U.S. PWR Core Barrel Specimens Laboratory Evaluation

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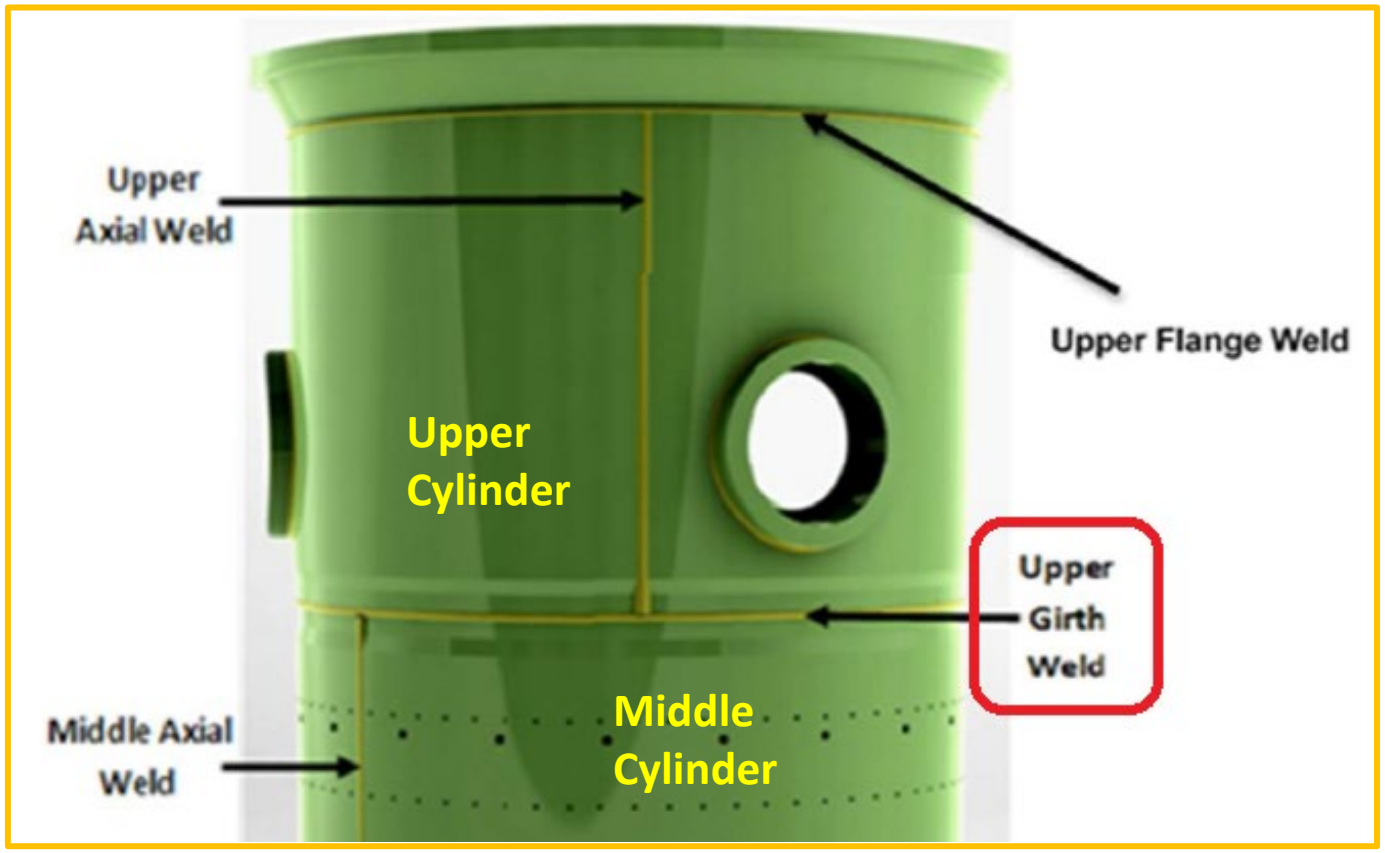
in collaboration with

