WCAP-11850

FRACTURE SENSITIVITY STUDY OF GIRTH WELD NO. 6 REPAIRED CONFIGURATION

INDIAN POINT UNIT 2

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W. H. Bamford
Y. S. Lee

Verified by: C. Bradley Bond
C. B. Bond

Approved by: S. S. Palusamy
S. S. Palusamy, Manager
Structural Materials Engineering

WESTINGHOUSE ELECTRIC CORPORATION
Power Systems Business Unit
P.O. Box 355
Pittsburgh, Pennsylvania 15230

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EXECUTIVE SUMMARY

In the fall of 1987 a series of surface flaws were found in the upper shell to cone weld of the Indian Point Unit 2 steam generators. These flaws were removed by grinding, appropriate evaluations performed, and the vessels returned to service.

During the discussions which took place with the Nuclear Regulatory Commission on this topic, a question was raised concerning the fracture toughness of the heat-affected zone (HAZ) region of the weld. Specifically, the high hardness of the HAZ region (as determined from tests on boat samples) was suspected to be an indication of low fracture toughness. As a result of this concern this sensitivity study was undertaken, in conjunction with an experimental program (reported separately) to characterize the HAZ properties.

The sensitivity study reported here shows that the fracture toughness of the upper shell to cone weld region is sufficient to ensure its integrity during future operation, even with a very long surface flaw. This conclusion results from the fracture calculations reported here as well as the experimental findings of the companion program.

SECTION 1
INTRODUCTION

The indications found in girth weld number six of the Indian Point Unit 2 steam generators have been removed by grinding. Boat samples removed during the repair process have shown that there are regions within the heat affected zone with relatively high hardness, and this has raised concerns relative to the integrity of the steam generator vessel.

This work has been carried out to investigate the integrity of the vessel, and to determine the sensitivity of the repaired vessel girth weld region to the presence of cracks, even though it is not expected that cracks would reinitiate in this region. Specifically, analyses were done to determine what level of fracture toughness or RT_{NDT} would be required to maintain the integrity of the vessel for a postulated surface flaw.

SECTION 2

LOAD CONDITIONS, FRACTURE ANALYSIS METHODS AND MATERIAL PROPERTIES

2.1 TRANSIENTS FOR THE STEAM GENERATOR

The design transients for the Indian Point Unit 2 steam generators are listed by umbrella groupings in table 2-1. The critical flaw sizes under normal operating conditions, or under faulted conditions, and the stress intensity factors, K_I, are a function of the stresses caused by these transients at the cross-section where the flaw of interest is located, and the material properties. Therefore, the first step for a fracture evaluation is to determine the appropriate limiting load conditions for the location of interest.

For the region of interest, the upper shell to cone weld, the full range of design transients was considered. Transients such as pressure tests, including both hydrostatic and leakage tests, can be controlled by setting the test temperature. Therefore, the operational transients were considered in one analysis and a separate determination was made of the toughness required for the pressure tests. On this basis, the governing operational transient was found to be the reactor trip condition, which is even more severe than emergency and faulted transients in the steam generator.

2.2 STRESS INTENSITY FACTOR CALCULATIONS

One of the key elements of the critical flaw size calculations is the determination of the driving force or stress intensity factor (K_I). This was done using expressions available from the literature. In all cases the stress intensity factor for the critical flaw size calculations utilized a representation of the actual stress profile rather than a linearization. This was necessary to provide the most accurate determination possible of the critical flaw size, and is particularly important where the stress profile is generally nonlinear and often very steep. The stress profile was represented by a cubic polynomial:

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

where x is the coordinate distance into the wall

t = wall thickness

σ = stress perpendicular to the plane of the crack

In the study of sensitivity to the presence of flaws (section 3) three flaw shapes were used, near-continuous (a/ℓ = 0.05) semielliptical with length six times the depth (a/ℓ = 0.167) and semi circular (a/ℓ = 0.5). As will be seen in Section 3, the study covers the full range of shapes between these values. All the postulated flaws were circumferentially oriented, and were presumed to be in the region of maximum griding depth.

For the surface flaw with length six times its depth (a/ℓ = 0.167), the stress intensity factor expression of McGowan and Raymund [2] was used. The stress intensity factor $K_I(\phi)$ can be calculated anywhere along the crack front, where ϕ is the angular position, as defined in figure 2-1. The point of maximum crack depth is represented by $\phi = 0$. The following expression is used for calculating $K_I(\phi)$:

$$K_I(\phi) = \left[\frac{\pi a}{Q}\right]^{0.5} \left(\cos^2\phi + \frac{a^2}{c^2}\sin^2\phi\right)^{1/4} \left(A_o H_o + \frac{2}{\pi}\frac{a}{t} A_1 H_1 + \frac{1}{2}\frac{a^2}{t^2} A_2 H_2 + \frac{4}{3\pi}\frac{a^3}{t^3} A_3 H_3\right)$$

The magnification factors $H_0(\phi)$, $H_1(\phi)$, $H_2(\phi)$ and $H_3(\phi)$ were obtained by the procedure outlined in reference [2].

