Attachment 3

WCAP-14984
Handbook on Flaw Evaluation, Surry Units 1 and 2
Steam Generators Upper Shell to Cone Weld Regions

(Non-Propriety)

Westinghouse Non-Proprietary Class 3

WCAP - 14984

Handbook on Flaw Evaluation Surry Units 1 and 2 Steam Generators Upper Shell to Cone Weld Regions

Westinghouse Energy Systems

WESTINGHOUSE NON-PROPRIETARY CLASS 3

WCAP-14984

Handbook on Flaw Evaluation Surry Units 1 and 2 Steam Generators Upper Shell to Cone Weld Regions

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TABLE OF CONTENTS

SECTION 1 INTRODUCTION

This flaw* evaluation handbook has been designed for the evaluation of indications which may be discovered during inservice inspection of the Surry Units 1 and 2 steam generators. This handbook was prepared as a result of the discovery of the indications in the upper shell to cone weld of the "B" steam generator of Surry Unit 2 in the spring of 1997. The indications in this weld were subsequently classified as embedded according to the Code rules, and were not associated with surface flaws. In 1985, indications in the surface of the upper shell to cone weld of the "B" steam generator of Surry Unit 2 were found. These surface flaws were removed by grinding.

The tables and charts provided herein allow the evaluation of any indication discovered in the upper shell to cone weld regions without further fracture mechanics calculations. The fracture analysis work is documented in this report. Use of the handbook will allow the acceptability (by analysis) of larger indications than would be allowable by only using the standards tables of the ASME Code Section XI. This report also provides the background and technical basis for the handbook charts.

The highlight of the handbook is the design of a series of flaw evaluation charts for both surface flaws and embedded flaws. Since the fracture mechanics characteristics of the two types of flaws are different, the evaluation charts are distinctively different in style. One section of this handbook deals with surface flaws, and another section concentrates on the evaluation of embedded flaws.

To use the flaw evaluation charts in this report, the user may turn directly to Section 6. This chapter contains simple instructions on the use of the handbook charts, along with examples. The only information needed to use the flaw evaluation charts is the results of the inspection itself, that is the flaw characterization.

The flaw evaluation charts were designed based on the Section XI code criteria of acceptance for continued service without repair. Through use of the charts, a flaw can be evaluated by code criteria instantaneously, and no follow-up hand calculation is required. Most important of all, no fracture mechanics knowledge is needed by the user of the handbook charts.

It is important to note that indications which are large enough that they exceed the standards limits, and must be evaluated by fracture mechanics, will also require additional inservice inspection in the future, as discussed in Section XI, paragraph IWC-2420[1]. Note that subsection IWC applies specifically to the upper shell to cone weld, but it is not yet complete, and the user is often referred to subsection IWB. This is presently the case for subsection IWC-3600, which refers the user to IWB-3600.

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*The use of the term "flaw" in this document should be taken to be synonymous with the term "indication" as used in Section XI of the ASME Code.

1.1 CODE ACCEPTANCE CRITERIA

There are two alternative sets of flaw acceptance criteria for continued service without repair in paragraph IWB-3600 of ASME Code Section XI [1]. Namely,

1. Acceptance Criteria Based on Flaw Size (IWB-3611)
2. Acceptance Criteria Based on Stress Intensity Factor (IWB-3612)

The choice of criteria is at the convenience of the user, per IWB-3610. Both criteria are comparable in accuracy for thick sections, and the acceptance criteria (2) have been assessed by past experience to be generally less restrictive for thin sections, and for outside surface flaws in many cases. In all cases, the most beneficial criteria have been used, generally criteria (2). Although the steam generator wall thickness in the region of concern is slightly less than 4 inches, both sets of criteria from IWB 3600 may be applied.

1.1.1 CRITERIA BASED ON FLAW SIZE

The code acceptance criteria stated in IWB-3611 of Section XI are:

$a_f < 1\, a_c$ For normal conditions (upset & test conditions inclusive)

and

$a_f < .5\, a_i$ For faulted conditions (emergency condition inclusive)

where

a_f = The maximum size to which the detected flaw is calculated to grow in a specified time period, which can be the next scheduled inspection of the component, or until the end of vessel design lifetime.

a_c = The minimum critical flaw size under normal operating conditions (upset and test conditions inclusive).

a_i = The minimum critical flaw size for initiation of nonarresting growth under postulated faulted conditions (emergency conditions inclusive).

To determine whether a flaw is acceptable for continued service without repair, both criteria must be met simultaneously. However, both criteria have been considered in advance before the charts were constructed. Only the most restrictive results were used in the charts.

1.1.2 CRITERIA BASED ON STRESS INTENSITY FACTOR

As mentioned in the preceding paragraphs, the criteria used for the construction of the charts in this handbook are from the least restrictive of IWB-3611 or IWB-3612 of Section XI. The criteria in IWB-3612 are based on safety margins between the applied stress intensity factor and the fracture toughness of the material.

The term stress intensity factor (K_I) is defined as the driving force on a crack. It is a function of the size of the crack and the applied stresses, as well as the overall geometry of the structure. In contrast, the fracture toughness (K_{Ia}, K_{Ic}) is a measure of the resistance of the material to propagation of a crack. It is a material property, and varies as a function of temperature.

The criteria are stated in IWB-3612:

$$K_I < \frac{K_{Ia}}{\sqrt{10}}$$ For normal conditions (upset & test conditions inclusive)

$$K_I < \frac{K_{Ic}}{\sqrt{2}}$$ For faulted conditions (emergency conditions inclusive)

where

K_I = The maximum applied stress intensity factor for the flaw size a_f to which a detected flaw will grow, for a specified time period, which must equal or exceed the time until the next inspection.

K_{Ia} = Fracture toughness based on crack arrest for the corresponding crack tip temperature.

K_{Ic} = Fracture toughness based on fracture initiation for the corresponding crack tip temperature.

To determine whether a flaw is acceptable for continued service without repair, both criteria for normal and faulted conditions must be met simultaneously. However, both criteria have been considered in advance before the charts were constructed. Only the most restrictive results (for either normal or faulted conditions) were used in the charts.

1.1.3 PRIMARY STRESS LIMITS

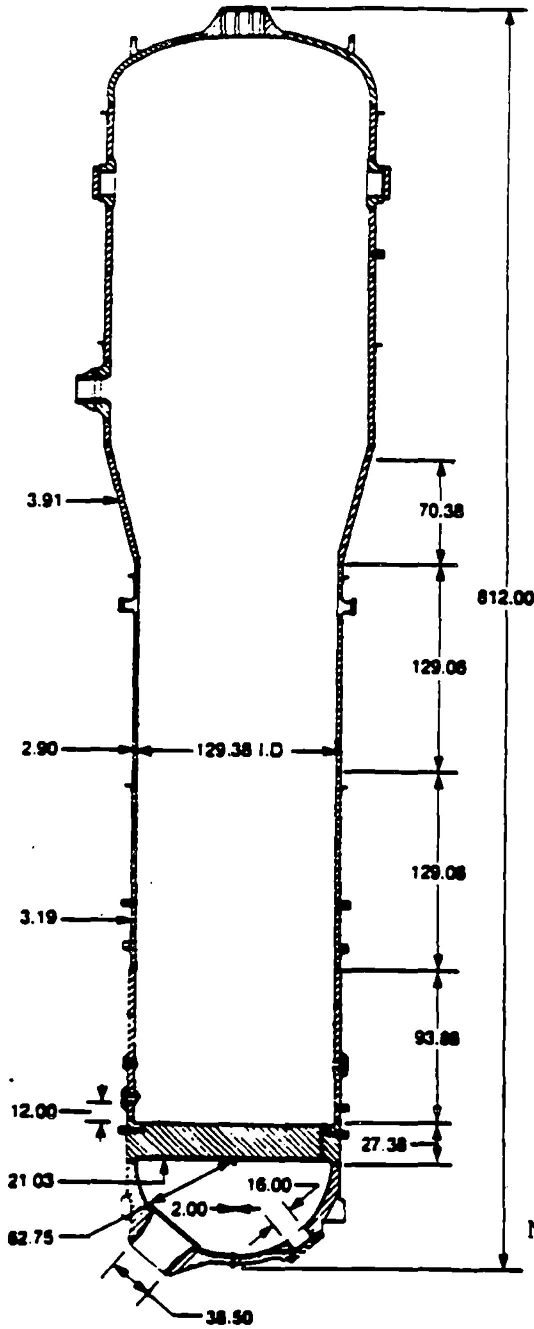
In addition to satisfying the fracture criteria, it is required that the primary stress limits of Section III, paragraph NB 3000 be satisfied. A local area reduction of the pressure retaining membrane must be used, equal to the area of the indication, and the stresses increased to reflect the smaller cross section. The allowable flaw depth is dependent on the design pressure, radius of the shell, and the design stress intensity. All the flaw acceptance tables provided in this handbook have included this consideration. The allowable flaw depths "a" determined using this criterion for inside surface flaws and embedded flaws are shown in Table 1-1 for both regions analyzed. The fracture mechanics criteria are more restrictive, and therefore governing.

1.2 GEOMETRY

The geometry of the Surry steam generators is shown in Figure 1-3. The dimensions shown are the minimum values from the design drawings. Detailed finite element analysis have been carried out on this repaired configuration are shown in Figure 1-1 and 1-2. For purposes of heat transfer, the outside surfaces have been assumed to be insulated. The notation used for both surface and embedded flaws in this work is illustrated in Figure 1-4.

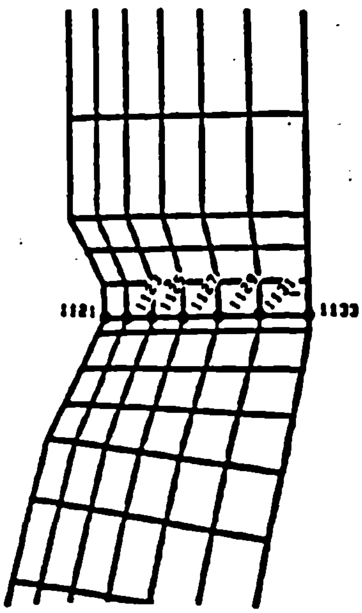
TABLE 1-1
ALLOWABLE FLAW DEPTHS BASED ON SECTION III, NB3000 REQUIREMENTS

Region	Allowable Depth (in)	
	Flaw Type	
	Inside Surface	Embedded
Upper Shell to Cone-Weld	1.45	1.45



Note: All dimensions in inches.

Figure 1-1 Geometry of Surry Units 1 and 2



NODE CO-ORDINATES - RADIAL

NODE	X CO-ORDINATE (IN.)
1121	84.750
1122	84.929
1123	85.108
1124	85.314
1125	85.520
1126	85.756
1127	85.992
1128	86.264
1129	86.535
1130	86.847
1131	87.159
1132	87.517
1133	87.875

Figure 1-2 Finite Element Model of Repaired Configuration of Surry Steam Generator

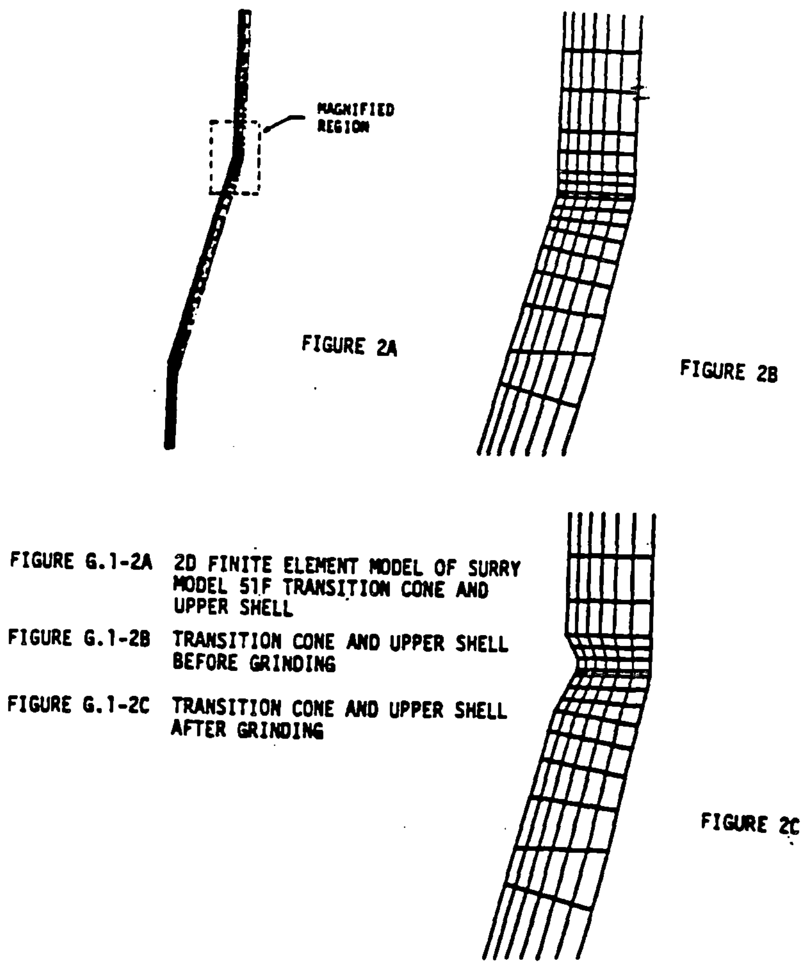


Figure 1-3 Detailed Finite Element Model of Repaired Configuration of Surry Steam Generator

