ATTACHMENT 6

AREVA Document 51-9263014-000, "PWSCC Evaluation of UHP Cavitation Peening for Byron and Braidwood Reactor Vessel Head Penetrations" (NON-PROPRIETARY)

AREVA

AREVA Inc.

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PWSCC Evaluation of UHP Cavitation Peening for Byron and Braidwood Reactor Vessel Head Penetrations

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Safety Related? ☒ YES ☐ NO

Does this document establish design or technical requirements? ☐ YES ☒ NO

Does this document contain assumptions requiring verification? ☐ YES ☒ NO

Does this document contain Customer Required Format? ☐ YES ☒ NO

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1.0 PURPOSE

AREVA will perform surface stress improvement remediation on Byron Units 1 and 2 and Braidwood Units 1 and 2 Reactor Vessel Head Penetrations (VHPs), both un-modified VHPs and VHPs modified by the inside diameter temper bead (IDTB) repair or embedded flaw/weld overlay repair. The purpose of this report is twofold:

1) Determine the susceptibility of the VHP locations remediated with surface stress improvement processes, either ultra-high pressure (UHP) cavitation peening or rotary peening, to Primary Water Stress Corrosion Cracking (PWSCC) in fulfilment of item 5.4 of the Surface Stress Improvement Via Peening Specification [1,2] and
2) Estimate the life of the remediated locations.

Item 5.4 of the Surface Stress Improvement Via Peening Specification [1] is as follows:

> An evaluation shall be performed to determine the PWSCC susceptibility of the locations where remediation has been performed. This evaluation will address the susceptibility of the peened locations to: 1) PWSCC crack initiation, 2) PWSCC crack growth of cracks within the depth of the compressive stress layer, and 3) PWSCC crack growth of cracks deeper than the compressive stress layer.

The remediated locations are described in Sections 2.0, 3.3 and 3.4 of the Surface Stress Improvement Via Peening Specification [1]. Remediation is to be performed on the weld, outside diameter (OD), and inside diameter (ID) of un-modified control rod drive mechanism (CRDM), core exit thermocouple (CETC), reactor vessel level indication system (RVLIS), spare CRDM and vent VHPs, as well as the OD and ID of VHPs that have been modified with an embedded flaw/weld overlay repair and the ID of VHPs modified by the IDTB weld repair process. [

] This is true for both modified and un-modified VHPs.

Information considered proprietary to AREVA is enclosed in the following brackets: [ ]

2.0 METHODOLOGY

The susceptibility of remediated locations to PWSCC is based on industry experience, AREVA experimental results, and a comparison of stress analysis results to the industry established requirements (the requirements are discussed in Section 4.0).

The estimated life of the remediated locations is based on consideration of the industry established requirements (see Section 4.0) for PWSCC initiation (for locations with no pre-existing PWSCC flaws) and the industry developed crack growth rate curves (for locations with pre-existing PWSCC flaws).

3.0 ASSUMPTIONS

3.1 Justified Assumptions

This evaluation contains no justified assumptions.

3.2 Assumptions Requiring Verification

This evaluation contains no assumptions requiring verification.

4.0 BACKGROUND

Stress corrosion cracking (including PWSCC) is attributed to a combination of three factors: a susceptible material, a corrosive environment, and a sustained tensile stress. If any of these factors are removed (or sufficiently reduced below a level considered necessary to initiate PWSCC during the life of the VHPs), stress corrosion cracking is mitigated. UHP Cavitation Peening, also described as water jet peening[1], and rotary peening are surface stress improvement PWSCC mitigation methods. UHP Cavitation Peening reduces surface stress in VHPs by directing cavitation bubbles onto the surface of VHPs. Shock waves from the collapsing cavitation bubbles result in local plastic deformation of the VHP surface inducing compressive residual stresses on the VHP surface and into the depth of the VHP. Rotary peening is a peening method using a rotary captive shot tool for surface residual stress improvement. Thus, the tensile residual stress from welding or grinding during fabrication is replaced with a compressive residual surface stress, removing the sustained tensile stress needed for PWSCC.

