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PROBABILISTIC TREATMENT OF STRESS CORROSION CRACKING IN SENSITIZED 304 STAINLESS STEEL WELDMENTS IN BWR PIPING

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ABSTRACT

The purpose of this report is to describe recent expansions of the previously developed PRAISE code to include recent information to make it more applicable to probabilistic analysis of sensitized weldments in BWR piping. The expansions of PRAISE are concentrated in three areas: (i) probabilistic treatment of stress corrosion crack initiation; (ii) probabilistic treatment of residual stresses; and (iii) benchmarking with field observations of cracking in BWR piping. This expanded version of PRAISE is called PRAISE-CC, and is a significant extension of earlier versions, which considered only piping failures due to fatigue crack growth of pre-existing weld defects. PRAISE-CC retains the earlier PRAISE capabilities.

The expansions incorporated into PRAISE-CC were made possible by the great amount of stress corrosion cracking test data and residual stress information that has become available over the past few years. This information was formulated into probabilistic models and incorporated into PRAISE-CC. Results generated by use of the code were then compared with field observations of crack indications and leaks in operating BWRS. Adjustments in residual stress levels were made in order to improve the agreement between calculations and observations. This improved the confidence in the code and provided improved credibility of code predictions under conditions for which field experience is not yet available. The generation of piping reliability results for a wide variety of problems and interpretation of the results is not a portion of the reported efforts.

1.0 INTRODUCTION

The purpose of this report is to describe recent expansions of the previously developed PRAISE code [1-3] to include recent information to make it more applicable to sensitized weldments in boiling water reactor piping. The expansions of PRAISE reported herein are concentrated in three areas: (i) crack initiation under stress corrosion cracking conditions; (ii) probabilistic treatment of residual stresses; and (iii) benchmarking with field observations of cracking in BWR piping. This expanded version of the code is called PRAISE-CC.

Figure 1 provides a schematic diagram of the components of the original version of PRAISE [1,2]. This version provided a probabilistic fracture mechanics treatment of piping failure due to fatigue propagation of crack-like weld defects introduced during fabrication. Since stress corrosion crack growth was not included, the resulting models were applicable to pressurized water reactors (PWRs), but not austenitic piping in early generations of boiling water reactors (BWRs). The fracture mechanics treatment was later expanded in the PRAISE-B code to include stress corrosion crack growth of pre-existing defects [3]. However, crack initiation is an important facet of cracking behavior in early commercial BWRs that was not included. In order to overcome this deficiency, the work reported herein was undertaken. This was made possible, to a large extent, by the great amount of test data that has become available since the inception of the original PRAISE code.

Another important aspect of cracking in BWRs is as-welded residual stresses. Previous treatments [3] considered representative residual stresses in a deterministic manner. In actuality, as-welded residual stresses in piping are expected to have a large variance; hence, statistical considerations are important. Recent expansion of information on residual stresses in BWR piping allowed a statistical treatment of this important factor to be incorporated into PRAISE-CC.

Figure 2 provides a schematic diagram of various components of PRAISE-CC. A comparison of Figures 1 and 2 shows the considerable expansion incorporated into PRAISE-CC.

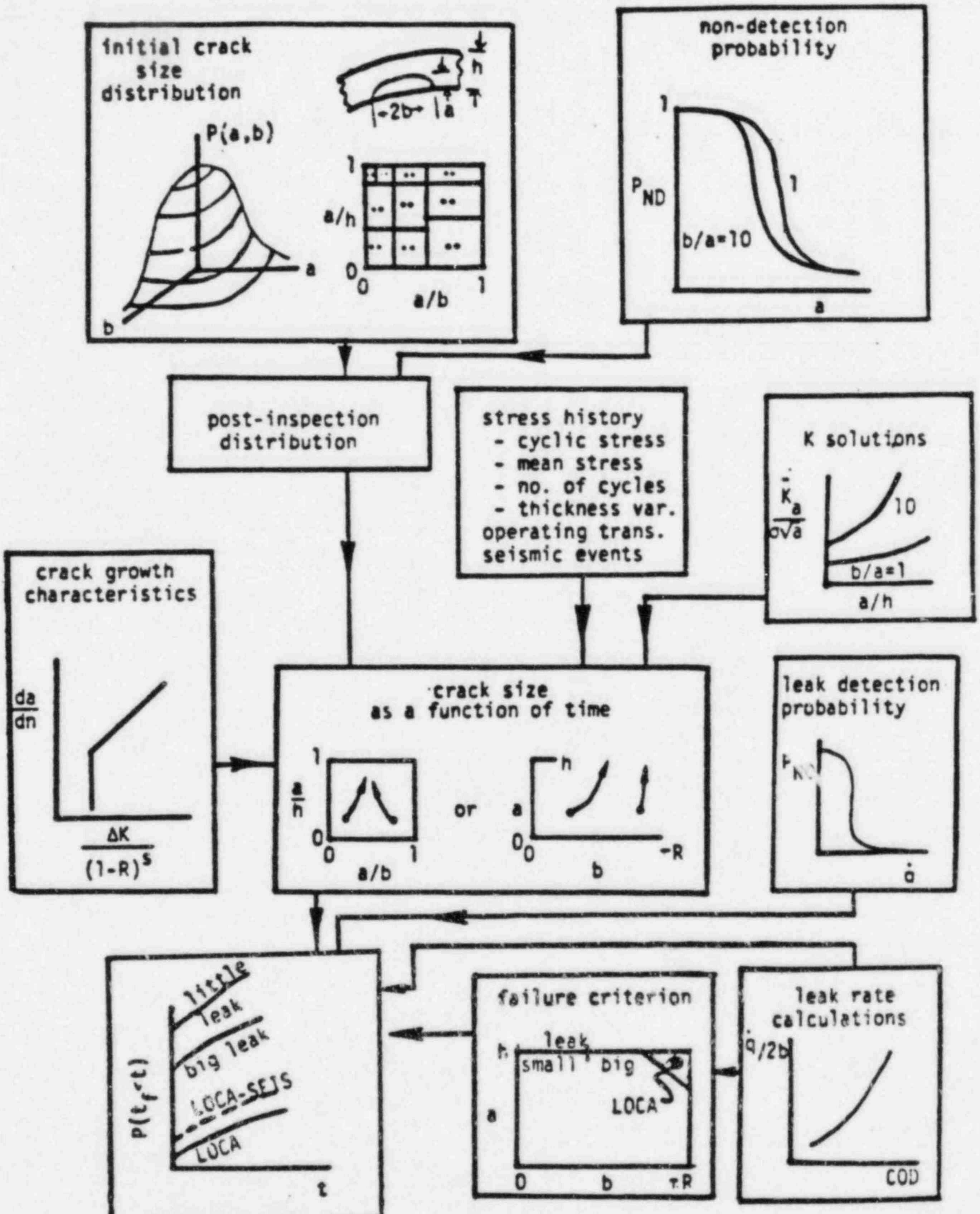

Figure 1. Schematic diagram of steps in analysis of reliability of a given weld location.

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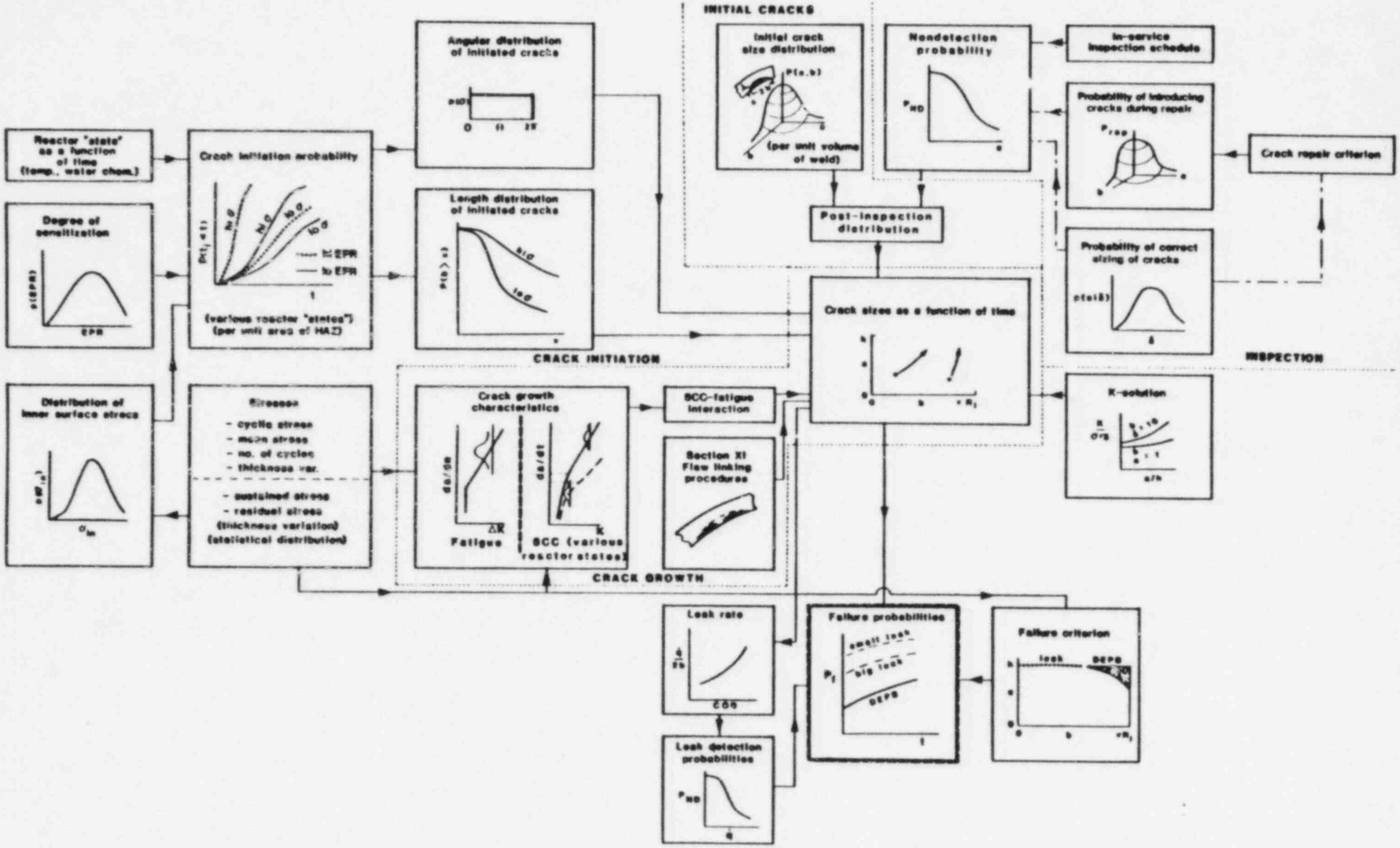

Figure 2. Schematic diagram of various components of an expanded PRAISE model suitable for application to stress corrosion cracking.

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Recent years have also provided a significant increase in field experience in operating BWRs. Hence, it is now possible to compare the results of a probabilistic treatment of stress corrosion crack growth with actual observed performance. Alterations to components of PRAISE-CC were made in order to improve the agreement between predictions and observations. Such alterations improve the confidence in the code and provide improved credibility of code predictions of piping behavior under conditions for which field experience is not yet available. Such predictions have obvious use in the assessment of the utility of various proposed countermeasures in current and future BWRs. The purpose of this report is to describe the engineering basis of the probabilistic treatment of stress corrosion cracking incorporated into PRAISE-CC; the generation and interpretation of results is not a portion of the reported efforts. Appendix A provides a detailed description of input cards to PRAISE-CC, and, in conjunction with Reference 2, serves as a User's Manual. Appendix B provides the results of several sample problems generated by PRAISE-CC, which serves as benchmarks for PRAISE-CC users.

2.0 PROBABILISTIC TREATMENT OF STRESS CORROSION CRACKING AND RESIDUAL STRESSES

The probabilistic treatment of stress corrosion cracking and residual stresses is the major expansion of capabilities for piping reliability analysis to be reported herein. The engineering basis for these added capabilities will be described in this section.

2.1 Stress Corrosion Crack Initiation

The initiation and early growth of stress corrosion cracks is currently not well understood, and cannot be treated from a fracture mechanics standpoint. A semi-empirical approach was therefore taken to predict the time-to-initiation of a crack for a given set of conditions. This section describes the modeling of test data for describing crack initiation under plant operating conditions.

2.1.1 Analysis of Test Data

Test results on sensitized 304 austenitic stainless steel generated under laboratory conditions were used to obtain an empirical relationship between initiation times and test conditions, as well as to characterize scatter in the test results.

As has been extensively documented elsewhere, three conditions are necessary for intergranular stress corrosion cracking (IGSCC) in austenitic stainless steels: stress, environment, and sensitization. Thus, it appears reasonable to assume a multiplicative relationship such as the following between observed crack size and the three governing conditions:

$$a = f_1(\text{material})f_2(\text{environment})f_3(\text{loading}) \tag{1}$$

The crack length is given by the value of a. The functions f_1, f_2, and f_3 were determined in earlier work [4] by nonlinear curve fitting to numerous experimental data for sensitized 304 stainless steel. These functions are given by the following expressions:

$$f_1 = C_1 \, Pa^{C_2} \tag{2}$$

Pa is a measure of the degree of sensitization,

Pa = EPR in C/cm^2

C_1, C_2 are constants

$$f_2 = [1 - C_3 \, e^{C_4 O_2}] \exp\left(\frac{C_5}{T + 273}\right) \tag{3}$$

O_2 = oxygen concentration (ppm)

T = temperature (°C)

C_3, C_4, C_5 are constants

$$f_3 = \dot{\varepsilon}^{C_7} \, t^{C_{11}} \quad \text{(for constant strain rate loading conditions)} \tag{4a}$$

$\dot{\varepsilon}$ = strain rate (sec^{-1})

t = time (sec)

C_7, C_{11} are constants

$$f_3 = C_{10} \sigma^{C_8} \, t^{C_9} \quad \text{(for constant load conditions)} \tag{4b}$$

where σ = applied stress (ksi)

C_8, C_9, C_{10} are constants

The constants in the above equations, as determined by curve-fitting to numerous test results, are given in Table 1. The model has been successfully applied [4] to experimental data generated by several EPRI and NRC projects over the past decade.

The data base of Reference 4 was updated to include results that have recently become available. Most of the data was actually time-to-failure and the value of "a" was taken as the size of the intergranular crack at failure (when such information was available) or the specimen size (when no crack size

Table 1
NUMERICAL VALUES OF CONSTANTS C_i

C_1	48.96
C_2	0.6
C_3	0.8654
C_4	-0.5036
C_5	-2734.0
C_6	-626.0
C_7	0.5
C_8	3.0
C_9	0.5
C_{10}	6.224×10^{-8}
C_{11}	1
C_{16}	0.00685

Pa = EPR in C/cm^2
O_2 = Oxygen content in parts per million
T = Temperature in degrees Celsius
$\dot{\varepsilon}$ = Strain rate in sec^{-1}
t = Time in seconds
σ = Stress in thousands of pounds per square inch

information was given). The data base contains both constant load (CL) and constant elongation rate test (CERT) data. Both furnance-sensitized and weld-sensitized specimens were included and covered a broad range in degree of sensitization. The range of test temperatures was 100-300°C and oxygen concentration varied between 0.2 and 100 ppm.

The model developed in Reference 4 was slightly modified to better suit the current purposes. First, CERT and CL data were treated separately to provide estimates for plant loading and steady-state operation, respectively. Secondly, for purposes of treating crack initiation, the time-to-failure was assumed to be equal to the time-to-initiation, t_I. The time-to-initiation for a given set of input variables (O_2, T, Pa, σ, or $\dot{\varepsilon}$) was considered to be a random variable whose mean and standard deviation are governed by the values of the input variables. In accordance with Reference 4, and as embodied in equation 1, two "damage parameters" were defined; one for constant load (CL) and one for plant loading (CERT). These "damage parameters" were defined as follows:

$$\Gamma_\sigma = C_1 Pa^{C_2} [1 - C_3 \exp(C_4 O_2)] \exp\left(\frac{C_5}{T + 273}\right) C_{10}\sigma^{C_8} \quad (5)$$

$$\Gamma_\varepsilon = C_1 Pa^{C_2} [1 - C_3 \exp(C_4 O_2)] \exp\left(\frac{C_5}{T + 273}\right) \dot{\varepsilon}^{C_7} \quad (6)$$

The above expressions are valid for $T \leq 150$°C. For $T > 150$°C, the term $[C_5/(T + 273)]$ is replaced by $C_{16} \exp[C_6/(T + 273)]$.

Figure 3 presents the time-to-initiation (t_I) as a function of the damage parameter for constant-loading conditions (Γ_σ). Corresponding results for CERT tests are presented in Figure 4. Data for both failures and non-failures are presented in both cases. These results show that t_I decreases with increasing damage parameters or severity of test conditions. However, considerable scatter in results is observed in all cases. The data of Figures 3 and 4 were partitioned into ranges of the damage parameters, and the mean

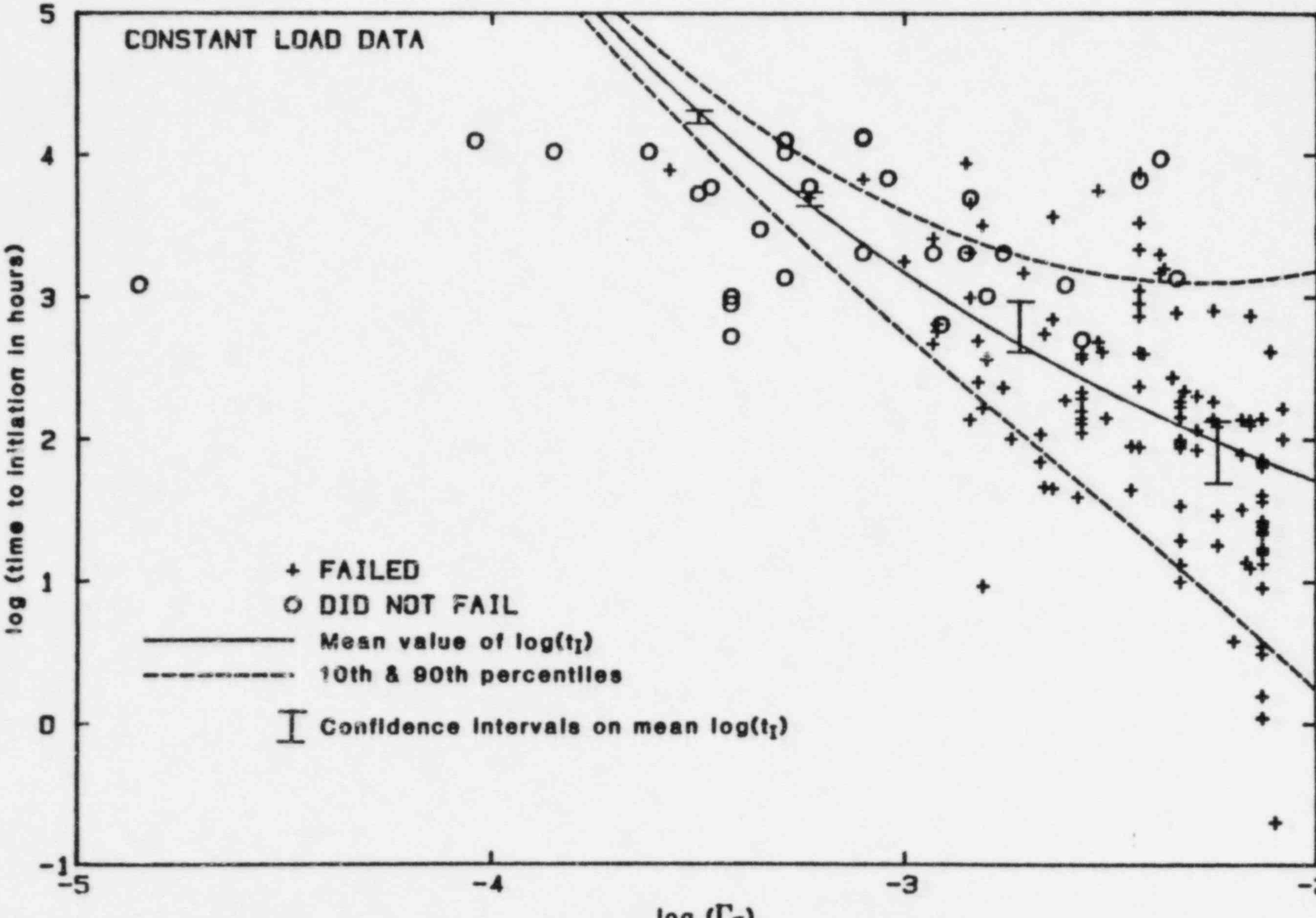

Figure 3. Time to initiation vs. Γ_σ.

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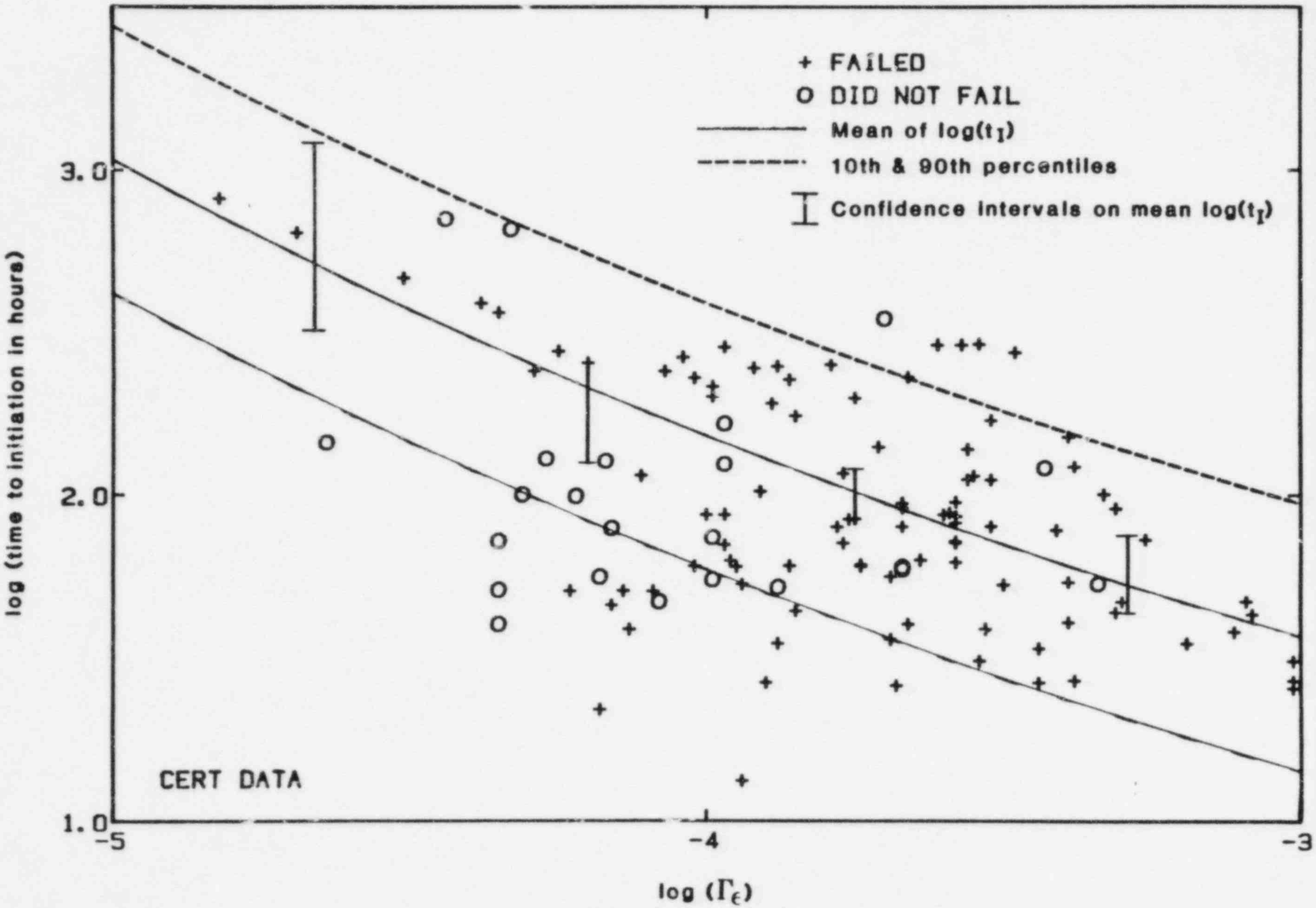

Figure 4. Time to initiation vs. Γ_ϵ.

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time-to-initiation, t_m, and standard deviation of time-to-initiation, t_{sd}, were evaluated for each range. Confidence intervals on t_m and t_{sd} were also generated. Standard maximum likelihood estimator procedures were employed, and it was assumed that t_I is lognormally distributed for any value of Γ_σ or Γ_ε. Such procedures utilize both failure and non-failure in estimation of the mean and standard deviation of the initiation time. Table 2 summarizes the results obtained for t_m and t_{sd} for both CL and CERT data. The 95% confidence intervals on the mean are shown as vertical bars on Figures 3 and 4.

Values of t_m and t_{sd} are dependent on the value of Γ_σ (or Γ_ε). A curve fit was performed in order to provide a means of describing this dependence, with the following results being obtained:

CL Data

$$\text{mean value of } \log t_I = 0.5\ \Gamma_\sigma^{-0.267}$$
$$\text{standard deviation of } \log t_I = 5.88 \times 10^{-6}\ (\log \Gamma_\sigma + 8)^{6.8} \qquad (7)$$

CERT Data

$$\text{mean of } \log t_I = 0.58\ \Gamma_\varepsilon^{-0.1437}$$
$$\text{standard deviation of } \log t_I = 0.32 \qquad (8)$$

In these equations, all times are in hours.

Figures 3 and 4 present a plot of the 10th, 50th, and 90th percentiles of the time-to-initiation as a function of the appropriate damage parameter based on the assumption of lognormality of t_I and equations 7 and 8. The fact that the data points are approximately symmetrically distributed about the median (on log paper) provides support for the assumption of a lognormal distribution of t_I.

Equations 7 and 8, in conjunction with the assumption of lognormal t_I for a given set of conditions, and equations 5 and 6 serve to define the statistical distribution of initiation time for any given set of conditions.

Table 2

ESTIMATES OF MEAN AND STANDARD DEVIATION, OBTAINED BY MAXIMUM LIKELIHOOD PROCEDURES

Range of Log r	Mean of Log r	Mean of Log t_f	95% Confidence Limits for Mean Log t_f	Std. Deviation of Log t_f	95% Confidence Limits for Std. Deviation of Log t_f	
-3.5 to -3.0	-3.29	1.756	±0.144	0.266	0.207 - 0.373)	CERT
-4.0 to -3.5	-3.75	1.997	±0.0706	0.293	0.250 - 0.351)	
-4.5 to -3.5	-4.20	2.243	±0.145	0.375	0.298 - 0.507)	
-5.0 to -4.5	-4.66	2.796	±0.288	0.157	0.0889 - 0.585)	
-2.5 to -2.0	-2.24	1.877	±0.183	0.855	0.744 - 1.015)	CL
-3.0 to -2.5	-2.72	2.78	±0.165	0.590	0.493 - 0.733)	
-4.5 to -3.0	-3.50	4.26	±0.0278	0.063	0.0487 - 0.0891)	

NOTES:

For mean r_{σ} = -3.50
95% confidence interval on mean is: 4.26 - 0.0278 to 4.26 + 0.0278.

2.1.2 Distribution of Degree of Sensitization

Data on the degree of sensitization of as-welded 304 stainless steel piping was collected from a wide range of sources in the literature. Measurements were mostly made on 4 inch pipes at the inside diameter. The data thus obtained were analyzed to determine the nature of the statistical distribution of sensitization at the ID, with the results shown in Figure 5 being obtained. This figure shows that the degree of sensitization is approximately Weibull distributed with the following cumulative distribution

$$P(Pa < x) = 1 - e^{-(x/b)^c} \tag{9}$$

$b = 17.3\ C/cm^2$

$c = 1.05$

The corresponding mean and standard deviation of the degree of sensitization are 17.0 C/cm^2 and 16.1 C/cm^2, respectively.

2.1.3 Crack Initiation Under Varying Reactor States

The treatment of the probability of crack initiation presented in Section 2.1.1 was for conditions that do not vary in time. An actual plant is operated under conditions that do vary with time, and a means of accounting for this is required. To simplify the treatment of crack initiation, the plant lifetime is considered to be composed of plant start-up (CERT) and steady-state operation (CL).

The procedure for combining two reactor states to generate the distribution of crack initiation time is illustrated with the aid of an example. Referring to Figure 6, reactor states A and B are combined as follows:

1. Generate cumulative distributions of probability of crack initiation as a function of time, for states A and B using results presented in Section 2.1.1.
2. For reactor in State A for time Δt_1, obtain segment A_1 [P(0) to P(1)].

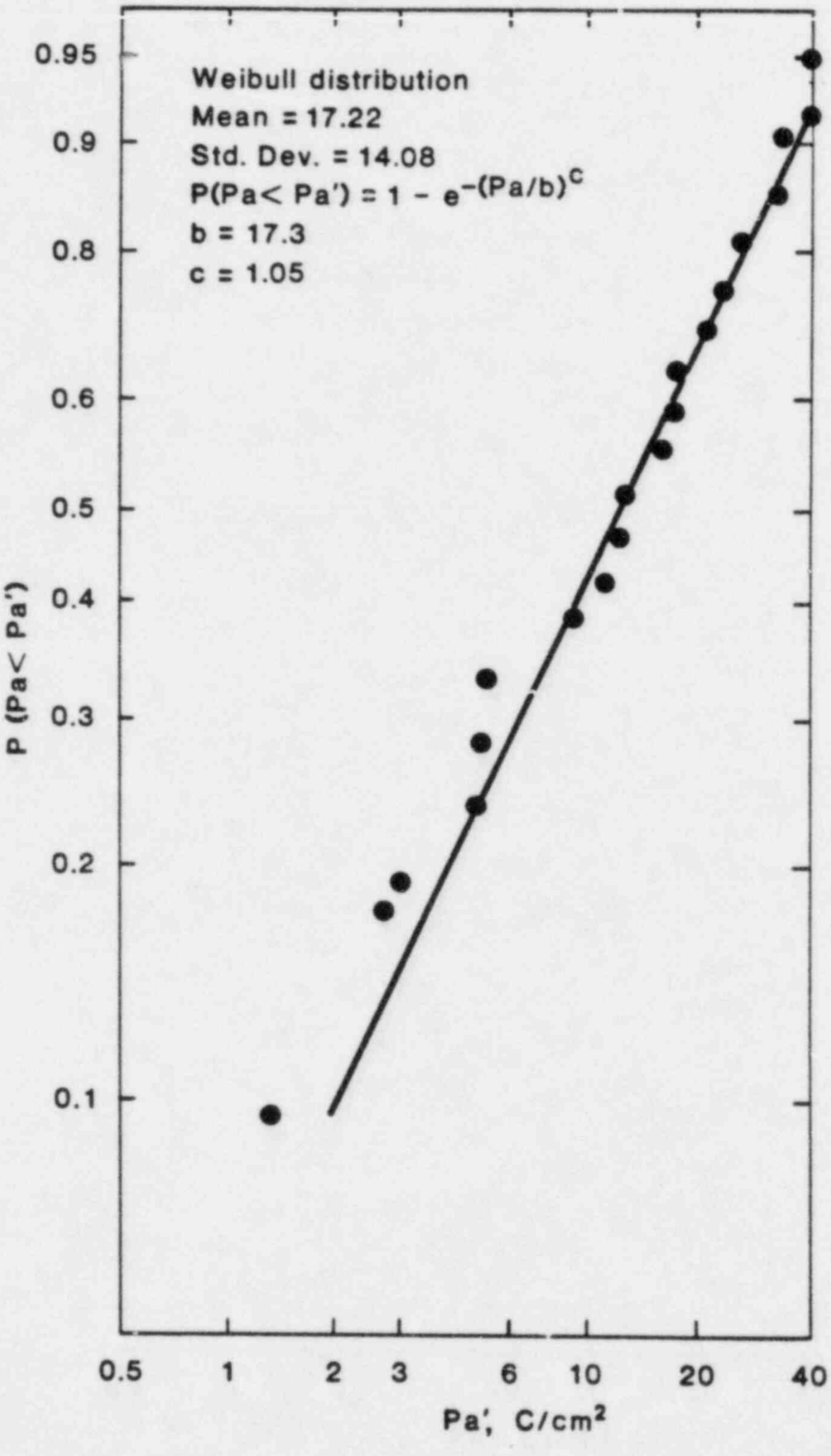

Figure 5. Cumulative distribution of degree of sensitization of as-welded 304 stainless steel piping showing fit of a Weibull distribution to the data points.

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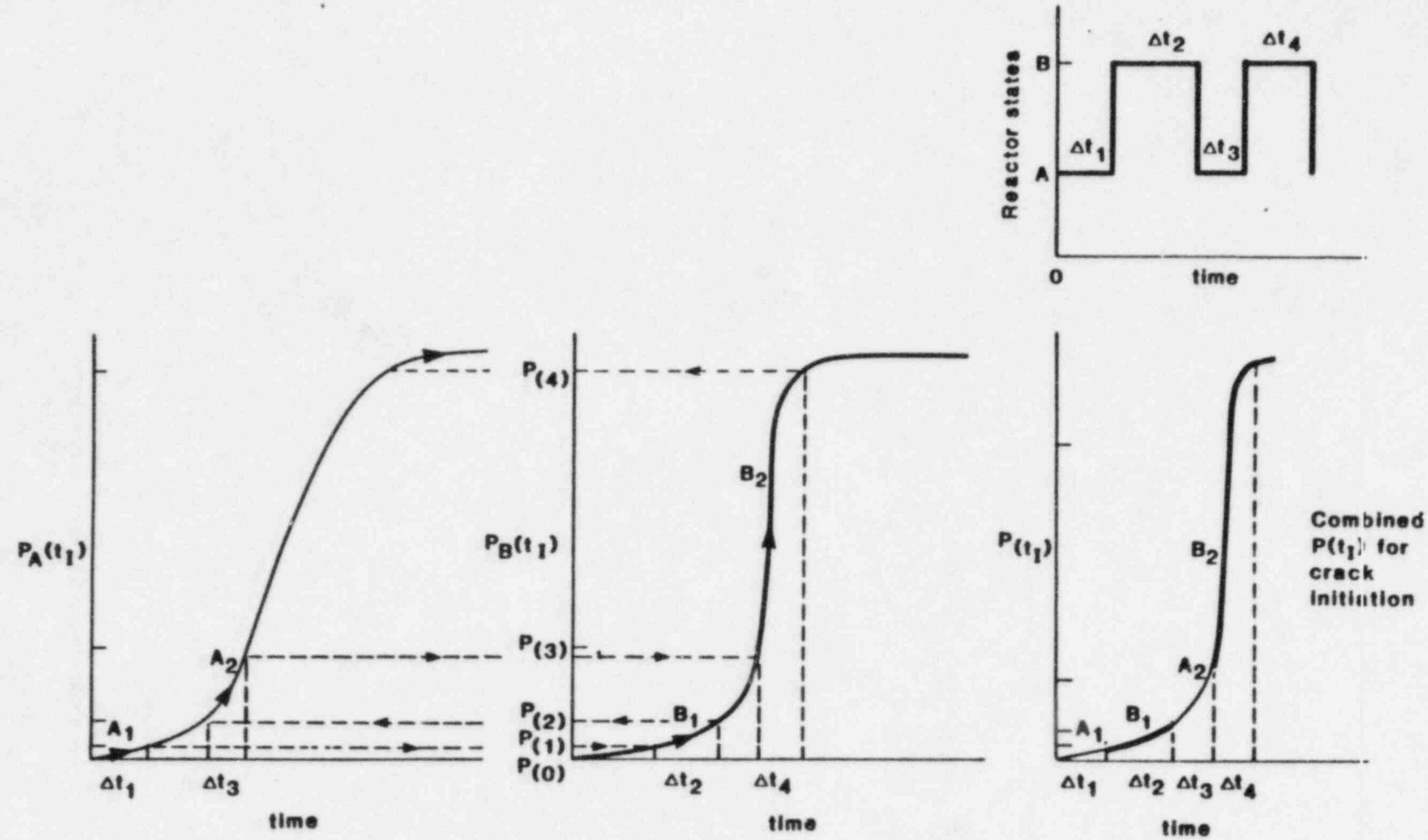

Figure 6. Schematic representation of combining reactor states to obtain overall probability of crack initiation.

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3. For reactor in state B for time Δt_2, find time corresponding to P(1) on $P_B(t)$ curve and obtain segment B_1 [P(1) to P(2)] on $P_B(t)$.

4. Repeat this procedure for all the reactor states that occur.

5. Combine segments A_1, B_1, A_2, ..., to obtain combined probability of crack initiation [P(t)].

This procedure provides the crack initiation probability as a function of time for varying operating reactor conditions.

2.1.4 Distribution of Initiated Crack Length

The distribution of initiated crack length ($\ell = 2b$) was assumed to be lognormal with the following characteristics:

median value of b = 0.0625 inch (1/16 inch)

$P(b > 0.5 \text{ inch}) = 0.01$

The depth of initiating cracks was fixed at 0.001 inch.

Subsequent sensitivity studies showed that calculated piping failure probabilities are only very weakly dependent on this assumed distribution of initiated crack lengths. Additional efforts to more precisely estimate the distribution were therefore not pursued.

2.1.5 Multiple Cracks in a Weld

Several cracks may initiate in a weld over the lifetime of a piping system. The number of possible initiation sites may be estimated by considering the length of weld to be made up of several "lab-sized" specimens. The laboratory specimens used in generating the data employed in Section 2.1.1 were typically 2 inches long. A weld in a 26 inch line (circumference ~ 68 inches) can therefore have 34 possible initiation sites. These cracks will initiate at various times. The initiation sites around the circumference of the weld are taken to be uniformly distributed.

The probability of crack initiation depends on (besides other factors) stress on the inside surface. The stress on the inside surface is described as

$$\sigma_s(\theta) = \sigma_p + \sigma_B \cos\theta + \sigma_{res}(0,\theta) \qquad (10)$$

where $\sigma_s(\theta)$ = stress on the inside surface
σ_p = stress due to pressure
σ_B = thermal expansion and dead weight stresses
$\sigma_{res}(0,\theta)$ = residual stresses on the inside surface
θ = angular location around pipe circumference

The thermal expansion and dead weight loads produce primarily a bending moment and σ_B is the maximum stress due to these bending moments. Values of σ_p and σ_B are obtained from a stress analysis of the piping, and the residual stresses are discussed in Section 2.5.

The initiated cracks are taken to be randomly located around the circumference. These random locations for cracks are generated by sampling from a uniform distribution of θ (0-360°). $\sigma_s(\theta)$ is calculated for each crack. The probability of crack initiation P(t) is generated for each of these cracks. Finally, a table of time of initiation is generated for all the cracks. This table of initiation times is ordered with increasing time and is used for "scheduling" crack initiation during the Monte Carlo simulations performed by PRAISE-CC.

2.2 Stress Corrosion Crack Propagation

The treatment of the growth of initiated cracks is described in this section. Such growth is considered to be composed of two phases: early growth not treatable by fracture mechanics and later growth which is treatable by fracture mechanics.

2.2.1 Crack Velocity at Initiation

Experimental observations of the growth of small cracks that have just initiated cannot be explained from a fracture mechanics standpoint. The growth of such cracks will therefore be treated by a means analogous to that employed above for time-to-initiation. An initiated crack is assumed to grow at a constant velocity until conditions are appropriate for treating crack growth by fracture mechanics. Such conditions are described below.

