Attachment A – Mitsubishi Responses to NRC WJP RAIs

Question No. 1
Provide refueling outage and date that the water jet peening was applied to the subject dissimilar metal welds.

Response to Question No. 1
Implementation of water jet peening (WJP) at Callaway was completed during RF22; Fall 2017 refueling outage.

Question No. 2
Section 5.2.2 of the relief request discusses peening process. Discuss deviations between the field application and the performance (mock-up) demonstration and/or peening procedure qualification.

Response to Question No. 2
With exception to one documented deviation (discussed below), all aspects of the qualification testing critical parameters, as implemented at Callaway, were achieved and stayed within the qualified acceptance criteria.

Vendor NCR SP-17-052 was written to document a post-calibration issue associated with the 'A' High Pressure Pumping System (HPPS). For reactor vessel nozzle WJP, a flow rate range of 45L/min [11.89 gpm] and 49L/min [12.94 gpm] has to be achieved to satisfy the qualification testing requirements; however, for the HPPS equipment an accuracy of ±0.514%[Ref. 10] was established to ensure stable flow control. Prior to implementation of WJP (beginning of RF22), a pre-calibration of the HPPS flowmeters was confirmed acceptable and achieved the required accuracy of ±0.514%[Ref. 10]. Upon completion of WJP implementation (end of RF22), a post-calibration was performed and the flowmeter accuracy was measured to be -3.39%[Ref. 10] which exceeded the established acceptance criteria.

A thorough review of the real time recorded parameter data files determined that with exception to the Bravo-Hot Leg (B-HL), all reactor vessel nozzles which were peened with the 'A' HPPS achieved the minimum required flowrate of 45L/min [11.89 gpm]. Based on WJP tooling position data, it was determined that this occurred only during the WJP process for this reactor vessel nozzle for only 3 seconds. Provided below is an extract of the real time recorded data applicable to the B-HL low flow instance. This particular reactor vessel nozzle required three WJP passes [called 'steps' per the Mitsubishi WJP process] to effectively cover the dissimilar metal weld (DMW) region. As can be seen, the low flow instance occurred on the 2nd of 4 WJP scanning passes (4 scans required to effectively WJP a given location before the WJP nozzle advances to the next step) on the 3rd WJP step.

(times)	(times)			(deg)	(in)	(psi)	(gal/min)	(in/min)		(L/min)
Number of times for step	Number of times for scanning	Data number	Date/Time	?axis angle	Y axis position	WJP pressure	WJP flow rate	WJP scan speed	Data Number (MNES)	WJP flow rate
3	2	13825	11:24:11	172	7.2008	9263.6	12.279	-3.85	13825	46.47602
3	2	13826	11:24:12	171.7	7.2008	9286.452	12.2845	-3.85	13826	46.49683
3	2	13827	11:24:13	171.5	7.2008	9286.452	12.2902	-3.856	13827	46.51841

*****Note that due to the increased uncertainty documented from the post-calibration of the 'A' HPPS, the allowable minimum flowrate was changed from 45L/min (11.89 gpm) to 46.526 L/min (12.291 gpm) to account for the -3.39% accuracy as part of the data file evaluation process.***

A visual representation of a typical reactor vessel WJP application, as it applies to the B-HL at Callaway, has been provided in Figure 1. On this figure, an overlay of the WJP process has been included and identifies the WJP steps and scans required.

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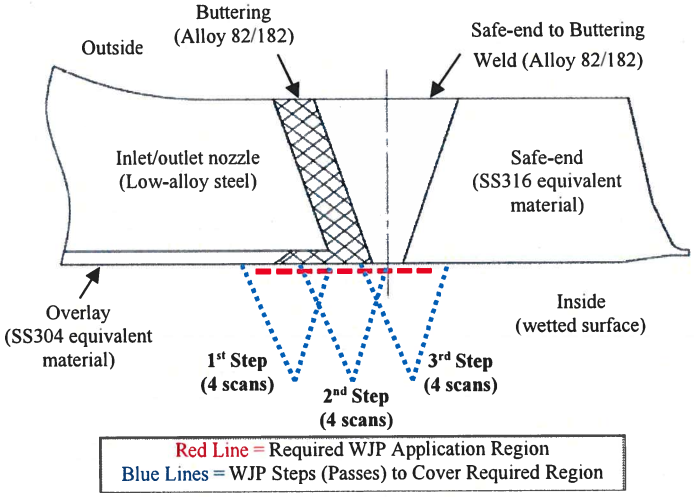

