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OYSTER CREEK VESSEL FRACTURE MECHANICS ANALYSIS FOR UPPER SHELF ENERGY REQUIREMENT

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1.0 INTRODUCTION AND BACKGROUND

1.1 General

The Oyster Creek Nuclear Generating Station has a 620 MWe rated, BWR type nuclear steam supply system. The reactor pressure vessel (RPV) was constructed to the requirements of Section I of the ASME Code (1959) with Addenda through Winter 1963, ASME Code Cases 1270N and 1273N [1-1]. The pressure-temperature (P-T) curves in the technical specifications meet the requirements of 10CFR50, Appendix G [1-2] to assure that the RPV temperatures and pressures during various operating conditions are such that the brittle fracture of the RPV is prevented. The P-T curves account for irradiation embrittlement effects in the core region, or beltline. The method described in Regulatory Guide 1.99, Revision 2 [1-3] was used in Reference 1-4 to account for irradiation embrittlement effects for the Oyster Creek RPV.

Reference 1-2 states that the RPV must maintain upper-shelf energy (USE) throughout its life of no less than 50 ft-lb, unless it is demonstrated in a manner approved by the Director, Office of Nuclear Reactor Regulation, that lower values of upper shelf energy will provide margins of safety against fracture equivalent to those required by Appendix G of Section III, ASME Code [1-5]. The analysis presented in the cover letter for Reference 1-4 indicated that the projected 32 effective full power year (EFPY) upper-shelf energy for some of the RPV plates in the beltline region will fall below the 50 ft-lb value. Based on this information, the NRC staff has requested an Oyster Creek specific analysis showing the basis for present and continued vessel structural integrity when the 50 ft-lb requirement is not satisfied.

In recognition of the need for such an analysis for light water reactors, Section XI of the ASME Code has developed procedures and acceptance criteria for the evaluation of low upper-shelf energy vessels. These procedures and acceptance criteria, currently in the form of a draft called Appendix XX, are expected to be approved by the Section XI Subcommittee in the near future. The text of the most recent draft of Appendix XX, approved at the Working Group level in May 1992, is included here as Attachment A of this report.

The objective of this report is to present a fracture mechanics evaluation of Oyster Creek RPV using the procedures and acceptance criteria outlined in Appendix XX. The Code of construction for the Oyster Creek RPV did not have the normal (Level A), upset (Level B), emergency (Level C) and faulted (Level D) condition categorization for the loadings and thermal transients defined in the loading diagram. Therefore, more recent BWR thermal cycle diagrams were used in categorizing the loadings and to define the appropriate loadings to consider for the evaluation of level C and D conditions.

1.2 Geometry and Material Property Data on Oyster Creek RPV

The geometry of the Oyster Creek RPV and the ASME Code stress analysis are documented in Reference 1-1. The part of the RPV evaluated in this report is the cylindrical beltline region. In that region, the inside radius and the thickness of the vessel is 106.7 inches and 7.125 inches, respectively. The chemical compositions of the beltline plates and welds, obtained from Reference 1-4, are shown in Table 1-1.

A review of Table 1-1 shows that the two lower shell plates (G-307-1 and G-308-1) have reported nickel content of 0.11%. This makes these two plates, which come from the same heat, confirm to the composition requirements of SA 302B. All the other plates have nickel contents between 0.4% and 0.7%, the requirement for SA 302B modified which was later designated as SA 533 Grade B. Due to nickel addition, the SA 302B modified has, on the average, better fracture toughness properties than the unmodified SA 302B. This distinction is important, as discussed later, in determining the appropriate material fracture toughness for the Appendix XX evaluations.

Table 1-2 from Reference 1-4 shows the projected Charpy USE values for 32 effective full power years (EFPY) of operation. It is seen that the projected USE values for the plates G-308-1, G-307-5, G-8-7 and G-8-6 are less than 50 ft-lbs. (Some of the projected USE values for the welds in Table 1-2 are also below 50 ft-lbs, but they were calculated based on the test temperature of 10° F. If this overconservatism is removed, all of the calculated USE values for the welds will exceed 50 ft-lbs [1-6].) Therefore, these plates were evaluated per Appendix XX procedures.

The projected USE values shown in Table 1-2 are for the transverse direction (normal to the rolling direction). For the rolled low alloy steel plates, such as those used in the fabrication of RPVs, the transverse direction gives lower USE as compared to the longitudinal direction (parallel to the rolling direction). For the plants constructed to the ASME Code effective prior to Summer 1972 (which is the case for Oyster Creek), only the longitudinal direction Charpy energy testing was required. Therefore, the initial transverse USE values shown in Table 1-2 were obtained by multiplying the initial longitudinal USE by 0.65, based on the guidelines given in Reference 1-7.

Since it is the projected transverse direction USE that falls below 50 ft-lbs, the postulated flaws are evaluated only in the orientation for which this direction toughness is relevant. This means, in the case of beltline plates, only the circumferential flaws need to be evaluated. Therefore, the evaluations in the following Sections considered only the circumferential cracks.

1.3 Report Outline

Section 2 describes the methodology of Appendix XX and how it was implemented in this evaluation. Irradiated fracture toughness properties of SA 302B and SA 302B modified published in the technical literature are reviewed in Section 3 to determine the initiation toughness (J_{Ic}) and the J-Resistance (J-R) curves based on the lower bound and the mean of the data. Section 4 describes the evaluation of Level A and B conditions based on the lower bound toughness values. Evaluation of Level C and D conditions is covered in Section 5. Section 6 presents the summary of results and conclusions.

1.4 References

1-1 Pierson, T.M., Larkin, T.A. and Kinyon, B.W., "Analytical Report for Jersey Central Reactor Vessel," General Electric VPF # 1238-148-1 (1970).

1-2 "Fracture Toughness Requirements," Appendix G to Part 50 of Title 10, the Code of Federal regulations, July 1983.

1-3 "Radiation Embrittlement of Reactor Vessel Materials," USNRC Regulatory Guide 1.99, Revision 2, May 1988.

1-4 "Pressure Temperature Curves per Regulatory Guide 1.99, Revision 2, for the Oyster Creek Nuclear Generating Station," GE Report No. SASR 90-89, DRF # 137-0010 (1990).

1-5 "Fracture Toughness Criteria for Protection Against Failure," Appendix G to Section XI of the ASME Boiler & Pressure Vessel Code, 1989 Edition.

1-6 "Unirradiated Upper Shelf Energy Values for Reactor Vessel Belt Line Welds," GPUN Letter to NRC, Letter # 5000-91-2056, dated July 17, 1991.

1-7 "Fracture Toughness Requirements," USNRC Branch Technical Position MTEB 5-2, Revision 1, July 1981.

TABLE 1-1

Chemical Composition of RPV Beltline Materials

Identification	Heat/Lot No.	Composition by Weight Percent							
		C	Mn	P	S	Si	Ni	Mo	Cu
Lower Shell Plates:									
G-307-1	T1937-2	0.2	1.4	0.011	0.022	0.24	0.11 [a]	0.51	0.17 [a]
G-308-1	T1937-1	0.2	1.4	0.011	0.022	0.24	0.11 [a]	0.51	0.17 [a]
G-307-5	P2076-2	0.2	1.28	0.019	0.030	0.21	0.53	0.52	0.27 [a]
Lower-Intermediate Shell Plates:									
G-8-7	P2161-1	0.19	1.35	0.019	0.021	0.24	0.48	0.46	0.21 [a]
G-8-8	P2136-2	0.19	1.36	0.006	0.024	0.26	0.46	0.48	0.18 [a]
G-8-6	P2150-1	0.2	1.25	0.013	0.026	0.23	0.51	0.46	0.20 [a]
Lower Shell Longitudinal Welds:									
2-564 A,B,C	RACO#3, 86054B ARCOS B-5 Lot 4E5F	0.12	1.64	0.015	0.02	0.34	0.2 [a]	0.51	0.35 [a]
Lower-Intermediate Longitudinal Weld:									
2-564 D,E,F	RACO#3, 86054B ARCOS B-5 Lot 4D4F	0.12	1.67	0.013	0.02	0.41	0.2 [a]	0.50	0.35 [a]
Lower to Lower-Intermediate Girth Weld:									
3-564	RACO#3, 1248 ARCOS B-5 Lot 4M2F	0.097	1.26	0.015	0.02	0.22	0.11 [a]	0.57	0.22 [a]

[a] Values reported in GPUN TDR 725

TABLE 1-2

Upper Shelf Energy Analysis for Oyster Creek Beltline Materials

LOCATION	IDENT	TEST TEMP	INITIAL LONGIT. USE	INITIAL TRANS. USE	%Cu	32 EFPY FLUENCE (x10^18)	% DECR. USE	32 EFPY TRANS. USE
PLATES:								
Lower	G-307-1	160	99	64.4	0.17	2.36	18.5	52.4
	G-308-1	212	92	59.8	0.17	2.36	18.5	48.7
	G-307-5	212	95	61.8	0.27	2.36	2[illegible]	45.7
Low-Int.	G-8-7	212	79	[illegible].4	0.21	2.36	21.5	40.3
	G-8-8	212	100	65.0	0.18	2.36	19.5	52.3
	G-8-6	212	81	52.7	0.2[illegible]	2.36	21	41.6
WELDS:								
Vertical	2-564 A,B,C	10		66	0.35	2.36	34	43.6*
	2-564 D,E,F	10		32	0.35	2.36	34	21.1*
Girth	3-564	10		65	0.22	2.36	2[illegible]	48.1*
Surveillance		350		83.5			34	55.1

* See discussion of paragraph 1.2 on page 1-3

2.0 EVALUATION METHODOLOGY

The evaluation methodology followed in this report is that prescribed in Appendix XX, the latest draft of which is included as Attachment A. There are essentially four steps in this methodology: (1) postulate flaws in the reactor vessel, (2) determine the loading conditions at the location of the postulated flaws for Level A, B, C and D Service loadings, (3) obtain the material properties, including E, σ_y, and the J-integral resistance curve (J-R curve), at the locations of the flaws, and (4) evaluate the postulated flaws according to the acceptance criteria.

Article A-3000 of the Appendix contains general description of procedures used to evaluate the applied fracture mechanics parameters, as well as requirements for selecting the J-R curve for the material. Detailed calculation procedures for Level A and B Service loadings are given in A-4000. The Appendix does not include a detailed calculation procedure for Level C and D Service loadings since it was concluded that the possible combinations of loadings and material properties which may be encountered during these Service conditions are too diverse.

The acceptance criteria and the calculations procedures from this Appendix as applicable to subject evaluation are described in this section.

2.1 Acceptance Criteria

2.1.1 Level A and B Service Loadings

An interior semi-elliptical surface flaw with a depth one-quarter of the wall thickness and a length six times the depth is postulated. Since it is the transverse direction USE that is projected to be below 50 ft-lb value, only a circumferentially oriented flaw is postulated for this evaluation. The flaw is assumed to be located in the base material.

Toughness properties for the corresponding orientation (transverse orientation) are to be used in the evaluation.

Two criteria which shall be satisfied are:

(1) The applied J-integral evaluated at a pressure which is 1.15 times the accumulation pressure as defined in the plant-specific Overpressure Protection Report, with a factor of safety of 1.0 on thermal loading for the plant specified heatup and cooldown conditions, shall be shown to be less than the J-integral characteristic of the material resistance to ductile tearing at a flaw growth of 0.10 in.

(2) The flaw shall be shown to be stable, with the possibility of ductile flaw growth, at a pressure which is 1.25 times the accumulation pressure defined in (1), with a factor of safety of 1.0 on thermal loading for the plant specified heatup and cooldown conditions.

The J-integral resistance versus crack growth curve (J-R curve) shall be a conservative representation for the vessel material under evaluation. The determination of the J-R curve for this evaluation is discussed in Section 3. The mathematical expressions for the calculation of applied J-integral and for the evaluation of stability are discussed in Subsection 2.2.

2.1.2 Level C Service Loadings

While the shape and the aspect ratio are the same as those for the Level A and B Service loadings, the depth of the postulated flaw for this service condition is 1/10 of the base metal wall thickness, plus the cladding thickness, with total depth not to exceed 1.0 inch. Smaller maximum flaw sizes may be used on an individual case basis when justified. Two criteria which shall be satisfied are:

(1) The applied J-integral shall be shown to be less than the J-integral characteristic of the material resistance to ductile tearing at a flaw growth of 0.10 in., using a factor of safety of 1.0 on loading.

(2) The flaw shall be shown to be stable, with the possibility of ductile flaw growth, using a factor of safety of 1.0 in loading.

The material J-R curve shall be the same as used in the evaluation of Level A and B conditions. Thus, the key differences between the Level A/B evaluation and the Level C evaluation are the postulated flaw size and the factor of safety.

2.1.3 Level D Service Loadings

The postulated flaw geometry for this service condition is the same as that for the evaluation of Level C loadings. The flaw shall be shown to be stable, with the possibility of ductile flaw growth, using a factor of safety of 1.0 on loading. The J-R curve shall be a best estimate representation for the vessel material under evaluation. The stable flaw depth shall not exceed 75% of the vessel wall thickness, and the remaining ligament shall be safe from tensile instability.

2.2 Calculation of the Applied J-Integral

The calculation of applied J-integral consists of two steps: Step 1 is to calculate the effective flaw depth which includes a plastic-zone correction; and Step 2 is to calculate the J-integral for small-scale yielding based on this effective flaw depth.

For the postulated circumferential flaw with a depth 'a', the stress intensity factor due to internal pressure with a safety factor (SF) on pressure, was calculated using the following:

$$K_{Ip} = (SF)\ p\ [1 + (R_i/(2t))]\ (\pi a)^{0.5}\ F_2 \qquad (2\text{-}1)$$

$$F_2 = 0.885 + 0.233(a/t) + 0.345(a/t)^2 \qquad (2\text{-}2)$$

where, R_i, t and a are vessel inside radius, vessel thickness and crack depth, respectively. This equation for K_{Ip} is valid for $0.2 \leq a/t \leq 0.50$, and includes the effect of pressure acting on the flaw faces. The units for K are ksi$\sqrt{in}$.

For an axial or circumferential flaw with a depth 'a', the stress intensity factor due to radial thermal gradient was calculated by using the following:

$$K_{It} = ((CR)/1000)\ t^{2.5}\ F_3 \qquad (2\text{-}3)$$

$$F_3 = 0.584 + 2.647(a/t) - 6.294(a/t)^2 + 2.990(a/t)^3 \qquad (2\text{-}4)$$

where CR is the cooling rate in °F/hour and the units of K are ksi$\sqrt{in}$. This equation for K_{It} is valid for $0.20 \leq a/t \leq 0.50$, and $0 \leq (CR) < 100$°F/hour.

The effective flaw depth, a_e, is then calculated by using:

$$a_e = a + (1/(6\pi))[(K_{Ip} + K_{It})/\sigma_y]^2 \qquad (2\text{-}5)$$

where, σ_y is the material yield stress.

The K'_{Ip} and K'_{It} are calculated by substituting a_e in place of a in equations 2-1 and 2-3. The J-integral due to the applied loads for small scale yielding is then given by:

$$J = 1000\ (K'_{Ip} + K'_{It})^2/E' \qquad (2\text{-}6)$$

$$E' = E/(1-\nu^2) \qquad (2\text{-}7)$$

where, E is Young's Modulus and ν is poisson's ratio (=0.3). The units of J are in-lb/in^2.

2.3 Evaluation Using Criterion for Flaw Growth of 0.1 Inch

The J-integral due to the applied loads, J_1, for this case is calculated using a factor of safety of 1.15 on the accumulation pressure. The acceptance criterion for Level A and B Service loadings based on a ductile flaw growth of 0.1 inch (Criterion 1 in 2.1.1) is satisfied when $J_1 < J_{0.1}$, where $J_{0.1}$ is the value of J-integral in the material J-R curve at a Δa of 0.1 inch. The thermal gradient contribution (K_{It}) to the J-integral due to the applied loads for the Level C and D conditions, was calculated using the finite element stress analysis and available K solutions in the literature.

2.4 Evaluation Procedures for Flaw Stability

Appendix XX provides three approaches that are equally acceptable for applying the flaw stability acceptance criteria. The first is the J-R curve - crack driving force diagram approach. In this approach, flaw stability is evaluated by a direct application of the flaw stability rules given in A-3400. The other approaches are the failure assessment diagram approach and the J-integral/tearing modulus approach. The first approach was used in this report.

The J-R curve - crack driving force diagram approach is illustrated graphically in Figure 2-1. The applied J-integral curve is evaluated at a constant load. The J-R curve intersects the horizontal axis at the postulated initial flaw depth, a_0. Flaw stability at a given load is demonstrated when the slope of the J-R curve at the point on the J-R curve where the two curves intersect. The onset of flaw instability occurs at an applied load corresponding to the point of tangency of the applied J-integral curve and the J-R curve.

2.5 Summary of Evaluation Methods

The acceptance criteria and the evaluation methods of Appendix XX of Section XI, relevant to the USE requirement evaluation of Oyster Creek plant RPV are summarized in this section. The key input in this evaluation are the appropriate material J-R curves and the applied J-integral values. The selection of appropriate material J-R curves considering Oyster Creek plant-specific irradiation data is described in Section 3. Sections 4 and 5 describe the rationale for the selection of appropriate pressure and thermal loadings and evaluation results for the Levels A/B and C and D conditions.

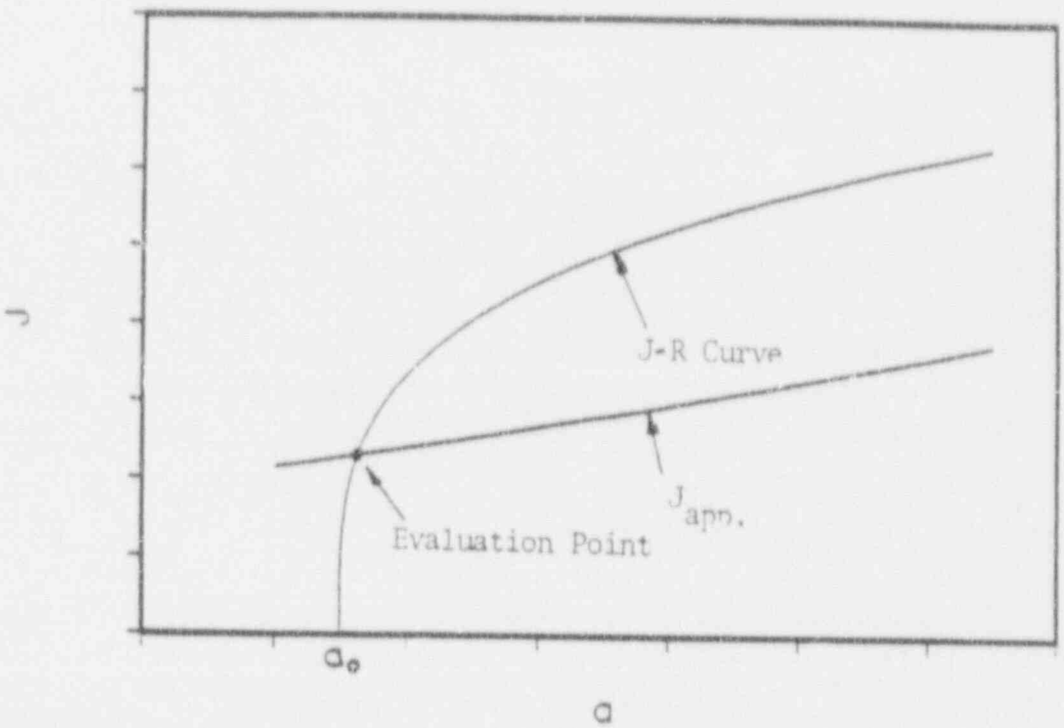

Figure 2-1 Comparison of the Slopes of the Applied J-integral Curve and the J-R Curve

3.0 IRRADIATION FRACTURE TOUGHNESS CHARACTERIZATION

A key input in the evaluations based on the procedures of Appendix XX is the material J-R curve. The beltline region material of the RPV wall undergoes irradiation-induced toughness changes during the operation of the plant. Therefore, the material J-R curves used in this evaluation must factor-in the irradiation effects on the fracture toughness. This section describes the selection of J-R curves for this evaluation considering the projected irradiated Charpy energies for the Oyster Creek RPV and the available correlations in the technical literature between the Charpy energy and the material J-R curves.

3.1 Charpy Energy Versus J-R Curve Correlations

The available information to assess the state of vessel wall embrittlement generally consists of initial Charpy energy values, the material chemistry and the fluence level at the vessel wall. Regulatory Guide 1.99, Revision 2 [Reference 1-3] provides method to calculate the Charpy USE at any irradiation level given the preceding information This information can be supplemented when the Charpy energy values from the testing of periodically removed surveillance specimens become available. Thus, most of the material fracture test data available in the technical literature include the Charpy energy values along with the J-R curve information.

