Westinghouse Non-Proprietary Class 3

WCAP 14330

HANDBOOK ON FLAW EVALUATION
PRAIRIE ISLAND UNITS 1 AND 2 STEAM GENERATORS
UPPER SHELL TO DOME WELD REGION

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S. Tandon
D. E. Prager
J. C. Schmertz
D. S. Drinon

Reviewed by: W. H. Bamford

Approved by: Jhon-Han Lin for SAS
S. A. Swamy, Manager
Structural Mechanics Technology

WESTINGHOUSE ELECTRIC CORPORATION
Nuclear Technology Division
P. O. Box 355
Pittsburgh, Pennsylvania 15230

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EXECUTIVE SUMMARY

This handbook has been prepared to allow quick, yet accurate, assessment of indications which may be discovered during inservice inspections of the Prairie Island Units 1 and 2 steam generators upper shell to dome region. This assessment capability is provided in the form of charts and these are contained in Appendix A of this document. Details of the derivation of the charts are provided in the main body of this handbook. To evaluate the acceptability of an indication, the user may proceed directly to Appendix A.

This revision of the report was prepared to incorporate minor revisions in the calculations of allowable flaw size in the construction of the charts. There are three revised pages, 4-6, 4-7, and 4-8. These revisions do not change the flaw charts published in the original report.

SECTION 1

INTRODUCTION

This flaw* evaluation handbook has been designed for the evaluation of indications which may be discovered during inservice inspection of the Prairie Island Units 1 and 2 steam generators. This handbook was prepared as a result of the discovery of the four indications in the upper shell to dome weld of Steam Generator 11 of Prairie Island Unit 1. Details of these indications and their evaluations are contained in Appendix A.

The tables and charts provided herein allow the evaluation of any indication discovered in the upper shell to dome weld region 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 the 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.

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.

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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.

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 dome 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.

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 preceeding 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. All the flaw acceptance tables provided in this handbook have included this consideration, as demonstrated herein. The allowable flaw depth "a" determined using this criterion is [

.]^{a,c,e} Thus the fracture mechanics criteria are governing.

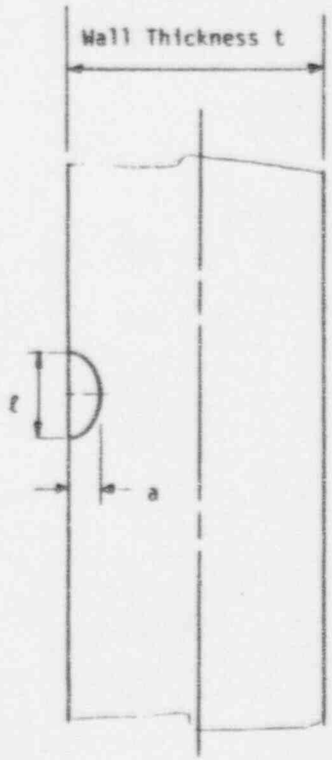
1.2 GEOMETRY

The geometry of the upper shell to dome weld region of the Prairie Island steam generators is shown in Figure 1-1. The dimensions shown are the minimum values from the design drawings. 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 1-2.

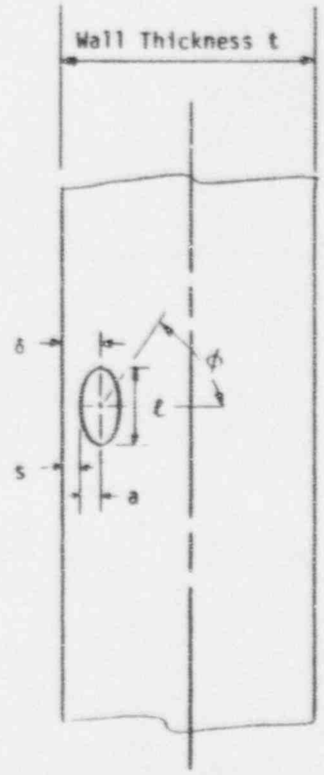
Figure 1-1

Geometry of Upper Shell to Dome Intersection for Prairie Island Units 1 and 2

a,c,e



TYPICAL SURFACE FLAW INDICATION



TYPICAL EMBEDED FLAW INDICATION

Figure 1-2 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

The design transients for the Prairie Island Units 1 and 2 steam generators are listed in Table 2-1. 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 region of interest, the upper shell to dome weld, the full range of design transients was considered. Transients such as pressure tests, including both hydrostatic and leakage tests, can be controlled by setting the test temperature. Therefore, 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 heatup/cooldown condition, while the governing emergency and faulted condition is the steam line break. 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 = 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) three flaw shapes were used, continuous (a/ℓ = 0.0) semielliptical, with length six times the depth (a/ℓ = 0.167) and semi circular (a/ℓ = 0.5). As will be seen in Section 4, the charts cover the full range of shapes between these values.

For the surface flaw with length six times its depth (a/ℓ = 0.167), the stress intensity factor expression of [ ]a,c,e was used.

The stress intensity factor $K_I(\phi)$ can be calculated anywhere along the crack front, where ϕ is the angular position, as defined in Figure 1-2. The point of maximum crack depth is represented by ϕ = 0. The following expression is used for calculating $K_I(\phi)$:

[

]a,c,e

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

The stress intensity factor calculation for a semi-circular surface flaw, (a/ℓ = 0.5) was carried out using the expressions developed by [ ].a,c,e Their expression utilizes the same cubic representation of the stress profile and gives precisely the same result as the expression of [ ]a,c,e for the flaw with a/ℓ = 0.167, and the form of the equation is similar to that of [ ]a,c,e above.

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:

[

][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 recent 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:

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

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

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

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$\sqrt{in}$ has been used here for both 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.

[

]a,c,e The Charpy impact properties of these materials are listed in Tables 2-2 and 2-3.

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 Tables 2-2 and 2-3 shows that in general the materials in the shell and dome region have excellent Charpy properties. The RT_{NDT} values for all four steam generators (considering both units) were determined to be equal to the test temperature of 10°F.

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 2 which has a minimum specified yield strength of 65 ksi.

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

Transient	Cycles
Heatup/Cooldown	210
Turbine Roll	
Unit Load/Unload	18300
Loss of Load	2400
Small Step Decrease	
Large Step Decrease	
Loss of Power	
Loss of Flow	
Hot Standby	20300
Step Load Increase	
OBE	50
Secondary Hydro	5

TABLE 2-2

MATERIAL PROPERTIES FOR UPPER SHELL-DOME REGION
PRAIRIE ISLAND NUCLEAR PLANT UNIT 1

Location	Material Type	Charpy Values 10°F) (ft-lb)	Lateral Expansion (inches)	RT_{NDT}
Dome materials, SG/11				
heat B9862-3	SA533A	75, 88, 87	.065, .071, .069	10°F
heat B9910-4	SA533A	93, 66, 78	.071, .075, .053	10°F
Upper Shell Materials SG/11				
heat B0064-4	SA533A	101, 95, 94	.087, .088, .090	10°F
heat 75E354	SA533A	100, 107, 103	.070, .069, .071	10°F
heat B006[illegible] 3	SA533A	100, 107, 106	.086, .087, .094	10°F
heat B-0169	SA533A	94, 99, 95	.081, .075, .076	10°F
Dome Materials SG/12				
heat C4272-4	SA533A	90, 83, 77	.072, .069, .076	10°F
heat B8493-5	SA533A	88, 92, 87	.070, .069, .064	10°F
Upper Shell Materials SG/12				
heat 66601	SA533A	45, 60, 68	N/A	10°F
heat 66601	SA533A	74, 86, 116	N/A	10°F
heat 66601	SA533A	74, 86, 116	N/A	10°F
heat 66601	SA533A	45, 60, 68	N/A	10°F

TABLE 2-3

MATERIAL PROPERTIES FOR UPPER SHELL-DOME REGION
PRAIRIE ISLAND NUCLEAR PLANT UNIT 2

Location	Material Type	Charpy Values 10°F) (ft-lb)	Lateral Expansion (inches)	RT_{NDT}
Dome materials, SG/21				
heat C6537-1	SA533A	62, 57, 63	.049, .046, .055	10°F
heat C6490-4	SA533A	72, 64, 57	.052, .057, .046	10°F
Upper Shell Materials SG/21				
heat C6876-3	SA533A	77, 77, 107	.061, .056, .074	10°F
heat C6876-1	SA533A	103, 87, 89	.064, .056, .071	10°F
heat C6876-2	SA533A	87, 87, 97	.073, .060, .075	10°F
heat B0721-2	SA533A	111, 119, 112	.080, .C78, .082	10°F
Dome Materials SG/22				
heat C6497-3	SA533A	71, 82, 82	.063, .071, .064	10°F
heat C6497-4	SA533A	96, 92, 97	.063, .081, .077	10°F
Upper Shell Materials SG/22				
heat 70E748	SA533A	85, 83, 72	.060, .054, .050	10°F
heat C6748-3	SA533A	94, 86, 107	.072, .079, .069	10°F
heat 75E613	SA533A	49, 58, 58	.040, .044, .044	10°F
heat C-6876-4	SA533A	67, 96, 91	.088, .081, .056	10°F

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 dome weld of the Prairie Island 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 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 length equal to six times its depth (a/ℓ = 0.1667). The second was a continuous surface flaw (a/ℓ = 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 flaw with aspect ratio 6:1 was 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:

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

The stress intensity factor $K_I(\phi)$ can be calculated anywhere along the crack front. The point of maximum crack depth is represented by $\phi = 0$. The following expression is used for calculating $K_I(\phi)$, where ϕ is the angular location defined in Figure 1-2.

[

]^{a,c,e}

The magnification factors $H_0(\phi$, $H_1(\phi$, $H_2(\phi$ and $H_3(\phi)$ are obtained by the procedure outlined in [.]^{a,c,e}

The stress intensity factor for a continuous surface flaw was calculated using an expression for [ ]^{a,c,e} The stress distribution is linearized through the wall thickness to determine membrane and bending stress and the applied K_I is calculated from:

[ ]^{a,c,e}

The magnification factors Y_m and Y_B are taken from [13] and a is the crack depth.

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. 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 were taken directly from Figure A4300-1 of Appendix A of Section XI of the ASME Code. Water environment curves were used for all inside surface flaws, and the air environment curve was used for embedded flaws and outside surface 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. The curves shown graphically in Figure 3-1 are given below.

For $R \leq 0.25$

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

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

where

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

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

For $R \geq 0.65$

$$\Delta K_I \leq 12 \text{ksi}\sqrt{in}) \quad \frac{da}{dN} = 1.20 \times 10^{-5} \Delta K_I \; 5.95$$

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

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 ΔK. This reference curve is also shown in Figure 3-1.

