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South Carolina Electric & Gas Co. (SCE&G)
Virgil C. Summer Nuclear Station Unit 1 (VCSNS)

Attachment 5
Westinghouse LTR-PAFM-12-86 “Flaw Tolerance Evaluation to Support Re-Categorization of V.C. Summer Unit 1 Steam Generator Nozzle to Safe End Dissimilar Metal Weld Inspection Requirements.”

LTR-PAFM-12-86-NP
Revision 0

Flaw Tolerance Evaluation to Support Re-categorization of V. C. Summer Unit 1 Steam Generator Nozzle to Safe End Dissimilar Metal Weld Inspection Requirements

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1.0 INTRODUCTION

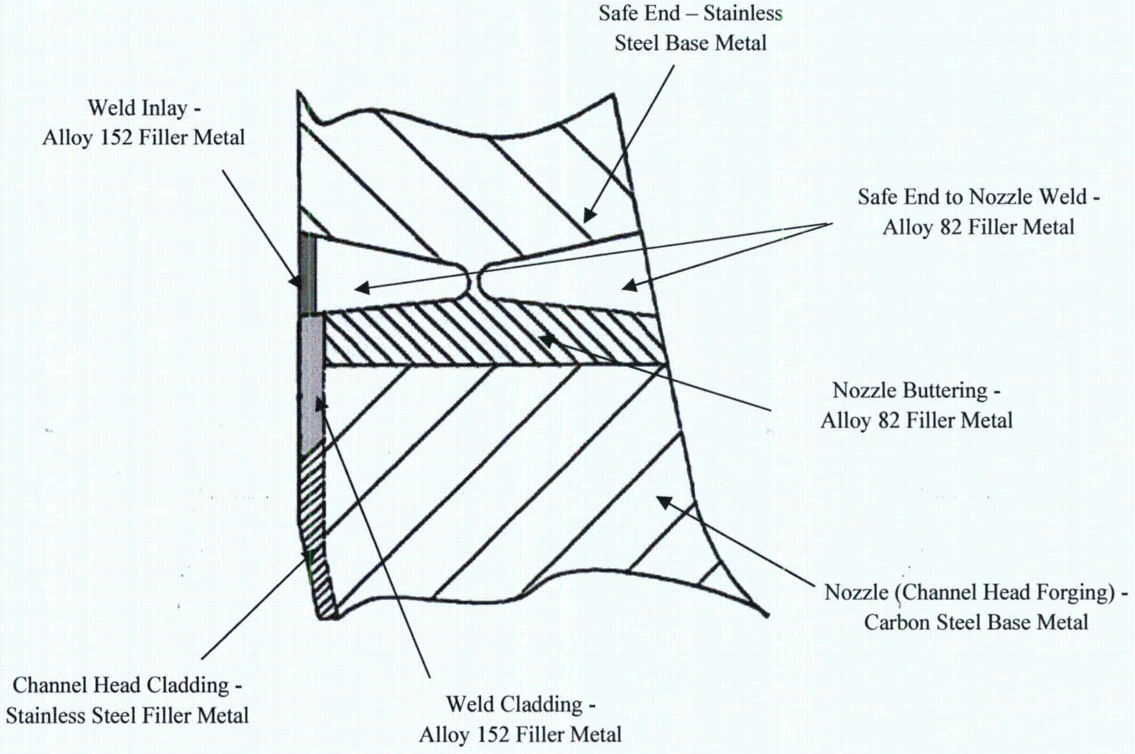
The V. C. Summer Unit 1 replacement steam generators were fabricated with factory welded forged stainless steel safe ends attached to the primary inlet and outlet nozzles with Alloy 82 welds (Figure 1-1). The Alloy 82 weld material is sealed with Alloy 152 cladding on the steam generator channel head integral nozzle inside diameter (including the Alloy 82 weld deposited buttering) and also with Alloy 152 inlay on the inside surface of the dissimilar metal (DM) nozzle to safe end welds (Reference 1). The nominal thicknesses for the Alloy 152 cladding and Alloy 152 weld inlay are 0.25 inch and 0.13 inch respectively (Reference 2). The Alloy 152 weld material provides a barrier to isolate the Primary Water Stress Corrosion Cracking (PWSCC) susceptible Alloy 82 weld material from the primary water environment.

According to the examination requirements of ASME Code Case N-770-1 (Reference 3), these DM weld regions must be inspected at a higher frequency than the 10 year frequency normally required by ASME Section XI even though they were manufactured in a factory controlled environment in 1994 before Code Case N-770-1 was made mandatory. The required inspection frequencies for the replacement steam generator inlet nozzle and outlet nozzle DM welds are 5 years and 7 years respectively in accordance with ASME Code Case N-770-1.

