NUREG-0726

Preliminary Analysis of the Effect of Fatigue Loading and Crack Propagation on Crack Acceptance Criteria for Nuclear Power Plant Components

U.S. Nuclear Regulatory Commission

Office of Standards Development

W. F. Anderson
G. H. Weidenhamer
E. C. Johns

RECEIVED
MAY 08 1981
U.S. NUCLEAR REGULATORY COMMISSION

Available from

GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, DC 20555

Printed copy price: $2.50

and

National Technical Information Service
Springfield, VA 22161

NUREG-0726

Preliminary Analysis of the Effect of Fatigue Loading and Crack Propagation on Crack Acceptance Criteria for Nuclear Power Plant Components

Manuscript Completed: September 1980
Date Published: April 1981

W. F. Anderson, G. H. Weidenhamer, E. C. Johns

Division of Engineering Standards
Office of Standards Development
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

ABSTRACT

The staff of the Division of Engineering Standards of the U.S. Nuclear Regulatory Commission (NRC) initiated a preliminary study to evaluate the conservatism of existing design methods regarding cyclic loadings and crack growth in nuclear power plant components. The study was based on the assumption that the application of the ASME Boiler and Pressure Vessel Code should be consistent throughout the design, operation, and inspection phases. Specifically, any undetectable or allowable crack subjected to fatigue stress levels permitted by Section III of the Code should not be expected to grow larger than the size permitted by Section XI inservice inspection criteria.

The objective of this preliminary analysis was to calculate the magnitude of acceptable crack sizes consistent with the maximum fatigue usage allowed by the Code and to identify some important parameters that may be useful in the development of crack acceptance standards. The results reported are for Class 1 components only. The results are not intended to be rigorous or comprehensive, but to show general trends from the effect of various parameters on crack size consistent with appropriate sections of the ASME Boiler and Pressure Vessel Code.

The results indicate that, if a component experiences a high level of cyclic stress that corresponds to a usage factor of 1.0, very small cracks can propagate to sizes that exceed code-specified limits.

CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The authors thank the members of the Structures and Components Standards Branch, Office of Standards Development, who assisted with the development of this report, in particular, Dr. P. N. Randall and Mr. W. E. Norris.

1. INTRODUCTION

The ASME Boiler and Pressure Vessel Code provides acceptance standards for flaws found by nondestructive examination (NDE). Section III of the Code (Ref. 1) provides acceptance standards for materials and fabrication of nuclear components. Section XI (Ref. 2) provides acceptance standards for preservice examinations and inservice examinations. Some inconsistency appears between the acceptance standards of these two sections. The Subcommittee on Section III formed an Ad Hoc Task Group on Nondestructive Examination Acceptance Standards in 1976 and charged this group with developing rational and reasonable NDE acceptance standards for welds in Section III Construction (Ref. 3). This is in addition to a Main Committee Ad Hoc Task Group on Examination and Acceptance Standards organized in 1974. Some changes resulting from the efforts of the Main Committee Task Group have already been made in the Code.

Section III of the Code provides a basis for design to avoid failure by fatigue. This is given in the form of design fatigue curves that were developed using fatigue data from polished specimens. These curves were developed before the study of crack propagation had progressed sufficiently to contribute to their basis.

In discussions during the development of acceptance standards for flaws[1] found in the preservice examination of nuclear power plant components, questions were raised regarding the relationship of the acceptance standards to

---

[1] In this report, the terms "flaw" and "crack" are used interchangeably.

other permissible design parameters. Responses to those questions indicated that no effort had been made to quantify the effect of the initially proposed standards relative to allowable cyclic stresses for design. Part of the basis for the proposed standards had included consideration of the cyclic loadings anticipated in service for some components rather than the maximum allowable cyclic loadings from the fatigue curves, i.e., a usage factor of 1.0. The allowable numbers of cyclic loadings is usually an order of magnitude greater than that anticipated in service. Therefore, this study was undertaken to obtain information on the relationship between allowable cyclic stresses and acceptable crack sizes for construction.

This work represents a preliminary step toward evaluating the conservatism of current design procedures and is not intended to be a rigorous or comprehensive attempt to form either a basis for design acceptance criteria or a basis for accepting or rejecting flaws found in service. Futhermore, it is not intended to be a contribution to the field of crack growth research but is intended to explain a potential application of the results of such research to those involved in the development and application of general design rules.

Two parameters that are likely to be considered in the development of future standards for initial flaw size are workmanship standards and flaw detection capabilities, but no attempt was made in this study to relate acceptable initial crack size to these parameters.

The objective of this study was to estimate the size of acceptable cracks consistent with maximum fatigue usage allowed by the Code and to investigate some important parameters that may be useful in the development of crack acceptance standards for nuclear power plant components.

2. DISCUSSION

This preliminary study includes calculations of the magnitude of acceptable initial crack sizes for a variety of fatigue loadings to which cracks could be subjected. The materials considered in this study are those for which both allowable cyclic stresses and crack growth data are available. This includes the pressure vessel steels.[2]

Because of varying characteristics during crack growth, the following simplifying assumptions were made in this study:

1. Instead of taking a spectrum of cyclic loads, as would be done for an actual design analysis, a single value of cyclic stress and its associated number of stress cycles were used to calculate each data point for initial crack size. The magnitude of the applied alternating stress intensity, S_a, and the associated number of stress cycles, N, are those given in Table I-9.1 (for pressure vessel steels) in Section III of the ASME Boiler and Pressure Vessel Code (Ref. 1).

2. The membrane and bending stress correction factors, M_m and M_b, are fixed at 1.0. The flaw shape parameter, Q, is selected as 1.0 for flaws with aspect ratios of 0 and 0.1 and as 2.1 for flaws with aspect ratios of 0.5. Because of the limited scope of this effort, variations of these three factors and the resulting effects on crack size, which could be either additive or compensatory, were not considered.

---

[2] The term "pressure vessel steels" in this study refers to the low alloy steels, ASME SA-508, Classes 2 and 3, and ASME SA-533, Grade B, Class 1.

3. Cracks grow in a self-similar manner; i.e., the aspect ratio[3] remains constant.

4. The stress ratio, R, is taken as 0.

5. Linear fracture mechanics and the data and methods of Appendix A to Section XI (Ref. 2) form a solid basis for calculating small crack sizes with stress values within the yield strength of the material.

6. The acceptable crack sizes of the inservice crack acceptance standards of Section XI constitute a reasonable upper limit for crack growth.

Assumptions 2 and 3 imply that subsurface cracks are close to the center of the section with membrane stress only.

It should be noted that, for cases in which the yield strength of a material is exceeded, large plastic deformations may occur. Since this analysis is based on linear elastic fracture mechanics, Figures 1 through 8 are plotted with solid curves for a stress range below the yield strength of the material and with broken curves above. No conclusions will be drawn from the data beyond yield.

Using the preceding assumptions, the analysis is consistent with the ASME code procedures and data as follows:

---

[3] Ratio of the minor half-diameter (half-depth) of an embedded flaw or the flaw depth of a surface flaw to the flaw length.

1. Section XI crack propagation techniques (Ref. 2),
2. Section XI crack acceptance standards (Ref. 2),
3. Section III allowable cyclic stress values (Ref. 1).

The assumptions implied by the application of the two sections of the Code have raised concerns from some reviewers. One specific concern is the implied stress distribution associated with Assumption 1. The basis for this concern is that a flaw can grow through the wall only if the stress at the tip of the crack remains large (at the level of the S-N data) across the thickness of the wall. If the stress level decreases rapidly enough throughout the thickness, crack depth could be expected to stabilize. In response to this concern, it should be pointed out that, since the crack depth permitted by the inservice inspection criteria is relatively small compared with the wall thickness, even stabilized cracks could be expected to exceed the criteria.

