# Enclosure 3

## 2021 Westinghouse Fuel Performance Update Meeting Slide Package

## (Non-Proprietary)

## (215 pages Including Coversheet)

## September 2021

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

# Welcome and Regulatory Update

Anthony Schoedel

Manager, eVinci™ Licensing and Configuration Management

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# Agenda

| Description | | Start Time |
|---|---|---|
| Welcome & Opening Remarks - Anthony Schoedel | | 8:30 AM |
| CE Reconstitution - Jeff Brown | | 8:40 AM |
| Machine Learning - Emre Tatli | | 9:10 AM |
| ATF – Kallie Metzger | | 9:40 AM |
| BREAK | | 10:40 AM |
| PWR Codes/Methods, Innovations, HEHB – Cenk Guler | | 10:50 AM |
| AXIOM - Andrew Atwood | | 11:50 AM |
| LUNCH | | 12:20 PM |
| PWR fuel performance – Jason Smith | | 1:20 PM |
| BWR fuel performance –Uffe Bergmann & Jean-Marie LeCorre | | 2:05 PM |
| BREAK | | 2:50 PM |
| PRIME – Brian Millare | | 3:00 PM |
| Additive manufacturing – Dave Huegel | | 3:30 PM |
| ADJOURN | | 4:30 PM |

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# LEADING NUCLEAR SAFETY

## QUICK REFERENCE

- Show Respect For Others
- Follow The Rules
- Stop When Unsure
- Promptly Report Problems
- My Signature Is My Word

# CE Fuel Assembly Reconstitution Topical Supplement (CENPD-289)

# CE Reconstitution Topical (CENPD-289)

- CENPD-289 describes methodology for analysis of reconstituted Westinghouse fuel containing inert replacement rods in Combustion Engineering plants
- Submitted in response to GL 90-02 which required NRC approval for methods used to analyze core configurations containing "inert" rods
  - Conservatism of DNB methodology was a primary concern
- Similar submittals were made by other fuel vendors

# CE Recon Topical

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# CE Reconstitution Topical

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# CE Reconstitution Topical

- Unresolved RAIs related to application of the CE Critical Heat Flux (CHF) correlation to configurations involving large numbers of inert rods resulted in the NRC SER giving approval to only Class A configurations
  - SER restriction was accepted by CE customers in order to perform recons in upcoming reloads
  - Was not a major concern at the time since rod swaps could be performed to meet Class A restrictions in most cases
- Note that the topical itself did not limit application to non-Class A requirements

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# CE16NGF Reconstitution Requirements

- Applicability of CENPD-289 to CE16NGF was approved in WCAP-16500-P-A
- The new features of CE16NGF supports relaxation of the SER limits for recon

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# CE Reconstitution Topical

- The CENPD-289 SER Restriction has resulted in several adverse consequences
  - It has resulted in the premature discharge of assemblies which has in some cases resulted in increased power peaking and core power tilts due to the asymmetric core redesign as well as fuel cost penalties
  - It has prevented implementation of fuel leaker risk reduction initiatives, such as placing inert rods in high risk locations adjacent to core shroud or in damaged grid cells as a protective measure
  - The rods swaps required to comply with current Class A constraints require that more rods be removed and reinserted resulting in an increased risk of fuel damage
- Elimination of this restriction would have direct operations, safety, and fuel cost benefits

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# CE Reconstitution Topical Revision

- To remedy this situation Westinghouse will submit a supplement to CENPD-289 for regulatory approval that will allow exemptions to the Class A restrictions, to relax restrictions on where inert rods can be placed in CE16NGF assemblies
- Additional DNB test data will be presented to demonstrate conservatism of current CE16NGF CHF correlations for inert rod configurations and that mixing vanes reduce the CHF cold wall effect
- Supplement would also utilize general conclusions from W-NSSS Recon topical WCAP-13060-P-A
  - CE16NGF has same rod and similar mixing vanes as the WEC RFA fuel described in WCAP-13060-P-A
- Targeting submittal by July 2022
- Waterford has indicated desire to be lead plant for this update

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# Questions/Discussions?

# DNB Predictive Modeling Using ML Technology

Emre Tatli

September 2021

# Westinghouse **VISION & VALUES**

**together**

we advance technology & services to power a clean, carbon-free future.

- Customer Focus & Innovation
- Speed & Passion to Win
- Teamwork & Accountability

Safety • Quality • Integrity • Trust

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# Outline

- Background
  - Departure from Nucleate Boiling (DNB)
  - Machine Learning (ML)

- Application of ML to DNB Predictive Modeling
  - Process
  - Initial Results

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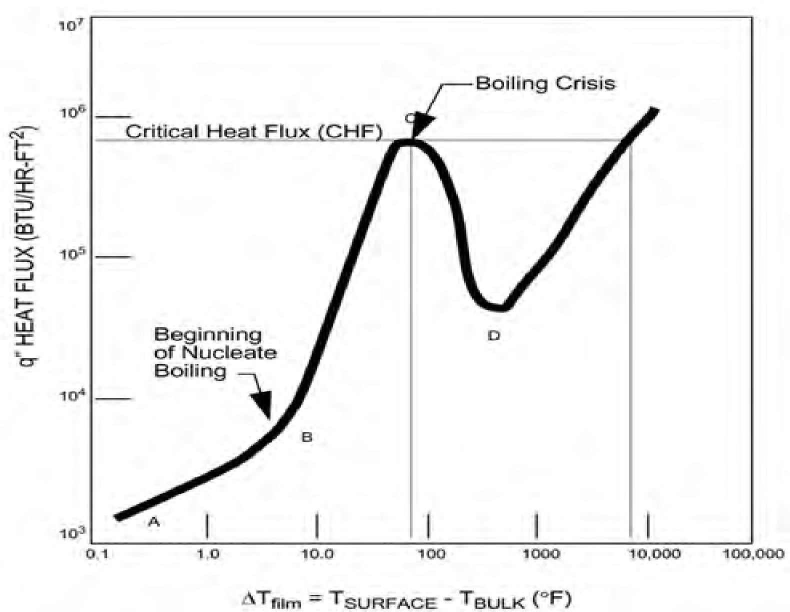
# Departure from Nuclear Boiling (DNB)

- DNB – PWR Specified Acceptable Fuel Design Limit (SAFDL) to prevent fuel cladding overheating
- DNB heat flux is also referred to as Critical Heat Flux (CHF)
- Margin to DNB is quantified as DNB Ratio (DNBR)

***DNBR = Predicted CHF / Local Heat Flux = P/M***




[ ] a,b,c

# Recent Challenges in DNB Testing & Modeling

- [
 ]a,c
  - Resolution of NSAL-14-5, "Lower Than Expected Critical Heat Flux Results Obtained During Departure from Nucleate Boiling Testing"
  - [
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[
]

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# DNB Correlation Development Process

- For PWR design applications, DNB predictive model is currently determined empirically based on test data for complicated fuel assembly component designs
  - [ ]a,c

[ ]a,c

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# Machine Learning (ML) Tool Overview

- Current Westinghouse ML tool kit
  - [ ]a,c
  - [ ]a,c
- ML tool provides new capabilities for DNB modeling
  - [ ]a,c
  - [ ]a,c
  - [ ]a,c
  - [ ]a,c
- [ ]a,c
- ML technology is being applied in Westinghouse in support of plant design and fuel manufacturing operations

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# ML-Based DNB Correlation Development

- Database [ ]a,c
  - Original tests [ ]a,c
  - New tests [ ]a,c
- Input parameters [ ]a,c
  - [ ]a,c
  - [ ]a,c
- Predictive model tested and evaluated in accordance with current practices and guidelines
  - NUREG-KM-0013 (Draft) reviewed
  - Available algorithms and optimization schemes explored
  - [ ]a,c
  - [ ]a,c
- Sensitivity check for Physics-Informed ML model

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# Data Description Table

[ ]a,c

[ ]a,b,c

# Westinghouse Machine Learning Tool Kit

- [ ]a,c
- [ ]a,c
- [ ]a,c
- [ ]a,c
- [ ]a,c

[ ]a,c

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[ ]a,b,c

# Initial ML Model & Results

- [ ]a,c
- [ ]a,c
- [ ]a,c
- [ ]a,c
- [ ]a,c

[ ]a,b,c

# "PIML" Sensitivity Check

- Physics informed model sensitivity checks ensure CHF predictions consistent with physical behaviors
  - [
  - ]a,c
- [
  - ]a,c

a,b,c

[ ]

# Summary

- ML is being applied to develop new DNB correlation [ ]a,c
- Initial results are [ ]a,c
- Work continues to improve the correlation development process through ML

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**QUESTIONS/COMMENTS?**

# Westinghouse EnCore® Licensing Plans

Kallie Metzger, Ph.D.
ATF Technology

Presentation to NRC, September 22, 2021

# Outline

**Goal**: Communicate the ongoing ATF strategy and anticipated licensing interactions

**Agenda**:

- Westinghouse EnCore® Fuel Program
- High Burnup Program Overview
- ADOPT™ Updates
- Coated Cladding Updates
- High Burnup Updates
- Topical Licensing Status
- Potential Technologies to Accelerate Development & Licensing



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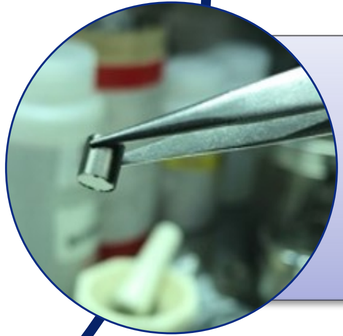
# Westinghouse's EnCore® Fuel Program

**The EnCore® Fuel program is developing and commercializing advanced fuel products to improve safety and economic performance**

## Advanced Cladding

- [ ]$^{a,c}$ -Coated Zirconium – increases safety and operational margin, and may enable high burnup
- Silicon Carbide Cladding – safety and operational benefits

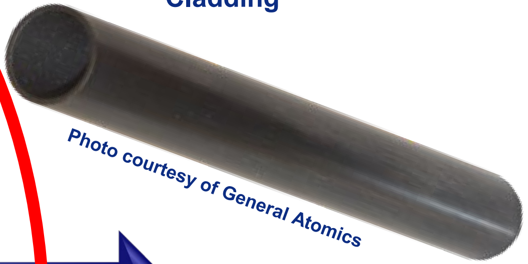


## Advanced Fuel

- ADOPT™ fuel pellets – higher density, benefits to fuel cycle costs, and may support high burnup
- Advanced Pellet (UN) - provide improved fuel cycle economics, thermal properties, and lower operating temperatures

**[ ]$^{a,c}$ Coated Zr Cladding**

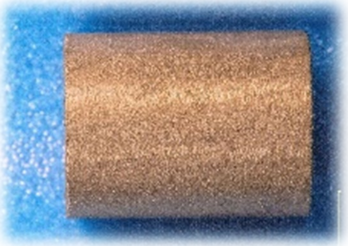
**SiGA® Silicon Carbide (SiC) Composite Cladding**




Product Evolution

**ADOPT™ Pellets**

**Uranium Nitride (UN) Pellets**



**$U^{15}N$ Fuel**

Photo courtesy of Los Alamos National Lab

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# High Energy Fuel Product and Voice of the Customer

[ ] a, c

**Right products at the right time to meet customer needs**

# 2021 Goals and Accomplishments

- **Licensing**
  - Respond to RAIs for High Burnup to 68 GWd/MTU and ADOPT Topicals
  - Preparing input to Coated Cladding Topical
  - Preparing input to High Burnup Topical to [ ]a,c
  - Work on Alternative Licensing Methods and FFRD (EPRI CRAFT)
  - High Enrichment Limit Licensing Impact
- **LTR / LTA programs**
  - Fuel Assembly ATF LTA program
  - Move forward on other LTR / LTA programs
- **Data Needs**
  - Irradiated Fuel Shipment to ORNL (this is critical to supporting our schedule for obtaining data for topicals)
  - Work with Labs, Universities and Hot Cells on tests to support ATF and High Burnup
  - Work with EPRI CRAFT Fuel Performance and Testing Working Group
- **Methods**
  - Update methods and codes for high burnup implementation
  - Work with EPRI CRAFT Guidance and Analysis Working Group
  - Work on Accelerated Fuel Qualification, leveraging lower length scale modeling & use of wireless fuel sensors
- **Manufacturing**
  - Scale up for ADOPT pellet and Coated Cladding production
  - Address impact of enrichment > 5 wt% on manufacturing facilities, transport, on site storage and back end

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# ADOPT

## WCAP-18482

# ADOPT Overview

## ADOPT Characteristics

- **ADOPT** (Advanced DOped Pellet Technology) fuel is a standard $UO_2$ fuel that has been doped with [ ] a,c
- The additives facilitate densification and diffusion during sintering resulting in a higher density and enlarged grain size compared to undoped $UO_2$.

## ADOPT Market Interest

[ ] d,e

[ ] a,c

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# ADOPT – Submittal Content (WCAP-18482)

[ ]d,e

# ADOPT – Forecasted Timeline

[ ] d,e

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# Coated Cladding

# Coated Cladding Overview

- Coated Cladding Characteristics
  - Thin [ ]a,c coating applied to fuel cladding
  - [ ]a,c coated cladding will provide reduced corrosion, oxidation, improved ballooning/burst performance, and improved wear resistance.
  - Demonstration of manufacturability and performance [ ]a,c

- Coated Cladding Market Interest

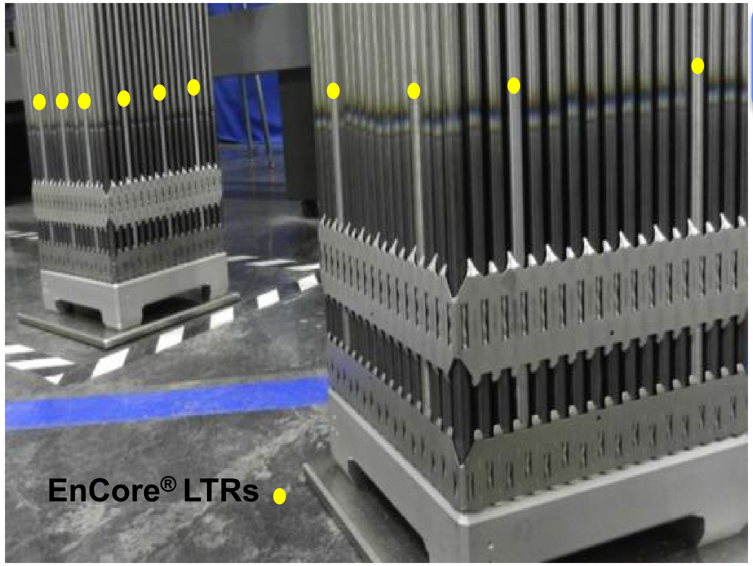
  [ ]d,e

a,c [ ]

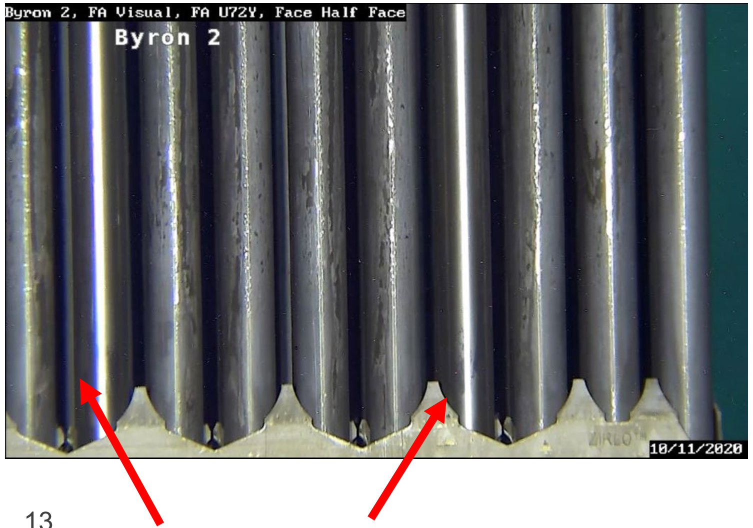
a,c [ ]

# Lead Test Rod and Lead Test Assembly Programs

- Byron 2: inserted Spring 2019
  - Two 17x17 assemblies
  - 16 rods with Cold Spray [ ]a,c
  - Coated Cladding
    - 4 rods with ADOPT™ pellets
  - 4 rods with $U_3Si_2$ pellets in 12” segments
  - Poolside PIE completed October 2020
- Doel Unit 4: inserted Spring 2020
  - Four 17x17 RFA XL assemblies
  - 32 rods with Cold Spray [ ]a,c
  - Coated Cladding with $UO_2$
- Other LTRs/LTAs planned for 2022 and 2023 incorporating Coated Cladding, ADOPT pellets




