#### Agenda and Slide Presentations for the 2017 Westinghouse Fuel Performance Update Meeting (Non-Proprietary)

#### August 2017

(203 pages attached)

Westinghouse Electric Company LLC 1000 Westinghouse Drive Cranberry Township, PA 16066

#### Westinghouse Fuel Performance Update Meeting (NRC Tour of CFFF) Wednesday, August 9, 2017, CFFF Room 101

12:00 pm - 1:30 pm	Pre-Tour Activities:		
	- Security Check-in		
	- Welcome, Introduction, and Safety Brief		
	- Review Agenda		
	- CFFF Overview Presentation		
	- Lunch		
	- Suit-up for Tour (shoe protectors, other)		
1:30 pm - 4:00 pm	Tour of CFFF:		
	- Mezzanine		
	- Mechanical Area		
	- Test Lab		
	- Scrubber Area		
4:00 pm - 4:30 pm	Post-Tour Activities:		
	- Return shoe protectors, other protection		
	- Security Check-out		

#### Westinghouse Fuel Performance Update Meeting (NRC and Customers) Thursday, August 10, 2017, CFFF Pavilion

8:30 am - 8:45 am	Welcome, Introduction, and Safety Brief
8:45 am - 9:00 am	Update on the S-1030 Scrubber Issue, and Security of Supply Efforts at the Columbia Fuel Fabrication Facility
9:00 am - 10:15 am	Pressurized Water Reactor (PWR) Fuel Performance Update
10:15 am - 10:30 am	BREAK
10:30 am - 11:15am	Westinghouse EnCore <sup>TM</sup> Accident Tolerant Fuel (ATF) Program
11:15 am - 11:45 am	Update on NSAL-14-5: Lower Than Expected Critical Heat Flux Results Obtained During Departure from Nucleate Boiling Testing and Future DNB & Transient Methods Development
11:45 am - 12:05 pm	Incremental High Burnup Extension Strategy
12:05 pm - 1:00 pm	LUNCH
1:00 pm - 1:30 pm	Additive Manufacturing (AM) Thimble Plugging Device
1:30 pm - 2:30 pm	Boiling Water Reactor (BWR) Fuel & Control Blade Performance Update
2:30 pm - 2:40 pm	BREAK
2:40 pm - 3:00 pm	Update on Cooling Deficiency Events at Leibstadt NPP (KKL)
3:00 pm - 3:40 pm	TRITON11 <sup>™</sup> Fuel Update
3:40 pm - 3:50 pm	BREAK
3:50 pm - 4:10 pm	Feedback on Presentations and Meeting
4:10 pm	Adjourn

LTR-NRC-17-60 NP-Attachment Page 3 of 203

#### Westinghouse Fuel Performance Update Meeting (NRC) Friday, August 11, 2017, CFFF Pavilion

8:30 am - 8:45 am	Welcome, Introduction, and Safety Brief		
8:45 am - 9:00 am	Westinghouse Organization Update		
9:00 am - 12:00 pm	- An update on the current Westinghouse Organizational Structure Open discussion topics including but not limited to:		
	- [		
	-		
	-		
	-		
	-	] <sup>e</sup>	
12:00 pm	Adjourn		

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## Update on the S-1030 Scrubber Issue, and Security of Supply Efforts at the Columbia Fuel Fabrication Facility

Michael Annacone Vice President, Columbia Fuel Operations



## S-1030 Scrubber Summary

- Event Overview
- Root Cause Investigation Overview
- Confirmatory Action Letter/Plant Restart
- On-going Regulatory Interactions



Extensive corrective actions completed prior to restart



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#### S-1030 Scrubber Improvements

- Extensive modifications completed to prevent material accumulation in the scrubber
- Rigorous inspection program:
  Engagement with Criticality Safety
  Documentation/evaluation of results
- Ventilation inspection program
- Additional actions are underway to sustain improvements



New S-1030 controls are working to prevent accumulation in the scrubber.

