INTERIM REPORT:

EVALUATION OF AN INDICATION IN THE BRAIDWOOD UNIT 2 LOOP 1 ELBOW TO VALVE WELD REGION

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TABLE OF CONTENTS

Section	Title	Page
1.0	INTRODUCTION AND CRITERIA	1-1
	1.1 Introduction	1-1
	1.2 Code Acceptance Criteria - Stainless Steel	1-1
2.0	LOADING CONDITIONS AND STRESS ANALYSIS	2-1
	2.1 Transients	2-1
	2.2 Pipe loadings	2-2
3.0	FRACTURE ANALYSIS METHODS AND MATERIAL PROPERTIES	3-1
	3.1 Fracture Toughness	3-1
	3.2 Allowable Flaw Size Determination	3-1
	3.3 Stress Corrosion Cracking Susceptibility	3-2
	3.4 Thermal Aging	3-3
4.0	FATIGUE CRACK GROWTH	4-1
	4.1 Analysis Methodology	4-1
	4.2 Stress Intensity Factor Calculations	4-1
	4.3 Crack Growth Rate Reference Curves	4-3
5.0	FLAW EVALUATION RESULTS	5-1
	5.1 IWB 3640 Evaluation	5-1
	5.2 Fracture Mechanics Evaluation	5-2
6.0	DISCUSSION AND CONCLUSIONS	6-1
7.0	REFERENCES	7-1

SECTION 1
INTRODUCTION AND CRITERIA

1.1 INTRODUCTION

During preservice ultrasonic inspection on Braidwood Unit 2 in 1987, an indication was detected in the elbow to valve weld region (weld number 2RC-01-04). A near surface indication was detected on the elbow side of the static cast austenitic stainless steel elbow to loop isolation valve weld. The ultrasonic examination was performed using a dual element nominal 45° refracted L-wave transducer. The flaw size was determined to be 1.5 inches long and 0.51 inches deep, oriented circumferentially and very close to the weld root, but not breaking through to the inside surface. Subsequent penetrant examinations performed on the inside surface revealed no indications, confirming the flaw to be subsurface.

Review of the construction radiographs identified a shrinkage type flaw acceptable to the ASME Section III Construction Code radiographic standards in this region. Ultrasonic examination performed to detect the axial component of the flaw was restricted due to the weld crown geometry. Therefore it is assumed that the flaw extends no greater than 0.8 inches in length axially and 0.51 inches deep.

To ensure the indications do not compromise the integrity of the reactor coolant system even in the unlikely event that they were actually flaws, a fracture evaluation has been carried out, using the rules of Section XI, paragraph IWB 3600 for both the circumferential and axial orientations. The indications are in the steam generator stainless steel inlet elbow near the weld. Both weld metal and base metal locations are considered in this analysis.

1.2 CODE ACCEPTANCE CRITERIA - STAINLESS STEEL

The evaluation procedures and acceptance criteria for indications in austenitic stainless piping are contained in paragraph IWB 3640 of Section XI.[1] The evaluation is applicable to all the materials within a specified distance from the weld centerline, $\sqrt{rt}$, where r = the pipe nominal outside radius and t is the wall thickness. For the inlet elbow to valve region, this distance is calculated to be 9.0 inches, which encompasses regions of the elbow and weld including the flaw indications given in figure 1.1.

The evaluation process begins with a flaw growth analysis, with the maximum growth due to fatigue and stress corrosion cracking. For pressurized water reactors only fatigue crack growth need be considered, as discussed in section 4.3. The methodology for the crack growth analysis is described in detail in section 5.

The calculated maximum flaw dimensions at the end of the evaluation period are then compared with the maximum allowable flaw dimensions for both normal operating conditions and emergency and faulted conditions, to determine acceptability for continued service. Provisions are made for considering flaws projected both circumferentially and axially.

In IWB 3640 the allowable flaw sizes have been defined in the tables based on maintaining specified safety margins on the loads at failure. These margins are 2.77 for normal and upset conditions and 1.39 for emergency and faulted conditions. The calculated failure loads are different for the base metal and the flux welds, which have different fracture toughness values, as discussed in section 4.2. The failure loads, and consequently the allowable flaw sizes, are larger for the base metal than for the welds. Allowable flaw sizes for welds are contained in separate tables, in IWB 3640.