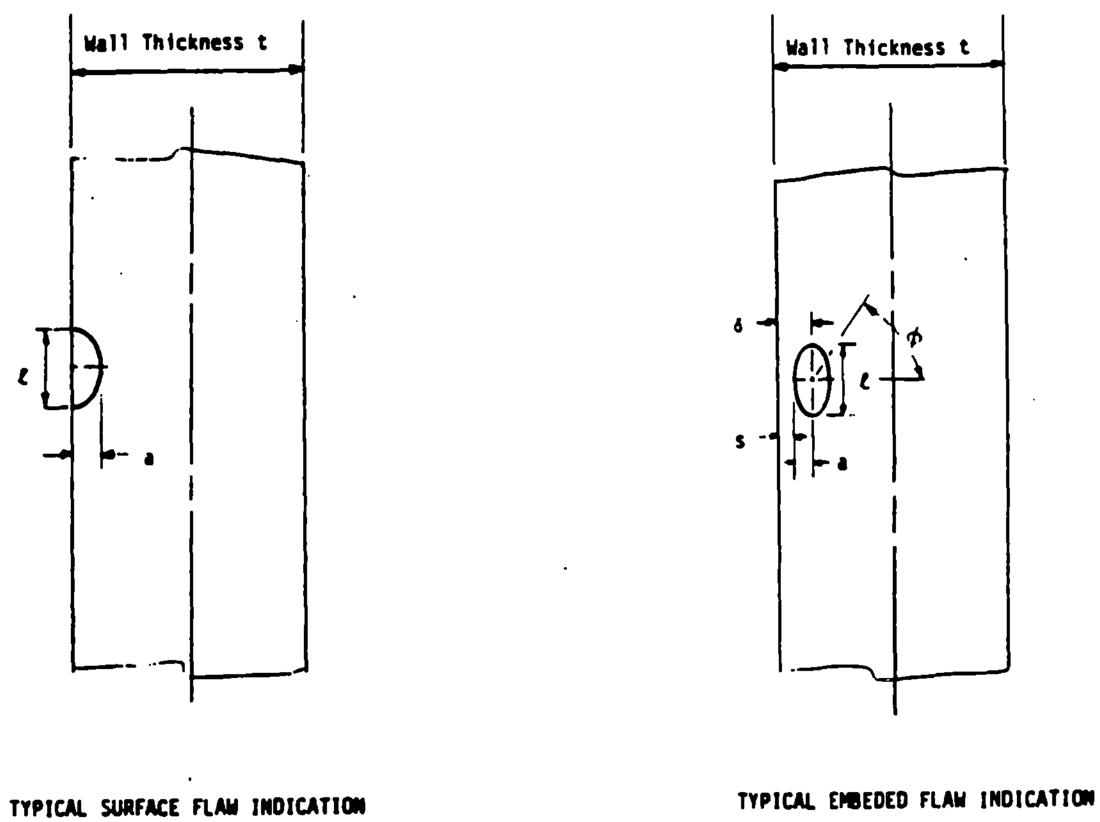


Figure 1-4 Typical Notation for Surface and Embedded Flaw Indications

SECTION 2 LOAD CONDITIONS, FRACTURE ANALYSIS METHODS AND MATERIAL PROPERTIES

2.1 TRANSIENTS FOR THE STEAM GENERATOR

Both the minimum critical flaw sizes, such as a_c under normal operating conditions, or a_i under faulted conditions for criteria (1) of IWB-3611, and the stress intensity factors, K_I, for criteria (2) of IWB-3612, are a function of the stresses at the cross-section where the flaw of interest is located, and the material properties. Therefore, the first step for the evaluation of a flaw indication is to determine the appropriate limiting load conditions for the location of interest.

For the regions of interest, the upper shell to cone welds, the full range of design transients was considered. The normal and upset design transients for the Surry Units 1 and 2 steam generators are listed in Table 2-1. Transients such as pressure tests, including both hydrostatic and leakage tests, can be controlled by setting the test temperature. Therefore, in determining the governing normal condition only the operational transients were considered, and a separate determination was made as to any required changes in the pressure test temperatures, to ensure that they would not be limiting. A discussion of this subject is provided in Section 6.2. On this basis, the governing normal condition is the Hot Standby for the upper shell to cone weld region. The governing emergency and faulted condition for both regions is the feedwater-line break combined with a safe shutdown earthquake (SSE). All the transients were considered in the calculation of fatigue crack growth, as discussed in Section 3.

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 for consideration of emergency and faulted conditions, 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 construction of the surface flaw charts (Section 4) four semielliptical flaw shapes were used, with length fifty, ten, six, three times the depth ($a/\ell = 0.167$) and semi circular ($a/\ell = 0.5$). As will be seen in Section 4, the charts cover the full range of shapes between these values.

The stress intensity factor calculations for a semi-elliptic surface flaws with a/ℓ=0.02, 0.1, 0.1667, 0.33, and a semi-circular surface flaw, ($a/\ell = 0.5$) were carried out using the expressions developed by [ ].^{a,c,e}. Their expression utilizes the same cubic representation of the stress profile.

The magnification factors for the loading conditions utilized for an inside surface flaw are given in tables in the paper (Reference 3). Magnification factors for various locations around the periphery of the crack (N) can be obtained by using an interpolation method. Stress intensity factors can be expressed by the general form:

$$K_I = \left(\frac{\pi a}{Q}\right)^{0.5} \sum_{j=0}^{3} G_j \, (a/c,\ a/t,\ t/R,\ \phi) \, A_j \, a^j$$

where

a/c: Ratio of crack dimensions

a/t: Ratio of crack depth to thickness of a cylinder

t/R: Ratio of thickness to inside radius

ϕ: Crack front location

G_j = G_1, G_2, G_3, G_4 are influence function coefficients (from reference 3)

$$Q^{1/2} = \int_o^{\pi/2} \left(\cos^2\phi + \frac{a^2}{c^2} \sin^2\phi\right)^{1/2} d\phi$$

The stress intensity factor expression used for a continuous surface flaw was that developed by [ ]^{a,c,e}. Again the stress profile is represented as a cubic polynomial, as shown above, and these coefficients as well as the magnification factors are combined in the expression for K_I below:

$$[\ K_I = [\pi a]^{0.5} \left[A_O F_1 + \frac{2a}{\pi} A_1 F_2 + \frac{a^2}{2} A_2 F_3 + \frac{4}{3\pi} a^3 A_3 F_4\right]\ ]^{a,c,e}$$

where F_1, F_2, F_3, F_4 are magnification factors, available in [ ]^{a,c,e}.

The embedded flaw charts were constructed for a wide range of flaw sizes and shapes. The stress intensity factor calculation for embedded flaws was taken from work by [ ]^{a,c,e} which is applicable to an embedded flaw in an infinite medium, subjected to an arbitrary stress profile. This expression has been shown to be applicable to embedded flaws in a pressure vessel in a paper by [ ]^{a,c,e}.

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:

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

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

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. An upper shelf value of 200 ksi$\sqrt{\text{in}}$ has been used here for K_{Ic} and K_{Ia}. This value is consistent with general practice in such evaluations, as shown for example in reference [7], which provides the background and technical basis of Appendix A of Section XI.

The fracture toughness of steam generator materials has been examined in recent years relative to the reference toughness curves of the ASME code. [

]a,c,e.

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 cone, upper and upper shell materials, a compilation was made of the properties listed on the original material test certificates. The materials used in this region of the steam generators of Units 1 and 2 were tested after a post-weld heat treatment cycle, as shown in Table 2-2. The Charpy impact properties of these materials are listed in Table 2-2. The U.S. Nuclear Regulatory Commission has established guidelines for estimating the value of RT_{NDT} from Charpy properties in their Standard Review Plan [12].

Review of Table 2-2 shows that in general the materials in the shell and cone region have excellent Charpy properties. [

]a,c,e.

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 SA533 grade A class 1, SA 302 grade B, and A533, class 1, which have been qualified as Code materials.

Unlike the welds in the reactor vessel, tests were not done on each weld seam in the steam generators. Instead, tests were typically accomplished as part of the wire electrode procurement process as normal and thereafter only on each weld wire/flux combination used, as part of the weld material qualification. A compilation of the weld qualification Charpy tests which are available reveals that the weld metal Charpy results were typically equal to or better than the results for the base metal, for a given vessel. The RT_{NDT} values for the weld metal for the Surry plants will be less than 10°F. Therefore it was concluded that the base metal Charpy values, and resulting RT_{NDT} values, would be governing for the development of the flaw evaluation charts.

2.4 CRITICAL FLAW SIZE DETERMINATION

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 normal, upset and test conditions, the critical flaw size a_c is determined as the depth at which the applied stress intensity factor K_I exceeds the arrest fracture toughness K_{Ia}.

For emergency and faulted conditions the minimum flaw size for crack initiation is obtained from the first intersection of the applied stress intensity factor (K_I) curve with the static fracture toughness (K_{IC}) curve.

TABLE 2-1
TRANSIENTS FOR FATIGUE CRACK GROWTH ANALYSIS

GROUP #	TRANSIENT	CYCLES FOR THIS TRANSIENT	TOTAL CYCLES IN GROUP
1	[		
2			
3			
4			
5			
6			
7			
8			
9			]a,c,e

*Occurrences indicates number for each transient group. For example the reactor trip group includes cycles for both turbine roll and loss of flow, since the reactor trip umbrellas the other two.

TABLE 2-2A
MATERIAL PROPERTIES FOR THE UPPER SHELL TO CONE REGIONS FOR SURRY UNIT 1

SG	Location	Heat	Material Type	Charpy Values (ft-lb)	Lateral Expansion (in)	RT_{NDT} (°F)
1	Upper Shell	[				
	Cone					
2	Upper Shell					
	Cone					
3	Upper Shell					
	Cone					
						]a,c,e

Note: N/R = Not reported

TABLE 2-2B
MATERIAL PROPERTIES FOR THE UPPER SHELL TO CONE REGIONS FOR SURRY UNIT 2

SG	Location	Heat	Material Type	Charpy Values (ft-lb)	Lateral Expansion (in)	RT_{NDT} (°F)
1	Upper Shell	[				
	Cone					
2	Upper Shell					
	Cone					
3	Upper Shell					
	Cone					
						]a,c,e

Note: N/R = Not Reported

SECTION 3 FATIGUE CRACK GROWTH

In applying code acceptance criteria as introduced in Section 1 of this report, the final flaw size a_f used in criteria (1) is defined as the flaw size to which the detected flaw is calculated to grow at the end of the specified service period. In this handbook, ten-, twenty-, and thirty-year service periods are assumed.

These crack growth calculations have been carried out for the upper shell to cone welds of the Surry Units 1 and 2 steam generators for which evaluation charts have been constructed. This section will examine the calculations, and provide the methodology used as well as the assumptions.

The crack growth calculations reported here are rather extensive, because a range of flaw shapes have been considered, to encompass the range of flaw shapes which could be encountered in service.

3.1 ANALYSIS METHODOLOGY

The fatigue crack growth analysis procedure involves postulating an initial flaw at a specific region and predicting the growth of that flaw due to an imposed series of loading transients. The input required for a fatigue crack growth analysis is basically the information necessary to calculate the parameter ΔK_I which depends on crack and structure geometry and the range of applied stresses in the area where the crack exists. Once ΔK_I is calculated, the growth due to that particular stress cycle can be calculated by equations given in Section 3.3 and Figure 3-1. This increment of growth is then added to the original crack size, and the analysis proceeds to the next transient. The procedure is continued in this manner until all the transients known to occur in the period of evaluation have been analyzed.

