A Destructive Validation of NDE Responses of Service-Induced PWSCC Found in North Anna 2 Control Rod Drive Nozzle 31

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Outline

- Motivation
- Control Rod Drive Nozzle Description
- Eddy Current Analysis of Nozzle 31
- Destructive Validation of Eddy Current Results
- Destructive Evaluation of Ultrasonic Leak Path Measurements

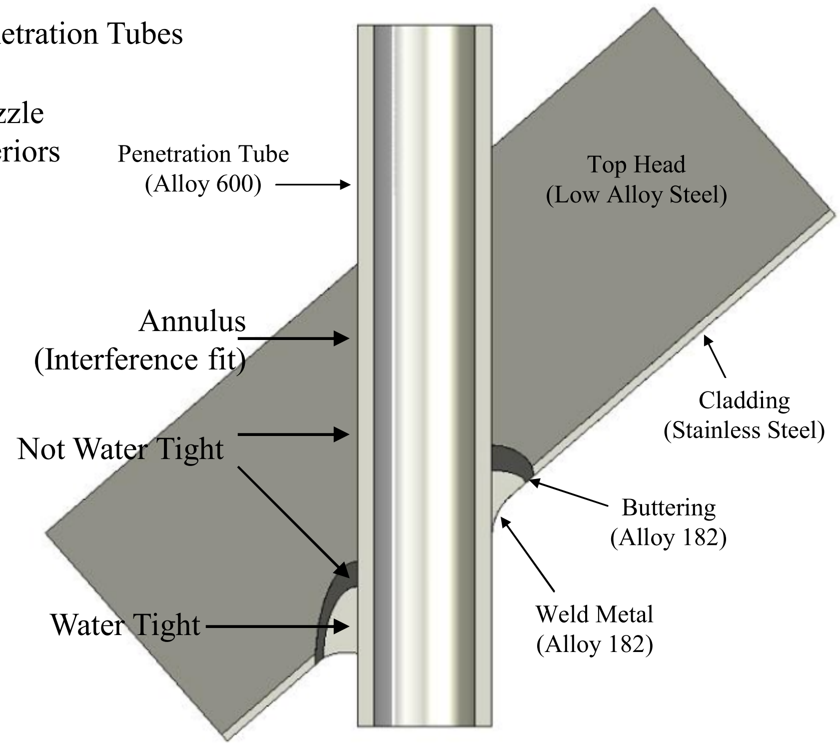
Motivation

- Some control rod drive mechanism (CRDM) nozzles in PWRs have been vulnerable to pressurized water stress corrosion cracking (PWSCC).
- Finding PWSCC in these nozzles using nondestructive evaluation (NDE) techniques has proven to be challenging.
- Destructive validation of PWSCC and a comparison of the NDE responses with the physical crack characteristics would be very helpful in future evaluations of CRDM nozzles.
- The U.S. Nuclear Regulatory Commission and the Electric Power Research Institute formed a joint venture to procure and examine service-induced PWSCC in a CRDM nozzle.
- This presentation focuses on the destructive validation/evaluation of two NDE techniques: eddy current testing and ultrasonic leak path measurements.

CRDM Nozzle Description

The reactor pressure vessel head is the "lid" to the reactor
Control rods are inserted through nozzles drilled and welded into the head.