The stress intensity factor calculation for a semi-circular surface flaw, (a/ℓ = 0.5) was carried out using the expressions developed by Raju and Newman [3]. Their expression utilizes the same cubic representation of the stress profile and gives precisely the same result as the expression of McGowan and Raymund for the flaw with a/ℓ = 0.167, and the form of the equation is similar to that of McGowan and Raymund above. The stress intensity factor expression used for a very long surface flaw ($a/\ell = 0.05$) was also carried out using the expression of Raju and Newman [3].

2.3 FRACTURE TOUGHNESS

The other key element in the determination of critical flaw sizes is the fracture toughness of the material. The fracture toughness has been taken directly from the reference curves of Appendix A, Section XI. In the transition temperature region, these curves can be represented by the following equations:

$$K_{Ic} = 33.2 + 2.806 \exp. [0.02 (T-RT_{NDT} + 100°F)]$$

$$K_{Ia} = 26.8 + 1.233 \exp. [0.0145 (T-RT_{NDT} + 160°F)]$$

where K_{Ic} and K_{Ia} are in ksi$\sqrt{\text{in}}$.

The upper shelf temperature regime requires utilization of a shelf toughness which is not specified in the ASME Code. A value of 200 ksi$\sqrt{\text{in}}$ has been used here. This value is consistent with general practice in such evaluations, as shown for example in reference [4], which provides the background and technical basis of Appendix A of Section XI.

The fracture toughness of steam generator materials has been well characterized, since A302B steel was used to fabricate many reactor vessels as well. This material was used in developing and verifying the reference toughness curves of the ASME code. Fracture toughness tests were conducted on base metal, weldments, and heat-affected zones, and were all found to be bounded by the ASME K_{Ia} curve for dynamic and arrest tests, and the K_{Ic} curve for static tests.

The other key element in the determination of the fracture toughness is the value of RT_{NDT}, which is a parameter determined from Charpy V-notch and drop-weight tests.

To allow determination of RT_{NDT} for the upper shell and cone materials, a compilation was made of the properties listed on the original material test certificates. The materials used in the steam generators were tested after a post-weld heat treatment cycle of 1050-1150°F for 18 to 28 hours, as shown in table 2-2. The Charpy impact properties of these materials are listed in tables 2-3 and 2-4.

The U.S. Nuclear Regulatory Commission has established guidelines for estimating the value of RT_{NDT} from Charpy properties in their Standard Review Plan [5]. Review of table 2-3 shows that in general the materials in the shell and cone region have excellent Charpy properties, and therefore the value of RT_{NDT} is equal to the test temperature, which is 10°F for all the base materials and 30°F for the welds.

Concern has been expressed relative to the RT_{NDT} estimation procedures being applied to the heat-affected zone material, and to answer this question completely further experimental work has been carried out [6]. The properties of the girth weld were expected to be quite good. Charpy tests made from the plug removed from the Indian Point Unit 3 girth weld number six showed very good results, as shown in table 2-5. The maximum hardness of the heat-affected zone of this plug was found to be very similar to that of boat samples removed from unit 2 during the recent investigation.

Results of the experimental study of the high hardness HAZ material [6] showed that RT_{NDT} was much lower than the original estimate of 30°F. Drawing a lower bound curve under the Charpy data of figure 3.53 of reference 6, the 50 ft-lb energy level was reached at 28°F, as reproduced here in figure 2-2. Using the procedure of the ASME Code Section III, paragraph NB-2300, the RT_{NDT} value is 60°F below this 50 ft-lb temperature, or -32°F. This is believed to be a reliable estimate of RT_{NDT} for the material, even though drop weight tests were not performed, since the Charpy curve is very steep and the transition is well-defined. The Charpy results from the experimental program [6] at room temperature (52-64 ft-lb) are similar to the results of the tests from the Indian Point Unit 3 material reported in table 2-5 and discussed above. The results of [6] are also comparable to the original weld qualification test results for Indian Point 2, in table 2-4, since the HAZ results at 0°F were approximately 50 ft-lb.