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

Crack growth calculations were carried out for a range of flaw depths, and three basic types. The first type was a surface flaw with three aspect ratios ($a/\ell = 0.1667, 0.333$ and 0.5). The second was a continuous surface flaw ($a/\ell = 0.0$), which represents a worst case for surface flaws, and the third was an embedded flaw, with length equal to five times its width. For all cases the flaw was assumed to maintain a constant shape as it grew. Calculations for other flaw shapes were unnecessary because the selected types conservatively model the crack growth of the other flaws of interest for construction of the charts.

3.2 STRESS INTENSITY FACTOR EXPRESSIONS

Stress intensity factors were calculated from methods available in the literature for each of the flaw types analyzed. The surface flaws with various aspect ratios were analyzed using an expression developed by [ ]^{a,c,e} where the stress intensity factor K_I is calculated from the actual stress profile through the wall at the location of interest.

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

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

The stress intensity factor $K_I(\phi)$ can be calculated anywhere along the crack front. The point of maximum crack depth is represented by $\phi = 0$. Crack growth calculations were carried out for angular locations of $\phi = 0$ and $\phi = 80°$, for each flaw shape. The maximum growth location was used in the development of the charts.

The stress intensity factor for a continuous surface flaw as calculated using the expression of [ ]^{a,c,e}

For embedded flaws, the stress intensity factor expression of [ ]^{a,c,e} was used, as discussed earlier in Section 2.2. The flaw shape was set with length equal to five times the width ($a/\ell = 0.10$), and the eccentricity was varied. This flaw shape was chosen to provide a worst case calculation of stress intensity factor for embedded flaws. Analyses of embedded flaws with a/ℓ values less than 0.10 have revealed that the maximum stress intensity factor is largely unchanged (less than one percent). The calculated crack growth was very small for this case, so no other shapes were considered necessary to analyze.

3.3 CRACK GROWTH RATE REFERENCE CURVES

The crack growth rate curves used in the analyses (see Figure 3-1) were taken directly from Figure A4300-1 of Appendix A of Section XI of the ASME Code. Water environment curves from the figure were used for all inside surface flaws, and the air environment curve was used for embedded flaws. The curves are directly applicable to reactor vessel steels.

[

]^{a,c,e}

[

]^{a,c,e}

For water environments the reference crack growth curves are shown in Fig. 3-1, and growth rate is a function of both the applied stress intensity factor range, and the R ratio (K_{min}/K_{max}) for the transient. Equations for the curves shown in Figure 3-1 are given below.

For R<0.25

$$(\Delta K_I < 19 \text{ ksi}\sqrt{\text{inch}}) \quad \frac{da}{dN} = (1.02 \times 10^{-6})\, \Delta K_I^{5.95}$$

$$(\Delta K_I > 19 \text{ ksi}\sqrt{\text{inch}}) \quad \frac{da}{dN} = (1.01 \times 10^{-1})\, \Delta K_I^{1.95}$$

where

$\frac{da}{dN}$ = Crack Growth rate, micro-inches/cycle.

ΔK_I = Stress intensity factor range, ksi $\sqrt{\text{in}}$

For R>0.65

$$(\Delta K_I < 12 \text{ ksi}\sqrt{\text{inch}}) \quad \frac{da}{dN} = (1.20 \times 10^{-5})\, \Delta K_I^{5.95}$$

$$(\Delta K_I > 12 \text{ ksi}\sqrt{\text{inch}}) \quad \frac{da}{dN} = (2.52 \times 10^{-1})\, \Delta K_I^{1.95}$$

For R ratio between these two extremes, interpolation is recommended.

The crack growth rate reference curve for air environments is a single curve, with growth rate being only a function of applied)K. This reference curve is also shown in Figure 3-1.

$$\frac{da}{dN} = (0.0267 \times 10^{-3})\, \Delta K_I^{3.726}$$

where

$$\frac{da}{dN} = \text{Crack growth rate, micro-inches/cycle}$$

$$\Delta K_I = \text{stress intensity factor range, ksi}\sqrt{\text{in}}$$

$$= (K_{Imax} - K_{Imin})$$

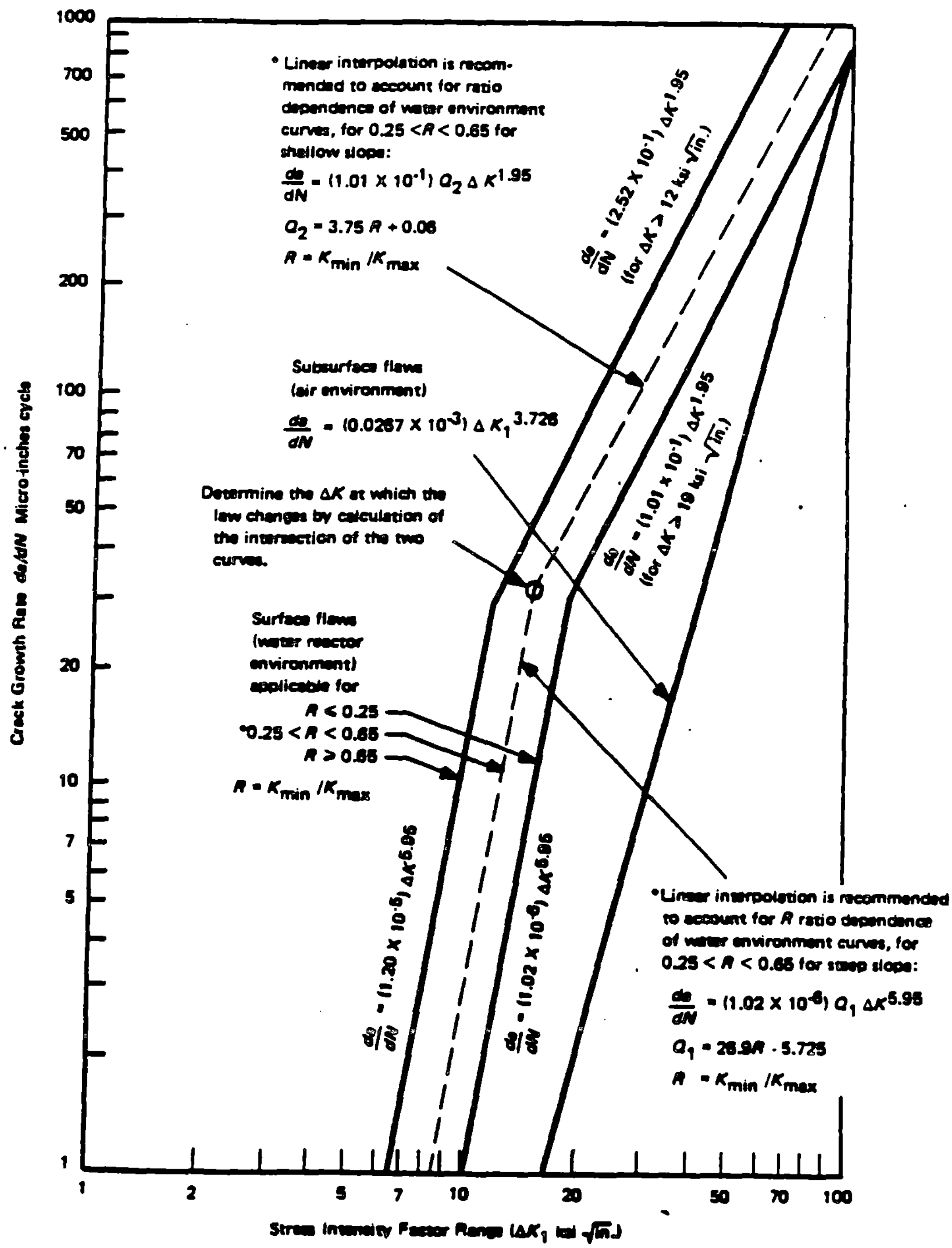


Figure 3-1 Reference Fatigue Crack Growth Curves for Carbon and Low Alloy Ferritic Steels

SECTION 4 SURFACE FLAW EVALUATION

4.1 SCOPE OF EVALUATION

This section provides the detailed calculations used to develop surface flaw charts for the upper shell to cone region. Some regions contain grid-outs resulting from the removal of the surface flaws found in earlier inspections. Therefore two sets of flaw evaluation charts were prepared, one for the surface flaws in the vicinity of the grindouts and one for the areas remote from the grindouts. The criteria for being remote from grindouts is a distance greater than or equal to $\sqrt{Rt}$ or about 18 inches.

4.2 CODE CRITERIA

The acceptance criteria for flaws have been already presented in Section 1. For convenience they are repeated as follows:

$a_f < .1\, a_c$ For normal conditions (upset & test conditions inclusive)

and

$a_f < 0.5\, a_i$ For faulted conditions (emergency condition inclusive)

where

a_f = The maximum size to which the detected flaw is calculated to grow for a specified period, which can be the next scheduled inspection of the component or until the end of vessel design lifetime.

a_c = The minimum critical flaw size under normal operating conditions (upset and test conditions inclusive)

a_i = The minimum critical flaw size for initiation of nonarresting growth under postulated faulted conditions (emergency conditions inclusive).

Alternatively, criteria based on applied stress intensity factors may be used:

$K_I < \dfrac{K_{Ia}}{\sqrt{10}}$ For normal conditions (upset & test conditions inclusive)

$K_I < \dfrac{K_{Ic}}{\sqrt{2}}$ For faulted conditions (emergency conditions inclusive) where

K_I = The maximum applied stress intensity factor for the flaw size a_f to which a detected flaw will grow, for a specified period, which must be at least until the next inspection.

K_{Ia} = Fracture toughness based on crack arrest for the corresponding crack tip temperature.

K_{Ic} = Fracture toughness based on fracture initiation for the corresponding crack tip temperature.

The larger flaw size determined by these two criteria is used to develop the flaw charts.

4.3 BASIC DATA

In view of the criteria, it is noticed that three groups of basic data are required for the construction of charts for surface flaw evaluation. Namely, a_f, driving force (K_I), and fracture toughness (K_{Ia} and K_{Ic}).

The preparation of these three groups of basic data will be discussed in the following paragraphs. They are the key elements of the allowable flaw size and fatigue crack growth calculations upon which the evaluation charts are based. A schematic diagram of the evaluation procedure is shown in Figure 4-1. K_{Ic} and K_{Ia} are the initiation and arrest fracture toughnesses (respectively) of the vessel material at which the flaw is located. They can be calculated by formulas:

$$K_{Ic} = 33.2 + 2.806 \exp. [0.02(T - RT_{NDT} + 100{}^\circ F)] \quad (1)$$

and

$$K_{Ia} = 26.8 + 1.233 \exp. [0.0145(T - RT_{NDT} + 160{}^\circ F)] \quad (2)$$

Notice that both K_{Ia} and K_{Ic} are a function of crack tip temperature T, and the material property RT_{NDT} at the tip of the flaw as discussed earlier, in Section 2.3. The upper shelf fracture toughness of the vessel steel is assumed to be 200 ksi$\sqrt{in}$, as discussed in Section 2.

The driving force, K_I, used in the determination of the flaw evaluation charts is the maximum stress intensity factor of the surface flaw under evaluation. The methods used for determining the stress intensity factors for surface flaws have been discussed in Section 2. It is important to note that the flaw size used for the calculation of K_I is not the flaw size detected by inservice inspection. Instead, it is the calculated flaw size which is projected to grow from the flaw size detected by inservice inspection. That means that the surface flaw size used for the calculation of K_I had to be determined by using fatigue crack growth results. This is equivalent to working backward in the chart of Figure 4-1 to determine the largest allowable flaw size.

As defined in IWB-3611 of Section XI, a_f is the maximum size resulting from growth during a specific time period, which can be the next scheduled inspection of the component, or until the end of vessel design lifetime. Therefore, the final depth, a_f after a specific service period of time must be used as the basis for evaluation. The charts have been constructed to allow the initial (measured) indication size to be used directly. Charts have been constructed for operational periods of 10, 20, and 30 years from the time of detection.

The final flaw size a_f has been calculated by fatigue crack growth analysis, which has been performed covering the range of postulated flaw sizes, and flaw shapes and locations within the wall needed for the construction of surface flaw evaluation charts in this handbook.

4.4 TYPICAL SURFACE FLAW EVALUATION CHART

The two basic dimensionless parameters, which can fully address the characteristics of a surface flaw are used for the evaluation chart construction. Namely,

- o Flaw Shape Parameter a/ℓ
- o Flaw Depth Parameter a/t

where,

t	-	wall thickness, in.
a	-	flaw depth, in.
ℓ	-	flaw length, in.