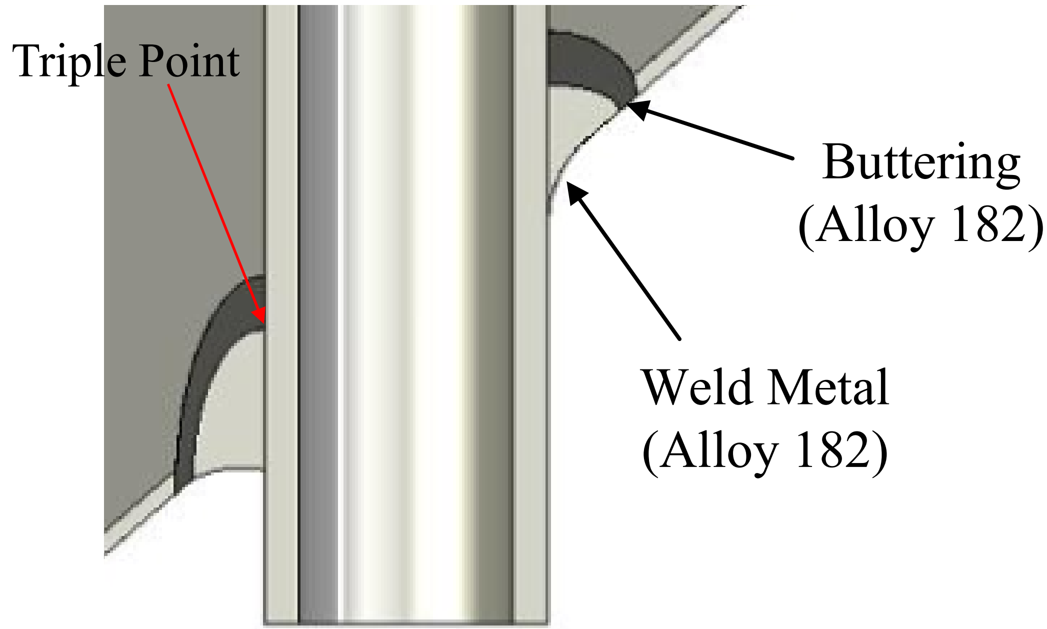
Cut-Away View of an RPV Head



CRDM J-groove Weld Diagram

J-Groove Weld and the Triple Point

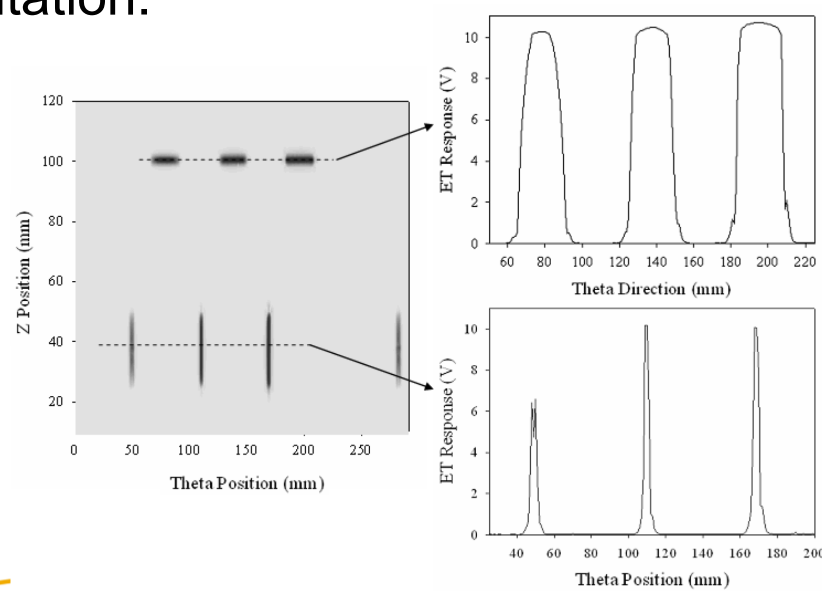
- The triple point is where the weld metal, buttering, and penetration tube come together.
- Any crack that penetrates past the triple point can cause leakage out of the reactor pressure vessel.



Eddy Current Examination of NA2 Nozzle 31

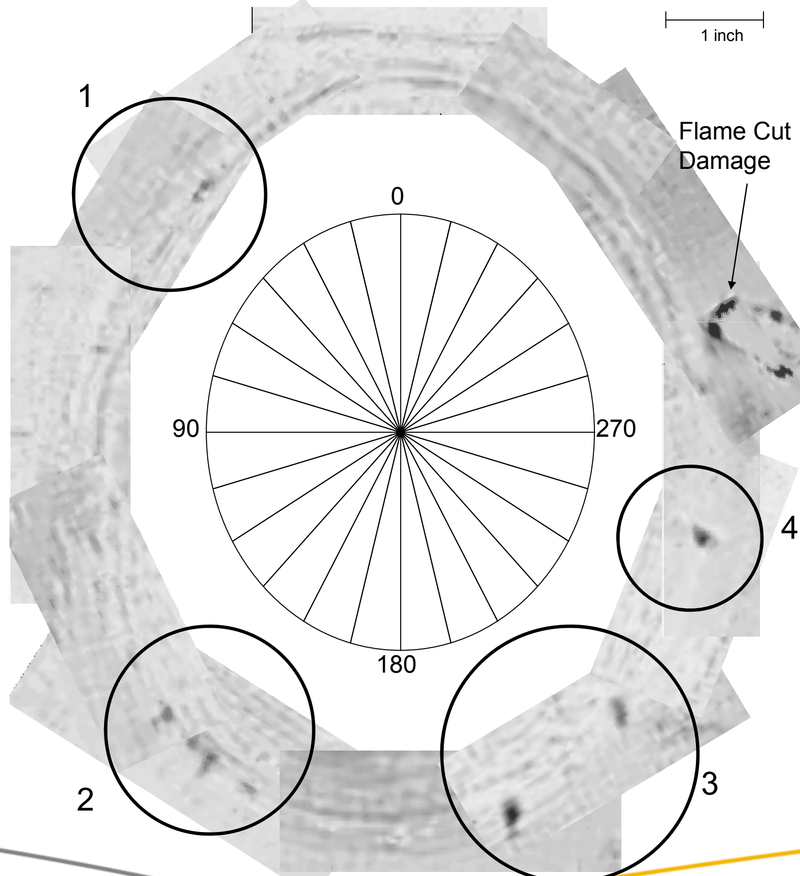
- The Nozzles have been examined using many NDE techniques.
  - Eddy current testing (ET) has proven to be the most effective.
- The J-groove weld of Nozzle 31 was examined using plus-point ET probes at 150 and 350 kHz.
- The ET probes were calibrated using a series of narrow electro discharge machining (EDM) notches.
- The J-groove weld was scanned with the ET probes oriented at 0 degrees and 45 degrees (relative to scan direction) to assure good sensitivity to flaws of every orientation.

