Edwin I. Hatch Nuclear Plant

Enclosure 2

Elastic-Plastic Fracture Mechanics Evaluation of the Plant Hatch Unit 1 Core Shroud V5 and V6 Welds

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Elastic-Plastic Fracture Mechanics Evaluation of the Plant Hatch Unit 1 Core Shroud V5 and V6 Welds

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1.0 INTRODUCTION

This report presents the elastic-plastic fracture mechanics (EPFM) evaluation of the Plant Hatch Unit 1 Core Shroud V5 and V6 welds. The EPFM analysis is consistent with the current Boiling Water Reactor Vessel and Internals Program (BWRVIP) documents pertaining to shroud cracking. Indications have been reported in the Plant Hatch, Unit 1 shroud vertical welds V5 and V6, with the most recent inspection occurring in early 2004 [1]. Using the methodology provided in BWRVIP-76 [2], Southern Nuclear Operating Company (SNOC) has requested that an elastic-plastic fracture mechanics analysis incorporating revised fluence estimates be performed to determine the re-inspection interval for the V5 and V6 vertical welds.

In September 2003, the fluence estimates for Plant Hatch Unit 1 were revised. The calculation was performed using the RAMA Fluence Methodology software, currently under development by TransWare, for the BWRVIP. The results of the fluence estimates showed that portions of the welds have exceeded the $1x10^{21}n/cm^2$ threshold for reduced fracture toughness and increased cracking growth the rates before the end of the 10-year reinspection interval. Based on the estimated results from the fluence analysis [3], an EPFM analysis was performed by Structural Integrity Associates (SI) using data from the 1999 shroud inspection [4]. According to BWRVIP-76 [2], if the fluence exceeds $3x10^{20}$ n/cm^2, linear elastic fracture mechanics (LEFM) or EPFM with limit load analysis is required. EPFM typically can provide more margin than limit load since it is a better representation of the problem. The results of the analysis presented in Reference 4 showed an 8 year reinspection interval for these vertical welds.

In 2004, the V5 and V6 welds were reinspected using improved inspection methods [1]. The results of this examination provided more accurate results than those used in the Reference 4 analysis. SI performed an updated EPFM analysis using the Reference 3 analysis fluence and the 2004 inspection results [1].

This EPFM analysis uses a crack growth rate of $5x10^{-5}$ in/hr for the assumed through-wall flaws. This crack growth rate was used to determine the flaw geometry for operation over a prescribed time from the 2004 inspection.

The EPFM analysis uses the J-integral – Tearing Modulus (J-T) approach with the use of a detailed elastic-plastic finite element model. Crack tip opening displacements (CTOD) were taken from the limiting location and used in the J-T analysis. The material J-T curves were obtained for the approximate fluence at the end of the prescribed operating time from the time of inspection in 2004.

Based on the results of the analysis, a safety factor can be calculated depending on the selected operating period to the next re-inspection. Results of the analysis show that the reinspection period of well over 10 years is justifiable and in fact can be shown to be up to at least 15 years.

1.1 Analysis Conservatisms

The analysis is described in detail in the following sections. The analysis is considered to be conservative and this section discusses some of these conservatisms.

The 2004 inspection results provided crack depth characterization of the flaws in welds V5 and V6. The inspection results showed that flaws were relatively shallow, generally on the order of 50% of the shroud wall, with one flaw of approximately 75% of wall over a small portion of its length. This analysis assumes that all flaws are through-wall regardless of the reported depth in Reference 1.

This assumption is considered conservative since BWR shroud inspection experience has shown that through-wall flaws in shroud welds has not occurred. A significant number of shroud inspections have been performed, and although shroud cracking is widespread, in most cases the deeper flaws tend to be in the vicinity of 50% of wall. The primary driving force for the crack growth is the weld residual stress since the applied loads, in this case the pressure stress, is quite low, especially during normal operation. The weld residual stress distribution [2], because of its self-equilibrium behavior through the wall (cosine shape), typically results in very low (if not negative) stress intensity factors near the center of the shroud wall. Many shroud inspections that have found mid-wall depth flaws confirm this general residual stress behavior. Thus, the assumption that all flaws regardless of depth are through-wall is considered conservative.

Another conservatism included in this analysis is that no credit is taken for the H4 or H5 welds. This analysis assumes that weld H4 and H5 are fully cracked. Thus, welds V5 and V6 essentially modeled as vertical welds in an open cylinder. Not taking any credit for H4 results in a "flap" type geometry at the top of Weld V6. In actuality, even small amounts of ligament in the H4 welds near the intersection with the V5 and V6 welds will provide significant structural support. But since H4 is not fully characterized, the conservative assumption was made that H4 was fully cracked. Once weld H4 is better characterized, this analysis can be updated to show even greater margin.

The EPFM methodology presented in this analysis also includes some conservatism. As will be discussed later, the applied J-T curves are generated based on the crack tip opening displacement (displacement across crack face measured at intersection of a line drawn at a 45° angle from the crack tip, Figure 4-1) obtained from the elastic-plastic finite element analysis. The results of this analysis showed a small amount of plasticity near the crack tip. Thus, for conservatism, the crack tip opening displacement was assumed to be the displacement based on the first node away from the crack tip along the crack face. This provides a conservative estimate of the crack tip opening displacement.