Figure 1 – B-HL Reactor Vessel Nozzle WJP Application

The adjusted actual lowest recorded flowrate for this occurrence by the WJP operational software, neglecting the -3.39% accuracy issue, was 46.476L/min [12.278 gpm]. However, once the -3.39% accuracy is accounted for, the actual flowrate was 44.900L/min [11.861 gpm], which equates to an approximate 0.24% deviation from the required minimum 45L/min [11.89 gpm]. This deviation is considered insignificant since the other scanning passes, i.e., scans 1, 3, and 4, at the 3rd step location, the adjusted flowrate was greater than the 45L/min minimum and given the 3 second duration, the region can be considered effectively peened. Furthermore, from the process qualification testing documented in DUS-150319[Ref. 7] the measurement uncertainty of the utilized flowmeter (for process qualification) was ±0.3% as documented in Section 11.9.7 of Report NS-RPT-100004[Ref. 8]. Accordingly, the reported deviation of 0.24% is less than to the 0.3% allowed uncertainty from WJP process qualification.

All other aspects of WJP critical parameters and associated acceptance criteria were achieved at Callaway. A full consideration and evaluation of all real time recorded data files and parameters has been performed in Report NS-RPT-100004[Ref. 8].

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Question No. 3 A) (1)
Difference in the uncertainties caused by the measurements in the calibration method and the measurements in a mockup.

Response to Question No. 3 A) (1)
There is no difference in the uncertainties of the X-ray residual stress measurements in the calibration method and the X-ray residual stress measurement in a mockup[Ref. 6].

The calibration contains the following two processes:

a) Determination of the X-ray Elastic Constant

As described in Appendix 1, stress is calculated from lattice spacing of the diffraction plane obtained by a diffractometer. In this calculation, an X-ray elastic constant is necessary. The X-ray elastic constant is a parameter indigenous to a diffraction plane of a material. Accordingly, the X-ray elastic constant was determined in accordance with ASTM E1426-98 and JSMS-SD-5-02[Ref. 1]. In these standards, a relationship between lattice spacing of a diffraction plane and stress is experimentally quantified by carrying out X-ray diffraction on bend specimens with known stress levels. The bend specimen was machined from the same heat of plate material used for the mockup test. The X-ray elastic constant was calculated according to the relationship between slopes of the regression lines of plots and given stress levels. All the X-ray stress measurement results for the mockup were obtained using this X-ray elastic constant.

b) Verification of the Alignment of X-ray Diffraction Instrumentation

This is the verification for the X-ray instrumentation to confirm the residual stress of the ferrite powder to be zero within the band of ±2ksi which is defined in ASTM E915-10. This verification was performed before and after measurement on each mockup.

Question No. 3 A) (2)
Difference in microstructure between the plate material and weld material that would demonstrate the residual stress in the plate is valid to represent the residual stress in the weld.

Response to Question No. 3 A) (2)
The microstructure of the plate material is different from that of the weld material. However, the two materials have similar elasto-plastic behavior (mechanical strength). Accordingly, the residual stress measured in the plate material is assumed to be a valid representation of the weld. See a) and b) below for additional descriptions of the microstructures and mechanical strength as they relate to these materials.

a) Difference in Microstructure
The plate material consists of fine equiaxed grains; whereas, the weld material has columnar grains. As mentioned above, given similarities in elasto-plastic behavior, the difference in microstructure provides that residual stress on the plate is representative of the weld material.

b) Similarities in Elasto-Plastic Behavior
Room temperature yield stress and ultimate tensile strength of Alloy 600 base metal and weld material are listed in Tables 1 and 2, respectively. As can be seen, the base metal and weld material yield stress values are very similar to one another. Due to this similarity, along with the consideration of an insignificant microstructure influence, the residual stress profiles of both materials after WJP are expected to be similar.