Byron 2 LTAs
As fabricated




[ ]a,c

Byron 2 LTAs
After 1 cycle

- Limited apparent crud accumulation (easily brushed off)
- No significant oxidation
- No deformation
- No apparent wear

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# Coated Cladding – Submittal Content

[ ]d,e

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# Coated Cladding – Forecasted Timeline

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# High Burnup

## WCAP-18446-P

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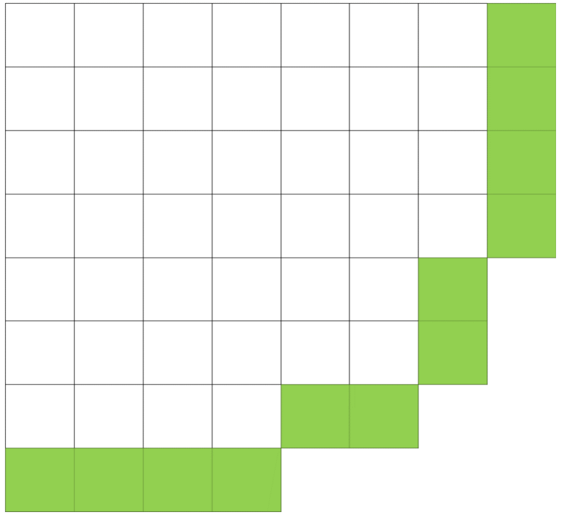
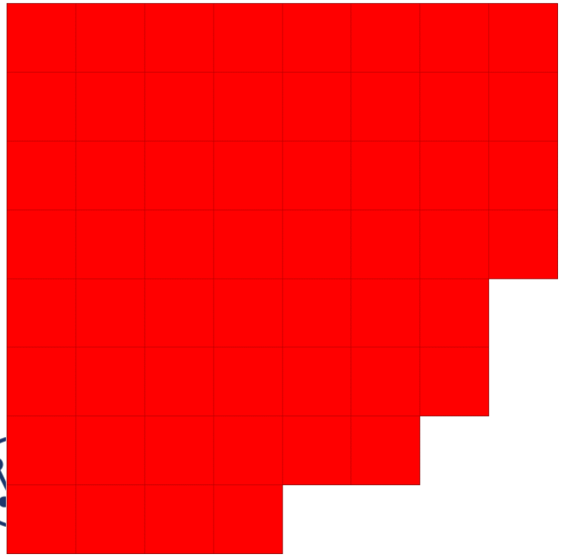
# Industry Interest in improved Fuel Cycle Economics can be achieved with Higher Burnup and Longer Fuel Cycles



Step 1: Increase burnup limit to ~68 GWd/MTU



Step 2: Increase burnup limit for entire core to [ ]a,c with enrichment increase

## Increase Burnup to 68 GWd/MTU

- Submitted Incremental burnup topical report to NRC
- Provides higher burnup benefits to customers sooner

## Increase Burnup to [ ]a,c

- Leverage advanced fuel products using >5% enrichment
- DOE support for High Burnup / High Enrichment within the ATF program
- Work with EPRI CRAFT program on Alternate Licensing Methods and consequences of fuel rod fragmentation and dispersal (FFRD)

**Develop & deliver 24-month cycles to meet market demand by mid-2020's**

# Step 1 – Incremental Burnup Increase Rod Average Burnup Limit of 68 GWd/MTU

- Applicable to current fuel products and current enrichments
- Demonstrate fuel designs can meet design criteria under extended burnup planned fuel cycles
- Address science behind rule changes for:
  - LOCA (Proposed 50.46c)
  - RIA (RG 1.236)

[ ] a, c

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# Step 2 – Increase rod burnup limit to [ ]$^{a,c}$ and enrichment to > 5 wt%

- Continue to expand database for high burnup fuel
- Demonstrate fuel designs can meet criteria with higher enrichment under extended burnup planned fuel cycles
  - Leverage advanced fuel products
- Address fuel fragmentation, relocation and dispersal (FFRD)
- Address impact of enrichment > 5 wt% on manufacturing facilities, transport, on site storage and back end

**Step 2, Westinghouse has a dedicated, multidiscipline team focused on this effort**

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# Incremental High Burnup ~68 GWd/MTU– Forecasted Timeline

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# Next Steps

# Licensing Status of Submitted Topicals

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# ATF Milestones

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# Novel Approaches May Accelerate Development & Licensing

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# Questions & Comments!

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# High Energy Fuel & PWR Core Methods for Fuel Performance Update Meeting

Cenk Güler
Manager, High Energy Fuel Technology
September 2021



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# Outline

- Customer Interest in High Energy Fuel (HEF)
- High Energy Fuel Product
- HEF Roadmap
- Topicals

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- High Burnup Topical Content

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# Customer Interest in HEF

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# High Energy Fuel Product

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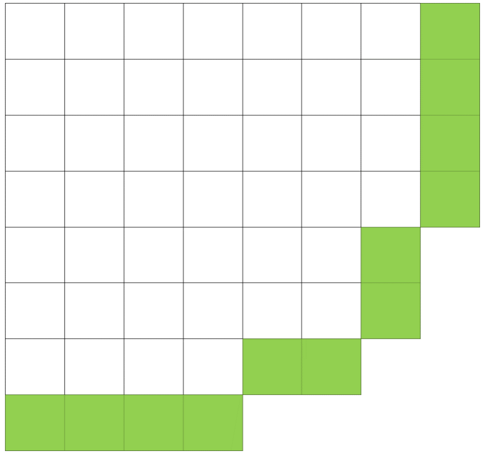
**Right products at the right time to meet customer needs**

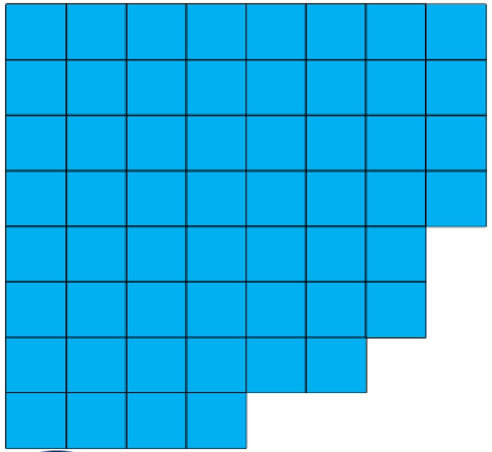
# Industry Interest in improved Fuel Cycle Economics can be achieved with Higher Burnup and Longer Fuel Cycles



Step 1: Increase burnup limit for rods in peripheral assemblies to ~68 GWd/MTU

## Increase Burnup to 68 GWd/MTU

- Submitted Incremental burnup topical report to NRC
- Provides higher burnup benefits to customers sooner



[ ]d,e

## Increase Burnup to [ ]d,e

- Leverage advanced fuel products using >5% enrichment
- DOE support for High Burnup / High Enrichment within the ATF program
- Work with EPRI CRAFT program on Alternate Licensing Methods and consequences of fuel rod fragmentation and dispersal (FFRD)

**Develop & deliver 24-month cycles to meet market demand by mid-2020's**

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# High Enrichment Lead Assembly Fabrication and Licensing

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# Overall High Energy Fuel Roadmap

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# High Enrichment Topical

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# Paragon 2 and Nexus Topicals

- WCAP-16045 Addendum 2 “Updated NEXUS Cross-Section Methodology”
- WCAP-18443 “Qualification of the Two-Dimensional Transport Code PARAGON2”

- We appreciated the timely review process for both topicals by the NRC

- These methods are going to allow Westinghouse to model >5% enrichment and High Burnup conditions to support future ATF programs across the industry

# Fuel Performance Topical

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# FSLOCA™ Evaluation Methodology

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# High Burnup Topical Report

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# High Burnup Topical Report
# Plans for Consequence Assessment of Fuel Dispersal

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# High Burnup Topical Report
# RIA Criteria (RG 1.236)

- Reactivity Insertion Accident (RIA) also referred to as Control Rod Ejection (RE) or CEA Ejection accidents
- New RIA criteria issued as Regulatory Guide (RG) 1.236 in June 2020
- Westinghouse is implementing RG 1.236 for High Energy Fuel (HEF)
  - **ADOPT** fuel pellets (WCAP-18482-P)
  - **AXIOM** cladding (WCAP-18546-P)
  - Incremental burnup to 68K (WCAP-18446-P)
  - Coated cladding (TBD)
  - Lead Test Rods / Assemblies (LTR/LTA) for rod average burnup to [ ][a,c]

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# High Burnup Topical Report
# RG 1.236 and New Fuel Product Features

- All criteria in RG 1.236 applicable [ ]a,c
- [ ]a,c Pellet-Clad Mechanical Interaction (PCMI) failure threshold
- Implement RG 1.236 for incremental burnup fuel
  - [ ]a,c

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[ ]

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# High Burnup Topical Report
# RIA Criteria and High Burnup LTR/LTA

- Applicability of RG 1.236 currently limited to rod average burnup of 68 GWd/MTU

- Conservative approach being taken in high burnup LTR/LTA evaluation and core loading plan
  - All RG 1.236 failure thresholds and criteria to be met
  - Confirm [ ]a,c
    - [ ]a,c
    - [ ]a,c

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# High Burnup Topical Report
# RAVE Methodology

- **RAVE**™ methodology documented in WCAP-16259-P-A
  - Applicable to [ ]a,c
  - Methodology based on coupled multi-physics code system containing USNRC-approved computer codes, such as
    - RETRAN for system transient
    - ANC(K) for 3D neutronic kinetics
    - VIPRE-W for reactor core thermal-hydraulics
- [ ]a,c
  - Simplified **RAVE** process is referred to as "SAVE"

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# High Burnup Topical Report
# RAVE Methodology

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# High Burnup Topical Report
# SAVE Data Flow Diagram

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# High Burnup Topical Report
# New SAVE Applications

- Simplified **RAVE** process (SAVE) is considered for new applications [ ]a,c
  - [ ]a,c
  - [ ]a,c
  - [ ]a,c

- New applications planned to be included [ ]a,c

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# Summary

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# FPUM 2021 Technical Update:

# Westinghouse AXIOM® Cladding for Use in Pressurized Water Reactor Fuel

September 22, 2021

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# Introductions and Agenda

- Purpose of the Meeting
- Overview of **AXIOM**® Cladding
- Licensing Plans
- Summary

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# Purpose of the Meeting

[ ]d

- Touch base on present review status and progress
- Obtain NRC input and feedback on the licensing topical report submitted for **AXIOM** cladding material in early 2021

# Agenda

- Purpose of the Meeting
- Overview of **AXIOM** Cladding
  - AXIOM in Review
  - Background and History
- Licensing Plans
- Summary

# AXIOM in Review

- **AXIOM** cladding: Next generation of robust zirconium alloy targeting very high fuel duties
  - Build on the successes of **ZIRLO** ® and **Optimized ZIRLO** ™ cladding to target increasingly challenging fuel management practices
  - Designed to exhibit improved corrosion resistance, lower hydrogen pick-up, and lower creep and growth
  - Further reduction of Sn, modification of pRXA as well as addition of other alloying elements to improve specific properties

**Table 1-1 The nominal chemical composition (%) of *AXIOM* with *ZIRLO* and *Optimized ZIRLO* cladding**

| Alloy | Micro-structure | Nb (%) | Sn (%) | Fe (%) | Cu (%) | V (%) | Zr (%) |
|---|---|---|---|---|---|---|---|
| **ZIRLO** | SRA | 1 | 1 | 0.1 | - | - | Bal. |
| **Optimized ZIRLO** | pRXA | 1 | 0.67 | 0.1 | - | - | Bal. |
| **AXIOM** | pRXA | 0.7 | 0.35 | 0.1 | 0.12 | 0.25 | Bal. |

SRA: Stress-relief annealed
pRXA: Partially-recrystallized annealed

# Background and History

- Material research and optimization for **AXIOM** cladding development began in 2000, with four major variants identified for further in-reactor testing.
- Poolside and hotcell PIE data from various lead test rod programs as well as extensive out-reactor characterization program
- The final **AXIOM** cladding composition was selected in 2015 based on best overall performance to ensure that all operating requirements were considered.
- Production size ingot with the final **AXIOM** composition has been melted and the fabrication processes including the tube and assembly fabrications have been qualified.
- Eight full **AXIOM** Lead Use Assemblies are currently being irradiated at Millstone now in their 3rd cycle of operation.

**AXIOM is progressing through licensing and looking forward to region implementation.**

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# Agenda

- Purpose of the Meeting
- Overview of **AXIOM** Cladding
- Licensing Plans
  - Applicable Regulations and NRC Guidance
  - Path to Compliance
  - Timeline of Key Activities
- Summary

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# Applicable Regulations and NRC Guidance

**AXIOM** cladding will be generically applicable to current regulatory requirements

- General Design Criteria (GDC) provide the minimum design requirements for LWRs
  - GDC 10: "The reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences."
  - GDC 2 as it relates to seismic design of structures, systems and components
  - GDCs 25, 26, 27, and 28 concerning reactivity control systems to ensure fuel design limits are met and capability to cool the core is maintained
  - GDC 35 as it relates to core cooling such that fuel and clad damage would not interfere with cooling and clad metal-water reaction is limited to negligible amounts
- 10 CFR 50.46 as it relates to cooling performance

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# Applicable Regulations and NRC Guidance (Continued)

- To demonstrate generic applicability, the guidance of Standard Review Plan (SRP), NUREG-0800, has been utilized
  - SRP Section 4.2, "Fuel System Design"
  - SRP Section 4.3, "Nuclear Design"
  - SRP Section 4.4, "Thermal and Hydraulic Design"
  - SRP Chapter 6.2.1, "Containment Functional Design"
  - SRP Chapter 15, "Transient and Accident Analysis"
- Pertinent Regulatory Guides (RG) also used
  - RG 1.236, Reactivity Initiated Accident (RIA) criteria

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# Path to Compliance

- The submitted topical WCAP-18546-P
  - Provides data demonstrating material properties and in-core behavior
  - Identifies performance boundaries for **AXIOM** cladding
  - Demonstrates capability to accurately model cladding properties to confirm satisfaction of fuel system safety criteria
- The overall topical approach to demonstrating regulatory compliance is similar to existing NRC-approved zirconium alloys (i.e., **ZIRLO** and **Optimized ZIRLO** cladding)

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# Timeline of Key Activities

[ ]d

- Insertion of first region Spring 2025

# Agenda

- Purpose of the Meeting
- Introduction of **AXIOM** Cladding
- Licensing Plans
- Summary

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# Summary and Alignment Strategy

[ ]d

- Coordination of resources with the NRC through heads-up approach via this meeting

**We appreciate your time and consideration today.**

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# Westinghouse PWR Fuel Performance Update

September 2021

Jason Smith, Manager
Product Performance Engineering

Fuel Performance info – Charles Haselden
Debris Mitigation info – Michael Conner

# Agenda

- **Fuel Performance Update**
- Changing in Performance Trends
  - Improvements in Debris Mitigation
- [ ] a,c Leaker Investigation
- [ ] a,c Leaker Investigation
- Summary

