Repair of the NRU Reactor Vessel: Technical Challenges and Lesson Learned

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- The NRU Reactor
- Leak location and condition assessment
- Inspection tool development
- Determination of degradation mechanism
- Development of repair methods
- Execution of weld repair
- Lessons Learned

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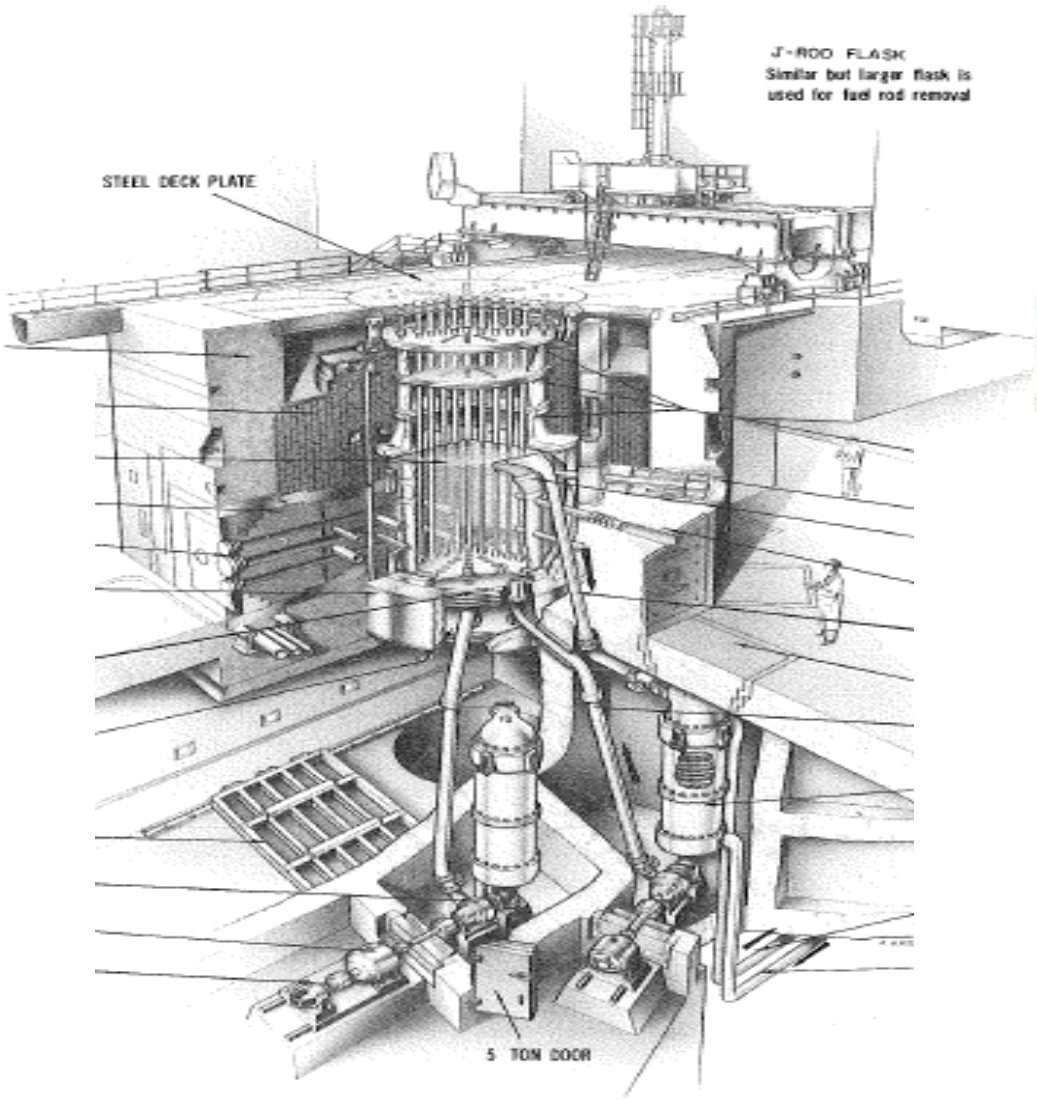
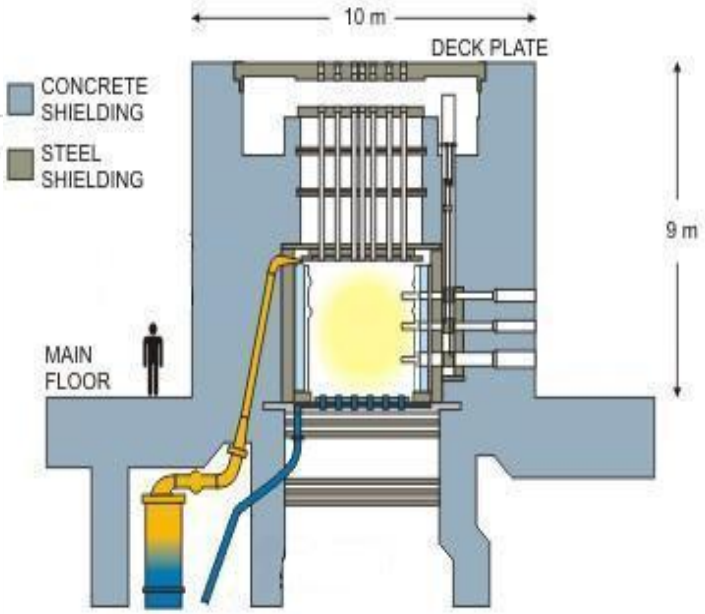
NRU - National Research Universal

- First operation 1957 November
- 200 MW design; current licence limit 135 MW
- Large, versatile research reactor
  - R&D support of CANDU® reactor fuel & materials irradiation
  - National Research Council Canadian Neutron Beam Centre
- Medical & industrial isotopes
  - Benefits more than 76,000 people internationally each day
  - Used for cancer treatment and early cancer detection, diagnosis of heart conditions, circulatory system & other organs
  - Mo-99, I-125, I-131, Xe-133, Co-60, Ir-192

- NRU obtained full WANO membership in late 2010

Cross Section of NRU





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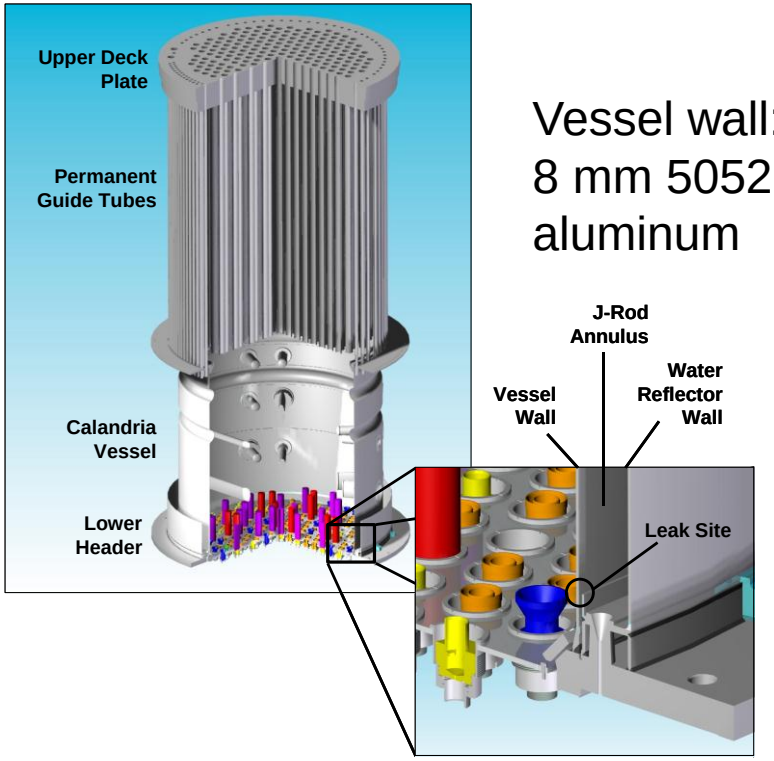
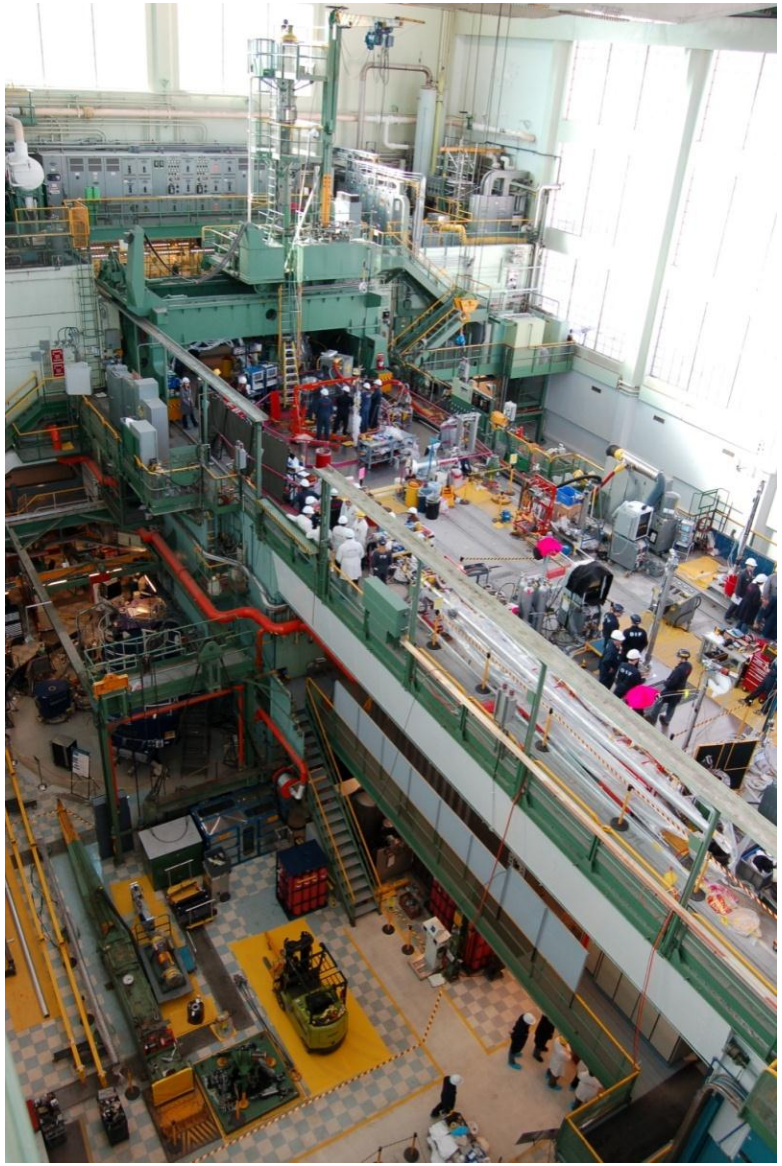
Heavy Water Leak- 2009 May 14



Vessel wall:
8 mm 5052 aluminum



Reaching the leak site:

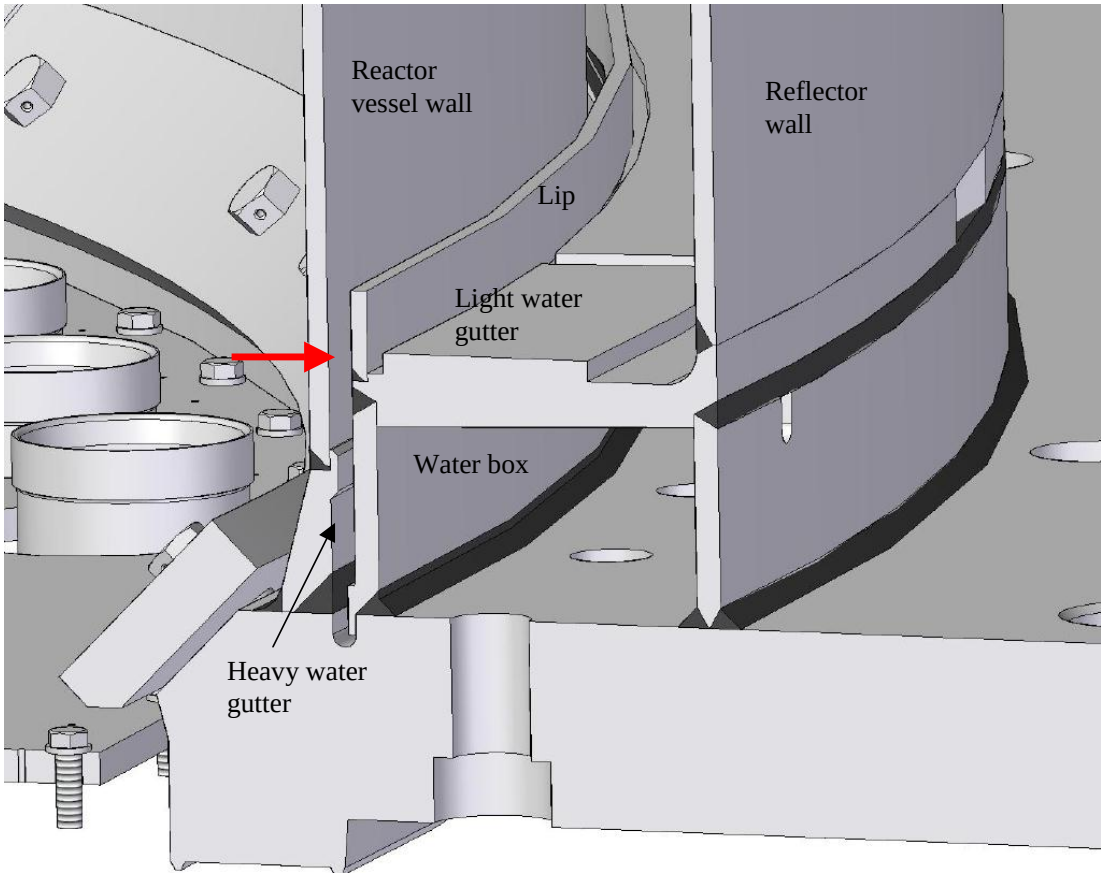
- Leak site is 9 m below the deck plate at the base of the vessel
- Access through 12 cm dia. tubes
- High radiation environment

Visual Inspections in 2009 May

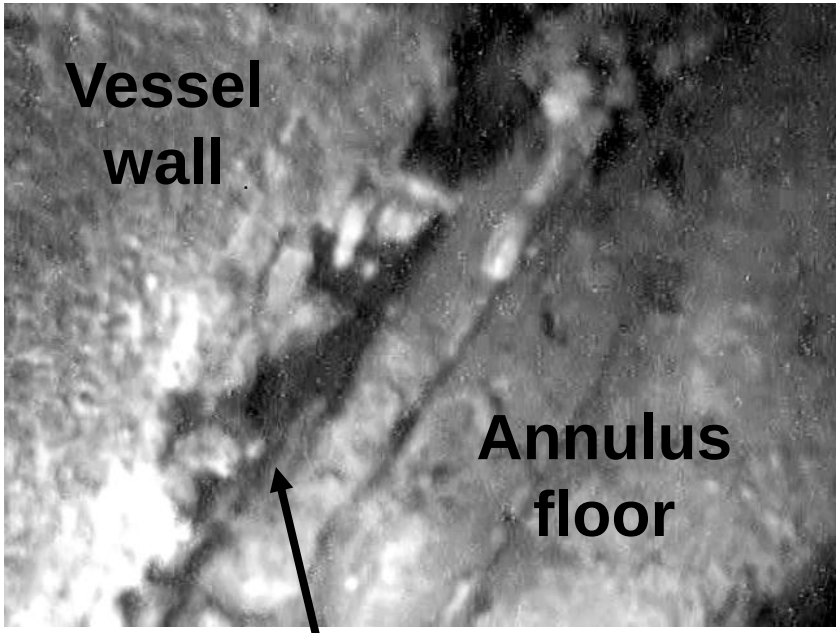
- Minor heavy water leak from the vessel into the surrounding annulus detected (~5 kg/h)
  - Visual inspection determined that the leak site was in the vessel wall at the bottom of the annulus
  - Determined that the heavy water leak was due to corrosion of the reactor vessel wall from the outside
  - Additional areas of corrosion around the base of the vessel also required remediation
  - Decision made to remain shutdown for an extended period to repair the vessel