Once the value of RT_{NDT} is established, the reference toughness curves of the ASME Code discussed above may be used directly, since the materials are SA302 grade B which has a minimum specified yield strength of 50 ksi. These toughness curves were used in the critical flaw size determinations to be discussed below.

2.4 CRITICAL FLAW SIZE DETERMINATION, AND SENSITIVITY APPROACH

The applied stress intensity factor (K_I) and the material fracture toughness values (K_{Ia} and K_{Ic}) were used to determine the allowable flaw size values used to construct the handbook charts. For this study, the critical flaw size was determined as the depth at which the applied stress intensity factor K_I exceeds the fracture toughness K_{Ic}.

In this study, since the fracture toughness of the material is in question the critical flaw size determination method was used in reverse, to decide what fracture toughness is necessary to maintain the integrity of the steam generator girth weld region in the presence of a postulated flaw. The results of these calculations will be discussed in Section 3.

TABLE 2-1
TRANSIENT GROUPING FOR FATIGUE CRACK GROWTH ANALYSIS [7]

Transient		Cycles
1	Cold Shutdown	200
2	No Load	200
3	100% Power (Plant Load/Unload)	14500
4	Small Step Load Decrease	2000
5	Steady-State Fluctuations (+)	1.0E+06
6	Steady-State Fluctuations (-)	1.0E+06
7	Large Step Load Decrease Small Step Load Decrease (2000)	2200
8	Loss of Power Loss of Load (40) Loss of Flow (80) Secondary Side Leak Test (5)	205
9	Reactor Trip	400
10	Feedwater Cycling	25000
11	Secondary Hydrotest (Init.)	1
12	Secondary Hydrotest (Subs.)	50

TABLE 2-2

POSTWELD HEAT TREATMENT OF UPPER SHELL - CONE WELDS

INDIAN POINT UNIT 2

Heatup to 1050°F	> 7 hours
Soak at 1050-1150°F	SG #1 - 26 hrs
	SG #2 - 27 hrs
	SG #3 - 18 hrs
	SG #4 - 28 hrs

Cooldown in Air

TABLE 2-3

MATERIAL PROPERTIES OF UPPER SHELL-CONE REGION

INDIAN POINT UNIT 2

Location	Material Type	Charpy Values (10°F) (ft-lb)	RT_{NDT}
Cone materials, SG #1			
heat A0058-3	SA 302-56 Gr B	64,67,63	10°F
heat A0991-2	SA 302-56 Gr B	58,62,50	10°F
heat A0042-2	SA 302-56 Gr B	61,74,77	10°F
heat A0042-4	SA 302-56 Gr B	55,64,60	10°F
Upper shell materials, SG #1			
heat 85012-2	SA 302-56 Gr B	70,67,68	10°F
heat 85012-3	SA 302-56 Gr B	73,83,48	10°F
heat A0310-4	SA 302-56 Gr B	105,95,104	10°F
heat B5012-1	SA 302-56 Gr B	78,78,74	10°F
Cone materials, SG #2			
heat C1108-4	SA 302-56 Gr B	124,120,125	10°F
heat A9941-1	SA 302-56 Gr B	95,81,90	10°F
heat A0091-1	SA 302-56 Gr B	72,60,59	10°F
heat C1108-2	SA 302-56 Gr B	85,68,97	10°F
heat A0042-4	SA 302-56 Gr B	55,64,60	10°F
Upper shell materials SG #2			
heat A0126-1	SA 302-56 Gr B	60,80,82	10°F
heat A0126-2	SA 302-56 Gr B	86,47,57	10°F
heat A0126-3	SA 302-56 Gr B	105,97,91	10°F
heat A0126-4	SA 302-56 Gr B	79,66,64	10°F

TABLE 2-3 (continued)

MATERIAL PROPERTIES OF UPPER SHELL-CONE REGION

INDIAN POINT UNIT 2

Location	Material Type	Charpy Values (10°F) (ft-lb)	RT_{NDT}
Cone materials, SG #3			
B5010-2	SA 302-56 Gr B	81,143,85	10°F
B5010-3	SA 302-56 Gr B	81,143,85	10°F
C1108-1	SA 302-56 Gr B	81,95,76	10°F
B4873-5	SA 302-56 Gr B	86,121,85	10°F
B5010-1	SA 302-56 Gr B	93,73,113	10°F
Upper Shell Materials, SG #3			
A0902-4	SA 302-56 Gr B	70,67,67	10°F
A0877-2	SA 302-56 Gr B	77,89,87	10°F
A0877-1	SA 302-56 Gr B	94,70,55	10°F
A0872-3	SA 302-56 Gr B	79,83,83	10°F
Cone Materials, SG #4			
heat C1488-4	SA 302-56 Gr B	82,88,89	10°F
heat C1488-3	SA 302-56 Gr B	81,77,74	10°F
heat B5387-1	SA 302-56 Gr B	84,84,88	10°F
heat B5387-2	SA 302-56 Gr B	90,98,110	10°F
Upper Shell Materials, SG #4			
A0877-4	SA 302-56 Gr B	83,92,95	10°F
A0902-2	SA 302-56 Gr B	51,78,45	10°F
A0877-3	SA 302-56 Gr B	72,96,75	10°F
B5973-2	SA 302-56 Gr B	66,74,70	10°F