The same data base used for initiation times is employed for crack velocity at initiation. The apparent crack velocity ($\dot{a}$) is calculated by dividing the depth of the intergranular crack of the failed specimens by time to failure. For failed specimens, $\dot{a}$ versus Γ (damage parameter) were tabulated separately for CL and CERT data. The $\dot{a}$ versus Γ for CERT and CL conditions are plotted in Figures 7 and 8. As expected, there is large scatter in both sets of data. Linear regression analysis of the data resulted in the following expressions:

$$\log(\dot{a}) = F_\sigma + G_\sigma \log(\Gamma_\sigma) \quad \text{(for CL data, Figure 7)} \tag{11}$$

where $F_\sigma = 0.984$
$G_\sigma = 1.244$

and

$$\log(\dot{a}) = F_\varepsilon + G_\varepsilon \log(\Gamma_\varepsilon) \quad \text{(for CERT data, Figure 8)} \tag{12}$$

where $F_\varepsilon = 0.208$
$G_\varepsilon = 0.567$

The units of $\dot{a}$ are inches per day. To account for the scatter in the data, the intercepts F_σ and F_ε are considered to be random variables. The distributions of F_σ and F_ε are estimated from the data, and histograms of F_σ and F_ε are shown in Figures 9 and 10. The parameters of the distributions are as follows:

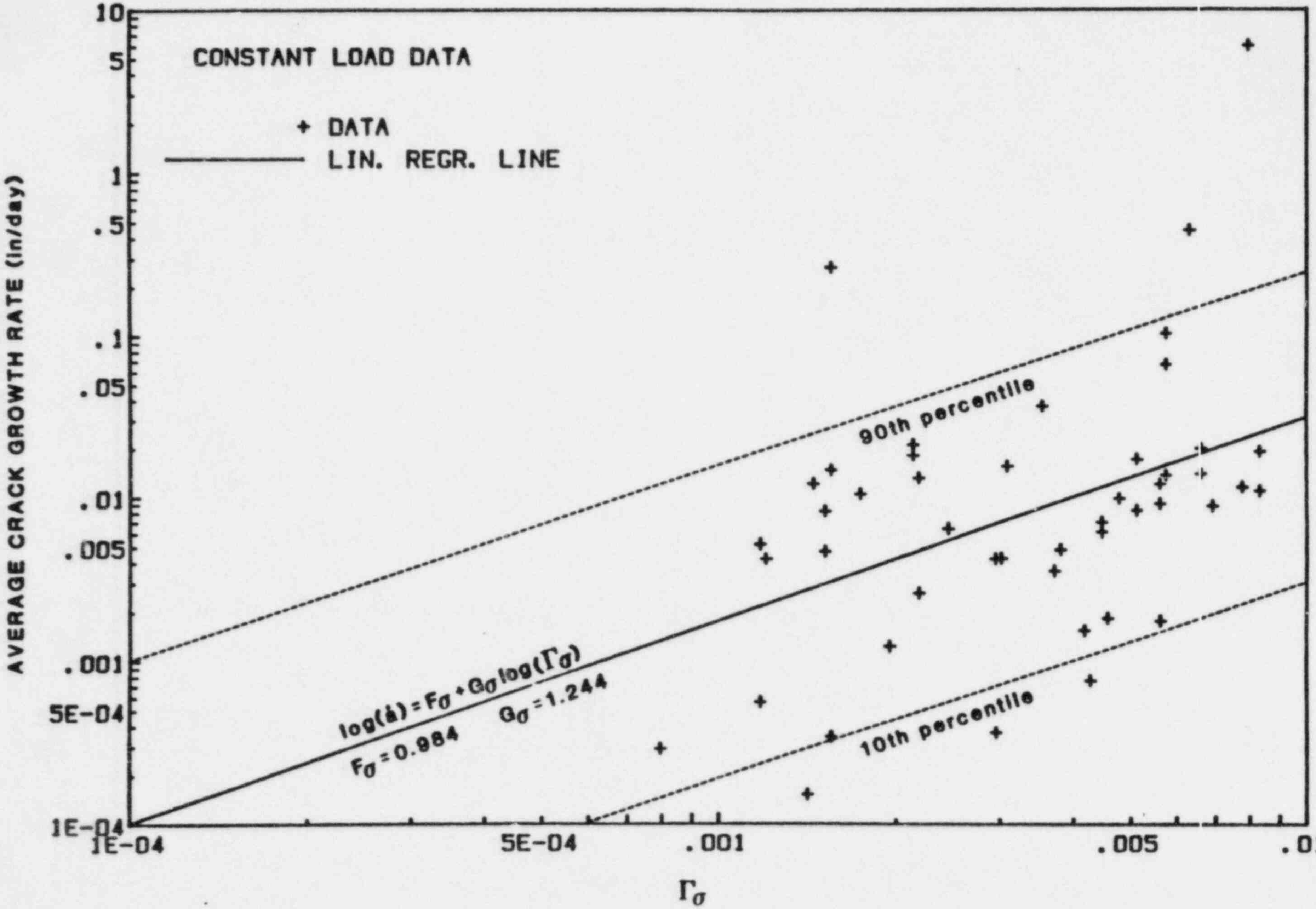

Figure 7. Average crack velocity at initiation vs. Γ_σ.

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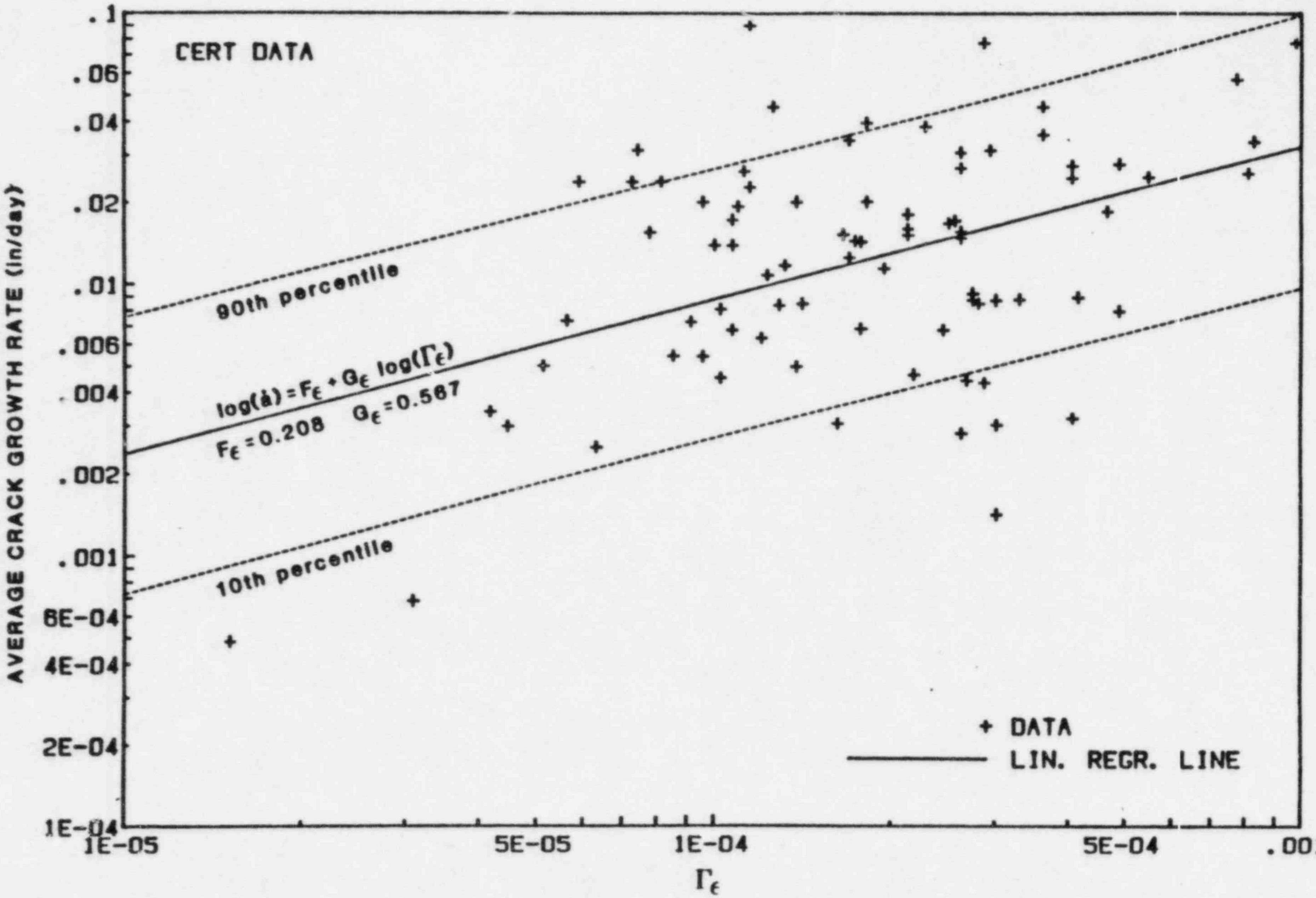

Figure 8. Average crack velocity at initiation vs. Γ_ϵ.

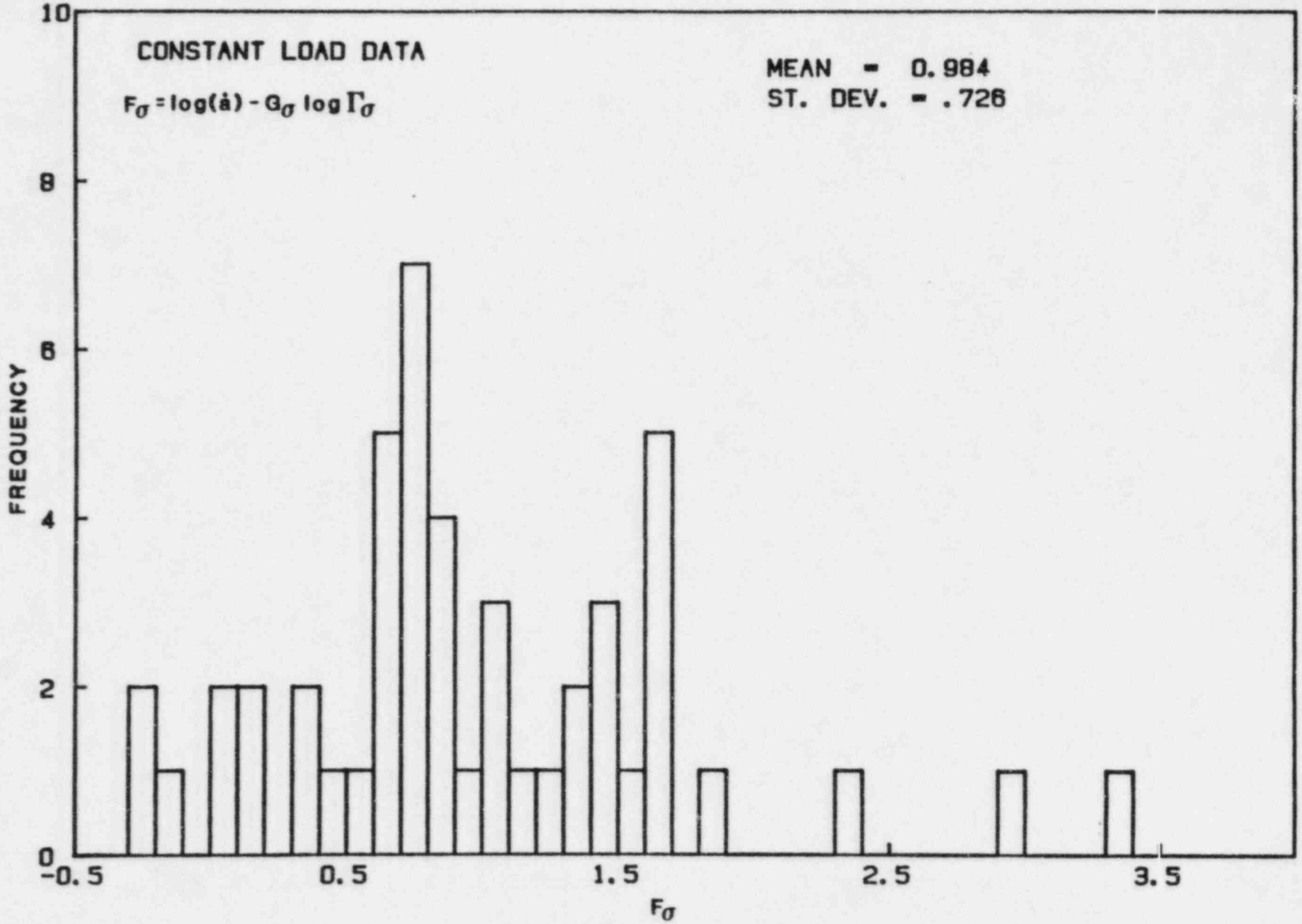

Figure 9. Distribution of F_σ (see Figure 7).

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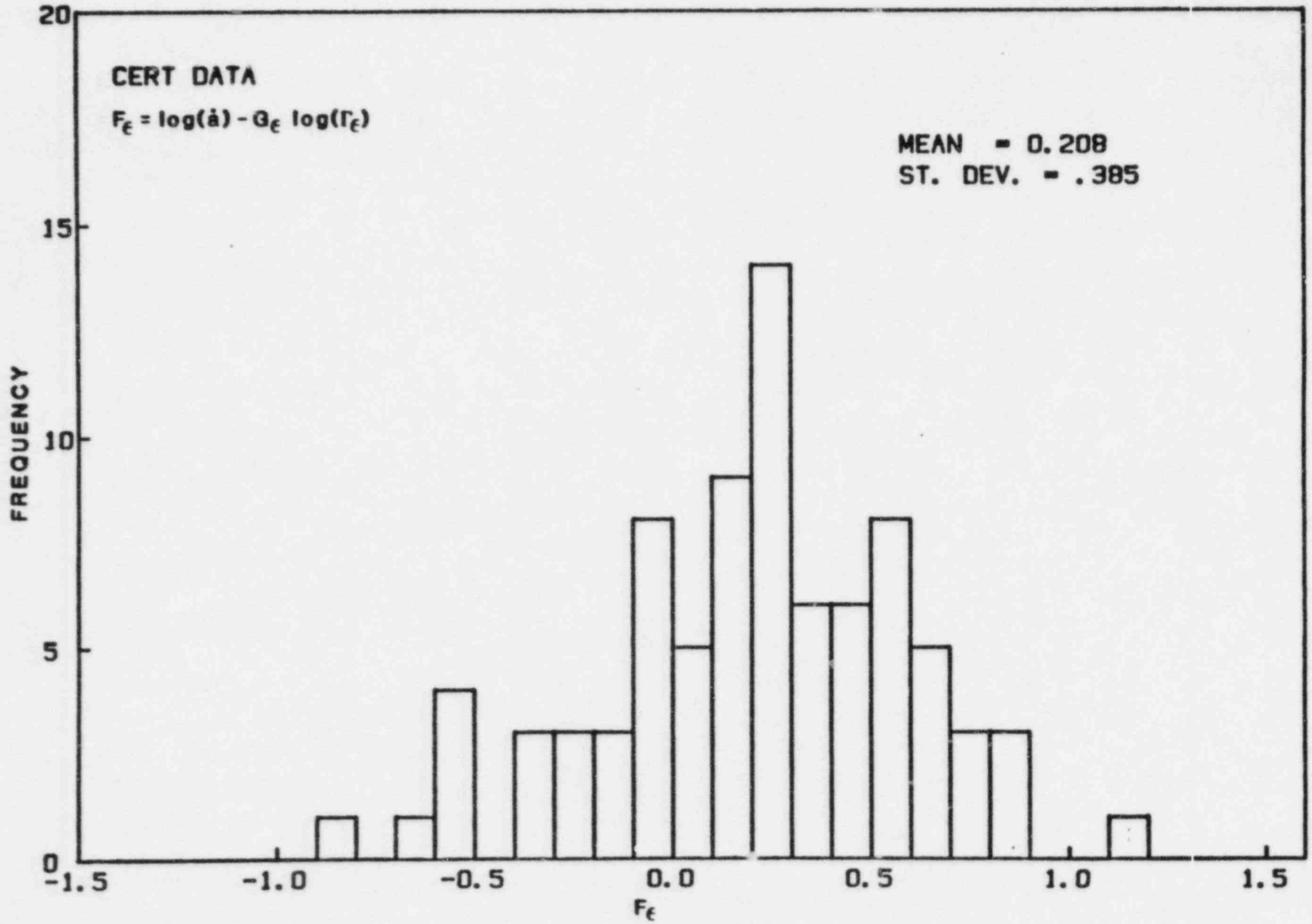

Figure 10. Distribution of F_ϵ (see Figure 8).

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mean of F_σ = 0.984
standard deviation of F_σ = 0.726

mean of F_ε = 0.208
standard deviation of F_ε = 0.385

Although no rigorous analysis of the distributions was performed, F_σ and F_ε were assumed to be normally distributed. Figures 9 and 10 show this to appear to be a reasonable assumption.

2.2.2 Crack Velocities by Fracture Mechanics

Once a crack has grown to a certain point, it can be treated from a fracture mechanics standpoint. The criteria for considering a crack to be governed by fracture mechanics are discussed in the next section. A literature search was performed to gather all the available crack growth rate information on sensitized 304 stainless steel generated by fracture mechanics testing. References 5-8 report the crack growth rate data considered here.

Preliminary analysis of $\dot{a}$-K data showed a linear relationship of log $\dot{a}$ and K (or $\dot{a} = 10^{C_{13}K}$). Taking the dependence of $\dot{a}$ on oxygen level and temperature to be the same as that employed in the treatment of initiation in Section 2.1.1, a damage parameter for crack growth was defined as

$$\Gamma_K = \{[1 - C_3 \exp(C_4 O_2)] \exp(\frac{C_5}{T + 273})\}^{C_{14}} 10^{C_{13}K} \qquad (13)$$

(The values of C_3, C_4, and C_5 are the same as defined earlier; as summarized in Table 1.) This assumed form is general enough that it is not overly restrictive to assume that

$$\dot{a} = C_{12} \Gamma_K \qquad (14)$$

and then use least square curve fitting procedures to evaluate the remaining undefined constants (C_{12}, C_{13}, C_{14}). As before, if T>150°C, the term $\exp[C_5/(T + 273)]$ is replaced by $C_{16} \exp[C_6/(T + 273)]$. The material sensitization term is not used in the definition of Γ_K because of the lack of information on sensitization in the data base of fracture mechanics crack growth results.

The following relationship is obtained by the least squares procedures discussed above

$$\log(\dot{a}) = \log(C_{12}\Gamma_K) = -2.208 + 0.5835 \log\{[1-C_3 \exp(C_4 O_4)] \exp(\frac{C_5}{T + 273})\} + 0.03537 K \quad (15)$$

($\dot{a}$ is in inches/day, C_{13} = 0.03537, and C_{14} = 0.5835.)

The experimental data are plotted in Figure 11, with the above expression superimposed as a solid line. To describe the scatter in the data, the constant ($\log C_{12}$ = -2.208) in equation 15 (which corresponds to an intercept) is considered to be a random variable. To avoid numerical problems with negative numbers, define

$$C_{12}'' = \log C_{12} + 4.4 \quad (16)$$

A value of C_{12}'' was calculated for each data point shown in Figure 11, and Figure 12 presents a histogram of the resulting values of $\log C_{12}''$. Figure 13 presents the corresponding cumulative distribution. These results indicate that C_{12}'' is lognormally distributed with the mean and standard deviation of $\log C_{12}''$ being 0.324 and 0.119, respectively. Figure 11 shows the 10th and 90th percentiles of $\dot{a}$ versus Γ_K, from which it is seen that this approach provides a reasonable fit to the data and a reasonable characterization of the scatter in the $\dot{a}$-K data.

The formulation of crack growth as represented by equation 15 predicts a finite crack growth velocity when K equals zero, even in the absence of oxygen and temperature contributions. A threshold was, therefore, set on the parameter $\log(\Gamma_K)$ at -1.6, which corresponds to a value of $\log(C_{12}\Gamma_K)$ of

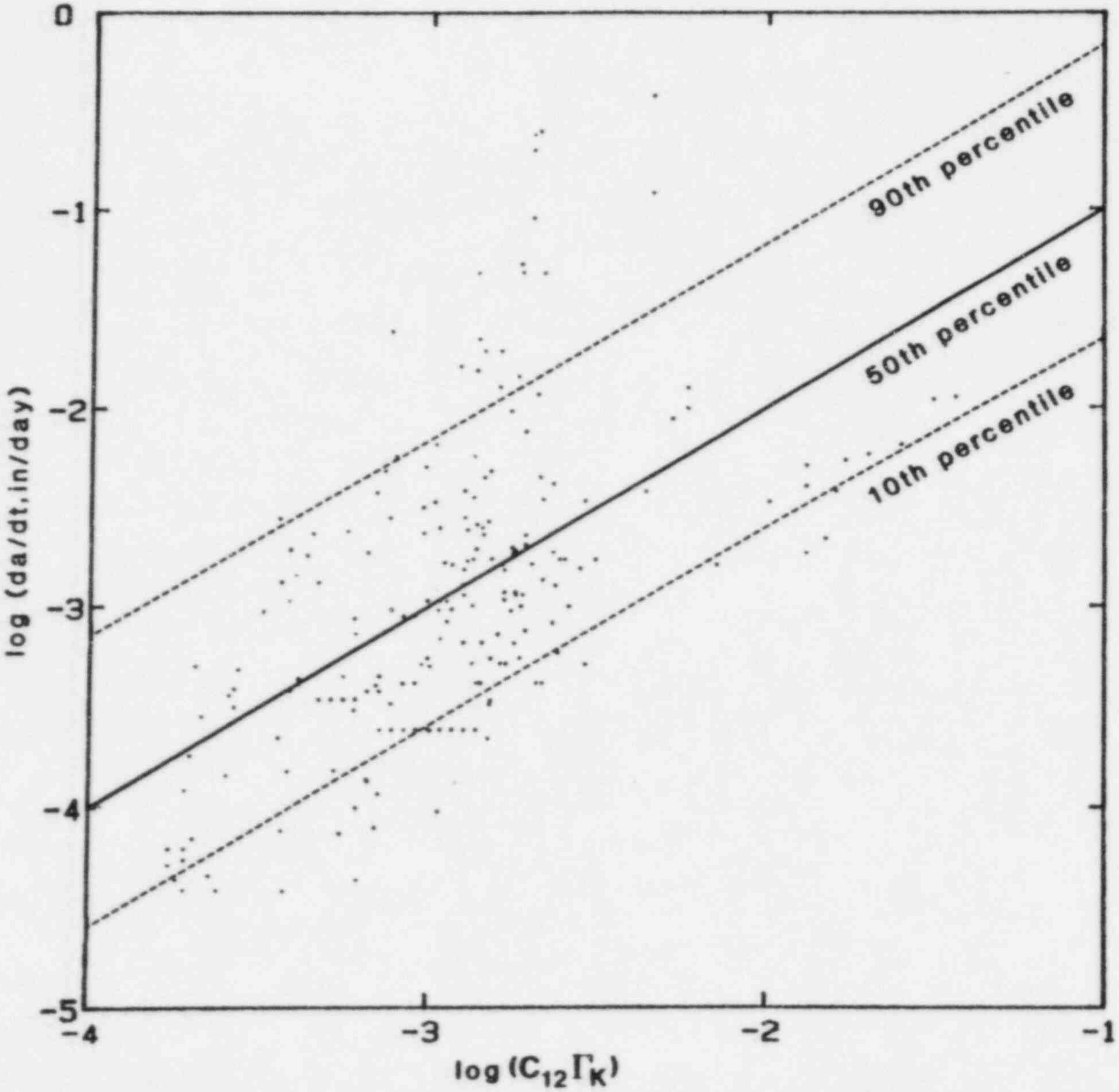

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Figure 11. Crack growth rate as a function of Γ_K.

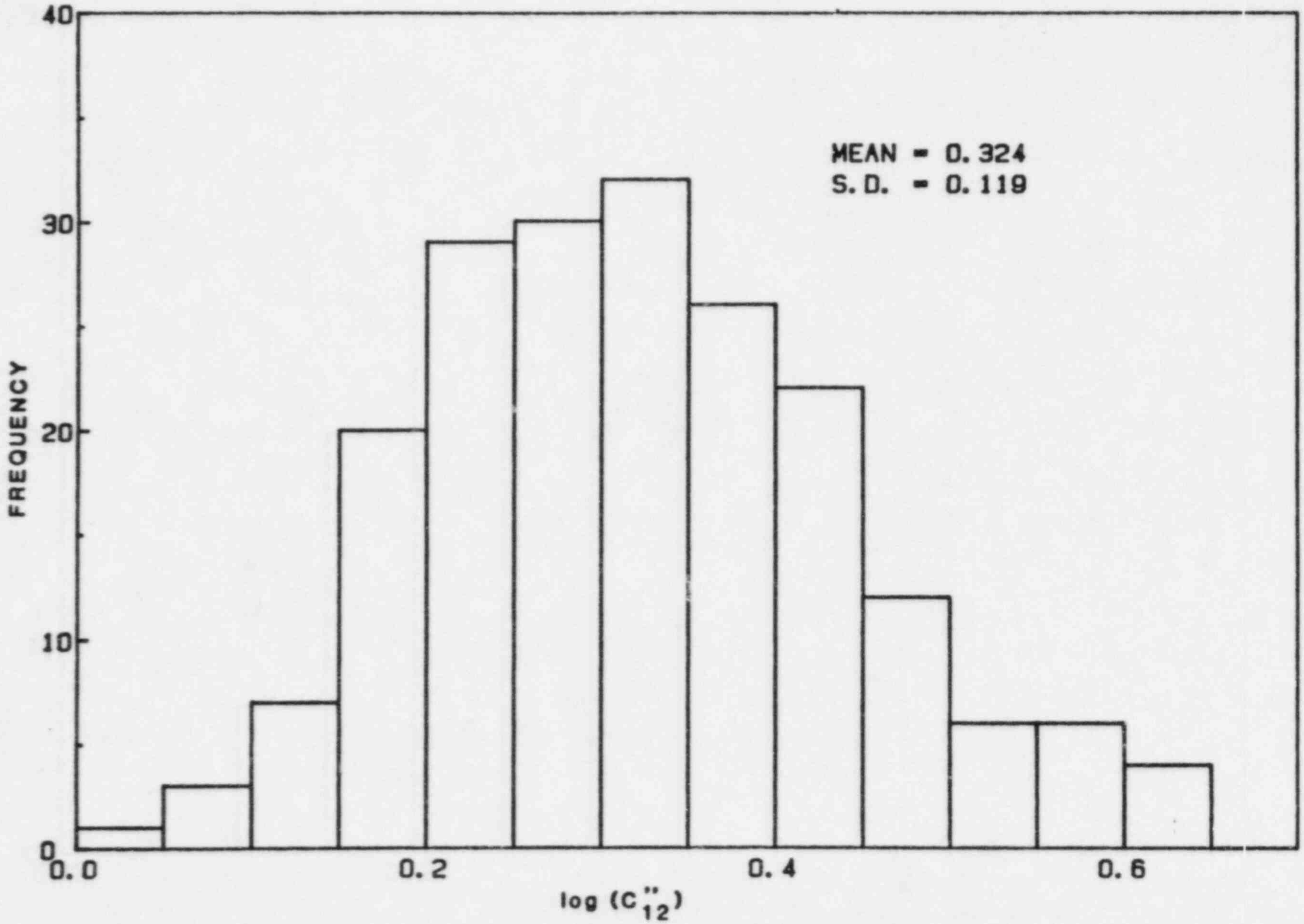

Figure 12. Histogram of values of $\log(C_{12}")$.

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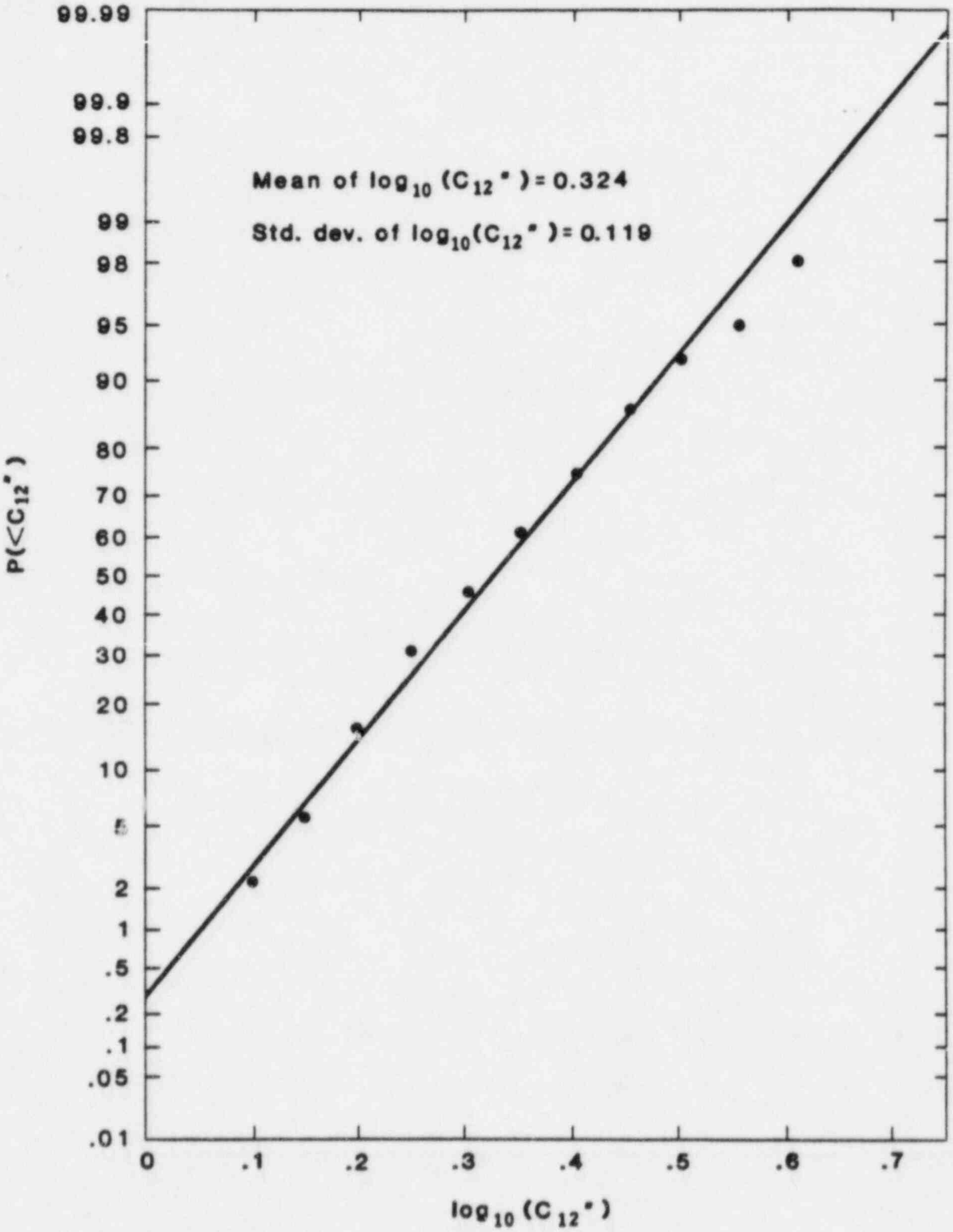

Figure 13. Cumulative distribution of $\log_{10}(C_{12}")$ plotted on normal probability paper.

-3.81. Figure 11 shows that no crack growth was reported at values of log $C_{12}\Gamma_K$ below this threshold.

For a given set of reactor state operating conditions, and a given value of K, equation 15 provides the fracture mechanics crack growth velocity, but with the "constant" -2.208 being a lognormally distributed random variable. This serves to characterize the observed scatter in the crack growth rate for a given set of conditions.

2.3 Stress Corrosion Crack Growth Calculations

As described previously, cracks can grow at an initiated or a fracture mechanics (FM) velocity. The following procedure is used to govern the transition from initiation to fracture mechanics velocity:

1. Pre-existing cracks will always grow at FM velocity,
2. Initiation velocity is always assigned to initiated cracks,
3. At any given time, if the FM velocity for a crack becomes higher than the initiation velocity, that particular crack grows at FM velocity thereafter (it does not revert back to initiation velocity even if the FM velocity becomes lower at a later time),
4. If the depth of the crack is greater than 0.1 inch, its growth will always be by fracture mechanics velocity,
5. If the stress intensity factor for a crack is negative, the crack will not grow.

For the application of stress corrosion (SC) crack growth to BWR pipes, the plant is considered to be either in heat-up or steady-state conditions. In heat-up, the initiated crack velocity is calculated from $\dot{a}$-Γ_ε relation (equation 12), and at steady-state the initiated velocity is calculated from $\dot{a}$-Γ_σ relation (equation 11). Once a crack has become treatable by fracture mechanics, its (FM) velocity is calculated by use of equation 15. Growth of semi-elliptical surface cracks is treated in the same manner as reported in References 1-3; the cracks are treated as having two degrees-of-freedom, with the growth rate in each degree-of-freedom being governed by the corresponding RMS-averaged stress intensity factor (see Section 3.8 of Reference 3).

2.4 Crack Link-Up Procedure

Multiple cracks can initiate and grow in a given weld. Hence, it is possible for these cracks to run into one another. Only interior surface cracks are considered, because SC cracks must be exposed to the environment inside the pipe in order to initiate.

The following procedure is used to check whether any two adjacent cracks will link-up:

1. If the separation "s" between two cracks is less than twice the depth of the deepest crack, the two cracks will link-up. In other words, cracks 1 and 2 in Figure 14 will link-up if

   $s < 2d_1$ or $s \leq 2d_2$

2. If two cracks link-up according to the above criteria, the depth of the new linked-up crack is the larger of the depth of the original cracks. The new length is the sum of the lengths of the original cracks and the distance separating them. As shown in Figure 14,

   $\ell = \ell_1 + \ell_2 + s$

3. The same procedure is used for a new crack that initiates next to an existing crack.

This procedure is based on Section XI, Article IWA-3000 of the ASME Boiler and Pressure Vessel Code.

2.5 Welding Residual Stresses

Welding residual stresses will be characterized for the following three ranges of pipe size:

small, 4-10 inch OD
intermediate, 10-20 inch OD
large, >20 inch OD

Cracks 1 and 2 will link together if $S < 2d_1$
or $S < 2d_2$

Once linked up, d = largest of d_1 and d_2
$\ell = \ell_1 + S + \ell_2$

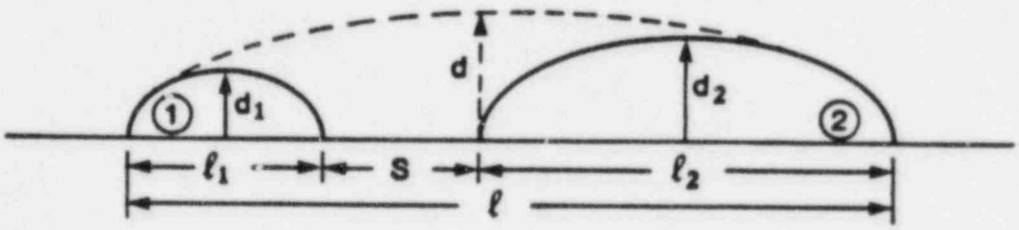

Figure 14. Schematic representation of the crack link-up procedure.

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A description of the spatial distribution of the residual stresses in the longitudinal pipe direction in the heat-affected zone is developed along with a characterization of the randomness of the residual stresses.

Residual stresses present after an induction heating stress improvement (IHSI) treatment will also be characterized.

2.5.1 Residual Stresses in Large Lines

The axial component of the as-welded residual stresses in the heat-affected zone are of interest because stress corrosion cracks form in the heat-affected zone. Circumferential cracks are also of concern. Experimental data suggest that the residual stresses are axisymmetric in these large lines. The stresses must therefore be self-equilibrating through the pipe wall thickness.

Experimental data on the radial variation of welding residual stresses for large diameter (20-26 inch) lines were obtained from References 9 and 10. A total of nine sets of data were obtained and are plotted in Figure 15. The following equation was used to analytically represent the radial variation of the axial stresses in the heat-affected zone.

$$\sigma_z = \frac{r_i}{r} [H_\phi \cos(2\pi x + \phi) + H_s e^{-sx} \cos(Bx + \phi_2)] \quad (17)$$

where r = radial coordinate

r_i = inside radius

$x = (r-r_i)/h$

h = wall thickness

H_ϕ, ϕ, H_s, s, B, ϕ_2 are constants

This stress can be self-equilibrating through the wall.

A preliminary curve fit of the nine sets of data to equation 17 revealed that $B \cong 2\pi$. The parameter B was therefore set equal to 2π. In order for the body to remain in equilibrium, the axisymmetric σ_z must be self-

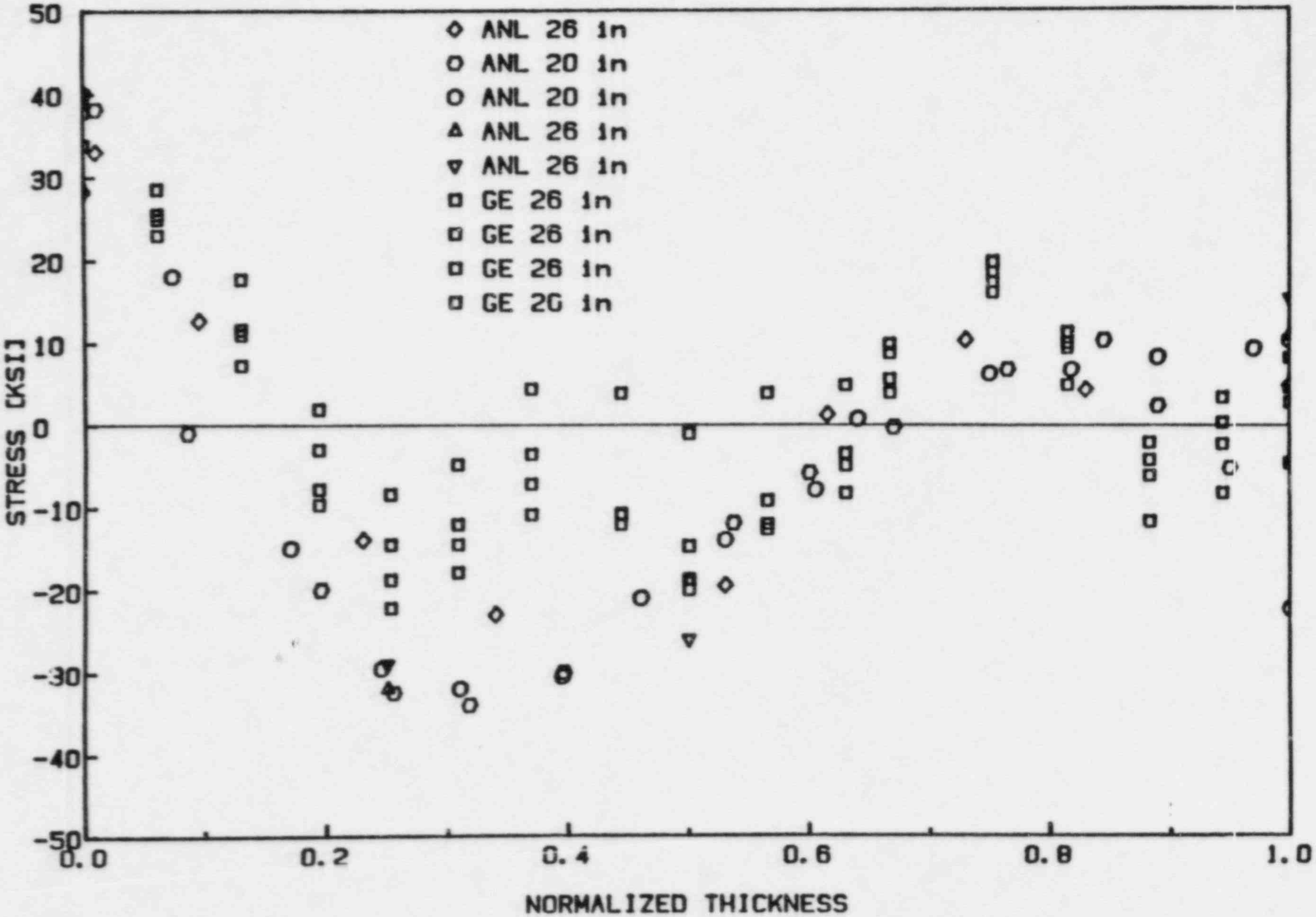

Figure 15. Experimental data on the radial distribution of residual stresses.