Since the DM welds of these steam generator nozzles do not have susceptible material exposed to the primary water environment because of the Alloy 152 weld inlay/cladding on the inside surface, it would be appropriate to re-categorize them as Inspection Item G "Un-cracked butt weld mitigated with an inlay" according to the Code Case. The DM welds for these nozzles are currently being categorized as Inspection Items A-2 and B as "unmitigated butt welds" in accordance with Code Case N-770-1. In order to support the re-categorization, a number of specific items must be addressed. These items (a total of 12) were specified in a response to public question number 29, shown in Appendix A of this report, which was received during a public meeting on Code Case N-770-1 implementation. The primary objective of this letter report is to provide the technical basis for re-categorizing the DM welds of these replacement steam generator primary nozzles. The following sections provide a discussion of the methodology, geometry, loading and the crack growth analysis performed to demonstrate the integrity of the Steam Generator inlet and outlet nozzle DM weld inlays. The crack growth analysis provides a treatment of the potential for PWSCC in the Alloy 152 weld inlay, corresponding to Items 11 and 12 in the public question response shown in Appendix A of this report.

Figure 1-1

V. C. Summer Unit 1 Replacement Steam Generator
Inlet/Outlet Nozzle to Safe End Dissimilar Metal Weld Configuration



2.0 METHODOLOGY

In order to demonstrate adequacy of the Steam Generator inlet and outlet nozzle DM weld inlay thickness against PWSCC, it is necessary to perform a crack growth analysis by postulating a flaw in the inlay. The size of the flaw was assumed to be that which might go undetected during the upcoming baseline inspection in 2014. The results of the crack growth analysis can be used to determine a lower bound service life required for the postulated flaw to grow through the thickness of the Alloy 152 weld inlay when subjected to PWSCC crack growth mechanism. The service life required to grow through the Alloy 152 weld inlay should be more than 10 Effective Full Power Years since the required examination interval is 10 years for Inspection Item G in accordance with Code Case N-770-1.

In order to perform the crack growth analysis, it is necessary to establish the stresses, crack geometry and the material properties at the locations of interest. The applicable loadings which must be considered consist of piping reaction loads acting at the dissimilar metal weld regions and the welding residual stresses which exist in the region of interest. The plant specific piping loads at the steam generator primary nozzle DM weld locations were based on the latest reactor coolant loop piping analysis of record (Reference 4). In addition to the piping loads, the effects of welding residual stresses (Reference 5) due to the fabrication process of the steam generator nozzle DM welds are also considered. For PWSCC, the crack growth model for the Alloy 152 weld inlay material is based on that given in MRP-115 (Reference 6) for Alloy 182 weld material with an improvement factor of 100. This improvement factor, although higher than that recommended in the public question response shown in Appendix A, is a more accurate improvement factor for Alloy 152 based on the reported data documented in NUREG/CR-7103 (Reference 7) as well as those from GE Global Research (Reference 8). A more detailed discussion of the improvement factor is provided in Section 5.0.

The nozzle geometry and piping loads used in the crack growth analysis are shown in Section 3.0. A discussion of the plant specific welding residual stress distributions used for the DM welds is provided in Section 4.0. The PWSCC crack growth analysis is discussed in Section 5.0. Section 6.0 provides a discussion on the adequacy of the Steam Generator inlet and outlet nozzle DM weld inlay thickness against PWSCC.

3.0 NOZZLE GEOMETRY AND LOADS

The dissimilar metal weld geometry for the V. C. Summer Unit 1 Steam Generator inlet and outlet nozzle is based on the nozzle details drawings (Reference 1). The Steam Generator inlet and outlet nozzle geometry and normal operating temperature are summarized in Table 3-1.

Table 3-1
V. C. Summer Unit 1 Steam Generator Nozzle DM weld Geometry and Normal Operating Temperature

Dimension	Inlet Nozzle	Outlet Nozzle
DM Weld Inside Diameter (inch)	31.03	31.03
DM Weld Thickness (inch)	4.81	4.81
DM Weld Alloy 152 Inlay Nominal Thickness (inch)	0.13	0.13
Normal Operating Temperature	618°F	556°F

The normal operating piping reaction loads at the Steam Generator inlet and outlet nozzle DM weld locations are based on the latest reactor coolant loop piping analysis of record (Reference 4) and are summarized in Table 3-2. These loads are used in PWSCC crack growth analysis.

Table 3-2

V. C. Summer Unit 1 Steam Generator Nozzle Normal Operating Piping Loads

Steam Generator Nozzle	Loading	Forces (kips)	Moments (in-kips)		
		Fx (Axial)	Mx (Torsion)	My (Bending)	Mz (Bending)
Inlet Nozzle	Deadweight	3.66	-43.9	1.5	173.8
Inlet Nozzle	Normal Operating Thermal	-225.4	1102.2	647.7	11750.3
Outlet Nozzle	Deadweight	13.01	62.9	14.4	32.3
Outlet Nozzle	Normal Operating Thermal	60.08	-1641.1	3882.2	-6424.8