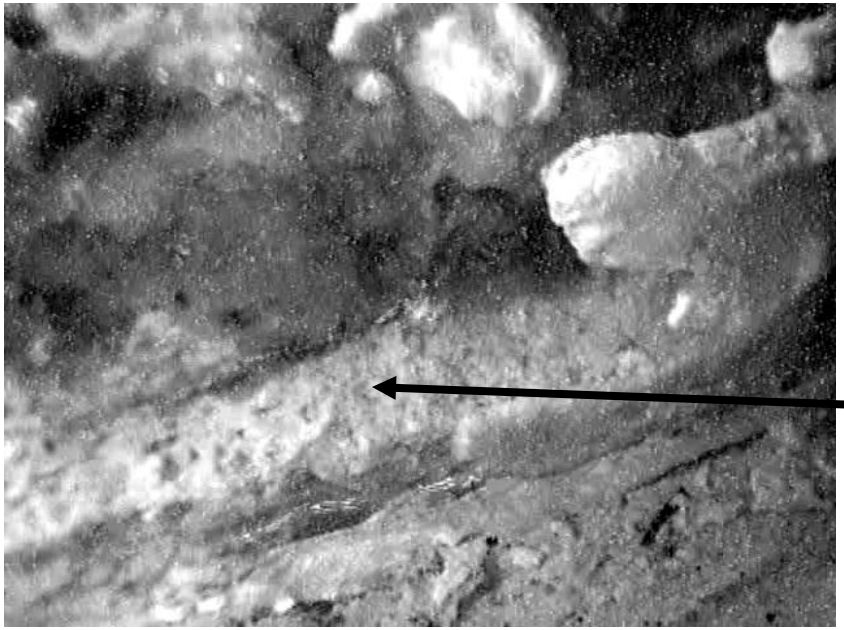
Leak Site

- Detailed non-destructive examination of lower vessel wall performed
  - Leak location determined accurately
  - Widespread corrosion identified in the lower portion of the J-rod annulus



A Closer Look at the Leak Site





Area of leak

Condition Assessment of Vessel

Non-destructive examination:

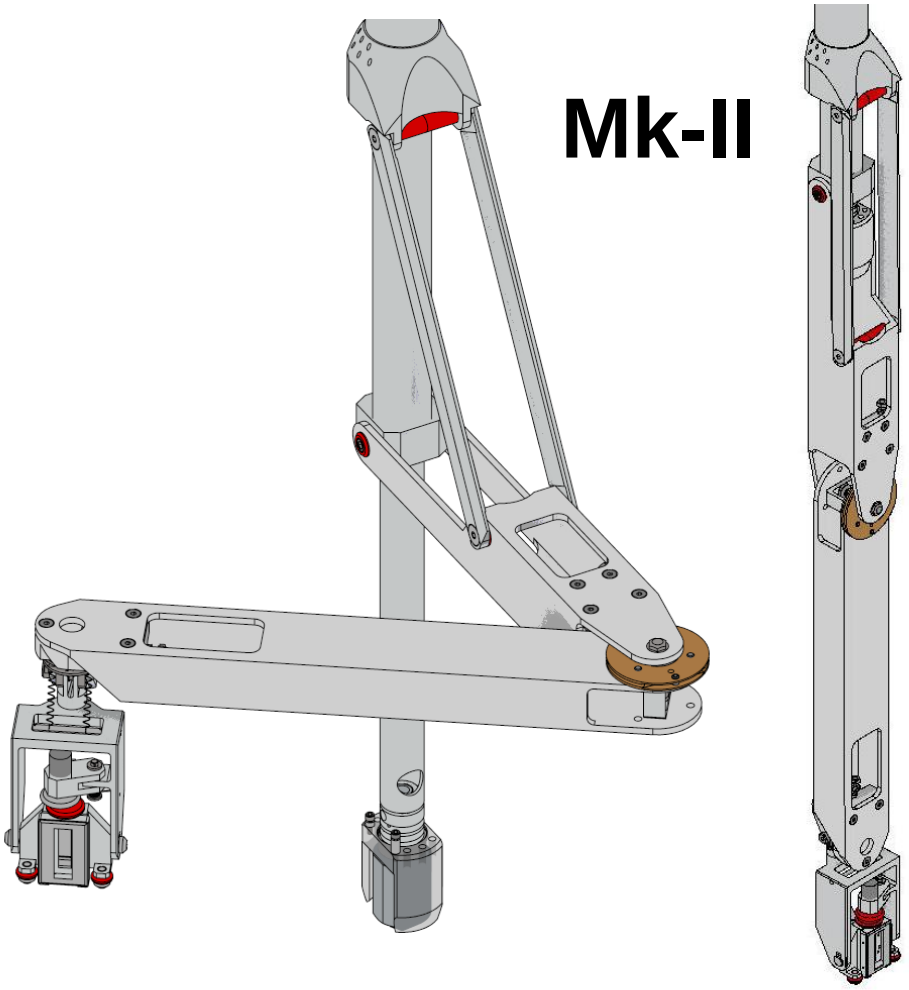
- Remote video inspections
- Ultra-sound examination
- Eddy current probes
- Over two million inspection results
- Four phases

One of largest single NDE inspection campaigns ever carried out in the nuclear industry.