## Nuclear Safety Culture

- Simplified NSC Traits
- Leadership alignment efforts
- Communications improvements
- NSC Training
- NSCMP
- Independent 3<sup>rd</sup> Party Assessment
- Oversight
- MRM
- Excellence plan Management Systems



A healthy NSC is the foundation of our improvement efforts

#### **Excellence Plan Development**

INPO 12-011; "A Strategic Framework for Significantly Improving Nuclear Plant Performance"



#### Sustainability Focus:

- Leadership behaviors/alignment
- Program/process rigor
- Ability to selfidentify/correct
- Oversight/Monitoring
- Industry Engagement



Using a time tested, proven approach to bring about sustained improved performance

#### CFFF Alternate Pellet Supply Update



#### Questions

# ?



## Pressurized Water Reactor (PWR) Fuel Performance Update Jeff Norrell, PhD Director Product Engineering



### Agenda

- Leak free plants
  - Nuclear fuel reliability progress
  - Historical trends
- Fuel reliability improvement process
- Update on recent Post Irradiation Exam (PIE) results
- **AXIOM<sup>TM</sup>** cladding update
- Summary



#### Westinghouse Fueled Plants by Region



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



#### Worldwide Map of Westinghouse-fueled Power Plants



#### Nuclear Fuel Reliability Progress – June 2017



#### Historical Performance of Westinghouse Fueled Plants





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## Driving to Flawless Fuel Through Design – Current Status



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## Driving to Flawless Fuel Through Design – Challenges



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## Driving to Flawless Fuel Through Design – Activities



## Agenda

- Leak free plants
  - Nuclear fuel reliability progress
  - Historical trends
- Fuel reliability improvement process
- Update on recent PIE results
- **AXIOM<sup>TM</sup>** cladding update
- Summary



### Fuel Reliability Improvement Process



### Fuel Reliability Improvement Process



#### Fuel Reliability Improvement Process



### Agenda

- Leak free plants
  - Nuclear fuel reliability progress
  - Historical trends
- Fuel reliability improvement process
- Update on recent PIE results
- **AXIOM<sup>TM</sup>** cladding update
- Summary



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#### Recent PIE Results:





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#### Recent PIE Results:



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## Inspection Results:



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#### Recent PIE Results:

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#### Recent PIE Results:

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# Recent PIE Results:

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# Agenda

- Leak free plants
  - Nuclear fuel reliability progress
  - Historical trends
- Fuel reliability improvement process
- Update on recent PIE results
- AXIOM<sup>™</sup> cladding update
- Summary



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# AXIOM Cladding Overview

- AXIOM High Performance Developmental Fuel Cladding Material builds on successes of Optimized ZIRLO<sup>™</sup> High Performance Fuel Cladding Material<sup>a,c</sup>
- Westinghouse has selected final AXIOM cladding composition
  - Based on extensive PIE database of poolside and hot-cell results from various irradiation programs as well as out-of-reactor testing.
- AXIOM alloy demonstrated
  - Significant performance improvement including in-reactor corrosion, hydrogen pick-up, dimensional stability as well as post irradiation ductility

 Full AXIOM clad LTA demonstrations currently ongoing to provide additional support for licensing and commercial introduction of AXIOM alloy



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#### Update on AXIOM Clad Lead Test Assemblies

- AXIOM Clad LTAs for
  - Eight fuel assemblies will be produced with all fuel rods clad in AXIOM tubing

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- Full size ingot of AXIOM material has been produced and tubing fabrication was completed earlier this year
  - LTA exemption request has been approved by NRC
  - Westinghouse appreciates the NRC's review efforts for [ ] licensing request
- These LTAs will demonstrate performance benefits of AXIOM clad materials in representative operating conditions

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- Lead Test Rods at
  - AXIOM clad Lead Test Rods have been fabricated and delivered to
    - Planned to operate for single annual cycle to provide fuel rod creep data to validate expected creep data in fuel rod applications
  - Information supplements existing data on irradiation creep obtained from Vogtle Creep and Growth program for AXIOM cladding



#### AXIOM Cladding Development Program Timeline



# Agenda

- Leak free plants
  - Nuclear fuel reliability progress
  - Historical trends
- Fuel reliability improvement process
- Update on recent PIE results
- **AXIOM<sup>TM</sup>** cladding update
- Summary



# Summary







# Westinghouse **EnCore**<sup>™</sup> Accident Tolerant Fuel (ATF) Program

Javier Romero Principal Engineer Global Accident Tolerant Fuel Technology



# Outline

- Westinghouse technologies for ATF
  - Chromium-coated zirconium cladding
  - Uranium silicide (U<sub>3</sub>Si<sub>2</sub>) fuel pellets
  - Silicon carbide (SiC) cladding
- Data acquisition
  - Out-of-pile testing of cladding
  - In-pile testing of cladding and  $U_3Si_2$  fuel pellets
- Licensing approach for LTRs/LTAs
- Summary