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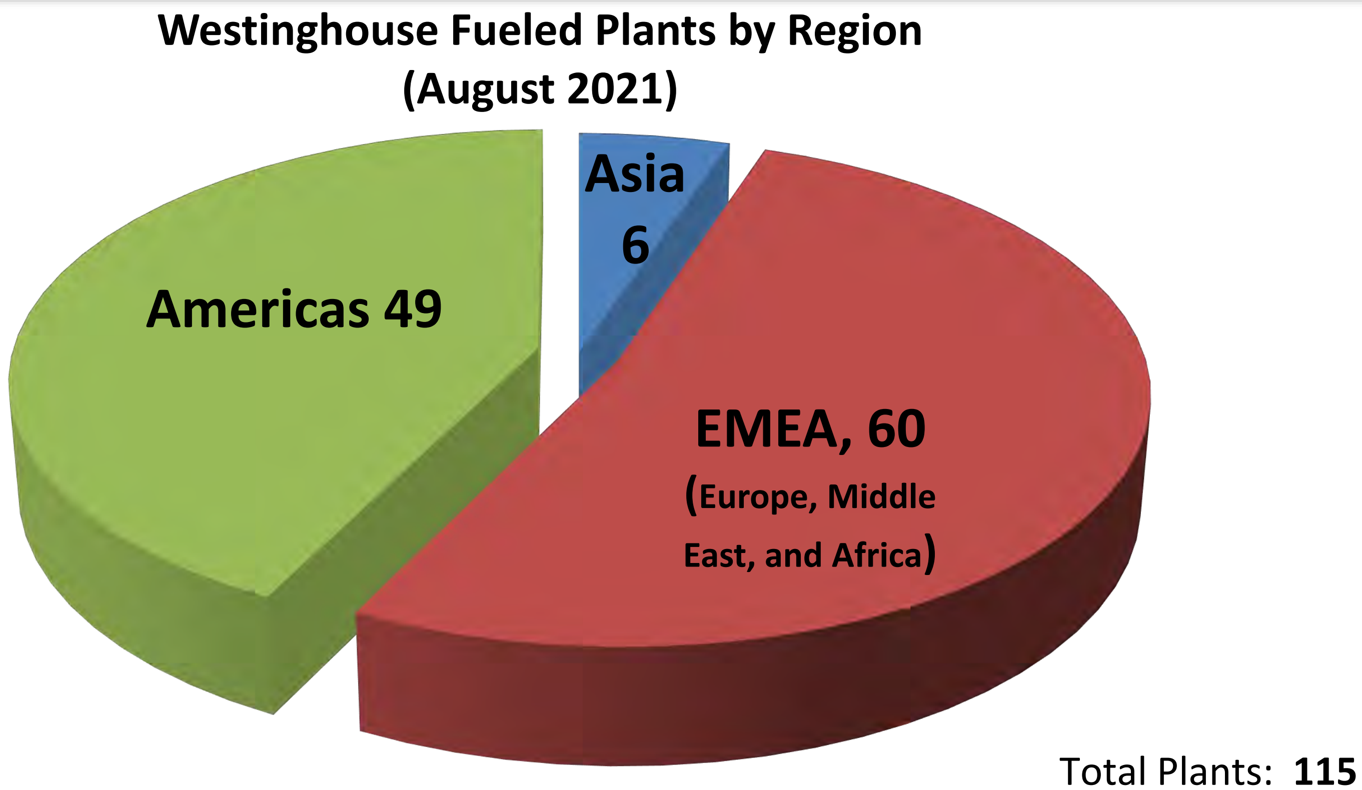
# Westinghouse Fueled Plants by Region




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

# Nuclear Fuel Reliability Improvement Progress As Of August 31, 2021

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# Historical Performance of Westinghouse Fueled Plants

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# Leaking Plants, August 31, 2021 worldwide

[ ] **a,c**

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# Historical Performance of Plants Currently Leaking As of August 31, 2021

a,c

# Driving to Flawless Fuel Through Design – Current Status (August 31, 2021)

a,c

# Historical Trend in Number of Leaking Fuel Rods

a,c

# Agenda

- Fuel Performance Update
- **Changing in Performance Trends**
  - **Improvements in Debris Mitigation**
- [ ] a,c Leaker Investigation
- [ ] a,c Leaker Investigation
- Summary

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# Changing in Performance Trends (PWR)

a,c

# Advanced Debris Protection Program

a,c

# PWR Filter Improvements:
# 1. Advanced Debris Filter Bottom Nozzle (ADFBN)

[ ]a,c

# Nozzle Skirt Design Details

a,c

# Final ADFBN – Design Criteria Met

a,c

# FACTS-Debris Testing Methodology

a,c

# Debris Test Details

a,c

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# FACTS-DS Test Results

a,c

Westinghouse

# PWR Filter Improvements:
# 2. Additive Manufactured Bottom Nozzle (AM BN)

a,c

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# AM BN Filter:
# New Fine Mesh Filter Design, “Spire”

a,c

# AM BN Printing

a,c

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# AM BN Primary Design Criteria are met

a,c

# Debris Filtering Test: AM BN

a,c

# Agenda

- Fuel Performance Update
- Changing in Performance Trends
  - Improvements in Debris Mitigation
- **[ ] a,c Leaker Investigation**
- [ ] a,c Leaker Investigation
- Summary

# [ ] a,c Leaker Status

[ ] a,c

# [ ] a,c Radiochemistry

[ ] a,c

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# Previous [ ] a,c Leakers

a,c

# W 14x14 Fleet Fuel Performance Status

a,c

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# [ ] a,c Outage Prep

[ ] a,c

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# [ ] a,c Plan Work Scope – (October 2021)

[ ] a,c

# [ ] a,c Plan Work Scope – (Cont.)

[ ] a,c

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# [ ] a,c Fuel Failure Contingency Measures

[ ] a,c

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# Agenda

- Fuel Performance Update
- Changing in Performance Trends
  - Improvements in Debris Mitigation
- [ ] a,c Leaker Investigation
- **[ ] a,c Leaker Investigation**
- Summary

# [ ] a,c Leaker

[ ] a,c

# Agenda

- Fuel Performance Update
- Changing in Performance Trends
  - Improvements in Debris Mitigation
- [ ] a,c Leaker Investigation
- [ ] a,c Leaker Investigation
- **Summary**

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# Summary

- Robust Westinghouse fuel designs performing well

a,c

[ ]

- Goal is 100% leak free performance through use of Fuel Reliability Improvement (FRI) process to drive continuous improvement and strong partnership with industry

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[ ]

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# Questions?

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# BWR Fuel Performance Update

Uffe Bergmann
Jean-Marie Le Corre

Westinghouse

# Westinghouse **VISION & VALUES**

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we advance technology & services to power a clean, carbon-free future.

Customer Focus & Innovation

Speed & Passion to Win

Teamwork & Accountability

Safety • Quality • Integrity • Trust

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# Outline

- Leaker Statistics
- Novel Method for Prediction of Localized Zinc-Rich Crud at Leibstadt NPP (KKL)
  1) Background on Core Flow Conditions in BWR/6 Plants
  2) Background on KKL Crud Event 2012-2016 (reviewed by NRC as part of D5 CPR Correlation Topical Report)
  3) MEFISTO-T Code Upgrade:
     New Models of Annular Two-Phase Flow and Localized Crud Deposition in BWR Fuel Bundles
  4) Validation of MEFISTO-T against Crud Inspections at KKL
  5) References

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# Leaker Statistics

## Uffe Bergmann

# BWR Primary Failure Statistics
# 10X10 BWR Fuel Designs using liner cladding

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# Core Flow Conditions in BWR/6 Plants

Uffe Bergmann

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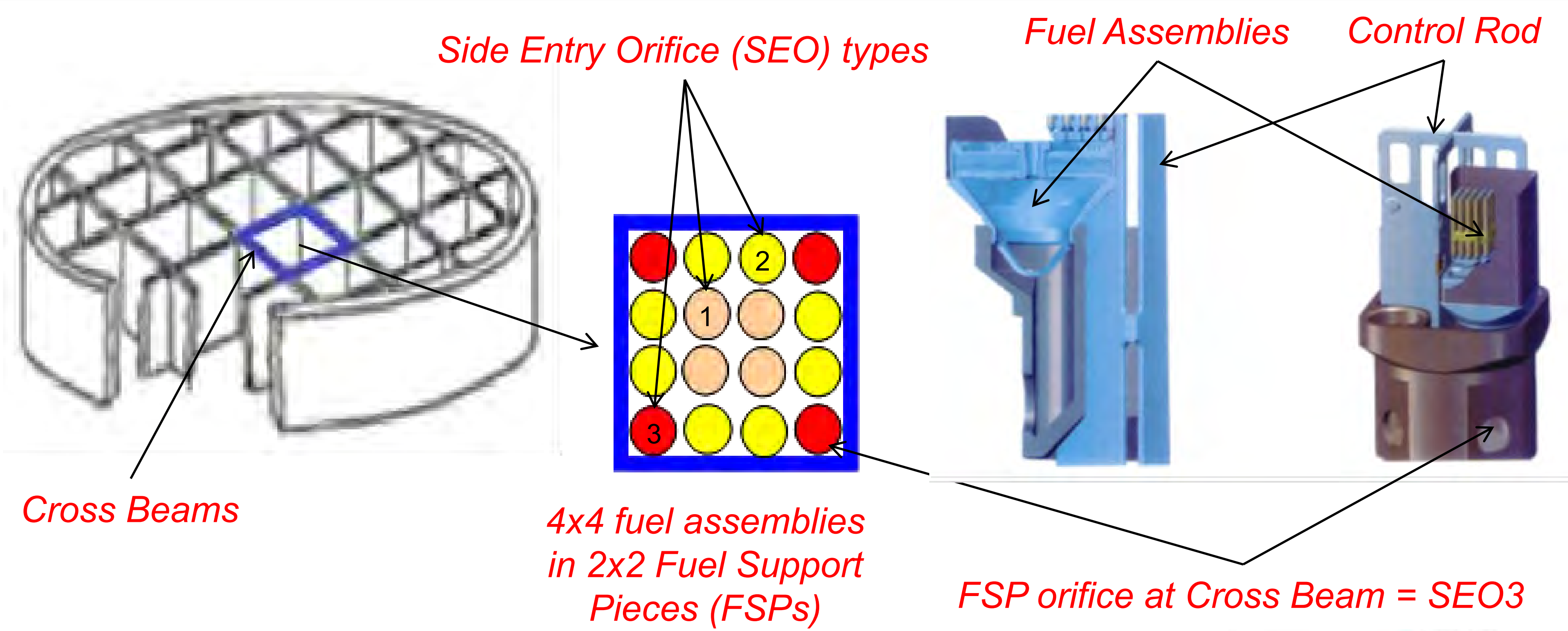
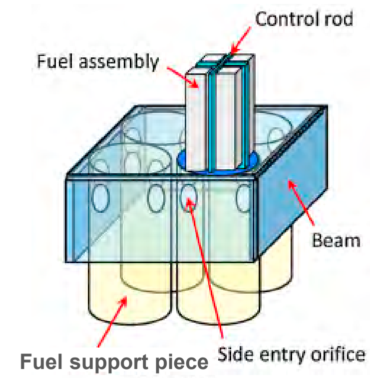
# Flow Paths in Plants with Cross Beams under Core Support Plate




Quarter-core symmetry assumed in loading pattern

- Sets of 4 symmetrical fuel assemblies (FAs) loaded: 1 FA in SEO1, 2 FAs in SEO2 and 1 FA in SEO3

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# Original 10 CFR Part 21 Notification from GE SC02-15 dated Oct 4, 2002

- Accounted for uneven hydraulic resistances due to tighter flow paths at SEO2 and SEO3 (see table)
  - Established current SEO pressure loss coefficients (PLCs) based on testing in [ ]a,c
  - 1% reduction in CPR margin (for limiting FA in SEO3)
  - **Did not account for the presence of flow vortices at SEO3 (and SEO2)**

[ ]a,c

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# [ ]a,c 16-Bundle Experiments

- To better characterize the flow conditions in a square beam section below the core support plate, and the influence on fuel assembly inlet flow, [ ]a,c performed a series of full-scale 16-bundle experiments [ ]a,c

[ ]a,c

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# Observation of Twin Vortices at SEO3

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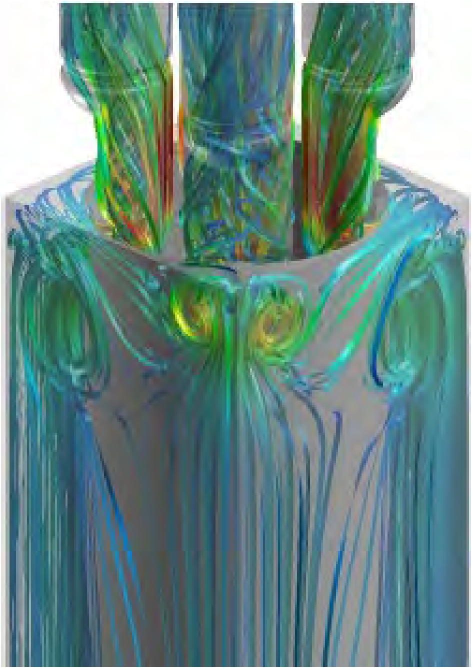
# Supporting CFD Studies

- Vortex development comprehensively studied by CFD simulations
- Phenomenon reported by [ ]a,c



**Many independent CFD studies confirmed twin vortices and flow reduction at SEO3**

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# KKL Gamma Scanning 2018

- Final evidence of reduced flow resulting from the existence of twin vortices came from a specifically tailored Ba-140 gamma-scanning campaign performed in 2018 by Westinghouse at KKL
  - 16 SEO quartets (1 FA in SEO1, 2 FAs in SEO2 and 1 FA in SEO3) measured
- The flow measured (indirectly via the resulting fuel assembly power) was approximately 15% lower in SEO3 as compared to SEO1 (facing no support beams), in full agreement with the 16-bundle experiments
- Results confirmed that twin-vortices are present essentially all the time at SEO3

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# Latest 10 CFR Part 21 Communication by GEH SC 21-04 dated April 19, 2021

- The existence of twin vortices at SEO3 and the consequences in terms of reduced fuel assembly flow were [ ]a,c
  - Pressure loss coefficient at SEO3 must be increased by a factor 1.9 (see table)
  - Results in a flow reduction of ~15%
  - Recommended interim action:
    5% CPR margin penalty for operating BWR/6 plants

a,c [ ]

HITACHI **10 CFR Part 21 Communication**

*SC 21-04 R0* *April 19, 2021*

**To:** *Affected and Potentially Affected Plants (Attachment 1)*

**Subject:** *Fuel Support Side Entry Orifice Meta-Stable Flow for 2 Beam Locations in the BWR/6 Reactors*

| | |
|---|---|
| [ ] Reportable Condition [21.21(d)] | [X] 60 Day Interim Report [21.21(a)(2)] |
| [ ] Transfer of Information [21.21(b)] | [X] Safety Information Communication |

# KKL Crud Event (2012-2016)

## Uffe Bergmann

Westinghouse

# Background on KKL Crud Event (2012-2016)

- Main basis
  - Around 300 inspected fuel assemblies from many cycles
  - 48 observed marks
  - Hot cell examination of 3 affected rods
  - [ ] a,c 16-bundle experiments
  - KKL gamma scanning

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[ ]

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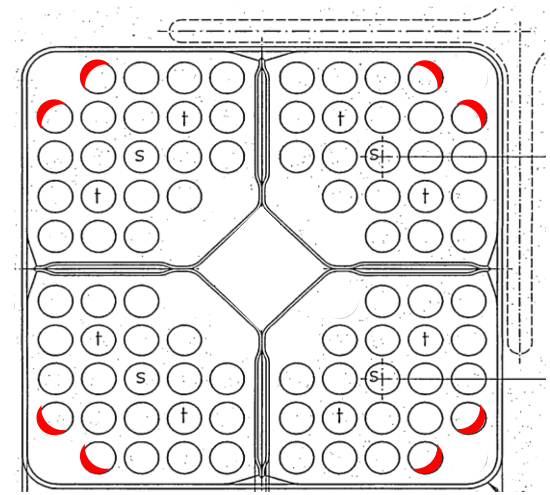
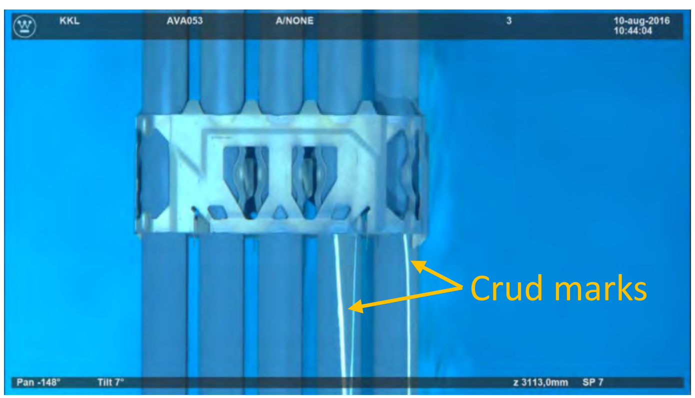
# Background on KKL Crud Event (2012-2016)

- Main observations
  - Localized V-shaped marks extending below upper spacers (7 & 8)
  - Next-to-corner rods only and oriented towards channel and opening above 1/3 corner rod
  - Fresh SVEA-96 Optima2 fuel only
  - Limited to Cycles 28-32
    - Coincides with increase in zinc injection
  - SEO3 mainly (few SEO2, no SEO1)
  - Zinc-rich crud (ZnO, $Zn_2SiO_4$), 100-200 $\mu$m, no significant cladding oxidation



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# Background on KKL Crud Event (2012-2016)

