Westinghouse Non-Proprietary Class 3

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Technical Basis for Relaxation Request from NRC Order EA-03-009 for Millstone Unit 3

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1.0 Introduction

As a result of the First Revised NRC Order EA-03-009 issued on February 2004, most of the nuclear power plants in the United States have encountered difficulties with the required inspection coverage for the reactor vessel upper head penetrations below the J-groove weld. To determine the extent of inspection coverage required for Millstone Unit 3 outermost upper head penetration nozzle numbers 74 through 78 to meet the requirements of the NRC Order, hoop stress distribution curves below the J-groove weld for these outermost penetration nozzles were generated and presented in this report.

In the event that the required inspection coverage below the J-groove weld cannot be achieved during the inspection, a request for relaxation from the inspection requirements in the NRC Order must be submitted to the NRC. To support such relaxation request, an axial through-wall crack growth curve for the downhill side region below the J-groove weld was generated for Millstone Unit 3 for the outermost penetration nozzles. Only the crack growth curve for the downhill side was generated since the crack growth curve on the downhill side is more limiting as demonstrated in this report. The minimum inspection requirements below the J-groove weld can then be determined from the crack growth curve to demonstrate that the intent of the requirements in the NRC Order is met.

The technical basis and methodology used in the generation of the hoop stress distribution curves and the axial through-wall crack growth curve are discussed in the following sections.

2.0 Hoop Stress Distribution below J-groove Weld

2.1 Finite Element Stress Analysis

The objective of the finite element stress analyses in Reference [1] is to obtain stresses in the outermost upper head penetration nozzle numbers 74 through 78 and their immediate vicinities for Millstone Unit 3. To do so requires a three-dimensional elastic-plastic finite element analysis that considers all the pertinent loadings on the penetrations. Since the nozzle angle and the nozzle design geometry for the outermost penetration nozzle numbers 74 through 78 are identical, only one three-dimensional finite element model comprising of iso-parametric brick and wedge elements is necessary to obtain the stresses. Taking advantage of the symmetry of the reactor vessel head, only half of an upper head penetration nozzle was modeled. The lower portion of the upper head penetration nozzle, the adjacent section of the reactor vessel closure head, and the J-groove weld were modeled. The locations of the outermost upper head penetration nozzle numbers 74 through 78 in the reactor vessel closure head are shown in Figure 2-1 for Millstone Unit 3. The finite element model for these outermost penetrations is shown in Figure 2-2.

The vessel to penetration nozzle J-groove weld was simulated with two weld passes. The actual J-groove weld fabrication may involve significantly more weld passes. Nevertheless, the analytical results using two weld passes had been correlated with the experimental and field data documented in Reference [2]. The penetration nozzle, weld metal, cladding and the vessel head were modeled in accordance with the relevant material properties. The most important loading conditions were found to be those which exist on the penetration nozzles for the majority of the time. These loadings included pressure and temperature loading associated with the steady state operation condition including the residual stress resulting from the fabrication of the J-groove weld. The duration of the non-steady state operation condition loading is in general very short and therefore will not have any significant impact on the overall primary stress corrosion crack (PWSCC) growth. The reactor vessel head temperature for Millstone Unit 3 is 558.4°F based on Reference [3].

The nozzle angle for the analyzed outermost head penetration nozzle is 48.7°. The results from the finite element analyses [1] were used to determine the hoop stress distribution below the J-groove weld for these outermost head penetration in Millstone Unit 3.