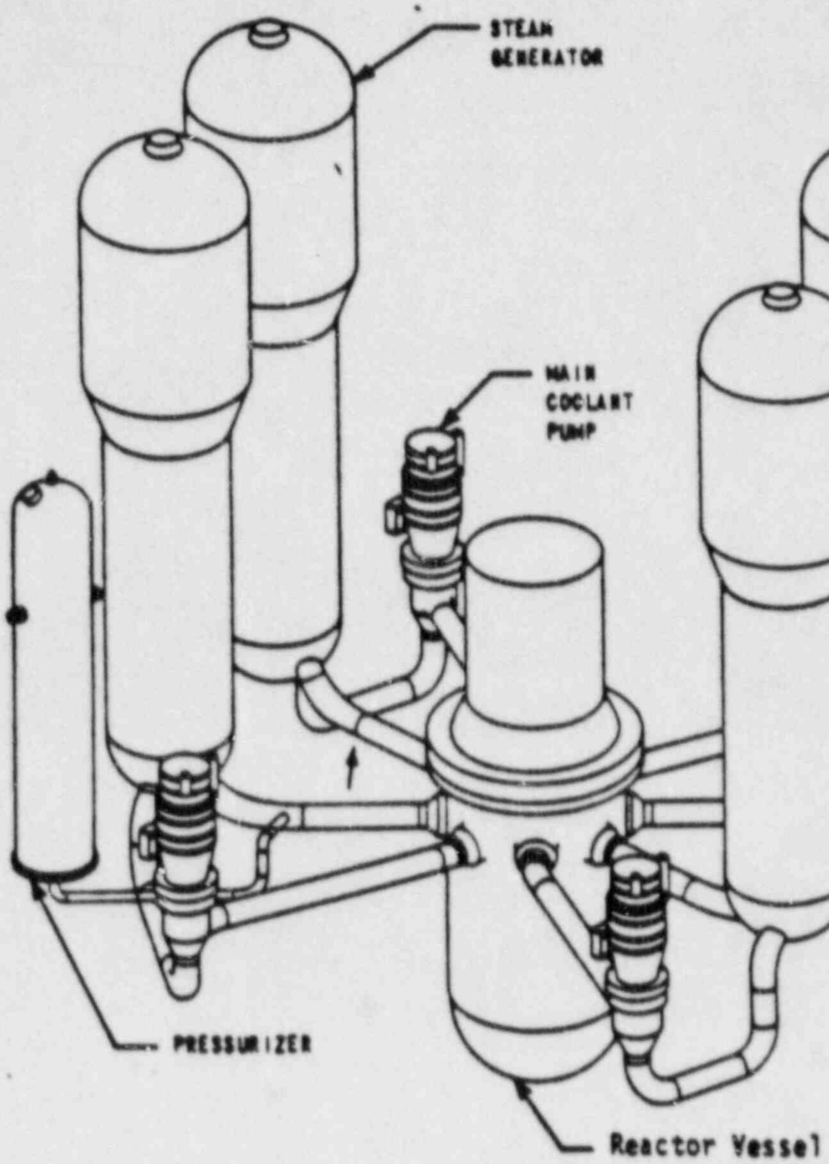

Figure 1-1. Geometry and Location of Inlet Nozzle Elbow to Pipe Weld

SECTION 2

LOADING CONDITIONS AND STRESS ANALYSIS

In performing the analyses necessary to determine allowable flaw depths and fatigue crack growth for the flaw evaluation process, it is important that all the applicable loadings be considered. Clearly the applicable design transients must be considered, but other loadings are also important. The residual stresses which exist in the region of interest have been considered. Note that for thinner sections these stresses are negligible, but for thick walled vessels like steam generators, and regions not stress-relieved, the stresses are important. There is another loading which must be considered, and that is the piping loads, which must be used in piping systems and connections to piping.

2.1 TRANSIENTS

The key parameters used in the evaluation of indications discovered during inservice inspection are two critical flaw depths. The first of these critical flaw depths is calculated using stresses from governing normal, upset, and test conditions. The second is calculated based on stresses for the governing emergency and faulted conditions. Critical flaw depths are calculated based on these two sets of conditions to correspond to the two ASME Code criteria outlined in section 1.