4.0 Dissimilar Metal Weld Residual Stress Distribution

The welding residual stresses used in the PWSCC crack growth analysis were obtained from the finite element stress analysis (Reference 5) based on the plant specific Steam Generator inlet and outlet nozzle DM weld configuration (Reference 1) as well as taking into consideration of the as-built configuration. Both steam generator inlet and outlet nozzle DM weld configurations are identical and Figure 1-1 shows a sketch of the steam generator nozzle DM weld configuration. The finite element analysis in Reference 5 is based on a two-dimensional axi-symmetric model of the steam generator inlet and outlet nozzle dissimilar metal weld region. The finite element model geometry includes a portion of the low alloy steel nozzle, the stainless steel safe end, a portion of the stainless steel piping, the DM weld attaching the nozzle to the safe end, and the stainless steel weld attaching the nozzle safe end to the piping. The finite element analysis also assumes a 360° inside surface weld repair with a repair depth of 50% through the dissimilar metal weld thickness, which is consistent with MRP-287 guidance (Reference 9). The following fabrication sequence including an assumed 50% inside surface weld repair was simulated in the finite element residual stress analysis based on the information provided in the Steam Generator nozzle details drawings (Reference 1):

- The steam generator nozzle is buttered with weld-deposited Alloy 82 material.
- The inside surface region of the buttering and the nozzle end is clad with weld deposited Alloy 152 material.
- The nozzle and buttering are post weld heat treated (PWHT).
- The nozzle is welded to the safe end forging with Alloy 82 weld and a layer of Alloy 152 on the inside surface.
- A repair cavity (50% of original weld thickness) is machined out of the weld region.
- The repair cavity is filled with Alloy 82 weld metal with a layer of Alloy 152 on the inside surface.
- The outside and inside diameters of the weld region are machined to final size.
- A shop hydrostatic test is performed.
- The safe end is machined with the piping side weld prep.
- In order to simulate the field weld between the safe end and the attached piping, the safe end is welded to a long segment of stainless steel piping using a stainless steel weld.
- A plant leakage test is performed.

A detailed discussion of the finite element residual stress analysis is provided in Reference 5. Based on the results of the residual stress analysis, residual stress profiles under normal operating condition along various paths through the DM weld and inlay thickness were obtained from Reference 5 and the limiting through-wall welding residual stress profiles were used in the crack growth analysis.

5.0 PWSCC CRACK GROWTH ANALYSIS

A PWSCC crack growth analysis was performed by postulating a surface flaw in the inlay that could go undetected during the baseline inspection to be performed in 2014. Eddy current testing (Reference 10) demonstrated the ability to detect a surface flaw as shallow as 0.3 mm (0.012 in.) in depth and as short as 1.5 mm (0.06 in.) in length at the weld inlay. An initial flaw with a depth (0.065 in.) which is half the inlay thickness is postulated in the Alloy 152 weld inlay. The length of the postulated axial flaw is assumed to be the width of the Alloy 152 weld inlay resulting in an aspect ratio (length/depth) of 10 and the length of the postulated circumferential flaw is assumed to be 360° around the circumference. As a result, the postulated flaws in the PWSCC crack growth analyses are much larger than those that could be reasonably missed during the 2014 baseline inspection.

The results of the crack growth analysis can be used to determine the service life required for the postulated flaw to grow through the thickness of the Alloy 152 weld inlay. Crack growth due to PWSCC is calculated for both axial and circumferential flaws using the normal operating condition steady-state stresses. For axial flaws, the stresses included pressure and residual stresses, while for circumferential flaws, the stresses considered are pressure, 100% power normal thermal expansion, deadweight and residual stresses. The input required for the crack growth analysis is basically the information necessary to calculate the crack tip stress intensity factor (K_I), which depends on the geometry of the crack, its surrounding structure and the applied stresses. The geometry and loadings for the nozzles of interest are discussed in Section 3.0 and the applicable residual stresses used are discussed in Section 4.0. Once K_I is calculated, stress corrosion crack growth can be calculated using the applicable crack growth rate for the nickel-base alloy material (Alloy 182) from MRP-115 (Reference 6) with an improvement factor for Alloy 152 weld inlay material since the crack growth rate for Alloy 152 is slower than that for Alloy 182.

Using the applicable stresses at the dissimilar metal welds, the crack tip stress intensity factors can be determined based on the stress intensity factor expressions from Reference 11. The through-wall stress distribution profile is represented by a 4th order polynomial:

$$\sigma\left(\frac{a}{t}\right)=\sigma_0+\sigma_1\left(\frac{a}{t}\right)+\sigma_2\left(\frac{a}{t}\right)^2+\sigma_3\left(\frac{a}{t}\right)^3+\sigma_4\left(\frac{a}{t}\right)^4$$

where,

σ_0, σ_1, σ_2, σ_3, and σ_4 are the stress profile curve fitting coefficients,

a is the distance from the wall surface where the crack initiates;

t is the wall thickness;

σ is the stress perpendicular to the plane of the crack.