Reviewers also questioned the validity of using a single fatigue stress level from the S-N data as the magnitude of the applied fatigue loading (Assumption 1). The basis for the concern is that loading at one stress level does not account for the variation in the loading as demonstrated by operating time histories. However, by evaluating the acceptable initial crack size in this way for a range of stress levels, one can observe the sensitivity of crack size to stress. It has also been suggested that there are very few cases in which a component is subjected to stress levels having a usage factor of 1.0. However, since designers are allowed to design to a usage factor of 1.0, it is considered unduly optimistic to disregard the possibility of having components that are subjected to stress levels associated with a usage factor of 1.0.

Although the analysis was made in accordance with the Code, further questions have been raised about using different parts of the Code that are based on data from unrelated physical phenomena. It is precisely the lack of relationship between these phenomena that has prompted this study. Attempts have been made to show that consideration should be given to the interrelationships between parameters involving crack growth, allowable cyclic stress, and acceptable crack sizes; failing to do so can lead to potentially serious inconsistencies.

Most of the calculations of initial crack size were made with the acceptable crack size criteria in Section XI of the ASME Code, but a through-wall crack was also used. The through-wall criterion was included only for trends as some of the assumptions used in the derivation of the crack equation are violated as the crack becomes very large.

3. RESULTS

The results of the calculations are shown in Figures 1 through 8. With the exception of the upper curve in Figure 1, the data show initial crack sizes that will not propagate to sizes larger than the acceptable crack sizes specified in Section XI when the cracks are subjected to cyclic stresses equal to the fatigue stress allowables given in Section III. In addition, these calculations were made for variations of the following parameters: wall thickness, crack geometry (aspect ratio), environment (air for embedded cracks or water for surface cracks), and usage factor. Table I shows the combinations of specific parameters considered in the study. It should be noted that the abscissa of Figures 1 and 2 represents both the number of cycles and the alternating stress intensity acting in the area where the crack is located. The stress values shown in brackets below the number of stress cycles are obtained from Table I-9.1 (for carbon, low alloy, and high tensile steels) in Section III of the Code (Ref. 1). Although the same relationship would also apply in Figures 3 through 8, only the stress values are shown in these six figures.

The equation used for calculating initial crack sizes is derived in Appendix A. Appendix B presents sample calculations to demonstrate how this equation is used.

The results of the calculation for the initial crack size are very sensitive to the rounding off of the stress values. The curves in Figures 1 through 8 were smoothed within a band that was based on the potential rounding-off error. A reviewer should not expect to reproduce these curves exactly.

To facilitate the presentation of the results of this study the effect of each of the parameters (identified earlier) will be discussed separately.

3.1 Cyclic Stress

Each point on the curves represents one alternating stress intensity, S_a, at a particular number of cycles taken from the S-N data. The stress values were from just below the design stress parameter, S_m (26.7 ksi), to a level much higher than the maximum allowable design stress $3S_m$ (80 ksi). The results show that there is a characteristic combination of stress and number of stress cycles at which the initial crack size is a maximum. For purposes of discussion, all crack sizes quoted from the figures are those near the maximum. A more realistic spectrum of cyclic stress and corresponding number of cycles for the same usage factor would give initial crack sizes less than that maximum. Figures 1 through 8 show that the alternating stress intensity, S_a, at which the initial crack size becomes a maximum is approximately 29 ksi.

It should also be noted that in calculating usage factors from the S-N data, cyclic stresses that would not add to the usage factor but would contribute to crack propagation can be anticipated. The Code does not require consideration of usage for cyclic stresses at values less than the minimum stress value of Table I.9-1.

3.2 Wall Thickness

Wall thickness appears to have little effect on the calculated initial crack size. The apparent reason for this is that, although the acceptable crack sizes given in Section XI vary linearly with thickness, the corresponding initial sizes do not vary significantly over a wide span of thicknesses. For example, the initial half-depth, a, for a subsurface flaw with an aspect ratio of 0.1 must not exceed 0.0278 inch for an 8-inch-thick wall, while that for a 5-inch-thick wall was calculated to be very similar at 0.0252 inch. Although wall thicknesses other than 8 inches were considered in this study, only the results for the 8-inch-thick wall are shown (see Appendix B, Section 2).

3.3 Crack Geometry

Crack geometry, which is measured in terms of aspect ratio, has a significant impact on calculated initial crack size. Although Figures 4 and 6 indicate that the aspect ratio has little effect on acceptable initial crack length, the effect of the aspect ratio on initial crack depth is pronounced (see Figures 5 and 7). For example, Figure 4 shows that the initial lengths for cracks with aspect ratios of 0.5 and 0.1 in an air environment were of the same magnitude at 25 ksi, having a difference of only 0.04 inch or 17%. However, Figure 5 shows the initial crack half-depth for an aspect ratio of 0.5 to be approximately 4 times that for an aspect ratio of 0.1. Figures 6 and 7 show the same general results for flaws in water environments. This suggests that consideration of crack depth may be of less importance in establishing acceptance standards. This may be useful since measurements of crack depth by different flaw detection techniques can be expected to be inconsistent, while the measurements of crack lengths may be more consistent.

3.4 Usage Factor

Usage factor is defined in Section III of the Code (Ref. 1). As used herein, it is considered to be the ratio of the number of cycles experienced by a component at a specific value of alternating stress intensity to the number of cycles that the component is allowed from the S-N data for the same value of alternating stress intensity. The results discussed thus far were determined for a usage factor of 1.0. Figure 8 shows that, for a component that experiences fatigue loadings corresponding to usage factors of 1.0 and 0.1, the initial crack lengths of an embedded flaw with an aspect ratio of 0.1 are 0.28 inch and 1.3 inches, respectively. The figure also shows that, as the usage factor decreases to 0.01, the acceptable initial crack length increases to 2.0 inches.

3.5 Environment

Of those parameters studied, the parameter that most significantly affects crack size is the environment. Comparisons of the curves in Figures 4 and 5 with those in Figures 6 and 7 show that allowable initial crack sizes in a water environment are 15 to 20 times smaller than those in an air environment. The growth relationships used to evaluate this parameter for ferritic steels were taken from Figure A-4300-1 in Appendix A to Section XI of the ASME Code (Ref. 2).

3.6 Threshold Stress Intensity Correlations

Results indicate that, if a component experiences a cyclic stress level corresponding to a usage factor of 1.0, fatigue failure may occur even when only very small cracks are present initially. However, very low stress intensities are associated with small crack sizes, and at low stress intensities, there may be a characteristic threshold value below which no cracks propagate. Because of this, it is necessary to examine the results and compare the associated stress intensities with threshold stress intensities.

In an air environment, the threshold stress intensity value for a stress ratio of zero is approximately 5 ksi$\sqrt{in}$ (page J-13 of Ref. 4). This compares with stress intensity values as low as about 5.6 ksi$\sqrt{in}$ obtained[4] in this study

---

[4] See Appendix B for details on this calculation.

for the lowest stresses with small initial cracks. For a water environment, initial crack sizes that would give stress intensities as low as 1.3 ksi$\sqrt{in}$ were calculated. This compares to a threshold stress intensity in water of approximately 2.6 ksi$\sqrt{in}$ (page 5-40 of Ref. 5).

Threshold stress intensities could be a factor in the development of crack acceptance standards. Unfortunately, these stress intensities are not completely understood, and the preliminary comparison contained herein does not provide a basis for conclusions.

3.7 Final Crack Size

One of the most surprising results of this study was that final crack size does not necessarily have a large impact on the calculated initial crack sizes. Stated differently, cracks having very similar initial sizes can have final sizes that differ greatly. Figure 1 shows that the initial crack size at beginning of life is essentially the same whether the crack propagates to Section XI criteria or whether the crack propagates through the wall. This implies that a substantial portion of usage is needed to propagate an initial crack to Section XI criteria and then only a small amount of usage is needed to propagate a crack from the Section XI size to a through-wall crack.

It is emphasized that, although the results imply that it is possible for a flaw to grow to a through-wall size from the allowable size, only the trend is meaningful because the equation for predicting initial flaw size is invalid for through-wall cracks. Specifically, as the flaw depth approaches the size of the wall thickness, the assumption that the membrane stress and bending stress correction factors are both unity becomes invalid. Results showing initial crack sizes are given in Figure 1, and sample calculations in Appendix B demonstrate how similar results were obtained for a subsurface flaw (air environment).

