Mitigation by Surface Improvement

Industry Briefing to NRC on PWSCC Mitigation Research
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Mitigation and Testing Issue Task Group
Materials Reliability Program
EPRI
Acknowledgement

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These organizations include:

– AREVA NP
– Curtiss-Wright
– FinTech
– GE-Hitachi Nuclear
– Lambda Technologies
– Mitsubishi Heavy Industries
– Toshiba-Westinghouse
Today’s Presentation

• Introduction
• Commercially Applied Nuclear Power Plant Mitigation Solutions
• Developing Mitigation Solutions
• Current Testing
• Technical Basis Document
• Plans for 2008 and 2009
Introduction

**Issue:** A key element of Industry’s primary water stress corrosion cracking management strategy is implementation of the dissimilar metal butt weld inspection guidance in MRP-139 - Alloy 82/182 Butt Weld Inspection and Evaluation Guidelines. In the upcoming years opportunities to apply mitigation while addressing MRP-139 requirements may occur.

**For example, Baseline Inspection Schedule in MRP-139**

- **General Requirement:**
  - **December 31, 2007:** Characterize all A82/182 DM welds to assess inspectability

- **Volumetric Examinations:**
  - **December 31, 2007:** Locations Operating at Pressurizer temperatures
  - **December 31, 2008:** ≤ 14” Locations Operating at Hot leg temperatures
  - **December 31, 2009:** > 14” Locations Operating at Hot leg temperatures
  - **December 31, 2010:** Locations Operating at Cold leg temperatures
Introduction - SCC Mitigation

• Mitigation is also important to PWSCC management
• Utilities may apply mitigative techniques
  – To reduce risk for locations where:
    • Repairs are not currently available
    • Available repair methods are not ideal for station life
    • No cracks have been identified in the field
    • Temperature is relatively low
    • Examinations are difficult to accomplish or not qualified/demonstrated (i.e., J-groove welds)
  – To justify extending inspection intervals beyond the current requirements in MRP-139
Introduction - Application of Surface Improvement Technologies

• Surface treatments were initially investigated for mitigation at Bottom Mounted Nozzles (BMNs);
  – BMNs are a lower temperature, pressure boundary
  – Complete BMN replacement is not practical
  – Other mechanical methods, i.e. MSIP and PWOL are not feasible due to component geometry and principle of operation of processes

• Surface treatments have been applied for mitigation at other Alloy 600 pressure boundary locations in nuclear power plants in Japan
Surface Improvement Mitigations

• Surface Stress Modification
  – Techniques that modify stresses from tensile to compressive
  – Accelerated, long-term (750 deg F, 2000 hours) tests reported in *MRP-61 Remediation for Alloy 600 CRDM* observed delayed PWSCC initiation equivalent to significant number of refueling cycles using multiple techniques
  – Studies reported in *MRP-162 Evaluation of Surface Stress Improvement Technologies for PWSCC Mitigation of Alloy 600 Nuclear Components* found surface stress improvements and motivated further testing of Fiber Laser and Water Jet Peening

• Surface Removal or Supplement
  – Techniques that remove, restore or supplement the surface
  – Elemental supplement (e.g., chrome or nickel)
  – Mechanical removal of aged surface material
  – Electrochemical removal of aged surface material
    (e.g., Stabilized Chrome, ReNew and Electropolishing)

- Mitigation techniques based on both approaches are being tested.
- Surface stress modification solutions have been applied in nuclear plants
Principle of laser peening

Preventive maintenance against SCC

- Focused short pulse laser irradiate metal surface in water (Pulse duration: ~10ns)

- High-pressure plasma forms on the metal surface (Plasma pressure: ~5GPa)

- Compressive stress remains in the surface layer by constraint of surrounding material
Effect and features of laser peening

- High stress improvement capability to create compressive surface layer with thickness of 1mm or more.

- No influence of heating without protective coating using small power laser sources.

- Excellent accessibility due to flexible optical fiber delivery and reaction force-less process.