The stress intensity factor calculations for semi-elliptical inside surface axial and circumferential flaws are expressed in the general form as follows:

$$K_I = \sqrt{\frac{\pi a}{Q}} \sum_{j=0}^{4} G_j(a/c, a/t, t/R, \Phi)\, \sigma_j \left(\frac{a}{t}\right)^j$$

where:

a:	Crack Depth
c:	Half Crack Length Along Surface
t:	Thickness of Cylinder
R:	Inside Radius
Φ:	Angular Position of a Point on the Crack Front
G_j:	G_j is influence coefficient for j^{th} stress distribution on crack surface (i.e., G_0, G_1, G_2, G_3, G_4).
Q:	The shape factor of an elliptical crack is approximated by: $Q = 1 + 1.464(a/c)^{1.65}$ for $a/c \leq 1$ or $Q = 1 + 1.464(c/a)^{1.65}$ for $a/c > 1$.

The influence coefficients at various points on the crack front can be obtained by using an interpolation method. Once the crack tip stress intensity factors are determined, PWSCC crack growth calculations can be performed using the crack growth rate below with the applicable normal operating temperature.

The PWSCC crack growth rate used in the crack growth analysis for Alloy 152 weld inlay material is based on the EPRI recommended crack growth curve for Alloy 182 material (Reference 6) with an improvement factor of 100 as follows:

$$\frac{da}{dt} = \frac{1}{IF} \exp\left[-\frac{Q_g}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \alpha(K)^{\beta}$$

where:

$\frac{da}{dt}$	=	Crack growth rate in m/sec (in/hr)
Q_g	=	Thermal activation energy for crack growth = 130 kJ/mole (31.0 kcal/mole)
R	=	Universal gas constant = 8.314×10^{-3} kJ/mole-K (1.103×10^{-3} kcal/mole-°R)
T	=	Absolute operating temperature at the location of crack, K (°R)
T_{ref}	=	Absolute reference temperature used to normalize data = 598.15 K (1076.67°R)

α = Crack growth amplitude
= 1.50×10^{-12} at 325°C (2.47×10^{-7} at 617°F)
β = Exponent = 1.6
K = Crack tip stress intensity factor MPa$\sqrt{m}$ (ksi$\sqrt{in}$)
IF = 100 for Alloy 152 weld

This improvement factor of 100, although higher than that recommended in the public question response shown in Appendix A of this report, is a more realistic improvement factor for Alloy 152 welds based on the reported data documented in NUREG/CR-7103 (Reference 7) as well as those from GE Global Research (Reference 8). As shown in Figure 5-1, nearly all the measured stress corrosion propagation rates for the Alloy 52/152 welds are less than $1\text{x}10^{-8}$ mm/s with most less than $3\text{x}10^{-9}$ mm/s. There is also no difference between the crack growth rates of Alloy 52 and 152 welds shown in Figure 5-1; therefore the improvement factor of 100 for Alloy 52 recommended in Appendix A public question response is also applicable to Alloy 152 welds. Similarly, the reported data from GE Global Research (Reference 8) that are shown in Figure 5-2 also indicated low PWSCC crack growth rates for Alloy 52/152 welds and supports the use of a more accurate improvement factor of 100 for Alloy 152 welds. Although one weld tested by one laboratory exhibited higher growth rate of $5.7\text{x}10^{-8}$ mm/s (References 12, 13), an improvement factor to bound this data point is not necessary, because the industry approach for these nickel base alloys has been to use the 75th percentile PWSCC crack growth curve (Reference 6) instead of an upper bound curve. Therefore, the use of an improvement factor of 100 for Alloy 152 welds in the crack growth analysis based on 75th percentile of the reported data is the most accurate portrayal now available. The reported data used here was not available at the time of the public question response shown in Appendix A.

The normal operating temperature used in the crack growth analysis is 618°F and 556°F for the Steam Generator inlet and outlet nozzle respectively. The resulting PWSCC crack growth rates used in the crack growth analysis for the Alloy 152 weld inlay are as follows:

Steam Generator Inlet Nozzle Alloy 152 weld inlay:

$$da/dt = 1.537\text{x}10^{-14}(K)^{1.6} \text{ m/sec}$$

Steam Generator Outlet Nozzle Alloy 152 weld inlay:

$$da/dt = 3.128\text{x}10^{-15}(K)^{1.6} \text{ m/sec}$$

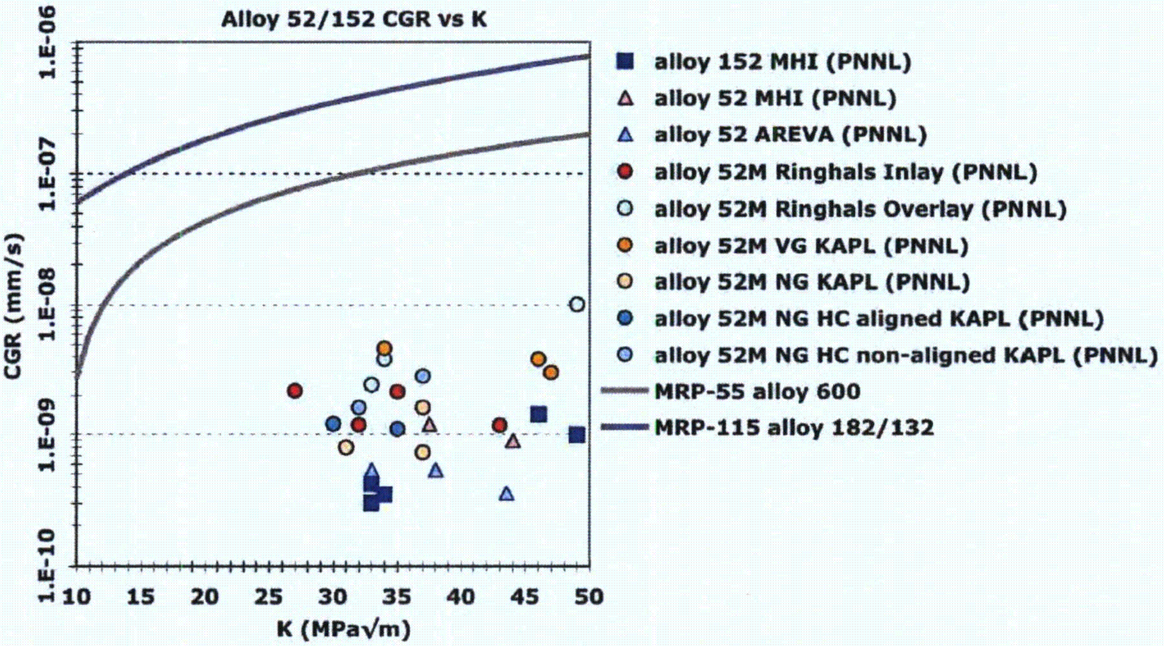


Figure 5-1: Summary of PNNL-Measured Constant K SCC Crack Growth Rates for Alloy 152/52/52M Weld Metals (Reference 7)

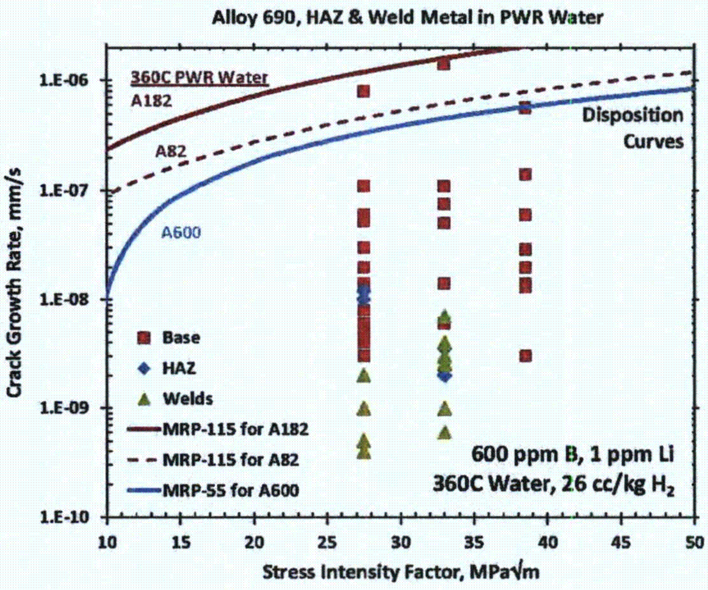


Figure 5-2: Summary of Crack Growth Rates Obtained by GE Research on Alloys 690, HAZ and Weld Metals in PWR Primary Water (Reference 8)

6.0 ADEQUACY OF DM WELD INLAY THICKNESS AGAINST PWSCC

In accordance with ASME Code Case N-770-1 (Reference 3), the volumetric examination interval for Inspection Item G "Un-cracked butt weld mitigated with an inlay" must not exceed 10 years. The PWSCC crack growth for a postulated surface flaw at the Alloy 152 weld inlay is calculated based on the normal operating condition piping loads and the plant specific welding residual stresses at the DM weld as well as the crack growth model in MRP-115 (Reference 6) with an improvement factor of 100. Both axial and circumferential inside surface flaws are considered in the crack growth analysis.

The PWSCC crack growth curves for the postulated axial and circumferential inside surface flaws in the replacement steam generator inlet and outlet nozzle Alloy 152 weld inlay are shown in Figures 6-1 and 6-2 respectively. The horizontal axis displays service life in Effective Full Power Years (EFPY), and the vertical axis shows the flaw depth in the weld inlay. The weld inlay thickness (0.13 inch nominal) is also shown in these figures for the respective flaw configurations. Based on the crack growth results from Figures 6-1 and 6-2, the service life required for the postulated surface flaws to grow through the weld inlay based on an improvement factor of 100 is tabulated in Table 6-1.