4. CONCLUSIONS AND RECOMMENDATIONS

The results of this study present an additional basis for determining acceptable flaw sizes. Although no specific acceptance standards can be recommended owing to the simplified nature of this analysis, it is concluded that the effects of allowable cyclic loading should be considered with the potential for crack propagation in establishing acceptance standards. In addition, it is concluded that, of the parameters evaluated in this study, usage factor and service environment have the most influence on crack growth.

As stated previously in Section 2, there are concerns and questions regarding the application of fatigue stresses allowed by the Code. The comment most frequently made is that evaluation on the basis of a usage factor of 1.0 is unrealistically conservative. This is principally because normal operating conditions rarely include such high levels of fatigue usage and, even when they do, declining stress gradients would limit crack growth. These concerns and others are important and must be considered when specific acceptance standards are developed.

It is also concluded that, because of the limited scope of this study, a complete understanding of the significance of these results is not possible without extensive additional effort. Therefore, it is premature either to define the extent of any immediate problem or to propose specific solutions. Further study considering realistic component design and service conditions is needed in order to provide more specific conclusions.

The Code bodies should provide practical limits on usage factor. For Section III of the Code, development of these limits should include consideration of many factors, including workmanship standards, flaw detection capability, threshold stress intensities, and service environment. Similarly, for Section XI of the Code, limits on usage factor should be included in the basis for the present acceptance standards. Also, consideration should be given to requiring special design acceptance standards and special inspection requirements for components that can be expected to experience either high usage factors or severe environmental conditions. In addition, it may be necessary to review the limits of the S-N data or require a crack propagation analysis or both if a component is subjected to a large number of cycles of stress below the apparent endurance limit.

Whether the results of this study have identified a potential practical shortcoming in code design procedures or whether occasions when components are subjected to high levels of alternating stress are unrealistically rare, the development of flaw acceptance standards should be consistent throughout the design, construction, and inspection phases of the Code.

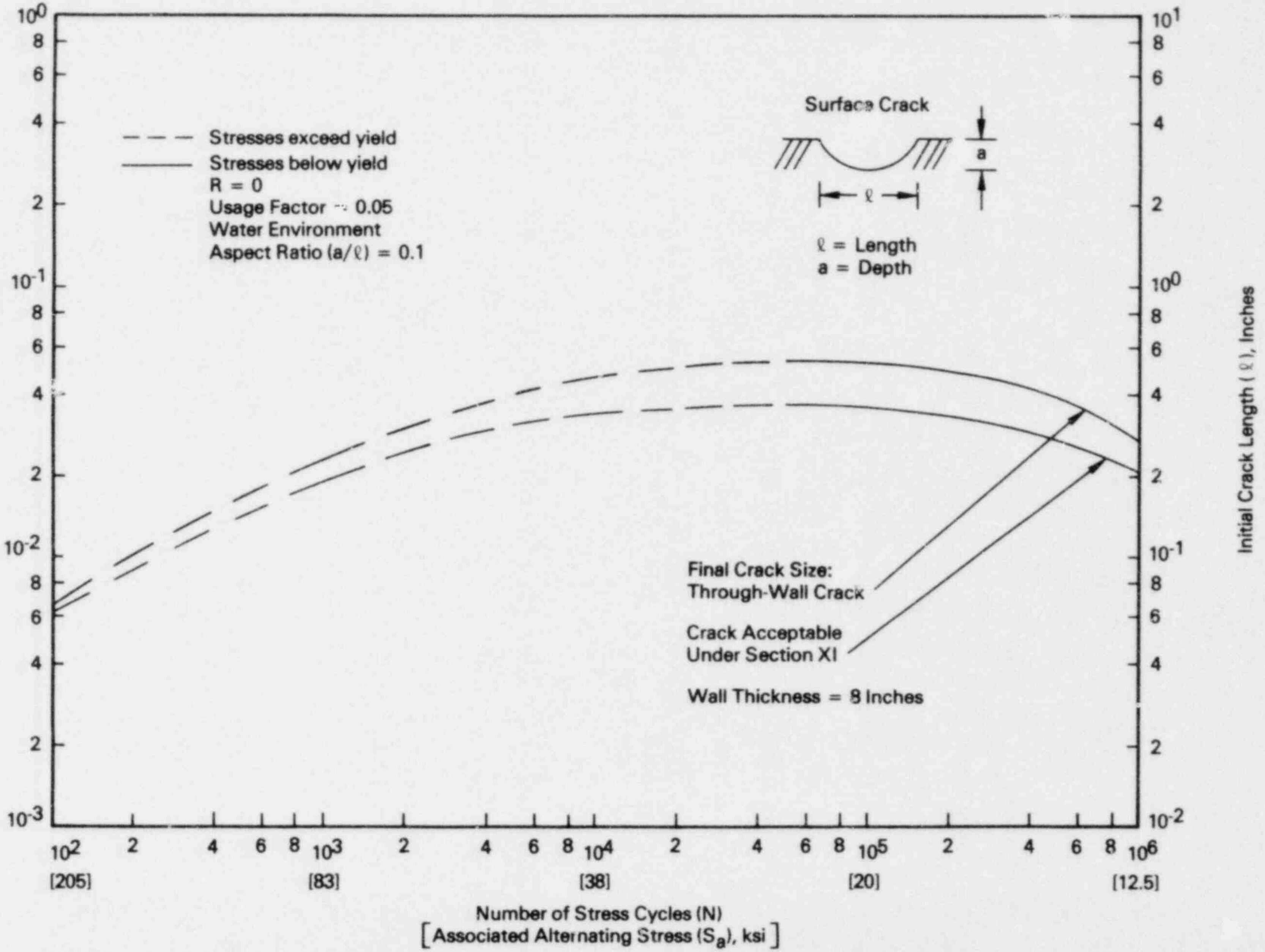

Figure 1. Initial Crack Size for Through-Wall Growth and Growth to Satisfy Section XI Criteria for a Typical Usage Factor