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

where:

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

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

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

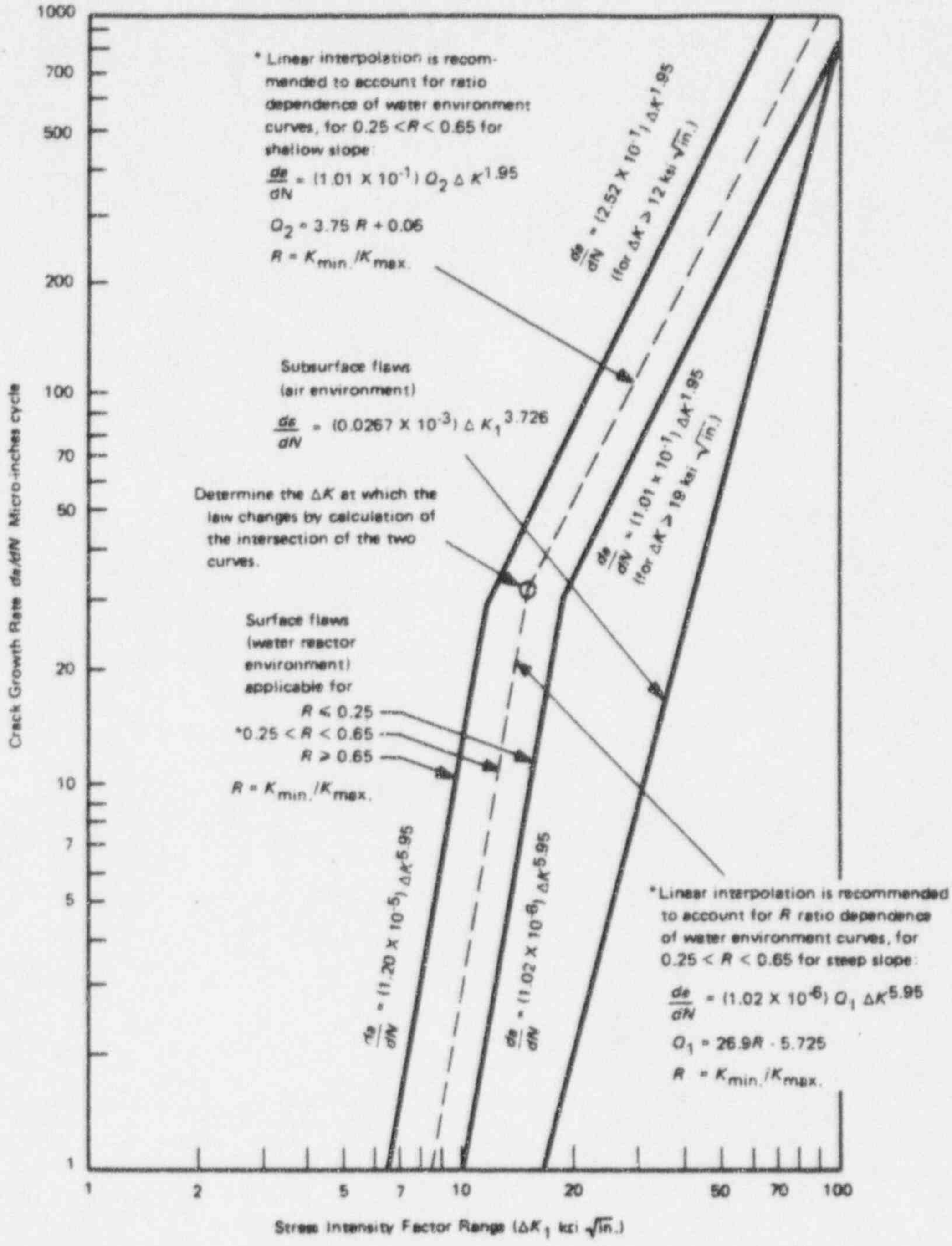


Figure 3-1 Reference Fatigue Crack Growth Curves for Carbon and Low Alloy Ferritic Steels

SECTION 4
SURFACE FLAW EVALUATION

4.1 SCOPE OF EVALUATION

The surface flaw evaluation covers the upper shell to dome weld region. This section describes the development of the inside surface flaw charts for that region.

4.2 CODE CRITERIA

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

$a_f < 0.1\ a_c$	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:

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

$$K_I < \frac{K_{Ic}}{\sqrt{10}}$$ 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:

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

and

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

Notice that both K_{Ic} and K_{Ia} are a function of crack tip temperature T, and the material property of 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.

All the finite surface flaws and embedded flaws analyzed are semi-elliptical in shape. Crack growth analyses for finite surface flaws with aspect ratio (a/ℓ) greater than 0.167 have utilized the results of 0.167, and for any flaw with aspect ratio less than 0.167, the results of the continuous flaw are used. This is conservative in both cases.

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,

- Flaw Shape Parameter a/ℓ
- 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 condition expected to occur during the remaining plant life is the heatup and cooldown transient. In addition, the governing emergency and faulted condition is the steam line break. The fracture and fatigue analyses showed that the heatup and cooldown is the most governing of these transients. Figure 4-2 shows the results for the heatup and cooldown transient, and it is constructed as follows:

[

]^{a,c,e}

[

]a,c,e

The inside surface flaw evaluation charts constructed for the upper shell to dome weld region of the Prairie Island Units 1 and 2 steam generators are presented in Figure 4-2, and repeated in Section 6, where instructions are given for their 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 dome weld region.

Step 1

[

]a,c,e

Step 2

[

]^{a,c,e}

Step 3

[

]^{a,c,e}

Step 4

[ ]^{a,c,e}

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* N/U/T normal, upset, and test conditions
E/F emergency and faulted conditions

[

]^{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.

[

]a,c,e

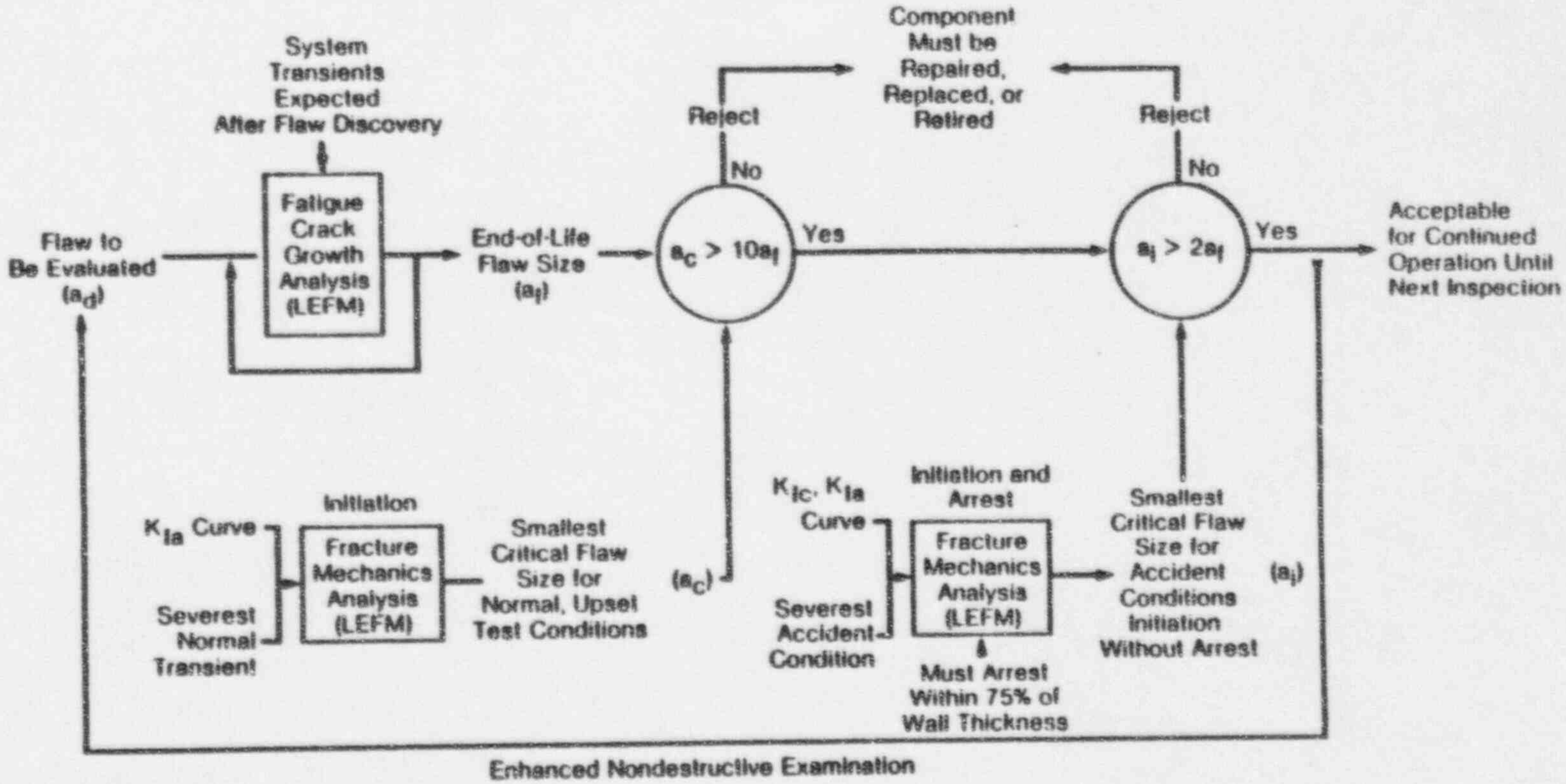
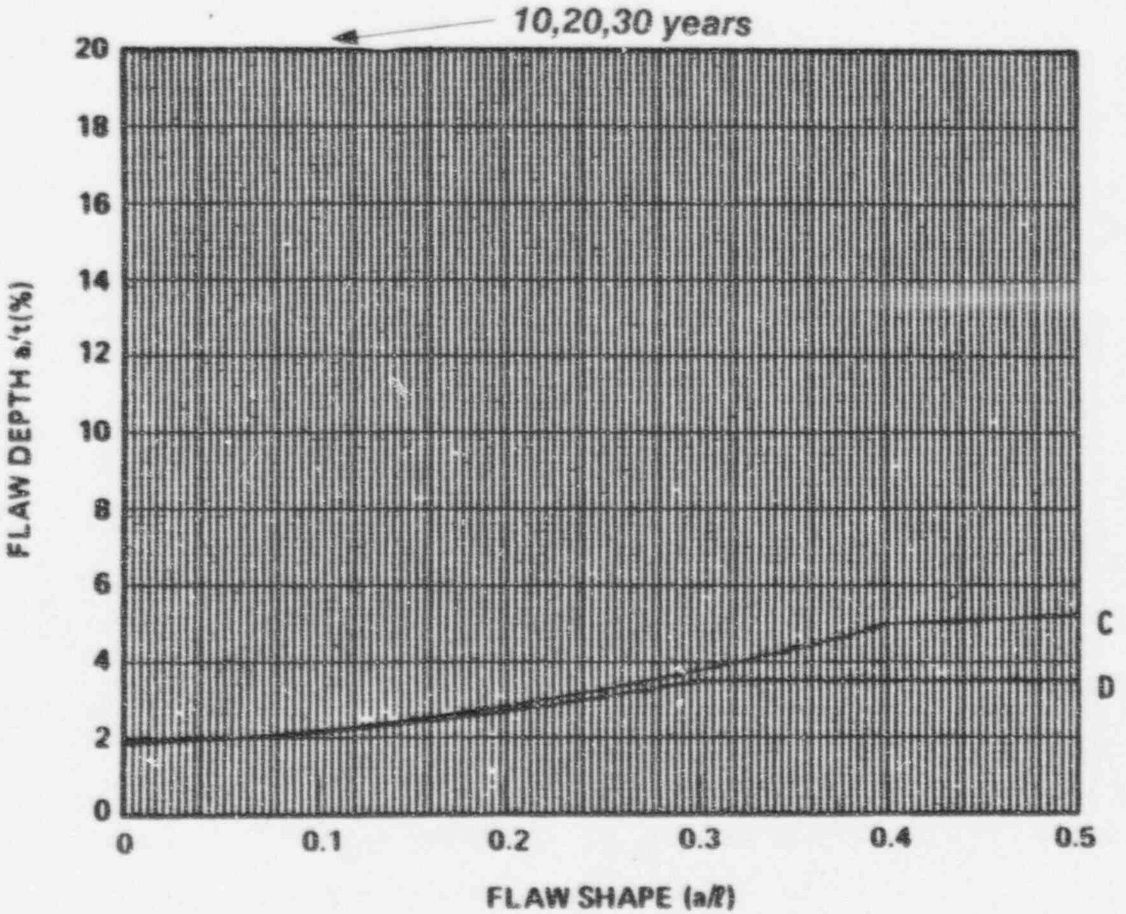


Figure 4-1 Schematic representation of Appendix A flaw evaluation process



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 allowable since 1983 Winter Addendum.