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equilibrating through the wall thickness. The imposition of this condition results in

$$\phi_2 = \tan^{-1}\left(\frac{s}{2\pi}\right)$$

Equation 17 can then be rewritten as

$$\sigma_z = \frac{r_i}{r}\{H_\phi \cos(2\pi x + \phi) + H_s e^{-sx} \cos[2\pi x + \tan^{-1}(\frac{s}{2\pi})]\} \qquad (18)$$

Values of H_ϕ, ϕ, H_s, and s were estimated by nonlinear regression analysis for each of the nine sets of data. This provides nine sets of values for these variables; each of which are included in Table 3. The mean and standard deviation for each of these variables can be calculated from these nine sets of values. Further analysis of these variables revealed that only H_s and H_ϕ were strongly correlated (correlation coefficient = 0.738). The relationship between H_s and H_ϕ can be described as follows:

$$H_s = H_I + 0.7381\ H_\phi \qquad (19)$$

H_I is another variable which was evaluated by regression analysis and has a mean value of 37.49 with standard deviation of 9.11. Numerical values of H_I are also included in Table 3.

Figures 16-19 show the distribution of each of the estimated variables (H_ϕ, ϕ, H_I, and s) plotted on normal probability paper. Although no rigorous analysis regarding the appropriate distributions was performed, normal distributions seem adequate.

The next step is to generate the curve-fits for stress intensity factors due to these residual stresses. Since the residual stresses are distributed (as opposed to deterministic), the curve-fits to stress intensity factors are much more complex than in the deterministic case. For the purpose of curve-fitting, the residual stresses described by equation 18 were rewritten as

Table 3

VALUES OF THE PARAMETERS H_ϕ, ϕ, H_S, s, AND H_I OBTAINED BY REGRESSION ANALYSIS

Set	Description	H_ϕ ksi	ϕ rad	H_S ksi	s	H_I ksi
1	ANL 26	8.41	1.93	39.49	1.55	33.28
2	ANL 20	43.80	2.84	83.05	0.962	50.72
3	ANL 20	16.11	0.941	40.84	3.60	28.95
4	ANL 26-5A	49.61	2.50	68.24	2.88	31.62
5	ANL 26-5B	36.76	2.23	49.91	0.16	22.78
6	GE-1	7.82	3.29	49.93	2.91	44.16
7	GE-2	5.75	2.45	45.83	2.35	41.59
8	GE-3	37.67	3.09	74.55	0.88	46.75
9	GE-4	2.83	1.11	39.62	2.42	37.53
	MEAN	23.20	2.26	54.61	1.68	37.49
	Standard Deviation	18.51	0.82	16.42	1.21	9.11

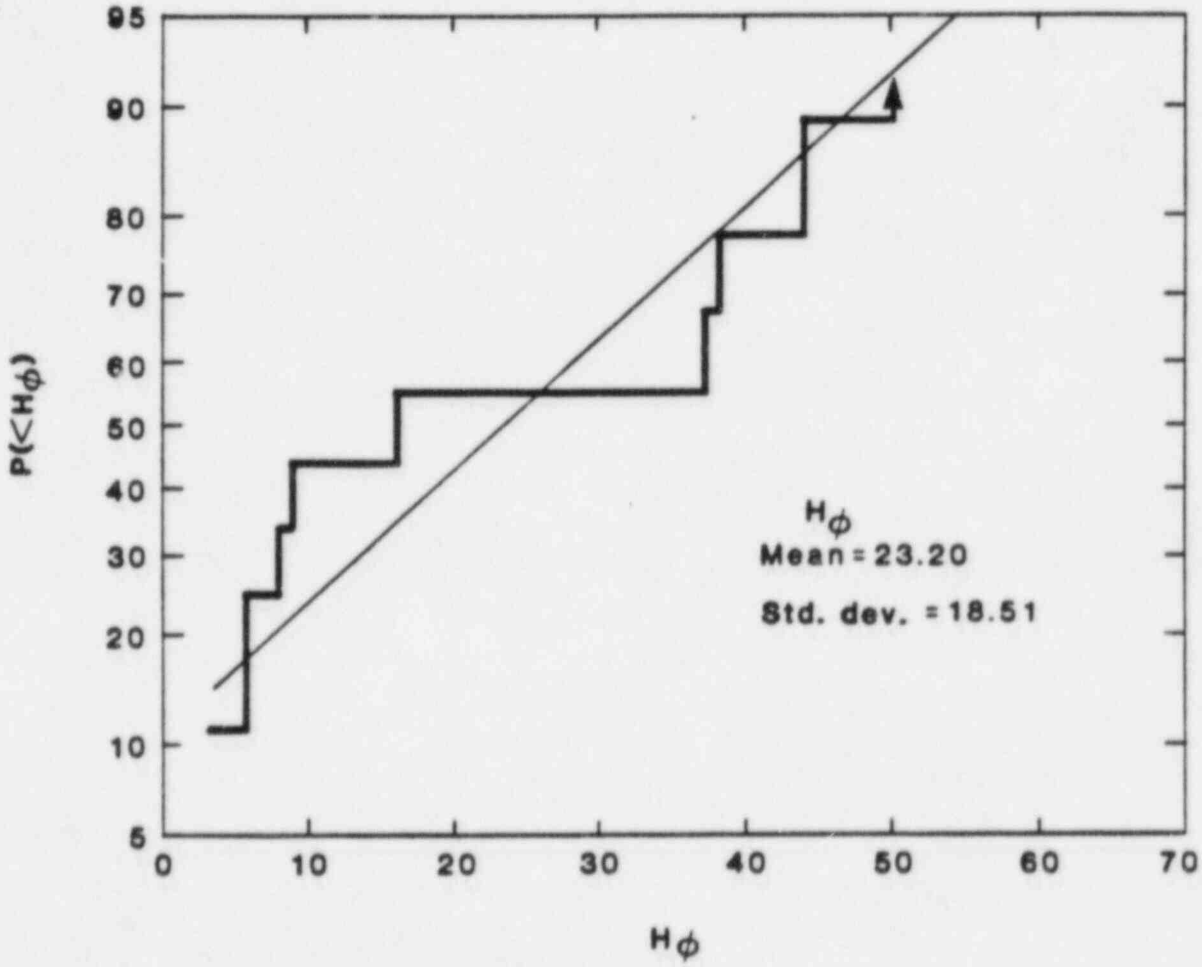

Figure 16. Distribution of H_{ϕ}.

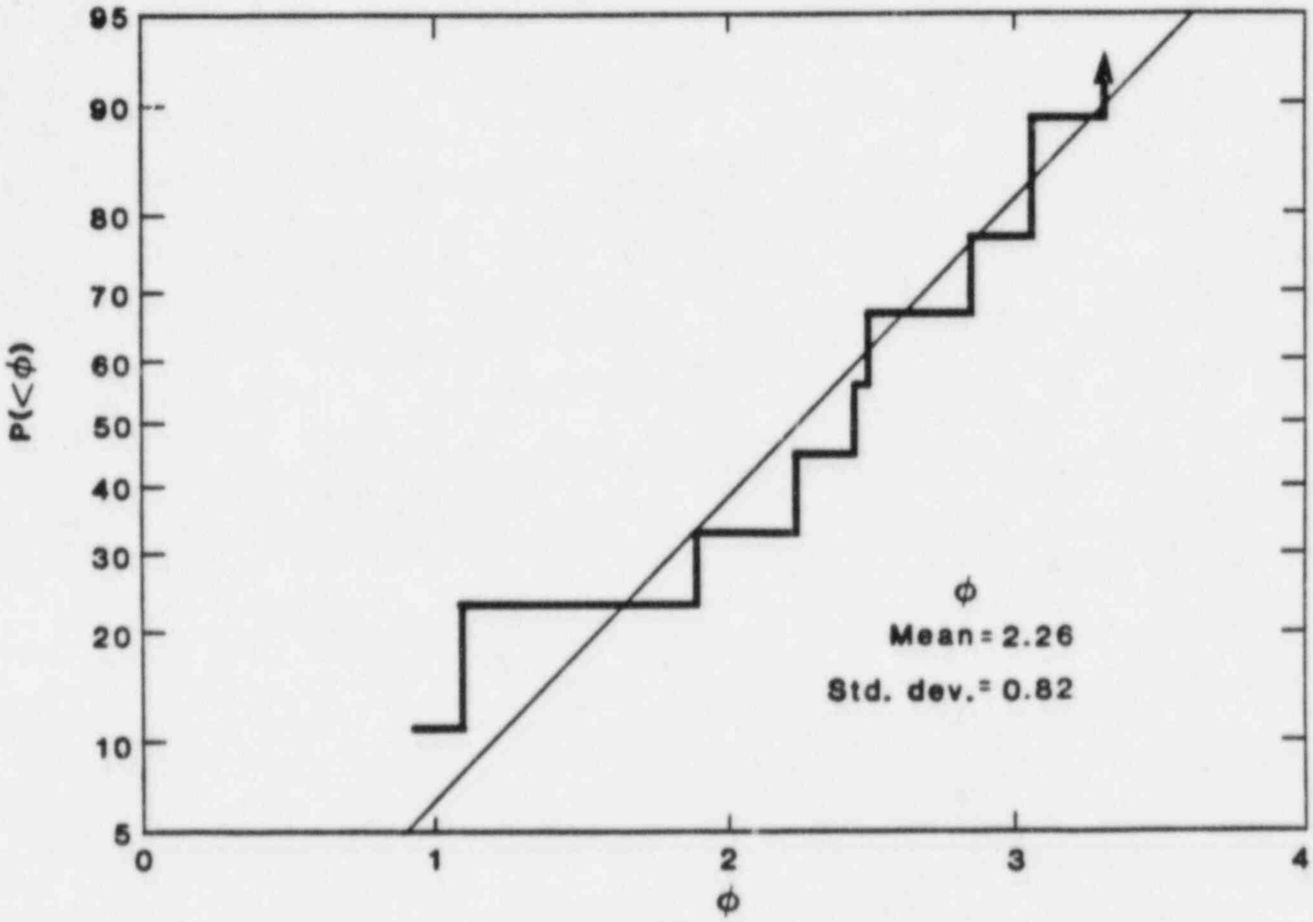

Figure 17. Distribution of ϕ.

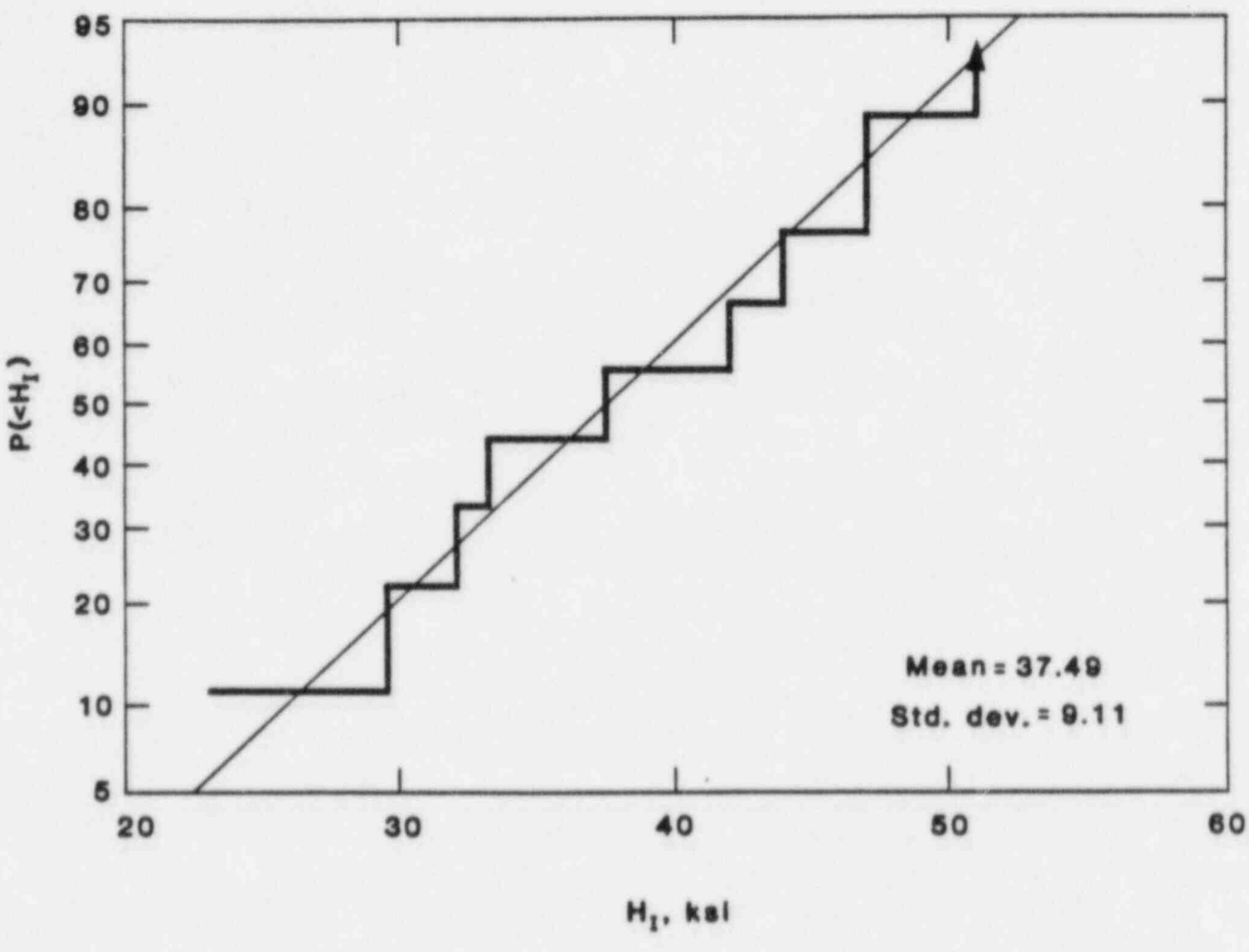

Figure 18. Distribution of H_I

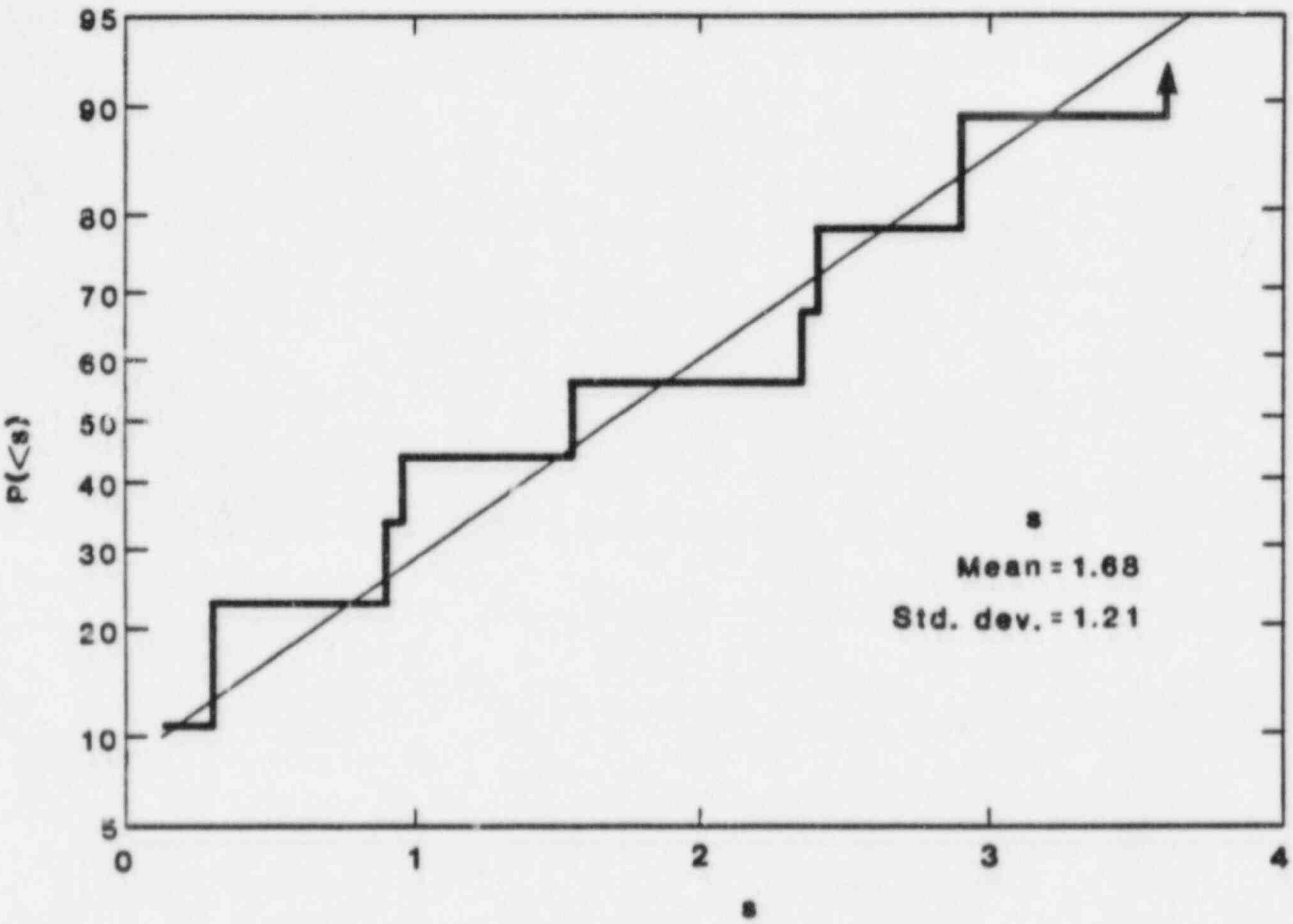

Figure 19. Distribution of s.

$$\sigma_z = \sigma_1 + \sigma_2 \tag{20}$$

where $\sigma_1 = H_\phi \frac{r_i}{r} \cos(2\pi x + \phi)$

$$\sigma_2 = H_s \frac{r_i}{r} e^{-sx} \cos[2\pi x + \tan^{-1}(\frac{s}{2\pi})]$$

Two sets of stress intensity factors ($\bar{K}_a$ and $\bar{K}_b$) were generated (for a wide range of crack geometries), one for σ_1 and another for σ_2. The stress intensity factors ($\bar{K}_i$) were normalized and polynomial expressions were obtained. Specifically, the two sets of $\bar{K}_i$ were

$$\left(\frac{\bar{K}_i}{a^{1/2} H_\phi}\right)_{\sigma_1} = f(\text{crack geometry}, \phi)$$

$$\tag{21}$$

$$\left(\frac{\bar{K}_i}{a^{1/2} H_s}\right)_{\sigma_2} = f(\text{crack geometry}, s)$$

In PRAISE-CC, the parameters H_ϕ, ϕ, s, and H_I are sampled randomly from their respective distributions. H_s is evaluated from its linear relation with H_ϕ as expressed in equation 19. For a given ϕ, s, H_ϕ, H_s, and crack geometry, the stress intensity factors can be evaluated by linear superposition of the above two terms.

As discussed in Section 3.2, the magnitude of residual stresses in large lines was adjusted in order to improve the agreement between the field observations and predicted pipe failure probabilities.

2.5.2 Residual Stresses in Small and Intermediate Lines

The residual stresses in small and intermediate lines vary through the wall thickness as well as around the circumference. Although very little information is available regarding the through-thickness variation of residual

stresses for either small or intermediate lines, there is a large amount of data available on the inside surface stresses at various angular locations [11-15]. Data on the axial component of the inside surface residual stresses were complied for locations of approximately 3mm from the weld fusion line where the peak sensitization levels generally occur [11]. These data were used to generate distributions of stress on the inside surface for both small and intermediate lines separately. The following results were obtained:

Small Lines

Mean residual stress on the inside surface = 24.4 ksi
Standard deviation = 14.58 ksi

Intermediate Lines

Mean residual stress on the inside surface = 9.30 ksi
Standard deviation = 14.47 ksi

The cumulative distributions of the stresses on the inside surface for small and intermediate lines are shown in Figures 20 and 21, respectively. Although no rigorous analysis was performed, these figures show that assumption of normally distributed inside surface stresses is reasonable for both small and intermediate lines. The calculated mean and standard deviations are used as the parameters of the normal distribution. This defines the distribution of residual stresses on the inside surface for the small and intermediate lines.

Since insufficient information is available to characterize the through-thickness variation of residual stresses, the following assumptions were made in order to sufficiently characterize the statistical and spatial residual stress distributions:

(i) For a given angular location, the stress on the inside surface is obtained by sampling from the normal distributions defined above.

(ii) The distribution of residual stresses on the outside surface is defined as follows:

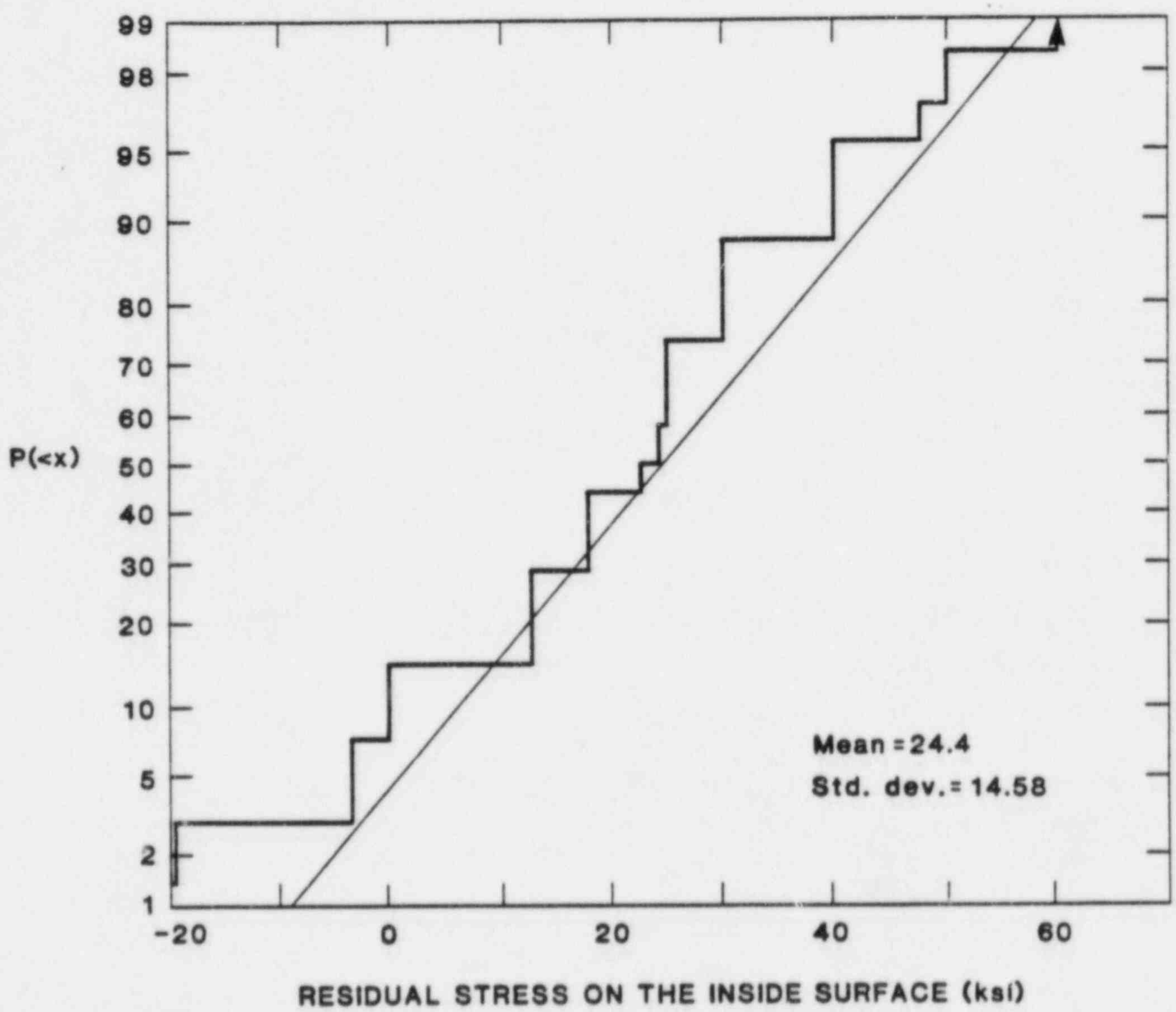

Figure 20. Statistical distribution of residual stress on the inside surface for small lines (<10 inches).

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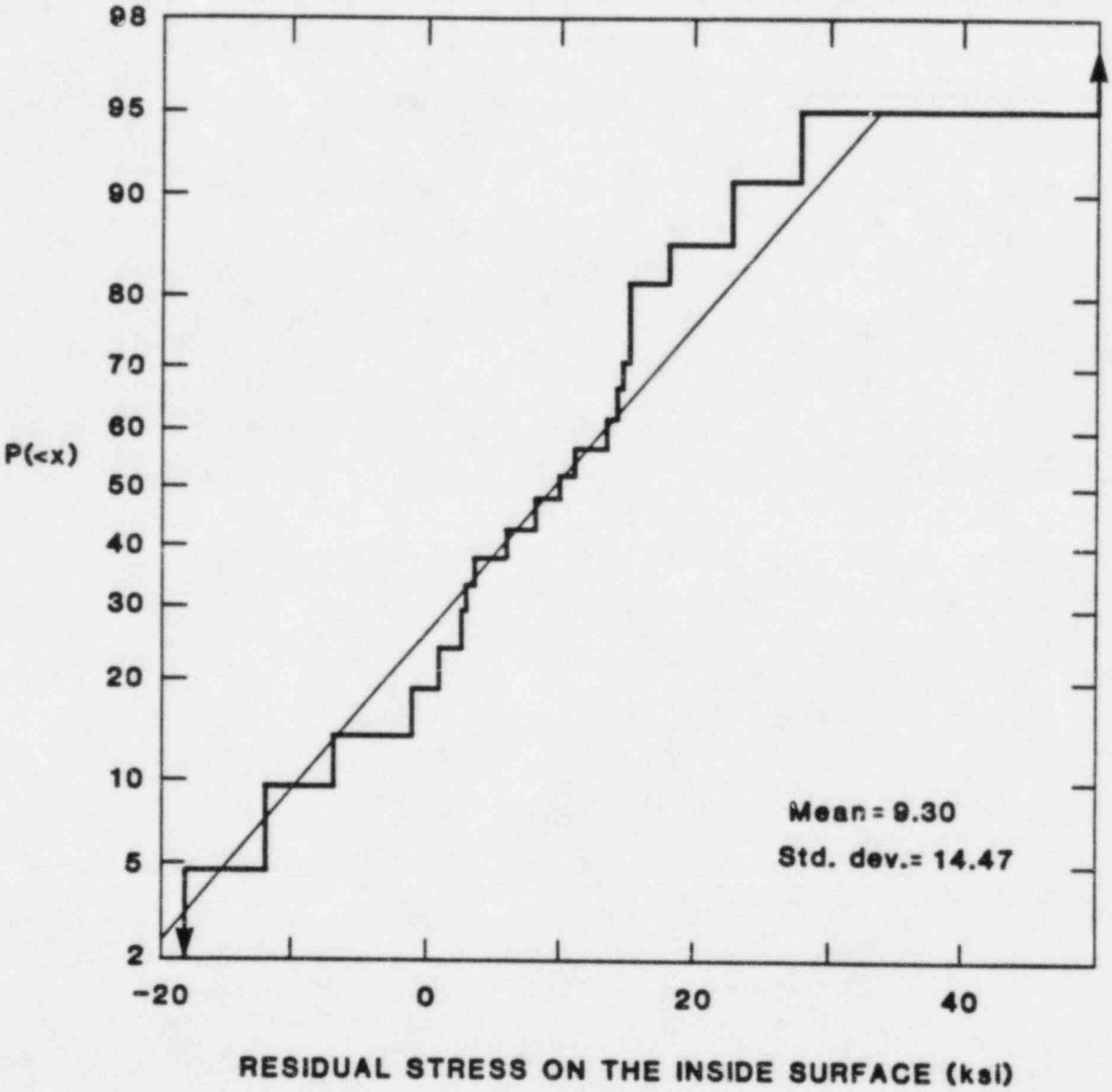

Figure 21. Statistical distribution of residual stress on the inside surface for intermediate lines.

Small lines

Mean of the stress on the outside surface
= - (mean of the stress on the inside surface)
= -24.4 ksi

Standard deviation of the stress on the outside surface
= standard deviation of the stress on the inside surface
= 14.58 ksi

Similarly for intermediate lines

Mean of the stress on the outside surface = -9.30 ksi
Standard deviation of the stress on the outside surface
= 14.47 ksi

(iii) After sampling for inside and outside surface stresses for a given angular location, the stresses are assumed to vary linearly through the wall between the values sampled from the appropriate distributions.

In the absence of more information, the above scheme reasonably models the through-thickness and angular variation of residual stresses in small and intermediate lines, and force equilibrium is satisfied on the average.

As discussed in Section 3.2, the mean and standard deviation of the surface stresses for small and intermediate sized lines were adjusted to improve agreement between calculated failure probabilities and field observations of pipe cracking.

2.5.3 Induction Heating Stress Improvement

Induction heating stress improvement (IHSI) provides a method of altering the residual stresses [15]. This method has been used [15] to change unfavorable stress distributions (that are tensile on the inside surface and may be tensile through the wall thickness) to more favorable stress distributions (which are compressive on the inside surface at all angular locations). The resulting stresses are axisymmetric and are tensile on the outside surface and vary approximately linearly through the wall [15]. A option is provided in PRAISE-CC wherein the user can model the IHSI-treated stresses by supplying the value of the stress at the inside surface and at the outside surface of the pipe. The code treats stresses as varying linearly through the wall. The

IHSI residual stresses are treated deterministically with stress levels estimated from Reference 15. Only IHSI performed prior to placing the weld in service can be currently treated in PRAISE-CC.

2.6 Miscellaneous Topics

Several other miscellaneous topics are detailed in this section.

2.6.1 Analysis of 316NG Stainless Steel Data

One of the remedial measures suggested for the mitigation of stress corrosion cracking in BWR pipes is to use materials that are less susceptible to IGSCC. The alloys 304NG and 316NG are promising candidates [16] for the replacement of IGSCC-damaged piping systems and for piping in future BWRs. Unlike the case of 304SS, only a limited amount of data are available for the 304NG and 316NG alloys. The crack growth rate data available from Reference 16 are presented in Figure 22 along with 304SS data. Two other sets of results are plotted in Figure 22: (i) the da/dt-K relation employed for 304SS in an earlier version of PRAISE [3, Section 2.1.2], and (ii) results from equation 13 (which is for 304SS) using mean values of the random variables and nominal steady-state reactor operating conditions. The earlier results fall close to those from equation 13. The crack growth velocities for the 316 and improved 304 fall somewhat below the 10th percentile of the original 304 and roughly an order of magnitude below the 50th percentile of earlier data. Hence, the newer materials provide some improvement over older ones, but stress corrosion cracks can still grow in the newer materials.

The CERT data available from Reference 17 are presented in the form of time-to-initiation as a function of Γ_ε in Figure 23, and crack initiation velocity as a function of Γ_ε is shown in Figure 24, along with 304SS data.The fracture mechanics crack velocities shown in Figure 22 are lower for the 316NG and 304NG as compared to 304SS. On the other hand, time-to-initiation and initiation velocity for the 316NG, as shown in Figures 23 and 24, show no improvement over 304SS data. These 316NG data have been obtained only for two heats of material. It is apparent at this time from the available data that the 316 and 304NG may provide some improvement over 304. The degree of

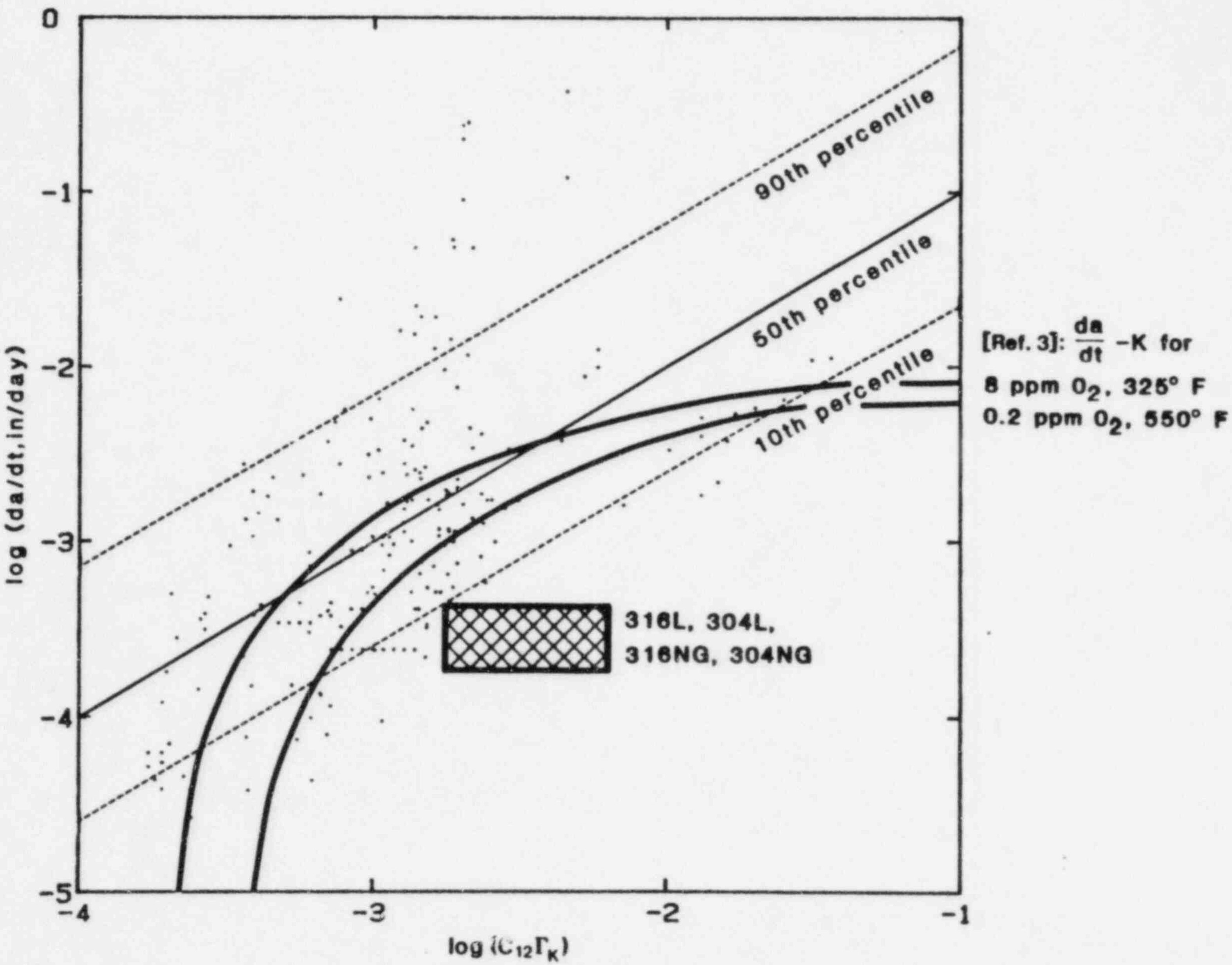

Figure 22. Crack growth rate as a function of Γ_K.

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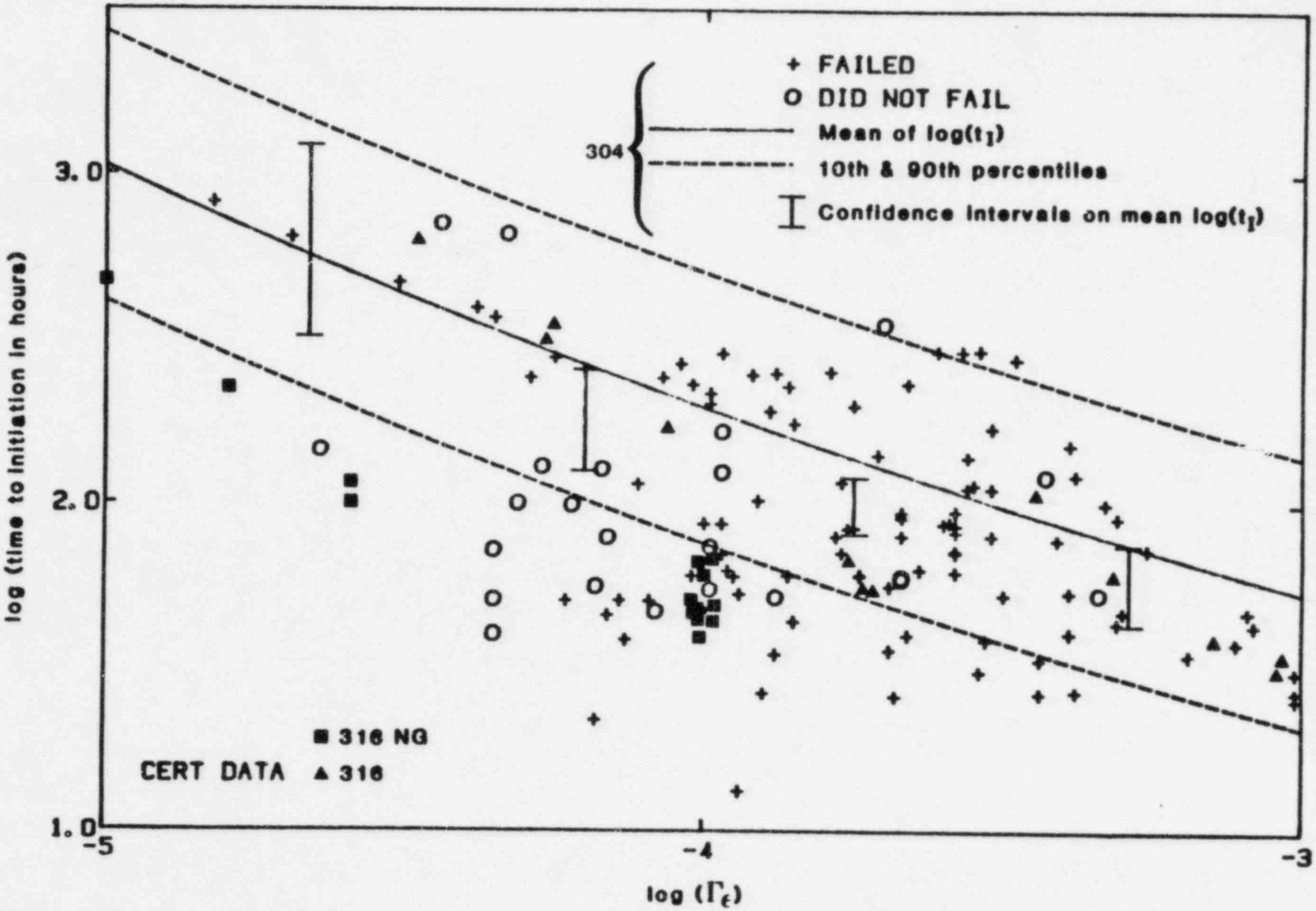

Figure 23. Time to initiation vs. Γ_{ε}.