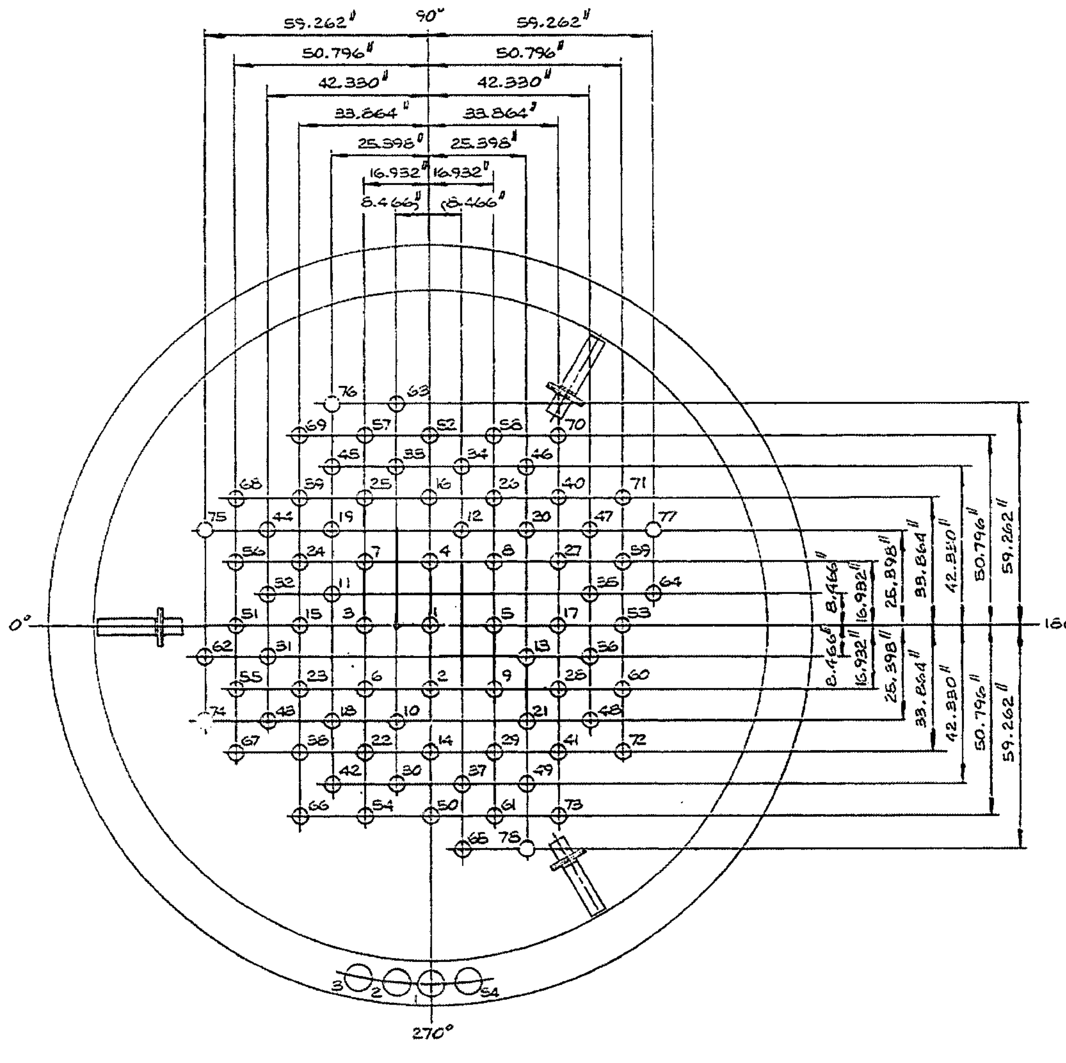
2.2 Hoop Stress Distribution Curves

The hoop stress distributions on the downhill and uphill sides along the length of the outermost penetration nozzles with nozzle angle of 48.7° below the J-groove weld are plotted in Figures 2-3 and 2-4 respectively. The stress distributions shown are for the inside and outside surfaces of the reactor vessel upper head penetration. These stress distributions are typical of those observed in the upper head penetration nozzles for other nuclear power plants. The stresses are highest in the vicinity of the J-groove weld and decrease rapidly as the distance below the toe of the J-groove weld increases. The highest tensile hoop stresses are found at the uphill and downhill side locations rather than midway around the penetration. Therefore cracks are more likely to be initiated in the vicinity of these locations.

As shown in Figures 2-3 and 2-4, the magnitude of both the downhill and uphill side hoop stress which are at a distance of 1 inch or more below the toe of the downhill side J-groove weld is less than 20 ksi for penetration nozzle numbers 74 through 78. The hoop stress drops to 20 ksi at a distance of 0.32 inch below the toe of the J-groove weld on the downhill side.