Considerable data on the unirradiated and irradiated low alloy steels have been reported in the technical literature [3-1 through 3-4]. Two broad categories of low alloy steels are generally covered in these studies: (1) SA 302 Grade B, and (2) SA 533 Grade B (equivalent to SA 302 Grade B, modified by nickel addition). The material for the beltline plate that has the lowest USE (G-8-7 in Table 1-2) is SA 302B modified. However, one of the SA 302B plate (G-308-1) in the beltline region has 32 EFPY transverse USE less than 50 ft-lbs. Therefore, to perform a bounding evaluation, Charpy USE to J-R curve correlations for both the materials are discussed in this section and the appropriate J-R curves are developed.

3.1.1 SA 302 Grade B Data

To establish a J_{Ic} versus Charpy USE correlation that can be used to assess the mean and mean minus two standard deviation J-R curve, test data on SA 302B base metal from References 3-2 and 3-4 were compiled and plotted in Reference 3-5. Figure 3-1 shows such a plot. The data in Figure 3-1 are for temperatures in the range of 400° F to 550° F for both the longitudinal and transverse orientations and irradiated as well as unirradiated material. Fluences ranged from 0.6 to 3.5 x 10^{19} n/cm^2.

The data in Figure 3-1 show a trend for decreasing J_{Ic} with decreasing Charpy USE. The mean and the mean minus two standard deviation lines shown in Figure 3-1 were obtained using linear regression analysis. The mean line was used to determine the best estimate J-R curve for the evaluation of Level D loadings. The mean minus two standard deviation line was used to establish a conservative representation of the J-R curve, as required in the evaluation of Levels A,B and C loading conditions.

The J-R curves for most materials can be represented by an equation of the following form:

$$J = C (\Delta a)^n \qquad (3\text{-}1)$$

This equation gives a convex upwards form of J-R curve in which the J values keep increasing with increase in Δa. Reference 3-3 suggests that SA 302 Grade B apparently exhibits a size effect where the J-R curve flattens significantly with increasing specimen thickness as illustrated in Figure 3-2. This result was also unusual in that the J-R curve of a thicker (larger) specimen was lower than that of a thinner (smaller) specimen. A subsequent evaluation [3-6] examined several possibilities for this unusual size effect but could not cite any clear cause. Consequently, an approximate method was used in Reference 3-5 to reflect this size effect.

Data in Reference 3-3 show that the effect of thickness on J_{Ic} is relatively small. Therefore, only the size effect on the J-R curve at larger Δa values was considered. Results plotted in Figure 3-2 show that the J-R curve for the 6TCT specimen rises above J_{Ic} by a factor of about 1.3 and reaches a plateau. While it is not clear that this size effect seen at 180° F would be also present at 400° F to 550° F temperature range, it was assumed that this was the case.

Therefore, it was assumed in Reference 3-5 that the J-R curves for both longitudinal and transverse direction will flatten out at 30% above J_{Ic}. The same conservative assumption was also used in this report to develop the J-R curve for SA 302B material.

3.1.2 SA 533 Grade B (302B modified) Data

A comprehensive multivariable modeling of RPV and piping J-R data is reported in References 3-7 and 3-8. Separate models were fitted for different materials groups, including RPV welds, Linde 80 welds, RPV base metals, piping welds, piping base metals, and a combined materials group. The material data base did not include SA 302B steel, but included SA 533 Grade B steel, which is relevant for SA 302B modified plate G-8-7.

The material J-R curve in Reference 3-8 is represented in the following form:

$$J_d = C1\ (\Delta a)^{C2}\ (\exp[C3(\Delta a)^{C4}]) \qquad (3\text{-}2)$$

J_d is the deformation J-integral. The use of deformation J-integral, rather than the modified J-integral, is currently favored in the fracture mechanics evaluations. The notation J is also used in this report to indicate deformation J-integral. The expressions for C2 and C3 terms are:

$$C2 = d_1 + d_2\ (\ln C1) \qquad (3\text{-}3)$$

$$C3 = d_4 + d_5\ (\ln C1) \qquad (3\text{-}4)$$

The parameter C1 can be calculated from the following expression when the pre-irradiation Charpy USE (CVN_p) and the fluence (ϕt) values are available:

$$\ln (C1) = a_1 + a_2 \ln (CVN_p) + a_3 T + a_5 \phi t \qquad (3\text{-}5)$$

The variable T is the test temperature. When only the irradiated Charpy USE (CVN) is used, C1 is determined as follows:

$$\ln (C1) = a_1 + a_2 \ln (CVN) + a_3 T \qquad (3\text{-}6)$$

The parameters a_1, a_2, a_3, a_5, d_1, d_2, d_4, d_5, and exponent C4 are constants, the values for which are given in Table 3-1. When CVN_p, ϕt and CVN are available, as is the case for present evaluation, the parameter C1 can be calculated by either equation (3-5) or equation (3-6). The J-R curves obtained by these two different approaches are, in general, different. For conservatism, the lowest of the two J-R curves was used in the evaluation.

Although not necessary in the Appendix XX evaluations, the J_{Ic} values may be obtained from the J-R curves using the definition given in ASTM Standard E 813, as the value of J_d at the intersection of the power law fit curve and the blunting line with 0.2 mm offset (see Figure 3-3).

The values of various parameters shown in Table 3-1 would give a best estimate or mean J-R curve. Such a J-R curve can be used for the evaluation of Level D loadings. A best estimate (or mean) minus two standard deviation J-R curve was considered a reasonably conservative representation of material toughness suitable for use in the evaluation of Level A through C condition loadings. Such a J-R curve was obtained by multiplying the J_d values obtained from equation (3-2) by the value of the ratio (at the bottom of Table 3-1) corresponding to $2S_e$. For example, the J_d values obtained using the CVN_p model were multiplied by 0.741 to obtain the mean minus two standard deviation value of J_d.

3.2 Charpy USE Values Selected for J-R Curve Determination

The lowest value of transverse USE in Table 1-2 is 40.3 ft-lbs. This value is for plate G-8-7 at 32 EFPY. This is based on the fluence value at 1/4 thickness. The postulated flaw for the Level C and D loadings is 1/10 thickness. The transverse USE for this case was calculated as 39.6 ft-lbs. In view of the small difference between the two energy levels, a single value of 40 ft-lbs was used in determining the J-R curve.

If the plant life extension (PLEX) is implemented at Oyster Creek plant, the fluence level would be higher than that calculated for 32 EFPY. To evaluate the PLEX case, a very conservative evaluation was conducted assuming a Charpy USE of 35 ft-lbs for plate G-8-7. This is quite conservative since the fluence level associated with 35 ft-lbs USE is estimated as 1.3×10^{19} n/cm^2, which is projected to be more than 170 EFPY of operation.

3.3 Determination of J-R Curves

Figures 3-4a and b show the J-R curves for SA 302B material at 40 and 35 ft-lbs USE levels. The mean minus two standard deviation J_{Ic} values for the preceding USE levels are 170 and 150 in-lb/in^2, respectively. The corresponding mean values are 340 and 315 in-lb/in^2, respectively. Figure 3-4a shows the mean and 3-4b shows the mean minus two standard deviation J-R curves. The J-R curves flatten out at a J-integral value equal to 1.3 times J_{Ic}, as described in Subsection 3.1.1.

As discussed in Subsection 3.1.2, the J-R curves for SA 302B modified material can be calculated in two ways: (1) using pre-irradiation Charpy USE and fluence level, and (2) irradiated Charpy USE. Figure 3-5 shows the results of mean or best estimate J-R curve calculations for plate G-8-7. The irradiated Charpy USE J-R curve was calculated using 35 ft-lbs energy. The other J-R curve was calculated using a CVN_p of 51.4 ft-lbs and a fluence level of 1.3×10^{19} n/cm^2. It is seen that the J-R curve based on irradiated Charpy USE is lower. Therefore, all of the J-R curve calculations for SA 302B modified material were conducted using only the irradiated Charpy USE.

Figure 3-6a and b show the mean and mean minus two standard deviation J-R curves for the 40 and 35 ft-lbs irradiated Charpy USE levels, respectively. A comparison of the J-R curves in Figures 3-4 and 3-6 shows that the J-R curves in Figure 3-4 (SA 302B material) are lower than those in Figure 3-6 (SA 302B modified or SA 533B). For completeness, the J-R curves for both the materials are shown in the evaluation of operating conditions presented in Sections 4 and 5.

3.4 Summary of J-R Curve Determination

J-R curves were developed for two Charpy USE levels (40 and 35 ft-lbs). The first one corresponds to the lowest predicted USE level for any beltline RPV plate at 32 EFPY and the latter energy level represents a bounding case. Although the material for plate G-8-7, which shows the lowest predicted USE, is SA 302B modified, one other beltline plate of SA 302B material is also predicted to have transverse USE below 50 ft-lbs. Therefore, J-R curves are determined for both the SA 302B (Figures 3-4a and b) and the SA 302B modified (Figures 3-6a and b). The mean minus two standard deviation J-R curves are to be used in the evaluation of Levels A through C loadings, and the mean or the best estimate J-R curves are to be used in evaluating the Level D loadings.

3.5 References

3-1 J.R. Hawthorne, B.H. Menke, F.J. Loss, H.E. Watson, A.L. Hiser, and R.A. Gray, "Evaluation and Prediction of Neutron Embrittlement in Reactor Pressure Vessel Materials," EPRI NP-2782, December 1982.

3-2 A.L. Hiser and D.B. Fishman, "J-R Curve Data Base Analysis of Irradiated Reactor Pressure Vessel Steels," EPRI Research Project 1757-24, MEA-2024, December 1983.

3-3 A.L. Hiser and J.B. Terrel, "Size Effects on J-R Curves for A 302-B Plate," NUREG/CR-5256, MEA-2320, January 1989.

3-4 J.R. Hawthorne and A.L. Hiser, "Influence of Fluence Rate on Radiation-Induced Mechanical Property Changes in Reactor Pressure Vessel Steels," NUREG/CR-5493, MEA-2376, March 1990.

3-5 "Reactor Pressure Vessel Evaluation Report for Yankee Nuclear Power Station," Report # YAEC-1735, July 1990, Chapter # 3, Yankee Atomic Electric Co., Boston, Mass.

3-6 Landes, J.D., "Extrapolation of the J-R Curve for Predicting Reactor Vessel Integrity," NUREG/CR-5650, January 1992.

3-7 E.D. Eason and E.E. Nelson, "Improved Model for Predicting J-R Curves from Charpy Data," NUREG/CR-5356, April 1989.

3-8 E.D. Eason, J.E Wright and E.E. Nelson, "Multivariable Modeling of Pressure Vessel and Piping J-R Data," NUREG/CR-5729, May 1991.

TABLE 3-1

Values of Variables for J-R Curve Estimation - Base Metal

Parameter	Variable	RPV Base Metals CVN_p Model	Combined Database Charpy Model
<u>*lnC1*</u>			
a_1	(constant)	-2.89	-4.13
a_2	$\ln CVN$ or $\ln CVN_p$	1.22	1.48
a_3	T	-0.00270	-.00239
a_5	ϕt	-0.0104	
<u>*C2*</u>			
d_1	(constant)	0.0770	0.0770
d_2	$\ln C1$	0.116	0.116
<u>*C3*</u>			
d_4	(constant)	-0.0812	-0.0812
d_5	$\ln C1$	-0.00920	-0.00920
<u>*C4*</u>	(exponent)	-0.417	-0.455
# Points		2295	8463
S_e	ln units	0.150	0.229
<u>Ratios</u>			
$-1.645\ S_e$		0.781	0.686
$-1\ S_e$		0.861	0.795
$-2\ S_e$		0.741	0.632
$-3\ S_e$		0.637	0.503

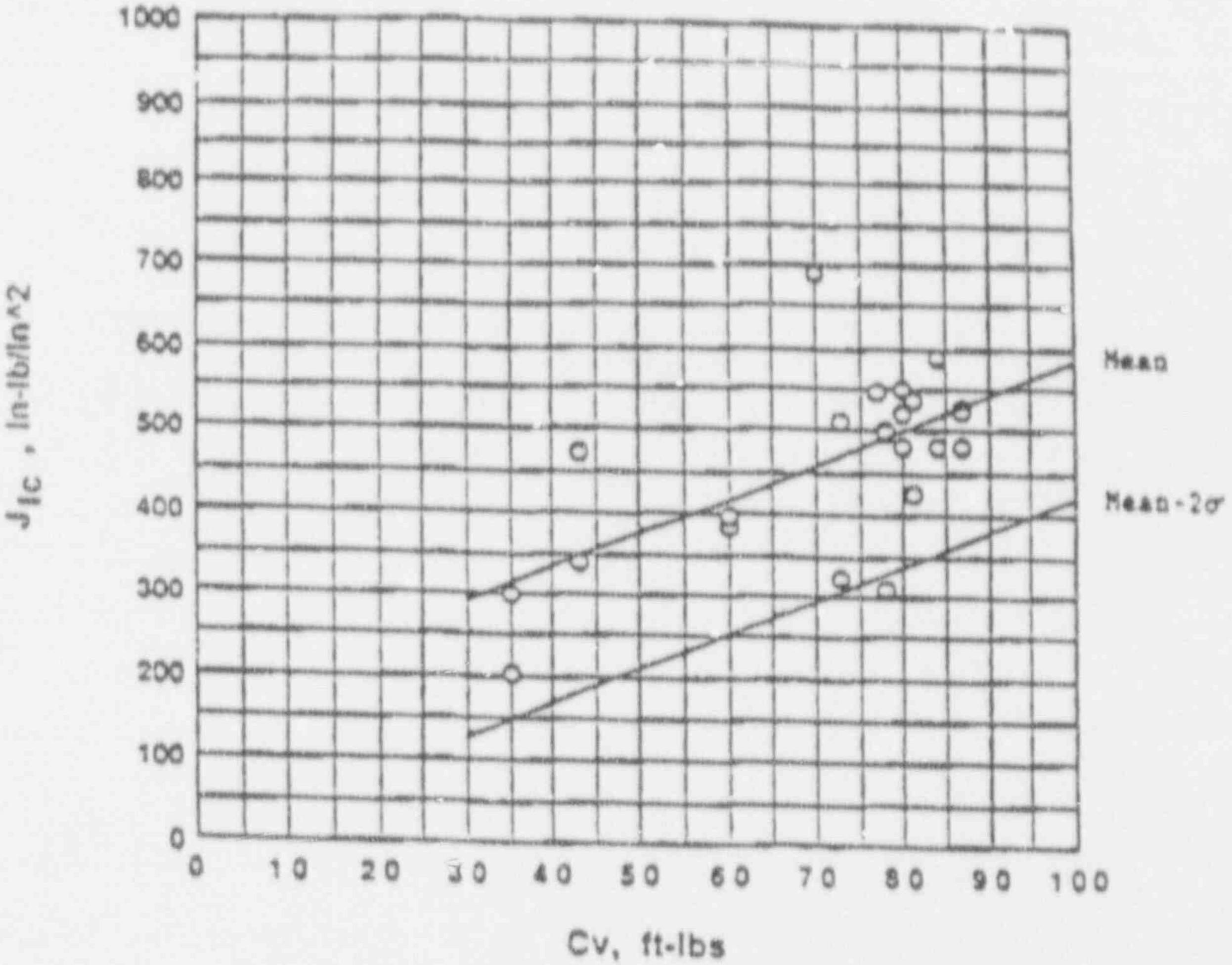

Figure 3-1 Least Squares Fit Mean and Mean Minus Two Sigma Lines, SA302B Plate, LT and TL Directions, 400-550° F (From Reference 3-5)

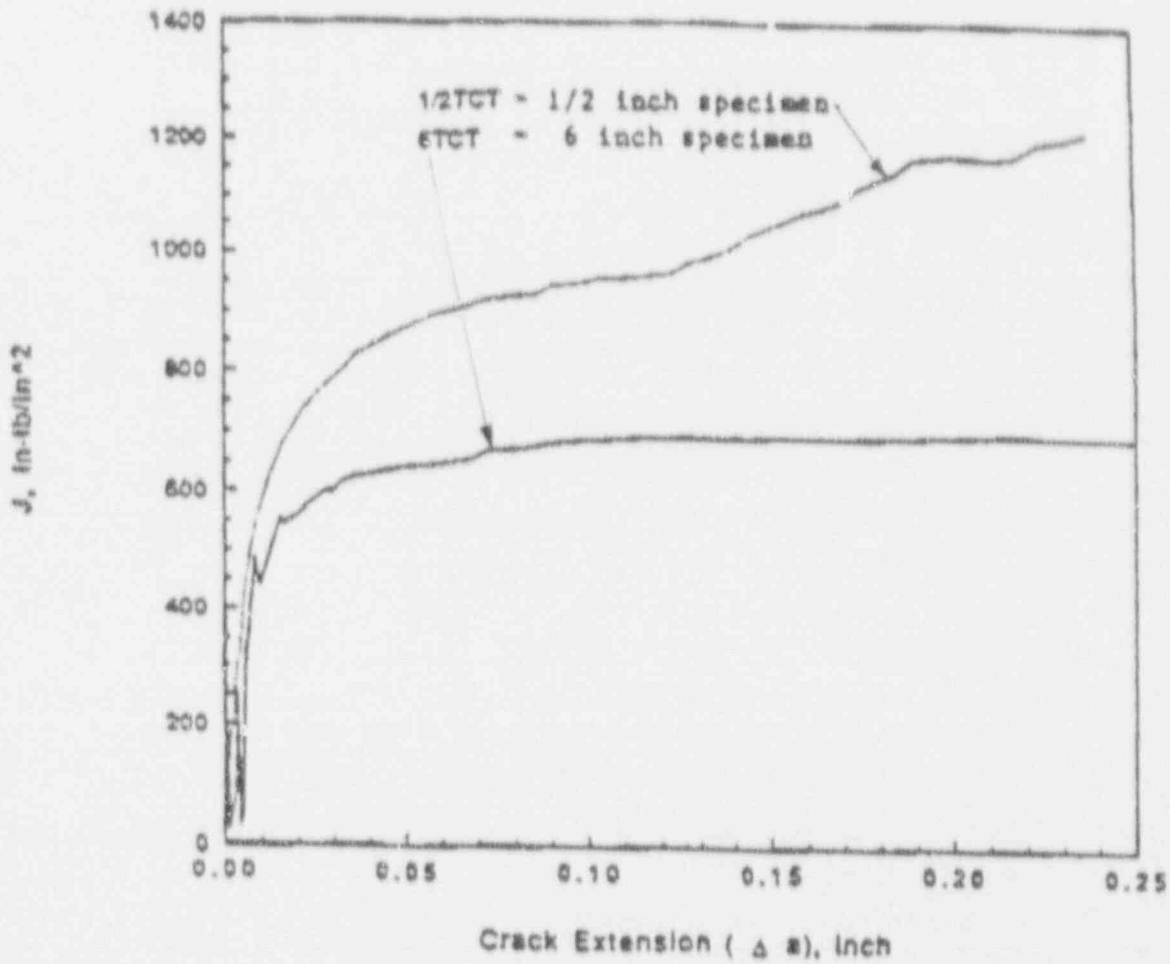

Figure 3-2 J-R Curves Illustrating Size Effect for SA 302B Plate, CVN Energy = 52 ft-lbs.,180° F