The design transients and the number of occurrences for the design life of the components are required for the stress, fracture and fatigue crack growth analyses. The design transients for the Braidwood Unit 2 steam generator are contained in table 2-1. Both the minimum critical flaw size (a_c under normal operation conditions, or a_i under faulted conditions) and K_I are functions of the stresses at the cross-section where the flaw of interest is located, and the material properties. Therefore, the first step for the evaluation of a flaw indication is to determine the appropriate limiting load conditions for the location of interest. This has been done, and is discussed in section 2.2.

C. Expansion Stress - Secondary Stress

i) Normal Thermal
ii) Upset Thermal

D. Normal/Upset - Total Stress

i) Pressure + Deadweight + OBE + Normal Thermal
ii) Pressure + Deadweight + Upset Thermal

E. Emergency/Faulted - Total Stress

i) Pressure + Deadweight + SSE + Normal Thermal
ii) Pressure + Deadweight + Faulted Thermal

In D and E above, load combination (i) is the governing case. The results below are based on the normal thermal loading conditions.

Results

The governing maximum stress intensity values are summarized below:

Condition	P_m Primary Membrane Stress	$P_m + P_b$ Primary Membrane Bending Stress	P_e Expansion Stress (ksi)
Normal/Upset	7.77	10.23	4.48
Emergency/ Faulted	9.20	14.93	4.48

C. Expansion Stress - Secondary Stress

i) Normal Thermal
ii) Upset Thermal

D. Normal/Upset - Total Stress

i) Pressure + Deadweight + OBE + Normal Thermal
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TABLE 2-1
SUMMARY OF STEAM GENERATOR TRANSIENTS - BRAIDWOOD UNIT 2

NUMBER	TRANSIENT IDENTIFICATION	SPECIFIED	USED IN THE ANALYSIS
	Normal Conditions		
1	Heatup and Cooldown at 100°F/hr (pressurizer cooldown 200°F/hr)	200	200
2	Load Follow Cycles (Unit loading and unloading at 5% of full power/min)	29,000	29,000
3	Step load increase and decrease of 10% of full power	2,000	2,000
4	Large step load decrease, with steam dump	200	200
5	Steady state fluctuations	Infinite	10^6
	Upset Conditions		
6	Loss of load, without immediate turbine or reactor trip	80	80
7	Loss of power (blackout with natural circulation in the Reactor Coolant System	40	40
8	Loss of flow (partial loss of flow, one pump only)	80	80
9	Reactor trip from full power	400	400
	Faulted Conditions		
10	Large Loss of Coolant Accident (LOCA)	1	1
11	Large Steam Line Break (LSB)	1	1
	Test Conditions		
12	Turbine roll test	10	10
13	Primary Side Hydrostatic test conditions	50	50
14	Cold Hydrostatic test	5	10

SECTION 3

FRACTURE ANALYSIS METHODS AND MATERIAL PROPERTIES

3.1 FRACTURE TOUGHNESS

The inlet elbow is cast stainless steel SA 351, type CF8A. The pipe to elbow weld was made by a shielded metal arc process.

The fracture toughness of the base metal has been found to be very high, even at operating temperatures [2], where the J_{Ic} values have been found to be well over 2000 in lb/in^2. Fracture toughness values for weld materials have been found to display much more scatter, with the lowest reported values significantly lower than the base metal toughness. Although the J_{Ic} values reported have been lower, the slope of the J-R-curve is steeper. Representative values for J_{Ic} were obtained from the results of Landes and co-workers [3], where the following value was obtained, and was used in the development of the fracture evaluation methods.

for shield metal arc welds: J_{Ic} = 990 in lb/in^2.

3.2 ALLOWABLE FLAW SIZE DETERMINATION

The critical flaw size is not directly calculated as part of the flaw evaluation process for stainless steels. Instead, the failure mode and critical flaw size is incorporated directly into the flaw evaluation technical basis, and therefore into the tables of "Allowable End-of-Evaluation Period Flaw Depth to Thickness Ratio," which are contained in paragraph IWB 3640.