LTR: Lead Test Rod LTA: Lead Test Assembly



# Westinghouse ATF Technologies

Chromium-coated Zirconium Cladding Uranium Silicide  $(U_3Si_2)$  Fuel Pellets Silicon Carbide (SiC) Cladding



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#### Chromium-coated Zirconium Cladding





### Chromium-coated Zirconium Cladding – Benefits

- Reduced oxidation during normal operation
  - Longer life and increased margins allow use of higher density fuels
- Improved corrosion resistance in steam and air at high temperature
  - Reduced exothermic reaction energy
  - During and beyond design basis conditions
  - Increased loss-off-coolant accident (LOCA) peak cladding temperature
  - Improved reactivity initiated accident (RIA) deposition limits
- Drastic reduction in hydrogen generation and pickup
  - Benefits for draft 10 CFR 50.46c rule
  - Potential for higher transient strain limit
  - Reduced embrittlement in dry storage
- Enhanced resistance to wear (debris, grid-to-rod or rod-to-grid)



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#### Chromium-coated Zirconium Cladding – Performance



# Uranium Silicide Fuel Pellets

Increased uranium density and higher thermal conductivity

	UO <sub>2</sub>	U <sub>3</sub> Si <sub>2</sub>
Uranium Density (g/cm³)	9.68	11.3
Thermal Conductivity (W/m-K)	5-2 (300-2000°C)	9-20 (300-1200°C)

#### **Fabrication**



ATF-W01

Testing



Corrosion testing in water at 300°C (50 hours) No measurable weight change or evolution in appearance









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#### Uranium Silicide Fuel Pellets - Benefits



# Silicon Carbide Cladding - Benefits

- No ballooning and bursting
  - Retention of tensile strength up to 1700°C
  - Slow degradation above 1700°C
- Eliminate oxidation driven temperature spikes
  - Slow reaction with steam to >1700°C
- Drastic reduction of hydrogen generation
- Maintain integrity under most severe beyond design basis accident conditions
- Improved economics for normal operation
  - Reasonably small cross section for thermal neutrons
- Predictable irradiation behavior
  - Swelling is small (<2%) and predictable



#### Data Acquisition

Out-of-pile Testing of Cladding In-pile Testing of Cladding and  $U_3Si_2$  fuel pellets



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# **Out-of-Pile Testing of Cladding**



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# Ultra-High Temperature Testing



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#### Ultra-High Temperature Testing - Results



EnCore<sup>™</sup> cladding technologies maintain integrity in accident conditions

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# In-pile Testing – Overall Status



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# U<sub>3</sub>Si<sub>2</sub> Fuel Irradiated in ATR



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### In-pile Testing – Innovation on Data Acquisition



Technologies now being developed and tested by Westinghouse

# Licensing Approach for LTRs/LTAs

Coated Cladding  $U_3Si_2$  Pellets SiC Cladding



#### LTR/LTA Licensing Approach - Coated Cladding



# LTR/LTA Licensing Approach – U<sub>3</sub>Si<sub>2</sub> Pellets



#### LTR/LTA Licensing Approach – SiC Cladding



#### LTR/LTA Licensing – Additional Considerations



# LTR/LTA Licensing – Manufacturing and Transport



#### Summary



# Summary

- Westinghouse **EnCore**<sup>™</sup> Fuel products
  - Chromium-coated zirconium cladding
  - U<sub>3</sub>Si<sub>2</sub> fuel pellets
  - SiC cladding
- Promising capabilities to achieve full safety benefits
- Ongoing testing program in preparation for LTRs/LTAs
- Licensing actions for LTRs/LTAs ongoing
  - Both on 10 CFR Part 50 and Part 70
  - Including active engagement with the NRC



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# EnCore<sup>™</sup> Fuel

We're changing nuclear energy ... again



Update on NSAL-14-5: Lower Than Expected Critical Heat Flux Results Obtained During Departure from Nucleate Boiling Testing and Future DNB & Transient Methods Development Zeses Karoutas Chief Engineer Fuel Engineering and Safety Analysis



#### Outline

- Update for DNB Issue Described in NSAL-14-5
- Planned CHF Testing for 17x17 OFA/IFM
- Thermal-Hydraulic Statistical DNB Program Status
- Statistical Transient Methodology
- Summary



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# Update for DNB Issue Described in NSAL-14-5

- Lower than expected CHF results were found during data analysis
  - Non-conservatism observed for WRB-1, WRB-2, WRB-2M and WNG-1 DNB correlations with new RFA without IFM test data
  - Almost all existing plant analyses were impacted but were unaffected due to analyses not reaching high quality conditions