D - ASME Code allowable prior to 1983 Winter Addendum.

Figure 4-2 Flaw Evaluation Chart for Circumferential Inside Surface Flaws in the Upper Shell to Dome Weld Region

SECTION 5
EMBEDDED FLAW EVALUATION

5.1 SCOPE OF EVALUATION

Embedded flaw evaluations were performed for the upper shell to dome weld region. This section describes the development of the embedded flaw charts for that region.

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,

$$S \geq 0.4 \qquad (5\text{-}1)$$

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.

$$a = \delta - S \qquad (5\text{-}2)$$

$$\delta \geq 1.4a \qquad (5\text{-}3)$$

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

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,

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

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

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:

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

and

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

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 K_I 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.

Following are the highlights of auxiliary charts used to construct the embedded flaw evaluation chart for the upper shell to dome weld region.

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]a,c,e

[

]a,c,e

[

]a,c,e

This embedded flaw evaluation chart, constructed for the upper shell to dome weld region of the steam generators, is presented in Figure 5-2 and their 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 dome weld region during the governing transient which is the heatup/cooldown condition. The example here is for the case of RT_{NDT} = 10°F.

Step 1

[

]a,c,e

Step 2

[ ]a,c,e

Step 3

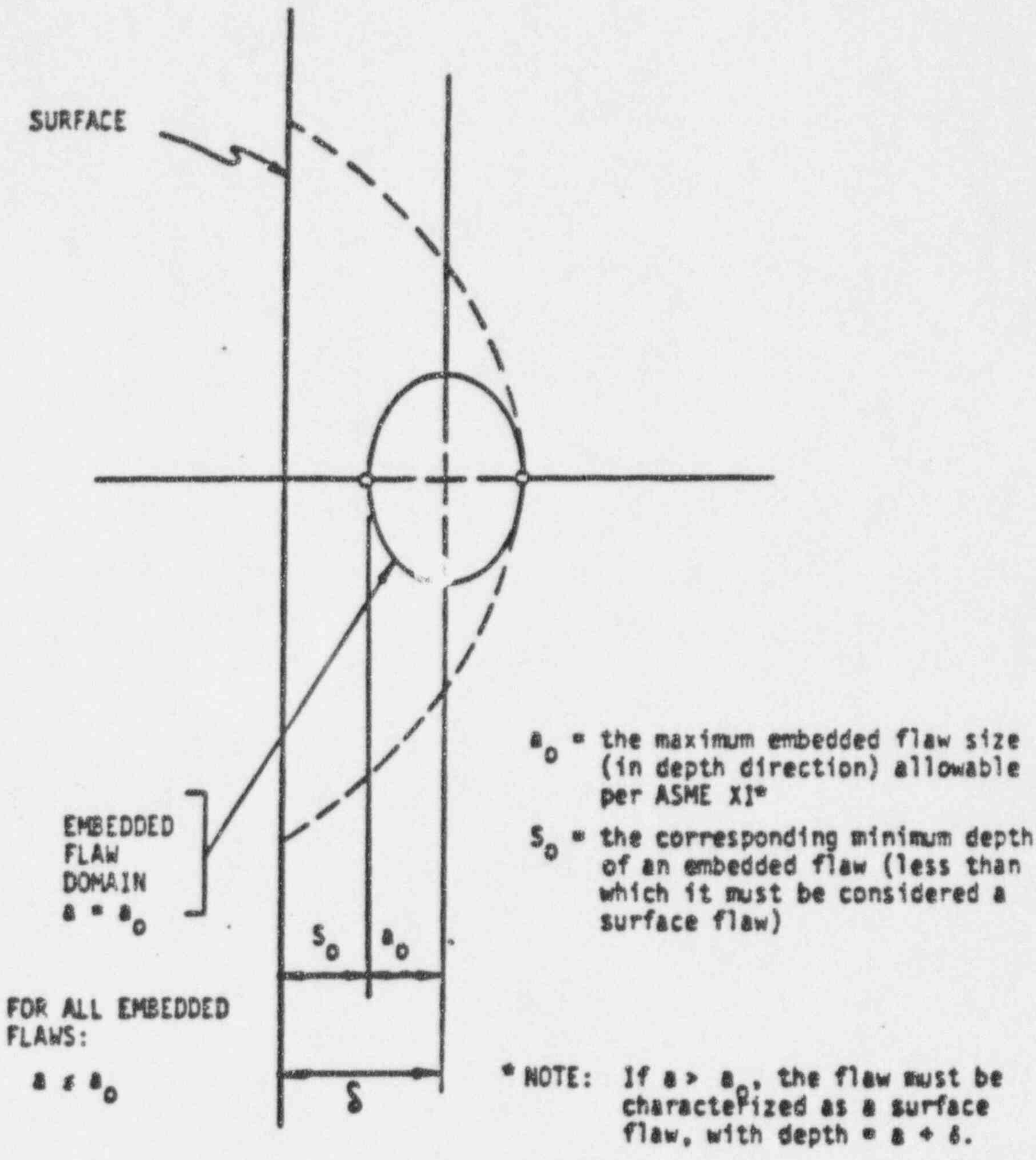
[

]a,c,e

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

[

]a,c,e



[a_o = 0.714δ for the 1980 Edition of the ASME Code and later editions]

Figure 5-1 EMBEDDED VS. SURFACE FLAW

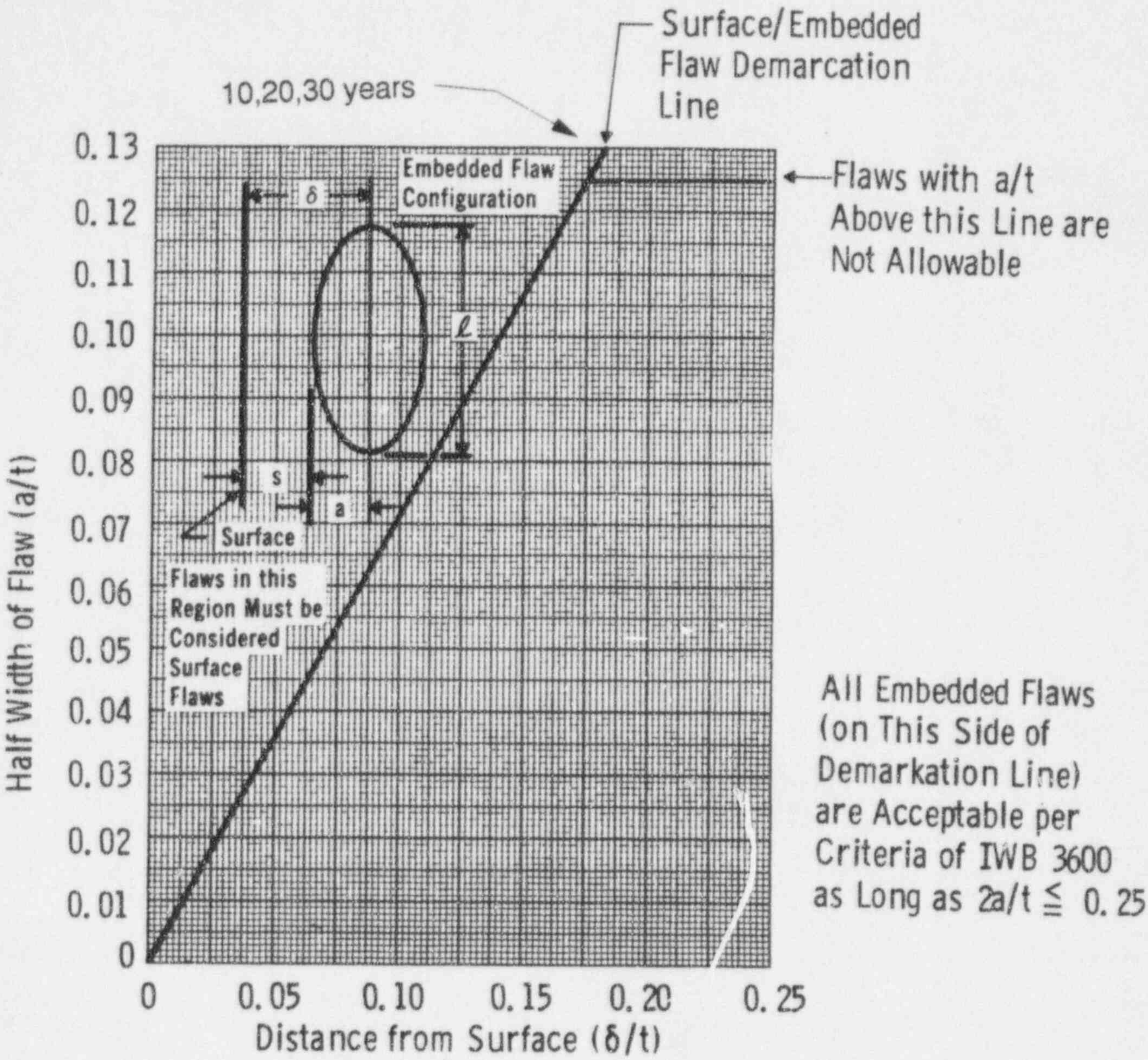


FIGURE 5-2 EMBEDDED FLAW EVALUATION CHART FOR CIRCUMFERENTIAL INDICATIONS IN THE UPPER SHELL TO DOME

a,c,e

Figure 5-3 Stress Intensity Factor Plots for $a/\ell = 0.010$ Used in Construction of Embedded Flaw Charts for Flaws Near the Inside Surface

a,c,e

Figure 5-4 Stress Intensity Factor Plots for $a/\ell = 0.10$ Used in Construction of Flaw Evaluation Flaw Evaluation Charts for Flaws Near the Outside Surface