Rapid, nonductile failure is possible for ferritic materials at low temperatures, but is not applicable to stainless steels. In stainless materials, the higher ductility leads to two possible modes of failure, plastic collapse or unstable ductile tearing. The second mechanism can occur when the applied J integral exceeds the J_{Ic} fracture toughness, and some stable tearing occurs prior to failure. If this mode of failure is dominant, the load carrying capacity is less than that predicted by the plastic collapse mechanism.

The allowable flaw sizes of paragraph IWB 3640 for the high toughness elbow materials were determined based on the assumption that plastic collapse would be achieved and would be the dominant mode of failure. However, due to the reduced toughness of the submerged arc and shielded metal arc welds, it is possible that crack extension and unstable ductile tearing could occur and be the dominant mode of failure. This consideration in effect reduces the allowable end of interval flaw sizes for flux welds relative to the austenitic wrought piping, and has been incorporated directly into the evaluation tables.

3.3 STRESS CORROSION CRACKING SUSCEPTIBILITY

In evaluating flaws, all mechanisms of subcritical crack growth must be evaluated to ensure that proper safety margins are maintained during service. Stress corrosion cracking has been observed to occur in stainless steel in operating BWR piping systems; the discussion presented here is the technical basis for not considering this mechanism in the present analysis.

For all Westinghouse plants, there is no history of cracking failure in the reactor coolant system loop piping. For stress corrosion cracking (SCC) to occur in piping, the following three conditions must exist simultaneously: high tensile stresses, a susceptible material, and a corrosive environment. Since some residual stresses and some degree of material susceptibility exist in any stainless steel piping, the potential for stress corrosion is minimized by proper material selection immune to SCC as well as preventing the occurrence of a corrosive environment. The material specifications consider compatibility with the system's operating environment (both internal and external) as well as other materials in the system, applicable ASME Code rules, fracture toughness, welding, fabrication, and processing.

The environments known to increase the susceptibility of austenitic stainless steel to stress corrosion are oxygen, fluorides, chlorides, hydroxides, hydrogen peroxide, and reduced forms of sulfur (e.g., sulfides, sulfites, and thionates). Strict pipe cleaning standards prior to operation and careful control of water chemistry during plant operation are used to prevent the occurrence of a corrosive environment. Prior to being put into service, the piping is cleaned internally and externally. During flushes and preoperational testing, water chemistry is controlled in accordance with written specifications. External cleaning for Class 1 stainless steel piping includes patch tests to monitor and control chloride and fluoride levels. For preoperational flushes, influent water chemistry is controlled. Requirements on chlorides, fluorides, conductivity, and pH are included in the acceptance criteria for the piping

During plant operation, the reactor coolant system (RCS) water chemistry is monitored and maintained within very specific limits. Contaminant concentrations are kept below the thresholds known to be conducive to stress corrosion cracking with the major water chemistry control standards being included in the plant operating procedures as a condition for plant operation. For example, during normal power operation, oxygen concentration in the RCS is expected to be less than 0.005 ppm by controlling charging flow chemistry and maintaining hydrogen in the reactor coolant at specified concentrations. Halogen concentrations are also stringently controlled by maintaining concentrations of chlorides and fluorides within the specified limits. This is assured by controlling charging flow chemistry and specifying proper wetted surface materials.

3.4 THERMAL AGING

Thermal aging at operating temperatures of reactor primary piping can embrittle cast stainless steels and, to a lesser degree, stainless steel weldments. The cast stainless steel piping and elbows of the primary loop are very tough, usually exhibiting J_{Ic} values exceeding 5000 in-lb/in^2 and a tearing modulus, T_{mat}, well over 200. NRC procedures exist for addressing the impact of thermal aging on fracture toughness for full-service life. The approved procedures were applied to the steam generator inlet elbow containing the indication. The elbow was fabricated of CF8A cast stainless, which is known to be less susceptible to thermal aging than other types which contain molybdenum. Because of this fact, it was found that the elbow qualified for the highest assignable end-of-service fracture toughness values, specifically, J_{Ic} = 750 in-lb/in^2, T_{mat} = 60.

Even with thermal aging, equivalent to full service for SMAW welds, the tearing modulus remains high (>100) and the unaged toughness, J_{Ic}, is not significantly reduced. Therefore the value of J_{Ic} = 990 in-lb/in^2 from section XI was retained for this analysis. Because of the larger tearing modulus, SMAW welds with full service life aging remain as good as the elbow material in question from a stability view point.