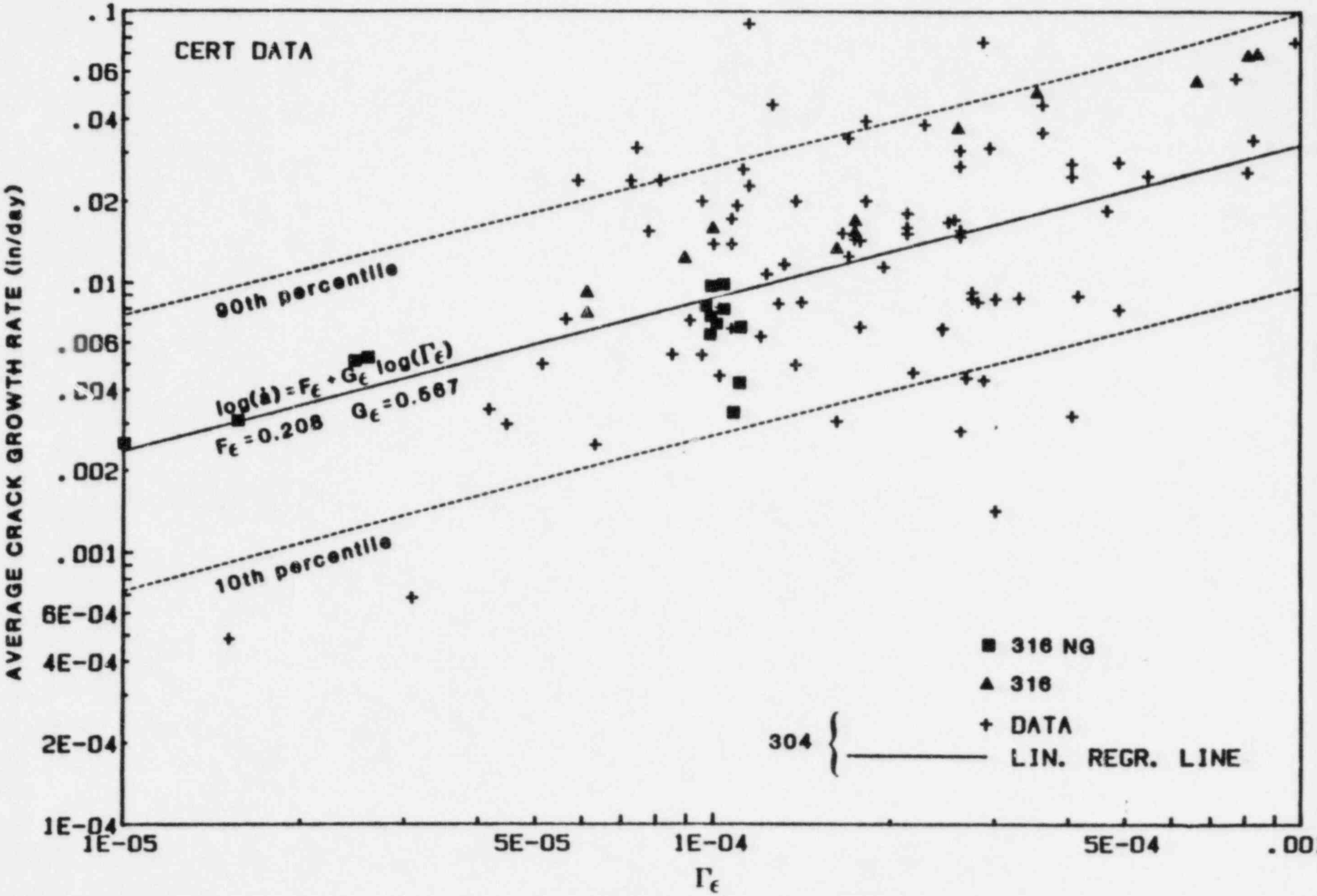

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Figure 24. Average crack velocity at initiation vs. Γ_ε.

improvement may be more than indicated in Figures 22-24, because the comparisons in these figures are for a given degree of sensitization. The degree of sensitization for as-fabricated 316 and 304NG may be considerably less than for corresponding 304.

It is apparent from the results of Figures 22-24 that insufficient data is available to characterize the randomness in the cracking behavior of the alternate newer piping materials.

2.6.2 Leak Rates

The formulation for the calculation of leak rates in PRAISE [1, Section 2.8] was applicable to the (generally) thicker pipes considered in PWR analyses. This formulation is revised for application to pipes of any thickness. The data of Table 2-7 of Reference 1 were curve-fitted to obtain the following expressions

$$\frac{\dot{Q}\, h^{1/2}}{2b} = 0.25\, \delta^2 \qquad \delta < 2 \text{ mils}$$

$$= 0.9375\delta - 0.875 \qquad \delta > 2 \text{ mils} \qquad (22)$$

The crack opening displacement, δ, is conservatively estimated following procedures described in Reference 1.

$$\delta = \text{crack opening displacement (mils)}$$

$$= 4000\, \frac{\sigma b\, (1-\nu^2)}{E} \qquad (23)$$

where $2b$ = crack length (inch)

E = Young's modulus (ksi)

ν = Poisson's ratio

σ = uniform stress (ksi)

h = pipe wall thickness (inch)

$\dot{Q}$ = leak rate (gpm)

2.6.3 Weld Repair

A new option was added to PRAISE which allows the user to eliminate a portion of the cracks in a weld when a leak is detected in that weld. At the time of repair, all the cracks in a weld that are leaking are eliminated. The cracks that are part-through are left intact and will continue to grow. The weld repair option does not have any effect in the case of only pre-existing cracks, and therefore would not influence previous results generated by PRAISE.

2.6.4 Quasi-Asymmetric Loading

The steady-state stresses at normal operating temperature and pressure consists of three parts: (i) pressure stress, (ii) stresses due to dead weight, and (iii) stresses due to restraint of thermal expansion. The stresses due to dead weight and thermal expansion result primarily in bending loads which produce stresses that vary around the pipe circumference and (weakly) through the wall thickness. Such variations were ignored in earlier versions of PRAISE, and the maximum bending stress at the inner pipe wall was taken to be uniformly distributed throughout the pipe cross section. This conservatism is relaxed in PRAISE-CC by considering the circumferential variation of the bending stresses as follows:

$$\sigma_B(\theta) = \sigma_B \cos\theta \tag{24}$$

where σ_B = maximum thermal expansion and dead weight stress
θ = angular location around the pipe circumference

The variation of stresses through the wall thickness at any angular location is small and is ignored. The stress intensity factor for a crack at a given angular location is calculated by assuming the stress at the mid-point of the surface length of the crack to be uniformly distributed throughout the pipe cross section. Hence, earlier stress intensity factor formulations for axisymmetric stresses can be utilized, but the angular variation of stresses can also be (approximately) accounted for.

2.6.5 Nondetection Inspection Probabilities

The formulation of probability of nondetection by ultrasonic inspection in PRAISE [1, Section 2.4.3] is as follows:

$$P_{ND}(A) = \frac{1}{2} \operatorname{erfc} \left(\nu \ln \frac{A}{A^*}\right) \tag{25}$$

where P_{ND} = probability of nondetection
A = crack area
$\nu = 1.6$
$A^* = (\pi/4)\, a^*\, D_B$
D_B = diameter of the ultrasonic transducer
$a^* = 1.25$ inch

In the above formulation a^* is the crack depth that has a 50% chance of being detected. The value of a^* of 1.25 inches is realistic for the centrifugally cast PWR stainless steel pipes considered in Reference 1, but is overly conservative for wrought BWR piping. A more realistic value for a^* is 0.25 inch [18]. This value of a^* is used in PRAISE-CC along with a ν of 1.6 and lower bound (ε) of 0.005 on P_{ND}.

This provides the following form of equation 25

$$P_{ND}(A) = \varepsilon + \frac{1}{2}(1-\varepsilon) \operatorname{erfc} \left(\nu \ln \frac{A}{A^*}\right) \tag{26}$$

A plot of equation 26 is provided in Figure 25 for various aspect ratios, b/a. Results to be reported that were generated by use of PRAISE-CC use the revised nondetection probabilities expressed in equation 26.

2.6.6 Revised Curve-Fits for Stress Intensity Factors due to Uniform and Linearly Varying Stresses (based on improved influence functions)

The stress intensity factors generated by the use of influence functions previously employed in PRAISE were of sufficient accuracy for engineering purposes for cracks of intermediate depths. These influence functions were improved [19] to provide greater accuracy for shallow cracks.

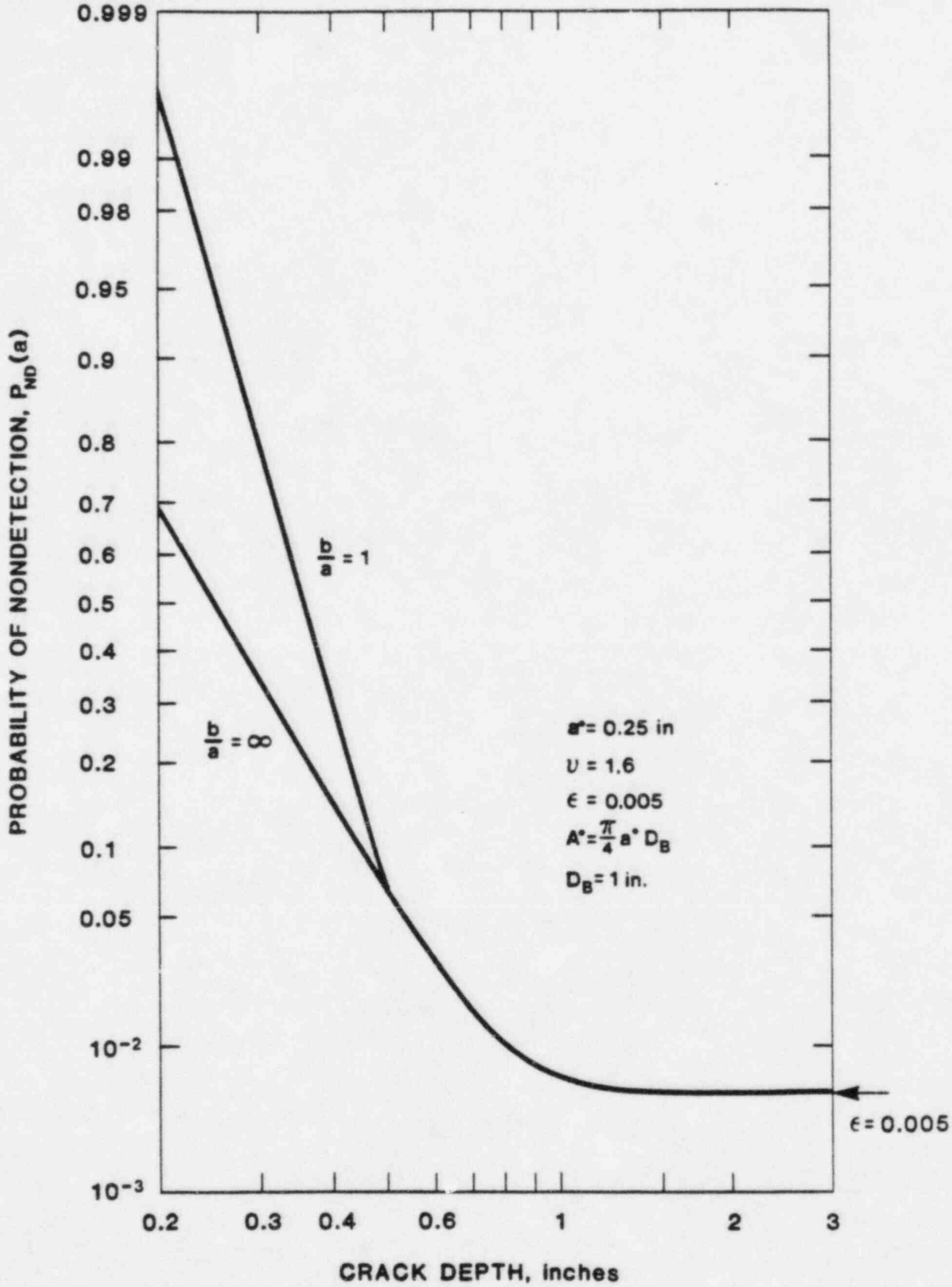

Figure 25. Probability of nondetection of a crack as a function of its depth for wrought piping material. (See equation 26.)

These improvements were incorporated in the subroutines for the calculation stress intensity factors due to uniform stress and stresses that vary linearly through the pipe wall thickness. The following expressions are curve-fits to the improved stress intensity factor results. These relations are incorporated into PRAISE-CC.

Defining α = a/h and ζ = a/b, the $\bar{K}_a$ and $\bar{K}_b$ for uniform stress are given by

$$\frac{\bar{K}_a}{\sigma a^{1/2}} = [\{1.8781 - 0.7248\zeta - 0.2035\zeta^2 + 0.2432\zeta^3\}$$
$$+ \{-0.68159 - 0.42330\zeta - 0.49695\zeta^2 + 0.96951\zeta^3\}\alpha$$
$$+ \{0.036574 + 11.798\zeta - 20.734\zeta^2 + 9.6933\zeta^3\}\alpha^2$$
$$+ \{0.42562 - 15.827\zeta + 29.538\zeta^2 - 15.044\zeta^3\}\alpha^3]$$
$$/(1 - \alpha)^{1/2}$$

(27)

$$\frac{\bar{K}_b}{\sigma a^{1/2}} = [\{0.97917 + 0.20174\zeta - 0.24769\zeta^2 + 0.05483\zeta^3\}$$
$$+ \{1.0621 - 6.6880\zeta + 9.2182\zeta^2 - 4.2890\zeta^3\}\alpha$$
$$+ \{-2.7479 + 21.818\zeta - 36.218\zeta^2 - 18.606\zeta^3\}\alpha^2$$
$$+ \{1.4344 - 17.705\zeta + 31.190\zeta^2 - 16.477\zeta^3\}\alpha^3]$$
$$/(1 - \alpha)^{1/2}$$

The stress intensity factors for stresses that vary linearly through the pipe wall thickness are given by:

$$\frac{\overline{K}_a}{\sigma_a a^{1/2}} = [\{1.01392 - 0.78506\alpha + 3.31506\alpha^2 - 0.991159\alpha^3\}$$
$$+ \{-0.34032 + 2.5896\alpha - 9.02996\alpha^2 + 2.88101\alpha^3\}\zeta$$
$$+ \{0.045722 - 1.90305\alpha + 6.05041\alpha^2 - 1.93187\alpha^3\}\zeta^2]$$

$$\tag{28}$$

$$\frac{\overline{K}_b}{\sigma_a a^{1/2}} = [\{0.47954 - 0.206885\alpha + 1.112738\alpha^2 - 0.19908\alpha^3\}$$
$$+ \{-0.0249092 + 0.144091\alpha - 1.61755\alpha^2 - 0.176543\alpha^3\}\zeta$$
$$+ \{0.0450383 - 0.223205\alpha + 1.97511\alpha^2 + 0.779899\alpha^3\}\zeta^2$$
$$+ \{-0.04859 + 0.37304\alpha - 1.5687\alpha^2 - 0.3790668\alpha^3\}\zeta^3]$$

Equations 28 are for a stress that varies linearly through the thickness, being zero at the inside surface and equal to σ_a at the location of the crack tip ($x = a$).

2.6.7 Combination of Pre-Existing and Initiated Cracks

Failure of pipes in BWRs due to the presence of cracks can be caused by either a pre-existing crack or a crack that initiates and grows to failure during the plant lifetime. Earlier versions of PRAISE [1-3] considered only the former cause of failure. The probabilistic treatment of crack initiation in Section 2.1.1 provides a means of treating failure due to the latter cause. In most instances, piping failures in commercial reactors are dominated by one or the other cause of failure. However, in some instances, both causes may be contributors to comparable degrees, in which case careful consideration of

procedures for combining the two causes of failure are necessary. This can be accomplished by the following procedure.

The cumulative probability of failure of a weld within a time t due to the presence of cracks can be written as

$$\begin{aligned} P(t_f<t) = &\ (\text{prob. of no initial crack}) \times [P(t_f<t)|\text{no initial crack}] \\ &+ (\text{prob. of 1 initial crack}) \times [P(t_f<t)|\text{1 initial crack}] \\ &+ (\text{prob. of 2 initial cracks}) \times [P(t_f<t)|\text{2 initial cracks}] \\ &+ \ldots . \end{aligned} \tag{29}$$

For the weld volumes typical of reactor piping, and for the crack existence probability estimates in Section 2.3.4 of Reference 1, the probability of having more than 1 initial crack is small. Taking

$$[P(t_f<t)|\text{N initial crack}] \sim [P(t_f<t)|\text{1 initial crack}] \tag{30}$$

and letting

$$p^* \sim p_0(1)$$

where p^* = probability of having one or more initial crack
$p_0(1)$ = probability of having 1 initial crack

allows equation 29 to be rewritten as

$$\begin{aligned} P(t_f<t) \equiv &\ (1-p^*)[P(t_f<t)|\text{no initial crack}] \\ &+ p^*[P(t_f<t)|\text{1 initial crack}] \end{aligned} \tag{31}$$

The term $[P(t_f<t)|\text{1 initial crack}]$ is generated by earlier versions of PRAISE for the case of any possible initiated crack not contributing significantly to the failure probability. This capability is retained in PRAISE-CC. The term $[P(t_f<t)|\text{no initial crack}]$ is generated directly by PRAISE-CC using the models described in earlier portions of Section 2. Hence, if equation 30 applies, then PRAISE-CC is capable of generating results for cases in which both pre-

existing and initiating (SCC) cracks are significant contributors to failure.

In some situations, it is possible that a weld may contain a pre-existing crack but initiating cracks may also be significant contributors to failure. This could occur if the pre-existing crack is small. PRAISE-CC can handle combined initiating and pre-existing cracks. In order to improve computational efficiencies, a user-defined boundary is provided such that if calculations for pre-existing cracks are being performed, initiated cracks are also included in the simulation only if the sampled pre-existing crack is smaller then the specified "boundary." This eliminates the unnecessary burden of combining (small) initiated cracks with large pre-existing cracks when the calculated failure probability is controlled by the large pre-existing crack. Such considerations are not important in reactor piping analyses performed to date, because either crack initiation does not occur (PWR primary piping) or the problem is totally dominated by crack initiation (304 stainless BWR piping). Appendix A describes the control cards for using this option (BNDRY of Card ØB).

In actuality, PRAISE-CC does not perform computations based on equation 31. Separate runs for pre-existing and initiating cracks with post-processing based on equation 31 is suggested.

3.0 BENCHMARKING

The accuracy of PRAISE-CC results generated by use of the inputs described in Section 2 can be assessed by comparisons with field observations of crack indications and leaks in actual BWRs. Disagreement between field observations and PRAISE-CC calculations would indicate that adjustments to PRAISE-CC inputs should be made in order to improve agreement and provide increased confidence in PRAISE-CC predictions made in cases where no comparable field data are available. This section will first review field observations, and then describe adjustments to PRAISE-CC that were made to improve agreement.

3.1 Analysis of Field Data

Considerable numbers of leaks and crack indications have been reported in 304 stainless steel piping in BWRs [20-22]. These results can be compared with PRAISE-CC computations to check on the accuracy of PRAISE. Results of such checks provide guidance in adjustments to PRAISE to improve agreement with field observations.

3.1.1 Crack Indications

Crack indications of circumferential orientation were considered in comparisons with PRAISE-CC results. Whenever a weld had more than one crack indication, only the deepest crack was considered. The crack indications were separated into two groups -- indicated depth greater than 10% of the wall thickness and greater than 50% of the wall thickness. Welds that developed leaks are not included in the population of welds with indicated cracks. Most of the inspections occurred when plants were approximately 2 years, 7.5 years, or 12.5 years old and, therefore, the results were grouped for these three plant ages. The results of inspections for large, intermediate, and small lines are summarized in Table 4.

The data of Table 4 are presented in Figures 26-28 as the proportion of cracked welds as a function of time. Also shown are the two-sided 90% confidence intervals evaluated according to procedures outlined in Reference 23.

Table 4

CRACK INDICATIONS FOR BWR PIPES

	Large (>20") Lines			Intermediate (10-20") Lines			Small (<10") Lines		
Time (yrs)	No. Inspected	Welds with $a \geq 0.1h$	Welds with $a \geq 0.5h$	No. Inspected	Welds with $a \geq 0.1h$	Welds with $a \geq 0.5h$	No. Inspected	Welds with $a \geq 0.1h$	Welds with $a \geq 0.5h$
2	57	7	0	51	21	0	0	0	0
7.5	503	62	2	474	49	15	150	15	7
12.5	197	42	6	279	75	21	28	7	3

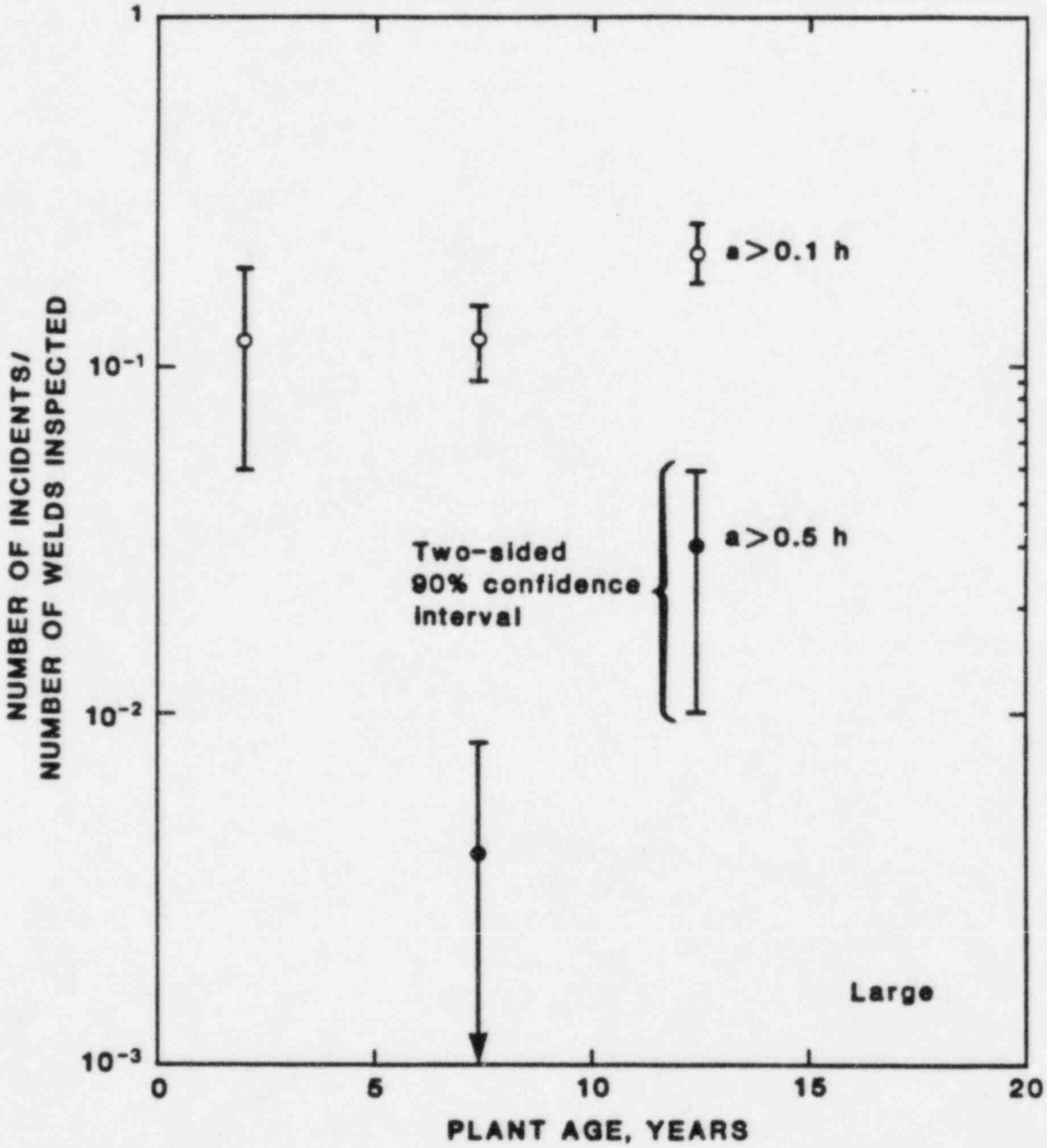

Figure 26. Normalized number of welds with indicated cracks deeper than 10% and 50% of the pipe wall thickness as a function of plant age for pipes with outside diameter greater than 20 inches.

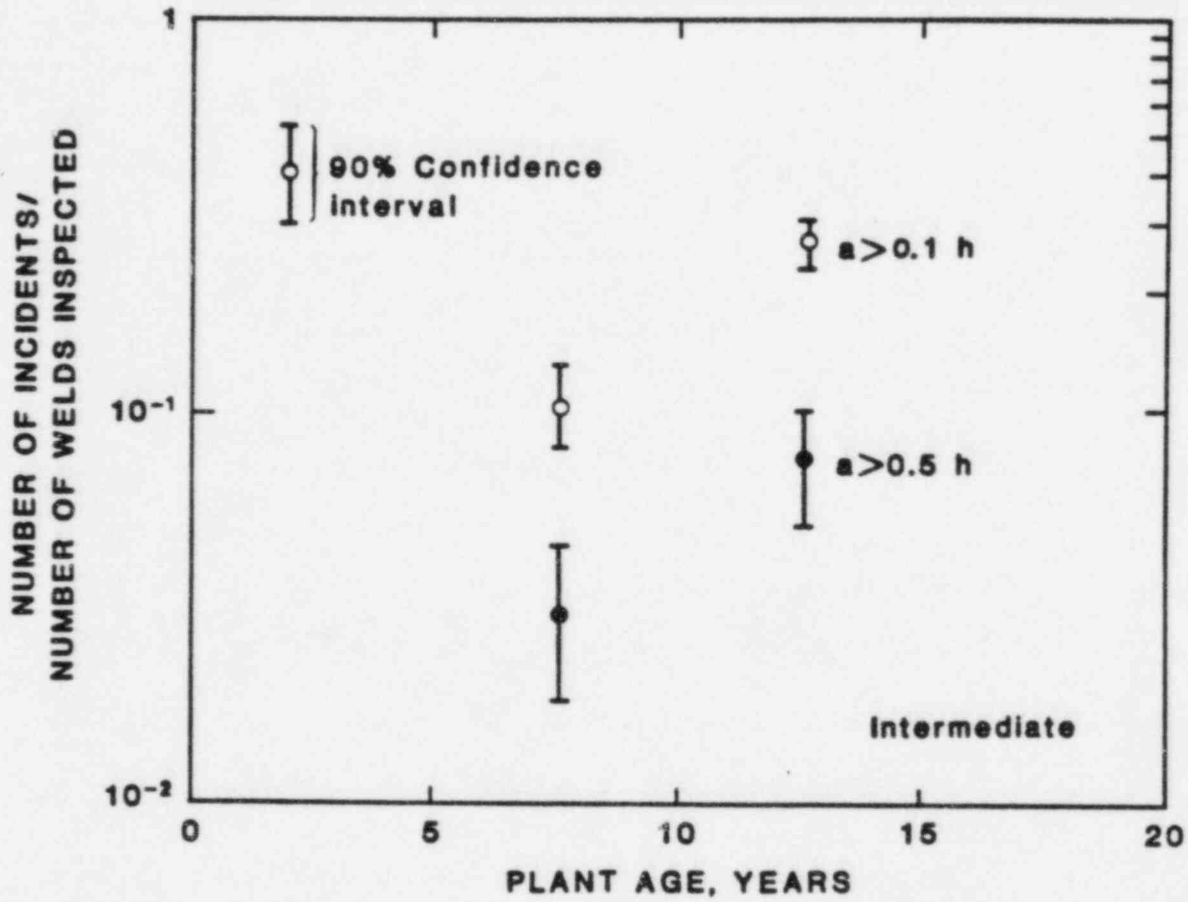

Figure 27. Normalized number of welds with indicated cracks deeper than 10% and 50% of the pipe wall thickness as a function of plant age for pipes with outside diameter between 10 and 20 inches.

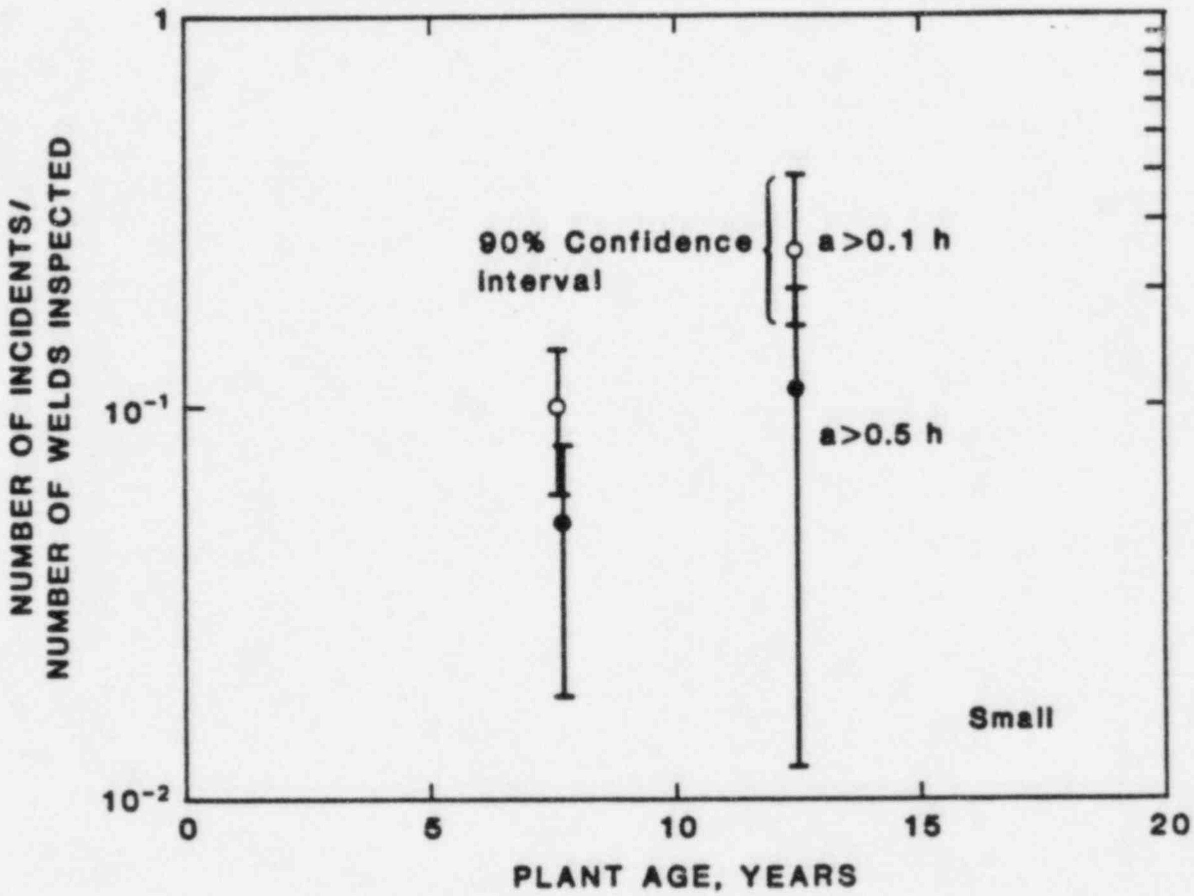

Figure 28. Normalized number of welds with indicated cracks deeper than 10% and 50% of the pipe wall thickness as a function of plant age for pipes with outside diameter less than 10 inches.

3.1.2 Leaks

For the analysis of field data, leaks of all orientations were grouped together. Since leaks occurred in welds of varying ages, and since the weld population varied with time, the simple procedure used for the analysis of crack indications cannot be used. A computer program SAFECC [24] was employed to generate the distribution of leaks as a function of plant age. The results of this analysis are presented in Figures 29-31 for large, intermediate, and small lines, respectively. In the case of large lines, only two leaks have been reported. Therefore only the rough estimate shown in Figure 29 could be provided for this line size.

3.2 PRAISE-CC Adjustments

The suitability of the stress corrosion cracking and growth models incorporated into PRAISE-CC and described in Section 2 can be assessed by comparing numerical results with the field observations summarized in Section 3.1. Adjustments to PRAISE-CC inputs will be made to improve the agreement.

Some sensitivity runs were made to determine the relative influence of various input variables on calculated leak and crack size probabilities. Attention was focused on the variables which were the least certain, which included the distribution of initiated crack depth, "unit length" of weld for crack initiation, crack depth at transition from initiated to fracture mechanics crack growth, threshold on Γ_K for crack growth, and level of residual stresses. It was found that the calculated leak and crack depth probabilities were not strongly influenced by reasonable alteration of these variables, with the exception of the residual stress levels. In spite of the voluminous information on surface residual stresses, as was reviewed in Section 2.5, the spatial variation is not well defined by available observations. In addition, the available residual stress data may not be representative of field data. Therefore, the level of residual stresses was adjusted for all three ranges of line sizes in order to minimize disagreement between predicted and observed behavior. Greater weight was placed on observed leaks, because crack depth indications are subject to inaccuracies -- especially for depths as small as 10% of the wall thickness.

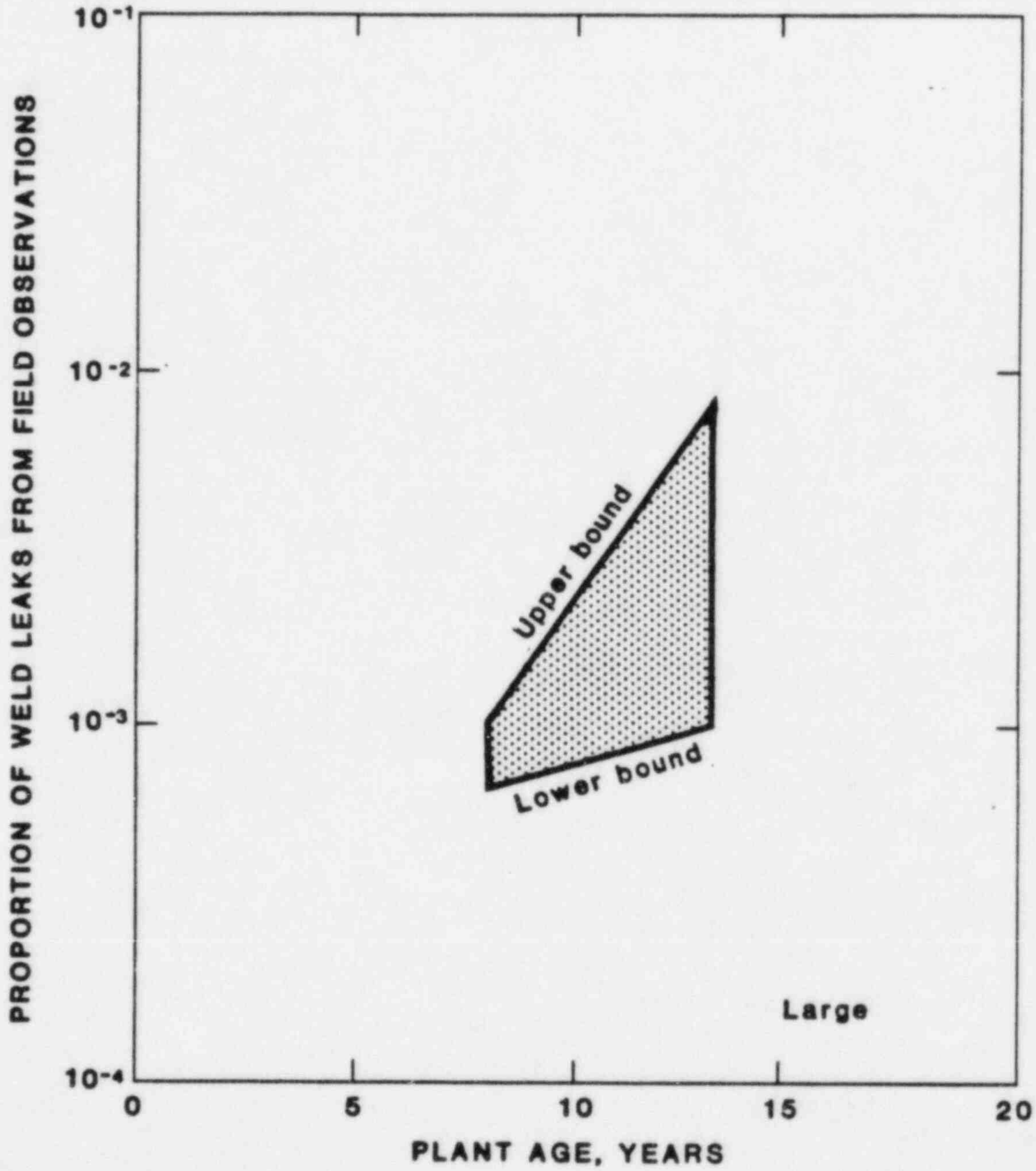

Figure 29. Proportion of welds with leaks as a function of plant age for field observations for pipes with outside diameter greater than 20 inches.

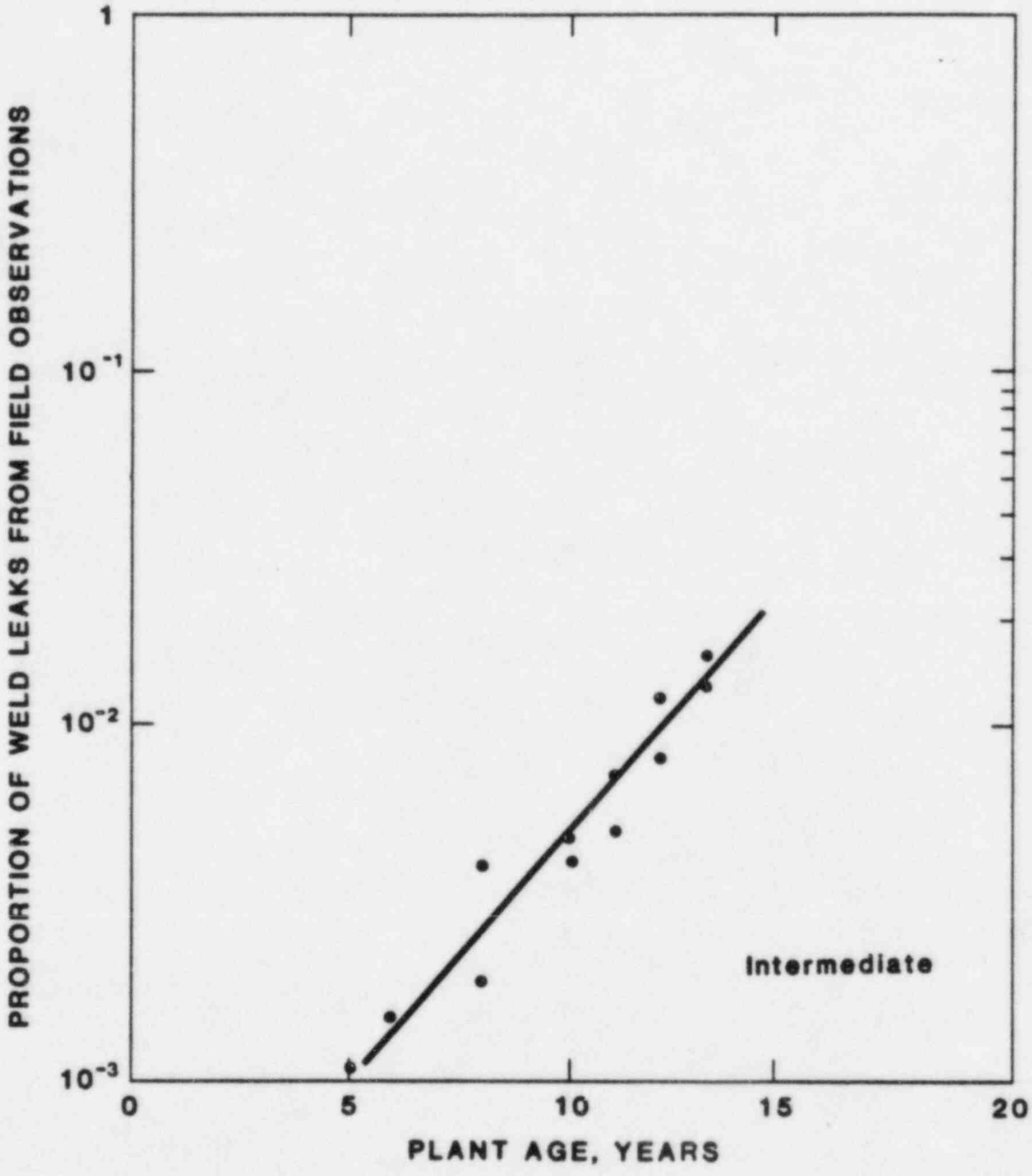

Figure 30. Proportion of welds with leaks as a function of plant age for field observations for pipes with outside diameter between 10 and 20 inches.

