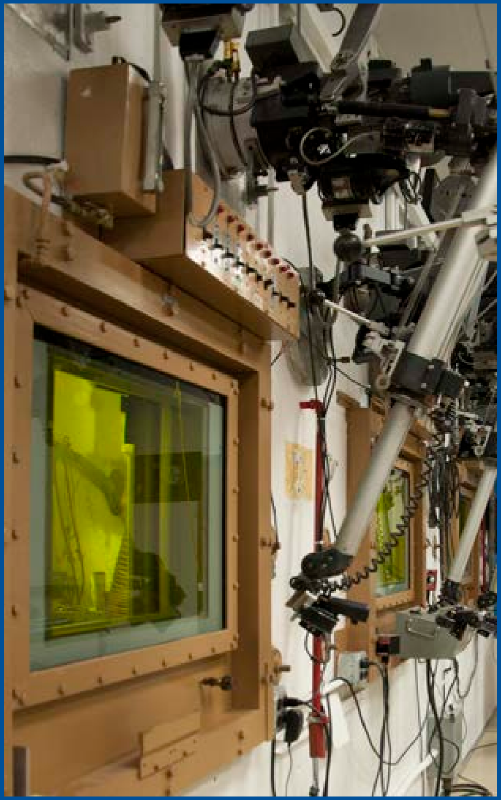
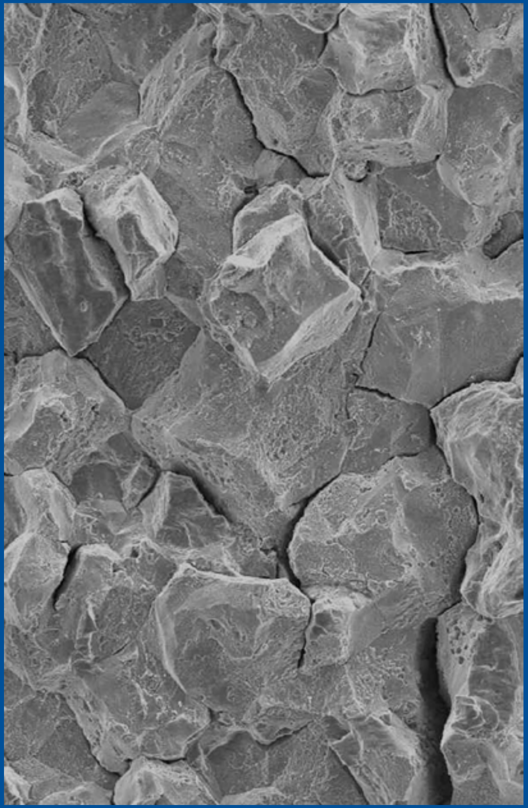
Nuclear Materials Research at the Westinghouse Hot Cells: Supporting Fleet Operations for 40 Years





Paula Freyer
Fellow Engineer
Materials Center of Excellence
Westinghouse Electric Company LLC

HOTLAB 2013

September 24, 2013
Idaho Falls, ID, USA

A Proud ATR NSUF Partner Laboratory

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Westinghouse Laboratories - Areas of Expertise

- Nearly 40 yrs experience in shipping, handling and evaluating activated and contaminated materials and components
- Mechanical performance testing and microstructural characterization
- Autoclave facilities for comprehensive corrosion evaluations
- Irradiated property measurements
- Custom design/fabrication of irradiated materials testing hardware/loops

1960s Surveillance Capsule Fabrication

- Nuclear materials R&D and technology/product development
- Fuel crud and steam generator sludge analysis
- RPV surveillance capsule design, fabrication and testing
- Irradiated component failure analysis

2013 AP1000 Surveillance Capsule Fabrication

May 2013: 16 new capsules shipped to China

Sept 2013: 16 capsules being fabricated for VC Summer Unit 2 and Vogtle Unit 3

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Westinghouse Hot Cells

- One of only 3 commercially available hot cell facilities available in the US
- 30,000 curie licensed hot cells
  - atomic numbers 1 through 96
- 5 hot cells
- Multi-functional, routinely re-configured to meet the needs of each specific program
- High and Low Level cells built in 1975 – have operated continuously since opening
- A and M cells built in 1994
- Extensive complimentary facilities/capabilities

High Level Cell - 1976

Today

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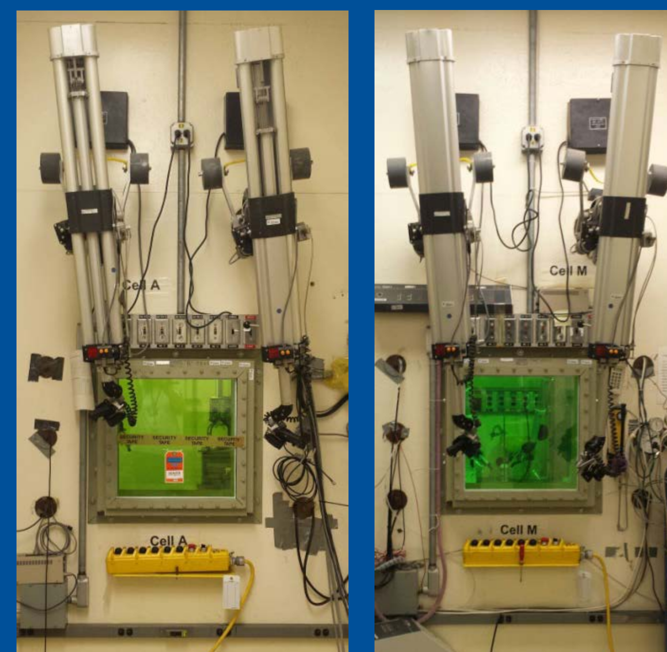
Westinghouse Hot Cells