Thus, the fracture toughness criteria for full service life are J_{Ic} = 750 in-lb/in^2, T_{mat} = 60 for the elbow, and J_{Ic} = 990 in-lb/in^2 and T_{mat} = 100 for the SMAW weld.

SECTION 4

FATIGUE CRACK GROWTH

In applying the code acceptance criteria as introduced in section 1, the final flaw size a_f used in the criteria is defined as the minimum flaw size to which the detected flaw is calculated to grow at the end of the design life, or until the next inspection time.

To estimate the fatigue crack growth rate behavior in the elbow to pipe weld region, and analysis is presented here for the vessel inlet nozzle safe-end region of a typical system. This region was selected because crack growth calculated here will be typical of that in the entire primary loop. Crack growths calculated at other locations can be expected to show less than 10% variation. Thermal aging has been shown not to impact fatigue crack growth.

4.1 ANALYSIS METHODOLOGY

The analysis procedure involves postulating an initial flaw at each specific region and predicting the growth of that flaw due to an imposed series of loading transients. The input required for a fatigue crack growth analysis is basically the information necessary to calculate the parameter ΔK_I which depends on crack and structure geometry and the range of applied stresses in the area where the crack exists. Once ΔK_I is calculated, the growth due to that particular stress cycle can be calculated by equations given in section 4.3. This increment of growth is then added to the original crack size, and the analysis proceeds to the next transient. The procedure is continued in this manner until all the transients known to occur in the period of evaluation have been analyzed.

The transients considered in the analysis are all the design transients contained in the vessel equipment specification, as shown for example in section 2, table 2-1. These transients are spread equally over the design lifetime of the vessel, with the exception that the preoperational tests are considered first. Faulted conditions are not considered because their frequency of occurrence is too low to affect fatigue crack growth.

4.2 STRESS INTENSITY FACTOR EXPRESSIONS

Stress intensity factors were calculated from methods available in the literature for each of the flaw types analyzed. The surface flaw with aspect ratio 6:1 is analyzed using an expression developed by McGowan and Raymund [4] where the stress intensity factor K_I is calculated from the actual stress profile through the wall at the location of interest.

The maximum and minimum stress profiles corresponding to each transient are represented by a third order polynomial such that:

$$\sigma (X) = A_0 + A_1 \frac{x}{t} + A_2 \frac{x^2}{t^2} + A_3 \frac{x^3}{t^3}$$

The stress intensity factor K_I (ϕ) can be calculated anywhere along the crack front. The point of maximum crack depth is represented by $\phi = 0$. The following expression is used for calculating K_I (ϕ).

$$K_I(\phi) = \left(\frac{\pi a}{Q}\right)^{0.5} \left(\cos^2\phi + \frac{a^2}{c^2} \sin^2\phi\right)^{1/4} \left(A_0 H_0 + \frac{2a}{t} A_1 H_1 \right.$$

$$\left. + \frac{1}{2} \frac{a^2}{t^2} A_2 H_2 + \frac{4}{3} \frac{a^3}{t^3} A_3 H_3\right)$$

The magnification factors H_0, H_1, H_2 and H_3 are a function of ϕ and are obtained by the procedure outlined in reference [4].

The stress intensity factor for a continuous surface flaw was calculated using an expression for an edge cracked plate [5]. The stress distribution is linearized through the wall thickness to determine the membrane and bending stresses; the applied K_I is calculated from:

$$K_I = \sigma_m Y_m (\pi a)^{0.5} + \sigma_B Y_B (a\pi)^{0.5}$$

The magnification factors Y_m and Y_B are taken from [5] and "a" is the crack depth.

4.3 CRACK GROWTH RATE REFERENCE CURVES

There is presently no reference fatigue crack growth rate curve in the ASME Code for austenitic stainless steels. However, a great deal of work has been done recently which supports the development of such a curve. An extensive study was done by the Metals Property Council working group on reference fatigue crack growth concerning the crack growth behavior of these steels in air environments, published in reference [6]. A reference curve for stainless steels in air environments, based on this work, will appear in the 1988 Addenda of Section XI.