Inspection Tools

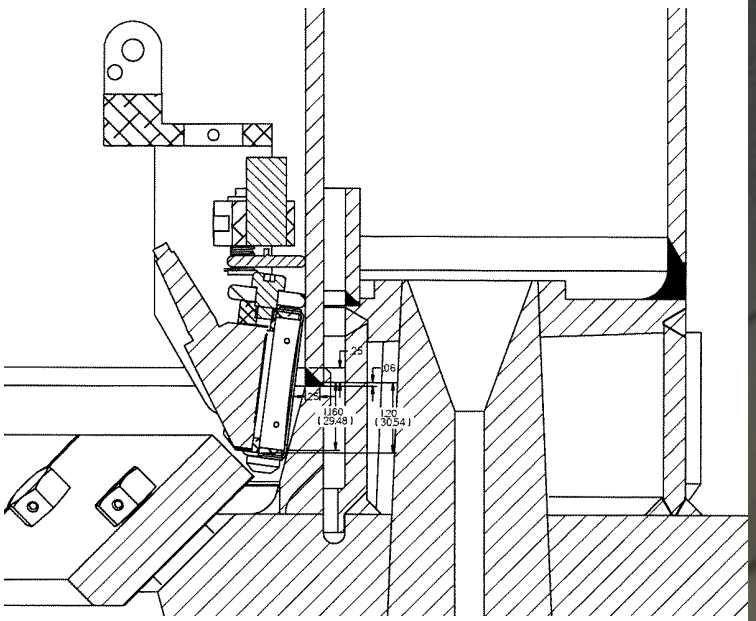
Mk-I

Mk-II

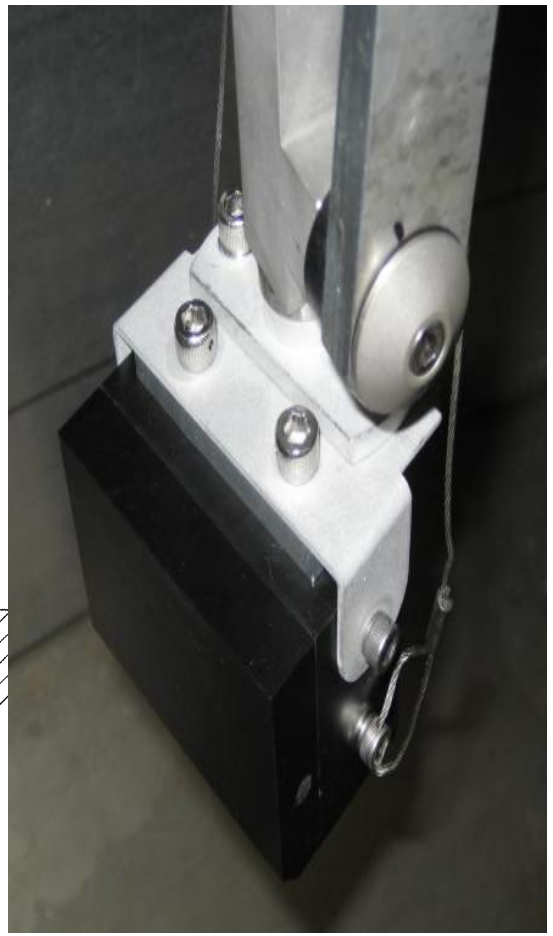


Phases I & II – Inspection Probes

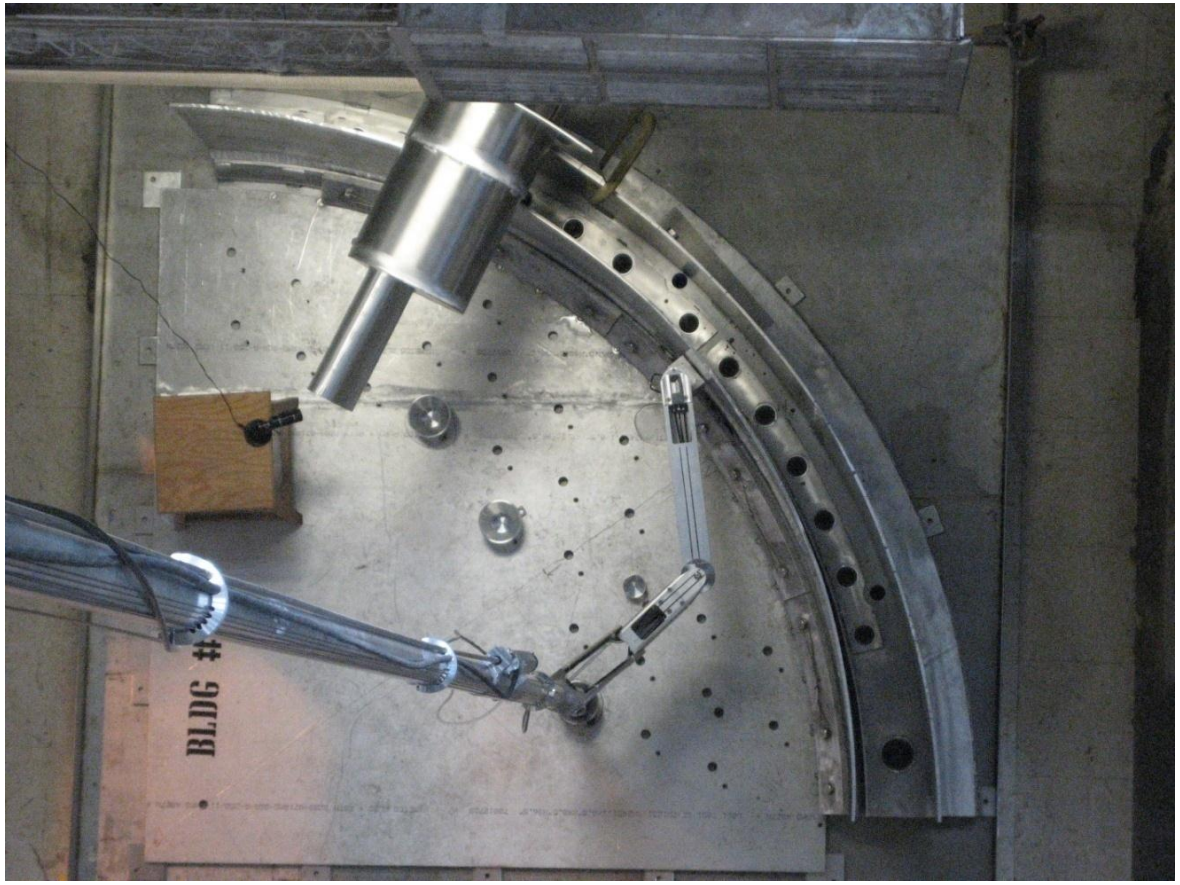
Phased Array UT



Hi-Resolution ET



Mk II Inspection Tool in Mock-Up



8 full-height mockups utilized through outage

Inspection Teams

Mk I deployment

Mk II deployment

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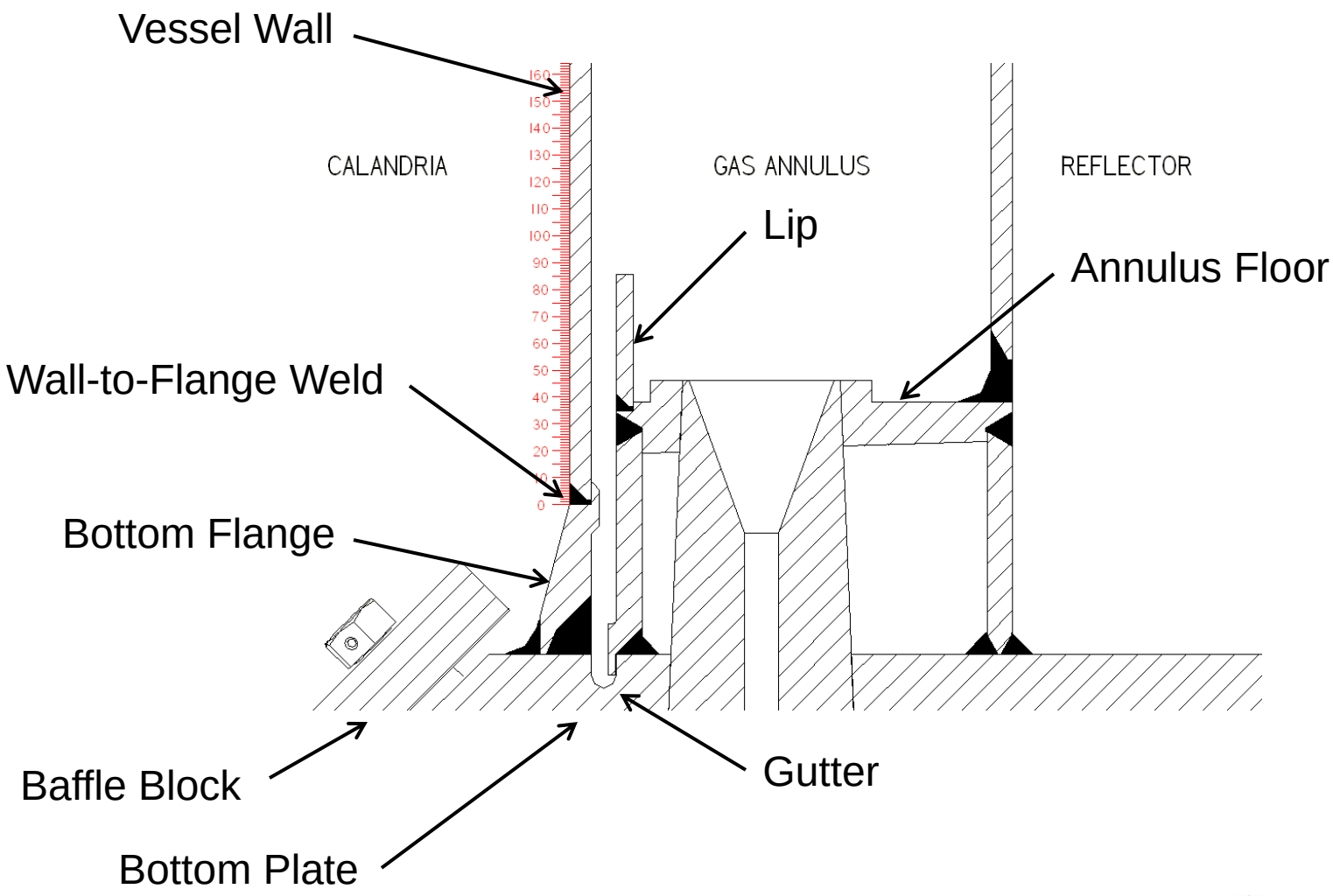
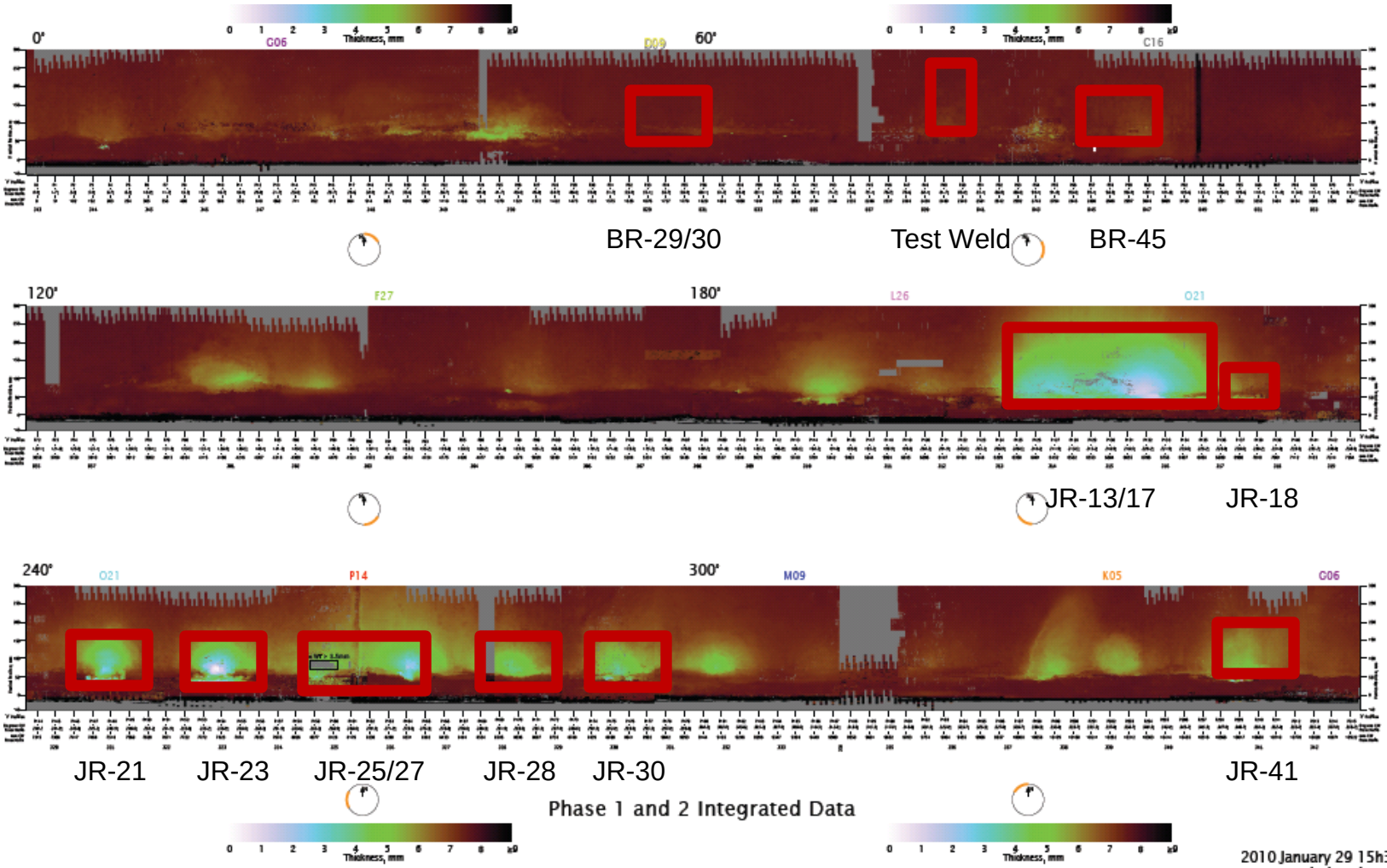
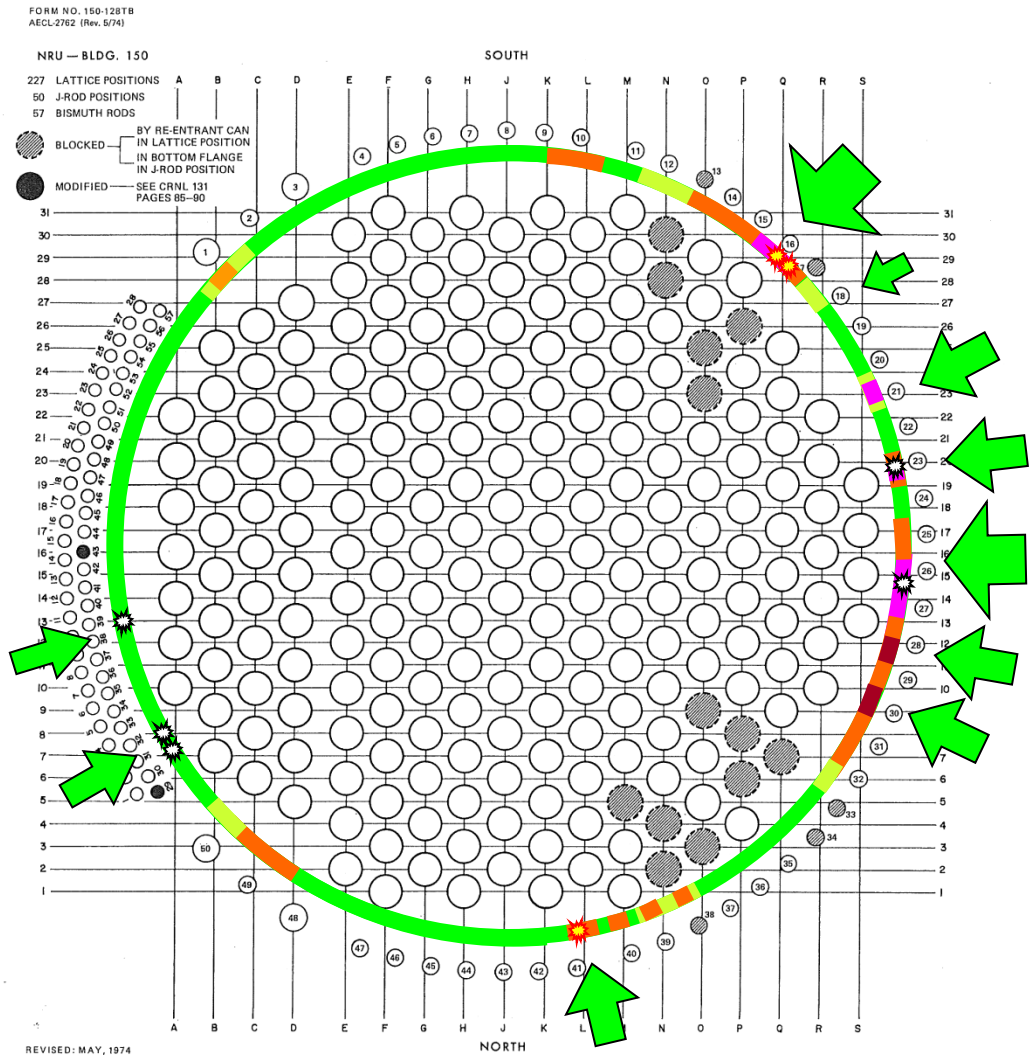
NRU Annulus Cross-Section



Map of Vessel Wall Thickness



Locations to Repair



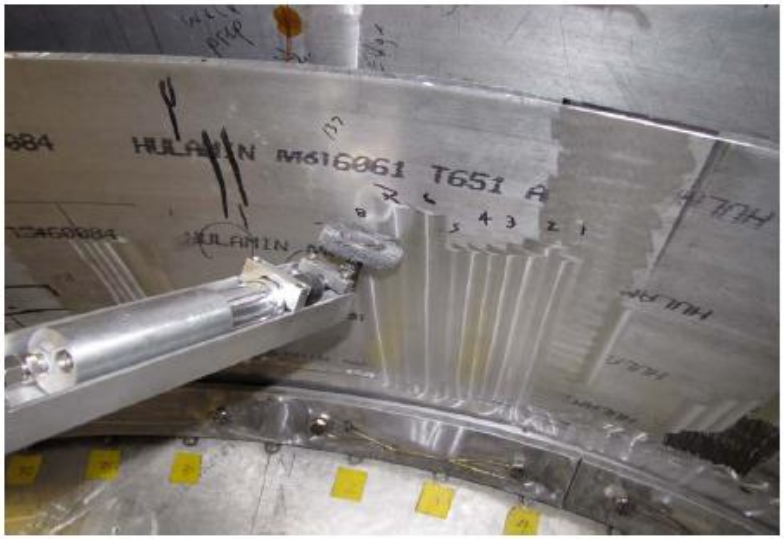
10 Repair Areas

1. BR-45
2. BR-29/30
3. JR-30
4. JR-28
5. JR-21
6. JR-41
7. JR-18
8. JR-23
9. JR-25/27
10. JR-13/17

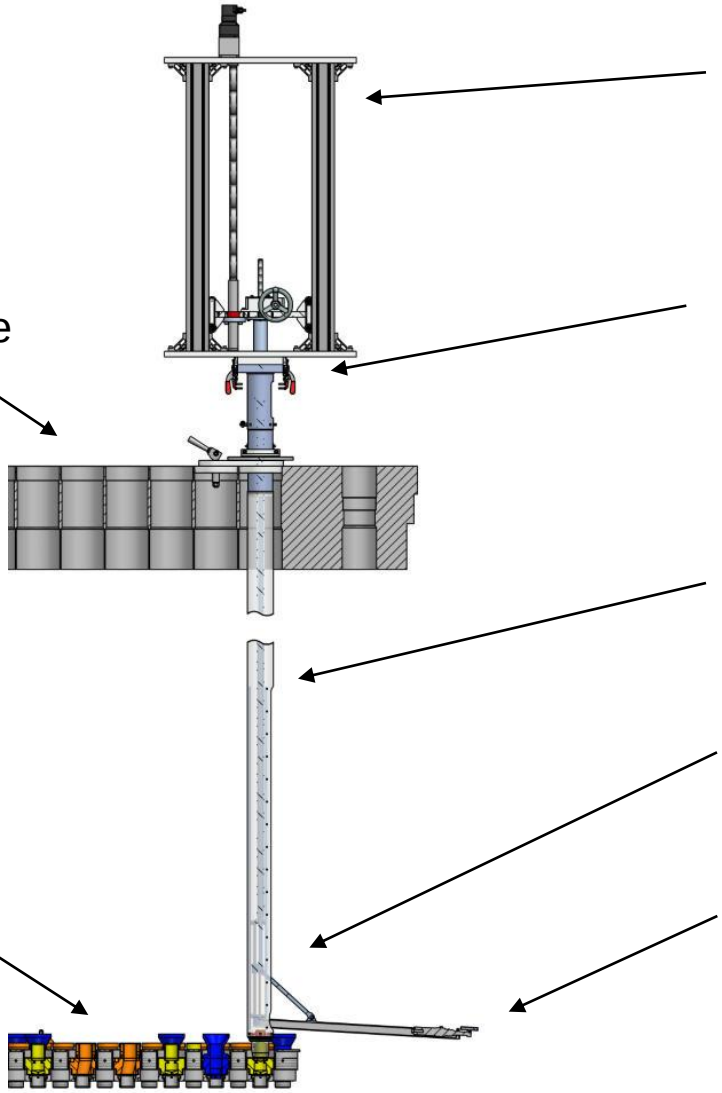
Tooling to Clean Vessel Wall

Cleaning of the vessel wall:

- Critical step in welding process
- Removal of gibbsite layer from vessel
- Articulating vacuum to recover debris



Mechanical Cleaning Tool



Actuation/ Control Dive

Quick Disconnect

Deck Plate

Delivery Tool Body

Deployment Mechanism

Cups

Tool Head

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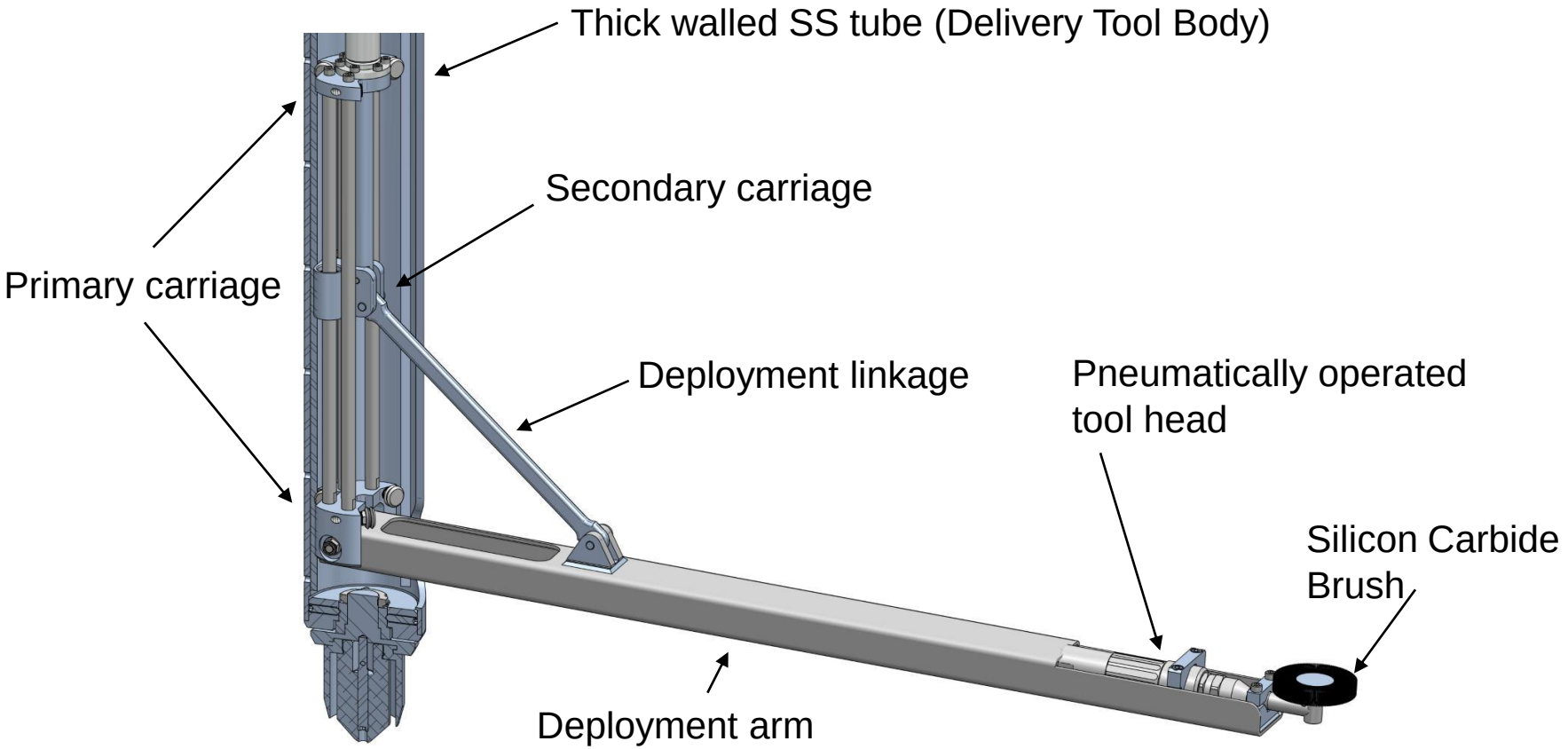
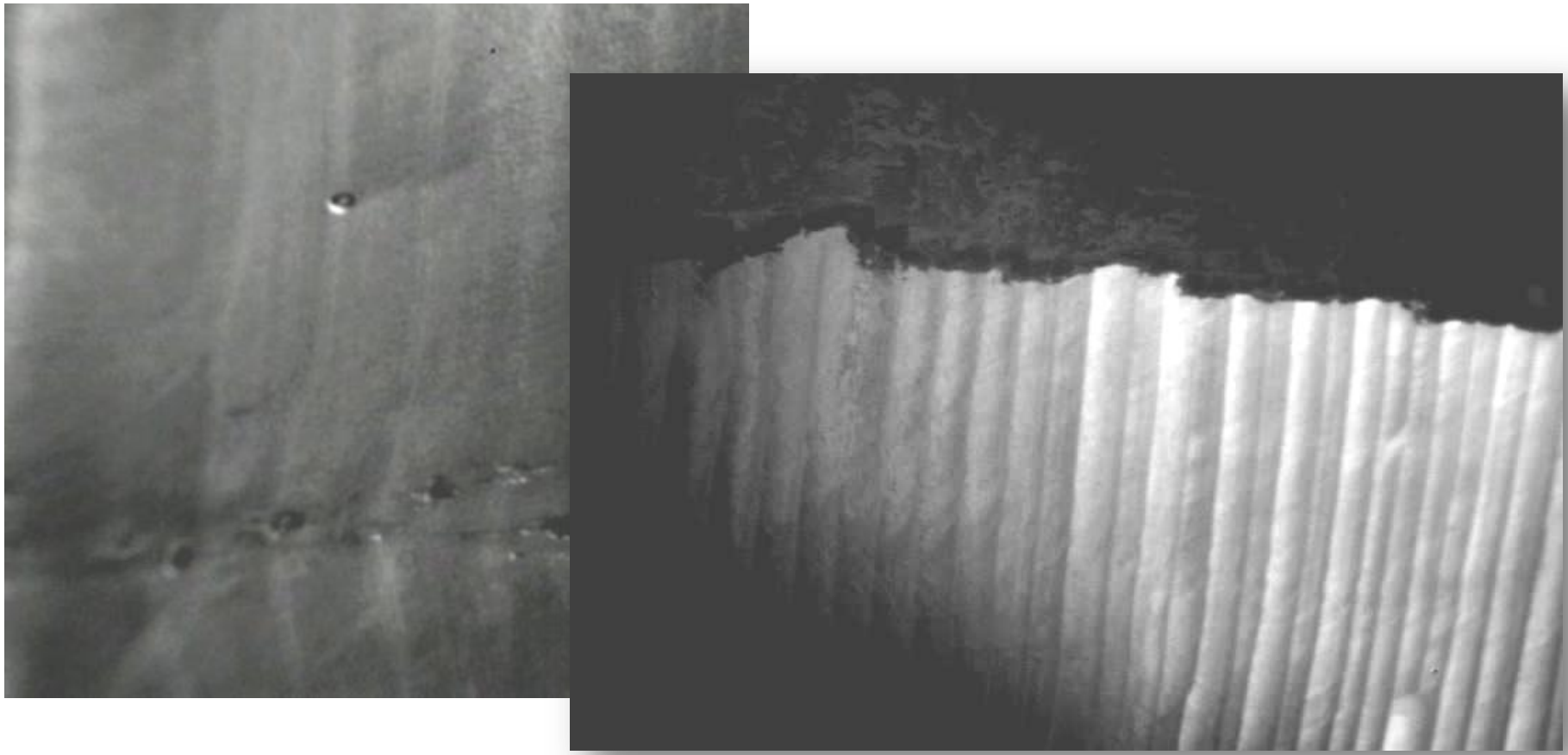
Cleaning Tool Deployment Arm