Now, consider the chart for the governing transient. Section 2.1 indicated that the most limiting normal or upset condition expected to occur during the remaining plant life is the reactor trip transient. In addition, the governing emergency and faulted condition is the feedwater line break. Figure 4-2 shows the flaw evaluation chart for surface flaws, and it is constructed as follows:

[

]a,c,e

[

]a,c,e Winter Addendum resulting in the middle curve. Beginning with the 1986 edition of the ASME Code, acceptance standards for this region are provided in Table IWC 3510-1 and these have also been plotted, and are slightly more liberal.

[

]a,c,e

The inside surface flaw evaluation chart constructed for the upper shell to cone weld (intact) region of the Surry Units 1 and 2 steam generators is presented in Figure 4-2, and repeated in Section 6, where instructions are given for its use.

4.5 PROCEDURE FOR THE CONSTRUCTION OF A SURFACE FLAW EVALUATION CHART

This section describes how the inside surface flaw evaluation charts were constructed for the upper shell to cone weld (intact) region. The development of the upper shell to cone weld region charts follows the same procedure.

Step 1

[

]a,c,e

[

]a,c,e

Step 2

[

]^{a,c,e}

Step 3

[

]^{a,c,e}

Step 4

[

]^{a,c,e}

Step 5

[

]^{a,c,e}

Step 6

[

]^{a,c,e}

Step 7

Plot a/ℓ vs. a/t data from the standards tables of Section XI as the lower curve of Figure 4-2.

The values of the acceptance standards for this region from the various editions of the ASME Code are:

Aspect Ratio, a/ℓ	IWB-3511-1 (1980) a/t, %	IWB-3510-1 (1983, W83 Add.) a/t, %	IWC-3510-1 (1986) a/t, %
0.00	2.0	1.9	1.9
0.05	2.1	2.0	2.0
0.10	2.3	2.2	2.2
0.15	2.6	2.5	2.5
0.20	2.9	2.8	2.8
0.25	3.2	3.3	3.3
0.30	3.7	3.8	3.8
0.35	3.7	4.4	4.4
0.40	3.7	5.0	5.0
0.45	3.7	5.1	5.1
0.50	3.7	5.2	5.2

The above six steps would complete the procedure for the construction of the surface flaw evaluation charts for 10 years, 20 years, or 30 years of operating life.

Table 4-1
Upper Limits of Acceptance by Analysis
(Allowable Flaw Depth Results for 10 Years of Service)

LOCATION	FLAW SHAPE		
	$a/\ell = 0$	$a/\ell = 0.167$	$a/\ell = 0.5$
Upper Shell-Core Junction	a/t(%) = 10.7	a/t(%) =38.3	a/t(%) = 99.3

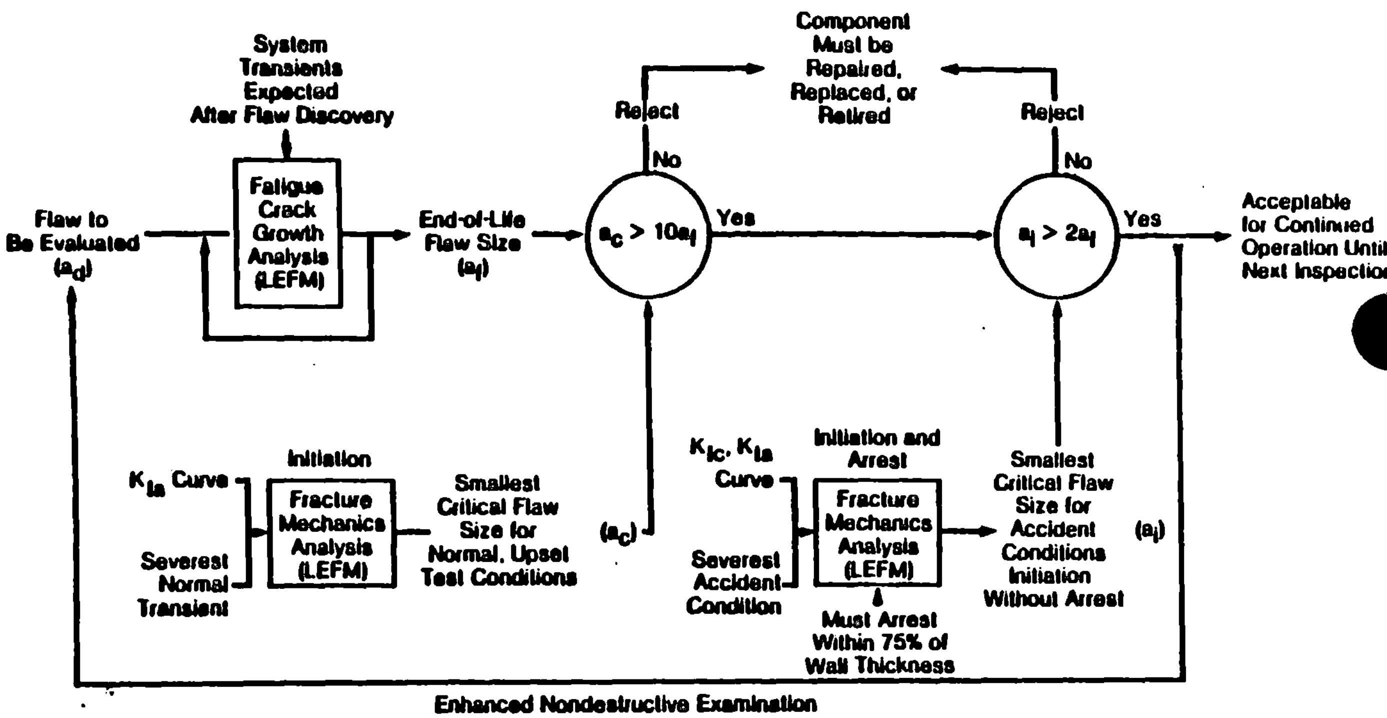
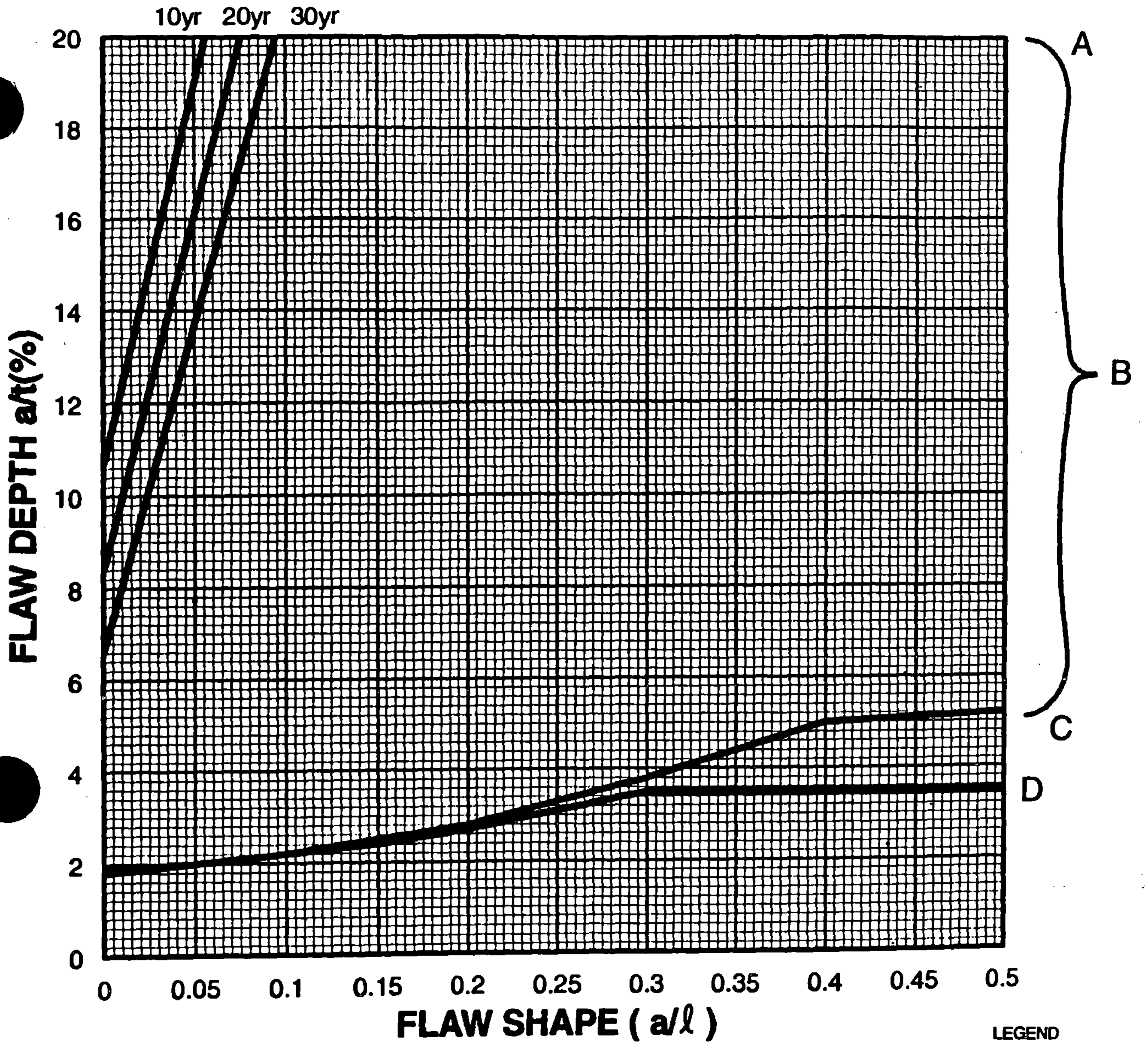


Figure 4-1 Schematic Representation of Appendix A Flaw Evaluation Process



LEGEND

A - The 10, 20, 30 year acceptable flaw limits.

B - Within this zone, the surface flaw is acceptable by ASME Code analytical criteria in IWB-3600

C - ASME Code IWC-3510.1 allowable since 1983 Winter Addendum

D - ASME Code allowable prior to 1983 Winter Addendum

Figure 4-2 Flow Evaluation Chart for Circumferential Inside Surface Flaw in the Upper Shell to Cone, Intact Weld Region

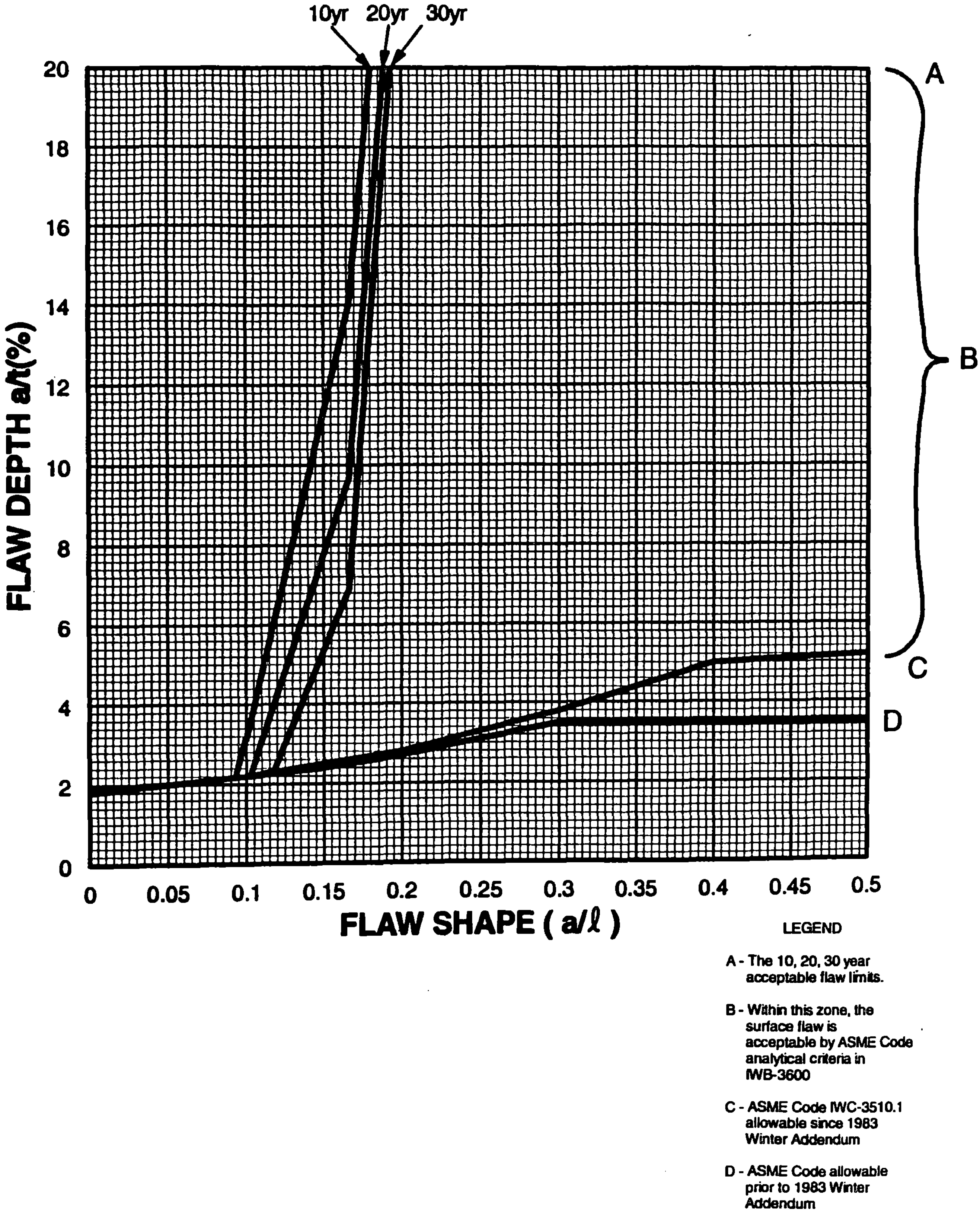


Figure 4-3 **Flaw Evaluation Chart for Circumferential Inside Surface Flaws in the Upper Shell to Cone Ground C Weld**