A compilation of data for austenitic stainless steels in a PWR water environment was made by Bamford [7], and it was found that the effect of the environment on the crack growth rate was very small. From this information it was estimated that the environmental factor should be conservatively set at 2.0 in the crack growth rate equation from reference [6]. Therefore the crack growth rate equation used in the analysis was:

$$\frac{da}{dn} = C\ F\ S\ E\ \Delta K^{3.30}$$

where:

C	=	2.42×10^{-20}
F	=	frequency factor ($F = 1.0$ for temperatures below 800°F)
S	=	R ratio correction ($S = 1.0$ for $R = 0$; $S = 1 + 1.8R$ for $0 < R < .8$; and $S = -43.35 + 57.97R$ for $R > 0.8$)
E	=	environmental factor ($E = 2.0$ for PWR environment)
ΔK	=	range of stress intensity factor, in psi $\sqrt{\text{in}}$

and R is the ratio of the minimum K to the maximum K.

4.4 FATIGUE CRACK GROWTH RESULTS

The results of the crack growth analysis work are shown in tables 4-1 and 4-2. Table 4-1 shows results for circumferential surface flaws of two different aspect ratios. Because the pipe loadings will affect a circumferential flaw more than an axial orientation, the circumferential flaw analysis was judged to conservatively bracket results for an axial flaw. Therefore the same fatigue crack growth analysis was used for both flaw orientations. The top table is for an indication extending entirely around the pipe, while the table below is for an indication with length six times its depth. It is clear from these tables that as the indication becomes shorter relative to its depth, the crack growth will be smaller than that shown in the bottom table. Thus a flaw 0.5 inches deep would grow to a depth of less than 0.578 inches in 10 years.

The actual indication is embedded, and thus the crack growth would be even less than the bounding number shown in table 4-1. Table 4-2 shows that crack growth for a buried flaw near the inside surface would actually be negligible.

TABLE 4-1

FATIGUE CRACK GROWTH FOR SURFACE FLAWS - STAINLESS STEEL

	Initial Crack Depth	Crack Depth After Year 10	20	30	40
Continuous Flaw	0.050	0.05855	0.06961	0.08426	0.10414
	0.100	0.12606	0.16329	0.21794	0.29977
	0.125	0.16177	0.21570	0.29638	0.41745
	0.250	0.34803	0.49392	0.70280	0.98313
	0.270	0.37806	0.53782	0.76350	1.06057
	0.375	0.53347	0.75767	1.05292	1.40512
	0.500	0.71151	0.99436	1.33862	1.69607
Aspect Ratio 1:6	0.050	0.05447	0.05959	0.06549	0.07233
	0.100	0.11302	0.12859	0.14733	0.16998
	0.125	0.14301	0.16475	0.19110	0.22303
	0.250	0.29400	0.34622	0.40709	0.47633
	0.270	0.31785	0.37418	0.43913	0.51202
	0.375	0.44011	0.51310	0.59242	0.67585
	0.500	0.57845	0.66136	0.74619	0.83053

TABLE 4-2

FATIGUE CRACK GROWTH FOR EMBEDDED FLAWS - STAINLESS STEEL

Initial Crack Depth	Crack Depth After Year			
	10	20	30	40
0.400	0.41146	0.42397	0.43777	0.45313
0.450	0.46691	0.48602	0.50796	0.53369
0.500	0.52436	0.55327	0.58859	0.63356

SECTION 5

FRACTURE EVALUATION OF INSPECTION RESULTS

5.1 IWB 3640 EVALUATION

The procedures of IWB 3640, Section XI, Division 1 of the ASME Code were used to evaluate the indications. Input parameters and a summary of results are given below. The flaw depth was rounded to 0.5 inches for this analysis.

Material: Elbow: SA351 CF 4
Weld: SMAW

Operating Temperature: 617°F

Flaw Size:

Circumferential:	Length = 1.5 in. Depth = 0.5 in.
Axial:	Length = 0.8 in. Depth = 0.5 in.
Nominal Dimensions:	Thickness = 2.55 in. Diameter = 31.55 in. (ID.= 29.0 in.)
Allowable Design Stress Intensity:	S_m = 19.1 ksi
Yield Stress:	S_y = 21.3 ksi
Loading: Normal (including upset);	P_m = 7.80 ksi P_b = 2.43 ksi P_e = 4.48 ksi

Emergency and Faulted; P_m = 9.20 ksi
P_b = 5.73 ksi
P_e = 4.48 ksi

Results:

1) P_m = 7.8 ksi which is less than 0.5 S_m (9.55 ksi) for normal condition.