Table 6-1
Service Life Required to Grow Through the Alloy 152 Weld Inlay at the Steam Generator Inlet and Outlet Nozzle Based on An Improvement Factor of 100 over Alloy 182 Weld Crack Growth Rate

	Steam Generator Inlet Nozzle	Steam Generator Outlet Nozzle
Axial Flaw	10.8 EFPY	53 EFPY
Circumferential Flaw	18.3 EFPY	>70 EFPY

As shown in Table 6-1 as well as Figures 6-1 and 6-2, the service life required to grow through the Alloy 152 weld inlay is more than 10 Effective Full Power Years which is more than the required examination interval for Inspection Item G "Un-cracked butt weld mitigated with an inlay" in accordance with Code Case N-770-1.

Alloy 690 and the associated weld metals, Alloy 52 and Alloy 152, have been used in PWSCC susceptible Alloy 600 component repairs, mitigation and replacements. These high chromium nickel base alloys have been shown to be highly resistant to PWSCC in laboratory testing and have been free from any observed cracking in operating reactors for more than 20 years. In addition, the reactor coolant water chemistry during plant operation is monitored and maintained within specific limits. Contaminant concentrations are kept below the threshold know to be conducive to stress corrosion cracking with the major water chemistry control standards being included in the plant operation procedures as a condition for plant operation. As a result of careful water chemistry control and the fact that the Alloy 152 weld inlay is highly resistant to PWSCC, the results presented in Table 6-1 are conservative because the service life required for crack initiation was ignored and that the postulated initial flaw sizes in the weld inlay are much larger that those that could be reasonably missed during the baseline inspection in 2014. Furthermore, the additional service life required to result in leakage and pipe rupture after the posulated flaws have penetrated the Alloy 152 weld inlay was not considered, rendering the results even more conservative.