However, the compressive stress layer imparted by the surface stress improvement process may not remain compressive during plant operation. To address this, MRP-335, Rev. 3 [4] established the following requirements:

- Section 4.3.8.1, Stress Effect, which requires that the residual stress plus normal operating stress on surfaces shall not exceed +10 ksi in the area of interest.

- Section 4.3.8.2, Sustainability, which again requires that the peening process maintains the surface stress no greater than +10 ksi tensile in the area of interest for the service life of the component, after considering any possible relief of the stresses due to shakedown or creep/stress relaxation.

The residual plus normal operating stresses on remediated VHPs (un-modified nozzles and nozzles modified by an embedded flaw/weld overlay) at Byron Units 1 and 2 and Braidwood Units 1 and 2 have been calculated [3]. The analysis includes the effect of cyclic loading that causes the compressive surface residual stresses to relax due to shakedown. Reduction of the compressive residual stresses due to creep/stress relaxation at normal operating temperature and stress levels was [ ] At all representative points evaluated (ID and OD), the surface residual plus normal operating stress is less than the +10 ksi required by MRP-335 Rev. 3, Sections 4.3.8.1 and 4.3.8.2 [4], with a maximum [ ]

[1] The AREVA Cavitation Peening process is termed ultra-high pressure (UHP) Cavitation Peening, so this terminology will be used throughout this document.

The residual plus operating surface stresses on remediated VHPs repaired by IDTB welds at Byron Units 1 and 2 and Braidwood Units 1 and 2 have been calculated [5]. The analysis includes the effect of cyclic loading which causes the compressive residual stresses to relax due to shakedown. [

] ; additionally, an analytic evaluation of stress relaxation indicated the limiting values of stress components determined in the shakedown analysis would be [

] At all representative points evaluated [

] the steady state residual plus operating stress is less than the +10 ksi required by MRP 335, Rev. 3, Sections 4.3.8.1 and 4.3.8.2 [4] with a [

] if cavitation peening is utilized and a [

] if rotary peening is utilized. Additionally, Appendix A of Reference [5] shows that stress would also remain compressive on any peened surfaces [ ]

5.0 EVALUATION

The susceptibility of PWSCC initiation in remediated surfaces is evaluated herein. The impact of remediation on pre-existing PWSCC cracks will also be discussed. Lastly, a qualitative assessment of the estimated life of the remediated locations will be performed. As discussed in Section 4.3 of References [3] and [5], the rotary peening process results in a higher ID compressive stress than the ID compressive stress resulting from the cavitation peening process. Therefore, the evaluation herein discusses the results of the compressive stress created by UHP cavitation peening, excluding the specific stress analyses, which consider both remediation processes.

5.1 PWSCC Crack Initiation

As stated above, PWSCC requires the following three synergistic components to occur: 1) susceptible material, 2) aggressive environment, and 3) sustained tensile stress. Extensive operating experience and laboratory testing indicates that 1) Alloy 600 base metal and Alloy 82/182 weld metal are susceptible materials, 2) normal Pressurized Water Reactor (PWR) operating conditions constitutes an aggressive environment, and 3) elevated tensile stresses from welding or grinding during fabrication meet the stress component of PWSCC.

This section will consider surface improvement operating experience, laboratory testing, and the results from the stress analyses to assess whether the effect of peening on the stress component of PWSCC is sufficient to mitigate PWSCC initiation.

5.1.1 Operating Experience

Operating experience related to surface stress improvement via peening is reviewed in detail in Section 3 of MRP-267, Revision 2 [6]. The following paragraphs are a partial summary of this review:

Starting in the mid 1980's, shot peening has been applied to Alloy 600 steam generator tubes to mitigate against PWSCC. Several hundred thousand steam generator tubes have been peened, with experience extending over 30 years. Peening generally reduced PWSCC initiation and reduced growth of cracks that initiated prior to peening, although pre-existing cracks deeper than the depth of the mitigation layer continued to grow.