SECTION 5 EMBEDDED FLAW EVALUATION

5.1 SCOPE OF EVALUATION

Embedded flaw evaluations were performed for the upper shell to cone weld region. This section describes the development of the embedded flaw charts for that region. As mentioned earlier, some regions contain grindouts resulting from the removal of flaws. The charts in the section have been developed to cover both the ground and unground regions with a single set of charts.

5.2 EMBEDDED VS. SURFACE FLAWS

According to IWA-3300 of the ASME Code Section XI, a flaw is defined as embedded, as shown in Figure 5-1, whenever,

$$S > 0.4\,a \tag{5-1}$$

where

S - the minimum distance from the flaw edge to the nearest vessel wall surface

a - the embedded flaw depth, (defined as the semi-minor axis of the elliptical flaw.)

The parameter δ has been defined in this document to facilitate the use of the charts. δ is defined as the distance from the centerline of the flaw to the surface of the vessel. Therefore, $\delta = S + a$. Substituting into the proximity limit in equation 5-1 gives a limiting definition of δ as a function of a, for the proximity limit.

$$a = \delta - S \tag{5-2}$$

$$\delta > 1.4\,a \tag{5-3}$$

Therefore, the limit for a flaw to be considered embedded is $a_o = 0.714\delta$.

A flaw lying within the embedded flaw domain is to be evaluated by the embedded flaw evaluation charts generated in this section of the handbook. On the other hand, a flaw lying beyond this domain should be evaluated as a surface flaw using the charts developed in Section 4 of the handbook instead. The demarcation lines between the two domains are shown graphically in Figure 5-2.

In other words, for any flaw indication detected by inservice inspection, the first step of evaluation is to define to which category the flaw actually belongs, and then to choose the appropriate charts for evaluation.

5.3 CODE CRITERIA

As mentioned in Section 1, the criteria used in most of the cases for embedded flaws are of IWB-3612 of Code Section XI. Namely,

$$K_I < \frac{K_{Ia}}{\sqrt{10}} \quad \text{For normal conditions (upset \& test conditions inclusive)} \qquad (5\text{-}4)$$

$$K_I < \frac{K_{Ic}}{\sqrt{2}} \quad \text{For faulted conditions (emergency conditions inclusive)} \qquad (5\text{-}5)$$

where

K_I = The maximum applied stress intensity factor for the flaw size a_f to which a detected flaw will grow, during the period of evaluation, which must be at least until the next inspection.

K_{Ia} = Fracture toughness based on crack arrest for the corresponding crack tip temperature.

K_{Ic} = Fracture toughness based on fracture initiation for the corresponding crack tip temperature.

The above two criteria must both be met. In this handbook only the most limiting results have been used as the basis of the flaw evaluation charts.

5.4 BASIC DATA

In view of the criteria based on stress intensity factor, three basic groups of data are needed for construction of embedded flaw evaluation charts. They are: a_f, driving force (K_I), and fracture toughness (K_{Ia} and K_{Ic}).

K_{Ic} and K_{Ia} are the initiation and arrest fracture toughness (respectively) of the vessel material at which the flaw is located. They can be calculated by formulas:

$$K_{Ic} = 33.2 + 2.806 \text{ exp. } [0.02(T - RT_{NDT} + 100^{\circ}F)] \qquad (5\text{-}6)$$

and

$$K_{Ia} = 26.8 + 1.233 \text{ exp. } [0.0145(T - RT_{NDT} + 160^{\circ}F)] \qquad (5\text{-}7)$$

K_I is the maximum stress intensity factor for the embedded flaw of interest. The methods used for determining the stress intensity factors for embedded flaws have been referenced in Section 2.

Notice that both K_{Ic} and K_{Ia} are functions of crack tip temperature T, and the material property of RT_{NDT} at the tip of the flaw as discussed in Section 2. The upper shelf fracture toughness of the vessel steel is assumed to be 200 ksi $\sqrt{}$ in.

K_I used in the determination of the flaw evaluation charts is the maximum stress intensity factor of the embedded flaw under evaluation. It is important to note that the flaw size used for the calculation of K_I is not the flaw size detected by inservice inspection. Instead, it is the calculated flaw size which is projected to grow from the flaw size detected by inservice inspection. That means that the embedded flaw size used for the calculation of KI had to be determined by using fatigue crack growth results, similar to the approach used for surface flaw evaluation, as illustrated in the previous section.

5.5 TYPICAL EMBEDDED FLAW EVALUATION CHART

The details of the procedures for the construction of an embedded flaw evaluation chart are provided in the next section.

In this section, instructions for developing a chart are provided by going through a typical chart, step by step. This would help the users to become familiar with the characteristics of each part of the chart, and make it easier to apply. This example utilizes the surface/embedded flaw demarcation criteria of the code, as discussed earlier.

[

][a,c,e]

[

]a,c,e

[ ]a,c,e

This embedded flaw evaluation chart, constructed for the upper shell to cone weld region of the steam generators, is presented in Figure 5-2 and its construction is discussed below. The charts are repeated along with instructions in Section 6.

5.6 PROCEDURE FOR THE CONSTRUCTION OF EMBEDDED FLAW EVALUATION CHARTS

This section shows how an embedded flaw evaluation chart was constructed for the upper shell to cone weld region during the governing transient which is equivalent to the hot standby condition.