- **In-cell:**
  - cutting, grinding, milling, machining
  - tensile, Charpy, fracture toughness, slow strain rate and fatigue testing
  - metallography and scanning electron microscopy
  - ultrasonic and eddy current measurements
  - corrosion testing
  - welding
  - dimensional and density measurements
  - hydrogen analysis

Low level hot cell (left) and high level hot cell (right)



A and M hot cells

*SEM hot cell not shown

Additional Key Facilities

Materials Performance and Characterization Laboratories

- Metallography
- Scanning electron microscopy
  - 4 SEMs including dual beam FIB, XEDS, EBSD, ‘ultra-hot’ SEM, large chamber
- Scanning transmission electron microscopy
  - FEI CM30, 300 KV, LaB_6, XEDS
- Auger electron spectroscopy
- X-Ray Diffraction
  - micro-diffraction and residual stress measurements
- Full analytical chemistry facilities
  - GC, UV-VIS, FTIR, TGA, Raman, IC, ICP-MS, microwave digestion
- Mechanical testing
  - multiple frames up to 100,000 lb load capability

Corrosion Laboratory

- 22 fully automated autoclaves
  - 34.5 MPa (5,000 psi) and 482°C (900°F)
  - 4 with load frames with capabilities up to 2,720 kg (6,000 lbs)
- Numerous specimen geometries and autoclave conditions utilized
- Corrosion, wear, SCC initiation, and SCC growth

Custom Testing Facilities

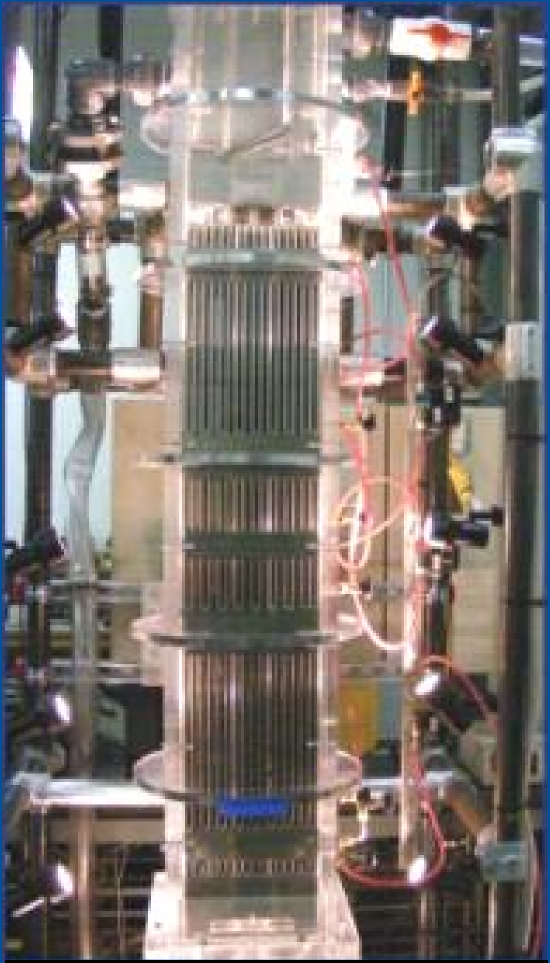
- Advanced Fuel Crud Deposition Test Loop
- LOCA Debris Blockage Test Facility
- Thermal Hydraulic Testing High Bay
- Zinc Effects Test Loop
- Wear Test Rig
- High Temperature Steam Oxidation Unit
- Reactor Coolant Pump Seal Testing Laboratory
- Laser Welding Facility

Routinely design and fabricate unique testing facilities for our customers

Examples of Unique Capabilities


High Temperature Steam Oxidation Unit


Core Inlet Blockage Intermediate Test Loop (under construction)


LOCA Debris Blockage Test Facility


Reactor Coolant Pump Seal Testing Laboratory


Zinc Effects Test Loop

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Laboratory Customers and Hot Cell Services

- All of the Westinghouse Product Lines
  - Nuclear Services
  - Nuclear Fuel
  - New Power Plants
  - Nuclear Automation
  - Research & Technology
- Westinghouse Subsidiaries and Affiliates
- US and International Utilities
- US and International Universities
- EPRI
- DOE and DOD
- PWROG
- International Organizations (e.g., International IASCC Advisory Committee)
- Consultants
- Other commercial organizations, manufacturers, etc.

- Laboratory facilities originally established to meet Westinghouse needs
- Today, wide range of 'outside' customers
- 'Dirty' failure analysis work to advanced R&D
- ATR NSUF Partner Laboratory since July 2013
  - Available for program collaborations and materials/specimen processing

Mission
Provide experimental evidence to support materials and processing solutions for our customers and to support industry technical initiatives.