Test ET Scan of CRDM Nozzle Removed from the Midland RPV head

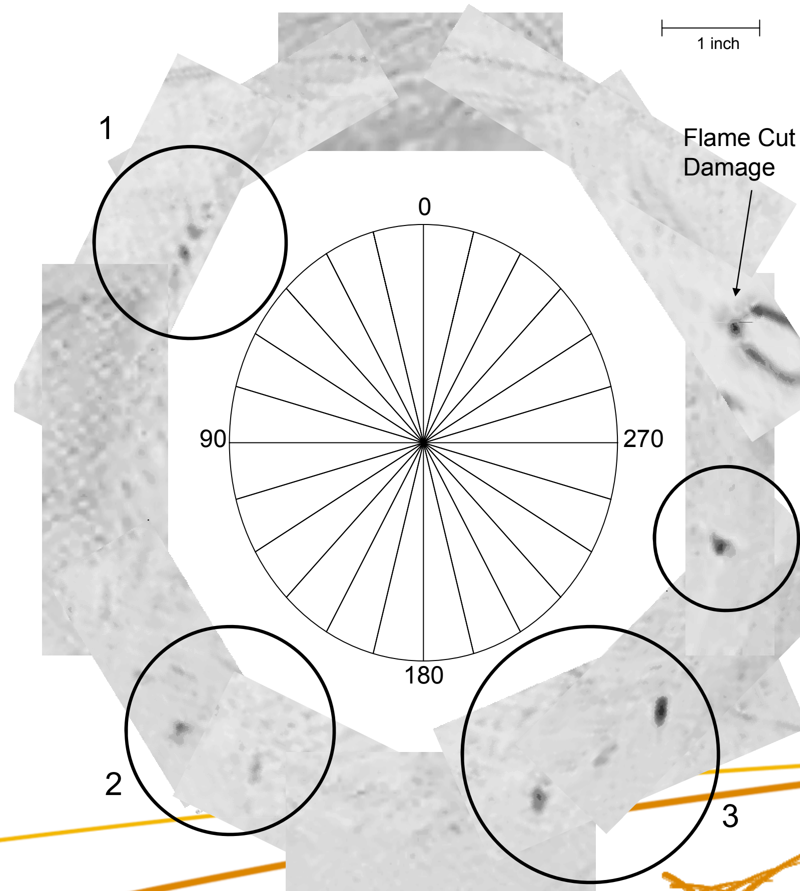


Eddy Current Results on Crown of J-Groove Weld and Buttering

Zero Degree Probe Rotation



45 Degree Probe Rotation



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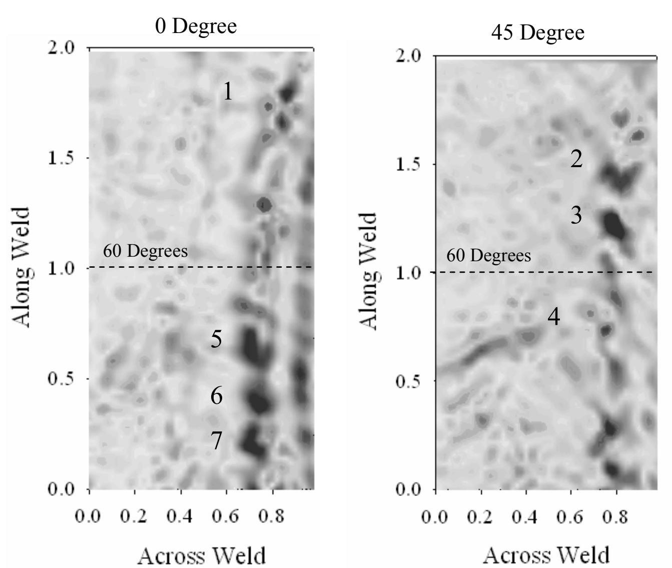
Summary of Eddy Current Indications

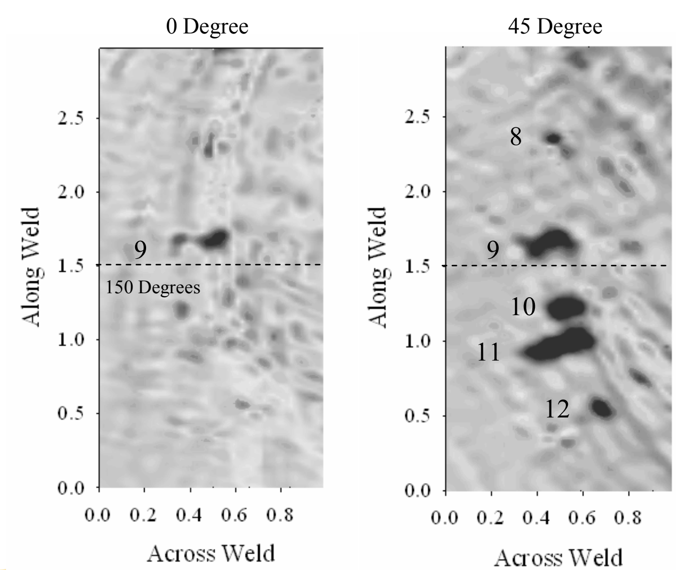
Centered on 60°

Indication	Length	Max Voltage
1	5 mm	2.1
2	3 mm	1.9
3	4 mm	3.3
4	2 mm	1.8
5	5 mm	2.2
6	3 mm	2.5
7	4 mm	2.3