- Refined understanding of crud deposition mechanism with MEFISTO-T code

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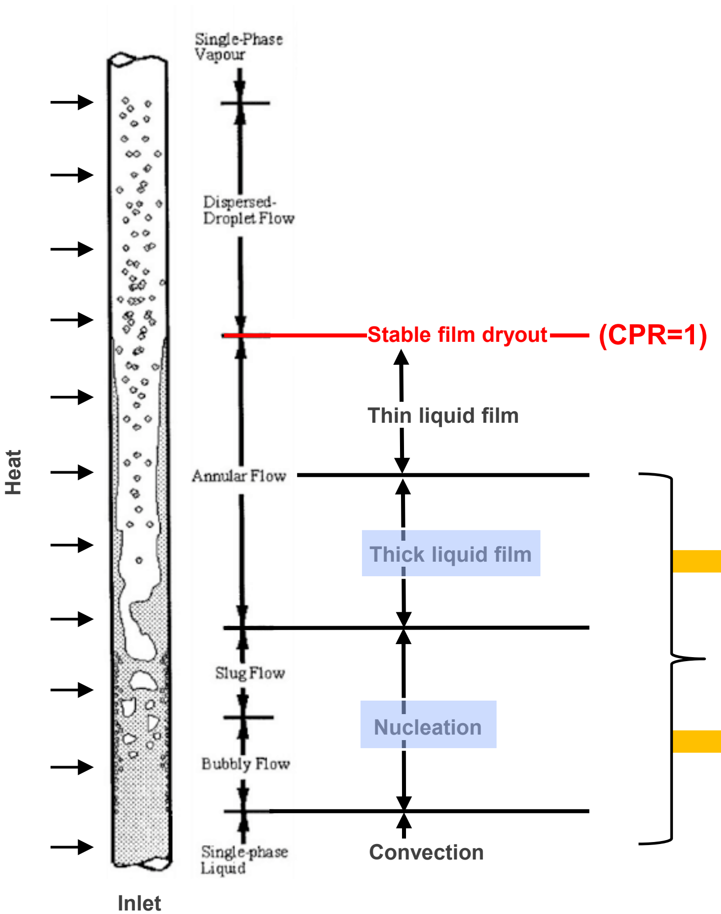
# MEFISTO-T Code Upgrade: New Models of Annular Two-Phase Flow and Localized Crud Deposition in BWR Fuel Bundles

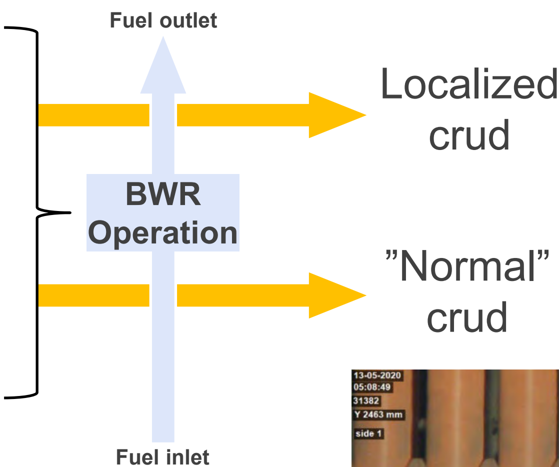
*Patent no. PCT/EP2021/057715*

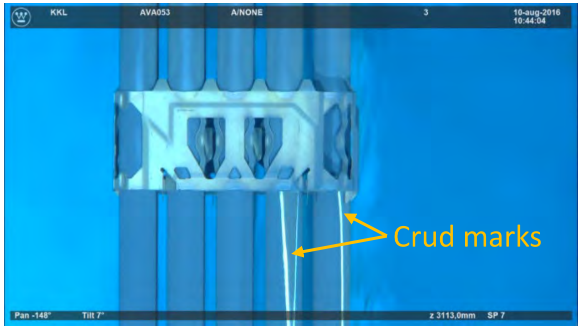
Jean-Marie Le Corre

Westinghouse

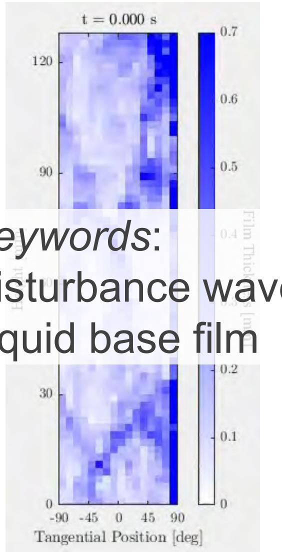
# BWR Coolant Conditions and Crud



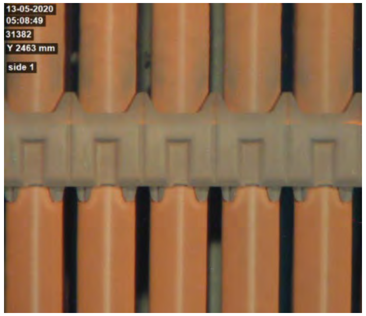




**Thick liquid film**

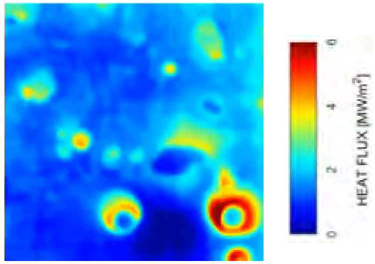



*Keywords*:
Disturbance waves
Liquid base film

Reference:
*Laboratory of Nuclear Energy Systems ETHZ*



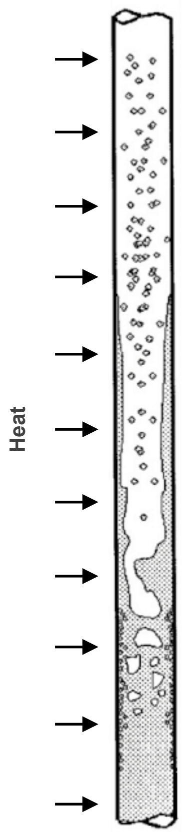
**Nucleation**

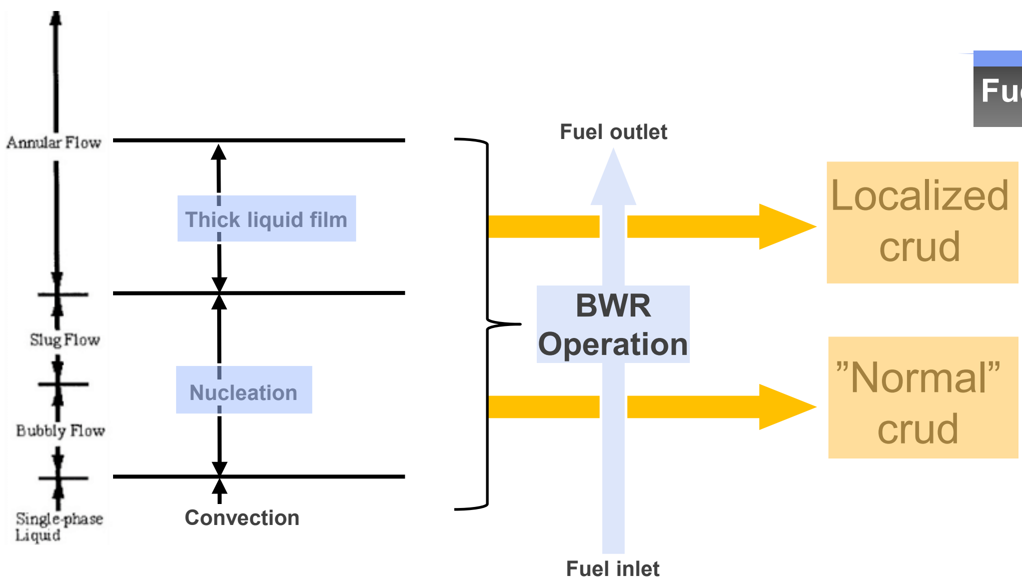


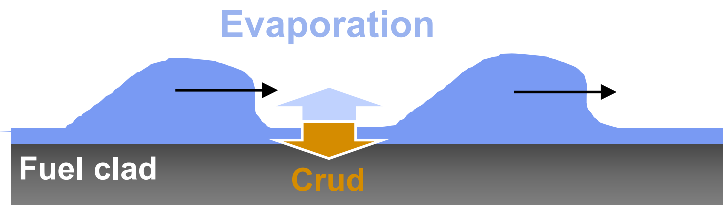

Reference:
*The Red Laboratory*
*Massachusetts Institute of Technology*

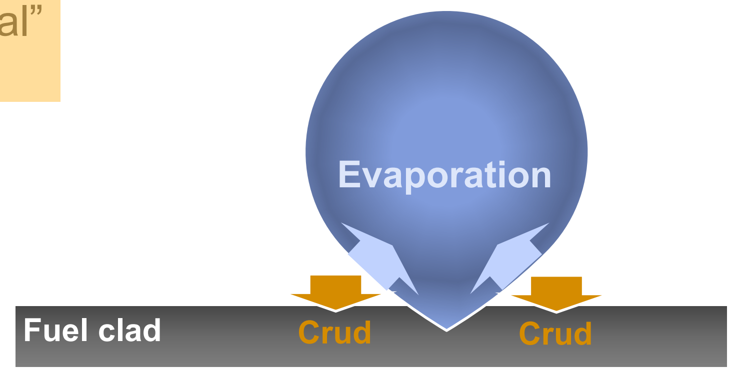
# Crud Deposition Mechanisms

- Coolant impurity concentration > precipitation limit
- Compound-dependent (e.g. ~100 ppb for $Zn_2SiO_4$)
- Reached through local evaporation

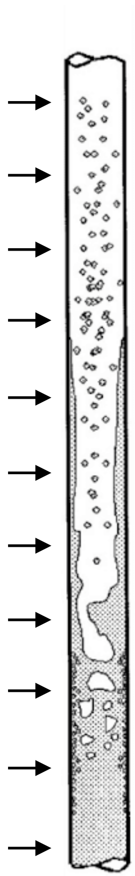


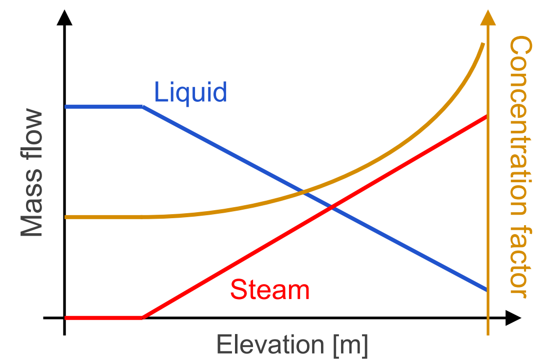



# Impurity Concentration Model (1)



- Goal: Quantify local (near wall) impurity concentration
- Physical model: Impurity conservation in liquid coolant
- Simple approach (1-D)
  - Based on e.g. POLCA7 TH output
  - Mixed liquid: $C_{Liquid} = \frac{1}{1-x}$
  - Insufficient approach ($C_{Liquid} \approx 2$)
- CFD approach
  - High spatial resolution
  - Complex models, high run time
  - Simplification of physical processes (mass exchange between fields)

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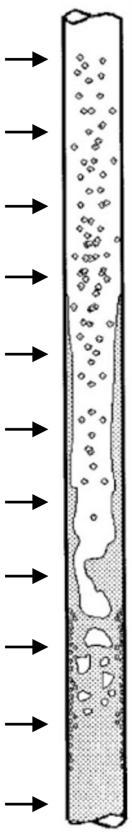
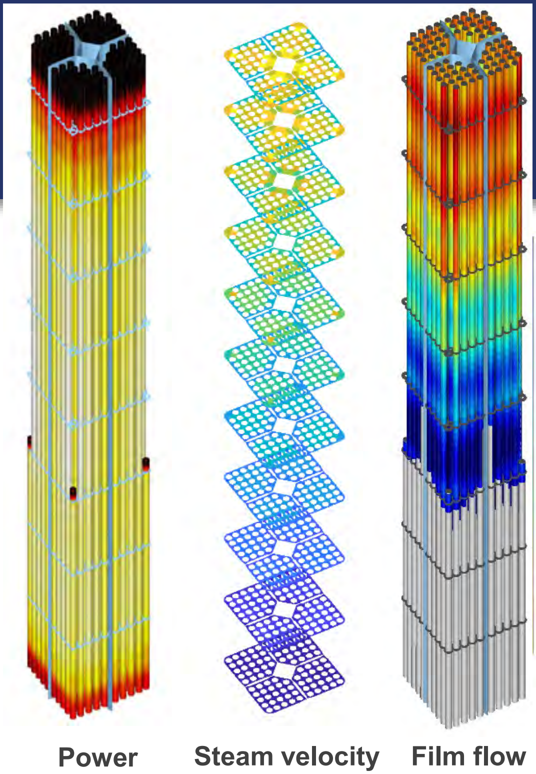
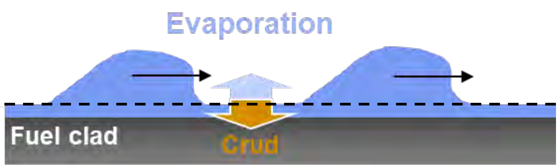
# Impurity Concentration Model (2)



- New proposed approach
  - MEFISTO-T sub-channel analysis code
    - 124 interconnected channels per assembly
    - Steam, film & drop fields separation (3-field)
    - Mechanistic CPR prediction based on film dryout
    - Presented to NRC during past topical report reviews
  - Missing information
    - Wave characteristics (e.g. frequency)
    - Base film characteristics (mass flow)
  - New models development
    - Base film & wave fields separation (4-field)
    - Base film dynamic evaporation model between waves
    - Multi-field coupled dissolved impurity transport equations
    - Calibration and validation under relevant BWR core operating conditions

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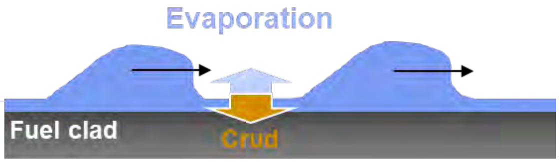
# Impurity Concentration Model (3)

- Transport of dissolved impurities
  - Mass impurity conservation in all liquid fields
  - Capture spacer effect (dilution) and part-length rods
- Dynamic base film between waves
  - During wave time period
    - Base film mass evaporation (local heat flux)
    - Impurity concentration increases before being quenched by next wave
  - **Base film concentration at end of wave cycle is the figure of merit**



# Validation of MEFISTO-T against Crud Inspections at KKL

Uffe Bergmann

# Considered Precipitation Limits

- Limits defined in terms of calculated maximum local zinc concentration in base film
  - Lower limit where crud deposition has been observed: **75 ppb**
  - Average (best-estimate) limit based on logistic regression analysis: **100 ppb**
- Historical reactor water zinc concentrations in KKL and concentration factors needed to reach the 75 ppb lower limit:

| Cycle | Zinc concentration at core inlet (ppb) | Reference concentration factor limit (75 ppb) |
|---|---|---|
| 20 – 25 | 6 | 12.5 |
| 26 | 3 | 25.0 |
| 27 | 4 | 18.8 |
| 28 | 8 | 9.4 |
| 29 – 35 | 10 | 7.5 |

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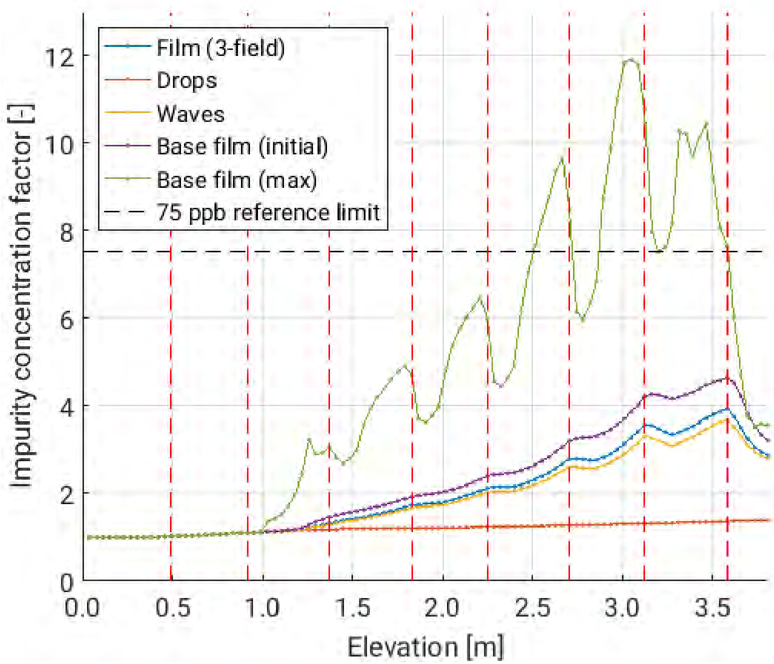
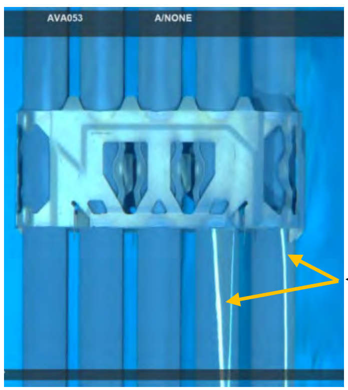
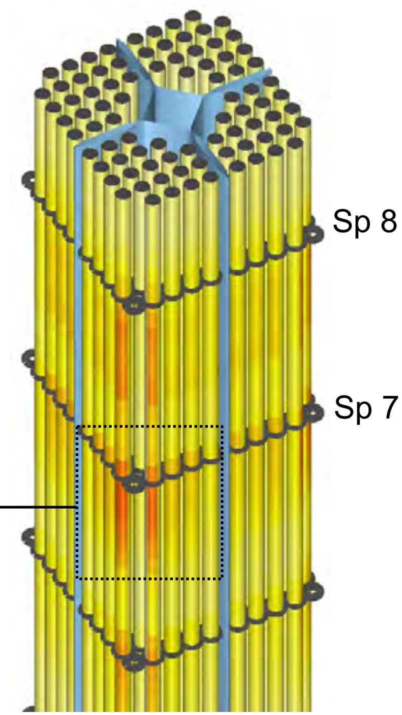
# MEFISTO-T Simulation Example