TABLE 2-4
MECHANICAL PROPERTIES AND TOUGHNESS
OF WELD QUALIFICATION SPECIMENS

Heat No.	Yield Strength (ksi)	Tensile Strength (ksi)	Charpy Energy (ft-lb) at 10°F	RT_{NDT}
B5012	67.7	83.4	30/37/29	30
			50/53/80	10
A0265	70.9	86.9	38/30/47	30
			37/111/48	10
C1108	64.6	83.4	41/40/41	30
			43/48/98	10
B4873	68.0	85.0	38/37/42	30
			80/33/83	10

TABLE 2-5

CHARPY RESULTS FROM MATERIAL REMOVED FROM THE INDIAN POINT UNIT 3 STEAM GENERATOR, TESTED AT 76°F

Notch Location	Cv (ft lbs)	Lateral Expansion (Mils)	% Shear
Trans cone	79	63	85
Trans cone	69	58	80
Upper shell	77	67	95
Upper shell	75	64	95
Weld cone	60	51	60
Repair weld	111	85	95
Crown to cone HAZ	83,74	59,59	90,85
Crown to upper shell	83,71	61,44	95,60

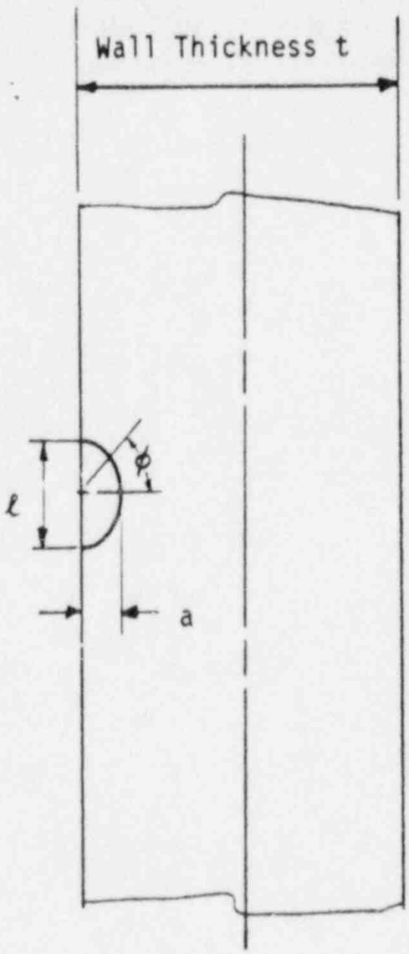

Figure 2-1. Geometry and Terminology of Flaws Evaluated

Curve 755645-A

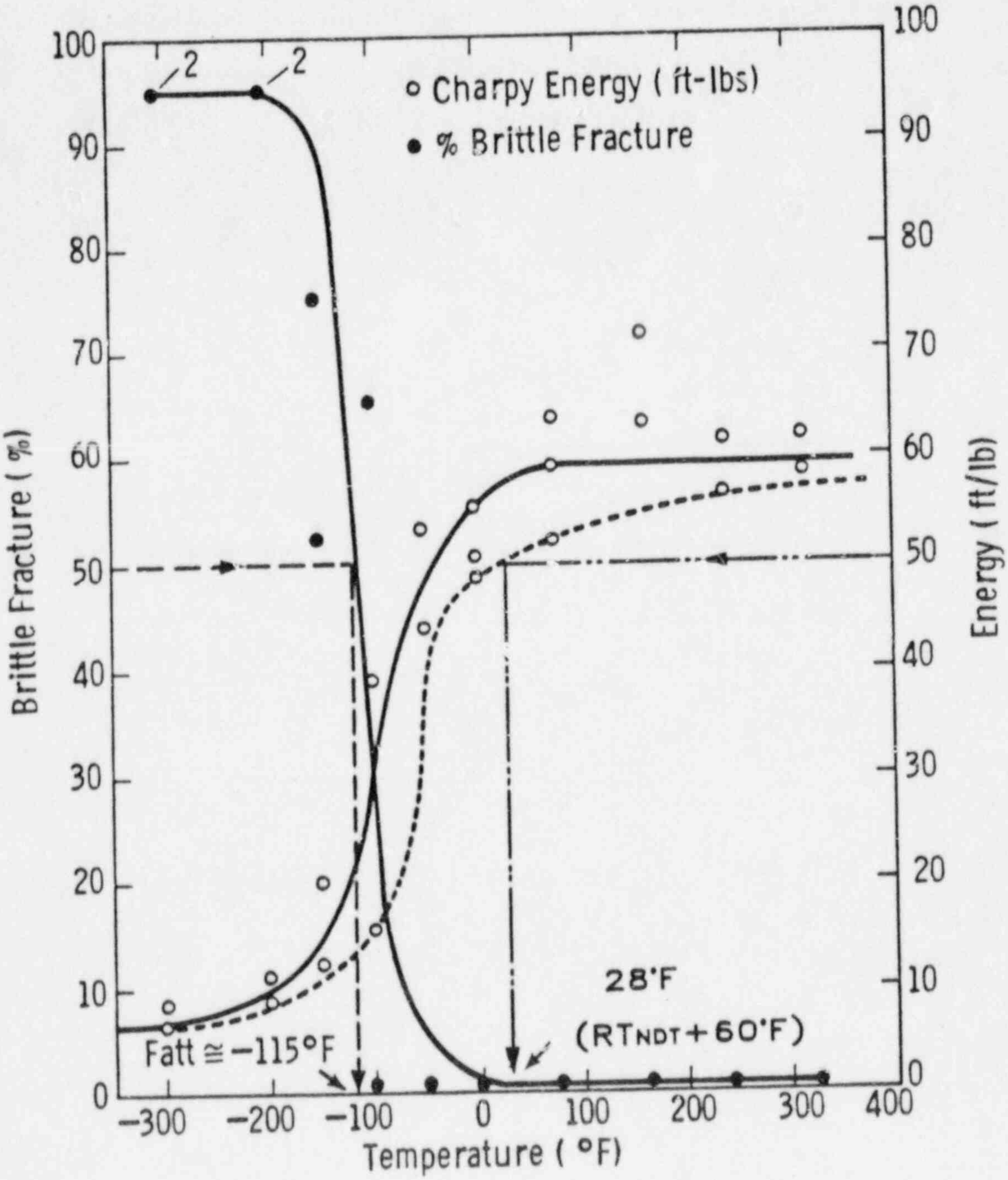

Figure 2-2. Charpy Results and RT_{NDT} Determination from Reference [6].

SECTION 3
FRACTURE ANALYSIS RESULTS AND CONCLUSIONS

Fracture analyses were carried out for both the reactor trip transient and a pressure test, to determine the sensitivity of the girth weld in its repaired configuration to the presence of cracks. The worst case repaired configuration was used, which incorporates a grinding depth of 1.1 inches [7].

The results of a typical pressure test are presented in figure 3-1, for three flaw shapes. The 1000 psi pressure was chosen as representative of the secondary side operational pressure tests, which generally range from 750-1085 psi. It can be seen from the figure that the girth