SCC test results (Type304SS)

Peened
Unpeened

Alloy600

Depth profile of residual stress

Type304SS (20%CW)
BWR and PWR Applications in Japan

- Development and application of a mirror-delivered system for BWR core shroud in 1999
- Development and application of a fiber-delivered system in 2002
- BWR applications since 1999: 8 plants
  - Core shroud
  - CRD stub tube
  - ICM housing
- PWR applications since 2004: 2 plants
  - BMI nozzle
  - Primary water inlet nozzle
  - Safety Injection nozzle
BWR Applications

- H1 (outside & inside)
- H2 & H3 (outside)
- H4 (outside)
- H6a & H6b (inside & outside)
- V2 (inside)
- V4 & V5 (inside)
- H7 (inside)

Peening Area

- CRD stub tube
- ICM housing

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PWR Applications

BMI Nozzles (ID)

BMI Nozzles (OD)

Safety Injection Nozzles

Primary Water Inlet Nozzles
New portable system

Small and robust system for world wide use

– Each device contains a compact laser unit instead of connecting to a fiber cable and a large laser container.
– This system is being customized in 2008 for the application to BMI nozzles of PWRs.
Water Jet Peening (WJP)
What is Water Jet Peening?

Water Jet Peening is a method to reduce tensile residual stress on metal surface caused by welding, which is very effective to mitigate SCC and fatigue failure.
How Does WJP Work?

- Cavitation bubbles form when pressure drops below vapor pressure.
- Bubbles collapse applying a local high pressure on a surface.
- Compressive stress results on the surface from plastic deformation being elastically constrained by surrounding metal.

Cavitation flow image

WJP nozzle

Water jet with cavitation

Metal surface

Pressure by cavitation collapse: around 1,000 MPa

Plastic deformation
Stress relief profile

Material:
304SS/316LSS/Alloy600
Initial residual tensile stress:
Heavily ground condition

Effect on the surface perpendicular to scanning direction

Effect on the subsurface at nozzle center line

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Stress Relaxation – Cyclic Strain test

WJP treatment

Specimen

Dimensions (mm): 100 x 8 x 6t

Materials: 316LSS, Alloy182, Alloy600

Cyclic strain test

WJP treatment under tensile strain loaded (equivalent to 300MPa)

Cyclic strain relaxation test

Residual stress (unloaded) [ksi]

Initial value 1 10 100

Number of cycles [N]

Strain amplitude [%]

0 0.15

-150.0 -100.0 -50.0 0 50.0 100.0 150.0

Actual loaded condition: around 0.1% strain amplitude at a maximum

Materials:

316LSS, Alloy182, Alloy600

Stress Relaxation – Cyclic Strain test

Hitachi-GE Nuclear
Mock-up Stress Measurement

[RV Nozzle Safe-End Weld Mock-up]

Welding/Base Metal Boundary

10mm from Boundary (HAZ)

Compressive stress up to a 1.3mm (0.05”) deep with a 10mm (0.39”) width
Mock-up Stress Measurement

[BMN J-welds & Nozzle Mock-up]

**J-Weld Surface**
- As Weld: Radial
- As Weld: Circumferential
- After WJP: Radial
- After WJP: Circumferential

**BMN Nozzle (Outer Surface)**
- As Weld: Radial
- As Weld: Circumferential
- After WJP: Radial
- After WJP: Circumferential

WJP parameters can be managed for J-Welds and Small Bore Nozzles.
Stress Relaxation – Cyclic Strain Test

Cyclic Load

Environmental Exposure

Residual Stress Ratio
(Measured)/(As-Peened)

Residual stress (MPa)

Stress amplitude $\Delta\sigma^*$ (MPa)

*Applied by 3-point bending
BMN Mock-up (Inner Surface)

[test piece]: tensile stress by welding
[results]:

- **Surface**: Max. +460MPa → -400MPa (compression)
  - (67ksi) → (-58ksi)
- **At 0.5mm depth**: Max. +530MPa → -20～-130MPa (compression)
  - (77ksi) → (-3ksi) → (-19ksi)

![Graph showing residual stress vs depth](image-url)
BWR and ABWR Plant Applications in Japan

14 Plants Completed and 8 Planned

- Instrumentation Nozzle ID
- Core Shroud ID/OD (Upper/Middle)
- Core Shroud ID/OD (Lower)
- Shroud Support
- Reactor Vessel
- Core Shroud
- Jet Pump ID
- ICM Housing OD
- CRD Stub Tube OD

ID ; Inner Diameter
OD ; Outer Diameter

: Already applied
: Ready to apply

Note: Applicability for each plant depends on its specific configuration and/or condition.