Centered on 150°

Indication	Length	Max Voltage
8	3	2.3
9	8	3.2
10	6	3.3
11	10	4.1
12	4	2.6

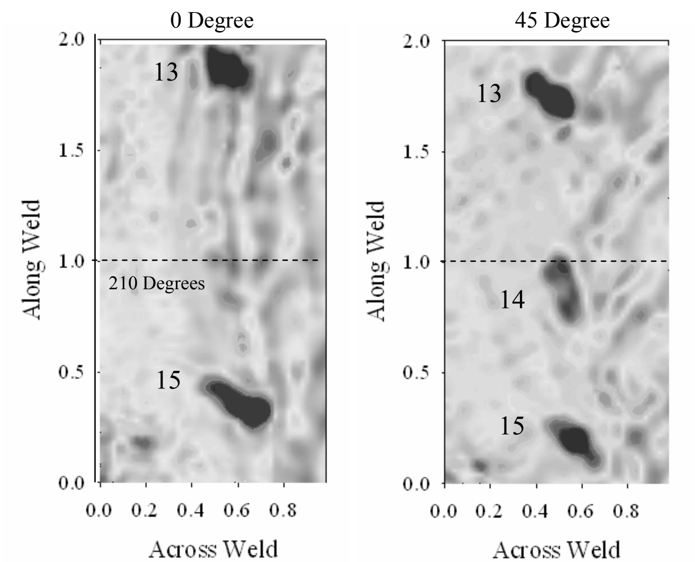




Summary of Eddy Current Indications

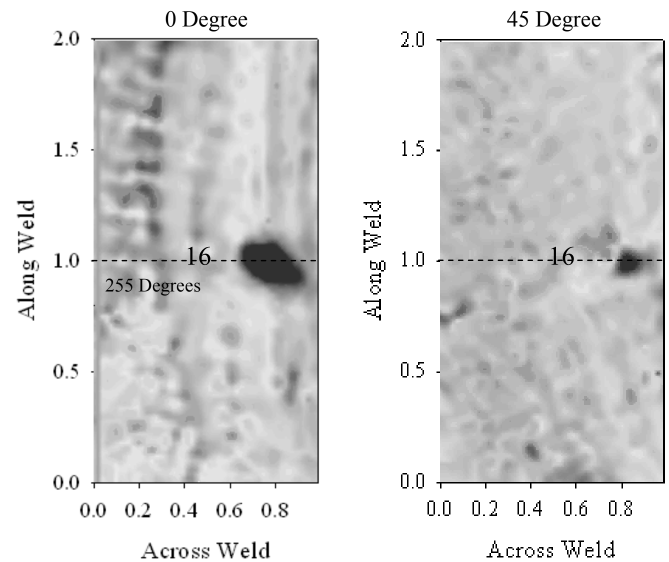
Centered on 210°

Indication	Length	Max Voltage
13	7	4.6
14	7	1.8
15	8	4.6



Centered on 255°

Indication	Length	Max Voltage
16	8	4.2



Destructive Evaluation

- Nozzle #31 was flame-cut from the retired vessel head for laboratory analysis.
- The four regions of interest were cut from the J-groove weld using a band saw.
- Nozzle 31 was cut just above the triple point to find a crack that had penetrated to the annulus.
- The leaking crack was identified at 155 degrees, and a second very deep crack was found at 255 degrees.
- The regions were then further sectioned to determine how far the cracks had penetrated into the weld metal.