Step 1

[

]a,c,e

Step 2

[ ]a,c,e

Step 3

[

] a,c,e

5.7 COMPARISON OF EMBEDDED FLAW CHARTS WITH ACCEPTANCE STANDARDS OF IWB-3500

[

] a,c,e

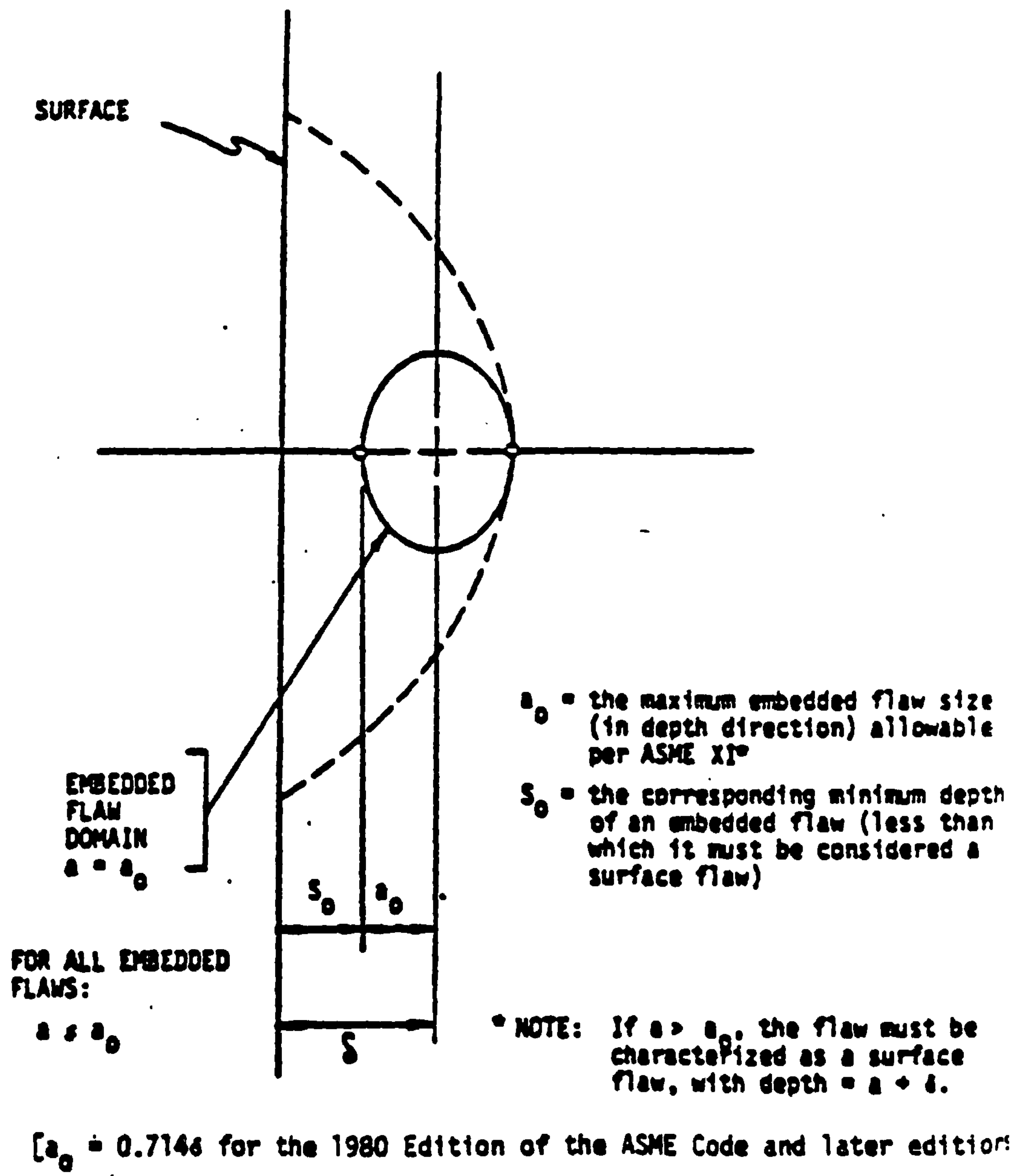


Figure 5-1 Embedded vs. Surface Flaw

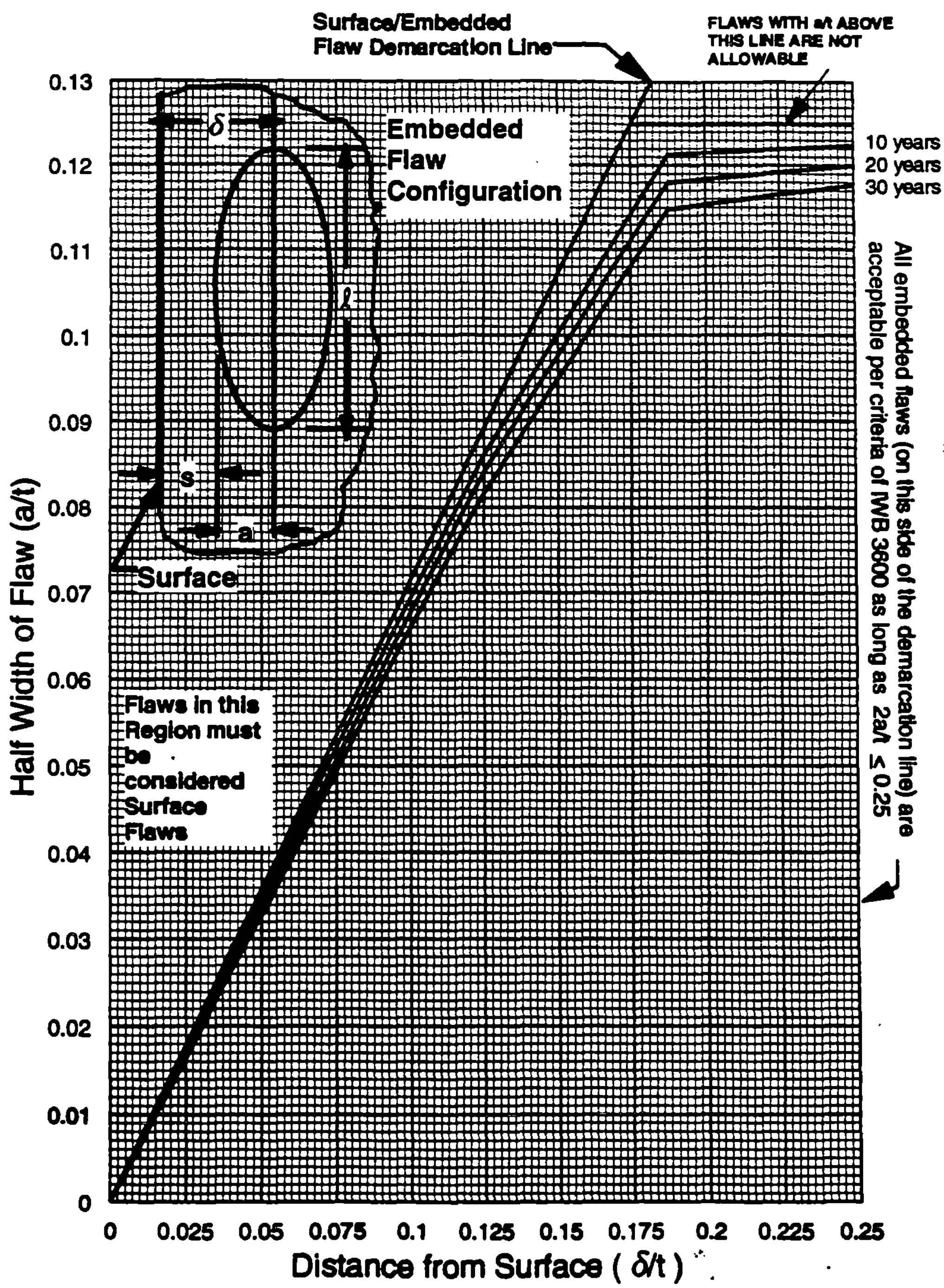


Figure 5-2 Embedded Flaw Chart for Circumferential Indications in the Upper Shell to Cone

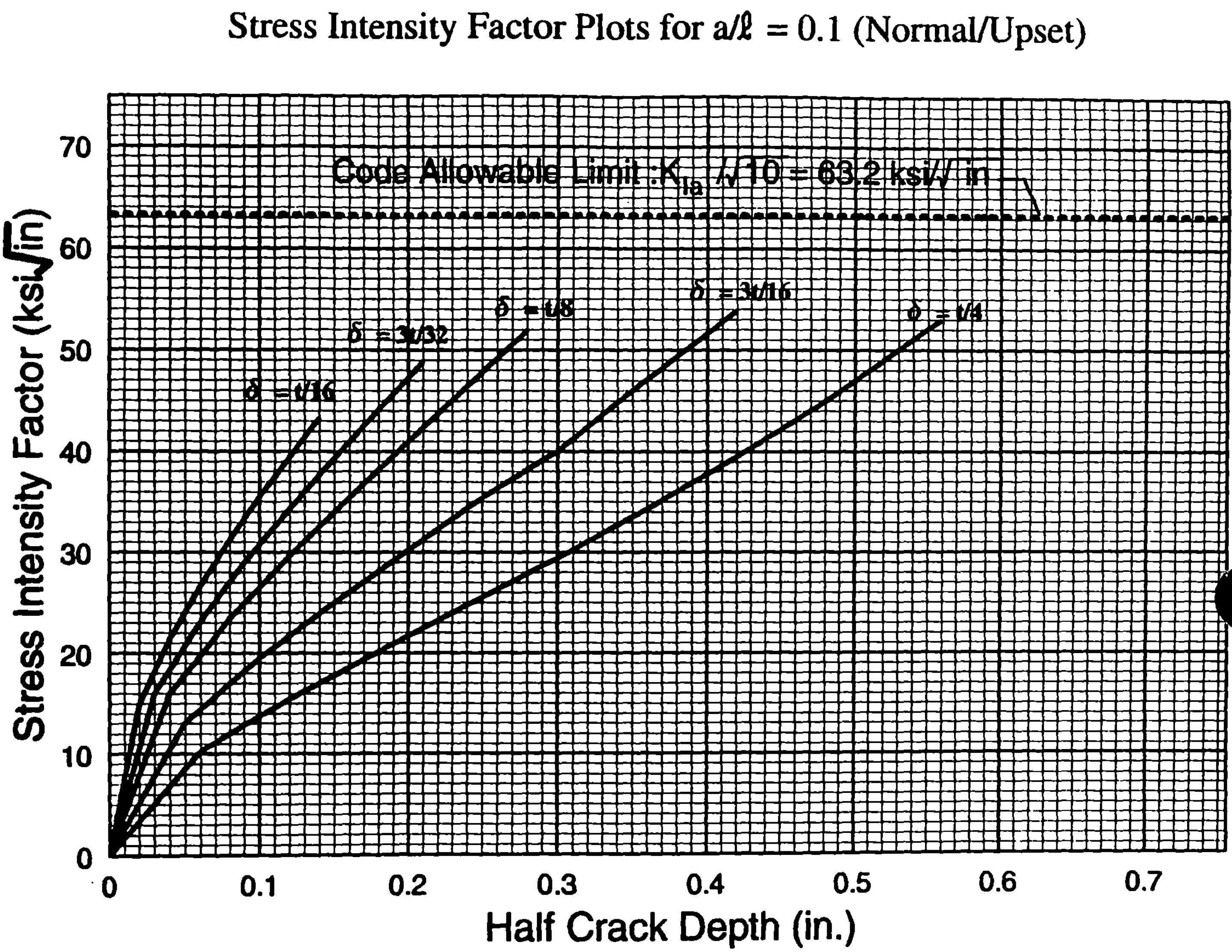


Figure 5-3 **Surry S/G Shell to Cone Weld Longitudinal Embedded Flaw**

SECTION 6 FLAW EVALUATION CHARTS-UPPER SHELL TO CONE WELD

6.1 EVALUATION PROCEDURE

The evaluation procedures contained in ASME Section XI are clearly specified in paragraph IWB-3600. Use of the evaluation charts herein follows these procedures directly, but the steps are greatly simplified.

Once the indication is discovered, it must be characterized as to its location, length (R) and depth dimension (a for surface flaws, 2a for embedded flaws), including its distance from the inside surface (S) for embedded indications. This characterization is discussed in further detail in paragraph IWA-3000 of Section XI.

The following parameters must be calculated from the above dimensions to use the charts (see Figure 1-4):

- o Flaw Shape parameter, a/ℓ
- o Flaw depth parameter, a/t
- o Surface proximity parameter (for embedded flaws only), δ/t

where

t = wall thickness of region where indication is located

ℓ = length of indication

a = depth of surface flaw; or half depth of embedded flaw in the width direction

δ = distance from flaw centerline to surface (for embedded flaws only) ($\delta = s + a$)

s = smallest distance from edge of embedded flaw to surface

Once the above parameters have been determined and the determination made as to whether the indication is embedded or surface, then the two parameters may be plotted directly on the appropriate evaluation chart. The location of the indication on the chart determines its acceptability immediately.

Important Observations on the Handbook Charts

Although the use of the handbook charts is conceptually straight forward, experience in their development and use has led to a number of observations which will be helpful.

It should be noted that the flaw evaluation charts provided herein cover circumferentially oriented flaws only. This approach is based on over twenty-five years of service experience, during which time a good number of indications have been discovered in these weld regions. Virtually all these indications, both surface and embedded have been oriented circumferentially. The stresses acting on circumferential indications are higher than those acting on a longitudinal flaw, so in the remote possibility that a longitudinal indication is discovered, the charts provided here will be conservative.

Surface Flaws

The handbook chart for inside surface flaws is shown in Figure 6-1. For outside surface flaws the chart is shown in Figure 6-2. The flaw indication parameters (whose calculation is described above) may be plotted directly on the chart to determine acceptability. The lower curves shown (labeled "code allowable limit") are simply the acceptance standards from IWB-3500 (or IWC-3500, for the newer code edition), which is tabulated in Section XI (and also listed in Section 4). If the plotted point falls below the appropriate line, the indication is acceptable without analytical justification having been required. If the plotted point falls between the code allowable limit line and the lines labeled "upper limits of acceptance by analysis" it is acceptable by virtue of its meeting the requirements of IWC 3600, which allow acceptance by fracture analysis. (Flaws between these lines would, however, require future monitoring per IWC-2420 of Section XI.) The analysis used to develop these lines is documented in this report. There are three of these lines shown in the charts, labeled 10, 20, and 30 years. The years indicate for how long the acceptance limit applies from the date that a flaw indication is discovered, based on fatigue crack growth calculations.

As may be seen for example in Figure 6-1, the chart gives results for surface flaw shapes up to a semi-circular flaw ($a/\ell = 0.5$). For the unlikely occurrence of flaws which the value of a/ℓ exceeds 0.5, the limits on acceptance for $a/\ell = 0.5$ should be used as required by article IWA-3300 of Section XI. The upper limits of acceptance have been set at (a maximum of) twenty percent of the wall thickness in all cases, as discussed in Section 4.

Embedded Flaws

[

]a,c,e

Surface Flaw Example

Suppose an indication has been discovered which is an inside surface flaw and has the following characterized dimensions:

$a = 0.122"$

$\ell = 1.22"$

$t = 3.80"$

The flaw parameters for the use of the charts are

$a/t = 0.032$ (3.2%)

$a/\ell = 0.10$

Plotting these parameters on Figure 6-1 it is quickly seen that the indication is acceptable by analysis. To support operation without repair it is necessary to submit this plot along with this document to the regulatory authorities.

Embedded Flaw Example

Assume that a circumferential embedded flaw of 0.58 x 2.75", located within 0.18" from the surface, was detected. Determine whether this flaw should be considered as an embedded flaw, and whether it is acceptable.

$2a = 0.58"$

$S = 0.18"$

$\delta = S + a = 0.18 + 1/2\ (0.58) = 0.47"$

G = maximum groove depth in SG B
= 1/4 in.

t' = total original thickness = 3.8 in

$t = t' - G = 3.55"$

$\ell = 1.22"$

and,

$a = 1/2 \times 0.58"$
$= 0.29"$

Using Figure 6-3:

$a/t' = 0.29/3.80 = 0.076$

$\delta/t' = 0.47/3.80 = 0.124$

Since the plotted point (X) is below the diagonal demarcation line, the flaw must be considered embedded. Since it is below the flaw acceptance limit lines for 10, 20, and 30 years, the indication is acceptable.

