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Theoretical and User's Manual for pc-PRAISE

A Probabilistic Fracture Mechanics Computer Code for Piping Reliability Analysis

Prepared by
D. O. Harris, D. D. Dedhia/FAA
S. C. Lu/LLNL

Failure Analysis Associates, Inc.

Lawrence Livermore National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission

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Prepared by
D. O. Harris, D. D. Dedhia, Failure Analysis Associates, Inc.
S. C. Lu, Lawrence Livermore National Laboratory

Failure Analysis Associates, Inc.
149 Commonwealth Drive
Menlo Park, CA 94025

Under Contract to:
Lawrence Livermore National Laboratory
7000 East Avenue
Livermore, CA 94550

Prepared for
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
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ABSTRACT

The purpose of this document is to collect under one cover and update the documentation related to the PRAISE Computer Code. pc-PRAISE is the most recent version of the code, which is a probabilistic fracture mechanics code that has recently been modified to run on an IBM personal computer to evaluate the reliability of welds in nuclear power plant piping systems. pc-PRAISE was adapted from the PRAISE Computer Code, which was originally developed in 1980-81 by Lawrence Livermore National Laboratory (LLNL) under funding from the U.S. Nuclear Regulatory Commission for assessment of the influence of seismic events on the failure probability of piping in pressurized water reactors. PRAISE is an acronym for Piping Reliability Analysis Including Seismic Events, and has been significantly expanded in recent years to allow consideration of both crack initiation and growth in a variety of piping materials in pressurized and boiling water reactors. PRAISE has a deterministic basis in fracture mechanics. Some of the inputs, such as initial crack size and inspection detection probability, are considered to be random variables, and the failure probability versus time for a given weldment is evaluated by Monte Carlo simulation. Complex realistic stress histories can be treated by the code, and sets of random material properties for representative piping materials are built into the code. This document provides a comprehensive summary of the deterministic basis of the code, along with description of statistical distributions of random variables. Code inputs are described and an extensive set of sample problems is provided, along with descriptions of representative outputs.

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EXECUTIVE SUMMARY

The reliability of piping in commercial power reactors is of paramount importance in the safe operation of these power sources. This is especially true of the large piping attached to the reactor pressure vessel. Questions arise concerning the influence of seismic events, inspection, plant operation, remedial measures, etc., on piping reliability. Such questions can be addressed by use of the PRAISE Computer Code. PRAISE is a acronym for **P**iping **R**eliability **A**nalysis **I**ncluding **S**eismic **E**vents, and is a code originally developed in 1980-81 by Lawrence Livermore National Laboratory to address questions concerning load combinations involving seismic events and loss of coolant accidents (LOCA). Over the intervening years, the code has been expanded to include additional piping materials and degradation mechanisms. Pre- and post-processors have also been implemented and an IBM personal computer version developed. The documentation on these expansions and enhancements is either nonexistent or distributed among a number of reports -- some of which are not readily available. This document gathers together, updates, and expands information on the PRAISE Code, and constitutes Theory and User's Manuals for the current version of the code: pc-PRAISE 2.4. This documentation, along with the recently developed pre- and post-processors, should make the code easier to use, and its implementation on a personal computer should facilitate its more widespread use. An extensive set of sample problems is included, many of them drawn from realistic problems analyzed by PRAISE in past studies.

The PRAISE Code considers the initiation and/or growth of crack-like defects in piping weldments. The initiation analyses are based on the results of laboratory studies and field observations in austenitic piping materials operating under boiling water reactor conditions. The considerable scatter in such results is quantified and incorporated into a probabilistic model. The crack growth analysis is based on (deterministic) fracture mechanics principles, in which some of the inputs (such as initial crack size) are considered to be random variables. Monte Carlo simulation, with stratified sampling on initial crack size, is used to generate weldment reliability results.

The PRAISE Computer Code should be useful to vendor, utility, and regulatory personnel and consultants concerned with the influence of a wide variety of factors on the reliability of reactor piping possibly subject to failure due to the initiation and unchecked growth of cracks in welds.

1. INTRODUCTION

The purpose of this document is to collect under one cover and update the documentation related to the PRAISE Computer Code. pc-PRAISE is a probabilistic fracture mechanics computer code written for the IBM personal computer to evaluate the reliability of welds in nuclear power plant piping systems. pc-PRAISE was adapted from the PRAISE Computer code which was originally developed for CDC 7600 in 1980-81 [Harris 81, Lim 81] by Lawrence Livermore National Laboratory (LLNL) under funding from the U.S. Nuclear Regulatory Commission, and has been considerably expanded and updated over the intervening years [Harris 82a, 83, 86, FaAA 90]. The documentation is distributed throughout the six references given above, plus a closely related document that describes a useful related tool [Dedhia 82]. Additionally, some code enhancements have been performed, such as putting the code on a personal computer and expanding it to include additional piping materials. This document consolidates and updates the earlier reports and provides a set of sample problems generated by use of the current version (pc-PRAISE 2.4).

The PRAISE Code was originally developed in 1980-81 [Harris 81, Lim 81] for assessment of the influence of seismic events on the failure probability of piping in pressurized water reactors (PWRs). PRAISE is an acronym for Piping Reliability Analysis Including Seismic Events and originally considered failure to occur due to the unchecked growth due to cyclic loading of pre-existing crack-like weld defects. PRAISE has a deterministic base that calculates the weld lifetime for a given deterministic set of inputs by fracture mechanics principles.

Some of the inputs, such as the initial crack size, are considered to be random variables. That is, their values fall within a given range with a defined probability. PRAISE generates the pipe failure probability as a function of time by performing a series of deterministic lifetime calculations for different sets of inputs drawn from their respective statistical distributions. In this way a histogram of lifetimes is generated, from which the failure probability as a function of time is derived. This process is called Monte Carlo simulation.

Figure 1-1 is a schematic diagram of the steps involved in analysis of the reliability of a given weld location. This figure also provides the locations within this document where each of these steps is discussed.

Soon after the completion of PRAISE, the code was expanded to consider the following:

- longitudinal welds (the original and current versions consider only circumferential welds)
- stress corrosion crack growth (the original version considered only fatigue crack growth)
- residual and vibratory stresses.

This version of the code was known as PRAISE-B [Harris 82a].

A major extension of the code capabilities was developed in the mid-1980s to allow a probabilistic treatment of the initiation and growth of stress corrosion cracks. (Recall that earlier versions considered only the growth of cracks from pre-existing defects.) This allows the analysis to be performed of the reliability of sensitized weldments in 304 stainless steel piping in boiling water reactor (BWR) piping. Provisions for analyzing 316 NG piping welds were also included. This version of the code is known as PRAISE-C [Harris 86]. Figure 1-2 is a schematic diagram of the expanded PRAISE model. Also shown in this figure are the locations within this document where each of the components of the code are discussed.

More recent code expansions include updated failure criteria based on tearing instability analysis [Harris 83, FaAA 90], adaptation to IBM personal computers, and an enhanced pre- and post-processor for pc-PRAISE [FaAA 90]. These recent expansions will be included in this document.

Concurrent with the code expansion and enhancements mentioned above, PRAISE has been applied to a variety of reactor piping reliability problems. This has included extensive studies on primary coolant piping of Westinghouse [LLNL 84b] and Babcock & Wilcox [LLNL 85] pressurized water reactors, as well as recirculation piping in boiling water

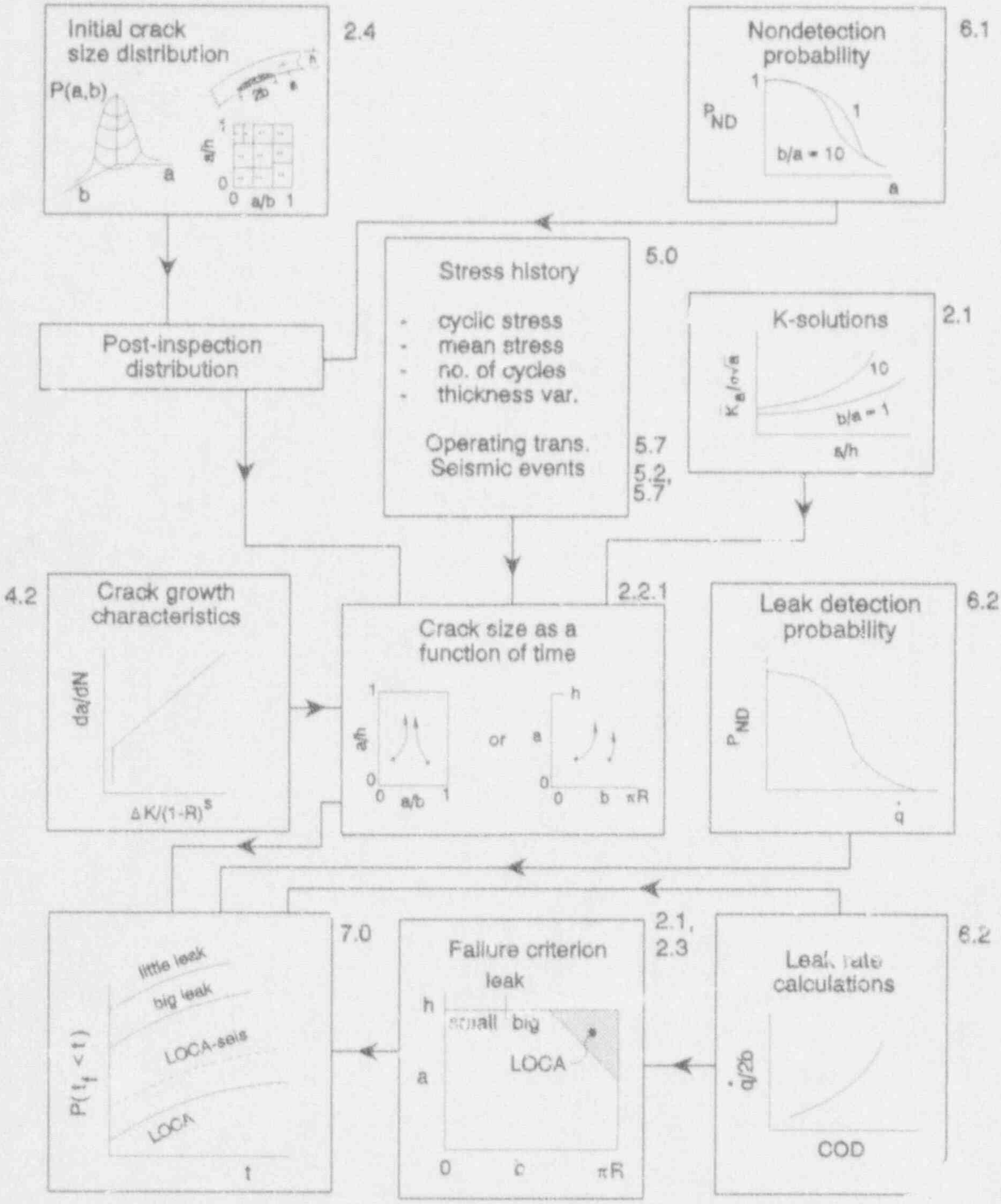

Figure 1-1. Schematic diagram of components of analysis of reliability of a given weld location and identification of sections in this document that describe these components.

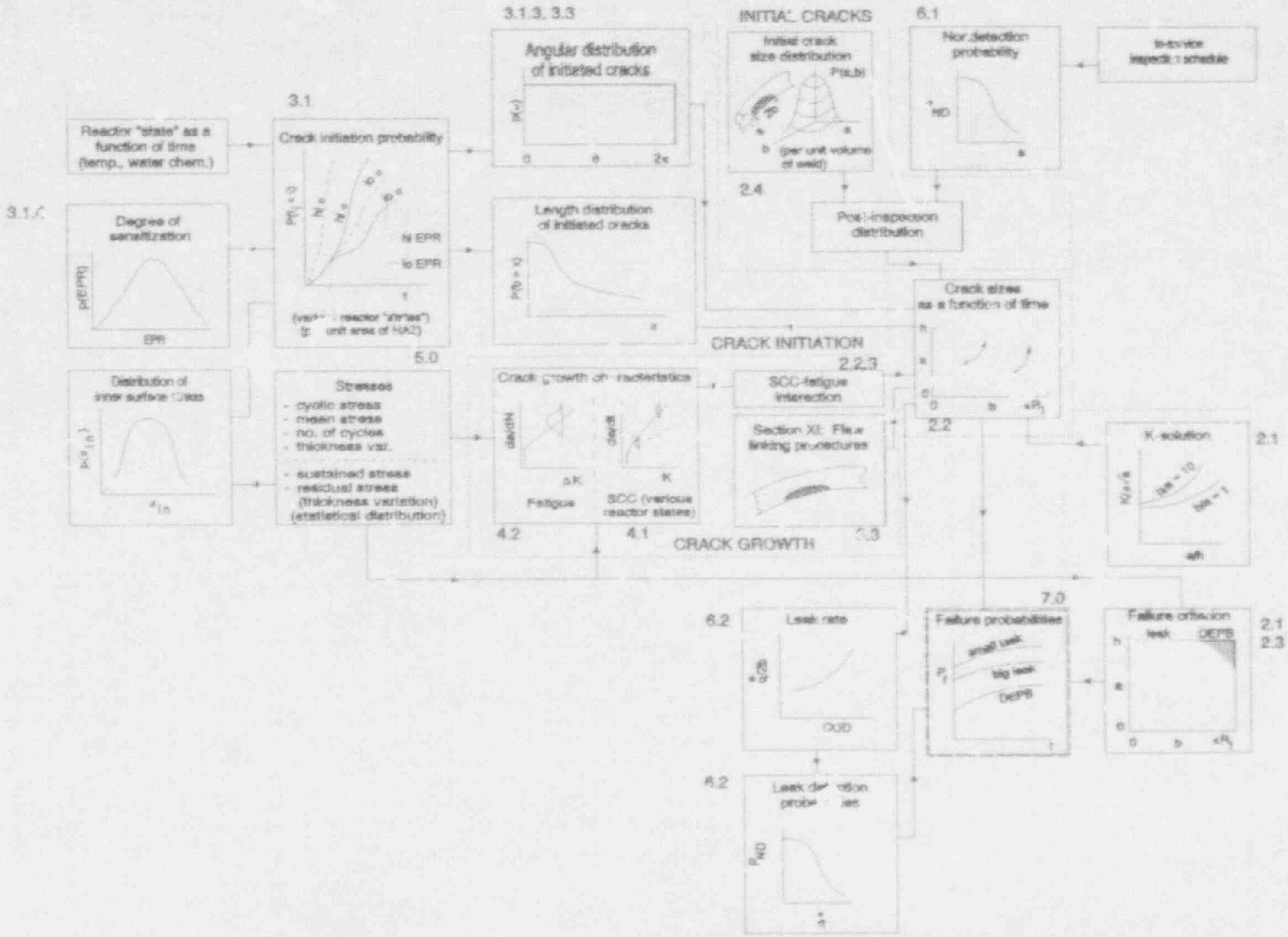

Figure 1-2. Schematic diagram of various components of an expanded PRAISE model suitable for application to stress corrosion cracking and identification of sections in this document that describe these components.

reactors [Holman 88, 89a, 89b, Lo 89]. Other applications in the U.S. include the work of Hong [Hong 84].

The PRAISE Code has also been used in Europe [Schomburg 86, Bruckner 89], and a modified version has been developed in Japan for high temperature breeder reactor piping [Matsumoto 87].

Sections 2 through 6 of this document describe the bases of the PRAISE Code, and can be considered as a Theory Manual for the code. Sections 8 and 9 describe inputs and outputs of the code, and Section 10 provides sample problems. Hence, these sections can be considered as a User's Manual. Section 8.1, entitled "Getting Started", is suggested as a starting point for the new user.

2. FRACTURE MECHANICS BASES

With notable exceptions, the PRAISE Code is a probabilistic fracture mechanics code with a deterministic fracture mechanics basis. Consequently, the code has a strong fracture mechanics base, which will be described in this section. Basically, the code considers pre-existing crack-like weld defects whose subcritical growth and final instability are treated by fracture mechanics principles. The notable exception is the initiation and early growth of stress corrosion cracks in sensitized austenitic stainless steel piping welds in boiling water reactors.

The purpose of this section is to describe the fracture mechanics procedures involved in PRAISE calculations. Considerable familiarity with fracture mechanics is assumed. Numerous fracture mechanics books are now available. The following are suggested for those readers desiring additional background [Broek 87, Kanninen 85, Anderson 91].

2.1 Evaluation of Stress Intensity Factors and J-integrals

The stress intensity factor (K) controls the level of stresses and strains near a crack tip in a linearly elastic body*, and the cyclic value of K has been observed to have the primary affect on the growth rate of a fatigue crack. In a nonlinear-elastic body, which is similar to an elastic-plastic body under monotonic loading, the stresses and strains near the crack tip are controlled by the value of Rice's J-integral. Procedures for calculating K and J for cases of interest in PRAISE are covered in the following section.

2.1.1 Stress Intensity Factors for Part-Through Cracks

All cracks considered by PRAISE start out as semi-elliptical interior surface cracks, generally circumferentially oriented, as shown in Figure 2-1. In some cases, such as elbows, there are longitudinal welds, and thus interest in longitudinal semi-elliptical cracks. For the pipe sizes and thicknesses used in commercial light water reactors (LWRs), to a good degree of accuracy, for a given stress, crack size, and wall thickness, the stress intensity factors for flat plates, circumferential cracks, and longitudinal cracks are the same. This is discussed in

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* Only Mode I stress intensity factors are considered in PRAISE and the "I" subscript is omitted.

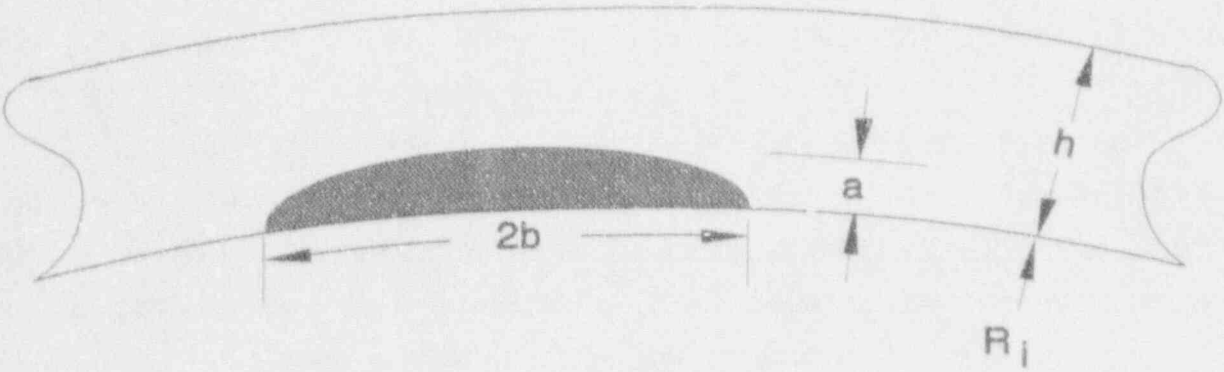


Figure 2-1. Geometry of part-circumferential interior surface crack considered.

Appendices A and B of Harris 81, as well as in Lim 83. More recent results, such as Poette 91 are consistent with this.

For a semi-elliptical surface crack, the stress intensity factor varies along the crack front. When considering the growth of such cracks due to cyclic loading, it is tempting to consider the local value of the crack growth rate to depend on the local value of K. However, this results in considerable complexity in the crack growth analysis, and quickly leads to cracks that are not semi-elliptical in shape. This, in turn, leads to the necessity of generating new stress intensity factor solutions for non-elliptical cracks. In order to circumvent such problems, it is generally assumed that the crack remains elliptical as it grows, and the growth rate in the depth and length directions (a and b directions) is controlled by either the local values at the deepest point and surface point or by RMS-averaged values of K associated with growth in the two directions. The RMS-averaged approach is used in PRAISE, because it seems reasonable that the growth rate is controlled by more than the local value of K, the RMS-averaged values are related to energy release rates, and the RMS-averaged values of K for arbitrary stress gradients can easily be evaluated by the use of influence functions.

Referring to Figure 2-2 for a semi-elliptical surface crack perturbed in the "a" degree of freedom direction

$$G_a = \frac{\bar{K}_a^2(1-\nu^2)}{E} = \frac{1-\nu^2}{E\Delta A_a}\int_{-\pi/2}^{\pi/2} K^2(\phi)\, d\left[\Delta A_a(\phi)\right] \qquad (2\text{-}1)$$

where G_a is the strain energy release rate for a crack perturbed in the manner shown in Figure 2-2, $\Delta A_a(\phi)$ is an incremental area [see Page 282 of Harris 81 for an expression for $\Delta A_a(\phi)$ and $\Delta A_b(\phi)$], $K(\phi)$ is the local value of K and $\bar{K}_a$ is the "RMS-averaged" value of K. There is an expression analogous to Equation 2-1 for growth in the "b" direction. If stresses are not symmetrical with respect to the "a" direction, then a third expression exists, but this situation is not considered in PRAISE (see, for instance, Section 2.3 of NASCRAC 90).

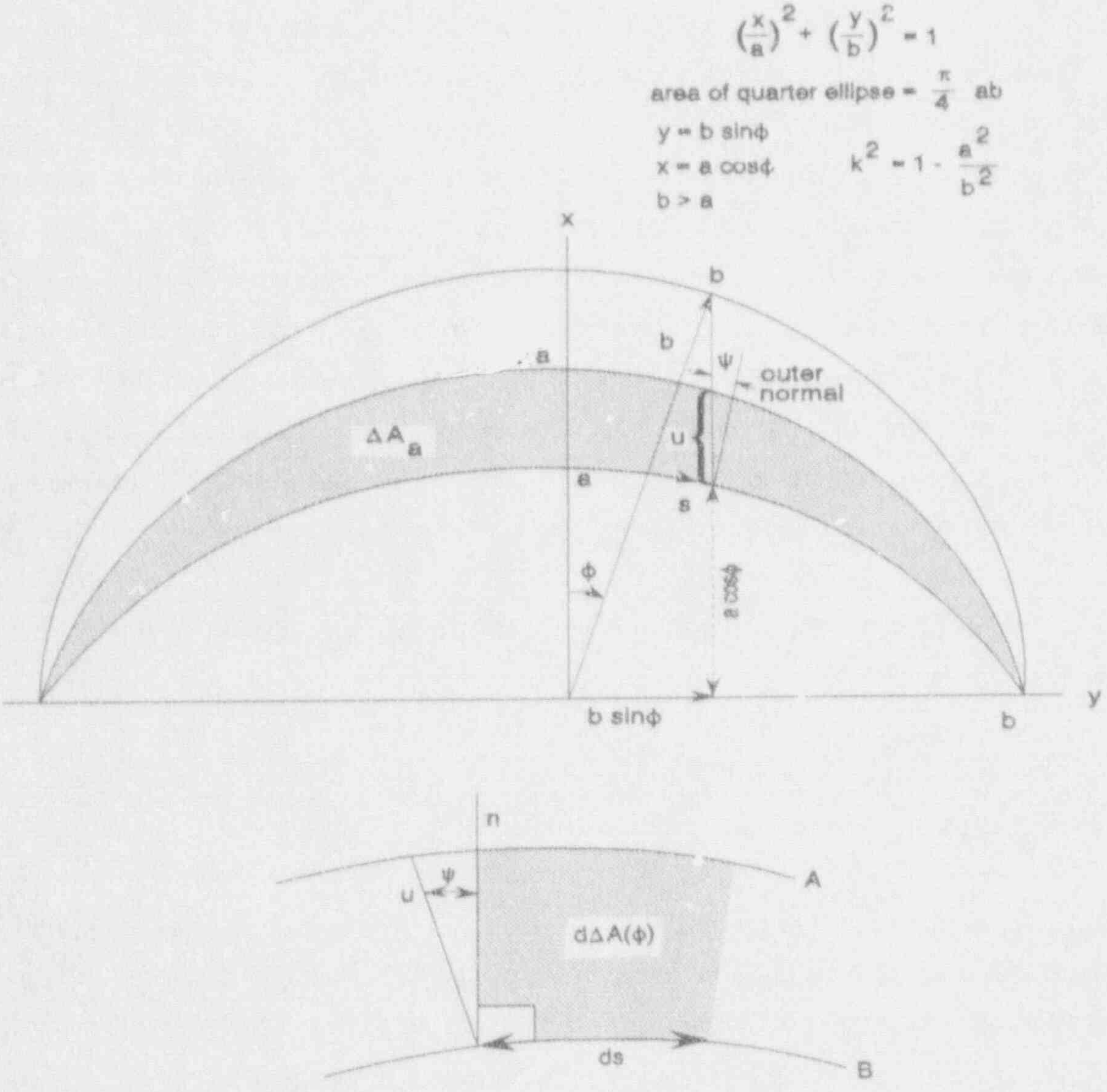


Figure 2-2. Schematic representation of a crack growing only in the "a" degree of freedom.

One major advantage of the use of RMS-averaged values of K for multi-degree-of-freedom cracks is the economy with which $\bar{K}_i$ can be evaluated for complex spatial stress gradients. If $\sigma(x,y)$ is the stress on the crack plane if the crack was not present, then $\bar{K}_i$ can be obtained by numerical integration of influence functions that, in turn, are determined by curve fits to numerical results for crack surface displacements [Rice 72, Cruse 75, Besuner 76, 77, 78], by use of the following expression

$$\bar{K}_i = \int_A \sigma(x,y)\ h_i(x,y,a,b,\text{geom})\,dA \tag{2-2}$$

There is an influence function, h_i, for each degree of freedom. In the current case, there are two, one for the depth direction, h_a, and one for the surface length direction, h_b. The integration is performed over the crack area, A, and $\sigma(x,y)$ is the stress normal to the crack that would be on the crack region if the crack was not present.

The influence functions, h_a and h_b, for a semi-elliptical surface crack in a body of thickness h was determined as part of the initial PRAISE development and reported in Appendix C of Harris 81. These influence functions were also reported in Lim 83, and their use for complex stress gradients was demonstrated in Dedhia 83. The original influence functions were not very accurate for shallow cracks and were improved for such cracks in Dedhia 84. These improved influence functions have been incorporated into the TIFFANY Code [Dedhia 82].

As described in Appendix C of Harris 81 and Dedhia 84, the influence function h_j (j = a or b) is written as

$$h_i = h_i^* \frac{\left[g_2 + w^* \dfrac{\partial g_2}{\partial a_i} \Big/ \dfrac{\partial w^*}{\partial a_i}\right]}{\left[g_1 + U^* \dfrac{\partial g_1}{\partial a_i} \Big/ \dfrac{\partial U^*}{\partial a_i}\right]^{1/2}}$$

$$\left.\begin{aligned} w^{*} &= \frac{2\sigma a}{E'\Phi}\,\xi^{1/2} \\ U^{*} &= \frac{4\pi\sigma^{2}a^{2}b}{3E'\Phi} \end{aligned}\right\}\ \text{uniform stress} \tag{2-3}$$

$$h_a^{*} = \frac{\left[\dfrac{1}{a} - \dfrac{1}{\Phi}\dfrac{\partial\Phi}{\partial a} + \dfrac{x^{2}}{a^{3}\xi}\right]\xi^{1/2}}{\pi b\left[\dfrac{1}{3}\Phi\left(\dfrac{2}{a} - \dfrac{1}{\Phi}\dfrac{\partial\Phi}{\partial a}\right)\right]^{1/2}}$$

$$h_b^{*} = \frac{\left[\dfrac{1}{\Phi}\dfrac{\partial\Phi}{\partial b} + \dfrac{y^{2}}{b^{3}\xi}\right]\xi^{1/2}}{\pi\left[\dfrac{ab}{3}\Phi\left(\dfrac{1}{b} - \dfrac{1}{\Phi}\dfrac{\partial\Phi}{\partial b}\right)\right]^{1/2}}$$

$$\Phi = \int_0^{\pi/2}\left[1-\left(1-\frac{a^{2}}{b^{2}}\right)\sin^{2}\psi\right]^{1/2}d\psi \sim \left[1+1.464\left(\frac{a}{b}\right)^{1.65}\right]^{1/2}$$

$$\xi = 1-\left(\frac{x}{a}\right)^{2}-\left(\frac{y}{b}\right)^{2}$$

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

x = coordinate in depth direction

y = coordinate in surface length direction

The "*" items above are for uniform stress, which was chosen as the reference stress for evaluation of the influence functions by numerical calculation of crack surface displacements. The curve fit to numerical results is embodied in the functions g_1 and g_2, which are the following for a semi-elliptical surface crack

$$g_1 = \left(1.1328 + 0.05753\beta - 0.007625\beta^2\right) + \left(-0.12727 + 0.4902\beta - 0.06515\beta^2\right)\alpha + \left(-0.3005 + 0.73192\beta - 0.2839\beta^2 + 0.03572\beta^3\right)\alpha^2 \tag{2-4}$$

$$\begin{aligned} g_2 = {} & A_0(\alpha) + A_1 R^{1.5}\theta^{0.15} + A_2 R^{1.5}\theta^{0.3} \\ & + A_3 R^{2.5}\theta^{0.15} + A_4(\alpha) R^{2.5}\theta^{0.3} \\ & + A_5(\alpha)\left(\frac{1}{\beta} - 1\right) + A_6(\alpha)\left(\frac{1}{\beta} - 1\right)^2 \end{aligned} \tag{2-5}$$

where $R = [(x/a)^2 + (y/b)^2]^{1/2}$

$\theta = 1 - \frac{2}{\pi}\left(\tan^{-1}\frac{y/b}{x/a}\right)$

$\alpha = {}'h$

$\beta = b/a$

$A_0(\alpha) = 1.323 + 0.13831\alpha + 0.60229\alpha^2$

$A_1 = 0.54443$

$A_2 = -1.27014$

$A_3 = -0.55144$

$A_4(\alpha) = 0.98756 - \alpha$

$A_5(\alpha) = -0.06579 - 0.52508\alpha + 0.43354\alpha^2$

$A_6(\alpha) = 0.01471 - 0.82792\alpha + 2.6834\alpha^2$

The numerical integration procedure used to evaluate Equation 2-2, which includes a singularity is the influence function h_i at the crack tip, are discussed in detail in Section D.1 of Harris 81. The integration procedures are incorporated in TIFFANY [Dedhia 82] to provide an easy way for the user to calculate K values.

The cases of uniform stress and linearly varying stress (in the depth direction) occur most frequently in PRAISE calculations. In fact, nonlinear stress gradients are only infrequently considered, because inclusion of radial gradient thermal stresses (see Section 5.2), which have nonlinear gradients, have been found to generally have a minimal influence on calculated weld reliability [Harris 81, Page 155], while adding significantly to the complexity of the analysis. Since constant and linearly varying stresses are of particular interest in PRAISE calculations, polynomial curve fits to results generated using the above influence functions have been obtained for computational efficiency. The following are the curve fits, with $\alpha = a/h$ and $\zeta = a/b$.

Uniform Stress

$$\begin{aligned}
\frac{\bar{K}_a}{\sigma a^{1/2}} = {} & [(1.8781 - 0.7248\zeta - 0.2035\zeta^2 + 0.2432\zeta^3) \\
& + (-1.9181 - 0.4252\zeta - 8.0667\zeta^2 - 7.4870\zeta^3)\alpha \\
& + (7.1762 - 11.3209\zeta - 10.4922\zeta^2 + 15.9368\zeta^3)\alpha^2 \\
& + (-6.0324 - 10.469\zeta + 2.0322\zeta^2 - 7.6101\zeta^3)\alpha^3]/(1-\alpha)^{1/2} \qquad (2\text{-}6)
\end{aligned}$$

$$\begin{aligned}
\frac{\bar{K}_b}{\sigma a^{1/2}} = {} & [(1.3003 + 0.1046\zeta - 0.1943\zeta^2 + 0.03935\zeta^3) \\
& + (-1.3745 - 0.7675\zeta + 1.3877\zeta^2 - 1.5430\zeta^3)\alpha \\
& + (4.0255 - 7.0179\zeta - 10.6008\zeta^2 - 7.7883\zeta^3)\alpha^2 \\
& + (-3.2410 - 5.3097\zeta - 7.8403\zeta^2 - 5.4374\zeta^3)\alpha^3]/(1-\alpha)^{1/2}
\end{aligned}$$

Linearly Varying Stress

$$
\begin{aligned}
\frac{\bar{K}_a}{\sigma_a a^{1/2}} &= [(1.01392 - 0.78506\alpha + 3.31506\alpha^2 - 0.991159\alpha^3) \\
&\quad + (-0.34032 + 2.5896\alpha - 9.02996\alpha^2 + 2.88101\alpha^3)\zeta \\
&\quad + (0.045722 - 1.90305\alpha + 6.05041\alpha^2 - 1.93187\alpha^3)\zeta^2] \qquad (2\text{-}7) \\
\frac{\bar{K}_b}{\sigma_a a^{1/2}} &= [(0.47954 - 0.206885\alpha + 1.112738\alpha^2 - 0.19908\alpha^3) \\
&\quad + (-0.0249092 + 0.144091\alpha - 1.61755\alpha^2 + 0.176543\alpha^3)\zeta \\
&\quad + (0.0450383 - 0.223205\alpha + 1.97511\alpha^2 + 0.779899\alpha^3)\zeta^2 \\
&\quad + (-0.04859 + 0.37304\alpha - 1.5687\alpha^2 - 0.3790668\alpha^3)\zeta^3]
\end{aligned}
$$

Equations 2-7 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 ($x = a$). The above K-relations are suitable for either axial or circumferential cracks.

Stress intensity factors due to radial gradient thermal stresses are generated by the TIFFANY Code [Dedhia 82] and input to PRAISE in dimensionless form as a table (see Sample Problem 3, Section 10.3). The dimensionless form allows the maximum temperature excursion of the transient to be easily considered as a random variable. A separate table of dimensionless stress intensity factors are needed for each transient type that considers radial gradient thermal stresses. Each such transient is considered as a perturbation on the steady-state normal operating stress, which is considered to be uniform through the pipe wall (see Section 5). If $\bar{K}_{op,i}(\alpha, \beta)$ is the K for the i-th degree of freedom, then $\bar{K}_{max,i}$ and $\bar{K}_{min,i}$ for a transient that includes radial gradient thermal stresses is considered to be

$$\begin{aligned} \bar{K}_{max,i} &= \bar{K}_{op,i} + \bar{K}^{RG}_{max,i}(\alpha,\beta) \\ \bar{K}_{min,i} &= \bar{K}_{op,i} - \bar{K}^{RG}_{min,i}(\alpha,\beta) \end{aligned} \tag{2-8}$$

where $\bar{K}^{RG}_{max,i}(\alpha,\beta)$ and $\bar{K}^{RG}_{min,i}(\alpha,\beta)$ are the maximum and minimum, respectively, of the K due to only the radial gradient stresses.

Dimensionless functions g^*_{max} and g^*_{min} are defined as

$$\begin{aligned} \bar{K}^{RG}_{max,i} &= \Delta T_{max} a^{1/2} g^*_{max,i}(\alpha,\beta) \\ \bar{K}^{RG}_{min,i} &= \Delta T_{max} a^{1/2} g^*_{min,i}(\alpha,\beta) \end{aligned} \tag{2-9}$$

The functions $g^*_{max,i}$ and $g^*_{min,i}$ can be evaluated directly by TIFFANY, using only the time-temperature-flow rate history of the coolant in the piping, and the dimensions and material(s) of the pipe wall. This is accomplished by numerically evaluating the time variation of $\bar{K}_i$ during the transient for a given crack size and picking off the maximum and minimum values as time progresses. The tabulated values of $g^*_{min,i}$ and $g^*_{max,i}$ are input to PRAISE. The values of b/a and a/h used in the tables can be varied by the user, but the tables are generally composed of six columns for b/a = 1 to 6 in increments of 1 and nine rows for a/h from 0.1 to 0.9 in increments of 0.1 (see Sections 5.4 and 8.2.6, and Sample Problem 3 of this document and Sections 3.6 and 4.6 of Lim 81 and Dedhia 82).

2.1.2 J-Integrals for Part-Through Cracks

The J-integral is the strain energy release rate and controls the stresses and strains near a crack tip in a material whose uniaxial stress-strain curve is expressed as

$$\epsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{D}\right)^n \tag{2-10}$$

This stress-strain relation is referred to as Ramberg-Osgood and provides a good representation of the elastic-plastic behavior observed in metals. Consideration of the J-integral and nonlinear stress-strain behavior allows extension of stress intensity factors to nonlinear behavior. When n = 1 or D = ∞, or σ is small, Equation 2-10 reduces to linear material behavior, in which case J can be expressed in terms of K

$$J = \begin{cases} \dfrac{K^2}{E} & \text{plane stress} \\ \dfrac{K^2(1-\nu^2)}{E} & \text{plane strain} \end{cases} \tag{2-11}$$

and J is equal to G of Equation 2-1.

Fatigue crack growth is treated by consideration of cyclic stress intensity factors. However, in order to include plasticity effects in calculation of final crack instability, a J-integral approach is used. Evaluation of J for a semi-elliptical surface crack of depth a and surface length 2b is on the current frontier of fracture mechanics. However, J-integral solutions are readily available for axisymmetric and planar problems, including a complete circumferential crack in a pipe [Kumar 81]. Hence, for the purposes of accounting for plasticity in crack stability calculations by use of handbook J-solutions, the semi-elliptical crack is idealized as being completely around the circumference with a depth a.

The following expression applies to the fully plastic value of J

$$J_p = \frac{\sigma^{n+1}}{D^n}\, a\, \frac{h_1(\alpha,n,\gamma)}{(1-\alpha)^n} \left[\frac{3^{1/2}}{2}\, \frac{2\gamma+1}{2\gamma+1+\alpha}\right]^{n+1} \tag{2-12}$$

where $\alpha = a/h$, $\gamma = R_i/h$, and σ is the uniform axial stress in the pipe. The functions h_1 are obtained by nonlinear finite elements and are tabulated for a complete circumferential crack in Kumar 81, as well as in Kanninen 85 and Anderson 91 for α = 0 to 0.75, n = 1 to 7, and γ = 5, 10, and 20. PRAISE uses bicubic spline interpolation for a fixed γ to obtain values of h_1 for values of n and α intermediate to the tabulated values.

The values of the J-integral for elastic-plastic conditions is obtained by an interpolation scheme that utilizes the value of J for n = 1 (elastic J, Equation 2-11) and the fully plastic value of J [Kumar 81]. This handbook approach involves use of the relation

$$J = J_e + J_p \qquad (2\text{-}13)$$

where J_p is the fully plastic value, such as expressed in Equation 2-12, and J_e is J_p for n = 1, but with a plasticity correction to the physical crack size a to provide an effective crack length, a_{ef}.

$$a_{ef} = a + \gamma r_y$$

$$r_y = \frac{1}{\beta\pi}\left(\frac{n-1}{n+1}\right)\frac{J_e}{\sigma_{ys}^2} \qquad (2\text{-}14)$$

(J_e is calculated from Equation 2-12 using a and n = 1)

$$\beta = \begin{cases} 2 & \text{plane stress} \\ 6 & \text{plane strain} \end{cases}$$

$$\gamma = \begin{cases} 1/[1+(\sigma/\sigma_{gy})^2] & \sigma < \sigma_{gy} \\ 1/2 & \sigma > \sigma_{gy} \end{cases}$$

σ_{gy} is the applied stress for general yield under perfectly plastic conditions with yield strength σ_{ys}.

In the case of a complete circumferential crack in a pipe

$$\sigma_{gy} = \frac{2}{3^{1/2}}(1-\alpha)\left(\frac{2\gamma+1-\alpha}{2\gamma+1}\right)\sigma_{ys} \qquad (2\text{-}15)$$

The above equations are generally applicable when the expression corresponding to Equations 2-12 and 2-15 for the specific geometry is available, along with the corresponding set of calibration functions, h_1.

2.1.3 Stress Intensity Factors and J-Integrals for Through-Wall Cracks

The part-through initial cracks considered in PRAISE can grow as fatigue or stress corrosion cracks, or can become unstable (in the depth direction), and become through-wall cracks. A crack of surface length 2b at the time of break-through is considered to transition to a through-wall crack of length 2b. The stability of this through-wall crack is checked (see Section 2.3) and the leak rate estimated (see Section 6.2). If the leak rate is below the detection limit and the crack remains stable, then the crack growth rate is evaluated by use of the stress intensity factor. The following K-solution is employed [Forman 85]

$$K = \sigma(\pi b)^{1/2} F_0 \tag{2-16}$$

$$F_0 = \left(\frac{I_0}{2\pi\beta}\right)^{1/2}$$

$$I_0 = \beta^2\left[g(\alpha) + \frac{\pi}{\lambda} C^2(\lambda) - 2^{3/2}\right]$$

$$C(\lambda) = \begin{cases} 1 + \frac{\pi}{15}\lambda^2 - 0.0293\lambda^3 & \lambda \le 1 \\ \left(\frac{2^{3/2}\lambda}{\pi}\right)^{1/2} + \left(\frac{0.179}{\lambda}\right)^{0.885} & \lambda > 1 \end{cases}$$

$$g(\beta) = 2^{3/2}\left\{1 + \frac{1 - \beta\cot\beta}{2\beta\cot\beta + 2^{1/2}\beta\cot\left(\frac{\pi - \beta}{2^{1/2}}\right)}\right\}^{1/2}$$

$$\beta = b/\left(R_i + \frac{h}{2}\right) \qquad \lambda = b/\left[h\left(R_i + \frac{h}{2}\right)\right]^{1/2}$$

σ = axial stress in pipe wall

The fully plastic J-solution for a through-wall crack of length 2b is required for stability analysis that accounts for plasticity. The following expression is used [Kumar 81]

$$J_p = \frac{\sigma^{n+1}}{D^n} b(1-\beta) \frac{h_1(\alpha, n, \gamma)}{[1-\beta - \frac{2}{\pi}\sin^{-1}(\frac{1}{2}\sin \pi\beta)]^{n+1}} \tag{2-17}$$

where β is given above. The stress at general yield is given by

$$\sigma_{gy} = \sigma_{ys}/[1-\beta - \frac{2}{\pi}\sin^{-1}(\frac{1}{2}\sin \pi\beta)]^{n+1} \tag{2-18}$$

Values of h_1 are available for $\gamma = R_i/h = 5$, 10, and 20, $n = 1$ to 7, and β from 1/16 to 1/2 [Kumar 84]. PRAISE uses bicubic spline interpolation for a fixed γ to obtain values of h_1 for values of n and β intermediate to tabulated values. The above expressions are used in the interpolation scheme described in Section 2.1.2 (at Equation 2-13) to estimate J for elastic-plastic conditions.

2.2 Calculation of Crack Growth

This section discusses the procedures for calculation of crack growth. The K-solutions from Section 2.1 are combined with the crack growth "laws" from Section 4 to calculate crack size as a function of number of fatigue cycles or time.

2.2.1 Fatigue Crack Growth

In the case of fatigue crack growth, the crack growth "law" can be expressed as

$$\frac{da}{dN} = F(\Delta K, R) \tag{2-19}$$

where a is crack size, N is number of fatigue cycles, $\Delta K = K_{max} - K_{min}$, and $R = K_{min}/K_{max}$. F is some general function of ΔK and R. Section 4 describes some specific examples of F.

Crack growth in PRAISE is generally calculated on a cycle-by-cycle basis or a group of n identical cycles. The stress intensity factor, $\overline{K}_{max,i}$ and $\overline{K}_{min,i}$ (where i refers to the degree of freedom) are evaluated for the transient based on the crack size at the beginning of the block of N cycles. The crack size after the block is given by

$$
\begin{aligned}
a_{after} &= a_{before} + N\ F(\Delta\bar{K}_a, R_a) \\
b_{after} &= b_{before} + N\ F(\Delta\bar{K}_b, R_b)
\end{aligned}
\qquad (2\text{-}20)
$$

(The case of cycle-by-cycle crack growth corresponds to $N = 1$.) N is referred to as the "blocking factor".

In some instances, it is not convenient to analyze crack growth on a cycle-by-cycle basis. Seismic events are a prime example. In such instances, the user inputs an equivalent stress history composed of groups of cycles of constant amplitude. The means of defining an equivalent stress history is left to the user, but a procedure suitable for the Walker relation (see Section 4.2.1) with $m = 4$ is described in Sections 2.6.2 and 3.7 of Harris 81 and Section 3.7.1 of Lim 81.

PRAISE also has the capability of performing deterministic fatigue crack growth calculations for a specified initial crack size and deterministic fatigue crack growth properties. The initial crack size is defined by specifying a small stratum surrounding the desired size and that a single sample is to be drawn from that stratum. The deterministic fatigue crack growth relation is specified by defining KONPRP = 1, in which case the median value of da/dN is used. This corresponds to a zero standard deviation of C if a Walker relation is used (Equation 4-3, but exponent of 4 not required), or $C_F = 0$ if the ferritic crack growth relation of Section 4.2.2 is used.

If the above conditions (1 stratum, 1 sample, KONPRP = 1) are met, then PRAISE performs a single simulation and automatically prints out the crack size as a function of time (rather than the usual failure probability results). Time can be reinterpreted as cycles knowing the frequency of the cycles.

In this manner, PRAISE can be used to analyze the growth of multi-degrees-of-freedom cracks subjected to complex stress histories involving arbitrary through-thickness stress gradients.

2.2.2 Stress Corrosion Crack Growth

Stress corrosion crack growth is time, rather than cycle, dependent. For a one degree of freedom crack, the crack growth rate can be expressed as

$$\frac{da}{dt} = G(K) \tag{2-21}$$

This is generalized to multi-degree-of-freedom cracks, and the stress intensity factor is evaluated at the beginning of a time step. The crack size after a time step, Δt, is given by

$$\begin{aligned} a_{after} &= a_{before} + G(\overline{K}_a)\Delta t \\ b_{after} &= b_{before} + G(\overline{K}_b)\Delta t \end{aligned} \tag{2-22}$$

The time step, Δt, is defined by the expression

$$\Delta t = \text{smallest of } [t_s \text{ or } 0.1 \text{ in}/(da/dt)] \tag{2-23}$$

where t_s is a time step defined by the user that is often taken to be 0.1 year, and da/dt is the growth rate in the depth direction at the beginning of the time step.

2.2.3 Combined Fatigue and Stress Corrosion Cracking

Crack growth under fatigue and stress corrosion cracking conditions is treated within PRAISE as simply the sum of the fatigue contribution and the stress corrosion cracking (SCC) contribution. That is, crack extension during a load cycle is governed by the da/dN-ΔK relation (see Section 4.2), and the crack growth while at load is governed by the da/dt-K relation (see Section 4.1).

2.3 Crack Instability

Initiated or initial defects grow subcritically by fatigue or stress corrosion cracking until they reach the point of final instability and the pipe breaks catastrophically. Reactor piping materials are tough and ductile, so the failure criterion considers plasticity. Two such criteria are used, net-section stress and tearing instability, and both are incorporated into the PRAISE Code.

2.3.1 Net-Section Stress

This criterion is applicable to very tough material where failure occurs because of insufficient remaining area to support the applied loads. For circumferential cracks, this is expressed as

$$\sigma_{LC}\, A_p > \sigma_{flo}(A_p - A_{crack}) \tag{2-24}$$

In this expression A_p is the cross-sectioned area of the pipe, A_{crack} is the area of the crack, σ_{LC} is the load controlled component of the axial stress (deadweight plus pressure, see Section 5.1), and σ_{flo} is the flow stress of the material. A complete and sudden pipe severance is considered to occur when Equation 2-24 is satisfied. Figure 2-3 shows the crack configuration considered.

The flow stress, σ_{flo}, is the average of the yield and ultimate strengths of the material and may be considered to be a random variable. The PRAISE Code allows σ_{flo} to be normally distributed, and the following default values for austenitic stainless steels are provided

mean σ_{flo} = 44.9 ksi
std. dev. of σ_{flo} = 1.9 ksi

The net-section stress criterion is not considered to be applicable to axial cracks.

2.3.2 Tearing Modulus

The PRAISE Code can treat crack instability (calculation of critical crack size) by the tearing instability approach [Paris 79, Hutchinson 79, Kumar 84, Kanninen 85]. This approach is suitable for fairly tough materials which exhibit extensive plasticity prior to failure, but can fail before the critical net-section stress (based on flow stress) is reached. In this case, the crack growth resistance is considered to increase linearly as the crack extends, as shown schematically in Figure 2-4.

$$A_p = \pi[(R_i^2+h) - R_i^2]$$

$$A_{cr} = [(R_i+a)^2 - R_i^2]\,b/R_i$$

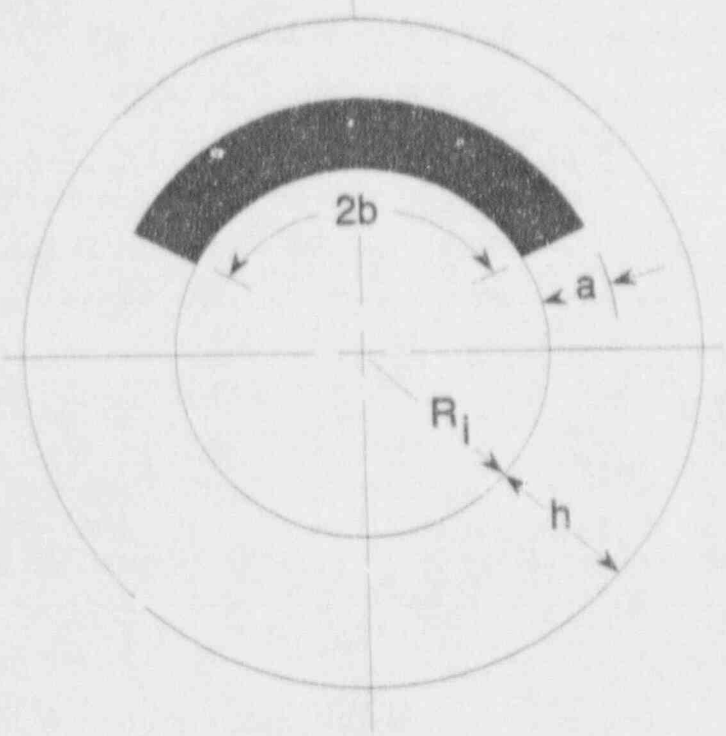
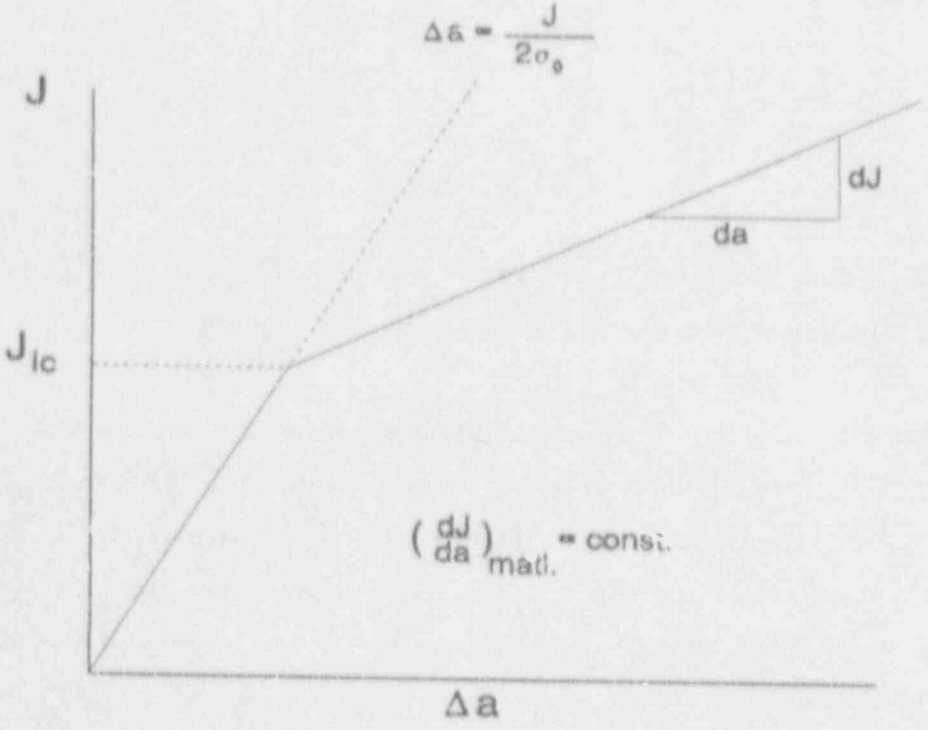


Figure 2-3. Geometry of part-circumferential interior surface crack used for calculation of critical crack area.



$$T_{mat} = \frac{E}{\sigma_{flo}^{2}} \left(\frac{dJ}{da}\right)_{matl.}$$

Figure 2-4. Schematic representation of J-integral R-curve.

The criteria for crack instability which results in a sudden and complete pipe severance, is

$$\begin{gathered} J_{\text{applied}} > J_{Ic} \\ \text{and} \\ T_{\text{applied}} > T_{\text{mat}} \end{gathered} \tag{2-25}$$

where

$$T = \frac{E}{\sigma_{\text{flo}}^2} \frac{dJ}{da} \tag{2-26}$$

J_{applied} is calculated by the interpolation scheme and fully plastic J values described in Sections 2.1.2 (part-through cracks) and 2.1.3 (through-wall cracks).

The discussion for the remainder of Section 2.3.2 draws heavily on Harris 83, which provides much additional detail, but is limited to $n = 1, 4$, or 5. The value of $(dJ/da)_{\text{applied}}$ can be influenced by load relaxation that occurs as the crack extends. The load controlled portion of the stresses (σ_{LC}) will not change with crack extension, but the displacement controlled portion (σ_{DC}) can relax as the crack grows. (See Section 5.1 for discussion of load controlled and displacement controlled stresses.)

For the case of complete circumferential crack in a pipe (where $\alpha = a/h$)

$$\begin{aligned} \frac{dJ}{da} &= \frac{d}{da}(J_e + J_p) = \frac{1}{h}\left(\frac{dJ_e}{d\alpha} + \frac{dJ_p}{d\alpha}\right) \\ &= \frac{1}{h}\left(\frac{dJ_e}{d\alpha_{ef}}\frac{d\alpha_{ef}}{d\alpha} + \frac{dJ_p}{d\alpha}\right) \\ &= \frac{1}{h}\left[\frac{d\alpha_{ef}}{d\alpha}\left(\left.\frac{\partial J_e}{\partial \alpha_{ef}}\right|_{\sigma} + \left.\frac{\partial J_e}{\partial \sigma}\right|_{\alpha_{ef}}\frac{d\sigma}{d\alpha_{ef}}\right)\right. \\ &\qquad \left. + \left.\frac{\partial J_p}{\partial \alpha}\right|_{\sigma} + \left.\frac{\partial J_p}{\partial \sigma}\right|_{\alpha}\frac{d\sigma}{d\alpha}\right] \end{aligned} \tag{2-27}$$

A set of analogous equations are easily obtained for the through-wall crack [replace α with β and h with $\pi(R_i+½h)$]. All of the derivatives are obtainable from the J-solution, except for $d\sigma/d\alpha$ (and $d\sigma/d\alpha_{ef}$). The derivatives are expressible in closed form except $\partial h_1/\partial\alpha$ (and $\partial h_1/\partial\alpha_{ef}$), which are evaluated numerically from the h_1 calibration functions.