In accordance with the NRC order, the minimum inspection coverage shall be 1 inch below the lowest point at the toe of the J-groove weld if the stress level beyond 1 inch can be shown to be less than 20 ksi. Therefore, based on the hoop stress distributions shown in Figures 2-3 and 2-4, the inspection requirements given in NRC Order EA-03-009 are satisfied for Millstone Unit 3 provided inspection coverage of at least 1 inch below the toe of the J-groove weld on the downhill side can be achieved. If the minimum inspection coverage of 1 inch required by the NRC order is met on the downhill side, no relaxation request is needed for the uphill side. This can be demonstrated by reviewing the head penetration design drawings [4] to determine the expected inspection coverage on the uphill side if 1 inch can be achieved below the toe of the J-groove weld on the downhill side. The inspection coverage on the uphill side is expected to be more due to the elevation differential between the toe of the J-groove weld on the downhill and uphill side. Based on a review of the head penetration design drawings on this elevation differential and the hoop stress distribution curves, the magnitude of the stress in the uphill side region would also be less than 20 ksi if the minimum inspection coverage of 1 inch below the toe of the J-groove weld can be achieved on the downhill side. Therefore, no relaxation request is needed for either the downhill or uphill side if the inspection coverage below the toe of the J-groove weld achieved on the downhill side is at least 1 inch.

Figure 2-1
Location of the Outermost Head Penetration Nozzles for Millstone Unit 3



Note:
The outermost penetration nozzles are numbered 74 through 78, they are at the same nozzle angle of 48.7° with respect to the center line of the reactor vessel.

Figure 2-2

Finite Element Model of Outermost Head Penetration Nozzle

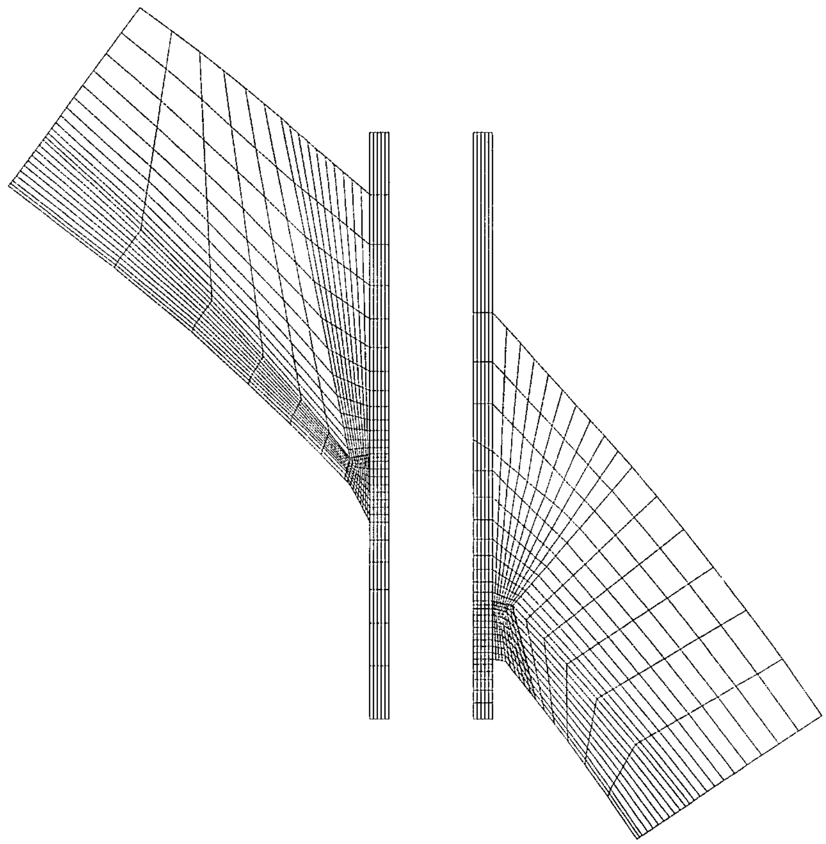


Figure 2-3

Hoop Stress Distribution On the Downhill Side for Penetration Nozzle Numbers 74 through 78