weld is not very sensitive to the presence of flaws under a pressure loading, since even the most elongated flaw has a stress intensity factor of less than 100 ksi$\sqrt{\text{in}}$ for a flaw one-half inch deep beyond the 1.10 inch grinding depth. The assumption here is that RT_{NDT} is a maximum of 30°F. This assumption was proven conservative by the Charpy tests of reference [6]. The pressure tests could be accomplished with no difficulty at 80°F (RT_{NDT} + 50°F) for a 1000 psi test, and at 60°F (RT_{NDT} + 30°F) for a 770 psi pressure test. These values were obtained from use of the K_{Ic} curve from section XI, which is reproduced in figure 3-3, and a reference flaw depth of one half inch deep, beyond the 1.1 inch grinding depth. The assumption here was that RT_{NDT} is no higher than 30°F. Since the tests [6] have shown that RT_{NDT} is much lower than 30°F, the base metal properties become governing (RT_{NDT} = 10°F) and the pressure tests can be accomplished at room temperature with a generous safety margin.

The results of the calculation for the reactor trip transient are shown in figure 3-2, for three different flaw shapes. The applied stress intensity factor is highest for the longest flaw (a/ℓ = 0.05), as expected. After increasing rather steeply with crack depth, the sensitivity to flaws decreases, as seen by the decreasing slope. The stress intensity factor for a flaw one half inch deep was found to be 160 ksi$\sqrt{\text{in}}$ for the most elongated flaw shape, and 132 ksi$\sqrt{\text{in}}$ for a six-to-one elliptical flaw (a/ℓ = 0.167).