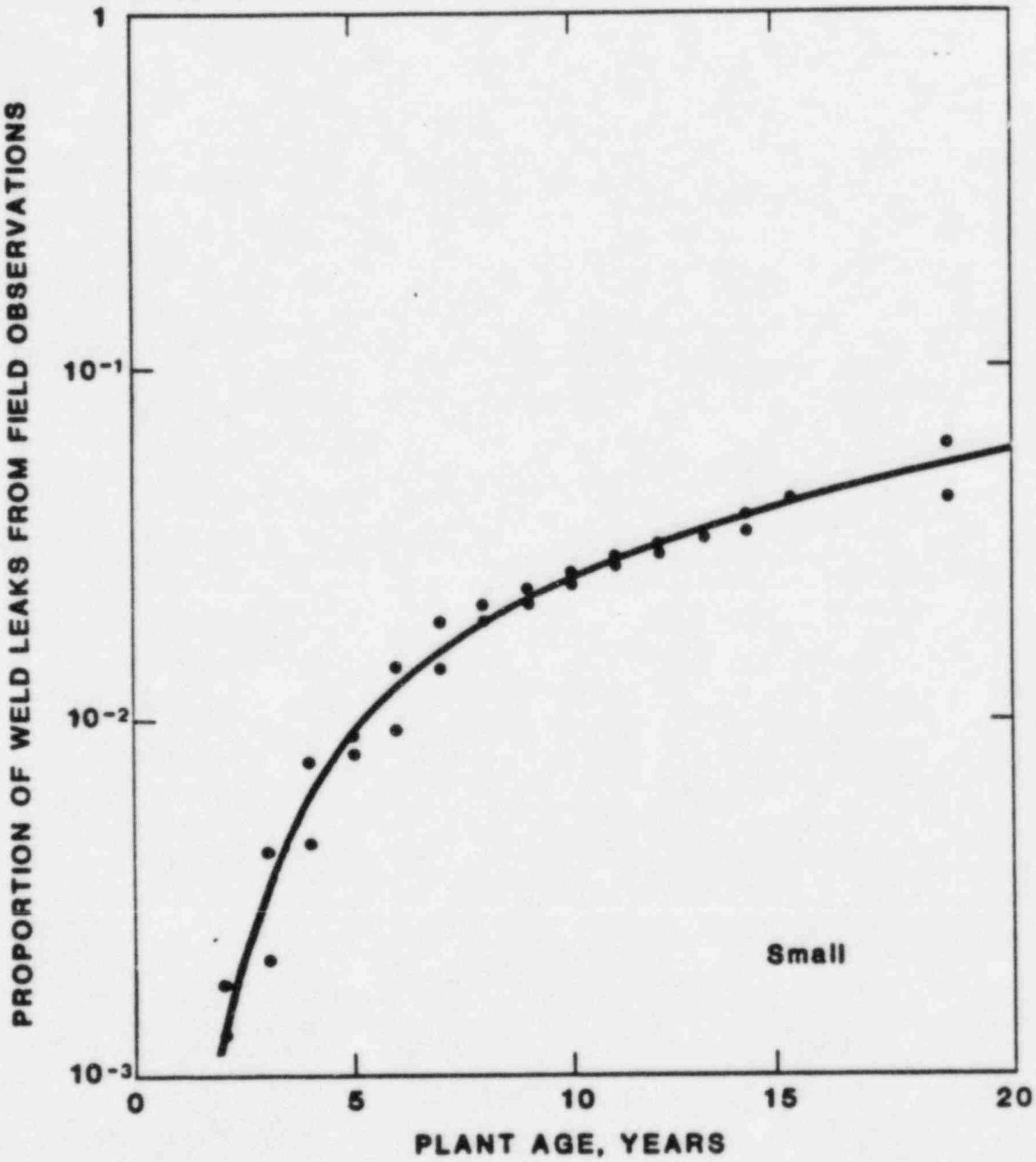

Figure 31. Proportion of welds with leaks as a function of plant age for field observations for pipes with outside diameter less than 10 inches.

Representative applied stresses and dimensions of the various size lines are required in order to perform the PRAISE-CC calculations. The representative sizes and stresses are presented in Table 5. These selected values are based on the following conditions:

- Pre-service inspection with nondetection probability given by equation 26.
- Plant loading and unloading only transient, occurs 5 times per year, 5 hours from zero to full load.
- No in-service inspection.
- Critical crack size controlled by critical net section stress.

All adjustments to the residual stresses were performed by considering the residual stresses for a given range of line sizes, and as described in Section 2.5, to be altered by multiplying by a factor, f. PRAISE-CC runs were performed for each range of line size for various values of f, and a value of f selected by comparing the results with corresponding field observations of crack indications and leaks. Values of f were selected that provided leak and crack indication probabilities somewhat above the field observations. Hence, the selected values of f are believed to be somewhat conservative.

Figures 32-37 provide the comparisons between field observations and PRAISE-CC results calculated using various values of f. Based on these results, a value of f was selected for each range of line size. Table 6 summarizes the results. The use of these values of f in conjunction with the crack initiation and growth model described in Section 2 is believed to provide a means of probabilistic analysis of BWR piping reliability of maximum accuracy within the current state-of-the-art of understanding of the governing phenomena.

Figure 37 shows the somewhat curious result of the proportion of welds with cracks greater than 50% of the wall thickness decreasing as plant age exceeds about 12 years. This is explainable because cracks that have resulted in leaks are not included in the population of cracks of depth greater than

Table 5

REPRESENTATIVE PIPE SIZES AND STRESSES FOR GENERATION OF PRAISE-CC RESULTS FOR COMPARISON WITH FIELD OBSERVATIONS

	Large	Intermediate	Small
normal operation, σ_{NO}, ksi	9.36	11.53	13.93
dead weight, σ_{DW}, ksi	0.01	0.50	0.01
pressure, σ_p, ksi	5.95	5.33	2.93
outside diameter, in	23.7	16.0	4.14
wall thickness, in	1.04	0.84	0.34

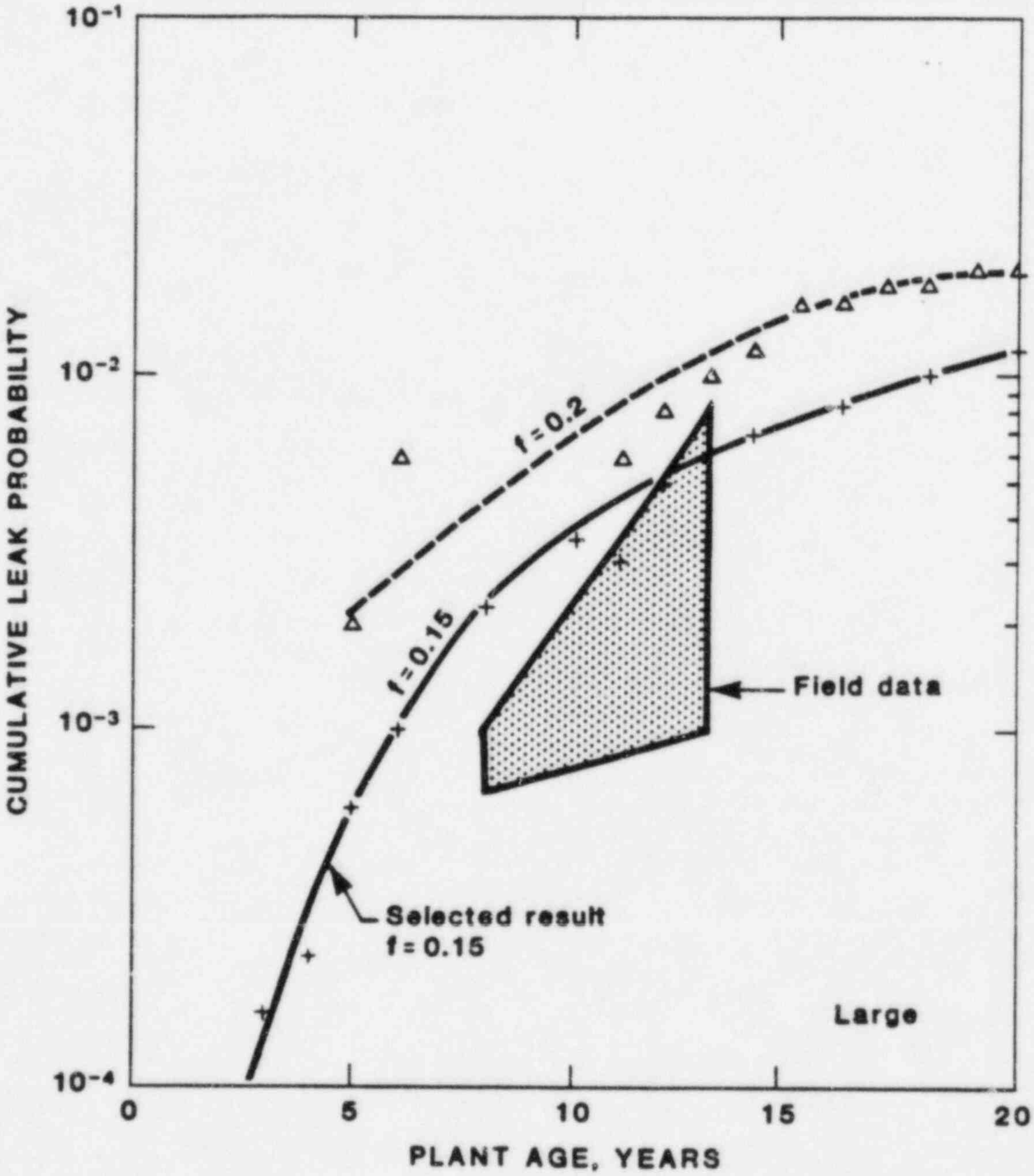

Figure 32. Field observations of leak probabilities compared with PRAISE-CC results for various values of the residual stress adjustment factor, f. (Outside diameter greater than 20 inches.)

FaAA-85-5-2

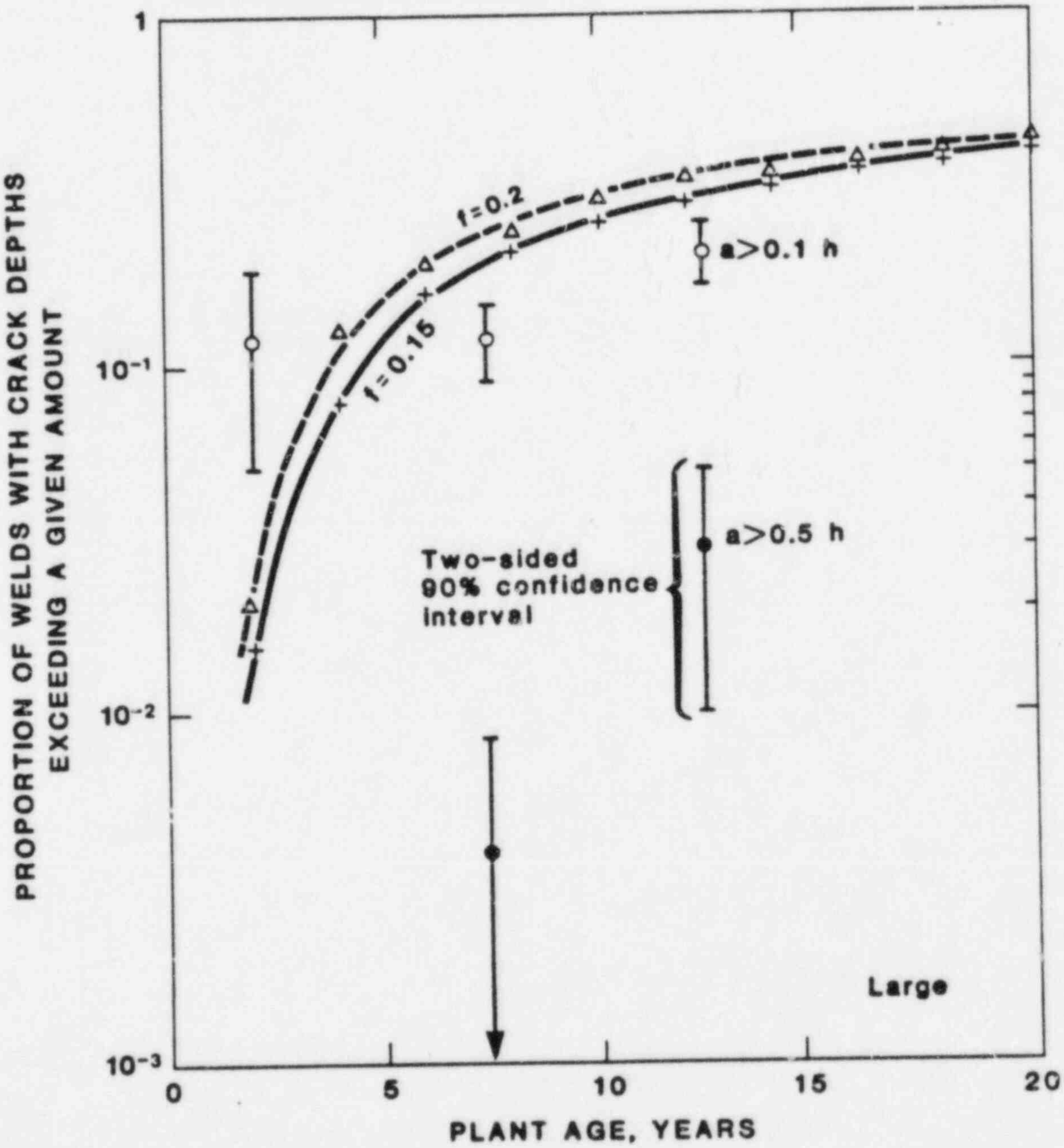

Figure 33. Field observations of indicated cracks compared with PRAISE-CC results for various values of the residual stress adjustment factor, f. (Outside diameter greater than 20 inches.)

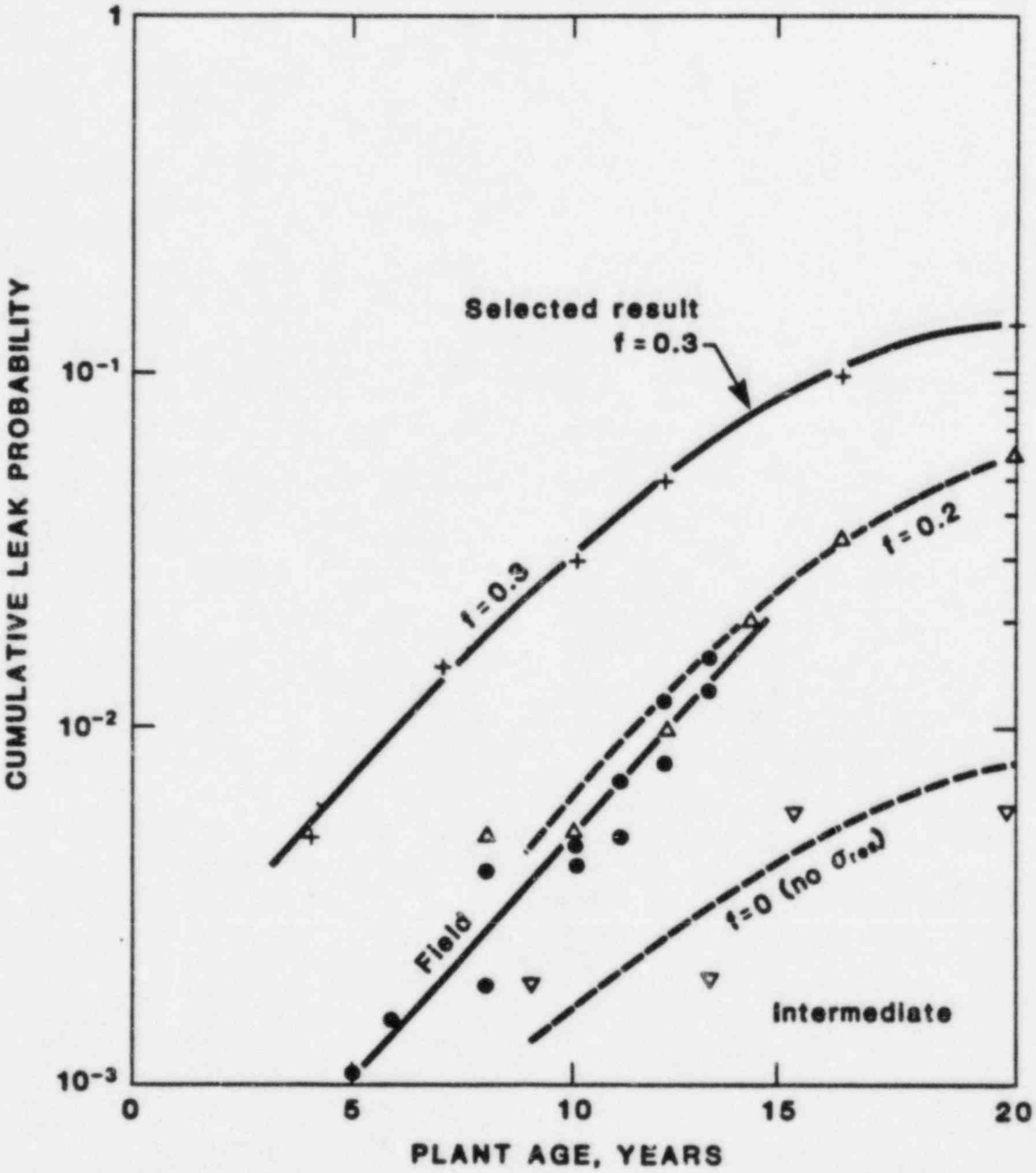

Figure 34. Field observations of leak probabilities compared with PRAISE-CC results for various values of the residual stress adjustment factor, f. (Outside diameter between 10 and 20 inches.)

FaAA-85-6-2

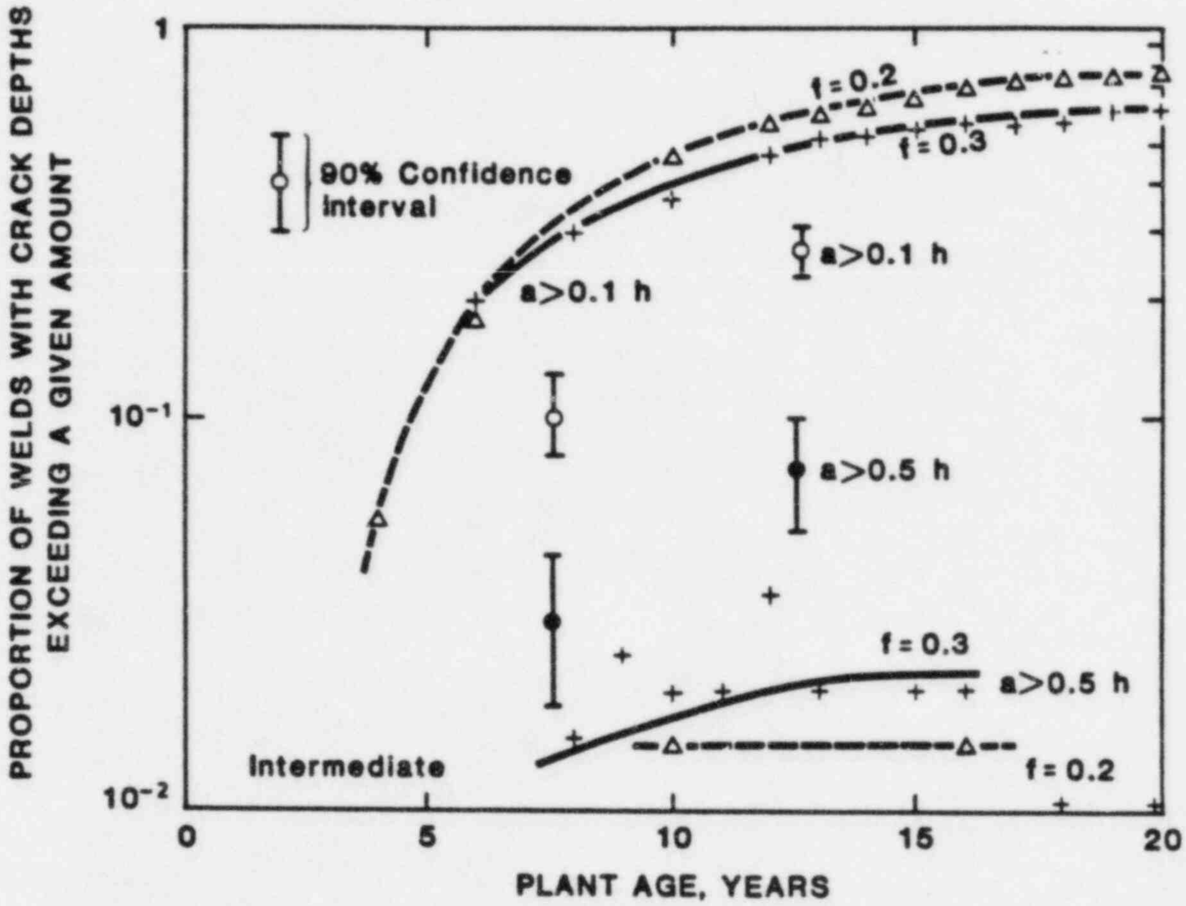

Figure 35. Field observations of indicated cracks compared with PRAISE-CC results for various values of the residual stress adjustment factor, f. (Outside diameter between 10 and 20 inches.)

FaAA-85-5-2

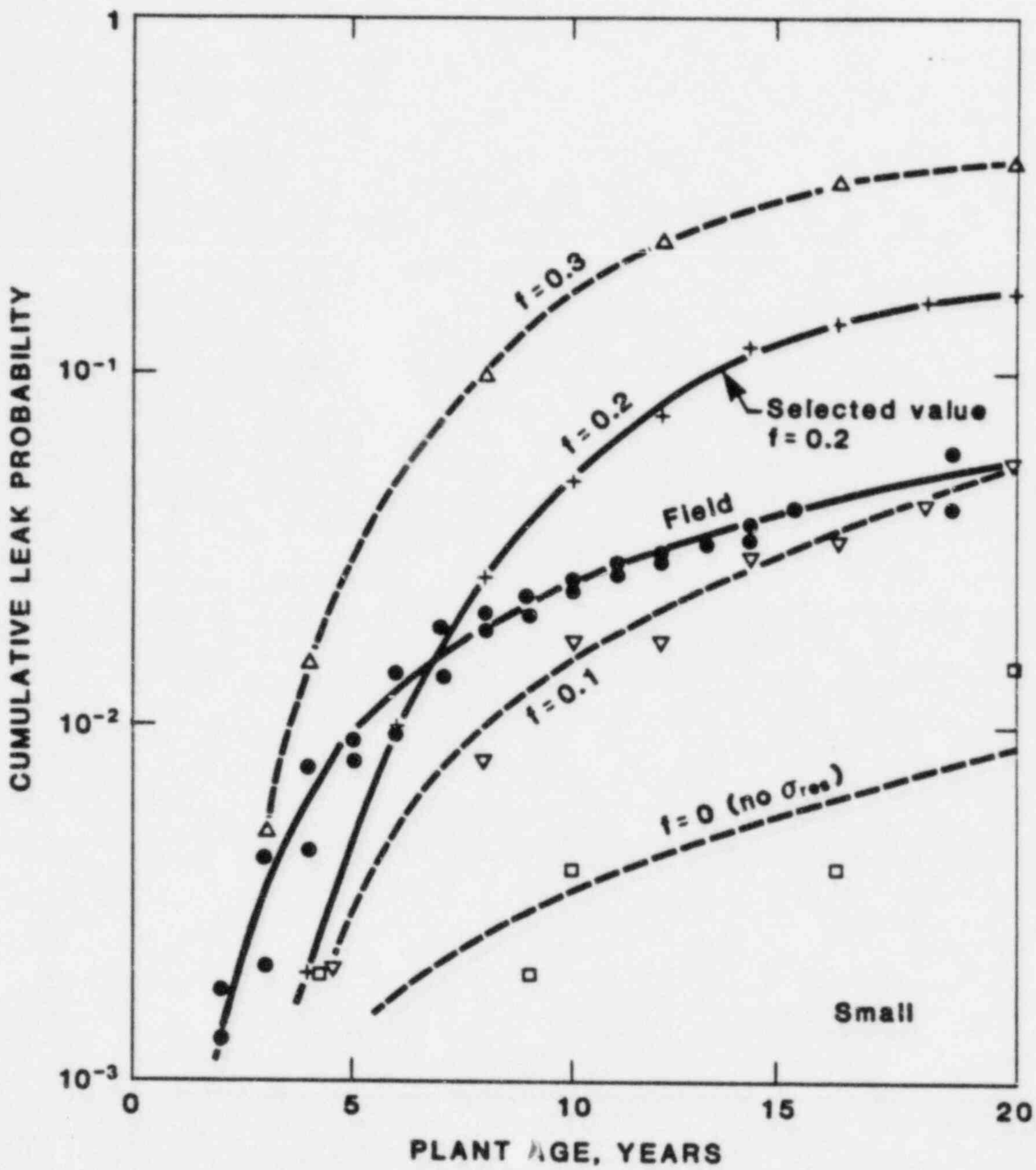

Figure 36. Field observations of leak probabilities compared with PRAISE-CC results for various values of the residual stress adjustment factor, f. (Outside diameter less than 10 inches.)

FaAA-85-5-2

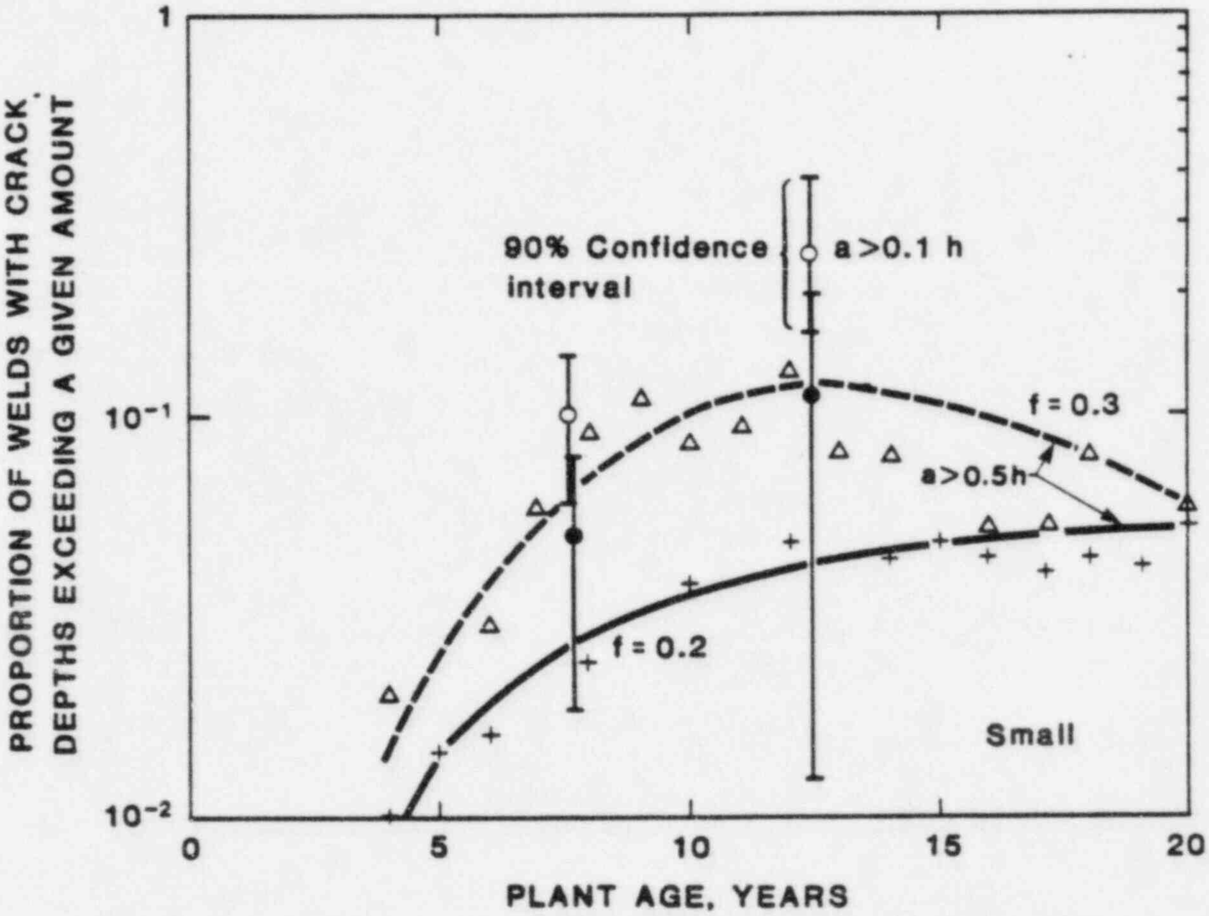

Figure 37. Field observations of indicated cracks compared with PRAISE-CC results for various values of the residual stress adjustment factor, f. (Outside diameter less than 10 inches.)

Table 6

VALUES OF ADJUSTMENT FACTOR TO RESIDUAL STRESSES, f, SELECTED TO IMPROVE AGREEMENT BETWEEN FIELD OBSERVATIONS AND PRAISE-CC CALCULATIONS

Line Size	Value of f
large (> 20 inches)	0.15
intermediate (10-20 inches)	0.30
small (< 10 inches)	0.20

0.5 h. Figure 36 shows the leak probabilities for these small lines to be approaching unity at longer times. Hence, most welds with deep crack have already leaked, thereby not leaving many welds left to have a > 0.5 h (but less than h).

3.3 Representative Results

Results presented previously in Section 3 concentrated on leak and crack indications, because field observations provide information comparable to such results. Values of f were selected to improve agreement between field observations and PRAISE-CC predictions. Now that f has been selected, representative results for the double-ended-pipe-break (DEPB) probability will be presented.* Table 7 summarizes leak and DEPB probabilities for the three ranges of line size. Once again, the stresses and specific pipe dimensions are summarized in Table 5.

There are some minor differences between the results in Table 7 and those of Figures 32, 34, and 36. These differences are due to differences in the number of replications in the Monte Carlo runs. The results in Figures 32, 34, and 36 were intended for selecting a value of f based on comparison with leak probabilities. Such probabilities are relatively high, and great accuracy in generating results to select a value of f was not required. The runs for generating the results of Table 7 used many more replications in order for some DEPBs to be included in the samples. Hence, the calculated leak probabilities were somewhat changed.

The results of Table 7 show that the calculated failure probabilities are lower for larger pipes, which is consistent with general field observations. Also, the DEPB probabilities are about three orders of magnitude lower than the corresponding leak probabilities. This supports the leak-before-break concept, but shows that sudden and complete pipe severance is within the realm of possibility.

* Double-ended-pipe-breaks have not been observed in the field in BWRs.

Table 7

SUMMARY OF CUMULATIVE LEAK AND DEPB PROBABILITIES FOR THE THREE RANGES OF LINE SIZE AS A FUNCTION OF TIME

	Leak Probabilities			DEPB Probabilities		
Time, yrs.	Large	Intermediate	Small	Large	Intermediate	Small
2	$<3 \times 10^{-5}$	2.4×10^{-4}	7×10^{-4}	--	$<2 \times 10^{-5}$	$<10^{-4}$
5	6×10^{-4}	8.3×10^{-3}	1.2×10^{-2}	--	4×10^{-5}	1×10^{-4}
10	3.4×10^{-3}	5.4×10^{-2}	6.7×10^{-2}	--	4×10^{-5}	3×10^{-4}
15	7.7×10^{-3}	1.2×10^{-1}	1.4×10^{-1}	$<3 \times 10^{-5}$	6×10^{-5}	4×10^{-4}
20	1.2×10^{-2}	1.8×10^{-1}	1.9×10^{-1}	3×10^{-5}	6×10^{-5}	5×10^{-4}
			No. of Replications →	30,000	50,000	10,000

The DEPB probabilities are much smaller than corresponding leak probabilities and therefore require considerably more computer time for their evaluation. In contrast to the case of failure due to pre-existing fatigue cracks, failures due to the initiation and growth of stress corrosion cracks are not dominated by a single identifiable factor. Hence, the computational economies provided by the stratified sampling employed in earlier PRAISE versions [2] cannot be employed for stress corrosion cracking, and the computer expenses involved in generating accurate DEPB probabilities are greatly increased.

The calculated failure probabilities for BWR piping, as summarized in Table 7, are generally much larger than calculated values for pressurized water reactors (PWRs) as reported in Reference 1. This is consistent with past experience with these two types of reactors, and is indicative of the detrimental nature of stress corrosion cracking in sensitized 304 stainless steel weldments in BWR operating conditions.

4.0 SUMMARY AND CONCLUSIONS

An engineering model of reactor piping reliability that incorporates failure due to the initiation and growth of stress corrosion cracks is developed in this report. Sensitized weldments in 304 stainless steel piping in boiling water reactors (BWRs) are specifically concentrated upon. The probabilistic model of crack initiation is combined with earlier procedures for treating pre-existing cracks in order to incorporate the growth portion of the lifetime into the analysis. The resulting code, which employs Monte Carlo simulation for estimation of piping failure probabilities, is called PRAISE-CC, and is an expansion of the previously developed PRAISE code. A probabilistic treatment of as-welded residual stresses is also incorporated into PRAISE-CC, which provides a significant advance over previous deterministic treatments of residual stresses.

The probabilistic model of stress corrosion crack initiation and early growth is based on voluminous test data generated in the laboratory during constant elongation rate testing (CERT) and constant load testing (CL). Piping reliability estimates based on PRAISE-CC calculations employing the statistical treatment of test results are compared with field observations of leaks and indicated cracks during in-service inspections of operating BWRs. In general, the PRAISE-CC results generated including the probabilistic treatment of residual stresses were well above field observations for all three ranges of pipe sizes considered (OD<10 inch, OD = 10-20 inch, OD>20 inch).

Sensitivity studies were performed to determine the components of the model that could be adjusted by reasonable amounts to improve the agreement between calculated and observed piping behavior. It was found that adjustments to the residual stresses were most effective in improving agreement. Adjustments were made for each of the three ranges of pipe sizes, and good agreement was obtained.

The generation and interpretation of results for various BWR piping systems is not a portion of the efforts reported here. However, results generated for comparison with field observations showed that calculated

failure probabilities (leak or double-ended-pipe-break -- DEPB) are lower for larger pipes, and the DEPB probabilities are about three orders of magnitude lower than the corresponding leak probabilities. This supports the leak-before-break concept, but indicates that sudden and complete pipe severance is within the realm of possibility. The calculated failure probabilities for stress corrosion cracking are generally much larger than calculated values for PWRs. This is consistent with field experience, and is indicative of the detrimental nature of SCC in sensitized 304 stainless steel weldments under BWR operating conditions. Analysis of the limited available data on cracking in alternative austenitic BWR piping materials (304NG, 316, 316NG) indicates that these materials would not provide substantial improvements in piping reliability unless they can be counted upon to be significantly less weld sensitized.

The calculated DEPB probabilities are quite small, and therefore require considerable computer time for their evaluation. In contrast to the case of failure due to pre-existing fatigue cracks, failure due to the initiation and growth of stress corrosion cracks is not dominated by a single identifiable factor. Hence, the computational economies provided by stratified sampling employed in earlier PRAISE versions cannot be employed at the present time for stress corrosion cracking.

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APPENDIX A
DETAILED FORMATS FOR INPUT CARDS

Detailed descriptions of the input cards read by PRAISE-CC are given in this section. The name, position on the card, format, and description of each variable is given.

CARD TITLE CARD ID 1A

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
TITLE	1-80	10A8	Problem description.

CARD **PROBLEM CONTROL VARIABLES** ID ØB

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
INCIAT	1-5	IS	Ø: Run for pre-existing cracks. Include initiated cracks only if the sampled crack is below the BNDRY. 1: SCC initiated cracks only.
IFAILC	6-10	I5	Failure criteria to be used: Ø: Net section failure. 1: J_{Ic}, dJ/da exceedence. 2: Both.
ICRAKS	11-15	I5	Stress corrosion crack initiation sites.
IREPLS	16-20	I5	Number of replications for crack initiation problem (not used for INCIAT = Ø).
IPRAIS	21-25	I5	Ø: Default to pre-existing cracks only.
IREPAR	26-30	I5	= Ø: Leakers not repaired. = 1: Leakers that are detected are repaired. At the time of repair, all leakers are repaired.
BNDRY	31-40	F10.3	Boundary in terms of a/h, above which initiated cracks are not included. For example 1.1: Initiated cracks will always be included. -0.1: Initiated cracks will never be included.

CARD **PROBLEM SPECIFICATION** ID **1B**

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
NTRIES	1-5	I5	Option for number of replications to be drawn from each cell When NTRIES < 0, then ABS(NTRIES) replications will be taken from each and every cell. If NTRIES = 0, not used. If NTRIES > 0, then user inputs a number for each cell. This number is then multiplied by NTRIES to obtain the number of samples for each cell.
ISQARE	6-10	I5	Cell definition option ISQARE = 0, User inputs coordinates for each cell in the state space. ISQARE = 1, PRAISE-B internally sets up a regular grid of rectangular cells. ISQARE = 2, If INCIAT = 1.
KTYPES	11-15	I5	Number of transient types experienced by plant.
KRKDIS	16-20	I5	Initial crack size distributions. KRKDIS = 1, Crack depth is log-normal. Aspect ratio is log-normal. KRKDIS = 2, Crack depth is log-normal. Aspect ration is exponential. KRKDIS = 3, Crack depth is exponential. Aspect ratio is log-normal. KRKDIS = 4, Crack depth is exponential. Aspect ratio is exponential.
NEVAL	21-25	I5	Option for times during plant lifetime when the reliability is to be evaluated NEVAL < 0, Evaluation is performed for every ABS(NEVAL) year. NEVAL > 0, Number of user supplied times that an evaluation is performed.
NINSPT	26-30	I5	Number of user specified in-service inspection times.

CARD **PROBLEM SPECIFICATION (Cont'd)** ID **1B (Cont'd)**

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
NQUAKE	31-35	I5	Seismic evaluation option. NQUAKE = 0, No earthquakes are modeled. NQUAKE = 1, Earthquakes at each evaluation time.
IDEBUG	36-40	I5	Debugging output option. IDEBUG = 0, Normal output is printed. IDEBUG = 1, Additional debugging output will be supplied.
KONPRP	41-45	I5	Option for material constant (C) in the fatigue crack growth relationship KONPRP = 0, C is log-normally distributed. KONPRP = 1, C is constant; i.e., the crack growth relationship is deterministic.
NEQINT	46-50	I5	Number of seismic intensity classes to be simulated. If NQUAKE = 0, set NEQINT = 0. PRAISE-B, as presently dimensioned, can handle up to 10 classes.
MCELLS	51-55	I5	Number of cells in the calculational grid. If ISQARE = 1, the value of MCELLS is ignored.
KNSFLO	56-60	I5	Option for flow stress definition. KNSFLO = 0, Flow stress is normally distributed. KNSFLO = 1, Flow stress is constant.
NSKIP	61-65	I5	Parameter to specify the number of evaluation times which are skipped in the printout of the indicator functions. Subroutine OUTS prints every NSKIP-th evaluation time.
NPSI	66-70	I5	Option for pre-service ultrasonic inspection. NPSI = 0, No pre-service inspection. NPSI = 1, A pre-service inspection is modeled.

CARD **PROBLEM SPECIFICATION (Cont'd)** ID **1B (Cont'd)**

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
ISCC	71-75	I5	Option for modeling stress corrosion cracking (SCC). ISCC = 1, stress corrosion cracking only. ISCC = 0, fatigue only (no SCC). ISCC = -1, both SCC and fatigue. [If INCIAT ≠ 0, then ISCC should be either 1 or -1.]
ISIGRS	76-80	I5	Option for modeling contribution of welding residual stresses. ISIGRS = 0, Residual stresses are not modeled. ISIGRS = 1, Contribution of residual stresses is modeled (coefficients to be entered by the user). ISIGRS = 2, Contribution of residual stresses is modeled. Built-in residual stresses for large (20-30 inch) line used. ISIGRS = 3, Contribution of residual stresses is modeled. Built-in residual stresses for intermediate (10-20 inch) line used. ISIGRS = 4, Contribution of residual stresses is modeled. Built-in residual stresses for small (<10 inch) line used. ISIGRS = 5, Contribution of IHSI residual stresses is modeled. User to input stresses on the inside and outside surface.

CARD **IHSI RESIDUAL STRESS DEFINITION** ID **1C∅**

READ Only if ISIGRS = 5 on Card 1B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
RSIN	1-10	E10.3	Residual stress on the inside surface of a pipe (ksi).
RSOUT	11-20	E10.3	Residual stress on the outside surface of a pipe (ksi).

CARD **RESIDUAL STRESSES MODEL DEFINITION** ID 1C

READ Only if ISIGRS = 1 on Card 1B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
KKA	1-5	I5	The number of (a/b) terms in the polynomial which defines the contribution of residual stress to the "RMS-averaged" stress intensity factor in the depth direction.
LLA	6-10	I5	The number of (a/h) terms in the polynominal which defines the contribution of residual stress to the "RMS-averaged" stress intensity factor in the depth direction.
KKB	11-15	I5	The number of (a/b) terms in the polynominal which defines the contribution of residual stress to the "RMS-averaged" stress intensity factor in the length direction.
LLB	16-20	I5	The number of (a/h) terms in the polynominal which defines the contribution of residual stress to the "RMS-averaged" stress intensity factor in the length direction.