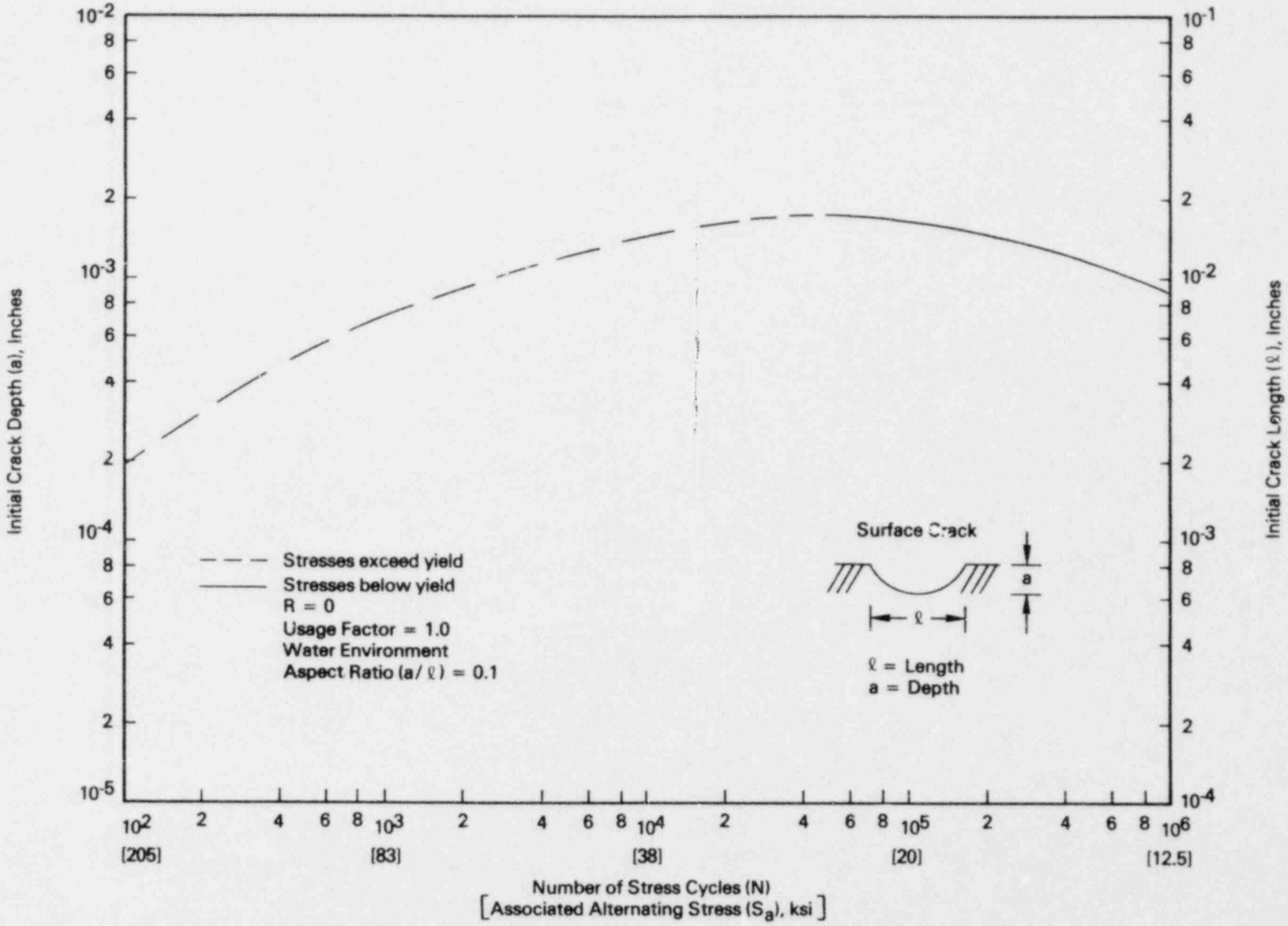

Figure 2. Initial Crack Size for Growth to Section XI Criteria With a Usage Factor of One