DUKE ENERGY® and PWROG PWR Owners Group

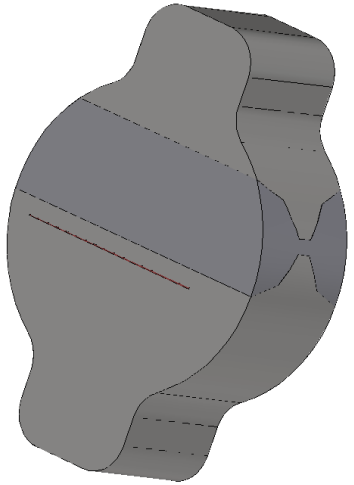
EPRI-Funded Work Scope



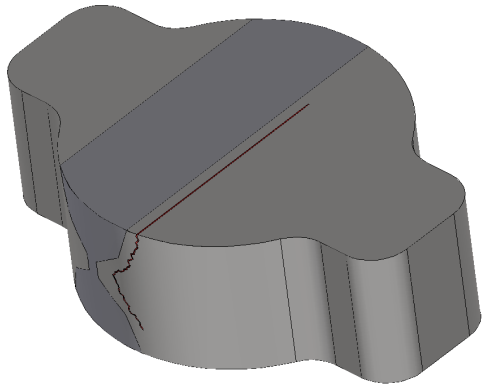
Laboratory Examination and Testing of 2 Core Drill Specimens (Indication #3 and Tip of Indication #4)

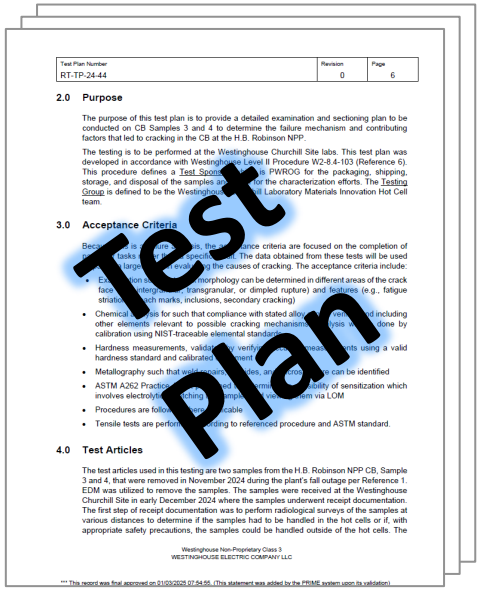
- **Identify Mode(s) of Degradation**
- **Identify Contributing Factors to the Degradation**

Sample 3



Sample 4

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2.0 Purpose

The purpose of this test plan is to provide a detailed examination and sectioning plan to be conducted on CB Samples 3 and 4 to determine the failure mechanism and contributing factors that led to cracking in the CB at the H.B. Robinson NPP.

The testing is to be performed at the Westinghouse Churchill Site labs. This test plan was developed in accordance with Westinghouse Level II Procedure W2-8.4-103 (Reference 6). This procedure defines a Test Sponsor and the PWROG for the packaging, shipping, storage, and disposal of the samples as well as the characterization efforts. The Testing Group is defined to be the Westinghouse Churchill Laboratory Materials Innovation Hot Cell team.

3.0 Acceptance Criteria

Because this is a forensic analysis, the acceptance criteria are focused on the completion of the tasks and the specific objectives. The data obtained from these tests will be used to support a larger effort evaluating the causes of cracking. The acceptance criteria include:

- Examination of fracture morphology can be determined in different areas of the crack face (intergranular, transgranular, or dimpled rupture) and features (e.g., fatigue striations, tool marks, inclusions, secondary cracking)
- Chemical analysis for such that compliance with stated alloy specifications including other elements relevant to possible cracking mechanisms is done by calibration using NIST-traceable elemental standards
- Hardness measurements, validation, verification of measurements using a valid hardness standard and calibrated equipment
- Metallography such that sensitization can be identified
- ASTM A262 Practice A is performed to evaluate susceptibility of sensitization which involves electrolytic etching of samples, examination via LOM
- Procedures are followed as applicable
- Tensile tests are performed according to referenced procedure and ASTM standard.