- Crud predicted by evaporation of base film between disturbance waves
- Crud is correctly predicted at SEO3 core positions, during second half of first cycle, on next-to-corner rods, below Spacers 7 and 8, and in direction towards fuel channel





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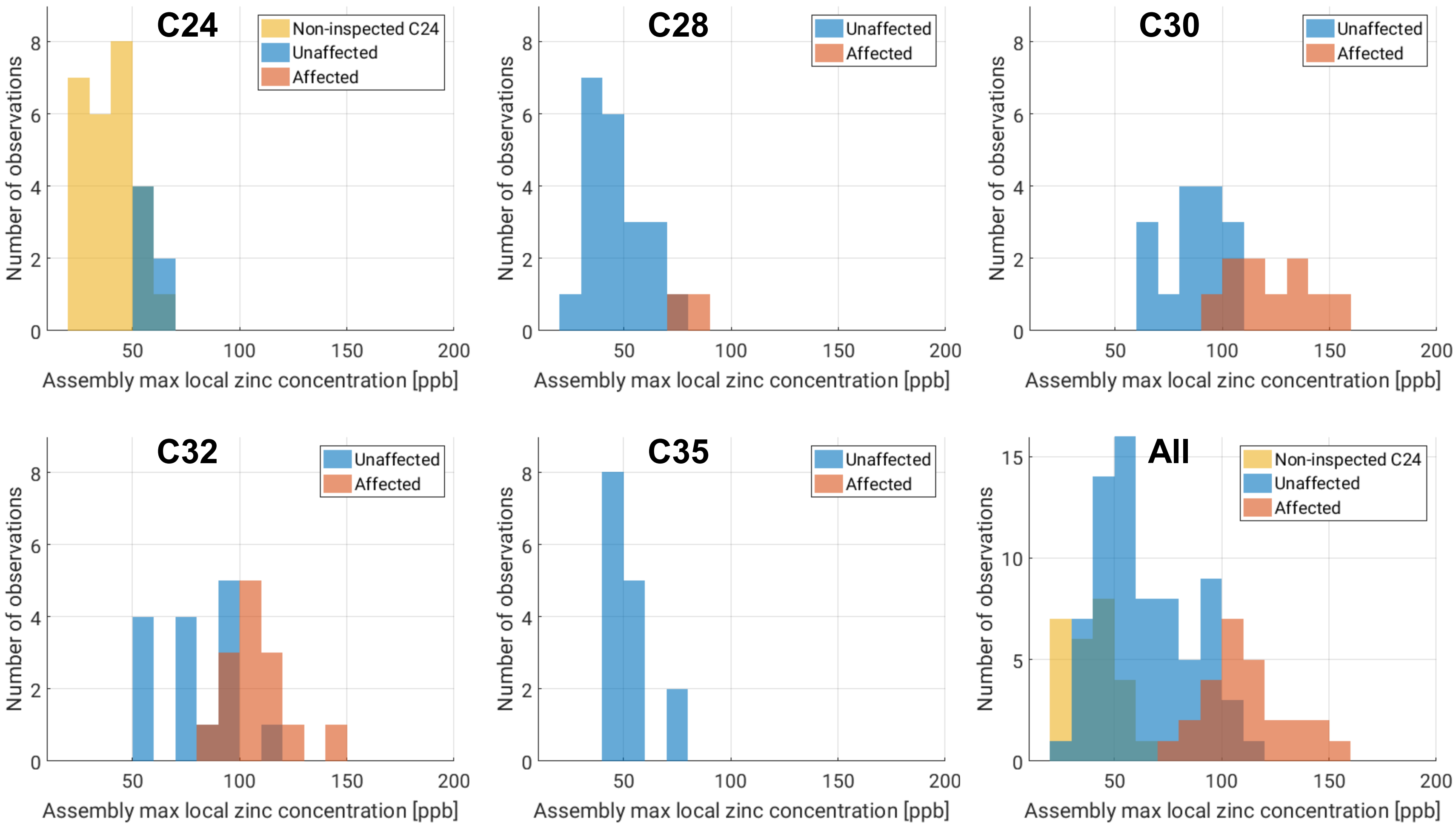
Affected = crud
Unaffected = no crud

# Summary of Results for Selected Cycles

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**MEFISTO-T can separate populations of affected/unaffected assemblies to a satisfactory extent (small overlap)**

# New Design Criterion for SVEA-96 **Optima3™** Fuel

- All affected assemblies in Cycles 28-32 have maximum local zinc concentration greater than 75 ppb
- The following design criterion is being used at KKL

$$\text{Maximum impurity concentration factor} < \mathbf{7.5}\,\frac{10\text{ ppb}}{\text{zinc concentration [ppb]}}$$

**Conservatively bounding approach**

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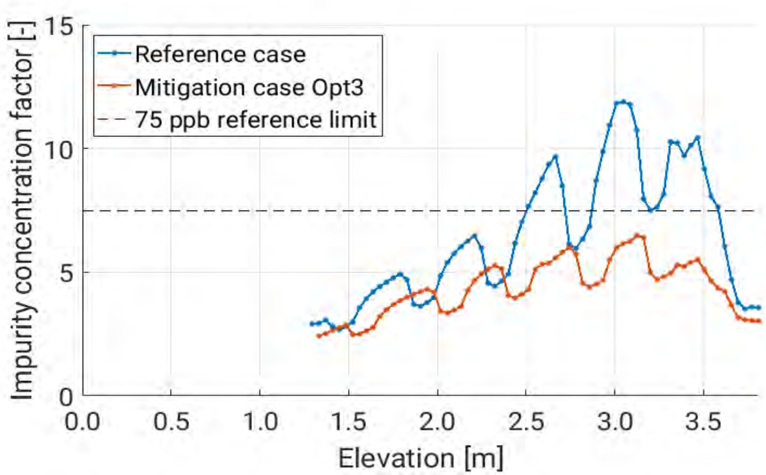
# Tailored Nuclear Designs of Optima3 for Crud Mitigation

- The 75 ppb acceptance criterion can be fulfilled by optimizing the U-235 enrichment in the next-to-corner rods during the nuclear design process
  - An axially graded design with lower enrichment in the top segment is most efficient
  - Impact on average enrichment (burnup capability) is acceptable
- Example below is relevant to KKL conditions (12-month cycle)
  - Optima3 generally has lower concentration factors in 24-month cycles due to further depletion of next-to-corner rods when power swings to top of core
  - [ ] a,c

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# Applicability to other BWR Fuel Designs and Plants

- New MEFISTO-T four-field model for crud prediction includes local (fuel design independent) empirical correlations that have been calibrated against equilibrium steam/water experiments in tube and annuli at conditions relevant of BWR operation
- MEFISTO-T was successfully validated against KKL crud inspection database for BWR fuel bundles (Optima2)
- MEFISTO-T may be applied to any fuel assembly design and operating condition in any BWR plant, provided that certain input data are made available
  - Fuel assembly geometrical information
  - Fuel assembly boundary conditions (from 3D nodal code)
  - Coolant chemistry data

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**MEFISTO-T is applicable for prediction of margin to crud deposition in any BWR fuel design and plant**

# References

## Uffe Bergmann and Jean-Marie Le Corre

# Future Publications

- U.C. Bergmann, J.-M. Le Corre, R. Bieli, D. Chionis, L. Robers, and H.-M. Prasser, "**Novel Method for Prediction of Localized Zinc-Rich Crud at Leibstadt NPP**," *TopFuel 2021*, Santander, Spain, October 24 – 28, 2021
  - High level model description and application to KKL
- J.-M. Le Corre, "**Non-equilibrium modeling of disturbance waves with phase change in fuel bundle**," *19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19)*, Brussels, Belgium, March 6 – 11, 2022
  - Detailed description of disturbance wave model
- J.-M. Le Corre, L. Robers and H.-M. Prasser, "**Multi-field transport model and local precipitation of dissolved reactor coolant impurities in BWR fuel bundle**," *19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19)*, Brussels, Belgium, March 6 – 11, 2022
  - Detailed description of impurity transport model
- B. Helmersson, K. Göransson, A. Kucuk, C. Hellwig, M. Martin, S. Nichenko and D. Kulik, "**Observations of dense zinc and silicon-rich V-shaped crud**," *International Conference on Water Chemistry in Nuclear Reactor Systems (NPC 2021)*, Juan-les-Pins, France, September 27 – 30, 2021
  - Characteristics of KKL crud

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# 2021 Fuel Performance Update Meeting

## **PRIME**TM Fuel Assembly Features

Brian Millare
Technical Lead

# Topics

a,c

- Scope and Schedule
- Design Overview / Verification
- Licensing
- Summary

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# Scope and Schedule

- Scope
  - Integration of Advanced Fuel Assembly Features
    - 17 Optimized Fuel Assembly (OFA)
    - 17 Robust Fuel Assembly
    - 15 Upgrade Fuel Assembly

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# Scope and Schedule

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**Improved Fuel Performance; Licensing effort will be discussed later**

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# Scope and Schedule

[ ] a,c

**First region of PRIME 17OFA fuel by end of 2021. 17RFA and 15 Upgrade are ongoing.**

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# Design Overview / Verification

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| Fuel Type | Feature | Current |
| --- | --- | --- |
| 15x15 | Mid and IFM Grids | **ZIRLO®** |
| | Dashpot | Tube-in-Tube |
| | Bottom Nozzle | mDFBN |
| 17OFA | Mid and IFM Grids | **ZIRLO** |
| | Dashpot | Swaged |
| | Bottom Nozzle | SDFBN |
| 17RFA | Mid and IFM Grids | **ZIRLO** |
| | Dashpot | Swaged |
| | Bottom Nozzle | SDFBN |

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# Design Overview / Verification

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# Design Overview / Verification – LTZ Grids

[ ]a,b

[ ]a,b

- Mechanical testing complete
- Analyses are ongoing

# Design Overview / Verification – PRIME Bottom Nozzle

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- Other analyses are still ongoing for 17RFA and 15Upg

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# Design Overview / Verification – PRIME Bottom Nozzle

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c

# Design Overview / Verification – Reinforced Dashpot

[ ] a,c

[ ] a,c

- Mechanical testing completed
- Analyses are ongoing for 17RFA and 15Upg

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# Licensing

- *New* fuel designs require NRC approval to ensure that the licensing requirements in Section 4.2 of the Standard Review Plan are met.
- Changes to *existing* fuel mechanical designs can be implemented without NRC approval provided they meet the criteria in the Westinghouse Fuel Criteria Evaluation Process (FCEP) (WCAP-12488-A).
  - Requires sending a letter to the NRC addressing the criteria
  - Can then be implemented by licensees via 10 CFR 50.59 provided no technical specification (TS) changes are needed and the 50.59 review concludes that prior NRC review and approval is not required

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# Licensing

- Based on past precedent and previous FCEP submittals, all **PRIME** features are anticipated to meet the NRC-approved design criteria in WCAP-12488-A.

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  - Advanced Debris Filter Bottom Nozzle licensed via FCEP (2020)

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# Utility Licensing

- Once the FCEP notification letter has been issued to the NRC, the current plan is to implement the **PRIME** fuel features at plants under 10 CFR 50.59 (provided no TS changes are needed and the 50.59 review concludes that prior NRC review and approval is not required).
- There are many instances within the UFSARs that discuss the components being changed as part of the **PRIME** fuel features. To fully incorporate **PRIME** fuel features into the licensing basis, the appropriate updates are required to the plant's UFSAR.
  - These changes can typically be made within the allowance of 10 CFR 50.59

# Summary

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- Customer Focus & Innovation
- Speed & Passion to Win
- Teamwork & Accountability

Safety • Quality • Integrity • Trust

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# Additive Manufacturing at Westinghouse

## 2021 Fuel Performance Update Meeting

David Huegel
September 2021

Westinghouse

# Overview

- AM at Westinghouse
- AM Development at Westinghouse
- First AM Nuclear Fuel Component Installed in Commercial Reactor
- Westinghouse Developed AM Nuclear Fuel Components
- Westinghouse AM Tooling Development
- Powder Metallurgy (PM) Hot Isostatic Pressing (HIP) Development
- AM Development Partnering with Industry/ Academia
- Q&A

# Additive Manufacturing at Westinghouse

# Advanced Manufacturing Objectives

- **Improve industry competitiveness, through the development and implementation of advanced manufacturing (AM) technologies**
  - Drive cost reductions in manufacturing
  - Enable new products and services that provide innovative customer solutions
  - Leverage external funding sources and collaborative development

**Thimble Plugging Device**
**Direct Metal Laser Sintering**

**RVI Quickloc Upper Support Assembly**
**Powder Metallurgy and Hot Isostatic Pressing (PM-HIP)**

**Passive Hydrogen Igniter Concepts**
**Binder Jetting Additive Manufacturing**

**Tooling - AM Laser Powder Bed Fusion**

# Additive Manufacturing at Westinghouse

- Additive Manufacturing will have a big impact in Nuclear:
  - Cost Effect
  - Improve Performance and Reliability
  - Improve Delivery and Schedule
- Westinghouse is fully invested in the AM technology:
  - Continue to performed significant testing on 3D parts (with and without radiation effects)
  - Utilizing 3D printing for tooling for manufacturing
  - Implemented a 3D AM part in reactor to gain experience
  - Building/designing numerous parts with AM for eventual employment in a nuclear reactor (grids, nozzles, etc.)