The derivatives remaining to be evaluated are $d\sigma/d\alpha$ and $d\sigma/d\alpha_{ef}$. In principle, they can be evaluated from the h_1 function for elastic-plastic conditions by integration, or by use of the h_3 functions of Kumar 81. The approach taken here is to evaluate the derivative (stress changes) for linear elastic conditions and fully plastic conditions by integration of the h_1 functions. This will also provide the variation of σ with α (and α_{ef}), which is needed to account for stress relaxation in the calculation of J versus a.

Consider the completely elastic case, then

$$J_e = \frac{\sigma^2}{E}\, a\, \frac{h_1(\alpha, 1, \gamma)}{(1-\alpha)}\, \frac{3}{4} \left(\frac{2\gamma+1}{2\gamma+1+\alpha} \right)^2 \tag{2-28}$$

Noting that [Kumar 81, Kanninen 85, Anderson 91]

$$J_e = \frac{K^2(1-\nu^2)}{E} = \frac{\partial U}{\partial A_{cr}}$$

and A_{cr} = crack area ≈ $2\,\pi R_i a$, along with the result

$$U = \frac{1}{2} P\delta^2 = \frac{1}{2} CP^2$$

(where δ is the load point displacement, P is the load, and C is the compliance, $\delta = CP$) leads to the following ordinary differential equation

$$\frac{dC}{d\alpha} = \frac{3}{2}\frac{h}{EA_p}\frac{\alpha h_1(\alpha,1,\gamma)}{1-\alpha}\left(\frac{2\gamma+1}{2\gamma+1+\alpha}\right)^2 \tag{2-29}$$

where A_p is the cross-sectional area of the pipe ($\approx 2\pi R_i h$). This can be solved by separating variables and integrating

$$C(\alpha) - C(0) = \frac{3h}{2EA_p}\int_0^{\alpha}\frac{x h_1(x,1,\gamma)}{1-x}\left(\frac{2\gamma+1}{2\gamma+1+x}\right)^2 dx \tag{2-30}$$

C(0) is the compliance of the pipe where no crack is present. For a pipe of length 2L (with the crack location at the center)

$$\delta = \frac{PL}{A_p E} = C(0)P$$

$$C(0) = \frac{L}{A_p E}$$

Using the definition

$$I(\alpha) = \int_0^{\alpha}\frac{x h_1(x,1,\gamma)}{1-x}\left(\frac{2\gamma+1}{2\gamma+1+x}\right)^2 dx \tag{2-31}$$

in conjunction with the definition of C(0) and Equation 2-30 provides the following result

$$C(\alpha) = \frac{L}{EA_p}\left[1 + \frac{3}{2}\frac{h}{L}I(\alpha)\right] \tag{2-32}$$

The integral in Equation 2-31 can be evaluated in closed form when $h_1(\alpha, 1, \gamma)$ is curve fit by a second order polynomial. This function is not highly dependent on γ (R_i/h) and the following provides a good fit in the range of α from zero to one

$$h_1(\alpha, 1, \gamma) \sim \pi(1 + 1.461\alpha - 1.388\alpha^2) \tag{2-33}$$

I(α) is then expressible in closed form, with the results included in the PRAISE Code. The function C(α) is then completely defined.

The change in stress as the crack grows is evaluated from C(α). Consider the displacement, δ, at the end of the pipe to be fixed, and let σ_{DC} be the displacement controlled portion of the applied axial stress. Then

$$\delta = \text{constant} = C(\alpha)\ P(\alpha) = A_p\ \sigma_{DC}(\alpha)\ C(\alpha)$$

This leads to

$$\frac{\sigma_{DC}(\alpha)}{\sigma_{DC}(0)} = \left[1 + \frac{2h}{L}\ I(\alpha)\right]^{-1} \tag{2-34}$$

$\sigma_{DC}(0)$ is the displacement controlled portion of the stress in the absence of the crack, which is a portion of the piping stress that is input to PRAISE. Once $\sigma_{DC}(\alpha)$ is available from Equation 2-34, the derivative $\partial\sigma/\partial\alpha$ (and $\partial\sigma/\partial\alpha_{ef}$) are easily evaluated. Additionally, the stress for the calculation of J is defined [$\sigma(\alpha) = \sigma_{LC} + \sigma_{DC}(\alpha)$], and J and dJ/da can be obtained.

Equation 2-34 is for a linearly elastic body. Corresponding results for a fully plastic body can be obtained using the h_3 tabulated functions from Kumar 81. It is found that the stress reduction for a given crack size is less for $n = 1$ than for $n > 1$. Thus, it is conservative to use the $n = 1$ results in evaluation of J and T, and this is done in PRAISE. This circumvents the need to perform interpolation to determine the elastic-plastic compliance.

Similar procedures are used to evaluate the compliance of a pipe with a through-wall crack. This is needed to calculate J and dJ/da for a pipe in tension with a circumferential through-wall crack. This leads to the following expression

$$C(\beta) = \frac{L}{A_p E} + \frac{\pi}{hE} \int_0^{\beta} \frac{x(1-x)dx}{[1-x-\frac{2}{\pi}\sin^{-1}(\frac{1}{2}\sin \pi x)]^2} \tag{2-35}$$

where $h_1(\beta,1,\pi) \approx \pi$ has been used. This approximation agrees well with reported linear elastic results. The integral can be evaluated in closed form for β small or nearly unity. For intermediate values of β, the integral was evaluated numerically and curve fitted. The results are included in PRAISE. Equation 2-35 is used to obtain the stress reduction as the crack extends $[\sigma(\alpha) = \sigma_{LC} + \sigma_{DC}(\alpha)]$, which provides results needed to calculate J(a) and dJ(a)/da. These, in turn, are compared to J_{Ic} and T_{mat} to check on crack stability.

It remains to define the length of the pipe, L, relevant to the stress reductions in the particular weld being considered. The relevant value of L is not necessarily the length to the nearest vessel, steam generator, or support. Calculations of the effective length can be made by finite element analysis; such as reported in Cotter 82. However, the value of L generally has a minimal impact on the calculated failure probability, and a large value of L is conservative. As L approaches infinity, stress reductions go to zero, and the calculated value of J corresponds to all of the stress being load controlled. Hence, the use of a large value of L is suggested, without significant effects on the calculated weld failure probability.

2.3.3 Axial Cracks

The critical net-section stress criterion of Section 2.3.1, and the J-integral solution of Section 2.3.2 are both applicable to circumferential cracks. In some instances, axial cracks are of concern, such as the case of longitudinal welds in elbows. The stress intensity factor solutions for part-through cracks covered in Section 2.1.1 are suitable for axial cracks, when used in conjunction with the appropriate stresses. However, in order to apply PRAISE to axial cracks, a failure criterion is required. A suitable failure criterion for axial cracks is not contained in PRAISE, but has been included in earlier studies [Section 2.6 of Harris 82a].

The failure criterion used for axial cracks was based on Kiefner 73, which can be expressed as part-through cracks

$$\frac{\frac{a_c}{h}\,\frac{\sigma_{LC}}{\sigma_{flo}}}{\frac{a_c}{h}+\frac{\sigma_{LC}}{\sigma_{flo}}-1} = \left(1+1.255\beta_c^2-0.0135\beta_c^4\right)^{1/2} \qquad (2\text{-}36)$$

$$\text{where} \quad \beta_c = b_c/[h(R_i+\frac{1}{2}h)]$$

through-wall cracks

$$\frac{\sigma_{LC}}{\sigma_{flo}} = \left(1+1.255\beta_c^2-0.0135\beta_c^4\right)^{1/2} \qquad (2\text{-}37)$$

If a crack is deeper than given by Equation 2-36 then it can unstably run through the wall. If it is then longer than given by Equation 2-37, it can grow unstably in the axial direction resulting in a large slot failure.

Results in Section 5.3 of Harris 82a indicate that the leak probabilities due to axial cracks are lower than nearby circumferential cracks. In the case of double-ended-pipe break (DEPB) and large slot failure, both have a very low probability, but the slot failures can have a higher probability.

The failure criteria in PRAISE must be changed by the user to use the criteria for axial cracks expressed in Equations 2-36 and 2-37.

2.3.4 Failure Due to Vibratory Stresses

Vibratory stresses can be set up in reactor piping. They result in many cycles being imposed over a relatively small time span. Consequently, failure is considered to occur if fatigue threshold conditions are exceeded due to vibratory stresses. As the crack grows through wall, crack growth in the length direction is taken equal to that in the depth direction ($\Delta b = \Delta a$). The stability of a through-wall crack of length equal to the interior surface length at break-through is then checked to see if a leak or DEPB occurs.

2.3.5 Failure of the Uncracked Pipe

Probability of failure of an uncracked pipe is estimated by calculating the probability of the load-controlled stress exceeding the ultimate tensile strength of the pipe material. The ultimate tensile strength is assumed to be normally distributed; the mean and the standard deviation are supplied by the user.

2.4 Crack Size Distribution

The initial crack size has a very strong influence on the (deterministic) lifetime of a component. The PRAISE Code considers only cracks that start out as semi-elliptical interior surface cracks, generally circumferentially oriented. Consequently, two variables are required to define the crack size, a and b.* In addition to the size distribution of cracks (given the presence of a crack) the probability of having a crack present is also required. Hence, the initial crack distribution is composed of three points

- crack depth distribution
- crack aspect ratio distribution
- crack existence frequencies

The PRAISE Code allows the user to consider a wide range of crack depth and aspect ratio distributions, but default distributions are provided. PRAISE generates the probability of failure (leak or DEPB) for a given weld as a function of time. The effect of crack existence probability is treated by the user outside the PRAISE Code.

2.4.1 Crack Depth Distribution

PRAISE is set up for considering either exponential or lognormal crack depth distribution, with the parameter of the distribution under control of the user. Section 2.3.1 of Harris 81 reviews the crack depth data available at that time. Additional data have become available since 1981, such as that reported in Wellein 81, Bruckner 83, and Dufresne 85. The most common depth distribution used in PRAISE runs is the Marshall distribution [Marshall 76],

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* In some cases, such as multiple initiation sites in stress corrosion cracking, the position of the crack around the circumference of a girth weld is also required (see Section 3.1.3).

which is exponential with a mean of 0.246 inch. The corresponding probability density function (pdf) is

$$p(a) = \frac{1}{\mu} e^{-a/\mu} \qquad 0 \le a \le \infty \qquad (2\text{-}38)$$

$$\mu = 0.246 \text{ inch}$$

This distribution was originally suggested for reactor pressure vessel welds, which are quite thick. The use of this distribution for thick pipes (3 to 4 inch wall thickness) is reasonable, but as the pipe wall gets thinner, a mean crack depth nearly equal to the wall thickness becomes questionable, and changes to the depth distribution are in order. Such possible changes include altering the distribution type and/or mean crack depth. A minimal change is to eliminate the possibility of having a crack deeper than the wall thickness. This can be accomplished by renormalizing an exponential distribution

$$p(a) = \frac{e^{-a/\mu}}{\mu(1 - e^{-h/\mu})} \qquad 0 \le a \le h \qquad (2\text{-}39)$$

This normalization is taken care of in PRAISE by sampling from the conventional exponential distribution (Equation 2-38), and discarding the sample if $a > h$.

PRAISE can also consider a lognormal depth distribution, whose density function is

$$p(a) = \frac{1}{\lambda a (2\pi)^{1/2}} \exp\left\{ -\left[\frac{\ln(a/a_{50})}{\lambda 2^{1/2}} \right]^{1/2} \right\} \qquad (2\text{-}40)$$

where PRAISE accepts as inputs the value of

a_{50} = median crack size
λ = shape parameter

The parameter λ is equal to the standard deviation of ln a.

2.4.2 Aspect Ratio Distribution

Section 2.4.1 discussed the distribution of the crack depth. The surface length is also required to specify the initial size of the semi-elliptical interior surface cracks considered by PRAISE. At the time the original PRAISE was developed, there was no information on surface length that also included depth data. Consequently, it was assumed that the depth and aspect ratio are independent, and PRAISE provides the capability of considering either an exponentially or lognormally distributed aspect ratio. In both cases, the distribution is modified to preclude the possibility of having $b < a$. Let $\beta = b/a$, then the shifted exponential pdf of β is given by

$$p(\beta) = \begin{cases} 0 & \beta < 1 \\ \lambda\, e^{-\lambda(\beta-1)} & \beta > 1 \end{cases} \tag{2-41}$$

The only required input is λ. For a shifted lognormal, the probability density function of β is given by

$$p(\beta) = \begin{cases} 0 & \beta < 1 \\ \dfrac{2\exp\left\{-\left[\ln(\beta/\beta_m)/(\lambda 2^{1/2})\right]^2\right\}}{\lambda\beta(2\pi)^{1/2}\,\mathrm{erfc}\left\{\left[\ln(1/\beta_m)/(\lambda 2)^{1/2}\right]\right\}} & \end{cases} \tag{2-42}$$

where β_m and λ are required inputs (erfc x is the complementary error function [Abramowitz 64]).

Values of λ and β_m in the above equations based on data are difficult to obtain. They were impossible to obtain from data at the time PRAISE was originally developed. Hence, estimates were made based on the proportion of cracks with $2b/a > 10$ (i.e., $\beta > 5$). Denoting this proportion as ρ, the value of λ in Equation 2-41 is easily shown to be

$$\lambda = \frac{4}{\ln(1/\rho)} \qquad \text{(exponential } \beta\text{)} \tag{2-43}$$

In the case of a lognormal β, with no cracks having $\beta < 1$, an additional requirement of a mode of the density function at $\beta = 1$ results in the following two equations for β_m and λ in terms of ρ

$$\beta_m e^{-\lambda^2} = 1$$

$$\rho \operatorname{erfc}\left[\frac{\ln(1/\beta_m)}{\lambda 2^{1/2}}\right] = \operatorname{erfc}\left[\frac{\ln(5/\beta_m)}{\lambda 2^{1/2}}\right] \tag{2-44}$$

These nonlinear equations can be solved for β_m and λ once ρ is specified. Once β_m and λ are known, the mean, median, and standard deviation of β are determinable from the density function, as also is the cumulative distribution of β. Values of the parameters and selected results are included in Table 2-1 for values of ρ of 10^{-2} and 10^{-4} (1 in 100 and 1 in 10,000 cracks having 2b/a > 10). Figure 2-5 plots the complementary cumulative distribution of β for the two distribution types and the two values of ρ. Once the density function and its parameters are specified, the distribution of crack area and crack length, b, can be derived. Such results are presented in Section 2.3.3 of Harris 81.

Table 2-1
VARIOUS VALUES OF PARAMETERS FOR LOGNORMAL β FOR SELECTED VALUES OF ρ

ρ =	10^{-2}	10^{-4}
λ	0.5382	0.3830
β_m	1.336	1.158
β_{50}	1.638	1.379
$\bar{\beta}$	1.883	1.494
β_{sd}	0.8570	0.4371
c.o.v.	0.46	0.29

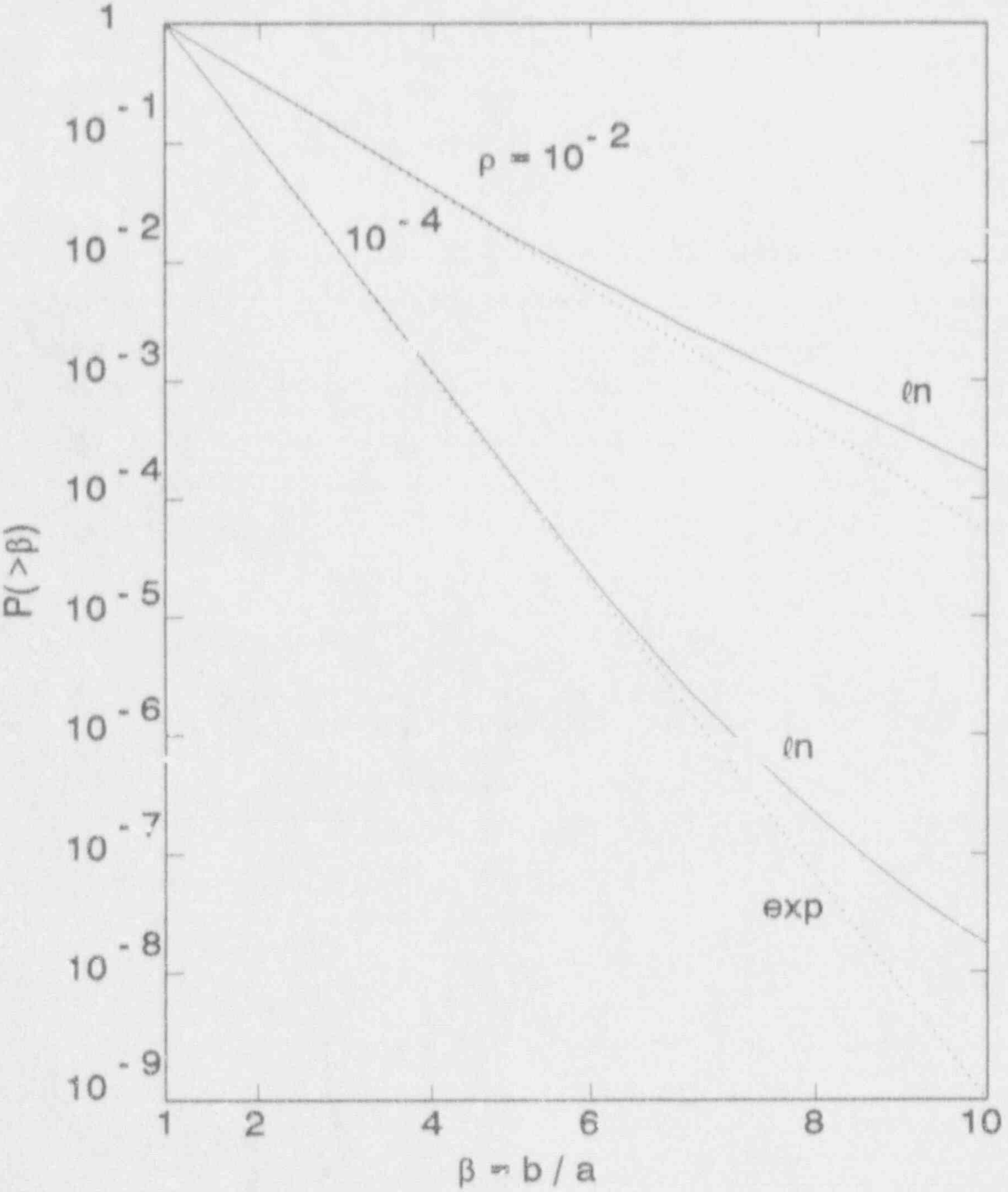


Figure 2-5. Various complementary cumulative marginal distributions of crack aspect ratio.

It has been found that the calculated pipe weld failure probability is not strongly dependent on the aspect ratio distribution type or value of ρ [Section 4.3.3 of Harris 81]. Such probabilities are much more dependent on the crack depth distribution. A lognormal distribution of β with $\rho = 10^{-2}$ was used as the baseline in the original PRAISE development [Harris 81].

The assumption of independent depth and aspect ratio has been adopted by others. This assumption was adopted because of the total lack of data on both depth and length for cracks at that time. Some such data has become available during the intervening years [Wellein 81, Dufresne 85] which could be used to evaluate the assumption and perhaps alter the treatment of surface length. The data of Dufresne 85 suggests that a and b/a are not independent.

2.4.3 Crack Existence Frequencies

The PRAISE Code considers piping weld failures to occur due to either the initiation and growth of stress corrosion cracks and/or the growth of pre-existing defects due to fatigue and/or stress corrosion cracking. In cases where only crack initiation is considered, multiple cracks within a weld are treated (see Section 3.3). In cases where only pre-existing cracks are considered, the PRAISE Code calculates the probability of a weld failure given that one crack exists. The probability of one crack existing must be accounted for outside of PRAISE. (In addition, the probability of failure in a piping system must be accounted for outside of PRAISE by combining PRAISE results for all the welds in the piping system, see Section 7.4.) PRAISE is generally applied to field welds in pipes, and shop welds are not considered. This is because shop welds are performed under much better conditions than field welds and are usually given a post-well stress relief. Field welds also tend to be located at high stress points (terminal ends, nozzles, elbows, etc.).

As mentioned earlier, attention is focussed on cracks located on the interior surface of the pipe. Even though surface cracks are considered, the probability of a crack being present is taken to be controlled by the weld volume, but all cracks present are conservatively assumed to be on the interior surface. Other parameters, such as length of weld or surface area of weld and heat-affected zone could have been considered. Which of these are taken will not have a large affect on the results, unless large variations in thickness are encountered.

The weld volume, V, will be taken to also include the heat-affected zone which will be taken to be two wall thicknesses wide. The weld volume V is then equal to

$$V = \pi D_i h(2h) = 2\pi D_i h^2 \tag{2-45}$$

The rate of cracks per unit volume will be denoted as p_v^*, and the number of cracks in a body of volume V will be taken to be Poisson distributed. There are theoretical reasons for making such an assumption (see for instance [Mood 50, Page 59]). The following expression for the probability of having N cracks in a body of volume V is therefore applicable [Hahn 67].

$$P(N) = \left(Vp_v^*\right)^N \frac{e^{-Vp_v^*}}{N!} \tag{2-46}$$

The probability of having at least one crack in a body of volume V is one minus the probability of having no cracks, which is given by the following expression

probability of having a crack in V:

$$\equiv p^* = 1 - e^{-Vp_v^*} \sim Vp_v^* \tag{2-47}$$

The probability of having exactly 1 crack is:

$$P(1) = Vp_v^* \, e^{-Vp_v^*} \sim Vp_v^* \tag{2-48}$$

The above approximations hold if $Vp_v^* \ll 1$. This shows that the probability of having a crack is approximately equal to the probability of having exactly 1 crack, and that p^* varies linearly with p_v^* (for $Vp_v^* \ll 1$). This also means that the probability of having more than one crack is small.

The remaining part of the problem is to estimate the parameter p_v^*. The data available in 1981 is reviewed in Section 2.3.4 of Harris 81. A wide range of values of p_v^* are included in the data reviewed, and a value of $p_v^* = 10^{-4}/\text{in}^3$ was suggested. This value was used in the baseline calculation in Harris 81. The value of p_v has at most a linear influence on the calculated failure probabilities.

Much additional data on weld defect frequencies has become available in recent years, which could be used to improve estimates of p_v^* (see for example [Dufresne 85]).

2.4.4 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. The original PRAISE Code considered only the former cause of failure. The probabilistic treatment of crack initiation in Section 3 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

$$\begin{aligned} P(t_f < t) &= (\text{prob. of no initial crack}) \times [P(t_f < t) | \text{ no initial crack}] \\ &+ (\text{prob. of 1 initial crack}) \times [P(t_f < t) | \text{ 1 initial crack}] \\ &+ (\text{prob. of 2 initial cracks} \times [P(t_f < t) | \text{ 2 initial cracks}] \\ &+ \ldots . \end{aligned} \tag{2-49}$$

As discussed in Section 2.4.3, the probability of having more than 1 initial crack is small. Therefore, using p* as defined in Equation 2-47, omitting terms with more than one crack, and noting that the probability of no initial crack is closely approximated by (1-p*), Equation 2-49 can be rewritten as

$$P(t_f < t) = (1-p^*)\,[P(t_f < t)|\text{ no initial crack}] + p^*[P(t_f < t)|\text{ 1 initial crack}] \tag{2-50}$$

The term $[P(t_f < t)|1$ initial crack$]$ is generated in PRAISE for the case of pre-existing cracks with no possibly initiated crack contributing significantly to the failure probability. The term $[P(t_f < t)|$no initial crack$]$ is generated directly by PRAISE considering initiating cracks in SCC. Hence, PRAISE is capable of generating results for cases in which either pre-existing or initiating (SCC) cracks are significant contributors to failure. In actuality, PRAISE does not perform computations based on Equation 2-50. Separate runs for pre-existing and initiating cracks with post-processing based on Equation 2-50 is suggested.

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 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). See Sample Problem 9.

3. INITIATION AND EARLY GROWTH OF STRESS CORROSION CRACKS

Crack initiation in large diameter reactor coolant piping has historically been limited to austenitic stainless steel in boiling water reactors (BWRs). The initiation and early growth of such cracks is not amenable to analysis but has been approached empirically. A statistical treatment of the empirical observations has been used in PRAISE to estimate the probability of crack initiation. The early growth of initiated cracks is treated from the same observations. Once the crack is large enough to treat by fracture mechanics, such procedures as described in Sections 2.2.2 and 4.1 are employed.

3.1 Time to Initiation

As depicted in Figure 3-1, three conditions are required for stress corrosion crack initiation in austenitic piping materials.

- <u>Sensitization:</u> This is a microstructural affect due to the material spending too much time within a critical temperature range, which can occur due to welding.
- <u>Stress:</u> Applied loading and/or residual stresses are required. Welding can produce considerable residual stress. This, along with sensitization at welds, leads to stress corrosion cracks being observed primarily at welds.
- <u>Environment:</u> An adverse environment is also required. The oxygen levels in BWR water are often sufficient to provide the adverse environment.

3.1.1 <u>Constant Conditions</u>

The time to stress corrosion crack initiation under constant load or strain rate conditions can be empirically related to operating conditions by use of laboratory tests and field observations [Eason 82, as described in Section 2.1 of Harris 86]. Most of the available test data is actually for time to failure, rather than time to initiation of a crack. In order to make use of the much more voluminous time to failure data, initiation is assumed to coincide with failure, for the purposes of the remainder of Section 3.1.1.

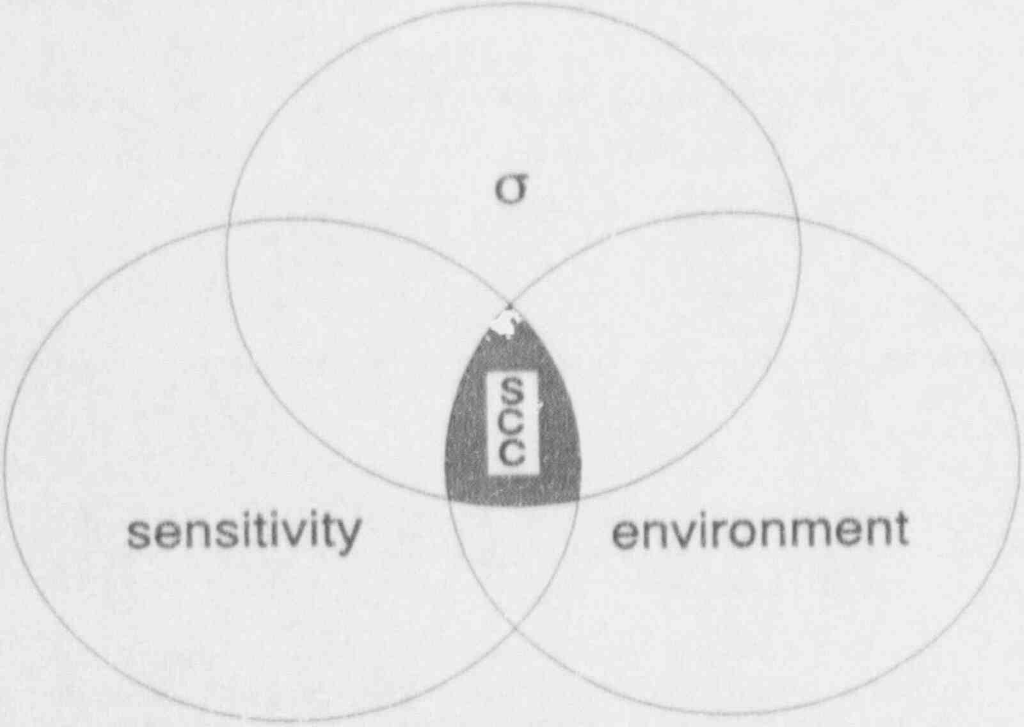


Figure 3-1. Three conditions required for stress corrosion crack initiation in austenitic piping material.

Since three simultaneous conditions are required for initiation of stress corrosion cracks, a damage parameter that includes three multiplicative terms is postulated

$$D = f_1(\text{material})\ f_2(\text{environment})\ f_3(\text{loading}) \tag{3-1}$$

The time to initiation is considered to be a random variable whose distribution depends on D. The above functions are assumed to have the following forms:

$$f_1 = C_1(P\,a)^{C_2} \tag{3-2}$$

where Pa is a measure of the degree of sensitization known as the EPR, which has units of C/cm^2,

$$f_2 = O_2^{C_3}\ \exp\left[C_4/(T+273)\right]\ \log(C_5\gamma^{C_6}) \tag{3-3}$$

where O_2 is the oxygen concentration in parts per million, T is temperature in degrees centigrade, and γ is the water conductivity in $\mu s/cm$. The loading term, f_3, is considered to be a function of strain rate if the applied load is changing, or stress, if the applied load is constant

$$f_{3_\epsilon} = \dot{\epsilon}^{C_7} \tag{3-4a}$$

where ϵ is the strain rate (sec^{-1}),

$$f_{3_\sigma} = \left(C_8\sigma^{C_9}\right)^{C_7} \tag{3-4b}$$

where σ = stress in ksi. In the above expression, C_i (i = 1 to 9) are constants that are evaluated by curve fitting procedures to laboratory and field data.

For convenience, separate damage parameters (as expressed by Equation 3-1) are considered for changing load and constant load conditions as follows:

$$D_\epsilon = f_1\, f_2\, f_{3\epsilon} \qquad \text{(changing load)} \tag{3-5a}$$

$$D_\sigma = f_1\, f_2\, f_{3\sigma} \qquad \text{(constant load)} \tag{3-5b}$$

The constants C_i (i = 1 to 9) were evaluated by least-squares procedures, as described in Section 2.1 of Harris 86, for 304 and 316 NG stainless steel. The value of the constants are summarized in Table 3-1. Once the values of C_i are defined, the damage parameters are known for a given set of conditions.

Table 3-1
NUMERICAL VALUES OF CONSTANTS C_i

	304	316 NG
C_1	23.0	1.879
C_2	0.51	0.0 (1)
C_3	0.18	0.24
C_4	-1123	-1123 (2)
C_5	8.7096	4.0
C_6	0.35	0.35
C_7	0.55	0.49
C_8	2.21×10^{-15}	2.21×10^{-15} (3)
C_9	6.0	6.0 (3)

(1) Taken to be zero because degree of sensitization for 316 NG is very low.
(2) C_4 for 316 NG assumed equal to C_4 for 304.
(3) Assumed same as 304 due to lack of data.

For a given set of conditions, i.e., a given value of D (D_σ or D_ϵ), the time to crack initiation exhibits considerable scatter. The available data for initiation time (or time to failure if initiation time was not available) was plotted as a function of D_σ and D_ϵ on a log-log scale. This initiation time for a given D was assumed to be lognormally distributed, and the mean and standard deviation of log t_i was evaluated by standard maximum likelihood estimations. This allows both failure and non-failure data to be used. This provides the mean and standard deviation of log t_I as a function of D_σ and D_ϵ. In all cases, the following functional form was found to provide a good representation of the data for the mean.

$$\text{mean value of } \log t_I = B_0 + B_1 \log(D) \tag{3-6}$$

(where D is D_σ or D_ϵ). The values to B_0 and B_1 are summarized in Table 3-2.

Table 3-2
VALUES OF CONSTANTS IN EQUATION 3-6
FOR MEAN OF log t_I

	Changing Load		**Constant Load**	
	B_0	**B_1**	**B_0**	**B_1**
304	10^{-5}	-0.108	-3.10	-4.21
316 NG	-0.65	-0.76	-7.72 (1)	-5.39 (1)

(1) Not based on data. See Page 20 of Harris 86 for basis of estimate.

The plotted data appear to be symmetrically distributed about the mean (on a log scale), which provides justification of the assumption of a lognormally distributed t_I. The following expression was found to provide a good fit to the standard deviation as a function of the damage parameter

$$\text{std. deviation of } \log t_I = B_2 + B_3 \log(D) \tag{3-7}$$

where D is D_σ or D_ϵ. The values of B_2 and B_3 are summarized in Table 3-3.

The above expressions for the mean and standard deviation of log t_I, combined with the assumption of a lognormal distribution, defines the statistical distribution of time to initiation of a stress corrosion crack under either constant load or constant strain rate conditions. However, reactor operating conditions change with time, being varying strains during start up and constant stress during steady operation. The following section discusses the procedures for estimating time to initiation under varying conditions.

Table 3-3
VALUE OF CONSTANTS IN EQUATION 3-8 FOR STANDARD DEVIATION OF log t_I

	Changing Load			Constant Load	
	Range of log D_ϵ	B_2	B_3	B_2	B_3
304	All	10^{-5}	-0.108	0.3081	0
316 NG	Less than -3.96	0.32744	0	(1)	(1)
	-3.96 to -3.32	-0.7461	-0.2731	(1)	(1)
	greater than -3.32	0.16056	0	(1)	(1)

(1) Assumed same as changing load due to lack of data.

3.1.2 Varying Conditions

Section 3.1.1 provided the distribution of time to initiation of a stress corrosion crack under either constant load or constant strain rate (changing load) conditions. Actual plants are operated under conditions that vary with time, and a procedure for accounting for this is described in Section 2.1.3 of Harris 86. Briefly, the procedure consists of generating a cumulative distribution of initiation time for each reactor condition to be considered, and them combining them by the method shown pictorially in Figure 3-2. The figure depicts two reactor conditions or states, A and B.

3.1.3 Multiple Cracks and Size at Initiation

Sections 3.1.1 and 3.1.2 describe the procedures for estimating the statistical distribution of time to initiation of a stress corrosion crack. Since the bulk of the data used is for laboratory specimens, the information is applicable to laboratory sized pieces of material, say about 2 inches long. Consequently, a given weld in a reactor pipe is considered to be composed of 2-inch segments of sufficient number to add up to the length of the weld. The initiation time for each segment is assumed to be independent, and the stress within each segment is assumed to be constant. The stress can vary from segment to segment, so angular variations of bending and residual stress can be accounted for [Section 2.1.5 of Harris 86].

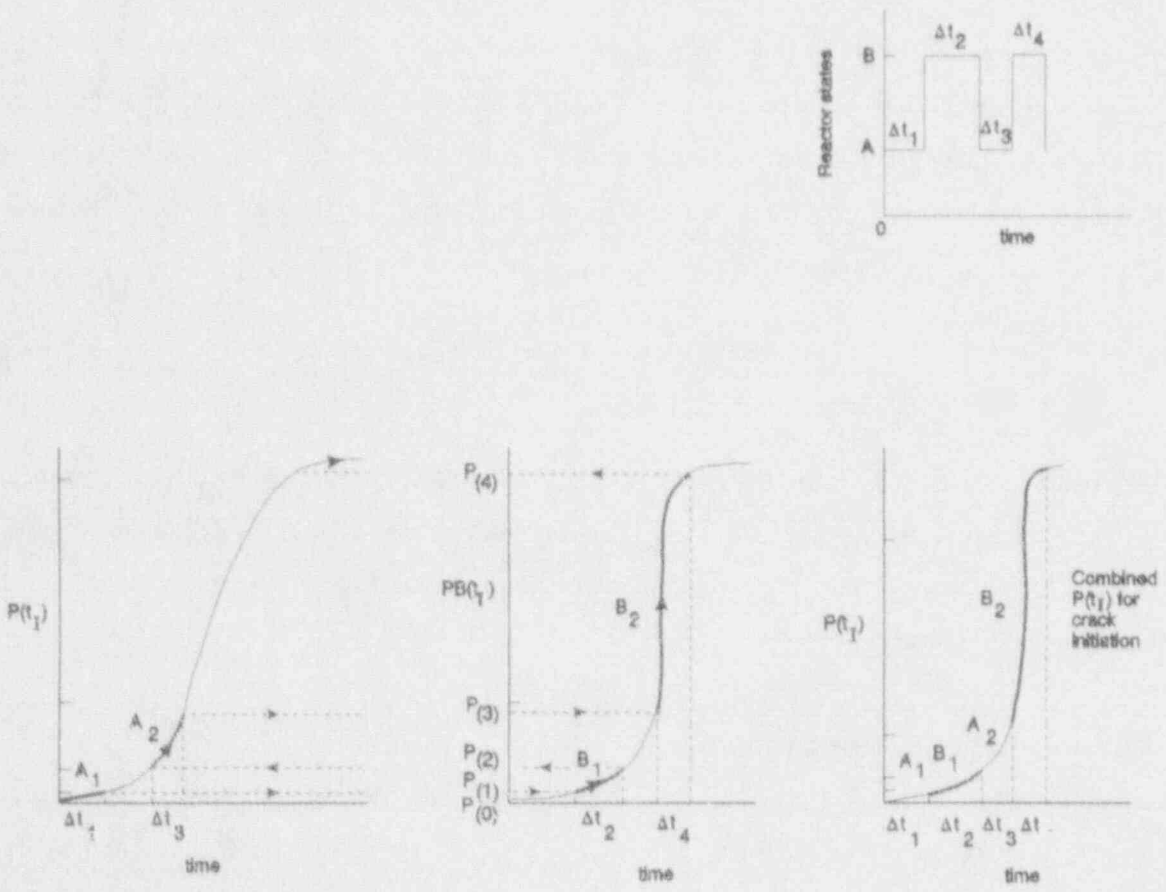


Figure 3-2. Schematic representation of combining reactor states to obtain overall probability of crack initiation.

The surface length of initiated cracks ($\ell = 2b$) is assumed to be lognormally distributed with a median value of 1/8 inch. The second parameter of the lognormal distribution follows from the assumption that $P(\ell > 1 \text{ inch}) = 10^{-2}$, which corresponds to the second parameter of the lognormal distribution of 0.85 (= std. dev. of ln b). The depth of initiating cracks is taken to be 10^{-3} inch. Sensitivity studies have shown that calculated pipe failure probabilities are only weakly dependent on the assumed distribution of surface length.

3.1.4 Distribution of Degrees of Sensitization

Data on the degree of sensitization of as-welded 304 stainless steel piping was collected from the literature and analyzed to estimate the statistical distribution of this important variable [Section 2.1.2 of Harris 86]. The data was found to be approximated Weibull distributed with the following cumulative distribution

$$P(Pa < x) = 1 - e^{-(x/b)^{c}} \qquad (3\text{-}8)$$

$$b = 17.3 \text{ C/cm}^{2}, \quad c = 1.05$$

The data used in determination of this distribution was most likely gathered from conditions with high degrees of sensitization, because it was mostly drawn from situations where cracks were observed. Consequently, Equation 3-8 is believed to be a conservative estimate of the sensitization distribution.

3.2 Growth Rate Following Initiation

Once a crack has initiated, its early growth may or may not be explainable by fracture mechanics. It is usually found that small cracks do not grow at a rate that correlates to fracture mechanics parameters, such as the stress intensity factor. Once the crack has grown to a larger size, fracture mechanics generally can be used to predict growth rate. Conditions for transition to fracture mechanics controlled crack growth are discussed in Section 4.1.2. Consequently, the growth of stress corrosion cracks is considered to consist of two parts: (i) an early phase treated by means analogous to those used for initiation, and (ii) a later phase treated by fracture mechanics principles. An initiated crack is assumed to grow at a constant velocity until conditions are appropriate for treating crack growth by fracture mechanics. The fracture mechanics controlled growth rates are presented in Section 4.1.1.

The same data that was used for initiation time in Section 3.1 is employed for crack velocity at initiation. The apparent crack growth velocity ($\dot{a}$) is calculated by dividing the depth of the intergranular crack of the failed specimen by time to failure, and correlating the results with the damage parameters of Section 3.1. In all cases, considerable scatter was observed, with the results being representable by a lognormal distribution of $\dot{a}$ for a given D, with the mean of log $\dot{a}$ varying linearly with log D, and the standard deviation of $\dot{a}$ being independent of D. This is represented by the following expression

$$\log(\dot{a}) = F + G \log(D) \tag{3-9}$$

where D is D_σ (or D_ϵ), G is a constant, and F is normally distributed. Values of G and the mean and standard deviation of F are summarized in Table 3-4. Crack growth rates are in inches per day.

3.3 Multiple Cracks and Linking

As mentioned in Section 3.1.3, the time to initiation, which is a random variable, is applicable to a laboratory sized length of sensitized material. Consequently, each weld is broken up into 2 inch long segments, and the initiation time is independent for each segment. The means that, with a certain probability, multiple cracks can be present in a given weld. These cracks can coalesce as they grow. Only inside surface cracks are considered, because stress corrosion cracks must be exposed to the environment inside the pipe in order to initiate. Figure 3-3 summarizes the crack linking criteria, which are based on Section XI, Article IWA-3000 of the ASME Boiler and Pressure Vessel Code (as it existed in 1986).

Table 3-4
VALUE OF CONSTANTS IN EQUATION 3-9 FOR EARLY GROWTH OF INITIATED STRESS CORROSION CRACKS

	Changing Load			Constant Load		
	F_ϵ		G_ϵ	F_σ		G_σ
	Mean	Std. Dev.		Mean	Std. Dev.	
304	0.4587	0.3578	0.7044	2.551	0.4269	1.3447
316 NG	-0.02266	0.2052	0.63136	(1)	(1)	(1)

(1) Assumed same as changing load due to lack of data. F_σ and F_ϵ are normally distributed. Crack growth rates are in inches per day.

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

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

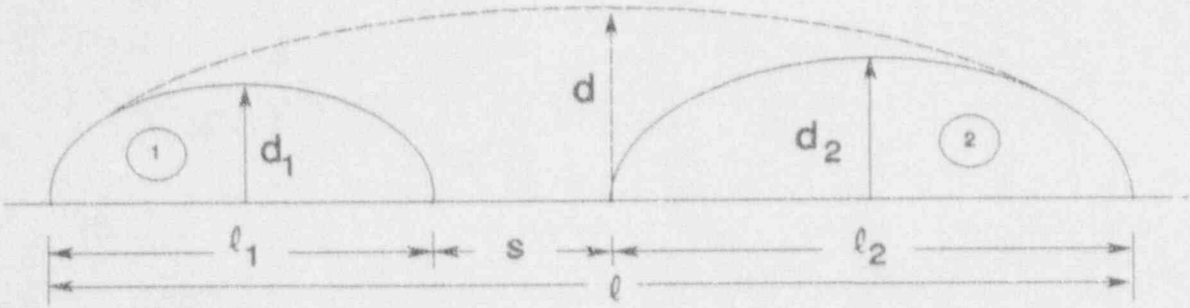


Figure 3-3. Schematic representation of the crack link-up procedure.

4. CRACK GROWTH RATES

The subcritical growth rate of cracks is discussed in this section. The growth of stress corrosion cracks once they are controlled by fracture mechanics is discussed in Section 4.1.1. Section 3.2 discusses stress corrosion crack growth rates following initiation but prior to being treatable by fracture mechanics. Section 4.1.2 discusses criteria for switching from initiated to fracture mechanics cracks. Fatigue crack growth is discussed in Section 4.2.

4.1 Stress Corrosion

Stress corrosion crack growth rates and criteria for switching to fracture mechanics related crack growth are described.

4.1.1 Growth Rate

Data on stress corrosion crack growth rates in fracture mechanics specimens of 304 and 316 NG tested under BWR environmental conditions was gathered and reviewed in Section 2.2.2 of Harris 86. Preliminary analysis of the data indicated a linear variation between log $\dot{a}$ and K. The dependence of $\dot{a}$ on environment was assumed to be described by the environmental term, f_2, in the treatment of stress corrosion crack initiation (see Equation 3-4 of Section 3.1.1) with the same set of constants. This led to the following K-related damage parameter

$$D_K = C_{12} \log[f_2(\text{env.})] + C_{13} K \tag{4-1}$$

The relation between $\dot{a}$ and D_K was then assumed

$$\log \dot{a} = C_{14} + C_{15} D_K \tag{4-2}$$

Curve fits were then made to determine C_{12}, C_{13}, C_{14}, and C_{15}. To describe the scatter in the data, C_{14} was taken to be a random variable, and a value of C_{14} was calculated for every data point using the value of C_{12}, C_{13}, and C_{15} from the curve fit. C_{14} was found to be representable by a normal distribution. Table 4-1 summarizes the results of this procedure.

Table 4-1
VALUES OF CONSTANTS IN EQUATIONS 4-1 AND 4-2 FOR FRACTURE MECHANICS STRESS CORROSION CRACK GROWTH RATE

	304	316 NG
C_{12}	0.8192	0.8192 (2)
C_{13}	0.03621	0.03621 (2)
C_{14} (1)		
Mean	- 3.1671	- 4.006
Std. Dev.	0.7260	0.5792
C_{15}	1.7935	1.19
Threshold ΔK_0	- 0.85	- 0.89

(1) C_{14} normally distributed.
(2) Assumed same as 304.

K in ksi-in$^{1/2}$
$\dot{a}$ in inches per day
Other units as in Section 3.1

A threshold value of D_K was selected. Otherwise there could be a finite $\dot{a}$ even where K is equal to zero. The crack growth rate data did not show a dependence on the degree of sensitization, so the f_1 term of Equation 3-1 was omitted.

4.1.2 Criteria for Transition to Fracture Mechanics

Stress corrosion cracks are considered to grow at an initiated velocity, as described in Section 3.2, or a fracture mechanics controlled velocity, as described in Section 4.1.1. The following procedure is used to govern the transition from initiation to fracture mechanics crack growth rate:

1. Pre-existing cracks always grow at fracture mechanics velocity.
2. Initiation velocity is always assigned to initiated cracks.

3. At any given time, if the fracture mechanics velocity for a crack is higher than the initiation velocity, that particular crack grows at fracture mechanics velocity thereafter.

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 (degree of freedom) is negative, the crack will not grow (in the direction corresponding to that degree of freedom).

The growth of semi-elliptical stress corrosion cracks is treated with multiple degrees of freedom, as described in Section 2.2.2.

4.2 Fatigue

The PRAISE Code has built in features for analysis of fatigue crack growth in the two most commonly used pipe materials in the primary piping of LWRs, ferritic and austenitic steels.

4.2.1 Austenitic Materials

The original PRAISE Code was constructed to analyze fatigue crack growth in austenitic stainless steel primary piping in PWRs. Section 2.5.1 of Harris 81 reviews the approach, which is described below. The available data (in 1981) on fatigue crack growth in 304 stainless steel was reviewed, including the influence of temperature, environment (air or water), and mean load affects. Within a scatter band of about one order of magnitude on crack growth rate, it was found that the data could be represented by the following relation

$$\frac{da}{dN} = C\left[\frac{\Delta K}{(1-R)^{1/2}}\right]^4 \tag{4-3}$$

where $\Delta K = K_{max}-K_{min}$

$R = K_{min}/K_{max}$

The scatter in the data is represented by a lognormal value of C with a median of 9.14×10^{-12} and standard deviation of 2.20×10^{-11} (where da/dN is inches per cycle and K is ksi-in$^{1/2}$). This relation is applicable to weld metal, base metal, and heat-affected zone, and is suitable for air or water.

A threshold value for fatigue crack growth is also applied, which provides for no crack growth if $\Delta\bar{K}_I$ is less than ΔK_{th}, where ΔK_{th} is given by [Section 2.4.2 of Harris 82a]

$$\Delta K_{th} = \begin{cases} 4.6\,(1-R)^{1/2} & R < R^* \\ 4.6\,(1-R^*) & R > R^* \end{cases} \tag{4-4}$$

$$R^* = 0.9$$

Much additional data on fatigue crack growth in austenitic stainless steels has become available since the original PRAISE development that provides finer discrimination between various environments and material states (see [James 85] for example).

4.2.2 Ferritic Materials

The original PRAISE Code considered only austenitic piping materials. It was later expanded to include ferritic piping materials [LLNL 84b, Vol. 2, Section 4.5], with the following representation of the fatigue crack growth rate being employed

$R \le 0.25$

$$\frac{da}{dN} = \begin{cases} 1.02\times10^{-12}\,\Delta K^{5.95}\,Q & \Delta K < 19 \\ 1.01\times10^{-7}\,\Delta K^{1.95}\,Q & \Delta K \ge 19 \end{cases}$$

$$Q = \exp(-0.408 + 0.542 C_F)$$

$0.25 < R < 0.65$

$$\frac{da}{dN} = \begin{cases} f_1 \, \Delta K^{5.95} \, Q & \Delta K \le f_3 \\ f_2 \, \Delta K^{1.95} \, Q & \Delta K > f_3 \end{cases}$$

$$\begin{aligned} f_1 &= 1.02\times10^{-12} \, (26.9R - 5.725) \\ f_2 &= 1.01\times10^{-7} \, (3.75R + 0.06) \\ f_3 &= (f_2/f_1)^{1/4} \\ Q &= \exp[0.1025R - 0.433625 + (0.6875R + 0.370125)C_F] \end{aligned} \tag{4-5}$$

$R \ge 0.65$

$$\frac{da}{dN} = \begin{cases} 1.20\times10^{-11} \, \Delta K^{5.95} \, Q & \Delta K < 12 \\ 2.52\times10^{-7} \, \Delta K^{1.95} \, Q & \Delta K \ge 12 \end{cases}$$

$$Q = \exp(-0.367 + 0.817C_F)$$

In the above expressions, C_F is normally distributed with a mean of 0 and standard deviation of unity.

The above equations provide a probabilistic representation of the fatigue growth relation for ferritic materials in water contained in Appendix A of the ASME Boiler and Pressure Vessel Code.

5. STRESSES

Stresses in the piping are required as inputs to the fracture mechanics calculations performed within the PRAISE Code. Thus, PRAISE does not perform stress analysis. The stresses are generally quite simplified. With several notable exceptions, the stresses on the crack plane (in the absence of the crack) are assumed to be uniform, and are generally based on the results of an elastic finite element piping analysis -- such as performed during design of the reactor.

5.1 Global Service Stresses

Global stresses are considered to be due to pressure, deadweight, and restraint of thermal expansion. Deadweight and pressure are considered to be load controlled, and restraint of thermal expansion is considered to be displacement controlled.

5.1.1 Girth Welds

PRAISE analyses usually concentrate on girth welds and axial stresses in the pipe are considered. This is because axial stresses are usually the largest and are oriented in a manner to most influence crack growth in circumferential girth butt welds. (Field welds are usually of this type.) In most cases, torsional components of the stress are negligible. In cases where they are not, they can be combined with the axial stress to provide the maximum principal stress, which is then taken to be oriented axially in the pipe.

Stresses resulting from bending loads will vary around the pipe circumference and through the wall thickness. With the exception of treatment of initiating stress corrosion cracks (see Section 5.1.2), such variations are ignored, and the maximum bending stress at the inner pipe wall is taken to be uniformly distributed throughout the pipe cross-section. Stresses from axial and transverse forces are usually neglected, but can be added onto bending and pressure stresses by the user.

For girth welds, the axial component of the pressure stress is taken to be

$$\sigma_p = \frac{pR_i}{2h} \tag{5-1}$$

where R_i is inside radius and h is the wall thickness of the pipe. For fatigue crack growth analyses, the minimum stress (neglecting radial gradient thermal and residual stress for the moment) is taken to occur at no pressure and room temperature. The stress is then the deadweight

$$\sigma_{min} = \sigma_{DW} \tag{5-2}$$

Residual stresses could be added at this point, but they have only a small influence on fatigue crack growth.

The maximum stress (again ignoring residual and radial gradient thermal stresses), is called the normal operating stress (σ_{NO}). It is composed of the pressure, deadweight, and restraint of thermal expansion stresses

$$\sigma_{max} = \sigma_{NO} = \sigma_p + \sigma_{DW} + \sigma_{TE} \tag{5-3}$$

Vibratory stress peak-to-peak values are defined by the user. They are combined with σ_{max} of Equation 5-3 to define a ΔK and R due to vibratory stresses. These are compared with threshold conditions for fatigue crack growth to see if threshold is exceeded. If it is, failure is considered to occur (see also Section 2.3.4).

5.1.2 Quasi-Axisymmetric Stresses

An exception to the omission of circumferential variation of service-induced stresses is the treatment of stress levels in girth welds subject to stress corrosion crack initiation. As discussed in Section 2.6.3 of Harris 86, for the purposes of initiation and growth of stress corrosion cracks, the stresses due to deadweight and restraint of thermal expansion (which are mostly bending) are taken to have a cosine variation around the pipe circumference. Initiation (and growth) cracks are considered to be uniformly distributed around the circumference, and the analysis is performed using the local (cos) values of the stress. Stress intensity factors are calculated using K-solutions for no circumferential variation of stress using the local stress at the mid-point of the surface length of the cracks.

5.1.3 Elbows

The only longitudinal welds in some primary piping systems are at elbows. Other primary piping systems have some seam welds, but they are shop welds, and generally have fairly low cyclic stresses. The stresses in elbows resulting from applied moments are considerably more complex than in straight piping runs [Rodabaugh 57]. Not only are the longitudinal stresses no longer given simply by My/I, but appreciable hoop stresses are also generated. These hoop stresses will tend to grow cracks in longitudinal elbow welds. Results from Rodabaugh 57 can be used to estimate bending-induced stresses in elbows.

Maximum stresses due to in-plane and out-of-plane bending are very similar, and the largest of these is employed. In regions of maximum hoop stress, the hoop stresses due to bending are nearly equal but of opposite sign on the inside and outside of the pipe. As a reasonable but conservative approach, the maximum hoop stresses can be taken to be applied across the longitudinal weld and to be tensile on the inside surface. Hence, the applied stresses can be approximated as varying linearly through the thickness, with levels to be defined by the user. Since the stress intensity factor for longitudinal and circumferential cracks are nearly the same (see Section 2.1.1), the PRAISE Code treats circumferential cracks and cracks in elbows in the same manner; the only difference being the stresses that are input. There is a difference, however, between the two crack orientations as far as failure criteria are involved. Failure criteria are provided in PRAISE for circumferential cracks. Failure criteria for axial cracks or elbows must be coded by the user. Section 2.3.3 discusses failure criteria for axial cracks, and Section 5.3 of Harris 82 provides results for longitudinal cracks in elbows.

5.2 Seismic Stresses

As its name implies, the PRAISE Code was originally developed to estimate the influence of seismic events on piping failure probability. Hence, seismic events are considered in some detail, but the stresses are again to be defined by the user. The seismic events then simply form part of the stress history which PRAISE considers in its crack growth analysis. As discussed more fully in Sections 5.7.3 and 8.2.4. PRAISE calculates the effects of various seismic events occurring at various times. The probability of the seismic event occurring is treated outside of PRAISE.