4.0 Test Articles

The test articles used in this testing are two samples from the H.B. Robinson NPP CB, Sample 3 and 4, that were removed in November 2024 during the plant's fall outage per Reference 1. EDM was utilized to remove the samples. The samples were received at the Westinghouse Churchill Site in early December 2024 where the samples underwent receipt documentation. The first step of receipt documentation was to perform radiological surveys of the samples at various distances to determine if the samples had to be handled in the hot cells or if, with appropriate safety precautions, the samples could be handled outside of the hot cells. The

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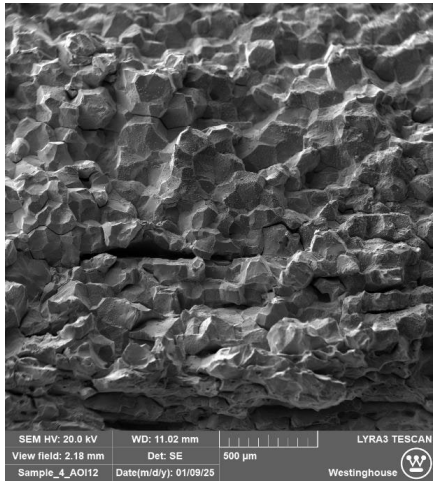
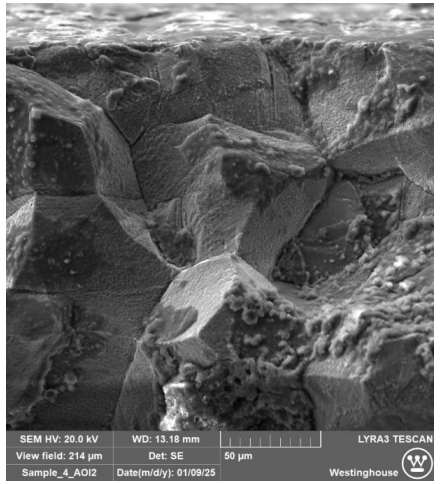
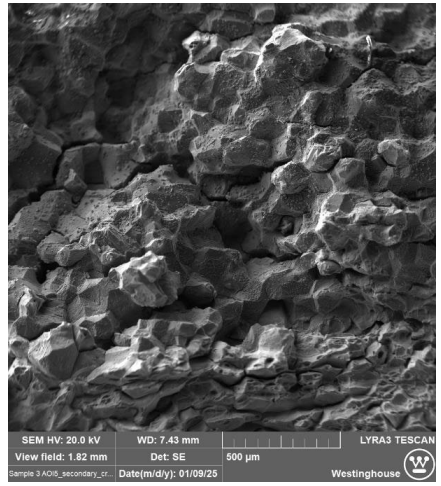
*** This record was final approved on 01/03/2025 07:54:56. (This statement was added by the PRIME system upon its validation)

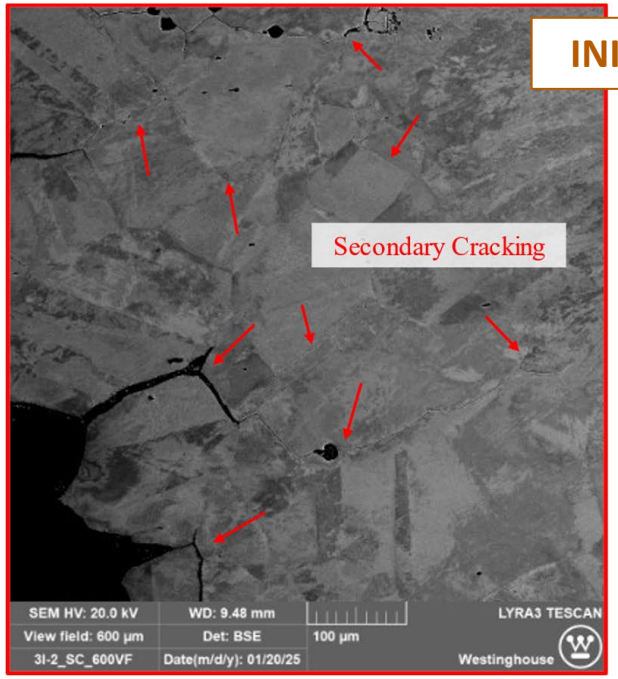
- Fractography
- Metallography
- Microscopy
- Chemistry
- Hardness Testing
- ASTM A262 Pr. A
- Dosimetry