**Our Goal is for AM to Help Transform the Nuclear Industry**

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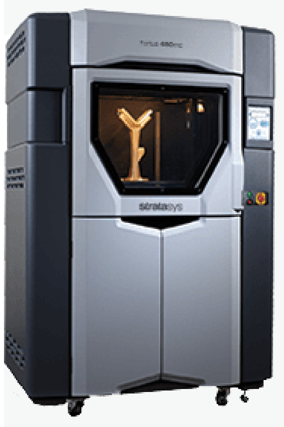
# Additive Manufacturing – Westinghouse Equipment

- Westinghouse owns one (1) EOS M 290 machine for printing in metal with access to additional machines at the same facility
  - Currently printing in:
    - Alloy 718
    - SS Types: 316L, 304,17-4 PH and MS-1
    - Copper and Aluminum
  - Build volume 250mm x 250mm x 325mm (9.85 x 9.85 x 12.8 in)



- Additively Manufactured (3D Printed) Plastic Parts

- CFFF installed a high quality Fortus 450 polymer FDM printer.
- Build volume 406mm x 355mm x 406 mm (16 x 14 x 16in)
- Variety of ABS and Nylon materials

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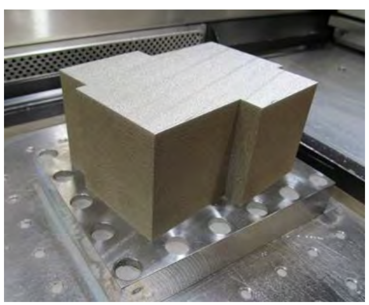
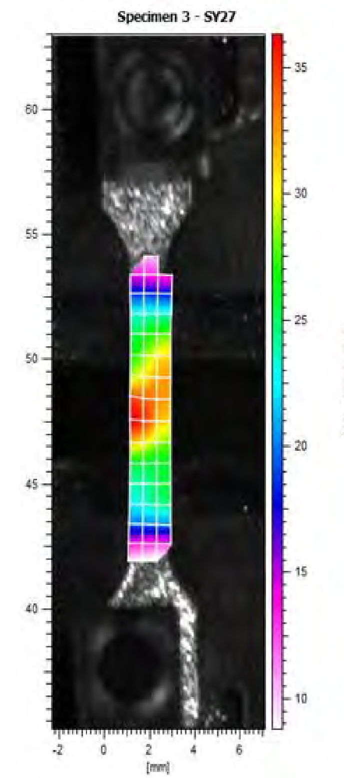
**Westinghouse AM Equipment**

# Additive Manufacturing Development at Westinghouse

# AM Materials Development

- **Westinghouse has funded material development and irradiation performance testing for 316L SS, Ni Alloy 718 and Zr**
  - Produced AM block and micro-tensile test specimens
  - Irradiating materials in MIT's test reactor (Oct. 2014 → 2018)
  - Completing post-irradiation examination (PIE) at Westinghouse Churchill laboratory (316 and 718 completed, Zr PIE DOE funded)
  - AM 316L irradiation performance consistent with wrought

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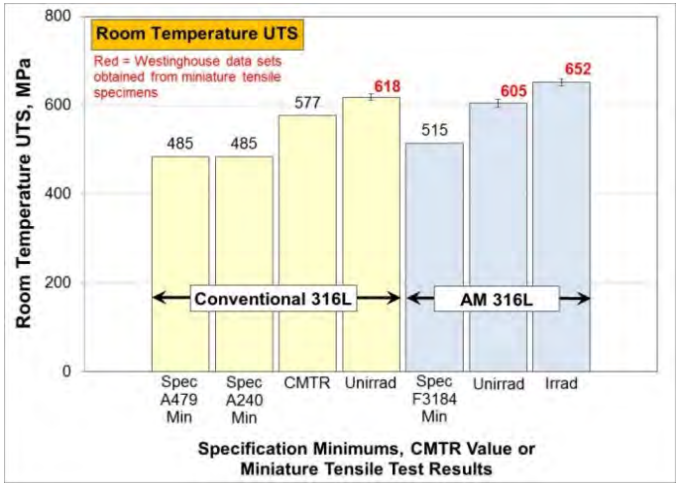
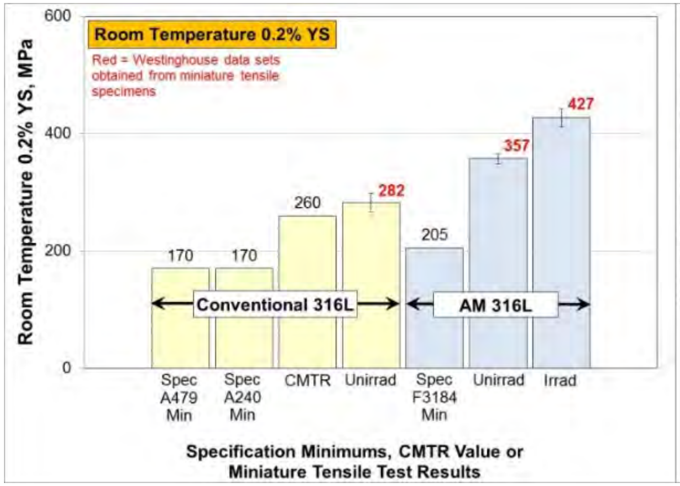
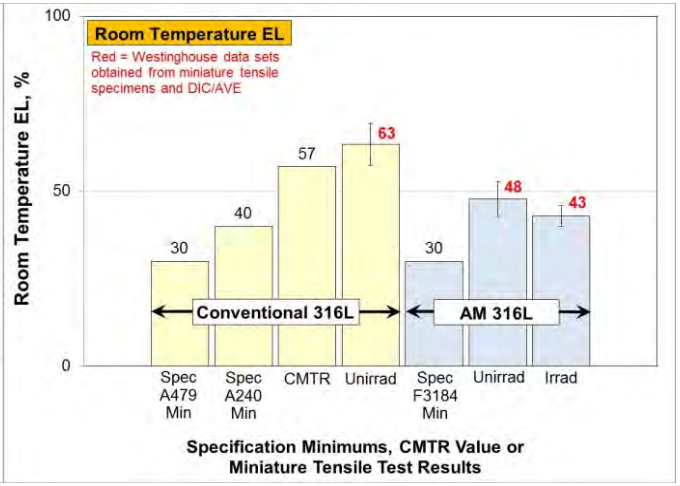
# AM Materials Development

- **316L samples have been tested and evaluated for mechanical properties**
  - The absolute values for the AM material Ultimate Tensile Strength (UTS), 0.2% Offset Yield Strength (YS) and percent elongation (% EL) were as expected and consistent with conventional material
  - Tensile strengths, both UTS and YS increased with irradiation as expected
  - % EL went down with irradiation as expected



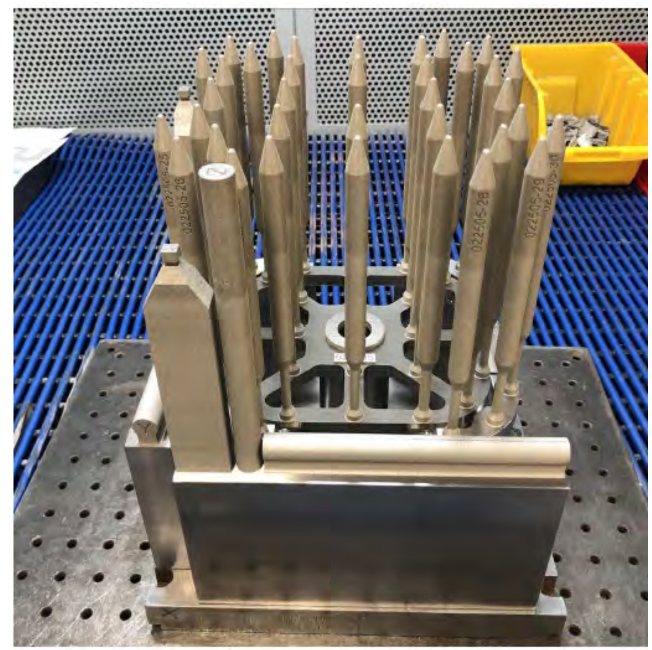



# First AM Nuclear Fuel Component Installed in Commercial Reactor

# First AM Component (TPD) Installed at Commercial Reactor

- AM Thimble Plugging Device (TPD) first AM fuels component successfully installed in a commercial reactor (Byron 1 March 2020)
  - Low Risk Component, moderate complexity
- Westinghouse met with NRC in May 2019 at the Westinghouse Rockville offices and discussed AM TPD in detail prior to installation.
  - Implemented using the 50.59 process



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# First AM Component (TPD) Installed at Commercial Reactor

- AM TPD was installed in Byron Unit 1 Cycle 24 in core location L11 which was predicted to have a FA power level of 1.179 at BOL and 1.003 at EOL (burnup of 24,500 MWd/MTU).
- The AM TPD will be/ has been re-inserted into the core for Cycle 25 into a twice-burned fuel assembly in location E15.

| | R | P | N | M | L | K | J | H | G | F | E | D | C | B | A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | 24B M46H | 25B N53H | 52A N08G | 24C M81N | 25A N03G | 25B N59H | 24B M59H | | | | |
| 2 | | | 24B M64H | 25B N57H | 26A A10J | 26B A47K | 26B A52K | 26A A12J | 26B A54K | 26B A63K | 26A A13J | 25B N65H | 24B M62H | | |
| 3 | | 24B M67H | 25C N76N | 26A A02J | 26C A70Y | 26B A64K | 25A N23G | 25C N89N | 25A N28G | 26B A46K | 26C A72Y | 26A A04J | 25C N84N | 24B M61H | |
| 4 | | 25B N54H | 26A A05J | 26C A82Y | 25A N41G | 25A N43G | 26A A23J | 26C A73Y | 26A A28J | 25A N44G | 25A N40G | 26C A84Y | 26A A06J | 25B N67H | |
| 5 | 24B M49H | 26A A18J | 26C A78Y | 25A N38G | 25A N10G | 26A A30J | 25A N29G | 25C N72N | 25A N17G | 26A A39J | 25A N14G | 25A N34G | 26C A79Y | 26A A19J | 24B M57H |
| 6 | 25B N64H | 26B A67K | 26B A48K | 25A N50G | 26A A40J | 25C N78N | 26A A22J | 26C A95Y | 26A A43J | 25C N86N | 26A A24J | 25A N51G | 26B A58K | 26B A59K | 25B N63H |
| 7 | 25A N06G | 26B A55K | 25A N49G | 26A A34J | 25A N35G | 26A N35J | 25A N13G | 25A N27G | 25A N12G | 26A A31J | 25A N36G | 26A A32J | 25A N18G | 26B A56K | 25A N05G |
| 8 | 24C M74N | 26A A09J | 25C N71N | 26C A69Y | 25C N82N | 26C A86Y | 25A N24G | 25C N79N | 25A N46G | 26C A87Y | 25C N80N | 26C A80Y | 25C N93N | 26A A20J | 24C M84N |
| 9 | 25A N01G | 26B A51K | 25A N31G | 26A A27J | 25A N48G | 26A A29J | 25A N16G | 25A N20G | 25A N09G | 26A A21J | 25A N21G | 26A A38J | 25A N42G | 26B A53K | 25A N07G |
| 10 | 25B N56H | 26B A45K | 26B A62K | 25A N[illegible]0G | 26A A26J | 25C N7[illegible]N | 26A A25J | 26C A81Y | 26A A42J | 25C N88N | 26A A41J | 25A N19G | 26B A50K | 26B A49K | 25B N68H |
| 11 | 24B M47H | 26A A11J | 26C A71Y | 25A N26G | 25A N15G | 26A A37J | 25A N52G | 25C N77N | 25A N37G | 26A A44J | 25A N11G | 25A N39G | 26C A76Y | 26A A16J | 24B M58H |
| 12 | | 25B N62H | 26A A07J | 26C A[illegible]8Y | 25A N47G | 25A N[illegible]G | 26A A36J | 26C A77Y | 26A A33J | 25A N33G | 25A N45G | 26C A83Y | 26A A10J | 25B N61H | |
| 13 | | 24B M65H | 25C N70N | 26A A08J | 26C A74Y | 26B A66K | 25A N22G | 25C N69N | 25A N32G | 26B A65K | 26C A75Y | 26A A03J | 25C N87N | 24B M66H | |
| 14 | | | 24B M63H | 25B N55H | 26A A17J | 26B A61K | 26B A68K | 26A A14J | 26B A60K | 26B A57[illegible] | 26A A15J | 25B N[illegible]6H | 24B M68H | | |
| 15 | | | | | 24B M54H | 25B N60H | 25A N02G | 24C M80N | 25A N04G | 25B N[illegible]8H | 24B M53H | | | | |

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# AM Component (TPD) Inspection Summary

- During the recent cycle 25 outage, an inspection of the AM TPD was performed and included:
  - A drag test was performed on the AM TPD as it was removed from the fuel assembly and a load cell measured the force.
    - Ensure no spike in the drag force outside of standard forces.
  - A detailed visual inspection from numerous angles was then performed using a high- resolution camera positioned perpendicular to the AM TPD in order to view all rodlets.
    - Goal to observe no anomalies/defects/discolorations/ distortions nor any physical damage to the AM TPD.
- The AM TPD was then re-inserted back into the core for a second cycle of irradiation.

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# Westinghouse Developed AM Nuclear Fuel Components

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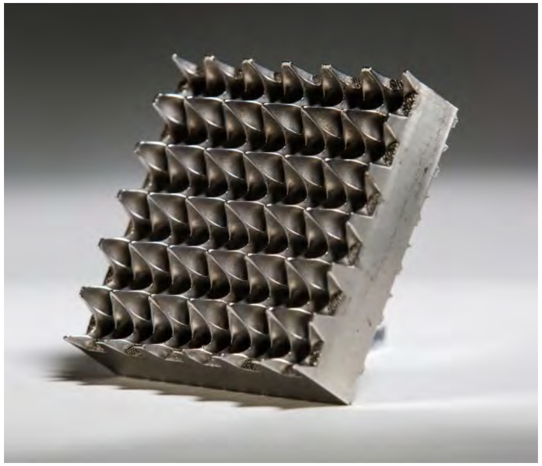
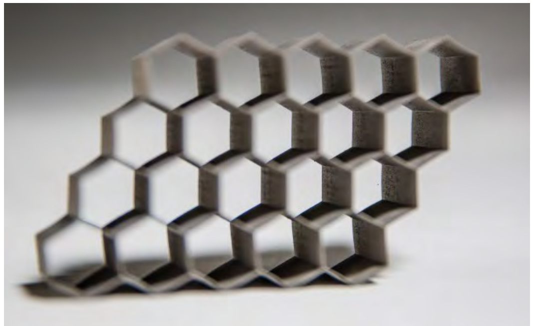
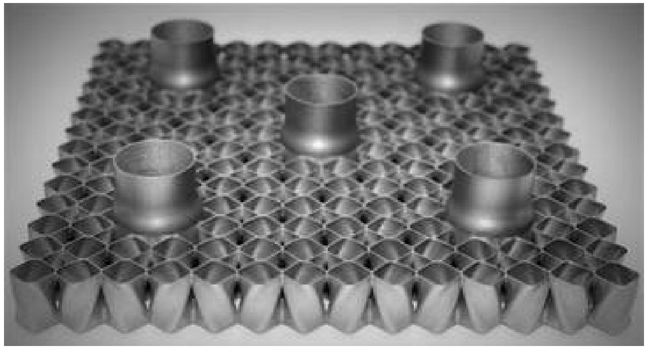
# AM Fuel Structures - Grids

- Improved flow characteristics are possible with AM resulting in better heat transfer from fuel rods to reactor coolant for better performance.
- Stronger, more efficient support of fuel rods with better mixing characteristics and less GTRF.

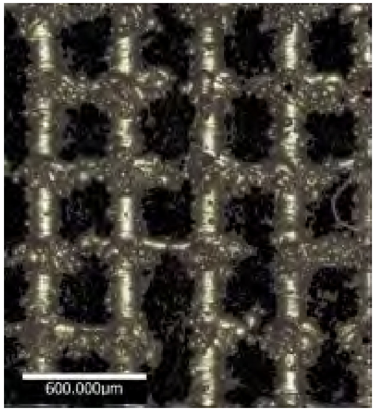






**Items requiring further investigation:**

- Corrosion characteristics in PWR chemistries
- Mechanical strength of small features

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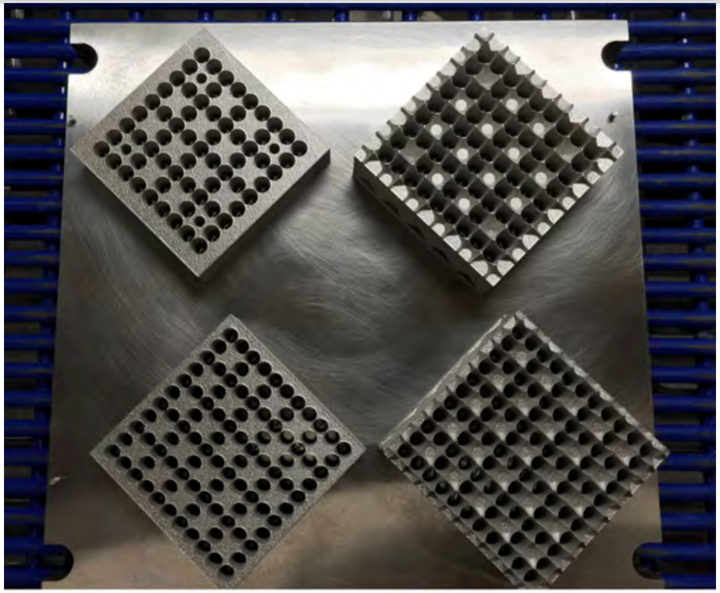
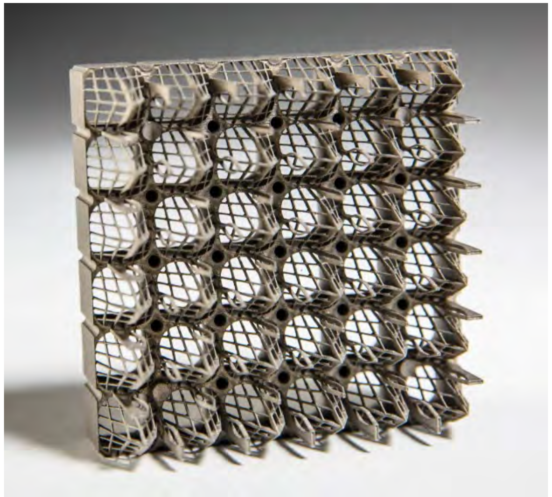
# AM Fuel Bottom Nozzle