The seismically-induced stresses are defined by the user. They are typically determined from seismically-induced bending moments in a manner analogous to that described in Section 5.1.1 for deadweight and restraint of thermal expansion bending moments. The stress history during the seismic event can be converted to an equivalent constant amplitude stress history of a selected number of cycles, as discussed in Section 5.7.3, as well as in Sections 2.6.2 and 3.7 of Harris 81 and Section 3.7.1 of Lim 81. Section 1.3.2 of Harris 81 discusses procedures employed for seismic stress histories in the analysis reported in that reference, which in turn, used seismically-induced stresses from Lu 81. The seismic stresses are considered to be load controlled, and the maximum stress during a seismic event is also needed in order to check on the possibility of failure (crack instability) during the seismic event.

5.3 Vibratory Stresses

Vibratory stresses induced while the plant is at load can be treated by the PRAISE code. The peak-to-peak amplitude of the vibratory stress, $\Delta\sigma_v$, is input by the user. This is superimposed on the normal operating stress (Equation 5-3), which is considered as the mean stress. PRAISE considers failure due to vibratory stresses to occur if $\Delta\sigma_v$ results in ΔK and R conditions that exceed threshold for fatigue crack growth (see also Section 2.3.4 of this document, and Section 3.9 of Harris 82a).

5.4 Radial Gradient Thermal Stresses

Temperature fluctuations of the coolant give rise to stresses in addition to those resulting from restraint of thermal expansion. Such stresses are called radial gradient thermal stresses. They are axisymmetric, self-equilibrating through the wall thickness, and determinable from the temperature and flow history of the coolant and the thermal and elastic properties of the piping material. The stresses and temperatures are considered to be uniform along a straight run of piping, and are both time and space (radial) dependent.

The TIFFANY Code [Dedhia 82] provides an easily used tool for evaluation of temperatures, stresses, and stress intensity factors due to excursions in the coolant conditions. Figure 5-1 summarizes the components of the TIFFANY Code.

The temperature field in the pipe is assumed to be axisymmetric and independent of distance along the pipe. This is consistent with the usual treatment of radial gradient thermal stresses in pipes. The temperature field is therefore a function of time and radial coordinate only, T(r,t). In principle this problem can be solved analytically for time-dependent boundary conditions (but constant material properties). However, the analytical solution would be quite unwieldy for the general case. This one-dimensional heat conduction problem is very amenable to a numerical procedure, and such an approach is adopted. Consideration of temperature dependent material properties, such as thermal conductivity, is straightforward in the numerical procedures, and this capability is included.

The outer surface is considered to be insulated. The boundary condition at the inner surface is the conventional one that considers convective resistance. The convection heat transfer coefficient, h_c, can be a function of time because it varies with fluid temperature (T_f) and coolant flow rate (V). In the case of clad piping, continuity conditions at the material interface are required for solution of the differential equation. The temperature and heat flux are taken to be continuous at the interface.

A numerical procedure for evaluation of the temperature in the pipe wall is employed. This is accomplished by employing a finite difference procedure that utilizes second order correct differing of the diffusion term (i.e., spatial variation) and first order correct backward differing of the temporal term.

The numerical scheme, along with analogous formulations of the boundary conditions and continuity conditions at the clad-base metal interface, leads to a set of simultaneous equations for the current nodal temperature in terms of material properties, geometrical terms, and temperature from the previous time-step. These equations are readily and efficiently solved by the method of successive substitutions. As described in Dedhia 82,

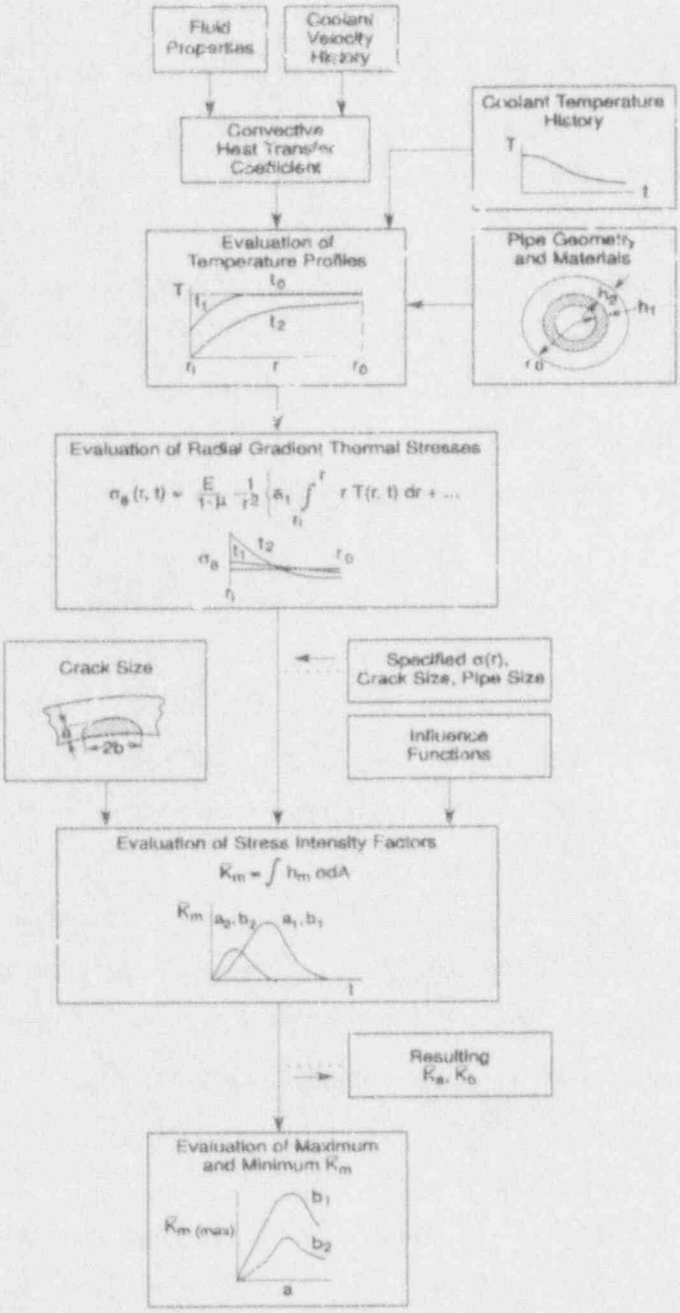


Figure 5-1. Components of TIFFANY Computer Code and their interrelationships.

convection heat transfer coefficient, h_c, in the boundary condition is described in terms of Reynolds, Prandtl, and Nusselt numbers.

The stresses in the pipe wall are evaluated by use of elasticity theory from the transient temperature field determined by the finite difference procedure described above. The idealization of only radial variations of the stresses and displacements leads to a particularly simple one-dimensional quasi-static elasticity problem. Such problems are discussed in Timoshenko 51, and the case of interest here when there is no cladding is treated in Section 135 of Timoshenko 51. That discussion can easily be generalized to provide results for a clad pipe. The treatment here will be for the two materials that have the same elastic constants but different coefficients of thermal expansion. This is applicable to ferritic steel with austenitic stainless steel cladding. In the case considered here, the axial strain , ϵ_z, is taken to be constant (not zero) at any instant, and equal to a value that produces a zero net axial load. In other words, ϵ_z is constant and has a value such that the following relation holds

$$\int_{r_i}^{r_0} r\,\sigma_z\,(r,t)\,dr = 0 \tag{5-4}$$

This is consistent with the usual treatment of radial gradient thermal stresses in piping. This condition, along with the boundary condition of zero radial stress at the inner and outer pipe wall and continuity of displacement and radial stress at the clad-base metal interface, allows the stresses to be expressed in terms of integrals involving the temperature field, as given in Section 2.2 of Dedhia 82.

Once the stresses are determined, the stress intensity factors at a given time for a given crack size are evaluated by numerical integration using the influence functions described in Section 2.1.1. For a given crack size, the value of $\bar{K}_{a,\,max}$, $\bar{K}_{a,\,min}$ and $\bar{K}_{b,\,max}$, $\bar{K}_{b,\,min}$ are determined from the peaks and valleys of the time variation of these K values. Their maximum and minimum are determined (for a given transient) for a range of crack size. The results are cast into dimensionless form (see Equation 2-9) and used as inputs to PRAISE in tabular form ($g^*_{max,\,i}$ and $g^*_{min,\,i}$).

The TIFFANY Code [Dedhia 82] provides a convenient means of evaluating the tables to be input to PRAISE, but other procedures could be used to generate analogous results. Default temperature-dependent material properties for austenitic and ferritic steels are provided in TIFFANY, as well as information needed for convection heat transfer coefficients for dry saturated steam and saturated water (liquid).

As indicated in Figure 5-1, the TIFFANY Code can also take a given $\sigma(r)$ as input, and generate output of stress intensity factors. This allows stresses with through-wall gradients other than thermally induced to be considered by PRAISE. This option allows the imaginative PRAISE user greater latitude in definition of stress histories.

5.5 Welding Residual Stresses

Residual stresses play a very important role in the initiation and growth of stress corrosion cracks. Hence they are important in the analysis of the reliability of sensitized welds in BWR piping, and PRAISE includes extensive provisions for their consideration. Alternatively, residual stresses play a secondary role in fatigue crack growth, because they do not affect ΔK (the primary driver of fatigue crack growth), but only R (K_{min}/K_{max}), which is a secondary variable in fatigue. Hence, residual stresses in austenitic piping materials are concentrated upon, because this is the material used in recirculation lines of BWRs (counterpart of large primary piping in PWRs).

Residual stresses are induced by the welding process and can be changed by procedures such as induction heating stress improvement (IHSI) and mechanical stress improvement process (MSIP). Measured values of stresses due to IHSI and MSIP are discussed in Section 5.6 Weld-induced residual stresses have shown considerable scatter and dependence on pipe size. They also exhibit a relatively complex spatial variation.

Residual stresses are input to PRAISE by seven different options, which are summarized in Table 5-1. These options are discussed in the following sections. The IHSI and MSIP residual stresses, which can be induced by mid-life treatments are discussed in Section 5.6. In all cases, the residual stresses in the axial direction of the pipe in the heat-affected zone are considered.

Table 5-1
SUMMARY OF VARIOUS FORMS OF RESIDUAL STRESSES USED IN PRAISE

No.	Deterministic or Random	Axisymmetric	User-Defined	Hardwired	Section	Description
0	D	--	--	--	--	No residual stresses
1	D	✓	✓		5.5.1	Coefficients in polynomial curve fit input by user
2	R	✓		✓	5.5.2	Large lines, includes adjustments.
3	R			✓	5.5.3	Intermediate lines, includes adjustments.
4	R			✓	5.5.3	Small lines, includes adjustments
5	D	✓	✓		5.5.1	Stress at ID and OD input by user, linear variation assumed
6	R	✓	✓		5.6.1	Mean and standard deviation of stress at ID input by user. Self-equilibrating linear variation through thickness employed. Mid-life change _must_ be of this type.

5.5.1 _Deterministically-Defined Residual Stresses_

Residual stresses can be deterministically defined in two ways: (i) an axisymmetric linear through wall variation (which will not necessarily be self-equilibrating) (Option 5 of Table 5-1), and (ii) coefficients in a polynomial curve fit to stress intensity factors due to residual stresses as a function of crack size (Option 1 of Table 5-1).

In the case of the linear through-thickness variation of stress, the stress intensity factors are calculated by use of the curve fits of Section 2.1.1.

The case of nonlinear stress gradients can be treated in a deterministic fashion by use of Option 1, which involves polynomial curve fits to stress intensity factors as a function of crack size. This is the procedure that was used in Section 2.5 of Harris 82. The stress intensity factors themselves can be evaluated from the residual stresses and influence functions in a manner analogous to that used for radial gradient thermal stresses (see Sections 2.1.1 and 5.3.2). In fact, the TIFFANY Code [Dedhia 82] has provisions for inputting stresses and calculating stress intensity factors. The polynomial curve fit coefficients must be generated by the user. The functional form of the curve fit is

$$\bar{K}_{I,Res} = \sum_{k=1}^{K} \sum_{\ell=1}^{L} b_{i,\ell k}\, \alpha^{\ell-1} \zeta^{k-1} \qquad (5\text{-}5)$$

where $\alpha = a/h$ and $\zeta = a/b$. The user inputs the values of K and L and the coefficients $b_{i,\ell k}$. Sections 2.5, 3.7, and 4.5 of Harris 82 provide additional details and examples.

5.5.2 Random Distribution of Residual Stress in Large Austenitic Lines (OD > 20 Inches)

Welding residual stresses were found to have considerable scatter and to differ significantly depending on the size of the line. The following three ranges of pipe sizes were selected for characterization of these weld-induced residual stresses

large: 20 inches < OD
intermediate: 10 inches ≤ OD ≤ 20 inches
small: 4 inches ≤ OD < 10 inches

This section deals with large lines, the following section discusses intermediate and small lines. 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.

As an additional consideration, the stress corrosion cracking portion of PRAISE was exercised and compared with field observations of failure (and successes) in BWR piping. Adjustments were made in PRAISE to improve agreement in this benchmarking procedure, which is described in Section 3 of Harri 86. Since residual stresses are one of the major uncertainties in PRAISE inputs, the weld-induced residual stresses were adjusted by a constant factor -- for a given pipe size. The adjustments for various line sizes are discussed in the following section.

The axial component of the as-welded residual stresses in the heat-affected zone is of interest because stress corrosion cracks form in the heat-affected zone, and the circumferential cracks are 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 Hale 82 and Shack 83. A total of nine sets of data were obtained and are plotted in Figure 5-2. The following equation was used to analytically represent the radial variation of the axial stresses in the heat-affected zone.

$$\sigma_z = (r_i/r)\ [H_\phi \cos(2\pi x + \phi) + H_s e^{-sx} \cos(Bx + \phi_2)] \qquad (5\text{-}6)$$

where r = radial coordinate $\quad r_i$ = inside radius
$x = (r-r_i)/h \quad h$ = wall thickness
$H_\phi, \phi, H_s, s, B, \phi_2$ are constants

This stress can be self-equilibrating through the wall.

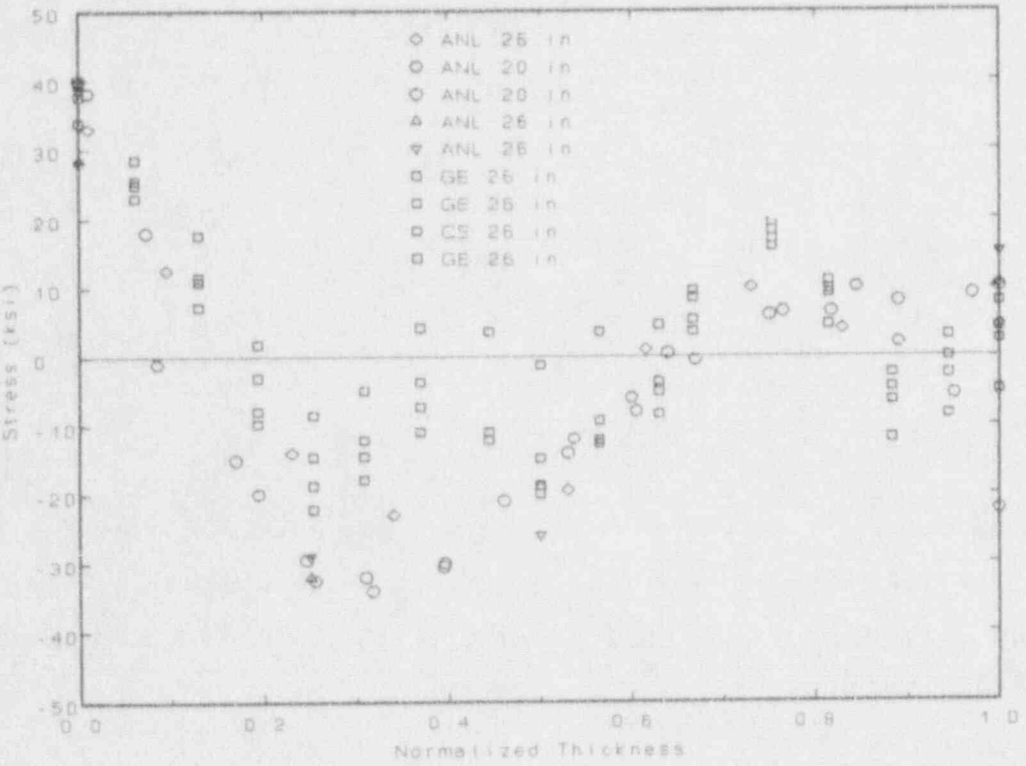
A preliminary curve fit of the nine sets of data to Equation 5-6 revealed that $B \approx 2\pi$. The parameter B was therefore set equal to 2π. In order for the body to remain in equilibrium, the axisymmetric σ_z must be self-equilibrating through the wall thickness. The imposition of this condition results in

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

Equation 5-6 can then be rewritten as

$$\sigma_z = \frac{r_i}{r}\ \{H_\phi \cos(2\pi x + \phi) + H_s e^{-sx} \cos[2\pi x + \tan^{-1}(\frac{s}{2\pi})]\} \qquad (5\text{-}7)$$

Values of H_ϕ, ϕ, H_s, and s were estimated by nonlinear regression analysis for <u>each</u> of the nine sets of data. This provides nine sets of values for these variables. The mean and standard deviation for each of these variables was calculated from these nine sets of values,



RESIDUAL DAT 01-23-1992

Figure 5-2. Experimental data on the radial distribution of residual stresses.

and plots of the values on normal probability paper showed them all to be reasonably well approximated by a normal distribution [Figures 22-25 of Harris 86]. Further analysis of these variables revealed that only H_s and H_ϕ were strongly correlated (correlation coefficient = 0.832). The relationship between H_s and H_ϕ can be described as follows:

$$H_s = H_l + 0.7381\, H_\phi \tag{5-8}$$

H_l is another variable which was evaluated by regression analysis and has a mean value of 37.49 ksi with standard deviation of 9.11 ksi. Table 5-2 summarizes the mean and standard deviations of the normal variates used to characterize the spatial and statistical distributions of residual stresses in large lines.

Table 5-2
MEAN AND STANDARD DEVIATION OF CURVE FIT PARAMETERS TO DESCRIBE RESIDUAL STRESSES IN LARGE AUSTENITIC LINES

	Mean	Standard Deviation
H_ϕ, ksi	23.20	18.51
H_l, ksi	37.49	9.11
ϕ, radians	2.26	0.82
s, radians	1.68	1.21

All variables are normally distributed.

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 in Equation 5-7 were rewritten as

$$\sigma_z = \sigma_1 + \sigma_2 \tag{5-9}$$

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

$$\left(\frac{\bar{K}_I}{a^{1/2} H_s}\right)_{\sigma_1} = F_1 \text{(crack geometry, } \phi\text{)} \tag{5-10}$$

$$\left(\frac{\bar{K}_I}{a^{1/2} H_s}\right)_{\sigma_2} = F_2 \text{(crack geometry, s)}$$

The polynomial curve fits for F_1 and F_2 in Equation 5-10 are very long, containing some 320 coefficients. The curve fits are, therefore, not provided here, but are contained in module BLOCK DATA COEFS in the source code of PRAISE.

In PRAISE-C, the parameters H_ϕ, ϕ, s, and H_1 are sampled randomly from their respective (normal) distributions. H_s is evaluated from its linear relation with H_ϕ as expressed in Equation 5-8. 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 mentioned at the beginning of this subsection, and discussed in Section 3 of Harris 86, line size dependent adjustments were made to residual stresses to improve the agreement between PRAISE predictions and field observations. In the case of the large lines under discussion here, the residual stresses (and stress intensity factors) are multiplied by 0.15 (see Figures 35 and 36 of Harris 86.

5.5.3 Random Distribution of Residual Stress in Small and Intermediate Austenitic 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 [Shack 80, Brust 81, NUREG 82, 83, Hughes 82]. Data on the axial component of the inside surface residual stresses were compiled for locations approximately 3 mm from the weld fusion line where the peak sensitization levels generally occur [Shack 80]. 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 (4 inch $\leq$ OD $<$ 10 inch)

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

Intermediate Lines (10 inch $\leq$ OD $\leq$ 20 inch)

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

These results do not include the adjustment factors to improve agreement between PRAISE predictions and field observations. A multiplier of 0.2 on these values was selected (see Figures 37-40 and Table 7 of Harris 86).

Plots of the cumulative distributions of the stresses on the inside surface for small and intermediate lines showed 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 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:

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.

5.6 Residual Stresses Following Remedial Treatment

As-welded residual stresses are discussed in Section 5.5. These stresses generally have a detrimental influence, most especially so in austenitic BWR piping. In order to reduce the propensity for SCC in BWR piping, it has been suggested that the residual stresses be altered to provide more favorable stress conditions. Induction heating stress improvement (IHSI) and mechanical stress improvement process (MSIP) are candidates for favorable alteration of residual stresses. The PRAISE Code provides capabilities for treating the affects of using one of these procedures after the plant has been in operation, i.e., a mid-life residual stress treatment.

5.6.1 Induction Heating Stress Improvement

The induction heating stress improvement (IHSI) process is suggested as one of the counter-measures for intergranular stress corrosion cracking (IGSCC) [Offer 83, Rybicki 82, Hughes 82]. The process results in axial residual stresses that are compressive on the ID and, thus, are favorable for impeding stress corrosion crack initiation and growth. The resulting residual stresses are also axisymmetric and self-equilibrating through the thickness.

Offer 83 and Rybicki 82 provide experimental and analytical post-IHSI residual stress distributions through the wall. In the context of PRAISE, only the axial stresses are of interest here. These references contain results for 4, 10, 12, 16, and 26 inch diameter lines. Based on the information available, these stresses vary approximately linearly through the wall.

Post-IHSI stresses at the ID and OD were gathered from Offer 83 and Rybicki 82. When the stresses are linearly varying through the wall, axisymmetric and self-equilibrating, the stresses at the ID and OD are related to one another by the expression

$$\sigma_{ID} = -\sigma_{OD} \frac{3R_i + 2h}{3R_i + h}$$

where R_i = inside radius of the pipe

h = wall thickness of the pipe

Thirty-one sets of through-wall stresses were available. From these 31 sets of data, 62 values of stresses at the ID were obtained; 31 values directly, and 31 values using the OD data converted to ID values by use of the above equation. The post-IHSI stresses from Offer 83 and Rybicki 82 were grouped in several different ways, and the mean and standard deviation for each group were calculated. The results are summarized in Table 5-3. For each of the categories shown in Table 5-3 (except the last one), the stresses were plotted in the form of histograms with the normal distribution based on the calculated mean and standard deviation superimposed [FaAA 90]. In each of the categories, the normal distribution seems to reasonably characterizes the scatter present in the data.

Table 5-3
SUMMARY OF POST-IHSI STRESSES AT THE ID

Category	Number of Data	Mean (ksi)	Standard Deviation (ksi)
All	62	-40.8	13.6
ID Data	31	-43.3	9.7
Projected from OD to ID	31	-38.4	16.4
All Experimental	46	-44.7	11.6
All Analytical	16	-29.9	13.2
All 4 Inch	4	-38.8	7.5
All 10 Inch	10	-29.2	16.3
All 12 Inch	36	-45.1	11.0
All 16 Inch	10	-41.5	13.5
All 26 Inch	2	-22.8	8.2

Based on the results summarized in Table 5-3, along with supporting results from Offer 83 and Rybicki 82, it appears that the post-IHSI residual stresses can be adequately described as axisymmetric with a linear through-wall gradient. For a given pipe size and thickness, such a spatial distribution can be characterized by a single number, such as the value of the stress at the ID. The results indicate that the statistical distribution of the ID residual stress is normally distributed, and Table 5-3 shows no consistent variation of the mean and standard deviation with pipe size. Hence, it is suggested that the mean and standard deviation of post-IHSI residual stresses be taken as the values based on "all experimental data", which are a mean of -44.7 ksi and a standard deviation of 11.6 ksi.

The mean and standard deviation of the post-IHSI residual stresses are input by the PRAISE user. The values referred to immediately above are suggested for use.

5.6.2 <u>Mechanical Stress Improvement Process</u>

The mechanical stress improvement process (MSIP) consists of applying a ring that squeezes a short portion of the pipe. The magnitude of the applied ring load is sufficient to produce permanent reduction of the diameter of the pipe under the ring, which produces compressive axial residual stresses on the ID that extend a short distance away from the location of the ring. This process can thus be used to produce favorable residual stresses in the vicinity of a circumferential weld to impede IGSCC.

O'Donnell 88a, 88b, 88c, and 88d provide numerical results for 4-, 10-, 12-, and 28-inch nozzles treated with MSIP. The through-wall stress distributions in the heat-affected zone (HAZ) (half-thickness away from weld centerline) on either side of the weld were obtained from the color contour plots included in the references. Shack 89 provided experimental measurements of through-wall post-MSIP stresses in 12- and 28-inch lines in the region of the HAZ. The data on post-MSIP stresses was collected and are summarized in FaAA 90, from which it was concluded: (i) the axial MSIP stresses in the HAZs of a weld can be characterized as varying linearly through the wall and axisymmetric, (the stresses are therefore self-equilibrating through the wall and, knowing the stress on the ID and the pipe geometry, the through-wall stress distribution can be obtained); (ii) the stresses on the ID are a function of the axial distance from the tool and are also a function of the applied compression under the tool. Generally, the stresses in the range of -20 to -40 ksi are produced on the ID of the pipe.

Based on the limited available information, it is not possible to statistically characterize the MSIP stresses. The through-wall stress distributions seem to be similar to those obtained by IHSI treatment. The post-MSIP stresses are input to PRAISE in a manner identical to the IHSI stresses, with the mean and standard deviation of the (normally distributed) ID residual stress defined by the user.

5.7 Stress Histories

Specification of the stress history is a key input to PRAISE. Earlier portions of Section 5 discuss stress levels. This subsection addresses the number of times each of the transient types occur.

5.7.1 Arrival Time of Transients

The operating stress history of a reactor is generally thought of as a list of transient types and the number of times each type will occur within the plant lifetime. This is handled in PRAISE by specifying for each transient type the time between transients. For instance, a value 0.5 for a given transient means that it will occur every half year.

PRAISE can also treat a random occurrence of transients. This is accomplished by considering the time between successive occurrences of a given transient type to be Poisson distributed with a specified mean time. The distribution of inter-arrival times (of a given transient, i) is taken to be exponentially distributed, i.e.,

$$p(t_i) = \frac{1}{\lambda_i} \exp\left(-t_i/\lambda_i\right)$$

The parameter λ_i is the mean time between arrivals of the i-th transient. λ_i is specified by the user. If λ_i is positive, the transient occurrence is treated in a deterministic manner. If the input value of λ_i is negative, then the transient is treated in a stochastic manner. PRAISE allows mixing of random and deterministic transients. When random transients are considered, a new sequence of transients is randomly generated for each Monte Carlo simulation.

5.7.2 Mid-Life Changes

PRAISE provides the capability of analyzing changes in some inputs during the life of the plant. Changes can be specified at no more than four times. The following items can be changed:

- oxygen level of coolant at plant start-up
- oxygen level of coolant during steady-state
- coolant conductivity
- deadweight stress
- deadweight stress and restraint of thermal expansion stress in the hot normal operating condition
- vibratory stresses
- wall thickness of pipe
- residual stresses

Whenever a change is made in one of the above items, all of the other items must be respecified, whether they are changed or not. If the pipe wall thickness is changed (such as to model weld overlay), the pressure stresses are recalculated in PRAISE. The user must specify any resulting changes in deadweight and restraint of thermal expansion stresses. Residual stresses are renormalized such that they are the same as before at any fractional depth through the wall. If mid-life changes to residual stresses are specified, they can be changed only to axisymmetric self-equilibrating stresses through the pipe wall (to model IHSI or MSIP, see Section 5.6).

5.7.3 Seismic Events

The timing and magnitude of seismic events to be considered are specified by the user. The probability of such events (and their magnitude) is considered outside of PRAISE, such as discussed in George 82 and Harris 82b. Crack growth is modeled for each seismic event, using the crack size existing before the event. After the seismic event, the crack size is returned to its size before the event. Hence, PRAISE provides the probability of failure given that a specified seismic event occurred at a given time.

For each seismic event to be considered, the following items are specified

- number of (equivalent) cycles
- equivalent cyclic stress (half of equivalent peak-to-peak value)
- maximum seismic stress

PRAISE can analyze the affects of seismic events only for materials that follow the growth law

$$\frac{da}{dN} = C\left[\frac{\Delta K}{(1-R)^{1/2}}\right]^m \qquad (5\text{-}11)$$

This is the same as Equation 4-3 for austenitic piping materials, but a general exponent (m) is allowed. The cyclic stress to be specified is selected to give an equivalent amount of fatigue crack growth as the stress history for the seismic event. Procedures for defining an equivalent stress are left to the user, but the following is one possible procedure.

Figure 5-3 schematically shows a stress history from a seismic analysis superimposed on the normal operating stress. This stress history can be considered to consist of the seven cycles tabulated in Figure 5-3. Fixing the number of cycles at seven (which is not required), a value of $\Delta\sigma$ that is equivalent to the tabulated stress history is derived as follows:

$$\frac{da}{dN} = C\left[\frac{\Delta K}{(1-R)^{1/2}}\right]^m = C\left[\frac{K_{max}-K_{min}}{1-(K_{min}/K_{max})^{1/2}}\right]^m$$

$$= C\left[\frac{K_{max}^{1/2}(K_{max}-K_{min})}{(K_{max}-K_{min})^{1/2}}\right]^m = C\left[K_{max}(K_{max}-K_{min})\right]^{m/2}$$

$$= C\left\{\sigma_{max}a^{1/2}F(\alpha,\beta)\left[\sigma_{max}a^{1/2}F(\alpha,\beta) - \sigma_{min}a^{1/2}F(\alpha,\beta)\right]\right\}^{m/2}$$

$$= C\left[a^{1/2}F(\alpha,\beta)\right]^{m/2}\left\{\sigma_{max}(\sigma_{max}-\sigma_{min})\right\}^{m/2}$$

$$\Delta a = C\left[a^{1/2}F(\alpha,\beta)\right]^{m/2}\sum_{i=1}^{7}\left[\sigma_{max,i}(\sigma_{max,i}-\sigma_{min,i})\right]^{m/2}$$

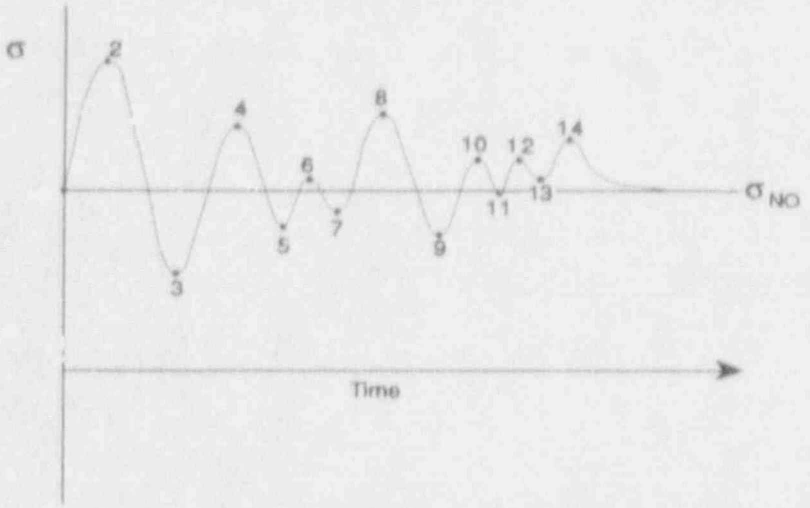
$$= C\left[a^{1/2}F(\alpha,\beta)\right]^{m/2}\,7\left\{(\sigma_{NO}+\Delta\sigma)\Delta\sigma\right\}^{m/2}$$

Hence,

$$\sum_{i=1}^{N}\left[\sigma_{max,i}(\sigma_{max,i}-\sigma_{min,i})\right]^{m/2} = N\left[(\sigma_{NO}+\Delta\sigma)\Delta\sigma\right]^{m/2}$$

The left hand side of the above equation is known from the seismic stress history, and the equation can be solved for $\Delta\sigma$. This is provided only as an example. The user can choose his own definition of an equivalent cyclic stress, but PRAISE is configured to handle only the crack growth law of Equation 5-11 for seismic events. Note that the above treatment assumes that the crack growth during the seismic event is not sufficient to produce a significant change in a or $F(\alpha,\beta)$. The example procedure for defining an equivalent stress history is easily expanded to allow a or $F(\alpha,\beta)$ to vary during the seismic event.

The above seismic stress information can be specified for up to ten classes (or categories or magnitudes). For each magnitude, up to ten different sets of seismic stress information can be specified. If more than one set of seismic stress information is specified for a given



Cycle	σ_{min}	σ_{max}
1	σ_1	σ_2
2	σ_3	σ_4
3	σ_5	σ_6
4	σ_7	σ_8
5	σ_9	σ_{10}
6	σ_{11}	σ_{12}
7	σ_{13}	σ_{14}

Figure 5-3. Schematic seismic stress history and the corresponding cyclic stress tabulations.

magnitude, then each of these sets is considered in the crack growth analysis and the total crack growth during the seismic event is then divided by the number of sets. For instance, if four different sets of stress information are input for a given magnitude, then crack growth is analyzed as the sum of the four events, and then divided by four. This feature allows a statistical distribution of stresses for a given magnitude event to be modeled. Sample Problem 3 of Lim 82 provides an example [Lim 82, Page 4-72].

The influence of seismic events is analyzed at each evaluation time. These times are defined by the user and are the same as the times at which results are printed out.

6. INSPECTION, MONITORING, AND TESTING

The PRAISE Code has the capability of analyzing the affects of inspection, monitoring, and testing on the pipe joint reliability. Pre-service and in-service inspections by nondestructive testing techniques can be modeled. Leak monitoring is considered, and proof testing can be included.

6.1 Detection Probabilities

Pre-service and in-service nondestructive inspections can be considered in PRAISE Code analyses. These enter into the analysis through the probability of detecting a defect during the inspection as a function of its size. If a crack is detected, it is assumed to be repaired, with the repaired joint being "perfect" (i.e., defect free). The probability of detection on successive examinations are assumed to be independent. That is, the fact that the crack was missed on an earlier inspection does not influence the probability of detecting it on the next inspection.

The inspection detection probability in PRAISE is expressed as

$$P_{ND}(A) = \epsilon + \frac{1}{2}(1-\epsilon)\ \mathrm{erfc}(\nu \ln A/A^*) \qquad (6\text{-}1)$$

where P_{ND} is the probability of <u>not</u> detecting a crack of Area A. The parameters, ν, ϵ, and A^* are input by the user and vary depending on the inspection procedure utilized.

If both a and b of the crack are less than the beam diameter of the ultrasonic probe, D_B, then

$$A = \frac{1}{2}\pi a b \qquad (6\text{-}2a)$$

If 2b is greater than D_B, then

$$A = \frac{1}{4} \pi a D_B \tag{6-2b}$$

Values of ν, ϵ, and A^* can be estimated from results reported in the literature. Section 2.4 of Harris 81 reviews the information available at that time. Considerable data has been generated since then. The following values were suggested in Harris 81 for thick-walled cast austenitic piping

$\nu = 1.60$
$A^* = (\pi/4)\, D_B\, a^*$
$a^* = 1.25$ inch
$D_B = 1$ inch
$\epsilon = 0$

The values of a^*, ϵ, and ν vary considerably depending on the material being inspected (as well as, of course, the inspection procedure employed). Section 2.4.1 of Harris 81 reviews detection data available at that time, and Harris 86 suggests the following values for wrought austenitic piping

$\nu = 1.60$
$a^* = 0.25$ inch
$\epsilon = 0.005$

These values also provide a reasonable approximation for ferritic piping. Figure 6-1 provides a plot of the corresponding non-detection probability.

The above estimates of ν and a^* could be improved based on the large amount of such information generated in the 1980s [see for example Doctor 90 and references cited therein]. PRAISE currently is restricted to the functional form given in Equation 6-1.

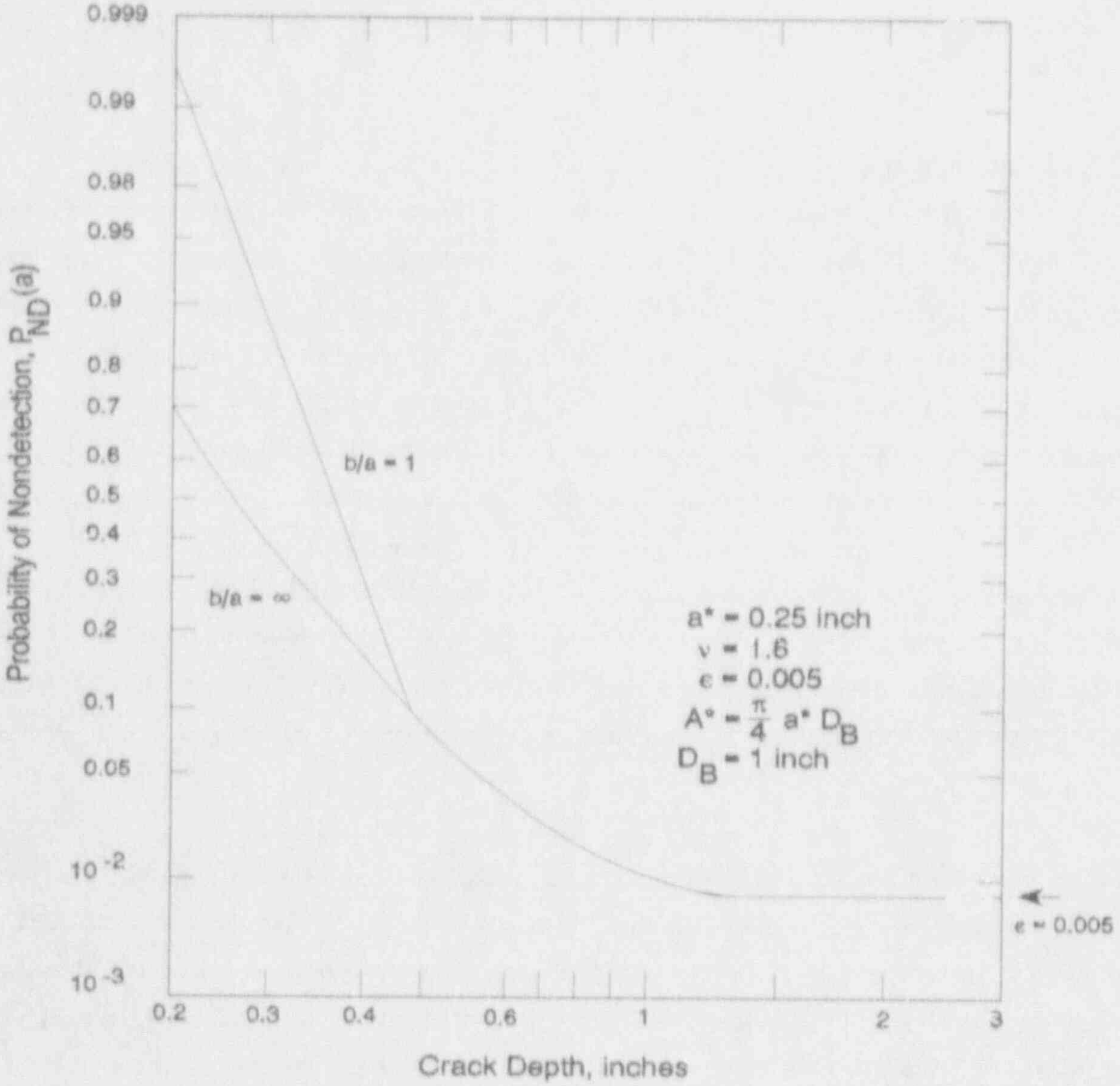


Figure 6-1. Probability of nondetection of a crack as a function of its depth for wrought piping material.

The treatment of repair in PRAISE could also be updated to include both the possibility of damage during repair and the uncertainty in sizing a crack once it is detected [Jacobs 84]. If a detected crack is incorrectly sized, it can be improperly dispositioned. For instance, if a crack is detected but undersized, it may be left in, which could lead to unexpected later problems.

6.2 Leak Detection

A defect that grows to become a through-wall crack is a leak. This leaking crack may or may not be of sufficient length to result in a complete pipe severance. At the user's disgression, repair of a leaking weld (that did not produce a complete pipe severance) involves either replacing the entire weld with perfect material or repairing only the cracks that are leaking detectably. If the leak is not detectable, the crack can continue to grow, perhaps leading to a complete pipe severance. If the leak is sufficiently large, it will be detectable, and the plant can be shut down and the leak repaired.

The probability of detecting a leak depends on its size, and PRAISE considers leaks below a user-defined value to be nondetectable and leaks above that value to be detected with a probability of unity. The plant technical specifications define the allowable unidentified leak rate, and this is often used as the detectable size. A value of 1 gallon per minute was used in Harris 81 (Page 105).

In order to determine if a leak is detectable, it is necessary to estimate the leak rate, which, in turn, requires an estimate of the crack opening area. The opening area and leak rate estimation procedures in PRAISE are quite rudimentary, because conservative scoping calculations in Harris 81 (Sections 2.8.2 and 2.8.3) showed that all leaks in the piping under consideration would be detectable. The treatment of opening area and leak rate in PRAISE could be greatly refined using results for crack opening area [Tada 85] and leak rate through cracks that have become available since the original PRAISE development.

As PRAISE now stands, the opening area is estimated by considering the crack to be rectangular in shape with a length 2b and width (opening displacement) of δ, where [Tada 85]

$$\delta = \frac{4\sigma b(1-\nu^2)}{E} \tag{6-3}$$

This expression comes from the result for a crack in an infinite plate and is conservative.

The basis of the leak rate estimate is described in Section 2.8.1 of Harris 81. The following expression is from Section 2.6.1 of Harris 86 and is used in PRAISE for leak rate estimates

$$\frac{\dot{Q}h^{1/2}}{2b} = \begin{cases} 0.25\delta^2 & \delta \le 2 \text{ mils} \\ 0.9375\delta - 0.875 & \delta > 2 \text{ mils} \end{cases} \tag{6-4}$$

where δ = total crack opening displacement (mils)
h = pipe wall thickness (inches)
$2b$ = through-wall crack length (inches)
$\dot{Q}$ = leak rate (gallons per minute, reactor conditions)

Equation 6-4 was developed for nominal pressurized water reactor conditions, i.e., 2250 psi and 550°F. This equation is not accurate for conditions other than this.

6.3 Proof Testing

The pressure boundary of commercial power reactors is subjected to a pre-service hydrostatic proof pressure. The proof test can have an influence on piping reliability by removing the cracks that fail during the proof (so they would not cause failure during subsequent service). PRAISE treats pre-service proof tests by checking sampled cracks during Monte Carlo simulation. The sampled crack is checked to see if it survives the proof pressure. If it does, the simulation is continued. If it does not, the pipe is considered to be repaired to as good as new, and another crack is sampled. Simulations which have failures during proof remain in the "denominator" of the Monte Carlo evaluation, but do not lead to failure in service. Separate "books" are not kept on proof failures, so the probability of failure during proof testing is not directly available.

In-service proof tests may also be performed. PRAISE can consider them as another part of the stress history by treating the proof as a radial gradient thermal stress and inputting the appropriate g^*_{min}, g^*_{max} tables (see Section 5.4). However, this will not directly separate failures during proof tests from failures in service.

7. MONTE CARLO SIMULATION

The PRAISE Computer Code uses Monte Carlo simulation techniques to estimate the cumulative distribution of time to first failure for a girth butt weld in nuclear reactor piping that is subjected to normal operating conditions, anticipated transients, and seismic events of various magnitudes. The basic equations in the PRAISE simulation are:

$$P(t_F \leq t) \sim \frac{N_F(t)}{N} \tag{7-1}$$

and

$$P[t_F \leq t | EQ(g,t)] \sim \frac{N_F(g,t)}{N} \tag{7-2}$$

where N is the number of simulations

$N_F(t)$ is the number of simulations in which failure has occurred at or before time (t)

$N_F(g, t)$ is the number of simulations in which failure has occurred at or before time (t), if it is subjected to an earthquake of intensity g at time t

$P(t_F \leq t)$ is the probability that the weld has failed at or before time t

$P[t_F \leq t | EQ(g, t)]$ is the probability that the weld has failed at or before time t; stress history includes a single earthquake of intensity g at time t.

7.1 Sample Space Definition

The two dimensional growth of cracks in PRAISE can be conveniently represented on a a/h - a/b (normalized crack depth and inverse of the aspect ratio) coordinates. These are also the variables that define the initial crack size distributions. This representation of the sample space is displayed in Figure 7-1. A small wedge-shaped portion adjacent to the a/b = 0 axis is infeasible because any crack located in this region would have lengths greater than the circumference of the pipe. The infeasible points satisfy

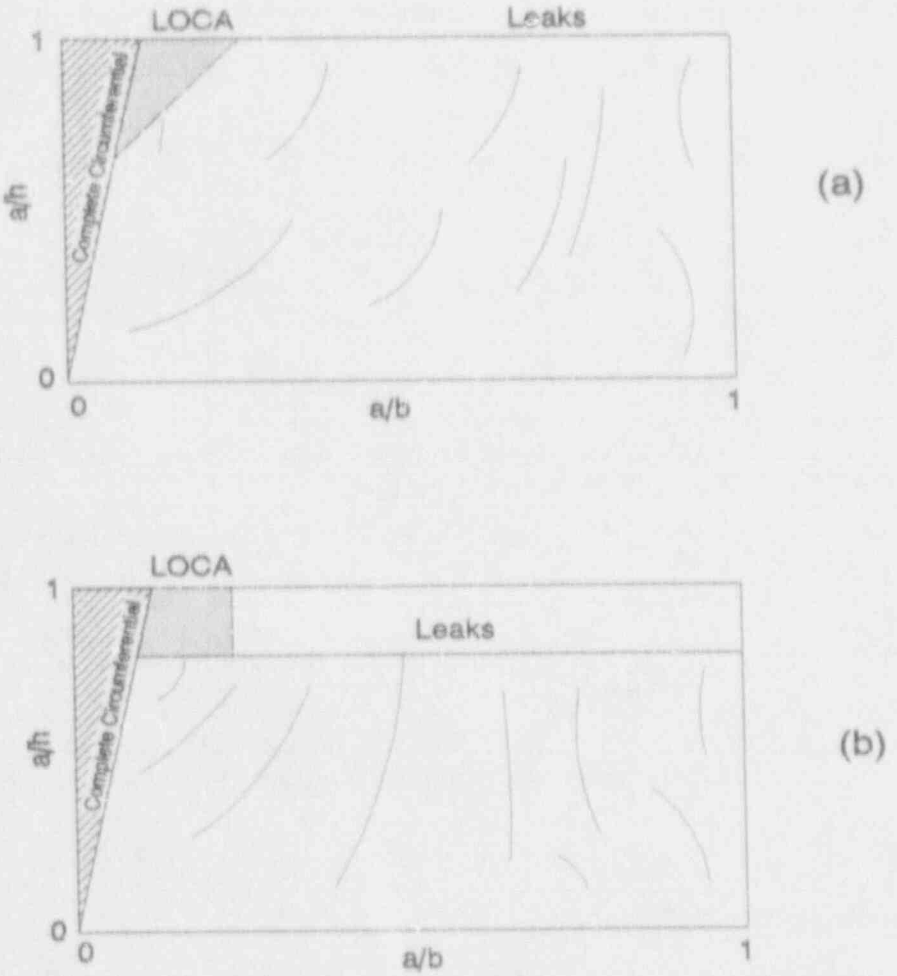


Figure 7-1. Sample space representation with (a) net-section failure criteria and (b) tearing modulus failure criteria.

$$\frac{a}{b} < \frac{h}{2\pi R_i}\left(\frac{a}{h}\right)$$

For the case of net-section failure criteria, the cracks that satisfy the following equation are considered to result in a double-ended pipe break

$$A_{crack} \geq \left(1 - \frac{\sigma_{LC}}{\sigma_{flo}}\right) A_{pipe} \tag{7-3}$$

where $A_{crack} = ab\,[2 + (a/R_i)]$
$A_{pipe} = \pi h(2R_i + h)$

In the case of multiple cracks, A_{crack} is the sum of areas of all the cracks. The loci of all the single cracks that would cause a LOCA are shown by a shaded-region in Figure 7-1a.

For tearing modulus based failure criteria, the points in the LOCA region satisfy

$$a > a_{crit} \ \ \underline{\text{and}} \ \ b > b_{crit} \tag{7-4}$$

where a_{crit} = the smallest depth of a complete circumferential crack for which $J \geq J_{Ic}$ <u>and</u> $T_{applied} \geq T_{mat}$
b_{crit} = the smallest half-length of a through-wall crack for which $J \geq J_{Ic}$ <u>and</u> $T_{applied} \geq T_{mat}$

The loci of all the cracks that would cause a LOCA is shown by shaded region in Figure 7-1b. In the case of multiple cracks in a weld, the above criteria is applied to each of the cracks.

Typical crack growth trajectories are also displayed on Figure 7-1. The trajectories are the loci of points showing the variation of crack dimensions with time as the crack grows under the cyclic loads. The crack depth variable is monotonically increasing while the value of a/b is free to either increase or decrease during the crack propagation process. These trajectories are a vivid demonstration of the two-degree-of-freedom model being used to represent crack growth in PRAISE.

If any of the cracks in the sample space is subjected to cyclic loads of sufficient magnitude for a long enough time, they would eventually fail either as a leak ($a \geq h$ in the case of net-section criteria or $a \geq a_{crit}$ in the case of tearing modulus criteria) or a catastrophic complete pipe severance. Figure 7-1 shows that many of the failures would occur as part-through defects that would leak. If these leaks are not detected, the length of the crack would continue to increase (a/b decreasing) and ultimately reach the large LOCA region. Cracks which exhibit this sequence of leak and LOCA are said to have experienced "leak before break". On the other hand, it is possible to have combinations of initial crack size and stress histories that lead to a large LOCA without first undergoing a leak. Although PRAISE routinely handles both situations, it presently does not display the fraction of LOCAs which experience the "leak-before-break" phenomenon.

7.2 Crack Sampling

PRAISE can calculate the probability of failure due to (i) the growth of a pre-existing defect, (ii) initiation and growth of a defect during the plant lifetime, or (iii) both considered simultaneously. Techniques used for sampling of the cracks for each of the above cases are discussed in this section.

7.2.1 Stratified Sampling for Pre-Existing Cracks

A direct evaluation of Equations 7-1 and 7-2 using simple random sampling in which the initial crack dimensions are selected in accordance with their postulated frequencies of physically occurring is computationally inefficient. For example, suppose that a relatively large defect must exist before failure occurs. However, if the probability of obtaining a large initial defect is small, a very large number of simple random samples may be required before a statistically significant number of failures is obtained. Furthermore, since the quantity of interest is the probability of failure rather than the time-dependent crack size distribution, simulation of cracks which do not eventually lead to failure is, in some sense, a wasted effort.

For the initial crack size distribution postulated in Harris 81, the overwhelming majority of the cracks that exist would not lead to a failure within the plant lifetime.

A variety of well-established techniques exist for increasing the accuracy and computational efficiency of Monte Carlo simulations [Mazumdar 75, McGrath 73]. These techniques are known by a variety of names; e.g., variance reduction method, stratified sampling, biased sampling, or importance sampling. For consistency in discussion, this report shall refer to the sampling scheme incorporated in PRAISE as the stratified sampling scheme. The basic idea is to partition the sample space into a set of mutually exclusive cells. A pre-determined number of samples is then selected from each cell. Within each cell, the individual crack dimensions are still selected according to the postulated initial crack size distribution. The distribution of time to first failure is modified so that Equations 7-1 and 7-2 become

$$P(t_F \leq t \,|\, \overline{EQ}) = \sum_{m=1}^{M} \frac{N_{F,m}(t)}{N_m} p_m \tag{7-5}$$

and

$$P[t_F \leq t \,|\, EQ(g,t)] = \sum_{m=1}^{M} \frac{N_{F,m}(g,t)}{N_m} p_m \tag{7-6}$$

where M is the total number of cells

N_m is the number of samples from the m-th cell

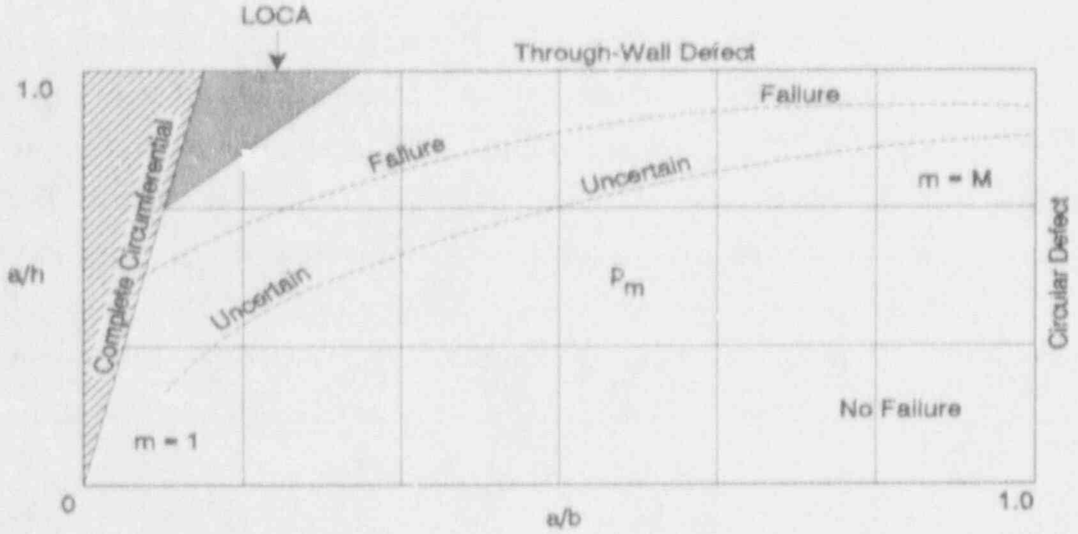
$N_{F,m}(t)$ is the number of samples drawn from the m-th cell which have failed at or before time, t

$N_{F,m}(g,t)$ is the number of samples drawn from the m-th cell which experience an earthquake of magnitude, g, at time, t, and have failed at or before time, t

p_m is the probability of an initial defect having coordinates within the boundaries of the m-th cell

$P(t_F \leq t \,|\, \overline{EQ})$ is the probability that the weld has failed at or before time t; stress history does not include earthquake.

A typical stratification of the sample space is illustrated in Figure 7-2. For illustrative purposes, three regions have been schematically identified. Points located in the upper portions of the sample space (near the LOCA or leak regions) are obviously more likely to



$$P(t_F \le t) = \sum_{m=1}^{M} \frac{N_{F,m}(t)}{N_m} p_m$$

$N_{F,m}(t)$ = Number of replications from m-th cell in which failure has occurred in time t

N_m = Number of replications from m-th cell

p_m = Probability of initial crack lying in cell m

Figure 7-2. Stratification of the sample space.

fail than points near the lower portions of the sample space. A region of uncertainty exists between these fail and no-fail regions. In many cases, computational experience with similar problems would allow one to draw, with a high degree of confidence, boundaries on the no-fail region. Since samples drawn from these regions would never lead to failure, a considerable computational improvement can be obtained by ignoring these cells in the sampling plan. In terms of Equations 7-5 and 7-6, the summation would be performed only over cells where there is failure or uncertainty regarding potential failure. Furthermore, a more efficient allocation of the total number of samples selected can be obtained by placing more of the sample into the uncertain region than into the fail region.