Fractography, Metallography, Microscopy

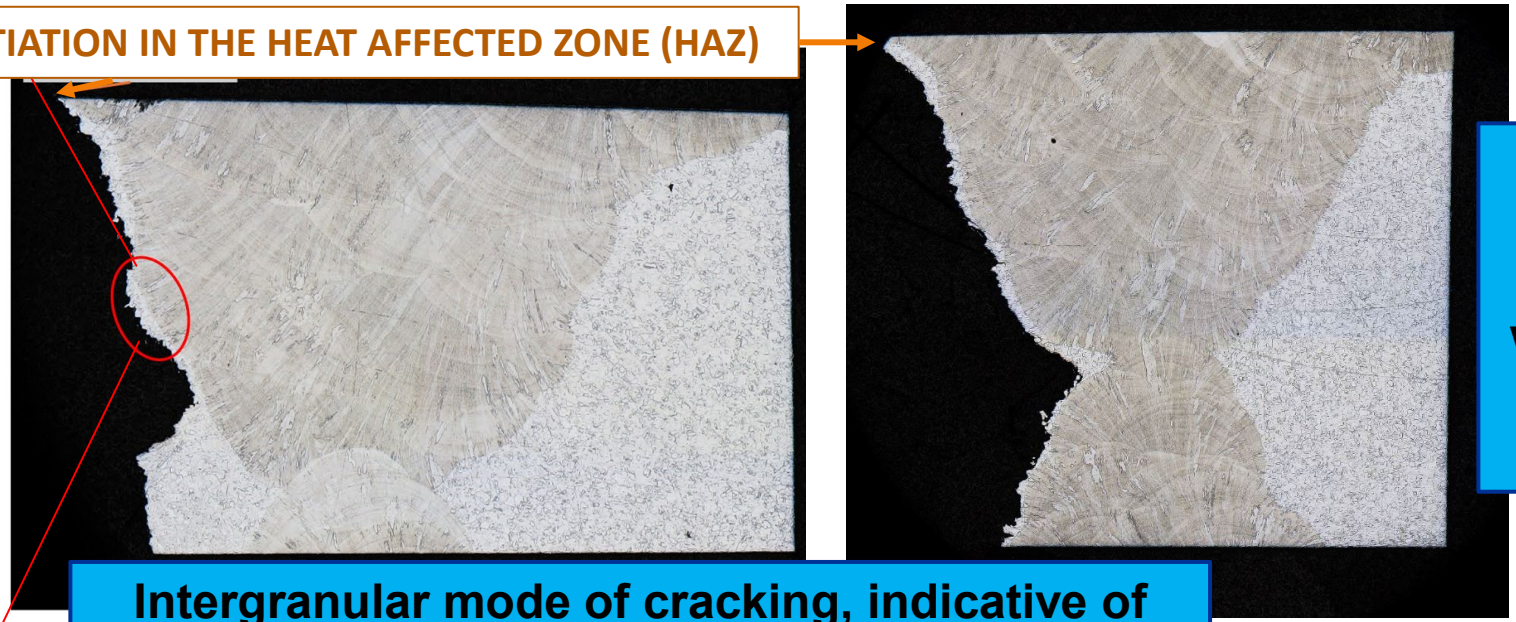








INITIATION IN THE HEAT AFFECTED ZONE (HAZ)