- Arm has 965 mm horizontal reach

JR-41 Leak Site After Cleaning

In-Vessel Cleaning completed for all repairs sites and material sampling locations



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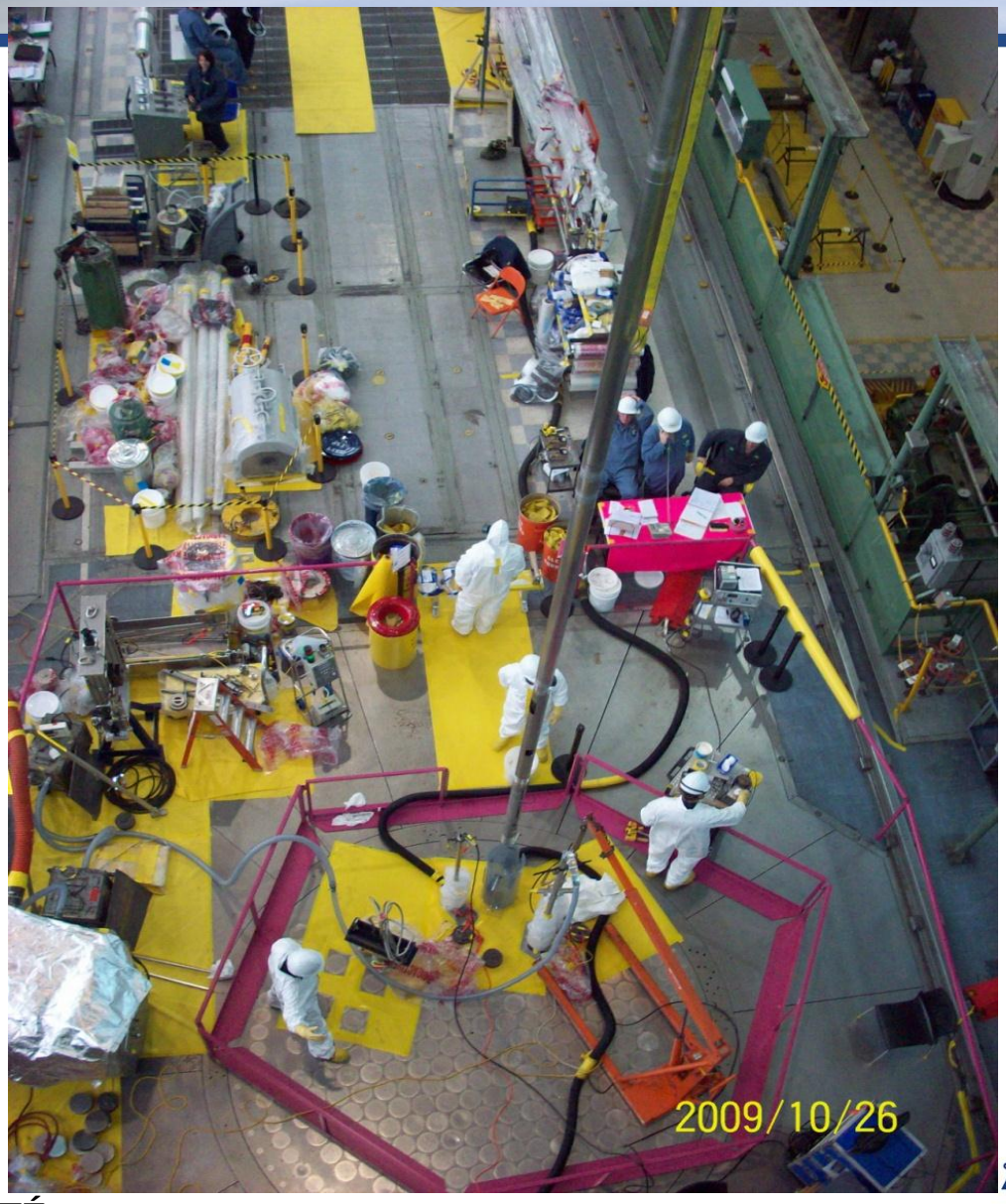
Obtaining Samples of the Vessel Wall



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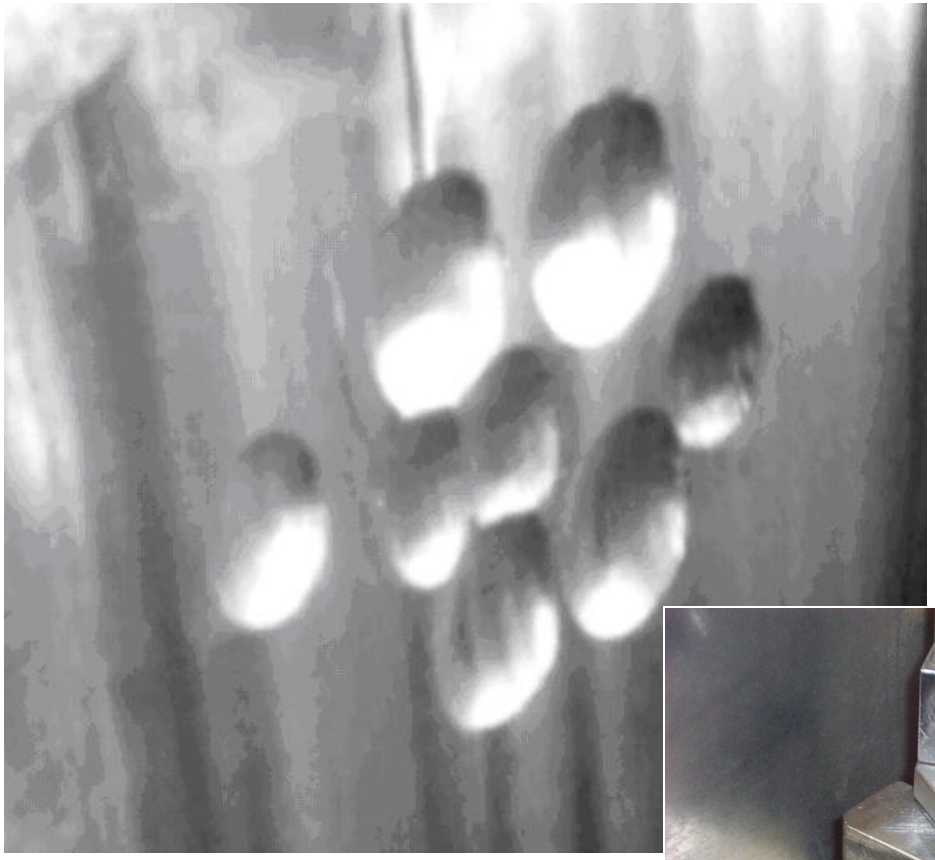
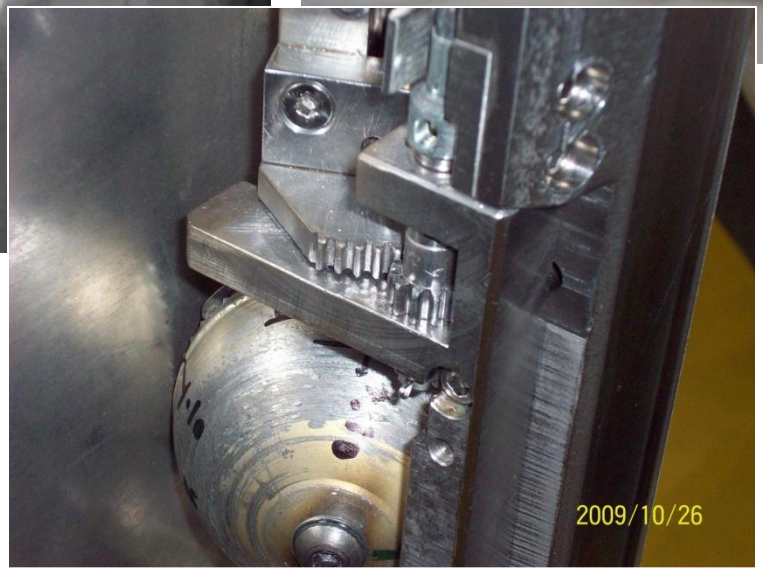
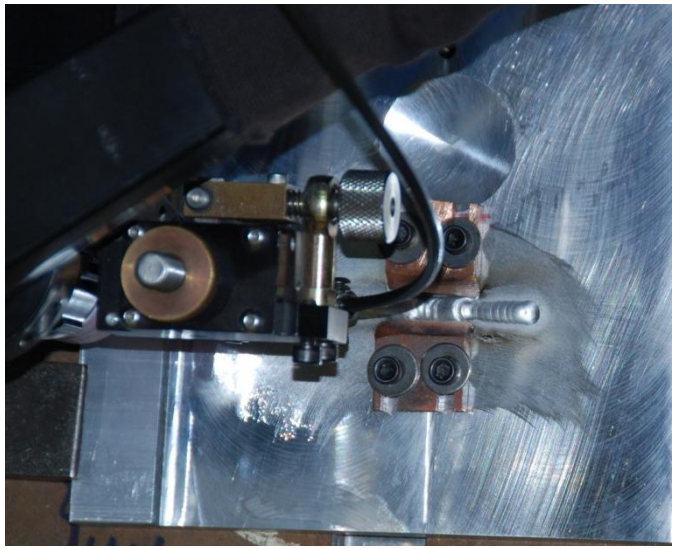
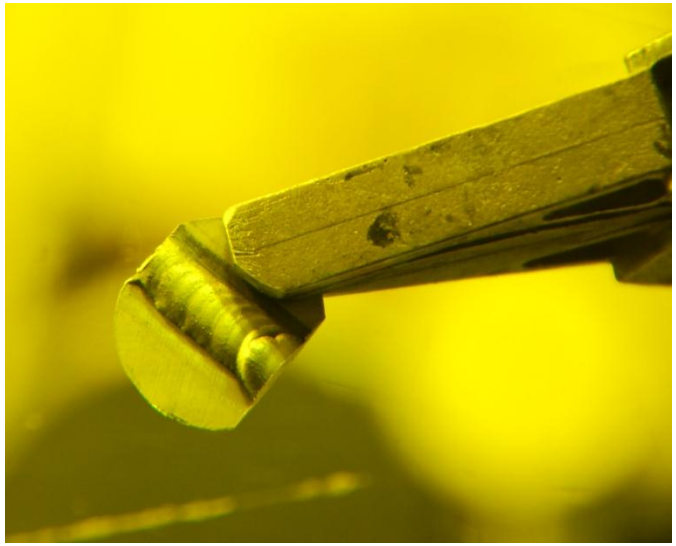
Scoop Samples