(as of May, 2008)
14 Plants Completed

ID 9.5 - 16mm
(0.37 - 0.6 in)

OD 38mm
(1.5 in)

Alloy600 base metal

Alloy600 weld

BMN penetration

Outlet/Inlet Nozzle safe-end

Safety Injection Nozzle safe-end

700mm
(27-29 in)

90mm
(3.5 in)

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# PWR Nozzles and Welds

<table>
<thead>
<tr>
<th>RV Outlet/Inlet Nozzle Safe-end</th>
<th>BMN-J Weld (outer surface &amp; weld)</th>
<th>BMN Inner Surface</th>
<th>Safety Injection Nozzle Safe-end</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="RV Outlet/Inlet Nozzle Safe-end" /></td>
<td><img src="image2.png" alt="BMN-J Weld (outer surface &amp; weld)" /></td>
<td><img src="image3.png" alt="BMN Inner Surface" /></td>
<td><img src="image4.png" alt="Safety Injection Nozzle Safe-end" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>14 Plants</th>
<th>13 Plants</th>
<th>14 Plants</th>
<th>4 Plants</th>
</tr>
</thead>
</table>

(As of June 2008)
Developing Mitigation Solutions
(Not yet applied for PWSCC mitigation in nuclear power plants)

- Cold Spray
- Laser Peening
- Low Plasticity Burnishing
- ReNew and ReNew + WJP Combination
- Stabilized Chrome Process
Cold Spray

- **Advantages:**
  - corrosion resistant coating, arrests existing PWSCC
  - compressive rather than tensile stresses
  - wrought-like microstructures for SS316 and Ni coatings
  - high density coatings
  - can customize hardness/ductility for various applications
  - Coatings free of oxides and other inclusions
  - inspectable surface
  - minimal pre- and post-machining required
  - no cover gas required and NO melting
  - high adhesion strength (compared to other coating processes)
  - rapid deposition (8 sq in/min typical)
### Cold Spray - Process

**Supersonic Flow**

**High Velocity Impact**

**Stages of Coating Formation**

- Surface cleaning and activation
- Formation of an adhesive interface
- Formation and densification of the layer by flow of high velocity particles
- Metalurgical diffusion bond via kinetic weld
Laser Shock Peening

Laser peening is integral to fabrication of critical components of the Trent engines of Boeing 777s, A340 -500s & 600s, Gulfstream Vs and the new Boeing 787s.

Over 30,000 blades peened since 2002

Laser peening is extending the lifetime of gas and steam turbine blades.
Laser Peening for Nuclear Plant Materials Mitigation

- Laser Peening of welds retards stress corrosion cracking in 316SS
- Laser Peening reduces stress corrosion cracking in Alloy 600

Welded 316SS plate
Cracks arrest when reaching the peened region

Alloy 600 U-bend samples tensioned and exposed to Thiosulfate to enhance SCC

Pre-cracked, no laser peening  → Extensive Cracking
Pre-cracked, then laser peened  → Cracking arrested
No pre-cracking, laser peened  → No Cracking
Laser Peening Systems are Transportable to Plants

- Allows deployment anywhere in the world
- UL qualified systems ease deployment at remote sites
- Completely self-contained, system needs only electrical power
- System can be located outside Containment Building (hundreds of yards away) with beam piped in for application
LOW PLASTICITY BURNISHING (LPB)

- High-hardness ball is rolled, under pressure, over surface
- Provides deep compression and a superior finish
- Patented hydrostatic bearing with constant volume flow
- Low cold work < 3.5-5% provides stable compression

LPB Advantages

- High resolution compressive field
- Deep compression up to 12 mm
- Treatment can be applied with existing machine tools or robots
- Turn-key system with minimal training required
- 100% continuous real-time process monitoring
- Automatic immediate acceptance testing
- Individual data files captured by part serial number
LPB APPLICATIONS

- Ti-6-4 Compressor Disks
- Titanium 6-4 Vanes
- Ti-6-4 Blade Edges
- Alloy 22 Nuclear Waste Containment Package
- Ti-6-4 Hip Implants
- Ti-6-4 Blades Dovetails
- Ti-6-2-4-6 IBR
- Aluminum Propeller Blades
- Steel Propeller Hubs

- Aerospace
- Nuclear
- Medical
- Automotive
- Power Generation
LPB Benefits - Nuclear Reactor Applications

• LPB can produce compression several millimeters deep in pressurizer nozzles for complete mitigation of PWSCC.

• LPB treatment can be performed underwater using existing weld repair or inspection tooling.

• LPB imparts a near mirror finish providing an optimal surface finish for NDE methods.

• LPB processing is a closed-loop feedback system providing precise tool pressure control exceeding 6-sigma.

• Tool pressures are collected in real time with respect to tool position for unparalleled process quality control.
ReNew

What is ReNew?