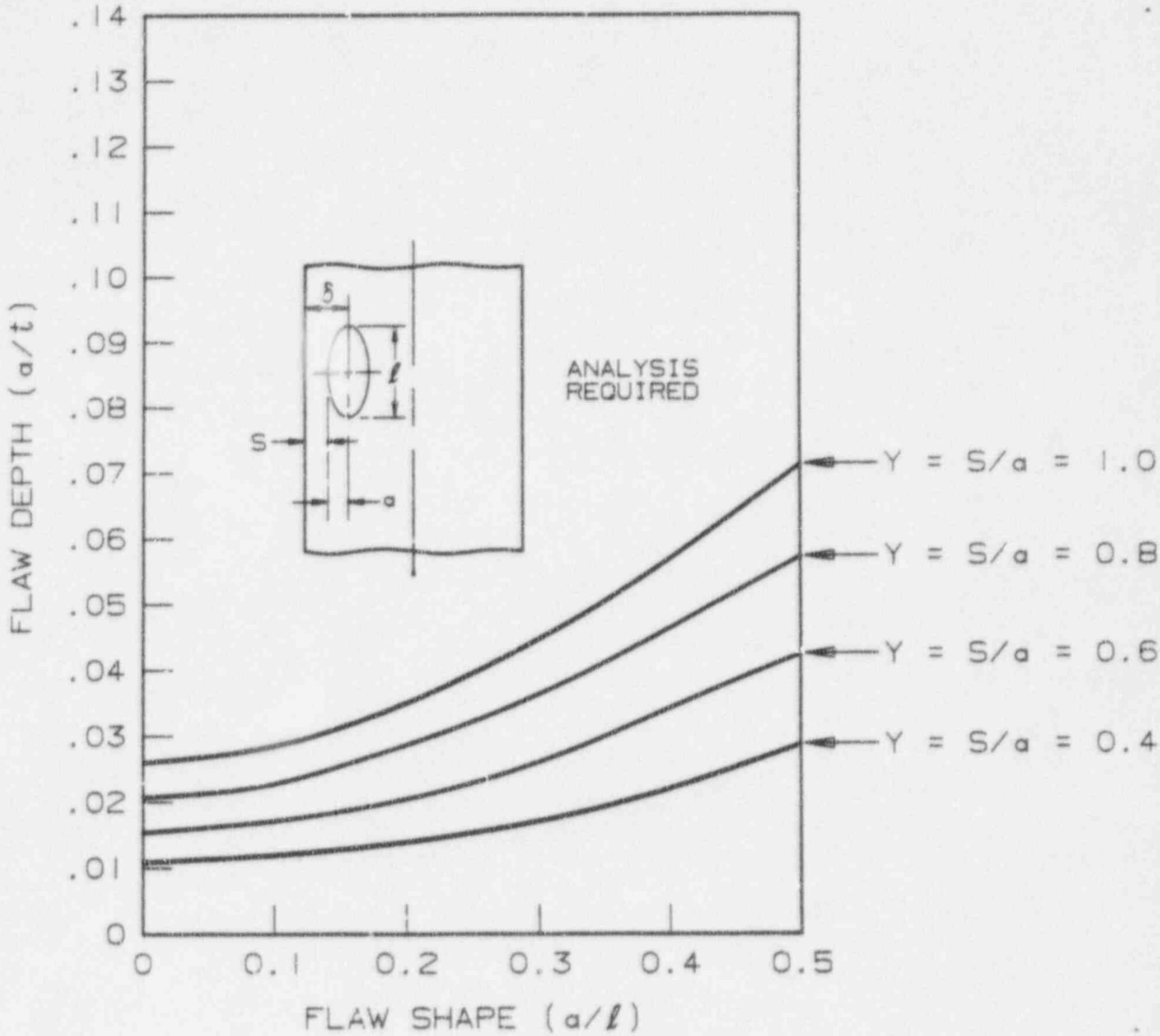


FIGURE 5-5 ACCEPTANCE STANDARDS FOR EMBEDDED FLAWS, FROM TABLE IWB-3511-1
(Note that for Y < 0.4 the flaw must be assumed to be a surface flaw)

SECTION 6

FLAW EVALUATION CHARTS-UPPER SHELL TO DOME 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 (ℓ) 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 1-2):

- Flaw Shape parameter, a/ℓ
- Flaw depth parameter, a/t
- 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. Its location 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.

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 (labelled "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 labelled "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, labelled 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

The evaluation chart for embedded flaws is shown in Figure 6-3. The heavy diagonal line in the figure can be used directly to determine whether the indication should be characterized as an embedded flaw or whether it is sufficiently close to the surface that it must be considered as a surface flaw (by the rules of Section XI). If the flaw parameters produce a plotted point below the heavy diagonal line, it is acceptable by analysis. If it is above the line, it must be considered a surface flaw and evaluated using the surface flaw chart in Figure 6-1 or Figure 6-2.

The standards for flaw acceptance without analysis cannot be shown in the embedded flaw charts because of their generality. Therefore, they have been plotted separately in Figure 6-4.

Detailed examples of the use of the charts for both surface and embedded flaws are presented in the following sections.

Surface Flaw Example

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

$a = 0.124"$
$\ell = 1.2"$
$t = 3.76"$

The flaw parameters for the use of the charts are

$a/t = 0.03310\ (3.31\%)$

$a/\ell = 0.10$

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 0.249 x 5.00", located within 0.293" from the surface, was detected. Determine whether this flaw should be considered as an embedded flaw.

$2a = 0.249"$
$S = 0.293"$
$\delta = S + a = 0.293 + 1/2\ (0.249) = 0.417"$
$t = 3.76"$
$\ell = 5.0"$

and,

$a = 1/2 \times 0.24"$
$= 0.12"$

Using Figure 6-3:

$$\frac{a}{t} = \frac{0.125}{3.76} = 0.0331$$

$$\frac{\delta}{t} = \frac{0.417}{3.76} = 0.111$$

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 Prairie Island Unit 1 or 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 to ensure the required margins of Section XI are maintained. In this section, charts are provided for determination of this temperature, which is a function of the size and location of the indications discovered. Separate treatments have been developed for embedded and surface indications.

6.2.1 Embedded Flaw Hydrostatic and Leakage Test Temperature Requirements

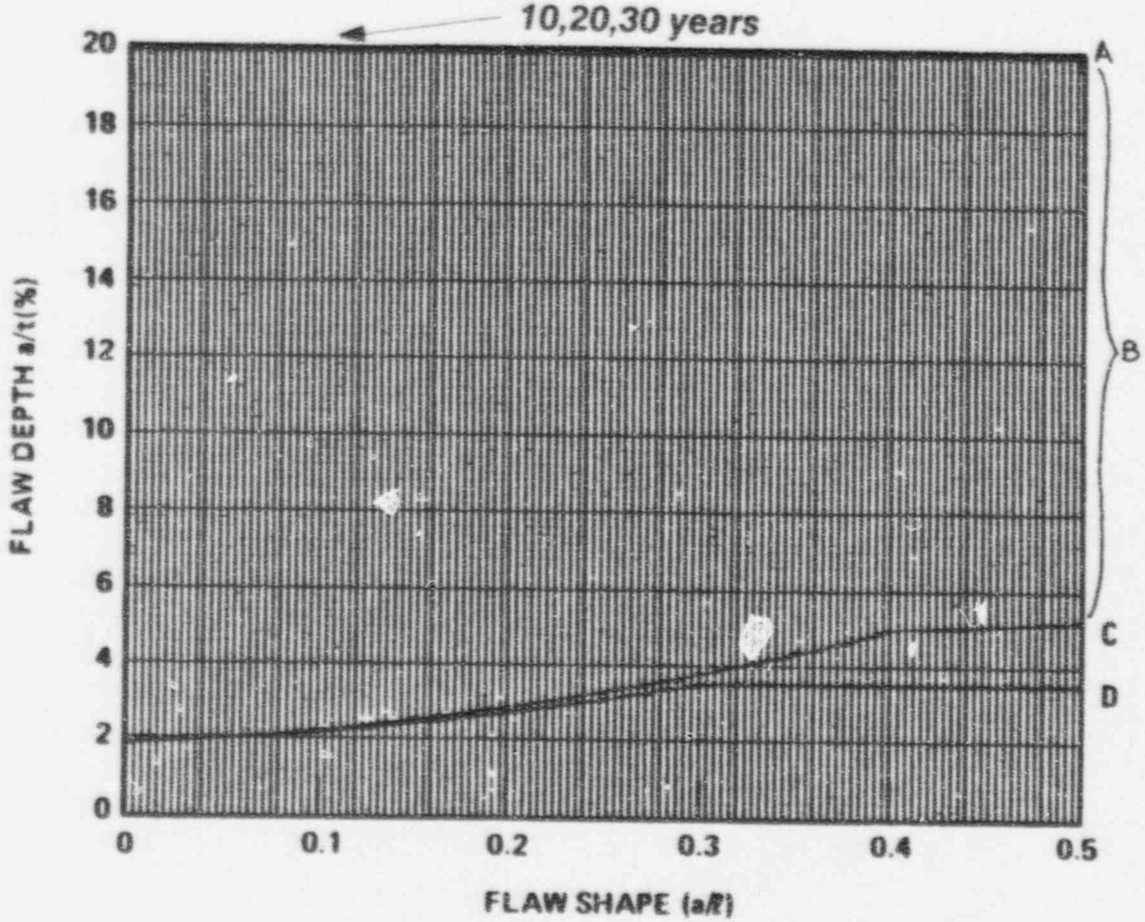
The charts herein provide a simple method for determining the required minimum temperature for any subsequent hydrostatic or leakage tests. Once an indication has been characterized, its size and location within the wall of the vessel (δ /t) determine the allowable hydrostatic or leakage test temperature. This may be done by simply plotting the indication on the appropriate chart.

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°F is conservatively applicable to all the steam generators of both Units. 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 Hydro 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 temperatures are required as the test pressure increases.



LEGEND

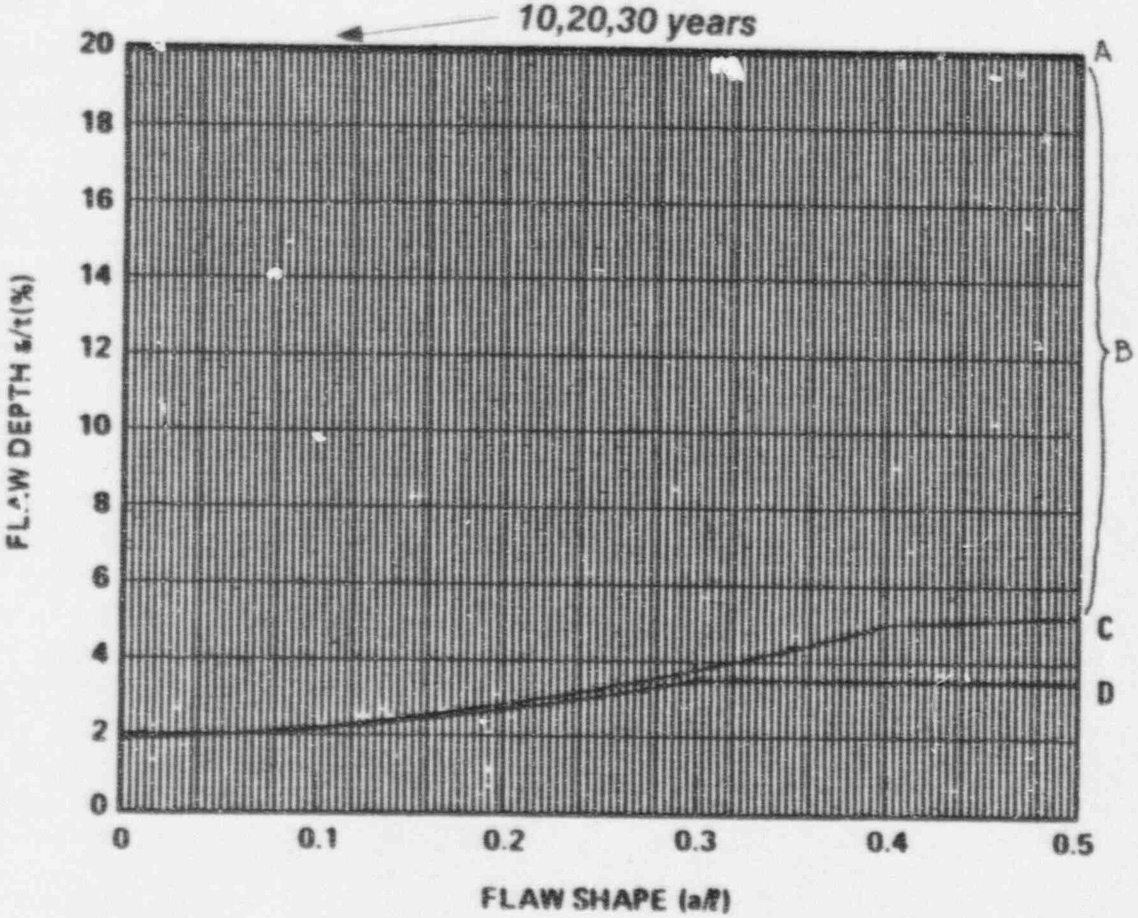
A - The 10, 20, 30 year acceptable flaw limits.