6.2 MODIFICATION OF HYDROSTATIC AND LEAKAGE TEST TEMPERATURES

If an indication is discovered in the Surry Units 1 and 2 steam generators which is justified for further service without repair by the flaw evaluation charts of this report, an increase in the minimum temperature at which the hydrotest and leak tests must be conducted may be necessary [

]^{a,c,e}

6.2.1 EMBEDDED FLAW HYDROSTATIC AND LEAKAGE TEST TEMPERATURE REQUIREMENTS

The charts herein provide a simple method for determining the required minimum temperature for any subsequent hydrostatic or leakage tests. [

]^{a,c,e}

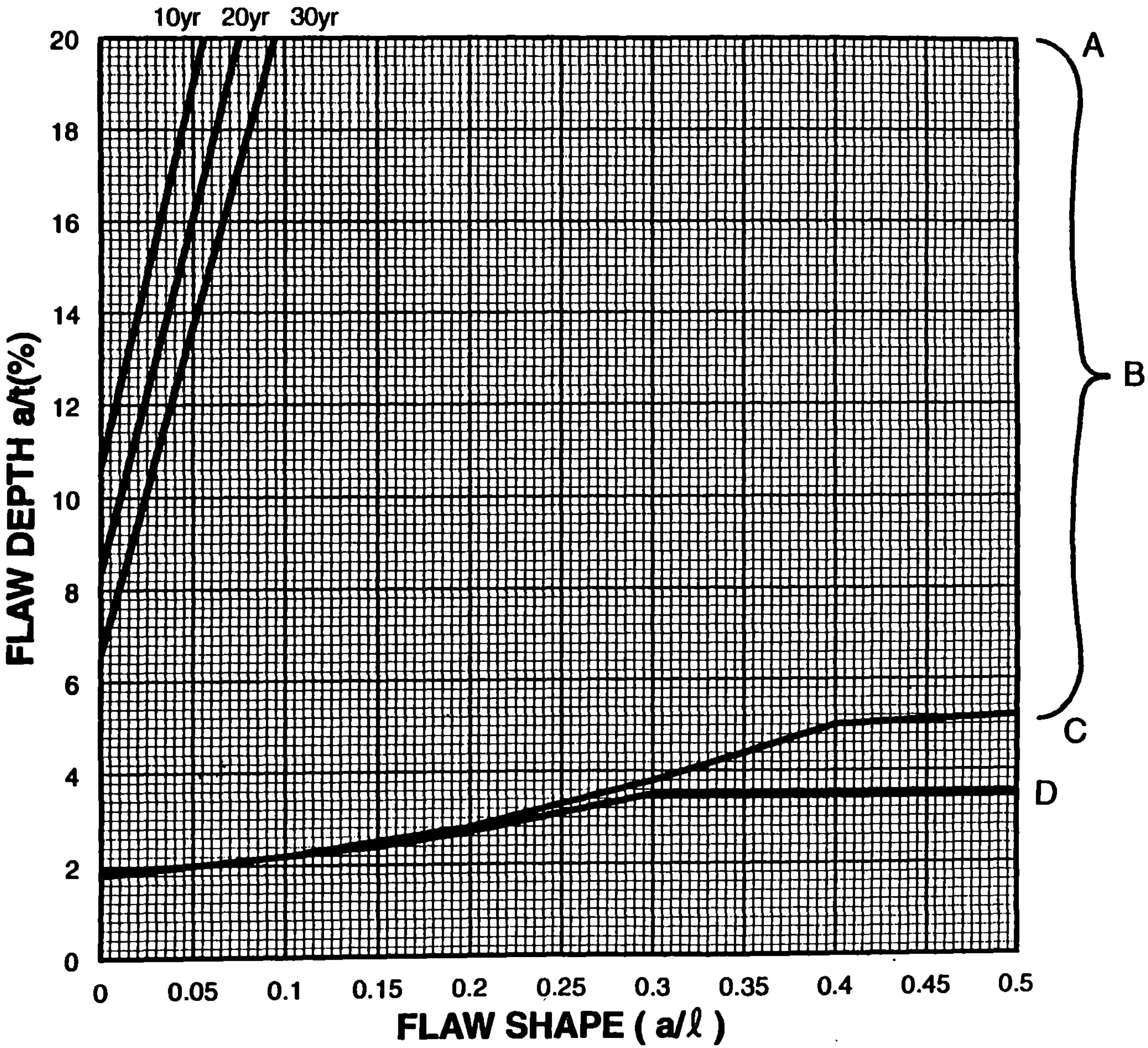
This determination has been made using the same methodology described earlier in Section 5. As discussed in Section 2 of this report, the value of $RT_{NDT} = 10^{\circ}F$ is applicable to both the steam generators. Figure 6-5 therefore covers the steam generator vessels for the hydrostatic test temperature, and Figures 6-6 and 6-7 cover test temperatures for a range of leakage test pressures for both units. These figures cover the entire range of embedded flaw sizes and shapes.

6.2.2 SURFACE FLAW HYDROSTATIC AND LEAK TEST TEMPERATURE

Figures 6-8 through 6-10 provide charts for the determination of hydrostatic and leakage test temperature requirements in the event that surface flaws are detected and shown to be acceptable by the surface flaw evaluation charts of Section 6.

These figures provide test temperatures for a range of pressures, and it can be seen from these charts that in some cases the test temperature must be increased above the presently specified value, for flaws in a small range of sizes. The figures show that slightly more restrictive value, for flaws in a small range of sizes. The figures show that slightly more restrictive temperatures are required as the test pressure increases.

Figure 6-1 Flaw Evaluation Chart for Circumferential Inside Surface Flaw in the Upper Shell to Cone Intact Weld Region



LEGEND

A - The 10, 20, 30 year acceptable flaw limits.

B - Within this zone, the surface flaw is acceptable by ASME Code analytical criteria in IWB-3600

C - ASME Code IWC-3510.1 allowable since 1983 Winter Addendum

D - ASME Code allowable prior to 1983 Winter Addendum

a,c,e

Figure 6-2 Flaw Evaluation Chart for Circumferential Inside Surface Flaw in the Upper Shell to Cone Ground Out Weld Region

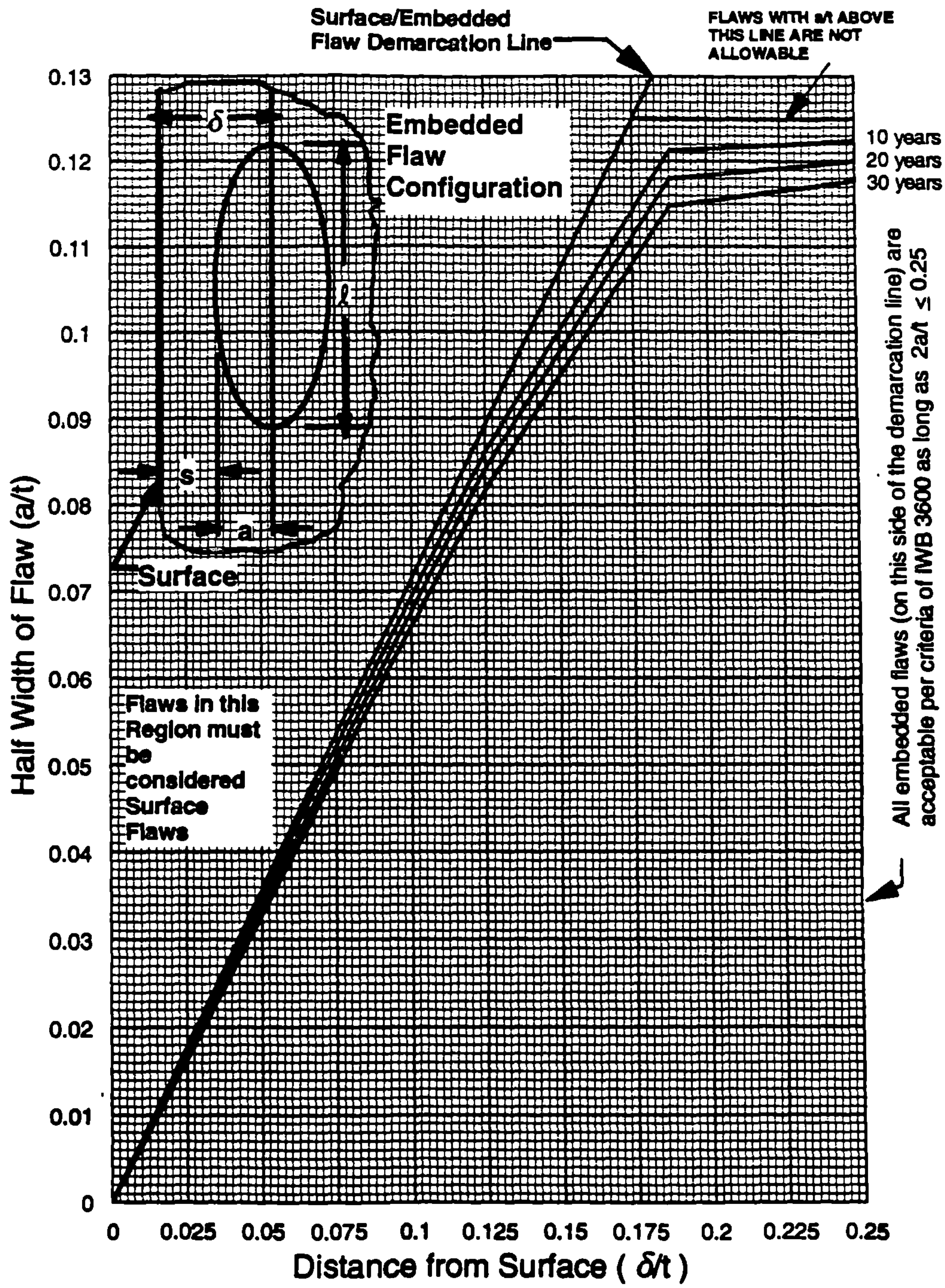


Figure 6-3 Embedded Flaw Evaluation Chart for Circumferential Indications in the Upper Shell to Cone Region, Surry Units 1 and 2

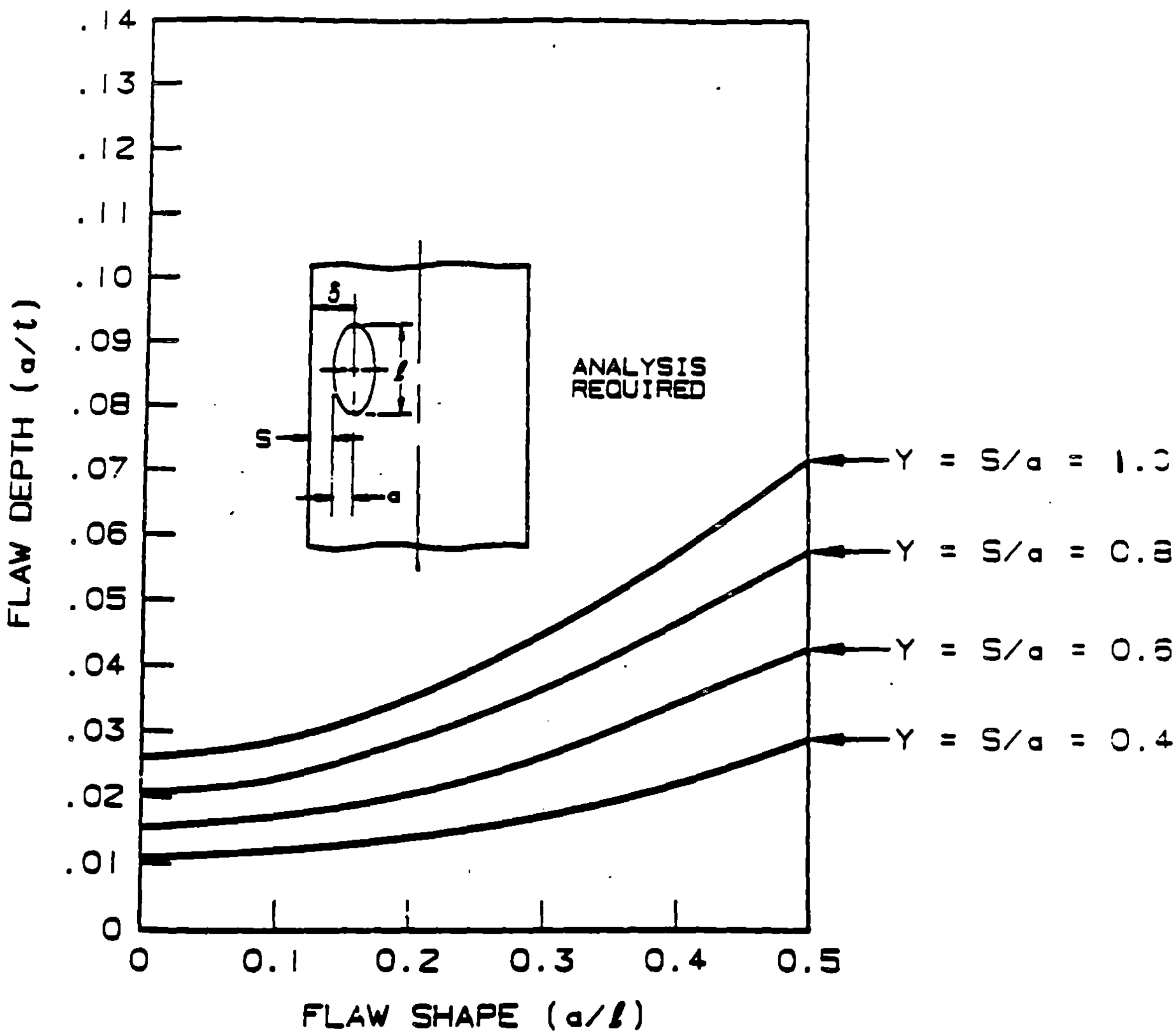


Figure 6-4 Acceptance Standards for Embedded Flaws, from Table IWB-3511-1
***Only Y = 1.0 curve applies to ASME Codes prior to 1980 Edition.**

a,c,e

Figure 6-5 Determination of Hydrostatic Test Temperatures (p = 1355 psi) for Circumferential Embedded Flaws with $a/\ell \leq 0.10$

a,c,e

Figure 6-6 Determination of Leakage Test Temperatures (p = 1185 psi) for Circumferential Embedded Flaws with $a/\ell \leq 0.10$

a,c,e

Figure 6-7 Determination of Hydrostatic Test Temperatures for Circumferential Surface Flaws (p = 1356 psi), Intact Weld Region

a,c,e

Figure 6-8 Determination of Leakage Test Temperature for Circumferential Surface Flaws (p = 1185 psi), Intact Weld Region

a,c,e

Figure 6-9 Determination of Hydrostatic Test Temperatures for Circumferential Surface Flaws (p = 1356 psi), Ground-out Weld Region

a,c,e

Figure 6-10 Determination of Leakage Test Temperatures for Circumferential Surface Flaws (p = 1185 psi), Ground-out Region

SECTION 7 REFERENCES

1. ASME Code Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components", 1980 Edition; 1983 and 1986 editions (used for updated standards tables, Section 4.5), and 1980 edition [Winter 1981 Addendum] (for revised reference crack growth curves).