The implication of this finding is that a half-inch deep surface flaw would remain unaffected during the most severe operational transient (reactor trip) as long as the fracture toughness exceeds the aforementioned values. The minimum inside surface temperature at the girth weld during the reactor trip was found to be 260°F, so this toughness requirement translates into a required RT_{NDT} of 190°F or less for the six-to-one elliptical flaw (a/ℓ = 0.167). Likewise, a maximum RT_{NDT} of 173°F is obtained for the very long flaw (a/ℓ = 0.05). Since the RT_{NDT} is in the range of -60°F [6], a very large margin of safety can be shown to exist.

The above assessment is very conservative, because it is based on the assumption that the ground region of 1.1 inches deep extends around the entire circumference of the steam generator girth weld. The grind depth of 1.1 inches deep is actually very localized. Only at one location is the actual maximum grinding depth of 1.07 inch reached. Further, the assumption of a flaw 0.5 inch deep is very conservative, since the girth weld area has been carefully ground to be defect-free, as proven by magnetic particle exams. Lower bound toughness curves have been used in the fracture analysis, which adds further conservatism.

As a result, even with a very long, 0.5 inch deep surface flaw in the repaired girth weld region, the structural integrity of the upper shell to cone girth welds in the Indian Point 2 steam generators will not be affected.