- **Goal**: Consistent/Reduced pressure drop and improved debris filtration
- Multiple complex designs enabled by AM
- Numerous polymer based bottom nozzles created for prototype flow testing
- AM BN (Design developed for PWR applications)



- **Innovation Projects**:
PWR Fuel Bottom Nozzle Advanced Design Through Multi-Physics Topology Optimization (TO) for Design with Additive Manufacturing



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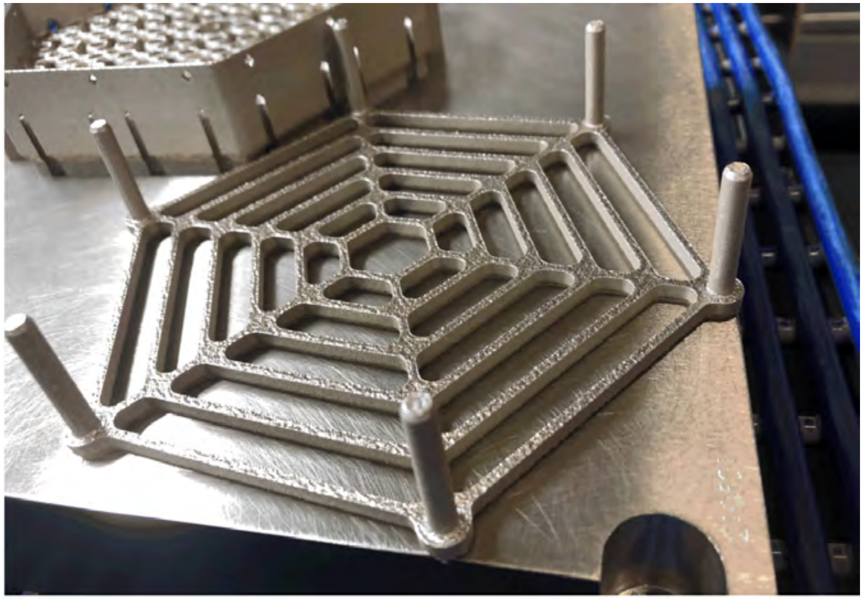
# VVER-440 AM Top Flow Plate

- Hexagonal Russian fuel design
- Plate printed in 304L SS
- Eliminates need for welding of pins
- Combines 7 pieces into 1
- Retains fuel rods in accident scenario
- Planned to be implemented on region basis in the Ukraine Rivne 2 plant in 2024



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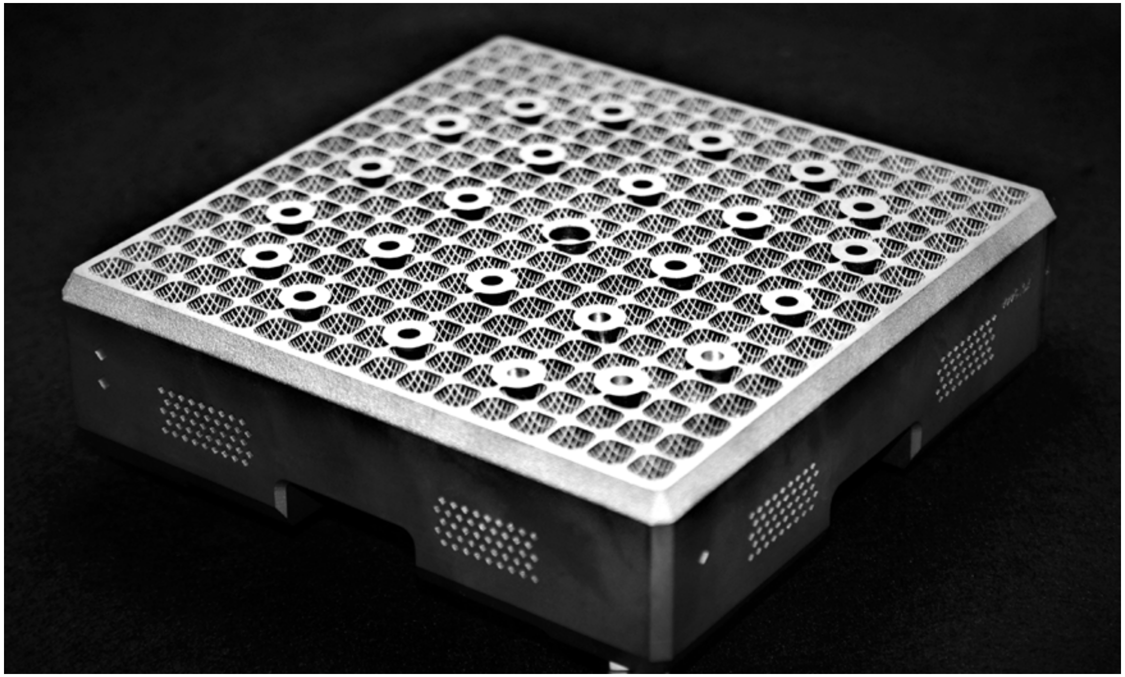
# AM Fuel Bottom Nozzle

## Full size AM produced Bottom Nozzle

- Equivalent pressure drop to existing bottom nozzle design
- All design and safety requirements satisfied
- Improved filtering ability
- All manufacturing interfaces satisfied
- No changes to basic BN envelop nor interfacing features; LCP pin "S" holes, thimble screw locations, instrumentation tube insert, etc.



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# AM Fuel Bottom Nozzle - Mesh Structural Testing

- Detailed Mechanical (and T&H) Testing of Fine Mesh Filter (Spire) Structure Performed.
  - Static loads applied to the fine mesh filter (spire) structure to determine strength
  - Dynamic Load testing also performed

[ ] a,b,c

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# AM Fuel Bottom Nozzle - Mesh Structural Testing

- Detailed Mechanical and T&H Testing of Fine Mesh Filter.
- Mechanical tests performed to ensure that the fine mesh filter (spire) does not fail during operation and become debris.
  - Static load testing (example shown to right) demonstrated significant fine mesh filter (spire) strength and margin to failure.
  - Ballistic testing performed - demonstrated "spire" will not fail when debris in flow field
- T&H testing:
  - Pressure drop - matches current bottom nozzle design
  - Debris filtering - significant improvement compared to current design

a,b,c

[ ]

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# AM Fuel Bottom Nozzle - GSI-191

- The AM BN has a significantly different adapter plate as compared to existing bottom nozzle design for the purposes of providing improved filtering capability.
- Given that the filtering capability is improved, Westinghouse examined the potential impacts to the Generic Safety Issue (GSI) 191 sump issue.
- This included GSI-191 testing performed consistent with the testing that was performed in the topical report WCAP-17788 Volume 6, *Comprehensive Analysis and Test Program for GSI-191 (PA-SEE-1090) - Subscale Head Loss Test Program Report.*

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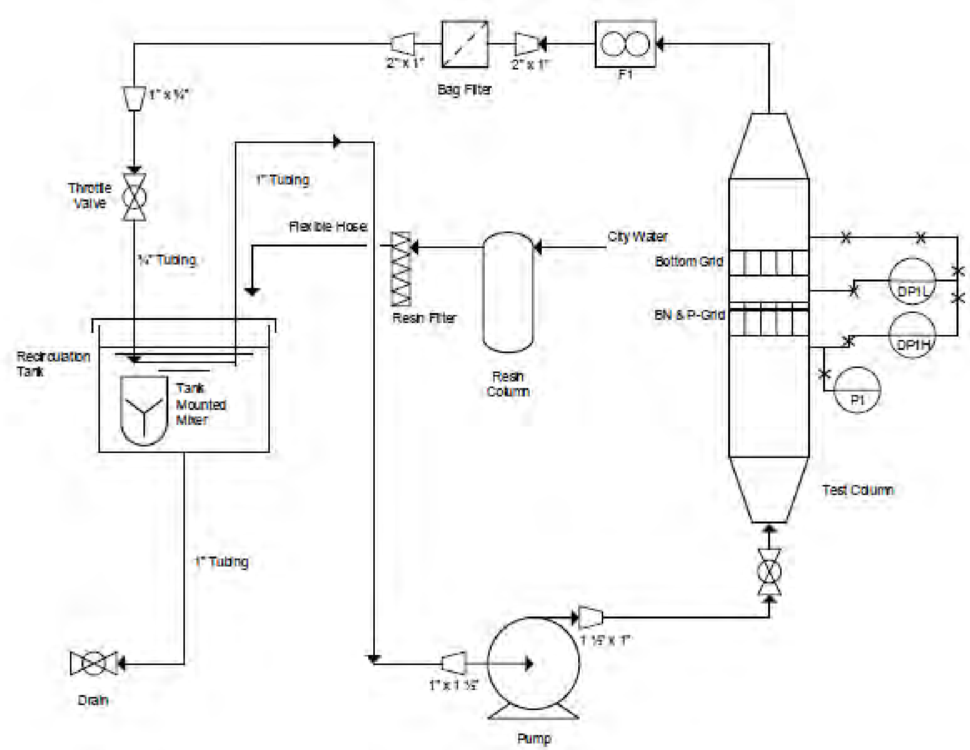
# AM Fuel Bottom Nozzle - GSI-191

- To qualify the AM BN, subscale testing is being performed consistent with the subscale testing performed as documented in the topical report WCAP-17788 Volume 6.
- The first step was to repeat the existing testing with current bottom nozzle design to demonstrate that the subscale loop was performing as intended.
- Test loop schematic:

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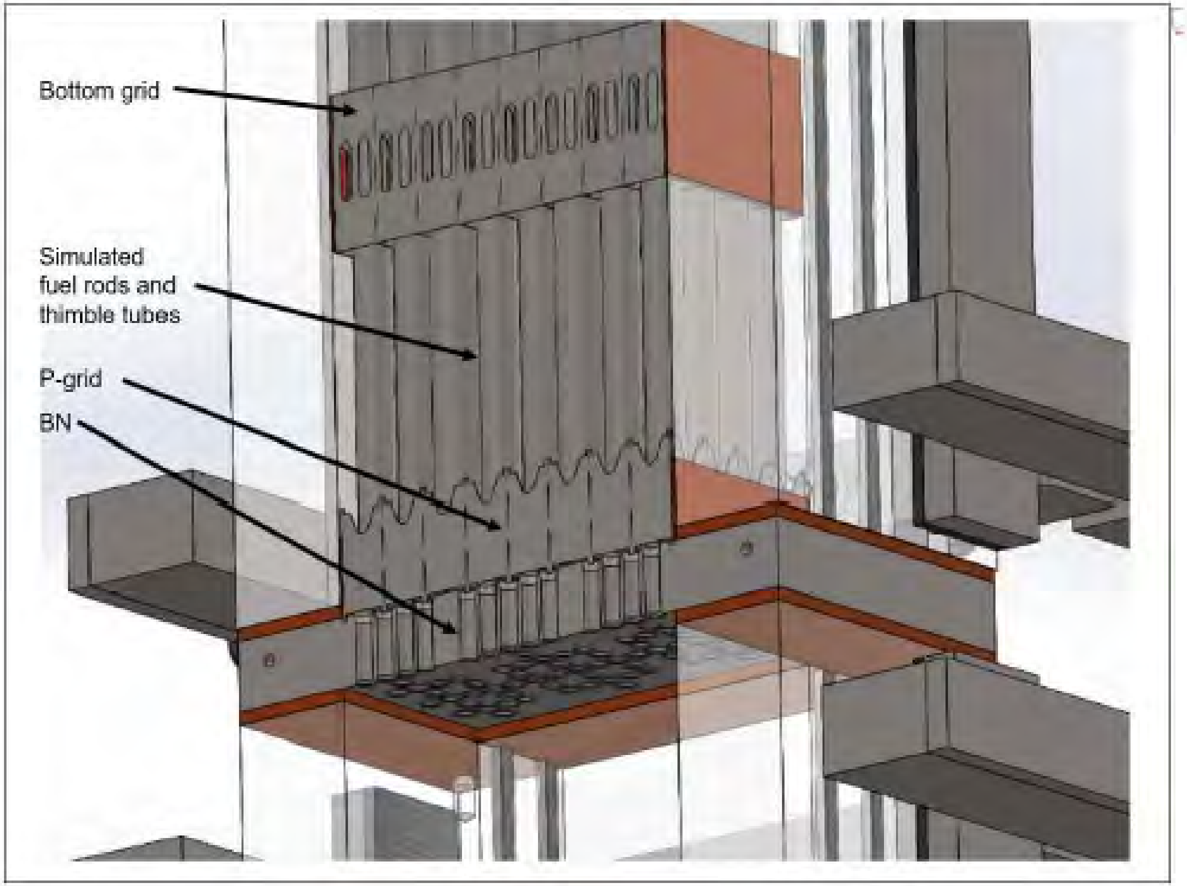
# AM Fuel Bottom Nozzle - GSI-191

- Subscale test loop - cross section showing the core inlet geometry.
- Results for current bottom nozzle design will be compared to the topical report
- AM bottom nozzle results are currently in progres



# AM Fuel Bottom Nozzle Licensing - LUAs

**LUA Licensing Approach:**

- Pursuing the licensing of Lead Use Assembly AM Bottom Nozzles (4 to 8) similar to used for AM TPD
- Following the NRC issued draft 50.59 guidance for AMTs (Subtask 2A)
- All design and safety criteria satisfied

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# AM Fuel Bottom Nozzle Licensing - Region

## Region Implementation Approach:

- Westinghouse plans on utilizing the NRC approved Westinghouse Fuel Criteria Evaluation Process (FCEP) process (WCAP-12488-A)

- Following the NRC issued draft 50.59 guidance for AMTs (Subtask 2A)

Westinghouse

# AM Fuel Bottom Nozzle Licensing - Region

- In the draft NRC 50.59 guidance for AMTs (Subtask 2A), it is noted that:

"Since AMT fabrication involves a significant change to the material and manufacturing process when compared to traditional fabrication methods, an AMT item is not identical to the original and therefore should not be considered a like-for-like replacement. "

"However, the licensee's technical evaluation process might include an equivalency evaluation to address the impact of the change in design, material and manufacturing on the ability of the AMT item to perform its intended design function."

"If there is no adverse impact on the design function, the AMT item may be considered "equivalent" to the original in its ability to perform its intended design function."

