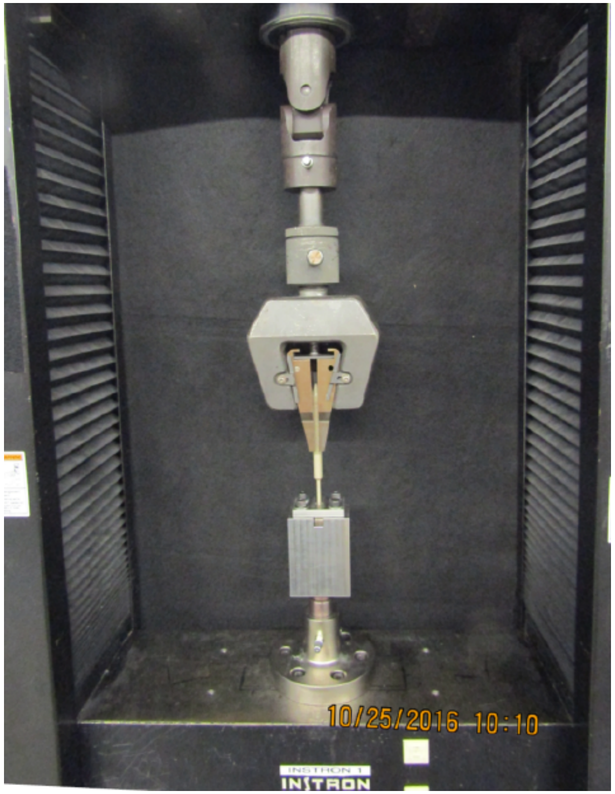
AM: Westinghouse AM TPD Testing

Mechanical Testing of AM TPDs

- Mechanical testing was performed for the existing and the AM TPDs. This testing included axial pull tests, lateral bending tests and baseplate weld integrity tests.
- The performance of the AM TPD was consistent with the existing TPD.
- The AM TPDs satisfied all of the TPD mechanical design criteria.
- AM TPD Witness rodlets tested for all production TPDs



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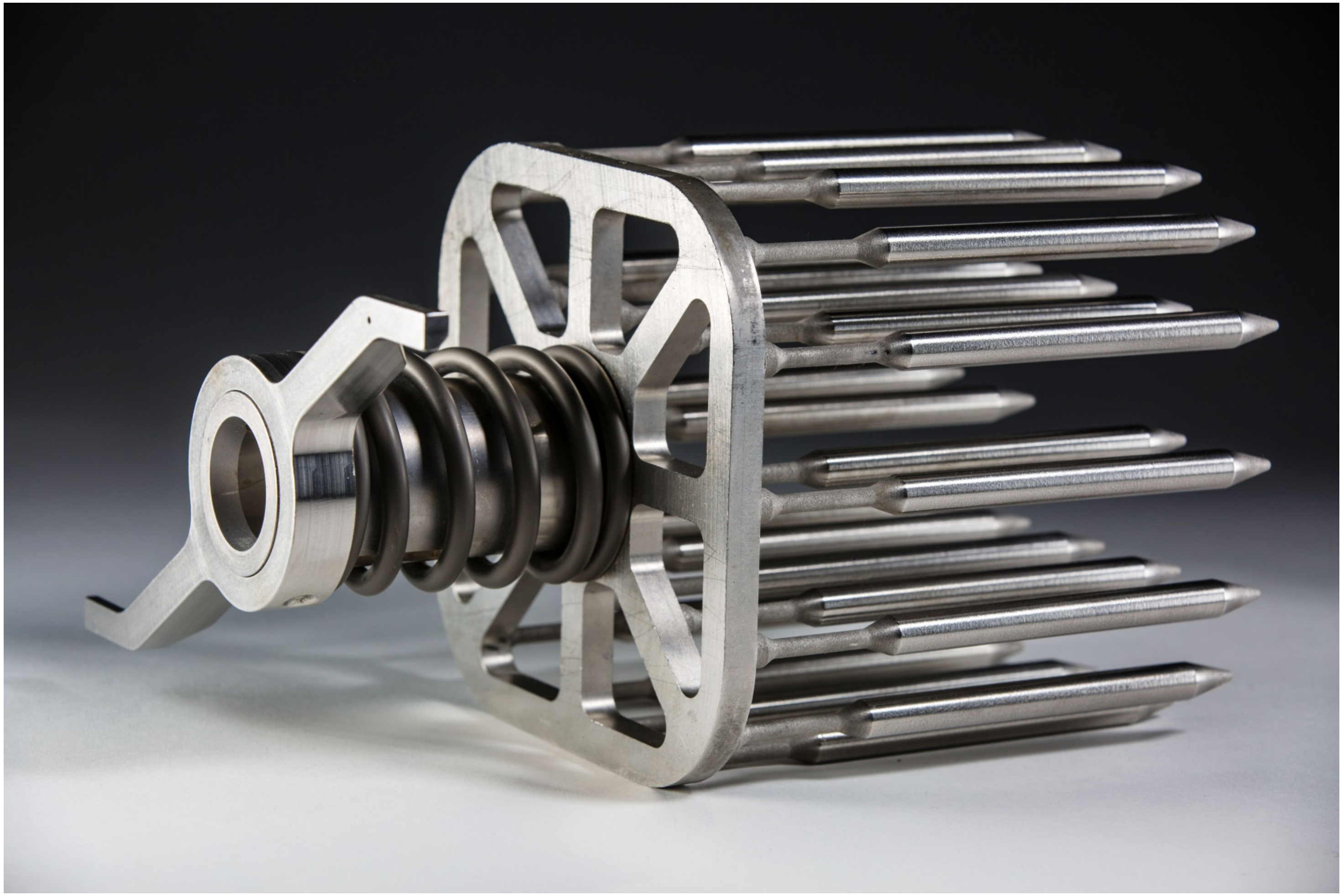
AM: Westinghouse AM TPD T&H Evaluation