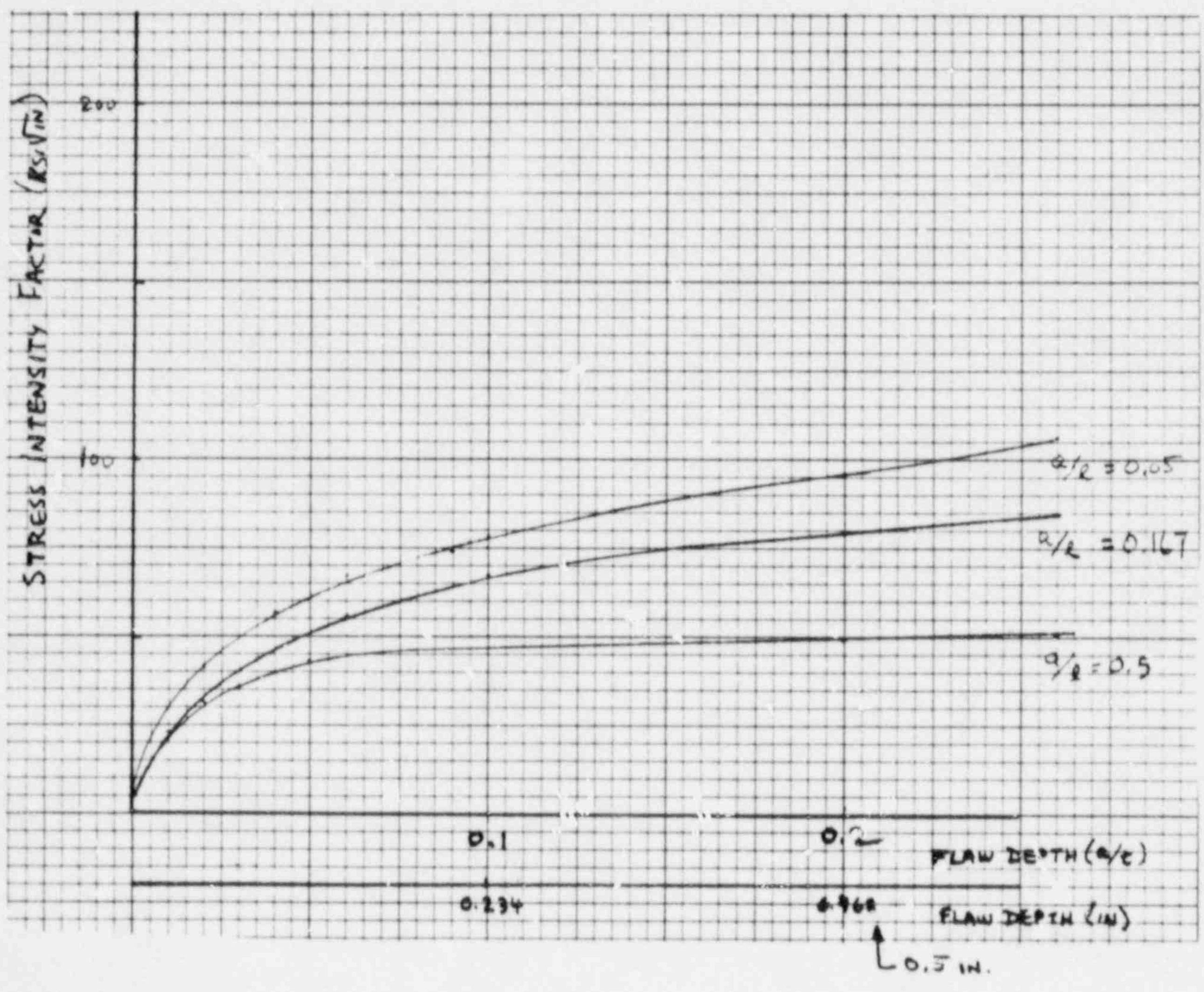

Figure 3-1. Stress Intensity Factor Calculations for Girth Weld #6 in the Repaired Configuration, Pressure Test at 1000 psi

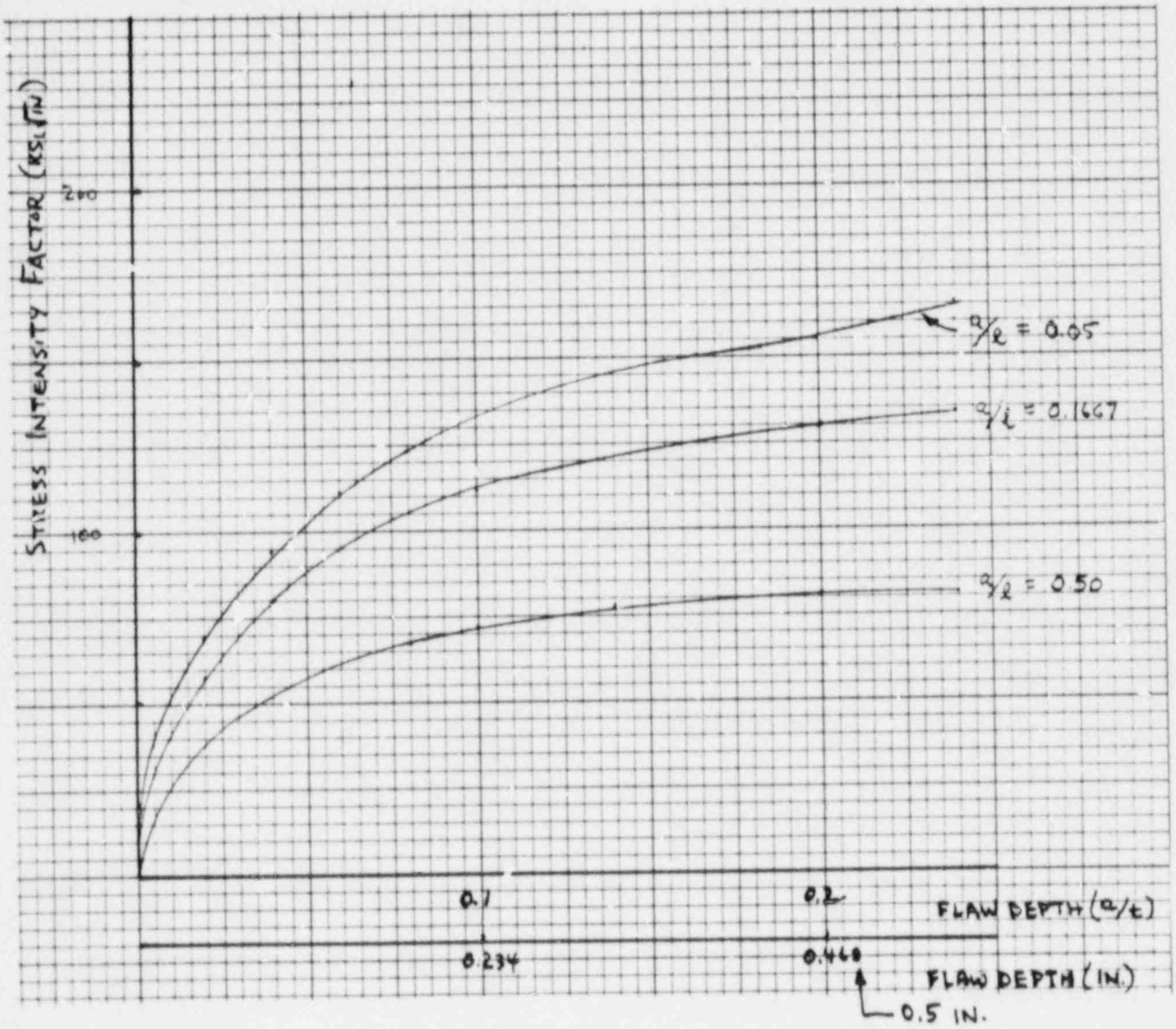

Figure 3-2. Stress Intensity Factor Calculations for Girth Weld #6 in the Repaired Configuration, Reactor Trip Transient at 445 Seconds