CARD **TIME PARAMETERS** ID **1D**

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
THRIZN	1-10	E10.3	Maximum plant lifetime for the simulation.
DTSCC	11-20	E10.3	Timestep to be used in calculating SCC growth. Used only if ISCC = 1 on Card 1B.

CARD PIPE DIMENSIONS ID 2A

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
THICK	1-10	E10.3	Wall thickness of the pipe (inches).
RIN	11-20	E10.3	Inside radius of the pipe (inches).
ELOVRR	21-30	E10.3	L/R ratio: Not required if IFAILC = 0.

CARD **FATIGUE CRACK GROWTH CHARACTERISTICS** ID **2B**

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
THRHLD	1-10	E10.3	Threshold value in the crack growth relationship (ksi-in$^{1/2}$).
EMEXP	11-20	E10.3	Exponent in the crack growth relationship.
CONSMU	21-30	E10.3	Parameter for the constant in the crack growth relationship. If KONPRP = 1, CONSMU is the constant. If KONPRP = 0, CONSMU is the median of the log-normal distribution that describes the constant.
CONS90	31-40	E10.3	Parameter for the constant in the crack growth relationship. If KONPRP = 1, CONS90 is ignored. If KONPRP = 0, CONS90 is the 90th percentile of the log-normal distribution.

CARD SCC VARIABLES ID 2B-1

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
OSTART	1-10	F10.5	0_2 at startup (ppm).
OSTEDY	11-20	F10.5	0_2 at steady-state (ppm).
TFSTDY	21-30	F10.5	Steady-state temperature (°F).
DURATN	31-40	F10.5	Duration of heat-up transient (in hours).

CARD **FLOW STRESS** ID **2C**

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION	
SFLOMU	1-10	E10.4	The mean value of the flow stress (ksi).	
SFLOSD	11-20	E10.4	Standard deviation of the flow stress (ksi). (Read if KNSFLO = 0.)	
XJIC	21-30	E10.4	J_{Ic} in (in-kips/in^2)	Required only if IFAILC ≠ 0.
DJDAMT	31-40	E10.4	dJ/da in ksi	Required only if IFAILC ≠ 0.
SIGØ	41-50	E10.4	Yield strength in ksi	Required only if IFAILC ≠ 0.
DEE	51-60	E10.4	D in ksi	Required only if IFAILC ≠ 0.
YOUNGS	61-70	E10.4	Youngs modulus in ksi	Required only if IFAILC ≠ 0.

CARD **INITIAL CRACK DEPTH DISTRIBUTION** ID **3A**

READ Only if INCIAT = Ø

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
AMEDIN	1-10	E10.3	Median of the log-normal distribution on crack depth. (Read if KRKDIS = 1,2.)
ASIGMA	11-20	E10.3	Shape factor (= standard deviation of logarithm of A) of the log-normal distribution on crack depth.
ALAMDA	1-10	E10.3	Rate parameter (IN^{-1}) for exponential distribution on crack depth. (Read if KRKDIS = 3,4.)

CARD **INITIAL CRACK ASPECT RATIO DISTRIBUTION** ID **3B**

READ Only if INCIAT = Ø

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
BOAMED	1-10	E10.3	Parameter analogous to the median in the truncated log-normal distribution on initial crack aspect ratio. (Read if KRKDIS = 1,3.)
BOASIG	11-20	E10.3	Parameter analogous to the shape factor in the truncated log-normal distribution on initial crack aspect ratio. (Read if KRKDIS = 1,3.)
BOANRM	21-30	E10.3	Normalization constant in the truncated log-normal distribution on initial crack aspect ratio. (Read if KRKDIS = 1,3.)
BOALDA	1-10	E10.3	Rate parameter for shifted exponential distribution on initial crack aspect ratio. (Read if KRKDIS = 2,4.)

CARD **EARTHQUAKE EVALUATION TIMES** ID **4A**

READ Only if NEVAL > Ø

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
TEVAL	1-80	8E10.3	Evaluation times (years).

CARD **IN-SERVICE INSPECTION TIMES** ID **4B**

READ Only if NINSPT > 0

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
TINSPT	1-80	8E10.3	In-service inspection time (years).

CARD **LEAK RATE AND DETECTION DEFINITIONS** ID **4C**

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
FNDLEK	1-10	E10.3	Threshold for leak rates which are detectable.
ALKBIG	11-20	E10.3	Threshold for discriminating between leaks and big leaks.

CARD **STRATIFIED SAMPLE SPACE** ID **5A**

READ Only if ISQARE = 1

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
NAOH	1-5	I5	Number of divisions of the a/h coordinate in the sample space definition. If the entire length of the a/h coordinate is to be used, read in as NAOH. If the length of the a/h coordinate is limited to the interval AOHLOW $\leq$ a/h $\leq$ AOHUP read in as -NAOH. The a/h coordinate is limited to the region AOHLOW $\leq$ a/h $\leq$ AOHUP.
NAOB	6-10	I5	Number of division of the a/b coordinate in the sample space definition. If the entire length of the a/b coordinate is to be used, read in as NAOB. If the length of the a/b coordinate is limited to the interval AOBLFT $\leq$ a/b $\leq$ AOBRGT read in as -NAOB. The a/b coordinate is limited to the region AOBLFT $\leq$ a/b $\leq$ AOBRGT.
AOHLOW	11-20	E10.3	Lower limit on the a/h coordinate. (Ignored if NAOH $<$ 0.)
AOHUP	21-30	E10.3	Upper limit on the a/h coordinate. (Ignored if NAOH $<$ 0.)
AOBLFT	31-40	E10.3	Lower limit on the a/b coordinate. (Ignored if NAOB $<$ 0.)
AOBRGT	41-50	E10.3	Upper limit on the a/b coordinate. (Ignored if NAOB $<$ 0.)

CARD **STRATIFIED SAMPLE SPACE (Cont'd)** ID **5A (Cont'd)**

READ Only if ISQARE = 0

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
AOHSIZ(M,1)	1-10	E10.4	Lower boundary of the a/h coordinate in the definition of the m-th stratification cell.
AOHSIZ(M,2)	11-20	E10.4	Upper boundary of the a/h coordinate in the definition of the m-th stratification cell.
AOBSIZ(M,1)	21-30	E10.4	Left boundary of the a/b coordinate in the definition of the m-th stratification cell.
AOBSIZ(M,2)	31-40	E10.4	Right boundary of the a/b coordinate in the definition of the m-th stratification cell.
NUMTRY	41-50	I10	Number of replications to be taken from the m-th cell.

CARD STRATIFIED SAMPLE SPACE (Cont'd) ID 5A (Cont'd)

READ Only if ISQARE = 1 and NTRIES > Ø

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
NUMTRY(M)	1-50	5I10	Number of replications to be taken from the m-th cell.

CARD STRESS VALUES ID 6A

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
SIGCLD	1-10	E10.3	Deadweight stress (ksi). This is the load controlled stress in the cold shutdown condition.
SGDWTE	11-20	E10.3	Deadweight and restraint of thermal expansion components of stress in the hot normal operating condition.
OPPRES	21-30	E10.3	Normal operating pressure of the system (ksi).
PRFPRS	31-40	E10.3	Pressure in the hydrostatic proof test (ksi). If no proof test is to be modeled, set this value to any arbitrary negative number.
SIGVIB	41-50	E10.3	Peak-to-peak amplitude of the high cycle vibratory stresses (ksi). If SIGVIB < 0, no vibratory stresses are modeled.
VBTHLD	51-60	E10.3	Threshold value of the load ratio (R* in Section 3.9 of NUREG/CR-2301) which is used in the vibratory stress model.

CARD SPECIFICATIONS FOR THE TABLES IN THE g_{min} AND g_{max} FUNCTIONS **ID** 6B

READ Only if KTYPES > 1

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
NX	1-5	I5	Number of entries in the a/b coordinate for the input of the g^*_{min} and g^*_{max} functions.
NY	6-10	I5	Number of entries in the a/h coordinate for the input of the g^*_{min} and g^*_{max} functions.
IX	11-15	I5	Number of entries in the a/b coordinate for the internal tables on g_{min} and g_{max}.
IY	16-20	I5	Number of entires in the a/h coordinate for the internal tables on g_{min} and g_{max}.

CARD **A/H COORDINATES FOR TABULAR INPUT OF CONTRIBUTION FROM RADIAL GRADIENT THERMAL STRESSES TO STRESS INTENSITY FACTOR** ID **6C**

READ Only if KTYPES > 1

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
AAOH(I)	1-80	8F10.3	Values of the a/h coordinate in the tabulated input for the contribution of radial gradient thermal stress to the stress intensity factor (I=1,...,NY).

CARD **B/A COORDINATE FOR TABULAR INPUT OF CONTRIBUTION FROM RADIAL GRADIENT THERMAL STRESSES TO STRESS INTENSITY FACTORS** **ID** **6D**

READ Only if KTYPES > 1

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
ABOA(I)	1-80	8F10.3	Values of the b/a coordinate in the tabulated input for the contribution of radial graident thermal stresses to the stress intensity problem (I=1,...,NY).

CARD **FREQUENCY OF HEATUP/COODOWN AND TRANSIENTS** ID **6E**

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
NCYBLK	1-5	I5	Number of cycles in the equivalent event.
BLAMDA(K)	6-10	F5.2	Arrival time parameter for transients. If BLAMDA(K) > 0.0, then k-th transient arrives at uniformly spaced intervals of BLAMDA(K) years. If BLAMDA(K) < 0.0, then k-th transient is treated as a Poisson process with ABS(BLAMDA (K)) as the average number of arrivals per unit time. If stress corrosion crack initiation is included, then BLAMDA(K) should always be greater than 0.0 (the transient arrival times uniformly spaced).
TEMP(K)	11-20	F10.5	Temperature excursion (°F) during the k-th transient.
TITLE(K)	21-80	6A10	Description for the k-th transient type.

CARD **TABULATED FUNCTIONS FOR g^*_{min} AND g^*_{max}** ID 6F

READ All transients except the heatup/cooldown, i.e., K > 1

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
			This outer loop is on the b/a coordinate and is read in reverse order or (I = NX, NX-1, ...,1).
GDAMIN(I,J,K)	1-72	9F8.5	$g^*_{min,a}$ (J = 1, ..., NY).
GDAMAX(I,J,K)	1-72	9F8.5	$g^*_{max,a}$ (J = 1, ..., NY).
GDAMIN(I,J,K)	1-72	9F8.5	$g^*_{min,b}$ (J = 1, ..., NY).
GDAMAX(I,J,K)	1-72	9F8.5	$g^*_{max,b}$ (J = 1, ..., NY).

CARD	COEFFICIENTS FOR THE POLYNOMINAL THAT DEFINES THE CONTRIBUTION OF WELDING RESIDUAL STRESSES TO THE STRESS INTENSITY FACTOR IN THE DEPTH DIRECTION	ID	6G
READ	Only if ISIGRS = 1 on Card 1B		

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
B(L,K)	1-80	8E10.3	(b(l,k), l = 1, LLA). A separate card is used for each value of k (k = 1, ..., KKA). LLA corresponds to L in Equation 3-11; KKA corresponds to K in Equation 3-11 (NUREG/CR-2301).

CARD	**COEFFICIENTS FOR THE POLYNOMINAL THAT DEFINES THE CONTRIBUTION OF WELDING RESIDUAL STRESSES TO THE STRESS INTENSITY FACTOR IN THE LENGTH DIRECTION**	ID	**6H**

READ Only if ISIGRS = 1 on Card 1B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
B(L,K)	1-80	8E10.3	(b(l,k), l = 1, ..., LLB). A separate card is used for each value of k (k = 1, ..., KKB). LLB corresponds to L in Equation 3-11; KKA corresponds to K in Equation 3-11 (NUREG/CR-2301).

CARD **EARTHQUAKES PER MAGNITUDE CATEGORY** ID **7A**

READ Only if NQUAKE = 1 on Card 1B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
NEQCLS(N)	1-80	16I5	Number of earthquakes in the n-th magnitude category. A maximum of ten earthquakes can be modeled in each category.

CARD **SEISMIC CRACK GROWTH PARAMETERS** ID 7B

READ Only if NQUAKE = 1 on Card 1B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
			The following card is repeated for each earthquake that is modeled. They are grouped by earthquake intensity category. N is the index on the intensity category, while LEQ is the index on earthquakes within a intensity category.
NCYCEQ(N,LEQ)	1-10	I10	Number of equivalent cycles used to represent the crack growth.
SIGEQ(N,LEQ)	11-20	F10.3	S^4 - The fourth power of the S-factor.
SGEQMX(N.LEQ)	21-30	F10.3	The load-controlled stress (ksi).
TITLE(N,LEQ)	31-80	5A10	Description for this particular earthquake.

APPENDIX B
SAMPLE PROBLEMS

The four sample problems presented in this appendix are intended to illustrate the new capabilities incorporated into the PRAISE-CC computer code. This appendix contains a discussion of the inputs with a brief description for each of the four following sample problems:

- Sample Problem 1. This problem employs the newly incorporated residual stress model for small lines; only stress corrosion initiated cracks are considered.
- Sample Problem 2. This problem employs the newly incorporated residual stress model for intermediate lines; only stress corrosion initiated cracks are considered.
- Sample Problem 3. This problem employs the newly incorporated axi-symmetric distributed model for residual stresses for large lines; again only the stress corrosion initiated cracks are included.
- Sample Problem 4. This problem demonstrates the newly incorporated IHSI residual stress model; only pre-existing cracks are considered.

Since all the sample problems presented here are for demonstrating the new capabilities of PRAISE-CC, some input data are hypothetical. Readers are advised not to interpret the results as final failure probabilities for any given piping system.

SAMPLE PROBLEM 1

This sample problem illustrates the use of the stress corrosion crack initiation model and the residual stress model for small lines. Specific inputs are:

- Twenty year plant lifetime (THRIZN = 20)
- 0.34 inch wall thickness (THICK = 0.34)
- 1.73 inch pipe inside radius (RIN = 1.73)
- 6 crack initiation sites (ICRAKS = 6)
- SCC-initiated crack only; no pre-existing cracks are considered (INCIAT = 1, ISCC = 1)
- Maximum time-step for stress corrosion crack growth computation is 0.2 year (DTSCC = 0.2)
- 8 ppm oxygen during plant loading (OSTART = 8.0)
- 0.2 ppm oxygen during steady-state operation (OSTEDY = 0.2)
- 550°F coolant temperature at steady-state operation (TFSTDY = 550°F)
- Five hours for plant heat-up (DURATN = 5.0)
- Flow stress distributed with a mean of 44.9 ksi and standard deviation of 1.9 ksi (SFLOMU = 44.9, SFLOSD = 1.9)
- Failure criteria minus applied stress exceeding flow stress (IFAILC = 0)
- Leak detected if it exceeds 0.1 gpm. Small and large leaks not differentiated (FNDLEK = 0.1, ALKBIG = 0.1)
- Leaks not repaired (IREPAR = 0)
- Dead weight stress of 0.01 ksi; stress due to dead weight and restraint of thermal expansion of 11 ksi (SIGCLD = 0.01, SGDWTE = 11)
- Operating pressure of 1.15 ksi (OPPRES = 1.15)
- Hydrostatic proof test pressure of 1.4375 ksi, although proof tests have no meaning when pre-existing cracks are not considered in the analysis (PRFPRS = 1.4375)

- Residual stress model for small line selected (ISIGRS = 4)
- No vibratory stresses included (SIGVIB = -1.0)
- Pre-service inspection modeled; again this has no meaning when pre-existing cracks are not considered in the analysis (NPSI = 1)
- No earthquakes are included (NQUAKE = 0)
- The only transient modeled is the heat-up/cool-down cycle which is assumed to occur regularly five times per year (KTYPES = 1, BLAMDA(1) = -0.2)
- 300 replications performed (IREPLS = 300)

The input file image and the input summary for this sample problem are given in Figures B1 and B2, respectively. The estimated failure probabilities are given in Figure B3. Additional output is shown in Figure B4.

```
P.V7 :  6 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB
    1     0     6  500     1     0    1.1
  -15     1     1     3    -1     0     0     0     0     0    14     0   02     1     1     6
20.0         0.2
0.36         1.73
4.5          4.0         9.1400E-12    3.5E-11
8.0          0.2         550.0         5.5
44.9         1.9
0.1          0.1
0.01         11.0        1.15       1.4375     -1.0
    1    -.2 480.0       HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
    1     1     1     1
          1      521.6         2.75      1 OBE   JOINT 1 LLNL DATA
          2     2958.5         9.05      1 SSE   JOINT 1 LLNL DATA
          2   63430.0         10.55      3 SSE   JOINT 1 LLNL DATA
          4  162000.0         10.62      5 SSE   JOINT 1 LLNL DATA
```

Figure B1. Input file image for Sample Problem 1.

```
--- PS97 : 6 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB
SCC-INITIATED CRACKS ONLY

A/H BOUNDARY              =     1.100

 MAXIMUM NO. OF CRACKS =    6
 NO. OF REPLICATIONS   =  300


SCC ONLY

 LEAKERS WILL NOT BE REPAIRED

FAILURE CRITERIA : APPLIED STRESS>FLOW STRESS

TIMESTEP FOR SCC =   0.200  YEARS

PIPE DIMENSIONS
          INSIDE RADIUS =        1.73  INCHES
          WALL THICKNESS         0.34  INCHES

CRACK GROWTH LAW PARAMETERS
          EXPONENT =                  4.00
          GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
               MEDIAN =              0.9140E-11
               90-TH PERCENT =       0.3500E-10
          THRESHOLD =                 4.60

SCC  PARAMETERS


          O2 AT STARTUP(PPM)=              8.00
     O2 AT STEADY STATE(PPM)=              0.20
TEMP. AT STEADY STATE(DEG F)=            550.00
HEATUP (100-550F) TIME (HRS)=              5.00

          FLOW STRESS NORMALLY DISTRIBUTED
          MEAN=               0.4490E+02
          STANDARD DEVIAT     0.1900E+01

PIPE STRESS VALUES
          CSD DEADWT STRESS (KSI)    0.01
          HOT UNIFORM STRESS (KSI)  13.93
          PRESSURE STRESS (KSI)      2.93
          SIG-DC          (KSI)     10.99
          PROOF TEST STRESS(KSI)     3.67

LEAK DETECTION AND DEFINITION PARAMETERS
          DETECTABLE LEAK(GPM)        0.1
          BIG LEAK(GPM)               0.1

RESIDUAL STRESSES FOR SMALL LINE SELECTED

NO VIBRATORY STRESSES ARE MODELED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELED

TIME INTERVALS
          PLANT LIFETIME        20.0  YEARS
          ENDPOINTS OF INTERVALS AT    0.0   1.0   2.0   3.0   4.0   5.0   6.0   7.0   8.0   9.0  YEARS
          ENDPOINTS OF INTERVALS AT   10.0  11.0  12.0  13.0  14.0  15.0  16.0  17.0  18.0  19.0  YEARS
          ENDPOINTS OF INTERVALS AT   20.0

NO IN-SERVICE INSPECTIONS ARE MODELED

                    - - - NO SEISMIC EVENTS EVALUATED - - -

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS     2

                    - - -  NORMAL OUTPUT REQUESTED - - -


      - - NUMBER OF TRANSIENT TYPES =     1  - -

TYPE  1     HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
REGULAR AT     0.200  YRS/EVENT
MAX DELTA TEMP =460.0  BLOCKING FACTOR =   1.
```

Figure B2. Input summary for Sample Problem 1.

- - - PSV7 : 5 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

- - RESULTS WITHOUT EARTHQUAKES - - -

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
1.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
2.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
3.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
4.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
5.0	6.66667E-03	6.66667E-03	0.00000E+00	4.70616E-03	4.70616E-03	0.00000E+00
6.0	6.66667E-03	6.66667E-03	0.00000E+00	4.70616E-03	4.70616E-03	0.00000E+00
7.0	1.00000E-02	1.00000E-02	0.00000E+00	5.75416E-03	5.75416E-03	0.00000E+00
8.0	2.00000E-02	2.00000E-02	0.00000E+00	8.09641E-03	8.09641E-03	0.00000E+00
9.0	2.66667E-02	2.66667E-02	0.00000E+00	9.31707E-03	9.31707E-03	0.00000E+00
10.0	4.66667E-02	4.66667E-02	0.00000E+00	1.21980E-02	1.21980E-02	0.00000E+00
11.0	7.00000E-02	7.00000E-02	0.00000E+00	1.47555E-02	1.47555E-02	0.00000E+00
12.0	8.00000E-02	8.00000E-02	0.00000E+00	1.56893E-02	1.56893E-02	0.00000E+00
13.0	9.33333E-02	9.33333E-02	0.00000E+00	1.68231E-02	1.68231E-02	0.00000E+00
14.0	1.20000E-01	1.20000E-01	0.00000E+00	1.87930E-02	1.87930E-02	0.00000E+00
15.0	1.26667E-01	1.26667E-01	0.00000E+00	1.92347E-02	1.92347E-02	0.00000E+00
16.0	1.43333E-01	1.43333E-01	0.00000E+00	2.02649E-02	2.02649E-02	0.00000E+00
17.0	1.53333E-01	1.53333E-01	0.00000E+00	2.08372E-02	2.08372E-02	0.00000E+00
18.0	1.56667E-01	1.56667E-01	0.00000E+00	2.10210E-02	2.10210E-02	0.00000E+00
19.0	1.63333E-01	1.63333E-01	0.00000E+00	2.13785E-02	2.13785E-02	0.00000E+00
20.0	1.66667E-01	1.66667E-01	0.00000E+00	2.15525E-02	2.15525E-02	0.00000E+00

Figure B3. Results for Sample Problem 1.

- - - PSM7 : ? INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

```
               TOTAL NUMBER OF REPLICATIONS =     300
NUMBER OF POSSSIBLE INITIATION SITES(USER SPEC.)=    6
  NO. OF TIMES INITIATED CRACKS CAUSED BIG LEAK =   50
NO. OF TIMES PRE-EXISTING CRACKS CAUSED BIG LEAK=    0
```

TIME (YRS)	TOTAL INITIATED CRACKS	FIRST INITIATED CRACKS
1	4	4
2	11	10
3	43	35
4	50	39
5	77	37
6	70	30
7	76	29
8	65	20
9	60	15
10	56	14
11	55	8
12	53	9
13	49	6
14	48	7
15	37	7
16	27	1
17	25	1
18	23	1
19	27	4
20	26	1
41	891	22

Figure B4. Additional output for Sample Problem 1.

- - - P3V7 : o INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 0.0

RANGE OF CRACK LENGTHS[B]	TOTAL COUNT	INITIATED COUNT	INITIATED NORMALIZED	PRE-EXISTING COUNT	PRE-EXISTING P(A)*COUNT	PRE-EXISTING NORMALIZED
0.000 -- 0.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.250 -- 0.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.500 -- 0.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.750 -- 1.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.000 -- 1.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.250 -- 1.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.500 -- 1.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.750 -- 2.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.000 -- 2.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.250 -- 2.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.500 -- 2.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.750 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 3.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.250 -- 3.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.500 -- 3.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.750 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 4.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.250 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 4.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.750 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.250 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

----------------------> 0.5*CIRCUM= 5.43

Figure B4. Additional output for Sample Problem 1 (continued).

- - - P[illegible] : 5 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 2.0

RANGE OF CRACK LENGTHS[B]	TOTAL COUNT	INITIATED		PRE-EXISTING		
		COUNT	NORMALIZED	COUNT	P(A)*COUNT	NORMALIZED
0.000 -- 0.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.250 -- 0.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.500 -- 0.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.750 -- 1.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.000 -- 1.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.250 -- 1.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.500 -- 1.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.750 -- 2.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.000 -- 2.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.250 -- 2.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.500 -- 2.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.750 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 3.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.250 -- 3.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.500 -- 3.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.750 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 4.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.250 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 4.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.750 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.250 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

----------------------> 0.5*CIRCUM= 5.43

Figure B4. Additional output for Sample Problem 1 (continued).

- - - PS97 : 6 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 5.0

RANGE OF CRACK LENGTHS[A]	TOTAL COUNT	-------INITIATED------ COUNT	NORMALIZED	------------PRE-EXISTING--------- COUNT	P(A)*COUNT	NORMALIZED
0.000 -- 0.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.250 -- 0.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.500 -- 0.750	1	1	5.000E-01	0	0.000E+00	0.000E+00
0.750 -- 1.000	1	1	5.000E-01	0	0.000E+00	0.000E+00
1.000 -- 1.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.250 -- 1.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.500 -- 1.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.750 -- 2.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.000 -- 2.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.250 -- 2.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.500 -- 2.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.750 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 3.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.250 -- 3.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.500 -- 3.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.750 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 4.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.250 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 4.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.750 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.250 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

----------------------> 0.5*CIRCUM= 5.43

Figure B4. Additional output for Sample Problem 1 (continued).

- - - P557 : ¢ INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 10.0

RANGE OF CRACK LENGTHS[B]	TOTAL COUNT	-------INITIATED------ COUNT	NORMALIZED	-----------PRE-EXISTING--------- COUNT	P(A)*COUNT	NORMALIZED
0.000 -- 0.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.250 -- 0.500	2	2	1.429E-01	0	0.000E+00	0.000E+00
0.500 -- 0.750	5	6	4.286E-01	0	0.000E+00	0.000E+00
0.750 -- 1.000	4	4	2.857E-01	0	0.000E+00	0.000E+00
1.000 -- 1.250	1	1	7.143E-02	0	0.000E+00	0.000E+00
1.250 -- 1.500	1	1	7.143E-02	0	0.000E+00	0.000E+00
1.500 -- 1.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.750 -- 2.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.000 -- 2.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.250 -- 2.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.500 -- 2.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.750 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 3.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.250 -- 3.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.500 -- 3.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.750 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 4.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.250 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 4.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.750 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.250 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

---------------------> 0.5*CIRCUM= 5.43

Figure B4. Additional output for Sample Problem 1 (continued).

- - - PS97 : o INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 20.0

RANGE OF CRACK LENGTHS[3]	TOTAL COUNT	INITIATED COUNT	INITIATED NORMALIZED	PRE-EXISTING COUNT	PRE-EXISTING P(A)*COUNT	PRE-EXISTING NORMALIZED
0.000 -- 0.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.250 -- 0.500	13	13	2.600E-01	0	0.000E+00	0.000E+00
0.500 -- 0.750	17	17	3.400E-01	0	0.000E+00	0.000E+00
0.750 -- 1.000	12	12	2.400E-01	0	0.000E+00	0.000E+00
1.000 -- 1.250	6	6	1.200E-01	0	0.000E+00	0.000E+00
1.250 -- 1.500	1	1	2.000E-02	0	0.000E+00	0.000E+00
1.500 -- 1.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.750 -- 2.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.000 -- 2.250	1	1	2.000E-02	0	0.000E+00	0.000E+00
2.250 -- 2.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.500 -- 2.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.750 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 3.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.250 -- 3.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.500 -- 3.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.750 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 4.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.250 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 4.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.750 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.250 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

----------------------> 0.5*CIRCUM= 5.43

Figure B4. Additional output for Sample Problem 1 (continued).

- - - PS97 : 5 INITIATED CRACKS ONLY , SCC ONLY, PES, NO ISI, NO VIB - - -

DISTRIBUTION OF DEPTH OF THE DEEPEST CRACK

TIME	(0.1H<AOH<0.5H) COUNT	NORMALIZED	(0.5H<AOH<1.0H) COUNT	NORMALIZED
0.0	0	0.00000E+00	0	0.00000E+00
1.0	0	0.00000E+00	0	0.00000E+00
2.0	3	1.00000E-02	0	0.00000E+00
3.0	14	4.66667E-02	2	6.66667E-03
4.0	30	1.00000E-01	3	1.00000E-02
5.0	51	1.70000E-01	4	1.33333E-02
6.0	73	2.43333E-01	4	1.33333E-02
7.0	105	3.50000E-01	10	3.33333E-02
8.0	122	4.06667E-01	10	3.33333E-02
9.0	131	4.36667E-01	13	4.33333E-02
10.0	144	4.80000E-01	15	5.00000E-02
11.0	156	5.20000E-01	13	4.33333E-02
12.0	165	5.50000E-01	14	4.66667E-02
13.0	170	5.66667E-01	18	6.00000E-02
14.0	172	5.73333E-01	16	5.33333E-02
15.0	176	5.86667E-01	16	5.33333E-02
16.0	179	5.96667E-01	17	5.66667E-02
17.0	179	5.96667E-01	16	5.33333E-02
18.0	181	6.03333E-01	17	5.66667E-02
19.0	185	6.16667E-01	17	5.66667E-02
20.0	184	6.13333E-01	19	6.33333E-02

Figure B4. Additional output for Sample Problem 1 (continued).

```
- - - PS97 :  6 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB                                  - - -
                              DISTRIBUTION OF LENGTH OF THE DEEPEST CRACK --[0.1H<ADH<0.5H]

                 TIME-->        0.0       2.0       5.0      10.0      20.0

RANGE OF CRACK LENGTHS[3]       ------------------ABSOLUTE COUNT -------------------
   0.000 ---     0.250           0         3        42       123       146
   0.250 ---     0.500           0         0         9        21        34
   0.500 ---     0.750           0         0         0         0         3
   0.750 ---     1.000           0         0         0         0         1
   1.000 ---     1.250           0         0         0         0         0
   1.250 ---     1.500           0         0         0         0         0
   1.500 ---     1.750           0         0         0         0         0
   1.750 ---     2.000           0         0         0         0         0
   2.000 ---     2.250           0         0         0         0         0
   2.250 ---     2.500           0         0         0         0         0
   2.500 ---     2.750           0         0         0         0         0
   2.750 ---     3.000           0         0         0         0         0
   3.000 ---     3.250           0         0         0         0         0
   3.250 ---     3.500           0         0         0         0         0
   3.500 ---     3.750           0         0         0         0         0
   3.750 ---     4.000           0         0         0         0         0
   4.000 ---     4.250           0         0         0         0         0
   4.250 ---     4.500           0         0         0         0         0
   4.500 ---     4.750           0         0         0         0         0
   4.750 ---     5.000           0         0         0         0         0
   5.000 ---     5.250           0         0         0         0         0
   5.250 ---     5.500           0         0         0         0         0
---------------------> 0.5*CIRCUM=   5.43
```

Figure B4. Additional output for Sample Problem 1 (continued).

- - - PS97 : 6 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF LENGTH OF THE DEEPEST CRACK --[0.5H<ADH<H]

RANGE OF CRACK LENGTHS[S]	TIME-->	0.0	2.0	5.0	10.0	20.0
		ABSOLUTE COUNT				
0.030 ---	0.250	0	0	2	5	2
0.250 ---	0.500	0	0	2	8	14
0.500 ---	0.750	0	0	0	1	2
0.750 ---	1.000	0	0	0	1	0
1.000 ---	1.250	0	0	0	0	1
1.250 ---	1.500	0	0	0	0	0
1.500 ---	1.750	0	0	0	0	0
1.750 ---	2.000	0	0	0	0	0
2.000 ---	2.250	0	0	0	0	0
2.250 ---	2.500	0	0	0	0	0
2.500 ---	2.750	0	0	0	0	0
2.750 ---	3.000	0	0	0	0	0
3.000 ---	3.250	0	0	0	0	0
3.250 ---	3.500	0	0	0	0	0
3.500 ---	3.750	0	0	0	0	0
3.750 ---	4.000	0	0	0	0	0
4.000 ---	4.250	0	0	0	0	0
4.250 ---	4.500	0	0	0	0	0
4.500 ---	4.750	0	0	0	0	0
4.750 ---	5.000	0	0	0	0	0
5.000 ---	5.250	0	0	0	0	0
5.250 ---	5.500	0	0	0	0	0

----------------------> 0.5*CIRCUM= 5.43

Figure B4. Additional output for Sample Problem 1 (continued).

- - - PS97 : 6 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF LENGTH OF THE DEEPEST CRACK --[0.1H<AOH<0.5H]

RANGE OF CRACK LENGTHS[H]		TIME--> 0.0	2.0	5.0	10.0	20.0
		NORMALIZED				
0.000 ---	0.250	0.00000	1.00000	0.82353	0.85417	0.79348
0.250 ---	0.500	0.00000	0.00000	0.17647	0.14583	0.18478
0.500 ---	0.750	0.00000	0.00000	0.00000	0.00000	0.01630
0.750 ---	1.000	0.00000	0.00000	0.00000	0.00000	0.00543
1.000 ---	1.250	0.00000	0.00000	0.00000	0.00000	0.00000
1.250 ---	1.500	0.00000	0.00000	0.00000	0.00000	0.00000
1.500 ---	1.750	0.00000	0.00000	0.00000	0.00000	0.00000
1.750 ---	2.000	0.00000	0.00000	0.00000	0.00000	0.00000
2.000 ---	2.250	0.00000	0.00000	0.00000	0.00000	0.00000
2.250 ---	2.500	0.00000	0.00000	0.00000	0.00000	0.00000
2.500 ---	2.750	0.00000	0.00000	0.00000	0.00000	0.00000
2.750 ---	3.000	0.00000	0.00000	0.00000	0.00000	0.00000
3.000 ---	3.250	0.00000	0.00000	0.00000	0.00000	0.00000
3.250 ---	3.500	0.00000	0.00000	0.00000	0.00000	0.00000
3.500 ---	3.750	0.00000	0.00000	0.00000	0.00000	0.00000
3.750 ---	4.000	0.00000	0.00000	0.00000	0.00000	0.00000
4.000 ---	4.250	0.00000	0.00000	0.00000	0.00000	0.00000
4.250 ---	4.500	0.00000	0.00000	0.00000	0.00000	0.00000
4.500 ---	4.750	0.00000	0.00000	0.00000	0.00000	0.00000
4.750 ---	5.000	0.00000	0.00000	0.00000	0.00000	0.00000
5.000 ---	5.250	0.00000	0.00000	0.00000	0.00000	0.00000
5.250 ---	5.500	0.00000	0.00000	0.00000	0.00000	0.00000
----------------------->		0.5*CIRCUM=	5.43			

Figure B4. Additional output for Sample Problem 1 (continued).

- - - PSN7 : 6 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF LENGTH OF THE DEEPEST CRACK --[0.5H<ADH<H]

RANGE OF CRACK LENGTHS[J]		TIME--> 0.0	2.0	5.0	10.0	20.0
		NORMALIZED				
0.000 ---	0.250	0.00000	0.00000	0.50000	0.33333	0.10526
0.250 ---	0.500	0.00000	0.00000	0.50000	0.53333	0.73684
0.500 ---	0.750	0.00000	0.00000	0.00000	0.06667	0.10526
0.750 ---	1.000	0.00000	0.00000	0.00000	0.06667	0.00000
1.000 ---	1.250	0.00000	0.00000	0.00000	0.00000	0.05263
1.250 ---	1.500	0.00000	0.00000	0.00000	0.00000	0.00000
1.500 ---	1.750	0.00000	0.00000	0.00000	0.00000	0.00000
1.750 ---	2.000	0.00000	0.00000	0.00000	0.00000	0.00000
2.000 ---	2.250	0.00000	0.00000	0.00000	0.00000	0.00000
2.250 ---	2.500	0.00000	0.00000	0.00000	0.00000	0.00000
2.500 ---	2.750	0.00000	0.00000	0.00000	0.00000	0.00000
2.750 ---	3.000	0.00000	0.00000	0.00000	0.00000	0.00000
3.000 ---	3.250	0.00000	0.00000	0.00000	0.00000	0.00000
3.250 ---	3.500	0.00000	0.00000	0.00000	0.00000	0.00000
3.500 ---	3.750	0.00000	0.00000	0.00000	0.00000	0.00000
3.750 ---	4.000	0.00000	0.00000	0.00000	0.00000	0.00000
4.000 ---	4.250	0.00000	0.00000	0.00000	0.00000	0.00000
4.250 ---	4.500	0.00000	0.00000	0.00000	0.00000	0.00000
4.500 ---	4.750	0.00000	0.00000	0.00000	0.00000	0.00000
4.750 ---	5.000	0.00000	0.00000	0.00000	0.00000	0.00000
5.000 ---	5.250	0.00000	0.00000	0.00000	0.00000	0.00000
5.250 ---	5.500	0.00000	0.00000	0.00000	0.00000	0.00000

---------------------> 0.5*CIRCUM= 5.43

Figure B4. Additional output for Sample Problem 1 (continued).

SAMPLE PROBLEM 2

This sample problem illustrates the use of the stress corrosion crack initiation model and the residual stress model for intermediate lines. Specific inputs are:

- Twenty year plant lifetime (THRIZN = 20)
- 0.84 inch wall thickness (THICK = 0.84)
- 7.16 inch pipe inside radius (RIN = 7.16)
- 23 crack initiation sites (ICRAKS = 23)
- SCC-initiated crack only; no pre-existing cracks are considered (INCIAT = 1, ISCC = 1)
- Maximum time-step for stress corrosion crack growth computation is 0.2 year (DTSCC = 0.2)
- 8 ppm oxygen during plant loading (OSTART = 8.0)
- 0.2 ppm oxygen during steady-state operation (OSTEDY = 0.2)
- 550°F coolant temperature at steady-state operation (TFSTDY = 550°F)
- Five hours for plant heat-up (DURATN = 5.0)
- Flow stress distributed with a mean of 44.9 ksi and standard deviation of 1.9 ksi (SFLOMU = 44.9, SFLOSD = 1.9)
- Failure criteria minus applied stress exceeding flow stress (IFAILC = 0)
- Leak detected if it exceeds 0.1 gpm. Small and large leaks not differentiated (FNDLEK = 0.1, ALKBIG = 0.1)
- Leaks not repaired (IREPAR = 0)
- Dead weight stress of 0.5 ksi; stress due to dead weight and restraint of thermal expansion of 6.2 ksi (SIGCLD = 0.5, SGDWTE = 6.2)
- Operating pressure of 1.25 ksi (OPPRES = 1.25)
- Hydrostatic proof test pressure of 1.4375 ksi, although proof tests have no meaning when pre-existing cracks are not considered in the analysis (PRFPRS = 1.4375)

- Residual stress model for intermediate line selected (ISIGRS = 3)
- No vibratory stresses included (SIGVIB = -1.0)
- Pre-service inspection modeled; again this has no meaning when pre-existing cracks are not considered in the analysis (NPSI = 1)
- No earthquakes are included (NQUAKE = 0)
- The only transient modeled is the heat-up/cool-down cycle which is assumed to occur regularly five times per year (KTYPES = 1, BLAMDA(1) = -0.2)
- 300 replications performed (IREPLS = 300)

The input file image and the input summary for this sample problem are given in Figures B5 and B6, respectively. The estimated failure probabilities are given in Figure B7. Additional output is shown in Figure B8.

```
PI97 :  23 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB
    1     0    23  300     1     0    1.1
  -15     1     1    3    -1     0     5     0     0     0    14     0    02     1     1     3
20.0       0.2
0.16       7.16
4.0        4.0        9.1400E-12   3.5E-11
3.0        0.2        550.0        5.0
44.9       1.9
0.1        0.1
0.50       6.20       1.25      1.4375     -1.0
    1   -.2 460.0     HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
    1     1     1     1
          1     521.6         5.76       1 0.5E   JOINT 1 LLNL DATA
          2    2758.3         9.05       1 SSE   JOINT 1 LLNL DATA
          2   63430.0        10.55       3 SSE   JOINT 1 LLNL DATA
          4  142000.0        10.62       5 SSE   JOINT 1 LLNL DATA
```

Figure B5. Input file image for Sample Problem 2.

```
SCC-INITIATED CRACKS ONLY

A/H BOUNDARY            =     1.100

 MAXIMUM NO. OF CRACKS =   23
 NO. OF REPLICATIONS   =  300


SCC ONLY

 LEAKERS WILL NOT BE REPAIRED

FAILURE CRITERIA : APPLIED STRESS>FLOW STRESS

TIMESTEP FOR SCC =   0.200  YEARS

PIPE DIMENSIONS
          INSIDE RADIUS =      7.16  INCHES
          WALL THICKNESS       0.84  INCHES

CRACK GROWTH LAW PARAMETERS
          EXPONENT =                  4.00
          GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
               MEDIAN =              0.9140E-11
               90-TH PERCENT =       0.3500E-10
          THRESHOLD =                 4.60

 SCC  PARAMETERS


          O2 AT STARTUP(PPM)=              8.00
     O2 AT STEADY STATE(PPM)=              0.20
TEMP. AT STEADY STATE(DEG F)=            550.00
HEATUP (100-550F) TIME (HRS)=              5.00

          FLOW STRESS NORMALLY DISTRIBUTED
          MEAN=               0.4490E+02
          STANDARD DEVIAT     0.1900E+01

PIPE STRESS VALUES
          CSD DEADWT STRESS (KSI)   0.50
          HOT UNIFORM STRESS (KSI) 11.53
          PRESSURE STRESS (KSI)     5.33
          SIG-DC          (KSI)     5.70
          PROOF TEST STRESS(KSI)    6.63

LEAK DETECTION AND DEFINITION PARAMETERS
          DETECTABLE LEAK(GPM)        0.1
          BIG LEAK(GPM)               0.1

RESIDUAL STRESSES FOR INTERMEDIATE LINE SELECTED

NO VIBRATORY STRESSES ARE MODELED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELED

TIME INTERVAL,
          PLANT LIFETIME        20.0  YEARS
          ENDPOINTS OF INTERVALS AT   0.0   1.0   2.0   3.0   4.0   5.0   6.0   7.0   8.0   9.0  YEARS
          ENDPOINTS OF INTERVALS AT  10.0  11.0  12.0  13.0  14.0  15.0  16.0  17.0  18.0  19.0  YEARS
          ENDPOINTS OF INTERVALS AT  20.0



NO IN-SERVICE INSPECTIONS ARE MODELED

                    - - - NO SEISMIC EVENTS EVALUATED - - -

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS     7

                    - - -  NORMAL OUTPUT REQUESTED - - -


        - - NUMBER OF TRANSIENT TYPES =     1  - -

TYPE  1     HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
REGULAR AT      0.200  YRS/EVENT
MAX DELTA TEMP =450.0  BLOCKING FACTOR =    1.
```

Figure B6. Input summary for Sample Problem 2.