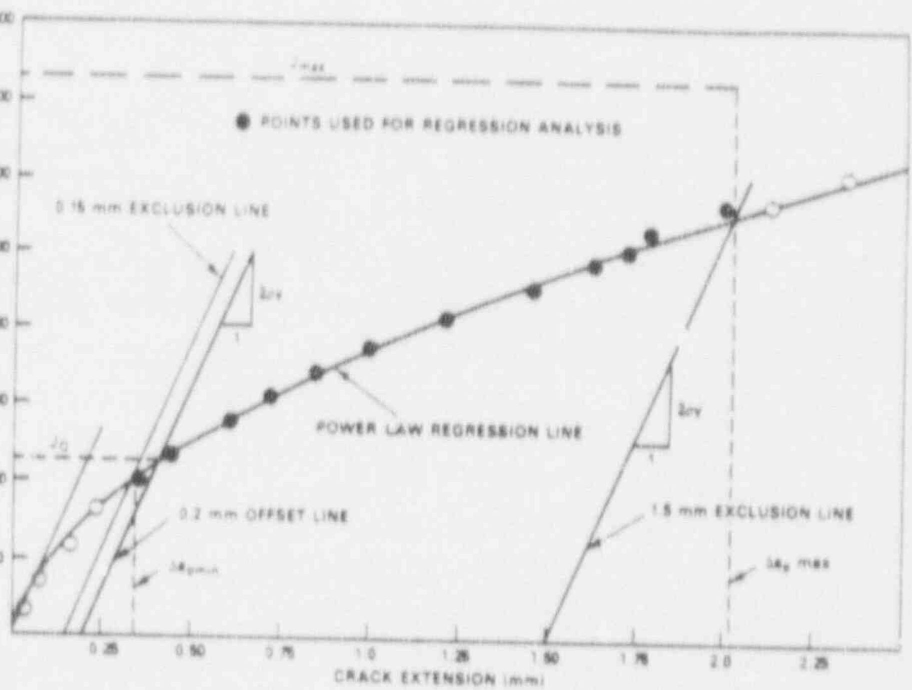

Figure 3-3 Schematic of ASTM Procedure for J_{Ic} Determination

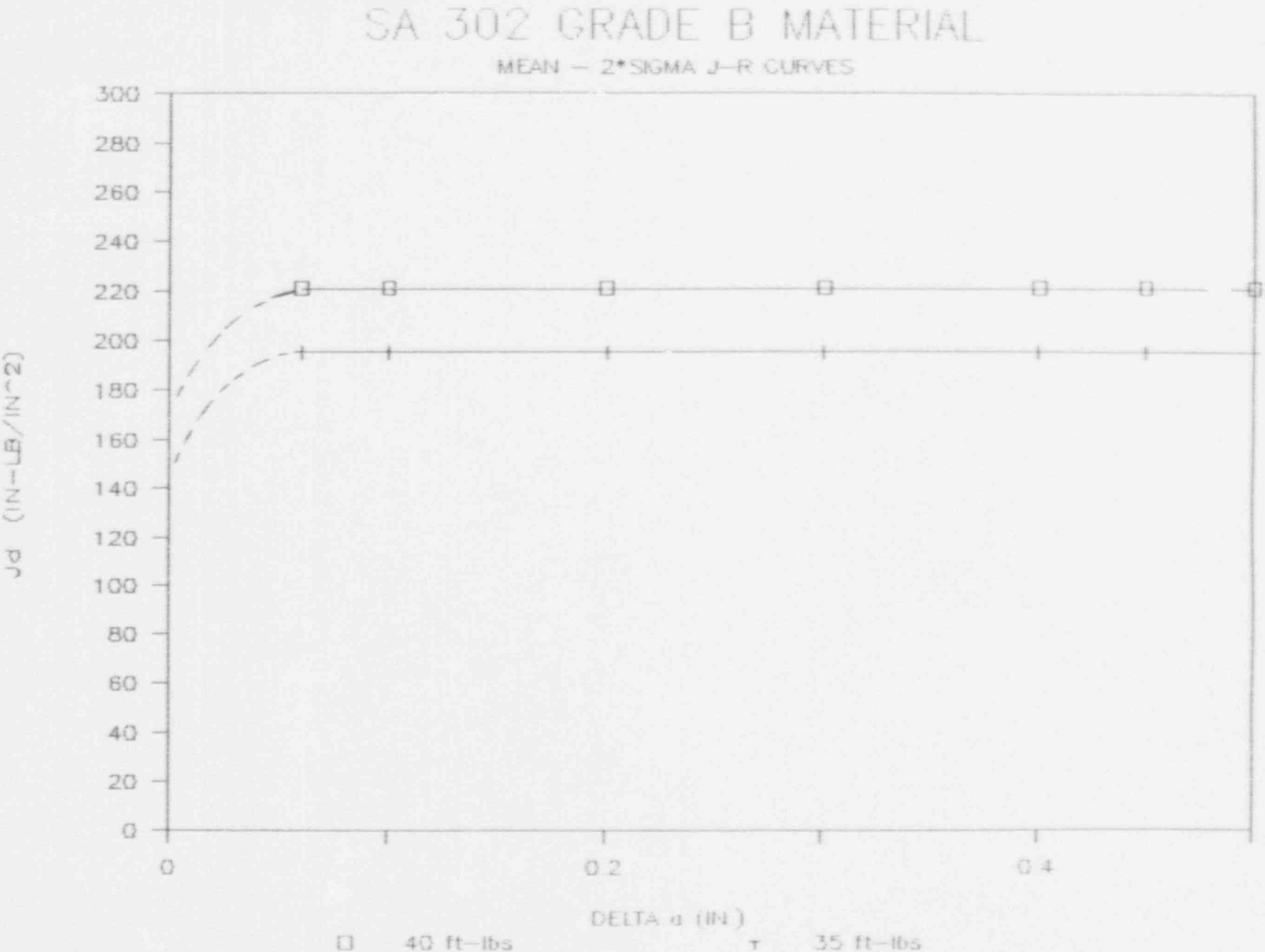

Figure 3-4a Mean Minus Two Sigma J-R Curves for SA 302B Material

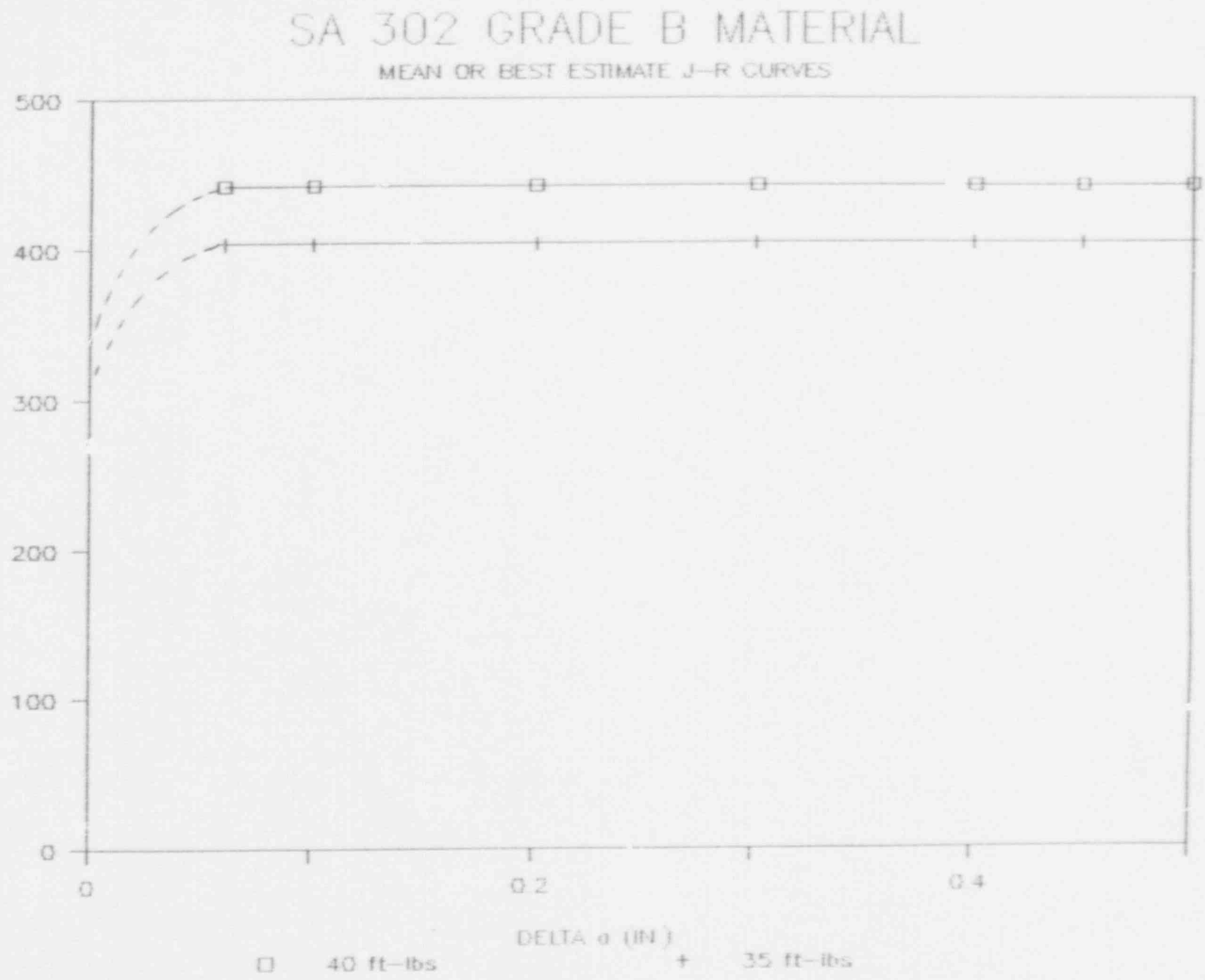

Figure 3-4b Mean or Best Estimate J-R Curves for SA 302B Material

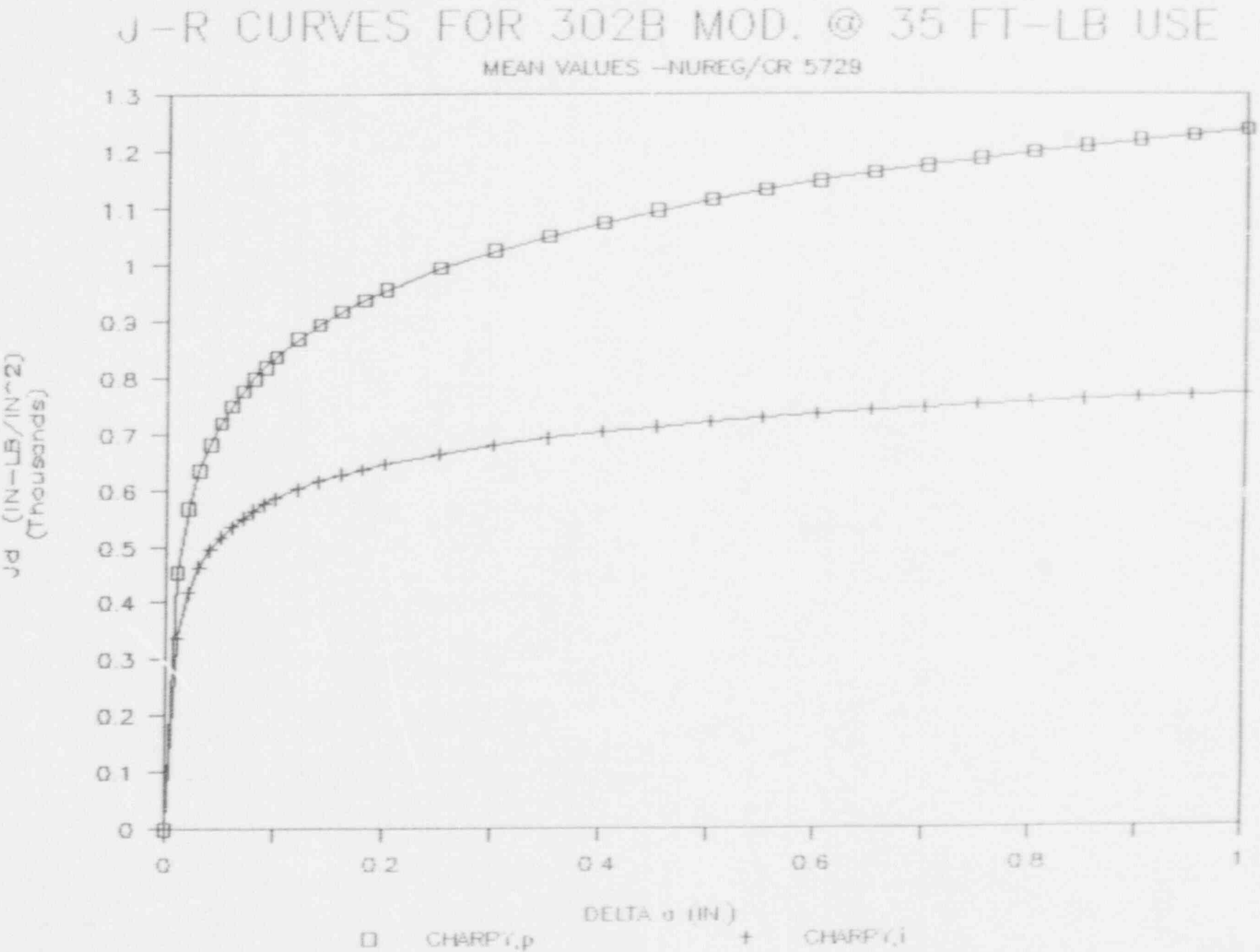

Figure 3-5 Mean J-R Curves for SA 302B Modified Material

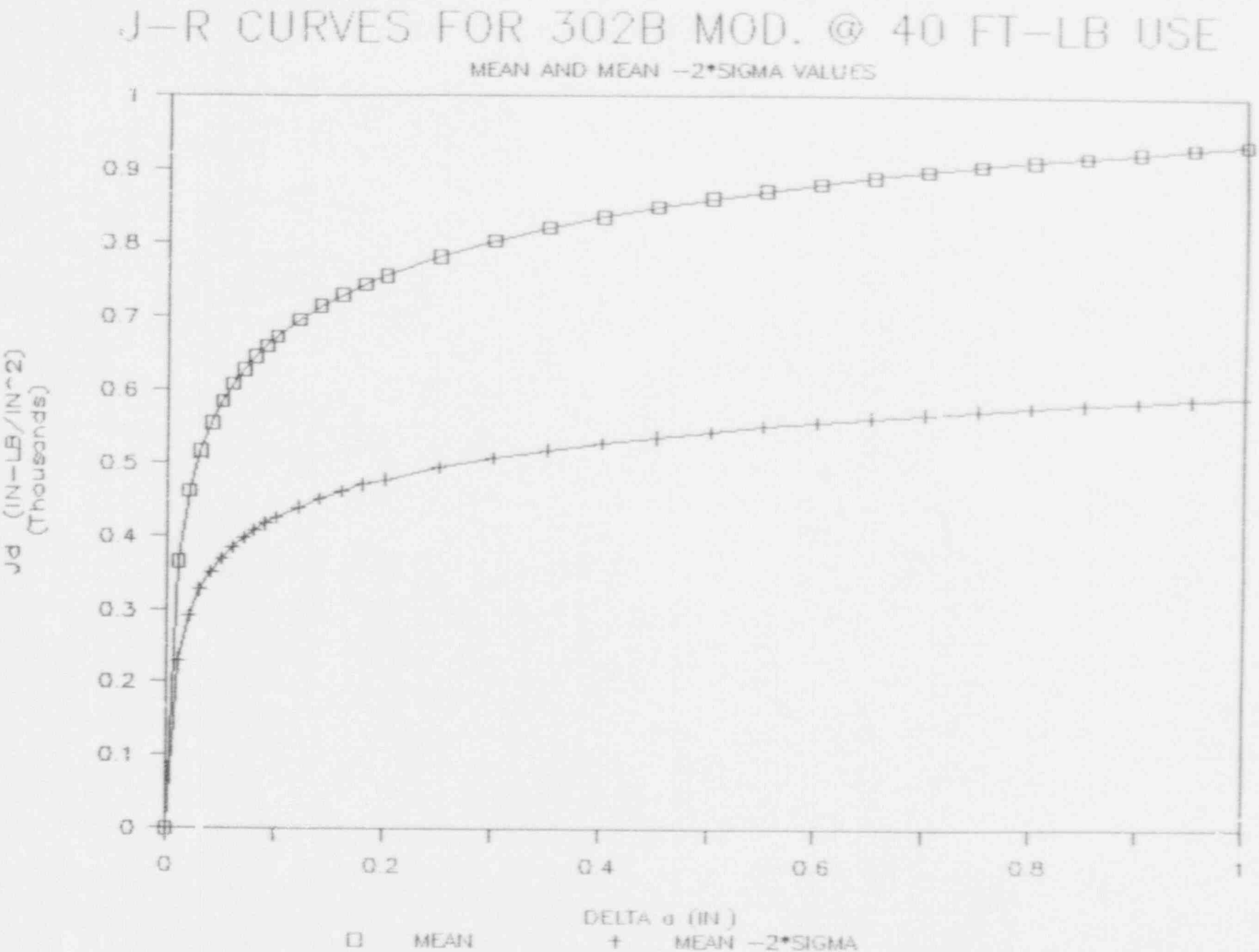

Figure 3-6a Mean and Mean Minus Two Sigma J-R Curves for SA 302B Modified Material at 40 ft-lbs USE

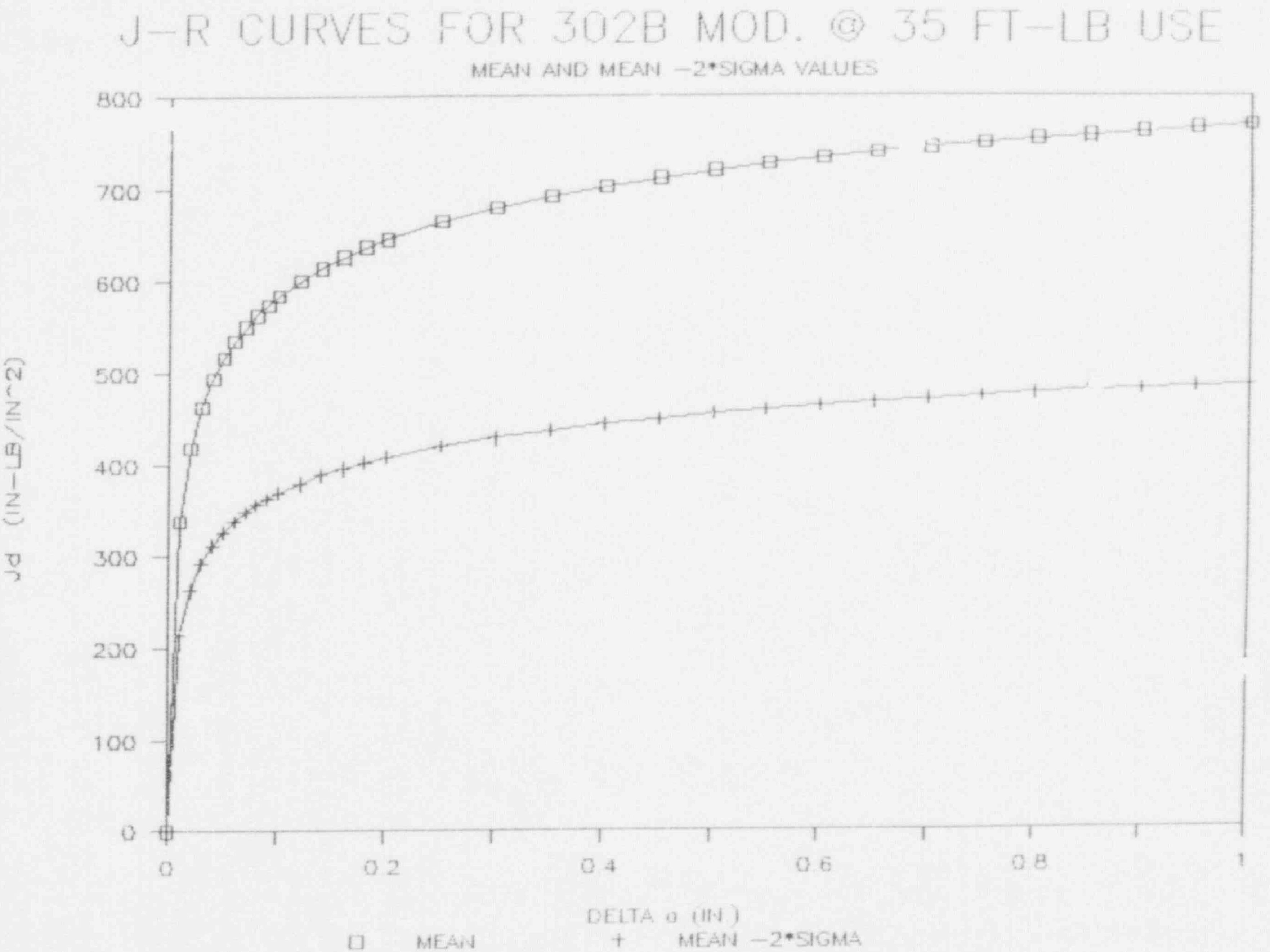

Figure 3-6b Mean and Mean Minus Two Sigma J-R Curves for SA 302B Modified Material at 35 ft-lbs USE

4.0 EVALUATION OF LEVEL A ANU B CONDITIONS

The methodology for the evaluation of Level A and B Service loadings was described in Section 2. Key steps in that evaluation are the calculation of applied J-integral and the flaw stability evaluation. This Section describes the selection and the evaluation of appropriate loadings for Service Levels A and B. The J-R curves determined in Section 3 are used to determine if the acceptance criteria of Appendix XX are satisfied.

4.1 Level A and B Service Loadings

The loadings for the Oyster Creek RPV are specified in Reference 4-1 and were used in the ASME Code analysis documented in Reference 1-1. A review of Reference 4-1 indicates that the Service Level A and B loadings are essentially internal pressure and a heatup/cooldown rate of 100° F per hour. The RPV design pressure is 1250 psig. The numerical values of pressures, cooling rate, material strength properties and the beltline geometry used in this evaluation are summarized in Table 4-1.

The postulated flaw for this case is a 1/4 t (i.e., 7.125x.25 or 1.78 inch) and its orientation is circumferential. The internal pressures and the cooldown rate shown in Table 4-1 along with the flaw geometry information were input in equations (2-1) through (2-7) of Section 2 to determine the applied J-integral values.