2) P_m = 9.2 ksi which is less than S_m (19.1 ksi) for emergency and faulted conditions.

3) $P_m + P_b$ = 14.93 ksi which is less than 2 S_y (42.6 ksi) for emergency and faulted conditions.

4) For the elbow, the allowable circumferential flaw depth from Section XI paragraph IWB 3640 is 1.9 inches for both normal and emergency and faulted loads. This value does not change for a flaw at least 25 times longer (38 inches long).

5) For the elbow, the allowable axial flaw depth from IWB 3640 is 1.9 in. For both normal and emergency and faulted loads. This value does not change for a flaw at least 5 times longer (4.0 inches long). For a flaw as long as 30 inches, the acceptable depth is still 28 percent of the wall, or 0.71 inches.

6) For the SMAW weld, the allowable circumferential flaw depth from IWB 3640 is 1.53 in. for both normal and emergency and faulted loads. This value does not change for a flaw at least 20 times longer (30 inches long).

5.2 FRACTURE MECHANICS EVALUATION AND DISCUSSION

The fracture toughnesses are the highest allowed for full service life thermal aging considerations. With little service temperature experience for the piping system, embrittlement by thermal aging has not initiated thus for the present and up at least to 1 EFPY (judgementally, based on experimental results), unaged toughness results prevail. For the small flaw size and faulted load condition the actual applied value of J is estimated to be less than 500 in-lb/in^2.

SECTION 6.0

DISCUSSION AND CONCLUSIONS

A fracture evaluation has been carried out for the steam generator inlet elbow to pipe weld for Braidwood Unit 2, to assess the acceptability of an indication found there. The indication is believed to be a casting defect in the elbow. To provide a complete treatment of the indication as it was characterized by a number of inspections, two different analyses were done. The first analysis considered the largest circumferential projection of the indication from all the inspections, while the second analysis considered the largest axial projection of the indication. The indication was considered to be in the elbow material, but was also evaluated as if it were in the weld material.

The dimensions of the indication use in the evaluation were as follows:

Circumferential Projection:	0.5" deep x 1.5" long
Axial Projection:	0.5" deep x 0.8" long

This indication was subjected to a fatigue crack growth analysis to determine its projected growth during service. Because the pipe loadings affect crack growth of a circumferential crack, it was judged that the crack growth calculated for the circumferential crack would conservatively envelope crack growth for an axially oriented crack. As shown in table 4-1, a circumferential crack with a depth of 0.5 inches would grow to a depth of 0.578 inches in ten years, or to a depth of 0.83 inches after 40 years of service. This projected crack growth is expected to be very conservative, since it was calculated for a surface flaw which is more elongated (6:1 vs. the actual 3:1 circumferential aspect ratio) and for a region where the fatigue loadings are somewhat more severe than the region of interest.

The actual indication is an embedded flaw, and not exposed to the water environment. A consideration of embedded flaws shows that the projected crack growth is very small, over even for a forty year period, where a 0.5 inch deep flaw grows 0.13 inches.

Allowable flaw sizes for both circumferential and axial orientations were determined, and both the cast elbow and the shielded metal arc weld were considered. The most governing of the circumferential flaw calculations was for the SMAW weld, which had an allowable flaw depth of 1.53 inches and allowable length exceeding 30 inches. Therefore we see that the circumferential projection of the indication is acceptable by a wide margin.

Consideration was also given to the axial orientation, and the allowable depth was 1.9 inches, with the allowable length for this 1.9 inch flaw found to be 4 inches. The allowable length for a flaw with a depth of 0.7 inches was found to be over 30 inches.

It is therefore evident that the indication in the elbow to valve weld is acceptable to the requirements of Section XI by a wide margin.

SECTION 7.0

REFERENCES

1. ASME Code Section XI, "Rules of Inservice Inspection of Nuclear Power Plant Components," 1974 Edition; 1983 edition (used for updated code allowable limits); and 1980 edition [Winter 1981 Addendum] (for revised reference crack growth curves); 1980 edition (used for updated proximity rules for embedded vs. surface flaws); 1986 edition (used for stainless steel flaw evaluation).

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