2. [ ][a,c,e]

3. [ ][a,c,e]

4. [ ][a,c,e]

5. [ ][a,c,e]

6. [ ][a,c,e]

7. [ ][a,c,e]

8. [ ][a,c,e]

9. [ ][a,c,e]

10. [ ][a,c,e]

11. [ ][a,c,e]

12. U. S. N. R. C. Standard Review Plan, (Rev. 1), Section 5.3.2, Report NUREG 0800, July 1981.

13. [

]a,c,e

14. WCAP-10916, "Surry Unit 2 Steam Generators Girth Weld Report No. 6 Repair Report", August 1985.

APPENDIX A

Section XI Evaluation
Surry Unit 1 Steam Generator
<u>Upper Shell to Cone Indications</u>

A fracture evaluation has been performed on the indications discovered during the recent in-service inspection. This evaluation has been based on the criteria for acceptance of an indication by fracture mechanics analysis, as contained in Section XI of the ASME Code, paragraph IWB 3600.

The results of this evaluation are presented in the form of a flaw evaluation chart, as shown on the attached figures and discussed in Section 6. This chart has been developed to allow expeditious evaluation of indications found during in-service inspection. The chart shows the largest flaws which may be shown acceptable according to the criteria of Section XI. The chart has been constructed for a circumferentially oriented embedded flaw in the upper shell to cone weld region. The chart for embedded flaws has been developed specifically for application to Surry Units 1 and 2, and its development has been discussed in Section 6. The governing transient for this region of the steam generator is the Loss of Power. The lowest fluid temperature in the region of the upper shell to cone junction during this transient is 234F. The metal temperature therefore exceeds 234F at this time.

This information, combined with the value of RTNDT = 10F, leads to the conclusion that the fracture toughness for the material is on the upper shelf. This conclusion results from use of the reference toughness curves of the ASME Code, as found in Section XI, Appendix A, in Figure A 4200-1. The upper shelf fracture toughness has been assumed to be 200 ksi sq-rt in., consistent with industry practice.

The fatigue crack growth analyses were carried out following the approach suggested in Section XI of the ASME Code, and using the reference crack growth curves provided in Figure 3-1. All the design transient cycles were considered, and the results for 10, 20, and 30 years have been reported in the flaw evaluation charts.

Embedded Flaws

The flaw acceptance chart for embedded flaws is shown in Figure 1. To use this figure, three parameters are required:

a/t : Flaw depth/wall thickness (%)

a/l : Flaw depth/flaw length

δ/t : Flaw surface proximity/wall thickness

where δ = S + a

S = Distance from the flaw to the nearest surface

Two characterizations of the indications are presently available, using 20% DAC and 50% DAC respectively. We have listed the characterizations of the three indications below. Using the terminology l = length and a = depth, with t = thickness, we have:

Ind.	% DAC	a	l	s	t	a/l	a/t(%)	δ	δ/t
45-18	20	.275	3.0	0.3	3.9	.092	7.05	.575	.147
45-18	50	.24	2.4	0.32	3.9	.10	6.15	.56	.144
60-3	20	.335	2.2	.46	3.9	.15	8.59	.795	.204
60-3	50	.195	1.8	.55	3.9	.108	5.0	.745	.191
60-4	20	.343	2.25	.871	3.7	.152	9.27	1.21	.328
60-4	50	.237	1.44	1.28	3.7	.164	6.41	1.52	.41

These two characterizations of the indications are shown as plotted points on the attached figures. It may be clearly seen that the indications are acceptable by Section XI analysis with either characterization.

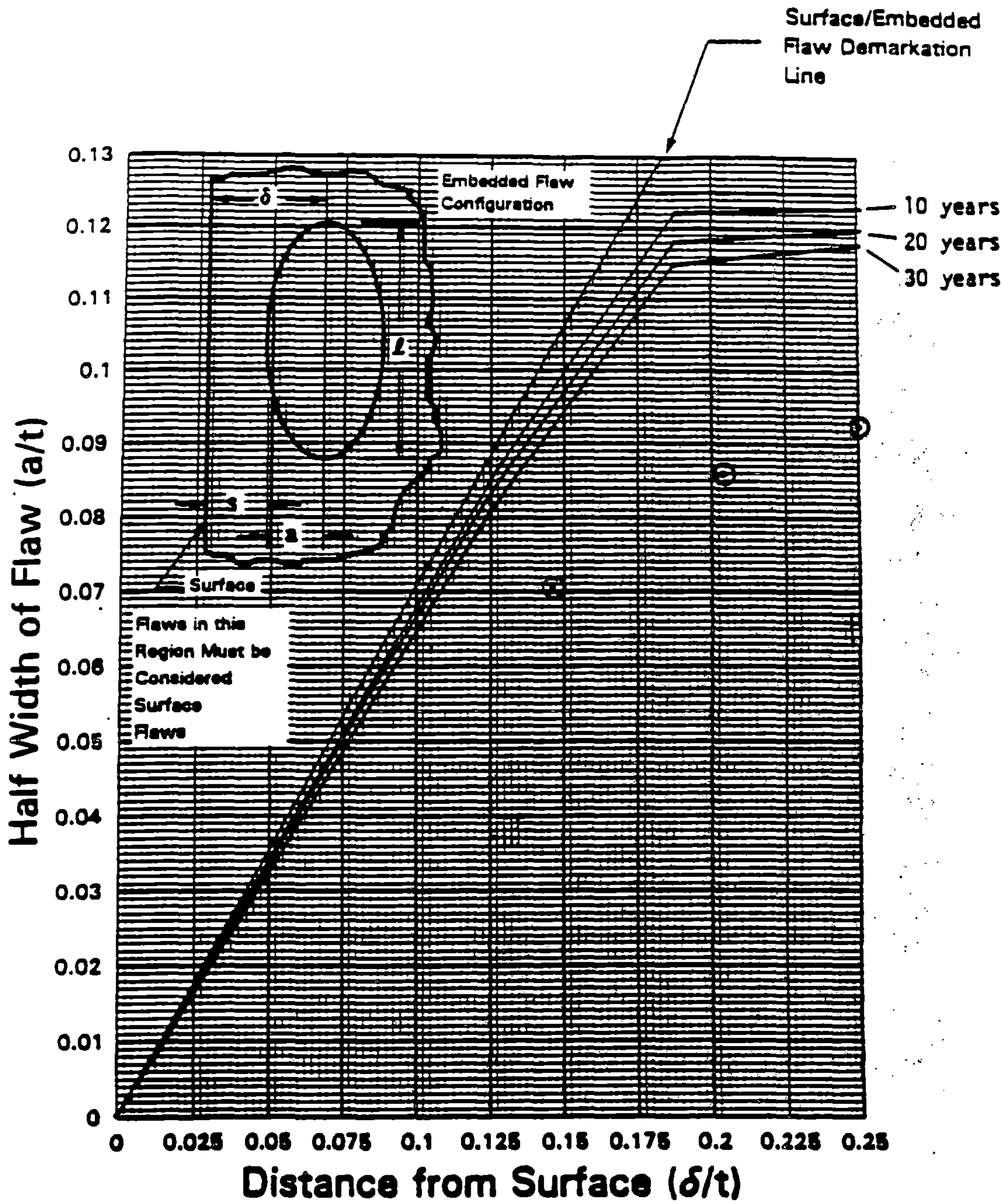


Figure 1A Flaw Evaluation Chart for Embedded Circumferential Flaws in the Lower Shell to Cone Region: 20% DAC sizing from the OD

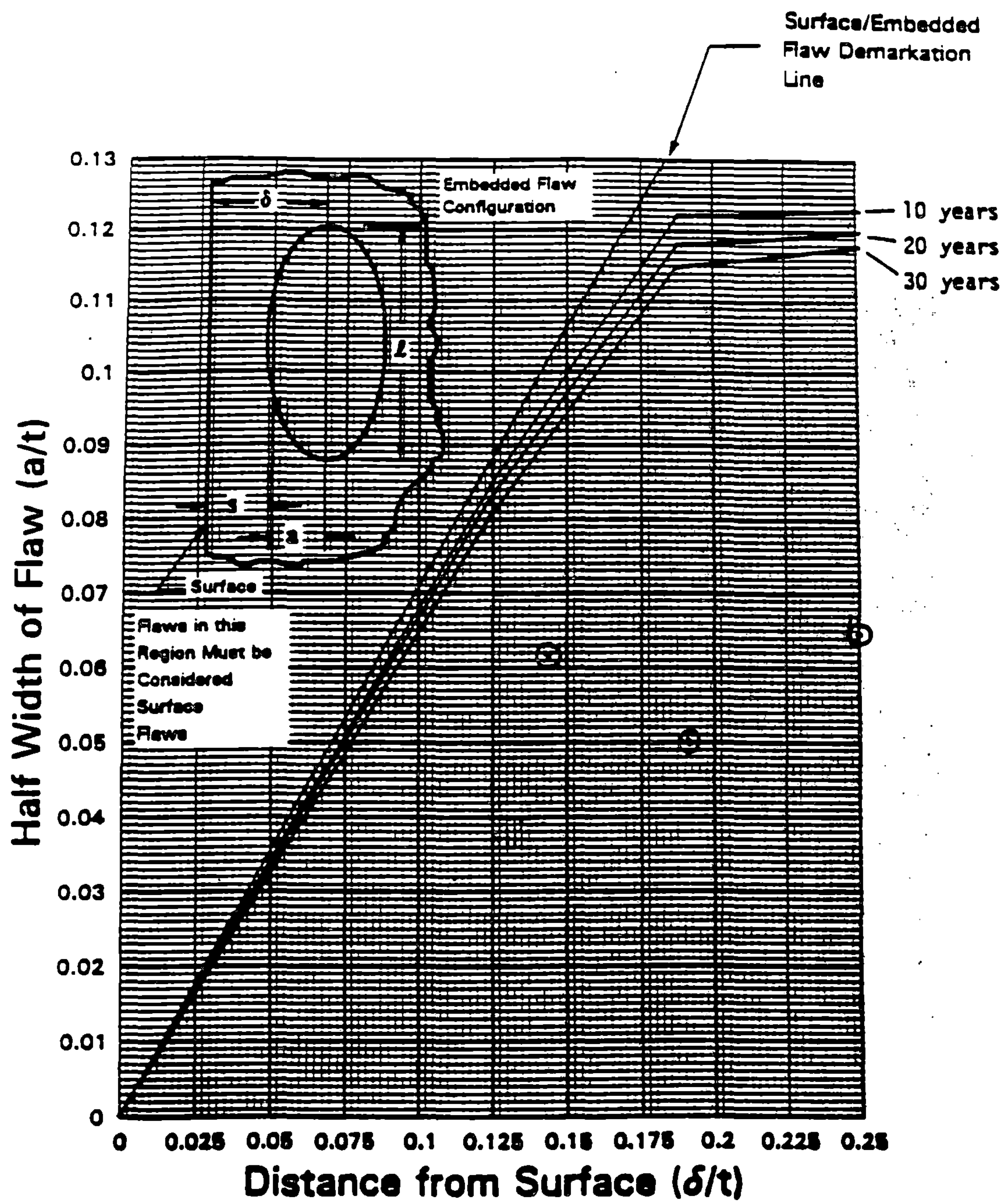


Figure 1B Flaw Evaluation Chart for Embedded Circumferential Flaws in the Upper Shell to Cone Region: 50% DAC Sizing from the OD