AREVA's patented abrasive waterjet machining (AWJM) process has been used since the late 1990's. This process removes a small layer of material with a stream of abrasive particles, which removes undetectable PWSCC damage and places the surface in compression. This process is different from UHP Cavitation Peening, which does not use particles in the water jet stream and does not remove material. Over 120 Alloy 600 VHPs have been treated with AWJM, with no report of subsequent PWSCC. Many of the reactor vessel heads

containing these VHP repairs have since been replaced. However, several nozzles have been in service for more than 6 years.

Based on steam generator tubing experience, other peening methods (including cavitation peening) were implemented in Japanese PWRs and Boiling Water Reactors (BWRs) around the turn of the century. In PWRs, cavitation peening has been applied to bottom mounted nozzles and reactor vessel inlet and outlet nozzles. There have been no reports in the technical literature of cracks being detected in peened locations in Japan.

5.1.2 Laboratory Testing

The effectiveness of surface stress improvement via Cavitation Peening is evaluated in detail in Section 4 of MRP-267, Revision 2 [6]. This report summarizes a series of stress profile measurements and corrosion tests demonstrating the effectiveness of surface stress improvement processes, including Cavitation Peening, to reliably preclude future PWSCC initiation and arrest the growth of shallow flaws in the mitigation zone. Additional tests by various vendors and EPRI demonstrate the long-term sustainability of residual stresses, accounting for shakedown and long-term stress relaxation.

The following paragraphs are a summary of laboratory experience with AREVA's AWJM surface mitigation technique and AREVA's internal research and development related to UHP Cavitation Peening:

In 2003, EPRI published results of a test program (MRP-61 [7]) to evaluate the effectiveness of various PWSCC remediation techniques, including AREVA's AWJM technique. In this test program, commercial heats of Alloy 600 tubing were ovalized (Figure 5-1) and constrained to maintain tensile residual stresses. Three specimens were then treated with AWJM, imparting a mitigation layer on a PWSCC-free surface. These specimens were then evaluated by measuring the time to PWSCC initiation in an accelerated doped steam test conducted at 752°F (400°C). A moderate amount of PWSCC initiation was experienced in untreated baseline Alloy 600 specimens tested during this program. However, no PWSCC was detected in the AWJM treated specimens after up to 2000 hours of testing. These accelerated testing results are estimated to be equivalent to fifty (50) eighteen (18) month cycles of 602.6°F operation, based on comparison to operating experience with Ringhals 2 materials included in the EPRI test program. This testing demonstrates the effectiveness of a mitigation layer at preventing PWSCC initiation.

In 2009, EPRI published results of a test program (MRP-265 [8]) where AREVA performed testing of various chemical and mechanical mitigation surface treatments, including Cavitation Peening. [

] This testing demonstrates the effectiveness of Cavitation Peening at preventing PWSCC initiation in heavily ground weld material.

AREVA has performed further internal Research and Development (R&D) of UHP Cavitation Peening as a means of mitigating PWSCC [9]. [

] This further demonstrates the effectiveness directly for UHP Cavitation Peening at preventing PWSCC initiation in heavily ground weld material.

5.1.3 Stress Analysis

As discussed in Section 4.0, the stress analysis performed on remediated VHPs (un-modified nozzles and nozzles modified by an embedded flaw/weld overlay repair) indicated that all representative ID and OD surface stresses remained compressive [ ] at operating conditions even after cyclic shakedown effects were considered. [ ]

[ ] This result is below the requirement specified in MRP-335, Rev. 3 that a surface tensile stress shall not exceed +10 ksi [4].