2.0 VERTICAL WELD CRACK CONFIGURATION

Figure 2-1, from Reference 1, shows the crack dimensions for the V5 and V6 welds based on the results of the 2004 inspection. All flaws were assumed through-wall. The calculations for the EPFM analysis evaluated the shroud condition for future crack growth using a crack growth rate in the length direction of $5x10^{-5}$ in/hr. After accounting for crack growth, the ligament between neighboring flaws must be evaluated to determine if the flaws need to be combined. Based on BWRVIP guidelines [2], two neighboring flaws must be combined if the ligament between them is less than two times the thickness of the shroud after accounting for crack growth.

For purposes of this calculation, no credit was taken for any un-cracked portions of the H4 weld since insufficient inspection information was available for the horizontal welds. If credit could be taken, this would reduce the loading at the crack tip location. Thus, the results of these calculations are considered conservative.

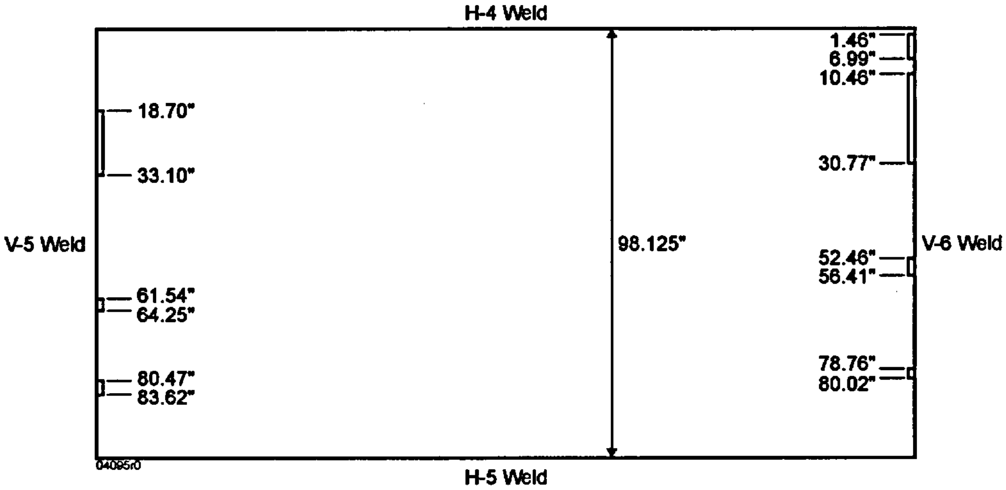


Figure 2-1. 2004 Inspection Results

(Dimensions shown are vertical distance from the H4 weld)

3.0 TECHNICAL APPROACH

This section describes the technical approach used to perform the EPFM analysis. The purpose of the analysis was to determine the required re-inspection interval for the V5 and V6 welds with the flaw sizing from the 2004 shroud inspection assuming a crack growth rate of $5\text{x}10^{-5}$ in/hr in the length direction. The initial re-inspection interval was selected as 15 years for this analysis, which is well above the maximum 10 year reinspection interval. Based on the results for fifteen years, additional shorter re-inspection intervals would be considered if structural integrity could not be demonstrated. If the 15 year calculation is acceptable, this demonstrates added conservatism and margin for a 10 year inspection interval. The general process used in the evaluation is outlined below:

1. Using crack dimensions from Reference 1 and a crack growth rate in the length direction of $5\text{x}10^{-5}$ in/hr, determine the crack dimensions for 15 years (assuming 8,000 hours/year).

2. The final crack lengths are input into a three-dimensional finite element model. The finite element model is used in an elastic-plastic stress analysis that includes crack tip elements. The applied loading is comprised of the internal pressure only for the faulted condition. The faulted condition is the limiting condition [13].

3. For the crack dimension used, determine the J-integral for the applied loading (internal pressure only).

4. Determine $J_{applied}$-$T_{applied}$ curves based on step 3, by incrementing the crack size.

5. Obtain J_{mat}-T_{mat} curves from BWRVIP-100 [11] for the shroud material at the appropriate fluence levels. Fluence levels at the crack tip at the end of the selected re-inspection interval were estimated by extrapolating using the results of Reference 3.

6. Determine if flaw pattern is stable by using J-T criterion.

7. Determine safety factor.

8. If the 15-year re-inspection interval calculation does not result in a safety factor (1.50) required by Reference 12, the re-inspection interval needs to be reduced and the process repeated.

4.0 ANALYSES

This section presents calculations and additional information required for the EPFM analysis. This analysis incorporates the revised fluence estimates from Reference 3. The fluence effects are incorporated through its effect on material properties (Section 4.2).

4.1 Applied J-Integral and Tearing Modules ($J_{applied}$-$T_{applied}$)

BWRVIP-76 [2] provides for EPFM analysis above fluences of 3×10^{20} n/cm^2. EPFM considers ductile crack extension in determining the load carrying capability of a cracked component such as the core shroud. The J-T approach considers the intensity of the plastic stress-strain field surrounding the crack tip (through the J-integral) and tearing stability theory, which examines the stability of ductile crack growth (through the tearing modulus).

The J-integral, can be calculated from the crack tip opening displacement (CTOD), Reference 5. The instability of unstable crack growth can be determined based on Tearing Modulus Method, Reference 6.