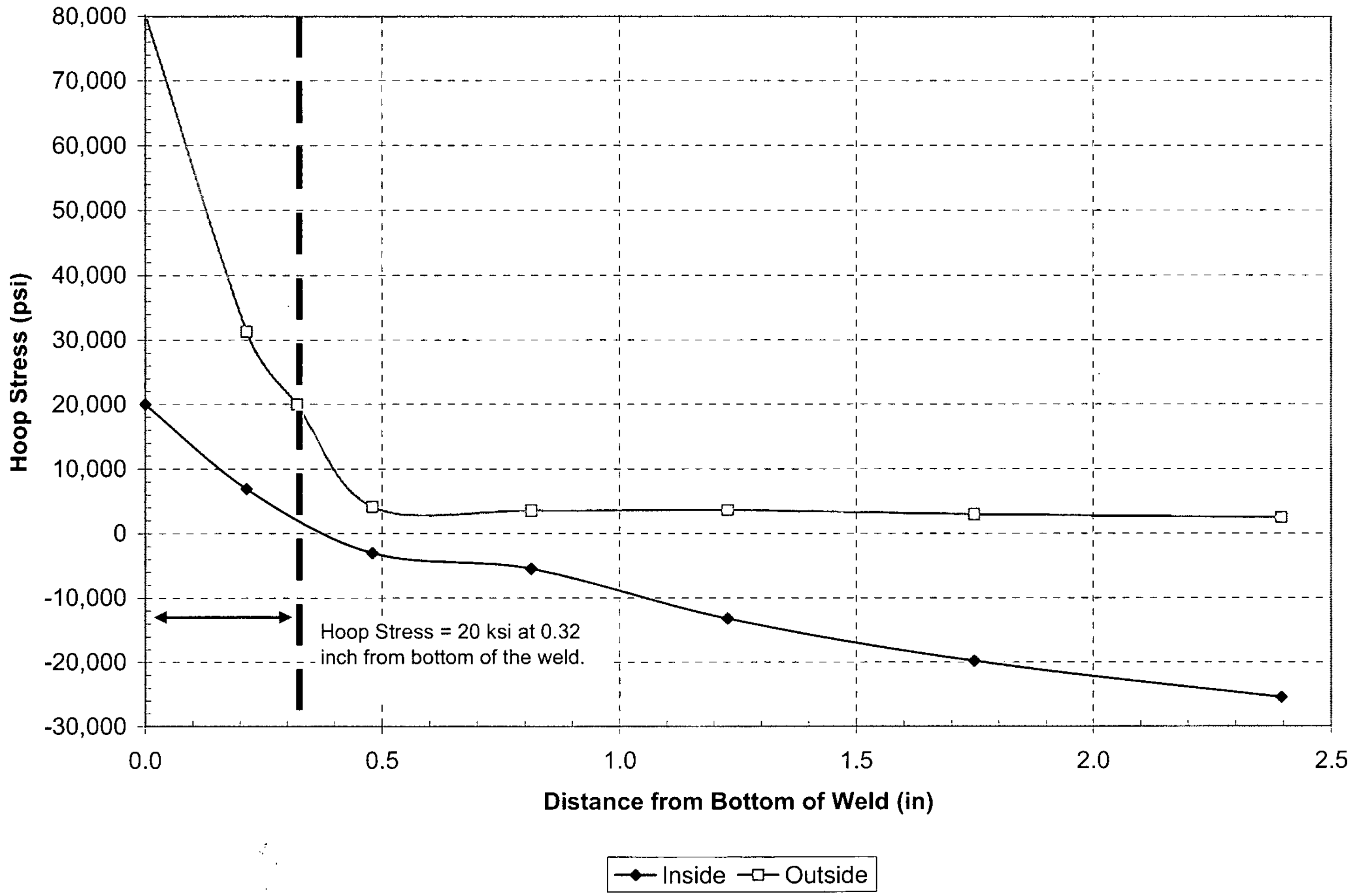
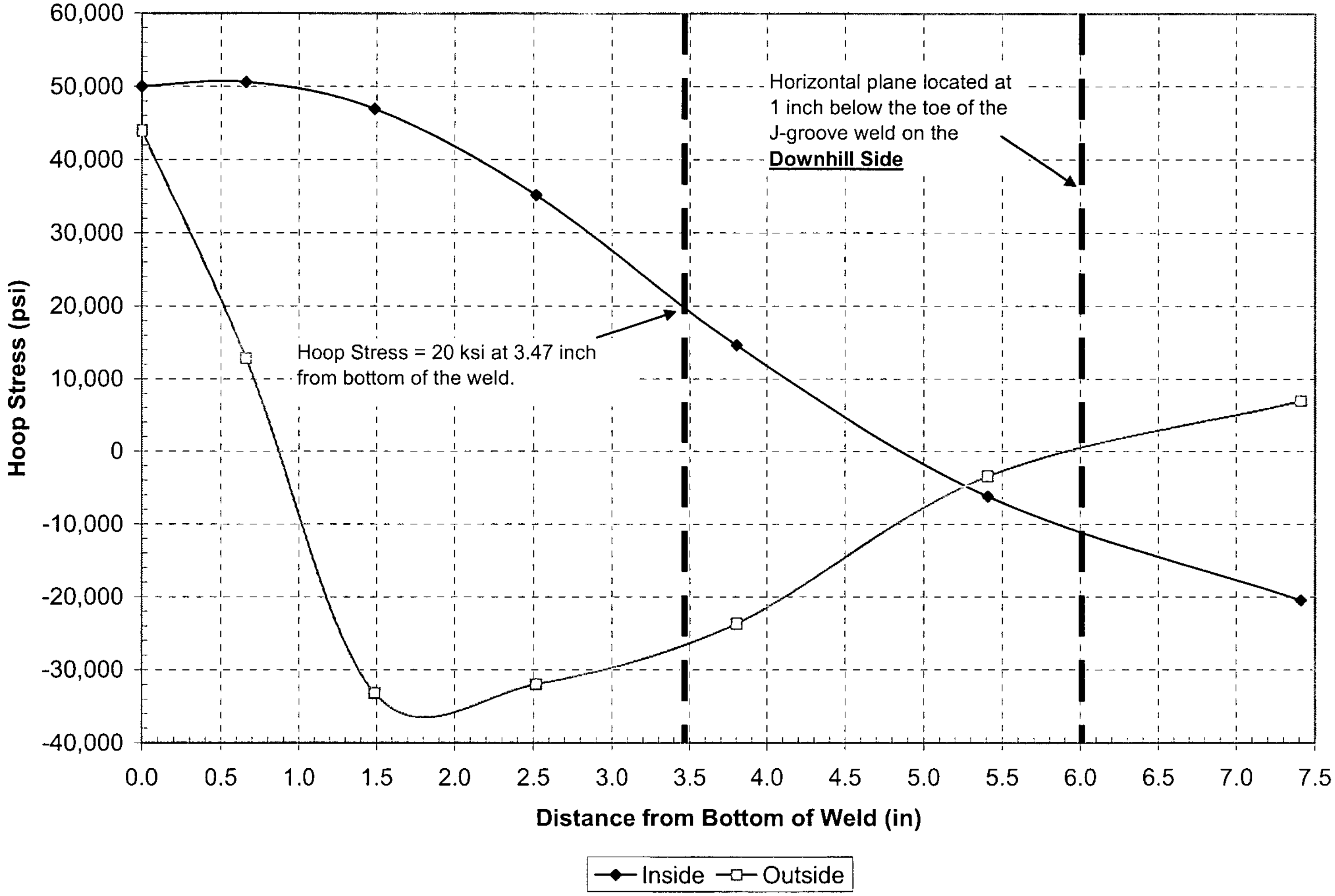