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Table 1 – Base Metal Room Temperature Yield Stress (YS) and Ultimate Tensile Strength (UTS) Ref. 2 [Table 4-6]

Room temperature	Thermo-mechanical treatment	UTS (MPa)	YS (MPa)	Elongation over 2" (%)
A600	Source: RCC-M. RPVH penetrations. In bolt: Figure at 350°C (662°F).	≥ 550	≥ 240 (240)	≥ 30
A600 (rods, bars, wire)	CW + annealed or HW + annealed	≥ 552	≥ 241	≥ 30
A600 (seamless pipe&tube <5")	HW or HW + annealed	≥ 552	≥ 207	≥ 35
A600 (seamless pipe&tube >5")	HW or HW + annealed	≥ 517	≥ 172	≥ 35
A600 (seamless pipe&tube <5")	CW + annealed	≥ 552	≥ 241	≥ 30
A600 (seamless pipe&tube >5")	CW + annealed	≥ 552	≥ 207	≥ 35
A600 (plate, sheet, strip HR plate)	Annealed	≥ 552	≥ 241	≥ 30
A600 (forgings)	Annealed	≥ 552	≥ 241	≥ 30
A690	Source: RCC-M Edition 2000. In bolt: Figure at 350°C (662°F).	≥ 550 (497)	240-400 (≥ 497)	≥ 30
A690 (rods, bars, wire)	CW + annealed or HW + annealed	≥ 586	≥ 241	≥ 30
A690 (seamless pipe&tube >5")	HW or HW + annealed	≥ 517	≥ 172	≥ 35
A690 (seamless pipe&tube <5")	CW + annealed	≥ 586	≥ 241	≥ 30
A690 (seamless pipe&tube >5")	CW + annealed	≥ 586	≥ 207	≥ 35
A690 (plate, sheet, strip HR plate)	Annealed	≥ 586	≥ 241	≥ 30
A690 (forgings)	Annealed	≥ 586	≥ 241	≥ 30

Table 2 – Weld Material Room Temperature Yield Stress (YS) and Ultimate Tensile Strength (UTS) Ref. 2 [Table 4-8]

	UTS (MPa)	YS (MPa)		Elongation (%)
		Room temperature	350°C (662°F)	
A182 – Coated electrode	≥ 550	≥ 250	≥ 190	≥ 30
A152 – Coated electrode	550 – 750	≥ 240	≥ 190	≥ 30

Question No. 3 A) (3)
Potential differences in residual stress profiles of the weld versus the plate.

Response to Question No. 3 A) (3)
Please consult the response provided to Question No. 3 A) (2).

There is no significant difference between the residual stresses at the weld and that of heat-affected zone (HAZ) in the plate. The measurement points utilized for residual stress measurements are taken in the HAZ and are considered representative of the weld itself.

In both the weld and HAZ of the plate, tensile residual stresses occur. Tensile residual stresses are caused by compression plastic strains which occur due to the high heat input caused by welding [Ref. 3]. Specifically, tensile residual stress in weld and HAZ occurs by the following described processes. During the heating caused by welding, the heated portion exhibits compressive strain because its thermal expansion is constrained by surrounding portions which received less heat input and do not significantly expand. Then

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during the cooling that follows, the heated portions like weld metal and HAZ exhibit tensile strain, because the surrounding relatively less heated portions do not significantly shrink. This process occurs in both weld metal and the HAZ. Since the HAZ yield at first in compression and then in tensile, generally speaking, tensile residual stresses at the yield stress level are caused by welding when the strains due to compressive yielding correspond to more than twice of the yield strain of the material. As for Alloy 600, the tensile residual stresses at the yield stress level are caused when the difference between the initial temperature of itself and the maximum temperature due to welding reaches more than approximately 300°C[Note 1].

The difference between the initial temperature and the maximum temperature of both the weld and HAZ in the plate made of Alloy 600 become bigger than 300°C due to welding. As a result and as mentioned above, tensile residual stresses occur as part of the cooling process. Therefore residual stresses at both the weld and the HAZ are considered to be on the same level.

Note 1:
Elastic stress σ is linearly related to elastic strain ε by means of the Young's modulus (Hook's law).

$$\sigma=E\varepsilon$$

Where E is the Young's modulus.

Thermal strain from constraining thermal expansion by the temperature difference ΔT is given by following relationship.

$$\varepsilon=\alpha\ \Delta T$$

Physical property values of Alloy 600 are as follows:

- Linear expansion coefficient: $1\times10^{-5}\,°C^{-1}$
- Yield stress: 300MPa
- Young's modulus: 200GPa

Using these relationships, the temperature difference ΔT which causes twice as high compressive strain as yield strain of the material is calculated.

$$2\ \sigma/E=\alpha\ \Delta T$$

$$\Delta T=2\sigma/E/\alpha = 2\times(300\times10^{6})\ /\ (200\times10^{-9})/\ (1\times10^{-5})$$

$$= 300\ °C$$

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Question No. 3 A) (4)
How is the error in the residual stress measurement on the plate as compared to the error of similar analytical residual stress values in the weld material?