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## 17x17 RFA without IFM Data: WRB-2M with New ODEN Data



Trend in Data was not Obvious from Previous Tests at Columbia University (HTRF)

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#### WNG-2 Correlation Under Development

- WNG-2 correlation database to include new tests
  - Expanded WNG-1 database for correlation development
  - Additional tests for validation

- Original WNG-1 correlation form in WCAP-16766-P-A modified
- Preliminary WNG-2 correlation currently under testing
  - To be applicable to high temperature testing conditions
  - Designed to be applicable to all Westinghouse 17x17 RFA and NGF fuel designs



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# Preliminary WNG-2 Correlation – Measured to Predicted CHF

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### Planned CHF Testing for 17x17 OFA/IFM



When deciding to take an action that may result in impacts to customers: communicate the plan, reasoning, potential impacts, and the plans/efforts to minimize potential impacts Westinghouse Non-Proprietary Class 3

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# Discovery of Need for Additional Testing for 17x17 OFA/IFM Geometry

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# Discovery of Need for Additional Testing for 17x17 OFA/IFM Geometry



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## Safety/Operability Significance



#### **Testing and Data Analysis**



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#### **Plan Forward**



# Thermal-Hydraulic Statistical DNB Program Status Zeses Karoutas



### Thermal-Hydraulic Statistical DNB Program Status

 Statistical DNB program consolidates existing methods for process simplification and more accurate solution

- Consolidated method referred to as WTDP:
  <u>Westinghouse Thermal Design Procedure</u>
- WTDP method similar to those approved and used for CE-NSSS plant applications

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#### T-H Statistical DNB Program Status (continued)

- No change to existing design interfaces and criteria
- Applications to W-NSSS currently using RTDP (Revised Thermal Design Procedure)

 Applications to CE-NSSS currently using SCU (Statistical Combination of Uncertainties)



## Statistical Transient Methodology Zeses Karoutas



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## STM - Methodology Overview

- Statistical Transient Methodology (STM)
  - Statistical combination of uncertainties for non-LOCA events that do not currently apply statistical approach
  - Method uses [
    - Will provide basis for sampling of selected initial condition uncertainties
    - Remainder continue to be bounded
  - Will utilize current code models
  - Applicability
    - Limited to events that use deterministic approach
    - Method code independent, applicable to both LOFTRAN and RETRAN
    - Initial method development focused on Westinghouse legacy PWRs (no AP1000<sup>®</sup> or CE plant designs)
      - Potential to extend method through future submittals



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## STM - Methodology Overview

Initial development is focused on [ ]<sup>a,c</sup> Chapter 15 non-LOCA safety analysis events

- Criterion
  - Statistical Statement to bound the 95<sup>th</sup> percentile with 95% confidence
  - Statistical statement will be compared to the current acceptance criterion for the event (margin to pressurizer overfill or margin to hot leg saturation).



Method change limited to uncertainty treatment

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# STM - Methodology Overview

Initial Condition Uncertainties Currently Investigating

- Other Event Specific Uncertainties under consideration such as
  ]<sup>a,c</sup>
- Project Plan
  - Developing topical report (WCAP)
    - Topical report will include
      - statistical basis,
      - justification for sampled inputs
      - sample analysis



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#### Summary

- DNB Testing and Correlations
  - Preliminary WNG-2 correlation addresses DNB issue for 17x17 RFA fuel and also 17x17 NGF and 16x16 NGF
  - Plan to submit topical or supplements for WNG-2 in [
  - 5x5 DNB tests planned next [ for comparisons to WRB-2 correlation
  - Westinghouse recommends plants which use the WRB-2 correlation take no action until test results are available and analyzed by [ ]<sup>a,c</sup>
- T-H Statistical DNB plan to submit in [ ]<sup>a,c</sup>
- Statistic Transient Methodology plan to submit in a few years

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Westinghouse is focused on making improvements in DNB & Transient areas

#### Acronyms

CHF - Critical Heat Flux (DNB)	Typ - Typical cell
DNB - Departure from Nucleate Boiling (CHF)	V+ - Vantage Plus, (OFA)
IFM - Intermediate Flow Mixing Vane	V5H - Vantage 5 Hybrid
NGF - Next Generation Fuel	WNG-1 - PWR DNB Correlation
OFA- Optimized Fuel Assembly, (V+)	WRB-1 - PWR DNB Correlation
RFA - Robust Fuel Assembly	WRB-2 - PWR DNB Correlation
Thm - Thimble cell	WRB-2M - PWR DNB Correlation