4.2 Evaluation per $J_{0.1}$ Criterion

Table 4-2 shows the calculated values of applied J-integral for internal pressure equal to 1581 psi (1.15x Accumulation pressure) and a cooldown rate of 100° F per hour. The applied J-integral value at 1.88 inch crack depth (1.78 + 0.1) is 63.8 in-lb/in^2.

Figure 4-1 shows the plot of this J-integral value along with the mean minus two sigma J-R curves (40 ft-lbs USE) for SA 302B and SA 302B modified. It is seen that the applied J value of 63.8 is considerably less than the $J_{0.1}$ value for both J-R curves. Figure 4-2 shows the same comparison with J-R curves corresponding to 35 ft-lbs USE. In all cases the $J_{0.1}$ criterion is satisfied.

4.3 Stability Evaluation

The applied J-integral values for the stability evaluation are calculated using an internal pressure of 1719 psi (1.25x Accumulation pressure). Figure 4-3 shows the applied J curve and the appropriate J-R curves for 35 ft-lbs USE. Flaw stability at a given applied load is assured when the slope of the applied J-integral curve is less than the slope of the material J-R curve at the point on the J-R curve where the two curves intersect (see Figure 2-1). This condition is clearly satisfied even for the 35 ft-lbs USE case.

To determine the pressure at which the instability occurs, applied J-integral curve was recalculated for a range of internal pressures. With SA 320B modified J-R curve for 35 ft-lbs USE, the instability was predicted for an internal pressure of 3250 psi, well in excess of any credible pressures in BWR operations. The stability assessment curve corresponding to 3250 psi pressure is shown in Figure 4-4.

4.4 Summary of Service Level A and B Evaluation

The evaluation for Service Level A and B loadings was conducted with the conservative J-R curves for SA 302B and SA 302B modified materials. The results of the evaluation show that even for the case with assumed USE of 35 ft-lbs and the SA 302B J-R curve, both the $J_{0.1}$ and stability criteria are satisfied.

4.5 References

4-1 "Reactor Vessel Loadings," GE Drawing No. 237E438, Revision 1, December 1964.

4-2 "Reactor Cycles - BWR-6 Standard," GE Drawing No. 795E949, Revision 0, July 1981.

TABLE 4-1

RPV Geometry and Loading Information

Vessel Geometry for Beltline Region

Vessel Radius	106.7 in.
Vessel Thickness	7.125 in.
Plate Analyzed	G-8-7
Flaw Orientation	Circumferential

Conditions for Level A & B Evaluation

Pressure (design)	1250 psi
Accumulation Pressure	1250x1.1 or 1375 psi
1.15xAccum. Pressure	1375x1.15 or 1581 psi
1.25xAccum. Pressure	1375x1.25 or 1719 psi
Temperature	550° F
Young's Modulus	27.7×10^6 psi
Poisson's Ratio	0.3
Cooldown Rate	100° F per hour

Unirradiated Properties of Plate G-8-7

Yield Strength	67.2 ksi @ room temperature
Ultimate Strength	88.6 ksi
Transv. USE	51.4 ft-lbs

Irradiated Material Properties

@ 32 EFPY

Fluence (1/4t)	2.36×10^{18} n/cm^2
S_y @ 550° F	69 ksi (estimated)
CVN Energy	40.3 ft-lbs

TABLE 4-2

Calculated Values of Applied J-Integral for 1.15xAccumulation Pressure Case

PRESSURE(PSI)= 1581
VESSEL RI (IN)= 106.7
VESSEL TH (IN)= 7.125
COOLING RATE(F/HR) .00
a0 (IN)= 1.78125
E(KSI)= 27700
YS (KSI)= 69

CIRCUMFERENTIAL FLAW

a	F2	F3	Kp	Kt	ae	F2'	F3'	Ktotal	Japp
1.78	0.96	0.90	30.63	12.18	1.80	0.97	0.90	43.02	60.81
1.83	0.97	0.90	31.15	12.19	1.85	0.97	0.90	43.55	62.30
1.88	0.97	0.90	31.66	12.18	1.90	0.97	0.90	44.06	63.79
1.93	0.97	0.90	32.18	12.18	1.95	0.97	0.90	44.57	65.27
1.98	0.98	0.90	32.69	12.16	2.00	0.98	0.90	45.08	66.75
2.03	0.98	0.90	33.20	12.15	2.05	0.98	0.90	45.57	68.23
2.08	0.98	0.89	33.71	12.12	2.10	0.98	0.89	46.06	69.70
2.13	0.99	0.89	34.22	12.10	2.16	0.99	0.89	46.54	71.17
2.18	0.90	0.89	34.73	12.06	2.21	0.99	0.89	47.02	72.64
2.23	0.99	0.89	35.24	12.03	2.26	0.99	0.89	47.49	74.10
2.28	0.99	0.88	35.74	11.98	2.31	1.00	0.88	47.96	75.57
2.33	1.00	0.88	36.25	11.94	2.36	1.00	0.88	48.42	77.03
2.38	1.00	0.88	36.75	11.89	2.41	1.00	0.88	48.88	78.49
2.43	1.00	0.87	37.26	11.83	2.46	1.01	0.87	49.33	79.95
2.48	1.01	0.87	37.76	11.77	2.51	1.01	0.87	49.78	81.40
2.53	1.01	0.86	38.27	11.71	2.56	1.01	0.86	50.22	82.86
2.58	1.01	0.86	38.77	11.64	2.61	1.02	0.86	50.66	84.31
2.63	1.02	0.85	39.28	11.57	2.66	1.02	0.85	51.10	85.77
2.6[illegible]	1.02	0.85	39.79	11.49	2.71	1.02	0.84	51.53	87.22
2.73	1.03	0.84	40.29	11.41	2.76	1.03	0.84	51.96	88.68
2.78	1.03	0.84	40.80	11.33	2.81	1.03	0.83	52.38	90.14

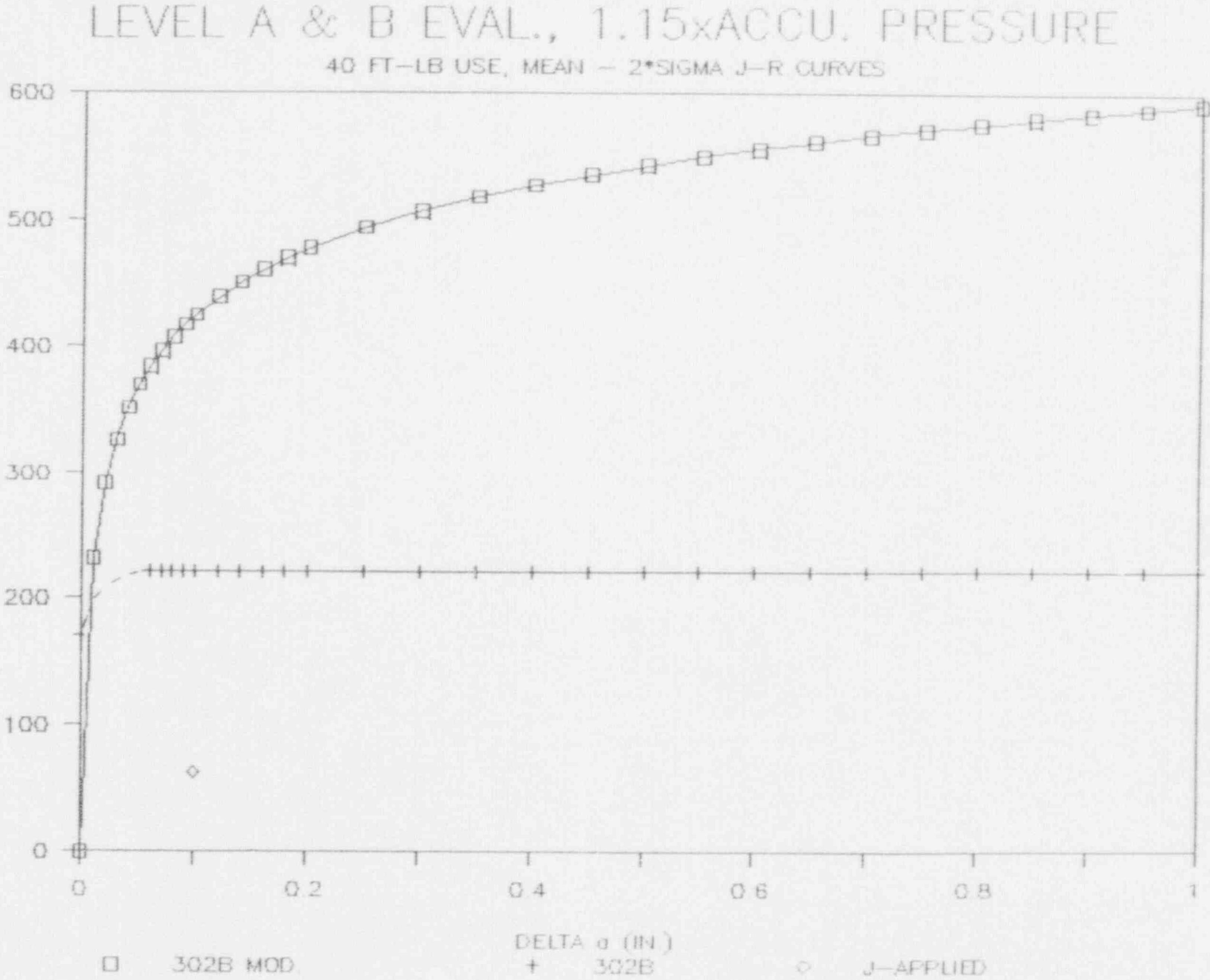

Figure 4-1 Evaluation Based on $J_{0.1}$ Criterion Based 40 ft-lbs USE

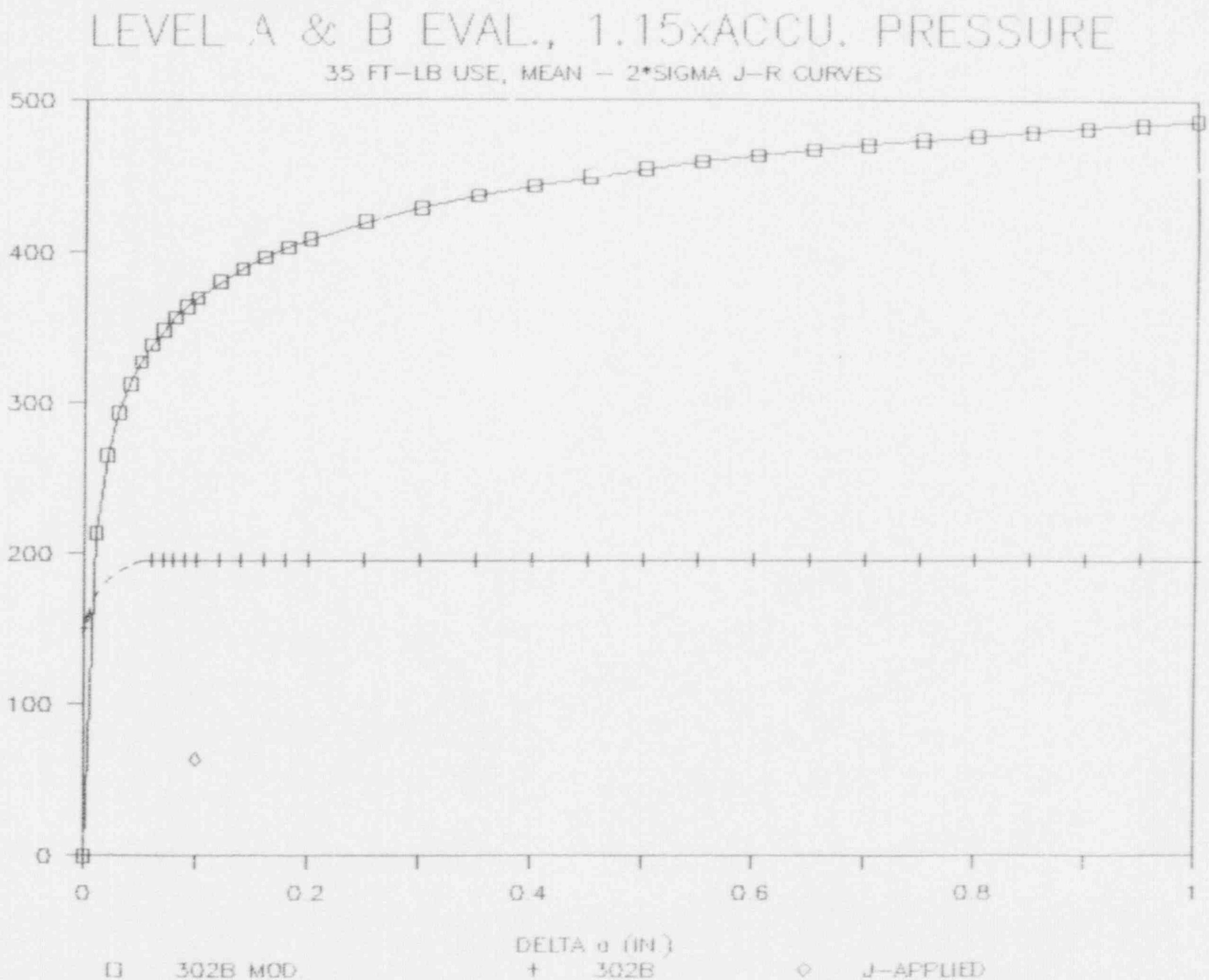

Figure 4-2 Evaluation Based on $J_{0.1}$ Criterion Based 35 ft-lbs USE

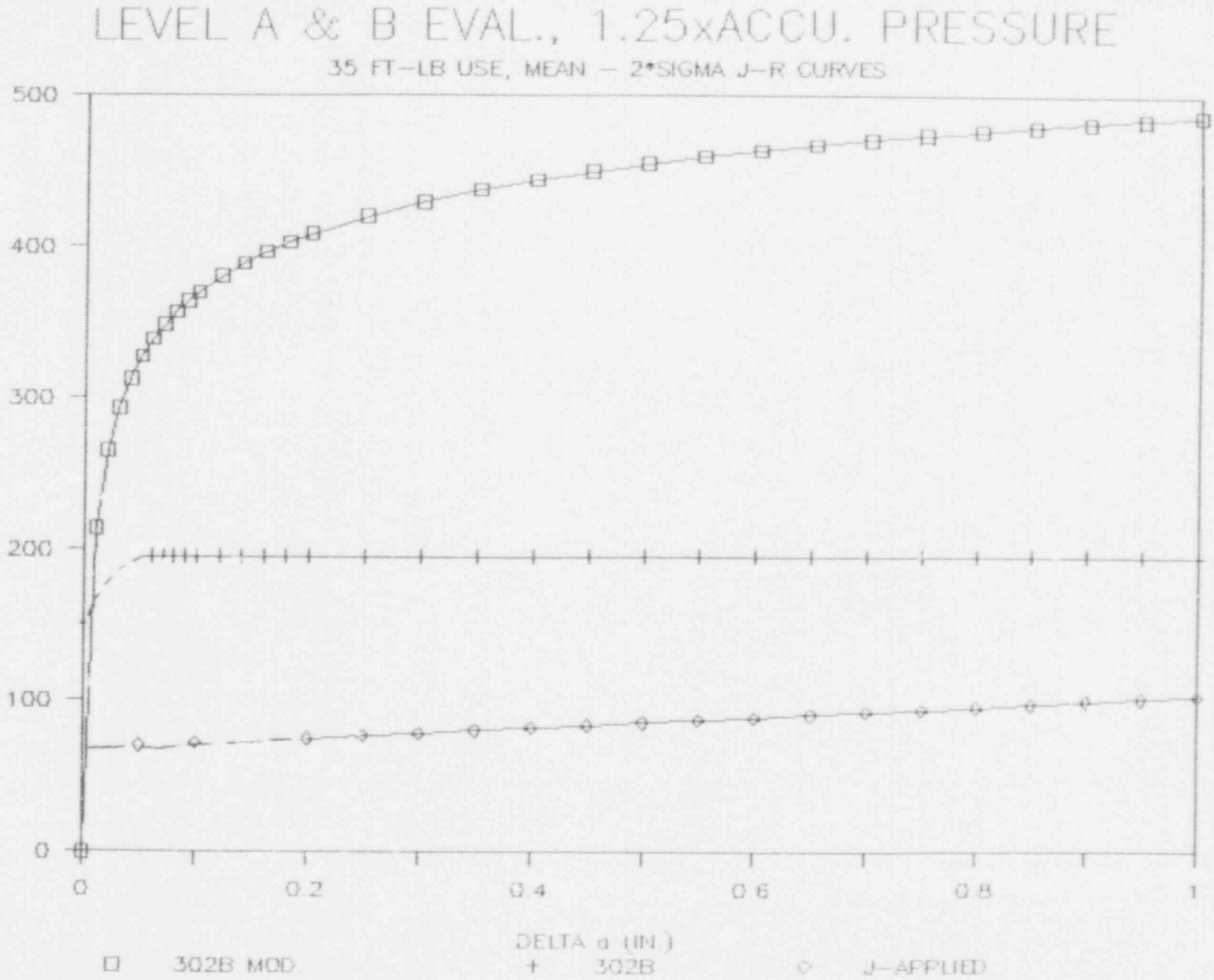

Figure 4-3 Stability Assessment for Level A and B Loadings Based on 35 ft-lbs USE

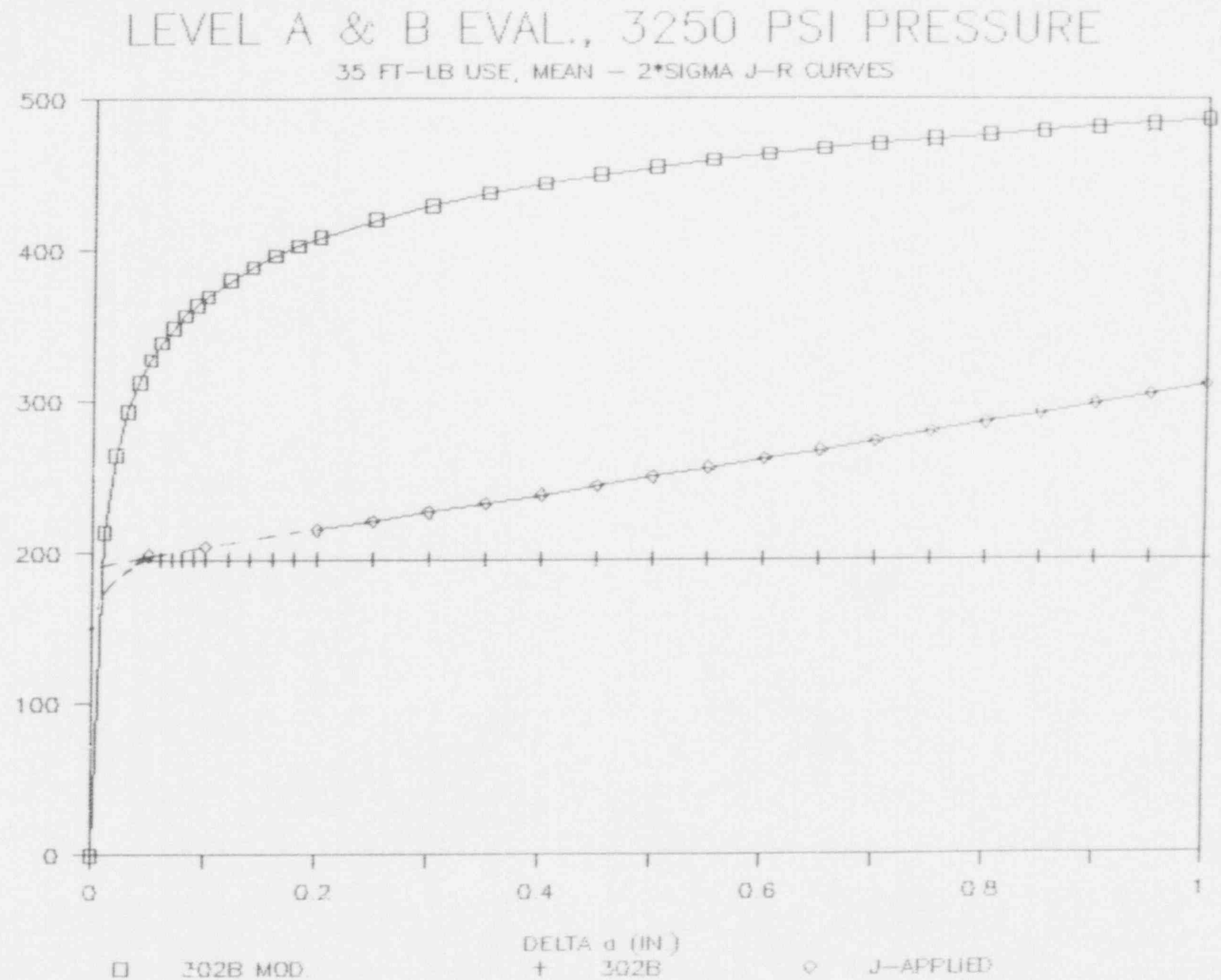

Figure 4-4 Stability Assessment at 3250 Psi Pressure

5.0 EVALUATION OF LEVEL C AND D CONDITIONS

The Appendix XX procedures call for the evaluation of Service Level C and D loadings with a safety factor of 1.0 and a postulated flaw equal to 1/10 of the vessel wall thickness. The ASME Code of construction of the Oyster Creek RPV did not have the Service Level classification for various loadings. The later editions of the Code first introduced the Normal, Upset, Emergency and Faulted classification for the various plant transients and component loadings. To avoid confusion between the plant or system operating conditions and the component operating conditions, this classification was then changed for the components to Service Levels A through D.