Response to Question No. 3 A) (4)
The question as stated in the RAI is related to the difference between residual stress measurements actually taken in-situ, compared to those produced from analytical simulation of residual stresses. This was not the intent of the residual stress analysis documented in the Report 1001077.401[Ref. 4].

In the documentation of the acceptance of waterjet peening for Callaway, Report 1001077.401[Ref. 4], the analytical analysis is not performed to demonstrate an accurate analytically determined stress state versus a measured stress state. Rather, the purpose of the analytical study is to confirm that the compressive inner diameter (ID) surface stress state created by WJP is maintained following the application of plant operating cycles of pressure and temperature.

As stated in Report 1001077.401[Ref. 4] the finite element analytical model of the peened component is manipulated to create a residual stress state on the ID surface that matches that stress state measured during WJP qualification testing (provided by the peening vendor). As stated in 1001077.401[Ref. 4] the analytically determined stress state is conservative relative to that actually measured in similar plates following peening. That is to say that the analytical stress state is less compressive in magnitude and depth than that actually measured following WJP.

As delineated in Section 4.3 of Report 1001077.401[Ref. 4], the approach taken analytically was to reproduce in a simulation the effects of WJP. The methodology developed for this simulation, as documented in Report 1001077.305[Ref. 5], is used to determine if there is any potential of compressive residual stress relaxation (stress washout) effects due to long term operations of the plant. Moreover, when this methodology was used to simulate the effect of WJP for Callaway, a comparison to the actual achieved test data (measured residual stress values from mockups) was performed and documented in Report 1001077.305[Ref. 5]. As concluded in Section 5.0 of Report 1001077.305[Ref. 5] and relative to the reactor vessel nozzles (hot and cold legs), the methodology was concluded to be representative of the peened stress state obtained from measured testing. The magnitude of the surface stress achieved analytically is conservative when compared to testing results, inclusive of the general slope of the compressive stresses and achieved compressive stress depth. Thus, the manner in which the analytical stress state is achieved is not an issue, only that the calculated stress state matches the measured residual stress state following peening in magnitude and profile (stress magnitude and stress depth).

This finite element model was then subjected to the full series of plant operating transients (pressure and temperature) in an elastic plastic analysis in order to show that the operating cycles did not "washout" or eliminate the compressive stresses on the ID surface at plant operating conditions. There is no concern relative to the error in the residual stress methodology, as the analytical results are compared directly and validated with measured WJP results, and it is demonstrated that the analytical results which are used in the subsequent stress analysis are conservative.

Given the conservative nature of the utilized analytical methodology and type of finite element model developed for the reactor vessel nozzle and weld area, the simulated effects of WJP on both plate and weld material can be considered representative of actual WJP effects at Callaway. Accordingly, errors or uncertainties attributed to residual stress measurements are limited to X-ray diffraction techniques for obtaining actual residual stress values from the mockups. An assessment of these uncertainties was performed in Report DUS-160056[Ref. 6], as summarized in Section 3.4 of Report 1001077.401[Ref. 4]. Based on this assessment and pursuant to ASTM standards E915 and E2860, the X-ray diffraction techniques utilized met the acceptance criteria requirements of these ASTM standards. As stated in Section 3.4 of Report 1001077.401[Ref. 4], accounting for this acceptance criteria in the as measured residual stress values of the mockups demonstrates mitigated stresses are produced to the specified depths, and that the threshold for crack initiation is at least +10-ksi, thus providing margin for acceptance of the measurement uncertainties.

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Question No. 3 A) (5)
How do the original tensile stresses in the plate mockup compare to stresses in the weld in the field?

Response to Question No. 3 A) (5)
The original tensile stresses in the plate mockup are assumed to be equivalent or higher than the weld in the field due to the process for which the mockup is fabricated. Especially, tensile stresses of the weld surface of the plate mockup are induced by grinding, which is recognized as the method that creates extremely high tensile stress. The presence of these original residual stresses prior to WJP was confirmed in Report DUS-150319[Ref. 7].

Question No. 3 B)
Provide the tabular data used to demonstrate compliance with the criteria for depth of compression in the mockup, including error associated with measurement.