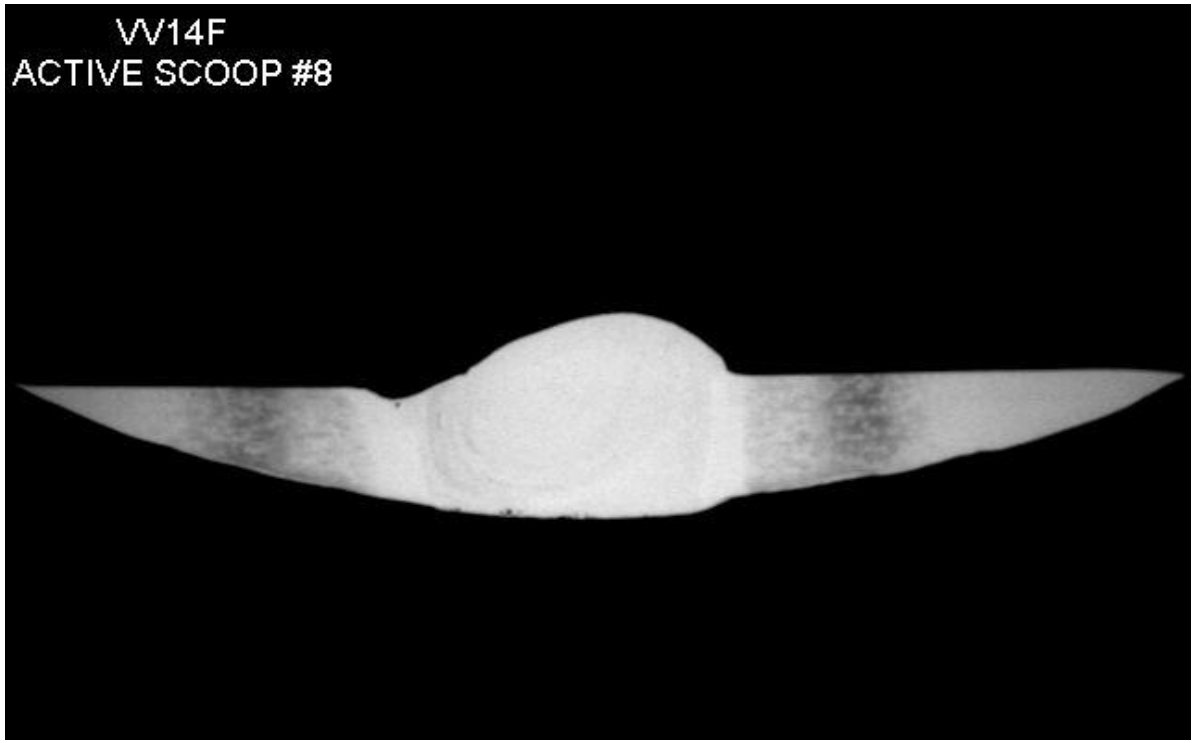




Welding on Irradiated Material





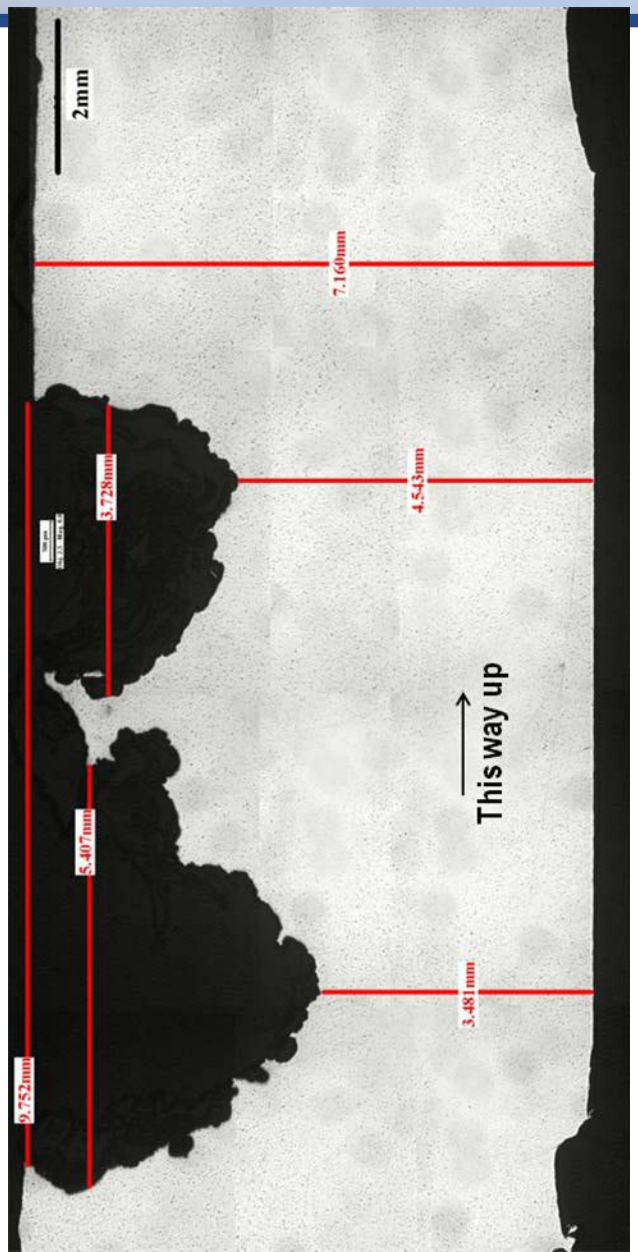


Coupon Cutting at Leak Site

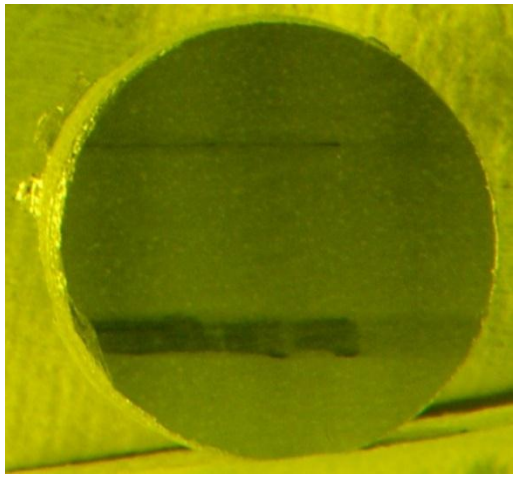
Corrosion Coupon

Coupon Removed from Vessel Wall

- J-rod Side



Heavy Water side

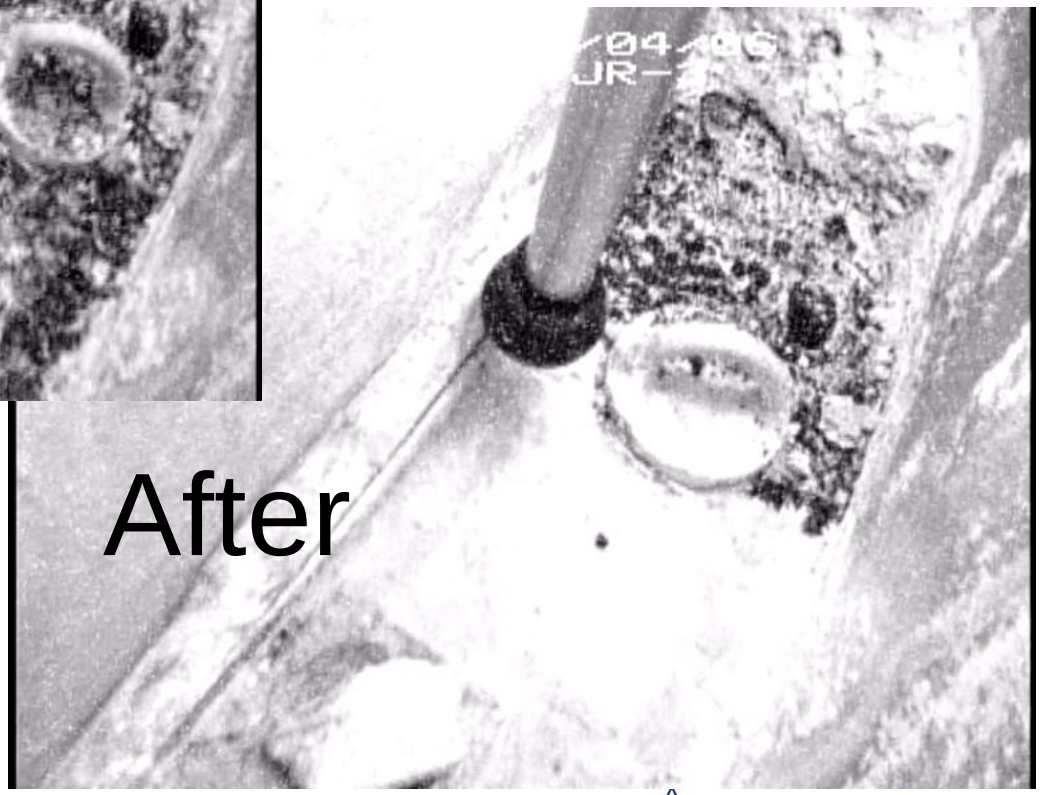


Corrosion Mechanism

- J-rod annulus designed to be filled with carbon dioxide gas and kept dry
- However:
  - Aging of CO_2 system reduced gas flow
  - Light water ingress from reflector leaks into J-rod annulus
  - Air ingress from openings in J-rod annulus
  - High radiation environment
- Created the conditions for radiolytic production of nitric acid
- General wastage corrosion in wetted regions, and localized corrosion at air/water interface

Cleaning the Annulus

Articulating J-Rod
Annulus Vacuum Tool
Near JR-3 position



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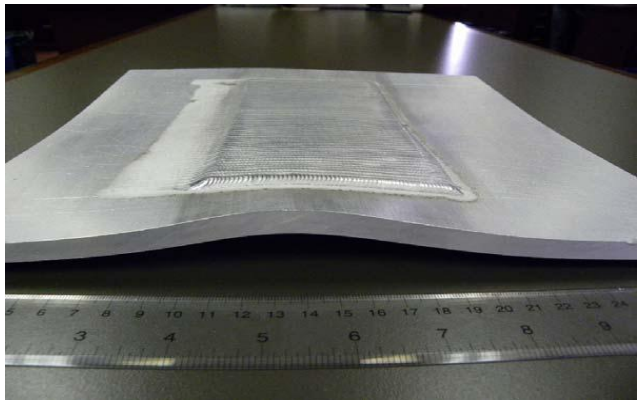
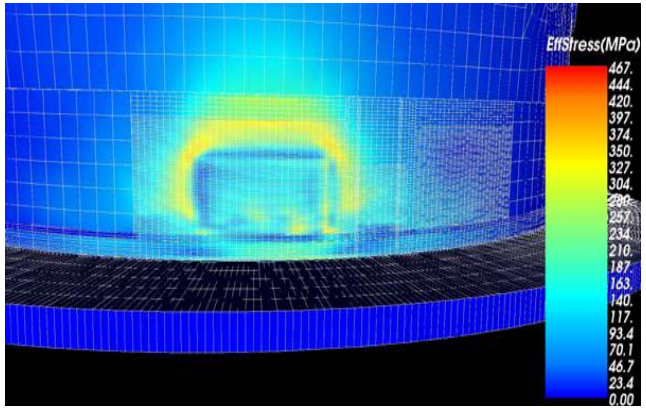
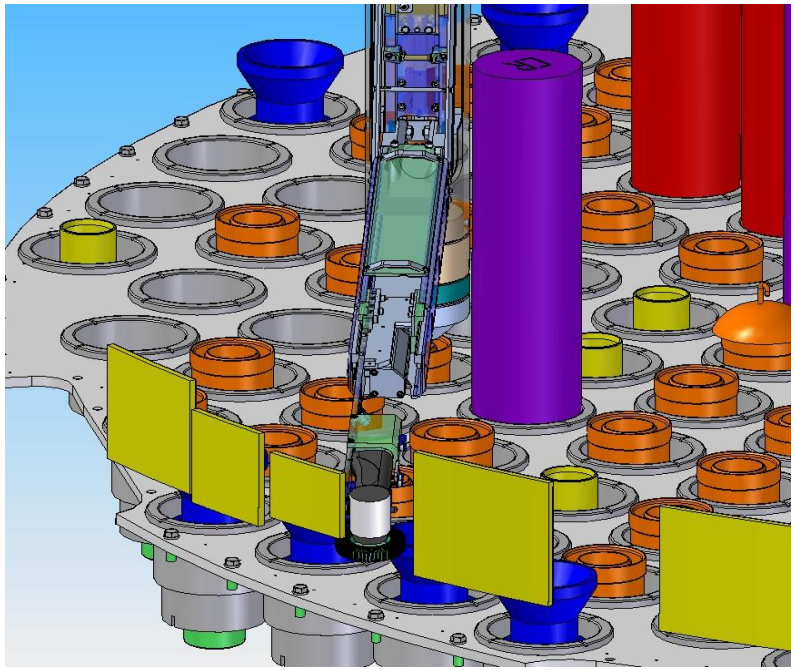
Welding Challenges

1. Geometry: 9 m remote through 12 cm diameter openings, reaching around obstructions in vessel
2. Vessel distortion from heat
3. High radiation fields on tooling







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Liburdi Welding & Support Tool Set

1. Horizontal weld tool
2. Vertical Weld Tool
3. Horizontal Cleaning & Repair Tool
4. Vertical Cleaning and Repair Tool
5. Patch Deployment Tool

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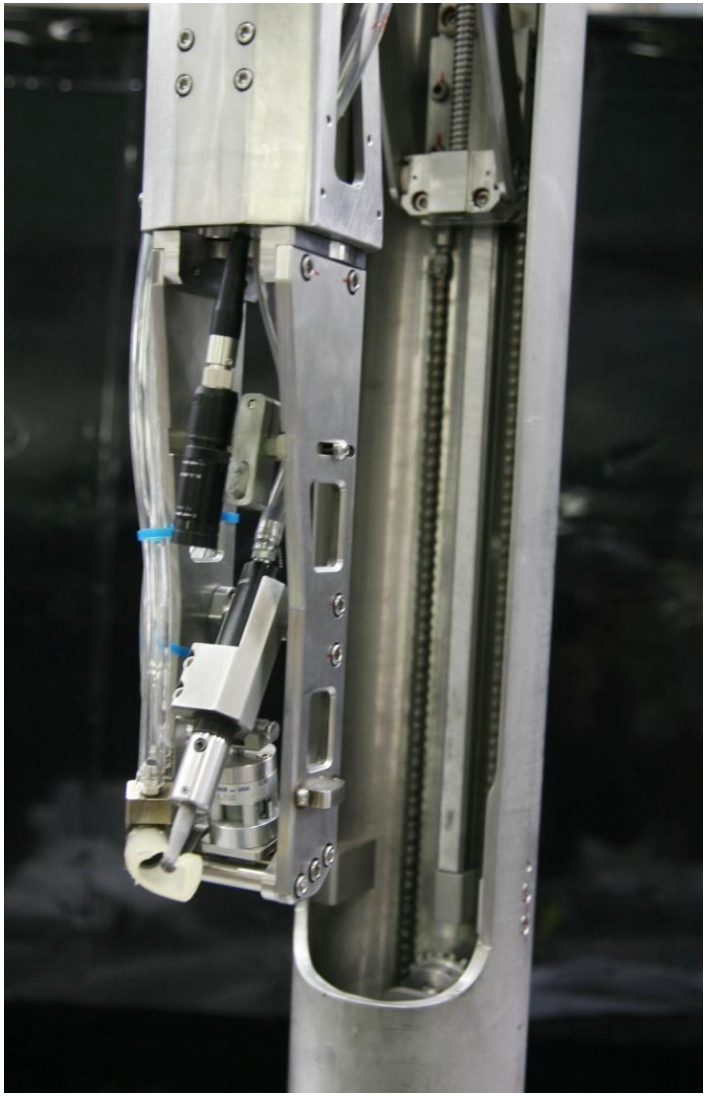
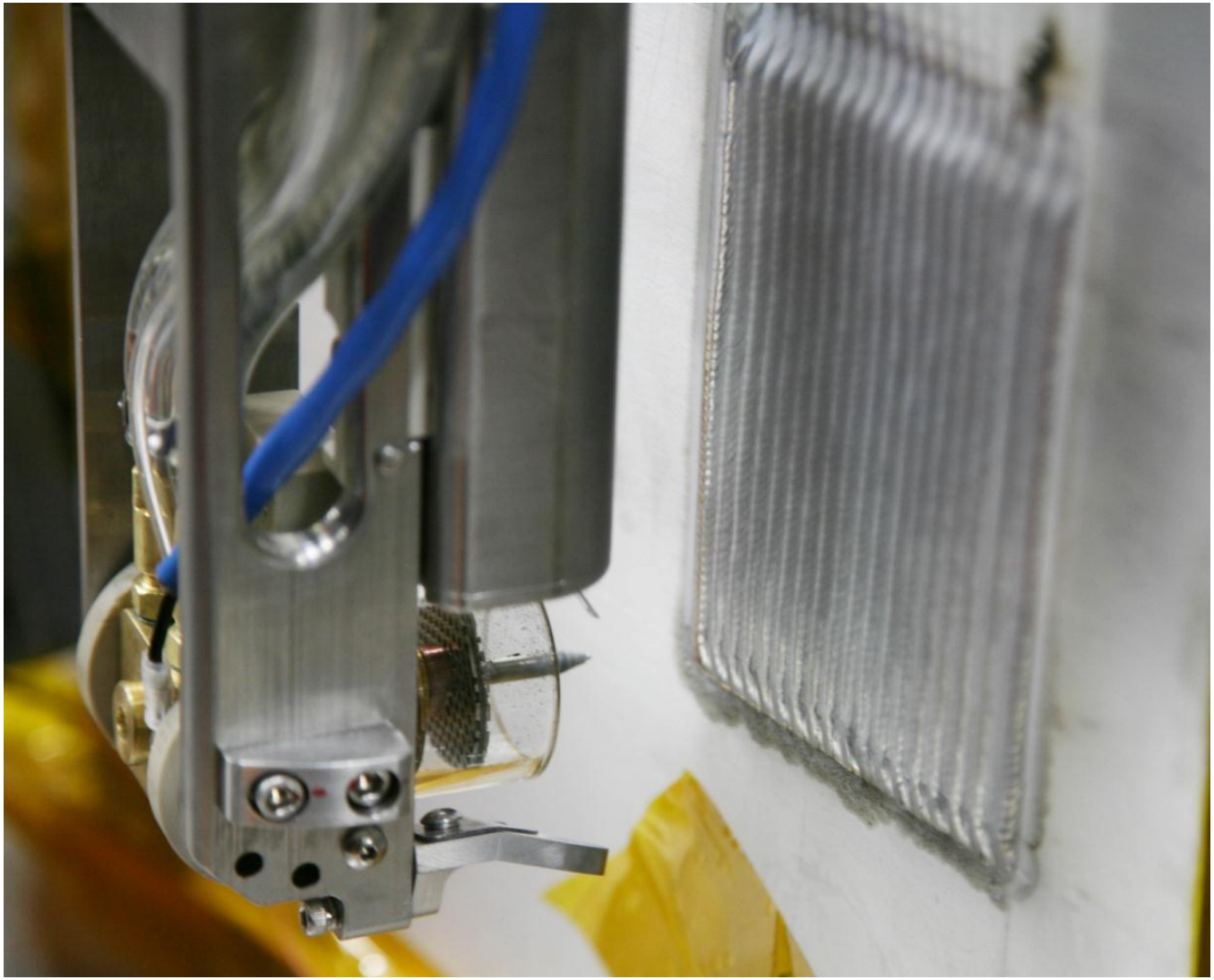
Liburdi Weld Delivery System