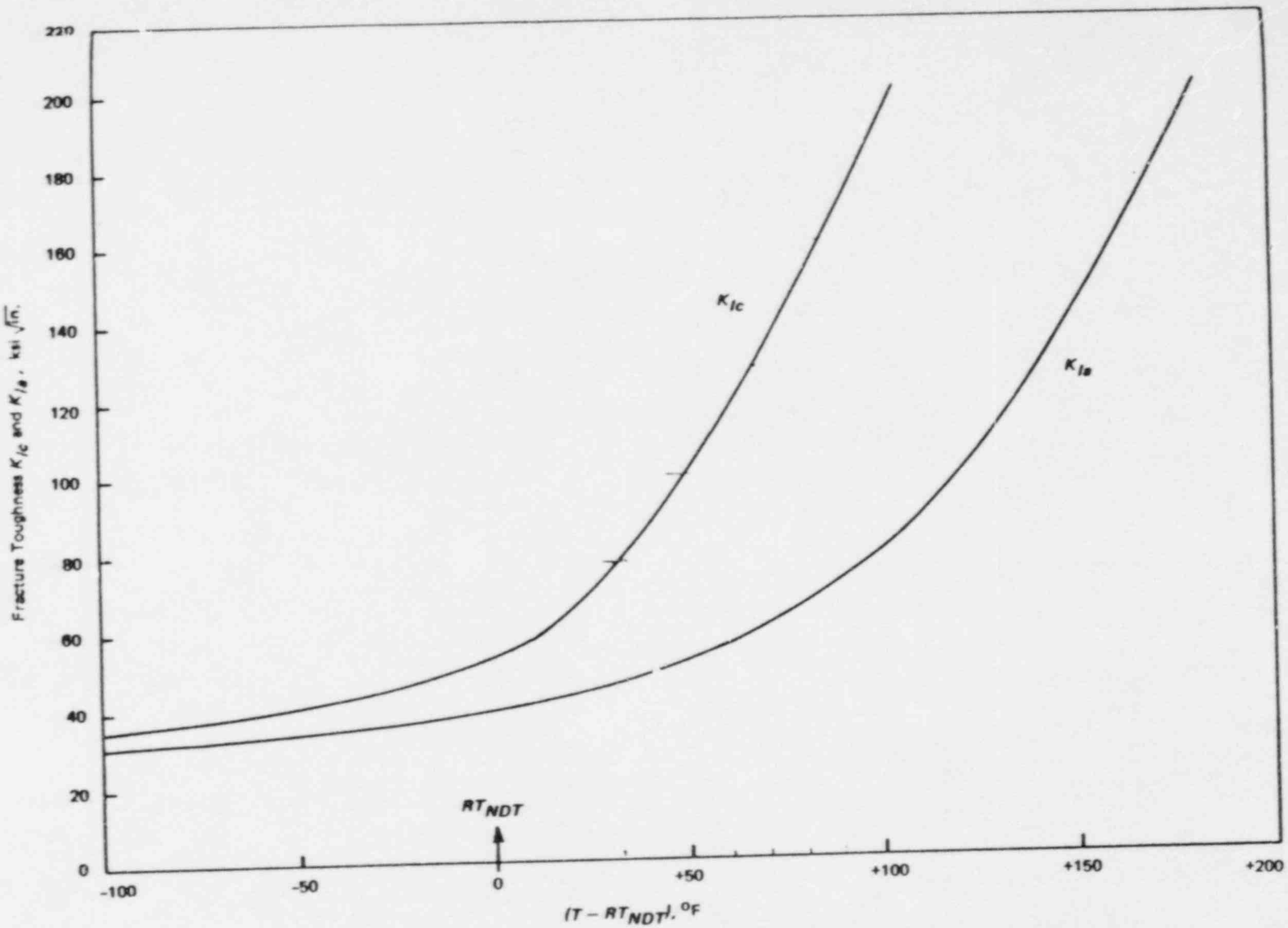

Figure 3-3. Reference Fracture Toughness Curves from Section XI, Appendix A [1]

2819s/011588:10

SECTION 4
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