T&H Evaluation of the AM TPDs:

- The TPDs are used to reduce the core bypass flow by impeding the flow in the guide thimble tubes and thereby increasing the flow in the core for heat removal.

- Detailed Thermal Hydraulic calculations were performed for the AM TPD and it was demonstrated that all of the thermal hydraulic design criteria, including the design core bypass flow, were satisfied.

AM: TPD Hybrid Design



AM: Westinghouse Industry/Regulatory Collaboration

W is fully engaged with Industry/Regulatory Organizations

- Following Industry standards/specifications for AM manufacturing process such as ASTM F3184*.
- Fully engaged with AM Industry including AM workshops/seminars
- On-going communications with the NRC including:
  - Detailed presentation to NRC and utilities at 2017 FPUM
  - Conducted tour of Churchill hot cell facility for several NRC members (2017)
  - Participated in NRC sponsored AM Workshop in late 2017.
  - Discussed AM TPD approach with members of NRR in early 2018.

* Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion

AM: Schedule

Task	Date
Design & Manufacturability Review	Complete
Irradiation of Small AM Tensile specimens in MIT reactor	Complete
Numerous AM prototype parts produced	On Going
Significant testing of AM properties by W	Complete
Build production version of AM TPD (3 – one for testing)	Complete
Design Closeout Review	Complete
Testing of Production version of the AM TPD	Complete
Perform 50.59 Assessment (working with specific utilities)	Complete
First AM TPDs inserted in Commercial Reactor	Planned for 2018
Post-Irradiation Exam (PIEs) will be performed on TPDs	Future

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AM: Summary

- Westinghouse has invested significant time and effort thoroughly evaluating the Additively Manufactured process for application to fuel components for a commercial reactor.
- Material and Mechanical Property Testing has concluded that AM Properties are consistent with conventional.
- First AM Thimble Plugging Device planned for insertion in a commercial reactor in 2018.
- Westinghouse continues to test other AM materials such as Zircaloy based metals for use in commercial reactor components.