Wide Range of Hot Cell Evaluations

- Small to large programs
- Rapid turn-around to multi-year programs
  - Few days to multi-year
  - 24/7 coverage for emergency evaluations
- Wide range of customers
- Vast diversity of components/specimens for study, inspection and testing/evaluation
  - Commercial reactor components
  - Test reactor irradiated components
  - Tiny parts/pieces to large components
  - High radiation level and/or high contamination level

In-Cell Ultrasonic Measurements of EBR-II Highly Irradiated 304 Stainless Steel

In-Cell Inspections of Commercial PWR Baffle Bolt

In-Cell Crack Growth Rate Test Assembly

Three Examples…Hot Cell Projects*

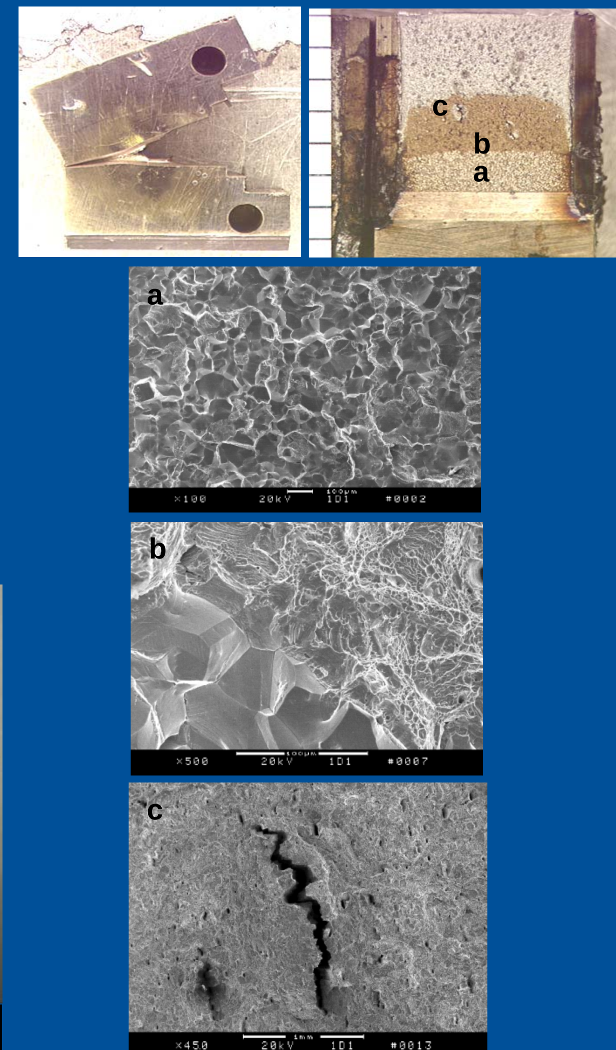
* Contract Hot Cell work for a variety of outside customers

1. **Failure Analysis**
2. **Effect of Service Exposure on Materials**
3. **Fundamental Science Evaluation**

In-Cell Eddy Current Examination of ~800 lb Retired Reactor Head Segment with Full Penetration

Miniature Tensile Specimen Machined In-Cell

In-Cell Irradiated Charpy Specimen Reconstitution



Specimen from PWR Baffle Plate - In-Cell Fracture Toughness Machining and Testing -

Three Examples…Studies of Highly Neutron Irradiated Stainless Steels

Description	Dose rates @ ~0.5" (R/hr)	dpa ranges
1. Highly irradiated 347 SS baffle bolts from a commercial PWR[a]	>5,000	~20 – 25
2. Highly irradiated 316 SS flux thimble tubes extracted from 3 commercial PWRs[b]	~1,000	~0 – 80
3. Highly irradiated 304 SS neutron reflector hex blocks from EBR-II[c]	~1,500	~0 – 35

Reference Point: Lethal Dose - $LD_{50/60}$ ~350 R

a *"Examination of Baffle-Former Bolts from D.C. Cook Unit 2,"* 16th International Conference on Environmental Degradation of Materials in Nuclear Power Plants, Aug 11-15, 2013, Asheville, NC, in press.

b *"Hot Cell Crack Initiation Testing of Various Heats of Highly Irradiated 316 Stainless Steel Components Obtained from Three Commercial PWRs,"* 13th International Conference on Environmental Degradation of Materials in Nuclear Power Systems 2007 Apr 19-23, Whistler, British Columbia, Canada.

c Extensively published and presented in 2012-2013 including:

"Development of a Nondestructive Inspection Method for Irradiation-Induced Microstructural Evolution of Thick 304 Stainless Steel Blocks," Journal of Nuclear Materials, in press.

"Ultrasonic NDE for Irradiation-Induced Material Degradations," ICONE-21, Jul 29-Aug 2, 2013, Chengdu, China.

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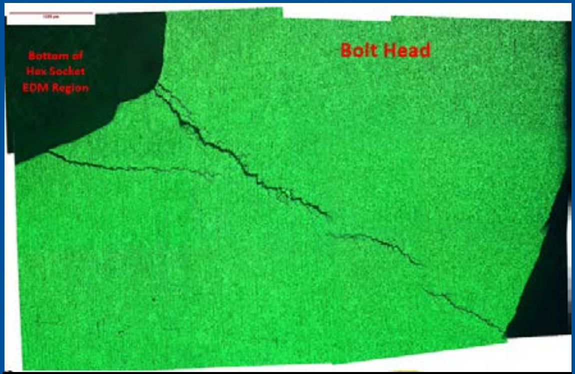
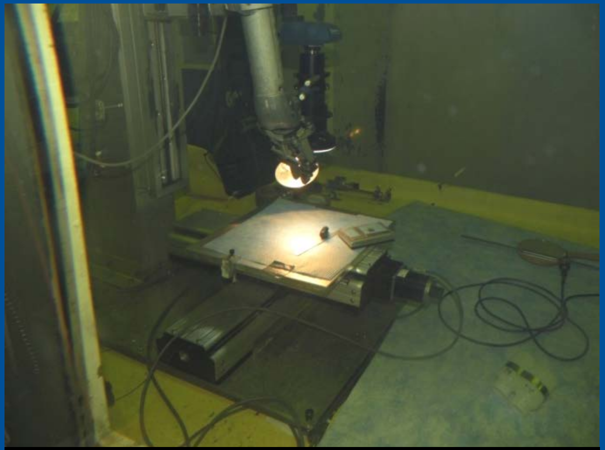
1. Failure Analysis - Background