## Incremental High Burnup Extension Strategy

Zeses Karoutas Chief Engineer, Fuel Engineering and Safety Analysis



### Agenda

- Industry Motivation
- Industry Trends for High Burnup
- Key Concern for High Burnup
- Industry Proposal for an Incremental Burnup Extension
- LOCA Analysis Considerations for High Burnup
- Cladding Database Supporting Extension
- Licensing Approaches
- Summary



#### **Industry Motivation**

- Industry core designs are frequently constrained by the lead 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 is increased
- EPRI received positive industry feedback at the February 2017 Core-tac meeting on an incremental burnup extension

Improved fuel cycle economics help support Nuclear Promise



#### Industry Trends for High burnup

- Fuel cycles being evaluated for high burnup generally fall into two categories
  - Mostly peripheral and center assembly fuel burnup extension
    reduce constraints on fuel cycle designs ≤ 65 GWd/MTU
    peak rod burnup
  - Higher energy cycles with high burnup fuel in interior burnups approaching 70 GWd/MTU.
- For the first category fuel rods in peripheral and center assemblies have low power for rods that may exceed 62 GWd/MTU



## Key Concern for High Burnup Fuel Fragmentation Relocation and Dispersal (FFRD)

- At high burnups, fuel pellets have increased fission gas loading and the rim region is highly porous. Under high temperatures fuel can fragment into fine particles.
- If cladding temperatures during a LOCA become high enough, cladding ballooning and rupture can occur
  - Fuel fragments can relocate from above, into the ballooned region (increases local linear heat rates)
  - Fuel fragment expulsion out of the burst region has been observed in some high burnup tests ("dispersal")
- NUREG-2121 discusses experimental observations in detail
- SECY-15-0148 contains justification for not including FFRD in 10 CFR 50.46c rulemaking

NRC expects that FFRD be addressed for high burnup



# Industry Proposal for an Incremental Burnup Extension

- For rods in fuel assemblies which exceed peak rod burnup of 62 GWd/MTU demonstrate these rods do not burst
- Although key fuel performance models have not been approved for > 62 GWd/MTU, benchmarking data demonstrates that models are applicable up to 70 GWd/MTU.
- It is expected that peak rod burnups will be less than or near 65 GWd/MTU
- Demonstrate that all methods and hardware satisfy design criteria for the small incremental burnup extension
- Address all key criteria from SRP 4.2
- Prepare licensing submittal

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Limited extended burnup can maintain safety margins

# LOCA Analysis Considerations for High Burnup Overview

- Westinghouse realistic LOCA methods account for fuel relocation into the burst region, when burst is predicted to occur
- Basic methods for evaluating the conditions necessary for cladding rupture were previously established by Westinghouse, and are recognized in NUREG-2121
- Analytical methods can be used for more robust prediction of cladding rupture

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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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# LOCA Analysis Considerations for High Burnup Key Uncertainties

- Burst Temperature
  - Uncertainty directly impacts burst prediction
- Fuel Performance Data
  - Fuel temperature and rod internal pressure uncertainties have impact on burst prediction
  - Simulations use data with overly conservative power history
- Application of LOCA Models Beyond Approved Burnup
  - Additional justification may be required
  - Simulations conservatively run with nominal+2 $\sigma$  decay heat



#### Structural and Fuel Performance Considerations

- Fuel rod peak oxide thickness as a function of burnup
- Fuel rod growth as a function of fast fluence
- Fuel Assembly Growth as a function of burnup
- Will use PAD5 to justify current safety setpoints for incremental high burnup extension



#### Fuel rod peak oxide thickness as a function of burnup



Sufficient well behaved oxide data at high burnup is available

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#### Fuel rod growth as a function of fast fluence



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

#### Fuel Assembly Growth as a function of burnup

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

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#### Licensing Approaches



Licensing Approaches and Schedule to be discussed with Customers

### Summary

- Two step process in transition to higher burnups provides value to utilities without impacting safety.
- FFRD issues are addressed by limiting fuel rod power at burnups > 62 GWd/MTU to prevent burst.
- Current cladding and ZIRLO<sup>®</sup> structural material are sufficient to support the small burnup extension
- Prepare and submit licensing document



## Additive Manufacturing (AM) Thimble Plugging Device

David Huegel Fuel Product Engineer



## 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
- Westinghouse AM Thimble Plugging Device Testing
- 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 component/ 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 process if fully understood and thus can be 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. Fast prototyping, mockups, fixtures, tooling, etc. to support advanced design development as well as manufacturing support.