7.2.2 Initiating Cracks

In the case of SCC-initiated cracks (and no pre-existing cracks), no stratification scheme is implemented. Unlike the case of pre-existing cracks only, more than one crack may initiate in a weld joint, and the time to initiation is a random variable. The depth of the initiating crack is deterministically defined as 0.001 inch. The surface length of the initiating crack is assumed to be lognormally distributed with median value of 1/8 inch and shape parameter of 0.85. These cracks grow by SCC and fatigue (if selected), and the failure probabilities are calculated by applying Equations 7-1 and 7-2.

7.2.3 Pre-Existing and Initiated Cracks

Pipe failures are usually dominated by either pre-existing weld cracks or by SCC-initiated cracks. However, in instances, where both may have similar contributions to failure, they should be included in the analysis simultaneously. In this case, the crack sampling is primarily driven by the pre-existing crack case as described earlier, with initiation due to SCC included during the plant lifetime. In order to improve computational efficiencies, a user-defined boundary is provided such that the initiated cracks are included only if the sample pre-existing crack is above the boundary. The assumption here is that the pre-existing crack is so big that the initiated cracks, which always have a depth of 0.001 inch, are not going to be significant compared to the "big" pre-existing crack. The failure probabilities are the same as given in Section 7.2.1.

7.3 Probability Estimates and Their Sampling Errors

Since a Monte Carlo technique has been used to estimate the failure probabilities, these estimates will have some sampling errors. Therefore, PRAISE also calculates the variance of these probabilities. The variances can be used to construct confidence intervals for the estimated probabilities. In order to derive the appropriate relationships, consider first the case of simple random sampling and no earthquakes. The probability of failure at or before time t can be estimated by,

$$F(t) = \frac{N_F(t)}{N} \sim P(t_F \leq t) \tag{7-8}$$

where	N	is the total number of replications
	$N_F(t)$	is the number of replications which have grown to failure at or before time t
	$P(t_F \leq t)$	is the true, but unknown, probability that the weld has failed at or before time t
	$F(t)$	is the estimator for $P(t_F \leq t)$

The estimator F(t) is simply the proportion of the samples which have failed at or before time t. At any time during a given replication, the weld joint is in one of two mutually exclusive states; namely, failed or not failed. Suppose that a Bernoulli random variable $I_n(t)$ is defined by

$$I_n(t) = \begin{cases} 1 & \text{if the weld is failed at time, t} \\ 0 & \text{if the weld is \underline{not} failed at time, t} \end{cases} \tag{7-9}$$

The subscript n indicates the particular replication.

In terms of $I_n(t)$, the number of failures is given by

$$N_F(t) = \sum_{n=1}^{N} I_n(t) \tag{7-10}$$

while the proportion of failures is estimated by

$$F(t) = \frac{1}{N} \sum_{N=1}^{N} I_n(t) \tag{7-11}$$

It can be easily shown [Yamane 67, Section 5.9, Equation 8] that an unbiased estimator for the variance of F(t) is

$$\begin{aligned} s^2(t) &= \frac{1}{N-1} F(t) \left[1 - F(t)\right] \\ &= \frac{1}{N-1} \left[F(t) - F^2(t)\right] \end{aligned} \tag{7-12}$$

$$s^2(t) = \frac{1}{N(N-1)} \left[\left(\sum_{n=1}^{N} I_n(t) \right) - \frac{1}{N} \left(\sum_{N=1}^{N} I_n(t) \right)^2 \right] \tag{7-13}$$

When stratification is used, these relationships have to be modified to accommodate the stratification. The proportion of cracks drawn from the m-th cell that fail at or before time t is given by

$$F_m(t) = \frac{N_{F,m}(t)}{N_m} \tag{7-14}$$

where N_m is the number of samples from the m-th stratum

$N_{F,m}(t)$ is the number of samples from the m-th stratum which have failed at or before time t

If, in analogy to Equation 7-8, Bernoulli random variables for initial cracks drawn from the m-th cell are defined as

$$I_{m,n}(t) = \begin{cases} 1 & \text{if the weld with an initial defect from the m-th cell is failed at time, t} \\ 0 & \text{if the weld with an initial defect from the m-th cell is \underline{not} failed at time, t} \end{cases} \tag{7-15}$$

then

$$N_{F,m}(t) = \sum_{n=1}^{N_m} I_{m,n}(t) \tag{7-16}$$

and

$$F_m(t) = \frac{1}{N_m} \sum_{n=1}^{N_m} I_{m,n}(t) \tag{7-17}$$

where n is an index for the cracks from the m-th stratum and $F_m(t)$ is an unbiased estimator for $P_m(t_F \leq t)$, the probability that cracks from the m-th stratum will fail at or before time t.

In a manner similar to Equation 7-11, an unbiased estimator for the variance of $F_m(t)$ is

$$s_m^2 = \frac{1}{N_m - 1} F_m(t) \left[1 - F_m(t)\right] \tag{7-18}$$

$$s_m^2 = \frac{1}{N_m(N_m - 1)} \left[\sum_{n=1}^{N_m} I_{m,n}(t) - \frac{1}{N_m} \left(\sum_{n=1}^{N_m} I_{m,n}(t) \right)^2 \right] \tag{7-19}$$

It can be shown [Yamane 67, Section 6.9] that $F_{st}(t)$ and s_{st}^2 are unbiased estimators for the overall failure probability and the variance of the overall failure probability, respectively, where

$$F_{st}(t) = \sum_{m=1}^{M} F_m(t)\, p_m \tag{7-20}$$

and

$$s_{st}^2(t) = \sum_{m=1}^{M} s_m^2(t)\, p_m^2 \tag{7-21}$$

Additional considerations with regard to computational efficiency suggest that Equation 7-14 should be modified to accommodate the pre-service and in-service inspections. The random variables are redefined so that

$$I_{m,n}(t) = \begin{cases} P_{ND,m} & \text{if the weld has failed by time, t} \\ 0 & \text{if the weld has } \underline{\text{not}} \text{ failed by time, t} \end{cases} \tag{7-22}$$

Equations 7-15 and 7-16 are then evaluated using $I_{m,n}(t)$ as defined in Equation 7-21.

When the influence of earthquakes is to be evaluated, separate random variables are constructed for each earthquake category, or

$$I_{m,n}(g,t) = \begin{cases} P_{ND,n} & \begin{array}{l}\text{if a category g earthquake occurs at time, t} \\ \text{and the weld with a crack from the m-th} \\ \text{stratum has failed at or before time, t}\end{array} \\ 0 & \begin{array}{l}\text{if a category g earthquake occurs at time, t} \\ \text{and the weld with a crack from the m-th} \\ \text{stratum has } \underline{\text{not}} \text{ failed at or before time, t}\end{array} \end{cases} \tag{7-23}$$

The corresponding estimators are:

1. Stratum Proportion

$$F_m(g,t) = \frac{1}{N_m} \sum_{n=1}^{N_m} I_{m,n}(g,t) \tag{7-24}$$

2. Variance of the Stratum Proportion

$$s_m^2(g,t) = \frac{1}{N_m - 1} F_m(g,t) \left[1 - F_m(g,t)\right] \tag{7-25}$$

3. Overall Failure Probability

$$F_{st}(g,t) = \sum_{m=1}^{M} p_m F_m(g,t) \qquad (7\text{-}26)$$

4. Variance of the Overall Failure Probability

$$s_{st}^2(g,t) = \sum_{m=1}^{M} p_m^2 s_m^2(g,t) \qquad (7\text{-}27)$$

7.4 Joint and System Reliability

The failure probability calculated by PRAISE is for a given weld joint. A piping section may consist of many weld joints, each of which may have a different geometry and subjected to different load history. The probability of failure in the piping system is governed by the probability of failure of the various joints in the system. If the failure probability of each of the joints is independent of other joints, then the system failure probability can be calculated as

$$P_{f(sys)}(t) = 1 - \prod_{k=1}^{J} \left[1 - P_{f(joint\ k)}(t)\right] \qquad (7\text{-}28)$$

If the failure probabilities in the joints were correlated, the above equation provides an upper bound estimate of the system failure probability. A lower bound on the system failure probability would be the probability of failure of the joint with the highest failure probability.

To calculate probability of a seismic-induced LOCA (or leak), information about the seismic hazard curve is required. PRAISE provides the probability of a LOCA (or leak) given that a seismic event of a given magnitude occurred at given time during the life of a plant. George 81 and Harris 82b discuss procedures for combining the seismic hazard curve with the PRAISE output.

8. INPUT INSTRUCTIONS

This section provides detailed instructions for creating an input file for PRAISE and executing the code. Section 8.1 is intended for the first time user of PRAISE. Sections 8.2 and 8.3 provide detailed instructions for assembling an input file. An interactive pre-processor for creating input files is discussed in Section 8.4.

8.1 Getting Started

This section is provided for the first time program user. It provides detailed instructions for solving a realistic piping analysis problem with PRAISE. The following discussion assumes that the software has been installed according to the instructions provided with it. It also assumes that the user is familiar with the basic operation of an IBM-compatible pc.

Analysis using PRAISE generally consists of three basic steps:

- gathering inputs and setting up the input file,
- executing the input file using PRAISE, and
- plotting and interpretation of the results.

Let us say that you wish to calculate the probability of leak in a weld joint in the hot-leg of a PWR plant. The following inputs relating to the geometry of the pipe, pipe material, and the operating history are required to calculate the leak probability due to the growth of a pre-existing crack by fatigue

Pipe Geometry:
Inside Radius = 14.5 in
Wall Thickness = [illegible] in

Operating Conditions:
Deadweight = 2.08 ksi
Deadweight + Thermal Expansion = 8.58 ksi
Operating Pressure = 2400 psi
Proof Pressure = 3000 psi
Heat-up Cool-down Frequency = 5 per year
Plant Lifetime = 40 years
Residual Stresses Not Considered

Vibratory Stresses Not Considered

Fatigue Crack Growth Properties for 304 SS:
C (median) = 9.14×10^{-12}
C (90th percentile) = 3.5×10^{-11}
Fatigue Exponent = 4.0
Fatigue Threshold = 4.6 ksi-in$^{1/2}$

Flow Stress for 304 SS:
Mean = 43.2 ksi
Standard Deviation = 4.2 ksi

Initial Crack Size Distribution:
Depth Distribution -- Exponential
Parameter = 4.07
Aspect Ratio Distribution -- Lognormal
Median = 1.4
Shape Parameter = 0.538

The sample space will be divided into 100 cells and 25 samples will be taken from each cell. This is an important input in the analysis involving pre-existing cracks. You can assemble these inputs in a file using a text-editor. A basic pre-processor provided with PRAISE software can also be used. In this case we will use the pre-processor. The pre-processor [illegible] to assemble an input file for the problem described above. To start the pre-processor, at the DOS prompt, type

```
PR_INPUT <Enter>
```

The pre-processor will display the default values and request the new inputs. Accept the default values in each case by pressing <Enter>. At the end, the pre-processor will request two filenames for saving the input data, for which there are no default provided. Type

```
DEMO.TMP <Enter>
```

in response to the prompt for template file, and type

```
DEMO.DAT <Enter>
```

when the name for the input file is requested. At this point, the pre-processor exits to DOS and a PRAISE-compatible input file is created. To carry out the analysis using the input file, at the DOS prompt, type

```
PRAISE DEMO <Enter>
```

PRAISE will display some information on the monitor while it is carrying out the analysis. It will take approximately 5 minutes (on a 386/20 PC) to complete the analysis. When the analysis is completed, the results will be saved in file DEMO.OUT. This file can be printed on any printer capable of printing 132 columns. If you have a HP LaserJet printer connected to LPT1 port, the output file can be printed using the following command:

```
HPLASER DEMO.OUT
```

The first two pages of the output file consists of verification of the inputs. The next two pages describe the stratification of the sample space for crack sizes. The last page provides the probabilities of leaks and LOCA as a function of time. In this case, the stratification was optimized for the calculation of leak probabilities only, and therefore, the LOCA probabilities are not estimated accurately.

Where to go from here:

- Section 9.1 for description of the output file.
- Section 9.2 for plotting the failure probabilities and the stratification scheme.
- Section 10 for more sample problems, and
- READ.ME file on the disk for any changes since this documentation was printed.

8.2 Input Descriptions

This section is intended for the pc-PRAISE user; i.e., the person who must construct the input deck to execute the problem. Eleven sample problems are also presented.

As shown in Figure 8-1, pc-PRAISE input can be roughly divided into the following eight categories.

1. problem control variables,
2. geometry and material properties,
3. initial crack size distribution,
4. in-service inspection, earthquake evaluation times, and leak detection,
5. stratified sample space definition,
6. stresses, operating conditions, and frequency of transients,
7. seismic intensity and stresses, and
8. mid-life changes.

8.2.1 Problem Control Variables

The first card read by pc-PRAISE is a problem description or title card. All 80 columns are used. The title is repeated as a heading on various pages of the output. The majority of the control variables are read from the second and third card of the input deck.

INCIAT -- Parameter to describe whether pre-existing (= 0), initiated (= 1), or both (= 2) are to be considered in the analysis. If INCIAT = 0 or 2, then stratified sampling of pre-existing cracks is effective, and the initiated cracks are included in the analysis depending on the value of BNDRY. If INCIAT = 1, then the analysis is performed using SCC-initiated cracks only. This is a major control variable and affects available options for many other variables.

IFAILC -- Flag to select the failure criteria. If IFAILC = 0, then the failure criteria based on net-section stress is applied. For IFAILC = 1, tearing modulus based failure criteria is applied. Both of these failure criteria are applied if IFAILC = 2.

1. **Problem Control Variables**

2. **Geometry and Material Properties**
   - pipe wall thickness
   - pipe inside radius
   - fatigue crack growth parameters
   - flow stress

3. **Initial Crack Size Distribution**
   - crack depth ratio
   - crack aspect ratio

4. **Evaluation and Inspection**
   - earthquake evaluation time
   - in-service inspection time
   - leak detection threshold
   - big/small leak discrimination

5. **Sample Space Definition**
   - internally generated by pc-PRAISE
   - user-specified

6. **Stress and Transient Data**
   - frequency of occurrence
   - maximum temperature excursion
   - normalized variation of stress intensity factor during transients
   - contribution of residual stresses to the stress intensity factor
   - vibratory stress parameters

7. **Earthquake Definitions**
   - S-factor
   - load-controlled stresses

8. **Mid-Life Changes**

Figure 8-1. pc-PRAISE input data categories.

For net-section stress failure criteria, only the flow stress is required. For tearing modulus based criteria, the tensile properties required are J_{Ic}, dJ/da, yield strength, elastic modulus, and D and n of the Ramberg-Osgood stress-strain equation.

ICRAKS -- Stress corrosion initiation sites. ICRAKS is the maximum number of cracks that can initiate by stress corrosion mechanisms. The length of the cracks at the time of initiation, its location around the circumference, and the time to initiation are all distributed variables.

IREPLS -- Number of replications for SCC-initiated cracks only analysis. When pre-existing cracks are not included in the analysis, IREPLS weld joints are simulated using SCC-initiated cracks. Stratification based on crack size is not available in this case. If INCIAT = 0 or 2, then IREPLS is not used.

IREPAR -- Option for repairing leaking cracks. If IREPAR = 1, then all the through-wall cracks are repaired, if one or more crack has a detectable leak rate. The cracks can continue to initiate and cracks that are not through-wall at the time of repair, can continue to grow. If IREPAR = 0 or if analysis is for pre-existing cracks only, then the leaking welds are replaced with perfect welds.

BNDRY -- a/h boundary above which initiated cracks are not included. If both pre-existing and initiated cracks are considered (INCIAT = 2), then the initiated cracks are not considered whenever the depth of a sampled pre-existing crack is greater than BNDRY.

ISF -- Flag for fatigue crack growth properties. Fatigue crack growth properties for ferritic material are hard-coded into the program and can be accessed by setting ISF = 1. If ISF = 0, then the fatigue crack growth coefficient is input by the user on Card 2B.

MTTYPE -- Material type. Material properties for SCC-initiation and growth are hard-wired into pc-PRAISE for 304 (MTTYPE = 1) and 316 NG (MTTYPE = 2). The user only needs to select one of these materials.

ISEED -- Random number seed 1.

ISEEDR -- Random number seed 2. The sequence of random numbers generated in pc-PRAISE depends on ISEED and ISEEDR. For a given pair of seeds, the same sequence of random numbers is obtained. The sequence can be changed by varying the seeds.

IREMED -- Number of future remedial actions. If IREMED > 0, then stresses, wall thickness, water chemistry, and residual stresses can be changed IREMED times during the plant lifetime. A maximum of four remedial actions can be modeled.

NTRIES -- Parameter to determine the number of replications to be taken from each cell. If the stratified sampling mesh is to be generated internally by the code, then NTRIES samples are to be taken from each cell. When the user defines the cells and NTRIES > 0, NTRIES is a multiplier on NUMTRY(M) (the user-defined number of replications in the M-th cell). If the user defines the cells and NTRIES < 0, <u>all</u> of the cells will have ABS (NTRIES) replications. This option is particularly convenient when a small number of replications from each cell is needed for testing purposes. NTRIES is not used if INCIAT = 1. For deterministic fatigue crack growth analysis, NTRIES should be set equal to 1.

ISQARE -- Option for definition of the cells in the stratification scheme. If ISQARE = 1, then pc-PRAISE internally generates the set of cells. The user specifies the extent of the sample space and the number of divisions in each coordinate direction. The range of coordinates is given by:

1. AOHLOW ≤ a/h ≤ AOHUP
2. AOBLFT ≤ a/b ≤ AOBRGT

The a/h and a/b coordinates are then divided into NAOH and NAOB equal intervals, respectively. In other words, the sample space is divided into (NAOH)(NAOB) cells, each cell with dimension

(AOHUP - AOHLOW)/NAOH by (AOBRGT - AOBLFT)/NAOB

If ISQARE = 0, the user must supply the a/h and a/b boundaries of each cell along with the number of replications to be performed in each cell. ISQARE is not used if INCIAT = 1.

KTYPES -- Total number of types of transient events that are to be modeled. pc-PRAISE assumes that the heat-up/cool-down cycle is the first transient event type. This does <u>not</u> include inspection events or evaluation earthquakes.

KRKDIS -- Parameter to select the type of probability distribution function that defines the initial crack size distribution.

NEVAL -- Option to define the points in time when the reliability is to be evaluated. If NEVAL < 0 is input, pc-PRAISE performs an evaluation every ABS (NEVAL) years. If NEVAL > 0 is supplied, the user reads NEVAL evaluation times into the vector (TEVAL(I), I = 1, ..., NEVAL).

NINSPT -- Option to define the number of times during the plant lifetime when in-service inspections are to be performed. The user reads NINSPT values into the vector (TINSPT(I), I = 1, ..., NINSPT).

NQUAKE -- Option for earthquake evaluations. If NQUAKE = 0, no earthquakes are evaluated. If NQUAKE > 0, evaluation earthquakes are inserted in at user specified intervals.

IDEBUG -- Option for additional debugging output. IDEBUG = 0 yields the normal output, while IDEBUG = 1 or 2 gives the additional output. The user is cautioned that this option not only generates a large volume of output, but also the output is presently not well formatted. The debug output is only intended for the programmers and not for the users of the code.

KONPRP -- Flag for the distribution of fatigue crack growth relationship. This flag affects both the ferritic crack growth, for which the constants are hard-coded, as well as the user-supplied inputs for austenitic or other material. If KONPRP = 1, then the fatigue crack growth is deterministic. If KONPRP = 1 and if the ferritic crack growth is selected (ISF = 1), then the median crack growth rate is used. If KONPRP = 1 and user-supplied C is used (ISF = 0), then the same value of C is used through out the simulation. If KONPRP = 0, then for ferritic material, the hard-coded distribution of crack growth is used; for user-supplied austenitic or other material, the C is considered to be lognormally distributed. For deterministic fatigue crack growth analysis, the value of KONPRP should be set equal to 1.

NEQINT -- Number of earthquake intensity categories.

MCELLS -- Number of cells in the stratified sample space when it is input by the user. If pc-PRAISE constructs the sample space, the value of MCELLS is ignored. For deterministic fatigue crack growth analysis, MCELLS should be set equal to 1.

KNSFLO -- Option for the flow stress model. If KNSFLO = 0, the flow stress is normally distributed and changed at the beginning of each replication. When KNSFLO = 1, a constant value is assumed throughout the calculation.

NSKIP -- Frequency of printout for the indicator functions. Normally, the value of the indicator function is printed out for every cell and every evaluation time. The user can reduce the amount of output by skipping some of the evaluation times in the printout. The number of evaluation times between successive printouts is equal to NSKIP. For example, if NSKIP = 5, then every fifth evaluation time is printed out. If NSKIP ≤ 0, then no indicator functions are printed out.

NPSI -- Option for modeling an ultrasonic pre-service inspection. If NPSI = 0, then no inspection is performed. If NPSI = 1, a pre-service inspection is performed.

ISCC -- Option for modeling stress corrosion cracking (SCC). If ISCC = 0, then no stress corrosion cracking is modeled, i.e., only fatigue crack growth is analyzed. If ISCC = 1, only stress corrosion cracking is modelled. If ISCC = -1, both fatigue and stress corrosion cracking are modeled simultaneously. If stress corrosion initiated cracks are considered, then ISCC should be 1 or -1.

ISIGRS -- Option for adding the contribution of welding residual stresses. If ISIGRS = 0, then no residual stresses are modeled. ISIGRS = 1 through 6 select various residual stress models.

Additional variables in the problem definition are:

THRIZN -- Plant lifetime (years). If no failures occur, this is the maximum length of time that a particular replication runs.

DTSCC -- Maximum time step (years) to be used in the SCC calculations.

8.2.2 Geometry and Material Properties

The variables that define the pipe geometry are:

THICK -- wall thickness of the pipe

RIN -- inside radius of the pipe.

ELOVRR -- Ratio of effective pipe length to radius. It is used to calculate relaxation of displacement-controlled stresses due to the presence of a crack. ELOVRR is used only if tearing modulus based failure criteria is selected (IFAILC = 1 or 2).

As shown in Section 4.2, the fatigue crack growth relationships in pc-PRAISE are:

$$\frac{da}{dN} = \begin{cases} 0 & \text{if } (\Delta\bar{K}_a)_{eff} \le K_o \\ C(\Delta\bar{K}_a)_{eff}^{m} & \text{otherwise} \end{cases} \qquad (8\text{-}1)$$

and

$$\frac{db}{dN} = \begin{cases} 0 & \text{if } (\Delta\bar{K}_b)_{eff} \le K_o \\ C(\Delta\bar{K}_b)_{eff}^{m} & \text{otherwise} \end{cases} \qquad (8\text{-}2)$$

where $(\Delta\bar{K}_i)_{eff} = \Delta\bar{K}_i/(1-R_i)$. The inputs for Equations 8-1 and 8-2 are:

THRHLD -- The threshold value for crack propagation (ksi-in$^{1/2}$). This corresponds to K_o in Equations 8-1 and 8-2.

EMEXP -- Value of the exponent denoted by m in Equations 8-1 and 8-2.

CONSMU -- Parameter for the constant in the crack growth law. If the constant is the same in each replication (ICONTRP = 1), then CONSMU is the value of the constant. If C is lognormally distributed (KONPRP = 0), then CONSMU is the median of the distribution.

CONS90 -- When C is lognormally distributed (KONPRP = 0), CONS90 is the 90th percentile of the distribution. If KONPRP = 1 this value is ignored.

Complete pipe severance is assumed to occur when (i) net-section stress exceeds the flow stress (if IFAILC = 0 or 2), or (ii) $J_{\text{applied}} \geq J_{\text{Ic}}$ <u>and</u> $(dJ/da)|_{\text{applied}} \geq (dJ/da)|_{\text{material}}$ (if IFAILC = 1 or 2). In the case of net-section failure criteria, material flow stress is the relevant parameter. pc-PRAISE can treat the flow stress as a constant or normally distributed.

SFLOMU -- Value of the flow stress (ksi). When it has a constant value throughout the calculation (KNSFLO = 1), this is σ_{flo}. When it is normally distributed (KNSFLO = 0), SFLOMU is the mean value.

SFLOSD -- Standard deviation of the flow stress (ksi) when it is normally distributed.

In the case of tearing modulus based failure criteria, the following material properties are used, all of which are treated as constants.

XJIC -- J_{Ic} of the material (in-kips/in^2).

DJDAMT -- dJ/da in ksi.

SIG0 -- Yield strength in ksi.

DEE -- Coefficient D (in ksi) in the power law hardening equation, $\epsilon = (\sigma/D)^n$.

XN -- Exponent n in the power law hardening equation.

YOUNGS -- Elastic modulus in ksi.

Probability of failure of an uncracked pipe is estimated by calculating the probability of the load-controlled stress (σ_{LC}) exceeding the ultimate tensile strength. The ultimate tensile strength of the pipe material is assumed to be normally distributed. The following inputs are required.

SULTMU -- The mean value of the ultimate tensile stress (ksi).

SULTSD -- The standard deviation of the ultimate tensile stress (ksi).

IULT -- Indicator flag. IULT can take values between -3 to +3. If IULT = 0, then probability of failure is calculated only for the given value of σ_{LC}. If IULT $\neq$ 0, then the probability of failure is calculated at additional ABS (IULT) stress values between zero and σ_{LC}. If IULT > 0, then the intermediate stress values are obtained by linear interpolation. Logarithmic interpolation is used if IULT < 0.

8.2.3 Initial Crack Size Distribution

In pc-PRAISE, the initial crack size distribution is given in terms of the crack depth distribution and an aspect ratio distribution. If the crack depth is lognormally distributed, the probability density function (pdf) is given by

$$p(a) = \frac{1}{\lambda a \sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln a - \ln a_{50}}{\lambda}\right)^2\right] \tag{8-3}$$

The relevant input parameters are:

AMEDIN -- The median value of the lognormal distribution. It is equal to a_{50} in Equation 8-3.

ASIGMA -- The shape factor in the lognormal distribution. It is also the standard deviation of ln a and corresponds to λ in Equation 8-3.

Both AMEDIN and ASIGMA have units of inches.

If the crack depth is exponentially distributed, the pdf is

$$p(a) = \lambda \exp(-\lambda a) \tag{8-4}$$

and the required input is

ALAMDA - The intensity or rate parameter (in^{-1}) for an exponential distribution. (λ in Equation 8-4 corresponds to $1/\mu$ in Equation 2-38.)

For both Equations 8-3 and 8-4, pc-PRAISE computes normalization factors such that the integrals of p(a) over the range $0 \leq a \leq h$ are unity.

pc-PRAISE can model the crack aspect ratio either as a truncated lognormal or a shifted exponential distribution. For the truncated lognormal, the pdf is

$$p(b/a) = \begin{cases} 0 & b/a<1 \\ \dfrac{C}{S\sqrt{2\pi}\,(b/a)} \exp\left[-\dfrac{1}{2}\left(\dfrac{\ln(b/a)-\ln M}{S}\right)^2\right] & b/a>1 \end{cases} \tag{8-5}$$

and the input parameters are:

BOAMED -- Parameter analogous to the median in a lognormal distribution. It is equal to M in Equation 8-5.

BOASIG -- Parameter analogous to the shape parameter in a lognormal distribution. It is equal to S in Equation 8-5.

BOANRM -- The normalization factor, C, in Equation 8-5, which is calculated internally by PRAISE.

pc-PRAISE assumes that the integral of Equation 8-5 over the range one to infinity is equal to unity. The values of M, S, and C are usually defined by requiring that the mode of p(b/a) occurs at b/a = 1 and the probability of exceeding a given b/a is a certain amount, or

$$p(b/a > \beta_0) = p \tag{8-6}$$

where β_0 and p are based on engineering judgement, heuristic arguments, or convenience. If p(b/a) is treated as an exponential distribution, or

$$p(b/a) = \lambda \exp\left[-\lambda(b/a - 1)\right] \quad (b/a) \geq 1 \tag{8-7}$$

The relevant input parameter is:

BOALDA -- The rate parameter in the shifted exponential distribution on b/a. pc-PRAISE automatically calculates a normalization constant to ensure that the integral of Equation 8-7 between one and infinity is unity.

8.2.4 Inspection Times, Earthquake Evaluation Times, and Leak Detection

The pc-PRAISE user specifies the time for both the in-service inspection and evaluation times. The earthquake evaluation times can be set to occur uniformly over the lifetime of the plant at constant intervals of YY years by setting the variable NEVAL in Card 1B to -YY, or

$$\text{NEVAL} = -\text{YY} \tag{8-8}$$

On the other hand, the user can specify an arbitrary number of evaluation times by setting NEVAL equal to the number of evaluations and then reading NEVAL values into the vector TEVAL(I), I = 1, ..., NEVAL. There must be at least one evaluation time; otherwise, no statistics will be recorded.

For in-service inspection times the user supplies NINSPT values into the vector TINSPT(I), I = 1, ..., NINSPT. If no in-service inspections are desired, pc-PRAISE must be followed by setting TINSPT(1) = XX, where XX is a number greater than the lifetime of the plant, or

$$\mathrm{TINSPT}(1) = \mathrm{XX} > \mathrm{THRIZN} \tag{8-9}$$

The pc-PRAISE model presently assumes that any leak rate above a given value will be detected and result in a plant shutdown. This input leak rate is given in the variable FNDLEK. pc-PRAISE also maintains statistics on the fraction of leaks which are classified as big leaks. The threshold value for big leaks is defined by ALKBIG.

8.2.5 Stratified Sample Space

The sample space used by pc-PRAISE has coordinates a/h and a/b. pc-PRAISE provides the user with two options for partitioning this space:

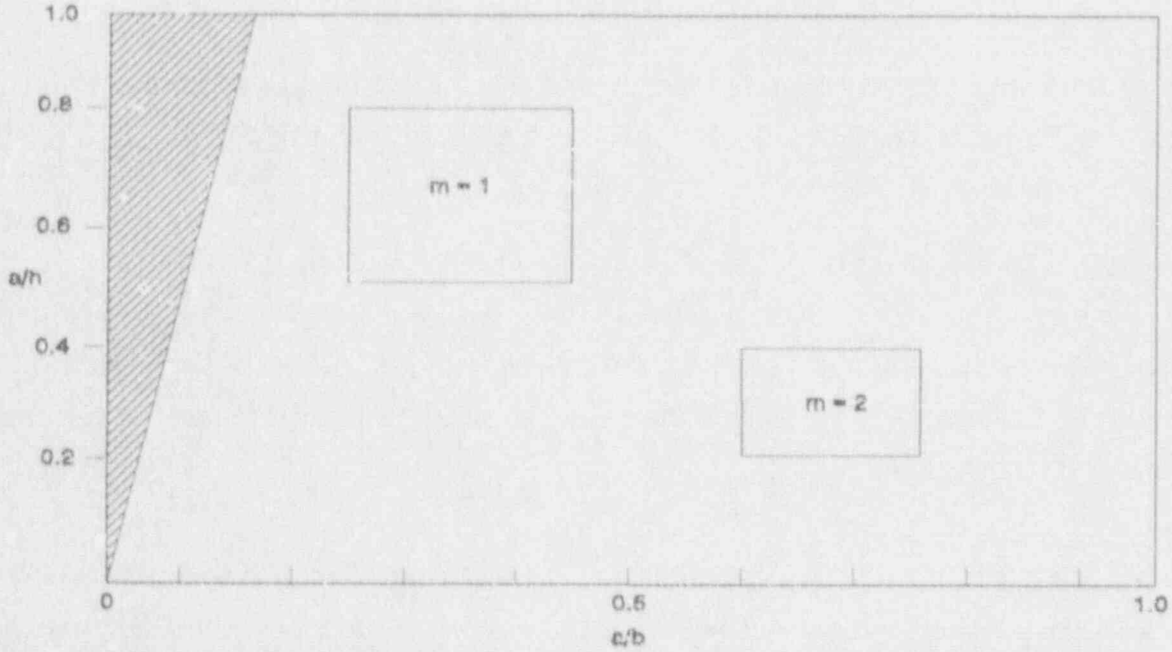
1. user specifies the coordinates of each stratification cell,
2. code internally partitions a portion of the sample space into a set of rectangular cells.

The present formulation of the initial crack size distributions restricts the stratification to rectangular cells.

For Option 1, the user specifies ISQARE = 0 on Card 1B and inputs for the M-th cell:

AOHSIZ(M,1) = the lower boundary of the a/h coordinate,
AOHSIZ(M,2) = the upper boundary of the a/h coordinate,
AOBSIZ(M,1) = the left boundary of the a/b coordinate,
AOBSIZ(M,2) = the right boundary of the a/b coordinate, and
NUMTRY(M) = the number of replications to be taken from the M-th cell.

The values of AOHSIZ and AOBSIZ for two typical cells are illustrated in Figure 8-2.



For the m = 1 cell

AOHSIZ (1,1) = 0.50
AOHSIZ (1,2) = 0.80

AOBSIZ (1,1) = 0.25
AOBSIZ (1,2) = 0.45

For the m = 2 cell

AOHSIZ (2,1) = 0.20
AOHSIZ (2,2) = 0.40

AOBSIZ (2,1) = 0.60
AOBSIZ (2,2) = 0.75

Figure 8-2. Specification of the stratification scheme by the pc-PRAISE user.

In Option 2, only a portion of the sample space is partitioned. The boundaries of this subspace are defined by:

AOHLOW = minimum value of the a/h coordinate,
AOHUP = maximum value of the a/h coordinate,
AOBLFT = minimum value of the a/b coordinate, and
AOBRGT = maximum value of the a/b coordinate.

If the coordinates of the sample space are to be divided into n_1 and n_2 uniform parts in the a/h and a/b directions, respectively. The user sets NAOH = n_1 and NAOB = n_2. Normally, each cell in the sample space will have dimensions.

(AOHUP - AOHLOW)/(-NAOH) by (AOBRGT - AOBLFT)/(-NAOB)

If a cell lies entirely within the infeasible region of the sample space, it is neglected. A cell which has both feasible and infeasible region is redefined, if necessary, to give the minimum amount of infeasible area.

Option 2 is a particularly convenient method of partitioning the sample space for an initial scoping of the problem. However, after the user has obtained some measure of experience with a particular problem, it is recommended that he exercise Option 1 and develop a stratification scheme which is most efficient for the problem at hand.

In Option 2, the same number of replications are drawn from each cell. The negative of this number is input as NTRIES on Card 1B. For example, if 25 samples are to be drawn from each cell, the user must input NTRIES = 25. In Option 1, the user must indicate the number of samples to be taken from each cell. These values are specified as NUMTRY(M) and are entered along with the coordinates of each cell. However, in this case, the user has an additional option. He can multiply the input values by a constant integer value or indicate that the same number of samples are to be taken from each cell. Specifically, if the value of NTRIES on Card 1B is negative, pc-PRAISE will internally reset the value of

NUMTRY(M) to ABS (NTRIES). If a positive value of NTRIES is input, the NUMTRY(M) is resent to NTRIES times the input value, or

$$NUMTRY(M) = NTRIES * NUMTRY(M) \qquad (8\text{-}10)$$

If the user specifies NTRIES = 1, the number of replications as input through NUMTRY(M) will be used by pc-PRAISE.

8.2.6 Stresses, Stress Intensity Factors, and Frequency of Transients

The sixth series of input cards is devoted to defining the stresses, stress intensity factors, and the frequency of the transients that cause crack growth. Card 6A has the following inputs:

SIGCLD -- The cold shutdown, i.e., deadweight stress in the axial direction of the pipe (ksi).

SGDWTE -- The hot operating axial stress (ksi). This is the vector sum of the deadweight stress and the restraint of thermal expansion stress.

OPPRES -- The normal operating pressure of the plant (ksi).

PRFPRS -- If a hydrostatic proof test is to be modeled, PRFPRS is the hydrostatic pressure. If no hydrostatic proof test is desired, then an arbitrary negative value is supplied.

SIGVIB -- Peak-to-peak amplitude of the vibratory stresses (ksi). If SIGVIB is positive, pc-PRAISE models vibratory stresses. If SIGVIB is negative or zero pc-PRAISE does not model vibratory stresses.

VBTHLD -- Threshold for the load ratio in the calculation of the stress intensity factors under vibratory stresses. This corresponds to R* in Equation 4-4.

The variation in the stress intensity factor during a transient where radial gradient thermal stresses are important can be modeled as:

$$\Delta\bar{K}_{min,i} = \Delta T \sqrt{a}\ g_{min,i}(k,\ a/h,\ a/b) \tag{8-11}$$

and

$$\Delta\bar{K}_{max,i} = \Delta T \sqrt{a}\ g_{max,i}(k,\ a/h,\ a/b) \tag{8-12}$$

where ΔT is the temperature variation during the transient

a is the current crack depth

k is the transient identification number

$g_{min,\,i}$ (k, a/h, a/b) is a normalized function which gives the reduction in the value of the stress intensity factor for degree of freedom i during the transient

$g_{max,\,i}$ (k, a/h, a/b) is a normalized function which gives the increase in the value of stress intensity factor for degree of freedom i during the transient

Tabulated values of $g^*_{min,\,i}$ (k, a/h, b/a) and $g^*_{max,\,i}$ (k, a/h, b/a) must be supplied by the user for each transient in both the a/h and the b/a (or ℓ/a) directions. The asterisk (*) indicates that one of the coordinates in g^*_{min} , and $g^*_{max,\,i}$ is b/a rather than the a/b which is used in the pc-PRAISE calculation. The coordinates of the tables are the same for all transients.

The contribution of the radial gradient thermal stresses to the RMS-stress intensity factors is modeled by the functions g_{min} and g_{max} as discussed above. Since both g_{min} and g_{max} must be evaluated for each degree-of-freedom every time a transient with radial gradient thermal stresses is encountered, the simulation may become quite expensive if the evaluation of g_{min} and g_{max} is complicated. Therefore, PRAISE uses a two-dimensional tabular representation. The evaluation of g_{min} and g_{max} is then reduced to finding the appropriate entry in the table. Since the entries in the table are constant, they need to be generated only once. Hence, the table can be expanded to meet the accuracy requirements of the user.

Values of g^*_{min}, g^*_{max} are input by the user in tabular form with a/h and b/a as the coordinates. The number of entries in the a/h and b/a directions is NY and NX, respectively. The asterisk indicates that the coordinate of the second dimension is b/a rather than a/b. The transformation from g^*_{min} and g^*_{max} is carried out in the subroutine INTERP which is called from the MAIN routine. The tables for g_{min} and g_{max} have IX and IY entries in the a/b and a/b directions, respectively. Since the locus of the g^*_{min} and g_{min} points will not coincide, Lagrangian interpolation is used to derive the g_{min} points from the g^*_{min} points. The values for these tables are stored in one-dimensional arrays. This minimizes the cost of retrieving the data from three-dimensional arrays. This process is illustrated in Figure 8-3. The procedure for g_{max} is identical to the g_{min} procedure.

Values of NX, NY, IX, and IY are input on Card 6B. The coordinate points in the a/h direction are read into the vector (AAOH(I), I = 1, ..., NY) through Card 6C. The coordinate points in the b/a direction are read into the vector (ABOA(I), I = 1, ..., NX) through Card 6D. pc-PRAISE converts the values into corresponding a/b values.

For each transient, pc-PRAISE then reads in Card 6E and a sequence of 6F cards. In the present version of pc-PRAISE, the first transient type (k = 1) is assumed to be the heat-up/cool-down cycle in which only uniform through-wall stresses exist. Hence, when k = 1, no 6F cards are input. The inputs on Card 6E are:

NCYBLK -- Number of actual events of the k-th transient that is to be treated as a single equivalent event,

BLAMDA(K) -- Arrival time parameter for the transients. When BLAMDA(K) > 0.0, then the k-th transient arrives at uniformly spaced intervals of BLAMDA(K) years. If BLAMDA(K) < 0.0, then the k-th transient is treated as a Poisson process with ABS (BLAMDA(K)) as the average number of arrivals per unit time.

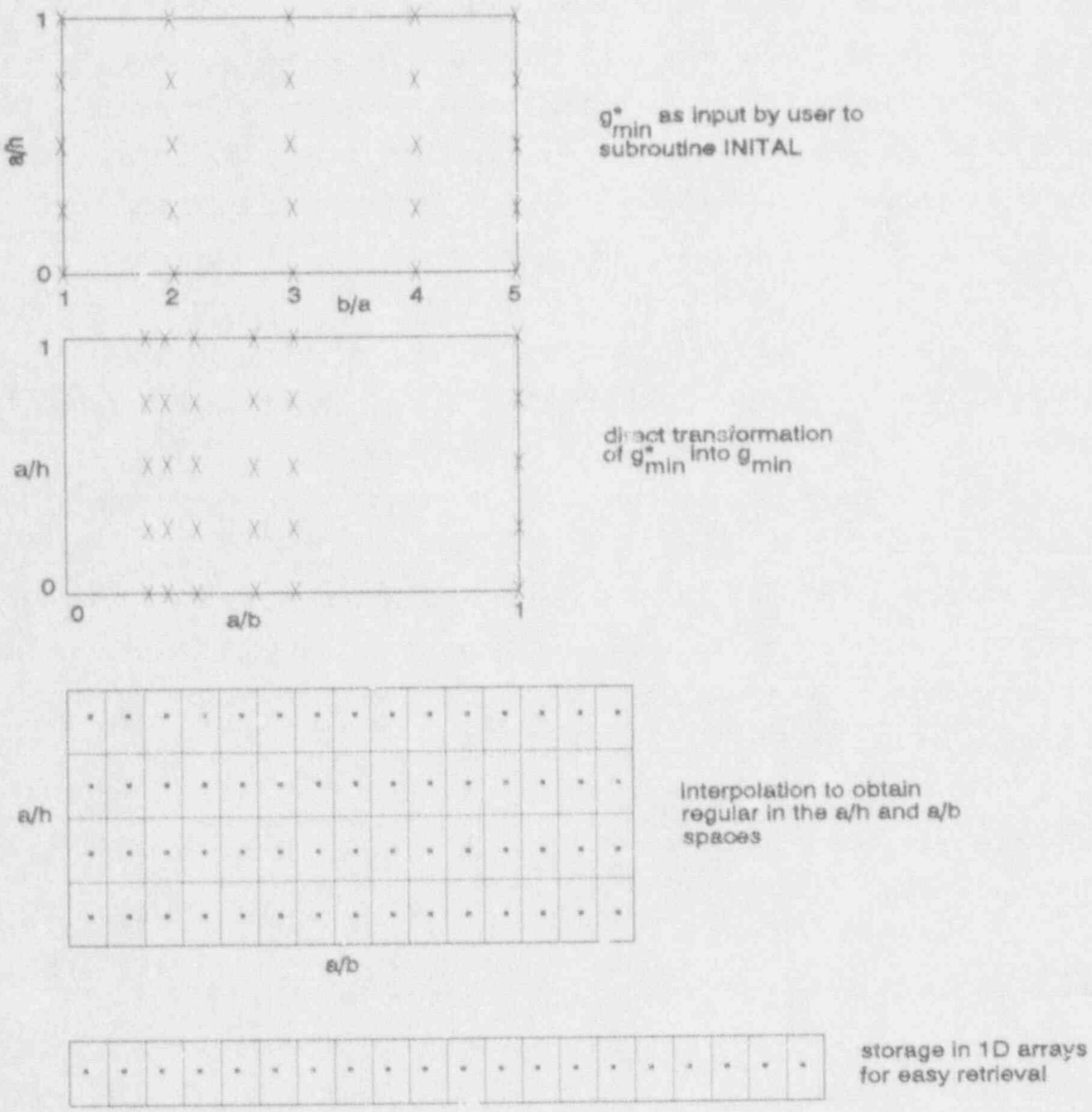


Figure 8-3. Derivation and storage of the g_{min} functions.

TEMP(K) -- The maximum temperature excursion during the k-th transient.

TITLE(K) -- A description of the k-th transient.

The 6F cards are arranged so that the user inputs the normalized stress intensity factors in the following order

A. $g^*_{min,a}$ (k, a/h, b/a)
B. $g^*_{max,a}$ (k, a/h, b/a)
C. $g^*_{min,b}$ (k, a/h, b/a)
D. $g^*_{max,b}$ (k, a/h, b/a)

For example, in the k-th transient, all of the $g^*_{min,a}$ values are read prior to reading any of the $g^*_{max,a}$ values. Within each of Items A through D, two DO loops are used to read the values of these functions. The outer loop is on the b/a coordinate and starts with the smallest value. All of the a/h values for a given value of b/a are input from the same READ statement. Hence, the smallest a/h value for a given b/a always appears as the first entry on a card.

The SCC-initiation and growth model also requires the following inputs:

OSTART -- Oxygen concentration (ppm) in the coolant during plant start-up operation.

OSTEDY -- Oxygen concentration (ppm) in the coolant during steady-state plant operation.

TFSTDY -- Coolant temperature (°F) at steady-state plant operation. This temperature is used for SCC calculations.

DURATN -- Duration (hrs.) of heat-up transient. This time is used to calculate strain rates for SCC calculations.

CONDUC -- Conductivity (μs/cm) of the coolant.

8.2.7 Residual Stresses

Six options (ISIGRS) are available for residual stresses. The Options 2, 3, 4 are for built-in residual stresses for large, intermediate, and small lines, respectively. No other inputs are required if Options 2, 3, or 4 are selected. Options 1, 5, and 6 require additional inputs.

Option 1 requires the user to input coefficients of the curve-fits to stress intensity factors due to residual stresses. The curve-fit equations are of the form

$$\bar{K}_{Res,i} = \sum_{k=1}^{K} \left\{ \sum_{\ell=1}^{L} b_{\ell k} (a/h)^{\ell-1} \right\} (a/b)^{k-1} \tag{8-13}$$

KKA = Limit K in Equation 8-13 for $\bar{K}_{Res,a}$
LLA = Limit L in Equation 8-13 for $\bar{K}_{Res,a}$
KKB = Limit K in Equation 8-13 for $\bar{K}_{Res,b}$
LLB = Limit L in Equation 8-13 for $\bar{K}_{Res,b}$
B(L,K) = Coefficients $b_{\ell,k}$ for evaluation of $\bar{K}_{Res,a}$
B(L,K) = Coefficients $b_{\ell,k}$ for evaluation of $\bar{K}_{Res,b}$

For Option 5, stresses at the ID and OD are input by the user. pc-PRAISE assumes the residual stresses to be axisymmetric and linearly varying through the wall. The residual stresses specified by Option 5 are considered deterministic.

RSIN -- Residual stress (ksi) at the inside surface of pipe.

RSOUT -- Residual stress (ksi) at the outside surface of pipe.

Option 6 is for probabilistic modeling of IHSI/MSIP residual stresses. The user specifies the mean and standard deviation of residual stresses at the ID. The residual stress at the ID is assumed to be normally distributed. pc-PRAISE assumes the residual stresses to be axisymmetric and linearly varying through the wall. By making the stresses self-equilibrating through-wall, the through-wall distribution is calculated internally.

RSINM -- Mean value of residual stress (ksi) at the inside of the pipe.

RSINSD -- Standard deviation of the residual stress (ksi) at the inside of the pipe.

8.2.8 Seismic Crack Growth Parameters

pc-PRAISE is designed to treat a spectrum of earthquake intensities by modeling several earthquakes from each intensity level. The number of earthquake intensity categories is denoted by NEQINT and input through the problem specification card (1B). The number of separate earthquakes to be considered within each intensity category is read from Card 7A into the vector NEQCLS. NEQCLS(N) is the number of earthquakes in the N-th category. The input for earthquake crack growth parameters is given on Card 7B and is controlled by two DO loops. The outer loop is over the categories of earthquake intensity, while the inner loop is on individual earthquakes within each intensity category.

The cyclic stresses caused by earthquakes are input as equivalent constant amplitude cycles. The maximum and minimum stresses for fatigue crack growth are calculated as follows:

Maximum stress = SIGHOT + SIGEQ
Minimum stress = SIGHOT - SIGEQ

The stress used in the failure criteria is calculated as

SIGPC + SGEQMX

where SIGHOT = SGDWTE + SIGPRS
SIGPC = SIGPRS + SIGCLD

The following inputs are required:

NEQCLS( ) -- Number of earthquakes in each category. Input on Record 7A.

For each earthquake in each category, the cyclic stresses are input on Record 7B.

NCYCEQ(,) -- Number of equivalent cycles in the earthquake.

SIGEQ(,) -- The equivalent amplitude of stress (ksi).

SGEQMX(,) -- The maximum amplitude of stress in the earthquake.

TITLE(,) -- Description of this earthquake.

The above data for each earthquake are read for each earthquake for each class, with the outer loop on NEQINT and the inner loop on NEQCLS( ).

8.2.9 Mid-Life Changes

The effect of changing stresses, water chemistry, and residual stresses can be modeled in pc-PRAISE. Number of mid-life changes (IREMED) is specified on one of the control cards, and the details are entered on Card 8A.

RTIMES( ) -- Time (years) at which one or more of the following variables are changed.

THICKS( ) -- Wall thickness (inches) [illegible] pipe. Thickness may change due to weld-overlay treatment. The parameters dependent on thickness are recalculated at the time when change occurs. These include pressure stress, distribution of the residual stresses, area of the uncracked pipe, etc.

OSTARS( ) -- Oxygen concentration (ppm) during start-up operation after RTIMES( ) years.

OSTDYS( ) -- Oxygen concentration (ppm) during steady-state operation after RTIMES( ) years.

CONDUS( ) -- Coolant conductivity (μs/cm) after RTIMES( ) years.

SGCLDS( ) -- Deadweight stress (ksi) after RTIMES( ) years.

SDWTES( ) -- Deadweight and thermal expansion stress (ksi) after RTIMES( ) years.

SGVIBS( ) -- Peak-to-peak amplitude of the vibratory stresses after RTIMES( ) years.

ISIGRX( ) -- A flag indicating whether or not residual stresses have changed at RTIMES( ) years. ISIGRX( ) = 6 indicates that there is no change in the residual stresses. If there is a change in the residual stresses (ISIGRX( ) = 7), the new residual stresses can only be characterized as MSIP or IHSI stresses. The mean and the standard deviation of residual stresses at the ID is required. The residual stresses at the ID are assumed to be normally distributed.

RSINMS( ) -- Mean value of IHSI/MSIP residual stress (ksi) at ID after RTIMES( ) years.

RSISDS -- Standard deviation of the IHSI/MSIP residual stress (ksi) at the ID after RTIMES( ) years.

The above values of thickness, operating stresses, coolant chemistry, and residual stresses remain effective until another mid-life change occurs.

8.3 Detailed Formats for Input Cards

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

CARD TITLE CARD ID **0A**
READ Always

VARIABLE	**COLUMNS**	**FORMAT**	**DESCRIPTION**
TITLE	1-80	20A4	Problem description

CARD **PROBLEM CONTROL VARIABLES** ID **0B**
READ Always

VARIABLE	**COLUMNS**	**FORMAT**	**DESCRIPTION**
INCIAT	1-5	I5	0: Run for pre-existing cracks only. 1: SCC initiated cracks only. 2: Pre-existing & initiated cracks.
IFAILC	6-10	I5	Failure criteria to be used: 0: Net section failure. 1: J_{Ic}, dJ/da exceedance. 2: Both.
ICRAKS	11-15	I5	Stress corrosion crack initiation sites (used only if INCIAT ≥ 1).
IREPLS	16-20	I5	Number of replications for crack initiation problem (not used for INCIAT = 0 or = 2).
IPRAIS	21-25	I5	Not used.
IREPAR	26-30	I5	= 0: Welds with cracks that leak and are detected and replaced with perfect welds. = 1: Cracks that leak and are detected and removed. At the time of repair, all leakers are repaired. If INCIAT = 0, then IREPAR is set to 1.
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. Used only if INCIAT = 2.
ISF	41-45	I5	Material type (for fatigue properties) 0: Austenitic or other. 1: Ferritic.
MTTYPE	51-55	I5	Material type (only for SCC). = 1: 304 = 2: 316NG

VARIABLE	**COLUMNS**	**FORMAT**	**DESCRIPTION**
ISEED	56-62	I7	Seed for the random number generator.
ISEEDR	63-70	I7	Seed for the random number generator.
IREMED	71-75	I5	Number of future remedial actions (change in water chemistry, IHSI, weld overlays, etc.). IREMED ≤ 4

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: The 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: pc-PRAISE 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 distribution. KRKDIS = 1: Crack depth is lognormal. Aspect ratio is lognormal. KRKDIS = 2: Crack depth is lognormal. Aspect ratio is exponential. KRKDIS = 3: Crack depth is exponential. Aspect ratio is lognormal. KRKDIS = 4: Crack depth is exponential. Aspect ratio is exponential.

CARD **PROBLEM SPECIFICATION [Continued]** ID **1B**
READ Always

VARIABLE	**COLUMNS**	**FORMAT**	**DESCRIPTION**
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.
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	Flag for distribution of fatigue crack growth. KONPRP = 0: C is lognormally distributed if ISF = 0, or built-in distribution for ferritic material used if ISF = 1. KONPRP = 1: C is constant if ISF = 0, or the median crack growth rate used if ISF = 1.

CARD **PROBLEM SPECIFICATION [Continued]** ID **1B**
READ Always

VARIABLE	**COLUMNS**	**FORMAT**	**DESCRIPTION**
NEQINT	46-50	I5	Number of seismic intensity classes to be simulated. If NQUAKE = 0: set NEQINT = 0. pc-PRAISE, as presently dimensioned, can handle up to 10 classes.
MCELLS	51-55	I5	Number of cells in the calculational grid. [illegible] = 1: The value of MCELLS is [illegible]
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. If NSKIP ≤ 0, indicator functions are not printed.
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 [Continued]** ID **1B**
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, 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. ISIGRS = 6: Contribution of IHSI or MSIP residual stresses is modeled. User to input the mean and the standard deviation of stress at the ID.

CARD **IHSI and MSIP RESIDUAL STRESS DEFINITION** ID **1C0**
READ Only if ISIGRS = 5 or 6, on Card 1B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
RSIN	1-10	E10.3	Residual stress on the inside surface of a pipe (ksi). (For ISIGRS = 5)
RSOUT	11-20	E10.3	Residual stress on the outside surface of a pipe (ksi). (For ISIGRS = 5)
RSINM	1-10	E10.3	Mean of the IHSI or MSIP residual stress on the ID in ksi. (For ISIGRS = 6)
RSINSD	1-10	E10.3	Standard deviation of the IHSI or MSIP stress on the ID in ksi. (For ISIGRS = 6)

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 define 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 polynomial which define 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 polynomial which define the contribution on 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 polynomial which define the contribution of residual stress to the "RMS-averaged" stress intensity factor in the length direction.