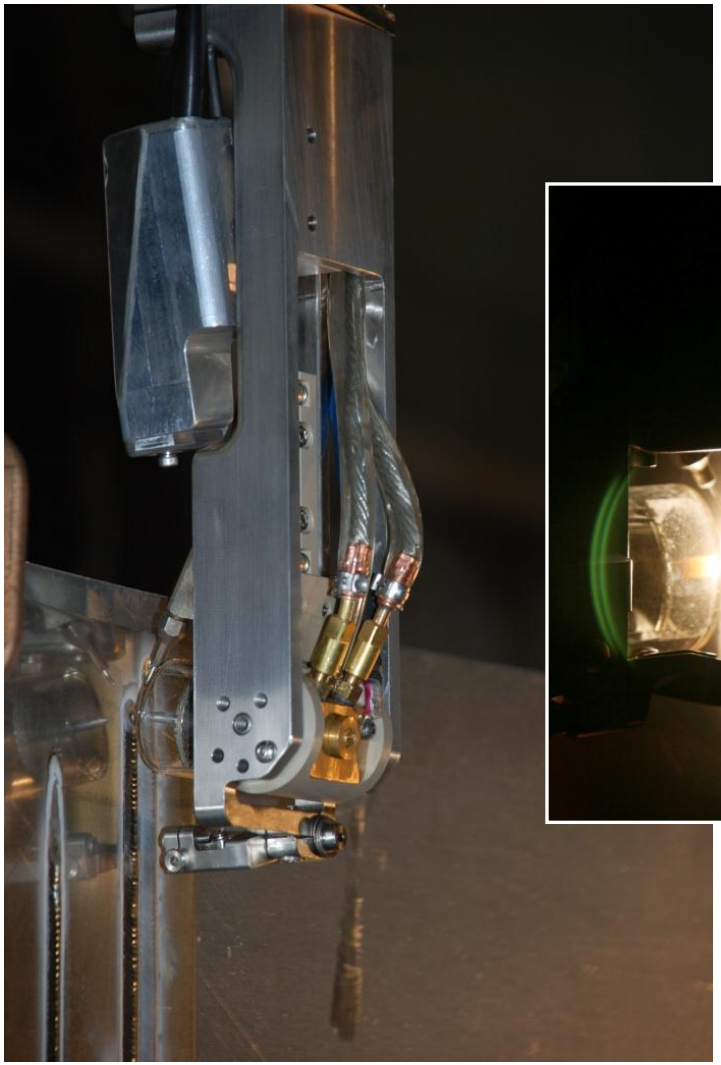


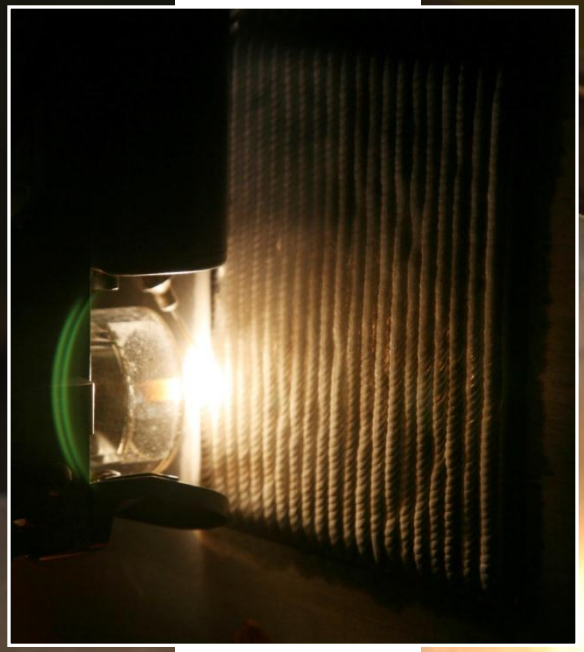
Liburdi Weld Delivery System

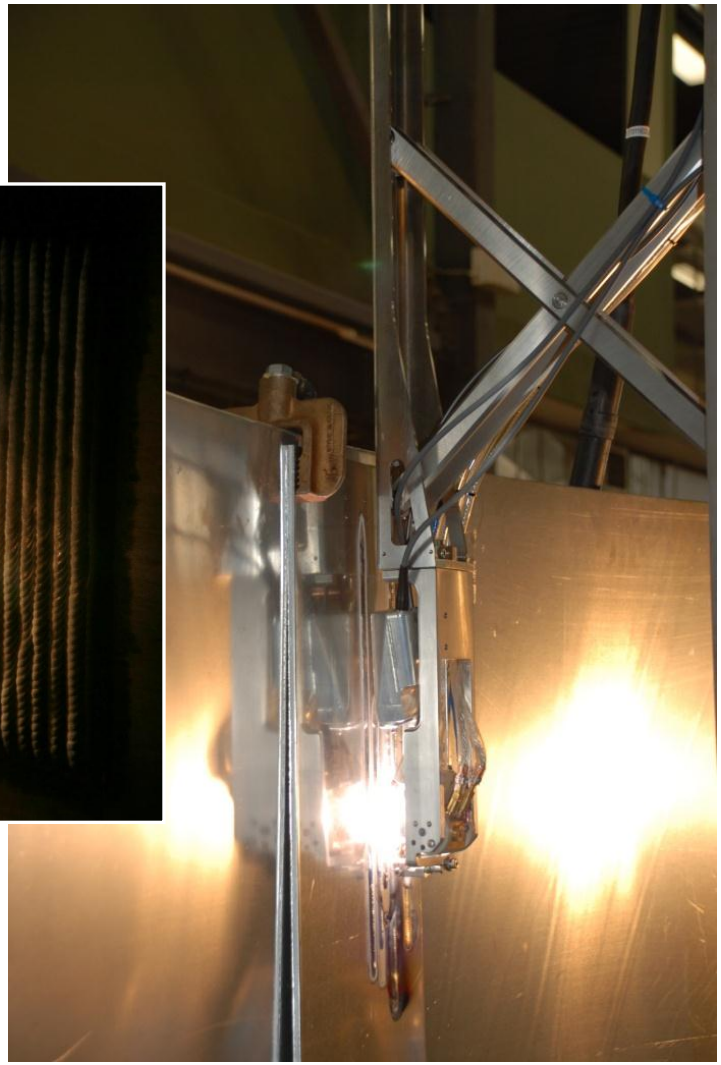


Welding Control Interface

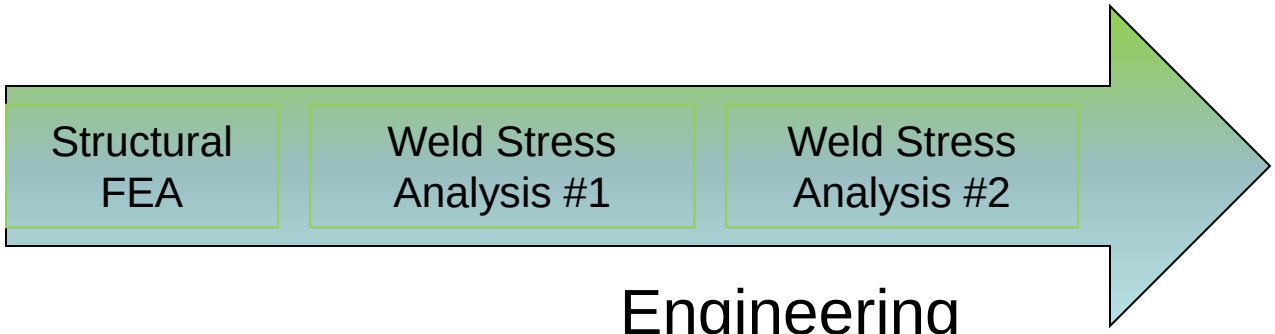
Vertical Welding Tool





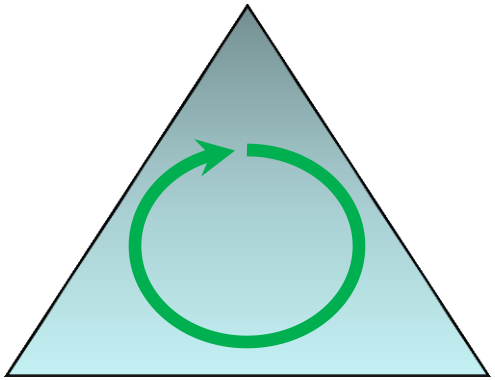


Weld Design Process



Weld Map

Engineering



NDE

Weld Development

Crack Examination Surface/HAZ

Thickness Lack of Fusion

Volumetric Fillets/Groove Welds

Vertical Welds

Horizontal Welds

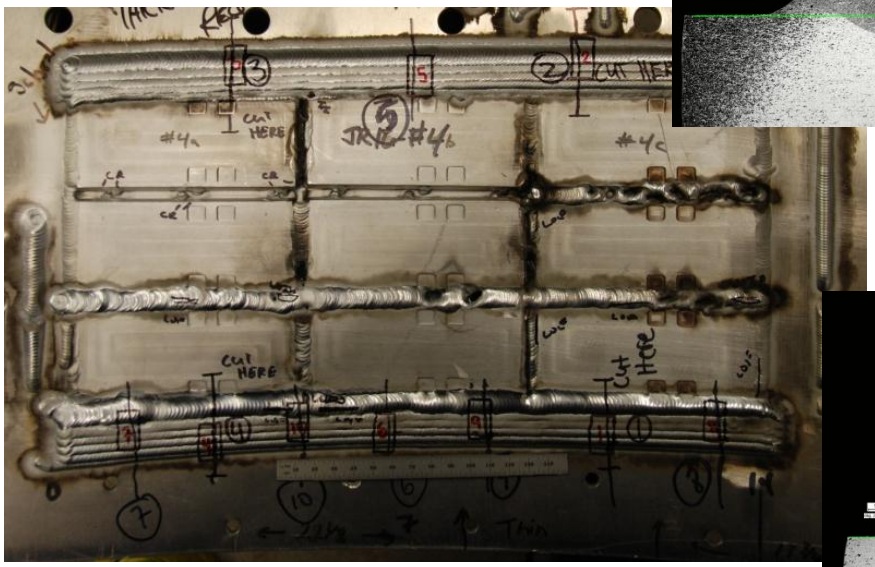
Fillet/Groove Welds

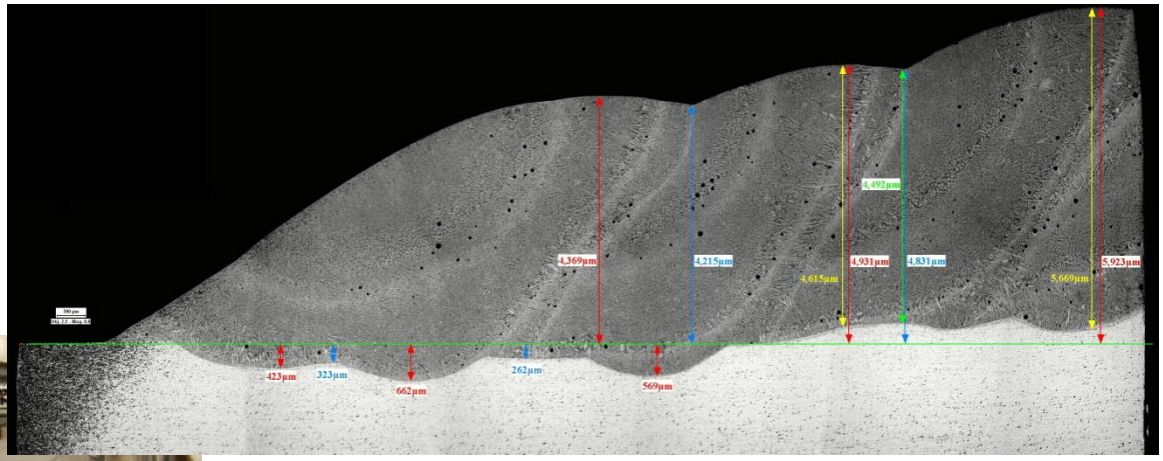
Window Frames

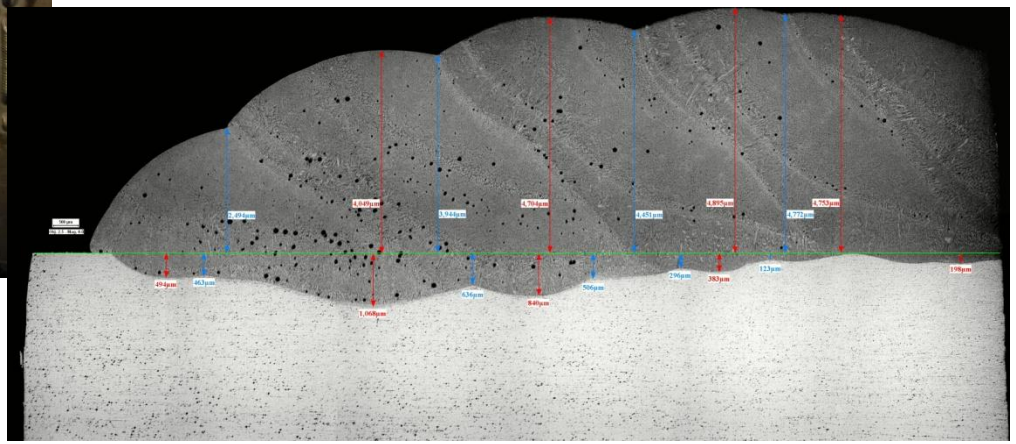
Plates

Qualification of the Welding

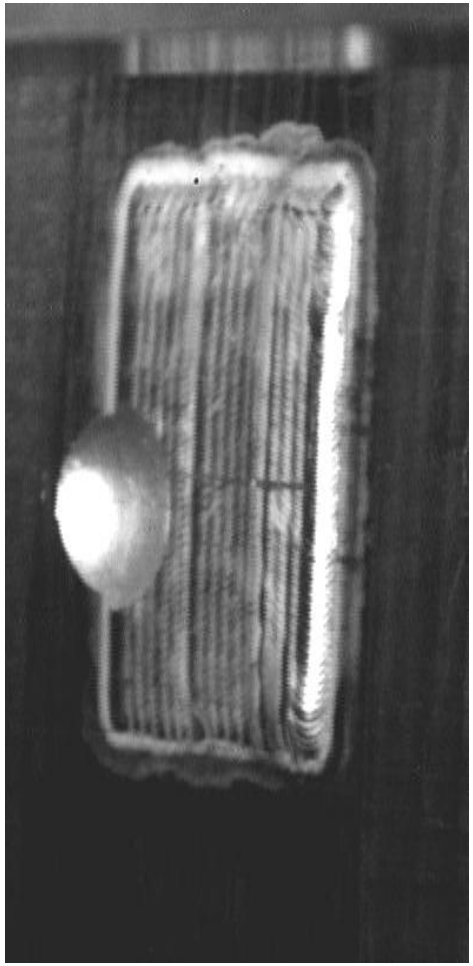
Cross Sections







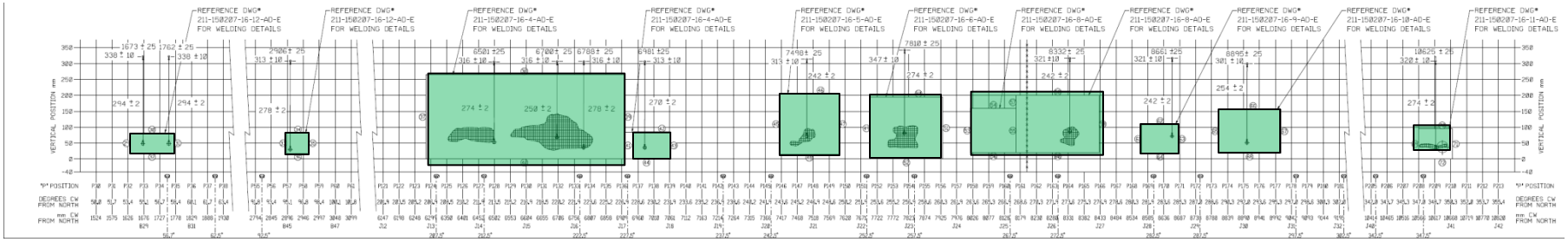
Test Weld (with Scoop)