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

C - ASME Code allowable since 1983 Winter Addendum.

D - ASME Code allowable prior to 1983 Winter Addendum.

FIGURE 6-1 FLAW EVALUATION CHART FOR CIRCUMFERENTIAL INSIDE SURFACE FLAWS IN THE UPPER SHELL TO DOME REGION, PRAIRIE ISLAND UNITS 1 AND 2



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 allowable since 1983 Winter Addendum.

D - ASME Code allowable prior to 1983 Winter Addendum.

FIGURE 6-2 FLAW EVALUATION CHART FOR CIRCUMFERENTIAL OUTSIDE SURFACE FLAW IN THE UPPER SHELL TO DOME WELD, PRAIRIE ISLAND UNITS 1 AND 2

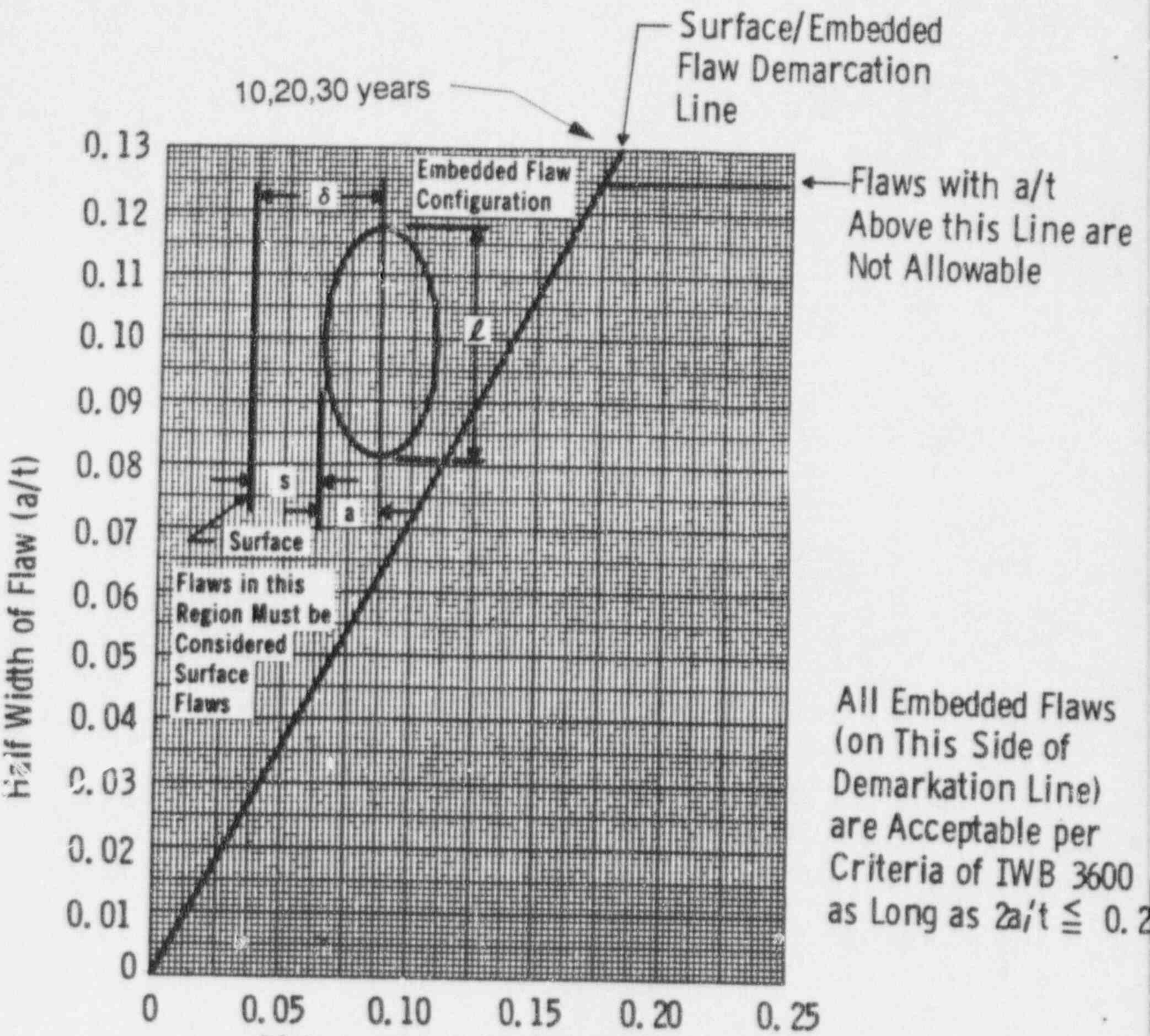


FIGURE 6-3 EMBEDDED FLAW EVALUATION CHART FOR CIRCUMFERENTIAL INDICATIONS IN THE UPPER SHELL TO DOME WELD REGION, PRAIRIE ISLAND UNITS 1 AND 2 (Note that this chart is a direct implementation of the rules of Section XI, IWB 3600.)

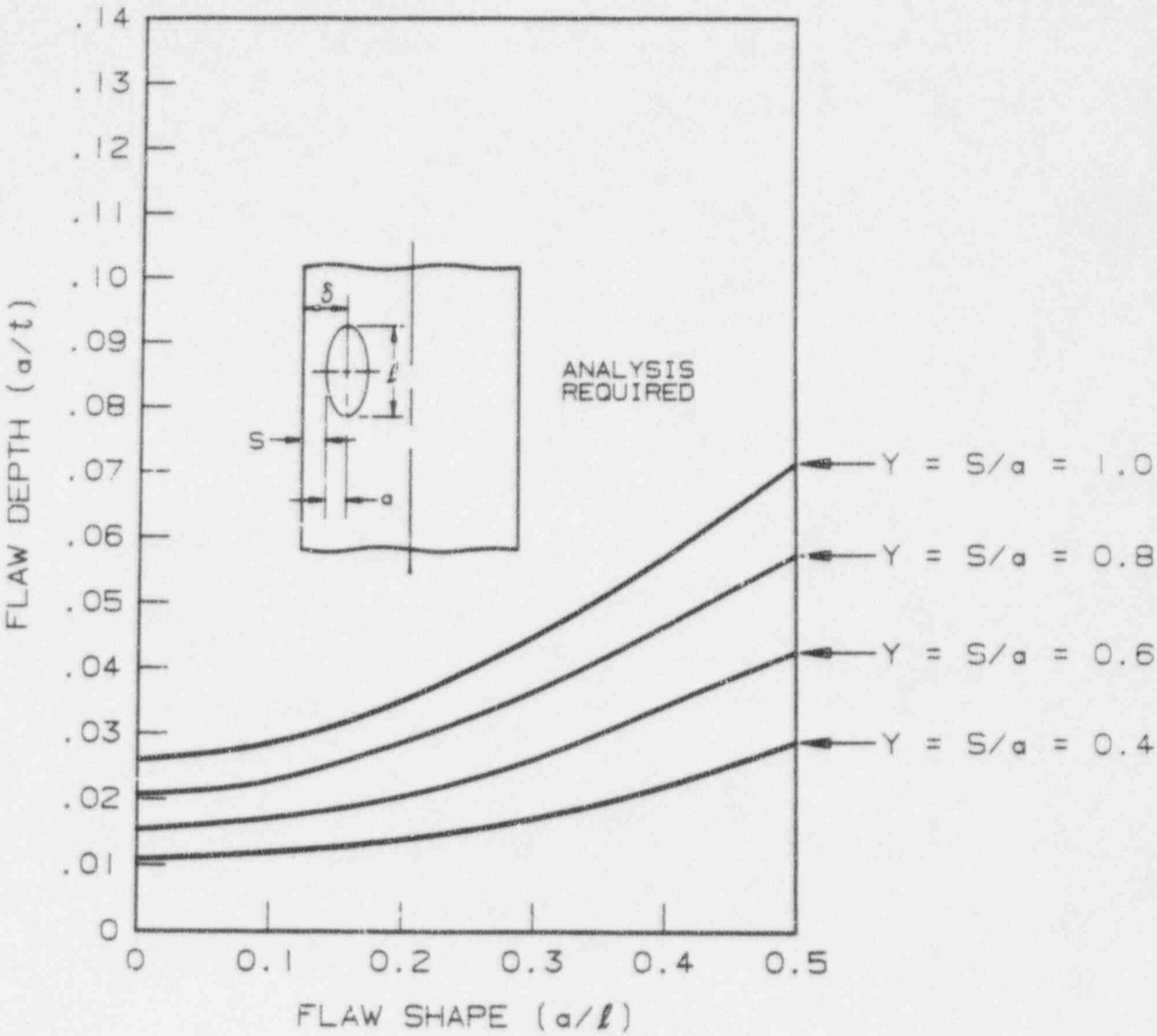


FIGURE 6-4 ACCEPTANCE STANDARDS FOR EMBEDDED FLAWS, FROM TABLE IWB-3511-1

*Only Y = 1.0 curve applies to ASME Codes prior to 1980 Edition.

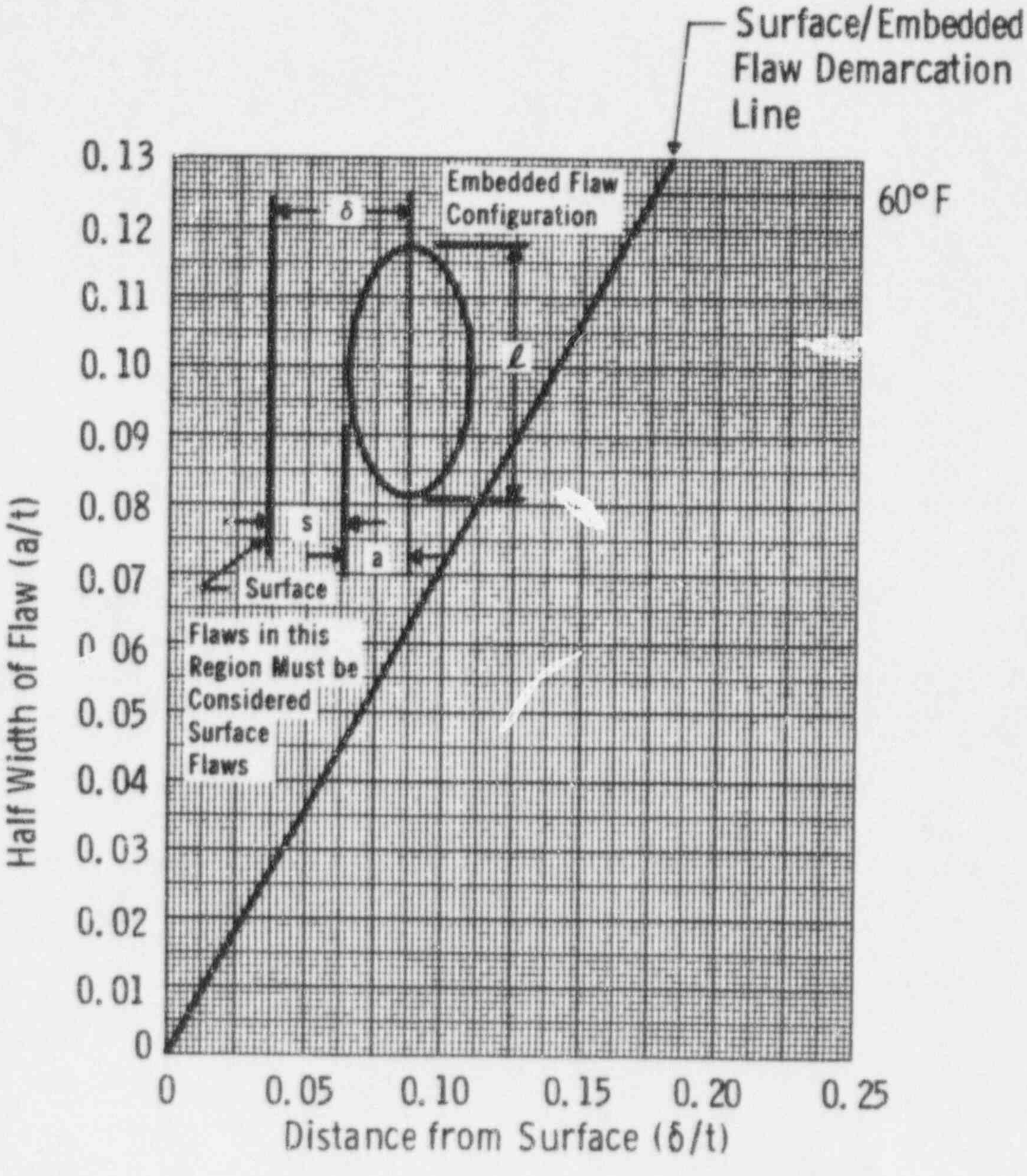


FIGURE 6-5 DETERMINATION OF HYDROSTATIC TEST TEMPERATURES FOR CIRCUMFERENTIAL EMBEDDED FLAWS (P = 1356 psi), PRAIRIE ISLAND UNITS 1 AND 2