Since the RPV loadings drawing [4-1] does not define Level C and D condition loads, guidance was taken from more recent RPV thermal cycle diagrams, such as Reference 4-2 for a BWR/5 standard plant, to select the appropriate transients. Once the transient is selected, the first step in the evaluation is to determine the throughwall stress distribution in the RPV wall when the stresses reach their peak. This was done by finite element analysis. The stress intensity factor, K, values and correspondingly the applied J integral values are then calculated using available handbook solutions for circumferential cracks. The handbook approach is used since Appendix XX does not provide procedures to calculate K for temperature transients where heatup/cooldown rate exceeds 100° F per hour.

5.1 Evaluation of Level C Conditions

5.1.1 Transient Definition

A review of Reference 4-2 indicates that among the transients specified for the Emergency (Level C) condition, Automatic Blow Down with Loss of High Pressure Feed (Event 23) is relevant for the Oyster Creek RPV.

is a more rapid blowdown than that occurs with a single relief or safety valve blowdown, a transient already postulated in Reference 4-1. The temperature change in the beltline region during this transient is shown in Figure 5-1. The temperature is assumed to drop to 375° F in 3.3 minutes or 200 seconds. The temperature is then assumed to drop to 259° F at the rate of 300° F per hour. The internal pressure in the beltline region throughout this event is the saturation pressure corresponding to fluid temperature. Thus the pressure at the end of 3.3 minute ramp is 170 psi.

5.1.2 Finite Element Stress Analysis

Figure 5-2 shows an axisymmetric finite element model of the RPV wall in the beltline region. The stainless steel clad on the ID surface, with a nominal thickness of 7/32 inch, is also included in the model. ANSYS computer program [5-1] was used in both the transient temperature and the stress analyses. The value for the convective heat transfer coefficient, h, at the ID surface was assumed as 10,000 Btu/hr-ft^2-°F, based on a previous analysis [5-2] of a more severe transient.

The transient temperature distributions were calculated at several time points along the transient which were then used in the subsequent stress analysis. A review of the stress distributions at different time points showed that the stresses reach a maximum at time equal to 200 seconds. Figure 5-3 shows this stress distribution. The increased stress level in the clad (over and above the extrapolated trend from the base metal stress) is due to the difference between the thermal expansion coefficients of low alloy steel and stainless steel. This additional thermal stress in the clad was approximated as a point force for the calculation of stress intensity factor, K.

5.1.3 Fracture Mechanics Evaluation

The geometry of the postulated flaw for the Level C service loadings is essentially the same as that for the Level A and B loadings except that the flaw depth is 1/10 of the base metal wall thickness. The flaw orientation is circumferential. For the calculation of applied K (and correspondingly, J) values, a fully circumferential (i.e., 360° around) flaw geometry was conservatively assumed, thereby it was possible to use a standard approach given in Reference 5-3. The stress distribution in this approach is characterized in the form of a third order polynomial across the thickness:

$$\sigma = a_0 + a_1 x + a_2 x^2 + a_3 x^3 \qquad (5\text{-}1)$$

The stress in the clad over and above that which would be present based on the extrapolation from base metal, was integrated over the clad thickness and the resulting force, P, was assumed to be located at the middle of the clad. The following equation based on a solution given in Reference 5-4 was used to calculate the K contributed by the force P:

$$K_{clad} = 2P \times 1.3/\sqrt{(\pi a)} \qquad (5\text{-}2)$$

where, a is crack depth.

Table 5-1 shows a summary of the calculated values of K and J-integral. Both the pressure and thermal loadings are based on a safety factor of 1.0. The last but one column (K'_{total}) in Table 5-1 shows the total value of K including the plastic zone size correction. Figure 5-4 shows a plot of K'_{total} as a function of crack depth/thickness.

The last column in Table 5-1 shows the applied J-integral values obtained from K'_{total} values by using equation (2-6). The J-integral values are then used in the acceptance criteria evaluation.

5.1.4 Acceptance Criteria Evaluation

Figure 5-5 shows the applied J-integral curve, and the J-R curves for SA 302B and SA 302B modified at 35 ft-lbs USE. The J-R curves for this evaluation are conservative representations (i.e., mean minus two sigma values). The J-integral value at 0.1 inch crack growth, J_1, was obtained as 64.98 in-lb/in^2 from Table 5-1 at 'a' = 1.031 inch (which is 0.1x7.125 +

clad thickness of 7/32 + 0.1). This value is clearly less than the $J_{0.1}$ values for either of the J-R curves in Figure 5-5. Therefore, the first criterion in Subsection 3.1.3 is satisfied. Figure 5-5 also demonstrates that the stability criteria is also satisfied since the applied J-integral value is less than J_{Ic} predicted by both J-R curves.

Based on the preceding, it is concluded that the both acceptance criteria for Level C loadings are satisfied.

5.2 Evaluation of Level D Conditions

As in the case of Level C loadings, there are no Level D condition loadings defined in the Oyster Creek RPV loading drawing. A review of more recent RPV thermal cycle diagram [4-2] shows that the Loss of Coolant Accident (LOCA) event is the most limiting among the Level D events. Therefore, this event was considered in the evaluation for Level D acceptance criteria.

A fracture mechanics evaluation of a BWR RPV following a postulated LOCA event has been described in Reference 5-2. The analysis in Reference 5-2 considered a 240 inch ID RPV with a thickness of 6 inches. These dimensions differ slightly from those of Oyster Creek RPV, but it was judged that these differences are insignificant and, therefore, the results of that analysis were used in this evaluation.

5.2.1 Description of LOCA Event

Two types of pipe rupture events can be postulated to cause a LOCA: (1) steam line break, (2) recirculation line break. Both events assume a guillotine rupture of the line when the reactor is operating at full power. Following pipe rupture, depressurization occurs rapidly in both cases.

During steam line break, because of its higher elevation, the annulus between the shroud and the beltline region continues to be filled with two phase mixture of water and steam, and the boiling continues for quite some time after the initial rapid depressurization. On the other hand, with a recirculation line break, the water in the annulus drains out after the initial depressurization and the beltline region is exposed to steam under natural convection heat transfer conditions. Therefore, higher heat transfer conditions, and consequently, higher temperature gradients are expected to develop in the case of steam line break. It was, therefore, concluded that the steam line break is more severe than the recirculation line break from the view point of thermal stresses and fracture failure mode. Therefore, steam line break was analyzed in Reference 5-2.

Figure 5-6 shows the pressure and temperature variations assumed during the LOCA event. Based on the consideration of thermodynamic and heat transfer conditions, the convective heat transfer coefficient, h, during the depressurization phase (time 0 to 300 seconds) was conservatively assumed as 10000 Btu/hr-ft^2-°F. After 300 seconds, there is significant subcooling from the ECCS flow and, therefore, the value of 'h' is much lower. A value of 500 Btu/hr-ft^2°F was assumed for that portion of the event.

5.2.2 Fracture Mechanics Analysis Results

Figures 5-7 and 5-8 show the calculated temperature and stress distributions, respectively, in the vessel wall at different times after the initiation of LOCA event. The calculated values of stress intensity factors based on the stress distributions of Figure 5-8, are shown in Figure 5-9. A 360° circumferential crack geometry was assumed in these calculations. It is seen that the stress intensity factor values are the highest at time equal to 300 seconds. The stress intensity factor value at a/t of 0.1 is approximately 90 ksi$\sqrt{in}$. This is equivalent to a applied J-integral value of 266 in-lb/in^2.

5.2.3 Acceptance Criteria Evaluation

The material J-R curves to be used for the evaluation of Level D loadings are those based on the best estimate or the mean values. Figure 5-10 shows the mean or best estimate J-R curves for 35 ft-lb USE and the calculated value of applied J-integral for Level D loading. It is seen that the value of applied J-integral, 266 in-lb/in^2, is even less than the J_{Ic} value for the lower of the two J-R curves (315 in-lb/in^2). Thus, both the $J_{0.1}$ and the stability criteria are satisfied.

5.3 Summary of Level C and D Loadings Evaluation

The evaluation for Service Level C was conducted with the assumed loading as that resulting from an Automatic Blowdown Transient. The applied J-integral values were based on a finite element stress analysis of Oyster Creek RPV wall. The mean minus two sigma J-R curves for SA 302B and SA 302B modified materials were used in the acceptance criteria evaluation. For the Service Level D evaluation, results from a previous fracture mechanics analysis of LOCA event were used to determine the applied J-integral values. The mean or best estimate J-R curves were used for this case.

The results of both the evaluations show that even for the case with assumed USE of 35 ft-lbs and the SA 302B J-R curve, both the $J_{0.1}$ and stability criteria are satisfied.

5.4 References

5-1 ANSYS Computer Program, Version 4.1, Swanson Analysis Systems, Inc.

5-2 Ranganath, S., "Fracture Mechanics Evaluation of a Boiling Water Reactor Vessel Following a Postulated Loss of Coolant Accident," Paper No. G 1/5, Transaction of the 5th SMiRT Conference, 1979.

5-3 C.B. Buchalet and W.H. Bamford, "Stress Intensity Factor Solutions for Continuous Surface Flaws in Reactor Pressure Vessels," ASTM STP 590, 1976, pp. 385-402.

5-4 H. Tada and P.C. Paris, "The Stress Analysis of Cracks Handbook," Del Research Corporation, 1985.

TABLE 5-1

Applied J-Integral Values for Level C Loading

Coefficients for Thermal Stress		Coefficients for Pressure Stress		Internal Pressure (psig)	Clad Force (lbs)
A0:	29800	A0:	24070.26	170	1549.9844
A1:	-21730	A1:	0		
A2:	4242	A2:	0		
A3:	-267.3	A3:	0		

a	Kth	Kclad	Kp	Ktotal	ae	Kth'	Kclad'	Kp'	Ktotal'	Japp
0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00
0.500	34.2232	3.6379	1.5891	39.4503	0.5173	34.5660	3.5597	1.6177	39.7434	51.89
0.734	37.7102	2.8760	1.9457	42.5319	0.7545	37.9149	2.[illegible]307	1.9741	42.7196	59.95
0.931	39.2444	2.5080	2.2111	43.9635	0.9528	39.3573	2.4757	2.2388	44.0719	63.81
1.000	39.5734	2.4092	2.2988	44.2814	1.0218	39.6595	2.3802	2.3263	44.3660	64.66
1.031	39.6940	2.3680	2.3380	44.4001	1.0532	39.7688	2.3403	2.3653	44.4745	64.98
1.500	39.9634	1.9281	2.8883	44.7797	1.5223	39.9243	1.9128	2.9132	44.7503	65.79
2.000	38.4939	1.6536	3.4304	43.5778	2.0212	38.4123	1.6444	3.4528	43.5095	62.10
2.500	36.3855	1.4705	3.9544	41.8104	2.5195	36.2987	1.4646	3.9787	41.7380	57.23
3.000	34.1314	1.3373	4.4762	39.9448	3.0178	34.0508	1.3332	4.4948	39.[illegible]788	52.25
3.500	31.8534	1.2348	5.0056	38.0937	3.5162	31.7787	1.2318	5.0229	38.0335	47.52
4.000	29.4625	1.1527	5.5497	36.1649	4.0146	29.3892	1.1505	5.5658	36.1055	42.83
4.500	26.7450	1.0851	6.1138	33.9438	4.5128	26.6685	1.0835	6.1205	33.8805	37.71
5.000	23.4115	1.0281	6.7020	31.1417	5.0108	23.3302	1.0270	6.7150	31.[illegible]722	31.72
5.500	19.1231	0.9793	7.3179	27.4203	5.5084	19.0410	0.9785	7.3205	27.3480	24.57
6.000	13.4991	0.9368	7.9645	22.4004	6.0056	13.4271	0.9364	7.9719	22.3353	16.39

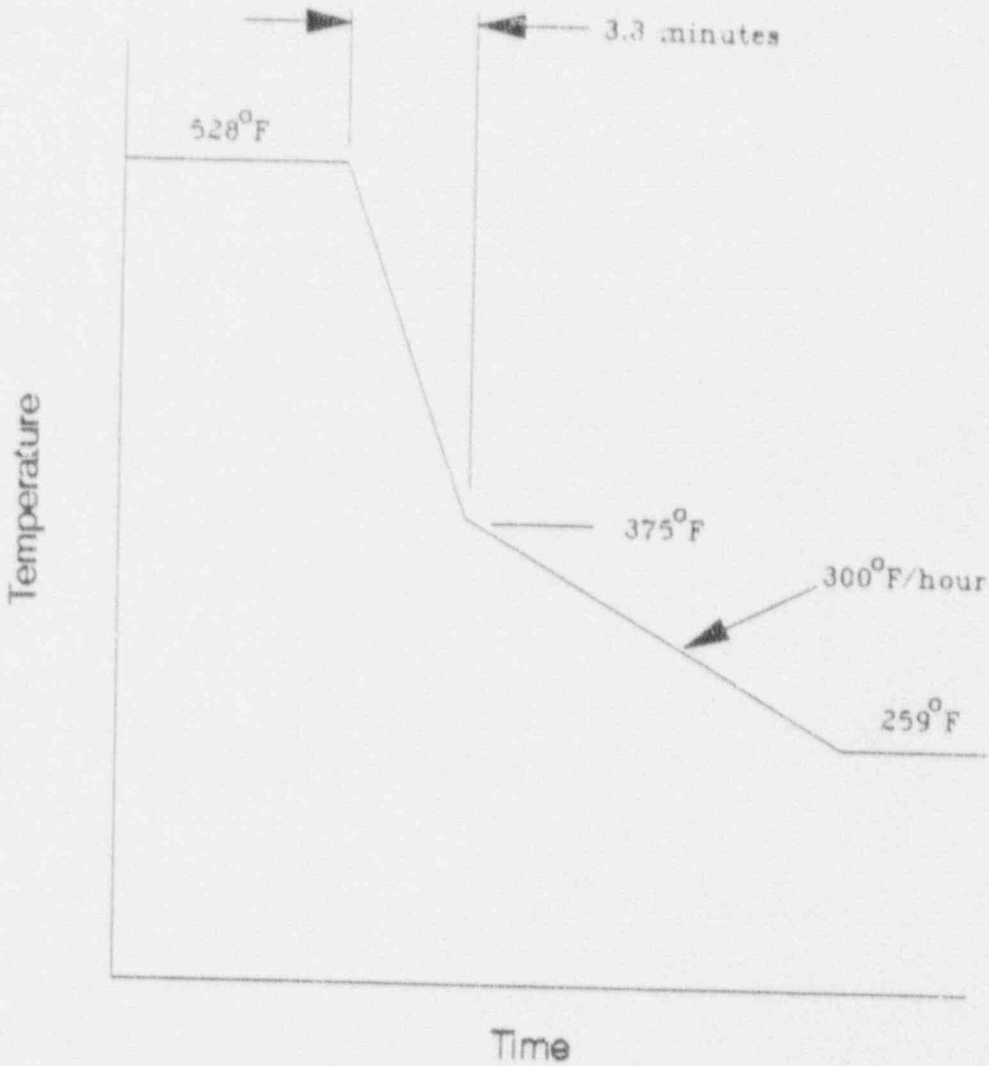

Figure 5-1 Temperature-Time Variations During Automatic Blowdown Transient (Level C Condition)