#### **AM: Benefits (continued)**

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

- Help minimize defects by reducing/eliminating manual 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** 

## **AM: Conceptual Models**

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

- Tubular grid
- "Egg Crate" Bottom Nozzle
- Debris filtering bottom nozzles
- Advanced spacer grids









#### AM: Westinghouse AM Material Testing

Westinghouse has spent significant time and resources over the last 5+ 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)



#### **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.
- Initial testing of un-irradiated and irradiated tensile specimens demonstrated AM material behaves similarly to wrought / cast materials.



## AM: Westinghouse Testing - Irradiation of AM Specimens

- Miniature AM 316L and Alloy 718 tensile specimens irradiated to ~ 0.8 dpa (displacements per atom) in MIT reactor
- Very high near contact radiation dose rates of ~ 100-400 R/hr
- Group of four (4) tensile specimens shown below:



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# AM: Westinghouse Testing - Irradiation of AM Specimens

- Unirradiated and irradiated tensile testing of AM 316 SS and Alloy 718 materials inside WEC hot cell.
- Room Temp and elevated Temp (i.e., 572°F) tensile testing of ~50 AM 316SS specimens and ~50 AM Alloy 718 specimens.
- Extensive unirradiated and irradiated materials evaluations completed.





Intact irradiated quad held with hot cell grips prior to separation into 4 individual miniature tensile specimens





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## AM: Westinghouse Testing - AM 316 SS Performance

Axial Strain,

%



~ 100 tensile specimens successfully tested remotely inside WEC hot cell





AM 316L Properties validated to be consistent with conventional SS !! AM Alloy 718 specimens showed similar consistency with conventional Alloy 718 properties !!

## 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) placed in a commercial reactor in 2018.
  - Final design of the AM TPD is a combination of wrought 304 SS (used on existing TPD) and AM 316L SS.
  - AM TPD is equivalent in Form, Fit and Function as existing TPD.
  - AM TPD is considered "low" risk as the AM TPD is contained in Guide Thimble Tubes at the top of fuel assembly.
  - One or two TPDs to be manufactured this Fall 2017.
  - TPDs to be delivered with the fuel in Spring of 2018.

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AM Thimble Plugging Device "Low" Risk Component

#### AM: TPD Hybrid Design



**316L Stainless** Steel AM rodlets grown on Stainless Steel Wrought 304 base plate

> Wrought 304 **Stainless Steel** base plate



## AM: Westinghouse AM TPD Testing

#### Mechanical Testing of Existing and 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.
- An Instron machine was used for the testing as shown in the enclosed figure (axial pull testing shown).
- The performance of the AM TPD was consistent with the existing TPD and in addition, the AM TPDs satisfied all of the TPD mechanical design criteria.





#### AM: Westinghouse AM TPD Testing

#### Mechanical Testing of Existing and AM TPDs:

 The existing and AM TPD Rodlets were demonstrated to have more than sufficient strength to meet the core component handling load requirement of 400 lbs.





#### 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.
- Specific 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: Schedule

Task	Date
Design & Manufacturability Review (Participation from 2 utility customers)	Complete
Irradiation of Small AM Tensile specimens in MIT reactor	Complete
Numerous AM prototype parts produced	On Going
Significant testing of AM properties by <u>W</u>	Complete
Testing of TPD	On Going
Perform 50.59 Assessment (working with specific utilities)	September 2017
Design Closeout Review	September 2017
TPD production (1 to 3)	Late 2017
First TPDs inserted in Commercial Reactor (On-going discussions with two utility customers)	Spring 2018
Post-Irradiation Exam (PIEs) will be performed on TPDs	Future



#### 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 Thimble Plugging Device LTAs (1 or 2) are to be inserted in 2018 in a commercial reactor.
- Westinghouse continues to test other AM materials such as Zircaloy based metals for use in commercial reactor components.