Figure 2-4

Hoop Stress Distribution On the Uphill Side for Penetration Nozzle Numbers 74 through 78



3.0 Crack Growth below J-groove Weld

3.1 Initial Flaw Postulation

Most of the power plants in the United States have encountered difficulties in meeting the inspection requirements of the NRC Order. For the outermost head penetration nozzle numbers 74 through 78 where the inspection coverage is less than 1 inch below the J-groove weld, a request for relaxation from the NRC Order is required.

To support the submittal of relaxation request, technical justification must be provided to demonstrate that any undetected flaws in the region below the J-groove weld not being inspected would not propagate into the pressure boundary formed by the J-groove weld before the next head penetration inspection. For this reason, a crack growth curve for the region below the J-groove weld on the downhill side was generated for the outermost upper head penetration nozzles. This crack growth curve can then be used to determine the service life required for an undetected flaw, postulated in the region below the J-groove weld not being inspected, to reach the toe of the J-groove weld.

The hoop stress in the penetration nozzle resulting from the steady state operation loadings and welding residual stresses is much higher than the axial stress. This is consistent with the field findings, where the cracks discovered are generally oriented axially. Typically, in-service cracks will orient themselves perpendicular to the largest stress component. Also, it should be noted that the highest tensile hoop stress is at the uphill side and downhill side rather than midway around the penetration nozzle where the stress is less limiting [1]. This is consistent with finding axial cracks primarily in the vicinity of the uphill and downhill side of the head penetration nozzles. It is these steady state hoop stresses that were used to determine the orientation of the postulated flaw and the crack growth in the outermost penetration nozzles below the J-groove weld.