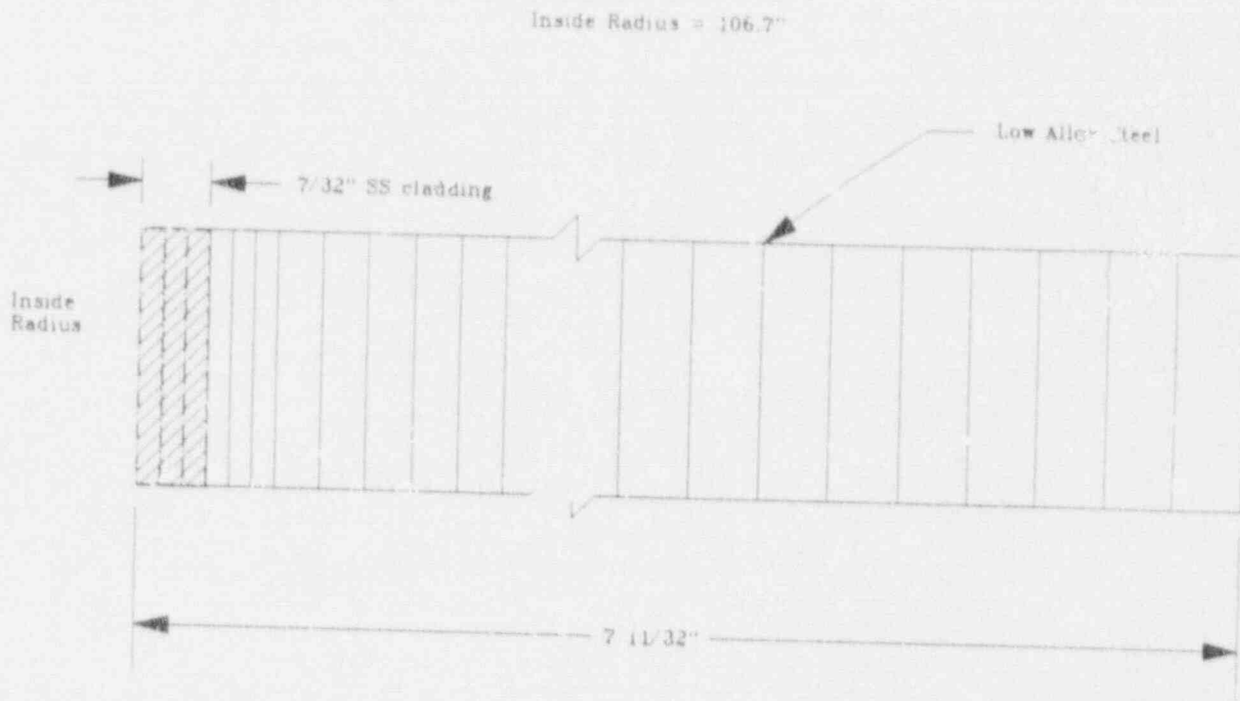

Figure 5-2 Axisymmetric Finite Element Model of RPV Wall

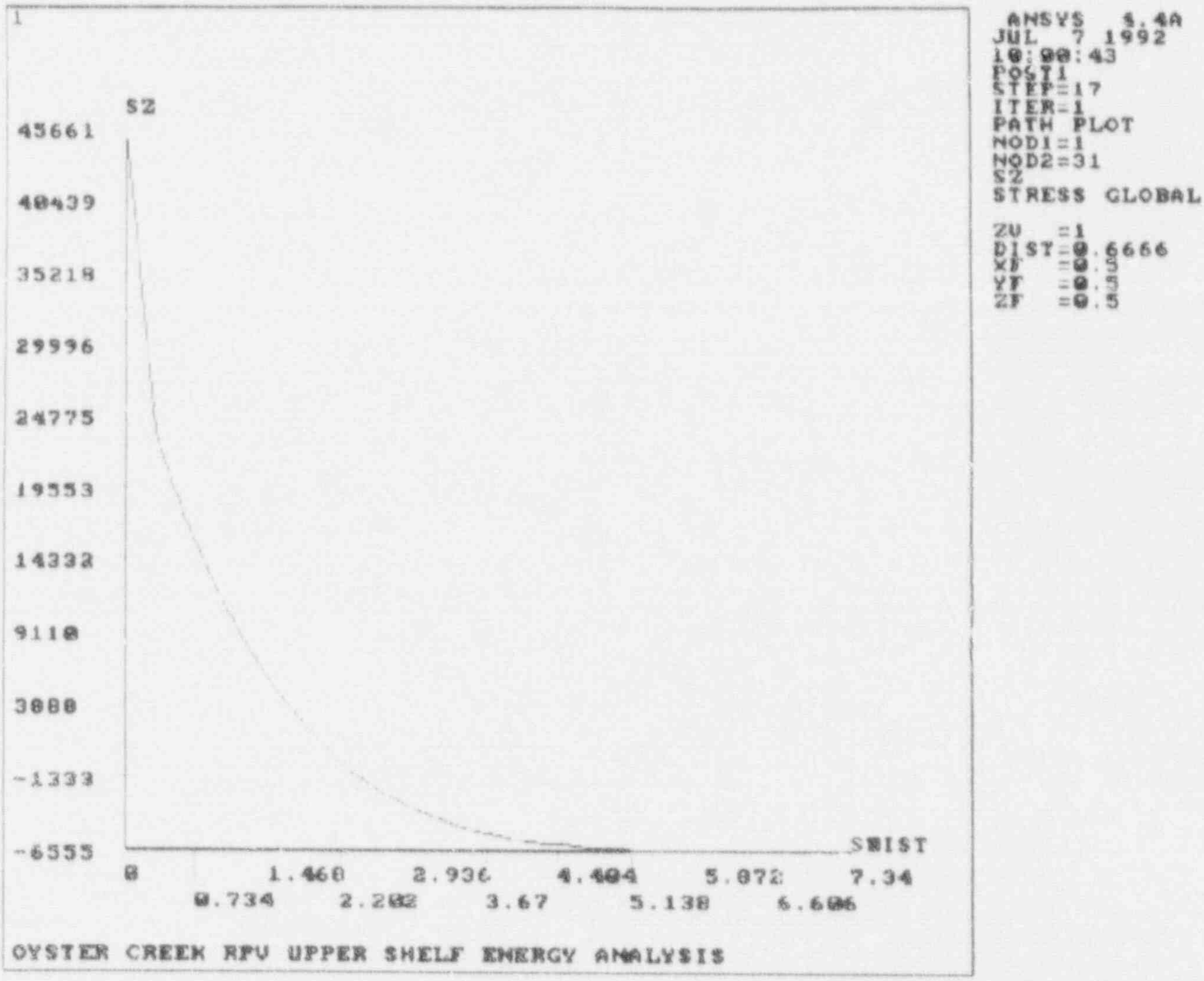

Figure 5-3 Stress Distribution in RPV Wall at 200 Seconds

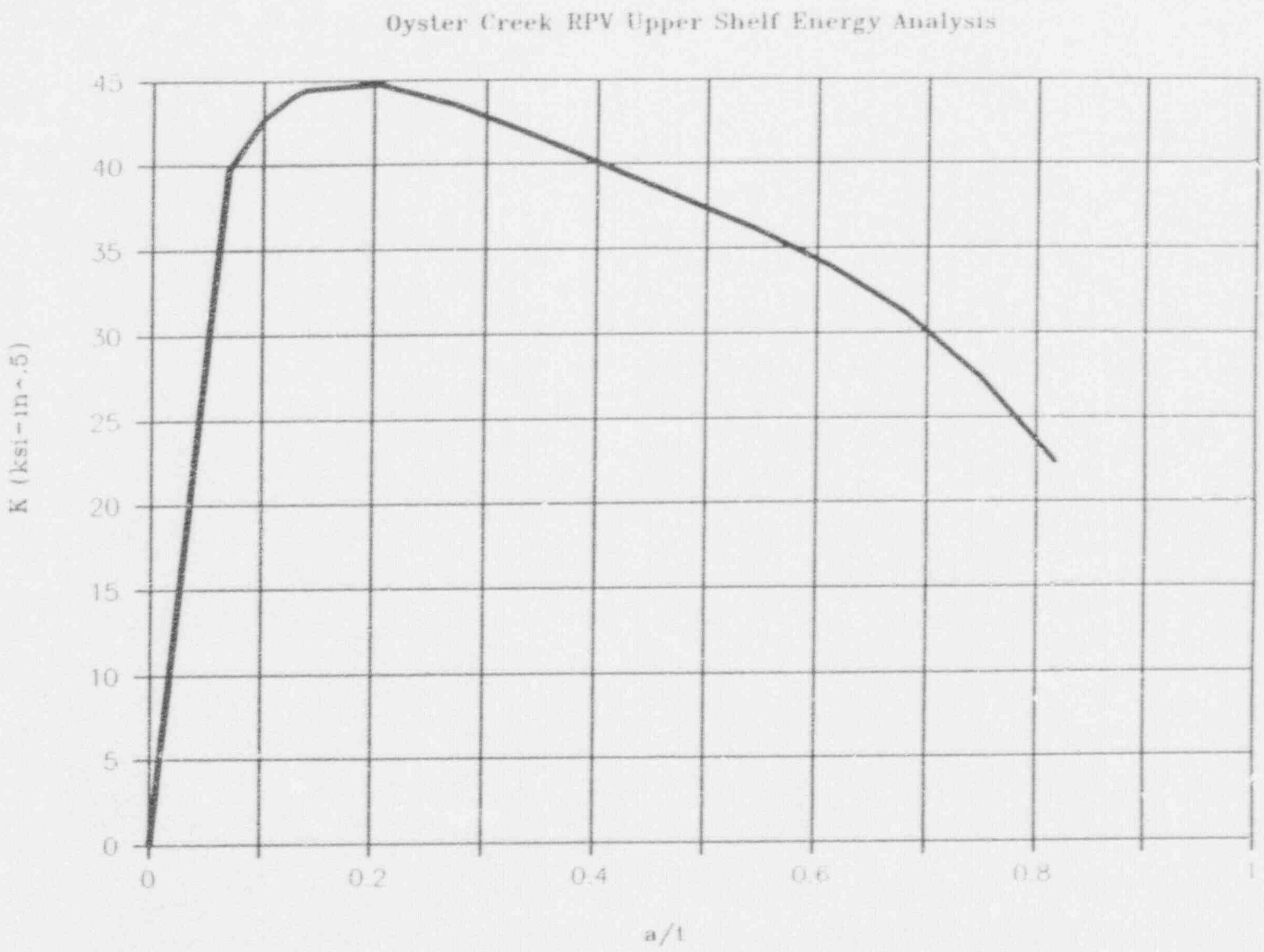

Figure 5-4 Plot of K'_{total} as a Function of Crack Depth/Thickness

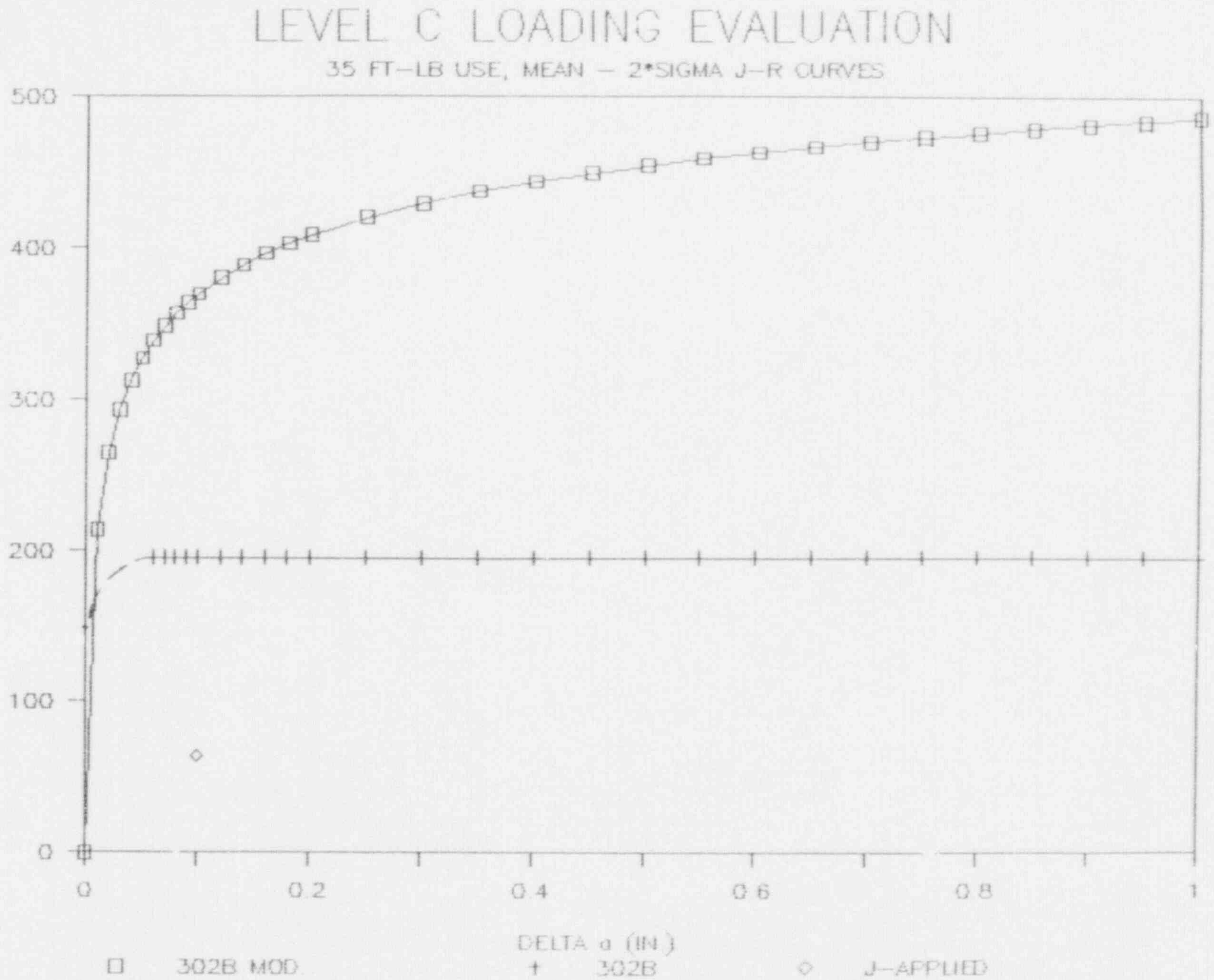

Figure 5-5 $J_{0.1}$ and Stability Assessment Diagram for Level C Loading

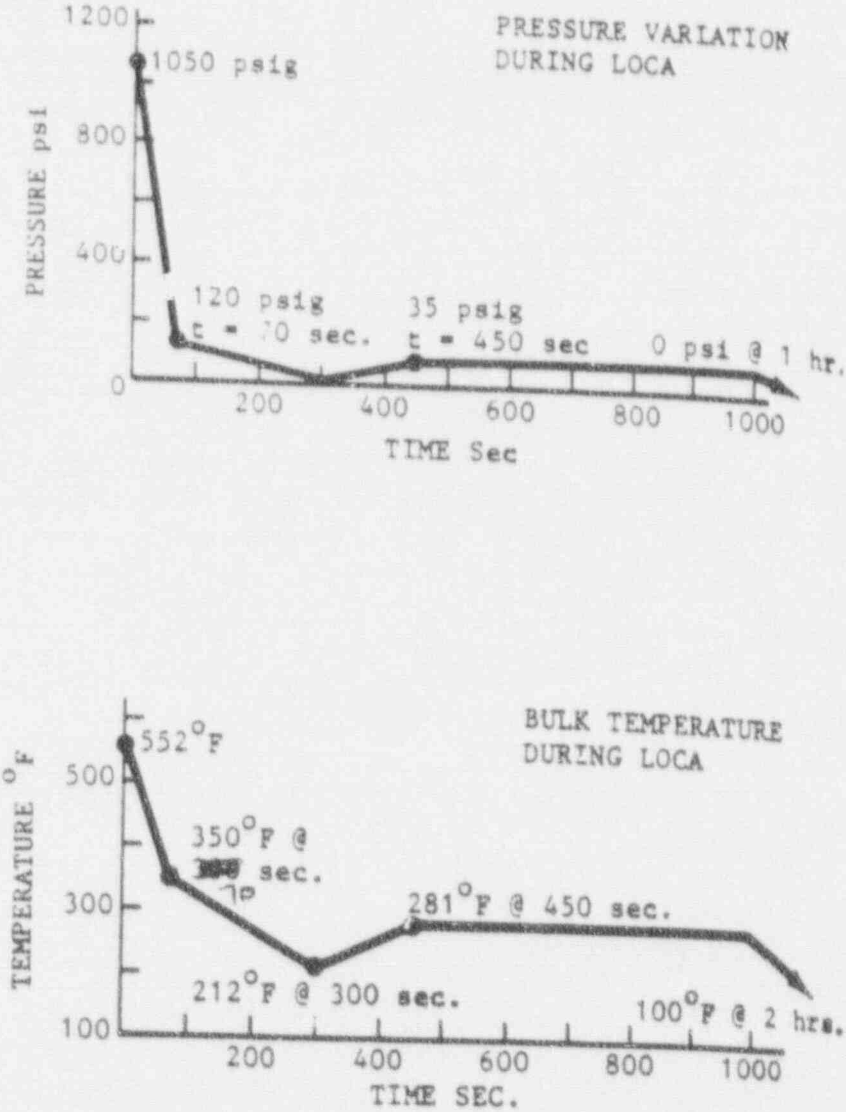

Figure 5-6 Va.iation of Pressure and Temperature Assumed in the LOCA Evaluation

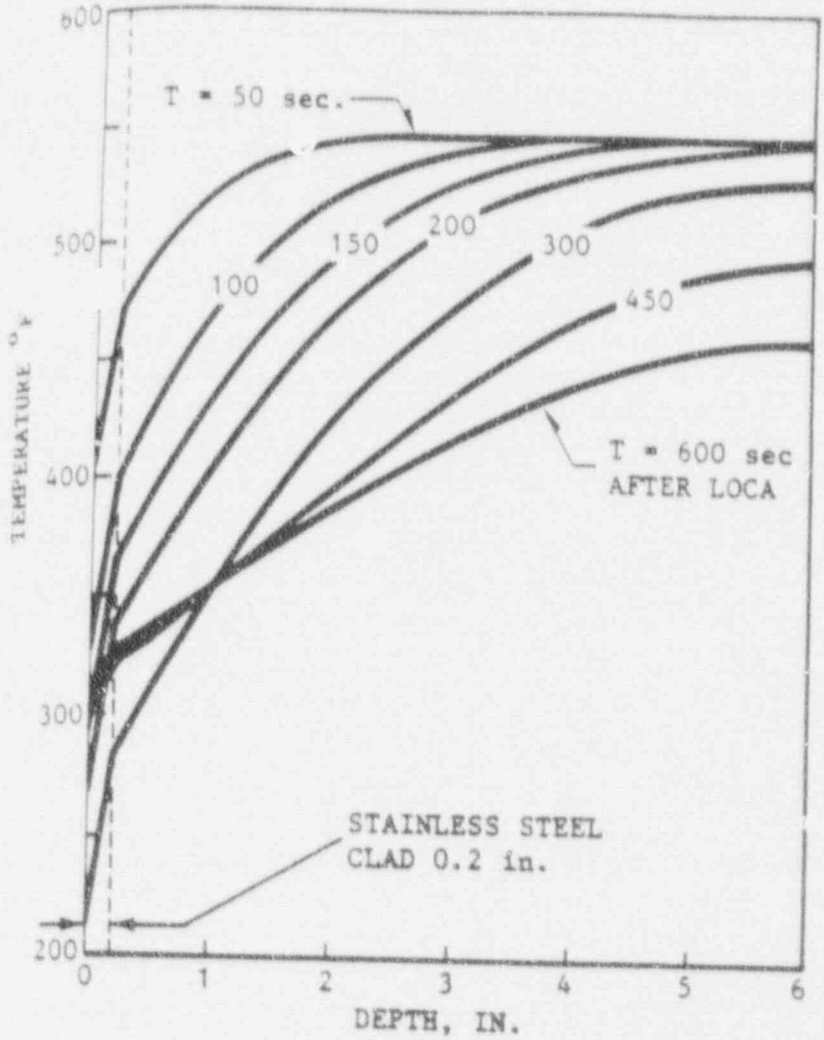

Figure 5-7 Temperature Distribution in Vessel Wall at Different Times After the LOCA

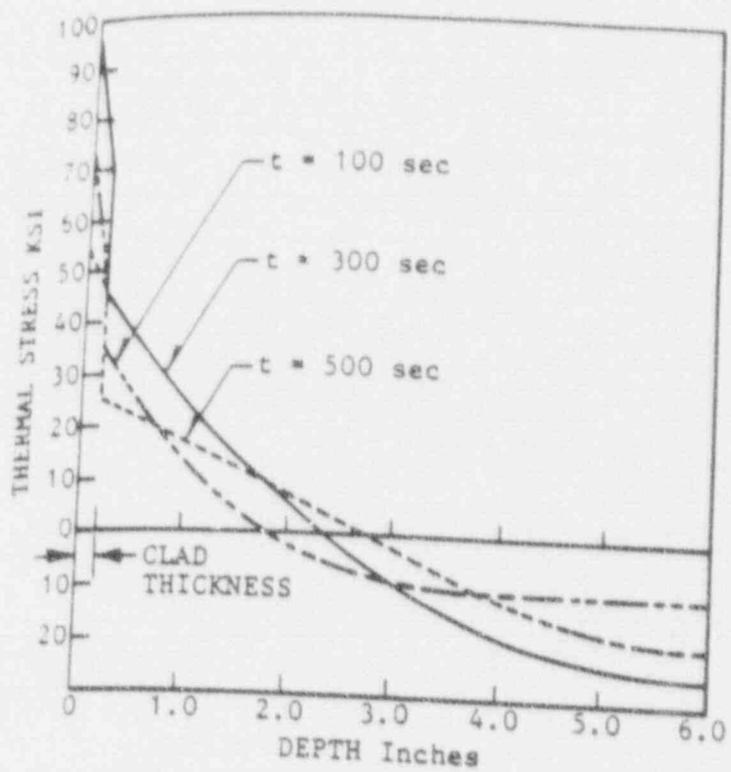

Figure 5-8 Thermal Stress Distribution at Different Times Following the LOCA

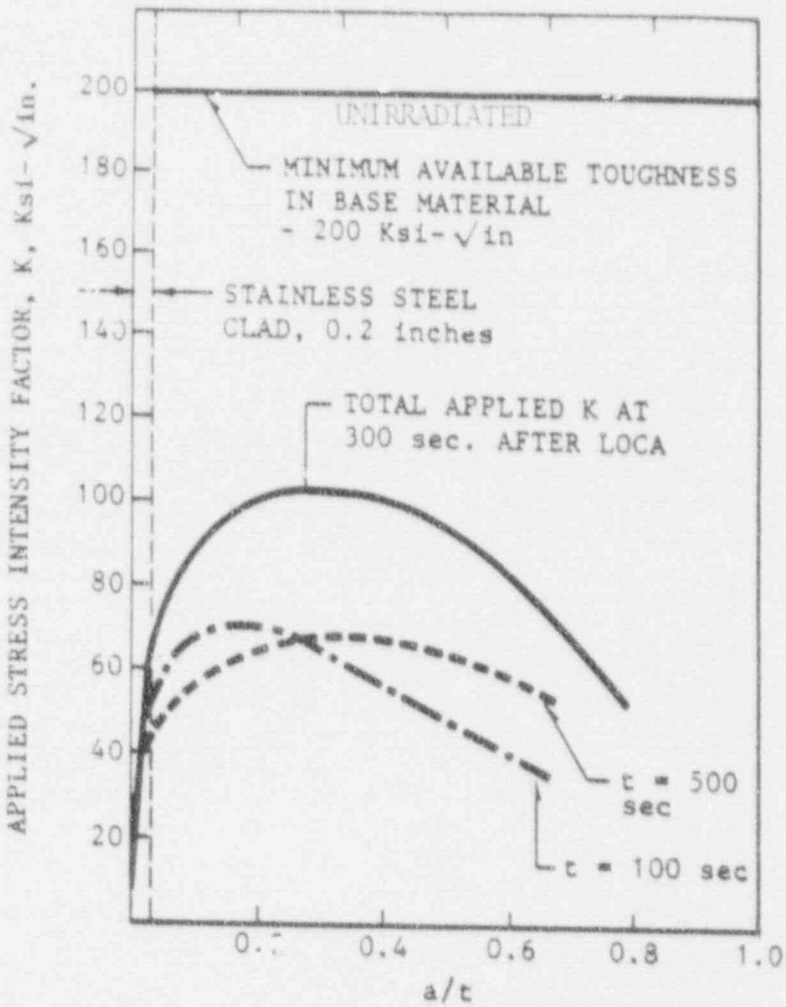

Figure 5-9 Applied Stress Intensity Factors for Different Crack Depths at Different Times Following the LOCA