- **Fall 2010 refueling outage - BFB pieces found on D.C. Cook Unit 2 lower core plate**
- **Lab response during commercial plant outage (24/7 coverage)**
- **Failure evaluations: bolts, bolt pieces (heads and shanks) and lock bars delivered to Westinghouse Hot Cell**
- **Intact bolt examinations**

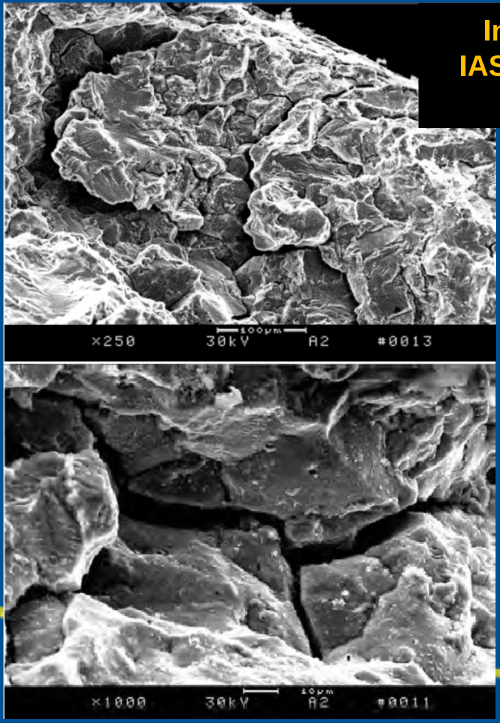


Sectioning and Metallography of Highly Activated Components

Examples of As-Received Components



Initial In-Cell Visual Inspections of As-Received Components



Intergranular IASCC on Failed Baffle Bolt

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1. Failure Analysis – Response and Results

Failure Evaluations:

- Non-destructive evaluations (VT)
- Cross-sectional metallography/light optical microscopy
- SEM fractography
- Hardness testing
- Chemical analysis

Intact Bolts Evaluations:

- Non-destructive evaluations (VT, PT, UT)
- Cross-sectional metallography/light optical microscopy
- Hardness testing
- Chemical analysis
- Tensile loading

Identification of Failure Mechanism(s) → Support Apparent Cause Analysis → Support Justification for Return to Operation

- Funded by utility
- Rapid turn-around response required

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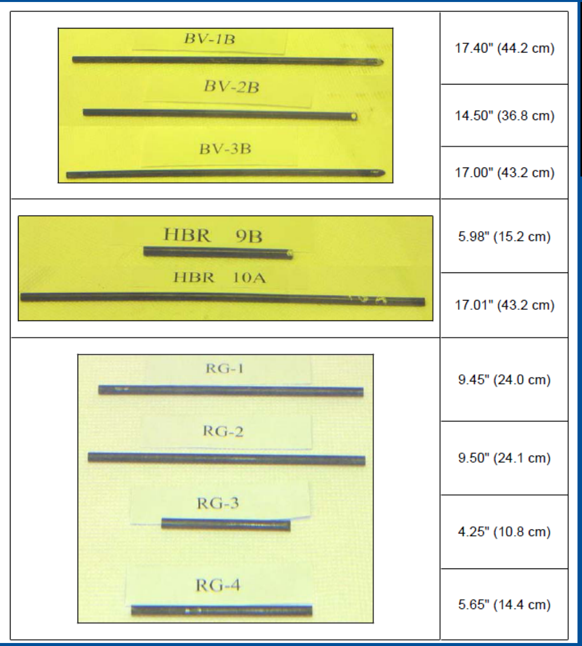
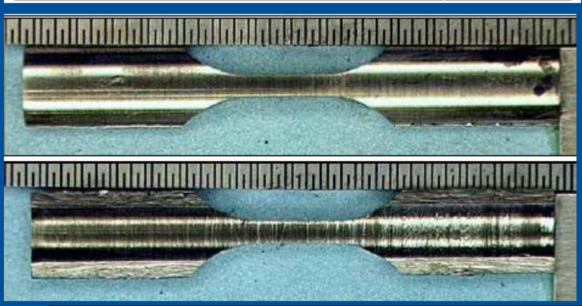
2. Effect of Service Exposure on Materials - Background

- Components removed from operating reactors
  - Real behavior
  - Neutron irradiated - no need to simulate or adjust for ion effects
  - Depth of penetration → machine realistic sized specimens for relevant data generation
- Study of materials structure and properties after (known) service exposure
  - Key property measurements (e.g. tensile, slow strain rate, IASCC initiation, crack growth)
  - Correlate with microstructural changes
- Provide the mechanisms and database for following and predicting plant internals aging