Westinghouse Fuel Performance Update Meeting
PWR Methods Update

July 19, 2018
Vefa Kucukboyaci
PWR Core Methods

Agenda

- Westinghouse Thermal Design Procedure (WTDP) Topical
- Improved NEXUS Cross-Section Representation Methodology
- Qualification of the 2D Transport Code PARAGON2
- Reactivity Initiated Accident (RIA) Update

Westinghouse Thermal Design Procedure (WTDP) Topical Report WCAP-18240-P

Westinghouse

Purpose and Scope

- One topical report which consolidates existing approved methods for all PWRs would facilitate future analysis work and review activities
  - Calculations of DNBR limits for Condition I and II events
  - Statistical rods-in-DNB evaluations for non-LOCA Condition III and IV events in support of radiological consequence analyses

- Applicable to all PWR designs (CE-NSSS, Westinghouse NSSS, VVER, AP1000, APR1400)

Technical Overview

- WTDP based on existing CE-PWR statistical methods enhanced with VIPRE-W code

- Maintains full compliance with current regulatory requirements and guidelines, including
  - NUREG-0800 Rev. 2 Section 4.4 (T/H Design)
  - NRC Information Notice 2014-01, "Fuel Safety Limit Calculation Inputs Were Inconsistent With NRC-Approved Correlation Limit Values"

- Topical report to be submitted for approval of extended applications of existing NRC-approved methods

WTDP Intended Applications – W-NSSS

- Applications will be on forward-fit basis for plants using RTDP:
  - Monte Carlo sampling for DNBR limit, and/or
  - Rods-in-DNB statistical convolution for Condition IV events
- Implementation requires [ ]a,c including:
  - Approved T/H code and DNB correlations
  - Design interface for reload evaluations
- Flexible input for applications with advanced methods
  - Input of uncertainty in new parameter justified on plant specific basis
  - Can be used with new, approved DNB correlations, transient evaluation methods, etc.
  - *Applicable to new plant designs*

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WTDP Intended Applications – CE-NSSS

- Applications to CE-NSSS currently using Statistical Combination of Uncertainties (SCU) or Modified SCU (MSCU)
  - Simplify DNBR limit calculation process to eliminate response surface as an intermediate step due to TORC code limitations
  - To be implemented with VIPRE-W code

- Support CETOP-D replacement with VIPRE-W under currently NRC-approved setpoint methodology and SER conditions
  - WCAP-16500-P-A, CE-NGF fuel topical report
  - WCAP-16500-P-A Supplement 1 Revision 1
  - [ ]a,c
  - [ ]a,c

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Topical Report Outline

- Report Outline:
  - Introduction & Applicable Regulatory Requirements
  - Method for DNBR Limit Calculation
  - Method for Rods-In-DNB Calculation
  - Intended Applications
    - W-NSSS plant DNBR limit
    - CE-NSSS plant DNBR limit
    - Non-LOCA rods-in-DNB events
  - Summary
  - Attachments of sample calculations

Summary

- Executive summary transmitted via LTR-NRC-18-41
- WTDP consolidates existing statistical DNB methods for all PWR applications into one topical report
  - 95/95 DNBR limit
  - Rods-in-DNB for Conditions III and IV events
- Analysis and review efficiencies
  - Improved ability to quantify analysis margin
  - Unnecessary penalties eliminated
- WTDP compatible with current design interfaces and complementary with Westinghouse advanced technologies
- Topical report to be submitted no later than August 30, 2018 for domestic plant applications

Improved NEXUS Cross-Section Representation Methodology

New NEXUS Cross-Section Reformulation (XSR) Model

- New NEXUS cross-section methodology (XSR) keeps basic concept of current ANC9 cross-section methodology
  - [ ]a,c
  - [ ]a,c
- Instead of using [ ]a,c

Highlights of XSR model

Westinghouse

New NEXUS Cross-Section Reformulation (XSR) Model (cont.)

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Highlights of XSR model (2)

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Contents of Topical Report

The topical report will include

- Highlight of new NEXUS cross-section representation methodology
- Qualification results of single assembly as comparing against PARAGON (WCAP-16045-NP-A, Addendum 1)
  - Cover all Westinghouse/CE fuel assembly types and with different burnable poisons
  - Single point reactivity comparison at different burnups and different conditions
  - Reactivity comparison for nominal and off-nominal single assembly depletions

Contents of Topical Report (cont.)