The relationship between J and CTOD is based on satisfying the Hutchinson, Rice and Rosengren (HRR) singularity presented in Reference 5, Appendix B, and summarized here. The definition of δ_t is the crack opening distance between the intercept of two 45° lines, drawn back from the crack tip with the deformed profile as shown in Figure 4-1. The value of δ that satisfies the displacements along the crack edge is given by

$$\delta_t = d_n \frac{J}{\sigma_o} \qquad (4\text{-}1)$$

where

$$d_n = \left(\frac{\alpha\sigma_o}{E}\right)^{\frac{1}{n}} \left(\tilde{u}_x + \tilde{u}_y\right)^{\frac{1}{n}} \frac{\tilde{\delta}}{I_n} \tag{4-2}$$

and

$$\tilde{\delta} = 2\tilde{u}_y \tag{4-3}$$

E = Young's Modulus

σ_o = yield stress

α, n = Ramberg-Osgood stress strain law parameters

The above equations are valid for both plane strain and plane stress conditions; with values of I_n tabulated by Hutchinson [7], and $\tilde{u}_x$ and $\tilde{u}_y$ are available for a wide range of n for plane strain and plane stress conditions [8, 9]. The value of d_n determined from Equation 4-2 for a wide range of n and σ_o/E for the plane stress and plane strain conditions are shown in Reference 8 and 9.

The Tearing Modulus is defined in Reference 6 as

$$T = \frac{E}{\sigma_o^2}\frac{dJ}{da} \tag{4-4}$$

The condition for unstable crack growth is expressed as

$$T_{applied} \geq T_{material} \tag{4-5}$$

or

$$\frac{d(J_{applied})}{da} \geq \frac{d(J_{material})}{da} \tag{4-6}$$

The $\frac{dJ}{da}$ can be calculated using a finite element model by incrementing the initial crack size to obtain the J-integral, and using the gradient to calculate the Tearing Modulus.

4.2 Material J-Integral and Tearing Modulus (J_{mat}-T_{mat})

The material J-T behavior is determined experimentally and is a function of various material properties and also the fluence. Reference 11 contains information to determine the J_{mat}-T_{mat} curve for irradiated Type 304 stainless steel. Figure 4-2 shows the J-Δa curves for stainless steel at different fluence levels [11]. Using this data, the tearing modulus can be determined from the following equation,

$$T_{mat} = (E/\sigma_f^2)(dJ_{mat}/da) \qquad (4\text{-}7)$$

The appropriate J_{mat}-T_{mat} curve was selected from Figure 4-2 based on the fluence estimate and used in the J-T analysis.

4.3 Elastic Plastic Finite Element Analysis

A detailed finite element model was developed using the predicted crack pattern for the selected re-inspection period. The finite element model generated is shown in Figures 4-3 and 4-4. Figure 4-3 is the model used for the 15-year re-inspection interval and Figure 4-4 shows the model for the 8-year re-inspection interval. The results of the crack growth calculations are discussed in Section 5.

4.3.1 Applied Loads

The applied loads are those corresponding to the limiting loading condition. Based on the loads in Reference 13, the bounding condition is the faulted condition and the stresses for which the internal pressure is 30 psi.

4.3.2 Stress-Strain Law

The material Ramberg-Osgood stress-strain law for irradiated stainless steel was obtained from Reference 10. The neutron fluence was estimated to be 2.0×10^{21} n/cm^2 for an additional 15 years of operation beyond the 2004 inspection. This fluence was determined by extrapolating the fluence results of Reference 3 to the end of the selected re-inspected interval. The Ramberg-Osgood stress-strain law for typical irradiated stainless steel at a fluence of 2.0×10^{21} n/cm^2 is,

$$(\varepsilon/\varepsilon_o) = (\sigma/\sigma_o) + \alpha(\sigma/\sigma_o)^n \qquad (4\text{-}8)$$

where $\alpha = 17.09$

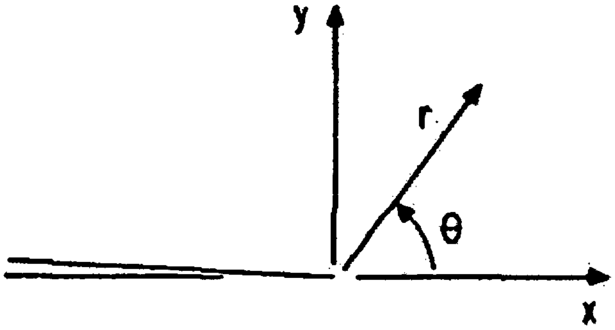
$n = 3.78$

$\sigma = 86$ ksi

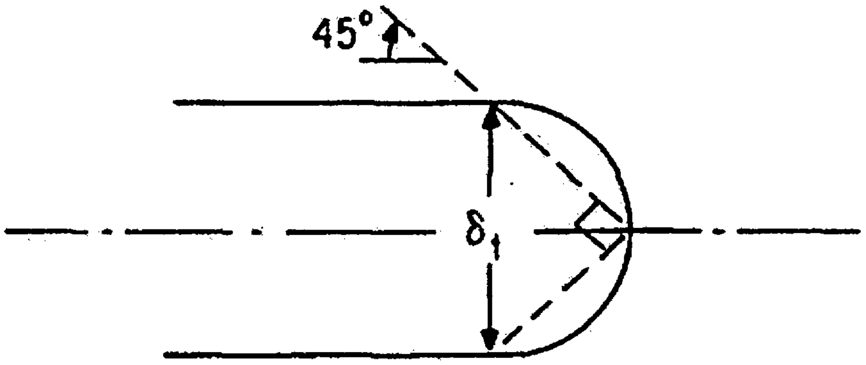
$\sigma_u = 97$ ksi

4.3.3 Crack Growth Rate

In this evaluation, a constant crack growth rate was used for crack extension in the length direction. Since the flaws were assumed through-wall, this is the only crack extension considered. The crack growth rate used was 5×10^{-5} in/hr. The actual crack length growth is determined by adding the product of 5×10^{-5} in/hr and re-inspection interval (in hours) to the crack lengths shown in Figure 2-1.