• ReNew is a fine surface polishing process
• Mitigates BWR SCC and PWSCC initiation
• Utilizes a durable, flexible abrasive media
• Well-suited to operating plant applications

What are the Benefits of ReNew?

• Removes cold work from fabrication
• Removes early initiation sites formed during plant operation
• Capable of removing localized, shallow surface cracking
• Produces surface compressive residual stress
• Produces excellent surface finish to resist future crack initiation
ReNew Surface Mitigation Technology

Comparison of surface stress improvement mitigation technologies:

- Surface As-Fabricated
  - No Mitigation
  - Aged, Susceptible Material
  - Reactor Coolant
  - Tensile Stress

- Surface After Various Stress Improvements
  - Single Mitigation
  - Aged, Susceptible Material
  - Reactor Coolant
  - Compressive Stress

- Surface After ReNew Surface Improvement
  - Double Mitigation
  - ReNew’ed Surface Material
  - Reactor Coolant
  - Compressive Stress

ReNew addresses two of three factors required for SCC
ReNew’s improvements confirmed in laboratory evaluations and studies
- Environmental tests conducted under BWR conditions quantify improvements

Material Improvements
- Cold Work Removal
- Crack Removal
- Aged Layer Removal

Stress Improvement
- Compressive Stresses

Finish Improvement
- Strain Intensity Reduction

Residual Stress Distribution

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Stabilized Chrome Process (SCrP)

- SCrP has been shown to dramatically lower the incorporation of Co-60 in replacement components
- It has been applied to over 100 PWR diaphragms, pump parts and many valves during the last few years
- SCrP is a three stage process that involves:
  - Intensive surface cleaning and electropolishing
  - Deposition of a very thin Cr layer by electroplating
  - Pre-oxidation in steam at ~ 600 °F for ~ 100 h
- It results in a Cr enriched layer (to > 90 weight %) from a depth of about 0.01 to 0.15 mils at the component surface
- Cr content plays a key role in PWSCC of Ni-base alloys
Current Testing

U-Bend Testing
- Weld-deposited, Alloy 600 U-Bends
- Observed to readily crack by PWSCC when not mitigated
- 1000 hours in primary water
- Treatments
  - Fiber Laser Peening
  - Water Jet Peening
  - Electropolishing
  - ReNew
  - ReNew + Water Jet Peening
  - Stabilized Chrome

Stress Relaxation Testing
- Alloy 600 Plate
- 240 hour cycles in primary water
- Loaded to 0.75 yield stress
- Surface stress measured for relaxation after 2, 4 and 8 cycles
- Fiber Laser Peening and Water Jet Peening
Technical Basis Document (TBD) for Surface Mitigation (MRP-169 is model for Document)

• Objectives of document
  – Provide guidance on technical requirements to Utilities and Vendors
  – Communicate Utility position on surface mitigation to the Regulator
  – Support ASME Code positions on surface mitigation and possible Code Case

• Technical Basis Document will be comprised of 3 major parts
  – Treatments, background, benefits, R&D testing, experience, solutions
  – Specific criteria that define an acceptable process treatment and the Utility requirements for an acceptable plant application
  – Description of inspection plan and technical justification for mitigated plants
    (with respect to the requirements of MRP-139 and revision to inspection frequencies)

• Use MRP-169 as template and guide for level of detail and approach
• Incorporate BWR and other relevant experience where possible
## Table in MRP-139 for Optimized Weld Overlay MRP-169