Destructive Validation of Indications

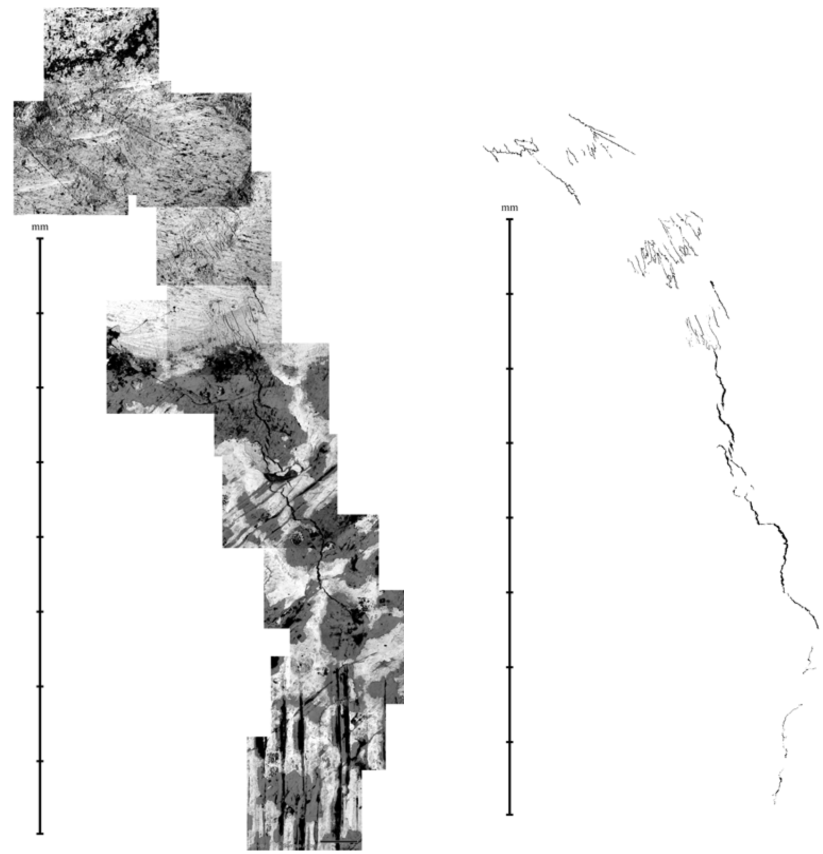
- The four regions of interest were cut 6-8 mm above the wetted surface and at 25 mm above the wetted surface to determine whether the ET indications coincided with cracks.
- Six of the sixteen indications were confirmed as cracks deeper than 6-8 mm. The six confirmed cracks all had ET indications with voltages higher than 30% of the calibration notch and a length of 7 mm or greater.

Indication	Angle	Length	Max Voltage	% EDM Notch	Verified Depth
1	45	2 mm	2.1	20%	Less than 6 mm
2	50	5 mm	1.9	18%	Less than 6 mm
3	55	4 mm	3.3	32%	Less than 6 mm
4	65°	2 mm	1.8	18%	Less than 6 mm
5	70°	4 mm	2.2	21%	Less than 6 mm
6	75°	3 mm	2.5	24%	Less than 6 mm
7	80°	3 mm	2.3	22%	Less than 6 mm
8	130°	4 mm	2.3	22%	Less than 8 mm
9	145°	10 mm	3.2	31%	Between 8 mm and 25 mm
10	155°	8 mm	3.3	32%	Through-Weld Leaking
11	160°	14 mm	4.1	40%	Between 8 mm and 25 mm
12	170°	5 mm	2.6	25%	Less than 8 mm
13	200°	8 mm	4.6	45%	Between 6 mm and 25 mm
14	215°	10 mm	1.8	18%	Less than 6 mm
15	225°	9 mm	4.6	45%	Between 6 mm and 25 mm
16	255°	7 mm	4.2	41%	Through-Weld Not Leaking

Electron Microscopy of Crack at 155 Degrees

- The crack was located at the weld/butter interface.
- The crack at the surface was tight and discontinuous.
- The main crack section was 4 mm long with short and segmented regions at each end.