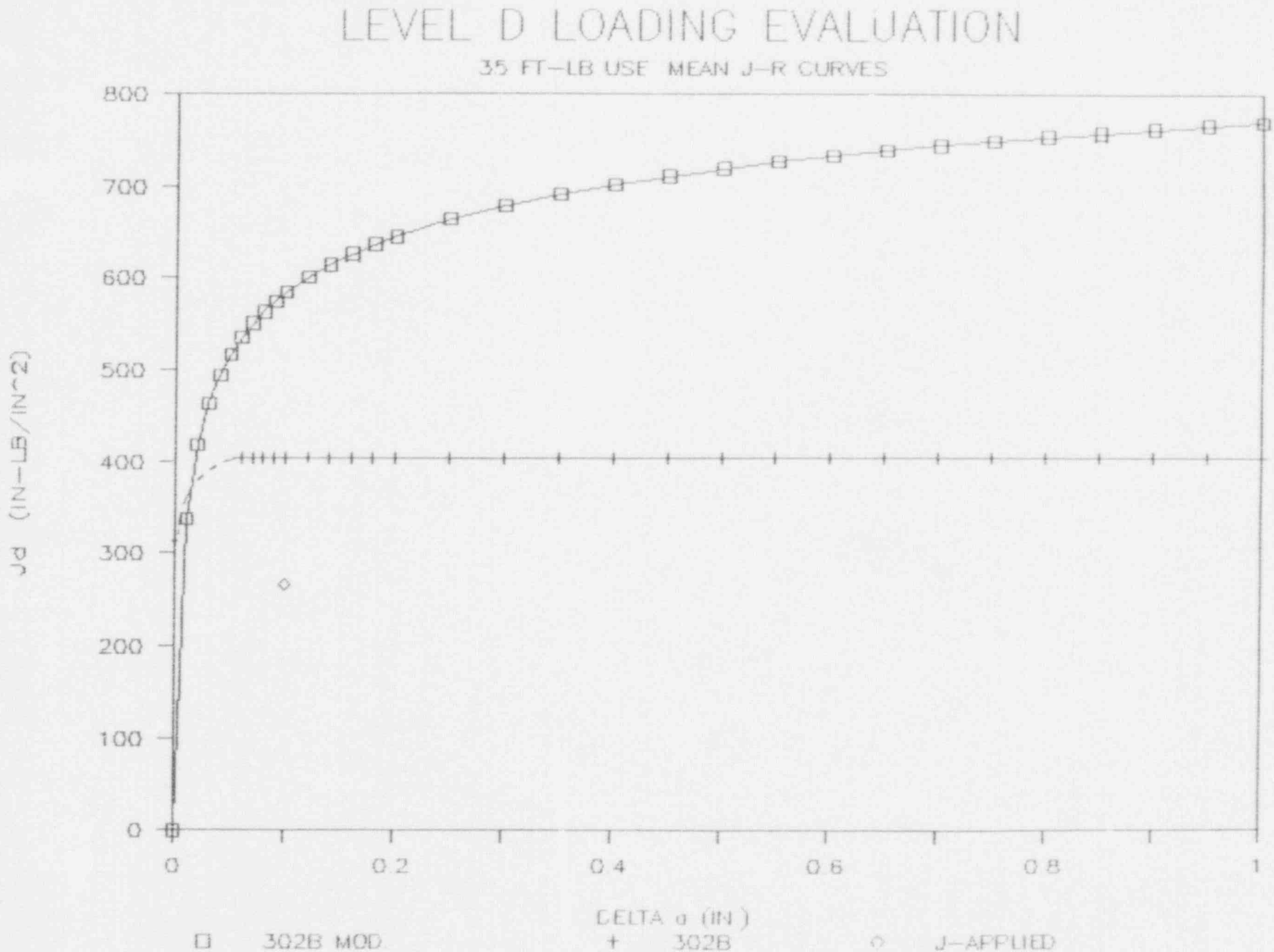

Figure 5-10 $J_{0.1}$ and St bility Assessment Diagram for Level D Loading

6.0 SUMMARY AND CONCLUSIONS

The P-T curve analysis for Oyster Creek RPV had indicated that the projected 32 EFPY upper-shelf energy for some of the RPV plates in the beltline region will fall below the 50 ft-lb value. Based on this information, the NRC staff has requested an Oyster Creek specific analysis showing the basis for present and continued vessel structural integrity when the 50 ft-lb requirement of 10CFR 50, Appendix G is not satisfied. A draft Appendix (Appendix XX) to ASME Section XI provides evaluation procedures and acceptance criteria for such cases. This report presents a fracture mechanics evaluation of Oyster Creek RPV using these procedures and acceptance criteria.

Levels A through D loading conditions were analyzed. For the Oyster Creek vintage vessels, the reactor loading diagrams did not define any Level C (emergency condition) and D (faulted condition) loadings. Therefore, based on a review of later BWR RPV thermal cycle diagrams, Automatic Blowdown transient and the LOCA event were selected as the limiting loadings for Level C and D conditions, respectively.

The beltline plates that have projected USE below 50 ft-lbs are made of SA 302B and SA 302B modified (equivalent to SA533 Grade B). Technical literature on fracture toughness testing of both the materials was reviewed to determine the appropriate J-Resistance or J-R curves. Best estimate minus two standard deviation J-R curves were used in the evaluation of Levels A, B and C service loadings. Level D loadings were evaluated using best estimate J-R curves. The J-R curves for SA 302B material was found to be always lower than those for the SA 302B modified material at the same USE level. The beltline plate (G-8-7) that has the lowest projected USE (40.3 ft-lbs) is made of SA 302B modified stock but there are other beltline plates, made of SA 302B, which are also projected to have USE slightly below 50 ft-lbs. Therefore, J-R curves of both materials were shown on the evaluation diagrams.

To cover the case of plant life extension, the evaluation was also conducted using a very conservative USE level of 35 ft-lbs (projected to be more than 160 EFPYs for plate G-8-7).

There are two acceptance criteria in Appendix XX. The first one compares the applied J-integral with J-R curve value at a flaw growth of 0.1 inch. The second criterion concerns with flaw stability. The evaluation results showed that even for the conservative case of 35 ft-lbs USE, both the acceptance criteria are satisfied for all four Service Level loadings.

Based on the results of this evaluation of Oyster Creek RPV per Appendix XX procedures, it is concluded that even though some beltline plates would have projected USE below 50 ft-lbs at the end of current design life of 32 EFPY, these lower values would still provide margins of safety against fracture equivalent to those required by Appendix G of Section III, ASME Code. Thus, the Oyster Creek RPV will continue to meet the requirements of 10CFR50, Appendix G. This conclusion would remain valid also for any realistic plant life extension that may be considered by the plant owner.

APPENDIX

DRAFT OF APPENDIX XX, SECTION XI, ASME CODE

DRAFT

CODE CASE N-XXX

ASSESSMENT OF REACTOR VESSELS WITH
LOW UPPER SHELF CHARPY ENERGY LEVELS

May 27, 1992

REVISION 11

DRAFT HISTORY

REVISION 0		AUGUST 25, 1987
REVISION 1		JANUARY 19, 1988
REVISION 2		APRIL 19, 1988
REVISION 3		AUGUST 30, 1988
REVISION 4		NOVEMBER 30, 1988
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REVISION 9		JANUARY 17, 1992
REVISION 10		APRIL 17, 1992
REVISION 11		CURRENT

ASSESSMENT OF REACTOR VESSELS WITH LOW UPPER SHELF CHARPY ENERGY LEVELS

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Case N-XXX
Assessment of Reactor Vessels With Low Upper Shelf Charpy Energy Levels
Section XI, Division 1

Inquiry: Section XI, Division 1, IWB-3730, requires that during reactor operation, load and temperature conditions shall be maintained to provide protection against failure due to the presence of postulated flaws in the ferritic portions of the reactor coolant pressure boundary. Under Section XI, Division 1, what procedure may be used to evaluate a reactor vessel with a low upper shelf Charpy impact energy level as defined in ASTM E 185-82 to demonstrate integrity for continued service at upper shelf conditions?

Reply: It is the opinion of the Committee that a reactor vessel with a low upper shelf Charpy impact energy level may be evaluated to demonstrate integrity for continued service for upper shelf conditions in accordance with the following.

1.0 EVALUATION PROCEDURES AND ACCEPTANCE CRITERIA

Section XI, Division 1, Appendix G, "Fracture Toughness Criteria for Protection Against Failure", provides analytical procedures based on the principles of linear-elastic fracture mechanics that may be used to define load and temperature conditions to provide protection against nonductile failure due to the presence of postulated flaws in the ferritic portions of the reactor coolant pressure boundary. To prevent ductile failure of a reactor vessel with a low upper shelf Charpy impact energy level the vessel shall be evaluated using the principles of elastic-plastic fracture mechanics. Flaws shall be postulated in the reactor vessel at locations of predicted low upper shelf Charpy impact energy and the applied J-integral for these flaws shall be calculated and compared with the J-integral fracture resistance of the material to determine acceptability. Factors of safety on applied load for limited ductile flaw growth, and on flaw stability due to ductile tearing, shall be satisfied. All specified design transients for the reactor vessel shall be considered. Evaluation procedures and acceptance criteria based on the principles of elastic-plastic fracture mechanics are given in Appendix A of this Code Case.

The evaluation shall be the responsibility of the Owner and shall be subject to review by the regulatory and enforcement authorities having jurisdiction at the plant site.

APPENDIX A TO CODE CASE N-XXX

ASSESSMENT OF REACTOR VESSELS WITH LOW UPPER SHELF CHARPY ENERGY LEVELS

ARTICLE A-1000

INTRODUCTION

A-1100 SCOPE

This Appendix provides acceptance criteria and evaluation procedures for determining the acceptability for operation of a reactor vessel when the vessel metal temperature is in the upper shelf range. The methodology is based on the principles of elastic-plastic fracture mechanics. Flaws are postulated in the reactor vessel at locations of predicted low upper shelf Charpy impact energy and the applied J-integral for these flaws is calculated and compared with the J-integral fracture resistance of the material to determine acceptability. All specified design transients for the reactor vessel shall be considered.

A-1200 PROCEDURE OVERVIEW

The following is a summary of the analytical procedure which may be used.

(a) Postulate flaws in the reactor vessel according to the criteria in A-2000.

(b) Determine the loading conditions at the location of the postulated flaws for Level A, B, C and D Service loadings.

(c) Obtain the material properties, including E, σ_y, and the J-integral resistance curve (J-R curve), at the locations of the postulated flaws. Requirements for determining the J-R curve are given in A-3300.

(d) Evaluate the postulated flaws according to the acceptance criteria in A-2000. Requirements for evaluating the applied J-integral are given in A-3200, and for determining flaw stability in A-3400. Three permissible evaluation approaches are described in A-3500. Detailed calculation procedures for Level A and B Service loadings are given in A-4000.

A-1300 GENERAL NOMENCLATURE

a	=	flaw depth which includes ductile flaw growth	(in.)
a_e	=	effective flaw depth which includes ductile flaw growth and a plastic-zone correction	(in.)
a_e^*	=	effective flaw depth at flaw instability, which includes ductile flaw growth and a plastic-zone correction	(in.)
a_o	=	postulated initial flaw depth	(in.)
Δa	=	amount of ductile flaw growth	(in.)
Δa^*	=	amount of ductile flaw growth at flaw instability	(in.)
C_1, C_2	=	material constants used to describe the power-law fit to the J-integral resistance curve for the material, $J_R = C_1(\Delta a)^{C_2}$	
(CR)	=	cooldown rate	(°F/hour)
E	=	Young's modulus	(ksi)
E'	=	$E/(1-\nu^2)$	(ksi)
F_1, F_2, F_3	=	geometry factors used to calculate the stress intensity factor	(dimensionless)
F_1^*, F_2^*, F_3^*	=	geometry factors used to calculate the stress intensity factor at flaw instability	(dimensionless)
J	=	J-integral due to the applied loads	(in.-lb/in.^{2})
J_R	=	J-integral fracture resistance for the material	(in.-lb/in.^{2})

$J_{0.1}$	=	J-integral fracture resistance for the material at a ductile flaw growth of 0.10 in.	(in.-lb/in.^{2})
J_1	=	applied J-integral at a flaw depth of a_o + 0.10 in.	(in.-lb/in.^{2})
J^*	=	J-integral at flaw instability	(in.-lb/in.^{2})
K_I	=	mode I stress intensity factor	(ksi √in.)
K_{Ip}	=	mode I stress intensity factor due to internal pressure, calculated with no plastic-zone correction	(ksi √in.)
K'_{Ip}	=	K_{Ip} calculated with a plastic-zone correction	(ksi √in.)
K^*_{Ip}	=	K_{Ip} at flaw instability, calculated with a plastic-zone correction	(ksi √in.)
K_{It}	=	mode I stress intensity factor due to a radial thermal gradient through the vessel wall, calculated with no plastic-zone correction	(ksi √in.)
K'_{It}	=	K_{It} calculated with a plastic-zone correction	(ksi √in.)
K^*_{It}	=	K_{It} at flaw instability, calculated with a plastic-zone correction	(ksi √in.)
K_r	=	ordinate of the failure assessment diagram curve	(dimensionless)
K'_r	=	ratio of the stress intensity factor to the fracture toughness for the material	(dimensionless)
p	=	internal pressure	(ksi)
p_a	=	accumulation pressure as defined in the plant-specific Overpressure Protection Report, but not exceeding 1.1 times the design pressure	(ksi)

p_a	=	pressure used to calculate the applied J-integral/tearing modulus line	(ksi)
p^*	=	internal pressure at flaw instability	(ksi)
p_o	=	reference limit-load internal pressure	(ksi)
R_i	=	inner radius of the vessel	(in.)
S_r	=	abscissa of the failure assessment diagram curve	(dimensionless)
S_r'	=	ratio of internal pressure to reference limit-load internal pressure	(dimensionless)
(SF)	=	safety factor	(dimensionless)
t	=	vessel wall thickness	(in.)
T	=	tearing modulus due to the applied loads	(dimensionless)
T_R	=	tearing modulus resistance for the material	(dimensionless)
W	=	parameter used to relate the applied J-integral to the applied tearing modulus	(dimensionless)
ν	=	Poisson's ratio	(dimensionless)
σ_f	=	reference flow stress, specified as 85 ksi	(ksi)
σ_y	=	yield strength for the material	(ksi)

ARTICLE A-2000

ACCEPTANCE CRITERIA

The adequacy of the upper shelf toughness of the reactor vessel shall be determined by analysis. The reactor vessel is acceptable for continued service when the criteria of Paragraphs (a), (b), and (c) are satisfied.

(a) Level A and B Service Loadings

When evaluating the adequacy of the upper shelf toughness for the weld material for Level A and B Service loadings, postulate an interior semi-elliptical surface flaw with a depth one-quarter of the wall thickness and a length six times the depth, with the flaw's major axis oriented along the weld of concern and the flaw plane oriented in the radial direction. When evaluating the adequacy of the upper shelf toughness for the base material, postulate both interior axial and circumferential flaws with depths one-quarter of the wall thickness and lengths six times the depth and use the toughness properties for the corresponding orientation. Smaller flaw sizes may be used on an individual case basis when justified. Two criteria shall be satisfied:

(1) The applied J-integral evaluated at a pressure which is 1.15 times the accumulation pressure as defined in the plant-specific Overpressure Protection Report, with a factor of safety of 1.0 on thermal loading for the plant specified heatup and cooldown conditions, shall be shown to be less than the J-integral characteristic of the material resistance to ductile tearing at a flaw growth of 0.10 in.

(2) The flaw shall be shown to be stable, with the possibility of ductile flaw growth, at a pressure which is 1.25 times the accumulation pressure defined in Subparagraph (1), with a factor of safety of 1.0 on thermal loading for the plant specified heatup and cooldown conditions.

The J-integral resistance versus crack growth curve shall be a conservative representation for the vessel material under evaluation.

(b) **Level C Service Loadings**

When evaluating the adequacy of the upper shelf toughness for the weld material for Level C Service loadings, postulate interior semi-elliptical surface flaws with depths up to 1/10 of the base metal wall thickness, plus the cladding thickness, with total depths not to exceed 1.0 in., and a surface length six times the depth, with the flaw's major axis oriented along the weld of concern and the flaw plane oriented in the radial direction. When evaluating the adequacy of the upper shelf toughness for the base material, postulate both interior axial and circumferential flaws, and use the toughness properties for the corresponding orientation. Flaws of various depths, ranging up to the maximum postulated depth, shall be analyzed to determine the most limiting flaw depth. Smaller maximum flaw sizes may be used on an individual case basis when justified. Two criteria shall be satisfied:

(1) The applied J-integral shall be shown to be less than the J-integral characteristic of the material resistance to ductile tearing at a flaw growth of 0.10 in., using a factor of safety of 1.0 on loading.

(2) The flaws shall be shown to be stable, with the possibility of ductile flaw growth, using a factor of safety of 1.0 on loading.

The J-integral resistance versus crack growth curve shall be a conservative representation for the vessel material under evaluation.

(c) **Level D Service Loadings**

When evaluating the adequacy of the upper shelf toughness for Level D Service loadings, postulate flaws as specified for Level C Service loadings in Paragraph b), and use the toughness properties for the corresponding orientation. Flaws of various depths, ranging up to the maximum postulated depth, shall be analyzed to determine the most limiting flaw depth. Smaller maximum flaw sizes may be used on an individual case basis when justified. The flaws shall be shown to be stable, with the possibility of ductile flaw growth, using a factor of safety of 1.0 on loading. The J-integral resistance versus crack growth curve shall be a best estimate representation for the vessel material under evaluation.

The stable flaw depth shall not exceed 75% of the vessel wall thickness, and the remaining ligament shall be safe from tensile instability.

ARTICLE A-3000

ANALYSIS

A-3100 SCOPE

This Article contains a general description of procedures which shall be used to evaluate the applied fracture mechanics parameters, as well as requirements for selecting the J-R curve for the material. References are made to acceptabl.. approaches to apply the criteria.

A-3200 APPLIED J-INTEGRAL

The calculation of the J-integral due to the applied loads shall account for the full elastic-plastic behavior of the stress-strain curve for the material. When the conditions fall into the category of elastic fracture mechanics with small-scale yielding, the J-integral may alternately be calculated by using crack-tip stress intensity factor formulae with a plastic-zone correction. The method of calculation shall be validated and documented.

A-3300 SELECTION OF THE J-INTEGRAL RESISTANCE CURVE

When evaluating the vessel for Level A, B and C Service loadings, the J-integral resistance versus crack growth curve (J-R curve) shall be a conservative representation of the toughness of the controlling beltline material at upper shelf temperatures in the operating range. When evaluating the vessel for Level D Service loadings, the J-R curve shall be a best estimate representation of the toughness of the controlling beltline material at upper shelf temperatures in the operating range. One of the following options shall be used to determine the J-R curve.

(a) A J-R curve generated for the actual material under consideration by following accepted test procedures may be used. The J-R curve shall be based on the proper combination of crack orientation, temperature and fluence level. The crack growth shall include ductile tearing with no occurrence of cleavage.

(b) A J-R curve generated from a J-integral database obtained from the same class of material under consideration with the same orientation using appropriate correlations for the effects of temperature, chemical composition and fluence level may be used. The crack growth shall include ductile tearing with no occurrence of cleavage.

(c) When the approaches of (a) or (b) are not possible, indirect methods of estimating the J-R curve may be used provided these methods are justified for the material under consideration.

A-3400 FLAW STABILITY

The equilibrium equation for stable flaw growth is

$$J = J_R$$

where J is the J-integral due to the applied loads for the postulated flaw in the vessel, and J_R is the J-integral resistance to ductile tearing for the material.

The inequality for flaw stability due to ductile tearing is

$$\frac{\partial J}{\partial a} < \frac{dJ_R}{da}$$

where $\partial J/\partial a$ is the partial derivative of the applied J-integral with respect to the flaw depth a with load held constant, and dJ_R/da is the slope of the J-R curve. Under a condition of increasing load, stable flaw growth will continue as long as $\partial J/\partial a$ remains less than dJ_R/da.

A-3500 EVALUATION APPROACH FOR LEVEL A AND B SERVICE LOADINGS

The procedure given in A-4200 shall be used to evaluate the applied J-integral for a specified amount of ductile flaw growth.

There are three approaches that are equally acceptable for applying the flaw stability acceptance criteria according to the governing flaw stability rules in A-3400. The first is a J-R curve - crack driving force diagram approach. In this approach flaw stability is evaluated by a direct application of the flaw stability rules given in A-3400. Guidelines for using this approach are given in A-4310. The second is a failure assessment diagram approach. A procedure based on this approach for the postulated initial one-quarter wall thickness flaw is given in A-4320. The third is a J-integral/tearing modulus approach. A procedure based on this approach for the postulated initial one-quarter wall thickness flaw is given in A-4330.

ARTICLE A-4000

EVALUATION PROCEDURES FOR LEVEL A AND B SERVICE LOADINGS

A-4100 SCOPE

This Article contains calculation procedures to be used to satisfy the acceptance criteria in A-2000 for Level A and B Service loadings. A procedure to be used to satisfy the J-integral criterion for a specified amount of flaw growth of 0.10 in. is given in A-4200. Procedures to satisfy the flaw stability criterion are given in A-4300. These procedures include the axial and circumferential flaw orientations.

A-4200 EVALUATION PROCEDURE FOR THE APPLIED J-INTEGRAL

A-4210 CALCULATION OF THE APPLIED J-INTEGRAL

The calculation of the applied J-integral consists of two steps: Step 1 is to calculate the effective flaw depth which includes a plastic-zone correction; and Step 2 is to calculate the J-integral for small-scale yielding based on this effective flaw depth.