## Boiling Water Reactor (BWR) Fuel and Control Blade Performance Update Jeremy King BWR Fuel Product Manager



#### Outline

- Delivery statistics
- Performed Inspections 2016
- **HiFi™** Cladding Update
- Control Rod Blade Inspections 2016
- Summary



#### Delivery Statistics Europe Up to End of 2016



#### Delivery Statistics US Up to End of 2016 (cont'd)





#### Outline

- Delivery statistics
- Performed Inspections 2016
- HiFi<sup>™</sup> Cladding Update
- Control Rod Blade Inspections 2016
- Summary



#### Performed Inspections 2016



a,c

### Inspection in [



a,c

a,c

#### Inspection SVEA-96 Optima3 in [

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#### Inspection SVEA-96 Optima3 in [ ]<sup>a,c</sup>



#### Inspection SVEA-96 Optima2 in [ ]<sup>a,c</sup>



a,c

#### Inspection SVEA-96 Optima2 in [ ]<sup>a,c</sup>

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#### [ ]<sup>a,c</sup> - Low Tin ZIRLO Channel, 47 MWd/kgU (Operated with a deeply inserted control blade during C34, third cycle of operation)



Westinghouse Non-Proprietary Class 3

#### Non-Proprietary Class 3 © 2017 Westinghouse Electric Company LLC. All Rights Reserved. ]a,c - SVEA-96 Optima3 LUA, BU ~28 MWd/kg U Visual Inspection Low Tin ZIRLO Channel (2 cycles with instrumentation tube)



a,c

#### ]<sup>a,c</sup> Low Tin ZIRLO Channels

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Westinghouse Non-Proprietary Class 3

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## SVEA-96 Optima3 Fuel Repair Campaign in [

]a,<u>c</u>\_\_



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a,c

## Optima3 - Fuel Repair Campaign

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a,c

#### Inspection of the Leaking Fuel Assembly in



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a,c

#### Inspection of the Leaking Fuel Assembly in




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# SVEA-96 Optima3 – End of Life Inspection [ ]<sup>a,c</sup> (6 cycles)



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# SVEA-96 Optima3 – End of Life Inspection [ ]<sup>a,c</sup> (6 cycles) (cont'd)



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# SVEA-96 Optima3 – End of Life Inspection [ ]<sup>a,c</sup> (6 cycles) (cont'd)



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a,c

# SVEA-96 Optima3 – End of Life Inspection [ ]<sup>a,c</sup> (6 cycles) (cont'd)



#### Outline

- Delivery statistics
- Performed Inspections 2016
- HiFi<sup>™</sup> Cladding Update
- Control Rod Blade Inspections 2016
- Summary



## Inspection in [



## HiFi Cladding Background

- Starting in the mid-1980s Japanese industry and government identified and supported development of low hydrogen pickup claddings. This led to HiFi cladding from NFI.
- **HiFi** cladding will be introduced in Japan with 10x10 fuel. Post-Fukushima **HiFi** cladding introduction to 9x9 fuel is also under discussion with Japanese customers.
- All elements apart from iron are within the Zry-2 specification.



Alloying elements used today in High Fe Zr-based alloys (ex. Alloy-2 and **HiFi** cladding):



### 3<sup>rd</sup> Cycle Inspection in [





### Inspection in [



### Inspection in [



# Westinghouse Non-Proprietary Class 3 © 2017 Westinghouse Electric Company LLC. All Rights Reserved. LTR-NRC-17-60 NP-Attachment, Page 154 of 203 First Cycle HiFi Cladding Inspection in

]a,c



#### Outline

- Delivery statistics
- Performed Inspections 2016
- HiFi<sup>™</sup> Cladding Update
- Control Rod Blade Inspections 2016
- Summary



#### CR 99 Surveillance – Nordic Plants



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#### [ 2013

]<sup>a,c</sup> CR 99 3<sup>rd</sup> Generation Inspections



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# CR 99 Experience Summary

 CR 99 3<sup>rd</sup> generation has shown flawless performance in US reactors for 10 years. Operation to NEOL continues.



#### Outline

- Delivery statistics
- Performed Inspections 2016
- **HiFi™** Cladding Update
- Control Rod Blade Inspections 2016
- Summary



#### Summary



# Update on Cooling Deficiency Events at Leibstadt NPP (KKL) Jeremy King BWR Fuel Product Manager



#### Discovery



#### Fuel Leaker: [



#### **Inspection Results**



#### Categorizing the Indications



#### **BWR/6 Fuel Support Piece Design**



Fuel Support Piece orifice at cross-beam



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#### Evaluation of inspections



#### **Data Evaluation**









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# US Patent Application 2003/0185334 A1 - Toshiba proposed vortex control solutions