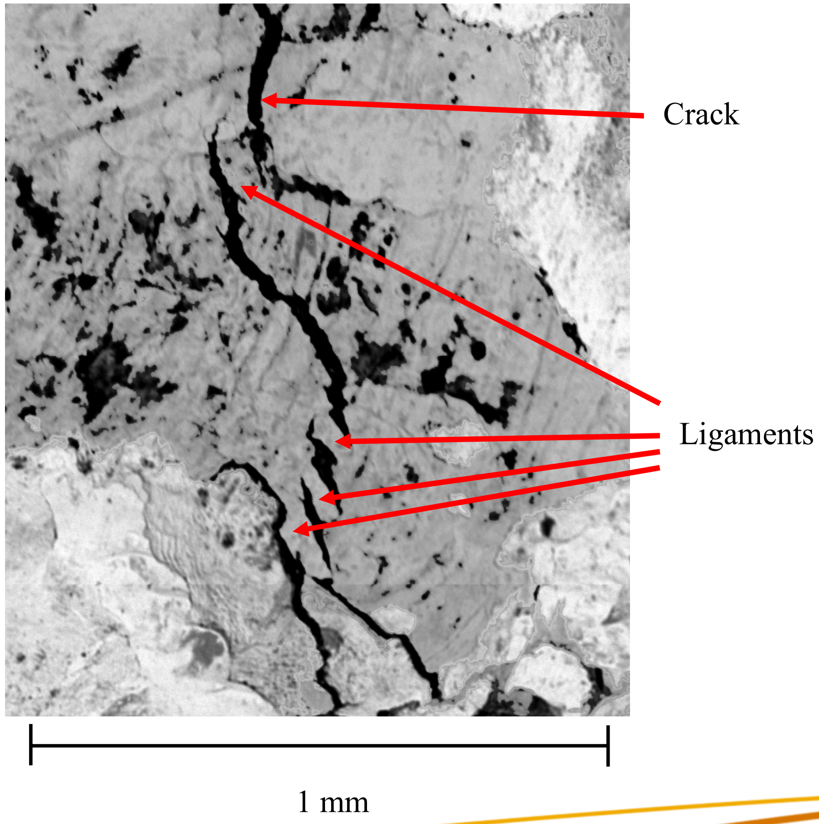
SEM of Crack Surface



Expanded View of Through-Weld Crack

- The through-weld crack had ligaments of metal crossing the crack in several places
- The meandering nature of the crack below the surface also allowed for electrical contact between the crack faces.
- This electrical contact between the crack faces is likely responsible for the reduced ET response relative to some of the less severe cracks.

SEM Image of crack on Wetted Surface

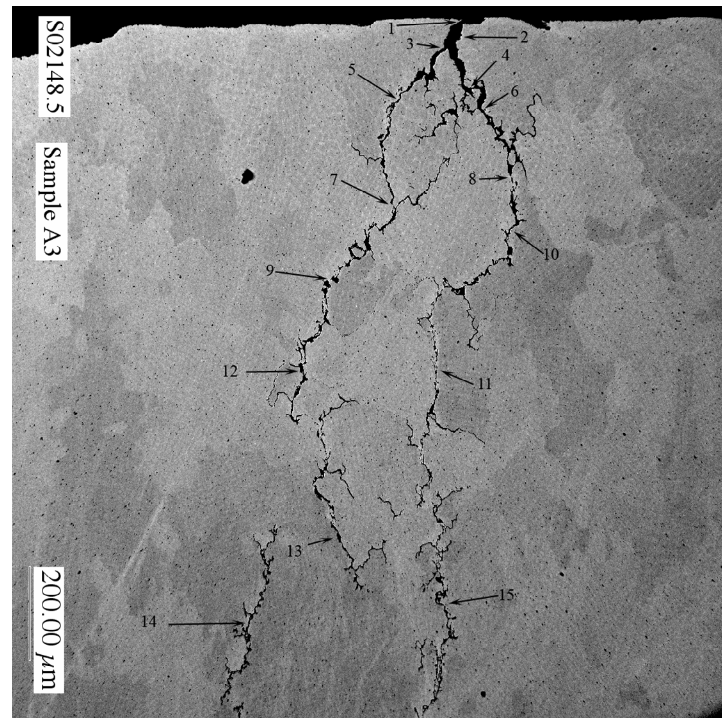


Crack Near-Surface Profile

- The crack has a branched and discontinuous profile into the weld metal.
- The crack branches largely follow the grain boundaries in the weld.
- The crack opening displacements along the crack depth are very tight and prevent penetrant testing from being effective.

Location	COD (μm)
1	10
2	29
3	6
4	2
5	6
6	6
7	2
8	Closed
9	Closed
10	4
11	2
12	9
13	7
14	3
15	2