Highly Irradiated Flux Thimble Tubes Removed from 3-Different Commercial Plants



In-Cell Machining of ~104 Test Specimens from Thimble Tubes Then Testing to Obtain Real Performance Data

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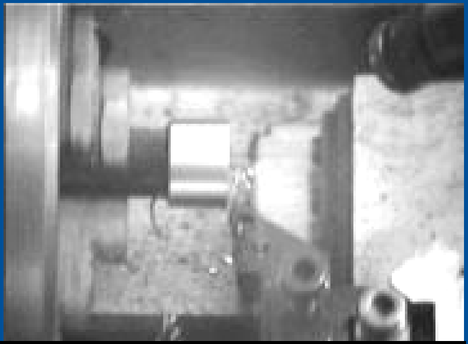
2. Effect of Service Exposure on Materials – Program Objectives & Scope

Objectives

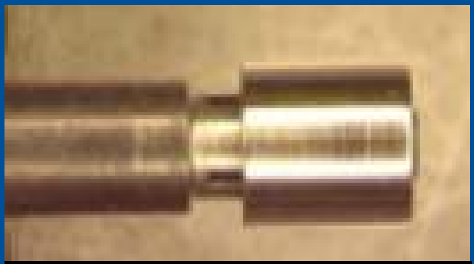
Develop a property database for the 3 heats of material, the comprehensive analysis of this test data, and the development of predictive equations for the forecasting of IASCC as a function of stress, dpa and material heat

Complex Scope

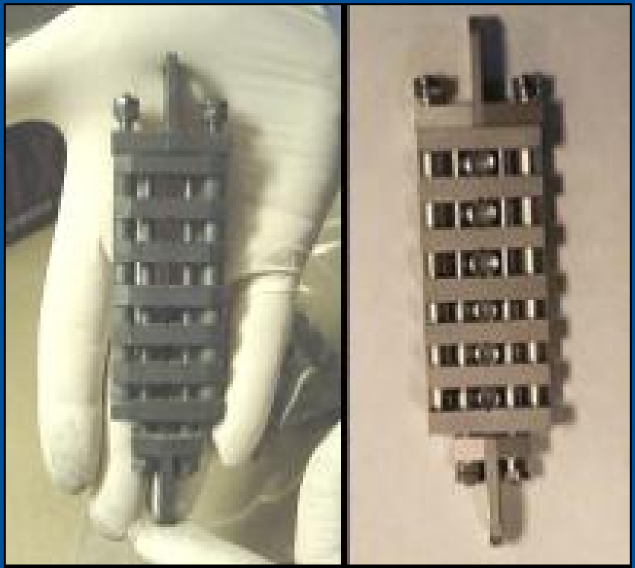
- dpa profile determination (plant-specific transport calculations)
- Tensile (18)
- Slow strain rate (9)
- O-ring crack initiation tests (76)
- Detailed ANSYS 3-D FE stress analysis of the O-ring specimen geometry and test loading conditions
- In-depth microstructural characterization



O-ring edge being machined down to target length using carbide cutting tool on lathe



Finished O-ring ready for autoclave testing (shown attached to a split mandrel)

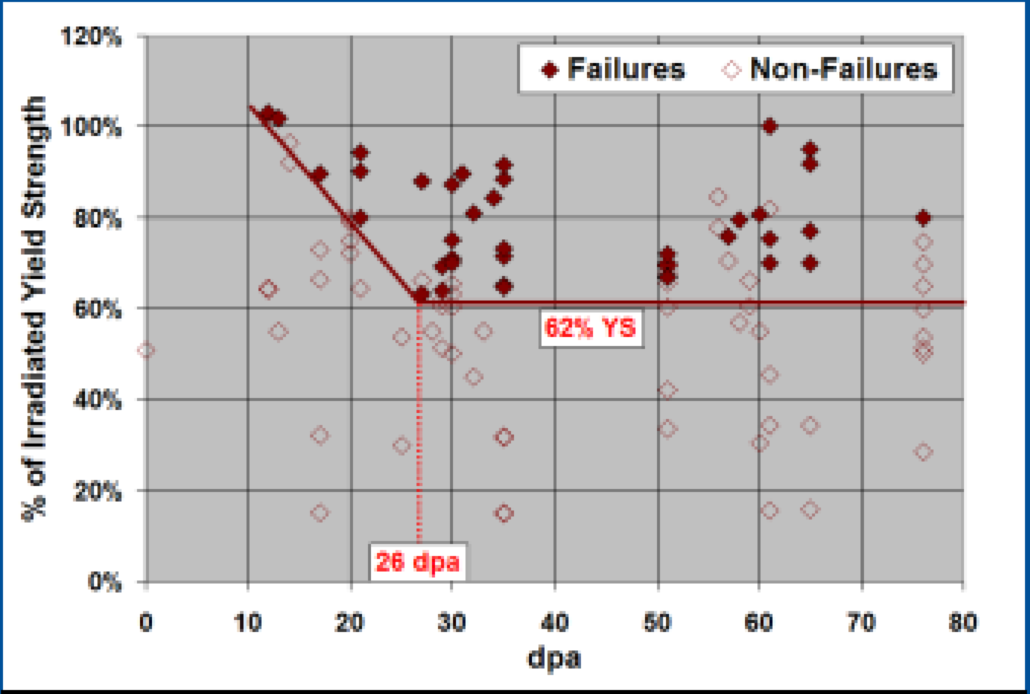


Six O-rings loaded into fixture for subsequent IASCC initiation testing under PWR simulated environmental conditions