The size of the axial through-wall flaw is conservatively postulated in the region below the J-groove weld by assuming its upper crack tip to be located at a given distance below the toe of the J-groove weld, while its lower crack tip is assumed to be located where the hoop stress drops below 0 ksi on either the inside or outside surface of the outermost head penetration nozzles. The location of the upper crack tip can be conservatively assumed to be the location where the inspection coverage ends. The location of the upper crack tip for the outermost penetration nozzle numbers 74 through 78 is assumed to be 0.2″ from the toe of the J-groove weld in generating the crack growth curve.

There is nearly universal agreement that high stresses, on the order of the material yield strength, are necessary to initiate PWSCC. There is no known case of stress corrosion cracking of Alloy 600 below the yield stress [5, 6]. Typical yield strengths for wrought Alloy 600 head penetration nozzles are in the range of 37 ksi to 65 ksi. Weld metal yield strengths are generally higher. The yield strength of the head penetration nozzles for Millstone Unit 3 varies from 38.5 ksi to 40 ksi [7]. In addition, based on MRP-95 the stress level of 20 ksi has been determined as a value below which PWSCC initiation is extremely unlikely [6]. Therefore, the postulation of the lower crack tip in the region of the penetration nozzle with a stress level of 0 ksi is very conservative.

3.2 Stress Intensity Factor Calculation

Once the location and size of the axial through-wall flaw is postulated, stress intensity factor for the postulated flaw can be calculated using the stress intensity factor expression for an axial through-wall flaw in a cylinder [8], where:

$$K_I = \sigma\sqrt{\pi a}\, F(\lambda)$$

Where: $\lambda = a/\sqrt{Rt}$

$F(\lambda) = (1+1.25\lambda^2)^{1/2}$ for $0 < \lambda \leq 1$

$F(\lambda) = 0.6+0.9\lambda$ for $1 \leq \lambda \leq 5$

and

- a = half flaw length
- R = penetration nozzle mean radius
- t = penetration nozzle wall thickness
- σ = average hoop stress through the nozzle wall thickness at the upper crack extremity

3.3 Crack Growth Prediction

Using the stress intensity factor determined, the crack growth for the postulated flaw can be calculated using the MRP-55 recommended PWSCC crack growth rate [9]:

$$\dot{a} = \exp\left[-\frac{Q_g}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]\alpha\,(K - K_{th})^{\beta}$$

where:

$\dot{a}$ = crack growth rate in m/sec (or inch/year)

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 location of crack (°K or °R)

T_{ref} = absolute reference temperature used to normalize data
= 598.15°K (1076.67°R)

α = crack growth amplitude

	=	$2.67\text{x}10^{-12}$ at 325°C for $\dot{a}$ in units of m/sec and K in units of MPa$\sqrt{m}$
		($3.69\text{x}10^{-3}$ at 617°F for $\dot{a}$ in units of inch/year and K in units of ksi$\sqrt{in}$)
K	=	crack tip stress intensity factor, MPa$\sqrt{m}$ (or ksi$\sqrt{in}$)
K_{th}	=	crack tip stress intensity factor threshold
	=	9 MPa$\sqrt{m}$ (8.19 ksi$\sqrt{in}$)
β	=	exponent
	=	1.16

The vessel head temperature for Millstone Unit 3 is 558.4°F. Therefore, the resulting crack growth rate is as follows:

$$\frac{da}{dt} = 5.94 \text{ x } 10^{-13} \, (K - 9)^{1.16} \text{ m/sec}$$

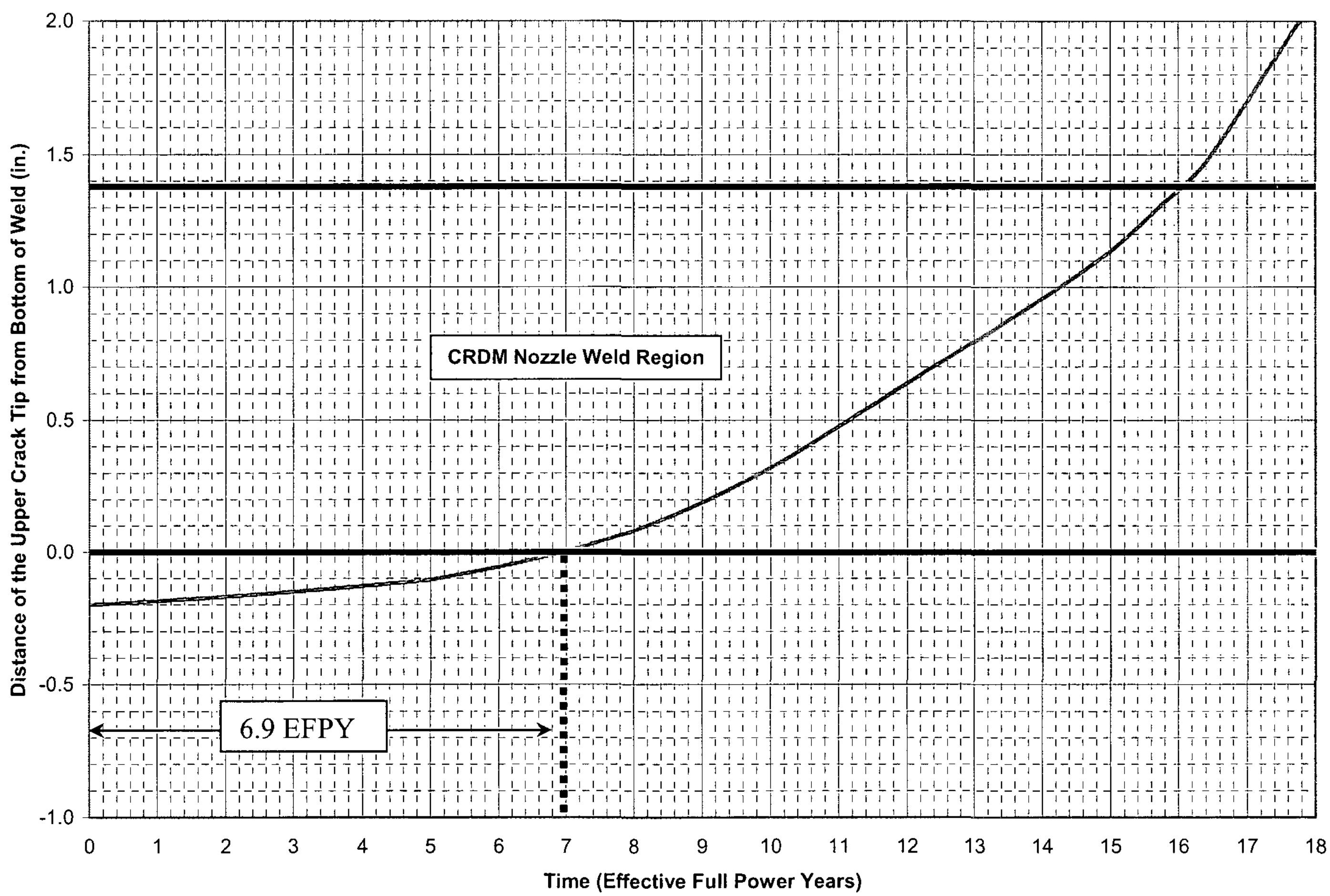
$$\frac{da}{dt} = 8.21 \text{ x } 10^{-4} \, (K - 8.19)^{1.16} \text{ inch/year}$$

The crack growth curve can then be generated as a function of time, which is in Effective Full Power Years (EFPYs), using the above crack growth rate and updating the stress intensity factor as the crack grows until the upper crack tip of the postulated flaw reaches the toe of the J-groove weld. The crack growth curve is shown in Figure 3-1.

Due to the elevation differential between the toe of the J-groove weld on the downhill and uphill side, the upper crack tip located at the end of the inspection zone would be farther away from the toe of the J-groove weld on the uphill side than that on the downhill side. In addition, the magnitude of the stress field at the crack tip on the uphill side is lower since the stress magnitude decreases rapidly as the distance from the toe of the J-groove weld increases. Therefore, with the crack tip closer to the toe of the J-groove weld and a higher stress field, the crack growth curve generated for the downhill side is more limiting in determining the adequacy of the inspection coverage less than the minimum required inspection coverage of 1 inch. Therefore, no crack growth curve for any other locations needs to be generated.

It should be noted that the locations of the upper crack tip were selected such that the resulting stress intensity factor at the crack tip exceeded the PWSCC stress intensity factor threshold of 8.19 ksi$\sqrt{in}$ (9 MPa$\sqrt{m}$) in order to produce meaningful crack growth, and at the same time, demonstrated that the upper crack tip would not reach the bottom of the J-groove weld before the next inspection cycle. The service life required for the upper crack tip shown in Figure 3-1 to reach the toe of the J-groove weld is 6.9 EFPYs if the inspection coverage ends at 0.2″ below the toe of the J-groove weld on the downhill side.