Additionally, the residual plus operating surface stresses on remediated VHPs repaired by IDTB welds at Byron Units 1 and 2 and Braidwood Units 1 and 2 have been calculated [5]. The analysis includes the effect of cyclic loading which causes the compressive residual stresses to relax due to shakedown. [ ] additionally, an analytic evaluation of stress relaxation indicated the limiting values of stress components determined in the shakedown analysis would be [ ] At all representative points evaluated [ ] the steady state residual plus operating stress is less than the +10 ksi required by MRP 335, Rev. 3, Sections 4.3.8.1 and 4.3.8.2 [4] with a [ ] if cavitation peening is utilized and a [ ] if rotary peening is utilized. Additionally, Appendix A of Reference [5] shows that stress would also remain compressive on any peened surfaces [ ]

Therefore, remediation of the VHPs at Byron Units 1 and 2 and Braidwood Units 1 and 2 by surface stress improvement, UHP cavitation peening or rotary peening, meets the stress requirements of MRP-335, Rev. 3 when performed on un-modified VHPs, as well as on those VHPs which have been repaired via an embedded flaw/ weld overlay or the IDTB repair process.

5.1.4 Summary

PWSCC initiation is not expected in locations that have undergone surface stress improvement remediation based on 1) excellent operating experience with surface stress improvement techniques, 2) laboratory experience with surface stress improvement, specifically AREVA's laboratory experience with UHP Cavitation Peening, and 3) stress analysis results considering residual stresses, operating conditions, and stress sustainability that meet the stated requirements of MRP-335, Rev. 3 [4].

5.2 Growth of Pre-existing PWSCC flaws

Similar to the discussion in Section 4.0, a tensile driving force is considered a necessary condition for PWSCC crack propagation. UHP Cavitation Peening creates a surface layer of some depth where stresses are compressive. An existing PWSCC flaw with its crack tip within this compressive stress layer has lost the tensile driving force for crack propagation.

As part of its R&D efforts [9], AREVA has developed [

]

[

.]

Table 5-1: [ ]

[ ]

[

]

In summary, cracks within the compressive stress layer are expected to arrest, [
]

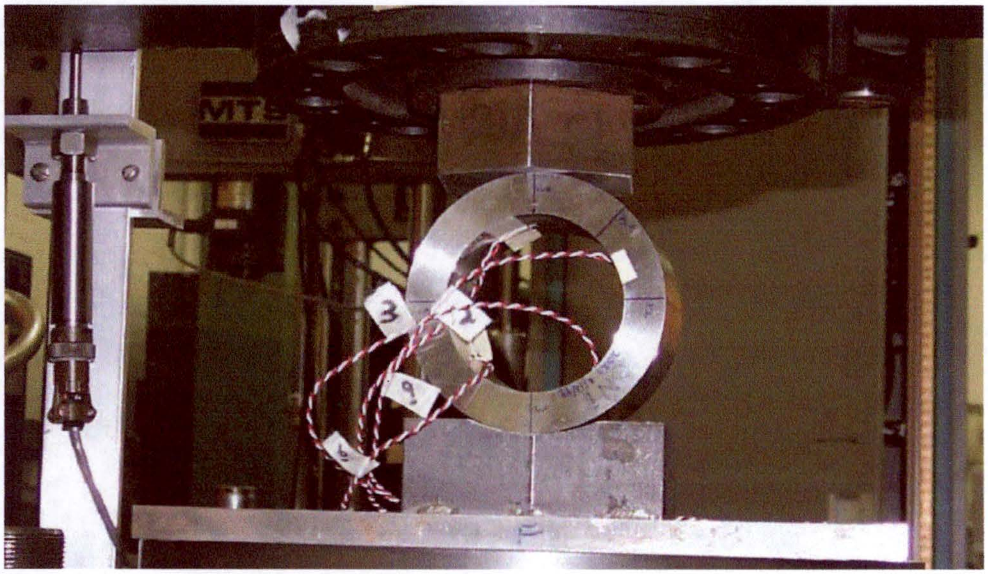

Figure 5-1: Ovalization of Alloy 600 CRDM Tubing [7]

[ ]

Figure 5-2: [ ]

[ ]

Figure 5-3: [ ]