#### CORE INLET STRUCTURE FOR COOLANT

Inventors: Toshihiro Fujii, Yokohama-Shi (JP); Shiho Fujita, Yokohama-Shi (JP); Akira Mototani, Yokohama-Shi (JP); Hideo Komita, Yokohama-Shi (JP); Miyuki Akiba, Tokyo (JP); Tadashi Narabayashi, Yokohama-Shi (JP); Masaru Ukai, Yokohama-Shi (JP); Shinichi Morooka, Tokyo (JP); Tetsuzo Yamamoto, Yokosuka-Shi (JP); Ryoma Kato, Yokohama-Shi (JP)

Correspondence Address: OBLON, SPIVAK, MCCLELLAND, MAIER & NEUSTADT, P.C. 1940 DUKE STREET ALEXANDRIA, VA 22314 (US)

Assignee: Kabushiki Kaisha Toshiba, Tokyo (JP)

Appl. No.: 10/403,283

Filed: Apr. 1, 2003





# US Patent Application 2016/0379722 A1 - GEH proposed re-design of Fuel Support Piece

#### SYSTEMS AND METHODS FOR <u>INCREASED</u> STABILITY NUCLEAR FUEL CASTINGS

- Applicant: GE-HITACHI NUCLEAR ENERGY AMERICAS LLC, Wilmington, NC (US)
- Inventors: Francis T. Bolger, Wilmington, NC (US); Wayne Marquino, Wilmington, NC (US); Charles L. Heck, Wilmington, NC (US); Randall H. Jacobs, Wilmington, NC (US)

Appl. No.: 14/754,645

Filed: Jun. 29, 2015

thereby combating pressure shock waves and resulting selfreinforcing flow oscillations following a flow disruption.



**[0017]** The inventors have recognized that existing flow structures in nuclear cores that create desired flow direction may have relatively high instability in the instance of thermo-hydraulic perturbation, such as when the inlet temperature or pumped flow is reduced. Boiling two-phase flow

**[0018]** However, the inventors have recognized that increasing pressure loss in the fuel support casting to correct such oscillations with an inlet orifice may detrimentally increase overall pressure loss, and reduce flow through the fuel assembly. To overcome these newly-recognized problems as well as others, the inventors have developed systems

**[0022]** Example embodiment fuel support casting **148** may further include a lower opening **194** that is relatively less or non-orificed. For example, lower opening **194** may be

seating in openings **190/290**. It is further possible to retrofit existing fuel castings as example embodiment fuel castings by extending a lower portion to form longer internal flow passages **196** and potentially further remove or relocate a side-entry orifice in such existing castings. In such a retrofit, a lower opening for may be drilled in a control rod guide tube to accommodate longer flow passages.

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#### Westinghouse Root Cause Analysis Root Cause (RC) & Apparent Cause (AC)



#### Understanding the failure mechanism



#### NRC Audit SVEA-96 Optima3 / D5 (April 21st-23rd)



### Summary



# TRITON11<sup>™</sup> Fuel Design Verification and Manufacturing

Jeremy King BWR Fuel Product Manager


#### Outline

- Project Overview and Schedule
- Design Overview
- Status of Verification Testing
- Manufacturing
- Summary





#### Westinghouse 11x11 BWR **TRITON11™** Fuel Design



## Westinghouse BWR fuel Evolution

- Main driver for **TRITON11** fuel development is improving fuel economy
- High fuel reliability is provided through long evolution of robust materials and proven mechanical design solutions
  - Important reliability features of SVEA-96 **Optima3™** fuel are maintained



### **TRITON11** Fuel Design - Project Status



#### **TRITON11** Fuel – High Level Schedule



## Design Overview & Status of Verification Testing



## Superior Fuel Economy





### **Robust Mechanical Design**



### **Robust Mechanical Design**



a,c

### **Robust Mechanical Design**



### **High-performance Materials**





Low Tin ZIRLO<sup>TM</sup> is a trademark or registered trademark of Westinghouse Electric Company LLC, its affiliates and/or its subsidiaries in the United States of America and may be registered in other countries throughout the world. All rights reserved. Unauthorized use is strictly prohibited. Other names may be trademarks of their respective owners.

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## Uncompromised Reliability



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## Design Verification - FRIGG Test



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## Design Verification - FRIGG Test



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## Design Verification - BURE Test



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## Design Verification - BURE Test



## Manufacturing



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# **TRITON11** Fuel Fabrication Preparedness LTA Status



## **TRITON11** Grid Production



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## **TRITON11** Fuel Rod Loading



21

## **TRITON11** Fuel Channel Manufacturing



## TRITON11 Water Rod



### TRITON11 Fuel Rods



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## **TRITON11** Fuel Design Verification and Manufacturing Summary