Crack path confined to base metal, within HAZ of the upper girth weld

Intergranular mode of cracking, indicative of stress corrosion cracking, on all fracture faces

Investigation of Potential Contributing Factors to Degradation

Chemistry Analysis

Element / Sample Identification	Co	Cr	Cu	Fe	Mn	Mo	Ni	P	Si	C	S
ASTM A240-69, Type 304	-	18.00-20.00	-	-	2.00 max	-	8.00-12.00	0.045 max	1.00 max	0.08 max	0.030 max
Upper CB Plate	0.11	18.36	0.09	69.66	1.47	0.19	9.58	0.01	0.49	0.039	0.015
Upper CB CMTR	0.13	18.32	0.08	69.53	1.53	0.21	9.60	0.031	0.51	0.045	0.015
Middle CB Plate	0.07	18.84	0.05	68.89	1.43	0.22	9.79	0.01	0.66	0.047	0.012
Middle CB CMTR	-	18.92	0.05	68.85	1.50	-	9.85	0.023	0.70	0.048	0.011
Weldment	0.08	20.05	0.08	67.29	2.07	0.06	9.89	0.00	0.43	0.050	0.007

- Chemistry measurements made by combustion analysis (C, S) and inductively coupled plasma optical emission spectroscopy (ICP-OES) for remaining elements
- Base metal chemistry conforms to plate specification ASTM A240 for Type 304
- Experimental data matches well with the respective plate certified material test report (CMTR) values
- Weld metal chemistry meets vintage SFA 5.4 weld metal specification for E308

Investigation of Potential Contributing Factors to Degradation

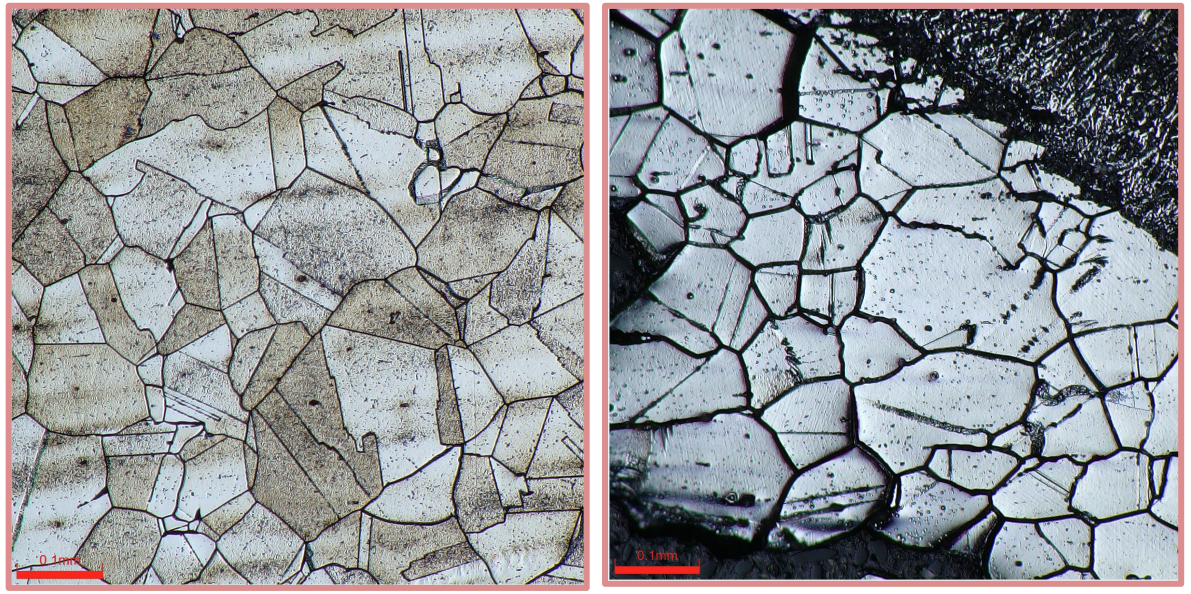
Microhardness Testing ($HV_{0.5}$)