(a) SHARP CRACK



(b) DEFORMED PROFILE

Figure 4-1. Schematic of Crack Opening Displacement

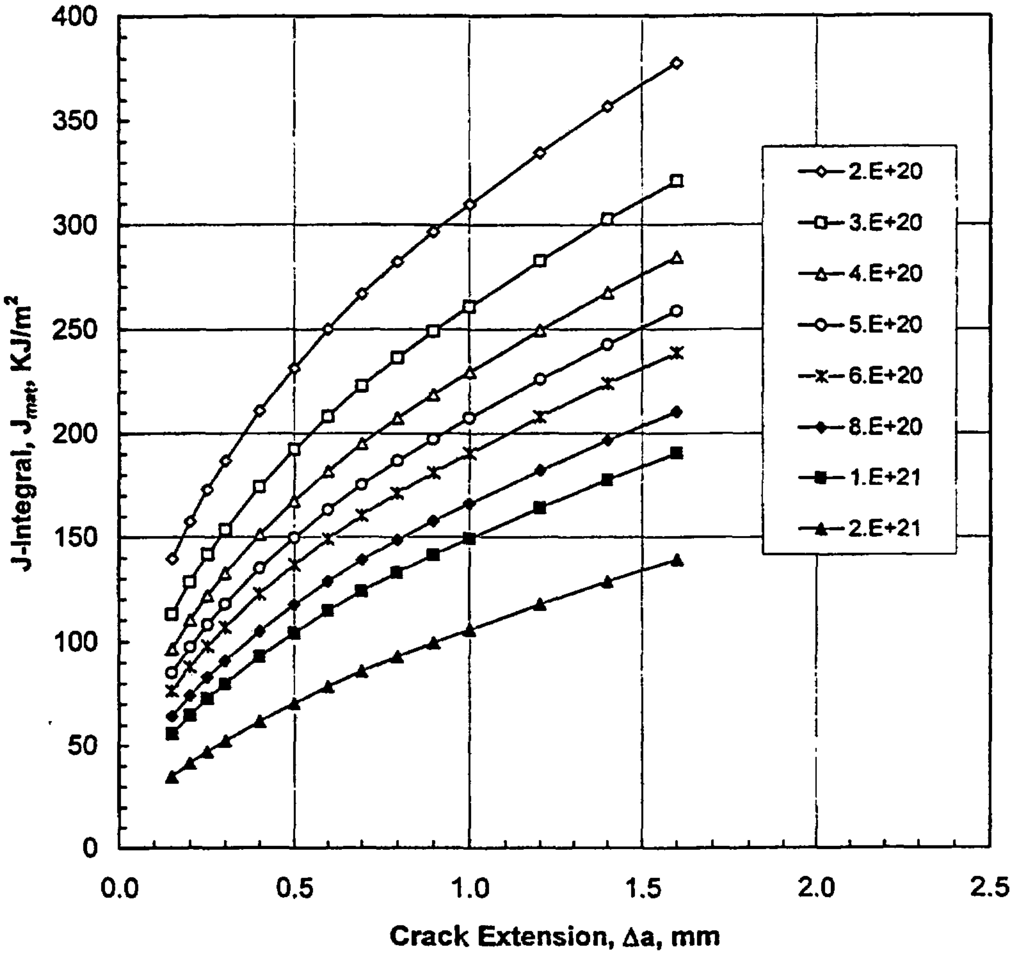


Figure 4-2. J-R Curves as a Function of Neutron Fluence for Structural Integrity Assessments of Stainless Steel