Response to Question No. 3 B)
Table 3 shows the residual stress measurement results of the plate mockup (TP No. 47 & 48) described in the Figure 5.1.6, Test 1, of Report DUS-150319[Ref. 7]. For Callaway, site implementation of WJP was conducted in a manner where the WJP application pattern was identical to that of what was utilized in for qualification testing to achieve the WJP effective range of a diameter of 40 mm [1.57"] (i.e., distance from the WJP nozzle application center is 20 mm [0.79"] radially). It is important to understand that the 20 mm [0.79"] radial boundary was established as part of the qualification program by measuring the effects of WJP at three depths (0 mm [0.000"], 0.5 mm [0.020"] and 1.0 mm [0.039"]) at six radial locations (0 mm [0.00"], 15 mm [0.59"], 20 mm [0.79"], 25 mm [0.98"], 30 mm [1.18"], and 35 mm [1.38"]). Table 3 shows that a measured WJP depth of 1 mm [0.039"] was achieved up to 20 mm [0.79"]; however, residual stress measurements beyond the 20 mm [0.79"] location did not achieve the depth requirement of 1 mm [0.039"] delineated in Ameren Specification S-1085(Q)[Ref. 11].

Table 3 shows that there is in fact a peening effect beyond the 20 mm [0.79"] radial boundary down to a depth of 0.5 mm [0.020"] and up to a radial distance of 35 mm [1.38"]. Since the depth of peening effect was less than the Ameren Specification S-1085(Q)[Ref. 11] required 1 mm [0.039"] depth, the effects of peening beyond 20 mm [0.79"] are not considered for qualification and demonstration of the Mitsubishi WJP process.

Please consult the response provided to Question No. 3 A) (1) to understand how measurement uncertainties have been accounted for in the WJP program.

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Table 3 – Qualification Test 1 (TP47 + TP48)

	Distance from the application center (mm)	Distance from the surface (mm)	Residual Stress: The weld line direction (MPa)	Residual Stress: The orthogonal direction to the weld line (MPA)	Residual Stress: The average of the weld line direction and the orthogonal direction to the weld line (MPa)	
Before WJP	0 [0.00"]	0 [0.000"]	227	902	565	n/a
After WJP	0 [0.00"]	0 [0.000"]	-486	-585	-536	Mitsubishi WJP Process Qualification and Demonstration Basis Note 1
	0 [0.00"]	0.5 [0.020"]	-284	-264	-274	
	0 [0.00"]	1.0 [0.039"]	-40	-26	-33	
	15 [0.59"]	0 [0.000"]	-462	-556	-509	
	15 [0.59"]	0.5 [0.020"]	-231	-279	-255	
	15 [0.59"]	1.0 [0.039"]	-30	-62	-46	
	20 [0.79"]	0 [0.000"]	-492	-572	-532	
	20 [0.79"]	0.5 [0.020"]	-268	-271	-270	
	20 [0.79"]	1.0 [0.039"]	-1	-84	-43	
	25 [0.98"]	*0 [0.000"]*	*-541*	*-556*	*-549*	Not Considered in Qualification and Demonstration of the Mitsubishi WJP Process Basis Note 2
	25 [0.98"]	*0.5 [0.020"]*	*-157*	*-237*	*-197*	
	25 [0.98"]	*1.0 [0.039"]*	*24*	*-31*	*-4*	
	30 [1.18"]	*0 [0.000"]*	*-457*	*-363*	*-410*	
	30 [1.18"]	*0.5 [0.020"]*	*-136*	*-118*	*-127*	
	30 [1.18"]	*1.0 [0.039"]*	*20*	*-24*	*-2*	
	35 [1.38"]	*0 [0.000"]*	*-434*	*-254*	*-344*	
	35 [1.38"]	*0.5 [0.020"]*	*-136*	*-114*	*-125*	
	35 [1.38"]	*1.0 [0.039"]*	*103*	*115*	*109*	

NOTES:

Note 1: All directions of residual stress measurements were determined to achieve a compressive state up to a depth of 1.0 mm [0.039"], thus the qualified radial boundary (from center of WJP nozzle) was established at 20 mm [0.79"].

Note 2: Not all directions of residual stress measurements (shaded areas) were determined to achieve a compressive state up to a depth of 1.0 mm [0.039"]. Since this did not meet Ameren Specification S-1085(Q)[Ref. 11] requirements for the reactor vessel nozzles, the effect of WJP beyond the 20 mm [0.79"] radial boundary is not considered in the qualification and demonstration of the Mitsubishi WJP process.

