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

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A Proud ATR NSUF Partner Laboratory
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
- 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

May 2013: 16 new capsules shipped to China
Sept 2013: 16 capsules being fabricated for VC Summer Unit 2 and Vogtle Unit 3
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
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, LaB₆, 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**

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**Routinely design and fabricate unique testing facilities for our customers**
Examples of Unique Capabilities

- High Temperature Steam Oxidation Unit
- Reactor Coolant Pump Seal Testing Laboratory
- Core Inlet Blockage Intermediate Test Loop (under construction)
- Zinc Effects Test Loop
- LOCA Debris Blockage Test Facility
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 Inspections of Commercial PWR Baffle Bolt

In-Cell Crack Growth Rate Test Assembly

In-Cell Ultrasonic Measurements of EBR-II Highly Irradiated 304 Stainless Steel
Three Examples...Hot Cell Projects*

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 -

* Contract Hot Cell work for a variety of outside customers
### Three Examples…Studies of Highly Neutron Irradiated Stainless Steels

<table>
<thead>
<tr>
<th>Description</th>
<th>Dose rates @ ~0.5” (R/hr)</th>
<th>dpa ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Highly irradiated 347 SS baffle bolts from a commercial PWR(^a)</td>
<td>&gt;5,000</td>
<td>~20 – 25</td>
</tr>
<tr>
<td>2. Highly irradiated 316 SS flux thimble tubes extracted from 3 commercial PWRs(^b)</td>
<td>~1,000</td>
<td>~0 – 80</td>
</tr>
<tr>
<td>3. Highly irradiated 304 SS neutron reflector hex blocks from EBR-II(^c)</td>
<td>~1,500</td>
<td>~0 – 35</td>
</tr>
</tbody>
</table>

**Reference Point: Lethal Dose - LD\(_{50/60}\) ~350 R**


\(^c\) Extensively published and presented in 2012-2013 including:


- “Ultrasonic NDE for Irradiation-Induced Material Degradations,” ICONE-21, Jul 29-Aug 2, 2013, Chengdu, China.
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
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
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 $\rightarrow$ 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

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

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

• 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 worldwide 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 $T_{\text{irr}}$
  • 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
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.
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......
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