Location	Average Vickers Microhardness Value	Standard Deviation
Middle Core Barrel Plate	218	30
Middle Core Barrel HAZ	224	33
Weldment	221	21
Upper Core Barrel HAZ	213	9
Upper Core Barrel Plate	194	12

- Weld metal hardness appears typical, with highest values near root of weld
- Upper shell and middle shell (away from weld HAZ/fracture face) hardness values appear typical
- ID Surface hardness does not appear to be significantly elevated, but fewer points available in HAZ

ASTM A262 Practice A Testing

- Middle cylinder plate
  - Base metal – Not sensitized (left image)
  - HAZ – Potentially sensitized (right image)
- Upper cylinder plate
  - Base metal – Potentially sensitized
  - HAZ – Potentially sensitized



Investigation of Potential Contributing Factors to Degradation

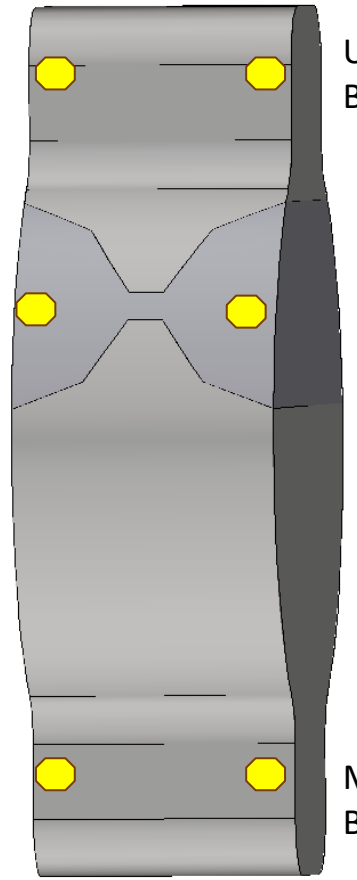
Retrospective Dosimetry Analysis

- One sample from each respective location in each Core Sample, both on ID and OD.
- Chemistry quantification supported by X-ray Fluorescence (XRF)

Average between Specimens	Upper CB Plate ID	Weldment ID	Middle CB Plate ID
Integrated Fluence (E > 1.0 MeV) (n/cm^2)	6.60E+17	8.01E+17	1.05E+18
Integrated Iron Atom Displacements (dpa)	9.85E-04	1.19E-03	1.56E-03
Integrated Fluence (E > 0.1 MeV) (n/cm^2)	1.10E+18	1.37E+18	1.87E+18

Maximum Best-Estimate Values	Upper CB Plate OD	Weldment OD	Middle CB Plate OD
Integrated Fluence (E > 1.0 MeV) (n/cm^2)	4.22E+17	4.99E+17	7.76E+17
Integrated Iron Atom Displacements (dpa)	6.30E-04	7.43E-04	1.16E-03
Integrated Fluence (E > 0.1 MeV) (n/cm^2)	7.77E+17	9.52E+17	1.52E+18

With irradiation damage less than 0.002 dpa, irradiation effects are considered **insignificant** with respect to the degradation observed



Key Observations Summary

- **Degradation Mode**: Intergranular cracking is observed throughout the crack surface of both indications. Intergranular stress corrosion cracking (IGSCC) is the only mechanism observed.

- **Contributing (or Unique) Factors**:
  - IGSCC is confined to the HAZ of middle core barrel shell
  - No indication of weld repairs in the vicinity of the cracks
  - Typical carbon and sulfur levels measured for Type 304 stainless steel of this vintage
  - ASTM A262 Practice A indicates some “suspect” microstructures present in samples, notably HAZs.
    - “Suspect” is language from A262 specification, meaning HAZ is *potentially sensitized*
  - Microstructure otherwise seems typical for base metal and weld metal
  - Moderately elevated hardness in some regions (notable near root pass), but not so high as to be a significant contributor to initiation
  - Irradiation damage is not a contributing factor to the degradation

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