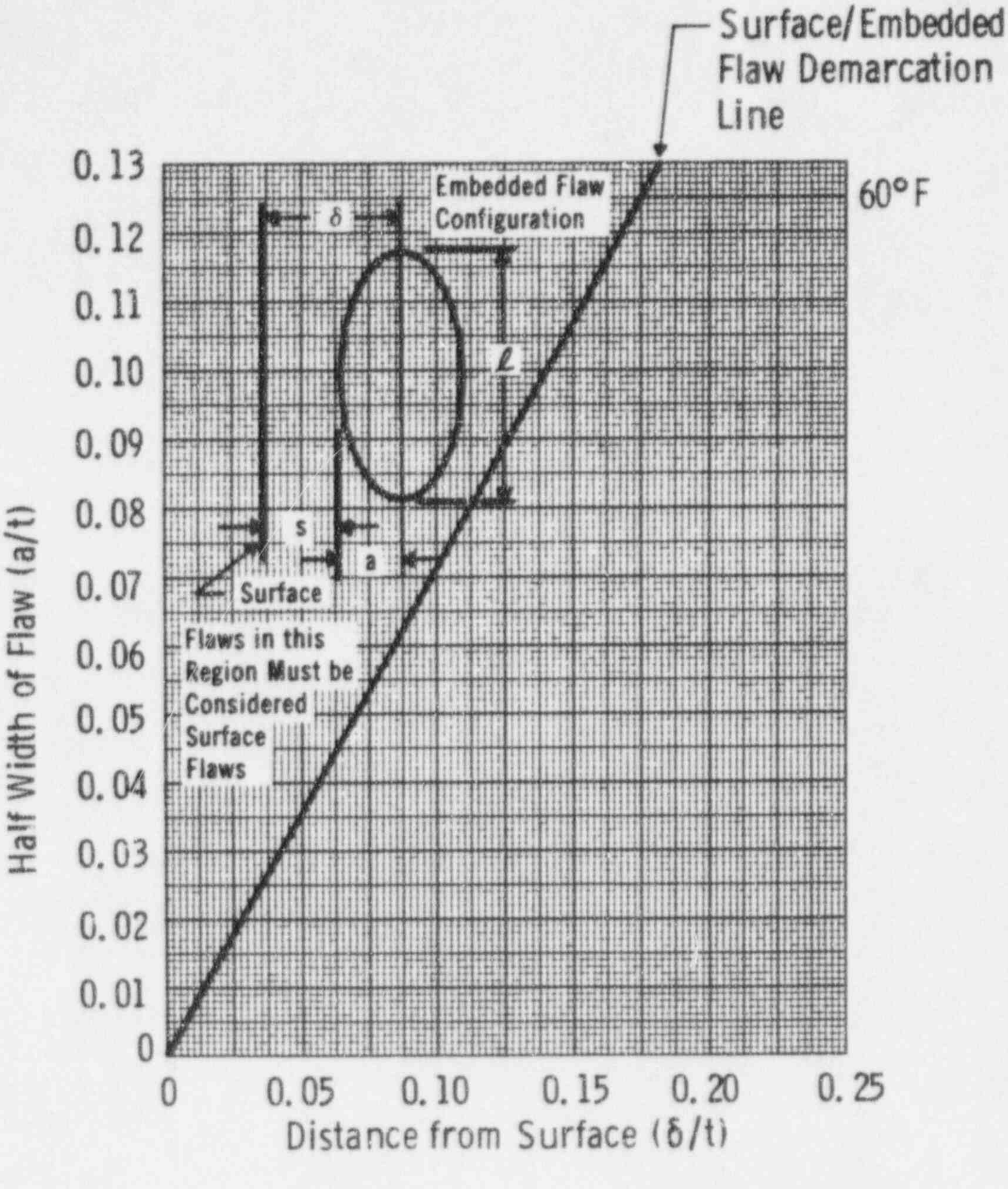


FIGURE 6-6 DETERMINATION OF LEAKAGE TEST TEMPERATURES FOR CIRCUMFERENTIAL EMBEDDED FLAWS (P = 1085 psi), PRAIRIE ISLAND UNITS 1 AND 2

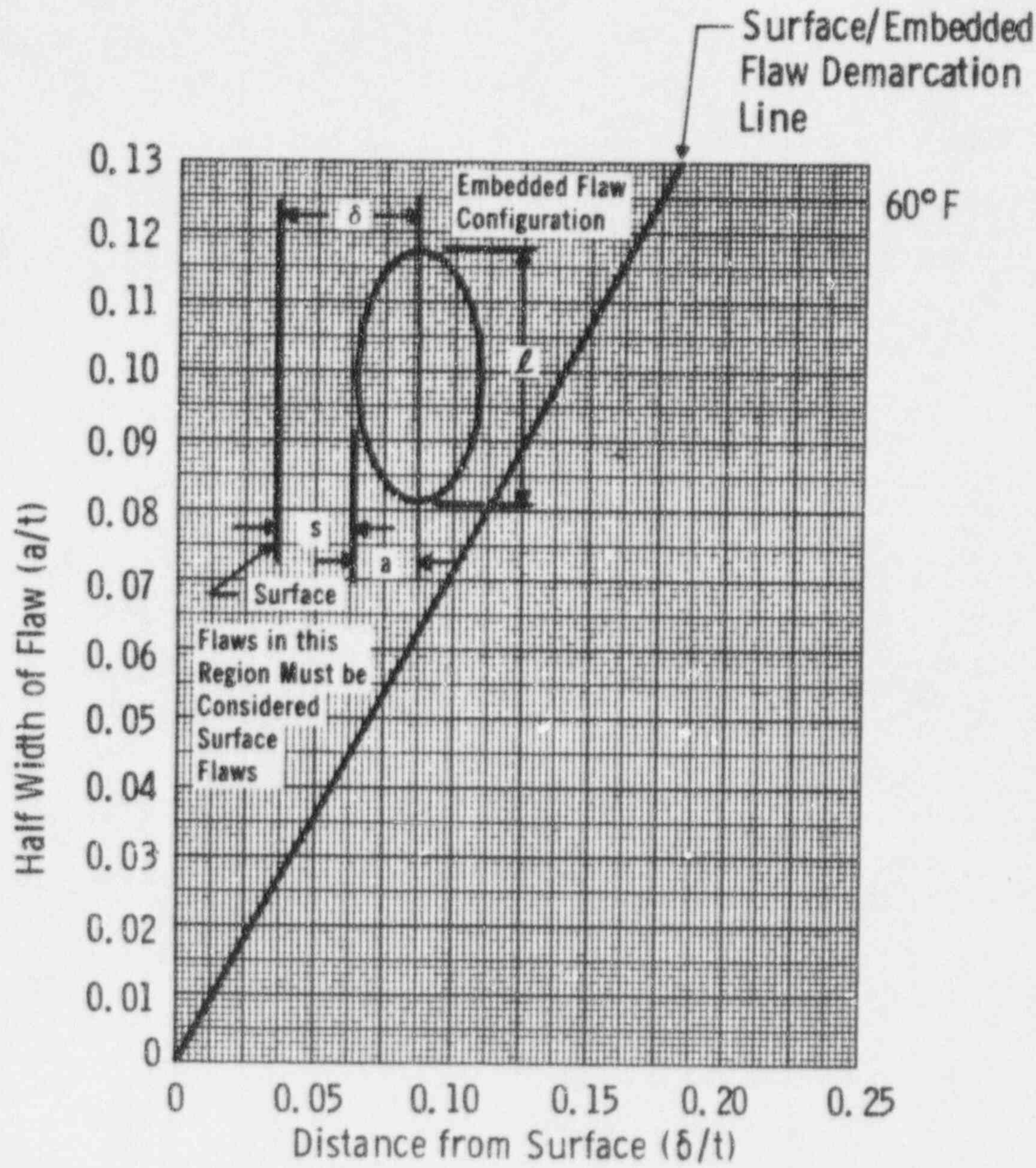


FIGURE 6-7 DETERMINATION OF LEAKAGE TEST TEMPERATURES FOR CIRCUMFERENTIAL EMBEDDED FLAWS (p = 750 psi), PRAIRIE ISLAND UNITS 1 AND 2