# Westinghouse AM Tooling Development

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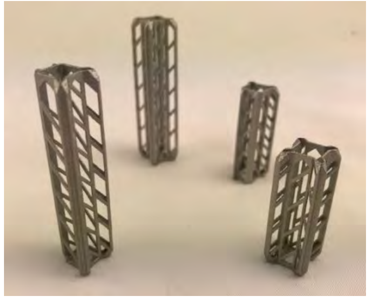
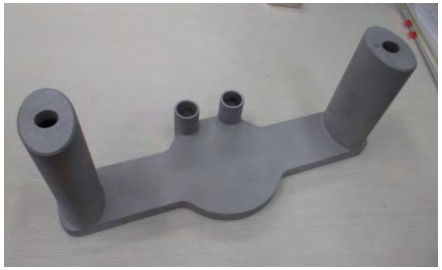
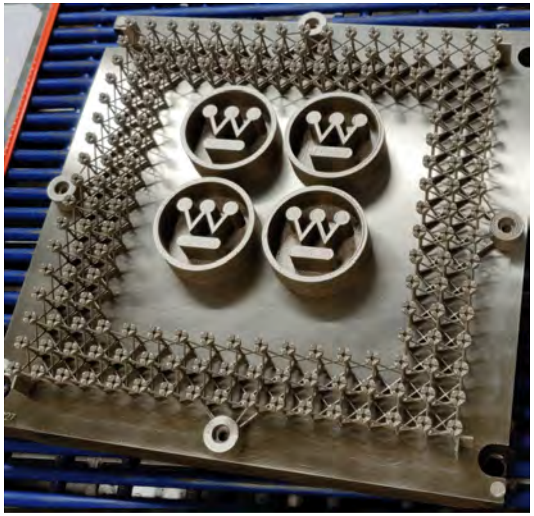
# Tooling for Manufacturing

- **Immediate benefit from tooling applications**
  - Lower the costs and improve performance
- **Improved safety for operators**
  - Reduction of leak points
  - Two hands touch control
  - Ergonomic designs resulting in less fatigue injuries







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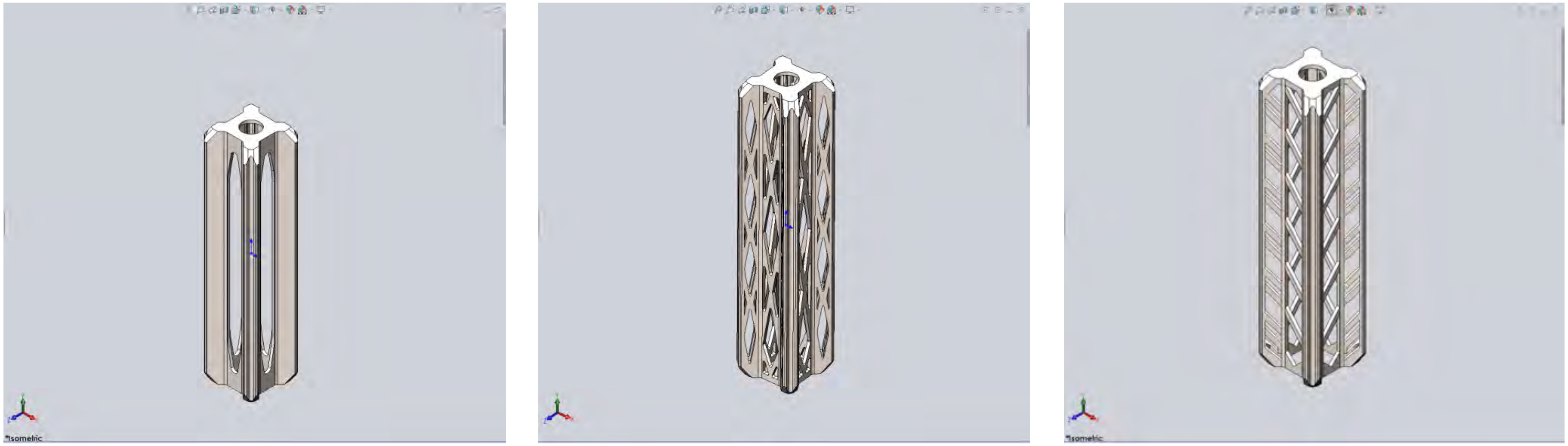
# AM Tooling - Strap Alignment Pins

- The strap alignment pins as shown below have gone through a number of design iterations to improve build times, increase part life and minimize weight.



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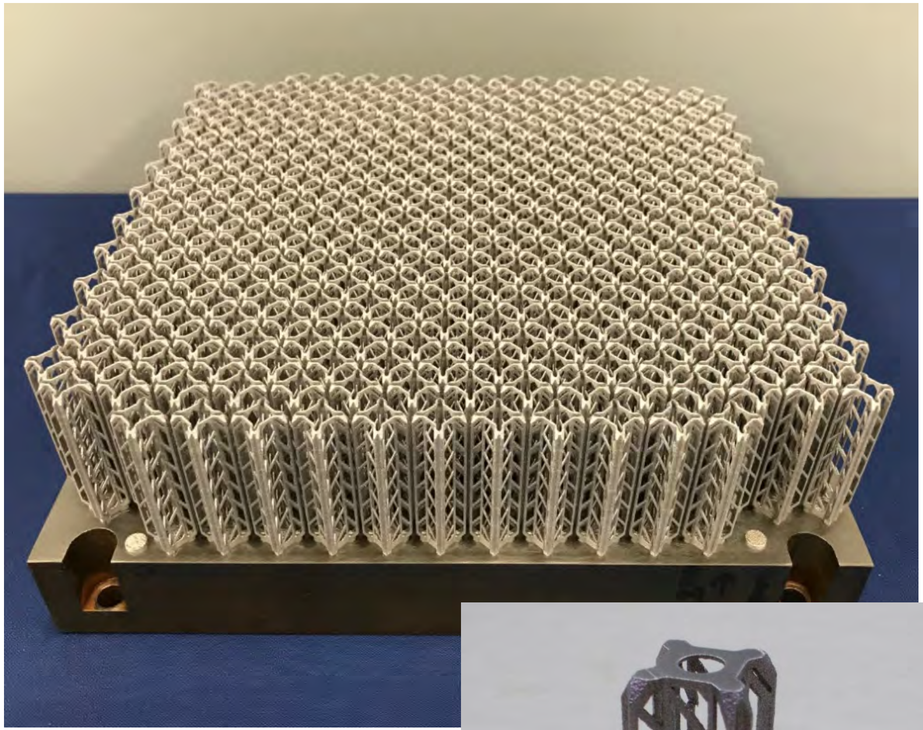
# AM Tooling - Strap Alignment Pins

- A complete set can be made on one build plate, or parts can be mismatched as required.  After they are printed, they are removed from the build plate using EDM and then bead blasted/ vibratory polished to improve surface finish.



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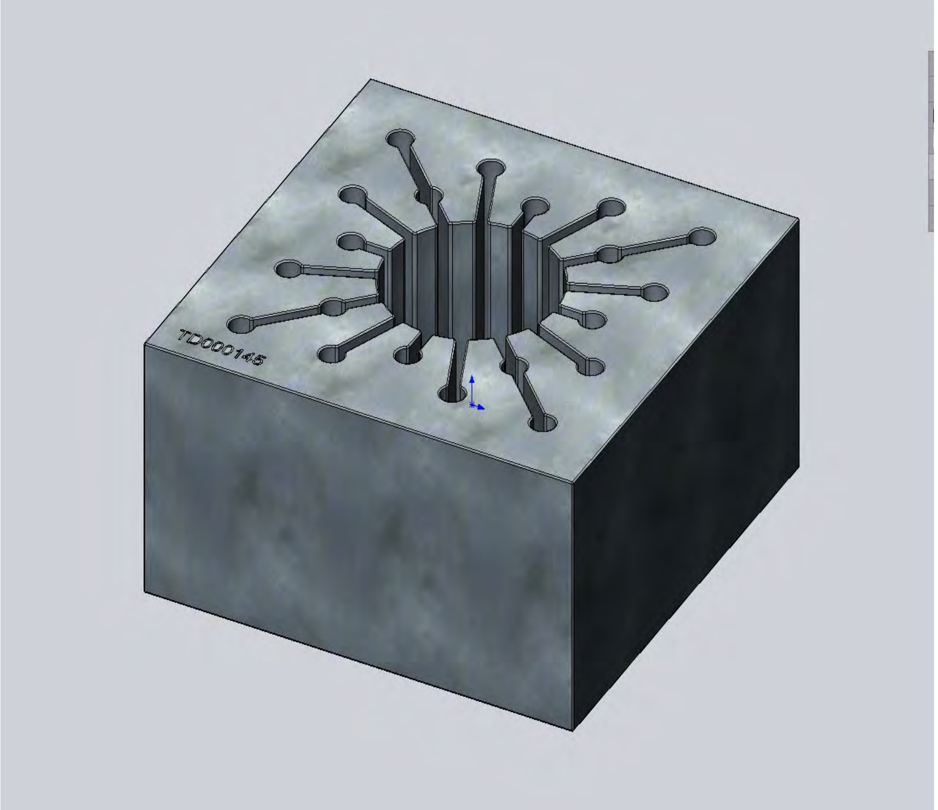
# AM Tooling - RCCA Spider Envelope Gage

- This gage is used to measure the locations of the RCCA spider fingers after welding/brazing.
- Because of the gage weighs (~60 lbs) inspectors are at risk of injury during movement of the gage.
- Redesign of gage was implemented using the AM process.

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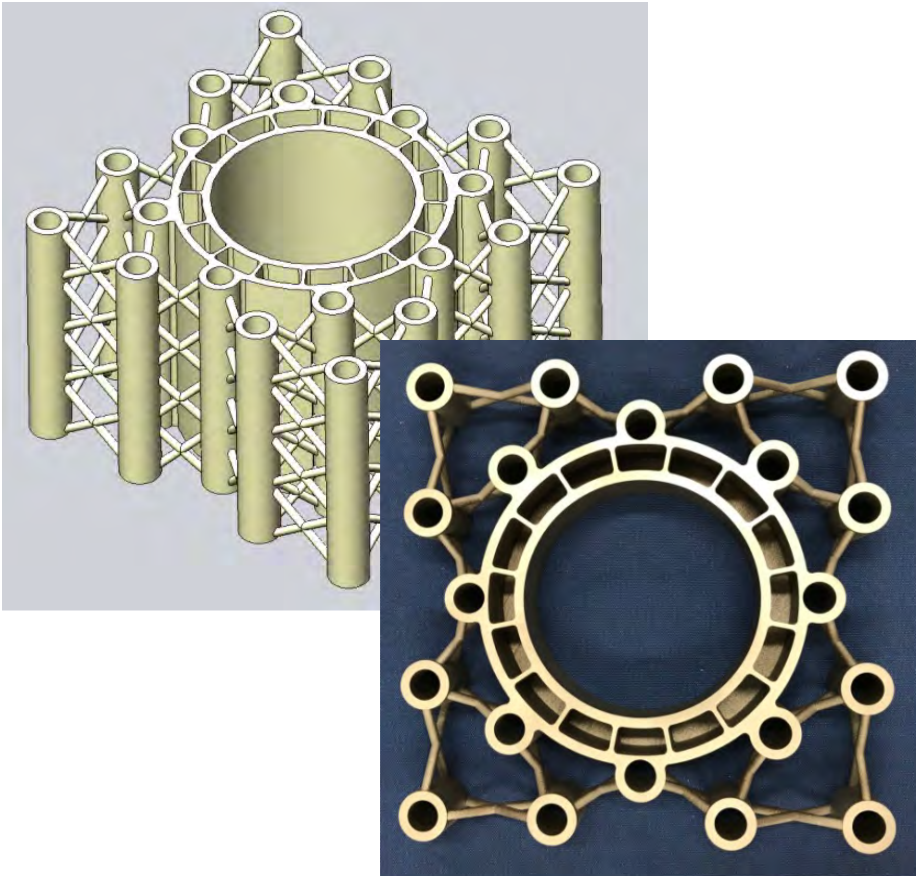
# AM Tooling - RCCA Spider Envelope Gage

- Using the AM technology, the required material was greatly minimized while maintaining gage functionality and stability.
- Redesigned gage total weight is less than 10 lbs.
- Test builds verified the gage functionality and stability.



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# Powder Metallurgy (PM) Hot Isostatic Pressing (HIP) Development

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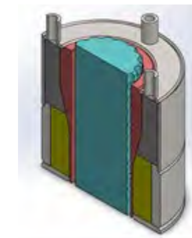
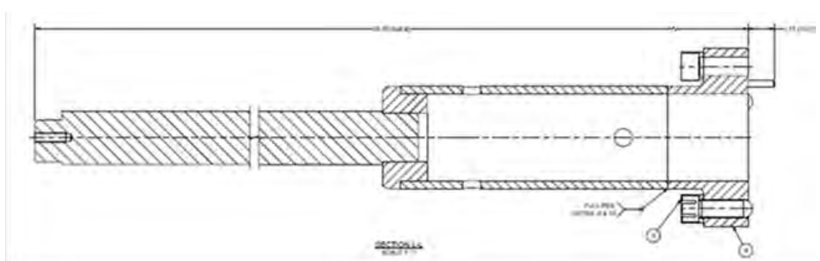
# Hot Isostatic Pressing (HIP) Development Efforts

- **NEER Project (Innovate UK-funded): Completed in May 2018**
  - Focused on reusable tooling, HIP development and demonstration of nuclear components, and UK supply based development
  - Produced demonstration components
    - Reactor Vessel Internals (RVIs): Quickloc Upper Support Assembly
    - Control Rod Drive Mechanisms (CRDMs): Guide Funnel Extension
    - Valves: 4” Motor Operated Gate Valve Body
- **Producing Prototypes / Mockups for Next Generation Plants**
- **Completing Cost-Benefit Analysis for Reactor Coolant Loop Piping and Critical Components**





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# Additive Manufacturing Development Partnering with Industry/Academia

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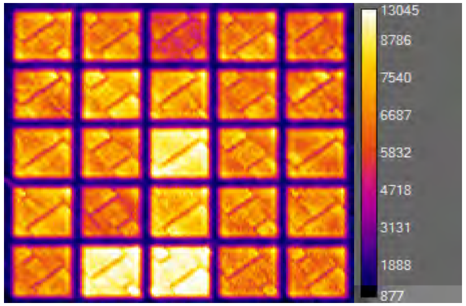
# Additive Manufacturing – Current Projects

- Department of Energy – *DE-FOA-0001281* - NEET-1- “**Integrated Computational Materials Engineering (ICME) and In-situ Process Monitoring for Rapid Qualification of Components Made by Laser-Based Powder Bed Additive Manufacturing (AM) Processes for Nuclear Structural and Pressure Boundary Applications**”
  - Project Lead Principal Investigator(PI) is EPRI
  - Project Co-PI’s – ORNL, Rolls Royce, and WEC
  - Completed in early 2020 with ASME code case submission for 316L




**Qualification of AM Components**

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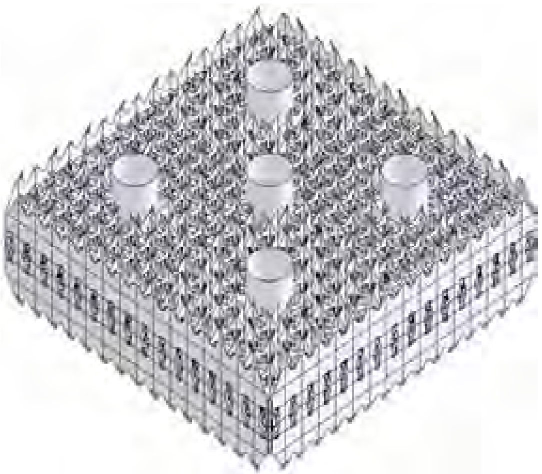
# Additive Manufacturing – Current Projects

- Department of Energy – *DE-FOA-0001858* – ARPA-E

**"ADDITIVE MANUFACTURING OF SPACER GRIDS FOR NUCLEAR REACTORS"**

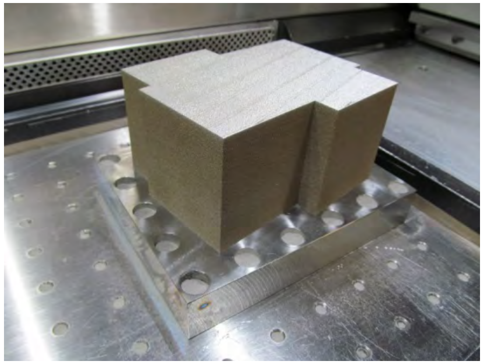
- Project Lead Principal Investigator (PI) is CMU (Carnegie Melon University)
- Initiated in 2019
- Effort to demonstrate feasibility of additively manufacturing thin-walled components for reactor use.
- Currently, thin-walled materials (Zirc based and Alloy 718) are commonly used in the manufacturing of grids.

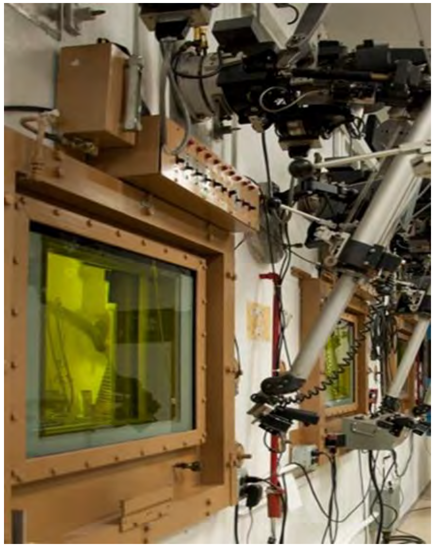


**Exploring Advanced Reactor Components**

# Additive Manufacturing – Current Projects

- Department of Energy – DE-FOA-0001515 - NSUF-2: Nuclear Science User Facilities Access Only - Radiation Effects on Zirconium Alloys Produced by Powder Bed Fusion Additive
  - Project Lead – William Cleary
  - Initiated in fiscal year 2018 – 3 year program
  - $1M Award
  - Demonstrating feasibility of AM zircaloy





**First of a Kind Research in AM Zirconium Alloys**

# Additive Manufacturing – Current Projects

- Partnering with KNF to develop Zr-4 for Laser Powder Bed Fusion systems
- Utilizing two methods for making Zr-4 powder from 2" diameter bars
- Targeting spacer grids with a secondary medical devices market
- **Challenges:**
  - Reactivity of zircalloy powder
  - Yield rates of the powderization processes

**Continuing Development of AM Zirconium Alloys**

Westinghouse

# Q & A

Westinghouse