- Qualification results of mini-core calculation
  - Compare 3x3 UO_2/MOX checker-board mini-core reactivity and power distribution against PARAGON calculations
- Qualification results for power plants
  - At least 5 PWR plants (3 or 4 cycles each) are modelled and the results are compared against measurements
  - The following core parameters will be evaluated
    - Core reactivity at HZP and HFP (boron letdown curve)
    - Temperature coefficients
    - Control rod worth
    - Core power distributions

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Development Status and Submittal Schedule

- The Engineering Peer Review was performed [ ]a,c and action items are completed
- The first Internal Licensing Challenge review meeting was held in [ ]a,c
- New NEXUS/ANC9 code system is ready for formal qualification calculations
- Topical report is targeted development by [ ]a,c

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Development Status and Submittal Schedule (cont.)

- NRC pre-submittal meeting is planned around [ ]a,c
- Submittal to the NRC is planned in [ ]a,c
- We anticipate using the new NEXUS methodology for design application by [ ]a,c

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Qualification of the 2D Transport Code PARAGON2

PARAGON2 Developments Summary

- PARAGON2 Cross-section Library
  - Employs Ultra-fine Energy Mesh Library (UFEML) with 6064 neutron and 97 gamma energy groups
  - Resonance Scattering Model (RSM) for all isotopes with high order anisotropic moments (except H in H_2O and graphite)
  - Based on ENDF/B7.1 (and JEFF3.2); Cross-sections are used **without any adjustment**
- PARAGON2 enhancements
  - Flux-solution based on energy fine mesh with 6064 groups
  - Resonance self-shielding calculation eliminated
  - Detailed depletion chains
  - Uses temperature profile for pellet instead of effective flat temperature
- PARAGON2 is part of APA and NEXUS code systems

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Contents of Topical Report

- Description of the new physics models implemented in PARAGON2
- Validation of PARAGON2 with Monte Carlo method
  - Numerical assembly benchmarks covering all PWR fuel types, including 14x14, 15x15, 16x16, 17x17 Westinghouse and CE assemblies with OFA and RFA fuel and IFBA, Gad, and Erbia burnable absorbers
- Critical Experiments Evaluation using PARAGON2
  - UO2 and MOX critical experiment cores
- PIE (Post Irradiation Experiments) Evaluation using PARAGON2
  - UO2 and MOX fuel pellets with various burnups, enrichments and compositions
- Plant data analyses using PARAGON2/ANC code system
  - All Westinghouse and CE 2-, 3-, and 4-loop core types
  - Analyses will cover HZP, HFP conditions and typical safety analysis.

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Schedule

- Current development status
  - Methodology is complete
    - Engineering Peer Review completed at the [ ]a,c
  - Plant analysis to be completed by the [ ]a,c
  - Criticals & PIE to be completed by the [ ]a,c
  - Topical report writing to be completed by the [ ]a,c
- Schedule and key milestones for completion (submittal)
  - Licensing Challenge Review by [ ]a,c
  - NRC Pre-submittal Meeting by [ ]a,c
  - Topical Report ready for submittal by [ ]a,c

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Reactivity Initiated Accident (RIA) Update

NRC Criterion November 2016 Revision

- At power failure criterion is presumed if heat flux exceeds thermal design limits (e.g. DNBR)
- At-power high clad temperature failure still relies on DNB but without the provision of using an alternative limit
- States that the new limits will be enforced whenever a license amendment is made

Westinghouse Response to Latest May 2018 Revision

- Draft Reg Guide Changes
  - Explicitly allows for alternate criteria
  - Did not include prompt critical threshold
- Westinghouse provided feedback through industry
  - Questioned basis of 5% power to go from Pellet-Clad Mechanical Interaction (PCMI) limit to high temperature failure limit
  - Westinghouse explicitly proposed alternate criteria based on prompt critical conditions
- Westinghouse provided feedback directly to NRC at June meeting
  - Assuming 5% power limit unchanged (less desirable)
    - Will require additional submittal to NRC
    - Requires an alternative failure criterion to DNB
- Westinghouse is continuing to complete the alternative high temperature failure criterion (in case 5% power limit remains)
- Westinghouse will work with industry (NEI) to provide further comments