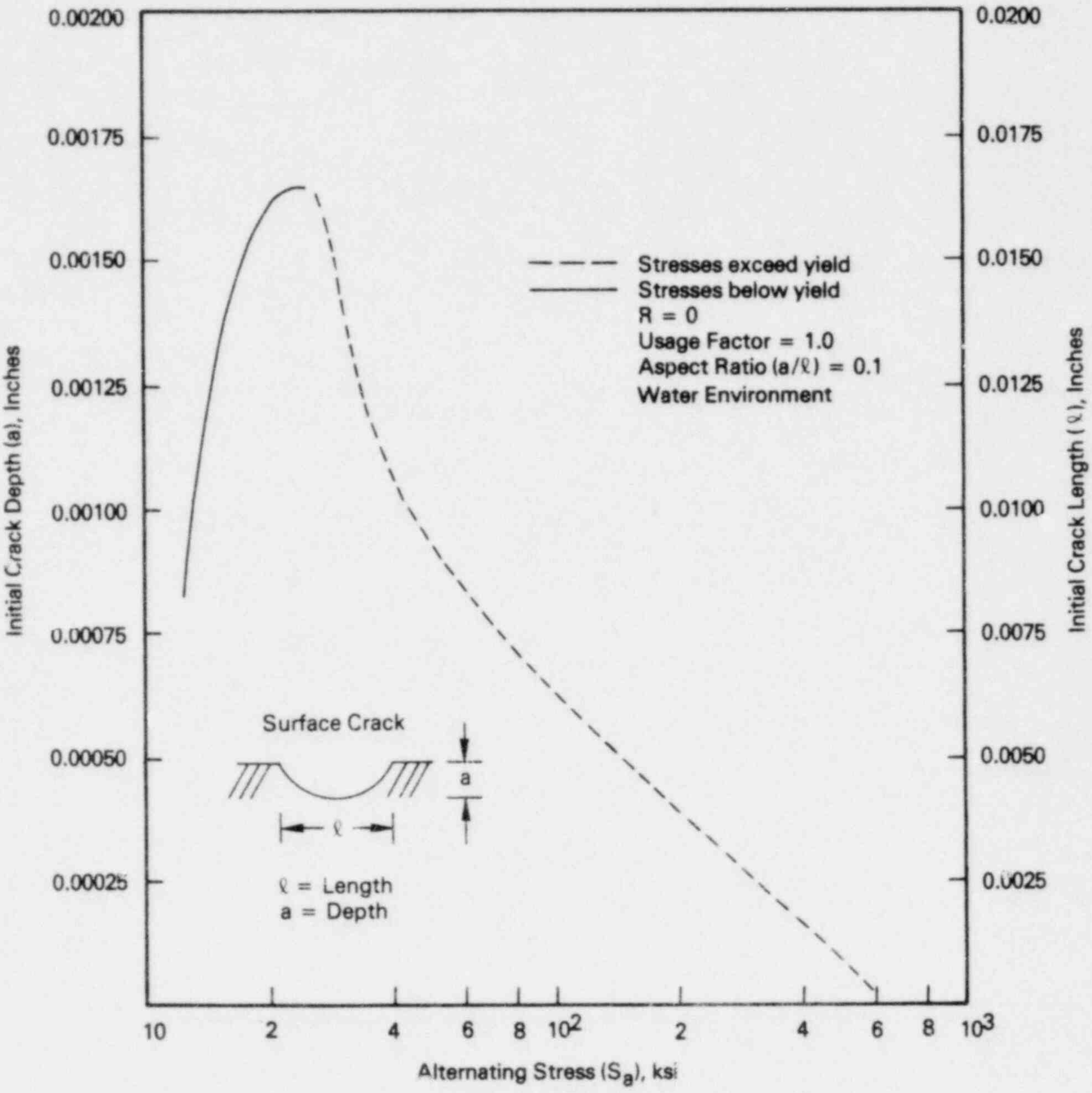

Figure 3. Initial Crack Size Plotted Against Alternating Stress

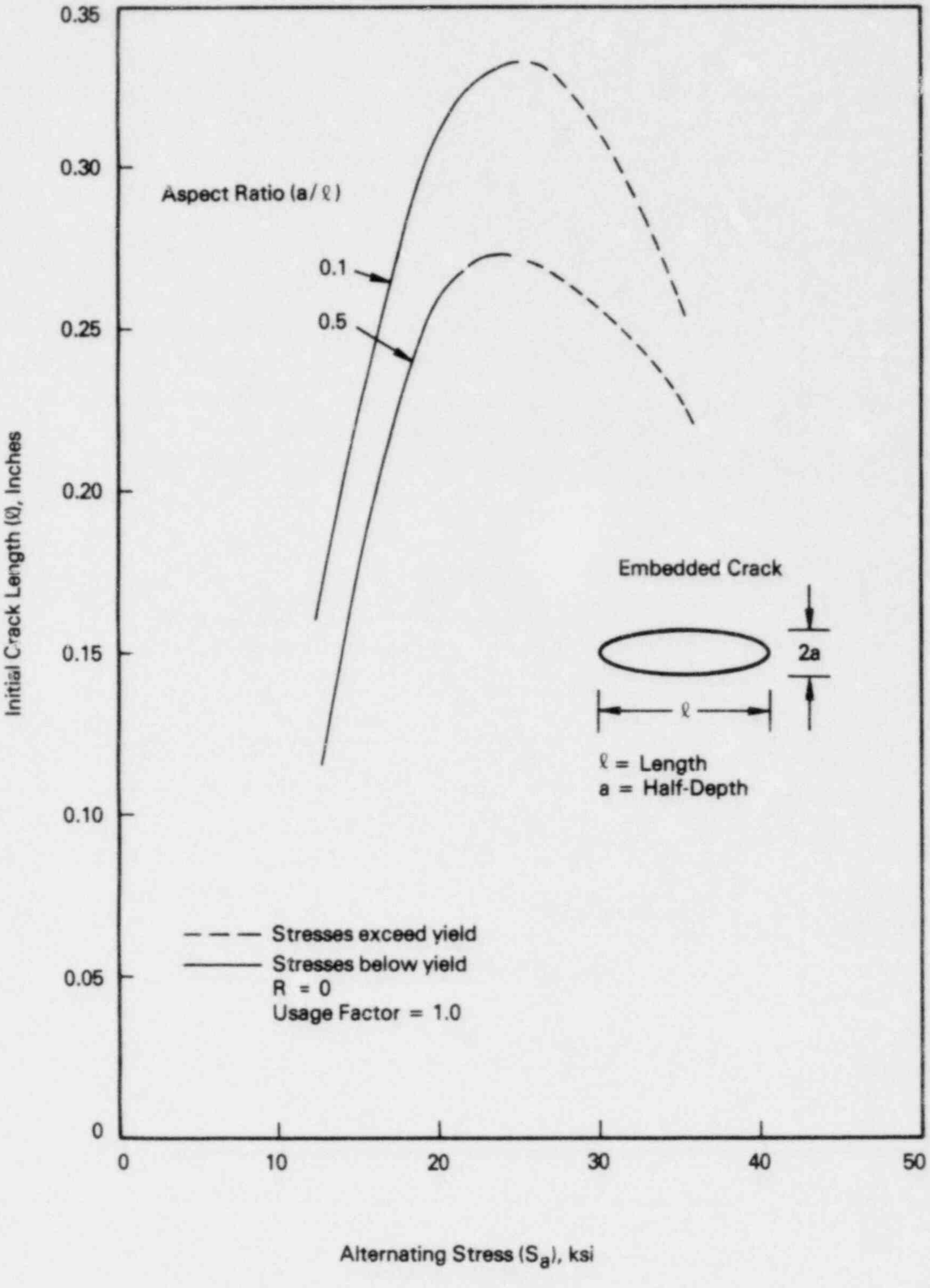

Figure 4. Effect of Aspect Ratio on Initial Crack Length in an Air Environment

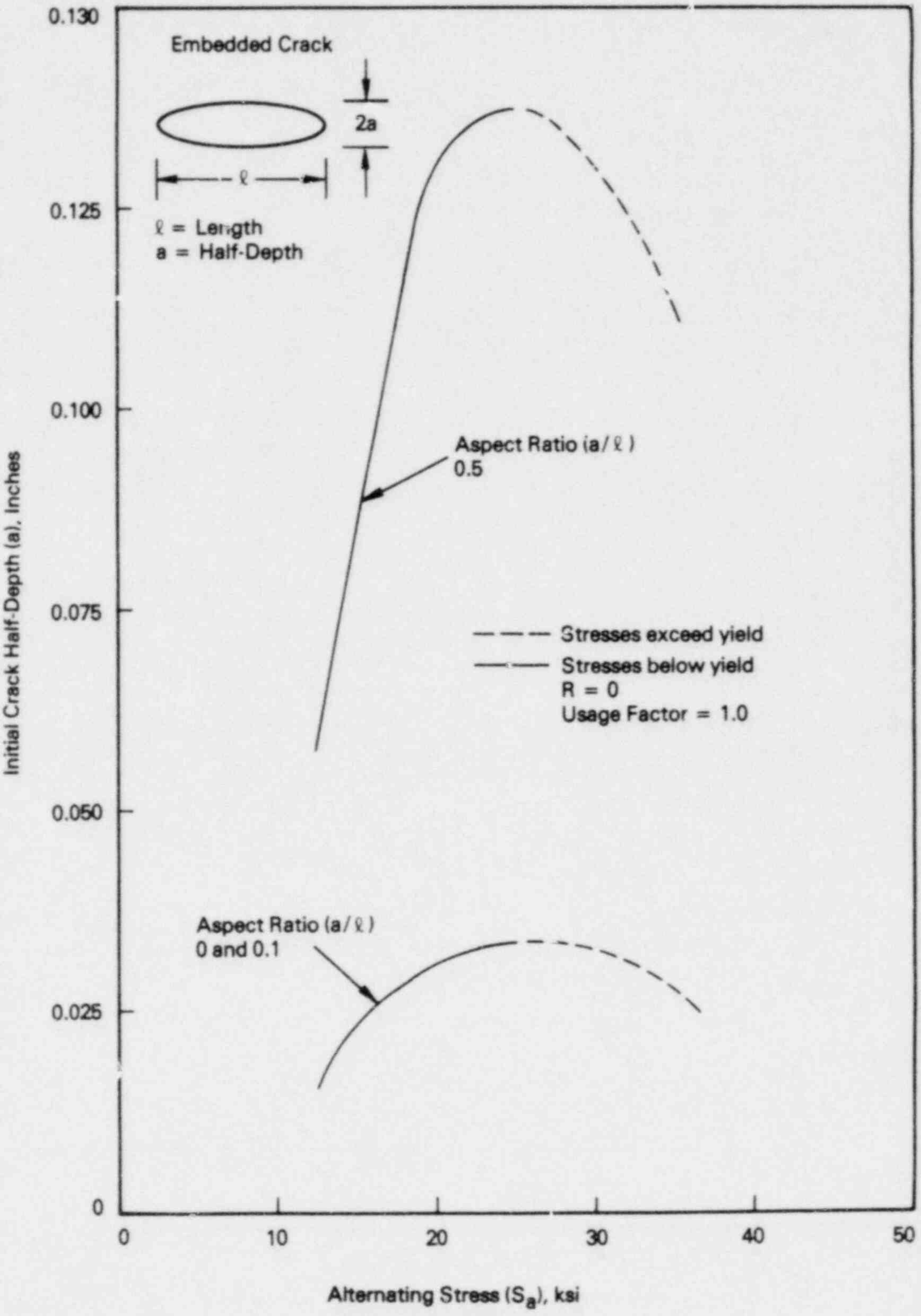

Figure 5. Effect of Aspect Ratio on Initial Crack Half-Depth in an Air Environment