CARD **TIME PARAMETERS, NDE PARAMETERS** ID **1D**
READ Always

VARIABLE	**COLUMNS**	**FORMAT**	**DESCRIPTION**
THRIZN	1-10	E10.3	Maximum plant lifetime for the simulation (years).
DTSCC	11-20	E10.3	Time step to be used in calculating SCC growth (years). Used only if ISCC = 1 or -1 on Card 1B.
ICTYPE	21-25	I5	Crack orientation flag. = 0: Circumferential crack analysis. = 1: Longitudinal crack analysis (disabled in current pc-PRAISE).

The following inputs on this card are not required if NPSI = 0 & NINSPT = 0.

VARIABLE	**COLUMNS**	**FORMAT**	**DESCRIPTION**
IPTYPE	26-30	I5	Default sets of NDE parameters EPST, ASTAR and ANUU for various pipe types. = 0: Thick-walled austenitic pipe = 1: Thick-walled ferritic pipe = 2: Thin-walled austenitic pipe Default values are as follows:

IPTYPE	EPST	ASTAR	ANUU
0	0.	0.5*THICK	1.6
1	0.005	0.25	3.0
2	0.005	0.25	1.33

VARIABLE	**COLUMNS**	**FORMAT**	**DESCRIPTION**
EPST	31-40	E10.0	User-specified value of "ϵ" parameter; overrides default value. Leave blank to use default.
ASTAR	41-50	E10.0	User-specified depth of crack with 50% probability of detection (inches); overrides default value. Leave blank to use default.
TRANSD	51-60	E10.0	Transducer diameter (inches); default = 1.0 inch.
ANUU	61-70	E10.0	User-specified value of "ν" parameter; overrides default value. Leave blank to use default.

CARD **PIPE DIMENSIONS** 1D **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 lognormal 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 lognormal distribution.

CARD **SCC VARIABLE** ID **2B-1**
READ If ISCC $\neq 0$ <u>or</u> INCIAT $\neq 0$

VARIABLE	**COLUMNS**	**FORMAT**	**DESCRIPTION**
OSTART	1-10	F10.5	0_2 at start-up (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).
CONDUC	41-50	F10.5	Coolant conductivity (μs/cm).

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-kips/in^2). Required only if IFAILC $\neq$ 0.
DJDAMT	31-40	E10.4	dJ/da (in ksi). Required only if IFAILC $\neq$ 0.
SIG0	41-50	E10.4	Yield strength in ksi. Required only if IFAILC $\neq$ 0.
DEE	51-60	E10.4	The constant D in ksi in the power law $\epsilon = (\sigma/D)^n$ for hardening material. Required only if IFAILC $\neq$ 0.
YOUNGS	61-70	E10.4	Young's modulus in ksi. Required only if IFAILC $\neq$ 0.
XN	71-80	E10.4	Exponent n in the power law $\epsilon = (\sigma/D)^n$ for hardening material. Required only if IFAILC $\neq$ 0.

CARD **ULTIMATE STRESS DEFINITION** ID **2D**
READ Always

VARIABLE	**COLUMNS**	**FORMAT**	**DESCRIPTION**
SULTMU	1-10	E10.0	The mean value of ultimate tensile stress (ksi).
SULTSD	11-20	E10.0	≥ 0: Standard deviation of ultimate tensile stress (ksi). < 0: Constant ultimate tensile stress.
IULT	21-25	I5	Indicator for interpolation of pipe break probability; ABS (IULT) = number of interpolated points. > 0: Linear interpolation. < 0: Logarithmic interpolation.

CARD **INITIAL CRACK DEPTH DISTRIBUTION** ID **3A**
READ Only if INCIAT ≠ 1

VARIABLE	**COLUMNS**	**FORMAT**	**DESCRIPTION**
AMEDIN	1-10	E10.3	Median of the lognormal distribution on crack depth. (Read if KRKDIS = 1, 2)
ASIGMA	11-20	E10.3	Shape factor (= standard deviation of logarithm of A) of the lognormal distribution on crack depth. (Read if KRKDIS = 1, 2)
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 $\neq$ 1

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
BOAMED	1-10	E10.3	Parameter analogous to the median in the truncated lognormal 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 lognormal 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 > 0

VARIABLE	**COLUMNS**	**FORMAT**	**DESCRIPTION**
TEVAL	1-80	8E10.3	Evaluation time (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 ≠ 0

VARIABLE	**COLUMNS**	**FORMAT**	**DESCRIPTION**
NAOH	1-5	I5	Number of divisions of the a/h coordinate in the sample space definition. The a/h coordinate is limited to the region AOHLOW ≤ a/h ≤ AOHUP.
NAOB	6-10	I5	Number of division of the a/b coordinate in the sample space definition. The a/b coordinate is limited to the region AOBLFT ≤ a/b ≤ AOBRGT.
AOHLOW	11-20	E10.3	Lower limit on the a/h coordinate.
AOHUP	21-30	E10.3	Upper limit on the a/h coordinate.
AOBLFT	31-40	E10.3	Lower limit on the a/b coordinate.
AOBRGT	41-50	E10.3	Upper limit on the a/b coordinate.

CARD **STRATIFIED SAMPLE SPACE [Continued]** ID **5A**
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 [Continued]** ID **5A**
READ Only if ISQARE ≠ 0 and NTRIES > 0

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 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 Equation 4-4 and Section 3.9 of NUREG-2301, Harris 82a] 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. In the current version, NX should always be 6.
NY	6-10	I5	Number of entries in the a/h coordinate for the input of the g^*_{min} and g^*_{max} functions. In the current version, NY should always be 9.
IX	11-15	I5	Number of entries in the a/b coordinate for the internal tables on the g_{min} and g_{max}.
IY	16-20	I5	Number of entries in the a/h coordinate for the internal tables on g_{min} and g_{max}. Optimum values for IX and IY are 20.

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 gradient thermal stresses to the stress intensity problem (I = 1, ..., NY).

CARD **FREQUENCY OF HEAT-UP/COOL-DOWN 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's 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 heat-up/cool-down, i.e., $\bar{K} > 1$

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 POLYNOMIAL 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 5-5; KKA corresponds to K in Equation 5-5.

CARD **COEFFICIENTS FOR THE POLYNOMIAL 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	$(b(\ell,k), \ell = 1, ..., LLB)$. A separate card is used for each value of k (k = 1, ..., KKB). LLB corresponds to L in Equation 5-5; KKA corresponds to K in Equation 5-5.

CARD **EARTHQUAKES PER MAGNITUDE CATEGORY** ID **7A**
READ Only if NQUAKE = [illegible] 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 an intensity category.
NCYCEQ(N,LEQ)	1-10	I10	Number of equivalent constant amplitude cycles used to represent the crack growth.
SIGEQ(N,LEQ)	11-20	F10.3	Stress amplitude (ksi).
SGEQMX(N,LEQ)	21-30	F10.3	Internally calculated.
TITLE(N,LEQ)	31-80	5A10	Description for this particular earthquake.

CARD INPUTS FOR MID-LIFE CHANGES IN OPERATING STRESSES, CHEMISTRY, OR RESIDUAL STRESSES ID 8A

READ Only if IREMED > 0

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
RTIMES(I)	1-10	E10.4	Time (in years) at which one or more of the following variables are changed.
THICKS(I)	11-20	E10.4	Wall thickness of pipe (inches).
OSTARS(I)	21-30	E10.4	O_2 at start-up (ppm).
OSTDYS(I)	31-40	E10.4	O_2 at steady state (ppm).
CONDUS(I)	41-50	E10.4	Coolant conductivity (μs/cm).
SGCLDS(I)	51-60	E10.4	Deadweight stress (ksi).
SDWTES(I)	61-70	E10.4	Deadweight and restraint of thermal expansion components of stress in the hot normal operating condition (ksi).
SGVIBS(I)	71-80	E10.4	Peak-to-peak amplitude of the high cycle vibratory stresses (ksi). If SIGVIB < 0, no vibratory stresses are modeled.

CARD **INPUTS FOR MID-LIFE CHANGES IN OPERATING STRESSES, CHEMISTRY, OR RESIDUAL STRESSES [Continued]** ID **8B**

READ Only if IREMED > 0

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
ISIGRX(I)	1-10	I10	IHSI or MSIP residual stress flag (6 or 7). A value of 7 indicates no change from the previous state.
RSINMS(I)	11-20	E10.4	Mean value of the stress at the ID in ksi (MSIP or IHSI stress). Not required if ISIGRX(I) is 7.
RSISDS(I)	21-30	E10.4	Standard deviation of the stress at the ID in ksi (MSIP or IHSI stress). Not required if ISIGRX(I) is 7.

8.4 PRAISE Input-Processor (PR_INPUT)

PR_INPUT is a utility to aide the user in setting up a PRAISE input file. It prompts the user to input values of the variables, one at a time. It displays the current value of the variable and also the valid range for the variable. When the PR-INPUT command is invoked, it first prompts the user with an option to read a template file. [A template file (extension.TPL) is a binary file containing the input data that are processed by PR_INPUT. A template file is written by the input processor at the end of the run.] If a template file is specified by the user, all the variables are initialized to values stored in the template file. Next, the processor requests inputs generally in the same order as they appear in Section 8.3. A typical prompt for input is as follows:

```
Failure Criteria (IFAILC)

0 : Net-section stress
1 : Jlc, Tmat exceedance
2 : Both

The current value is   0   [valid range is > =   0   and < = 2]
Press ENTER to accept the current values, or Enter a new value.
```

For every prompt, the input-processor displays the FORTRAN variable name of the requested input as well as the valid range of inputs. The input-processor requests only the information required for the selected analysis and, if necessary, fills in the PRAISE compatible input file with dummy values. For example, the input processor will request the values of J_{Ic} and T_{mat} only if the selected failure criteria requires those values (IFAILC = 1 or 2).

The input-processor expects the following group of inputs, each of which requires a large number of data, to be saved in a file. The input processor requests the name of the file and then includes the file in a PRAISE input file. These groups of inputs are as follows:

1. **Stratification.** If the user selects to input coordinates of each cell (ISQARE = 0), then the user is expected to create a file containing the information requested on Card 5A.

2. **Stress Intensity Factors for Radial Gradient Thermal Stresses.** If more than one transient (KTYPES > 1) are to be considered in the analysis, the tabular inputs required on Cards 6E through 6F should be contained in a file.

3. **Seismic Data.** If seismic events are to be considered in the analysis (NQUAKE = 1), then the inputs required on Cards 7A and 7B should be contained in a file.

4. **Residual Stresses.** If the user selects the residual stress option (ISIGRS = 1), it requires coefticients of the polynomials defining the contribution of residual stresses to the stress intensity factors. The inputs required on Cards 6G and 6H should be saved in a file.

When all the inputs are completed, the input-processor prompts the user to enter file names for storing data in a template file and in a PRAISE-compatible input file.

9. OUTPUT

This section describes contents of the output files generated by PRAISE. A plotting utility for post-processing the results is also discussed.

9.1 Output Description

The output from a pc-PRAISE calculation consists of five basic parts:

A. input summary,

B. description of the stratification scheme and the number of samples taken from each cell (if pre-existing cracks are considered),

C. if required, listing of the indicator functions used in the calculation of the failure probabilities,

D. tabular summary of the failure probabilities (leak and LOCA) and their sampling standard deviation, and

E. statistics of initiated cracks, if SCC-initiation is considered.

Specific examples are given with the sample problems in the following section.

The input summary is intended to verify the user's problem specification. Pipe length to thickness ratio (ELOVRH) is computed as follows:

$$\mathrm{ELOVRH} = \mathrm{ELOVRR} * \mathrm{RIN/THICK}$$

ELOVRR and ELOVRH are used only if tearing modulus based failure criteria is used (IFAILC = 1 or 2). The outside radius of the pipe (ROUT) is computed as

$$\mathrm{ROUT} = \mathrm{RIN} + \mathrm{THICK}$$

ROUT is not printed on the output, but is used for the calculation of stresses. The user should note that the hot uniform stress shown in the summary represents

$$\sigma_{\mathrm{HOT}} = \sigma_{\mathrm{DW}} + \sigma_{\mathrm{TE}} + \sigma_{\mathrm{P}}$$

and is computed from

SIGHOT = SGDWTE+2.0*OPPRES*RIN*RIN / [(ROUT+RIN)*(ROUT-RIN)]

The stress under hydrostatic proof test is given by

$$\sigma_{Prf} = \sigma_P + \sigma_{DW}$$

or

SIGPRF = 2.0*PRFPRS*RIN*RIN / [(ROUT+RIN)*(ROUT-RIN)] + SIGCLD

The input variables are OPPRES and PRFPRS, while the output variables are SIGHOT and SIGPRF.

The description of the stratification cells includes the lower and upper boundaries for both the a/h and a/b coordinates, the conditional probability of occurrence, and the number of samples to be taken from each cell. The sum of the individual cell probabilities is also given. The stratification table also contains the number of leaks, big-leaks, and LOCAs that occurred in each cell, for the case of no earthquakes. The stratification section of the output does not appear if the case of only initiating cracks is selected.

The listing of the indicator function is intended to give the analyst a more detailed breakdown of the failures calculated for each cell. PRAISE is capable of showing every evaluation interval for all the cells. The user can reduce the volume of output by printing data at each NSKIP evaluation time. The first set of output is the number of failures obtained during an evaluation interval. For the cases of pre-service and/or in-service inspections, the numbers are weighted by the nondetection probability of the crack at the time it failed. These data are presented only for the no earthquake case. A second set of output gives the cumulative number of observed failures that have occurred prior to the evaluation time. This second set of data is given for the no earthquake case and for each of the earthquake intensity categories.

Finally, a tabular summary of the failure probabilities (leak, big leak, and LOCA) and estimated sampling standard deviation are given for the no earthquake case and for each of the earthquake intensity categories. The leak probability includes all leaks. It therefore includes large leaks, small leaks, and LOCAs. The large leak probability includes large leaks and LOCAs. The LOCA probability includes only sudden and complete pipe severances. All failure probabilities are cumulative. That is, they are the failure probability since beginning of plant lifetime. In the analysis of pre-existing cracks, the probabilities are conditional on a crack being initially present. Hence, to get absolute probabilities, they must be adjusted to account for the probability of a crack being initially present (see Section 2.4.3). The equations used in the estimation of failure probabilities and their standard deviations are described in Section 7.3. This section of the output also contains probability of failure for uncracked pipe, at several stress values requested by the user. If SCC-initiated cracks are included in the analysis, then the statistics of the time to initiation is also printed out.

Results for failure probabilities including seismic events include the effects of plant operation up to the time considered and are then conditional on a seismic event of the specified magnitude occurring at that time.

9.2 PRAISE Post-Processor (PR_PLOT)

PR_PLOT is a plotting program to provide plots of leak and LOCA probabilities and also to display stratification maps with number of samples and failures from each stratum. The program is invoked as follows:

```
PR_PLOT FNAME
```

where FNAME is the file name (without the extension). The program then searches for files FNAME.SLK, FNAME.BLK, FNAME.LOC, and FNAME.STT, and displays the plot selection menu, which typically looks as follows:

```
PRAISE - Plot Selection Menu

1 : Time versus Probability of Leak
2 : Time versus Probability of Big Leak
3 : Time versus Probability of LOCA
4 : Stratification Map
0 : Exit

Make a selection (Enter a number)          ?
```

If plot option 1, 2, or 3 is selected, the following menu appears:

```
A : MIN-MAX VALUES   X-MINIMUM      X-MAXIMUM      Y-MINIMUM      Y-MAXIMUM
                     0              10             0              0.0025
B : TIC INTERVALS    X-MAJOR        X-MINOR        Y-MAJOR        Y-MINOR
                     2              1              0.0005         0
E : X-AXIS LABEL = 'Time (years)'
F : Y-AXIS LABEL = 'Probability of leak'
M : MODE (LINEAR/LOG) :      X-AXIS...LIN                  Y-AXIS...LIN
F : PHYSICAL PLOT SIZE :     X-AXIS... 3.5 - 2.5 cms       Y-AXIS... 3.5 - 18.5 cms
G : DATA SETS :        1
   SYMBOLS    :        11
P : PEN NUMBER :       1
S : SAVE THE PLOTTING PARAMETERS IN A FILE
L : LOAD PLOTTING PARAMETERS FROM A FILE
X : PLOT ON THE SCREEN
Z : PLOT ON THE 7470A PLOTTER
O : OVERPLOT OPTION TOGGLE (ON/OFF)
N : READ A NEW DATA FILE                             Q : QUIT
CURRENT FILE IS ... FATIG.SLK

                    Enter desired option to change format or to plot
```

When this menu appears, a plot can be made on the screen by entering X (or Z for plotting on a pen plotter). Any of the parameters listed on this menu can be changed by entering the corresponding letter that appears in the first column. A brief description of each of the options follows:

Min-Max Values (A) -- By default, the minimum and maximum values of data are used as plotting limits. When this option is selected, the user will be prompted to enter minimum and maximum limits for plotting on the X- and Y-axes. Data that fall outside these plotting limits will not be plotted.

Tic Intervals (B) -- By default, there are five major tic intervals on each axis where labels are printed. Also by default, five minor tics are drawn between two major tic intervals. These can be redefined by the user. To completely suppress minor tics, enter the minor tic interval as 0 (zero).

Axis Labels (E) -- This option can be used to redefine axis labels. Both upper and lower case characters can be used.

Plotting Mode (M) -- One of the following four plotting modes can be selected.

1. linear on X, linear on Y
2. linear on X, log on Y
3. log on X, linear on Y
4. log on X, log on Y

By default, both axes are plotted on a linear scale.

Physical Plot Size (F) -- *This option is applicable only to pen plotters.* By selecting this option, the physical size of the plot can be defined in terms of dimensions of X- and Y-axis and coordinates of the left-bottom corner of the plot with reference to a 8-1/2 x 11-inch paper in landscape mode.

Symbols (G) -- A set of ten discrete symbols and ten different types of lines are provided. By selecting this option, the user can reassign symbols to data sets.

Pen Number (P) -- *This option is applicable only to multi-pen plotters like the HP 7470A plotter.* By selecting this option, different colors can be assigned to data sets.

Save Plotting Parameters in a File (S) -- When this option is selected, the user will be prompted to enter a file name for saving the plotting parameters. The parameters saved are -- minimum and maximum plotting limits, tic intervals, axes labels, plotting mode, physical plot size, assigned symbols, and pen numbers.

Load Plotting Parameters from a File (L) -- By selecting this option, the user can recall the plotting parameters that were saved using the "S" option. A file name is requested from the user when this option is selected.

Plot on the Screen (X) -- This option is used to plot the data on the screen.

Plot on a Pen Plotter (Z) -- This option is used to plot the data on a HP 7470A or compatible pen plotter. Follow the instructions that appear on the screen.

Overplot Option (O) -- *This option is applicable only for the pen plotters.* By default, the overplot option is turned off. When the overplot option is turned on, tics, labels, and axes are not plotted.

Read a New Data File (N) -- This option is used to select another file for plotting. When this option is selected, display returns to Plotting File Menu, from which another plot file can be selected.

Quit (Q) -- This option is used to EXIT from the plotting program.

If Option 4 is selected from the plot selection menu, a color-coded stratification scheme as shown in Figure 9-1 is displayed. By default, leak results are provided. If all the samples from a stratum resulted in a leak, the cell is painted red; if no leaks occurred for a stratum, it is painted green; if some leaks occurred, the stratum is painted yellow. At the bottom of the screen, six options are listed for altering the display or for exiting to the plot selection menu.

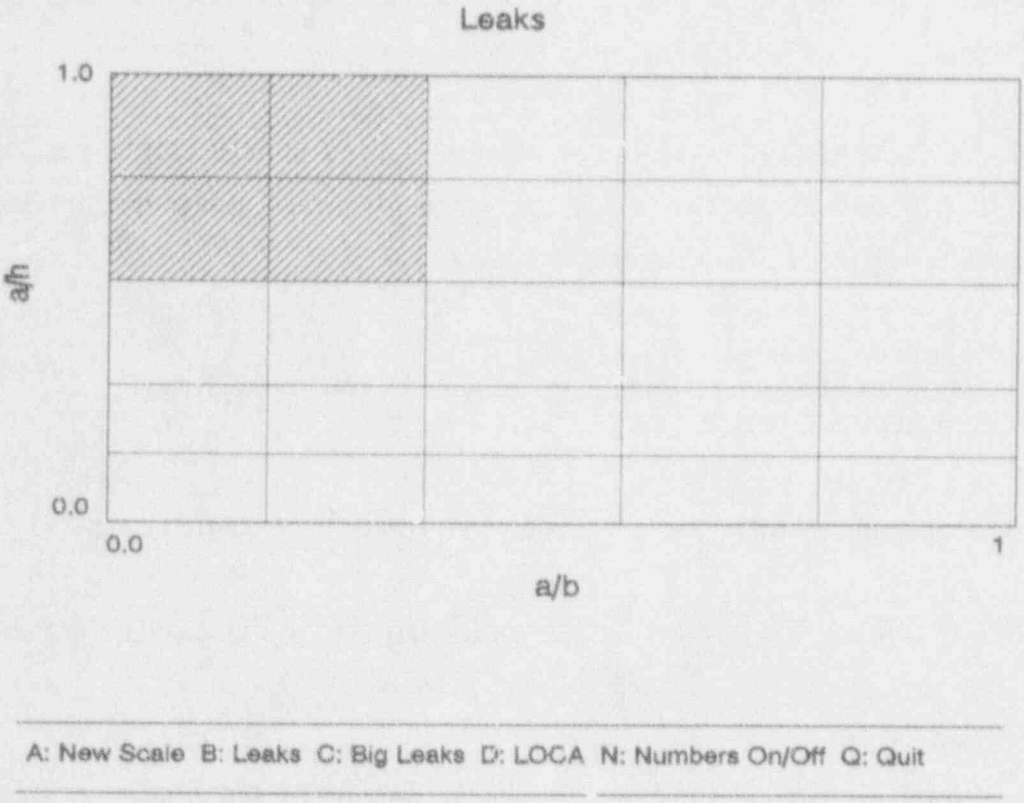


Figure 9-1. A typical display of leak results on the stratification map.

Option A (New Scale): By selecting this option, a selective display of the stratification map can be obtained. The user is promoted to enter new limits of a/b and a/h for display.

Option B (Leaks): This is the default display. When this option is selected, the results of leaks are displayed.

Option C (Big Leaks): When this option is selected, the results of big leaks are displayed.

Option D (LOCA): When this option is selected, the results of LOCA are displayed.
Option N (Numbers On/Off): When this option is selected, the user is provided with options to display any or all of the following:

Number of samples in each cell.
Number of failures (leaks, big leaks, or LOCA) in each cell.
Stratum number.

By default, none of these are displayed when the display is first generated.

Option Q (Quit): This option is selected to return to the plot selection menu.

The program does not have the capability to generate a hard copy of the stratification display on a pen-plotter. A hard copy of the display can be obtained by a graphics-dump of the screen if a compatible printer is connected to the computer.

10. SAMPLE PROBLEMS

Eleven sample problems are described in this section. These problems generally fail into three groups.

- Problems 1-5 consider only the pre-existing cracks
- Problems 6-8 consider only the SCC-initiated cracks
- Problems 9-11 consider both the pre-existing and SCC-initiated cracks simultaneously

In each group, the problems are arranged in order of increasing complexity. The following table lists the features of the PRAISE Code that are exercised in each of the problems. Each problem is discussed in detail in this section. The input and output files for each of these problems is included with the software. These sample problems were run on a 386/33 PC with a 387/33 math coprocessor.

INDEX TO SAMPLE PROBLEMS

	1	2	3	4	5	6	7	8	9	10	11
CRACKS											
Pre-existing	✓	✓	✓	✓	✓				✓	✓	✓
SCC-initiated						✓	✓	✓	✓	✓	✓
CRACK GROWTH											
Fatigue	✓	✓	✓	✓	✓				✓	✓	✓
SCC						✓	✓	✓	✓	✓	✓
FAILURE CRITERIA											
Net-section	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Tearing instability					✓						✓
OPERATION											
PSI	✓	✓	✓	✓	✓				✓	✓	✓
Proof test	✓	✓		✓	✓				✓	✓	✓
ISI									✓	✓	✓
Mid-life changes								✓			✓
STRESSES											
HU-CD	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Radial gradient thermal			✓	✓							✓
Seismic				✓							✓
Residual					✓		✓	✓	✓	✓	✓
Mid-life change								✓		✓	✓
FAILURE MODE											
Leak	✓				✓	✓	✓	✓	✓	✓	✓
LOCA		✓	✓	✓							

10.1 Sample Problem 1: Fatigue Baseline Case

This sample problem illustrates the most basic analysis that can be performed with pc-PRAISE. This case calculates probability of leak due to the growth of a pre-existing crack by fatigue mechanism. The only load cycle used is the heat-up/cool-down cycle. The weld location is subjected to pre-service inspection and a proof-test. Failure criteria used is the net-section stress exceeding the flow stress. The major inputs related to the geometry of the pipe, the pipe material, the welding process used, and the operating history are described below.

Pipe Geometry:
Inside Radius = 14.5 in
Wall Thickness = 2.5 in

Stresses:
Deadweight = 2.08 ksi
Deadweight + Thermal Expansion = 8.58 ksi
Operating Pressure = 2400 psi
Proof Pressure = 3000 psi

Fatigue Crack Growth Properties:
C (median) = 9.14×10^{-12}
C (90th percentile) = 3.5×10^{-11}
Fatigue Exponent = 4.0
Fatigue Threshold = 4.6 ksi-in$^{1/2}$

Flow Stress:
Mean = 43.2 ksi
Standard Deviation = 4.2 ksi

Initial Crack Size Distribution:
Depth Distribution -- Exponential
Parameter = 4.07
Aspect Ratio Distribution -- Lognormal
Median = 1.34
Shape Parameter = 0.538

The a/h - a/b sample space is divided into 100 cells and 100 samples are taken from each cell. Plant lifetime of 40 years is simulated and results are printed at two year intervals. Residual stresses and vibratory stresses are not considered in the analysis. The heat-up/cool-down cycles are assumed to occur regularly five times a year.

The input file for Sample Problem 1 is shown in Figure 10-1a. Each variable in the input file is described in Table 10-1. The output file is shown in Figures 10-1b through 10-1d. Description of the inputs is given in Figure 10-1b. The stratification scheme used is shown in Figure 10-1c. Coordinates of each cell are shown along with the number of samples and the conditional probability of crack from that cell. The last three columns of that table show the number of cracks that resulted in leak, big-leak, and LOCA, respectively. The probabilities of leak as a function of time are shown in Figure 10-1d. Leak and big-leak probabilities are the same at any given time, indicating that all the leaks that were found were less than 10 gpm. The LOCA probability calculations for this case are not accurate because the stratification used is not optimized for the estimation of LOCA probabilities. The stratification scheme employed is shown in Figure 10-1e and the cell from which at least one failure occurred are cross-hatched. No leaks occurred for cells with a/h < 0.6, and hence, it would have been adequate to ignore the sample space below a/h = 0.6.

Table 10-1
VARIABLE INPUT FILE FOR
SAMPLE PROBLEM 1: FATIGUE BASELINE CASE

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #1 Title				
TITLE( )		Analysis title	1 - 80	20A4
Line #2 Control Variables (Card 0B)				
INCIAT	0	Pre-existing cracks only	1 - 5	I5
IFAILC	0	Net-section stress criteria	6 - 10	I5
ICRAKS	0	Not used	11 - 15	I5
IREPLS	0	Not used	16 - 20	I5
IREPAR	0	Not used	26 - 30	I5
BNDRY	1.1	Not used	31 - 40	F10.3
ISF	0	Fatigue crack growth data input by the user	41 - 50	I10
MTTYPE	1	Not used	51 - 55	I5
ISEED	688	Random number seed 1	56 - 62	I7
ISEEDR	7225	Random number seed 2	63 - 70	I8
IREMED	0	Number of remedial actions during the plant life	71 - 75	I5
Line #3 Control Variables (Card 1B)				
NTRIES	-100	Number of replications from each cell = abs (NTRIES)	1 - 5	I5
ISQARE	1	Rectangular grid to be set up	6 - 10	I5
KTYPES	1	Number of transients experienced by the plant	11 - 15	I5
KRKDIS	3	Crack depth exponential, aspect ratio lognormal	16 - 20	I5
NEVAL	-2	Interval for printing results (years)	21 - 25	I5
NINSPT	0	No in-service inspections	26 - 30	I5
NQUAKE	0	No earthquakes to be modeled	31 - 35	I5
IDEBUG	0	Normal output to be printed	36 - 40	I5
KONPRP	0	C lognormally distributed	41 - 45	I5
NEQINT	0	Not used	46 - 50	I5

Table 10-1 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #3 Control Variables (Card 1B) [Continued]				
MCELLS	0	Not used	51 - 55	I5
KNSFLO	0	Flow stress normally distributed	56 - 60	I5
NSKIP	0	No indicator function printout	61 - 65	I5
NPSI	1	A pre-service inspection is modeled	66 - 70	I5
ISCC	0	Crack growth by fatigue only	71 - 75	I5
ISIGRS	0	Residual stresses not modeled	75 - 80	I5
Line #4 Time and NDE Parameters (Card 1D)				
THRIZN	40	Maximum plant life time simulated (years)	1 - 10	E10.3
DTSCC	0.2	Not used	11 - 20	E10.3
ICTYPE	0	Crack orientation is circumferential	21 - 25	I5
IPTYPE	0	Default NDE parameters for thick austenitic pipe used	26 - 30	I5
EPST		Not used	31 - 40	E10.0
ASTAR		Not used	41 - 50	E10.0
TRANSD		Not used	51 - 60	E10.0
ANUU		Not used	61 - 70	E10.0
Line #5 Pipe Dimensions (Card 2A)				
THICK	2.5	Wall thickness of the pipe (inches)	1 - 10	E10.3
RIN	14.5	Inside radius (inches)	11 - 20	E10.3
ELOVRR		Not used	21 - 30	E10.3
Line #6 Fatigue Crack Growth Characteristics (Card 2B)				
THRHLD	4.6	Threshold for fatigue crack growth (ksi-in$^{1/2}$)	1 - 10	E10.3
EMEXP	4	Exponent for fatigue crack growth equation	11 - 20	E10.3
CONSMU	9.14×10^{-12}	50th percentile of C	21 - 30	E10.3
CONS90	3.50×10^{-11}	90th percentile of C	31 - 40	E10.3

Table 10-1 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #7 Flow Stress (Card 2C)				
SFLOMU	43.2	Mean value of flow stress (ksi)	1 - 10	E10.4
SFLOSD	4.2	Standard deviation of flow stress (ksi)	11 - 20	E10.4
XJIC		Not used	21 - 30	E10.4
DJDAMT		Not used	31 - 40	E10.4
SIG0		Not used	41 - 50	E10.4
DEE		Not used	51 - 60	E10.4
YOUNGS		Not used	61 - 70	E10.4
XN		Not used	71 - 80	E10.4
Line #8 Ultimate Stress Definition (Card 2D)				
SULTMU	0	Not used	1 - 10	E10.0
SULTSD	0	Not used	11 - 20	E10.0
IULT	0	Not used	21 - 25	I5
Line #9 Initial Crack Depth Distribution (Card 3A)				
AMEDIAN	4.07	Rate parameter for exponential distribution of depth (1/in)	1 - 10	E10.3
ASIGMA		Not used	11 - 20	E10.3
ALAMDA		Not used	21 - 30	E10.3
Line #10 Initial Aspect Ratio Distribution (Card 3B)				
BOAMED	1.34	Median of truncated lognormal distribution of b/a	1 - 10	E10.3
BOASIG	0.538	Shape factor of truncated lognormal distribution of b/a	11 - 20	E10.3
BOALDA		Not used	21 - 30	E10.3
Line #11 Leak Rate and Detection Parameters (Card 4C)				
FNDLEK	3	Threshold for detectable leak rate (gpm)	1 - 10	E10.3
ALKBIG	10	Threshold for defining big leaks (gpm)	11 - 20	E10.3

Table 10-1 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #12 Stratified Sample Space (Card 5A)				
NAOH	10	Number of divisions in a/h direction	1 - 5	I5
NAOB	10	Number of divisions in a/b direction	6 - 10	I5
AOHLOW	0	Lower limit of a/h	11 - 20	E10.3
AOHUP	1	Upper limit of a/h	21 - 30	E10.3
AOBLFT	0	Lower limit of a/b	31 - 40	E10.3
AOBRGT	1	Upper limit of a/b	41 - 50	E10.3
Line #13 Operating Stresses (Card 6A)				
SGCLD	2.08	Deadweight stress (ksi)	1 - 10	E10.4
SGDWTE	8.58	Deadweight and thermal expansion stress (ksi)	11 - 20	E10.4
OPPRES	2.4	Normal operating pressure (ksi)	21 - 30	E10.4
PRFPRS	3	Pressure in hydrostatic proof test (ksi)	31 - 40	E10.4
SIGVIB	-1	Vibratory stresses not modeled	41 - 50	E10.4
VBTHLD	0	Not used	51 - 60	E10.4
Line #14 Frequency of Heat-up/Cool-down Transient 1 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.2	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	460	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10

```
P           R           A           I           S           E

PIPING RELIABILITY ANALYSIS INCLUDING SEISMIC EVENTS

                 PC-PRAISE VERSION 2.40

            EXECUTED ON  12/06/91 AT  3:25p


            ECHO-PRINT OF INPUT DATA IN FILE  SAMPLE1.DAT

LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
   1> PROBLEM 1 : Fetigue baseline                                                  <
   2>    0    0    0    0         0     1.100         0    1    688    7225    0     <
   3> -100    1    1    3   -2    0    0    0    0    0    0    0    0    1    0    0<
   4>  .400E+02  .500E+00    0    0                                                 <
   5>  .250E+01  .145E+02                                                           <
   6>  .460E+01  .400E+01  .914E-11  .350E-10                                       <
   7> .4300E+02 .4200E+01                                                           <
   8>  .000E+00  .000E+00    0                                                      <
   9>  .407E+01                                                                     <
  10>  .134E+01  .538E+00                                                           <
  11>  .300E+01  .100E+02                                                           <
  12>    10   10      .000     1.000      .000     1.000                            <
  13>  2.08      8.58     2.400     3.00     -.100E+01  .000E+00                    <
  14>     1 .2   460.00000Heat-up and Cool-down                                      <
LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
 ****** NEW SEED (L,R)          688         7225*****
```

Figure 10-1a. Echo of input file for Sample Problem 1.

```
---  PROBLEM 1 : Fatigue baseline                                                      ---

CIRCUMFERENTIAL CRACK ANALYSIS

PARAMETERS THAT DETERMINE NON-DETECTION PROBABILITY
    EPST  =      .000E+00
    ASTAR =    1.250
    TRANSDUCER DIAMETER =  1.00000 INCHES
    ANUU  =    1.600

PRE-EXISTING CRACKS ONLY

FATIGUE CRACK GROWTH ONLY

LEAKERS WILL BE REPAIRED

FAILURE CRITERIA = APPLIED STRESS>FLOW STRESS

PIPE DIMENSIONS
    WALL THICKNESS =   2.50 INCHES
    INSIDE RADIUS  =  14.50 INCHES
      L/H RATIO    =       .00
      L/R RATIO    =       .00
    AREA OF PIPE         =   247.40 SQ. INCHES
    FLOW AREA OF PIPE    =   660.52 SQ. INCHES

INITIAL CRACK SIZE DISTRIBUTION
CRACK DEPTH IS EXPONENTIAL
    PARAMETER =    4.0700
ASPECT RATIO IS LOG-NORMAL
    MEDIAN                  =    1.3400
    SHAPE PARAMETER         =     .5380
    NORMALIZATION CONSTANT =    1.4149

CRACK GROWTH LAW PARAMETERS
    EXPONENT  =   4.000
    GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
         MEDIAN        =   .9140E-11
         90-TH PERCENT =   .3500E-10
    THRESHOLD =   4.600

FLOW STRESS NORMALLY DISTRIBUTED
    MEAN                =   .4300E+02
    STANDARD DEVIATION =   .4200E+01

DISTRIBUTION PARAMETERS FOR ULTIMATE STRESS IN PIPE
    MEAN                =   .0000E+00
    STANDARD DEVIATION =   .0000E+00
    STANDARD DEVIATION =  0.0 MEANS THE ULTIMATE STRESS IS CONSTANT
    INTERPOLATION FLAG =   0  ( IULT ) FOR WHOLE PIPE BREAK PROBABILITY
    ABS ( IULT ) IS THE NUMBER OF INTERPOLATION POINTS
    IF  IULT .GT. 0  LINEAR INTERPOLATION
    IF  IULT .EQ. 0  NO INTERPOLATION
    IF  IULT .LT. 0  LOGARITHMIC INTERPOLATION
```

Figure 10-1b. Input summary for Sample Problem 1.

```
PIPE LOADING VALUES
    STRESS (KSI) DUE TO COLD DEADWEIGHT  =      2.08
    STRESS (KSI)  DUE TO DWGHT + THERMAL =      8.58
    STRESS (KSI)  DUE TO         THERMAL =      6.50
    OPERATING PRESSURE (KSI)             =      2.40
    STRESS (KSI) DUE TO OPER. PRESSURE   =      6.41
    STRESS (KSI) DUE TO DWGHT + OP PRESR =      8.49
    STRESS (KSI) DUE TO DWT+THML+OP PRES =     14.99
    PROOF PRESSURE (KSI)                 =      3.00
    STRESS (KSI) DUE TO DWGHT + PRF PRES =     10.09

    HYDROSTATIC PROOF TEST IS MODELLED

LEAK DETECTION AND DEFINITION PARAMETERS
    DETECTABLE LEAK (GPM) =    3.00
    BIG LEAK        (GPM) =   10.00

NO RESIDUAL STRESSES ARE MODELLED

NO VIBRATORY STRESSES ARE MODELLED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELLED

TIME INTERVALS
    PLANT LIFETIME =  40.0 YEARS
    ENDPOINTS OF INTERVALS AT     .0   2.0   4.0   6.0   8.0 YEARS
    ENDPOINTS OF INTERVALS AT   10.0  12.0  14.0  16.0  18.0 YEARS
    ENDPOINTS OF INTERVALS AT   20.0  22.0  24.0  26.0  28.0 YEARS
    ENDPOINTS OF INTERVALS AT   30.0  32.0  34.0  36.0  38.0 YEARS
    ENDPOINTS OF INTERVALS AT   40.0

NO IN-SERVICE INSPECTIONS ARE MODELLED

NO SEISMIC EVENTS EVALUATED

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS   0

NORMAL OUTPUT REQUESTED


NUMBER OF TRANSIENT TYPES =  1

TYPE  1    Heat-up and Cool-down
    REGULAR AT         .200 YEARS/EVENT
    MAX DELTA TEMP = 460.0  BLOCKING FACTOR =  1.0
```

Figure 10-1b. (Continued)

```
                  - - - SUMMARY OF CELL   Y SAMPLE SPACE - - -

                          - - - UNIFORM MESH - - -

CELL    AOH1     AOH2     AOB1     AOB2        PROBABILITY      SAMPLES   LEAKS   B-LEAKS   LOCAS
  1     .9000   1.0000    .0000    .1000      .8910199E-08       100       80       80       11
  2     .9000   1.0000    .1000    .2000      .6761020E-06       100       70       70        0
  3     .9000   1.0000    .2000    .3000      .3614825E-05       100       71       71        0
  4     .9000   1.0000    .3000    .4000      .7434238E-05       100       51       51        0
  5     .9000   1.0000    .4000    .5000      .1001263E-04       100       41       41        0
  6     .9000   1.0000    .5000    .6000      .1088032E-04       100       30       30        0
  7     .9000   1.0000    .6000    .7000      .1048585E-04       100       21       21        0
  8     .9000   1.0000    .7000    .8000      .9406688E-05       100       16       16        0
  9     .9000   1.0000    .8000    .9000      .8069847E-05       100       17       17        0
 10     .9000   1.0000    .9000   1.0000      .6728002E-05       100       17       17        0
 11     .8000    .9000    .0000    .1000      .2464802E-07       100       18       18        1
 12     .8000    .9000    .1000    .2000      .1870281E-05       100       11       11        0
 13     .8000    .9000    .2000    .3000      .9999583E-05       100        2        2        0
 14     .8000    .9000    .3000    .4000      .2056511E-04       100        2        2        0
 15     .8000    .9000    .4000    .5000      .2769764E-04       100        0        0        0
 16     .8000    .9000    .5000    .6000      .3009792E-04       100        2        2        0
 17     .8000    .9000    .6000    .7000      .2900669E-04       100        0        0        0
 18     .8000    .9000    .7000    .8000      .2602144E-04       100        0        0        0
 19     .8000    .9000    .8000    .9000      .2232338E-04       100        0        0        0
 20     .8000    .9000    .9000   1.0000      .1861147E-04       100        0        0        0
 21     .7000    .8000    .0000    .1000      .6818309E-07       100        1        1        0
 22     .7000    .8000    .1000    .2000      .5173703E-05       100        0        0        0
 23     .7000    .8000    .2000    .3000      .2766155E-04       100        0        0        0
 24     .7000    .8000    .3000    .4000      .5688866E-04       100        0        0        0
 25     .7000    .8000    .4000    .5000      .7661917E-04       100        0        0        0
 26     .7000    .8000    .5000    .6000      .8325897E-04       100        0        0        0
 27     .7000    .8000    .6000    .7000      .8024034E-04       100        0        0        0
 28     .7000    .8000    .7000    .8000      .7198235E-04       100        0        0        0
 29     .7000    .8000    .8000    .9000      .6175250E-04       100        0        0        0
 30     .7000    .8000    .9000   1.0000      .5148437E-04       100        0        0        0
 31     .6000    .7000    .0000    .1000      .1886129E-06       100        0        0        0
 32     .6000    .7000    .1000    .2000      .1431186E-04       100        0        0        0
 33     .6000    .7000    .2000    .3000      .7651933E-04       100        0        0        0
 34     .6000    .7000    .3000    .4000      .1573694E-03       100        0        0        0
 35     .6000    .7000    .4000    .5000      .2119493E-03       100        0        0        0
 36     .6000    .7000    .5000    .6000      .2303168E-03       100        0        0        0
 37     .6000    .7000    .6000    .7000      .2219665E-03       100        0        0        0
 38     .6000    .7000    .7000    .8000      .1991226E-03       100        0        0        0
 39     .6000    .7000    .8000    .9000      .1708241E-03       100        0        0        0
 40     .6000    .7000    .9000   1.0000      .1424197E-03       100        0        0        0
 41     .5000    .6000    .0000    .1000      .5217542E-06       100        0        0        0
 42     .5000    .6000    .1000    .2000      .3959048E-04       100        0        0        0
 43     .5000    .6000    .2000    .3000      .2116732E-03       100        0        0        0
 44     .5000    .6000    .3000    .4000      .4353264E-03       100        0        0        0
 45     .5000    .6000    .4000    .5000      .5863092E-03       100        0        0        0
 46     .5000    .6000    .5000    .6000      .6371187E-03       100        0        0        0
 47     .5000    .6000    .6000    .7000      .6140193E-03       100        0        0        0
 48     .5000    .6000    .7000    .8000      .5508271E-03       100        0        0        0
 49     .5000    .6000    .8000    .9000      .4725457E-03       100        0        0        0
 50     .5000    .6000    .9000   1.0000      .3939714E-03       100        0        0        0
```

Figure 10-1c. Stratification description for Sample Problem 1.

```
 51    .4000    .5000    .0000    .1000       .1443313E-05    100    0    0    0
 52    .4000    .5000    .1000    .2000       .1095180E-03    100    0    0    0
 53    .4000    .5000    .2000    .3000       .5855452E-03    100    0    0    0
 54    .4000    .5000    .3000    .4000       .1204231E-02    100    0    0    0
 55    .4000    .5000    .4000    .5000       .1621890E-02    100    0    0    0
 56    .4000    .5000    .50[illegible]    .6000       .1762442E-02    100    0    0    0
 57    .4000    .5000    .6000    .7000       .1698543E-02    100    0    0    0
 58    .4000    .5000    .7000    .8000       .1523737E-02    100    0    0    0
 59    .4000    .5000    .8000    .9000       .1307189E-02    100    0    0    0
 60    .4000    .5000    .9000   1.0000       .1089831E-02    100    0    0    0
 61    .3000    .4000    .0000    .1000       .3992595E-05    100    0    0    0
 62    .3000    .4000    .1000    .2000       .3029563E-03    100    0    0    0
 63    .3000    .4000    .2000    .3000       .1619776E-02    100    0    0    0
 64    .3000    .4000    .3000    .4000       .3331227E-02    100    0    0    0
 65    .3000    .4000    .4000    .5000       .4486586E-02    100    0    0    0
 66    .3000    .4000    .5000    .6000       .4875393E-02    100    0    0    0
 67    .3000    .4000    .6000    .7000       .4698630E-02    100    0    0    0
 68    .3000    .4000    .[illegible]00    .8000       .4215068E-02    100    0    0    0
 69    .3000    .4000    .8000    .9000       .3616039E-02    100    0    0    0
 70    .3000    .4000    .9000   1.0000       .3014768E-02    100    0    0    0
 71    .2000    .3000    .0000    .1000       .1104460E-04    100    0    0    0
 72     2000    .3000    .1000    .2000       .8380591E-03    100    0    0    0
 73    .2000    .3000    .2000    .3000       .4480739E-02    100    0    0    0
 74    .2000    .3000    .3000    .4000       .9215076E-02    100    0    0    0
 75    .2000    .3000    .4000    .5000       .1241111E-01    100    0    0    0
 76    .2000    .3000    .5000    .6000       .1348665E-01    100    0    0    0
 77    .2000    .3000    .6000    .7000       .1299768E-01    100    0    0    0
 78    .2000    .3000    .7000    .8000       .1166002E-01    100    0    0    0
 79    .2000    .3000    .8000    .9000       .1000294E-01    100    0    0    0
 80    .2000    .3000    .9000   1.0000       .8339665E-02    100    0    0    0
 81    .1000    .2000    .0000     1000       .3055234E-04    100    0    0    0
 82    .1000    .2000    .1000    .2000       .2318298E-02    100    0    0    0
 83    .1000    .2000    .2000    .3000       .1239494E-01    100    0    0    0
 84    .1000    .2000    .3000    .4000       .2549139E-01    100    0    0    0
 85    .1000    .2000    .4000    .5000       .3433249E-01    100    0    0    0
 86    .1000    .2000    .5000    .6000       .3730773E-01    100    0    0    0
 87    .1000    .2000    .6000    .7000       .3595510E-01    100    0    0    0
 88    .1000    .2000    .7000    .8000       .3225476E-01    100    0    0    0
 89    [illegible]    .2000    .8000    .9000       .2767084E-01    100    0    0    0
 90    [illegible]    .2000    .9000   1.0000       .2306977E-01    100    0    0    0
 91    [illegible]    .1000    .0000    .1000       .8451604E-04    100    0    0    0
 92    [illegible]    .1000    .1000    .2000       .6413040E-02    100    0    0    0
 93    [illegible]    .1000    .2000    .3000       .3428775E-01    100    0    0    0
 94    .0000    .1000    .3000    .4000       .7051608E-01    100    0    0    0
 95    .0000    .1000    .4000    .5000       .9497294E-01    100    0    0    0
 96    .0000    .1000    .5000    [illegible]       .1032033E+00    100    0    0    0
 97    .0000    .1000    .6000    [illegible]       .9946154E-01    100    0    0    0
 98    .0000    .1000    .7000    .8000       .8922539E-01    100    0    0    0
 99    .0000    .1000    .8000    .9000       .7654503E-01    100    0    0    0
100    .0000    .1000    .9000   1.0000       .6381722E-01    100    0    0    0
                                              --------------
                SUM OF CELL PROBABILITIES =   .1000000E+01
```

Figure 10-1c. (Continued).

```
---  PROBLEM 1 : Fatigue baseline                                                              ---


                          - - - RESULTS WITHOUT EARTHQUAKES - - -

                           SEISMIC CLASS INFORMATION
                   CLASS     SIGEQ       SGLCEQ     CYCLES   COV F-BM
                     0     .0000E+00      .000         0       .0000

                PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                                SULTMU           SULTSD     IULT
                             .00000E+00       .00000E+00     0
                              STRESS(1)
                             .84876E+01
                              PBREAK(1)
                             .10000E+01

 TIME     AVG LEAK       AVG BIG LEAK      AVG LOCA       SIGMA LEAK     SIGMA BIG LEAK    SIGMA LOCA
   .0   6.76355E-08     6.76355E-08     5.50011E-12     1.79180E-08     1.79180E-08     5.50011E-12
  2.0   3.67769E-07     3.67769E-07     3.57538E-11     4.11955E-08     4.11955E-08     1.42733E-11
  4.0   5.07700F-07     5.07700F-07     4.22709E-11     4.78571E-08     4.78571E-08     1.55400E-11
  6.0   5.78136E-07     5.78136E-07     4.99843E-11     5.02547E-08     5.02547E-08     1.71582E-11
  8.0   6.62045E-07     6.62045E-07     4.99843E-11     5.33486E-08     5.33486E-08     1.71582E-11
 10.0   7.69206E-07     7.69206E-07     5.71474E-11     5.71999E-08     5.71999E-08     1.83978E-11
 12.0   8.31618E-07     8.31618F-07     5.71474E-11     5.92733E-08     5.92733E-08     1.83978E-11
 14.0   8.95061E-07     8.95061E-07     5.71474E-11     6.08774E-08     6.08774E-08     1.83978E-11
 16.0   9.66354E-07     9.66354E-07     8.95945E-11     6.35513E-08     6.35513E-08     3.19005E-11
 18.0   9.94823E-07     9.94823E-07     8.95945E-11     6.41155E-08     6.41155E-08     3.19005E-11
 20.0   1.05641E-06     1.05641E-06     8.95945E-11     6.52628E-08     6.52628E-08     3.19005E-11
 22.0   1.12244E-06     1.12244E-06     9.68247E-11     6.69069E-08     6.69069E-08     3.25655E-11
 24.0   1.14694E-06     1.14694E-06     9.68247E-11     6.76794E-08     6.76794E-08     3.25655E-11
 26.0   1.16854E-06     1.16854E-06     9.68247E-11     6.79369E-08     6.79369E-08     3.25655E-11
 28.0   1.25533E-06     1.25533E-06     9.68247E-11     7.77824E-08     7.77824E-08     3.25655E-11
 30.0   1.33121E-06     1.33121E-06     9.68247E-11     7.91557E-08     7.91557E-08     3.25655E-11
 32.0   1.41626E-06     1.41626E-06     9.68247E-11     8.65201E-08     8.65201E-08     3.25655E-11
 34.0   1.46651E-06     1.46651E-06     9.68247E-11     8.92042E-08     8.92042E-08     3.25655E-11
 36.0   1.49150E-06     1.49150E-06     9.68247E-11     8.93621E-08     8.93621E-08     3.25655E-11
 38.0   1.50409E-06     1.50409E-06     9.68247E-11     8.94359E-08     8.94359E-08     3.25655E-11
 40.0   1.51351E-06     1.51351E-06     9.68247E-11     8.94015E 08     8.94015E-08     3.25655F-11


          PC-PRAISE VERSION 2.40
          Execution Start -    12/06/91 at   3:25p
          Execution End   -    12/06/91 at   3:46p
```

Figure 10-1d. Failure probabilities for Sample Problem 1.

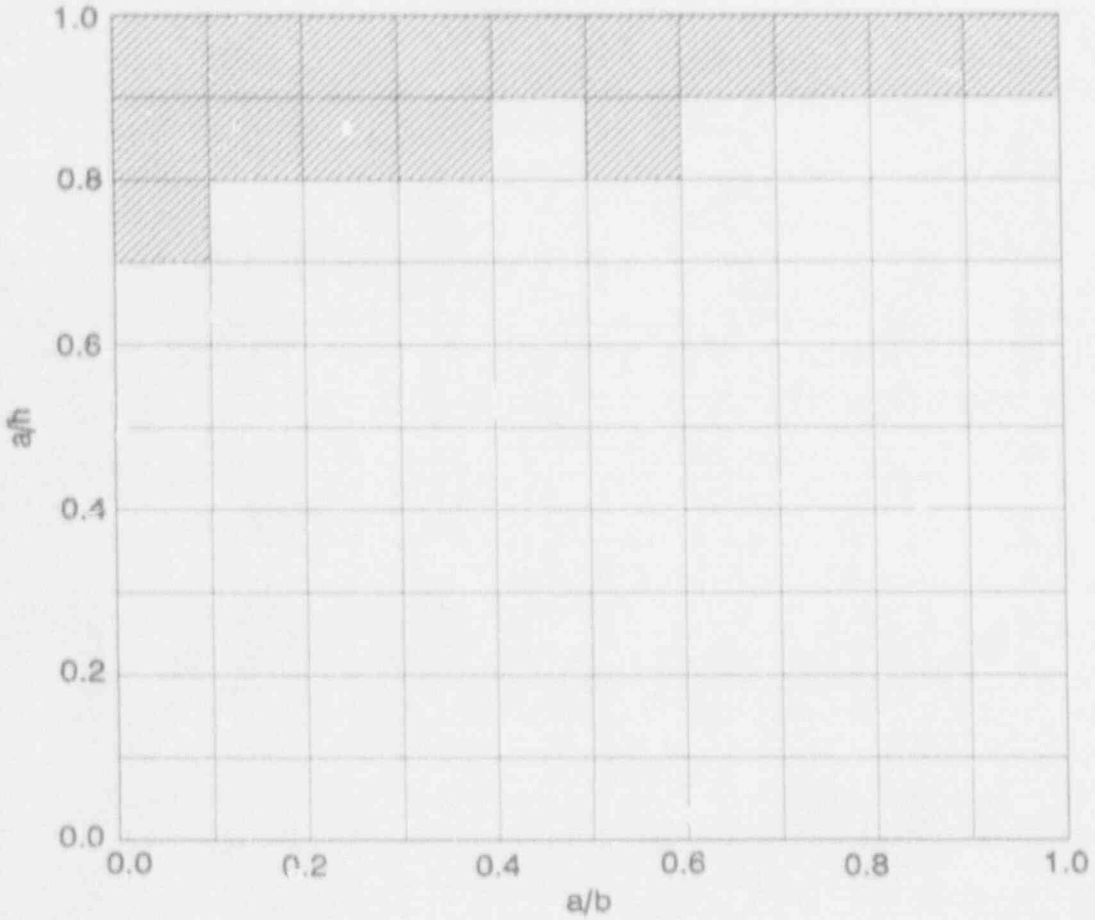


Figure 10-1e. Stratification scheme for Sample Problem 1.