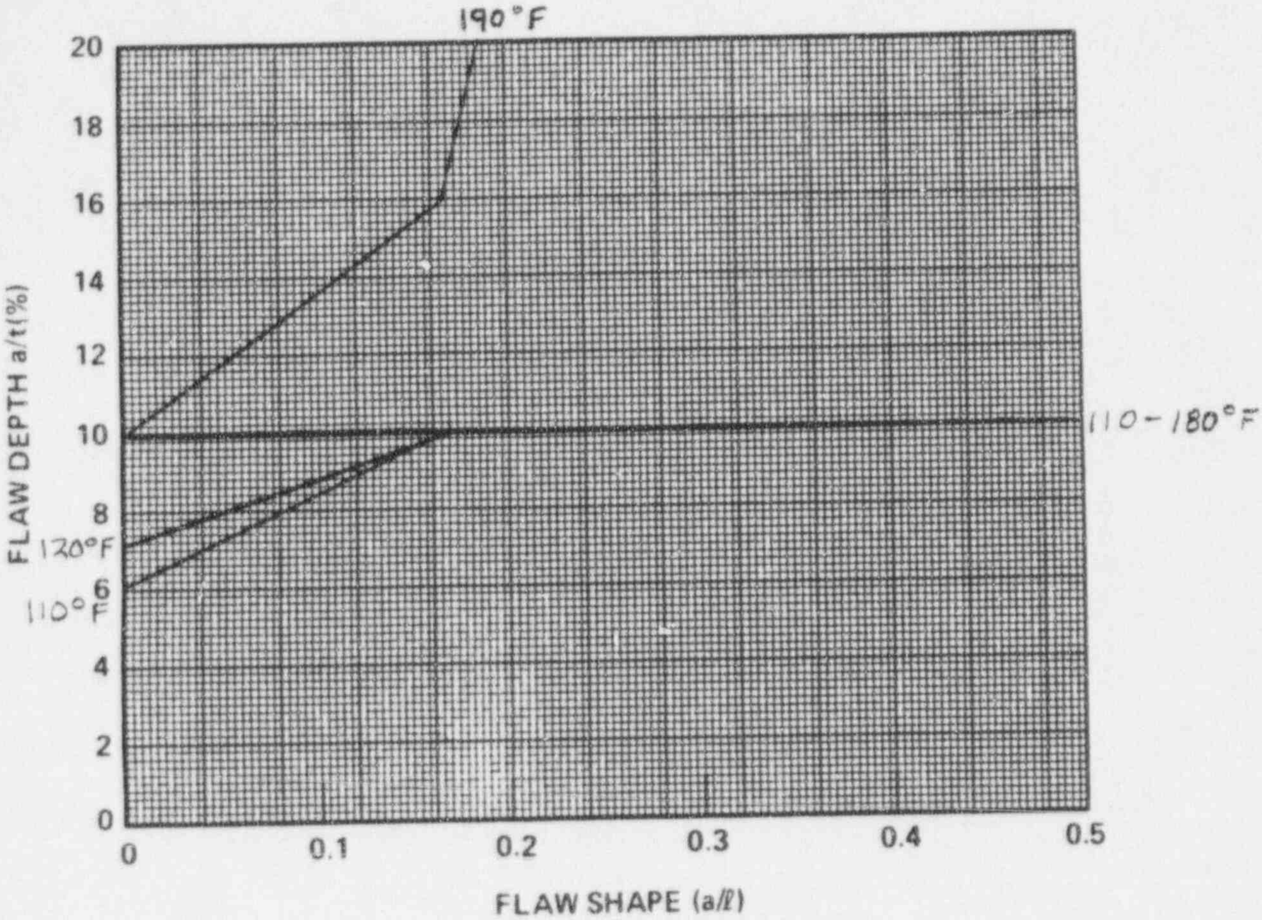


FIGURE 6-8 DETERMINATION OF HYDROSTATIC TEST TEMPERATURES FOR CIRCUMFERENTIAL SURFACE FLAWS (p = 1356 psi), PRAIRIE ISLAND UNITS 1 AND 2

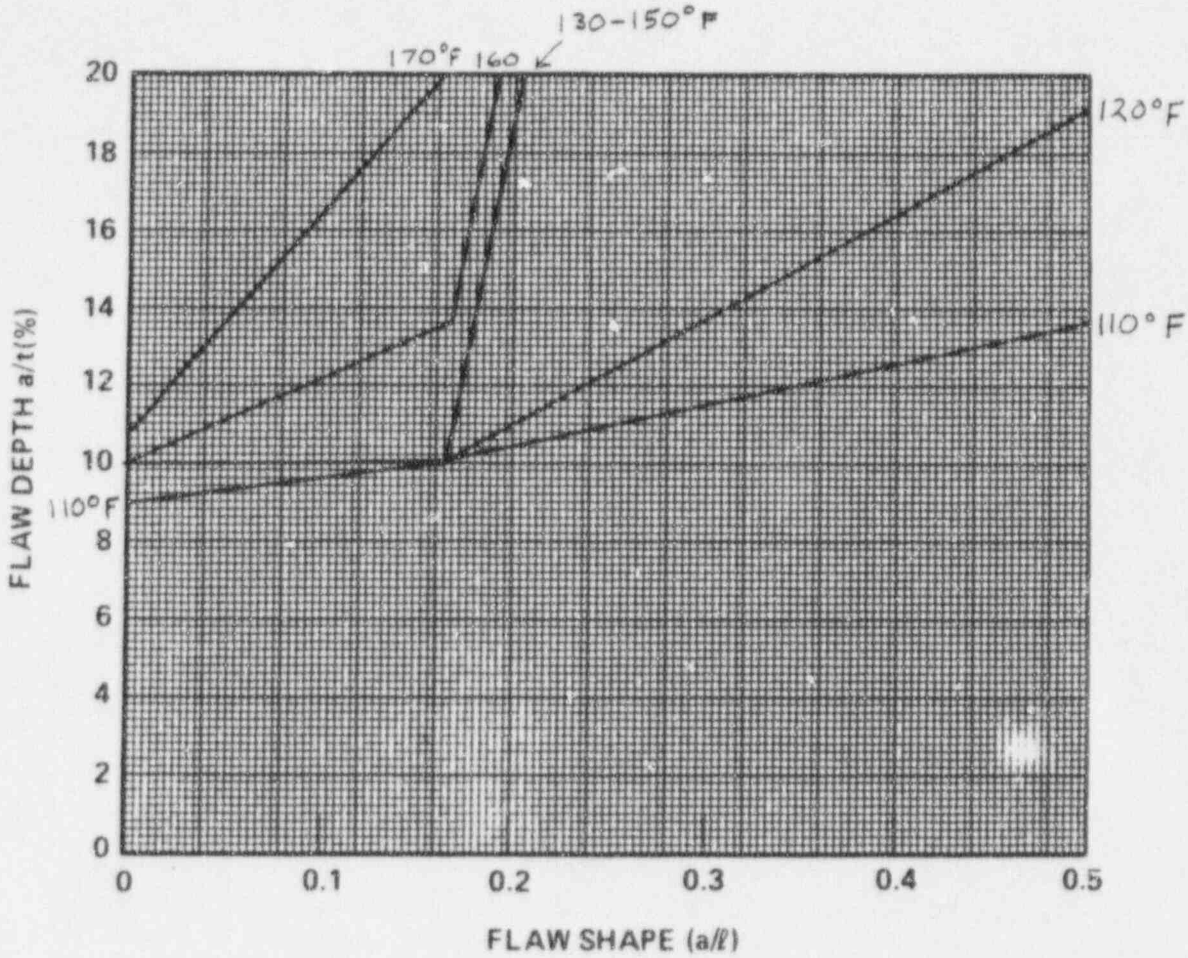


FIGURE 6-9 DETERMINATION OF LEAKAGE TEST TEMPERATURES FOR CIRCUMFERENTIAL SURFACE FLAWS (p = 1085 psi), PRAIRIE ISLAND UNITS 1 AND 2

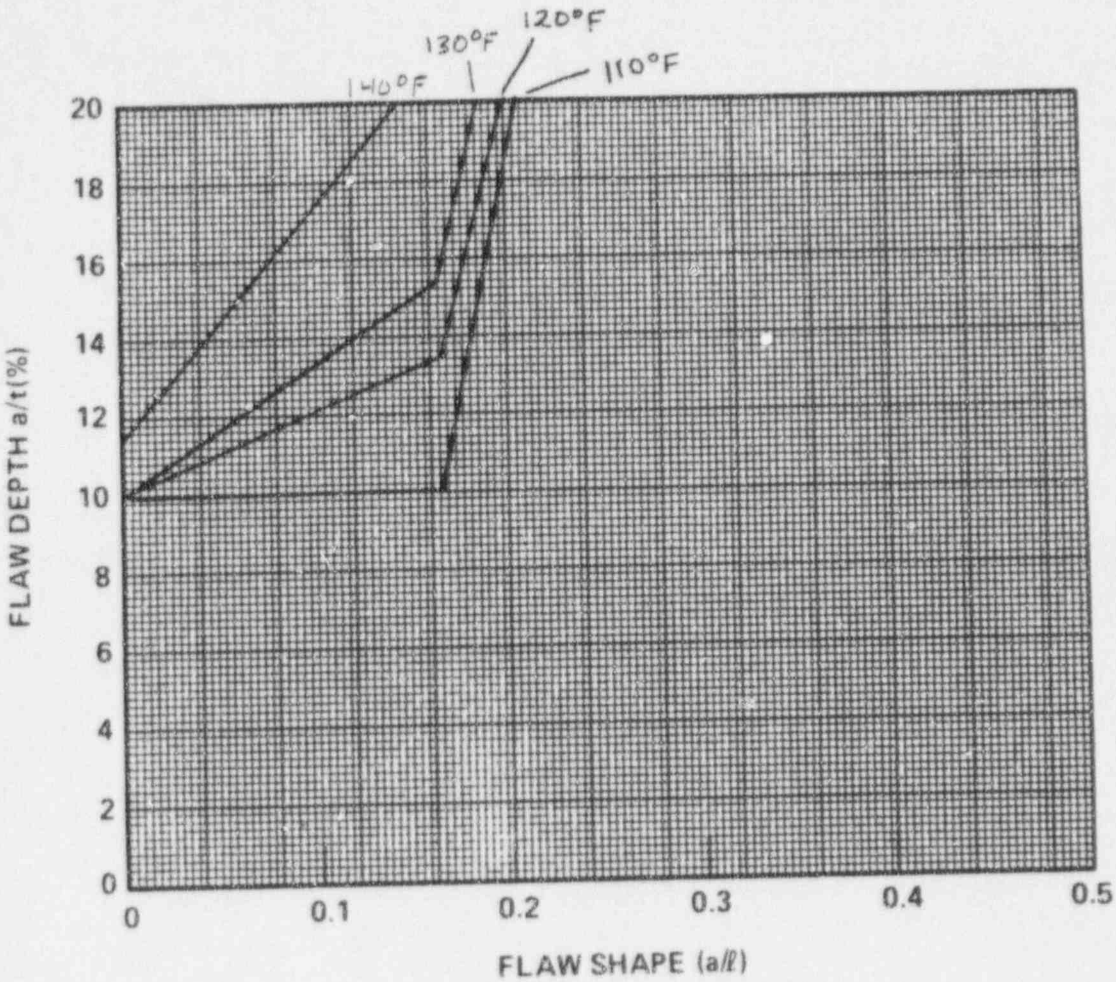


FIGURE 6-10 DETERMINATION OF LEAKAGE TEST TEMPERATURES FOR CIRCUMFERENTIAL SURFACE FLAWS (p = 750 psi), PRAIRIE ISLAND UNITS 1 AND 2

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).

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]a,c,e

7. Marston, T. U. et.al. "Flaw Evaluation Procedures: ASME Section XI" Electric Power Research Institute Report EPRI-NP-719-SR, August 1978.

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]a,c,e

[

]a,c,e

14. Logsdon, W. A., Liaw, P. K., and Begley, J. A., "Fatigue Crack Growth Rate Properties of SA508 and SA533 Pressure Vessel Steels and Submerged Arc Weldments in Room and Elevated Temperature Air Environments" Engr. Fracture Mechanics, Vol. 2, No. 3, 1985.

APPENDIX A
RESULTS OF THE INSPECTION OF SPRING 1991

A-1 SUMMARY

During the Spring 1991 ultrasonic examination of the Prairie Island Unit 1 Steam Generator "11" upper shell to dome girth weld, several recordable indications exceeded the acceptance criteria. The location of these indications in the weld and past experience with the same weld in other steam generators at other plants indicate that all the indications are subsurface in nature (i.e., small weld inclusions and/or voids). An evaluation of these indications (using -6 dB drop or half maximum amplitude sizing criteria) to the acceptance standards in Table IWB-3511-1 of the ASME Code Section XI (1980 Edition with the Winter 1981 Addenda) results in these indications exceeding the standards.

Using the fracture analysis rules of IWB-3600 and the guidelines of Appendix A, both from the ASME Code Section XI, 1981 Edition with the Winter 1981 Addenda, the indications are acceptable.

A-2 NONDESTRUCTIVE EXAMINATION RESULTS

A-2.1 Inservice Inspection - 1991 Examinations

During the Spring 1991 outage Steam Generator 11 upper shell to dome girth weld inspection, several indications exceeded the acceptance standards of the ASME Code Section XI (1980 Edition up to and including the Winter 1981 Addenda). The largest of these indications is located approximately 167" clockwise from the centerline of the feedwater nozzle.

