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
• 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
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

Vessel wall: 8 mm 5052 aluminum
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

- Vessel wall
- Annulus floor
- 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
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

- Deck Plate
- Quick Disconnect
- Delivery Tool Body
- Deployment Mechanism
- Tool Head
- Actuation/Control Dive
- Cups
Cleaning Tool Deployment Arm

- Thick walled SS tube (Delivery Tool Body)
- Secondary carriage
- Deployment linkage
- Pneumatically operated tool head
- Silicon Carbide Brush
- Deployment arm
- Primary carriage

• Arm has 965 mm horizontal reach
In-Vessel Cleaning completed for all repairs sites and material sampling locations
Obtaining Samples of the Vessel Wall
Welding on Irradiated Material

VV14F
ACTIVE SCOOP #8

UNRESTRICTED / ILLIMITÉ
Coupon Cutting at Leak Site
Coupon Removed from Vessel Wall

- J-rod Side

Heavy Water side

UNRESTRICTED / ILLIMITÉ
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

Before

After
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
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
Liburdi Weld Delivery System
Liburdi Weld Delivery System
Welding Control Interface

PARAM CMD TELEM

FWD AMPS 120.0 94.9
REV AMPS 160.0 124.1
VOLTS 9.5 9.8
WIRE 105.0 152.5
TRAVEL 0.0 1.8
Z -1.150
R 34.710
TIME 123.9

Manual Control Enabled

WIRE FEED

OUT
IN

AVC

OUT
IN
Vertical Welding Tool
Weld Design Process

Engineering

- Structural FEA
- Weld Stress Analysis #1
- Weld Stress Analysis #2
- Weld Map

NDE

- Crack Examination
  - Surface/HAZ
- Thickness
  - Lack of Fusion
- Volumetric
  - Fillets/Groove Welds

Weld Development

- Vertical Welds
- Horizontal Welds
- Fillet/Groove Welds
- Window Frames
- Plates
Qualification of the Welding Cross Sections
Test Weld (with Scoop)
## Summary of Repair Areas

<table>
<thead>
<tr>
<th>Site</th>
<th>Weld Area (cm²)</th>
<th>Lowest Elevation Weld/Plate (mm)</th>
<th>Min. Wall Thickness (mm)</th>
<th>Welding Operations</th>
<th>2nd Layer</th>
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<tbody>
<tr>
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<td>H/- V Buildup (mm)</td>
<td>Backing Strips/Structural Plates</td>
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<td>H&amp;V-3.0</td>
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<td>0-1</td>
<td>H&amp;V-4.0</td>
<td>9-SP</td>
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</tbody>
</table>
Repair at JR-41 – The Leak Site

Backing strip placement

Backin 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

-251.97mm (-9.133°) CIRCLUM
-316.00mm (-12.441°) AXIAL
FROM THE 6501.97mm WELD TOOL
SCRIBE AREA MEASUREMENT

+47.62mm (+1.875°) CIRCLUM
-316.00mm (-12.441°) AXIAL
FROM THE 6807.38mm WELD TOOL
SCRIBE AREA MEASUREMENT

UNRESTRICTED / ILLIMITÉ
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
- 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
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)