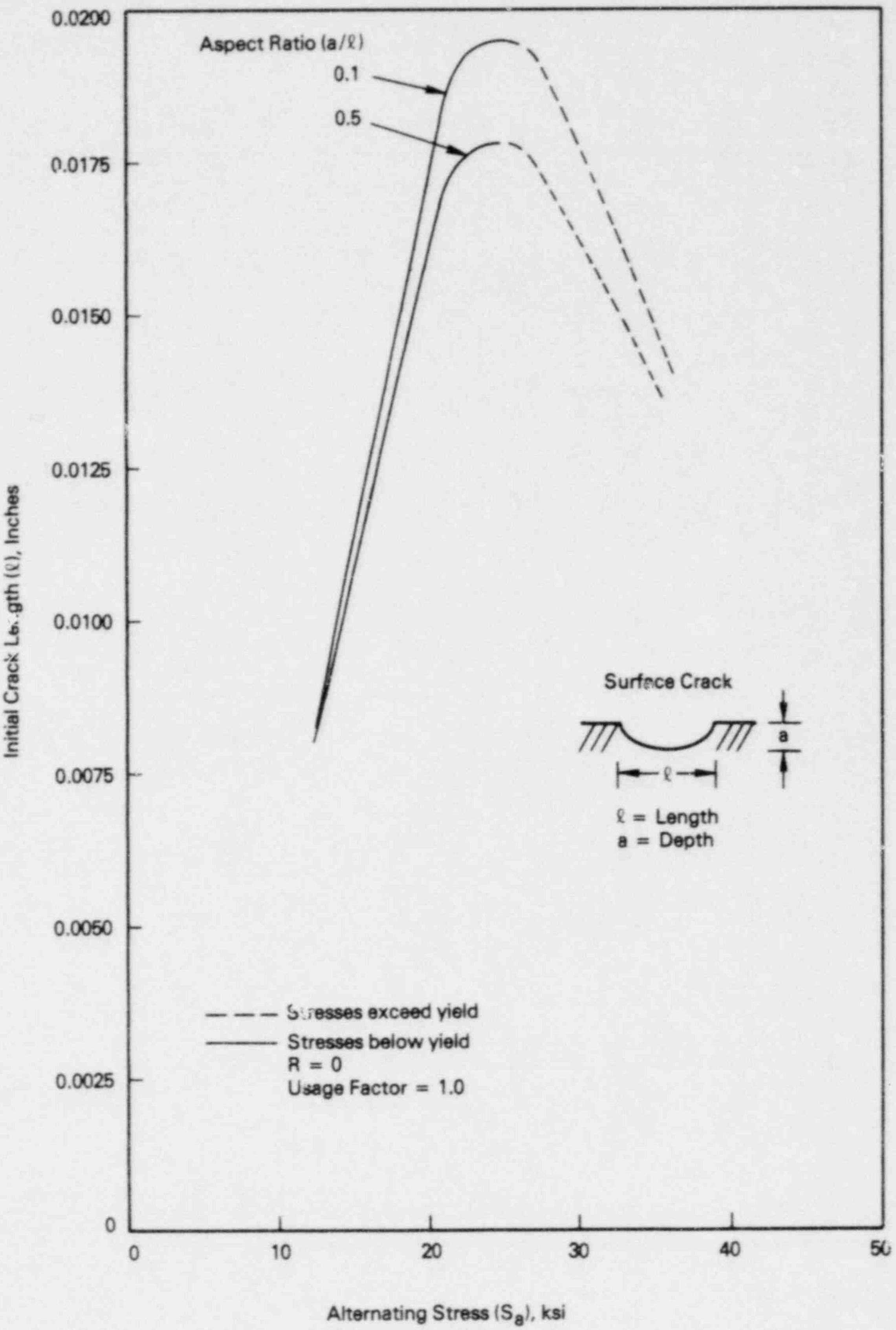

Figure 6. Effect of Aspect Ratio on Initial Crack Length in a Water Environment

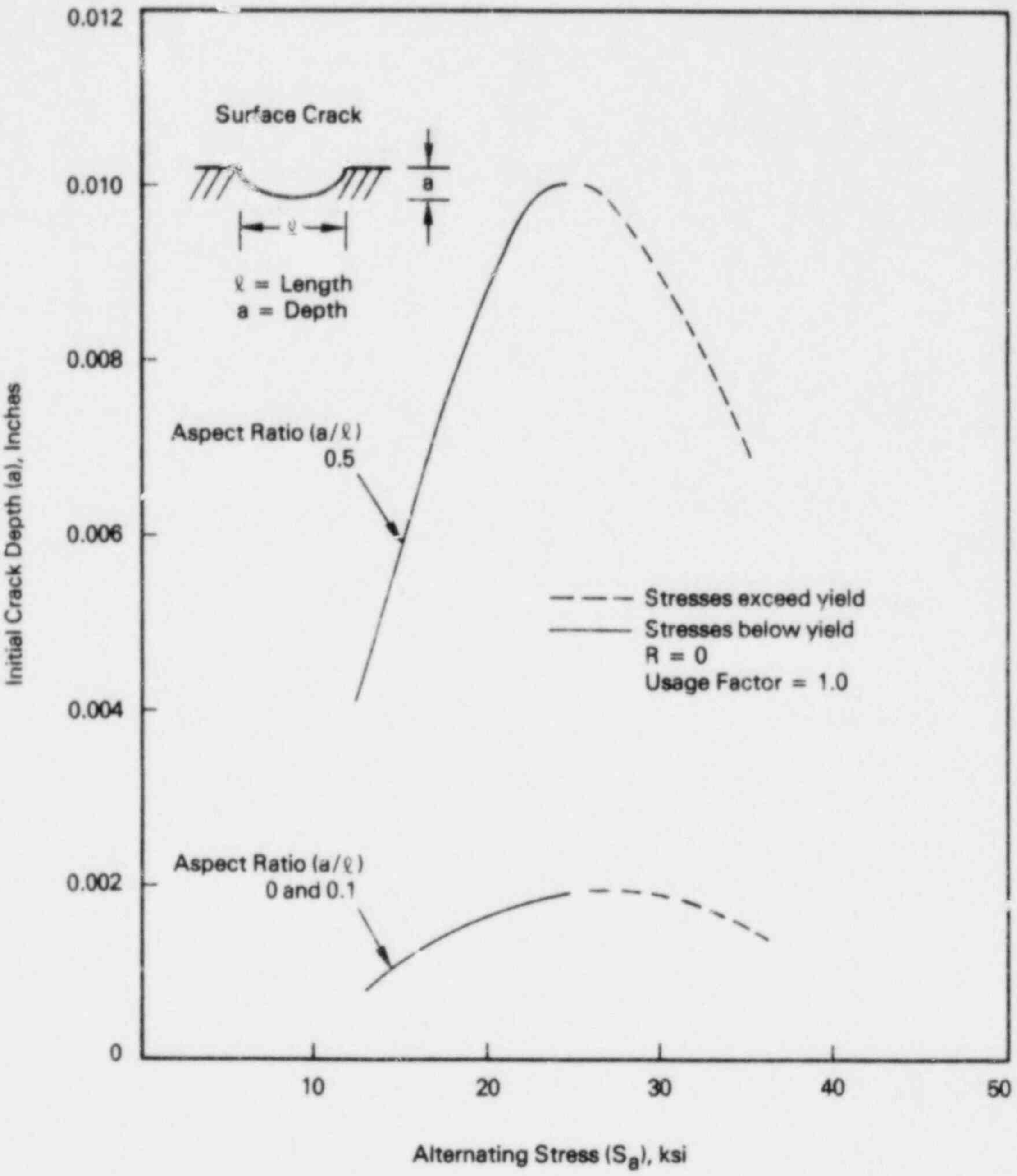

Figure 7. Effect of Aspect Ratio on Initial Crack Depth in a Water Environment

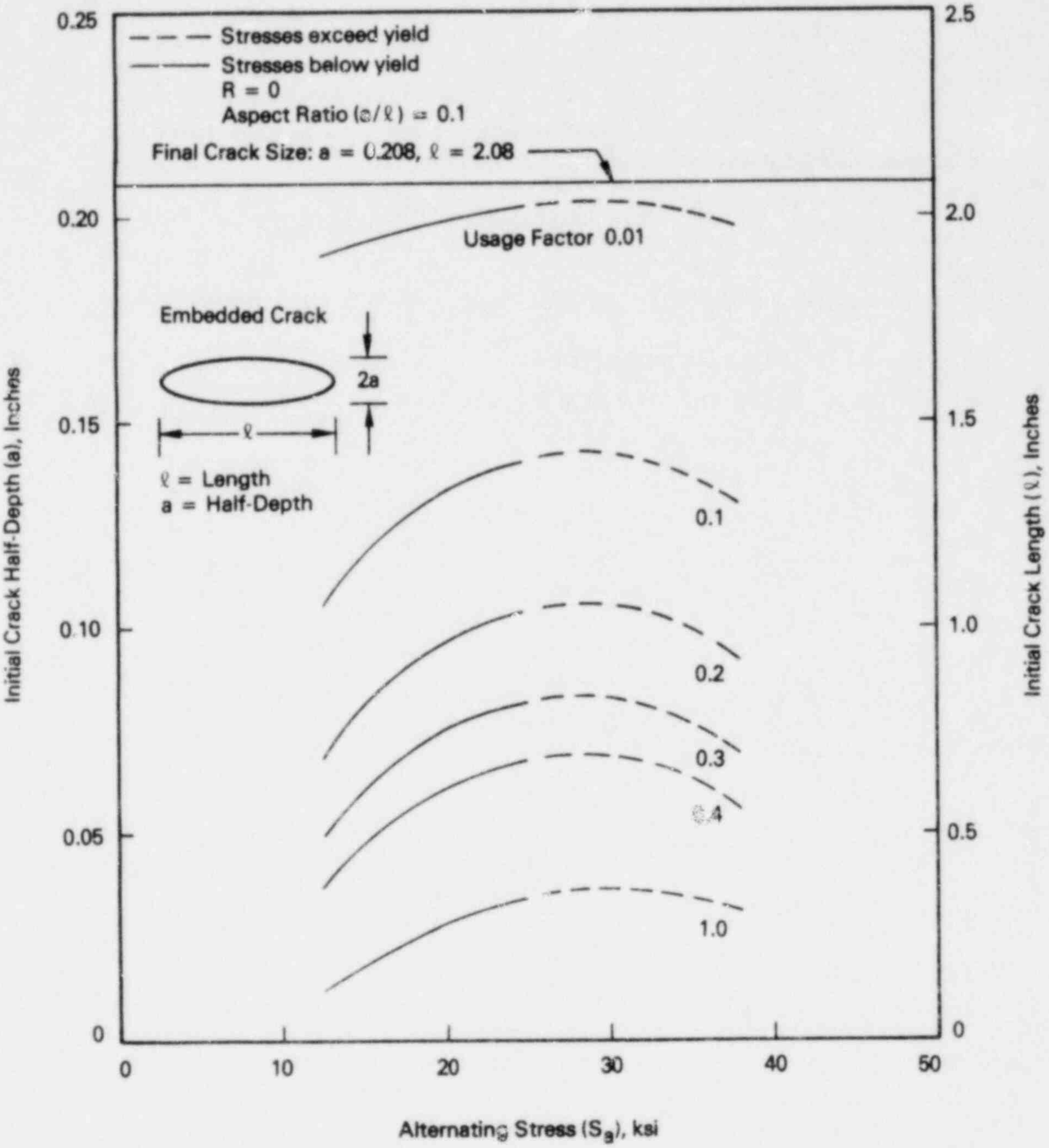

Figure 8. Effect of Usage Factor on Initial Crack Size in an Air Environment

Table I.

MATRIX IDENTIFYING PARAMETERS THAT ARE VARIED IN FIGURES 1-8

Parameter	Figure No.							
	1	2	3	4	5	6	7	8
Final Crack Size								
Section XI Criteria	X	X	X	X	X	X	X	X
Through-Wall*	X							
Environment (da/dN from Section XI)								
Embedded flaw (air environment)				X	X			X
Surface flaw (water environment)	X	X	X			X	X	
Aspect Ratio	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
				0.5	0.5	0.5	0.5	
					0**		0	
Usage Factor	0.05	1.0	1.0	1.0	1.0	1.0	1.0	0.01
								0.1
								0.2
								0.3
								0.4
								1.0

---

*A through-wall crack is a mathematical exercise for representing the upper limit of crack size. The results are interpreted for trends only.

**An aspect ratio of 0 is a mathematical exercise for representing the upper limit for a long flaw. The results are interpreted for trends only.

REFERENCES

1. American Society of Mechanical Engineers, "Rules for Construction of Nuclear Power Plant Components," ASME Boiler and Pressure Vessel Code, Section III, Division 1 and Appendices, Winter 1979 Addenda.

2. American Society of Mechanical Engineers, "Rules for Inservice Inspection of Nuclear Power Plant Components," ASME Boiler and Pressure Vessel Code, Section XI, Division 1 and Appendices, 1977 Edition, Winter 1979 Addenda.

3. Doty, W. D., "Section III Ad Hoc Task Group on Nondestructive Examination Acceptance Standards," Text of Address, Proceedings, Forty-eighth General Meeting, National Board of Boiler and Pressure Vessel Inspectors, April 30-May 4, 1979.

4. American Society of Mechanical Engineers - Section XI Task Group on Flaw Evaluation, "Flaw Evaluation Procedures: ASME Section XI," Edited by T. V. Marston, Nuclear Power Division, Electric Power Research Institute, EPRI NP-719-SR, August 1978.

5. Mayfield, M. E., Forte, T. P., Rodabaugh, E. C., Leis, B. N., Eiber, R. J., "Cold Leg Integrity Evaluation," NUREG/CR-1319, Prepared by Battelle Columbus Laboratories for the U.S. Nuclear Regulatory Commission, February 1980. Available for purchase from the NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission, Washington, DC 20555, and/or the National Technical Information Service, Springfield, VA 22161.

APPENDIX A

CRACK PROPAGATION ANALYSIS

The American Society of Mechanical Engineers (ASME) Code gives a standardized procedure for performing crack propagation analyses. In the ASME procedure, a method for approximating crack shapes is coupled with crack growth equations to determine the final size of the flaw after being subjected to operational loads. The cracks are approximated by ellipses of the same general size and shape.

Two equations for crack propagation are given in Appendix A to ASME Section XI. The first gives the stress intensity variation, ΔK_I, as

$$\Delta K_I = (M_m \Delta\sigma_m + M_b \Delta\sigma_b)\sqrt{\pi a/Q} \tag{1A}$$