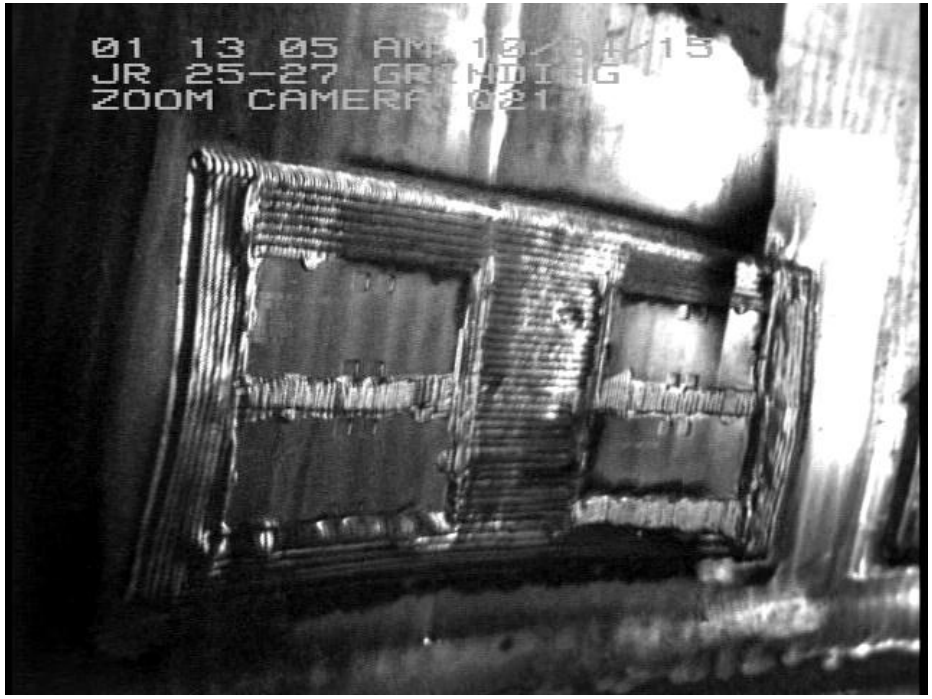


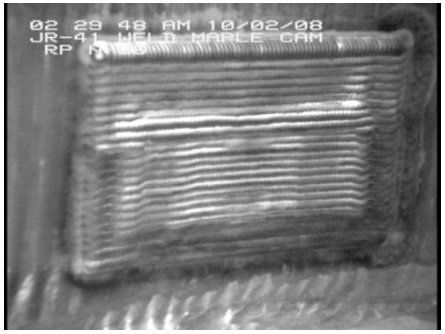
Summary of Repair Areas

Site	Weld Area (cm^2)	Lowest Elevation Weld/Plate (mm)	Min. Wall Thickness (mm)	Welding Operations			
				H/- V Buildup (mm)	Backing Strips/ Structural Plates	Plate Build-up	2nd Layer
BR-45	45.4	18	7	V-3	N	N	N
BR-29/30	90.2	18	7	V-3	N	N	N
JR-30	139.6	25	4	V-3	N	N	N
JR-28	106.2	65	4	V-3	N	N	N
JR-21	347.7	15	3	H-3	N	N	N
JR-41	153.9	0/15	4	H-3	1-BS	Y	N
JR-18	83.2	25	4	H-3	0	N	N
JR-23	433.6	2/35	1-2	H&V-2.5	2-BS	3 mm	Y
JR-25/27	619.1	37/60	0-1	H&V-3.0	4-SP	N	N
JR-13/17	1250.6	5/25	0-1	H&V-4.0 H 3.0	9-SP	N	N

Weld Repair







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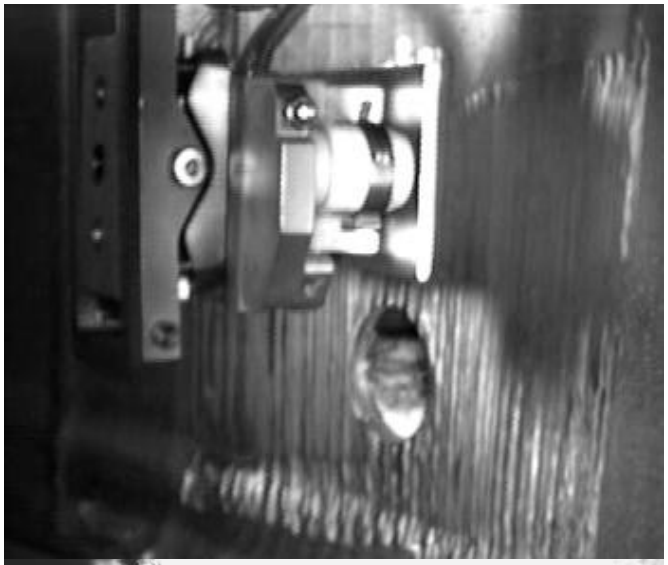
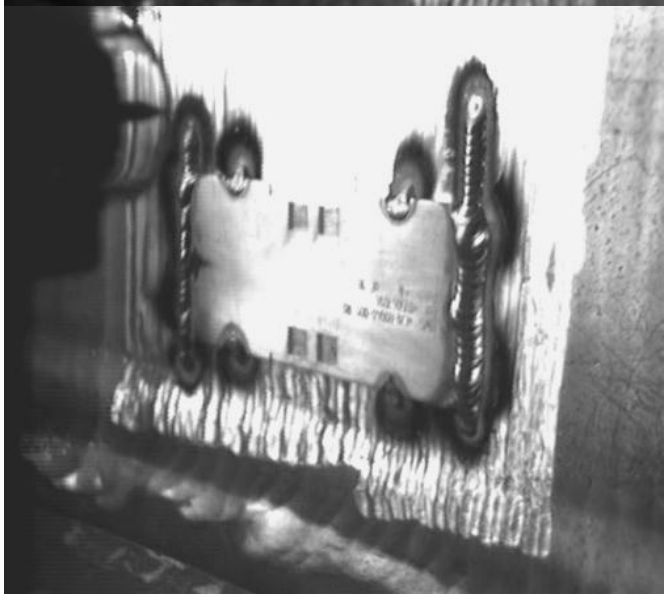
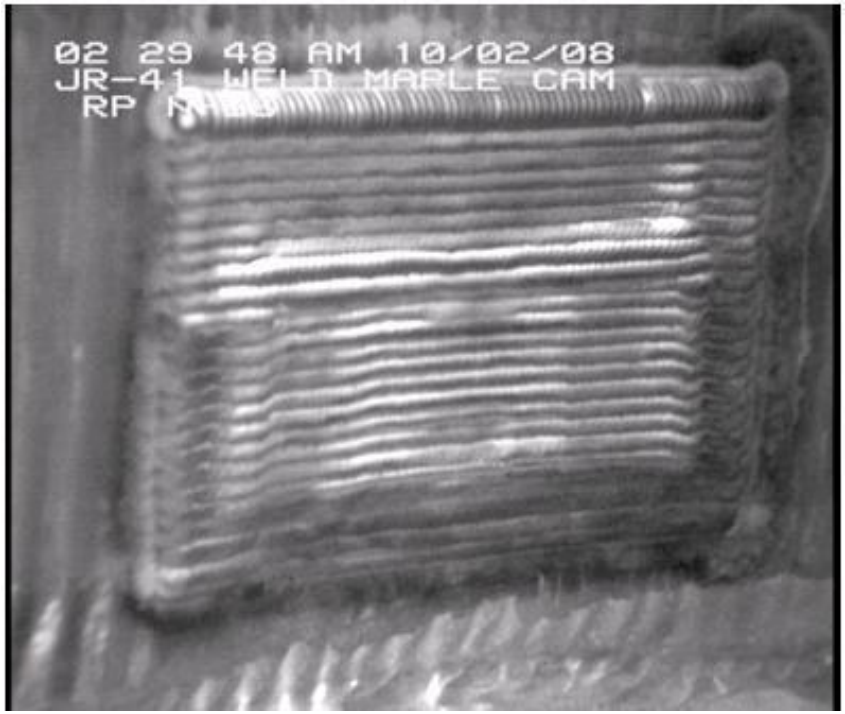
Repair at JR-41 – The Leak Site



Backing strip placement



Backing strip welding

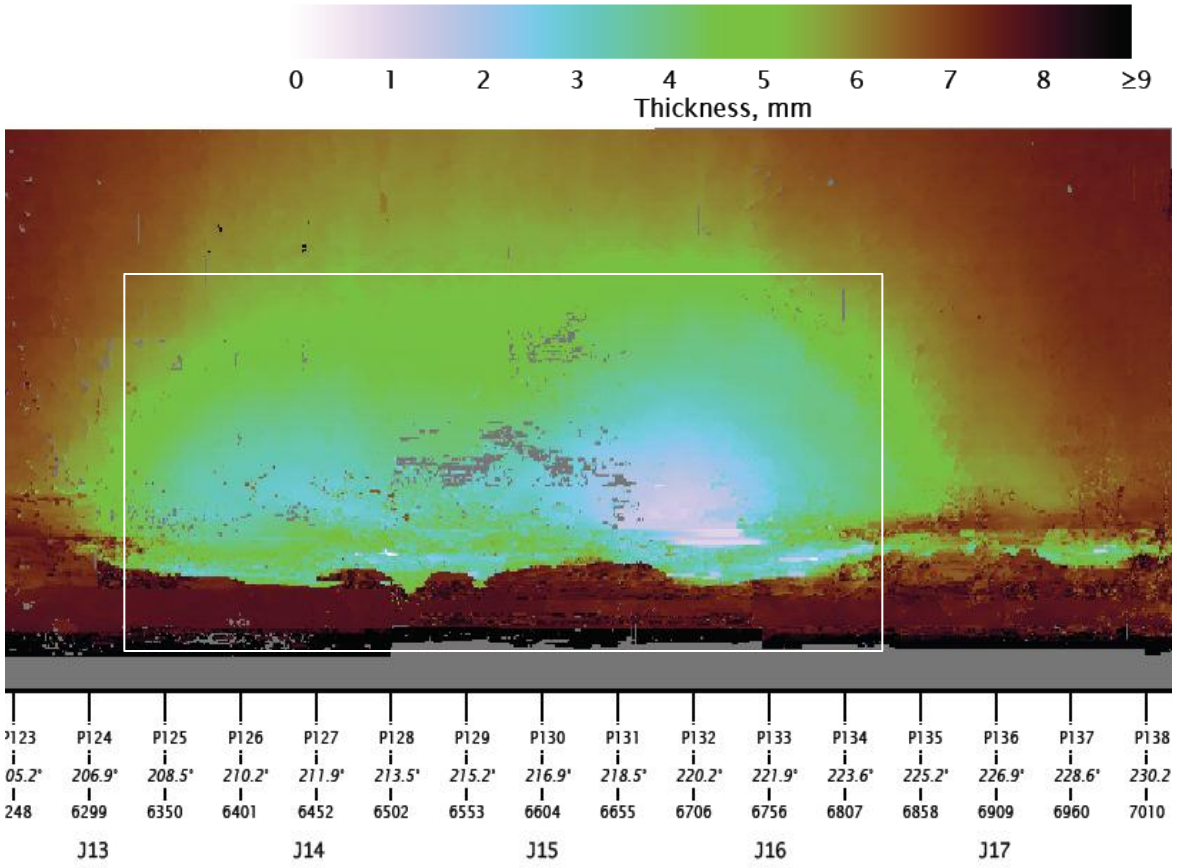


Final Weld Overlay

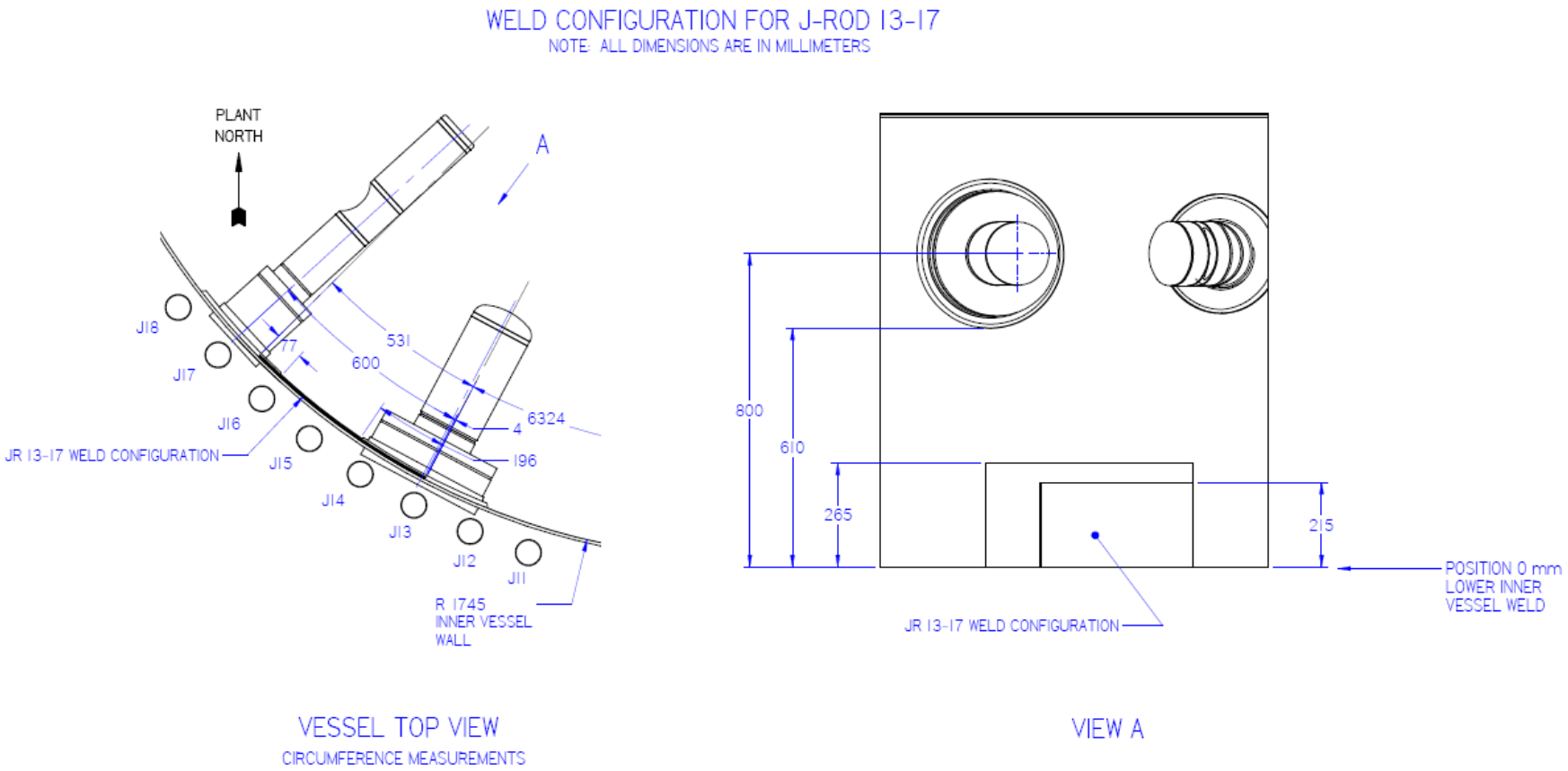
Final Repair – JR-13/17

Challenges:

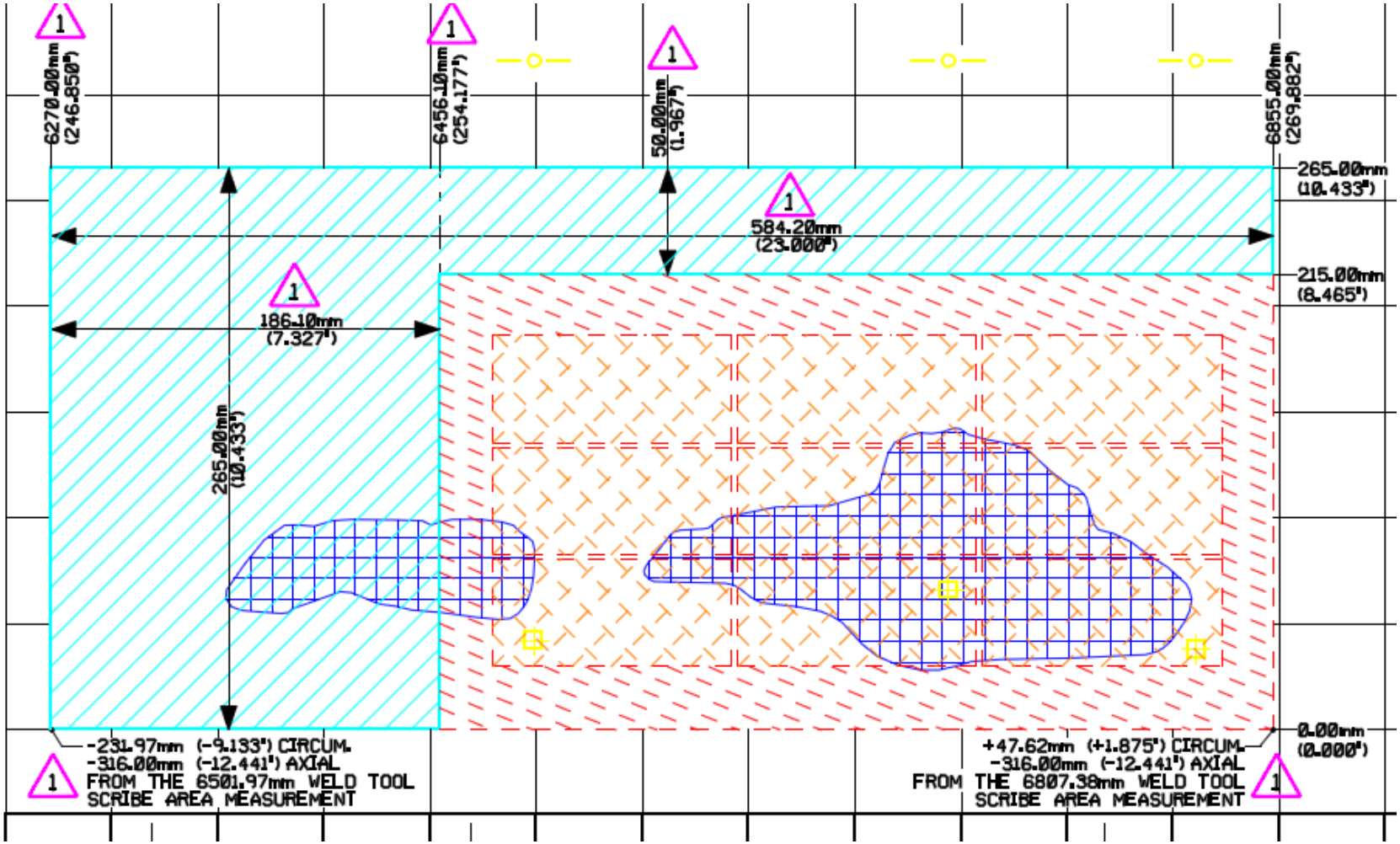
- Two through wall penetrations
- Thinning to less than 1mm
- Located below and between two re-entrant cans
- Large area: W x H
  - 59 cm x 26 cm
  - 10.4” x 23”