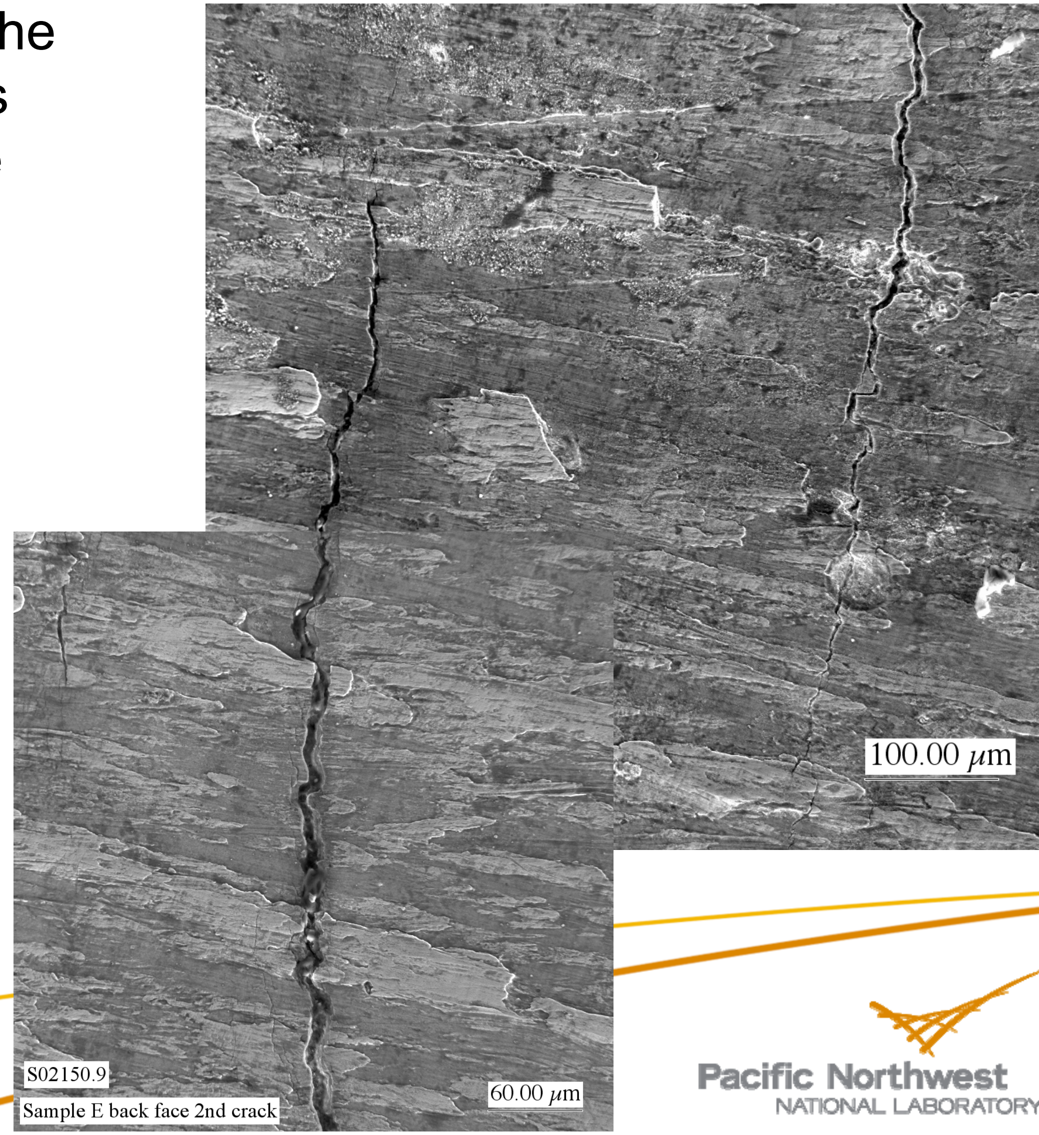
SEM of Crack Section



Crack Propagation into Annulus

The crack was tracked from the wetted surface to the annulus between the penetration tube and the vessel head.

SEM of Through-Weld Crack in the Annulus



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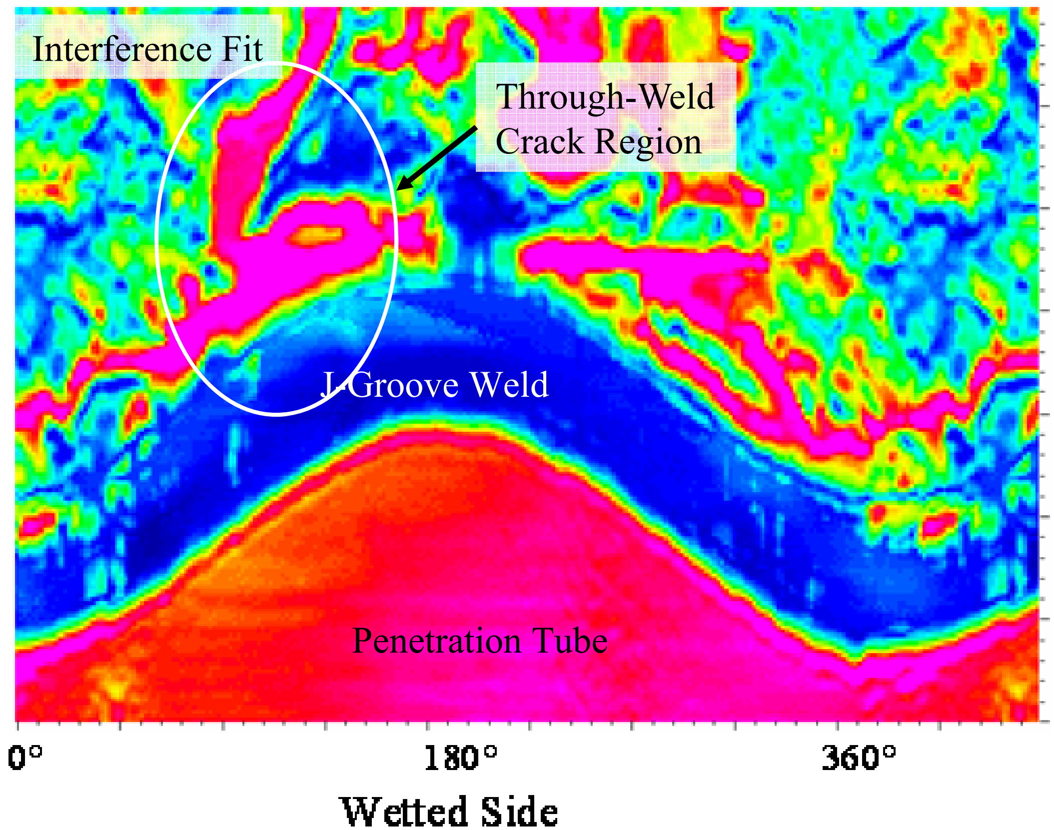
Evaluation of the Ultrasonic Leak Path Measurement Technique

- There is interest by some in the inspection community to apply an ultrasonic examination to the annulus
- It has been thought that the interference fit would transmit ultrasound, while a leak path would create damage to the carbon steel (wastage) that would result in a detectable UT signal.
- The ISI performed in the field and UT performed at PNNL both found what appeared to be a leakage path close to the location of the through-weld leaking crack.