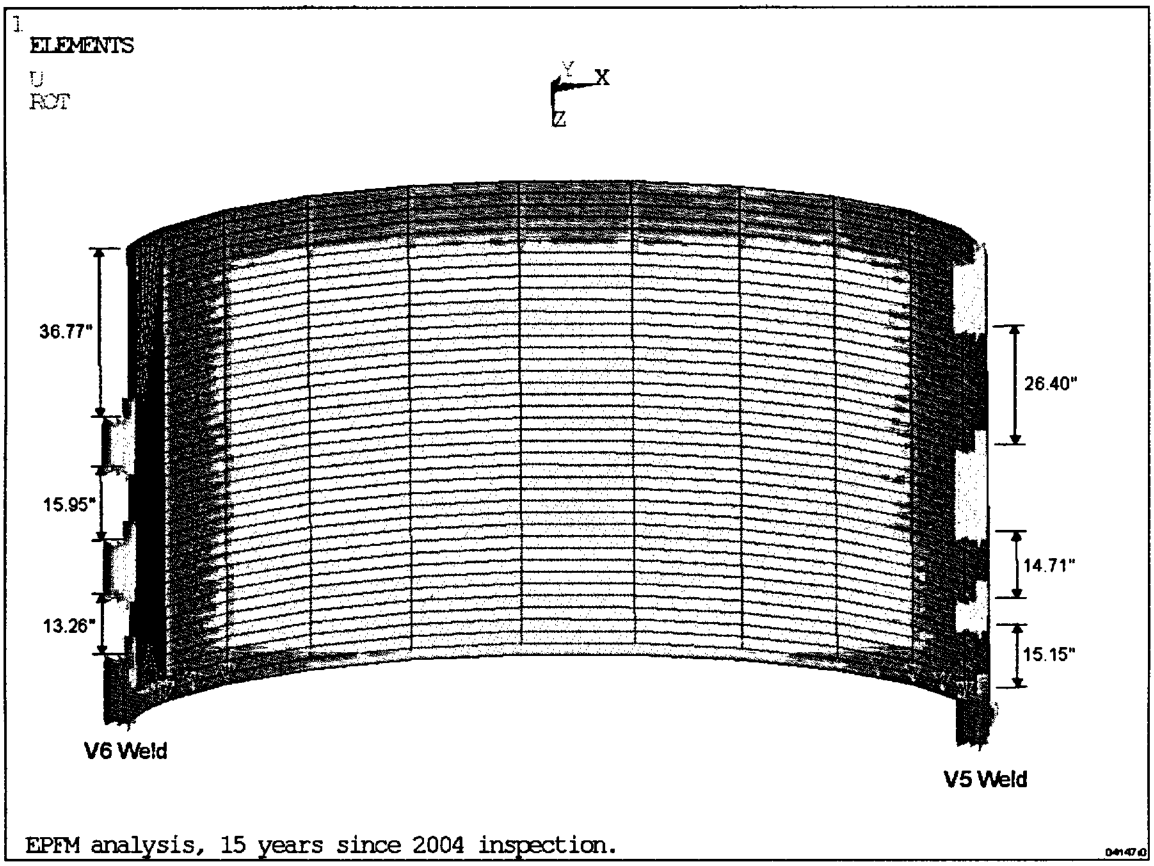


Figure 4-3. Finite Element Model for 15-Year Re-inspection Interval

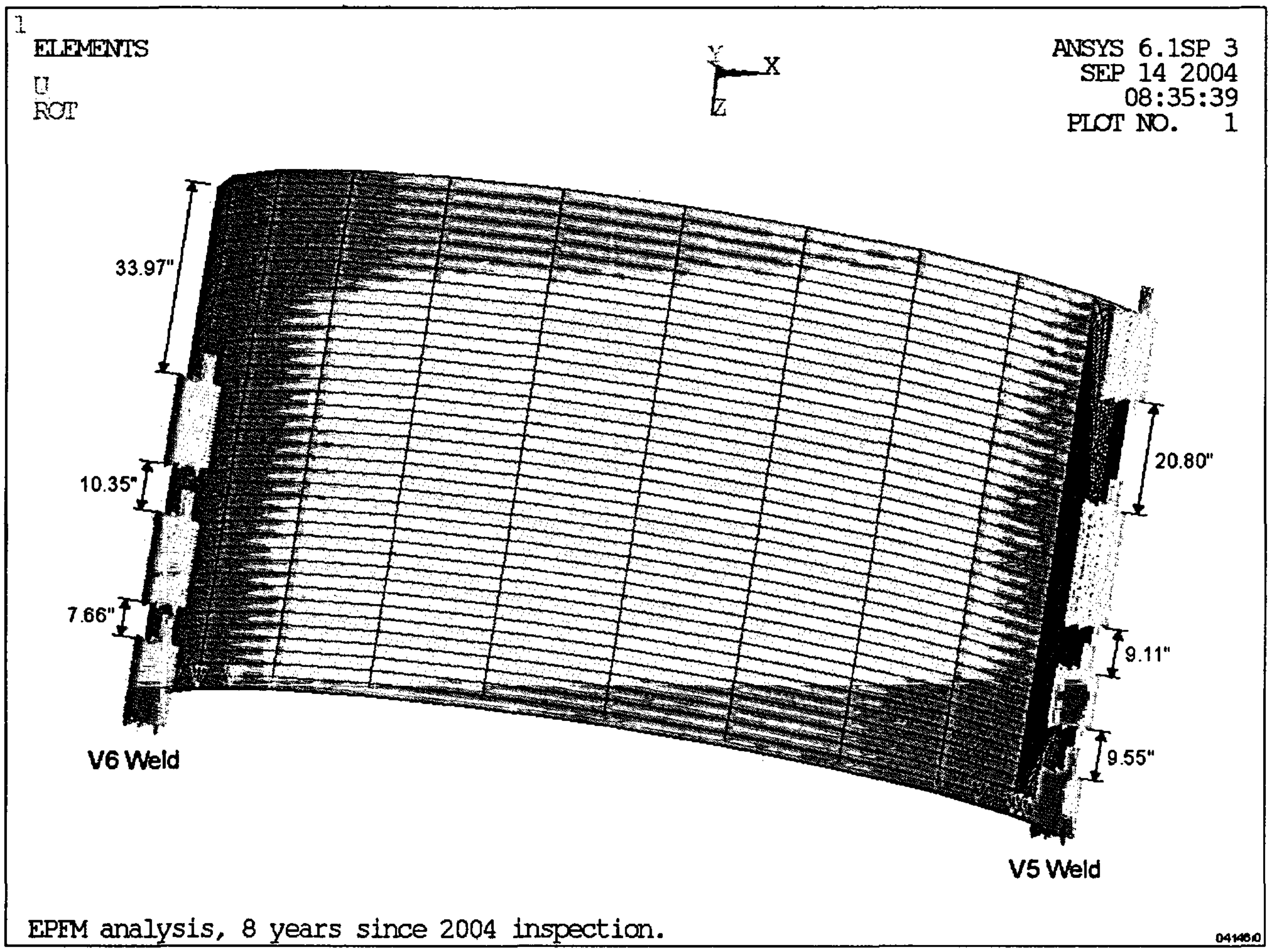


Figure 4-4. Finite Element Model for 8-Year Re-inspection Interval

5.0 RESULTS

The initial re-inspection interval selected was 15 years. For this case, crack growth at the end of each flaw in Figure 2-1 was 6 inches ($5\text{x}10^{-5}$ in/hr × 120,000hr). Adding the growth to the end of each flaw causes the top two flaws of V6 Weld in Figure 2-1 to be combined into a single long flaw. Figure 5-1 shows the crack pattern for 15 years using a crack growth rate of $5\text{x}10^{-5}$ in/hr starting with the 2004 inspection results shown in Figure 2-1 for the V5 and V6 welds. Figure 5-2 shows the crack pattern for 8-year re-inspection case, the length added to the end of each flaw in Figure 2-1 was 3.2 inches ($5\text{x}10^{-5}$ in/hr × 64,000hrs). Note that for the eight-year case, like the fifteen-year case, the top two flaws in Figure 2-1 need to be combined. This is due to the fact that the remaining ligament between the two flaws in V6 weld is less than two times the thickness of the shroud (2t = 2x1.5in = 3in). This flaw in V6 weld will be the limiting flaw for our EPFM analysis and its results will be conservative.

Using the results of the finite element analysis, the J_{appied}-$T_{applied}$ curve can be superimposed on the J_{mat}-T_{mat} curve. The intersection of the $J_{applied}$-$T_{applied}$ curve with the J_{mat}-T_{mat} curve defines the instability point for this crack configuration, material and loading.

Figure 5-3 shows the J-T diagram. The diagram shows the material J-T curve and the applied J-T curve. The intersection denotes the instability points. Tables 5-1 through 5-3 summarize the results of the J-T calculation, which is illustrated in Figure 5-3.