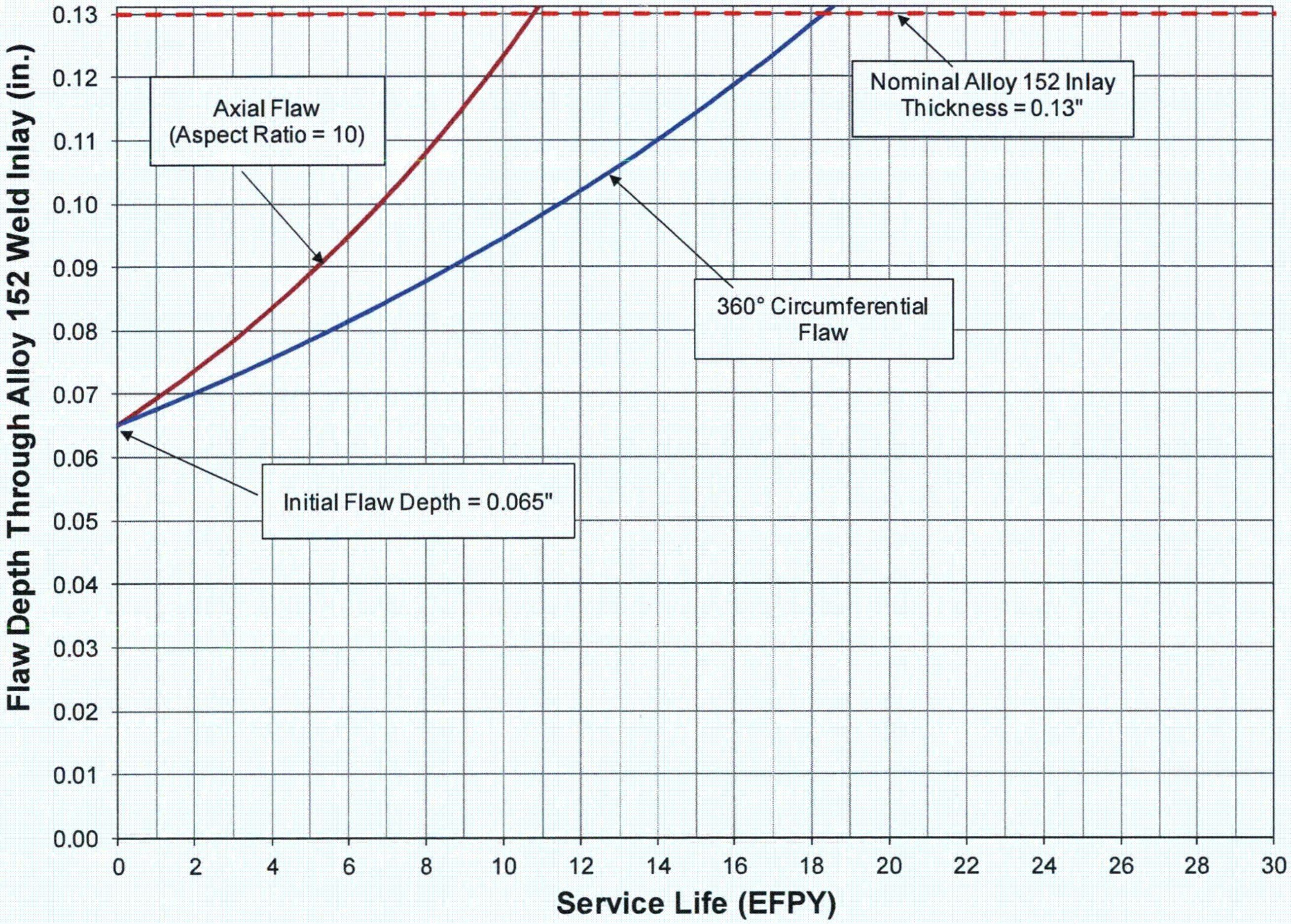
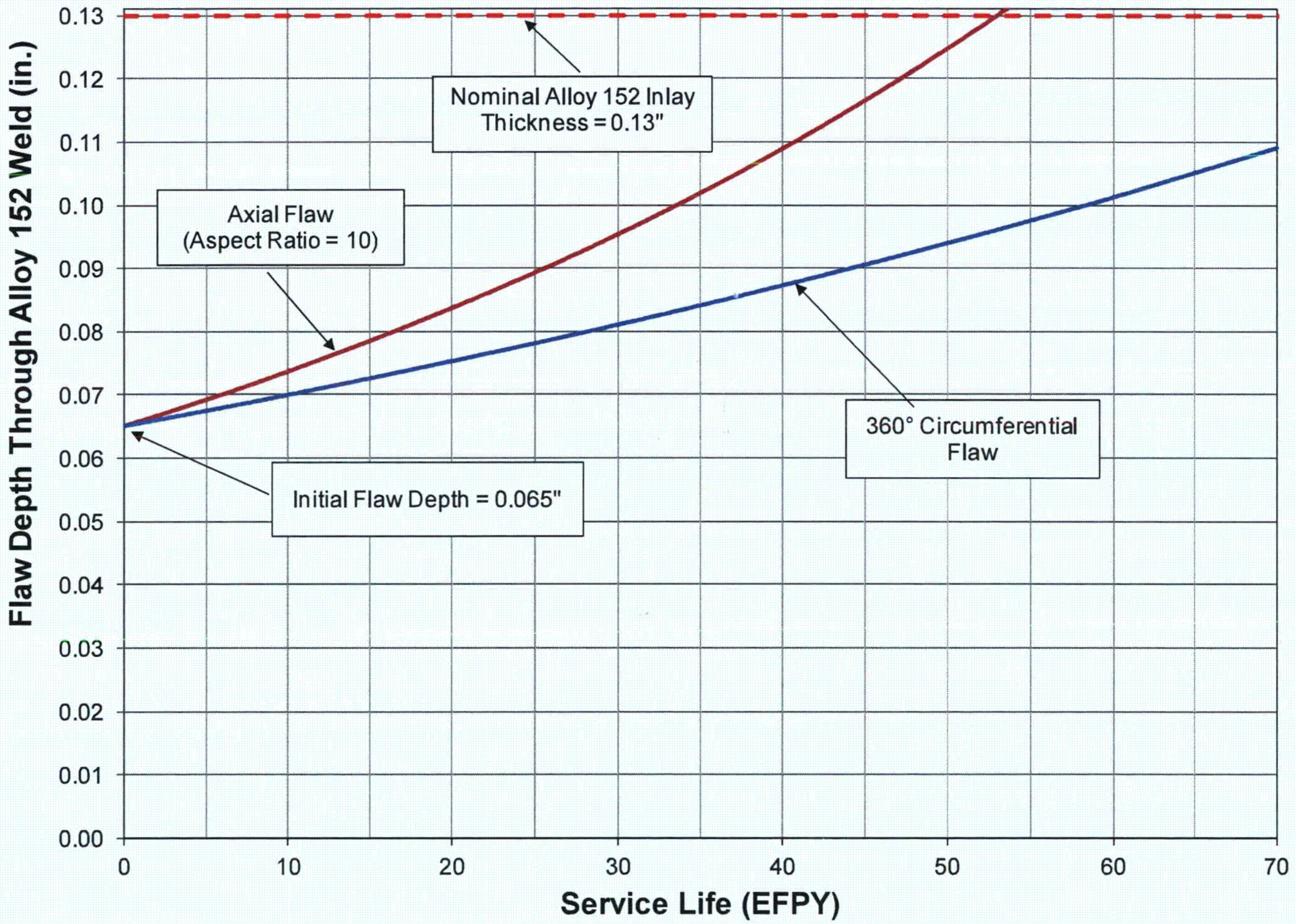


Figure 6-1: PWSCC Crack Growth Curve in Steam Generator Inlet Nozzle Alloy 152 Weld Inlay



*F*igure 6-2: PWSCC Crack Growth Curve in Steam Generator Outlet Nozzle Alloy 152 Weld Inlay