10.2 Sample Problem 2: Fatigue Baseline Case -- LOCA

This sample problem illustrates the use of pc-PRAISE to calculate probabilities of LOCA due to the growth of a pre-existing crack by fatigue mechanism. The inputs are similar to Sample Problem [illegible] The load cycle used is the heat-up/cool-down cycle. The weld location is subjected to pre-service inspection and a proof-test. Failure criteria used is the net-section stress exceeding the flow stress. The major inputs related to the geometry of the pipe, the pipe material, the welding process used, and the operating history are described below.

Pipe Geometry:
Inside Radius = 14.5 in
Wall Thickness = 2.5 in

Stresses:
Deadweight = 2.08 ksi
Deadweight + Thermal Expansion = 8.58 ksi
Operating Pressure = 2400 psi
Proof Pressure = 3000 psi

Fatigue Crack Growth Properties:
C (median) = $9.14\text{x}10^{-12}$
C (90th percentile) = $3.5\text{x}10^{-11}$
Fatigue Exponent = 4.0
Fatigue Threshold = 4.6 ksi-in$^{1/2}$

Flow Stress:
Mean = 43.2 ksi
Standard Deviation = 4.2 ksi

Initial Crack Size Distribution:
Depth Distribution -- Lognormal
Median = .05 in
Shape Parameter = 0.82
Aspect Ratio Distribution -- Exponential
Parameter = 1.15

Only a portion of the a/h - a/b sample space is used for sampling the initial cracks. LOCAs are caused generally by cracks that are long (small a/b) and deep (large a/h), particularly if the leak detection is set to a reasonable value. Therefore, only the cracks with a/h > 0.4 and a/b < 0.14 are considered in the analysis. The plant lifetime of 40 years is simulated and results are printed at two year intervals. Residual stresses and vibratory stresses are not considered in the analysis. The heat-up/cool-down cycles are assumed to occur regularly five times a year.

The input file for Sample Problem 2 is shown in Figure 10-2a. Each variable in the input file is described in Table 10-2. The output file is shown in Figures 10-2b through 10-2f. Description of the inputs is summarized in Figure 10-2b. The indicator functions for Cells 3, 4, and 40 are shown in Figure 10-2c. The output file for the sample problem on the disk contains indicator functions for all the cells. The stratification scheme used is shown in Figure 10-2d. Coordinates of each cell are shown along with the number of samples and the conditional probability of crack from that cell. The last three columns of that table show the number of cracks that resulted in leak, big-leak, and LOCA, respectively. The probabilities of LOCA as a function of time are shown in Figure 10-2e. The leak probability calculations for this case are not accurate because the stratification used is optimized only for the estimation of LOCA probabilities. The stratification used is plotted in Figure 10-2f, and the cells with no failures are cross-hatched. The stratification is considered satisfactory since at least one layer of cells with no failures separates the cells with failures and cells not considered in the analysis. This stratification was arrived at after several iterations.

Table 10-2
VARIABLE INPUT FILE FOR SAMPLE PROBLEM 2: FATIGUE BASELINE CASE -- LOCA

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #1 Title				
TITLE( )		Analysis title		
Line #2 Control Variables (Card 0B)				
INCIAT	0	Pre-existing cracks only	1 - 5	I5
IFAILC	0	Net-section stress criteria	6 - 10	I5
ICRAKS	0	Not used	11 - 15	I5
IREPLS	0	Not used	16 - 20	I5
IREPAR	0	Not used	26 - 30	I5
BNDRY	1.1	Not used	31 - 40	F10.3
ISF	0	Fatigue crack growth data input by the user	41 - 50	I10
MTTYPE	0	Not used	51 - 55	I5
ISEED	688	Random number seed 1	56 - 62	I7
ISEEDR	7225	Random number seed 2	63 - 70	I8
IREMED	0	Number of remedial actions during the plant life	71 - 75	I5
Line #3 Control Variables (Card 1B)				
NTRIES	-500	Number of replications from each cell = abs (NTRIES)	1 - 5	I5
ISQARE	1	Rectangular grid to be set up	6 - 10	I5
KTYPES	1	Number of transients experienced by the plant	11 - 15	I5
KRKDIS	2	Crack depth lognormal, aspect ratio exponential	16 - 20	I5
NEVAL	-2	Interval for printing results (years)	21 - 25	I5
NINSPT	0	No in-service inspections	26 - 30	I5
NQUAKE	0	No earthquakes to be modeled	31 - 35	I5
IDEBUG	0	Normal output to be printed	36 - 40	I5
KONPRP	0	C lognormally distributed	41 - 45	I5
NEQINT	0	Not used	46 - 50	I5
MCELLS	0	Not used	51 - 55	I5

Table 10-2 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #3 Control Variables (Card 1B) [Continued]				
KNSFLO	0	Flow stress is normally distributed	56 - 60	I5
NSKIP	2	Indicator function printout interval = 2 years	61 - 65	I5
NPSI	1	A pre-service inspection is modeled	66 - 70	I5
ISCC	0	Crack growth by fatigue only	71 - 75	I5
ISIGRS	0	Residual stresses not modeled	75 - 80	I5
Line #4 Time and NDE Parameters (Card 1D)				
THRIZN	40	Maximum plant life time simulated (years)	1 - 10	E10.3
DTSCC	0.2	Not used	11 - 20	E10.3
ICTYPE	0	Crack orientation is circumferential	21 - 25	I5
IPTYPE	0	Default NDE parameters for thick austenitic pipe used	26 - 30	I5
EPST		Not used	31 - 40	E10.0
ASTAR		Not used	41 - 50	E10.0
TRANSD		Not used	51 - 60	E10.0
ANUU		Not used	61 - 70	E10.0
Line #5 Pipe Dimensions (Card 2A)				
THICK	2.5	Wall thickness of the pipe (inches)	1 - 10	E10.3
RIN	14.5	Inside radius (inches)	11 - 20	E10.3
ELOVRR		Not used	21 - 30	E10.3
Line #6 Fatigue Crack Growth Characteristics (Card 2B)				
THRHLD	4.6	Threshold for fatigue crack growth (ksi-in$^{1/2}$)	1 - 10	E10.3
EMEXP	4	Exponent for fatigue crack growth equation	11 - 20	E10.3
CONSMU	$9.14x10^{-12}$	50th percentile of C	21 - 30	E10.3
CONS90	$3.50x10^{-11}$	90th percentile of C	31 - 40	E10.3

Table 10-2 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #7 Flow Stress (Card 2C)				
SFLOMU	43.2	Mean value of flow stress (ksi)	1 - 10	E10.4
SFLOSD	4.2	Standard deviation of flow stress (ksi)	11 - 20	E10.4
XJIC		Not used	21 - 30	E10.4
DJDAMT		Not used	31 - 40	E10.4
SIG0		Not used	41 - 50	E10.4
DEE		Not used	51 - 60	E10.4
YOUNGS		Not used	61 - 70	E10.4
XN		Not used	71 - 80	E10.4
Line #8 Ultimate Stress Definition (Card 2D)				
SULTMU	0	Not used	1 - 10	E10.0
SULTSD	0	Not used	11 - 20	E10.0
IULT	0	Not used	21 - 25	I5
Line #9 Initial Crack Depth Distribution (Card 3A)				
AMEDIAN	0.05	Median of the lognormal distribution of crack depth (in)	1 - 10	E10.3
ASIGMA	0.82	Shape factor of the lognormal distribution of crack depth	11 - 20	E10.3
ALAMDA		Not used	21 - 30	E10.3
Line #10 Initial Aspect Ratio Distribution (Card 3B)				
BOALDA	1.15	Rate parameter for shifted exponential distribution of b/a	1 - 10	E10.3
Line #11 Leak Rate and Detection Parameters (Card 4C)				
FNDLEK	1	Threshold for detectable leak rate (gpm)	1 - 10	E10.3
ALKBIG	1	Threshold for defining big leaks (gpm)	11 - 20	E10.3
Line #12 Stratified Sample Space (Card 5A)				
NAOH	12	Number of divisions in a/h direction	1 - 5	I5
NAOB	7	Number of divisions in a/b direction	6 - 10	I5
AOHLOW	0.4	Lower limit of a/h	11 - 20	E10.3

Table 10-2 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #12 Stratified Sample Space (Card 5A) [Contined]				
AOHUP	1	Upper limit of a/h	21 - 30	E10.3
AOBLFT	0	Lower limit of a/b	31 - 40	E10.3
AOBRGT	0.14	Upper limit of a/b	41 - 50	E10.3
Line #13 Operating Stresses (Card 6A)				
SGCLD	2.08	Deadweight stress (ksi)	1 - 10	E10.4
SGDWTE	8.58	Deadweight and thermal expansion stress (ksi)	11 - 20	E10.4
OPPRES	2.4	Normal operating pressure (ksi)	21 - 30	E10.4
PRFPRS	3	Pressure in hydrostatic proof test (ksi)	31 - 40	E10.4
SIGVIB	-1	Vibratory stresses not modeled	41 - 50	E10.4
VBTHLD	0	Not used	51 - 60	E10.4
Line #14 Frequency of Heat-up/Cool-down Transient 1 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.2	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	460	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10

```
                    P      R          A        I        S      E

                    PIPING RELIABILITY ANALYSIS INCLUDING SEISMIC EVENTS

                                  PC-PRAISE VERSION 2.40

                              EXECUTED ON  12/06/91 AT  3:46p


                            ECHO-PRINT OF INPUT DATA IN FILE  SAMPLE2.DAT

LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
   1> PROBLEM 2 : Fatigue baseline + LOCA                                            <
   2>    0    0    0    0          0       1.100         0    1    688    7225    0    <
   3> -500    1    1    2   -2     0    0    0    0    0    0    0    2    1    0   0<
   4>  .400E+02  .200E+00    0    0                                                   <
   5>  .250E+01  .145E+02  .500E+01                                                  <
   6>  .460E+01  .400E+01  .914E-11  .350E-10                                        <
   7> .4300E+02 .4200E+01                                                            <
   8>  .000E+00  .000E+00     0                                                      <
   9>       .05      0.82                                                            <
  10>      1.15                                                                      <
  11>       1.0       1.0                                                            <
  12>   12    7      .400     1.000      .000     0.140                              <
  13>  2.08      8.00      2.400     3.00     -.100E+01  .000E+00                     <
  14>    1 .2   460.00000Heat-up and Cool-down                                       <
LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
****** NEW SEED (L,R)         688        7225*****
```

Figure 10-2a. Echo of input file for Sample Problem 2.

```
***  PROBLEM 2 : Fatigue baseline + LOCA                                       ***

CIRCUMFERENTIAL CRACK ANALYSIS

PARAMETERS THAT DETERMINE NON-DETECTION PROBABILITY
    EPST  =      .000E+00
    ASTAR =     1.250
    TRANSDUCER DIAMETER =  1.00000 INCHES
    ANUU  =     1.600

PRE-EXISTING CRACKS ONLY

FATIGUE CRACK GROWTH ONLY

LEAKERS WILL BE REPAIRED

FAILURE CRITERIA = APPLIED STRESS>FLOW STRESS

PIPE DIMENSIONS
    WALL THICKNESS =   2.50 INCHES
    INSIDE RADIUS  =  14.50 INCHES
      L/H RATIO    =    29.00
      L/R RATIO    =     5.00
    AREA OF PIPE          =   247.40 SQ. INCHES
    FLOW AREA OF PIPE     =   660.52 SQ. INCHES

INITIAL CRACK SIZE DISTRIBUTION
CRACK DEPTH IS LOG-NORMAL
    MEDIAN =      .0500
    SHAPE PARAMETER =       .8200
ASPECT RATIO IS EXPONENTIAL
    PARAMETER =    1.1500

CRACK GROWTH LAW PARAMETERS
    EXPONENT  =   4.000
    GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
         MEDIAN         =   .9140E-11
         90-TH PERCENT  =   .3500E-10
    THRESHOLD =   4.600

FLOW STRESS NORMALLY DISTRIBUTED
    MEAN                =   .4300E+02
    STANDARD DEVIATION  =   .4200E+01

DISTRIBUTION PARAMETERS FOR ULTIMATE STRESS IN PIPE
    MEAN                =   .0000E+00
    STANDARD DEVIATION  =   .0000E+00
    STANDARD DEVIATION  =  0.0 MEANS THE ULTIMATE STRESS IS CONSTANT
    INTERPOLATION FLAG  =   0  ( IULT ) FOR WHOLE PIPE BREAK PROBABILITY
    ABS ( IULT ) IS THE NUMBER OF INTERPOLATION POINTS
    IF  IULT .GT. 0  LINEAR INTERPOLATION
    IF  IULT .EQ. 0  NO INTERPOLATION
    IF  IULT .LT. 0  LOGARITHMIC INTERPOLATION
```

Figure 10-2b. Input summary for Sample Problem 2.

```
PIPE LOADING VALUES
    STRESS (KSI) DUE TO COLD DEADWEIGHT  =     2.08
    STRESS (KSI)  DUE TO DWGHT + THERMAL =     8.58
    STRESS (KSI)  DUE TO         THERMAL =     6.50
    OPERATING PRESSURE (KSI)             =     2.40
    STRESS (KSI) DUE TO OPER. PRESSURE   =     6.41
    STRESS (KSI) DUE TO DWGHT + OP PRESR =     8.49
    STRESS (KSI) DUE TO DWT+THML+OP PRES =    14.99
    PROOF PRESSURE (KSI)                 =     3.00
    STRESS (KSI) DUE TO DWGHT + PRF PRES =    10.09

    HYDROSTATIC PROOF TEST IS MODELLED

LEAK DETECTION AND DEFINITION PARAMETERS
    DETECTABLE LEAK (GPM) =    1.00
    BIG LEAK        (GPM) =    1.00

NO RESIDUAL STRESSES ARE MODELLED

NO VIBRATORY STRESSES ARE MODELLED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELLED

TIME INTERVALS
    PLANT LIFETIME =  40.0 YEARS
    ENDPOINTS OF INTERVALS AT     .0   2.0   4.0   6.0   8.0 YEARS
    ENDPOINTS OF INTERVALS AT   10.0  12.0  14.0  16.0  18.0 YEARS
    ENDPOINTS OF INTERVALS AT   20.0  22.0  24.0  26.0  28.0 YEARS
    ENDPOINTS OF INTERVALS AT   30.0  32.0  34.0  36.0  38.0 YEARS
    ENDPOINTS OF INTERVALS AT   40.0

NO IN-SERVICE INSPECTIONS ARE MODELLED

NO SEISMIC EVENTS EVALUATED

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS   2

NORMAL OUTPUT REQUESTED


NUMBER OF TRANSIENT TYPES =  1

TYPE  1    Heat-up and Cool-down
    REGULAR AT         .200 YEARS/EVENT
    MAX DELTA TEMP = 460.0  BLOCKING FACTOR =  1.0
```

Figure 10-2b. (Continued).

```
                          - - - INDICATOR FUNCTIONS WITHOUT EARTHQUAKES - - -

CELL  TIME  SUM LEAK      SUM BIG LEAK  SUM LOCA      SUM2 LEAK     SUM2 BIG LEAK    SUM2 LOCA      LEAK  BLEAK  LOCA

  3     .0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
  3    4.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
  3    8.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
  3   12.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
  3   16.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
  3   20.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
  3   24.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
  3   28.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
  3   32.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
  3   36.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
  3   40.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0

  4     .0  .46840E+01    .46840E+01    .39131E+01    .28136E+00    .28136E+00       .23564E+00       78     78    65
  4    4.0  .22518E+02    .22518E+02    .15497E+02    .14667E+01    .14667E+01       .10130E+01      347    347   238
  4    8.0  .26012E+02    .26012E+02    .16688E+02    .17110E+01    .17110E+01       .10967E+01      397    397   255
  4   12.0  .27924E+02    .27924E+02    .17256E+02    .18464E+01    .18464E+01       .11370E+01      424    424   263
  4   16.0  .28693E+02    .28693E+02    .17256E+02    .19003E+01    .19003E+01       .11370E+01      435    435   263
  4   20.0  .28766E+02    .28766E+02    .17256E+02    .19056E+01    .19056E+01       .11370E+01      436    436   263
  4   24.0  .28839E+02    .28839E+02    .17256E+02    .19109E+01    .19109E+01       .11370E+01      437    437   263
  4   28.0  .28839E+02    .28839E+02    .17256E+02    .19109E+01    .19109E+01       .11370E+01      437    437   263
  4   32.0  .28982E+02    .28982E+02    .17256E+02    .19211E+01    .19211E+01       .11370E+01      439    439   263
  4   36.0  .28982E+02    .28982E+02    .17256E+02    .19211E+01    .19211E+01       .11370E+01      439    439   263
  4   40.0  .29053E+02    .29053E+02    .17256E+02    .19262E+01    .19262E+01       .11370E+01      440    440   263

 40     .0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
 40    4.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
 40    8.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
 40   12.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
 40   16.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
 40   20.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
 40   24.0  .00000E+00    .00000E+00    .00000E+00    .00000E+00    .00000E+00       .00000E+00        0      0     0
 40   28.0  .20039E+00    .20039E+00    .00000E+00    .40157E-01    .40157E-01       .00000E+00        1      1     0
 40   32.0  .40727E+00    .40727E+00    .00000E+00    .82956E-01    .82956E-01       .00000E+00        2      2     0
 40   36.0  .60680E+00    .60680E+00    .00000E+00    .12277E+00    .12277E+00       .00000E+00        3      3     0
 40   40.0  .11938E+01    .11938E+01    .00000E+00    .23775E+00    .23775E+00       .00000E+00        6      6     0
```

Figure 10-2c. Selected portions of indicator functions for Sample Problem 2.

```
                         - - - SUMMARY OF CELLS IN SAMPLE SPACE - - -

                                   - - - UNIFORM MESH - - -

CELL      AOH1       AOH2       AOB1       AOB2          PROBABILITY         SAMPLES    LEAKS    B-LEAKS    LOCAS
  1      .9500     1.0000      .0000      .0200          .1119121E-30         500          0          0        0
  2      .9500     1.0000      .0200      .0400          .3426444E-18         500          0          0        0
  3      .9500     1.0000      .0400      .0600          .4975107E-14         500          0          0        0
  4      .9500     1.0000      .0600      .0800          .5945764E-12         500        440        440      263
  5      .9500     1.0000      .0800      .1000          .1002776E-10         500        498        498        6
  6      .9500     1.0000      .1000      .1200          .6161991E-10         500        497        497        0
  7      .9500     1.0000      .1200      .1400          .2118003E-09         500        496        496        0
  8      .9000      .9500      .0000      .0200          .1596537E-30         500          0          0        0
  9      .9000      .9500      .0200      .0400          .4888160E-18         500          0          0        0
 10      .9000      .9500      .0400      .0600          .7097481E-14         500         60         60       60
 11      .9000      .9500      .0600      .0800          .8482219E-12         500        395        395      181
 12      .9000      .9500      .0800      .1000          .1430559E-10         500        368        368        1
 13      .9000      .9500      .1000      .1200          .8790688E-10         500        383        383        0
 14      .9000      .9500      .1200      .1400          .3021540E-09         500        369        369        0
 15      .8500      .9000      .0000      .0200          .2312790E-30         500          0          0        0
 16      .8500      .9000      .0200      .0400          .7081128E-18         500          0          0        0
 17      .8500      .9000      .0400      .0600          .1028162E-13         500        189        189      189
 18      .8500      .9000      .0600      .0800          .1228759E-11         500        211        211       66
 19      .8500      .9000      .0800      .1000          .2072348E-10         500        181        181        0
 20      .8500      .9000      .1000      .1200          .1273444E-09         500        169        169        0
 21      .8500      .9000      .1200      .1400          .4377089E-09         500        153        153        0
 22      .8000      .8500      .0000      .0200          .3407355E-30         500          8          8        8
 23      .8000      .8500      .0200      .0400          .1043239E-17         500          5          5        5
 24      .8000      .8500      .0400      .0600          .1514756E-13         500         91         91       91
 25      .8000      .8500      .0600      .0800          .1810289E-11         500         66         66       20
 26      .8000      .8500      .0800      .1000          .3053122E-10         500         60         60        0
 27      .8000      .8500      .1000      .1200          .1876123E-09         500         68         68        0
 28      .8000      .8500      .1200      .1400          .6448619E-09         500         44         44        0
 29      .7500      .8000      .0000      .0200          .5114497E-30         500         71         71       71
 30      .7500      .8000      .0200      .0400          .1565919E-17         500         72         72       72
 31      .7500      .8000      .0400      .0600          .2273674E-13         500         35         35       35
 32      .7500      .8000      .0600      .0800          .2717273E-11         500         21         21        0
 33      .7500      .8000      .0800      .1000          .4582786E-10         500         17         17        0
 34      .7500      .8000      .1000      .1200          .2816091E-09         500         17         17        0
 35      .7500      .8000      .1200      .1400          .9679484E-09         500         20         20        0
 36      .7000      .7500      .0000      .0200          .7838089E-30         500         45         45       45
 37      .7000      .7500      .0200      .0400          .2399808E-17         500         34         34       34
 38      .7000      .7500      .0400      .0600          .3484460E-13         500         13         13       13
 39      .7000      .7500      .0600      .0800          .4164287E-11         500          9          9        1
 40      .7000      .7500      .0800      .1000          .7023230E-10         500          6          6        0
 41      .7000      .7500      .1000      .1200          .4315728E-09         500          8          8        0
 42      .7000      .7500      .1200      .1400          .1483404E-08         500          4          4        0
 43      .6500      .7000      .0000      .0200          .1229505E-29         500         10         10       10
 44      .6500      .7000      .0200      .0400          .3764407E-17         500          3          3        3
 45      .6500      .7000      .0400      .0600          .5465822E-13         500          4          4        4
 46      .6500      .7000      .0600      .0800          .6532218E-11         500          4          4        0
 47      .6500      .7000      .0800      .1000          .1101684E-09         500          2          2        0
 48      .6500      .7000      .1000      .1200          .6769772E-09         500          1          1        0
 49      .6500      .7000      .1200      .1400          .2326910E-08         500          3          3        0
 50      .6000      .6500      .0000      .0200          .1980044E-29         500          2          2        2
 51      .6000      .6500      .0200      .0400          .6062351E-17         500          1          1        1
 52      .6000      .6500      .0400      .0600          .8802377E-13         500          1          1        1
 53      .6000      .6500      .0600      .0800          .1051974E-10         500          2          2        0
 54      .6000      .6500      .0800      .1000          .1774195E-09         500          1          1        0
 55      .6000      .6500      .1000      .1200          .1090231E-08         500          0          0        0
 56      .6000      .6500      .1200      .1400          .3747348E-08         500          0          0        0
 57      .5500      .6000      .0000      .0200          .3285810E-29         500          0          0        0
 58      .5500      .6000      .0200      .0400          .1006025E-16         500          0          0        0
 59      .5500      .6000      .0400      .0600          .1460723E-12         500          1          1        1
```

Figure 10-2d. Stratification description for Sample Problem 2.

```
60     .5500     .6000     .0600     .0800        .1745713E-10     500     1     1     0
61     .5500     .6000     .0800     .1000        .2944213E-09     500     1     1     0
62     .5500     .6000     .1000     .1200        .1809199E-08     500     0     0     0
63     .5500     .6000     .1200     .1400        .6218588E-08     500     0     0     0
64     .5000     .5500     .0000     .0200        .5644327E-29     500     1     1     1
65     .5000     .5500     .0200     .0400        .1728138E-16     500     0     0     0
66     .5000     .5500     .0400     .0600        .2509212E-12     500     0     0     0
67     .5000     .5500     .0600     .0800        .2998766E-10     500     0     0     0
68     .5000     .5500     .0800     .1000        .5057534E-09     500     0     0     0
69     .5000     .5500     .1000     .1200        .3107821E-08     500     0     0     0
70     .5000     .5500     .1200     .1400        .1068222E-07     500     0     0     0
71     .4500     .5000     .0000     .0200        .1009432E-28     500     0     0     0
72     .4500     .5000     .0200     .0400        .3090605E-16     500     0     0     0
73     .4500     .5000     .0400     .0600        .4487478E-12     500     0     0     0
74     .4500     .5000     .0600     .0800        .5362997E-10     500     0     0     0
75     .4500     .5000     .0800     .1000        .9044900E-09     500     0     0     0
76     .4500     .5000     .1000     .1200        .5558031E-08     500     0     0     0
77     .4500     .5000     .1200     .1400        .1910409E-07     500     0     0     0
78     .4000     .4500     .0000     .0200        .1893425E-28     500     0     0     0
79     .4000     .4500     .0200     .0400        .5797149E-16     500     0     0     0
80     .4000     .4500     .0400     .0600        .8417311E-12     500     0     0     0
81     .4000     .4500     .0600     .0800        .1005955E-09     500     0     0     0
82     .4000     .4500     .0800     .1000        .1696582E-08     500     0     0     0
83     .4000     .4500     .1000     .1200        .1042538E-07     500     0     0     0
84     .4000     .4500     .1200     .1400        .3583418E-07     500     0     0     0
                                                ...............
               SUM OF CELL PROBABILITIES =      .1099190E-06
```

Figure 10-2d. (Continued).

```
***  PROBLEM 2 : Fatigue baseline + LOCA                                                ***


                                                   * * * RESULTS WITHOUT EARTHQUAKES * * *

                SEISMIC CLASS INFORMATION
                        CLASS      SIGEQ        SGLCEQ     CYCLES   COV F-BM
                          0     .0000E+00        .000         0        .0000

                     PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                        SULTMU          SULTSD      IULT
                     .00000E+00      .00000E+00      0
                      STRESS(1)
                     .84876E+01
                      PBREAK(1)
                     .10000E+01

               TIME       AVG LEAK      AVG BIG LEAK      AVG LOCA        SIGMA LEAK    SIGMA BIG LEAK    SIGMA LOCA
                 .0     2.72676E-12     2.72676E-12     8.29855E-15     2.14353E-13     2.14353E-13     2.16885E-15
                2.0     1.09714E-11     1.09714E-11     2.98298E-14     3.45339E-13     3.45339E-13     4.06000E-15
                4.0     1.59377E-11     1.59377E-11     3.64187E-14     4.05617E-13     4.05617E-13     4.13467E-15
                6.0     2.00412E-11     2.00412E-11     4.38484E-14     4.89258E-13     4.89258E-13     4.23492E-15
                8.0     2.35379E-11     2.35379E-11     4.98603E-14     5.61288E-13     5.61288E-13     4.35200E-15
               10.0     2.70219E-11     2.70219E-11     5.64639E-14     6.23418E-13     6.23418E-13     4.50265E-15
               12.0     3.03522E-11     3.03522E-11     6.03941E-14     6.82103E-13     6.82103E-13     4.58530E-15
               14.0     3.44590E-11     3.44590E-11     6.29158E-14     8.96003E-13     8.96003E-13     4.63090E-15
               16.0     3.76129E-11     3.76129E-11     6.55856E-14     9.59166E-13     9.59166E-13     4.69702E-15
               18.0     4.30022E-11     4.30022E-11     6.72479E-14     1.72852E-12     1.72852E-12     4.71894E-15
               20.0     4.64942E-11     4.64942E-11     6.86740E-14     1.77918E-12     1.77918E-12     4.75681E-15
               22.0     4.98434E-11     4.98434E-11     7.04643E-14     1.85590E-12     1.85590E-12     4.79804E-15
               24.0     5.33784E-11     5.33784E-11     7.21118E-14     1.90849E-12     1.90849E-12     4.82417E-15
               26.0     5.66662E-11     5.66662E-11     7.36440E-14     1.97565E-12     1.97565E-12     4.86880E-15
               28.0     6.11241E-11     6.11241E-11     7.54638E-14     2.13045E-12     2.13045E-12     4.89719E-15
               30.0     6.50661E-11     6.50661E-11     7.59720E-14     2.22483E-12     2.22483E-12     4.90262E-15
               32.0     7.21732E-11     7.21732E-11     7.60492E-14     2.73728E-12     2.73728E-12     4.9[illegible]E-15
               34.0     7.65041E-11     7.65041E-11     7.82979E-14     2.85552E-12     2.85552E-12     4.9[illegible]352E-15
               36.0     8.14077E-11     8.14077E-11     7.87923E-14     3.11961E-12     3.11961E-12     4.96875E-15
               38.0     8.55944E-11     8.55944E-11     8.29901E-14     3.19100E-12     3.19100E-12     5.36890E-15
               40.0     8.96073E-11     8.96073E-11     8.43355E-14     3.25307E-12     3.25307E-12     5.40352E-15


PC-PRAISE VERSION 2.40
Execution Start -    12/06/91 at  3:46p
Execution End   -    12/06/91 at  5.03p
```

Figure 10-2e. Failure probabilities for Sample Problem 2.

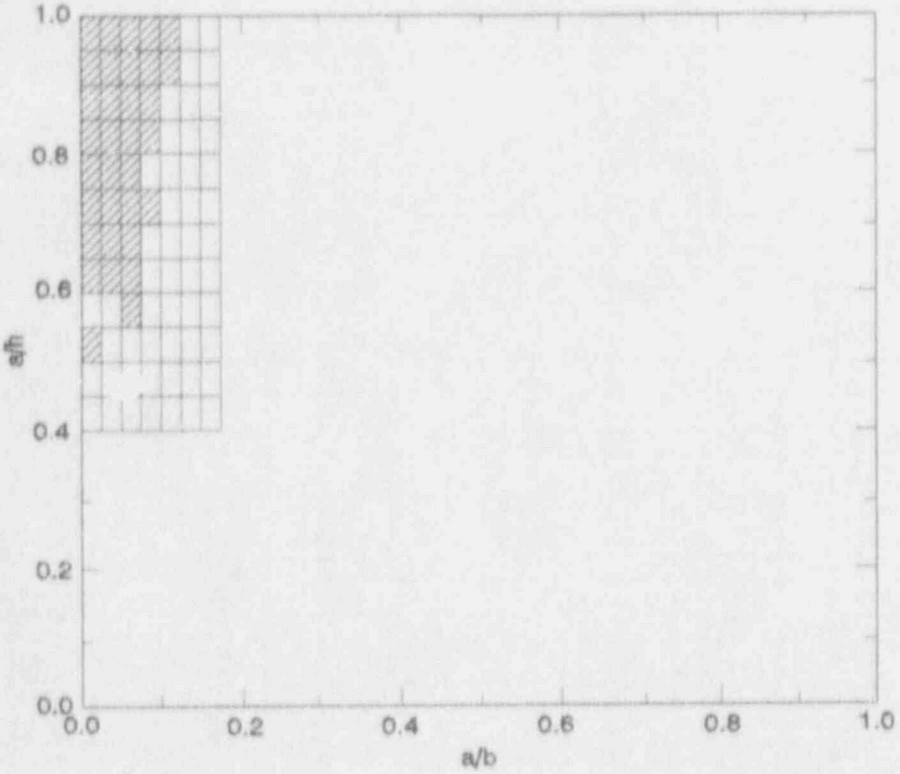


Figure 10-2f. Stratification scheme for Sample Problem 2.

10.3 Sample Problem 3: Fatigue Baseline Case -- LOCA, Radial Gradient Stresses

This sample problem illustrates the use of pc-PRAISE to calculate probabilities of LOCA due to the growth of a pre-existing crack by fatigue mechanism. Two transients are modeled in this case. The first is the heat-up/cool-down cycle occurring regularly at the rate of 5 per year. The second transient is the reactor-trip-from-full-power, occurring twice per year, with the temperature excursions during the transient being a drop of 73°F. The time variation of the coolant closely resembles that given for T_H in Figure D-15 of Harris 81. The weld location is subjected to pre-service inspection but no proof-test. Failure criterion used is the net-section stress exceeding the flow stress. The major inputs related to the geometry of the pipe, the pipe material, the welding process used, and the operating history are described below.

Pipe Geometry:
- Inside Radius = 14.5 in
- Wall Thickness = 2.5 in

Stresses:
- Deadweight = 2.08 ksi
- Deadweight + Thermal Expansion = 8.58 ksi
- Operating Pressure = 2400 psi

Fatigue Crack Growth Properties:
- C (median) = 9.14×10^{-12}
- C (90th percentile) = 3.5×10^{-11}
- Fatigue Exponent = 4.0
- Fatigue Threshold = 4.6 ksi-in$^{1/2}$

Flow Stress:
- Mean = 43.2 ksi
- Standard Deviation = 4.2 ksi

Initial Crack Size Distribution:
- Depth Distribution -- Exponential
  - Parameter = 4.07
- Aspect Ratio Distribution -- Lognormal
  - Median = 1.34
  - Shape Parameter = 0.538

Only a portion of the a/h - a/b sample space is used for sampling the initial cracks. LOCAs are caused generally by cracks that are long (small a/b) and deep (large a/h), particularly if the leak detection is set to a reasonable value. Therefore, only cracks with a/h > 0.4 and a/b < 0.14 are considered in the analysis. The stratification is similar to that used in Sample Problem 2, except that the option to specify coordinates of cells is used. The plant lifetime of 40 years is simulated and results are printed at two year intervals. Residual stresses and vibratory stresses are not considered in the analysis.

For transients other that the heat-up/cool-down transient, the cyclic stress intensity factors for a range of crack sizes are input by the user, in a tabular form. In this case, the minimum and the maximum $\Delta\bar{K}_a$ and $\Delta\bar{K}_b$ were calculated using the TIFFANY code [Dedhia 82], for a matrix of crack depth and aspect ratio combinations. The resulting data are entered here on Lines 97-100 and 103-126. The details for generating this information is discussed in Section 5.4 and Dedhia 82. Sample Problem 1 of Dedhia 82 generates the g^*_{min} - g^*_{max} tables included in Lines 103 - 126. The data is tabulated in the following order: $g^*_{min,\,a}$, $g^*_{max,\,a}$, $g^*_{min,\,b}$, and $g^*_{max,\,b}$ (as discussed further in Section 8.2.6).

The input file for Sample Problem 3 is shown in Figure 10-3a. Each variable in the input file is described in Table 10-3. The output file is shown in Figures 10-3b through 10-3d. Description of the inputs is summarized in Figure 10-3b. The stratification scheme used is shown in Figure 10-3c. Coordinates of each cell are shown along with the number of samples and the conditional probability of crack from that cell. The last three columns of that table show the number of cracks that resulted in leak, big-leak, and LOCA, respectively. The probabilities of LOCA as a function of time are shown in Figure 10-3d. The leak probability calculations for this case are not accurate because the stratification used is optimized only for the estimation of LOCA probabilities. The stratification used is plotted in Figure 10-3e, and the cells with no failures are cross-hatched. The stratification is considered satisfactory since at least one layer of cells with no failures separates the cells with failures and cells not considered in the analysis.

Table 10-3
VARIABLE INPUT FILE FOR SAMPLE PROBLEM 3: FATIGUE BASELINE CASE -- LOCA, RADIAL GRADIENT STRESSES

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #1 Title				
TITLE( )		Analysis title		
Line #2 Control Variables (Card 0B)				
INCIAT	0	Pre-existing cracks only	1 - 5	I5
IFAILC	0	Net-section stress failure criteria	6 - 10	I5
ICRAKS	0	Not used	11 - 15	I5
IREPLS	0	Not used	16 - 20	I5
IREPAR	0	Not used	26 - 30	I5
BNDRY	1.1	Not used	31 - 40	F10.3
ISF	0	Fatigue crack growth data input by the user	41 - 50	I10
MTTYPE	0	Not used	51 - 55	I5
ISEED	688	Random number seed 1	56 - 62	I7
ISEEDR	7225	Random number seed 2	63 - 70	I8
IREMED	0	Number of remedial actions during the plant life	71 - 75	I5
Line #3 Control Variables (Card 1B)				
NTRIES	50	Used as a multiplier for samples from each cell	1 - 5	I5
ISQARE	0	User-defined stratification space	6 - 10	I5
KTYPES	2	Number of transients experienced by the plant	11 - 15	I5
KRKDIS	3	Crack depth exponential, aspect ratio lognormal	16 - 20	I5
NEVAL	-2	Interval for printing results (years)	21 - 25	I5
NINSPT	0	Number of in-service inspections	26 - 30	I5
NQUAKE	0	No earthquakes to be modeled	31 - 35	I5

Table 10-3 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #3 Control Variables (Card 1B) [Continued]				
IDEBUG	0	Normal output to be printed	36 - 40	I5
KONPRP	0	C lognormally distributed	41 - 45	I5
NEQINT	0	Number of seismic intensity classes to be modeled	46 - 50	I5
MCELLS	84	Number of user-specified cells in the sample space	51 - 55	I5
KNSFLO	0	Flow stress normally distributed	56 - 60	I5
NSKIP	0	No indicator function printout	61 - 65	I5
NPSI	1	A pre-service inspection is modeled	66 - 70	I5
ISCC	0	Crack growth by fatigue only	71 - 75	I5
ISIGRS	0	Residual stresses are not modeled	75 - 80	I5
Line #4 Time and NDE Parameters (Card 1D)				
THRIZN	40	Maximum plant life time simulated (years)	1 - 10	E10.3
DTSCC	0.2	Not used	11 - 20	E10.3
ICTYPE	0	Crack orientation is circumferential	21 - 25	I5
IPTYPE	0	Default NDE parameters for thick austenitic pipe used	26 - 30	I5
EPST		Not used	31 - 40	E10.0
ASTAR		Not used	41 - 50	E10.0
TRANSD		Not used	51 - 60	E10.0
ANUU		Not used	61 - 70	E10.0
Line #5 Pipe Dimensions (Card 2A)				
THICK	2.5	Wall thickness of the pipe (inches)	1 - 10	E10.3
RIN	14.5	Inside radius (inches)	11 - 20	E10.3
ELOVRR		Not used	21 - 30	E10.3

Table 10-3 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #6 Fatigue Crack Growth Characteristics (Card 2B)				
THRHLD	4.6	Threshold for fatigue crack growth (ksi-in$^{1/2}$)	1 - 10	E10.3
EMEXP	4	Exponent for fatigue crack growth equation	11 - 20	E10.3
CONSMU	9.14×10^{-12}	50th percentile of C	21 - 30	E10.3
CONS90	3.50×10^{-11}	90th percentile of C	31 - 40	E10.3
Line #7 Flow Stress (Card 2C)				
SFLOMU	43.2	Mean value of flow stress (ksi)	1 - 10	E10.4
SFLOSD	4.2	Standard deviation of flow stress (ksi)	11 - 20	E10.4
XJIC		Not used	21 - 30	E10.4
DJDAMT		Not used	31 - 40	E10.4
SIG0		Not used	41 - 50	E10.4
DEE		Not used	51 - 60	E10.4
YOUNGS		Not used	61 - 70	E10.4
XN		Not used	71 - 80	E10.4
Line #8 Ultimate Stress Definition (Card 2D)				
SULTMU	0	Not used	1 - 10	E10.0
SULTSD	0	Not used	11 - 20	E10.0
IULT	0	Not used	21 - 25	I5
Line #9 Initial Crack Depth Distribution (Card 3A)				
AMEDIAN	4.07	Rate parameter for exponential distribution of depth (1/in)	1 - 10	E10.3
ASIGMA		Not used	11 - 20	E10.3
ALAMDA		Not used	21 - 30	E10.3

Table 10-3 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #10 Initial Aspect Ratio Distribution (Card 3B)				
BOAMED	1.34	Median of truncated lognormal distribution of b/a	1 - 10	E10.3
BOASIG	0.538	Shape factor of truncated lognormal distribution of b/a	11 - 20	E10.3
BOALDA		Not used	1 - 10	E10.3
Line #11 Leak Rate and Detection Parameters (Card 4C)				
FNDLEK	3	Threshold for detectable leak rate (gpm)	1 - 10	E10.3
ALKBIG	3	Threshold for defining big leaks (gpm)	11 - 20	E10.3
Line #12-95 Stratified Sample Space (Card 5A)				
AOHSIZ(1)	0.95	Cell 1 : Lower a/h	1 - 10	E10.4
AOHSIZ(2)	1	Cell 1 : Upper a/h	11 - 20	E10.4
AOBSIZ(1)	0	Cell 1 : Lower a/b	21 - 30	E10.4
AOBSIZ(2)	0.02	Cell 1 : Upper a/b	31 - 40	E10.4
NUMTRY	10	Number of samples from Cell 1	41 - 50	I10
Line #96 Operating Stresses (Card 6A)				
SGCLD	2.08	Deadweight stress (ksi)	1 - 10	E10.4
SGDWTE	8.58	Deadweight and thermal expansion stress (ksi)	11 - 20	E10.4
OPPRES	2.4	Normal operating pressure (ksi)	21 - 30	E10.4
PRFPRS	-3	Proof test is not modeled	31 - 40	E10.4
SIGVIB	-1	Vibratory stresses not modeled	41 - 50	E10.4
VBTHLD	0	Not used	51 - 60	E10.4
Line #97 Specifications for g_{min} and g_{max} Tables (Card 6B)				
NX	6	Number of entries in a/b direction for the input table	1 - 5	I5
NY	9	Number of entries in a/h direction for the input table	6 - 10	I5

Table 10-3 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #97 Specifications for g_{min} and g_{max} Tables (Card 6B) [Continued]				
IX	10	Number of entries in a/b direction for the internal table	11 - 15	I5
IY	10	Number of entries in a/h direction for the internal table	16 - 20	I5
Line #98-99 (Card 6C)				
AAOH( )	0.01, 0.1, ..	a/h coordinates for g_{min}, g_{max} tables	1 - 80	8F10.3
Line #100 (Card 6D)				
AAOB( )	1, 2, ..	a/b coordinates for g_{min}, g_{max} tables	1 - 80	8F10.3
Line #101 Frequency of Heat-up/Cool-down Transient 1 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.2	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	460	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10
Line #102 Frequency of Transient 2 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.5	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	73	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10
Line #103-126 g_{min} and g_{max} Tables (Card 6F)				

```
                 P       R       A       I       S       E

             PIPING RELIABILITY ANALYSIS INCLUDING SEISMIC EVENTS

                          PC-PRAISE VERSION 2.40

                       EXECUTED ON  12/06/91 AT  5:03p


                    ECHO-PRINT OF INPUT DATA IN FILE  SAMPLE3.DAT

LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
   1> PROBLEM 3 : Fatigue baseline + LOCA + RGTS - PROOF                            <
   2>    0    0    0    0         0    1.100         0    0   688    7225    0     <
   3>   50    0    2    3   -2    0    0    0    0    0   84    0    0    1    0   0<
   4>  .400E+02  .200E+00    0    0                                                <
   5>  .250E+01  .145E+02                                                          <
   6>  .460E+01  .400E+01  .914E-11  .350E-10                                      <
   7> .4300E+02 .4200E+01                                                          <
   8>  .000E+00  .000E+00    0                                                     <
   9>  .407E+01                                                                    <
  10>  .134E+01  .538E+00                                                          <
  11>  .300E+01  .300E+01                                                          <
  12>      .9500    1.0000     .0000     .0200         10                          <
  13>      .9500    1.0000     .0200     .0400         10                          <
  14>      .9500    1.0000     .0400     .0600         10                          <
  15>      .9500    1.0000     .0600     .0800         10                          <
  16>      .9500    1.0000     .0800     .1000         10                          <
  17>      .9500    1.0000     .1000     .1200         10                          <
  18>      .9500    1.0000     .1200     .1400         10                          <
  19>      .9000     .9500     .0000     .0200         10                          <
  20>      .9000     .9500     .0200     .0400         10                          <
  21>      .9000     .9500     .0400     .0600         10                          <
  22>      .9000     .9500     .0600     .0800         10                          <
  23>      .9000     .9500     .0800     .1000         10                          <
  24>      .9000     .9500     .1000     .1200         10                          <
  25>      .9000     .9500     .1200     .1400         10                          <
  26>      .8500     .9000     .0000     .0200         10                          <
  27>      .8500     .9000     .0200     .0400         10                          <
  28>      .8500     .9000     .0400     .0600         10                          <
  29>      .8500     .9000     .0600     .0800         10                          <
  30>      .8500     .9000     .0800     .1000         10                          <
  31>      .8500     .9000     .1000     .1200         10                          <
  32>      .8500     .9000     .1200     .1400         10                          <
  33>      .8000     .8500     .0000     .0200         10                          <
  34>      .8000     .8500     .0200     .0400         10                          <
  35>      .8000     .8500     .0400     .0600         10                          <
  36>      .8000     .8500     .0600     .0800         10                          <
  37>      .8000     .8500     .0800     .1000         10                          <
  38>      .8000     .8500     .1000     .1200         10                          <
  39>      .8000     .8500     .1200     .1400         10                          <
  40>      .7500     .8000     .0000     .0200         10                          <
  41>      .7500     .8000     .0200     .0400         10                          <
  42>      .7500     .8000     .0400     .0600         10                          <
  43>      .7500     .8000     .0600     .0800         10                          <
  44>      .7500     .8000     .0800     .1000         10                          <
  45>      .7500     .8000     .1000     .1200         10                          <
  46>      .7500     .8000     .1200     .1400         10                          <
  47>      .7000     .7500     .0000     .0200         10                          <
  48>      .7000     .7500     .0200     .0400         10                          <
  49>      .7000     .7500     .0400     .0600         10                          <
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Figure 10-3a. Echo of input file for Sample Problem 3.

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 51>     .7000      .7500      .0800      .1000         10                                  <
 52>     .7000      .7500      .1000      .1200         10                                  <
 53>     .7000      .7500      .1200      .1400         10                                  <
 54>     .6500      .7000      .0000      .0200         10                                  <
 55>     .6500      .7000      .0200      .0400         10                                  <
 56>     .6500      .7000      .0400      .0600         10                                  <
 57>     .6500      .7000      .0600      .0800         10                                  <
 58>     .6500      .7000      .0800      .1000         10                                  <
 59>     .6500      .7000      .1000      .1200         10                                  <
 60>     .6500      .7000      .1200      .1400         10                                  <
 61>     .6000      .6500      .0000      .0200         10                                  <
 62>     .6000      .6500      .0200      .0400         10                                  <
 63>     .6000      .6500      .0400      .0600         10                                  <
 64>     .6000      .6500      .0600      .0800         10                                  <
 65>     .6000      .6500      .0800      .1000         10                                  <
 66>     .6000      .6500      .1000      .1200         10                                  <
 67>     .6000      .6500      .1200      .1400         10                                  <
 68>     .5500      .6000      .0000      .0200         10                                  <
 69>     .5500      .6000      .0200      .0400         10                                  <
 70>     .5500      .6000      .0400      .0600         10                                  <
 71>     .5500      .6000      .0600      .0800         10                                  <
 72>     .5500      .6000      .0800      .1000         10                                  <
 73>     .5500      .6000      .1000      .1200         10                                  <
 74>     .5500      .6000      .1200      .1400         10                                  <
 75>     .5000      .5500      .0000      .0200         10                                  <
 76>     .5000      .5500      .0200      .0400         10                                  <
 77>     .5000      .5500      .0400      .0600         10                                  <
 78>     .5000      .5500      .0600      .0800         10                                  <
 79>     .5000      .5500      .0800      .1000         10                                  <
 80>     .5000      .5500      .1000      .1200         10                                  <
 81>     .5000      .5500      .1200      .1400         10                                  <
 82>     .4500      .5000      .0000      .0200         10                                  <
 83>     .4500      .5000      .0200      .0400         10                                  <
 84>     .4500      .5000      .0400      .0600         10                                  <
 85>     .4500      .5000      .0600      .0800         10                                  <
 86>     .4500      .5000      .0800      .1000         10                                  <
 87>     .4500      .5000      .1000      .1200         10                                  <
 88>     .4500      .5000      .1200      .1400         10                                  <
 89>     .4000      .4500      .0000      .0200         10                                  <
 90>     .4000      .4500      .0200      .0400         10                                  <
 91>     .4000      .4500      .0400      .0600         10                                  <
 92>     .4000      .4500      .0600      .0800         10                                  <
 93>     .4000      .4500      .0800      .1000         10                                  <
 94>     .4000      .4500      .1000      .1200         10                                  <
 95>     .4000      .4500      .1200      .1400         10                                  <
 96>  2.08       8.58       2.400     -3.00      -.100E+01  .000E+00                         <
 97>    6    9    10   10                                                                   <
 98>      .010       .100       .200       .300       .400       .500       .600       .700<
 99>      .800                                                                              <
100>     1.000      2.000      3.000      4.000      5.000      6.000                       <
101>     1 .2    460.00000 Heat-up and Cool-down                                            <
102>     1 .5     73.00000 Reactor Trip from Full Power                                     <
103>   .0190    .0084    .0038    .0020    .0013    .0009    .0007    .0006    .0004        <
104>   .0241    .0116    .0060    .0038    .0026    .0019    .0013    .0009    .0005        <
105>   .0258    .0127    .0069    .0045    .0031    .0023    .0016    .0010    .0005        <
106>   .0268    .0133    .0072    .0046    .0032    .0022    .0014    .0008    .0001        <
107>   .0281    .0140    .0074    .0045    .0029    .0019    .0011    .0003   -.0007        <
108>   .0293    .0143    .0073    .0042    .0026    .0015    .0006   -.0002   -.0036        <
109>   .3283    .2513    .1926    .1482    .1146    .0882    .0667    .0486    .0337        <
```

Figure 10-3a. (Continued).

```
110>   .4151    .3290    .2641    .2137    .1723    .1370    .1060    .0783    .0537        <
111>   .4437    .3516    .2839    .2365    .1995    .1684    .1403    .1139    .0891        <
112>   .4598    .3614    .2948    .2510    .2183    .1909    .1655    .1402    .1143        <
113>   .4814    .3792    .3109    .2665    .2335    .2054    .1783    .1503    .1204        <
114>   .5023    .3945    .3233    .2776    .2434    .2136    .1837    .1518    .1167        <
115>   .0210    .0135    .0090    .0064    .0048    .0037    .0029    .0023    .0018        <
116>   .0218    .0138    .0090    .0063    .0046    .0033    .0023    .0015    .0009        <
117>   .0226    .0139    .0085    .0053    .0032    .0018    .0009    .0001   -.0006        <
118>   .0235    .0136    .0074    .0039    .0018    .0006   -.0002   -.0029   -.0095        <
119>   .0234    .0124    .0059    .0025    .0007   -.0003   -.0035   -.0126   -.0236        <
120>   .0224    .0109    .0046    .0015    .0000   -.0026   -.0109   -.0222   -.0362        <
121>   .3536    .3064    .2642    .2295    .1998    .1736    .1505    .1298    .1114        <
122>   .3679    .3104    .2669    .2365    .2143    .1967    .1814    .1673    .1536        <
123>   .3802    .3190    .2742    .2444    .2233    .2067    .1919    .1772    .1620        <
124>   .3973    .3300    .2809    .2472    .2208    .1986    .1775    .1558    .1327        <
125>   .3969    .3224    .2689    .2324    .2043    .1796    .1555    .1293    .1005        <
126>   .3819    .3035    .2476    .2090    .1781    .1503    .1223    .0922    .0591        <
LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
 ****** NEW SEED (L,R)          688        7225*****
```

Figure 10-3a. (Continued).

```
***  PROBLEM 3 : Fatigue baseline + LOCA + RGTS - PROOF                      ***

CIRCUMFERENTIAL CRACK ANALYSIS

PARAMETERS THAT DETERMINE NON-DETECTION PROBABILITY
    EPST  =      .000E+00
    ASTAR =    1.250
    TRANSDUCER DIAMETER =  1.00000 INCHES
    ANUU  =     1.600

PRE-EXISTING CRACKS ONLY

FATIGUE CRACK GROWTH ONLY

LEAKERS WILL BE REPAIRED

FAILURE CRITERIA = APPLIED STRESS>FLOW STRESS

PIPE DIMENSIONS
    WALL THICKNESS =   2.50 INCHES
    INSIDE RADIUS  =  14.50 INCHES
      L/H RATIO    =       .00
      L/R RATIO    =       .00
    AREA OF PIPE         =   247.40 SQ. INCHES
    FLOW AREA OF PIPE    =   660.52 SQ. INCHES

INITIAL CRACK SIZE DISTRIBUTION
CRACK DEPTH IS EXPONENTIAL
    PARAMETER =     4.0700
ASPECT RATIO IS LOG-NORMAL
    MEDIAN                  =    1.3400
    SHAPE PARAMETER         =     .5380
    NORMALIZATION CONSTANT =    1.4149

CRACK GROWTH LAW PARAMETERS
    EXPONENT  =   4.000
    GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
         MEDIAN         =   .9140E-11
         90-TH PERCENT =   .3500E-10
    THRESHOLD =   4.600

FLOW STRESS NORMALLY DISTRIBUTED
    MEAN                 =   .4300E+02
    STANDARD DEVIATION =   .4200E+01

DISTRIBUTION PARAMETERS FOR ULTIMATE STRESS IN PIPE
    MEAN                 =   .0000E+00
    STANDARD DEVIATION =   .0000E+00
    STANDARD DEVIATION =  0.0 MEANS THE ULTIMATE STRESS IS CONSTANT
    INTERPOLATION FLAG =    0  ( IULT ) FOR WHOLE PIPE BREAK PROBABILITY
    ABS ( IULT ) IS THE NUMBER OF INTERPOLATION POINTS
    IF  IULT .GT. 0  LINEAR INTERPOLATION
    IF  IULT .EQ. 0  NO INTERPOLATION
    IF  IULT .LT. 0  LOGARITHMIC INTERPOLATION
```

Figure 10-3b. Input summary for Sample Problem 3.

```
PIPE LOADING VALUES
    STRESS (KSI) DUE TO COLD DEADWEIGHT  =      2.08
    STRESS (KSI)  DUE TO DWGHT + THERMAL =      8.58
    STRESS (KSI)  DUE TO         THERMAL =      6.50
    OPERATING PRESSURE (KSI)             =      2.40
    STRESS (KSI) DUE TO OPER. PRESSURE   =      6.41
    STRESS (KSI) DUE TO DWGHT + OP PRESR =      8.49
    STRESS (KSI) DUE TO DWT+THML+OP PRES =     14.99

    NO HYDROSTATIC PROOF TEST IS MODELLED

LEAK DETECTION AND DEF[illegible]TION PARAMETERS
    DETECTABLE LEAK ([illegible] =      3.00
    BIG LEAK         ([illegible]       5.00

NO RESIDUAL STRESSES ARE MODELLED

NO VIBRATORY STRESSES ARE MODELLED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELLED

TIME INTERVALS
    PLANT LIFETIME =  40.0 YEARS
    ENDPOINTS OF INTERVALS AT     .0   2.0   4.0   6.0   8.0 YEARS
    ENDPOINTS OF INTERVALS AT   10.0  12.0  14.0  16.0  18.0 YEARS
    ENDPOINTS OF INTERVALS AT   20.0  22.0  24.0  26.0  28.0 YEARS
    ENDPOINTS OF INTERVALS AT   30.0  32.0  34.0  36.0  38.0 YEARS
    ENDPOINTS OF INTERVALS AT   40.0

NO IN-SERVICE INSPECTIONS ARE MODELLED

NO SEISMIC EVENTS EVALUATED

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS    0

NORMAL OUTPUT REQUESTED


NUMBER OF TRANSIENT TYPES =  2

TYPE  1      Heat-up and Cool-down
    REGULAR AT        .200 YEARS/EVENT
    MAX DELTA TEMP = 460.0  BLOCKING FACTOR =  1.0

TYPE  2      Reactor Trip from Full Power
    REGULAR AT        .500 YEARS/EVENT
    MAX DELTA TEMP =  73.0  BLOCKING FACTOR =  1.0
```