Based on the results of this J-T evaluation, the safety margins can be estimated for the critical location. The safety factor is 1.91 for the 15-year re-inspection interval. Since the safety factor for the 15-year re-inspection interval case satisfy the safety factor requirements in Reference 12 of 1.5 for an axial flaw, 10-year re-inspection must also satisfy the safety factor requirements in Reference 12 of 1.5 for emergency and faulted conditions for an axial flaw. The crack pattern for the eight-year case is shown in Figure 5-2. The safety factor for the eight-year case was determined to be 2.08, which exceeds the required minimum safety factor of 1.5 for emergency and faulted conditions. The safety factor was determined by the following expression:

$$SF = (J_{instability}/J_{applied})^{1/2} \tag{5-1}$$

Note that the square root appears in Equation 5-1 due to the relationship between the J-integral and stress intensity factor as given in Equation 5-2:

$$J \propto K^2 \propto \sigma^2 \tag{5-2}$$

Table 5-1.

Calculated J-T Values for the 15-Year Re-inspection Interval at the Limiting V6 Flaw.

15 year		*J-Integral (psi-in)*		*dJ/da*		*Tearing Modulus*	
a	*δt*	*Pln Strn*	*Pln Strs*	*Pln Strn*	*Pln Strs*	*Pln Strn*	*Pln Strs*
36.77	0.0029382	486.73	372.66	-	-	-	-
36.78	0.0029398	487.00	372.86	26.51	20.29	0.0914	0.0700
36.79	0.0029416	487.30	373.09	28.16	21.56	0.0971	0.0743
36.80	0.0029432	487.56	373.29	27.61	21.14	0.0952	0.0729
36.81	0.002945	487.86	373.52	28.16	21.56	0.0971	0.0743
	Average:	487.43	373.19			0.0952	0.0729

Table 5-2.

Calculated J-T Values for the 8-Year Re-inspection Interval at the Limiting V6 Flaw.

8 year		*J-Integral (psi-in)*		*dJ/da*		*Tearing Modulus*	
a	*δt*	*Pln Strn*	*Pln Strs*	*Pln Strn*	*Pln Strs*	*Pln Strn*	*Pln Strs*
33.97	0.002494	413.08	316.27	-	-	-	-
33.98	0.002495	413.35	316.47	26.51	20.29	0.0914	0.0700
33.99	0.002497	413.58	316.65	24.85	19.02	0.0857	0.0656
34.00	0.002498	413.84	316.85	25.40	19.45	0.0876	0.0671
34.01	0.0025	414.08	317.03	24.85	19.02	0.0857	0.0656
	Average:	413.71	316.75			0.0876	0.0671

Table 5-3.