[ ]

Figure 5-4: [ ]

[ ]

Figure 5-5: [ ]

5.3 Estimated Life of Remediated Locations

The life of remediated locations is estimated for three scenarios: 1) locations where no PWSCC cracking is present; 2) locations where undetected PWSCC cracking is shallower than the depth of compression; and 3) locations where undetected PWSCC cracking is deeper than the depth of compression. Example flaws from Scenario 2 and Scenario 3 are shown in Figure 5-6 to indicate their relative position to the compressive layer and the region of ultrasonic testing (UT) detection (note that this figure is not to scale).

Scenario 1: No PWSCC Cracking is Present

As described in Section 5.1.4, PWSCC initiation is not expected in surfaces remediated using surface stress improvement.

Since PWSCC initiation is not expected in mitigated surfaces, the dominant degradation mechanism is considered to be [

]

Scenario 2: Undetected PWSCC Cracking is Present – shallower than compressive stress layer

As described in Section 5.2, flaws not detected with non-destructive examination techniques that are within the depth of compression are expected to arrest [6]. However, an undetected shallow flaw within the depth of compression may eventually propagate via fatigue crack growth or PWSCC, [

] There is insufficient information to estimate the life in this scenario. A flaw with a crack tip beyond the depth of compression is addressed in Scenario 3.

Scenario 3: Undetected PWSCC Cracking is Present – deeper than the compressive stress layer

A pre-existing flaw with a crack tip beyond the depth of mitigation is expected to continue to propagate as if no surface remediation was performed. Since a flaw in Scenario 3 is not mitigated by the surface stress improvement process and such a flaw is addressed by existing inspection requirements, additional evaluation is not required.