Step 1

For an axial flaw with a depth a, calculate the stress intensity factor due to internal pressure with a safety factor (SF) on pressure by using

$$K_{Ip} = (SF)\, p\, [1 + (R_i/t)]\, (\pi a)^{0.5}\, F_1 \qquad (1)$$

$$F_1 = 0.982 + 1.006(a/t)^2$$

This equation for K_{Ip} is valid for $0.20 \le a/t \le 0.50$, and includes the effect of pressure acting on the flaw faces.

For a circumferential flaw with a depth a, calculate the stress intensity factor due to internal pressure with a safety factor (SF) on pressure by using

$$K_{Ip} = (SF)\ p\ [1 + (R_i/(2t))]\ (\pi a)^{0.5}\ F_2 \qquad (2)$$

$$F_2 = 0.8\text{C}5 + 0.233(a/t) + 0.345(a/t)^2$$

This equation for K_{Ip} is valid for $0.20 \le a/t \le 0.50$, and includes the effect of pressure acting on the flaw faces.

For an axial or circumferential flaw with a depth a, calculate the stress intensity factor due to radial thermal gradients by using

$$K_{It} = ((CR)/1000)\ t^{2.5}\ F_3 \qquad (3)$$

$$F_3 = 0.584 + 2.647(a/t) - 6.294(a/t)^2 + 2.990(a/t)^3$$

This equation for K_{It} is valid for $0.20 \le a/t \le 0.50$, and $0 \le (CR) \le 100°$F/hour.

Calculate the effective flaw depth for small-scale yielding, a_e, by using

$$a_e = a + (1/(6\pi))[(K_{Ip} + K_{It})/\sigma_y]^2$$

Step 2

For an axial flaw, calculate the stress intensity factor due to internal pressure for small-scale yielding, K'_{Ip}, by substituting a_e in place of a in equation (1), including the equation for F_1. For a circumferential flaw, calculate K'_{Ip} by substituting a_e in place of a in equation (2), including the equation for F_2. For an axial or circumferential flaw, calculate the stress intensity factor due to radial thermal gradients for small-scale yielding, K'_{It}, by substituting a_e in place of a in equation (3), including the equation for F_3. Equations (1), (2) and (3) are valid for $0.20 \le a_e/t \le 0.50$.

The J-integral due to the applied loads for small-scale yielding is given by

$$J = 1000(K'_{Ip} + K'_{It})^2/E'$$

A-4220 EVALUATION USING CRITERION FOR FLAW GROWTH OF 0.1 IN.

Calculate the J-integral due to the applied loads, J_1, by following A-4210. Use a flaw depth *a* equal to 0.25*t* + 0.10 in.; a pressure *p* equal to the accumulation pressure for Level A and B Service loadings, p_a; and a safety factor *(SF)* on pressure equal to 1.15. The acceptance criterion for Level A and B Service loadings based on a ductile flaw growth of 0.10 in. in A-2000(a)(1) is satisfied when the following inequality is satisfied.

$$J_1 < J_{0.1}$$

where J_1 = the applied J-integral for a safety factor on pressure of 1.15, and a safety factor of 1.0 on thermal loading,

$J_{0.1}$ = the J-integral resistance at a ductile flaw growth of 0.10 in.

A-4300 EVALUATION PROCEDURES FOR FLAW STABILITY

A-4310 J-R CURVE - CRACK DRIVING FORCE DIAGRAM PROCEDURE

In this procedure flaw stability is evaluated by a direct application of the flaw stability rules given in A-3400. The applied J-integral is calculated for a series of flaw depths corresponding to increasing amounts of ductile flaw growth. The applied J-integral for Level A and B Service loadings shall be calculated by using the procedures given in A-4210. The applied pressure *p* is set equal to the accumulation pressure for Level A and B Service loadings, p_a; and the safety factor *(SF)* on pressure is equal to 1.25. The applied J-integral is plotted against crack depth on the crack driving force diagram to produce the applied J-integral curve, as illustrated in Figure A-4310-1. The J-R curve is also plotted on the crack driving force diagram, and intersects the horizontal axis at the initial flaw depth, a_0. Flaw stability at a given applied load is demonstrated when the slope of the applied J-integral curve is less than the slope of the J-R curve at the point on the J-R curve where the two curves intersect.

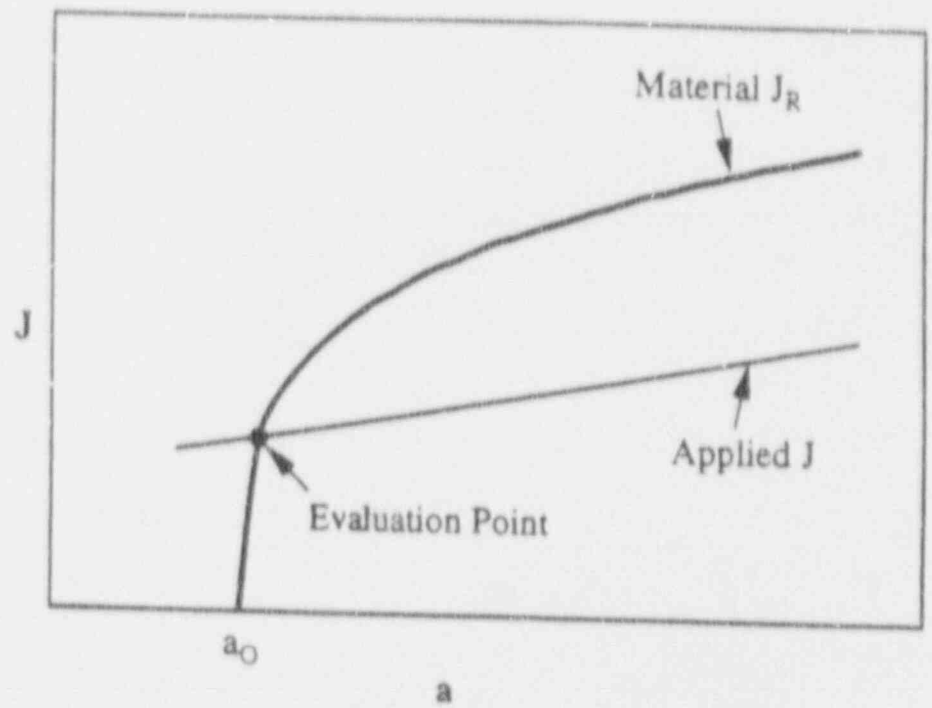

FIGURE A-4310-1 COMPARISON OF THE SLOPES OF THE APPLIED J-INTEGRAL CURVE AND THE J-R CURVE.

A-4320 FAILURE ASSESSMENT DIAGRAM PROCEDURE

This procedure is restricted to a postulated initial flaw depth equal to one-quarter of the wall thickness.

A-4321 FAILURE ASSESSMENT DIAGRAM CURVE

The same failure assessment diagram curve shall be used for axial and circumferential flaws, and is given in Figure A-4320-1. The coordinates (S_r, K_r) of the failure assessment diagram curve are given in Table A-4320-1. This curve is based on material properties which are characteristic of reactor pressure vessel steels.

A-4322 FAILURE ASSESSMENT POINT COORDINATES

The flaw depth a for a ductile flaw growth of Δa is given by

$$a = 0.25t + \Delta a$$

The failure assessment point coordinates (S_r', K_r') for a ductile flaw growth of Δa shall be calculated by using the following expressions:

$$K_r' = K_I \, [1000/(E'J_R)]^{0.5}$$

where the stress intensity factor shall be calculated using the flaw depth a without the plastic-zone correction, and is given by

$$K_I = K_{Ip} + K_{It}$$

and

$$S_r' = (SF) \, p/p_o$$

where (SF) is the required safety factor on pressure. The procedure for calculating K_{Ip}, K_{It} and p_o for axial flaws is given in A-4322.1, and for circumferential flaws in A-4322.2.

A-4322.1 Axial Flaws

The stress intensity factor due to internal pressure for axial flaws with a safety factor *(SF)* on pressure is given by equation (1). The stress intensity factor due to radial thermal gradients is given by equation (3).

The reference limit-load pressure is given by

$$p_o = \frac{(2/\sqrt{3})\,\sigma_y\,[0.905 - 0.379(\Delta a/t)]}{[0.379 + (R_i/t) + 0.379(\Delta a/t)]}$$

For materials with a yield strength σ_y greater than 85 ksi, set σ_y equal to 85 ksi in this equation. This equation for p_o is valid for $0 \le \Delta a/t \le 0.10$.

A-4322.2 Circumferential Flaws

The stress intensity factor due to internal pressure for circumferential flaws with a safety factor *(SF)* on pressure is given by equation (2). The stress intensity factor due to radial thermal gradients is given by equation (3).

The reference limit-load pressure is given by

$$p_o = \frac{\sigma_y\,[1 - 0.91(0.25 + (\Delta a/t))^2\,(t/R_i)]}{[1 + (R_i/(2t))]}$$

For materials with a yield strength σ_y greater than 85 ksi, set σ_y equal to 85 ksi in this equation. This equation for p_o is valid for $0 \le \Delta a/t \le 0.25$.

A-4323 EVALUATION USING CRITERION FOR FLAW STABILITY

Assessment points shall be calculated for each loading condition according to A-4322, and plotted on Figure A-4320-1 as follows. Plot a series of assessment points for various amounts of ductile flaw growth Δa up to the validity limit of the J-R curve. Use a pressure p equal to the accumulation pressure for Level A and B Service loadings, p_a; and a safety factor *(SF)* on pressure equal to 1.25. When one or more assessment points lie inside the failure assessment curve, the acceptance criterion based on flaw stability in A-2000(a)(2) is satisfied.

TABLE A-4320-1

COORDINATES OF THE FAILURE ASSESSMENT DIAGRAM CURVE OF FIGURE A-4320-1

S_r	K_r
0.000	1.000
0.050	1.000
0.100	0.999
0.150	0.998
0.200	0.996
0.250	0.993
0.300	0.990
0.350	0.987
0.400	0.981
0.450	0.973
0.500	0.960
0.550	0.939
0.600	0.908
0.650	0.864
0.700	0.807
0.750	0.737
0.800	0.660
0.850	0.581
0.900	0.505
0.950	0.435
1.000	0.374
1.050	0.321
1.100	0.276
1.150	0.238

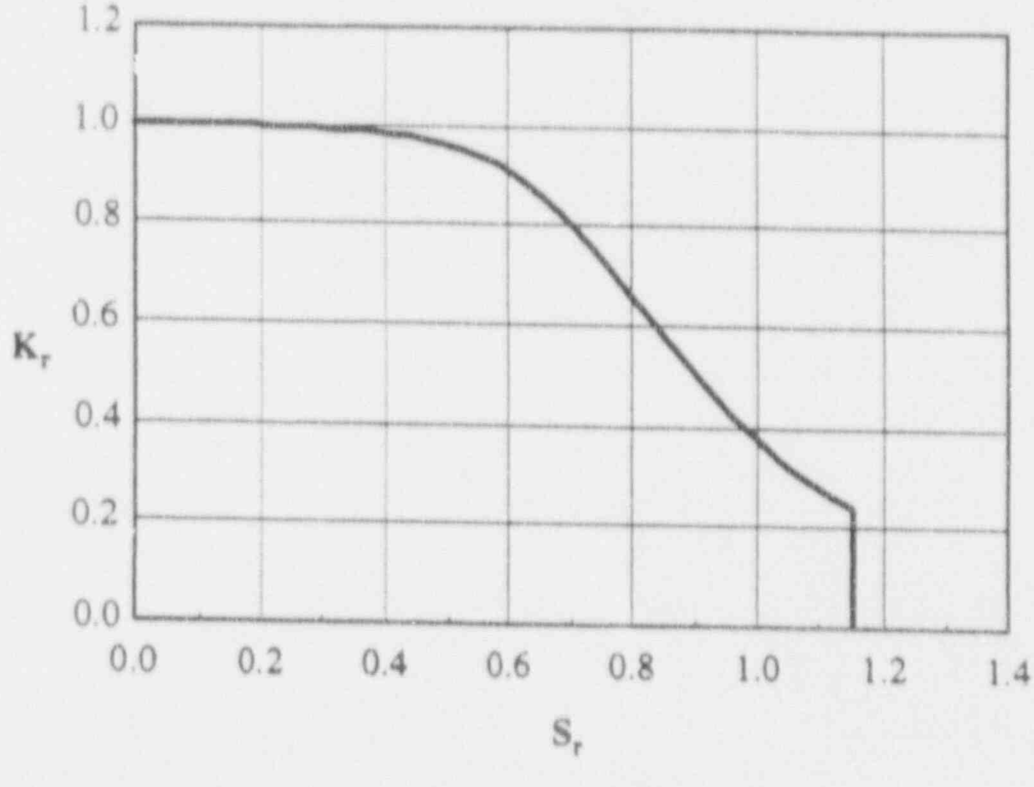

FIGURE A-4320-1 FAILURE ASSESSMENT DIAGRAM FOR THE ONE-QUARTER WALL THICKNESS FLAW.

A-4330 J-INTEGRAL/TEARING MODULUS PROCEDURE

This procedure is restricted to a postulated initial flaw depth equal to one-quarter of the wall thickness.

A-4331 J-INTEGRAL AT FLAW INSTABILITY

Referring to Figure A-4330-1, the onset of flaw instability is the point of intersection of the applied and material curves plotted on a graph of the J-integral versus tearing modulus (J versus T). The expression for the applied J/T curve is given by

$$J = (1000\ W\ t\ \sigma_f^2/E)\ T \quad (4)$$

where σ_f is a reference flow stress which is set to 85 ksi in equation (4). For axial flaws

$$W = 0.235[1 + (0.083 \times 10^{-3})(CR)t^2/((SF)p_a)] \quad (5)$$

where p_a is the pressure under evaluation. Equation (5) is valid for $6 \le t \le 12$ in., $2.25 \le ((SF)p_a) \le 5.00$ ksi, and $0 \le (CR) \le$ 100°F/hour.

For circumferential flaws

$$W = 0.21[1 + (0.257 \times 10^{-3})(CR)t^2/((SF)p_a)] \quad (6)$$

Equation (6) is valid for $6 \le t \le 12$ in., $2.25 \le ((SF)p_a) \le 9.00$ ksi, and $0 \le (CR) \le$ 100°F/hour. Equations (4), (5) and (6) are based on material properties which are characteristic of reactor pressure vessel steels.

The tearing modulus for the material is determined by differentiation of the J-R curve with respect to flaw depth a.

$$T_R = (E/(1000\ \sigma_f^2))\ dJ_R/da \quad (7)$$

The same values for E and σ_f shall be used in equations (4) and (7). The J-integral versus tearing modulus J_R/T_R curve for the material is given by plotting J_R against T_R for a series of increments in ductile flaw growth. Each coordinate for J_R is evaluated at the same amount of ductile flaw growth as the coordinate for T_R.

The value of the J-integral at the onset of flaw instability, J^*, corresponds to the intersection of the applied J/T curve given by equation (4) with the material J_R/T_R curve, as illustrated in Figure A-4330-1.

The J-integral at the onset of flaw instability may be determined analytically when a power-law curve fit to the J-R curve of the form

$$J_R = C_1(\Delta a)^{C_2}$$

is available. The J-integral at the onset of flaw instability, J^*, in this case is given by

$$J^* = C_1(W\,t\,C_2)^{C_2}$$

A-4332 INTERNAL PRESSURE AT FLAW INSTABILITY

The calculation of the internal pressure at the onset of flaw instability is based on the value of the J-integral at the onset of flaw instability, J^*. The ductile flaw growth at the onset of flaw instability, Δa^*, is taken from the J-R curve. The effective flaw depth at the onset of flaw instability includes the ductile flaw growth Δa^*, and is given by

$$a_e^* = 0.25t + \Delta a^* + (1/(6\pi))[J^*E'/(1000\ \sigma_y^2)]$$

The stress intensity factor due to radial thermal gradients at the onset of flaw instability, K_{It}^*, for axial or circumferential flaws is given by

$$K_{It}^* = ((CR)/1000)\ t^{2.5}\ F_3^*$$

$$F_3^* = 0.584 + 2.647(a_e^*/t) - 6.294(a_e^*/t)^2 + 2.990(a_e^*/t)^3$$

This equation for K_{It}^* is valid for $0.20 \le a_e^*/t \le 0.50$, and $0 \le (CR) \le 100$°F/hour. The stress intensity factor for small-scale yielding due to internal pressure at the onset of flaw instability, K_{Ip}^*, is given by

$$K_{Ip}^* = (J^*E'/1000)^{0.5} - K_{It}^*$$

For a given value of K'_{Ip}, the internal pressure at the onset of flaw instability for axial flaws is given by

$$p' = K'_{Ip} / [(1 + (R_i/t))(\pi a'_e)^{0.5} F'_1]$$

$$F'_1 = 0.982 + 1.006(a'_e/t)^2$$

and for circumferential flaws by

$$p' = K'_{Ip} / [(1 + (R_i/(2t)))(\pi a'_e)^{0.5} F'_2]$$

$$F'_2 = 0.885 + 0.233(a'_e/t) + 0.345(a'_e/t)^2$$

These equations for p' are valid for $0.20 \leq a'_e/t \leq 0.50$, and include the effect of pressure acting on the flaw faces.

A-4333 EVALUATION USING CRITERION FOR FLAW STABILITY

Calculate the value of the J-integral at the onset of flaw instability, J', by following A-4331 using a pressure p, in equations (5) and (6) equal to the accumulation pressure for Level A and B Service loadings, p_a; and a safety factor *(SF)* on pressure equal to 1.25. Calculate the internal pressure at the onset of flaw instability, p', by following A-4332. The acceptance criterion based on flaw stability in A-2000(a)(2) is satisfied when the following inequality is satisfied.

$$p' > 1.25\ p_a$$

ARTICLE A-5000

LEVEL C AND D SERVICE LOADINGS

The possible combinations of loadings and material properties which may be encountered during Level C and D Service loadings are too diverse to allow the application of pre-specified procedures and it is recommended that each situation be evaluated on an individual case basis.

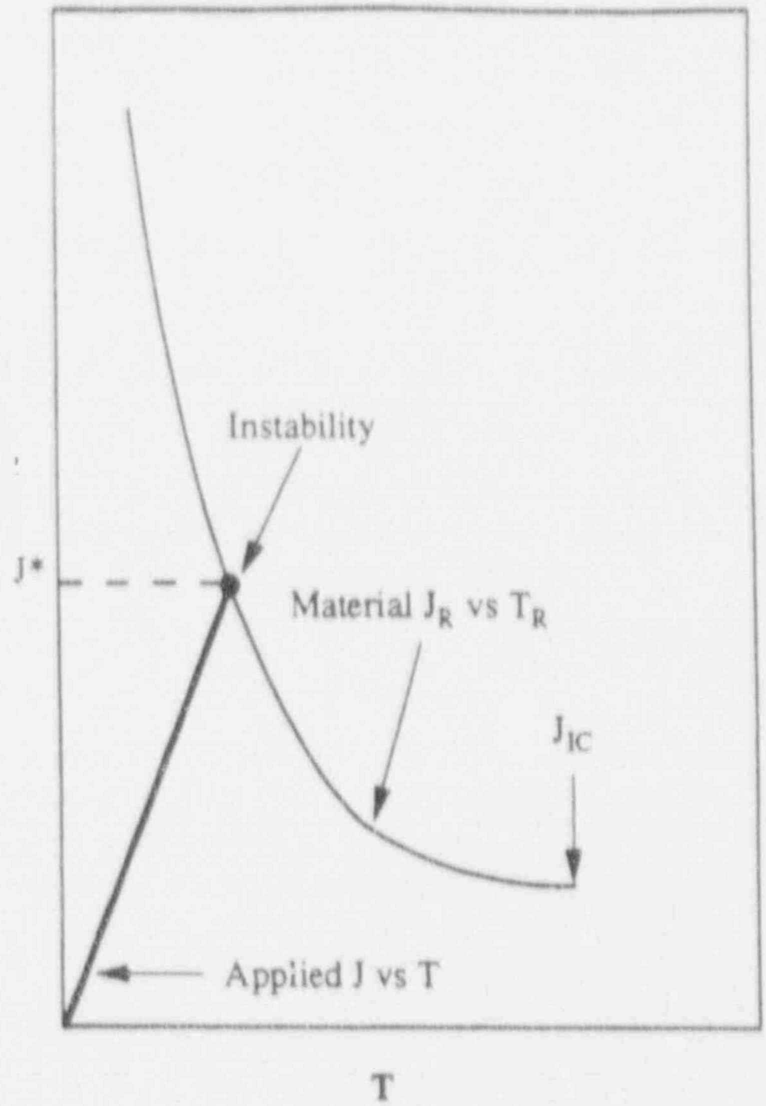

FIGURE A-4330-1 ILLUSTRATION OF THE J-INTEGRAL/TEARING MODULUS PROCEDURE

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