This indication was detected and sized with a 60-degree, 2.25 MHz shear wave examination, directed downward from the dome side. A summary table of sizing data providing the measured "2a" value, the measured "S" value, and the measure length, all with respect to the normal to the inside pressure retaining surface of the component is provided as Table A-1. These results were obtained using a 2.25 MHz transducer and a -6 dB drop or half maximum amplitude sizing criteria.

The evaluation scheme satisfies the flaw indication characterization criteria provided in IWA-3300 and Table ISB-3511-1 of Section XI. The primary sizing data used for the fracture mechanics analysis was based on that taken with the 2.25 MHz transducer. Experience has shown that 2.25 MHz testing using a 0.5" x 1.0" transducer is excellent for detection in this application, but tends to oversize when used in conjunction with the Section XI criteria and volumetric-type embedded reflectors.

The 2.25 MHz, 0.5" x 1.0" transducer produces a wide beam spread. This typically results in an unavoidable overestimate of the true size of volumetric reflectors such as weld inclusions, which are believed to be present in this case. Since the flaw indications are much smaller than the measured beam size, effectively the measured size is a function of this beam spread rather than the true dimensions of the discontinuities.

The raw indication data from the examinations in steam generator 11 clearly indicate that the detected reflector is embedded rather than surface. This is seen in the location. The peak response is not observed at or near the inner diameter surface which would be expected for a surface breaking flaw. The indication is likely a result of weld discontinuities lying approximately 1" of the inner diameter surface. Furthermore, the absence of recordable indications exceeding the 20% DAC recording level on the ID surface suggests that the Prairie Island Unit 1 steam generator 11 is not experiencing the cracking found at other plants.

All examination data, therefore, clearly suggest embedded type discontinuities.

A-2.2 Experience with Other Plants

The indications in steam generator 11 at Prairie Island Unit 1 appear to be quite characteristic of experience with various welds in steam generators and pressurizers at other plants where preservice ultrasonic examination results (based on 2.25 MHz, shear wave, 50% DAC sizing methods) showed reflectors in weld backchip regions which had dimensions in excess of those allowable values provided in Section XI of the ASME Code. Attempts were made at other plants to confirm the size, location, and orientation of these indications by complementary nondestructive examination methods, i.e. 0 degree longitudinal wave examinations, and both fabrication and field radiography. No reliable responses could be observed from the shear wave indications using the straight beam examinations. In terms of radiography, the fabrication radiographs of the areas in question were reviewed with no conclusive results. Additionally, field radiography was performed in selected areas at these plants but again no confirmation of the shear wave examination indications could be obtained.

These inconclusive results led to physical removal of some of the suspect indications by mechanical means for complete metallurgical characterization.

The indications were found to have been caused by small slag inclusions and voids between weld passes in the weld backchip area near the inside surface. Measurements made during the destructive analysis showed that the ultrasonic sizing using 2.25 MHz, shear wave, 50% DAC sizing methods exaggerated the true size of the discontinuities in terms of length and/or through-wall dimensions.

Furthermore, this experience correlates well with investigations to date which have shown that when sizing volumetric-type reflectors by amplitude drop methods, i.e. 2.25 MHz, 50% DAC, the typical result is that the beam size rather than the reflector size is measured. For example, the lower the test frequency, the larger the beam width, resulting in a larger than actual apparent flaw size [1-6].

A-2.3 Evaluation Results

The sizing approach consisted of using a 2.25 MHz transducer and a -6 dB or half maximum amplitude sizing criteria. The beam angle used for sizing was identical to that of which detected the indication.

The -6 dB or half maximum sizing criteria was selected because it has provided the better accuracies when compared with 50% DAC or 20% DAC sizing levels [7].

Using the 2.25 MHz data in Table A-1, evaluation calculations were performed. This evaluation compared the characteristics of the sizing data to the acceptance standards described in Table IWB-3511-1 of the ASME Code Section XI, 1980 Edition with the Winter 1981 Addenda. These evaluation resulted in the indication exceeding the standards, and therefore a fracture evaluation was performed. Table A-2 summarizes the final sizing of the governing indications. All three indications are classified as subsurface.

A-2.4 References

1. Gruber, G. J., Hendrix, G. J. and Schick, W. R., "Characterization of Flaws in Piping Welds Using Satellite Pulses," Materials Evaluation, April 1984.

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A-3 RESULTS OF FRACTURE EVALUATION

The indications in the upper shell to dome girth weld were found to exceed the allowable standards of the ASME Code, and therefore, was subjected to a fracture mechanics evaluation. The fracture mechanics analysis methods and material properties are documented in the main body of this report.

Using the flaw evaluation chart from Figure 6-3, the indications were found to be acceptable, as seen in Figure A-1.

The dimensions of the indication, as sized by the final inspection with the 2.25 MHz frequency are given in Table A-3.

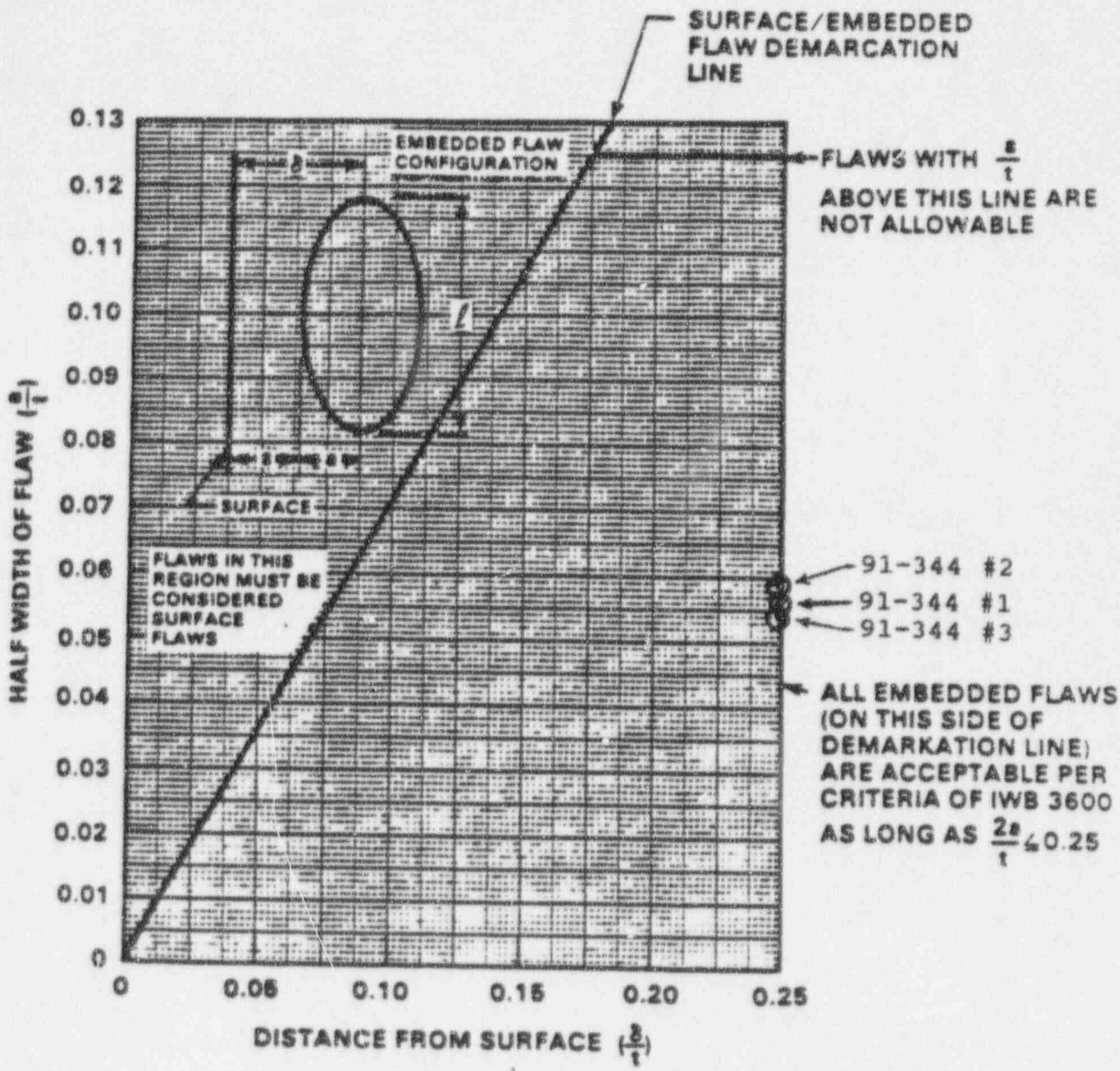

Figure A-1 Results of Flaw Evaluation for the Upper Shell to Dome Region, Prairie Island Unit 1, Spring 1991

TABLE A1 - SUMMARY OF INDICATION DIMENSIONS

PRAIRIE ISLAND UNIT 1
UPPER SHELL TO DOME WELD UT INDICATIONS - JUNE 1991
ASME CODE SECTION XI 1980 EDITION, WINTER 1981 ADDENDA
2.25 MHZ DATA

Indication	Date	Dim 2a	Dim 1	Dim S	Value Y	Surface of Subsurface	% DAC Amplitude
<u>Steam Generator 11 - 45°</u>							
91-348 #1d	6/18/91	0.47	6.00	1.02	1.0	Sub	23
<u>Steam Generator 11 - 60°</u>							
91-344 #1d	6/18/91	0.47	6.00	1.02	1.0	Sub	24
91-344 #2**	6/18/91	0.49	7.00	1.04	1.0	Sub	25
91-344 #3**	6/18/91	0.45	11.00	1.33*	1.0	Sub	28

ϕ - Evaluated according to the proximity rules (coplaner) - dimensions for 91-344 #1, bound 91-348 #1 & 91-344 #1.

* - Dimension S is taken from the OD. ID distance is 2.18.

**- Indications #91-344 #2 & 91-344 #3 were evaluated according to IWA-3300. They were classified as discontinuous and evaluated as separate indications.

TABLE A2 - SUMMARY OF INDICATION DIMENSIONS

PRAIRIE ISLAND UNIT 1
SUBSURFACE INDICATIONS - JUNE 1991
ASME CODE SECTION XI 1980 EDITION, WINTER 1981 ADDENDA
2.25 MHZ DATA

Ind.	Date	Dim 2a	Dim 1	Value S	Value Y	Surface or Subsurface	Value a/1	Actual a/t *	Allowable a/t% *	Accept ?
Steam Generator - 45°										
91-348 #1	6/18/91	0.47	6.00	1.02	1.0	Sub	0.04	5.66	2.8	NO
Steam Generator 11 - 60°										
91-344 #1	6/18/91	0.47	6.00	1.02	1.0	Sub	0.04	5.66	2.8	NO
91-344 #2	6/18/91	0.49	7.00	1.04	1.0	Sub	0.04	5.90	2.8	NO
91-344 #3	6/18/91	0.45	11.00	1.33*	1.0	Sub	0.02	5.42	2.7	NO

* - t = 4.15"

TABLE A3 - SUMMARY OF FRACTURE ANALYSIS RESULTS PER IWB 3600

PRAIRIE ISLAND UNIT 1

INDICATIONS EXCEEDING IWB-3511-1

ASME CODE SECTION XI 1980 EDITION, WINTER 1981 ADDENDA

2.25 MHZ DATA

EXAM DATE: JUNE 1991

Ind.	Exam Date	Dim 2a	Dim S	Value w	Actual a/t %	Value w/t *	Accept ?
Steam Generator 11							
91-344 #1	6/18/91	0.47	1.02	1.255	5.66	0.3024	YES
91-344 #2	6/18/91	0.49	1.04	1.285	5.90	0.3096	YES
91-344 #3	6/18/91	0.45	1.33	1.555	5.42	0.3747	YES

* - t = 4.15"