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Question No. 3 C)
Does the number of water jet peening applications used in the mockup equal the number of applications used in the field at Callaway for the subject welds?

Response to Question No. 3 C)
Yes, the number of WJP applications are the same as WJP was applied 4 times for qualification testing and as part of implementation at Callaway, as documented in Report NS-RPT-100004[Ref. 8]. Note the following:

- Qualification Testing: WJP nozzle travel speed was set at 100 mm/min [3.94 "/min], i.e., the upper limit in allowable range of 96mm/min [3.78"/min] to 100 mm/min [3.94"/min], in each application of WJP and repeated 4 times on the mockup.

- Callaway Implementation: WJP nozzle travel speed was set nominally at 98 mm/min [3.86 "/min], i.e., conservatively stay within the allowable range of 96mm/min [3.78"/min] to 100 mm/min [3.94"/min], since higher travel speeds beyond 100 mm/min [3.94"/min] will result in less WJP effect, in each application and repeated 4 times on the Callaway nozzles.

Question No. 3 D)
Discuss whether the peening qualification was performed on a mock up that is the same size as in the field (i.e., same pipe diameter and wall thickness). If not, discuss the impact of this difference on the peening applied to the mock-up specimens, and how it will provide the same results as peening on the welds in the field.

Response to Question No. 3 D)
The mockup used for qualification testing was not the same size as found in the field. As described in Report DUS-150319[Ref. 7] it was a flat plate with a thinner cross-section. The flat plate (200 mm [7.87"] × 200 mm [7.87"] × 20 mm [0.78"]) was used because the diameter of the actual reactor vessel nozzle inner diameter is nominally 700 mm [27.56"] and large enough to ignore the curvature when considering the size of the WJP effective range of 20 mm [0.78"] radially (refer to the image below). As shown below in Figure 2, the comparative difference between a flat plate and the inner curvature of the reactor vessel nozzle is 0.57 mm [0.022"]. The effect of this small differences is considered insignificant since the as implemented application distance, i.e., distance between the bottom of the WJP nozzle and the peened surface, was set and controlled at 130 mm [5.12"]; however, qualification testing as it relates to WJP effectiveness was performed at the upper allowable limit 140 mm [5.51"], as found in Report DUS-150319[Ref. 7].

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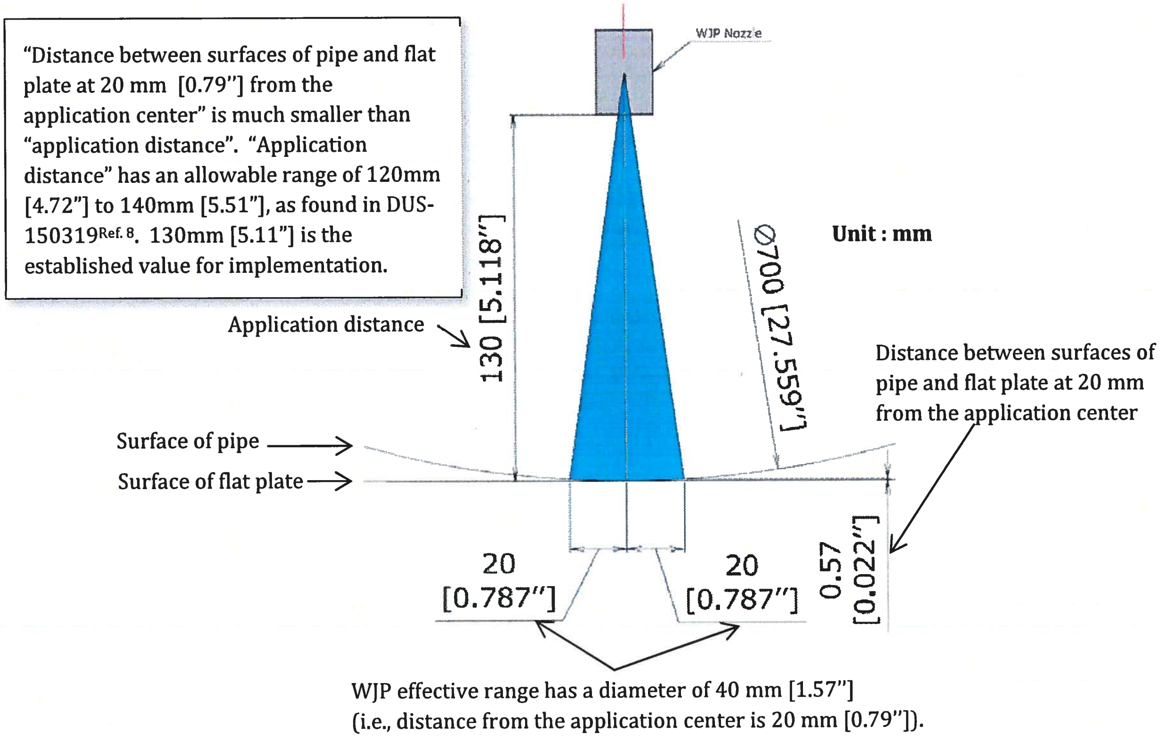