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PAD5 and FULL SPECTRUM™ LOCA (**FSLOCA™**) Evaluation Model Implementation

July 19, 2018
Amy Colussy
Manager, LOCA Integrated Services I

FSLOCA Methodology Background

- Provide margin for small break LOCA-limited plants with an improved analysis method
  - Allow for operational flexibility
- Prepare plants for addressing the 10 CFR 50.46c rulemaking
  - Gain margin to accommodate expected margin loss due to rule change
    - Reduced allowable equivalent cladding reacted (ECR) with burnup
- Incorporate thermal conductivity degradation (TCD) and burnup-related effects
  - Fuel rod initialization is based on PAD5 fuel performance data

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Typical Analysis Schedule with the FSLOCA EM

- Divided into two phases: model development and analysis
- Phase 1 (Model Development)
  - Input Data Request – one month following kick-off meeting
  - Completion of WCOBRA/TRAC-TF2 Model Development – six to twenty-four months following the receipt of all inputs
- Phase 2 (Uncertainty Analysis)
  - Completion of Uncertainty Analysis Execution – nine months following the start of Phase 2
  - Completion of Licensing/Reporting Documents – three months following completion of uncertainty analysis execution

Westinghouse analysis durations:
Phase 1 approx. 7-24 months
Phase 2 approx. 12 months

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FSLOCA Methodology Implementation

- Westinghouse has initiated Phase 1 only for some PWRs, and the combination of Phase 1 and Phase 2 for other PWRs
- Current Phase 1 Status, Model Development
  - [ ]a,c
- Current Phase 2 Status, Uncertainty Analysis Execution
  - [ ]a,c
- First FSLOCA project completion (delivery to customer) expected [ ]a,c

[ ]a,c have initiated implementation of PAD5 and thermal conductivity degradation for LOCA

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PAD5 Code Background

- PAD5 was submitted to the NRC in WCAP-17642-P, "Westinghouse Performance Analysis and Design Model (PAD5)"
  - Revision 1 was issued to incorporate a more detailed methodology section, and incorporate changes based on RAIs
  - Final SE was received on September 28, 2017
- The PAD5 code includes the effects of TCD on pellet thermal conductivity plus additional changes in methodology some of which were requested during NRC review
- PAD5 is the fuel performance code that will replace PAD 3.4 & 4.0 and FATES3B for Westinghouse and Combustion Engineering plants, respectively

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PAD5 will replace all existing Westinghouse PWR fuel performance codes and analyses

PAD5 Implementation for Not-LOCA

- PAD5 generates fuel performance elements that are used in the Nuclear Design, Fuel Rod Design, T/H Design, Transient Analysis and Containment M&E Analysis areas
- Implementation will utilize current NRC-approved methodologies using input from PAD5
- Approximately ten to twelve month duration for re-analysis with licensing actions and NRC review to update the fuel melt Technical Specification limit, where needed, occurring in parallel or after completion of re-analysis

Projected Analysis Timeline

- Projections based on preliminary licensee feedback
- Not including NRC review time
- Not inclusive of entire fleet

[ ]a,c

The projected timeline for completion of all currently planned NRC submittals or analysis extends through 2021

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Summary of Implementation Plan

- Significant level of effort is needed to perform analyses using NRC-approved codes that incorporate the effects of TCD
  - LOCA: 18-36 months, excluding NRC review and reload implementation
  - Not LOCA: 10-12 months, excluding NRC review and reload implementation
- Projections based on industry survey indicates that analysis work for PAD5 implementation could extend 5 years or more, not including NRC review time
- Westinghouse is committed to working with Industry to support implementation of NRC-approved methods that explicitly incorporate modeling of TCD

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