- **Funded by 10-member international consortium (International IASCC Advisory Committee)**
- **~3 year program**

2. Effect of Service Exposure on Materials – Results & Implementation

- **Crack initiation portion of the scope: 80% of specimen failures occur rapidly, i.e., within ~150 hours (6 days)**
  - **Suggests that under adequate stress, crack initiation in sufficiently irradiated materials will occur rapidly**
- **Apparent 'stress threshold' controlled by irradiated yield strength which saturates by ~ 26 dpa**
- **No significant effect of material heat**
- **Applicability of results: predict IASCC behavior in highly irradiated stainless steels (i.e., baffle materials during Aging Management of Reactor Internals)**
- **This type of relevant property data: basis for Plant Life Extension technology**



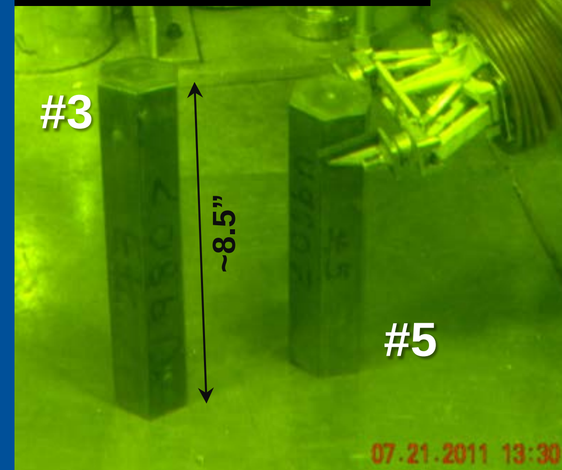
104-data point O-Ring IASCC database has led to the largest IASCC crack initiation database world wide for highly irradiated stainless steels

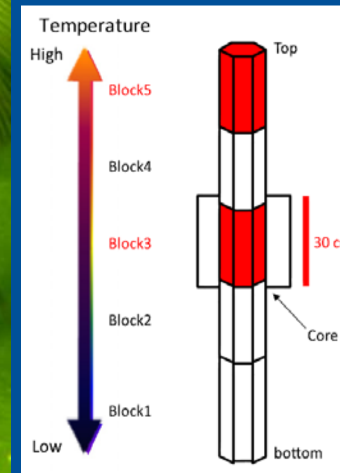
3. Fundamental Science Evaluation - Background

- Swelling of 304 SS neutron reflector hex blocks from EBR-II exposure
- US-Japan program conducted with:
  - The Ministry of Education, Culture, Sports, Science and Technology (MEXT)
  - University of Tokyo
  - Nuclear Fuel Industries Ltd.
  - Radiation Effects Consulting
  - Idaho National Lab
  - Westinghouse Hot Cell
  - University of Pittsburgh & University of Wisconsin
- Objectives:
  - Quantify irradiation-induced microstructural changes in thick section austenitic stainless steels as a function of dpa and T_{irr}
  - Develop a nondestructive inspection technique to measure same above changes

- Funded by MEXT
- ~9 month program

As-Received Hex Blocks





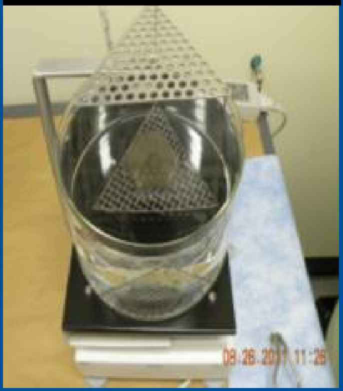
In-Cell Dimensional Measurements to Quantify Physical Distortion due to Swelling

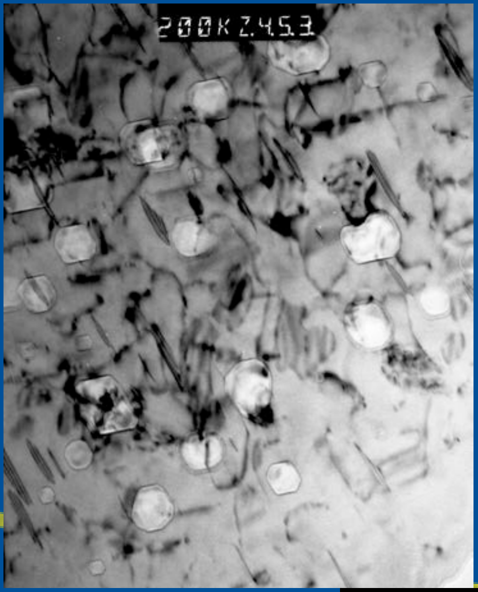
3. Fundamental Science Evaluation - Techniques

- Detailed non-destructive UT:
  - ~25,000 UT data scans!
- Detailed destructive characterization:
  - Dimensional swelling measurements
  - Precise sectioning of hex blocks into >225 sub-sections
  - Immersion density
    - Machining to obtain appropriate surface finish and obtain flat and parallel surfaces
    - Custom design and build of immersion density equipment for hot cell measurements of ~ 1 lb coins
  - ICP-MS chemical analysis
  - Metallography, GS
  - Shear punch tests (specimen prep)
  - TEM characterization of 14 material conditions (~75 high quality foils)
    - Quantify void/precipitate/dislocation/loop densities