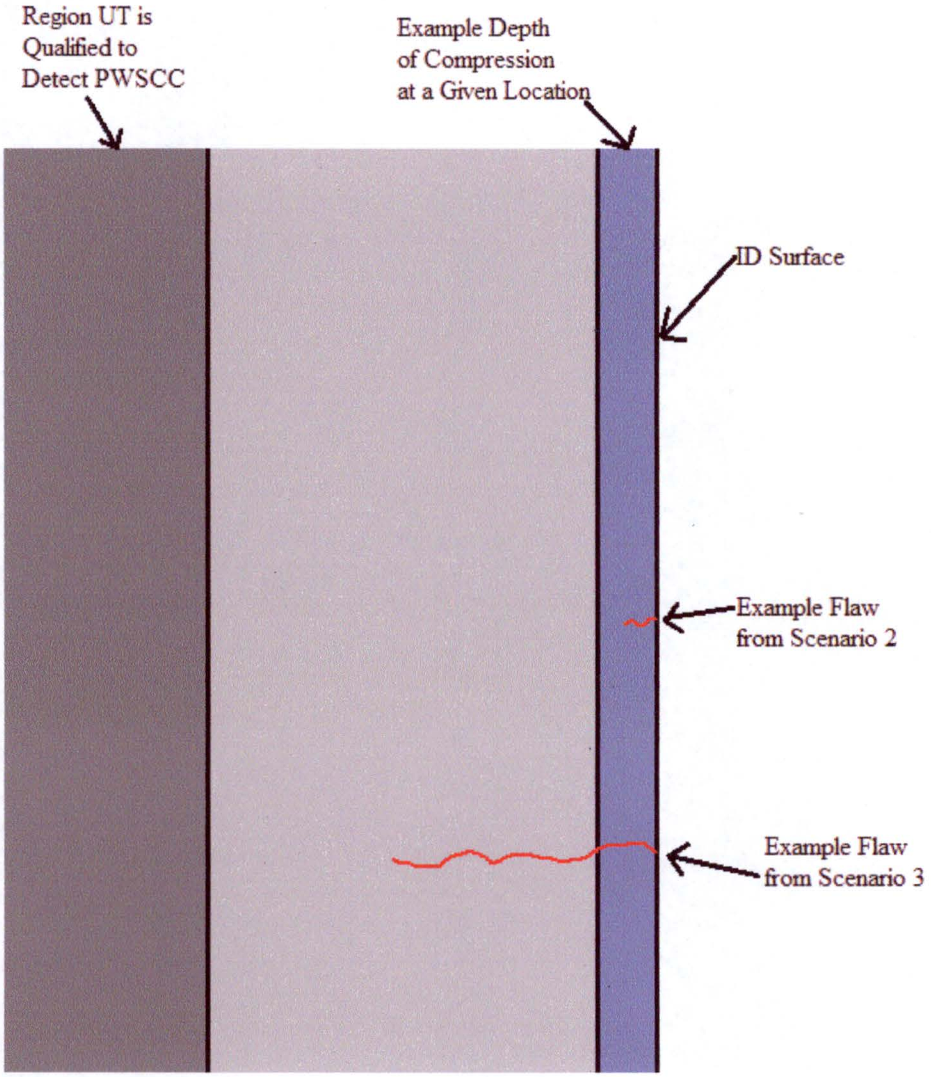

Figure 5-6: Illustration of Example Flaws for Scenarios 2 and 3 (Not to Scale)

6.0 SUMMARY

PWSCC initiation in VHPs is mitigated by replacing significant levels of residual tensile stress from weld shrinkage and fabrication grinding with a surface remediated via surface stress improvement. The remediated surfaces by both rotary and UHP cavitation peening meet the stress effect and sustainability requirements stated in MRP-335, Rev. 3 [4]. The residual plus normal operating stresses of the representative peened surfaces (after consideration of shakedown and stress relaxation) have been shown to generally be compressive, [

]

The life of remediated locations where no undetected PWSCC flaws are present (Scenario 1) is estimated to be beyond the period of a 60-year plant license. The life of remediated locations where an undetected flaw is beyond the depth of the compressive stress layer (Scenario 3) could be very short. On the other hand, the reduced tensile stresses near the surface may reduce crack growth rates and result in a longer life. For remediated locations where

an undetected PWSCC flaw is within than the compressive stress layer (Scenario 2), the estimated life could be between these two cases.

7.0 REFERENCES

References identified with an (*) are maintained within Exelon Records System and are not retrievable from AREVA Records Management. These are acceptable references per AREVA Administrative Procedure 0402-01, Attachment 8. See page 2 for Project Manager Approval of customer references.

1. AREVA Inc. Document 08-9237101-004, "Byron and Braidwood RVCH Penetration Surface Stress Improvement Via Peening Specification," 2016. Proprietary.
2. AREVA Inc. Drawing 02-9237082D-003, "Byron Units 1 and 2 / Braidwood Units 1 and 2 RVCH Penetration UHP Cavitation Peening Implementation," 2016. Proprietary.
3. AREVA Inc. Calculation 32-9241722-001, "Byron & Braidwood Peening Residual Plus Operating Stress Analysis," 2016. Proprietary.
4. Materials Reliability Program: Topical Report for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement (MRP-335 Revision 3), EPRI, Palo Alto, CA: 2016. 3002007392.
5. AREVA Inc. Calculation 32-9245768-001, "Byron and Braidwood IDTB Repair Peening Residual Plus Operating Stress Analysis," 2016. Proprietary.
6. Materials Reliability Program: Technical Basis for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement (MRP-267, Revision 2). EPRI, Palo Alto, CA: 2016. 3002008083.
7. Materials Reliability Program: An Assessment of the Control Rod Drive Mechanism (CRDM) Alloy 600 Reactor Vessel Head Penetration PWSCC Remedial Techniques (MRP-61), EPRI, Palo Alto, CA: 2003. 1008901.
8. [.]
9. [ ]
10. [ ]
11. [ ]
12. H. R. Copson, and W. E. Berry, "Qualification of Inconel for Nuclear Power Plant Applications," Corrosion, Vol. 16, 1960.
13. [ ]