Figure 10-3b. (Continued).

```
                     - - - SUMMARY OF CELLS IN SAMPLE SPACE - - -

                           - - - USER-SUPPLIED MESH - - -

CELL      AOH1      AOH2      AOB1      AOB2      PROBABILITY   SAMPLES   LEAKS  B-LEAKS   LOCAS
   1     .9500    1.0000     .0000     .0200     .3105396E-15   500         500      500     500
   2     .9500    1.0000     .0200     .0400     .9598055E-12   500         500      500     500
   3     .9500    1.0000     .0400     .0600     .4906271E-10   500         500      500     500
   4     .9500    1.0000     .0600     .0800     .5431150E-09   500         499      499     389
   5     .9500    1.0000     .0800     .1000     .2752523E-08   500         497      497      11
   6     .9500    1.0000     .1000     .1200     .8838161E-08   500         499      499       0
   7     .9500    1.0000     .1200     .1400     .2121764E-07   500         496      496       0
   8     .9000     .9500     .0000     .0200     .5164929E-15   500         500      500     500
   9     .9000     .9500     .0200     .0400     .1596359E-11   500         500      500     500
  10     .9000     .9500     .0400     .0600     .8160163E-10   500         478      478     478
  11     .9000     .9500     .0600     .0800     .9033148E-09   500         404      404     248
  12     .9000     .9500     .0800     .1000     .4578026E-08   500         398      398       2
  13     .9000     .9500     .1000     .1200     .1469973E-07   500         364      364       0
  14     .9000     .9500     .1200     .1400     .3528942E-07   500         380      380       0
  15     .8500     .9000     .0000     .0200     .8590366E-15   500         500      500     500
  16     .8500     .9000     .0200     .0400     .2655082E-11   500         500      500     500
  17     .8500     .9000     .0400     .0600     .1357207E-09   500         322      322     322
  18     .8500     .9000     .0600     .0800     .1502403E-08   500         202      202      90
  19     .8500     .9000     .0800     .1000     .7614222E-08   500         180      180       0
  20     .8500     .9000     .1000     .1200     .2444874E-07   500         167      167       0
  21     .8500     .9000     .1200     .1400     .5869374E-07   500         141      141       0
  22     .8000     .8500     .0000     .0200     .1428759E-14   500         462      462     462
  23     .8000     .8500     .0200     .0400     .4415961E-11   500         459      459     459
  24     .8000     .8500     .0400     .0600     .2257322E-09   500         126      126     126
  25     .8000     .8500     .0600     .0800     .2498813E-08   500          96       96      43
  26     .8000     .8500     .0800     .1000     .1266406E-07   500          73       73       0
  27     .8000     .8500     .1000     .1200     .4066342E-07   500          56       56       0
  28     .8000     .8500     .1200     .1400     .9762007E-07   500          47       47       0
  29     .7500     .8000     .0000     .0200     .2376328E-14   500         213      213     213
  30     .7500     .8000     .0200     .0400     .7344674E-11   500         198      198     198
  31     .7500     .8000     .0400     .0600     .3754402E-09   500          37       37      37
  32     .7500     .8000     .0600     .0800     .4156053E-08   500          34       34      12
  33     .7500     .8000     .0800     .1000     .2106300E-07   500          22       22       0
  34     .7500     .8000     .1000     .1200     .6763184E-07   500          19       19       0
  35     .7500     .8000     .1200     .1400     .1623628E-06   500          12       12       0
  36     .7000     .7500     .0000     .0200     .3952334E-14   500          40       40      40
  37     .7000     .7500     .0200     .0400     .1221574E-10   500          44       44      44
  38     .7000     .7500     .0400     .0600     .6244363E-09   500          13       13      13
  39     .7000     .7500     .0600     .0800     .6912393E-08   500          12       12       2
  40     .7000     .7500     .0800     .1000     .3503221E-07   500           3        3       0
  41     .7000     .7500     .1000     .1200     .1124860E-06   500           5        5       0
  42     .7000     .7500     .1200     .1400     .2700435E-06   500           5        5       0
  43     .6500     .7000     .0000     .0200     .6573565E-14   500           8        8       8
  44     .6500     .7000     .0200     .0400     .2031735E-10   500           8        8       8
  45     .6500     .7000     .0400     .0600     .1038569E-08   500           5        5       5
  46     .6500     .7000     .0600     .0800     .1149677E-07   500           3        3       0
  47     .6500     .7000     .0800     .1000     .5826595E-07   500           2        2       0
  48     .6500     .7000     .1000     .1200     .1870880E-06   500           1        1       0
  49     .6500     .7000     .1200     .1400     .4491393E-06   500           1        1       0
  50     .6000     .6500     .0000     .0200     .1093322E-13   500           5        5       5
  51     .6000     .6500     .0200     .0400     .3379204E-10   500           1        1       1
  52     .6000     .6500     .0400     .0600     .1727360E-08   500           1        1       1
  53     .6000     .6500     .0600     .0800     .1912155E-07   500           0        0       0
  54     .6000     .6500     .0800     .1000     .9690856E-07   500           1        1       0
  55     .6000     .6500     .1000     .1200     .3111667E-06   500           1        1       0
  56     .6000     .6500     .1200     .1400     .7470134E-06   500           1        1       0
  57     .5500     .6000     .0000     .0200     .1818426E-13   500           1        1       1
  58     .5500     .6000     .0200     .0400     .5620329E-10   500           0        0       0
  59     .5500     .6000     .0400     .0600     .2872963E-08   500           0        0       0
```

Figure 10-3c. Stratification description for Sample Problem 3.

```
60    .5500    .6000    .0600    .0800     .3180317E-07    500    1    1    0
61    .5500    .6000    .0800    .1000     .1611794E-06    500    0    0    0
62    .5500    .6000    .1000    .1200     .5175359E-06    500    0    0    0
63    .5500    .6000    .1200    .1400     .1242441E-05    500    0    0    0
64    .5000    .5500    .0000    .0200     .3024426E-13    500    0    0    0
65    .5000    .5500    .0200    .0400     .9347793E-10    500    0    0    0
66    .5000    .5500    .0400    .0600     .4778344E-08    500    0    0    0
67    .5000    .5500    .0600    .0800     .5289537E-07    500    0    0    0
68    .5000    .5500    .0800    .1000     .2680753E-06    500    0    0    0
69    .5000    .5500    .1000    .1200     .8607713E-06    500    0    0    0
70    .5000    .5500    .1200    .1400     .2066441E-05    500    0    0    0
71    .4500    .5000    .0000    .0200     .5030257E-13    500    0    0    0
72    .4500    .5000    .0200    .0400     .1554735E-09    500    0    0    0
73    .4500    .5000    .0400    .0600     . 947393E-08    500    0    0    0
74     4500    .5000    .0600    .0800     .8797616E-07    500    0    0    0
      .4500    .5000    .0800    .1000     .4458657E-06    500    0    0    0
       4500    .5000    .1000    .1200     .1431644E-05    500    0    0    0
        500    .5000    .1200    .1400     .3436927E-05    500    0    0    0
         00    .4500    .0000    .0200     .8366379E-13    500    0    0    0
          0    .4500    .0200    .0400     .2585852E-09    500    0    0    0
          0    .4500    .0400    .0600     .1321819E-07    500    0    0    0
         00    .4500    .0600    .0800     .1463229E-06    500    0    0    0
         00    .4500    .0800    .1000     .7415687E-06    500    0    0    0
         00    .4500    .1000    .1200     .2381126E-05    500    0    0    0
        .00    .4500    .1200    .1400     .5716335E-05    500    0    0    0
                                          ---------------
               SUM OF CELL PROBABILITIES =  .2251705E-04
```

Figure 10-3c. (Continued).

```
---  PROBLEM 3 : Fatigue baseline + LOCA + RGTS - PROOF                                        ---

                                              - - - RESULTS WITHOUT EARTHQUAKES - - -

                    SEISMIC CLASS INFORMATION
                              CLASS      SIGEQ        SGLCEQ      CYCLES   COV F-BM
                                0      .0000E+00        .000         0         .0000

                         PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                            SULTMU           SULTSD       IULT
                         .00000E+00       .00000E+00     0
                          STRESS(1)
                         .84876E+01
                          PPREAK(1)
                         .10000E+01

                 TIME     AVG LEAK       AVG BIG LEAK     AVG LOCA       SIGMA LEAK     SIGMA BIG LEAK    SIGMA LOCA
                   .0    3.81576E-10    3.81576E-10    2.27562E-11    2.42393E-11    2.42393E-11    9.74239E-13
                  2.0    1.41321E-09    1.41321E-09    4.38468E-11    4.09787E-11    4.09787E-11    1.88027E-12
                  4.0    1.99072E-09    1.99072E-09    5.49138E-11    5.03839E-11    5.03839E-11    2.10296E-12
                  6.0    2.54323E-09    2.54323E-09    6.28060E-11    6.05115E-11    6.05115E-11    2.25220E-12
                  8.0    3.11901E-09    3.11901E-09    7.43902E-11    7.42046E-11    7.42046E-11    2.64821E-12
                 10.0    3.71024E-09    3.71024E-09    8.60693E-11    8.84666E-11    8.84666E-11    3.31887E-12
                 12.0    4.24798E-09    4.24798E-09    9.52022E-11    1.00394E-10    1.00394E-10    3.63060E-12
                 14.0    4.75439E-09    4.75439E-09    1.02817E-10    1.10114E-10    1.10114E-10    3.94571E-12
                 16.0    5.23149E-09    5.23149E-09    1.09387E-10    1.23203E-10    1.23203E-10    4.18834E-12
                 18.0    5.73745E-09    5.73745E-09    1.18211E-10    1.37883E-10    1.37883E-10    4.64758E-12
                 20.0    6.54574E-09    6.54574E-09    1.26476E-10    1.99559E-10    1.99559E-10    4.95005E-12
                 22.0    7.06688E-09    7.06688E-09    1.29770E-10    2.11208E-10    2.11208E-10    4.99002E-12
                 24.0    8.01634E-09    8.01634E-09    1.39690E-10    3.58748E-10    3.58748E-10    6.09245E-12
                 26.0    8.72481E-09    8.72481E-09    1.45427E-10    3.81021E-10    3.81021E-10    6.22936E-12
                 28.0    9.31416E-09    9.31416E-09    1.49754E-10    4.04535E-10    4.04535E-10    6.32346E-12
                 30.0    9.94987E-09    9.94987E-09    1.55917E-10    4.16531E-10    4.16531E-10    6.64358E-12
                 32.0    1.09475E-08    1.09475E-08    1.62418E-10    6.57092E-10    6.57092E-10    6.97006E-12
                 34.0    1.17924E-08    1.17924E-08    1.69453E-10    6.72732E-10    6.72732E-10    7.64672E-12
                 36.0    1.25890E-08    1.25890E-08    1.73365E-10    6.91363E-10    6.91363E-10    7.70353E-12
                 38.0    1.30658E-08    1.30658E-08    1.78392E-10    6.94124E-10    6.94124E-10    7.89796E-12
                 40.0    1.38072E-08    1.38072E-08    1.85383E-10    7.12993E-10    7.12993E-10    8.34579E-12


    PC-PRAISE VERSION 2.40
    Execution Start  -    12/06/91  at   5:03p
    Execution End    -    12/06/91  at   6:46p
```

Figure 10-3d. Failure probabilities for Sample Problem 3.

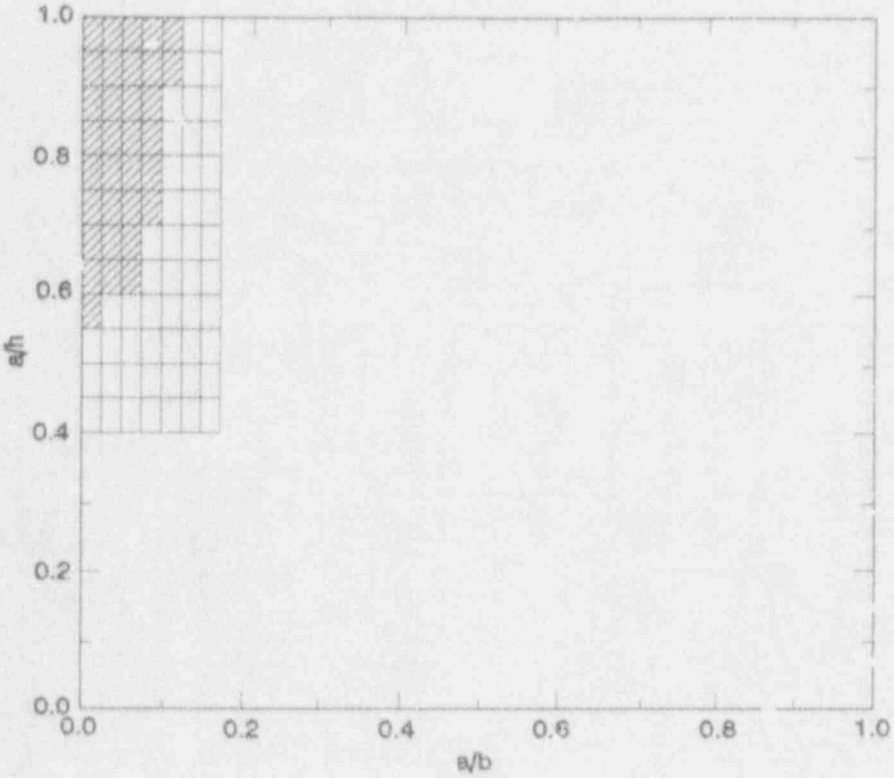


Figure 10-3e. Stratification scheme for Sample Problem 3.

10.4 Sample Problem 4: Fatigue Baseline Case -- LOCA, Radial Gradient Stresses and Seismic Stresses

This sample problem illustrates the use of pc-PRAISE to calculate probabilities of LOCA due to the growth of a pre-existing crack by fatigue mechanism. Two transients are modeled in this case. The first is the heat-up/cool-down cycle occurring regularly at the rate of 5 per year. The second transient is the reactor-trip-from-full-power, occurring twice per year, with temperature variations during the transient being 73°F. The weld location is subjected to pre-service inspection and a proof-test. Four categories of earthquakes are modeled. Failure criteria used is the net-section stress exceeding the flow stress. The major inputs related to the geometry of the pipe, the pipe material, the welding process used, and the operating history are described below.

Pipe Geometry:
    Inside Radius = 14.5 in
    Wall Thickness = 2.5 in

Stresses:
    Deadweight = 2.08 ksi
    Deadweight + Thermal Expansion = 8.58 ksi
    Operating Pressure = 2400 psi
    Proof Pressure = 3000 psi

Fatigue Crack Growth Properties:
    C (median) = 9.14×10^{-12}
    C (90th percentile) = 3.5×10^{-11}
    Fatigue Exponent = 4.0
    Fatigue Threshold = 4.6 ksi-in$^{1/2}$

Flow Stress:
    Mean = 43.2 ksi
    Standard Deviation = 4.2 ksi

Initial Crack Size Distribution:
    Depth Distribution -- Exponential
        Parameter = 4.07
    Aspect Ratio Distribution -- Lognormal
        Median = 1.34
        Shape Parameter = 0.538

Only a portion of the a/h - a/b sample space is used for sampling the initial cracks. LOCAs are caused generally by cracks that are long (small a/b) and deep (large a/h), particularly if the leak detection is set to a reasonable value. Therefore, only the cracks with a/h > 0.4 and a/b < 0.14 are considered in the analysis. The stratification is similar to that used in Sample Problem 2. The plant lifetime of 40 years is simulated and [illegible] are printed at two year intervals. Residual stresses and vibratory stresses are not considered in the analysis.

For transients other that the heat-up/cool-down transient, the cyclic stress intensity factors for a range of crack sizes are input by the user, in a tabular form. In this case, the minimum and the maximum $\Delta\bar{K}_a$ and $\Delta\bar{K}_b$ were calculated using the TIFFANY [Dedhia 82] code, for a matrix of crack depth and aspect ratio combinations. The resulting data are entered here on Lines 97-100 and 103-126. The details for generating this information are discussed in Section 5.4 and Dedhia 82.

The input file for Sample Problem 4 is shown in Figure 10-4a. Each variable in the input file is described in Table 10-4. The output file is shown in Figures 10-4b through 10-4f. Description of the inputs is summarized in Figure 10-4b. The stratification scheme used is shown in Figure 10-4c. Coordinates of each cell are shown along with the number of samples and the conditional probability of crack from that cell. The last three columns of that table show the number of cracks that resulted in leak, big-leak, and LOCA, respectively, for the case without the earthquakes. The probabilities of LOCA as a function of time for the case with no earthquakes are shown in Figure 10-4d. The LOCA probabilities when earthquakes are considered, are shown in Figures 10-4e and 10-4f, for Earthquake Classes 1 through 4. The leak probability calculations for this case are not accurate because the stratification used is optimized only for the estimation of LOCA probabilities.

Table 10-4
VARIABLE INPUT FILE FOR SAMPLE PROBLEM 4: FATIGUE BASELINE CASE -- LOCA, RADIAL GRADIENT STRESSES AND SEISMIC STRESSES

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #1 Title				
TITLE( )		Analysis title		
Line #2 Control Variables (Card 0B)				
INCIAT	0	Pre-existing cracks only	1 - 5	I5
IFAILC	0	Net-section stress failure criteria	6 - 10	I5
ICRAKS	0	Not used	11 - 15	I5
IREPLS	0	Not used	16 - 20	I5
IREPAR	0	Not used	26 - 30	I5
BNDRY	1.1	Not used	31 - 40	F10.3
ISF	0	Fatigue crack growth data input by the user	41 - 50	I10
MTTYPE	0	Not used	51 - 55	I5
ISEED	688	Random number seed 1	56 - 62	I7
ISEEDR	7225	Random number seed 2	63 - 70	I8
IREMED	0	Number of remedial actions during the plant life	71 - 75	I5
Line #3 Control Variables (Card 1B)				
NTRIES	-500	Number of replications from each cell = abs (NTRIES)	1 - 5	I5
ISQAPE	1	Rectangular grid to be set up	6 - 10	I5
KTYPES	2	Number of transients experienced by the plant	11 - 15	I5
KRKDIS	3	Crack depth exponential, aspect ratio lognormal	16 - 20	I5
NEVAL	-2	Interval for printing results (years)	21 - 25	I5
NINSPT	0	Number of in-service inspections	26 - 30	I5
NQUAKE	1	Earthquakes to be modeled	31 - 35	I5

Table 10-4 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #3 Control Variables (Card 1B) [Continued]				
IDEBUG	0	Normal output to be printed	36 - 40	I5
KONPRP	0	C lognormally distributed	41 - 45	I5
NEQINT	4	Number of seismic intensity classes to be modeled	46 - 50	I5
MCELLS	0	Not used	51 - 55	I5
KNSFLO	0	Flow stress normally distributed	56 - 60	I5
NSKIP	0	No indicator function printout	61 - 65	I5
NFSI	1	A pre-service inspection is modeled	66 - 70	I5
ISCC	0	Crack growth by fatigue only	71 - 75	I5
ISIGR3	0	Residual stresses not modeled	75 - 80	I5
Line #4 Time and NDE Parameters (Card 1D)				
THRIZN	40	Maximum plant lifetime simulated (years)	1 - 10	E10.3
DTSCC	0.2	Not used	11 - 20	E10.3
ICTYPE	0	Crack orientation is circumferential	21 - 25	I5
IPTYPE	0	Default NDE parameters for thick austenitic pipe used	26 - 30	I5
EPST		Not used	31 - 40	E10.0
ASTAR		Not used	41 - 50	E10.0
TRANSD		Not used	51 - 60	E10.0
ANUU		Not used	61 - 70	E10.0
Line #5 Pipe Dimensions (Card 2A)				
THICK	2.5	Wall thickness of the pipe (inches)	1 - 10	E10.3
RIN	14.5	Inside radius (inches)	11 - 20	E10.3
ELOVRR		Not used	21 - 30	E10.3

Table 10-4 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #6 Fatigue Crack Growth Characteristics (Card 2B)				
THRHLD	4.6	Threshold for fatigue crack growth (ksi-in$^{1/2}$)	1 - 10	E10.3
EMEXP	4	Exponent for fatigue crack growth equation	11 - 20	E10.3
CONSMU	9.14×10^{-12}	50th percentile of C	21 - 30	E10.3
CONS90	3.50×10^{-11}	90th percentile of C	31 - 40	E10.3
Line #7 Flow Stress (Card 2C)				
SFLOMU	43.2	Mean value of flow stress (ksi)	1 - 10	E10.4
SFLOSD	4.2	Standard deviation of flow stress (ksi)	11 - 20	E10.4
XJIC		Not used	21 - 30	E10.4
DJDAMT		Not used	31 - 40	E10.4
SIG0		Not used	41 - 50	E10.4
DEE		Not used	51 - 60	E10.4
YOUNGS		Not used	61 - 70	E10.4
XN		Not used	71 - 80	E10.4
Line #8 Ultimate Stress Definition (Card 2D)				
SULTMU	0	Not used	1 - 10	E10.0
SULTSD	0	Not used	11 - 20	E10.0
IULT	0	Not used	21 - 25	I5
Line #9 Initial Crack Depth Distribution (Card 3A)				
AMEDIAN	4.07	Rate parameter for exponential distribution of depth (1/in)	1 - 10	E10.3
ASIGMA		Not used	11 - 20	E10.3
ALAMDA		Not used	21 - 30	E10.3

Table 10-4 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #10 Initial Aspect Ratio Distribution (Card 3B)				
BOAMED	1.34	Median of truncated lognormal distribution of b/a	1 - 10	E10.3
BOASIG	0.538	Shape factor of truncated lognormal distribution of b/a	11 - 20	E10.3
BOALDA		Not used	1 - 10	E10.3
Line #11 Leak Rate and Detection Parameters (Card 4C)				
FNDLEK	3	Threshold for detectable leak rate (gpm)	1 - 10	E10.3
ALKBIG	3	Threshold for defining big leaks (gpm)	11 - 20	E10.3
Line #12 Stratified Sample Space (Card 5A)				
NAOH	12	Number of divisions in a/h direction	1 - 5	I5
NAOB	7	Number of divisions in a/b direction	6 - 10	I5
AOHLOW	0.4	Lower limit of a/h	11 - 20	E10.3
AOHUP	1	Upper limit of a/h	21 - 30	E10.3
AOBLFT	0	Lower limit of a/b	31 - 40	E10.3
AOBRGT	0.14	Upper limit of a/b	41 - 50	E10.3
Line #13 Operating Stresses (Card 6A)				
SGCLD	2.08	Deadweight stress (ksi)	1 - 10	E10.4
SGDWTE	8.58	Deadweight and thermal expansion stress (ksi)	11 - 20	E10.4
OPPRES	2.4	Normal operating pressure (ksi)	21 - 30	E10.4
PRFPRS	3	Pressure in hydrostatic proof test (ksi)	31 - 40	E10.4
SIGVIB	-1	Vibratory stresses not modeled	41 - 50	E10.4
VBTHLD	0	Not used	51 - 60	E10.4

Table 10-4 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #14 Specifications for g_{min} and g_{max} Tables (Card 6B)				
NX	6	Number of entries in a/b direction for the input table	1 - 5	I5
NY	9	Number of entries in a/h direction for the input table	6 - 10	I5
IX	10	Number of entries in a/b direction for the internal table	11 - 15	I5
IY	10	Number of entries in a/h direction for the internal table	16 - 20	I5
Line #15-16 (Card 6C)				
AAOH( )	.01, .1, ..	a/h coordinates for g_{min}, g_{max} tables	1 - 80	8F10.3
Line #17 (Card 6D)				
AAOB( )	1, 2, ..	b/a coordinates for g_{min}, g_{max} tables	1 - 80	8F10.3
Line #18 Frequency of Heat-up/Cool-down Transient 1 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.2	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	460	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10
Line #19 Frequency of Transient 2 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.5	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	73	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10
Line #20-43 g_{min} and g_{max} Tables (Card 6F)				
Line #44 Earthquakes per Magnitude Category (Card 7A)				
NEQCLS( )	1, 1, ..	Number of earthquakes in each category	1 - 80	10I5

Table 10-4 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #45 Seismic Stresses and Cycles (Card 7B)				
NCYCEQ( )	1	Number of equivalent cycles in Category 1	1 - 10	I10
SIGEQ( )	8.757	Equivalent cyclic stress (ksi)	11 - 20	F10.3
SGEQMX( )	8.757	Maximum cyclic stress during this category (ksi)	21 - 30	F10.3
TITLE( )		Earthquake title	31 - 80	5A10
Line #46-48 Seismic Stresses for Other Categories (Card 7B)				

```
                  P        R          A        I        S        E

                  PIPING RELIABILITY ANALYSIS INCLUDING SEISMIC EVENTS

                                    PC-PRAISE VERSION 2.40

                               EXECUTED ON  12/06/91 AT  6:47p


                          ECHO-PRINT OF INPUT DATA IN FILE  SAMPLE4.DAT

LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
   1> PROBLEM 4 : Fatigue baseline + LOCA + RGTS                                    <
   2>    0    0    0    0          0     1.100          0    1    688    7225    0    <
   3> -300    1    2    3   -2     0    1    0    0    4    0    0    0    1    0    0<
   4>  .400E+02  .200E+00    0    0                                                  <
   5>  .250E+01  .145E+02  .500E+01                                                 <
   6>  .460E+01  .400E+01  .914E-11  .350E-10                                       <
   7> .4300E+02 .4200E+01                                                           <
   8>  .000E+00  .000E+00    0                                                      <
   9>  .407E+01                                                                     <
  10>  .134E+01  .538E+00                                                           <
  11>  .300E+01  .300E+01                                                           <
  12>   12   07      .400     1.000      .000     0.140                             <
  13>  2.08      8.58      2.400     3.00     -.100E+01  .000E+00                   <
  14>    6    9   10   10                                                           <
  15>      .010      .100      .200      .300      .400      .500      .600      .700<
  16>      .800                                                                     <
  17>     1.000     2.000     3.000     4.000     5.000     6.000                   <
  18>    1 .2   460.00000 Heat-up and Cool-down                                     <
  19>    1 .5    73.00000 Reactor Trip from Full Power                              <
  20>    .0190    .0084    .0038    .0020    .0013    .0009    .0007    .0006    .0004    <
  21>    .0241    .0116    .0060    .0038    .0026    .0019    .0013    .0009    .0005    <
  22>    .0258    .0127    .0069    .0045    .0031    .0023    .0016    .0010    .0005    <
  23>    .0268    .0133    .0072    .0046    .0032    .0022    .0014    .0008    .0001    <
  24>    .0281    .0140    .0074    .0045    .0029    .0019    .0011    .0003   -.0007    <
  25>    .0293    .0143    .0073    .0042    .0026    .0015    .0006   -.0002   -.0036    <
  26>    .3283    .2513    .1926    .1482    .1146    .0882    .0667    .0486    .0337    <
  27>    .4151    .3290    .2641    .2137    .1723    .1370    .1060    .0783    .0537    <
  28>    .4437    .3516    .2839    .2365    .1995    .1684    .1403    .1139    .0891    <
  29>    .4598    .3614    .2948    .2510    .2183    .1909    .1655    .1402    .1143    <
  30>    .4814    .3792    .3109    .2665    .2335    .2054    .1783    .1503    .1204    <
  31>    .5023    .3945    .3233    .2776    .2434    .2136    .1837    .1518    .1167    <
  32>    .0210    .0135    .0090    .0064    .0048    .0037    .0029    .0023    .0018    <
  33>    .0218    .0138    .0090    .0063    .0046    .0033    .0023    .0015    .0009    <
  34>    .0226    .0139    .0085    .0053    .0032    .0018    .0009    .0001   -.0006    <
  35>    .0235    .0136    .0074    .0039    .0018    .0006   -.0002   -.0029   -.0095    <
  36>    .0234    .0124    .0059    .0025    .0007   -.0003   -.0035   -.0126   -.0236    <
  37>    .0224    .0109    .0046    .0015    .0000   -.0026   -.0109   -.0222   -.0362    <
  38>    .3536    .3064    .2642    .2295    .1998    .1736    .1505    .1298    .1114    <
  39>    .3679    .3104    .2669    .2365    .2143    .1967    .1814    .1673    .1536    <
  40>    .3802    .3190    .2742    .2444    .2233    .2067    .1919    .1772    .1620    <
  41>    .3973    .3300    .2809    .2472    .2208    .1986    .1775    .1558    .1327    <
  42>    .3969    .3224    .2689    .2324    .2043    .1796    .1555    .1293    .1005    <
  43>    .3819    .3035    .2476    .2090    .1781    .1503    .1223    .0922    .0591    <
  44>    1    1    1    1                                                            <
  45>           1 8.757     8.757      ONE OBE                                        <
  46>           2 9.059     9.059      ONE SSE                                        <
  47>           3 10.557    10.557     THREE SSE                                      <
  48>           4 10.617    10.617     FIVE SSE                                       <
LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
 ****** NEW SEED (L,R)          688          7225*****
```

Figure 10-4a. Echo of input file for Sample Problem 4.

```
---  PROBLEM 4 : Fatigue baseline + LOCA + RGTS                                    ---

CIRCUMFERENTIAL CRACK ANALYSIS

PARAMETERS THAT DETERMINE NON-DETECTION PROBABILITY
    CDST  =      .000E+00
    ASTAR =     1.250
    TRANSDUCER DIAMETER =  1.00000 INCHES
    ANUU  =     1.600

PRE-EXISTING CRACKS ONLY

FATIGUE CRACK GROWTH ONLY

LEAKERS WILL BE REPAIRED

FAILURE CRITERIA = APPLIED STRESS>FLOW STRESS

PIPE DIMENSIONS
    WALL THICKNESS =   2.50 INCHES
    INSIDE RADIUS  =  14.50 INCHES
      L/H RATIO    =    29.00
      L/R RATIO    =     5.00
    AREA OF PIPE          =   247.40 SQ. INCHES
    FLOW AREA OF PIPE     =   660.52 SQ. INCHES

INITIAL CRACK SIZE DISTRIBUTION
CRACK DEPTH IS EXPONENTIAL
    PARAMETER =    4.0700
ASPECT RATIO IS LOG-NORMAL
    MEDIAN                   =    1.3400
    SHAPE PARAMETER          =     .5380
    NORMALIZATION CONSTANT =    1.4149

CRACK GROWTH LAW PARAMETERS
    EXPONENT  =   4.000
    GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
         MEDIAN          =   .9140E-11
         90-TH PERCENT =   .3500E-10
    THRESHOLD =   4.600

FLOW STRESS NORMALLY DISTRIBUTED
    MEAN                 =   .4300E+02
    STANDARD DEVIATION =   .4200E+01

DISTRIBUTION PARAMETERS FOR ULTIMATE STRESS IN PIPE
    MEAN                 =   .0000E+00
    STANDARD DEVIATION =   .0000E+00
    STANDARD DEVIATION =  0.0 MEANS THE ULTIMATE STRESS IS CONSTANT
    INTERPOLATION FLAG =   0  ( IULT ) FOR WHOLE PIPE BREAK PROBABILITY
    ABS ( IULT ) IS THE NUMBER OF INTERPOLATION POINTS
    IF  IULT .GT. 0  LINEAR INTERPOLATION
    IF  IULT .EQ. 0  NO INTERPOLATION
    IF  IULT .LT. 0  LOGARITHMIC INTERPOLATION
```

Figure 10-4b. Input summary for Sample Problem 4.

```
PIPE LOADING VALUES
    STRESS (KSI) DUE TO COLD DEADWEIGHT  =      2.08
    STRESS (KSI)  DUE TO DWGHT + THERMAL =      8.58
    STRESS (KSI)  DUE TO         THERMAL =      6.50
    OPERATING PRESSURE (KSI)             =      2.40
    STRESS (KSI) DUE TO OPER. PRESSURE   =      6.41
    STRESS (KSI) DUE TO DWGHT + OP PRESR =      8.49
    STRESS (KSI) DUE TO DWT+THML+OP PRES =     14.99
    PROOF PRESSURE (KSI)                 =      3.00
    STRESS (KSI) DUE TO DWGHT + PRF PRES =     10.09

    HYDROSTATIC PROOF TEST IS MODELLED

 LEAK DETECTION AND DEFINITION PARAMETERS
    DETECTABLE LEAK (GPM) =    3.00
    BIG LEAK        (GPM) =    3.00

 NO RESIDUAL STRESSES ARE MODELLED

 NO VIBRATORY STRESSES ARE MODELLED

 SEISMIC CLASS INFORMATION
    CLASS      AMPL.      MAX.AMPL  CYCLES
      1        8.757       8.757       1     ONE OBE
      2        9.059       9.059       2     ONE SSE
      3       10.557      10.557       3     THREE SSE
      4       10.617      10.617       4     FIVE SSE

 PRE-SERVICE ULTRASONIC INSPECTION IS MODELLED

 TIME INTERVALS
    PLANT LIFETIME =  40.0 YEARS
    ENDPOINTS OF INTERVALS AT      .0   2.0   4.0   6.0   8.0 YEARS
    ENDPOINTS OF INTERVALS AT    10.0  12.0  14.0  16.0  18.0 YEARS
    ENDPOINTS OF INTERVALS AT    20.0  22.0  24.0  26.0  28.0 YEARS
    ENDPOINTS OF INTERVALS AT    30.0  32.0  34.0  36.0  38.0 YEARS
    ENDPOINTS OF INTERVALS AT    40.0

 NO IN-SERVICE INSPECTIONS ARE MODELLED

 EARTHQUAKE AT EACH EVALUATION INTERVAL

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS    0

 NORMAL OUTPUT REQUESTED


 NUMBER OF TRANSIENT TYPES =  2

 TYPE          Heat-up and Cool-down
    REGULAR AT          .200 YEARS/EVENT
    MAX DELTA TEMP = 460.0  BLOCKING FACTOR =  1.0

 TYPE  2       Reactor Trip from Full Power
    REGULAR AT          .500 YEARS/EVENT
    MAX DELTA TEMP =  73.0  BLOCKING FACTOR =  1.0
```

Fiagure 10-4b. (Continued).

```
                    - - - SUMMARY OF CELLS IN SAMPLE SPACE - - -

                              - - - UNIFORM MESH - - -

CELL      AOH1      AOH2      AOB1      AOB2       PROBABILITY   SAMPLES    LEAKS   B-LEAKS    LOCAS
   1     .9500    1.0000     .0000     .0200      .3105396E-15       500        0         0        0
   2     .9500    1.0000     .0200     .0400      .9598055E-12       500        0         0        0
   3     .9500    1.0000     .0400     .0600      .4906271E-10       500        0         0        0
   4     .9500    1.0000     .0600     .0800      .5431150E-09       500      403       403      267
   5     .9500    1.0000     .0800     .1000      .2752523E-08       500      498       498       12
   6     .9500    1.0000     .1000     .1200      .8838161E-08       500      497       497        0
   7     .9500    1.0000     .1200     .1400      .2121764E-07       500      493       493        0
   8     .9000     .9500     .0000     .0200      .5164929E-15       500        0         0        0
   9     .9000     .9500     .0200     .0400      .1596359E-11       500        0         0        0
  10     .9000     .9500     .0400     .0600      .8160163E-10       500       37        37       37
  11     .9000     .9500     .0600     .0800      .9033148E-09       500      397       397      232
  12     .9000     .9500     .0800     .1000      .4578026E-08       500      370       370        2
  13     .9000     .9500     .1000     .1200      .1469973F-07       500      384       384        0
  14     .9000     .9500     .1200     .1400      .3528942E-07       500      363       363        0
  15     .8500     .9000     .0000     .0200      .8590366E-15       500        0         0        0
  16     .8500     .9000     .0200     .0400      .2655082E-11       500        0         0        0
  17     .8500     .9000     .0400     .0600      .1357207E-09       500      136       136      136
  18     .8500     .9000     .0600     .0800      .1502403E-08       500      198       198       99
  19     .8500     .9000     .0800     .1000      .7614222E-08       500      185       185        2
  20     .8500     .9000     .1000     .1200      .2444874E-07       500      169       169        0
  21     .8500     .9000     .1200     .1400      .5869374E-07       500      152       152        0
  22     .8000     .8500     .0000     .0200      .1428759E-14       500        7         7        7
  23     .8000     .8500     .0200     .0400      .4415961E-11       500        6         6        6
  24     .8000     .8500     .0400     .0600      .2257322E-09       500       87        87       87
  25     .8000     .8500     .0600     .0800      .2498813E-08       500       73        73       33
  26     .8000     .8500     .0800     .1000      .1266406E-07       500       58        58        0
  27     .8000     .8500     .1000     .1200      .4066342E-07       500       67        67        0
  28     .8000     .8500     .1200     .1400      .9762007E-07       500       41        41        0
  29     .7500     .8000     .0000     .0200      .2376328E-14       500       84        84       84
  30     .7500     .8000     .0200     .0400      .7344674E-11       500       75        75       75
  31     .7500     .8000     .0400     .0600      .3754402E-09       500       43        43       43
  32     .7500     .8000     .0600     .0800      .4156053E-08       500       18        18        3
  33     .7500     .8000     .0800     .1000      .2106300E-07       500       23        23        0
  34     .7500     .8000     .1000     .1200      .6763184E-07       500       17        17        0
  35     .7500     .8000     .1200     .1400      .1623628E-06       500       20        20        0
  36     .7000     .7500     .0000     .0200      .3952334E-14       500       43        43       43
  37     .7000     .7500     .0200     .0400      .1221574E-10       500       36        36       36
  38     .7000     .7500     .0400     .0600      .6244363E-09       500       13        13       13
  39     .7000     .7500     .0600     .0800      .6912393E-08       500        7         7        1
  40     .7000     .7500     .0800     .1000      .3503221E-07       500        5         5        0
  41     .7000     .7500     .1000     .1200      .1124860E-06       500        8         8        0
  42     .7000     .7500     .1200     .1400      .2700435E-06       500        5         5        0
  43     .6500     .7000     .0000     .0200      .6573565E-14       500       10        10       10
  44     .6500     .7000     .0200     .0400      .2031735E-10       500        4         4        4
  45     .6500     .7000     .0400     .0600      .1038569E-08       500        4         4        4
  46     .6500     .7000     .0600     .0800      .1149677E-07       500        4         4        0
  47     .6500     .7000     .0800     .1000      .5826595E-07       500        1         1        0
  48     .6500     .7000     .1000     .1200      .1870880E-06       500        1         1        0
  49     .6500     .7000     .1200     .1400      .4491393E-06       500        3         3        0
  50     .6000     .6500     .0000     .0200      .1093322E-13       500        3         3        3
  51     .6000     .6500     .0200     .0400      .3379204E-10       500        1         1        1
  52     .6000     .6500     .0400     .0600      .1727360E-08       500        1         1        1
  53     .6000     .6500     .0600     .0800      .1912155E-07       500        1         1        0
  54     .6000     .6500     .0800     .1000      .9690856E-07       500        2         2        0
  55     .6000     .6500     .1000     .1200      .3111667E-06       500        0         0        0
  56     .6000     .6500     .1200     .1400      .7470134E-06       500        0         0        0
  57     .5500     .6000     .0000     .0200      .1818426E-13       500        0         0        0
  58     .5500     .6000     .0200     .0400      .5620329E-10       500        0         0        0
  59     .5500     .6000     .0400     .0600      .2872963E-08       500        1         1        1
```

Figure 10-4c. Stratification description for Sample Problem 4.

```
60    .5500   .6000   .0600   .0800      .3180317E-07    500    1    1    0
61    .5500   .6000   .0800   .1000      .1611794E-06    500    1    1    0
62    .5500   .6000   .1000   .1200      .5175359E-06    500    0    0    0
63    .5500   .6000   .1200   .1400      .1242441E-05    500    0    0    0
64    .5000   .5500   .0000   .0200      .3024426E-13    500    1    1    1
65    .5000   .5500   .0200   .0400      .9347793E-10    500    0    0    0
66    .5000   .5500   .0400   .0600      .4778344E-08    500    0    0    0
67    .5000   .5500   .0600   .0800      .5289537E-07    500    0    0    0
68    .5000   .5500   .0800   .1000      .2680753E-06    500    0    0    0
69    .5000   .5500   .1000   .1200      .8607713E-06    500    0    0    0
70    .5000   .5500   .1200   .1400      .2066441E-05    500    0    0    0
71    .4500   .5000   .0000   .0200      .5030257E-13    500    0    0    0
72    .4500   .5000   .0200   .0400      .1554735E-09    500    0    0    0
73    .4500   .5000   .0400   .0600      .7947393E-08    500    0    0    0
74    .4500   .5000   .0600   .0800      .8797616E-07    500    0    0    0
75    .4500   .5000   .0800   .1000      .4458657E-06    500    0    0    0
76    .4500   .5000   .1000   .1200      .1431644E-05    500    0    0    0
77    .4500   .5000   .1200   .1400      .3436927E-05    500    0    0    0
78    .4000   .4500   .0000   .0200      .8366379E-13    500    0    0    0
79    .4000   .4500   .0200   .0400      .2585852E-09    500    0    0    0
80    .4000   .4500   .0400   .0600      .1321819E-07    500    0    0    0
81    .4000   .4500   .0600   .0800      .1463229E-06    500    0    0    0
82    .4000   .4500   .0800   .1000      .7415687E-06    500    0    0    0
83    .4000   .4500   .1000   .1200      .2381126E-05    500    0    0    0
84    .4000   .4500   .1200   .1400      .5716335E-05    500    0    0    0
                                        ---------------
              SUM OF CELL PROBABILITIES =  .2251705E-04
```

Figure 10-4c. (Continued).

```
---  PROBLEM 4 : Fatigue baseline + LOCA + RGTS                                                        ---

                                                      - - - RESULTS WITHOUT EARTHQUAKES - - -

                    SEISMIC CLASS INFORMATION
                          CLASS      SIGEQ        SGLCEQ     CYCLES   COV F-BM
                            0      .0000E+00        .000        0        .0000

                              PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                                 SULTMU          SULTSD      IULT
                              .00000E+00      .00000E+00      0
                                STRESS(1)
                              .84876E+01
                                PBREAK(1)
                              .10000E+01

                 TIME      AVG LEAK      AVG BIG LEAK     AVG LOCA       SIGMA LEAK    SIGMA BIG LEAK   SIGMA LOCA
                   .0    3.02036E-10     3.02036E-10    4.41197E-12     2.18581E-11     2.18581E-11    7.31425E-13
                  2.0    1.29990E-09     1.29990E-09    2.62136E-11     3.77377E-11     3.77377E-11    2.77844E-12
                  4.0    1.90549E-09     1.90549E-09    3.51304E-11     4.69964E-11     4.69964E-11    3.01015E-12
                  6.0    2.48414E-09     2.48414E-09    4.44119E-11     6.12455E-11     6.12455E-11    3.22654E-12
                  8.0    2.94757E-09     2.94757E-09    5.34335E-11     7.02483E-11     7.02483E-11    3.55188E-12
                 10.0    3.56207E-09     3.56207E-09    6.33759E-11     8.73184E-11     8.73184E-11    3.94874E-12
                 12.0    4.06532E-09     4.06532E-09    7.09466E-11     9.72970E-11     9.72970E-11    4.21951E-12
                 14.0    4.70569E-09     4.70569E-09    7.70041E-11     1.38470E-10     1.38470E-10    4.35033E-12
                 16.0    5.34820E-09     5.34820E-09    8.32728E-11     1.86816E-10     1.86816E-10    4.51614E-12
                 18.0    6.22784E-09     6.22784E-09    8.98900E-11     3.28699E-10     3.28699E-10    4.68210E-12
                 20.0    6.76911E-09     6.76911E-09    9.58594E-11     3.37026E-10     3.37026E-10    4.84507E-12
                 22.0    7.32753E-09     7.32753E-09    1.02089E-10     3.48581E-10     3.48581E-10    5.13080E-12
                 24.0    7.93820E-09     7.93820E-09    1.08386E-10     3.56212E-10     3.56212E-10    5.30882E-12
                 26.0    8.57030E-09     8.57030E-09    1.14495E-10     3.69786E-10     3.69786E-10    5.79224E-12
                 28.0    9.31724E-09     9.31724E-09    1.18179E-10     3.95030E-10     3.95030E-10    5.92935E-12
                 30.0    9.91687E-09     9.91687E-09    1.25018E-10     4.11312E-10     4.11312E-10    6.31681E-12
                 32.0    1.14756E-08     1.14756E-08    1.27204E-10     5.38042E-10     5.38042E-10    6.33650E-12
                 34.0    1.22934E-08     1.22934E-08    1.31879E-10     5.52503E-10     5.52503E-10    6.47062E-12
                 36.0    1.31090E-08     1.31090E-08    1.38018E-10     6.01222E-10     6.01222E-10    7.19149E-12
                 38.0    1.37866E-08     1.37866E-08    1.41999E-10     6.10586E-10     6.10586E-10    7.28351E-12
                 40.0    1.42157E-08     1.42157E-08    1.44118E-10     6.16952E-10     6.16952E-10    7.31218E-12
```

Figure 10-4d. Failure probabilities for no earthquake case for Sample Problem 4.

```
---  PROBLEM 4 : Fatigue baseline + LOC' + RGTS                                                    ---

                                                   - - - RESULTS INCLUDING SEISMIC EVENTS - - -

              SEISMIC CLASS INFORMATION
                      CLASS      SIGEQ        SGLCEQ     CYCLES   COV F-BM
                        1     .8757E+01      8.757         1        .0000 ONE OBE

                  PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                     SULTMU           SULTSD     IULT
                  .00000E+00      .00000E+00     0
                   STRESS(1)
                  .87570E+01
                   PBREAK(1)
                  .10000E+01

         TIME      AVG LEAK     AVG BIG LEAK      AVG LOCA       SIGMA LEAK    SIGMA BIG LEAK    SIGMA LOCA
           .0    1.17499E-05    1.17499E-05    1.17496E-05    9.45638E-09     9.45638E-09    9.45641E-09
          2.0    1.17499E-05    1.17499E-05    1.17486E-05    9.45638E-09     9.45638E-09    9.45647E-09
          4.0    1.17499E-05    1.17499E-05    1.17481E-05    9.45638E-09     9.45638E-09    9.45651E-09
          6.0    1.17499E-05    1.17499E-05    1.17475E-05    9.45638E-09     9.45638E-09    9.45660E-09
          8.0    1.17499E-05    1.17499E-05    1.17471E-05    9.45638E-09     9.45638E-09    9.45666E-09
         10.0    1.17499E-05    1.17499E-05    1.17464E-05    9.45638E-09     9.45638E-09    9.45682E-09
         12.0    1.17500E-05    1.17500E-05    1.17460E-05    9.45638E-09     9.45638E-09    9.45693E-09
         14.0    1.17500E-05    1.17500E-05    1.17453E-05    9.45638E-09     9.45638E-09    9.45749E-09
         16.0    1.17500E-05    1.17500E-05    1.17447E-05    9.45638E-09     9.45638E-09    9.45842E-09
         18.0    1.17500E-05    1.17500E-05    1.17438E-05    9.45638E-09     9.45638E-09    9.46199E-09
         20.0    1.17500E-05    1.17500E-05    1.17433E-05    9.45638E-09     9.45638E-09    9.46229E-09
         22.0    1.17500E-05    1.17500E-05    1.17427E-05    9.45638E-09     9.45638E-09    9.46269E-09
         24.0    1.17500E-05    1.17500E-05    1.17422E-05    9.45638E-09     9.45638E-09    9.46297E-09
         26.0    1.17500E-05    1.17500E-05    1.17415E-05    9.45638E-09     9.45638E-09    9.46352E-09
         28.0    1.17500E-05    1.17500E-05    1.17408E-05    9.45638E-09     9.45638E-09    9.46454E-09
         30.0    1.17500E-05    1.17500E-05    1.17402E-05    9.45638E-09     9.45638E-09    9.46526E-09
         32.0    1.17500E-05    1.17500E-05    1.17386E-05    9.45638E-09     9.45638E-09    9.47143E-09
         34.0    1.17500E-05    1.17500E-05    1.17378E-05    9.45638E-09     9.45638E-09    9.47233E-09
         36.0    1.17500E-05    1.17500E-05    1.17370E-05    9.45638E-09     9.45638E-09    9.47535E-09
         38.0    1.17500E-05    1.17500E-05    1.17364E-05    9.45638E-09     9.45638E-09    9.47592E-09
         40.0    1.17500E-05    1.17500E-05    1.17359E-05    9.45638E-09     9.45638E-09    9.47633E-09
```

Figure 10-4e. Failure probabilities for Earthquake Classes 1 and 2 for Sample Problem 4.

```
   SEISMIC CLASS INFORMATION
           CLASS      SIGEQ        SGLCEQ     CYCLES  COV F-BM
             2      .9059E+01      9.059        2         .0000 ONE SSE

         PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
            SULTMU            SULTSD     IOPT
         .00000E+00       .00000E+00     0
          STRESS(1)
         .90590E+01
          PBREAK(1)
         .10000E+01

TIME      AVG LEAK       AVG BIG LEAK       AVG LOCA        SIGMA LEAK     SIGMA BIG LEAK    SIGMA LOCA
  .0     1.17498E-05     1.17498E-05     1.17495E-05     9.45638E-09     9.45638E-09     9.45641E-09
 2.0     1.17499E-05     1.17499E-05     1.17486E-05     9.45638E-09     9.45638E-09     9.45647E-09
 4.0     1.17499E-05     1.17499E-05     1.17480E-05     9.45638E-09     9.45638E-09     9.45651E-09
 6.0     1.17499E-05     1.17499E-05     1.17475E-05     9.45638E-09     9.45638E-09     9.45660E-09
 8.0     1.17499E-05     1.17499E-05     1.17470E-05     9.45638E-09     9.45638E-09     9.45666E-09
10.0     1.17499E-05     1.17499E-05     1.17464E-05     9.45638E-09     9.45638E-09     9.45682E-09
12.0     1.17499E-05     1.17499E-05     1.17459E-05     9.45638E-09     9.45638E-09     9.45693E-09
14.0     1.17499E-05     1.17499E-05     1.17453E-05     9.45638E-09     9.45638E-09     9.45749E-09
16.0     1.17499E-05     1.17499E-05     1.17447E-05     9.45638E-09     9.45638E-09     9.45842E-09
18.0     1.17499E-05     1.17499E-05     1.17438E-05     9.45638E-09     9.45638E-09     9.46199E-09
20.0     1.17499E-05     1.17499E-05     1.17433E-05     9.45638E-09     9.45638E-09     9.46229E-09
22.0     1.17499E-05     1.17499E-05     1.17427E-05     9.45638E-09     9.45638E-09     9.46269E-09
24.0     1.17500E-05     1.17500E-05     1.17421E-05     9.45638E-09     9.45638E-09     9.46297E-09
26.0     1.17500E-05     1.17500E-05     1.17415E-05     9.45638E-09     9.45638E-09     9.46352E-09
28.0     1.17500E-05     1.17500E-05     1.17408E-05     9.45638E-09     9.45638E-09     9.46454E-09
30.0     1.17500E-05     1.17500E-05     1.17402E-05     9.45638E-09     9.45638E-09     9.46576E-09
32.0     1.17500E-05     1.17500E-05     1.17386E-05     9.45638E-09     9.45638E-09     9.47143E-09
34.0     1.17500E-05     1.17500E-05     1.17378E-05     9.45638E-09     9.45638E-09     9.47233E-09
36.0     1.17500E-05     1.17500E-05     1.17370E-05     9.45638E-09     9.45638E-09     9.47535E-09
38.0     1.17500E-05     1.17500E-05     1.17363E-05     9.45638E-09     9.45638E-09     9.47592E-09
40.0     1.17500E-05     1.17500E-05     1.17359E-05     9.45638E-09     9.45638E-09     9.47633E-09
```

Figure 10-4e. (Continued).

```
---  PROBLEM 4 : Fatigue baseline + LOCA + RGTS                                                   ---

                                              - - - RESULTS INCLUDING SEISMIC EVENTS - - -

                SEISMIC CLASS INFORMATION
                      CLASS      SIGEQ        SGLCEQ     CYCLES   COV  F-BM
                        3     .1056E+02      10.557         3          .0000 THREE SSE

                    PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                      SULTMU           SULTSD       IULT
                   .00000E+00       .00000E+00      0
                    STRESS(1)
                   .10557E+02
                    PBREAK(1)
                   .10000E+01

      TIME       AVG LEAK       AVG BIG LEAK       AVG LOCA        SIGMA LEAK    SIGMA BIG LEAK     SIGMA LOCA
        .0     1.17496E-05     1.17496E-05     1.17493E-05     9.45640E-09     9.45640E-09     9.45643E-09
       2.0     1.17496E-05     1.17496E-05     1.17483E-05     9.45639E-09     9.45639E-09     9.45648E-09
       4.0     1.17496E-05     1.17496E-05     1.17478E-05     9.45639E-09     9.45639E-09     9.45653E-09
       6.0     1.17497E-05     1.17497E-05     1.17472E-05     9.45639E-09     9.45639E-09     9.45661E-09
       8.0     1.17497E-05     1.17497E-05     1.17468E-05     9.45640E-09     9.45640E-09     9.45668E-09
      10.0     1.17497E-05     1.17497E-05     1.17462E-05     9.45640E-09     9.45640E-09     9.45683E-09
      12.0     1.17497E-05     1.17497E-05     1.17457E-05     9.45640E-09     9.45640E-09     9.45694E-09
      14.0     1.17497E-05     1.17497E-05     1.17451E-05     9.45639E-09     9.45639E-09     9.45750E-09
      16.0     1.17497E-05     1.17497E-05     1.17444E-05     9.45639E-09     9.45639E-09     9.45843E-09
      18.0     1.17497E-05     1.17497E-05     1.17436E-05     9.45640E-09     9.45640E-09     9.46200E-09
      20.0     1.17497E-05     1.17497E-05     1.17430E-05     9.45640E-09     9.45640E-09     9.46230E-09
      22.0     1.17497E-05     1.17497E-05     1.17425E-05     9.45640E-09     9.45640E-09     9.46270E-09
      24.0     1.17497E-05     1.17497E-05     1.17419E-05     9.45640E-09     9.45640E-09     9.46297E-09
      26.0     1.17497E-05     1.17497E-05     1.17413E-05     9.45640E-09     9.45640E-09     9.46353E-09
      28.0     1.17497E-05     1.17497E-05     1.17405E-05     9.45640E-09     9.45640E-09     9.46455E-09
      30.0     1.17497E-05     1.17497E-05     1.17399E-05     9.45641E-09     9.45641E-09     9.46527E-09
      32.0     1.17497E-05     1.17497E-05     1.17384E-05     9.45640E-09     9.45640E-09     9.47144E-09
      34.0     1.17497E-05     1.17497E-05     1.17376E-05     9.45640E-09     9.45640E-09     9.47234E-09
      36.0     1.17497E-05     1.17497E-05     1.17368E-05     9.45641E-09     9.45641E-09     9.47537E-09
      38.0     1.17497E-05     1.17497E-05     1.17361E-05     9.45640E-09     9.45640E-09     9.47593E-09
      40.0     1.17497E-05     1.17497E-05     1.17357E-05     9.45640E-09     9.45640E-09     9.47634E-09
```

Figure 10-4f. Failure probabilities for Earthquake Classes 3 and 4 for Sample Problem 4.

```
     SEISMIC CLASS INFORMATION
                CLASS      SIGEQ        SGLCEQ     CYCLES  COV F-BM
                  4      .1062E+02      10.617        4         .0000 FIVE SSE

             PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                SULTMU            SULTSD      IULT
             .00000E+00        .00000E+00     0
              STRESS(1)
             .10617E+02
              PBREAK(1)
             .10000E+01

   TIME      AVG LEAK       AVG BIG LEAK      AVG LOCA       SIGMA LEAK    SIGMA BIG LEAK    SIGMA LOCA
     .0    1.17495E-05     1.17495E-05     1.17492E-05     9.45640E-09     9.45640E-09     9.45643E-09
    2.0    1.17496E-05     1.17496E-05     1.17483E-05     9.45640E-09     9.45640E-09     9.45648E-09
    4.0    1.17496E-05     1.17496E-05     1.17477E-05     9.45640E-09     9.45640E-09     9.45653E-09
    6.0    1.17496E-05     1.17496E-05     1.17472E-05     9.45640E-09     9.45640E-09     9.45661E-09
    8.0    1.17496E-05     1.17496E-05     1.17468E-05     9.45640E-09     9.45640E-09     9.45668E-09
   10.0    1.17497E-05     1.17497E-05     1.17462E-05     9.45640E-09     9.45640E-09     9.45683E-09
   12.0    1.17497E-05     1.17497E-05     1.17457E-05     9.45640E-09     9.45640E-09     9.45694E-09
   14.0    1.17497E-05     1.17497E-05     1.17450E-05     9.45640E-09     9.45640E-09     9.45750E-09
   16.0    1.17497E-05     1.17497E-05     1.17444E-05     9.45640E-09     9.45640E-09     9.45843E-09
   18.0    1.17497E-05     1.17497E-05     1.17435E-05     9.45640E-09     9.45640E-09     9.46201E-09
   20.0    1.17497E-05     1.17497E-05     1.17430E-05     9.45640E-09     9.45640E-09     9.46230E-09
   22.0    1.17497E-05     1.17497E-05     1.17425E-05     9.45640E-09     9.45640E-09     9.46270E-09
   24.0    1.17497E-05     1.17497E-05     1.17419E-05     9.45640E-09     9.45640E-09     9.46298E-09
   26.0    1.17497E-05     1.17497E-05     1.17413E-05     9.45640E-09     9.45640E-09     9.46353E-09
   28.0    1.17497E-05     1.17497E-05     1.17405E-05     9.45641E-09     9.45641E-09     9.46455E-09
   30.0    1.17497E-05     1.17497E-05     1.17399E-05     9.45641E-09     9.45641E-09     9.46527E-09
   32.0    1.17497E-05     1.17497E-05     1.17384E-05     9.45640E-09     9.45640E-09     9.47144E-09
   34.0    1.17497E-05     1.17497E-05     1.17376E-05     9.45640E-09     9.45640E-09     9.47234E-09
   36.0    1.17497E-05     1.17497E-05     1.17367E-05     9.45641E-09     9.45641E-09     9.47537E-09
   38.0    1.17497E-05     1.17497E-05     1.17361E-05     9.45640E-09     9.45640E-09     9.47593E-09
   40.0    1.17497E-05     1.17497E-05     1.17357E-05     9.45640E-09     9.45640E-09     9.47634E-09

PC-PRAISE VERSION 2.40
Execution Start -    12/06/91 at  6:47p
Execution End   -    12/06/91 at  9:19p
```

Figure 10-4f. (Continued).