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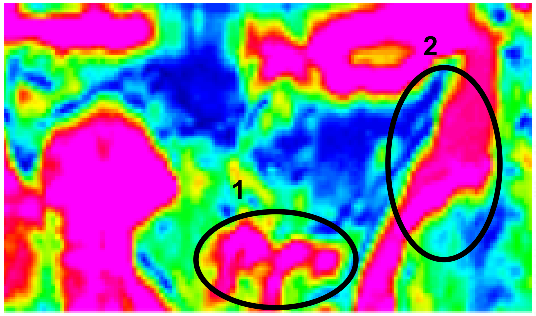
UT Leak Path Evaluation- The Effects of Boric Acid Deposits

- When the nozzle was cut for destructive evaluation, boric acid deposits were found in the annulus.
- The area with boric acid deposits in the annulus was similar to the pattern found by ultrasonic examination.
- The possible leak path identified by UT measurements did not correspond to wastage of the carbon steel, but instead showed a region with no boric acid deposits.



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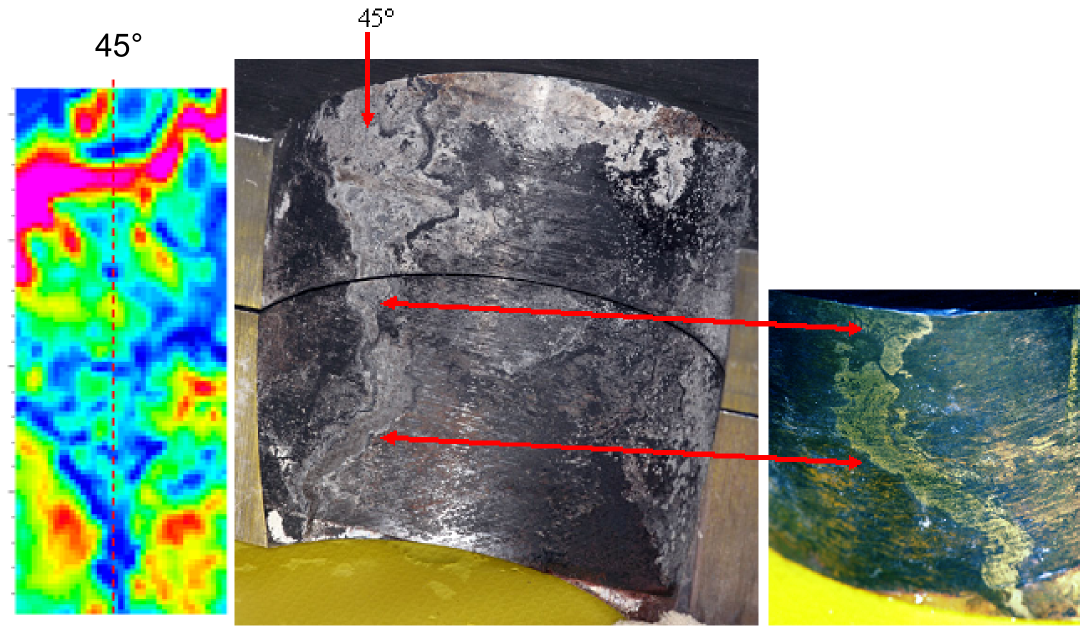
UT Leak Path Evaluation- No Signal from Shallow Wastage/Steam Cutting

- A region of shallow wastage on the penetration tube and carbon steel was observed, but the UT examination found no related indications.
- The depth of the damage was not measured, but machining marks were still present on the penetration tube and in the annulus.
- The UT leak path measurement appeared to be more sensitive to the presence and absence of boric acid deposits than to shallow wastage.
- No significant wastage of the carbon steel was present in the nozzle, preventing an evaluation of the effects of severe wastage on the UT signals.



Carbon Steel Annulus ID

Penetration Tube OD

Conclusions

- PNNL detected sixteen possible cracks in the J-groove weld of Nozzle 31 using Eddy Current examination.
- Eddy Current testing using Plus point probes at 350 kHz is effective at finding PWSCC in the J-groove weld in CRDM nozzles.
- The six indications that were confirmed as cracks deeper than 6-8 mm all had surface lengths longer than 7 mm and ET amplitudes greater than 30% of an 8 mm EDM notch.
- The amplitudes of the eddy current indications were strongly affected by the crack morphology at the surface and near the surface. The through-weld and leaking PWSCC at 155 degrees had many ligaments connecting the crack faces. Many shallow cracks provided larger ET signals than the through-weld leaking crack.
- The UT leak path detection technique is more sensitive to boric acid deposits than to shallow wastage.

Acknowledgements

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