Figure 2 – Image of WJP Application to Plate Versus Pipe with Curvature

Question No. 3 E)
Page 8 of 14 of the relief request states that the test coupons are thinner than the actual pipe wall thickness, but it is thick enough. Discuss whether this statement is verified and validated based on the testing on mockup of the actual pipe wall thickness and the thinner test coupon.

Response to Question No. 3 E)
The test coupons used for qualification testing are thinner than the actual Callaway reactor vessel nozzles. As found in Section 3.1.2.6 and 5.1.4 of Report 1001077.401[Ref. 4], components which are fabricated from thicker materials (greater than a few millimeters), will see a greater influence from the WJP effect. The surface compressive residual stresses are created by the WJP process when a small surface layer of the material undergoes plastic deformation. This small plastic deformation only affects the surface of the material since the unaffected material underneath works to restrain the surface deformation which results in a surface compressive surface layer. If the materials are thin (less than a few millimeters), then the induced stresses at the surface can cause the material underneath the surface layer to deform, thus reducing its ability to restrain the surface deformation.

Based on this, utilizing a test coupon which is thinner than the actual reactor vessel nozzle wall thickness is conservative. For the qualification testing performed, the thinner test coupon provides less material restraint due to lack of surrounding material, which allows the resultant compressive residual stress to partially relax at application of WJP.

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Question No. 4 (a)
Describe whether during qualification tests a thin layer of oxide is applied to the mockup so that qualification test is performed to mimic the field condition. If not, justify why a thin oxide layer was not removed prior to peening in the field.

Response to Question No. 4 (a)
A thin layer of oxide was not applied to the mockup given its lack of ability to influence the effects of WJP. The reasoning for this is found in Section 3.3.2 of Report MRP-335[Ref. 9], as quoted below:

"The oxide thickness on plant materials are in the neighborhood of 1 μm thick, and thus are much too thin and too structurally weak to interfere with peening, which involves dimensions on the order of 1 mm, i.e., 1000 times larger."

Question No. 4 (b)
Discuss whether peening qualification tests were performed to show that the thin oxide layer does not change the peening effect on the subject weld. If not, discuss how the qualification tests are sufficient to demonstrate the compressive effect of peening in the field.

Response to Question No. 4 (b)
Please consult the response provided to Question No. 4 (a).

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References

Ref. 1: "Standard for X-Ray Stress Measurement (2002) Iron and Steel (JSMS-SD-5-02)", The Society of Materials Science, Japan

Ref. 2: François Cattant, "Materials Ageing in Light Water Reactors - Handbook of Destructive Assays", Editions Lavoisier, 2014

Ref. 3: T.Terasaki, Journal of the Japan Welding Society, Vol. 78, No. 2 P55, 2008.

Ref. 4: Report 1001077.401, "Mitigation of Reactor Vessel Hot and Cold Leg Nozzle DMWs and Reactor Vessel Bottom Mounted Nozzles and Associated DMWs by Water Jet Peening"

Ref. 5: Report 1001077.305, "Development of Water Jet Peening Simulation Finite Element Models"

Ref. 6: Report DUS-160056, "Calculation Method and Uncertainties of Residual Stress by the X-rays Stress Measurement"

Ref. 7: Report DUS-150319, "Water Jet Peening Process Qualification Test Report"

Ref. 8: Report NS-RPT-100004, "WJP Implementation Final Report for Callaway"

Ref. 9: Report EPRI MRP-335, Revision 3-A, "Materials Reliability Program Topical Report for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement [Peening]"

Ref. 10: WJP Work Instruction WJP-WI-103-A-02, "High Pressure Pump System (HPPS) Flow Meter Calibration"

Ref. 11: Ameren Specification S-1085 (Q), "Specification for Mitigation of Reactor Vessel Hot and Cold Leg Nozzle Dissimilar Metal Welds and Reactor Vessel Bottom Mounted Nozzles and Associated Dissimilar Meta Welds at Callaway Energy Center"

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Appendix 1 – Principle and Method of X-ray Stress Measurement Ref. 1

(1) Principle

In X-ray stress measurement of a crystalline material, the strain in the crystal lattice is measured and the associated residual stress is determined from the elastic constants assuming a linear elastic distortion of the appropriate crystal lattice plane (Figure 1).