### Table 1 – Weld Overlay Design Types and Associated Design and Inspection Requirements

<table>
<thead>
<tr>
<th>Weld Overlay Type</th>
<th>Pre-WOL Inspection Completed?</th>
<th>Design Basis Flaw for WOL</th>
<th>Crack Growth Design Basis</th>
<th>Post-WOL Exam Volume (PSI and ISI)</th>
<th>Post-WOL Inservice Inspection Schedule (MRP-139/169 vs. ASME Code Cases)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repair – Full Structural</td>
<td>Yes</td>
<td>100% thru-wall, full circ.</td>
<td>Actual observed flaw shall not exceed design basis flaw size in next inspection interval</td>
<td>WOL + outer 25% of Code DMW Exam Volume</td>
<td>MRP-139/169: (Cat. F) Once in the next 5 years, and then if no growth 100% in subsequent 10 year interval</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CC N-740-1.: Once in the next two RFOs, and then if no growth, a 25% sample population on a 10 year basis</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>100% thru-wall, full circ.</td>
<td>Assumed 75% flaw shall not exceed design basis flaw size in next inspection interval</td>
<td>WOL + outer 25% of Code DMW Exam Volume</td>
<td>MRP-139/169: (Cat. F) Once in the next 5 years, and then if no growth 100% in subsequent 10 year interval</td>
</tr>
<tr>
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<td></td>
<td>CC N-740-1.: Once in the next two RFOs, and then if no growth, a 25% sample population on a 10 year basis</td>
</tr>
<tr>
<td>Preemptive – Full Structural</td>
<td>Yes</td>
<td>100% thru-wall, full circ.</td>
<td>Assumed 10% flaw shall not exceed design basis flaw size in next inspection interval</td>
<td>WOL + outer 25% of Code DMW Exam Volume</td>
<td>MRP-139/169: (Cat. B) 100% every interval (10 years)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CC N-740-1.: A 25% sample population on a 10 year basis</td>
</tr>
<tr>
<td>Repair – Optimized</td>
<td>Yes</td>
<td>75% thru-wall, full circ.</td>
<td>Actual observed flaw shall not exceed design basis flaw size in next inspection interval</td>
<td>WOL + outer 50% of Code DMW Exam Volume</td>
<td>*MRP-139/169: (Cat. F) Once in the next 5 years, and then if no growth 100% in subsequent 10 year interval</td>
</tr>
<tr>
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<td></td>
<td>CC N-754.: Once in the next two RFOs, and then if no growth, a 25% sample population on a 10 year basis (outer 50%)</td>
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<tr>
<td>Preemptive – Optimized</td>
<td>Yes</td>
<td>75% thru-wall, full circ.</td>
<td>Assumed 10% flaw shall not exceed design basis flaw size in next inspection interval</td>
<td>WOL + outer 50% of Code DMW Exam Volume</td>
<td>*MRP-139/169: (Cat. B) 100% every interval (10 years)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CC N-754.: A 25% sample population on a 10 year basis</td>
</tr>
</tbody>
</table>

* Current MRP-139 requirement is that overlays must be full structural to qualify as Cat. B or F, however, a revision to MRP-139 is planned to support these categories for optimized overlays (similar to MRP-139, Section 6).
## Planning for Fall 2009 Demonstrations

<table>
<thead>
<tr>
<th>2008</th>
<th>2009</th>
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</thead>
<tbody>
<tr>
<td>Apr</td>
<td>May</td>
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<tr>
<td>✓ ITG Webcast on Technical Basis Document (TBD)</td>
<td>✓ ITG Webcast on Technical Basis Document (TBD)</td>
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<tr>
<td>✓ MRP Summer Meeting</td>
<td>✓ MRP Summer Meeting</td>
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<tr>
<td>✓ Complete Peening U-Bends</td>
<td>✓ Complete Peening U-Bends</td>
</tr>
<tr>
<td>✓ U-Bend and Relaxation Confirmatory Testing</td>
<td>✓ U-Bend and Relaxation Confirmatory Testing</td>
</tr>
<tr>
<td>✓ MRP Testing Complete</td>
<td>✓ MRP Testing Complete</td>
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<tr>
<td>✓ Testing Reports</td>
<td>✓ Testing Reports</td>
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<tr>
<td>Main Sections of TBD</td>
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</tr>
<tr>
<td>- Section 1 - Process Background and Description</td>
<td>- Section 1 - Process Background and Description</td>
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<tr>
<td>- Section 2 - Specifications</td>
<td>- Section 2 - Specifications</td>
</tr>
<tr>
<td>- Section 3 - Inspection Basis, Plan and Guidance</td>
<td>- Section 3 - Inspection Basis, Plan and Guidance</td>
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<tr>
<td>✓ Input from Vendors, Utilities and NDE</td>
<td>✓ Input from Vendors, Utilities and NDE</td>
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<tr>
<td>✓ Draft TBD</td>
<td>✓ Draft TBD</td>
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<tr>
<td>✓ Final TBD (EPRI MRP Report)</td>
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</tr>
<tr>
<td>✓ Submit to NRC and ASME Code (as necessary)</td>
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</tr>
<tr>
<td>Resolve Comments and RAI’s</td>
<td>Resolve Comments and RAI’s</td>
</tr>
<tr>
<td>✓ Plant Demonstration</td>
<td>✓ Plant Demonstration</td>
</tr>
</tbody>
</table>

**Mitigation Treatments in Testing**
- Electropolishing
- Fiber Laser Peening
- ReNew™
- Stabilized Chrome Process
- Water Jet Peening
Together…Shaping the Future of Electricity