Safety Factor Calculation at the Limiting V6 Flaw.

Inspection Interval	J applied (in-lb/in)	J instability (in-lb/in)	Safety Factor
15 Years	487.4	1790	1.91
8 Years	413.7	1790	2.08

Safety Factor = $\sqrt{[(\text{J instability})/(\text{J applied})]}$

Square root since J $\propto$ load^2

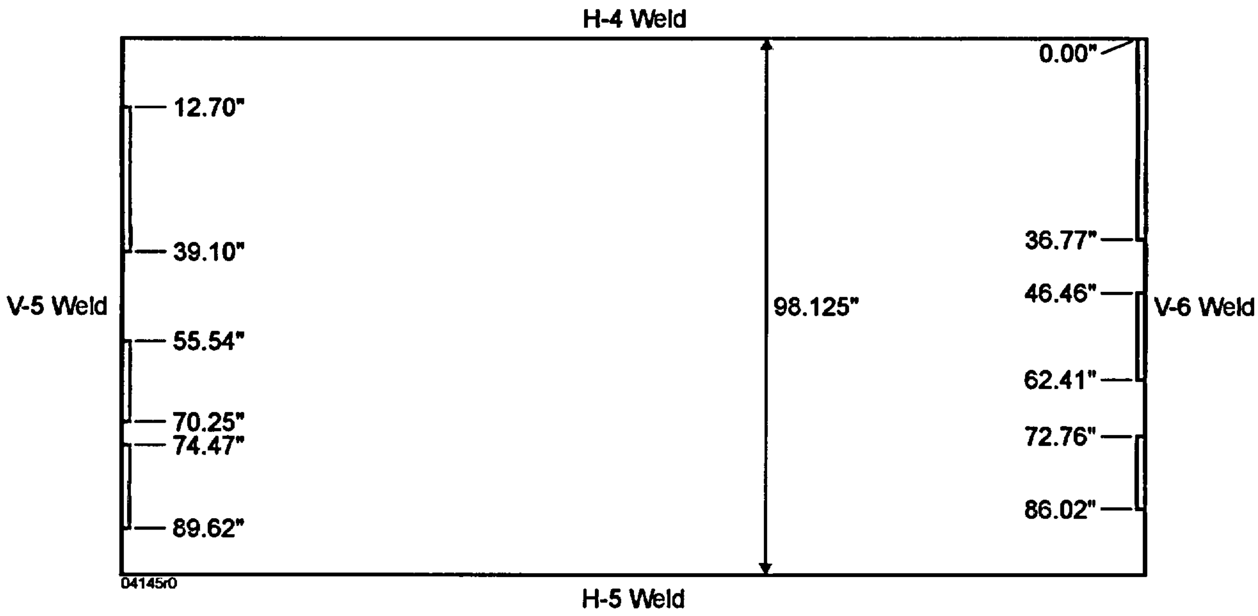


Figure 5-1. End-of-Evaluation Period Flaw Characterization (15 Years)

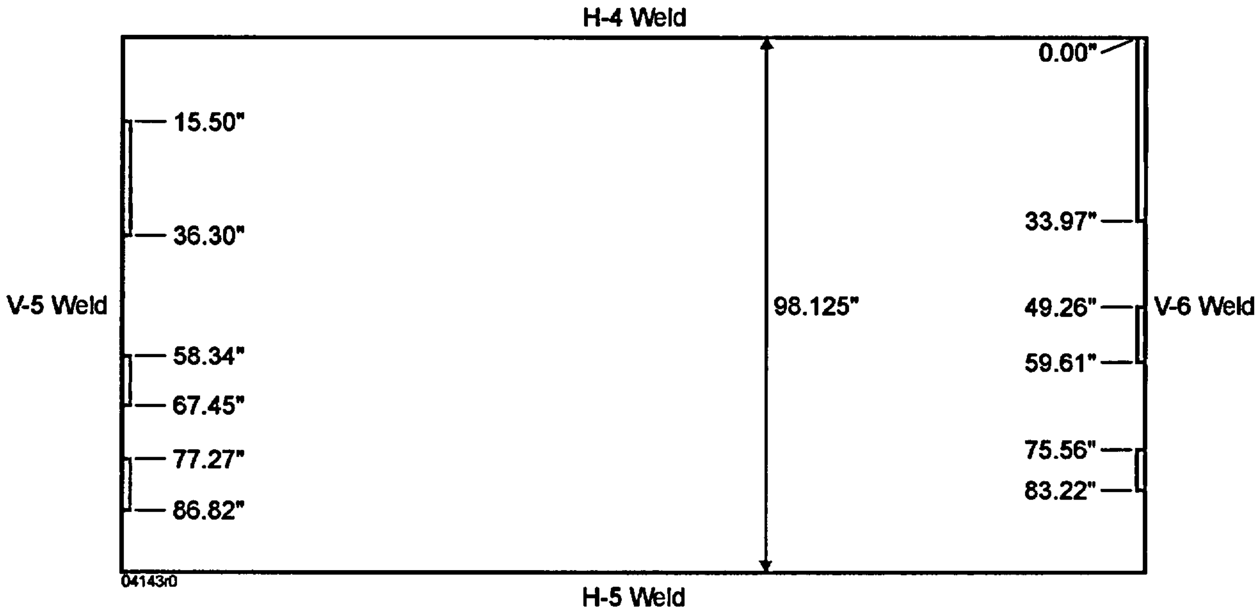


Figure 5-2. End-of-Evaluation Period Flaw Characterization (8 Years)