When the X-ray beam reaches the surface of a crystalline material, it is diffracted by crystal lattice. The diffraction occurs only when the wavelength of X-ray, the beam angle and the lattice spacing satisfy the relationship called Bragg's Law (Figure 2). By using this relationship, lattice spacing *d* is estimated.

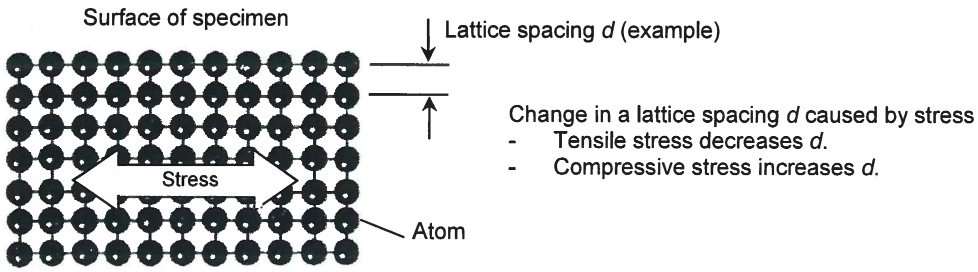

Figure 1 – Schematic Illustration for Effect of Stress on Lattice Spacing of a Metal

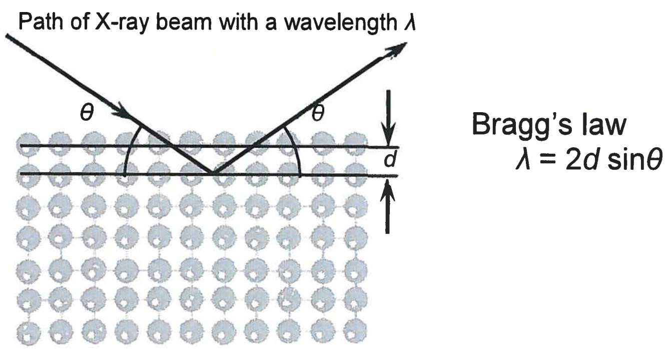

Figure 2 – Bragg's Law

(2) Apparatus and Method

- Figure 3 shows an example of the apparatus for X-ray stress measurement system (diffractometer). This consists of a head equipped with an X-ray emission source and a detector, a sample stage and computer system for data processing.
- To carry out X-ray stress measurements, the specimen is placed on the sample stage of the X-ray diffractometer and exposed to an X-ray beam that causes diffraction patterns depending on the beam angle and the lattice spacing of the sample. By scanning through an arc of the radius about the specimen (changing the beam angle), the intensity of diffracted X-ray is measured. As a result, the diffraction peaks can be positioned and the necessary calculations are made for quantification of stress.
- The residual stress profile in the depth direction can be determined by successive material removal by electro polishing and subsequent stress analyses.

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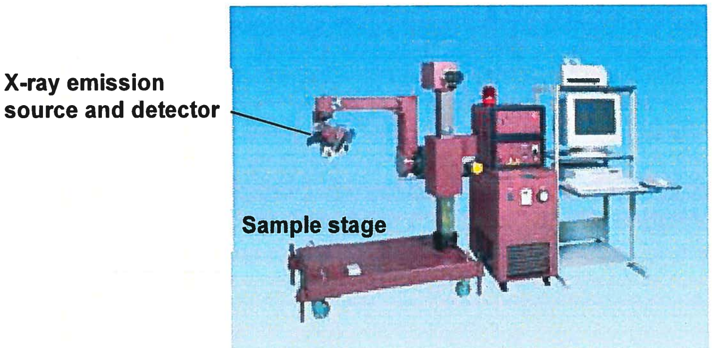

Figure 3 – Appearance of X-ray Stress Measurement System

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