- - - PIP7 : 23 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

- - RESULTS WITHOUT EARTHQUAKES - - -

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
1.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
2.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
3.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
4.0	6.66667E-03	6.66667E-03	0.00000E+00	4.70616E-03	4.70616E-03	0.00000E+00
5.0	6.66667E-03	6.66667E-03	0.00000E+00	4.70616E-03	4.70616E-03	0.00000E+00
6.0	1.00000E-02	1.00000E-02	0.00000E+00	5.75416E-03	5.75416E-03	0.00000E+00
7.0	2.00000E-02	2.00000E-02	0.00000E+00	8.09641E-03	8.09641E-03	0.00000E+00
8.0	2.66667E-02	2.66667E-02	0.00000E+00	9.31707E-03	9.31707E-03	0.00000E+00
9.0	3.33333E-02	3.33333E-02	0.00000E+00	1.03911E-02	1.03811E-02	0.00000E+00
10.0	4.00000E-02	4.00000E-02	0.00000E+00	1.13326E-02	1.13326E-02	0.00000E+00
11.0	5.00000E-02	5.00000E-02	0.00000E+00	1.26041E-02	1.26041E-02	0.00000E+00
12.0	6.00000E-02	6.00000E-02	0.00000E+00	1.37342E-02	1.37342E-02	0.00000E+00
13.0	8.33333E-02	8.33333E-02	0.00000E+00	1.59838E-02	1.59838E-02	0.00000E+00
14.0	1.06667E-01	1.06667E-01	0.00000E+00	1.78519E-02	1.78519E-02	0.00000E+00
15.0	1.13333E-01	1.13333E-01	0.00000E+00	1.83326E-02	1.83326E-02	0.00000E+00
16.0	1.23333E-01	1.23333E-01	0.00000E+00	1.90161E-02	1.90161E-02	0.00000E+00
17.0	1.46667E-01	1.46667E-01	0.00000E+00	2.04592E-02	2.04592E-02	0.00000E+00
18.0	1.50000E-01	1.50000E-01	0.00000E+00	2.06500E-02	2.06500E-02	0.00000E+00
19.0	1.53333E-01	1.53333E-01	0.00000E+00	2.08372E-02	2.08372E-02	0.00000E+00
20.0	1.63333E-01	1.63333E-01	0.00000E+00	2.13785E-02	2.13785E-02	0.00000E+00

Figure B7. Results for Sample Problem 2.

```
- - - PIV7 :  23 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB                    - - -


                  TOTAL NUMBER OF REPLICATIONS =      300
NUMBER OF POSSSIBLE INITIATION SITES(USER SPEC.)=      23
  NO. OF TIMES INITIATED CRACKS CAUSED BIG LEAK =      49
NO. OF TIMES PRE-EXISTING CRACKS CAUSED BIG LEAK=       0

 TIME    TOTAL INITIATED      FIRST INITIATED
 (YRS)       CRACKS               CRACKS

     1            5                  6
     2           52                 44
     3          133                 67
     4          236                 53
     5          222                 32
     6          255                 24
     7          265                 20
     8          250                  8
     9          239                  7
    10          216                  4
    11          194                  6
    12          197                  5
    13          133                  2
    14          177                  3
    15          150                  2
    16          140                  0
    17          135                  1
    18          124                  3
    19          119                  1
    20          113                  0

    41         3455                 11
```

Figure B8. Additional output for Sample Problem 2.

- - - P197 : 25 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 0.0

RANGE OF CRACK LENGTHS[B]	TOTAL COUNT	INITIATED COUNT	INITIATED NORMALIZED	PRE-EXISTING COUNT	PRE-EXISTING P(A)*COUNT	PRE-EXISTING NORMALIZED
0.000 -- 0.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.500 -- 1.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.000 -- 1.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.500 -- 2.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.000 -- 2.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.500 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 3.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.500 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.500 -- 6.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.000 -- 6.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.500 -- 7.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.000 -- 7.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.500 -- 8.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.000 -- 8.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.500 -- 9.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.000 -- 9.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.500 -- 10.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.000 -- 10.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.500 -- 11.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.000 -- 11.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.500 -- 12.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.000 -- 12.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.500 -- 13.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.000 -- 13.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.500 -- 14.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.000 -- 14.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.500 -- 15.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.000 -- 15.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.500 -- 16.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.000 -- 16.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.500 -- 17.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.000 -- 17.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.500 -- 18.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.000 -- 18.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.500 -- 19.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.000 -- 19.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.500 -- 20.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.000 -- 20.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.500 -- 21.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.000 -- 21.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.500 -- 22.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
22.000 -- 22.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

---------------------> 0.5*CIRCUM= 22.49

Figure B9. Additional output for Sample Problem 2 (continued)

- - - P1V7 : 25 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 2.0

RANGE OF CRACK LENGTHS(M)	TOTAL COUNT	INITIATED COUNT	INITIATED NORMALIZED	PRE-EXISTING COUNT	PRE-EXISTING P(A)*COUNT	PRE-EXISTING NORMALIZED
0.000 -- 0.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.500 -- 1.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.000 -- 1.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.500 -- 2.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.000 -- 2.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.500 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 3.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.500 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.500 -- 6.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.000 -- 6.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.500 -- 7.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.000 -- 7.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.500 -- 8.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.000 -- 8.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.500 -- 9.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.000 -- 9.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.500 -- 10.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.000 -- 10.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.500 -- 11.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.000 -- 11.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.500 -- 12.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.000 -- 12.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.500 -- 13.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.000 -- 13.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.500 -- 14.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.000 -- 14.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.500 -- 15.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.000 -- 15.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.500 -- 16.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.000 -- 16.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.500 -- 17.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.000 -- 17.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.500 -- 18.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.000 -- 18.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.500 -- 19.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.000 -- 19.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.500 -- 20.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.000 -- 20.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.500 -- 21.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.000 -- 21.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.500 -- 22.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
22.000 -- 22.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

-----------------------> 0.5*CIRCUM= 22.49

Figure B8. Additional output for Sample Problem 2 (continued).

- - - PI97 : 23 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 5.0

RANGE OF CRACK LENGTHS[9]	TOTAL COUNT	-------INITIATED------ COUNT	NORMALIZED	-----------PRE-EXISTING--------- COUNT	P(A)*COUNT	NORMALIZED
0.000 -- 0.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.500 -- 1.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.000 -- 1.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.500 -- 2.000	1	1	5.000E-01	0	0.000E+00	0.000E+00
2.000 -- 2.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.500 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 3.500	1	1	5.000E-01	0	0.000E+00	0.000E+00
3.500 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.500 -- 6.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.000 -- 6.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.500 -- 7.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.000 -- 7.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.500 -- 8.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.000 -- 8.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.500 -- 9.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.000 -- 9.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.500 -- 10.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.000 -- 10.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.500 -- 11.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.000 -- 11.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.500 -- 12.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.000 -- 12.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.500 -- 13.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.000 -- 13.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.500 -- 14.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.000 -- 14.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.500 -- 15.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.000 -- 15.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.500 -- 16.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.000 -- 16.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.500 -- 17.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.000 -- 17.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.500 -- 18.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.000 -- 18.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.500 -- 19.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.000 -- 19.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.500 -- 20.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.000 -- 20.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.500 -- 21.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.000 -- 21.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.500 -- 22.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
22.000 -- 22.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

---------------------> 0.5*CIRCUM= 22.49

Figure B9. Additional output for Sample Problem 2 (continued)

- - - PIP7 : 23 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 10.0

RANGE OF CRACK LENGTHS[3]	TOTAL COUNT	INITIATED COUNT	INITIATED NORMALIZED	PRE-EXISTING COUNT	PRE-EXISTING P(A)*COUNT	PRE-EXISTING NORMALIZED
0.000 -- 0.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.500 -- 1.000	2	2	1.667E-01	0	0.000E+00	0.000E+00
1.000 -- 1.500	1	1	9.333E-02	0	0.000E+00	0.000E+00
1.500 -- 2.000	3	3	2.500E-01	0	0.000E+00	0.000E+00
2.000 -- 2.500	3	3	2.500E-01	0	0.000E+00	0.000E+00
2.500 -- 3.000	2	2	1.667E-01	0	0.000E+00	0.000E+00
3.000 -- 3.500	1	1	8.333E-02	0	0.000E+00	0.000E+00
3.500 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.500 -- 6.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.000 -- 6.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.500 -- 7.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.000 -- 7.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.500 -- 8.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.000 -- 8.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.500 -- 9.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.000 -- 9.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.500 -- 10.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.000 -- 10.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.500 -- 11.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.000 -- 11.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.500 -- 12.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.000 -- 12.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.500 -- 13.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.000 -- 13.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.500 -- 14.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.000 -- 14.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.500 -- 15.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.000 -- 15.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.500 -- 16.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.000 -- 16.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.500 -- 17.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.000 -- 17.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.500 -- 18.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.000 -- 18.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.500 -- 19.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.000 -- 19.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.500 -- 20.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.000 -- 20.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.500 -- 21.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.000 -- 21.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.500 -- 22.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
22.000 -- 22.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

----------------------> 0.5*CIRCUM= 22.49

Figure B8. Additional output for Sample Problem 2 (continued).

- - - P177 : 23 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 20.0

RANGE OF CRACK LENGTHS(B)	TOTAL COUNT	INITIATED COUNT	INITIATED NORMALIZED	PRE-EXISTING COUNT	PRE-EXISTING P(A)*COUNT	PRE-EXISTING NORMALIZED
0.000 -- 0.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.500 -- 1.000	5	5	1.020E-01	0	0.000E+00	0.000E+00
1.000 -- 1.500	5	5	1.020E-01	0	0.000E+00	0.000E+00
1.500 -- 2.000	12	12	2.449E-01	0	0.000E+00	0.000E+00
2.000 -- 2.500	13	13	2.653E-01	0	0.000E+00	0.000E+00
2.500 -- 3.000	7	7	1.429E-01	0	0.000E+00	0.000E+00
3.000 -- 3.500	4	4	8.163E-02	0	0.000E+00	0.000E+00
3.500 -- 4.000	1	1	2.041E-02	0	0.000E+00	0.000E+00
4.000 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.500 -- 6.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.000 -- 6.500	2	2	4.082E-02	0	0.000E+00	0.000E+00
6.500 -- 7.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.000 -- 7.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.500 -- 8.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.000 -- 8.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.500 -- 9.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.000 -- 9.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.500 -- 10.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.000 -- 10.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.500 -- 11.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.000 -- 11.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.500 -- 12.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.000 -- 12.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.500 -- 13.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.000 -- 13.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.500 -- 14.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.000 -- 14.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.500 -- 15.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.000 -- 15.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.500 -- 16.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.000 -- 16.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.500 -- 17.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.000 -- 17.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.500 -- 18.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.000 -- 18.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.500 -- 19.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.000 -- 19.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.500 -- 20.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.000 -- 20.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.500 -- 21.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.000 -- 21.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.500 -- 22.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
22.000 -- 22.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

--- -----------------> 0.5*CIRCUM= 22.49

Figure B8. Additional output for Sample Problem 2 (continued).

- - - PI#7 : 23 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF DEPTH OF THE DEEPEST CRACK

TIME	(0.1H<AOH<0.5H) COUNT	(0.1H<AOH<0.5H) NORMALIZED	(0.5H<AOH<1.0H) COUNT	(0.5H<AOH<1.0H) NORMALIZED
0.0	0	0.00000E+00	0	0.00000E+00
1.0	0	0.00000E+00	0	0.00000E+00
2.0	3	1.00000E-02	0	0.00000E+00
3.0	15	5.00000E-02	1	3.33333E-03
4.0	32	1.06667E-01	0	0.00000E+00
5.0	45	1.50000E-01	1	3.33333E-03
6.0	67	2.23333E-01	2	6.66667E-03
7.0	82	2.73333E-01	2	6.66667E-03
8.0	93	3.10000E-01	3	1.00000E-02
9.0	105	3.53333E-01	6	2.00000E-02
10.0	111	3.70000E-01	8	2.66667E-02
11.0	131	4.36667E-01	8	2.66667E-02
12.0	139	4.63333E-01	12	4.00000E-02
13.0	152	5.06667E-01	6	2.00000E-02
14.0	156	5.20000E-01	4	1.33333E-02
15.0	160	5.33333E-01	7	2.33333E-02
16.0	170	5.66667E-01	5	1.66667E-02
17.0	169	5.63333E-01	3	1.00000E-02
18.0	171	5.70000E-01	6	2.00000E-02
19.0	172	5.73333E-01	8	2.66667E-02
20.0	175	5.83333E-01	7	2.33333E-02

Figure B8. Additional output for Sample Problem 2 (continued).

- - - PI-7 : 13 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF LENGTH OF THE DEEPEST CRACK --[0.1H<AOH<0.5H]

RANGE OF CRACK LENGTHS[?]		TIME--> 0.0	2.0	5.0	10.0	20.0
		ABSOLUTE COUNT				
0.000 ---	0.500	0	3	43	98	159
0.500 ---	1.000	0	0	2	11	13
1.000 ---	1.500	0	0	0	2	3
1.500 ---	2.000	0	0	0	0	0
2.000 ---	2.500	0	0	0	0	0
2.500 ---	3.000	0	0	0	0	0
3.000 ---	3.500	0	0	0	0	0
3.500 ---	4.000	0	0	0	0	0
4.000 ---	4.500	0	0	0	0	0
4.500 ---	5.000	0	0	0	0	0
5.000 ---	5.500	0	0	0	0	0
5.500 ---	6.000	0	0	0	0	0
6.000 ---	6.500	0	0	0	0	0
6.500 ---	7.000	0	0	0	0	0
7.000 ---	7.500	0	0	0	0	0
7.500 ---	8.000	0	0	0	0	0
8.000 ---	8.500	0	0	0	0	0
8.500 ---	9.000	0	0	0	0	0
9.000 ---	9.500	0	0	0	0	0
9.500 ---	10.000	0	0	0	0	0
10.000 ---	10.500	0	0	0	0	0
10.500 ---	11.000	0	0	0	0	0
11.000 ---	11.500	0	0	0	0	0
11.500 ---	12.000	0	0	0	0	0
12.000 ---	12.500	0	0	0	0	0
12.500 ---	13.000	0	0	0	0	0
13.000 ---	13.500	0	0	0	0	0
13.500 ---	14.000	0	0	0	0	0
14.000 ---	14.500	0	0	0	0	0
14.500 ---	15.000	0	0	0	0	0
15.000 ---	15.500	0	0	0	0	0
15.500 ---	16.000	0	0	0	0	0
16.000 ---	16.500	0	0	0	0	0
16.500 ---	17.000	0	0	0	0	0
17.000 ---	17.500	0	0	0	0	0
17.500 ---	18.000	0	0	0	0	0
18.000 ---	18.500	0	0	0	0	0
18.500 ---	19.000	0	0	0	0	0
19.000 ---	19.500	0	0	0	0	0
19.500 ---	20.000	0	0	0	0	0
20.000 ---	20.500	0	0	0	0	0
20.500 ---	21.000	0	0	0	0	0
21.000 ---	21.500	0	0	0	0	0
21.500 ---	22.000	0	0	0	0	0
22.000 ---	22.500	0	0	0	0	0

--------------------> 0.5*CIRCUM= 22.49

Figure D8. Additional output for Sample Problem 2 (continued)

- - - PIV7 : 23 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB

DISTRIBUTION OF LENGTH OF THE DEEPEST CRACK --[0.5H<AOH<H]

RANGE OF CRACK LENGTHS[']		TIME--> 0.0	2.0	5.0	10.0	20.0
		ABSOLUTE COUNT				
0.000 ---	0.500	0	0	0	0	0
0.500 ---	1.000	0	0	1	6	3
1.000 ---	1.500	0	0	0	1	3
1.500 ---	2.000	0	0	0	0	1
2.000 ---	2.500	0	0	0	1	0
2.500 ---	3.000	0	0	0	0	0
3.000 ---	3.500	0	0	0	0	0
3.500 ---	4.000	0	0	0	0	0
4.000 ---	4.500	0	0	0	0	0
4.500 ---	5.000	0	0	0	0	0
5.000 ---	5.500	0	0	0	0	0
5.500 ---	6.000	0	0	0	0	0
6.000 ---	6.500	0	0	0	0	0
6.500 ---	7.000	0	0	0	0	0
7.000 ---	7.500	0	0	0	0	0
7.500 ---	8.000	0	0	0	0	0
8.000 ---	8.500	0	0	0	0	0
8.500 ---	9.000	0	0	0	0	0
9.000 ---	9.500	0	0	0	0	0
9.500 ---	10.000	0	0	0	0	0
10.000 ---	10.500	0	0	0	0	0
10.500 ---	11.000	0	0	0	0	0
11.000 ---	11.500	0	0	0	0	0
11.500 ---	12.000	0	0	0	0	0
12.000 ---	12.500	0	0	0	0	0
12.500 ---	13.000	0	0	0	0	0
13.000 ---	13.500	0	0	0	0	0
13.500 ---	14.000	0	0	0	0	0
14.000 ---	14.500	0	0	0	0	0
14.500 ---	15.000	0	0	0	0	0
15.000 ---	15.500	0	0	0	0	0
15.500 ---	16.000	0	0	0	0	0
16.000 ---	16.500	0	0	0	0	0
16.500 ---	17.000	0	0	0	0	0
17.000 ---	17.500	0	0	0	0	0
17.500 ---	18.000	0	0	0	0	0
18.000 ---	18.500	0	0	0	0	0
18.500 ---	19.000	0	0	0	0	0
19.000 ---	19.500	0	0	0	0	0
19.500 ---	20.000	0	0	0	0	0
20.000 ---	20.500	0	0	0	0	0
20.500 ---	21.000	0	0	0	0	0
21.000 ---	21.500	0	0	0	0	0
21.500 ---	22.000	0	0	0	0	0
22.000 ---	22.500	0	0	0	0	0

--------------------> 0.5*CIRCUM= 22.49

Figure B8. Additional output for Sample Problem 2 (continued).

- - - PI?7 : 23 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB

DISTRIBUTION OF LENGTH OF THE DEEPEST CRACK --[0.1H<AOH<0.5H]

	TIME-->	0.0	2.0	5.0	10.0	20.0
RANGE OF CRACK LENGTHS[J]		-----	-----	NORMALIZED	-----	-----
0.000 ---	0.500	0.00000	1.00000	0.95556	0.88288	0.90857
0.500 ---	1.000	0.00000	0.00000	0.04444	0.09910	0.07429
1.000 ---	1.500	0.00000	0.00000	0.00000	0.01802	0.01714
1.500 ---	2.000	0.00000	0.00000	0.00000	0.00000	0.00000
2.000 ---	2.500	0.00000	0.00000	0.00000	0.00000	0.00000
2.500 ---	3.000	0.00000	0.00000	0.00000	0.00000	0.00000
3.000 ---	3.500	0.00000	0.00000	0.00000	0.00000	0.00000
3.500 ---	4.000	0.00000	0.00000	0.00000	0.00000	0.00000
4.000 ---	4.500	0.00000	0.00000	0.00000	0.00000	0.00000
4.500 ---	5.000	0.00000	0.00000	0.00000	0.00000	0.00000
5.000 ---	5.500	0.00000	0.00000	0.00000	0.00000	0.00000
5.500 ---	6.000	0.00000	0.00000	0.00000	0.00000	0.00000
6.000 ---	6.500	0.00000	0.00000	0.00000	0.00000	0.00000
6.500 ---	7.000	0.00000	0.00000	0.00000	0.00000	0.00000
7.000 ---	7.500	0.00000	0.00000	0.00000	0.00000	0.00000
7.500 ---	8.000	0.00000	0.00000	0.00000	0.00000	0.00000
8.000 ---	8.500	0.00000	0.00000	0.00000	0.00000	0.00000
8.500 ---	9.000	0.00000	0.00000	0.00000	0.00000	0.00000
9.000 ---	9.500	0.00000	0.00000	0.00000	0.00000	0.00000
9.500 ---	10.000	0.00000	0.00000	0.00000	0.00000	0.00000
10.000 ---	10.500	0.00000	0.00000	0.00000	0.00000	0.00000
10.500 ---	11.000	0.00000	0.00000	0.00000	0.00000	0.00000
11.000 ---	11.500	0.00000	0.00000	0.00000	0.00000	0.00000
11.500 ---	12.000	0.00000	0.00000	0.00000	0.00000	0.00000
12.000 ---	12.500	0.00000	0.00000	0.00000	0.00000	0.00000
12.500 ---	13.000	0.00000	0.00000	0.00000	0.00000	0.00000
13.000 ---	13.500	0.00000	0.00000	0.00000	0.00000	0.00000
13.500 ---	14.000	0.00000	0.00000	0.00000	0.00000	0.00000
14.000 ---	14.500	0.00000	0.00000	0.00000	0.00000	0.00000
14.500 ---	15.000	0.00000	0.00000	0.00000	0.00000	0.00000
15.000 ---	15.500	0.00000	0.00000	0.00000	0.00000	0.00000
15.500 ---	16.000	0.00000	0.00000	0.00000	0.00000	0.00000
16.000 ---	16.500	0.00000	0.00000	0.00000	0.00000	0.00000
16.500 ---	17.000	0.00000	0.00000	0.00000	0.00000	0.00000
17.000 ---	17.500	0.00000	0.00000	0.00000	0.00000	0.00000
17.500 ---	18.000	0.00000	0.00000	0.00000	0.00000	0.00000
18.000 ---	18.500	0.00000	0.00000	0.00000	0.00000	0.00000
18.500 ---	19.000	0.00000	0.00000	0.00000	0.00000	0.00000
19.000 ---	19.500	0.00000	0.00000	0.00000	0.00000	0.00000
19.500 ---	20.000	0.00000	0.00000	0.00000	0.00000	0.00000
20.000 ---	20.500	0.00000	0.00000	0.00000	0.00000	0.00000
20.500 ---	21.000	0.00000	0.00000	0.00000	0.00000	0.00000
21.000 ---	21.500	0.00000	0.00000	0.00000	0.00000	0.00000
21.500 ---	22.000	0.00000	0.00000	0.00000	0.00000	0.00000
22.000 ---	22.500	0.00000	0.00000	0.00000	0.00000	0.00000

--------------------> 0.5*CIRCUM= 22.49

Figure B8. Additional output for Sample Problem 2 (continued).

- - - PI97 : 23 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB

DISTRIBUTION OF LENGTH OF THE DEEPEST CRACK --[0.5H<AOH<H]

RANGE OF CRACK LENGTHS[L]		TIME--> 0.0	2.0	5.0	10.0	20.0
		NORMALIZED				
0.000 ---	0.500	0.00000	0.00000	0.00000	0.00000	0.00000
0.500 ---	1.000	0.00000	0.00000	1.00000	0.75000	0.42857
1.000 ---	1.500	0.00000	0.00000	0.00000	0.12500	0.42857
1.500 ---	2.000	0.00000	0.00000	0.00000	0.00000	0.14286
2.000 ---	2.500	0.00000	0.00000	0.00000	0.12500	0.00000
2.500 ---	3.000	0.00000	0.00000	0.00000	0.00000	0.00000
3.000 ---	3.500	0.00000	0.00000	0.00000	0.00000	0.00000
3.500 ---	4.000	0.00000	0.00000	0.00000	0.00000	0.00000
4.000 ---	4.500	0.00000	0.00000	0.00000	0.00000	0.00000
4.500 ---	5.000	0.00000	0.00000	0.00000	0.00000	0.00000
5.000 ---	5.500	0.00000	0.00000	0.00000	0.00000	0.00000
5.500 ---	6.000	0.00000	0.00000	0.00000	0.00000	0.00000
6.000 ---	6.500	0.00000	0.00000	0.00000	0.00000	0.00000
6.500 ---	7.000	0.00000	0.00000	0.00000	0.00000	0.00000
7.000 ---	7.500	0.00000	0.00000	0.00000	0.00000	0.00000
7.500 ---	8.000	0.00000	0.00000	0.00000	0.00000	0.00000
8.000 ---	8.500	0.00000	0.00000	0.00000	0.00000	0.00000
8.500 ---	9.000	0.00000	0.00000	0.00000	0.00000	0.00000
9.000 ---	9.500	0.00000	0.00000	0.00000	0.00000	0.00000
9.500 ---	10.000	0.00000	0.00000	0.00000	0.00000	0.00000
10.000 ---	10.500	0.00000	0.00000	0.00000	0.00000	0.00000
10.500 ---	11.000	0.00000	0.00000	0.00000	0.00000	0.00000
11.000 ---	11.500	0.00000	0.00000	0.00000	0.00000	0.00000
11.500 ---	12.000	0.00000	0.00000	0.00000	[illegible]	0.00000
12.000 ---	12.500	0.00000	0.00000	[illegible]	[illegible]	0.00000
12.500 ---	13.000	0.00000	0.00000	[illegible]	0.00000	0.00000
13.000 ---	13.500	0.00000	0.00000	0.00000	0.00000	0.00000
13.500 ---	14.000	0.00000	0.00000	0.00000	0.00000	0.00000
14.000 ---	14.500	0.00000	0.00000	0.00000	0.00000	0.00000
14.500 ---	15.000	0.00000	0.00000	0.00000	0.00000	0.00000
15.000 ---	15.500	0.00000	0.00000	0.00000	0.00000	0.00000
15.500 ---	16.000	0.00000	0.00000	0.00000	0.00000	0.00000
16.000 ---	16.500	0.00000	0.00000	0.00000	0.00000	0.00000
16.500 ---	17.000	0.00000	0.00000	0.00000	0.00000	0.00000
17.000 ---	17.500	0.00000	0.00000	0.00000	0.00000	0.00000
17.500 ---	18.000	0.00000	0.00000	0.00000	0.00000	0.00000
18.000 ---	18.500	0.00000	0.00000	0.00000	0.00000	0.00000
18.500 ---	19.000	0.00000	0.00000	0.00000	0.00000	0.00000
19.000 ---	19.500	0.00000	0.00000	0.00000	0.00000	0.00000
19.500 ---	20.000	0.00000	0.00000	0.00000	0.00000	0.00000
20.000 ---	20.500	0.00000	0.00000	0.00000	0.00000	0.00000
20.500 ---	21.000	0.00000	0.00000	0.00000	0.00000	0.00000
21.000 ---	21.500	0.00000	0.00000	0.00000	0.00000	0.00000
21.500 ---	22.000	0.00000	0.00000	0.00000	0.00000	0.00000
22.000 ---	22.500	0.00000	0.00000	0.00000	0.00000	0.00000

---------------------> 0.5*CIRCUM= 22.4[illegible]

Figure B8. Additional output for Sample Problem 2 (continued).

SAMPLE PROBLEM 3

This sample problem illustrates the use of stress corrosion crack initiation model and the new residual stress model for large lines. Specific inputs are:

- Twenty year plant lifetime (THRIZN = 20)
- 1.043 inch wall thickness (THICK = 1.043)
- 10.8 inch pipe inside radius (RIN = 10.8)
- 35 crack initiation sites (ICRAKS = 35)
- SCC-initiated crack only; no pre-existing cracks are considered (INCIAT = 1, ISCC = 1)
- Maximum time-step for stress corrosion crack growth computation is 0.2 year (DTSCC = 0.2)
- 8 ppm oxygen during plant loading (OSTART = 8.0)
- 0.2 ppm oxygen during steady-state operation (OSTEDY = 0.2)
- 550°F coolant temperature at steady-state operation (TFSTDY = 550°F)
- Five hours for plant heat-up (DURATN = 5.0)
- Flow stress distributed with a mean of 44.9 ksi and standard deviation of 1.9 ksi (SFLOMU = 44.9, SFLOSD = 1.9)
- Failure criteria minus applied stress exceeding flow stress (IFAILC = 0)
- Leak detected if it exceeds 0.1 gpm. Small and large leaks not differentiated (FNDLEK = 0.1, ALKBIG = 0.1)
- Leaks not repaired (IREPAR = 0)
- Dead weight stress of 0.01 ksi; stress due to dead weight and restraint of thermal expansion of 3.41 ksi (SIGCLD = 0.01, SGDWTE = 3.41)
- Operating pressure of 1.15 ksi (OPPRES = 1.15)
- Hydrostatic proof test pressure of 1.4375 ksi, although proof tests have no meaning when pre-existing cracks are not considered in the analysis (PRFPRS = 1.4375)

- Residual stress model for large line selected (ISIGRS = 2)
- No vibratory stresses included (SIGVIB = -1.0)
- Pre-service inspection modeled; again this has no meaning when pre-existing cracks are not considered in the analysis (NPSI = 1)
- No earthquakes are included (NQUAKE = 0)
- The only transient modeled is the heat-up/cool-down cycle which is assumed to occur regularly five times per year (KTYPES = 1, BLAMDA(1) = -0.2)
- 200 replications performed (IREPLS = 200)

The input file image and the input summary for this sample problem are given in Figures B9 and B10, respectively. The estimated failure probabilities are given in Figure B11. Additional output is shown in Figure B12.

```
PV7 :  55 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB
    1     0   55  203     1     0    1.1
  -15     1     1     3    -1     0     0     0     0     0    14     0    02     1     1     2
23.0        0.2
1.043       10.5
4.5         4.0         9.1400E-12    3.5E-11
[illegible].0         0.2         550.0         5.0
44.9        1.9
[illegible].1         0.1
[illegible].01         3.41        1.15        1.4375     -1.0
    1   -.2 460.0      HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
    1     1     1     1
          1     521.5          4.75       1 OBE   JOINT 1 LLNL DATA
          2    2938.3          9.35       1 SSE   JOINT 1 LLNL DATA
          2   63430.0         10.55       3 SSE   JOINT 1 LLNL DATA
          4  162000.0         10.52       5 SSE   JOINT 1 LLNL DATA
```

Figure B9. Input file image for Sample Problem 3.

```
SCC-INITIATED CRACKS ONLY

A/H BOUNDARY              =      1.100

 MAXIMUM NO. OF CRACKS =   35
 NO. OF REPLICATIONS    =  200

SCC ONLY

 LEAKERS WILL NOT BE REPAIRED

FAILURE CRITERIA : APPLIED STRESS>FLOW STRESS

TIMESTEP FOR SCC =   0.200  YEARS

PIPE DIMENSIONS
          INSIDE RADIUS =      10.80  INCHES
          WALL THICKNESS        1.04  INCHES

CRACK GROWTH LAW PARAMETERS
          EXPONENT =                   4.00
          GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
               MEDIAN =              0.9140E-11
               90-TH PERCENT =       0.3500E-10
          THRESHOLD =                  4.40

 SCC  PARAMETERS


          O2 AT STARTUP(PPM)=               8.00
     O2 AT STEADY STATE(PPM)=               0.20
TEMP. AT STEADY STATE(DEG F)=             550.00
HEATUP (100-550F) TIME (HRS)=               5.00

          FLOW STRESS NORMALLY DISTRIBUTED
          MEAN=              0.4490E+02
          STANDARD DEVIAT    0.1900E+01

PIPE STRESS VALUES
          CSD DEADWT STRESS (KSI)   0.09
          HOT UNIFORM STRESS (KSI)  9.36
          PRESSURE STRESS (KSI)     5.95
          SIG-DC          (KSI)     3.40
          PROOF TEST STRESS(KSI)    7.45

LEAK DETECTION AND DEFINITION PARAMETERS
          DETECTABLE LEAK(GPM)        0.1
          BIG LEAK(GPM)               0.1

RESIDUAL STRESSES FOR LARGE LINE SELECTED

NO VIBRATORY STRESSES ARE MODELED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELED

TIME INTERVALS
          PLANT LIFETIME        20.0  YEARS
          ENDPOINTS OF INTERVALS AT   0.0   1.0   2.0   3.0   4.0   5.0   6.0   7.0   8.0   9.0  YEARS
          ENDPOINTS OF INTERVALS AT  10.0  11.0  12.0  13.0  14.0  15.0  16.0  17.0  18.0  19.0  YEARS
          ENDPOINTS OF INTERVALS AT  20.0



NO IN-SERVICE INSPECTIONS ARE MODELED

                    - - - NO SEISMIC EVENTS EVALUATED - - -

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS     2

                    - - -  NORMAL OUTPUT REQUESTED - - -


      - - NUMBER OF TRANSIENT TYPES =     1  - -

 TYPE  1     HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
 REGULAR AT     0.200  YRS/EVENT
 MAX DELTA TEMP =450.0  BLOCKING FACTOR =    1.
```

Figure B10. Input summary for Sample Problem 3.

- - - P27 : SS INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

- - RESULTS WITHOUT EARTHQUAKES - - -

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
1.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
2.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
3.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
4.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
5.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
6.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
7.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
8.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
9.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
10.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
11.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
12.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
13.0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
14.0	5.00000E-03	5.00000E-03	0.00000E+00	5.00000E-03	5.00000E-03	0.00000E+00
15.0	5.00000E-03	5.00000E-03	0.00000E+00	5.00000E-03	5.00000E-03	0.00000E+00
16.0	1.00000E-02	1.00000E-02	0.00000E+00	7.05328E-03	7.05328E-03	0.00000E+00
17.0	1.00000E-02	1.00000E-02	0.00000E+00	7.05328E-03	7.05328E-03	0.00000E+00
18.0	2.00000E-02	2.00000E-02	0.00000E+00	9.92434E-03	9.92434E-03	0.00000E+00
19.0	2.00000E-02	2.00000E-02	0.00000E+00	9.92434E-03	9.92434E-03	0.00000E+00
20.0	2.00000E-02	2.00000E-02	0.00000E+00	9.92434E-03	9.92434E-03	0.00000E+00

Figure B11. Results for Sample Problem 3.

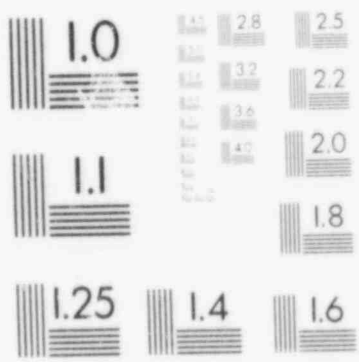
- - - PWR : 35 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB

TOTAL NUMBER OF REPLICATIONS = 200
NUMBER OF POSSIBLE INITIATION SITES(USER SPEC.)= 35
NO. OF TIMES INITIATED CRACKS CAUSED BIG LEAK = 4
NO. OF TIMES PRE-EXISTING CRACKS CAUSED BIG LEAK= 0

TIME (YRS)	TOTAL INITIATED CRACKS	FIRST INITIATED CRACKS
1	129	13
2	139	30
3	176	39
4	227	25
5	215	10
6	229	9
7	185	6
8	214	6
9	203	3
10	192	2
11	155	1
12	149	2
13	139	1
14	163	1
15	135	0
16	115	0
17	123	0
18	101	0
19	102	0
20	64	0
41	3341	54

Figure B12. Additional output for Sample Problem 3.

IMAGE EVALUATION TEST TARGET (MT-3)



150mm

6"

- - - [illegible] : 35 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 0.0

RANGE OF CRACK LENGTHS[9]	TOTAL COUNT	INITIATED COUNT	INITIATED NORMALIZED	PRE-EXISTING COUNT	PRE-EXISTING P(A)*COUNT	PRE-EXISTING NORMALIZED
0.000 -- 1.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.000 -- 2.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.000 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 6.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.000 -- 7.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.000 -- 8.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.000 -- 9.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.000 -- 10.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.000 -- 11.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.000 -- 12.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.000 -- 13.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.000 -- 14.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.000 -- 15.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.000 -- 16.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.000 -- 17.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.000 -- 18.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.000 -- 19.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.000 -- 20.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.000 -- 21.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.000 -- 22.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
22.000 -- 23.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
23.000 -- 24.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
24.000 -- 25.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
25.000 -- 26.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
26.000 -- 27.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
27.000 -- 28.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
28.000 -- 29.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
29.000 -- 30.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
30.000 -- 31.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
31.000 -- 32.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
32.000 -- 33.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
33.000 -- 34.000	0	0	0.000E+00	0	0.000E+00	0.000E+00

---------------------> 0.5*CIRCUM= 33.93

Figure B12. Additional output for Sample Problem 3 (continued).

- - - [illegible] : 35 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 2.0

RANGE OF CRACK LENGTHS[B]	TOTAL COUNT	INITIATED COUNT	INITIATED NORMALIZED	PRE-EXISTING COUNT	PRE-EXISTING P(A)*COUNT	PRE-EXISTING NORMALIZED
0.000 -- 1.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.000 -- 2.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.000 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 6.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.000 -- 7.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.000 -- 8.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.000 -- 9.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.000 -- 10.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.000 -- 11.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.000 -- 12.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.000 -- 13.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.000 -- 14.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.000 -- 15.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.000 -- 16.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.000 -- 17.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.000 -- 18.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.000 -- 19.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.000 -- 20.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.000 -- 21.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.000 -- 22.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
22.000 -- 23.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
23.000 -- 24.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
24.000 -- 25.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
25.000 -- 26.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
26.000 -- 27.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
27.000 -- 28.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
28.000 -- 29.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
29.000 -- 30.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
30.000 -- 31.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
31.000 -- 32.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
32.000 -- 33.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
33.000 -- 34.000	0	0	0.000E+00	0	0.000E+00	0.000E+00

----------------------> 0.5*CIRCUM= 33.93

Figure B12. Additional output for Sample Problem 3 (continued).

- - - P37 : 3) INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 5.0

RANGE OF CRACK LENGTHS(M)	TOTAL COUNT	--------INITIATED------ COUNT	NORMALIZED	------------PRE-EXISTING---------- COUNT	P(A)*COUNT	NORMALIZED
0.000 -- 1.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.000 -- 2.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.000 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 6.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.000 -- 7.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.000 -- 8.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.000 -- 9.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.000 -- 10.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.000 -- 11.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.000 -- 12.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.000 -- 13.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.000 -- 14.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.000 -- 15.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.000 -- 16.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.000 -- 17.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.000 -- 18.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.000 -- 19.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.000 -- 20.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.000 -- 21.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.000 -- 22.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
22.000 -- 23.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
23.000 -- 24.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
24.000 -- 25.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
25.000 -- 26.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
26.000 -- 27.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
27.000 -- 28.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
28.000 -- 29.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
29.000 -- 30.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
30.000 -- 31.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
31.000 -- 32.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
32.000 -- 33.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
33.000 -- 34.000	0	0	0.000E+00	0	0.000E+00	0.000E+00

----------------------> 0.5*CIRCUM= 33.93

Figure B12. Additional output for Sample Problem 3 (continued).