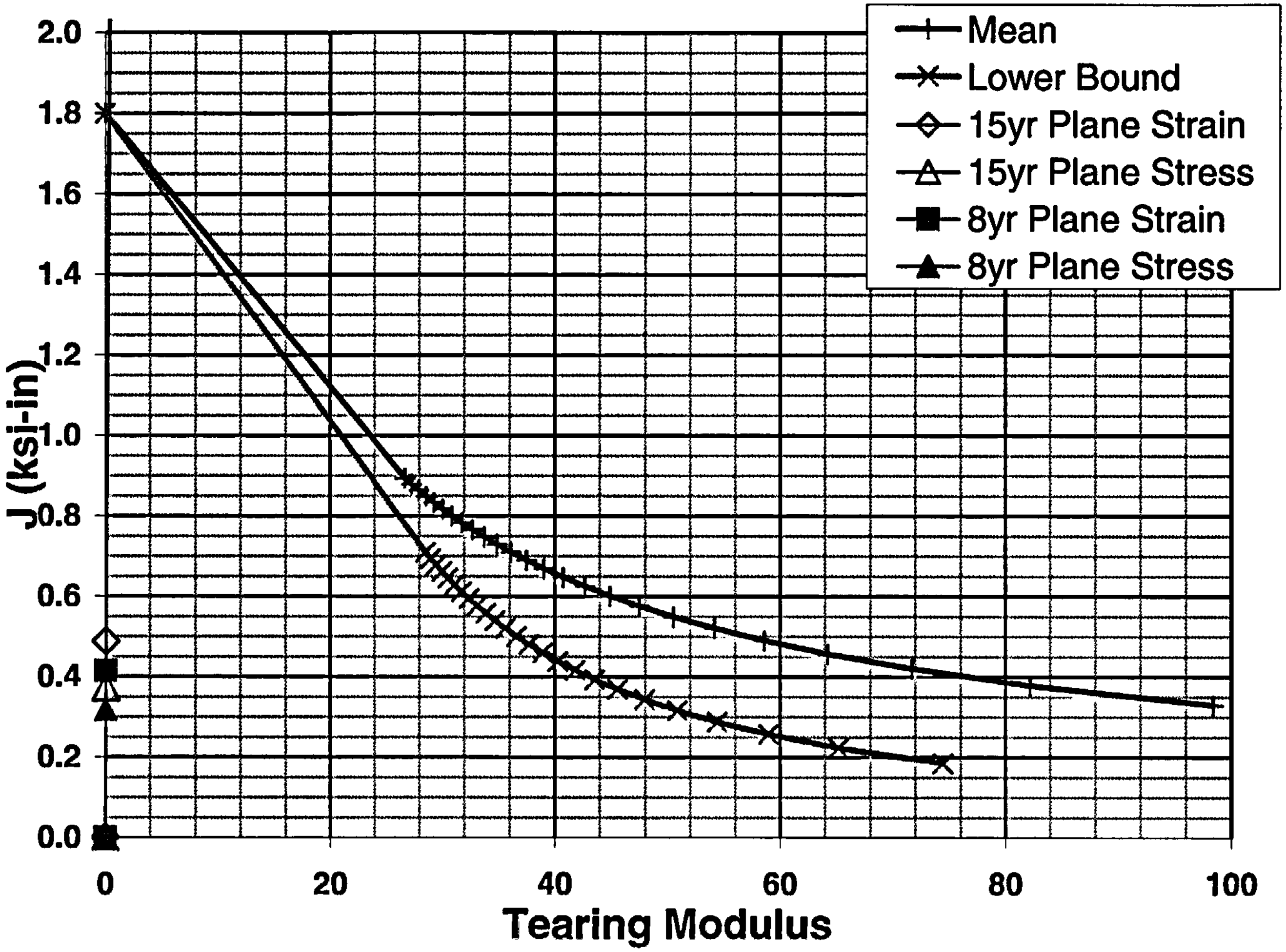


Figure 5-3. J-T Diagram at the Limiting V6 Flaw

6.0 CONCLUSION

A conservative EPFM analysis has been performed for the Plant Hatch Unit 1 core shroud V5 and V6 Weld. The analysis was performed for the limiting weld, which was weld V6. This weld is subjected to significant fluence and cracking was detected during the shroud inspection in 2004.

The crack growth rate used in the analysis was independent of the stress intensity factor. The crack growth rate used was 5×10^{-5} in/hr. A detailed three-dimensional finite element model was generated using the 2004 inspection crack profiles and adding crack growth for selected re-inspection intervals. The faulted condition limiting loading was applied to the model to determine the acceptability of the flaws.

Results of the evaluation show that the reinspection interval is well above 10 years. The results of the analysis showed a safety factor of 1.91 for fifteen years of operation beyond the 2004 inspection, which compares against the required safety factor of 1.5 for the faulted condition. The fifteen years of operation is equivalent to 120,000 hours assuming 8,000 hours per year. The results demonstrate substantial added margin if a 10 year reinspection interval is used. Based on these results, a re-inspection interval of ten years (or 80,000 hours) from the last inspection is justified.

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