Challenges - Final Repair



Challenges - Final Repair



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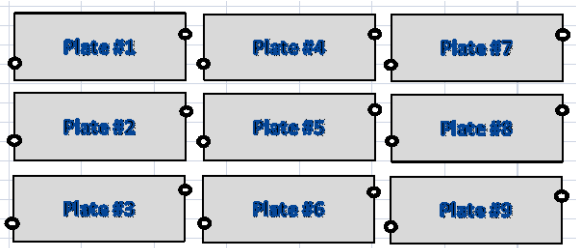
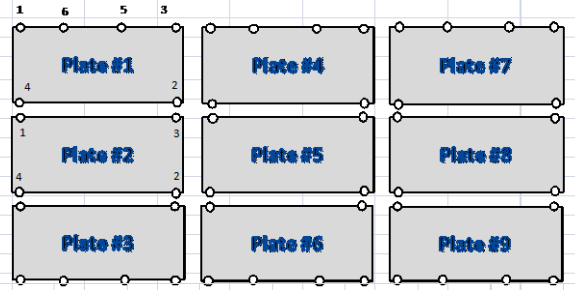
Weld Process Map – JR-13/17

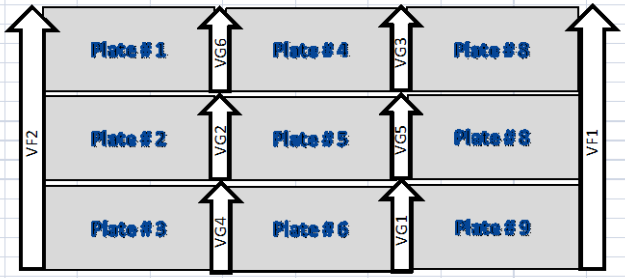
Patching



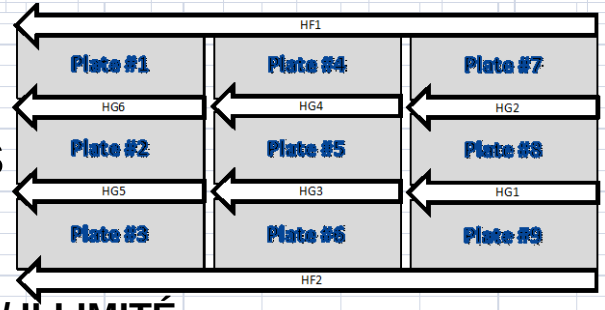
Tacking

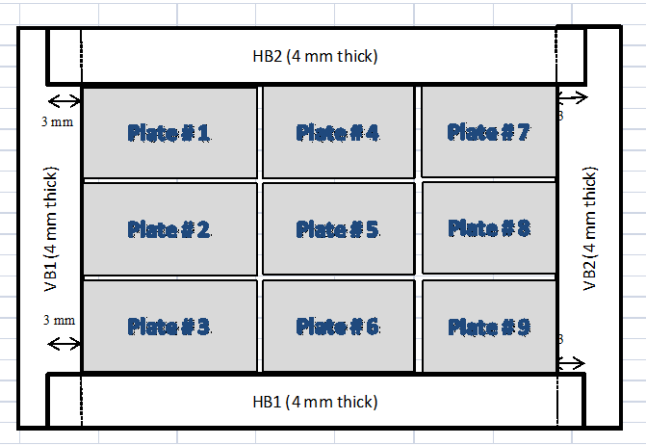


Verticals

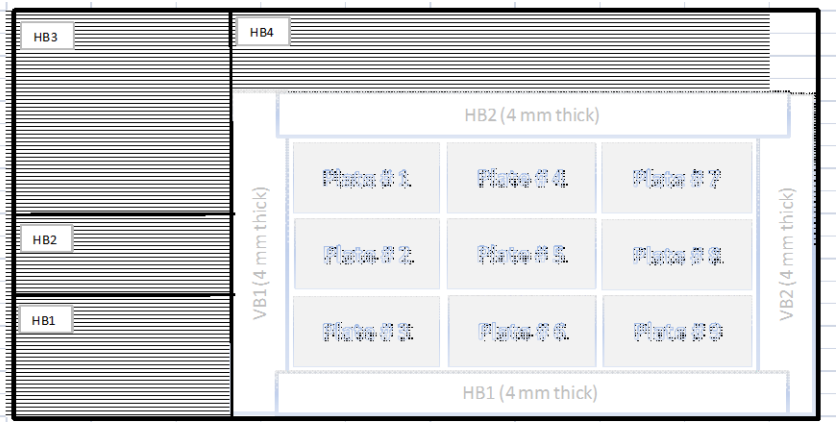


Horizontals





4mm Overlay



3mm Overlay

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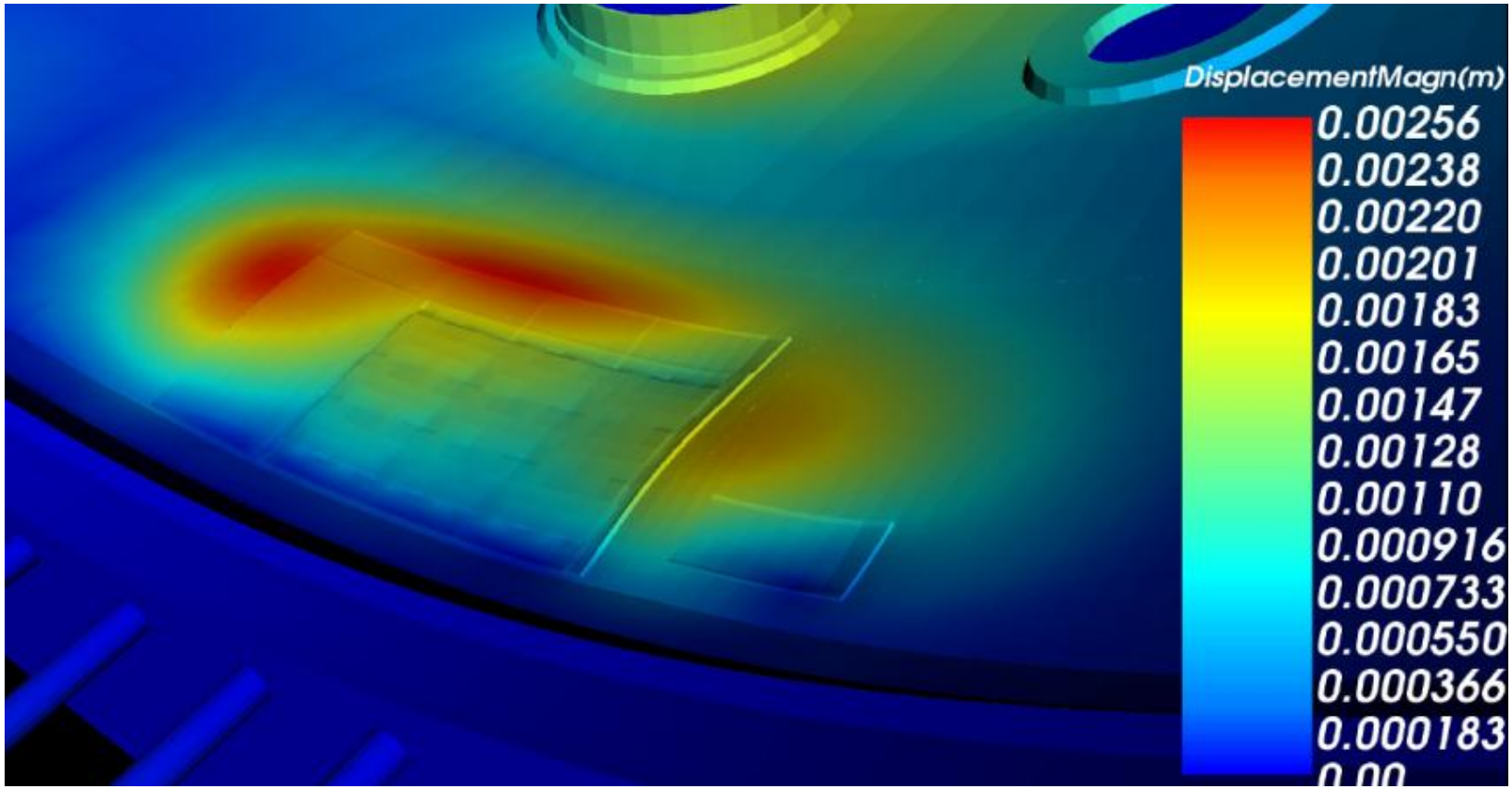
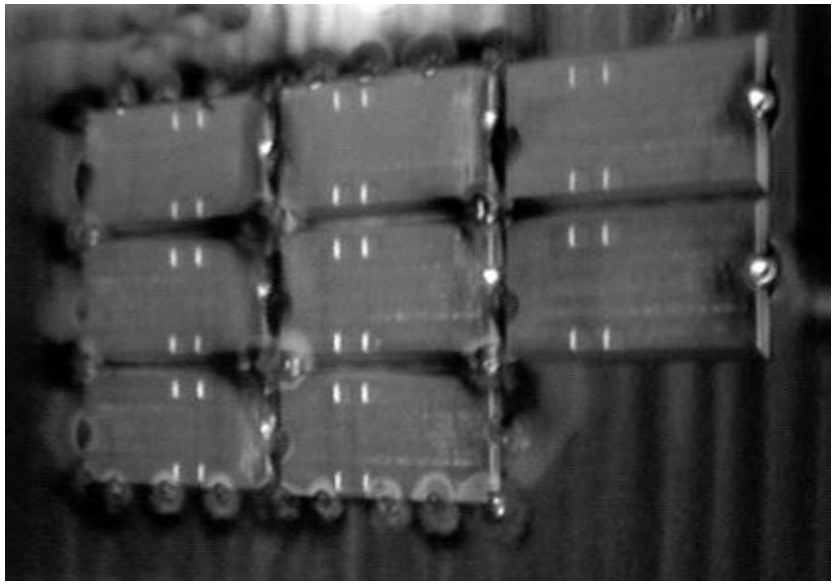
Weld Stress Analysis

Prediction of loading on vessel seal, and displacement of vessel wall, in response to weld stresses

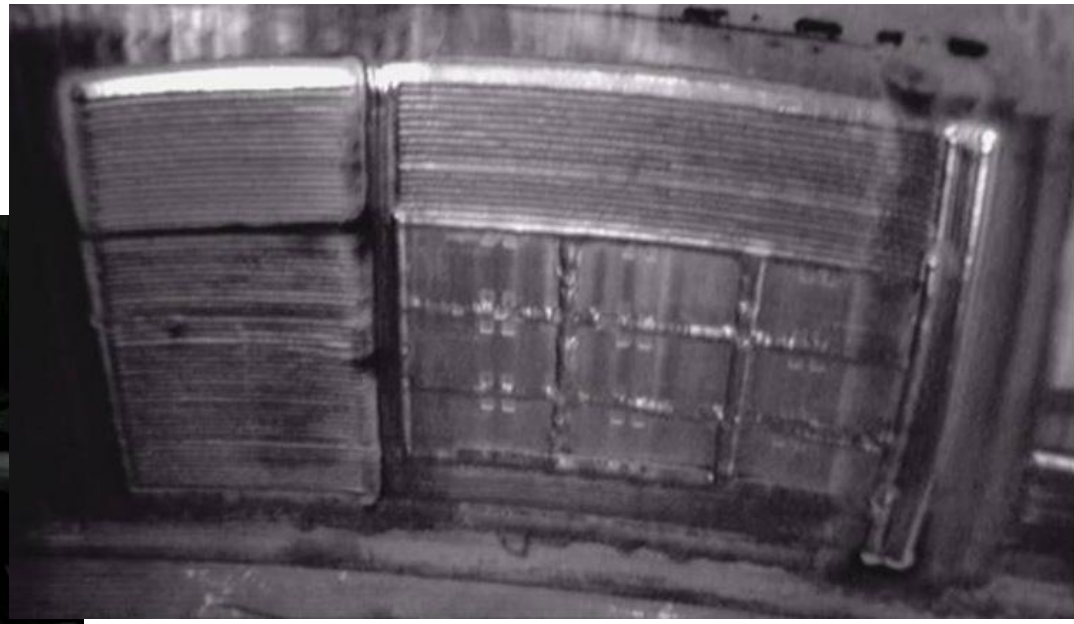


Repair at JR-13/17



Multiple challenges encountered:

- **Plate attachment**
- **Design change**
- **Crack repair and re-inspection**



Other Parallel Outage Work

- System Refurbishment Program
  - –Heavy Water System major maintenance & inspections
  - –Process Water maintenance & inspections
  - –Moderator change (66 Mg heavy water)
    - – 26 Ci/L replaced with ~ 2.5 Ci/L
  - –Fuelling Machine major maintenance (Fuel Rod Flask)
  - –Installation of seismic supports for loop piping

2010 August 17 - Return to Service

- Commission approval to refuel past hold point: 2010 July 5th
- Return to Service and high power operation, safely achieved 2010 August 17

Lessons Learned - Repair

1. Necessary to establish broad design requirements early for repair tooling and proceed into fab/testing in absence of final specifications
   - Pursued multiple repair methods until final decision made
2. Full size mock-ups that simulated important spatial constraints for tooling were essential
3. Thermal/mechanical simulations of each weld repair were necessary to limit plastic strains and protect vessel seals
4. Practice, practice, practice to establish process control under conditions in mock-ups that simulate in-vessel conditions to the extent possible

Lessons Learned - Continued

5. Close interaction with Regulatory at multiple levels provided clarity to licensing requirements
   - Protocol signed by CNSC and AECL Presidents
   - Defined regulatory deliverables and timeline for approvals
   - Transparent process brings certainty
6. Important to provide regular communications to Public and Stakeholders
   - Weekly media updates
   - Video presentations
   - Website

   www.NRUCanada.ca

Key Suppliers to AECL:

- Liburdi Automation
- Promation Nuclear
- Eclipse Scientific
- Equity Engineering
- The Welding Institute
- Goldak & Associates

Closing Facts

- 40 remote operated tools designed and fabricated for inspection, sampling, cleaning, repair
- 1 km of weld bead applied
- 3 tonnes of aluminum plate consumed for weld development and training work (300 plates)
- 4,000 hours of in-vessel inspections
- 2 million NDE inspection results
- 1.8 terabytes of in-vessel video record
- 650 quality surveillance inspections
- 200 reactor assemblies moved/installed
- 73 Stakeholder status updates and 27 information videos issued to public
- 75,000 unique website visits (www.NRUCanada.ca)