where $\Delta\sigma_m$, $\Delta\sigma_b$ = variation of membrane and bending stresses (ksi)
M_m, M_b = membrane stress and bending stress correction factors
Q = flaw shape parameter
a = minor half-diameter (half-depth) for embedded flaw or flaw depth for surface flaw (in)
ℓ = crack length (in)

The second equation relates the crack growth rate, da/dN (in/cycle), to the stress intensity variation, ΔK_I (ksi$\sqrt{\text{in}}$),

$$da/dN = C\Delta K_I^{3.726} \tag{2A}$$

where C is an empirically derived coefficient. For a crack in an air environment, C is given as 2.67×10^{-11}. For a crack in a water environment, C is given as 37.95×10^{-11}.

To proceed with the derivation of the desired relationships, it is necessary to first employ the assumption that M_m and M_b are unity. Also, using the assumption that the sum of the variations of membrane stress and bending stress is equivalent to twice the alternating stress intensity, S_a, given in the Appendices to Section III of the code, Equation 1A can be rewritten as:

$$\Delta K_I = 2S_a\sqrt{\pi a/Q}. \tag{3A}$$

Employing the third assumption that cracks grow in a self-similar manner and separating variables in Equation 2A, integrating, and then substituting Equation 3A, one obtains:

$$a_i = [a_f^{-0.863} + 0.863CN(2S_a\sqrt{\pi/Q})^{3.726}]^{-1.159} \tag{4A}$$

where

a_i = initial value of a (in)

a_f = final value of a (in)

N = number of stress cycles

S_a = alternating stress intensity from Table I-9.1 of ASME Section III (ksi)

A similar equation can be found on page F-73 of Reference 4. The results from Equation 4A and the equation in Reference 4 were compared, and adequate correlation was obtained.

One additional item of information that can be obtained from Equation 4A is for the case in which a_f is allowed to become very large, i.e., grow through the wall. For the cases considered in this study, the first term in the brackets in Equation 4A becomes negligible and Equation 4A reduces to:

$$a_i = [0.863CN(2S_a\sqrt{\pi/Q})^{3.726}]^{-1.159}. \qquad (5A)$$

Although a crack can become very large and grow through a wall, some of the assumptions that were employed in deriving Equation 4A are violated; hence, Equation 5A is not valid. However, Equation 5A represents an upper limit for crack growth, and the results can be interpreted for trends.

APPENDIX B

SAMPLE CALCULATIONS

1. CALCULATION OF INITIAL CRACK SIZES OF EMBEDDED FLAW

1.1 Section XI Criteria

In order to use Section XI criteria, the wall thickness and the crack aspect ratio must be known. For this example, a wall thickness of 8 inches and an aspect ratio of 0.1 (subsurface flaw) are chosen. With these parameters, the final crack size, a_f, as determined from Table IWB-3510-1 in Section XI must not exceed 2.6% of the wall thickness. Therefore,

$$a_f = 0.208 \text{ inch.}$$

Equation 4A may then be used to calculate the initial crack size:

$$a_i = [a_f^{-0.863} + 0.863(2.67 \times 10^{-11})N(2S_a\sqrt{\pi/Q})^{3.726}]^{-1.159}$$

where

a_i is the initial value of a

a_f is the final value of a

S_a,N are the alternating stress intensity and number of stress cycles, respectively, from the S-N data

Q is the flaw shape factor.