Two of Several Coins Precision Cut from Blocks

Immersion Density Set-up for Large Coins





Voids of 1-10 nm

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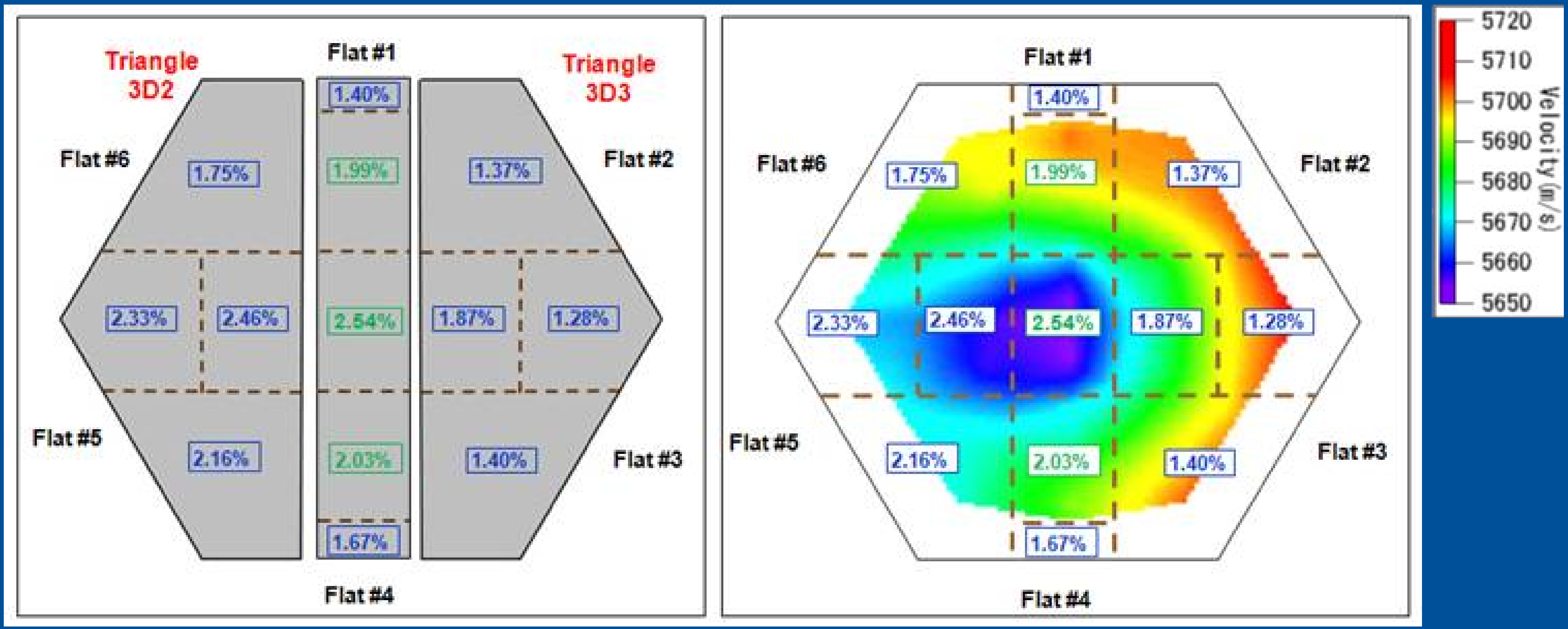
3. Fundamental Science Evaluation - Key Results



Extensive in-cell sectioning and immersion density measurements of high dose coins to determine swelling of individual pieces

Note: 3.2% swelling maximum determined ultrasonically

Believed to be the most comprehensive ultrasonic evaluation AND microstructural characterization ever performed for highly irradiated 304 stainless steel.

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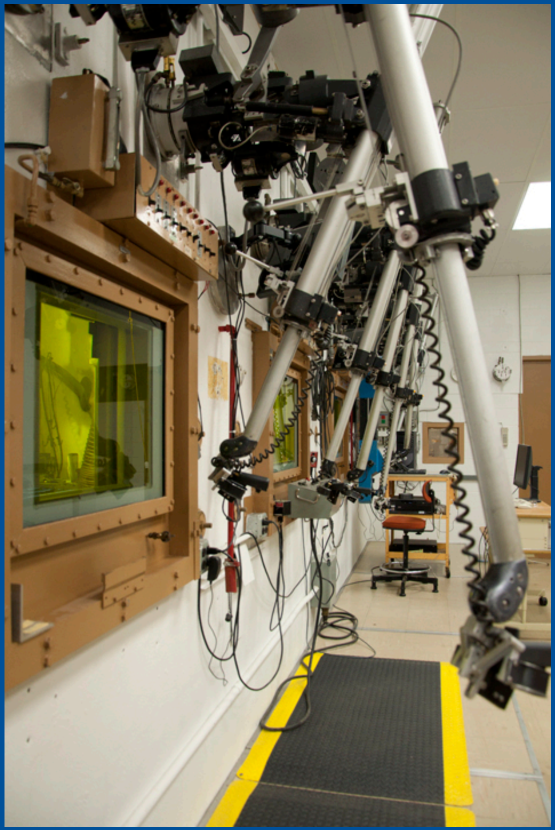
3. Fundamental Science Evaluation - Findings and Implications

- **Key characterization of swelling under known service conditions in thick components**
  - **Complex distribution of swelling observed**
  - **Material shows maximum of ~ 3% swelling**
- **Exceptionally sensitive UT data successfully obtained in-cell**
  - **Ultrasonic techniques demonstrated to be a valid method of measuring average void swelling across thick components**
  - **Development of an in-situ measurement tool appears to be possible**
- **TEM and immersion density agree well with anticipated swelling distribution**
- **Basis for analysis of commercial plant exposed samples, etc.**



The Westinghouse Hot Cells were a key enabler in delivering the results of this complex multi-national program ……

The Westinghouse Hot Cells are now a proud ATR-NSUF Partner Laboratory!