7.0 SUMMARY AND CONCLUSIONS

The V. C. Summer Unit 1 replacement steam generator inlet and outlet nozzle Alloy 82 DM welds including the buttering were sealed with Alloy 152 weld inlay/cladding to provide a barrier to isolate the Primary Water Stress Corrosion Cracking (PWSCC) susceptible DM weld material from the primary water environment. Since these DM welds do not have susceptible material exposed to the primary water environment, it would be appropriate to re-categorize them as Inspection Item G "Un-cracked butt weld mitigated with an inlay" according to Code Case N-770-1. The DM welds for the inlet and outlet nozzle DM welds are currently being categorized as Inspection Items A-2 and B as "unmitigated butt welds" in accordance with Code Case N-770-1 which must be inspected at a higher frequency than the 10 year frequency normally required by ASME Section XI. In order to support the re-categorization, PWSCC crack growth analyses were performed to provide a technical basis for re-categorizing the DM welds of these replacement steam generator primary nozzles by demonstrating the adequacy of the Steam Generator inlet and outlet nozzle DM weld inlay thickness against PWSCC corresponding to Items 11 and 12 in the public question response shown in Appendix A of this report.

For PWSCC, the crack growth model for the Alloy 152 weld inlay material is based on that given in MRP-115 for Alloy 182 weld material with an improvement factor of 100. This improvement factor, although higher than that recommended in the public question response shown in Appendix A, is a more accurate improvement factor for Alloy 152 weld based on the reported data documented in NUREG/CR-7103 as well as those from GE Global Research. Based on the PWSCC crack growth analysis results from Section 6.0 using an improvement factor of 100, the service life required to grow through the Alloy 152 weld inlay is more than 10 Effective Full Power Years, which is more than the required examination interval of 10 years for Inspection Item G "Un-cracked butt weld mitigated with an inlay" in accordance with Code Case N-770-1. As a result of careful water chemistry control and the fact that Alloy 152 weld inlay is highly resistant to PWSCC, the crack growth results are conservative since the crack initiation time was ignored. Also, the postulated initial flaw sizes in the weld inlay are much larger that those that could be reasonably missed during the baseline inspection in 2014. Furthermore, the additional service life required to result in leakage and pipe rupture after the posulated flaws have penetrated the Alloy 152 weld inlay was not considered. Based on the crack growth results, adequacy of the Steam Generator inlet and outlet nozzle DM weld inlay thickness against PWSCC has been demonstrated. Therefore, it is technically justified to recategorize the V. C. Summer Unit 1 replacement steam generator inlet and outlet nozzle DM welds as Inspection Item G "Un-cracked butt weld mitigated with an inlay" in Code Case N-770-1.

8.0 REFERENCES

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3. ASME Code Case N-770-1, Section XI Division 1. "Alternative Examination Requirements and Acceptance Standards for Class 1 PWR Piping and Vessel Nozzle Butt Welds Fabricated with UNS N06082 or UNS W86182 Weld Filler Material With or Without Application of Listed Mitigation Activities, Section XI, Division 1," ASME Approval Date January 26, 2009, Final Rule effective July 21, 2011 (76 FR 36232).
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Appendix A

Response to Public Meeting Question Number 29 on Code Case N-770-1 implementation

Q 29 What are the NRC's expectations for a licensee to include in a request to re-categorize welds mitigated by techniques similar to cladding, inlay or onlay mitigation?

A 29 ASME Section XI has been working on draft Code Case N-766, "Nickel Alloy Reactor Coolant Inlay and Onlay for Mitigation of PWR Full Penetration Circumferential Nickel Alloy Dissimilar Metal Welds of Class 1 Items." This Code Case has not been approved by ASME, pending resolution of comments from the NRC. The outstanding NRC comments deal with flaw analysis to include stress corrosion cracking calculations and eddy-current qualifications.

Despite the issues that NRC has with this draft Code Case, draft ASME Code Case N-766 provides useful guidance for preparing a request for alternative categorization to Inspection Items G–K of Code Case N-770-1. Any request to the NRC for alternative categorization should address the following items at a minimum:

1. Pre-inlay/onlay examinations performed including eddy current examination and acceptance criteria followed.
2. Repairs performed and any filler materials used.
3. Inlay/onlay materials used, including chromium content and the method used to determine the as-deposited weld bead chromium content.
4. Methods used to identify the dissimilar metal weld fusion zones and the accuracy of the methods used.
5. Qualifications of the weld procedure specifications, welders and welding operators.
6. Pre- and post-weld heat treatment or temper bead welding requirements followed.
7. Design and analysis requirements used, in detail.
8. Preservice and inservice inspections performed since installation of the inlays/onlays.
9. ASME Code Editions and Addenda associated with requirements used, where applicable, and figures, as applicable, to assist in describing the information submitted in conjunction with the request for alternative categorization.
10. Thickness of inlay/onlay.
11. Flaw evaluation to show adequate thickness against stress corrosion cracking.
12. For primary water stress corrosion crack growth rates for Alloy 52/152 weld materials, at this time, NRC recommends using the Alloy 182 crack growth rate curve provided in MRP-115, with an improvement factor (IF) of 100 for Alloy 52 welds and an IF of 10 for Alloy 152 welds.