The values for S_a and N are determined from Table I-9.1 in the Appendices to Section III of the code. They will be taken as $S_a = 20$ ksi with the corresponding value for $N = 10^5$ cycles. The specified minimum yield strength for ferritic steels of the type considered is 50 ksi; therefore, the value of $(\sigma_m + \sigma_b)/\sigma_{ys}^*$ is 0.4. For an aspect ratio (a/ℓ) of 0.1 and a stress ratio of 0.4, the value of the flaw shape factor (Q) from Figure A-3300-1 of Section XI is approximately 1.0. On substituting the appropriate values into Equation 4A, the initial value of a (a_i) is found to be:

$$a_i = [0.208^{-0.863} + 0.863(2.67 \times 10^{-11})(10^5)$$

$$(2 \times 20\sqrt{\pi/1.0})^{3.726}]^{-1.159}.$$

$$a_i = 2.782 \times 10^{-2} \text{ inch.}$$

1.2 Through-Wall Crack

To determine the size of an initial crack that might be expected to propagate through the wall, Equation 5A is used. On substituting the values for S_a, N, and Q that were used in the previous calculation, the initial crack size for this case is found to be:

$$a_i = 3.483 \times 10^{-2} \text{ inch.}$$

---

[*] σ_{ys} represents the minimum yield strength for the material considered in this example.

It is clear that the difference between the initial crack size for the through-wall crack and the initial crack size based on the Section XI criteria is 0.007 inch. Since the aspect ratio is 0.1, the difference between the lengths of the initial cracks is 0.070 inch.

2. EFFECT OF WALL THICKNESS ON INITIAL CRACK SIZE CALCULATIONS

Although there is some effect of wall thickness on the calculated initial crack size, this effect is not as significant as one might expect. This is shown by the following calculation:

Using Table IWB-3514-2 for an embedded flaw in a 5-inch-thick wall, the final flaw size can be calculated to be:

$$a_f = 5 \times 0.026 = 0.130 \text{ inch.}$$

Using Equation 4A, the initial flaw size can then be calculated:

$$a_i = 2.52 \times 10^{-2} \text{ inch.}$$

This result is not drastically different from the value obtained for a wall thickness of 8 inches (2.782×10^{-2} inch).

3. CALCULATION OF STRESS INTENSITY VARIATION

Employing the assumptions stated in Appendix A, the stress intensity variation is given as:

$$\Delta K_I = 2S_a\sqrt{\pi a/Q}$$

Using values determined previously, the initial stress intensity variation may be determined as:

$$\Delta K_I = 2 \times 12.5\sqrt{\pi(0.016)/1} \quad \text{ksi}\sqrt{\text{in}}$$

$$\Delta K_I = 5.6 \ \text{ksi}\sqrt{\text{in}}$$

APPENDIX C

NUMERICAL RESULTS IN TABULAR FORM

TABLE C-I

Initial Size of Surface Flaw with a Usage Factor of 0.05 and an Aspect Ratio of 0.1 for Through-Wall Growth and Growth to Satisfy Section XI Criteria in a Water Environment (See Figure 1)

N	S_a(ksi)	Initial Crack Depth (in)	
		Section XI Criteria	Through-Wall Growth
10^2	205	6.3E-3	6.7E-3
10^3	83	1.9E-2	2.3E-2
10^4	38	3.4E-2	4.7E-2
10^5	20	3.7E-2	5.2E-2
10^6	12.5	2.2E-2	2.7E-2

TABLE C-II

Effect of Aspect Ratio on Initial Size of Embedded Flaw with a Usage Factor of 1.0 in an Air Environment (See Figure 5)

N	S_a(ksi)	Initial Crack Half-Depth (in)	
		$a/\ell = 0$ & 0.1	$a/\ell = 0.5$
10	580	7.2E-4	4.5E-2
10^3	83	1.4E-2	6.3E-2
10^4	38	2.6E-2	1.1E-1
10^5	20	2.8E-2	1.2E-1
10^6	12.5	1.6E-2	5.7E-2

TABLE C-III

Effect of Aspect Ratio on Initial Size of Surface Flaw with a Usage Factor of 1.0 in a Water Environment (See Figure 7)

N	S_a(ksi)	Initial Crack Depth (in) a/ℓ = 0 & 0.1	a/ℓ = 0.5
10	580	3.4E-5	2.4E-3
10^3	83	7.1E-4	3.5E-3
10^4	38	1.4E-3	6.9E-3
10^5	20	1.6E-3	7.6E-3
10^6	12.5	8.4E-4	4.1E-3

TABLE C-IV

Effect of Usage Factor* on Initial Size of Embedded Flaw with an Aspect Ratio of 0.1 in an Air Environment (See Figure 8)

		Initial Crack Half-Depth (in)					
N	S_a(ksi)	U=0.01	U=0.1	U=0.2	U=0.3	U=0.4	U=1.0
10	580		9.7E-3	4.5E-3	2.9E-3	2.1E-3	7.2E-4
10^3	83	1.9E-1	9.7E-2	6.1E-2	4.4E-2	3.4E-2	1.4E-2
10^4	38	2.0E-1	1.3E-1	9.2E-2	7.1E-2	5.7E-2	2.6E-2
10^5	20	2.0E-1	1.3E-1	9.7E-2	7.5E-2	6.1E-2	2.8E-2
10^6	12.5	1.9E-1	1.1E-1	6.8E-2	5.0E-2	3.9E-2	1.6E-2

---

*Usage factor is defined as the ratio of the number of cycles experienced by a component at a specific value of alternating stress intensity to the number of cycles that the component is capable of withstanding (from the S-N data) for the same value of alternating stress intensity.

NRC FORM 335
(7-77)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG-0726

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
Preliminary Analysis of the Effect of Fatigue Loading and Crack Propagation on Crack Acceptance Criteria for Nuclear Power Plant Components

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

7. AUTHOR(S)
W. F. Anderson, G. H. Weidenhamer, Earl R. C. Johns

5. DATE REPORT COMPLETED

MONTH	YEAR
September	1980

DATE REPORT ISSUED

MONTH	YEAR
April	1981

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Office of Standards Development
U.S. Nuclear Regulatory Commission
Washington, D. C. 20555

6. *(Leave blank)*

8. *(Leave blank)*

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Office of Standards Development
U.S. Nuclear Regulatory Commission
Washington, D. C. 20555

10. PROJECT/TASK/WORK UNIT NO.

11. CONTRACT NO.

13. TYPE OF REPORT
Technical Report

PERIOD COVERED *(Inclusive dates)*

15. SUPPLEMENTARY NOTES

14. *(Leave blank)*

16. ABSTRACT *(200 words or less)*

A preliminary study was initiated to evaluate the conservatism of existing design methods regarding cyclic loadings and crack growth in nuclear power plant components. The study was based on the assumption that the application of the ASME Boiler and Pressure Vessel Code (the Code) should be consistent throughout the design, operation, and inspection phases. Specifically, any undetectable or allowable crack subjected to fatigue stress levels permitted by Section III of the Code should not be expected to grow larger than the size permitted by Section XI inservice inspection criteria.

The objective of this analysis was to estimate the magnitude of acceptable initial crack sizes under various conditions and to identify some important parameters that may be used in the development of crack acceptance standards. The results are intended not to be rigorous but to show general trends from the effect of various parameters on crack size consistent with appropriate sections of the Code.

The results indicate that very small cracks can propagate to sizes larger than postulated Code limits if they experience the total number of cycles of stress that are allowed by the Code (a usage factor of one). The two parameters that have the most effect on crack propagation are found to be usage factor and environment.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
Unlimited

19. SECURITY CLASS *(This report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

21. NO. OF PAGES

22. PRICE
$

NRC FORM 335 (7-77)