Summary

- **Extensive expertise in testing and evaluations of irradiated materials**
- **Proficiency in one-of-a-kind, first-of-a-kind testing and evaluations**
- **Three examples of hot cell testing of highly irradiated stainless steels**
- **Critical importance of generating relevant test data on components removed from actual reactors**

Thank you for your attention.

- **And one more important thing……**

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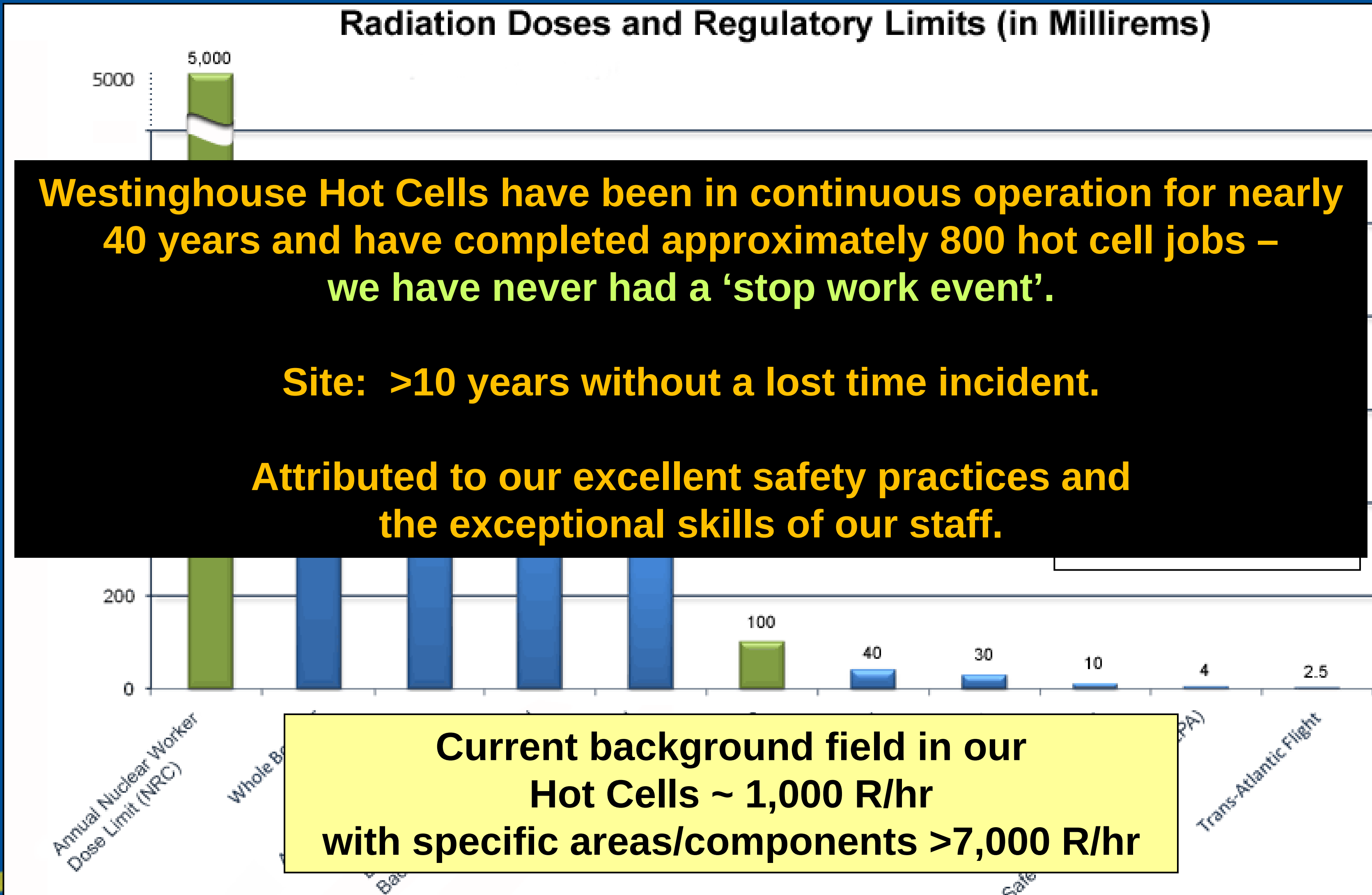
And We Do It All Safely - ALARA



Westinghouse Hot Cells have been in continuous operation for nearly 40 years and have completed approximately 800 hot cell jobs – we have never had a 'stop work event'.

Site: >10 years without a lost time incident.

Attributed to our excellent safety practices and the exceptional skills of our staff.

Current background field in our Hot Cells ~ 1,000 R/hr with specific areas/components >7,000 R/hr

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