- - - P27 : 35 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 10.0

RANGE OF CRACK LENGTHS[9]	TOTAL COUNT	INITIATED COUNT	INITIATED NORMALIZED	PRE-EXISTING COUNT	PRE-EXISTING P(A)*COUNT	PRE-EXISTING NORMALIZED
0.000 -- 1.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.000 -- 2.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.000 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 6.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.000 -- 7.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.000 -- 8.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
8.000 -- 9.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.000 -- 10.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.000 -- 11.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.000 -- 12.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.000 -- 13.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.000 -- 14.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.000 -- 15.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.000 -- 16.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.000 -- 17.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.000 -- 18.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.000 -- 19.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.000 -- 20.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.000 -- 21.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.000 -- 22.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
22.000 -- 23.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
23.000 -- 24.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
24.000 -- 25.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
25.000 -- 26.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
26.000 -- 27.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
27.000 -- 28.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
28.000 -- 29.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
29.000 -- 30.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
30.000 -- 31.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
31.000 -- 32.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
32.000 -- 33.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
33.000 -- 34.000	0	0	0.000E+00	0	0.000E+00	0.000E+00

----------------------> 0.5*CIRCUM= 33.93

Figure B12. Additional output for Sample Problem 3 (continued).

- - - P27 : 35 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 20.0

RANGE OF CRACK LENGTHS[B]	TOTAL COUNT	--------INITIATED-------		------------PRE-EXISTING---------		
		COUNT	NORMALIZED	COUNT	P(A)*COUNT	NORMALIZED
0.000 -- 1.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.000 -- 2.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.000 -- 3.000	2	2	5.000E-01	0	0.000E+00	0.000E+00
3.000 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 5.000	1	1	2.500E-01	0	0.000E+00	0.000E+00
5.000 -- 6.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
6.000 -- 7.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
7.000 -- 8.000	1	1	2.500E-01	0	0.000E+00	0.000E+00
8.000 -- 9.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
9.000 -- 10.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
10.000 -- 11.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
11.000 -- 12.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
12.000 -- 13.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
13.000 -- 14.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
14.000 -- 15.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
15.000 -- 16.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
16.000 -- 17.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
17.000 -- 18.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
18.000 -- 19.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
19.000 -- 20.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
20.000 -- 21.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
21.000 -- 22.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
22.000 -- 23.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
23.000 -- 24.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
24.000 -- 25.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
25.000 -- 26.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
26.000 -- 27.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
27.000 -- 28.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
28.000 -- 29.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
29.000 -- 30.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
30.000 -- 31.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
31.000 -- 32.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
32.000 -- 33.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
33.000 -- 34.000	0	0	0.000E+00	0	0.000E+00	0.000E+00

----------------------> 0.5*CIRCUM= 33.93

Figure B12. Additional output for Sample Problem 3 (continued).

- - - 227 : 55 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF DEPTH OF THE DEEPEST CRACK

TIME	(0.1H<AOH<0.5H) COUNT	(0.1H<AOH<0.5H) NORMALIZED	(0.5H<AOH<1.0H) COUNT	(0.5H<AOH<1.0H) NORMALIZED
0.0	0	0.00000E+00	0	0.00000E+00
1.0	5	2.50000E-02	0	0.00000E+00
2.0	11	5.50000E-02	0	0.00000E+00
3.0	15	7.50000E-02	0	0.00000E+00
4.0	21	1.05000E-01	0	0.00000E+00
5.0	27	1.35000E-01	0	0.00000E+00
6.0	30	1.50000E-01	0	0.00000E+00
7.0	33	1.65000E-01	0	0.00000E+00
8.0	34	1.70000E-01	0	0.00000E+00
9.0	37	1.85000E-01	0	0.00000E+00
10.0	37	1.85000E-01	0	0.00000E+00
11.0	39	1.90000E-01	2	1.00000E-02
12.0	41	2.05000E-01	2	1.00000E-02
13.0	42	2.10000E-01	2	1.00000E-02
14.0	43	2.15000E-01	2	1.00000E-02
15.0	45	2.25000E-01	3	1.50000E-02
16.0	47	2.35000E-01	2	1.00000E-02
17.0	50	2.50000E-01	2	1.00000E-02
18.0	52	2.60000E-01	0	0.00000E+00
19.0	52	2.60000E-01	0	0.00000E+00
20.0	52	2.60000E-01	0	0.00000E+00

Figure B12. Additional output for Sample Problem 3 (continued).

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- - - PV7 :  55 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB                       - - -

                          DISTRIBUTION OF LENGTH OF THE DEEPEST CRACK --[0.1H<AOH<0.5H]

                TIME-->        0.0       2.0       5.0      10.0      20.0

RANGE OF CRACK LENGTHS[I]     ------------------ABSOLUTE COUNT ------------------

   0.000 ---    1.000          0        11        27        35        51
   1.000 ---    2.000          0         0         0         1         1
   2.000 ---    3.000          0         0         0         1         0
   3.000 ---    4.000          0         0         0         0         0
   4.000 ---    5.000          0         0         0         0         0
   5.000 ---    6.000          0         0         0         0         0
   6.000 ---    7.000          0         0         0         0         0
   7.000 ---    8.000          0         0         0         0         0
   8.000 ---    9.000          0         0         0         0         0
   9.000 ---   10.000          0         0         0         0         0
  10.000 ---   11.000          0         0         0         0         0
  11.000 ---   12.000          0         0         0         0         0
  12.000 ---   13.000          0         0         0         0         0
  13.000 ---   14.000          0         0         0         0         0
  14.000 ---   15.000          0         0         0         0         0
  15.000 ---   16.000          0         0         0         0         0
  16.000 ---   17.000          0         0         0         0         0
  17.000 ---   18.000          0         0         0         0         0
  18.000 ---   19.000          0         0         0         0         0
  19.000 ---   20.000          0         0         0         0         0
  20.000 ---   21.000          0         0         0         0         0
  21.000 ---   22.000          0         0         0         0         0
  22.000 ---   23.000          0         0         0         0         0
  23.000 ---   24.000          0         0         0         0         0
  24.000 ---   25.000          0         0         0         0         0
  25.000 ---   26.000          0         0         0         0         0
  26.000 ---   27.000          0         0         0         0         0
  27.000 ---   28.000          0         0         0         0         0
  28.000 ---   29.000          0         0         0         0         0
  29.000 ---   30.000          0         0         0         0         0
  30.000 ---   31.000          0         0         0         0         0
  31.000 ---   32.000          0         0         0         0         0
  32.000 ---   33.000          0         0         0         0         0
  33.000 ---   34.000          0         0         0         0         0
-----------------------> 0.5*CIRCUM=  33.93
```

Figure B12. Additional output for Sample Problem 3 (continued).

- - - P97 : 2S INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF LENGTH OF THE DEEPEST CRACK --[0.5H<AOH<H]

RANGE OF CRACK LENGTHS[J]	TIME--> 0.0	2.0	5.0	10.0	20.0
	ABSOLUTE COUNT				
0.000 --- 1.000	0	0	0	0	0
1.000 --- 2.000	0	0	0	0	0
2.000 --- 3.000	0	0	0	0	0
3.000 --- 4.000	0	0	0	0	0
4.000 --- 5.000	0	0	0	0	0
5.000 --- 6.000	0	0	0	0	0
6.000 --- 7.000	0	0	0	0	0
7.000 --- 8.000	0	0	0	0	0
8.000 --- 9.000	0	0	0	0	0
9.000 --- 10.000	0	0	0	0	0
10.000 --- 11.000	0	0	0	0	0
11.000 --- 12.000	0	0	0	0	0
12.000 --- 13.000	0	0	0	0	0
13.000 --- 14.000	0	0	0	0	0
14.000 --- 15.000	0	0	0	0	0
15.000 --- 16.000	0	0	0	0	0
16.000 --- 17.000	0	0	0	0	0
17.000 --- 18.000	0	0	0	0	0
18.000 --- 19.000	0	0	0	0	0
19.000 --- 20.000	0	0	0	0	0
20.000 --- 21.000	0	0	0	0	0
21.000 --- 22.000	0	0	0	0	0
22.000 --- 23.000	0	0	0	0	0
23.000 --- 24.000	0	0	0	0	0
24.000 --- 25.000	0	0	0	0	0
25.000 --- 26.000	0	0	0	0	0
26.000 --- 27.000	0	0	0	0	0
27.000 --- 28.000	0	0	0	0	0
28.000 --- 29.000	0	0	0	0	0
29.000 --- 30.000	0	0	0	0	0
30.000 --- 31.000	0	0	0	0	0
31.000 --- 32.000	0	0	0	0	0
32.000 --- 33.000	0	0	0	0	0
33.000 --- 34.000	0	0	0	0	0

---------------------> 0.5*CIRCUM= 33.93

Figure B12. Additional output for Sample Problem 3 (continued).

- - - P27 : 35 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB - - -

DISTRIBUTION OF LENGTH OF THE DEEPEST CRACK --[0.1H<AOH<0.5H]

RANGE OF CRACK LENGTHS[M]	TIME-->	0.0	2.0	5.0	10.0	20.0
		NORMALIZED				
0.000 ---	1.000	0.00000	1.00000	1.00000	0.94595	0.98077
1.000 ---	2.000	0.00000	0.00000	0.00000	0.02703	0.01923
2.000 ---	3.000	0.00000	0.00000	0.00000	0.02703	0.00000
3.000 ---	4.000	0.00000	0.00000	0.00000	0.00000	0.00000
4.000 ---	5.000	0.00000	0.00000	0.00000	0.00000	0.00000
5.000 ---	6.000	0.00000	0.00000	0.00000	0.00000	0.00000
6.000 ---	7.000	0.00000	0.00000	0.00000	0.00000	0.00000
7.000 ---	8.000	0.00000	0.00000	0.00000	0.00000	0.00000
8.000 ---	9.000	0.00000	0.00000	0.00000	0.00000	0.00000
9.000 ---	10.000	0.00000	0.00000	0.00000	0.00000	0.00000
10.000 ---	11.000	0.00000	0.00000	0.00000	0.00000	0.00000
11.000 ---	12.000	0.00000	0.00000	0.00000	0.00000	0.00000
12.000 ---	13.000	0.00000	0.00000	0.00000	0.00000	0.00000
13.000 ---	14.000	0.00000	0.00000	0.00000	0.00000	0.00000
14.000 ---	15.000	0.00000	0.00000	0.00000	0.00000	0.00000
15.000 ---	16.000	0.00000	0.00000	0.00000	0.00000	0.00000
16.000 ---	17.000	0.00000	0.00000	0.00000	0.00000	0.00000
17.000 ---	18.000	0.00000	0.00000	0.00000	0.00000	0.00000
18.000 ---	19.000	0.00000	0.00000	0.00000	0.00000	0.00000
19.000 ---	20.000	0.00000	0.00000	0.00000	0.00000	0.00000
20.000 ---	21.000	0.00000	0.00000	0.00000	0.00000	0.00000
21.000 ---	22.000	0.00000	0.00000	0.00000	0.00000	0.00000
22.000 ---	23.000	0.00000	0.00000	0.00000	0.00000	0.00000
23.000 ---	24.000	0.00000	0.00000	0.00000	0.00000	0.00000
24.000 ---	25.000	0.00000	0.00000	0.00000	0.00000	0.00000
25.000 ---	26.000	0.00000	0.00000	0.00000	0.00000	0.00000
26.000 ---	27.000	0.00000	0.00000	0.00000	0.00000	0.00000
27.000 ---	28.000	0.00000	0.00000	0.00000	0.00000	0.00000
28.000 ---	29.000	0.00000	0.00000	0.00000	0.00000	0.00000
29.000 ---	30.000	0.00000	0.00000	0.00000	0.00000	0.00000
30.000 ---	31.000	0.00000	0.00000	0.00000	0.00000	0.00000
31.000 ---	32.000	0.00000	0.00000	0.00000	0.00000	0.00000
32.000 ---	33.000	0.00000	0.00000	0.00000	0.00000	0.00000
33.000 ---	34.000	0.00000	0.00000	0.00000	0.00000	0.00000

---------------------> 0.5*CIRCUM= 33.73

Figure B12. Additional output for Sample Problem 3 (continued).

--- PWR : 55 INITIATED CRACKS ONLY , SCC ONLY, RES, NO ISI, NO VIB ---

DISTRIBUTION OF LENGTH OF THE DEEPEST CRACK --[0.5H<ADH<H]

RANGE OF CRACK LENGTHS[ ]		TIME--> 1.0	2.0	5.0	10.0	20.0
		-----	-----	NORMALIZED	-----	-----
0.000 ---	1.000	0.00000	0.00000	0.00000	0.00000	0.00000
1.000 ---	2.000	0.00000	0.00000	0.00000	0.00000	0.00000
2.000 ---	3.000	0.00000	0.00000	0.00000	0.00000	0.00000
3.000 ---	4.000	0.00000	0.00000	0.00000	0.00000	0.00000
4.000 ---	5.000	0.00000	0.00000	0.00000	0.00000	0.00000
5.000 ---	6.000	0.00000	0.00000	0.00000	0.00000	0.00000
6.000 ---	7.000	0.00000	0.00000	0.00000	0.00000	0.00000
7.000 ---	8.000	0.00000	0.00000	0.00000	0.00000	0.00000
8.000 ---	9.000	0.00000	0.00000	0.00000	0.00000	0.00000
9.000 ---	10.000	0.00000	0.00000	0.00000	0.00000	0.00000
10.000 ---	11.000	0.00000	0.00000	0.00000	0.00000	0.00000
11.000 ---	12.000	0.00000	0.00000	0.00000	0.00000	0.00000
12.000 ---	13.000	0.00000	0.00000	0.00000	0.00000	0.00000
13.000 ---	14.000	0.00000	0.00000	0.00000	0.00000	0.00000
14.000 ---	15.000	0.00000	0.00000	0.00000	0.00000	0.00000
15.000 ---	16.000	0.00000	0.00000	0.00000	0.00000	0.00000
16.000 ---	17.000	0.00000	0.00000	0.00000	0.00000	0.00000
17.000 ---	18.000	0.00000	0.00000	0.00000	0.00000	0.00000
18.000 ---	19.000	0.00000	0.00000	0.00000	0.00000	0.00000
19.000 ---	20.000	0.00000	0.00000	0.00000	0.00000	0.00000
20.000 ---	21.000	0.00000	0.00000	0.00000	0.00000	0.00000
21.000 ---	22.000	0.00000	0.00000	0.00000	0.00000	0.00000
22.000 ---	23.000	0.00000	0.00000	0.00000	0.00000	0.00000
23.000 ---	24.000	0.00000	0.00000	0.00000	0.00000	0.00000
24.000 ---	25.000	0.00000	0.00000	0.00000	0.00000	0.00000
25.000 ---	26.000	0.00000	0.00000	0.00000	0.00000	0.00000
26.000 ---	27.000	0.00000	0.00000	0.00000	0.00000	0.00000
27.000 ---	28.000	0.00000	0.00000	0.00000	0.00000	0.00000
28.000 ---	29.000	0.00000	0.00000	0.00000	0.00000	0.00000
29.000 ---	30.000	0.00000	0.00000	0.00000	0.00000	0.00000
30.000 ---	31.000	0.00000	0.00000	0.00000	0.00000	0.00000
31.000 ---	32.000	0.00000	0.00000	0.00000	0.00000	0.00000
32.000 ---	33.000	0.00000	0.00000	0.00000	0.00000	0.00000
33.000 ---	34.000	0.00000	0.00000	0.00000	0.00000	0.00000

---------------------> 0.5*CIRCUM= 33.93

Figure B12. Additional output for Sample Problem 3 (continued).

SAMPLE PROBLEM 4

This sample problem illustrates the use IHSI-treated residual stresses applied to a small line. Specific inputs are:

- Twenty year plant lifetime (THRIZN = 20)
- 0.34 inch wall thickness (THICK = 0.34)
- 1.73 inch pipe inside radius (RIN = 1.73)
- Only pre-existing cracks considered (INCIAT = 0, IPRAISE = 1; BNDRY = -1.1)
- Exponential distribution of crack depth and log-normal distribution of aspect ratio for pre-existing cracks (KRKDIS = 3, ALAMDA = 4.065, BOAMED = 1.336, BOASIG = 0.538, BOANRM = 1.419)
- Entire sample space divided into 10 × 10 grid (ISQARE = 1, NAOH = -10, NAOB = -10, AOHLOW = 0.0, AOHUP = 1.0, AOBLFT = 0.0, AOBRGT = 1.0)
- Ten samples taken from each cell (NTRIES = -10)
- Maximum time-step for stress corrosion crack growth computation is 0.2 year (DTSCC = 0.2)
- 8 ppm oxygen during plant loading (OSTART = 8.0)
- 0.2 ppm oxygen during steady-state operation (OSTEDY = 0.2)
- 550°F coolant temperature at steady-state operation (TFSTDY = 550°F)
- Five hours for plant heat-up (DURATN = 5.0)
- Flow stress distributed with a mean of 44.9 ksi and standard deviation of 1.9 ksi (SFLOMU = 44.9, SFLOSD = 1.9)
- Failure criteria minus applied stress exceeding flow stress (IFAILC = 0)
- Leak detected if it exceeds 0.1 gpm. Small and large leaks not differentiated (FNDLEK = 0.1, ALKBIG = 0.1)
- Leaks not repaired (IREPAR = 0)
- Dead weight stress of 0.01 ksi; stress due to dead weight and restraint of thermal expansion of 11 ksi (SIGCLD = 0.01, SGDWTE = 11)

- Operating pressure of 1.15 ksi (OPPRES = 1.15)
- Hydrostatic proof test pressure of 2.8125 ksi, although proof tests have no meaning when pre-existing cracks are not considered in the analysis (PRFPRS = 2.8125)
- IHSI model for residual stresses included (ISIGRS = 5)
- IHSI resulting stresses varying linearly from -45 ksi on the inside surface to +45 ksi on the outside surface (RSIN = -45, RSOUT = +45)
- No vibratory stresses included (SIGVIB = -1.0)
- Pre-service inspection modeled; again this has no meaning when pre-existing cracks are not considered in the analysis (NPSI = 1)
- No earthquakes are included (NQUAKE = 0)
- The only transient modeled is the heat-up/cool-down cycle which is assumed to occur regularly five times per year (KTYPES = 1, BLAMDA(1) = -0.2)

The input file image and the input summary for this sample problem are given in Figures B13 and B14, respectively. The summary of the stratification scheme is shown in Figure B15. The failure probabilities and additional outputs are given in Figures B16 and B17, respectively.

```
PR1 : PRE-EXISTING , SCC ONLY, NO RES, NO INITIATED, NO ISI, NO VIP -LEAKS ONLY
    3     0     1  100     0     0  -1.1
  -10     1     1    3    -1     0     0     0     0     0    14     0    10     1     1     5
-45.0      45.0
29.0        0.2
1.34       1.75
4.5        4.0        9.1430E-12   3.5E-11
5.0        0.2        550.0        5.0
44.9       1.9
4.065
1.136      0.538      1.419
0.1        0.1
  -10   -10   0.09    1.0        0.0        1.0
.01        11.0       1.15       2.8125     -1.0
    1   -.2 430.0     HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
    1     1     1     1
          1     521.6        3.76      1 ONE   JOINT 1 LLNL DATA
          2    2956.3        9.05      1 SSE   JOINT 1 LLNL DATA
          2   63430.0       10.56      3 SSE   JOINT 1 LLNL DATA
          4  152000.0       10.62      5 SSE   JOINT 1 LLNL DATA
```

Figure B13. Input file image for Sample Problem 4.

```
PRE-EXISTING CRACKS ONLY

A/H BOUNDARY              =    -1.100

 MAXIMUM NO. OF CRACKS =    1
 NO. OF REPLICATIONS   =  100


SCC ONLY

 LEAKERS WILL NOT BE REPAIRED

FAILURE CRITERIA : APPLIED STRESS>FLOW STRESS

TIMESTEP FOR SCC =   0.200  YEARS

PIPE DIMENSIONS
          INSIDE RADIUS =       1.73  INCHES
          WALL THICKNESS        0.34  INCHES

INITIAL CRACK SIZE DISTRIBUTION
CRACK DEPTH IS EXPONENTIAL
          PARAMETER =          6.0650
ASPECT RATIO IS LOG-NORMAL
          MEDIAN =             1.3360
          SHAPE PARAMETER      0.5380
          NORMALIZATION CONSTANT =      1.4187

CRACK GROWTH LAW PARAMETERS
          EXPONENT =                  4.00
          GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
               MEDIAN =             0.9140E-11
               90-TH PERCENT =      0.3500E-10
          THRESHOLD =                 4.63

 SCC  PARAMETERS


          O2 AT STARTUP(PPM)=               8.00
     O2 AT STEADY STATE(PPM)=               0.20
TEMP. AT STEADY STATE(DEG F)=             550.00
HEATUP (100-550F) TIME (HRS)=               5.00

          FLOW STRESS NORMALLY DISTRIBUTED
          MEAN=                0.4490E+02
          STANDARD DEVIAT      0.1900E+01

PIPE STRESS VALUES
          CSD DEADWT STRESS (KSI)   0.01
          HOT UNIFORM STRESS (KSI) 13.93
          PRESSURE STRESS (KSI)     2.93
          SIG-DC          (KSI)    10.99
          PROOF TEST STRESS(KSI)    7.17

LEAK DETECTION AND DEFINITION PARAMETERS
          DETECTABLE LEAK(GPM)        0.1
          BIG LEAK(GPM)               3.1

IHSI-RESIDUAL STRESSES SELECTED
             INSIDE  STRESS (KSI) =    -45.000
              OUTSIDE STRESS (KSI) =    45.000


NO VIBRATORY STRESSES ARE MODELED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELED

TIME INTERVALS
          PLANT LIFETIME        20.0  YEARS
          ENDPOINTS OF INTERVALS AT   0.0   1.0   2.0   3.0   4.0   5.0   6.0   7.0   8.0   9.0  YEARS
          ENDPOINTS OF INTERVALS AT  10.0  11.0  12.0  13.0  14.0  15.0  16.0  17.0  18.0  19.0  YEARS
          ENDPOINTS OF INTERVALS AT  20.0

NO IN-SERVICE INSPECTIONS ARE MODELED

                      - - - NO SEISMIC EVENTS EVALUATED - - -

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS   10

                      - - -  NORMAL OUTPUT REQUESTED - - -


      - - NUMBER OF TRANSIENT TYPES =     1  - -

TYPE  1    HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
REGULAR AT      0.200  YRS/EVENT
MAX DELTA TEMP =450.0  BLOCKING FACTOR =   1.

     ---DEFINITIONS OF CELLS IN STATE SPACE---
```

Figure B14. Input Summary for Sample Problem 4.

$$$ UNIFORM MESH $$$

CELL	ADM1	ADM2	ADU1	ADU2	PROBABILITY	SAMPLES
1	0.9000	1.0000	0.0563	0.1000	0.6394451E-05	10
2	0.9000	1.0000	0.1000	0.2000	0.4927263E-03	10
3	0.9000	1.0000	0.2000	0.3000	0.2645946E-02	10
4	0.9000	1.0000	0.3000	0.4000	0.5459142E-02	10
5	0.9000	1.0000	0.4000	0.5000	0.7371144E-02	10
6	0.9000	1.0000	0.5000	0.6000	0.8026338E-02	10
7	0.9000	1.0000	0.6000	0.7000	0.7748644E-02	10
8	0.9000	1.0000	0.7000	0.8000	0.6961440E-02	10
9	0.9000	1.0000	0.8000	0.9000	0.5979845E-02	10
10	0.9000	1.0000	0.9000	1.0000	0.4991246E-02	10
11	0.8000	0.9000	0.0500	0.1000	0.7383497E-05	10
12	0.8000	0.9000	0.1000	0.2000	0.5657566E-03	10
13	0.8000	0.9000	0.2000	0.3000	0.3039004E-02	10
14	0.8000	0.9000	0.3000	0.4000	0.6269277E-02	10
15	0.8000	0.9000	0.4000	0.5000	0.8463670E-02	10
16	0.8000	0.9000	0.5000	0.6000	0.9215975E-02	10
17	0.8000	0.9000	0.6000	0.7000	0.8897122E-02	10
18	0.8000	0.9000	0.7000	0.8000	0.7993241E-02	10
19	0.8000	0.9000	0.8000	0.9000	0.6866157E-02	10
20	0.8000	0.9000	0.9000	1.0000	0.5731032E-02	10
21	0.7000	0.8000	0.0433	0.1000	0.8494745E-05	10
22	0.7000	0.8000	0.1000	0.2000	0.6496111E-03	10
23	0.7000	0.8000	0.2000	0.3000	0.3488287E-02	10
24	0.7000	0.8000	0.3000	0.4000	0.7197340E-02	10
25	0.7000	0.8000	0.4000	0.5000	0.9719127E-02	10
26	0.7000	0.8000	0.5000	0.6000	0.1058194E-01	10
27	0.7000	0.8000	0.6000	0.7000	0.1021582E-01	10
28	0.7000	0.8000	0.7000	0.8000	0.9177973E-02	10
29	0.7000	0.8000	0.8000	0.9000	0.7883836E-02	10
30	0.7000	0.8000	0.9000	1.0000	0.6580467E-02	10
31	0.6000	0.7000	0.0375	0.1000	0.9759424E-05	10
32	0.6000	0.7000	0.1000	0.2000	0.7458943E-03	10
33	0.6000	0.7000	0.2000	0.3000	0.4005309E-02	10
34	0.6000	0.7000	0.3000	0.4000	0.8264106E-02	10
35	0.6000	0.7000	0.4000	0.5000	0.1115852E-01	10
36	0.6000	0.7000	0.5000	0.6000	0.1215036E-01	10
37	0.6000	0.7000	0.6000	0.7000	0.1172998E-01	10
38	0.6000	0.7000	0.7000	0.8000	0.1053830E-01	10
39	0.6000	0.7000	0.8000	0.9000	0.9052352E-02	10
40	0.6000	0.7000	0.9000	1.0000	0.7555801E-02	10
41	0.5000	0.6000	0.0313	0.1000	0.1120734E-04	10
42	0.5000	0.6000	0.1000	0.2000	0.8564482E-03	10
43	0.5000	0.6000	0.2000	0.3000	0.4598962E-02	10
44	0.5000	0.6000	0.3000	0.4000	0.9489934E-02	10
45	0.5000	0.6000	0.4000	0.5000	0.1281239E-01	10
46	0.5000	0.6000	0.5000	0.6000	0.1395124E-01	10
47	0.5000	0.6000	0.6000	0.7000	0.1346856E-01	10
48	0.5000	0.6000	0.7000	0.8000	0.1210025E-01	10

Figure B15. Stratification description for Sample Problem 4

49	0.5000	0.6000	0.8000	0.9000	0.1039406E-01	10
50	0.5000	0.6000	0.9000	1.0000	0.6675697E-02	10
51	0.4000	0.5000	0.0250	0.1000	0.1256869E-04	10
52	0.4000	0.5000	0.1000	0.2000	0.9833431E-03	10
53	0.4000	0.5000	0.2000	0.3000	0.5280605E-02	10
54	0.4000	0.5000	0.3000	0.4000	0.1089541E-01	10
55	0.4000	0.5000	0.4000	0.5000	0.1471140E-01	10
56	0.4000	0.5000	0.5000	0.6000	0.1601905E-01	10
57	0.4000	0.5000	0.6000	0.7000	0.1546482E-01	10
58	0.4000	0.5000	0.7000	0.8000	0.1389371E-01	10
59	0.4000	0.5000	0.8000	0.9000	0.1193463E-01	10
60	0.4000	0.5000	0.9000	1.0000	0.9961590E-02	10
61	0.3000	0.4000	0.0188	0.1000	0.1477606E-04	10
62	0.3000	0.4000	0.1000	0.2000	0.1129143E-02	10
63	0.3000	0.4000	0.2000	0.3000	0.6063279E-02	10
64	0.3000	0.4000	0.3000	0.4000	0.1251029E-01	10
65	0.3000	0.4000	0.4000	0.5000	0.1689188E-01	10
66	0.3000	0.4000	0.5000	0.6000	0.1839334E-01	10
67	0.3000	0.4000	0.6000	0.7000	0.1775696E-01	10
68	0.3000	0.4000	0.7000	0.8000	0.1595299E-01	10
69	0.3000	0.4000	0.8000	0.9000	0.1370355E-01	10
70	0.3000	0.4000	0.9000	1.0000	0.1143805E-01	10
71	0.2000	0.3000	0.0125	0.1000	0.1696612E-04	10
72	0.2000	0.3000	0.1000	0.2000	0.1296500E-02	10
73	0.2000	0.3000	0.2000	0.3000	0.6961957E-02	10
74	0.2000	0.3000	0.3000	0.4000	0.1436452E-01	10
75	0.2000	0.3000	0.4000	0.5000	0.1939554E-01	10
76	0.2000	0.3000	0.5000	0.6000	0.2111954E-01	10
77	0.2000	0.3000	0.6000	0.7000	0.2038894E-01	10
78	0.2000	0.3000	0.7000	0.8000	0.1831749E-01	10
79	0.2000	0.3000	0.8000	0.9000	0.1573464E-01	10
80	0.2000	0.3000	0.9000	1.0000	0.1313336E-01	10
81	0.1000	0.2000	0.0063	0.1000	0.1948078E-04	10
82	0.1000	0.2000	0.1000	0.2000	0.1488663E-02	10
83	0.1000	0.2000	0.2000	0.3000	0.7993835E-02	10
84	0.1000	0.2000	0.3000	0.4000	0.1649359E-01	10
85	0.1000	0.2000	0.4000	0.5000	0.2227028E-01	10
86	0.1000	0.2000	0.5000	0.6000	0.2424980E-01	10
87	0.1000	0.2000	0.6000	0.7000	0.2341081E-01	10
88	0.1000	0.2000	0.7000	0.8000	0.2103245E-01	10
89	0.1000	0.2000	0.8000	0.9000	0.1806677E-01	10
90	0.1000	0.2000	0.9000	1.0000	0.1507994E-01	10
91	0.0000	0.1000	0.0000	0.1000	0.2236816E-04	10
92	0.0000	0.1000	0.1000	0.2000	0.1709308E-02	10
93	0.0000	0.1000	0.2000	0.3000	0.9178655E-02	10
94	0.0000	0.1000	0.3000	0.4000	0.1893821E-01	10
95	0.0000	0.1000	0.4000	0.5000	0.2557110E-01	10
96	0.0000	0.1000	0.5000	0.6000	0.2784403E-01	10
97	0.0000	0.1000	0.6000	0.7000	0.2688066E-01	10
98	0.0000	0.1000	0.7000	0.8000	0.2414981E-01	10
99	0.0000	0.1000	0.8000	0.9000	0.2074457E-01	10
100	0.0000	0.1000	0.9000	1.0000	0.1731504E-01	10

SUM OF CELL PROBABILITIES = 0.7697999183E+00

Figure B15. Stratification description for Sample Problem 4 (continued).

\- - - 221 : PRE-EXISTING , SCC ONLY, NO RES, NO INITIATED, NO ISI, NO VIB -LEAKS ONLY - - -

\- - RESULTS WITHOUT EARTHQUAKES - - -

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.0	3.04310E-05	3.04310E-05	0.00000E+00	3.04310E-05	3.04310E-05	0.00000E+00
1.0	3.75283E-04	3.75283E-04	0.00000E+00	1.60003E-04	1.60003E-04	0.00000E+00
2.0	6.19625E-04	6.19625E-04	0.00000E+00	2.92068E-04	2.92068E-04	0.00000E+00
3.0	6.19625E-04	6.19625E-04	0.00000E+00	2.92068E-04	2.92068E-04	0.00000E+00
4.0	6.19625E-04	6.19625E-04	0.00000E+00	2.92068E-04	2.92068E-04	0.00000E+00
5.0	6.19625E-04	6.19625E-04	0.00000E+00	2.92068E-04	2.92068E-04	0.00000E+00
6.0	1.64645E-03	1.64645E-03	0.00000E+00	7.44254E-04	7.44254E-04	0.00000E+00
7.0	1.64645E-03	1.64645E-03	0.00000E+00	7.44254E-04	7.44254E-04	0.00000E+00
8.0	2.00763E-03	2.00763E-03	0.00000E+00	8.17884E-04	8.17884E-04	0.00000E+00
9.0	2.00763E-03	2.00763E-03	0.00000E+00	8.17884E-04	8.17884E-04	0.00000E+00
10.0	2.00763E-03	2.00763E-03	0.00000E+00	8.17884E-04	8.17884E-04	0.00000E+00
11.0	2.45993E-03	2.45993E-03	0.00000E+00	9.34617E-04	9.34617E-04	0.00000E+00
12.0	2.45993E-03	2.45993E-03	0.00000E+00	9.34617E-04	9.34617E-04	0.00000E+00
13.0	2.45993E-03	2.45993E-03	0.00000E+00	9.34617E-04	9.34617E-04	0.00000E+00
14.0	2.45993E-03	2.45993E-03	0.00000E+00	9.34617E-04	9.34617E-04	0.00000E+00
15.0	2.45993E-03	2.45993E-03	0.00000E+00	9.34617E-04	9.34617E-04	0.00000E+00
16.0	2.45993E-03	2.45993E-03	0.00000E+00	9.34617E-04	9.34617E-04	0.00000E+00
17.0	2.45993E-03	2.45993E-03	0.00000E+00	9.34617E-04	9.34617E-04	0.00000E+00
18.0	2.45993E-03	2.45993E-03	0.00000E+00	9.34617E-04	9.34617E-04	0.00000E+00
19.0	2.45993E-03	2.45993E-03	0.00000E+00	9.34617E-04	9.34617E-04	0.00000E+00
20.0	2.94685E-03	2.94685E-03	0.00000E+00	1.05385E-03	1.05385E-03	0.00000E+00

Figure B16. Results for Sample Problem 4.

- - - PP4 : PRE-EXISTING , SCC ONLY, NO RES, NO INITIATED, NO ISI, NO VIB -LEAKS ONLY - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 0.0

RANGE OF CRACK LENGTHS[B]	TOTAL COUNT	-------INITIATED------ COUNT	NORMALIZED	-----------PRE-EXISTING--------- COUNT	P(A)*COUNT	NORMALIZED
0.000 -- 0.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.250 -- 0.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.500 -- 0.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.750 -- 1.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.000 -- 1.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.250 -- 1.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.500 -- 1.750	1	0	0.000E+00	1	6.496E-04	1.000E+00
1.750 -- 2.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.000 -- 2.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.250 -- 2.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.500 -- 2.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.750 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 3.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.250 -- 3.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.500 -- 3.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.750 -- 4.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.000 -- 4.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.250 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 4.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.750 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.250 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

----------------------> 0.5*CIRCUM= 5.43

Figure B17. Additional output for Sample Problem 4.

- - - PVT : PRE-EXISTING , SCC ONLY, NO RES, NO INITIATED, NO ISI, NO VIB -LEAKS ONLY - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 2.0

RANGE OF CRACK LENGTHS(B)	TOTAL COUNT	INITIATED COUNT	INITIATED NORMALIZED	PRE-EXISTING COUNT	PRE-EXISTING P(A)*COUNT	PRE-EXISTING NORMALIZED
0.000 -- 0.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.250 -- 0.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.500 -- 0.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.750 -- 1.000	1	0	0.000E+00	1	6.268E-03	3.646E-01
1.000 -- 1.250	3	0	0.000E+00	3	9.114E-03	5.302E-01
1.250 -- 1.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.500 -- 1.750	2	0	0.000E+00	2	1.215E-03	7.070E-02
1.750 -- 2.000	1	0	0.000E+00	1	5.658E-04	3.291E-02
2.000 -- 2.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.250 -- 2.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.500 -- 2.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.750 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 3.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.250 -- 3.500	3	0	0.000E+00	3	2.116E-05	1.231E-03
3.500 -- 3.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.750 -- 4.000	1	0	0.000E+00	1	6.394E-06	3.720E-04
4.000 -- 4.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.250 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 4.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.750 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.250 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

----------------------> 0.5*CIRCUM= 5.43

Figure B17. Additional output for Sample Problem 4 (continued).

- - - P/1 : PRE-EXISTING , SCC ONLY, NO RES, NO INITIATED, NO ISI, NO VIB -LEAKS ONLY - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 5.0

RANGE OF CRACK LENGTHS[9]	TOTAL COUNT	INITIATED COUNT	INITIATED NORMALIZED	PRE-EXISTING COUNT	PRE-EXISTING P(A)*COUNT	PRE-EXISTING NORMALIZED
0.000 -- 0.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.250 -- 0.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.500 -- 0.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.750 -- 1.000	1	0	0.000E+00	1	6.268E-03	3.646E-01
1.000 -- 1.250	3	0	0.000E+00	3	9.114E-03	5.302E-01
1.250 -- 1.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.500 -- 1.750	2	0	0.000E+00	2	1.215E-03	7.070E-02
1.750 -- 2.000	1	0	0.000E+00	1	5.658E-04	3.291E-02
2.000 -- 2.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.250 -- 2.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.500 -- 2.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.750 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 3.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.250 -- 3.500	3	0	0.000E+00	3	2.116E-05	1.231E-03
3.500 -- 3.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.750 -- 4.000	1	0	0.000E+00	1	6.394E-06	3.720E-04
4.000 -- 4.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.250 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 4.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.750 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.250 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

---------------------> 0.5*CIRCUM= 5.43

Figure B17. Additional output for Sample Problem 4 (continued).

- - - P91 : PRE-EXISTING , SCC ONLY, NO RES, NO INITIATED, NO ISI, NO VIB -LEAKS ONLY - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 10.0

RANGE OF CRACK LENGTHS[B]	TOTAL COUNT	INITIATED COUNT	INITIATED NORMALIZED	PRE-EXISTING COUNT	PRE-EXISTING P(A)*COUNT	PRE-EXISTING NORMALIZED
0.000 -- 0.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.250 -- 0.500	2	0	0.000E+00	2	1.599E-02	3.721E-01
0.500 -- 0.750	1	0	0.000E+00	1	9.216E-03	2.145E-01
0.750 -- 1.000	1	0	0.000E+00	1	6.268E-03	1.459E-01
1.000 -- 1.250	3	0	0.000E+00	3	9.114E-03	2.122E-01
1.250 -- 1.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.500 -- 1.750	2	0	0.000E+00	2	1.215E-03	2.829E-02
1.750 -- 2.000	2	0	0.000E+00	2	1.132E-03	2.634E-02
2.000 -- 2.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.250 -- 2.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.500 -- 2.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.750 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 3.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.250 -- 3.500	3	0	0.000E+00	3	2.116E-05	4.926E-04
3.500 -- 3.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.750 -- 4.000	1	0	0.000E+00	1	6.394E-06	1.488E-04
4.000 -- 4.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.250 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 4.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.750 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.250 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

----------------------> 0.5*CIRCUM= 5.43

Figure B17. Additional output for Sample Problem 4 (continued).

- - - P/T : PRE-EXISTING , SCC ONLY, NO RES, NO INITIATED, NO ISI, NO VIB -LEAKS ONLY - - -

DISTRIBUTION OF CRACK LENGTHS THAT CAUSED LEAKS AT TIME = 20.0

RANGE OF CRACK LENGTHS(R)	TOTAL COUNT	INITIATED COUNT	INITIATED NORMALIZED	PRE-EXISTING COUNT	PRE-EXISTING P(A)*COUNT	PRE-EXISTING NORMALIZED
0.000 -- 0.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
0.250 -- 0.500	3	0	0.000E+00	3	2.483E-02	4.041E-01
0.500 -- 0.750	2	0	0.000E+00	2	1.893E-02	3.075E-01
0.750 -- 1.000	1	0	0.000E+00	1	6.268E-03	1.018E-01
1.000 -- 1.250	3	0	0.000E+00	3	9.114E-03	1.480E-01
1.250 -- 1.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
1.500 -- 1.750	2	0	0.000E+00	2	1.215E-03	1.974E-02
1.750 -- 2.000	2	0	0.000E+00	2	1.132E-03	1.838E-02
2.000 -- 2.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.250 -- 2.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.500 -- 2.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
2.750 -- 3.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.000 -- 3.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.250 -- 3.500	3	0	0.000E+00	3	2.116E-05	3.437E-04
3.500 -- 3.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
3.750 -- 4.000	1	0	0.000E+00	1	6.394E-06	1.038E-04
4.000 -- 4.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.250 -- 4.500	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.500 -- 4.750	0	0	0.000E+00	0	0.000E+00	0.000E+00
4.750 -- 5.000	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.000 -- 5.250	0	0	0.000E+00	0	0.000E+00	0.000E+00
5.250 -- 5.500	0	0	0.000E+00	0	0.000E+00	0.000E+00

----------------------> 0.5*CIRCUM= 5.43

Figure B17. Additional output for Sample Problem 4 (continued).