Figure 3-1
Crack Growth Below the Weld
for Penetration Nozzle Numbers 74 through 78



4.0 Summary and Conclusion

As a result of the First Revised NRC Order EA-03-009 issued on February 2004, many nuclear power plants have encountered difficulties with meeting the required inspection coverage for the reactor vessel upper head penetrations below the J-groove weld. Consequently, submittal to the NRC of a request for relaxation from the requirements in the NRC Order is required. To support the relaxation request, technical justification has been provided in this report for the outermost head penetration nozzle numbers 74 through 78 to demonstrate that any undetected flaws in the uninspected region below the J-groove weld will not propagate into the J-groove weld before the next head penetration inspection for Millstone Unit 3. Results from the hoop stress distribution curves (Figures 2-3 and 2-4) and axial through-wall crack growth curve (Figure 3-1) were used as the basis for the technical justification. As shown in Figures 2-3 and 2-4, the hoop stress drops to 20 ksi at a distance of 0.32 inch below the toe of the J-groove weld on the downhill side. Therefore, no relaxation request is needed if the inspection coverage below the toe of the J-groove weld achieved on the downhill side is at least 1 inch because the stress level in the region below 1 inch is less than 20 ksi. If the actual inspection coverage that can be achieved is less than 1 inch below the J-groove weld, the result of the crack growth curve shown in Figure 3-1 demonstrates that any undetected flaw located at least 0.2″ below the J-groove weld on the downhill side would take at least 6.9 EFPYs (more than four refueling cycles) for its upper crack extremity to reach the toe of the J-groove weld. Therefore, the intent of the inspection requirements in the NRC Order for the head penetration nozzle numbers 74 through 78 can be met if the minimum inspection coverage of 0.2″ below the J-groove weld on the downhill side can be achieved.

5.0 References

1. Dominion Engineering, Inc. Calculation C-8740-00-1, Revision 0, "Stress Analysis of Outermost CRDM Nozzle at Millstone Unit 3." (Proprietary to Westinghouse)

2. EPRI Report TR-103696, "PWSCC of Alloy 600 Materials in PWR Primary System Penetrations," July 1994. (Proprietary to EPRI)

3. "PWR Materials Reliability Program Response to NRC Bulletin 2001- 01," EPRI MRP Report MRP-48, August 2001. (Proprietary to EPRI)

4. Millstone Unit 3 Drawings (Proprietary to Westinghouse):

    a. CE Drawing No. D-7272-102-001, Rev. 2, "Closure Head Dome - Westinghouse Electric Corp. 173″ ID PWR."

    b. CE Drawing No. E-7272-101-002, Rev. 0, "Closure Head Penetrations Machining and Cladding - Westinghouse Electric Corp. 173″ ID PWR."

    c. CE Drawing No. E-7272-101-003, Rev. 0, "Closure Head Penetrations Final Machining - Westinghouse Electric Corp. 173″ ID PWR."

    d. CE Drawing No. E-7272-101-004, Rev. 1, "Closure Head Final Machining - Westinghouse Electric Corp. 173″ ID PWR."

    e. CE Drawing No. E-7272-101-005, Rev. 3, "Closure Head Assembly - Westinghouse Electric Corp. 173″ ID PWR."

    f. CE Drawing No. E-7272-112-002, Rev. 2, "Control Rod Mechanism Housing Details - Westinghouse Electric Corp. 173″ ID PWR."

5. "Effect of Strain Rate on SCC in High Temperature Primary Water, Comparison between Alloys 690 and 600", ANS 11th Environmental Degradation Meeting, August 2003, K. M. Boursier et al (EDF).

6. "Material Reliability Program: Generic Evaluation of Examination Coverage Requirements for Reactor Pressure Vessel Head Penetration Nozzles (MRP-95)," EPRI, Palo Alto, CA: 2003. 1009129. (Proprietary to EPRI)

7. Westinghouse Report WCAP-13493, "Reactor Vessel Closure Head Penetration Key Parameters Comparison," September 1992. (Proprietary to Westinghouse)

8. "The Stress Analysis of Cracks Handbook," page 34.1, Hiroshi Tada, 2nd Edition.

9. "Materials Reliability Program (MRP) Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick Wall Alloy 600 Material (MRP-55) Revision 1," EPRI, Palo Alto, CA:, November 2002. 1006695. (Proprietary to EPRI)