10.5 Sample Problem 5: Fatigue Baseline Case with Tearing Modulus Failure Criteria and Residual Stresses

This sample problem illustrates the use of tearing modulus failure criteria and residual stresses in pc-PRAISE. This case calculates probability of leak due to the growth of a pre-existing crack by fatigue mechanism. The only load cycle used is the heat-up/cool-down cycle. The weld location is subjected to pre-service inspection and a proof-test. Only the tearing modulus based failure criteria is applied. The default characterization of residual stresses for large lines is used. The major inputs related to the geometry of the pipe, the pipe material, the welding process used, and the operating history are described below.

Pipe Geometry:
Inside Radius = 14.5 in
Wall Thickness = 2.5 in
L/R Ratio = 5

Stresses:
Deadweight = 2.08 ksi
Deadweight + Thermal Expansion = 8.58 ksi
Operating Pressure = 2400 psi
Proof Pressure = 3000 psi

Fatigue Crack Growth Properties:
C (median) = 9.14×10^{-12}
C (90th percentile) = 3.5×10^{-11}
Fatigue Exponent = 4.0
Fatigue Threshold = 4.6 ksi-in$^{1/2}$

Initial Crack Size Distribution:
Depth Distribution -- Lognormal
Median = 0.05 in
Shape Parameter = 0.82
Aspect Ratio Distribution -- Exponential
Parameter = 1.15

The a/h - a/b sample space is divided into 100 cells and 100 samples are taken from each cell. Plant lifetime of 40 years is simulated and results are printed at two year intervals. The vibratory stresses are not considered in the analysis. The heat-up/cool-down cycles are assumed to occur regularly five times a year.

The input file for Sample Problem 5 is shown in Figure 10-5a. Each variable in the input file is described in Table 10-5. The output file is shown in Figures 10-5b through 10-5d. Description of the inputs is summarized in Figure 10-5b. The stratification scheme used is shown in Figure 10-5c. Coordinates of each cell are shown along with the number of samples and the conditional probability of crack from that cell. The last three columns of that table show the number of cracks that resulted in leak, big-leak, and LOCA, respectively. The probabilities of leak as a function of time are shown in Figure 10-5d. Leak and big-leak probabilities are the same at any given time, because the same threshold leak rate is used for identifying small and big leak. The LOCA probability calculations for this case are not accurate because the stratification used is not optimized for the estimation of LOCA probabilities.

Table 10-5
VARIABLE INPUT FILE FOR SAMPLE PROBLEM 5: FATIGUE BASELINE CASE WITH TEARING MODULUS CRITERIA AND RESIDUAL STRESSES

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #1 Title				
TITLE( )		Analysis title		
Line #2 Control Variables (Card 0B)				
INCIAT	0	Pre-existing cracks only	1 - 5	I5
IFAILC	1	Tearing modulus based failure criteria	6 - 10	I5
ICRAKS	0	Not used	11 - 15	I5
IREPLS	0	Not used	16 - 20	I5
IREPAR	0	Not used	26 - 30	I5
BNDRY	1.1	Not used	31 - 40	F10.3
ISF	0	Fatigue crack growth data input by the user	41 - 50	I10
MTTYPE	1	Not used	51 - 55	I5
ISEED	688	Random number seed 1	56 - 62	I7
ISEEDR	7225	Random number seed 2	63 - 70	I8
IREMED	0	Number of remedial actions during the plant life	71 - 75	I5
Line #3 Control Variables (Card 1B)				
NTRIES	-100	Number of replications from each cell = abs (NTRIES)	1 - 5	I5
ISQARE	1	Rectangular grid to be set up	6 - 10	I5
KTYPES	1	Number of transients experienced by the plant	11 - 15	I5
KRKDIS	2	Crack depth lognormal, aspect ratio exponential	16 - 20	I5
NEVAL	6	Number of user-supplied times at which results are printed	21 - 25	I5
NINSPT	0	No in-service inspections	26 - 30	I5
NQUAKE	0	No earthquakes to be modeled	31 - 35	I5
IDEBUG	0	Normal output to be printed	36 - 40	I5

Table 10-5 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #3 Control Variables (Card 1B) [Continued]				
KONPRP	0	C lognormally distributed	41 - 45	I5
NEQINT	0	Not used	46 - 50	I5
MCELLS	0	Not used	51 - 55	I5
KNSFLO	0	Not used	56 - 60	I5
NSKIP	0	No indicator function printout	61 - 65	I5
NPSI	1	A pre-service inspection is modeled	66 - 70	I5
ISCC	0	Crack growth by fatigue only	71 - 75	I5
ISIGRS	2	Built-in residual stresses for large lines are used	75 - 80	I5
Line #4 Time and NDE Parameters (Card 1D)				
THRIZN	40	Maximum plant life time simulated (years)	1 - 10	E10.3
DTSCC	0.2	Not used	11 - 20	E10.3
ICTYPE	0	Crack orientation is circumferential	21 - 25	I5
IPTYPE	0	Default NDE parameters for thick austenitic pipe used	26 - 30	I5
EPST		Not used	31 - 40	E10.0
ASTAR		Not used	41 - 50	E10.0
TRANSD		Not used	51 - 60	E10.0
ANUU		Not used	61 - 70	E10.0
Line #5 Pipe Dimensions (Card 2A)				
THICK	2.5	Wall thickness of the pipe (inches)	1 - 10	E10.3
RIN	14.5	Inside radius (inches)	11 - 20	E10.3
ELOVRR	5	Pipe length/radius ratio	21 - 30	E10.3

Table 10-5 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #6 Fatigue Crack Growth Characteristics (Card 2B)				
THRHLD	4.6	Threshold for fatigue crack growth (ksi-in$^{1/2}$)	1 - 10	E10.3
EMEXP	4	Exponent for fatigue crack growth equation	11 - 20	E10.3
CONSMU	9.14×10^{-12}	50th percentile of C	21 - 30	E10.3
CONS90	3.50×10^{-11}	90th percentile of C	31 - 40	E10.3
Line #7 Flow Stress (Card 2C)				
SFLOMU	43.2	Not used	1 - 10	E10.4
SFLOSD	4.2	Not used	11 - 20	E10.4
XJIC	10	J_{Ic} (in-kips/in^2)	21 - 30	E10.4
DJDAMT	25	dJ/da (ksi)	31 - 40	E10.4
SIG0	30.6	Yield strength (ksi)	41 - 50	E10.4
DEE	106	Constant D in the power-law hardening equation (ksi)	51 - 60	E10.4
YOUNGS	25000	Elastic modulus (ksi)	61 - 70	E10.4
XN	5	Exponent n in the power-law hardening equation	71 - 80	E10.4
Line #8 Ultimate Stress Definition (Card 2D)				
SULTMU	75	Mean UTS (ksi)	1 - 10	E10.0
SULTSD	10	Standard deviation of UTS (ksi)	11 - 20	E10.0
IULT	3	P_{break} at three stress values	21 - 25	I5
Line #9 Initial Crack Depth Distribution (Card 3A)				
AMEDIAN	0.05	Median of the lognormal distribution of crack depth (in)	1 - 10	E10.3
ASIGMA	0.82	Shape factor of the lognormal distribution of crack depth	11 - 20	E10.3
ALAMDA		Not used	21 - 30	E10.3

Table 10-5 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #10 Initial Aspect Ratio Distribution (Card 3B)				
BOALDA	1.15	Rate parameter for shifted exponential distribution of b/a	1 - 10	E10.3
Line #11 Evaluation Times (Card 4A)				
TEVAL	1, 5, 10, ...	Evaluation Times (years)	1 - 80	8E10.3
Line #12 Leak Rate and Detection Parameters (Card 4C)				
FNDLEK	3	Threshold for detectable leak rate (gpm)	1 - 10	E10.3
ALKBIG	3	Threshold for defining big leaks (gpm)	11 - 20	E10.3
Line #13 Stratified Sample Space (Card 5A)				
NAOH	10	Number of divisions in a/h direction	1 - 5	I5
NAOB	10	Number of divisions in a/b direction	6 - 10	I5
AOHLOW	0	Lower limit of a/h	11 - 20	E10.3
AOHUP	1	Upper limit of a/h	21 - 30	E10.3
AOBLFT	0	Lower limit of a/b	31 - 40	E10.3
AOBRGT	1	Upper limit of a/b	41 - 50	E10.3
Line #14 Operating Stresses (Card 6A)				
SGCLD	2.08	Deadweight stress (ksi)	1 - 10	E10.4
SGDWTE	8.58	Deadweight and thermal expansion stress (ksi)	11 - 20	E10.4
OPPRES	2.[illegible]	Normal operating pressure (ksi)	21 - 30	E10.4
PRFPRS	3	Pressure in hydrostatic proof test (ksi)	31 - 40	E10.4
SIGVIB	-1	Vibratory stresses not modeled	41 - 50	E10.4
VBTHLD	0	Not used	51 - 60	E10.4

Table 10-5 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line K-5 Frequency of Heat-up/Cool-down Transient 1 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.2	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	460	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10

```
              P       R         A       I       $     E

              PIPING RELIABILITY ANALYSIS INCLUDING SEISMIC EVENTS

                           PC-PRAISE VERSION 2.40

                       EXECUTED ON  12/06/91 AT  9:19p


                       ECHO-PRINT OF INPUT DATA IN FILE  SAMPLES.DAT

LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
   1> PROBLEM 5 : Fetigue baseline + Tmat failure criteria                           <
   2>    0    1    0    0         0     1.100         0    1    688    7225    0     <
   3> -100    1    1    2    6    0    0    0    0    0    0    0    0    1    0    2<
   4>  .400E+02  .200E+00    0    0                                                  <
   5>  .250E+01  .145E+02  .500E+01                                                  <
   6>  .460E+01  .400E+01  .914E-11  .350E-10                                        <
   7> .4300E+02 .4200E+01      10.0      25.0      30.6     106.0   25000.0      5.00<
   8>  .750E+02  .100E+02    3                                                       <
   9>      0.05      0.82                                                            <
  10>      1.15                                                                      <
  11>       1.0       5.0      10.0      15.0      20.0      40.0                    <
  12>  .300E+01  .300E+01                                                            <
  13>   10   10      .000     1.000      .000     1.000                              <
  14>  2.08      8.58      2.400     3.00     -.100E+01  .000E+00                    <
  15>    1 .2    460.00000Heat-up and Cool-down                                      <
LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
 ****** NEW SEED (L,R)         688       7225*****
```

Figure 10-5a. Echo of input file for Sample Problem 5.

```
---  PROBLEM 5 : Fatigue baseline + Tmat failure criteria                      ---

CIRCUMFERENTIAL CRACK ANALYSIS

PARAMETERS THAT DETERMINE NON-DETECTION PROBABILITY
    EPST  =      .000E+00
    ASTAR =     1.250
    TRANSDUCER DIAMETER =  1.00000 INCHES
    ANUU  =     1.600

PRE-EXISTING CRACKS ONLY

FATIGUE CRACK GROWTH ONLY

LEAKERS WILL BE REPAIRED

FAILURE CRITERIA = JIC AND DJDA EXCEEDENCE

PIPE DIMENSIONS
    WALL THICKNESS =   2.50 INCHES
    INSIDE RADIUS  =  14.50 INCHES
      L/H RATIO    =    29.00
      L/R RATIO    =     5.00
    AREA OF PIPE         =   247.40 SQ. INCHES
    FLOW AREA OF PIPE    =   660.52 SQ. INCHES

INITIAL CRACK SIZE DISTRIBUTION
CRACK DEPTH IS LOG-NORMAL
    MEDIAN =      .0500
    SHAPE PARAMETER =       .8200
ASPECT RATIO IS EXPONENTIAL
    PARAMETER =     1.1500

CRACK GROWTH LAW PARAMETERS
    EXPONENT  =   4.000
    GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
         MEDIAN          =   .9140E-11
         90-TH PERCENT =   .3500E-10
    THRESHOLD =   4.600

FLOW STRESS NORMALLY DISTRIBUTED
    MEAN                  =   .4300E+02
    STANDARD DEVIATION =   .4200E+01

DISTRIBUTION PARAMETERS FOR ULTIMATE STRESS IN PIPE
    MEAN                  =   .7500E+02
    STANDARD DEVIATION =   .1000E+02
    STANDARD DEVIATION =  0.0 MEANS THE ULTIMATE STRESS IS CONSTANT
    INTERPOLATION FLAG =   3  ( IULT ) FOR WHOLE PIPE BREAK PROBABILITY
    ABS ( IULT ) IS THE NUMBER OF INTERPOLATION POINTS
    IF  IULT .GT. 0  LINEAR INTERPOLATION
    IF  IULT  EQ. 0  NO INTERPOLATION
    IF  IULT .LT. 0  LOGARITHMIC INTERPOLATION

    JIC (IN-KIPS/IN.IN) =      10.0000
        DJDA        (KSI) =      25.0000
    YIELD STRESS  (KSI) =      30.6000
          D        (KSI) =     106.0000
    YOUNGS MODULUS(KSI) =  25000.0000
    EXPONENT, N           =       5.0000
```

Figure 10-5b. Input summary for Sample Problem 5.

```
PIPE LOADING VALUES
    STRESS (KSI) DUE TO COLD DEADWEIGHT  =      2.08
    STRESS (KSI)  DUE TO DWGHT + THERMAL =      8.58
    STRESS (KSI)  DUE TO         THERMAL =      6.50
    OPERATING PRESSURE (KSI)             =      2.40
    STRESS (KSI) DUE TO OPER. PRESSURE   =      6.41
    STRESS (KSI) DUE TO DWGHT + OP PRESR =      8.49
    STRESS (KSI) DUE TO DWT+THML+OP PRES =     14.99
    PROOF PRESSURE (KSI)                 =      3.00
    STRESS (KSI) DUE TO DWGHT + PRF PRES =     10.09

    HYDROSTATIC PROOF TEST IS MODELLED

LEAK DETECTION AND DEFINITION PARAMETERS
    DETECTABLE LEAK (GPM) =    3.00
    BIG LEAK        (GPM) =    3.00

RESIDUAL STRESSES FOR LARGE IN LINE SELECTED

NO VIBRATORY STRESSES ARE MODELLED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELLED

TIME INTERVALS
    PLANT LIFETIME =  40.0 YEARS
    ENDPOINTS OF INTERVALS AT      .0   1.0   5.0  10.0  15.0 YEARS
    ENDPOINTS OF INTERVALS AT   20.0  40.0

NO IN-SERVICE INSPECTIONS ARE MODELLED

NO SEISMIC EVENTS SIMULATED

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS   0

NORMAL OUTPUT REQUESTED


NUMBER OF TRANSIENT TYPES =  1

TYPE  1    Heat-up and Cool-down
    REGULAR AT         .200 YEARS/EVENT
    MAX DELTA TEMP = 460.0  BLOCKING FACTOR =  1.0
```

Figure 10-5b. (Continued).

```
                         - - - SUMMARY OF CELLS IN SAMPLE SPACE - - -

                                   - - - UNIFORM MESH - - -

CELL      AOH1      AOH2      AOB1      AOB2          PROBABILITY      SAMPLES    LEAKS    B-LEAKS    LOCAS
  1      .9000    1.0000     .0000     .1000         .2578822E-10      100         0         0          0
  2      .9000    1.0000     .1000     .2000         .8076629E-08      100         0         0          0
  3      .9000    1.0000     .2000     .3000         .4697992E-07      100         0         0          0
  4      .9000    1.0000     .3000     .4000         .8853644E-07      100         0         0          0
  5      .9000    1.0000     .4000     .5000         .1116105E-06      100         0         0          0
  6      .9000    1.0000     .5000     .6000         .1192347E-06      100         0         0          0
  7      .9000    1.0000     .6000     .7000         .1179428E-06      100         0         0          0
  8      .9000    1.0000     .7000     .8000         .1122508E-06      100         0         0          0
  9      .9000    1.0000     .8000     .9000         .1047176E-06      100         0         0          0
 10      .9000    1.0000     .9000    1.0000         .9668818E-07      100         0         0          0
 11      .8000     .9000     .0000     .1000         .5431918E-10      100        13        13         13
 12      .8000     .9000     .1000     .2000         .1701226E-07      100         9         9          0
 13      .8000     .9000     .2000     .3000         .9895646E-07      100         6         6          0
 14      .8000     .9000     .3000     .4000         .1864893E-06      100         2         2          0
 15      .8000     .9000     .4000     .5000         .2350916E-06      100         0         0          0
 16      .8000     .9000     .5000     .6000         .2511508E-06      100         1         1          0
 17      .8000     .9000     .6000     .7000         .2484296E-06      100         0         0          0
 18      .8000     .9000     .7000     .8000         .2364402E-06      100         0         0          0
 19      .8000     .9000     .8000     .9000         .2205726E-06      100         0         0          0
 20      .8000     .9000     .9000    1.0000         .2036598E-06      100         0         0          0
 21      .7000     .8000     .0000     .1000         .1229993E-09      100         6         6          5
 22      .7000     .8000     .1000     .2000         .3852223E-07      100         1         1          0
 23      .7000     .8000     .2000     .3000         .2240751E-06      100         0         0          0
 24      .7000     .8000     .3000     .4000         .4222829E-06      100         0         0          0
 25      .7000     .8000     .4000     .5000         .5323368E-06      100         0         0          0
 26      .7000     .8000     .5000     .6000         .5687011E-06      100         0         0          0
 27      .7000     .8000     .6000     .7000         .5625392E-06      100         0         0          0
 28      .7000     .8000     .7000     .8000         .5353907E-06      100         0         0          0
 29      .7000     .8000     .8000     .9000         .4994603E-06      100         0         0          0
 30      .7000     .8000     .9000    1.0000         .4611632E-06      100         0         0          0
 31      .6000     .7000     .0000     .1000         .3047825E-09      100         0         0          0
 32      .6000     .7000     .1000     .2000         .9545505E-07      100         0         0          0
 33      .6000     .7000     .2000     .3000         .5552404E-06      100         0         0          0
 34      .6000     .7000     .3000     .4000         .1046383E-05      100         0         0          0
 35      .6000     .7000     .4000     .5000         .1319089E-05      100         0         0          0
 36      .6000     .7000     .5000     .6000         .1409196E-05      100         0         0          0
 37      .6000     .7000     .6000     .7000         .1393928E-05      100         0         0          0
 38      .6000     .7000     .7000     .8000         .1326656E-05      100         0         0          0
 39      .6000     .7000     .8000     .9000         .1237623E-05      100         0         0          0
 40      .6000     .7000     .9000    1.0000         .1142726E-05      100         0         0          0
 41      .5000     .6000     .0000     .1000         .8480165E-09      100         0         0          0
 42      .5000     .6000     .1000     .2000         .2655908E-06      100         0         0          0
 43      .5000     .6000     .2000     .3000         .1544882E-05      100         0         0          0
 44      .5000     .6000     .3000     .4000         .2911421E-05      100         0         0          0
 45      .5000     .6000     .4000     .5000         .3670187E-05      100         0         0          0
 46      .5000     .6000     .5000     .6000         .3920899E-05      100         0         0          0
 47      .5000     .6000     .6000     .7000         .3878416E-05      100         0         0          0
 48      .5000     .6000     .7000     .8000         .3691241E-05      100         0         0          0
 49      .5000     .6000     .8000     .9000         .3443520E-05      100         0         0          0
 50      .5000     .6000     .9000    1.0000         .3179482E-05      100         0         0          0
 51      .4000     .5000     .0000     .1000         .2756588E-08      100         0         0          0
 52      .4000     .5000     .1000     .2000         .8633376E-06      100         0         0          0
 53      .4000     .5000     .2000     .3000         .5021839E-05      100         0         0          0
 54      .4000     .5000     .3000     .4000         .9463953E-05      100         0         0          0
 55      .4000     .5000     .4000     .5000         .1193042E-04      100         0         0          0
 56      .4000     .5000     .5000     .6000         .1274537E-04      100         0         0          0
 57      .4000     .5000     .6000     .7000         .1260730E-04      100         0         0          0
 58      .4000     .5000     .7000     .8000         .1199886E-04      100         0         0          0
 59      .4000     .5000     .8000     .9000         .1119361E-04      100         0         0          0
```

Figure 10-5c. Stratification Description for Sample Problem 5.

```
 60    .4000    .5000    .9000   1.0000       .1033532E-04     100      0      0      0
 61    .3000    .4000    .0000    .1000       .1118886E-07     100      0      0      0
 62    .3000    .4000    .1000    .2000       .3504246E-05     100      0      0      0
 63    .3000    .4000    .2000    .3000       .2038340E-04     100      0      0      0
 64    .3000    .4000    .3000    .4000       .3841373E-04     100      0      0      0
 65    .3000    .4000    .4000    .5000       .4842500E-04     100      0      0      0
 66    .3000    .4000    .5000    .6000       .5173294E-04     100      0      0      0
 67    .3000    .4000    .6000    .7000       .5117241E-04     100      0      0      0
 68    .3000    .4000    .7000    .8000       .4870280E-04     100      0      0      0
 69    .3000    .4000    .8000    .9000       .4543433E-04     100      0      0      0
 70    .3000    .4000    .9000   1.0000       .4195057E-04     100      0      0      0
 71    .2000    .3000    .0000    .1000       .6440611E-07     100      0      0      0
 72    .2000    .3000    .1000    .2000       .2017139E-04     100      0      0      0
 73    .2000    .3000    .2000    .3000       .1173324E-03     100      0      0      0
 74    .2000    .3000    .3000    .4000       .2211199E-03     100      0      0      0
 75    .2000    .3000    .4000    .5000       .2787475E-03     100      0      0      0
 76    .2000    .3000    .5000    .6000       .2977889E-03     100      0      0      0
 77    .2000    .3000    .6000    .7000       .2945623E-03     100      0      0      0
 78    .2000    .3000    .7000    .8000       .2803466E-03     100      0      0      0
 79    .2000    .3000    .8000    .9000       .2615324E-03     100      0      0      0
 80    .2000    .3000    .9000   1.0000       .2414789E-03     100      0      0      0
 81    .1000    .2000    .0000    .1000       .7149251E-06     100      0      0      0
 82    .1000    .2000    .1000    .2000       .2239079E-03     100      0      0      0
 83    .1000    .2000    .2000    .3000       .1302421E-02     100      0      0      0
 84    .1000    .2000    .3000    .4000       .2454490E-02     100      0      0      0
 85    .1000    .2000    .4000    .5000       .3094172E-02     100      0      0      0
 86    .1000    .2000    .5000    .6000       .3305536E-02     100      0      0      0
 87    .1000    .2000    .6000    .7000       .3269721E-02     100      0      0      0
 88    .1000    .2000    .7000    .8000       .3111922E-02     100      0      0      0
 89    .1000    .2000    .8000    .9000       .2903079E-02     100      0      0      0
 90    .1000    .2000    .9000   1.0000       .2680430E-02     100      0      0      0
 91    .0000    .1000    .0000    .1000       .3119816E-04     100      0      0      0
 92    .0000    .1000    .1000    .2000       .9770971E-02     100      0      0      0
 93    .0000    .1000    .2000    .3000       .5683553E-01     100      0      0      0
 94    .0000    .1000    .3000    .4000       .1071099E+00     100      0      0      0
 95    .0000    .1000    .4000    .5000       .1350246E+00     100      0      0      0
 96    .0000    .1000    .5000    .6000       .1442482E+00     100      0      0      0
 97    .0000    .1000    .6000    .7000       .1426852E+00     100      0      0      0
 98    .0000    .1000    .7000    .8000       .1357992E+00     100      0      0      0
 99    .0000    .1000    .8000    .9000       .1266856E+00     100      0      0      0
100    .0000    .1000    .9000   1.0000       .1169717E+00     100      0      0      0
                                             ---------------
               SUM OF CELL PROBABILITIES =    .1000000E+01
```

Figure 10-5c. (Continued).

```
***  PROBLEM 5 : Fatigue baseline + Tmat failure criteria                                  ***


                                         - - - RESULTS WITHOUT EARTHQUAKES - - -

                SEISMIC CLASS INFORMATION
                      CLASS      SIGEQ        SGLCEQ     CYCLES  COV F-BM
                        0     .0000E+00        .000        0        .0000

                    PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                        SULTMU          SULTSD      IULT
                    .75000E+02       .10000E+02      3
                     STRESS(1)        STRESS(2)        STRESS(3)        STRESS(4)        STRESS(5)
                    .84876E+01       .63657E+01       .42438E+01       .21219E+01       .00000E+00
                     PBREAK(1)        PBREAK(2)        PBREAK(3)        PBREAK(4)        PBREAK(5)
                    .14610E-10       .33817E-11       .74894E-12       .15870E-12       .32173E-13

               TIME      AVG LEAK     AVG BIG LEAK      AVG LOCA       SIGMA LEAK    SIGMA BIG LEAK    SIGMA LOCA
                 .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
                5.0   0.00000E+00     0.00000E+00     0.00000E+00     0.00000E+00     0.00000E+00     0.00000E+00
               10.0   3.95124E-11     3.95124E-11     6.60403E-14     2.77526E-11     2.77526E-11     6.60403E-14
               15.0   6.04158E-11     6.04158E-11     6.58225E-13     3.41563E-11     3.41563E-11     2.96000E-13
               20.0   6.88793E-10     6.88793E-10     8.57448E-13     4.03281E-10     4.03281E-10     3.14573E-13
               40.0   1.76430E-09     1.76430E-09     1.95019E-12     5.45959E-10     5.45959E-10     5.20296E-13


   PC-PRAISE VERSION 2.40
   Execution Start  -   12/06/91 at  9:19p
   Execution End    -   12/06/91 at 10:05p
```

Figure 10-5d. Failure probabilites for Sample Problem 5.

10.6 Sample Problem 6: SCC Baseline Case

This sample problem illustrates the use of pc-PRAISE to simulate initiation and growth of cracks in the weld by stress corrosion mechanism. The material properties required for stress corrosion crack initiation and growth for 304 and 316 steels are hard-wired in the code. Stress corrosion properties for 304 are selected in this case. The only load cycle used is the heat-up/cool-down cycle. Failure criteria used is the net-section stress exceeding the flow stress. Pre-service inspection and the proof test are not modeled since pre-existing cracks are not considered in the analysis. The major inputs related to the geometry of the pipe, the pipe material, and the operating conditions are described below.

Pipe Geometry:
- Inside Radius = 7.16 in
- Wall Thickness = 0.84 in

Stresses:
- Deadweight = 0.5 ksi
- Deadweight + Thermal Expansion = 10.2 ksi
- Operating Pressure = 1250 psi

Water Chemistry and Conditions that Affect SCC:
- Oxygen at Plant Start-Up = 8 ppm
- Oxygen at Steady-State Operation = 0.2 ppm
- Water Temperature at Steady-State = 550°F
- Duration of Plant Heat-Up = 5 hrs
- Coolant Conductivity = 0.2 μs/cm

Flow Stress:
- Mean = 44.9 ksi
- Standard Deviation = 1.9 ksi

SCC Properties:
- AISI 304 Stainless Steel

Plant lifetime of 20 years is simulated and results are printed at two year intervals. The maximum time step for stress corrosion crack growth is limited to 0.1 years, meaning that even during long periods of steady-state operation, crack size, stress intensity factors, and other calculations are updated every 0.1 year. Residual stresses and vibratory stresses are not considered in the analysis. The heat-up/cool-down cycles are assumed to occur regularly 10 times a year.

The input file for Sample Problem 6 is shown in Figure 10-6a. Each variable in the input file is described in Table 10-6. The output file is shown in Figures 10-6b through 10-6d. Description of the inputs is summarized in Figure 10-6b. Indicator functions are shown in Figure 10-6c. The probabilities of leak, big leak, and LOCA as a function of time are shown in Figure 10-6d. Unlike the case of pre-existing cracks with stratified sampling, the leak and LOCA probabilities are obtained in the same run. Figure 10-6e provides statistics on initiated cracks as a function time. Many cracks are predicted to initiate, but none of these grow to become a through-wall crack within the simulated plant lifetime of 20 years.

Table 10-6
VARIABLE INPUT FILE FOR SAMPLE PROBLEM 6: SCC BASELINE CASE

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #1 Title				
TITLE( )		Analysis title		
Line #2 Control Variables (Card 0B)				
INCIAT	1	SCC-initiated cracks only	1 - 5	I5
IFAILC	0	Net-section stress criteria	6 - 10	I5
ICRAKS	23	Number of stress corrosion initiation sites	11 - 15	I5
IREPLS	200	Number of replications for crack initiation problem	16 - 20	I5
IREPAR	0	Leakers will not be repaired	26 - 30	I5
BNDRY	0.5	Not used	31 - 40	F10.3
ISF	0	Not used	41 - 50	I10
MTTYPE	1	Use 304 properties for SCC	51 - 55	I5
ISEED	688	Random number seed 1	56 - 62	I7
ISEEDR	7225	Random number seed 2	63 - 70	I8
IREMED	0	Number of remedial actions during the plant life	71 - 75	I5
Line #3 Control Variables (Card 1B)				
NTRIES	-5	Not used	1 - 5	I5
ISQARE	2	Not used	6 - 10	I5
KTYPES	1	Number of transients experienced by the plant	11 - 15	I5
KRKDIS	0	Not used	16 - 20	I5
NEVAL	-2	Interval for printing results (years)	21 - 25	I5
NINSPT	0	Number of in-service inspections	26 - 30	I5
NQUAKE	0	No earthquakes to be modeled	31 - 35	I5
IDEBUG	0	Normal output to be printed	36 - 40	I5
KONPRP	0	Not used	41 - 45	I5
NEQINT	0	Number of seismic intensity classes to modeled	46 - 50	I5
MCELLS	0	Not used	51 - 55	I5
KNSFLO	0	Flow stress normally distributed	56 - 60	I5
NSKIP	1	Indicator functions printout interval in years	61 - 65	I5
NPSI	0	No pre-service inspection to be performed	66 - 70	I5
ISCC	1	Crack growth by SCC only	71 - 75	I5
ISIGRS	0	Residual stresses not modeled	75 - 80	I5

Table 10-6 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #4 Time and NDE Parameters (Card 1D)				
THRIZN	20	Maximum plant lifetime simulated (years)	1 - 10	E10.3
DTSCC	0.1	Maximum time step for SCC growth (years)	11 - 20	E10.3
ICTYPE	0	Crack orientation is circumferential	21 - 25	I5
IPTYPE	0	Default NDE parameters for thick austenitic pipe used	26 - 30	I5
EPST		Not used	31 - 40	E10.0
ASTAR		Not used	41 - 50	E10.0
TRANSD		Not used	51 - 60	E10.0
ANUU		Not used	61 - 70	E10.0
Line #5 Pipe Dimensions (Card 2A)				
THICK	0.84	Wall thickness of the pipe (inches)	1 - 10	E10.3
RIN	7.16	Inside radius (inches)	11 - 20	E10.3
ELOVRR	5	Not used	21 - 30	E10.3
Line #6 Fatigue Crack Growth Characteristics (Card 2B)				
THRHLD	4.6	Not used	1 - 10	E10.3
EMEXP	4	Not used	11 - 20	E10.3
CONSMU	9.14×10^{-12}	Not used	21 - 30	E10.3
CONS90	3.50×10^{-11}	Not used	31 - 40	E10.3
Line #7 SCC Variables (Card 2B-1)				
OSTART	8	Oxygen at plant start-up (ppm)	1 - 10	F10.5
OSTEDY	0.2	Oxygen at steady-state operation (ppm)	11 - 20	F10.5
TFSTDY	550	Steady-state temperature (°F)	21 - 30	F10.5
DURATN	5	Duration of plant heat-up (hrs)	31 - 40	F10.5
CONDUC	0.2	Coolant conductivity (µs/cm)	41 - 50	F10.5
Line #8 Flow Stress (Card 2C)				
SFLOMU	44.9	Mean value of flow stress (ksi)	1 - 10	E10.4
SFLOSD	1.9	Standard deviation of flow stress (ksi)	11 - 20	E10.4
XJIC	0	Not used	21 - 30	E10.4
DJDAMT	0	Not used	31 - 40	E10.4
SIG0	0	Not used	41 - 50	E10.4
DEE	0	Not used	51 - 60	E10.4
YOUNGS	0	Not used	61 - 70	E10.4

Table 10-6 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #8 Flow Stress (Card 2C) [Continued]				
XN	0	Not used	71 - 80	E10.4
Line #9 Ultimate Stress Definition (Card 2D)				
SULTMU	0	Not used	1 - 10	E10.0
SULTSD	0	Not used	11 - 20	F10.0
IULT	0	Not used	21 - 25	I5
Line #10 Leak Rate and Detection Parameters (Card 4C)				
FNDLEK	0.1	Threshold for detectable leak rate (gpm)	1 - 10	E10.3
ALKBIG	0.1	Threshold for defining big leaks (gpm)	11 - 20	E10.3
Line #11 Operating Stresses (Card 6A)				
SGCLD	0.5	Deadweight stress (ksi)	1 - 10	E10.4
SGDWTE	10.2	Deadweight and thermal expansion stress (ksi)	11 - 20	E10.4
OPPRES	1.25	Normal operating pressure (ksi)	21 - 30	E10.4
PRFPRS	-1.5625	Pressure in hydrostatic proof test (ksi)	31 - 40	E10.4
SIGVIB	-1	Vibratory stresses not modeled	41 - 50	E10.4
VBTHLD	0	Not used	51 - 60	E10.4
Line #12 Frequency of Heat-up/Cool-down Transient 1 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.1	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	430	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10

```
                  P     R         A       I       S     E

                  PIPING RELIABILITY ANALYSIS INCLUDING SEISMIC EVENTS

                                  PC-PRAISE VERSION 2.40

                              EXECUTED ON  12/06/91 AT 10:05p


                              ECHO-PRINT OF INPUT DATA IN FILE  SAMPLE6.DAT

LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
   1>PROBLEM 6 : SCC Baseline                                                       <
   2>    1    0   23  200         0      .500         0    1   688   7225    0      <
   3>   -5    2    1    0   -2    0    0    0    0    0    0    0    1    0    1    0<
   4>  .200E+02  .100E+00                                                           <
   5>  .840E+00  .716E+01  .500E+01                                                 <
   6>  4.6       4.0       .914E-11  .350E-10                                       <
   7>  .800E+01  .200E+00  .550E+03  .500E+01  .200E+00                             <
   8> .4490E+02 .1900E+01                                                           <
   9>  .000E+00  .000E+00    0                                                      <
  10>  .010E+01  .010E+01                                                           <
  11>       0.5      10.2      1.25 -1.5625   -.100E+01  .000E+00                     <
  12>    1 .100 480.00000                                                     <
LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
 ****** NEW SEED (L,R)          688        7225*****
```

Figure 10-6a. Echo of input file for Sample Problem 6.

```
--- PROBLEM 6 : SCC Baseline                                                                    ---

CIRCUMFERENTIAL CRACK ANALYSIS

PARAMETERS THAT DETERMINE NON-DETECTION PROBABILITY
    EPST  =      .000E+00
    ASTAR =      .420
    TRANSDUCER DIAMETER =  1.00000 INCHES
    ANUU  =     1.600

SCC-INITIATED CRACKS ONLY

MAXIMUM NO. OF CRACKS =   23
NO. OF REPLICATIONS   =  200
A/H BOUNDARY          =      .5000

SCC ONLY

                    MATERIAL SELECTED (FOR SCC) - S304

LEAKERS WILL NOT BE REPAIRED

FAILURE CRITERIA = APPLIED STRESS>FLOW STRESS

TIMESTEP FOR SCC =    .100 YEARS

PIPE DIMENSIONS
    WALL THICKNESS =    .84 INCHES
    INSIDE RADIUS  =   7.16 INCHES
      L/H RATIO    =   42.62
      L/R RATIO    =    5.00
    AREA OF PIPE        =    40.01 SQ. INCHES
    FLOW AREA OF PIPE   =   161.06 SQ. INCHES

CRACK GROWTH LAW PARAMETERS
    EXPONENT  =   4.000
    GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
         MEDIAN         =   .9140E-11
        95TH PERCENT =    .3500E-10
    THRESHOLD =   4.000

SCC PARAMETERS
               O2 AT STARTUP(PPM) =     8.00
          O2 AT STEADY STATE(PPM) =      .20
     TEMP. AT STEADY STATE(DEG F) =   550.00
     HEATUP (100-550F) TIME (HRS) =     5.00
     COOLANT CONDUCTIVITY (US/CM) =      .20


FLOW STRESS NORMALLY DISTRIBUTED
    MEAN                =   .4490E+02
    STANDARD DEVIATION =   .1900E+01

DISTRIBUTION PARAMETERS FOR ULTIMATE STRESS IN PIPE
    MEAN                =   .0000E+00
    STANDARD DEVIATION =   .0000E+00
    STANDARD DEVIATION =  0.0 MEANS THE ULTIMATE STRESS IS CONSTANT
    INTERPOLATION FLAG =    0  ( IULT ) FOR WHOLE PIPE BREAK PROBABILITY
    ABS ( IULT ) IS THE NUMBER OF INTERPOLATION POINTS
    IF  IULT .GT. 0  LINEAR INTERPOLATION
    IF  IULT .EQ. 0  NO INTERPOLATION
    IF  IULT .LT. 0  LOGARITHMIC INTERPOLATION
```

Figure 10-6b. Input summary for Sample Problem 6.

```
PIPE LOADING VALUES
    STRESS (KSI) DUE TO COLD DEADWEIGHT  =      .50
    STRESS (KSI)  DUE TO DWGHT + THERMAL =    10.20
    STRESS (KSI)  DUE TO         THERMAL =     9.70
    OPERATING PRESSURE (KSI)             =     1.25
    STRESS (KSI) DUE TO OPER. PRESSURE   =     5.03
    STRESS (KSI) DUE TO DWGHT + OP PRESR =     5.53
    STRESS (KSI) DUE TO DWT+THML+OP PRES =    15.23

    NO HYDROSTATIC PROOF TEST IS MODELLED

LEAK DETECTION AND DEFINITION PARAMETERS
    DETECTABLE LEAK (GPM) =     .10
    BIG LEAK        (GPM) =     .10

NO RESIDUAL STRESSES ARE MODELLED

NO VIBRATORY STRESSES ARE MODELLED

NO PRE-SERVICE ULTRASONIC INSPECTION

TIME INTERVALS
    PLANT LIFETIME =  20.0 YEARS
    ENDPOINTS OF INTERVALS AT     .0   2.0   4.0   6.0   8.0 YEARS
    ENDPOINTS OF INTERVALS AT   10.0  12.0  14.0  16.0  18.0 YEARS
    ENDPOINTS OF INTERVALS AT   20.0

NO IN-SERVICE INSPECTIONS ARE MODELLED

NO SEISMIC EVENTS EVALUATED

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS   1

NORMAL OUTPUT REQUESTED


NUMBER OF TRANSIENT TYPES =  1

TYPE  1
    REGULAR AT        .100 YEARS/EVENT
    MAX DELTA TEMP = 480.0  BLOCKING FACTOR =  1.0
```

Figure 10-6b. (Continued).

```
                          - - - INDICATOR FUNCTIONS WITHOUT EARTHQUAKES - - -

CELL  TIME    SUM LEAK    SUM BIG LEAK  SUM LOCA     SUM2 LEAK   SUM2 BIG LEAK   SUM2 LOCA   LEAK  BLEAK  LOCA

1       .0   .00000E+00   .00000E+00   .00000E+00   .00000E+00  .00000E+00   .00000E+00    0     0     0
1      2.0   .00000E+00   .00000E+00   .00000E+00   .00000E+00  .00000E+00   .00000E+00    0     0     0
1      4.0   .10000E+01   .10000E+01   .00000E+00   .10000E+01  .10000E+01   .00000E+00    1     1     0
1      6.0   .10000E+01   .10000E+01   .00000E+00   .10000E+01  .10000E+01   .00000E+00    1     1     0
1      8.0   .50000E+01   .50000E+01   .00000E+00   .50000E+01  .50000E+01   .00000E+00    5     5     0
1     10.0   .70000E+01   .70000E+01   .00000E+00   .70000E+01  .70000E+01   .00000E+00    7     7     0
1     12.0   .70000E+01   .70000E+01   .00000E+00   .70000E+01  .70000E+01   .00000E+00    7     7     0
1     14.0   .90000E+01   .90000E+01   .00000E+00   .90000E+01  .90000E+01   .00000E+00    9     9     0
1     16.0   .13000E+02   .13000E+02   .00000E+00   .13000E+02  .13000E+02   .00000E+00   13    13     0
1     18.0   .15000E+02   .15000E+02   .00000E+00   .15000E+02  .15000E+02   .00000E+00   15    15     0
1     20.0   .17000E+02   .17000E+02   .00000E+00   .17000E+02  .17000E+02   .00000E+00   17    17     0
```

Figure 10-6c. Indicator Functions for Sample Problem 6.

```
*** PROBLEM 6 : SCC Baseline                                                  ***

                                   * * * RESULTS WITHOUT EARTHQUAKES * * *

          SEISMIC CLASS INFORMATION
                  CLASS      SIGEQ         SGLCEQ     CYCLES   COV F-BM
                    0      .0000E+00        .000         0        .0000

              PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                 SULTMU            SULTSD      IULT
              .00000E+00       .00000E+00      0
                 STRESS(1)
              .55322E+01
                 PBREAK,1)
              .10000E+01

      TIME       AVG LEAK      AVG BIG LEAK      AVG LOCA        SIGMA LEAK    SIGMA BIG LEAK    SIGMA LOCA
        .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
       4.0     5.00000E-03     5.00000E-03     0.00000E+00     5.00000E-03     5.00000E-03     0.00000E+00
       6.0     5.00000E-03     5.00000E-03     0.00000E+00     5.00000E-03     5.00000E-03     0.00000E+00
       8.0     2.50000E-02     2.50000E-02     0.00000E+00     1.10674E-02     1.10674E-02     0.00000E+00
      10.0     3.50000E-02     3.50000E-02     0.00000E+00     1.30278E-02     1.30278E-02     0.00000E+00
      12.0     3.50000E-02     3.50000E-02     0.00000E+00     1.30278E-02     1.30278E-02     0.00000E+00
      14.0     4.50000E-02     4.50000E-02     0.00000E+00     1.46954E-02     1.46954E-02     0.00000E+00
      16.0     6.50000E-02     6.50000E-02     0.00000E+00     1.74758E-02     1.74758E-02     0.00000E+00
      18.0     7.50000E-02     7.50000E-02     0.00000E+00     1.86713E-02     1.86713E-02     0.00000E+00
      20.0     8.50000E-02     8.50000E-02     0.00000E+00     1.97694E-02     1.97694E-02     0.00000E+00
```

Figure 10-6d. Failure probabilities for Sample Problem 6.

```
--- PROBLEM 6 : SCC Baseline                                                                    ---


                         TOTAL NUMBER OF REPLICATIONS =   200
NUMBER OF POSSSIBLE INITIATION SITES(USER SPEC.) =    23
NO. OF TIMES    INITIATED CRACKS CAUSED BIG LEAK =    17
NO. OF TIMES PRE-EXISTING CRACKS CAUSED BIG LEAK =     0

       TIME   TOTAL INITIATED     FIRST INITIATED
      (YRS)       CRACKS              CRACKS

          1         50                  46
          2        194                  96
          3        26[illegible]                  45
          4        291                   7
          5        213                   3
          6        224                   2
          7        196                   0
          8        181                   0
          9        137                   0
         10        128                   0
         11        102                   0
         12        103                   1
         13         79                   0
         14         68                   0
         15         63                   0
         16         66                   0
         17         54                   0
         18         49                   0
         19         47                   0
         20         40                   0

         41          0                   0


   PC-PRAISE VERSION 2.40
   Execution Start -    12/06/91 at 10:05p
   Execution End   -    12/06/91 at 10:14p
```

Figure 10-6e. Statistics of time to initiation for Sample Problem 6.

10.7 Sample Problem 7: SCC Baseline Case with Residual Stresses

This sample problem illustrates the use of pc-PRAISE to simulate initiation and growth of cracks in the weld by stress corrosion mechanism. The material properties required for stress corrosion crack initiation and growth for 304 and 316 steels are hard-wired in the code. Stress corrosion properties for 304 are selected in this case. The only load cycle used is the heat-up/cool-down cycle. Failure criteria used is the net-section stress exceeding the flow stress. Pre-service inspection and the proof test are not modeled since pre-existing cracks are not considered in the analysis. The default residual stress distribution for small lines is used. The major inputs related to the geometry of the pipe, the pipe material, and the operating conditions are described below.

Pipe Geometry:
  Inside Radius = 1.73 in
  Wall Thickness = 0.34 in

Stresses:
  Deadweight = 0.01 ksi
  Deadweight + Thermal Expansion = 11 ksi
  Operating Pressure = 1250 psi

Water Chemistry and Conditions that Affect SCC:
  Oxygen at Plant Start-Up = 8 ppm
  Oxygen at Steady-State Operation = 0.2 ppm
  Water Temperature at Steady-State = 550°F
  Duration of Plant Heat-Up = 5 hrs
  Coolant Conductivity = 0.2 μs/cm

Flow Stress:
  Mean = 44.9 ksi
  Standard Deviation = 1.9 ksi

SCC Properties:
  AISI 304 Stainless Steel

Plant lifetime of 40 years is simulated and results are printed at two year intervals. The maximum time step for stress corrosion crack growth is limited to 0.1 years, meaning that even during long periods of steady-state operation, crack size, stress intensity factors, and other calculations are updated every 0.1 year. The vibratory stresses are not considered in the analysis. The heat-up/cool-down cycles are assumed to occur regularly 5 times a year.

The input file for Sample Problem 7 is shown in Figure 10-7a. Each variable in the input file is described in Table 10-7. The output file is shown in Figures 10-7b through 10-7d. Description of the inputs is summarized in Figure 10-7b. The probabilities of leak, big leak, and LOCA as a function of time are shown in Figure 10-7c. Unlike the case of pre-existing cracks with stratified sampling, the leak and LOCA probabilities are obtained in the same run. The probability of leak at 40 years is calculated as 0.43 and no LOCAs occurred during the simulation of 5000 weld joints. Figure 10-7d provides statistics on initiated cracks as a function time.

Table 10-7
VARIABLE INPUT FILE FOR SAMPLE PROBLEM 7: SCC BASELINE CASE WITH RESIDUAL STRESS

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #1 Title				
TITLE( )		Analysis title		
Line #2 Control Variables (Card 0B)				
INCIAT	1	SCC-initiated cracks only	1 - 5	I5
IFAILC	0	Net-section stress criteria	6 - 10	I5
ICRAKS	6	Number of stress corrosion initiation sites	11 - 15	I5
IREPLS	5000	Number of replications for crack initiation problem	16 - 20	I5
IREPAR	0	Leakers will not be repaired	26 - 30	I5
BNDRY	0.5	Not used	31 - 40	F10.3
ISF	0	Not used	41 - 50	I10
MTTYPE	1	Use 304 properties for SCC	51 - 55	I5
ISEED	688	Random number seed 1	56 - 62	I7
ISEEDR	7225	Random number seed 2	63 - 70	I8
IREMED	0	Number of remedial actions during the plant life	71 - 75	I5
Line #3 Control Variables (Card 1B)				
NTRIES	-5	Not used	1 - 5	I5
ISQARE	2	Not used	6 - 10	I5
KTYPES	1	Number of transients experienced by the plant	11 - 15	I5
KRKDIS	0	Not used	16 - 20	I5
NEVAL	-2	Interval for printing results (years)	21 - 25	I5
NINSPT	0	Number of in-service inspections	26 - 30	I5
NQUAKE	0	No earthquakes to be modeled	31 - 35	I5
IDEBUG	0	Normal output to be printed	36 - 40	I5
KONPRP	0	Not used	41 - 45	I5
NEQINT	0	Number of seismic intensity classes to modeled	46 - 50	I5
MCELLS	0	Not used	51 - 55	I5
KNSFLO	0	Flow stress normally distributed	56 - 60	I5
NSKIP	1	Indicator function printout interval = 1 year	61 - 65	I5
NPSI	0	No pre-service inspection to be performed	66 - 70	I5
ISCC	1	Crack growth by SCC only	71 - 75	I5
ISIGRS	4	Residual stresses for small lines modeled	75 - 80	I5

Table 10-7 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #4 Time and NDE Parameters (Card 1D)				
THRIZN	40	Maximum plant lifetime simulated (years)	1 - 10	E10.3
DTSCC	0.1	Maximum time step for SCC growth (years)	11 - 20	E10.3
ICTYPE	0	Crack orientation is circumferential	21 - 25	I5
IPTYPE	0	Default NDE parameters for thick austenitic pipe used	26 - 30	I5
LPST		Not used	31 - 40	E10.0
ASTAR		Not used	41 - 50	E10.0
TRANSD		Not used	51 - 60	E10.0
ANUU		Not used	61 - 70	E10.0
Line #5 Pipe Dimensions (Card 2A)				
THICK	0.34	Wall thickness of the pipe (inches)	1 - 10	E10.3
RIN	1.73	Inside radius (inches)	11 - 20	E10.3
ELOVRR		Not used	21 - 30	E10.3
Line #6 Fatigue Crack Growth Characteristics (Card 2B)				
THRHLD	4.6	Not used	1 - 10	E10.3
EMEXP	4	Not used	11 - 20	E10.3
CONSMU	9.14×10^{-12}	Not used	21 - 30	E10.3
CONS90	3.50×10^{-11}	Not used	31 - 40	E10.3
Line #7 SCC Variables (Card 2B-1)				
OSTART	8	Oxygen at plant start-up (ppm)	1 - 10	F10.5
OSTEDY	0.2	Oxygen at steady-state operation (ppm)	11 - 20	F10.5
TFSTDY	550	Steady-state temperature (°F)	21 - 30	F10.5
DURATN	5	Duration of plant heat-up (hrs)	31 - 40	F10.5
CONDUC	0.2	Coolant conductivity (μS [illegible]	41 - 50	F10.5
Line #8 Flow Stress (Card 2C)				
SFLOMU	44.9	Mean value of flow stress (ksi)	1 - 10	E10.4
SFLOSD	1.9	Standard value of flow stress (ksi)	11 - 20	E10.4
XJIC		Not used	21 - 30	E10.4
DJDAMT		Not used	31 - 40	E10.4
SIG0		Not used	41 - 50	E10.4
DEE		Not used	51 - 60	E10.4

Table 10-7 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #8 Flow Stress (Card 2C) [Continued]				
YOUNGS		Not used	61 - 70	E10.4
XN		Not used	71 - 80	E10.4
Line #9 Ultimate Stress Definition (Card 2D)				
SULTMU	0	Not used	1 - 10	E10.0
SULTSD	0	Not used	11 - 20	E10.0
IULT	0	Not used	21 - 25	I5
Line #10 Leak Rate and Detection Parameters (Card 4C)				
FNDLEK	0.1	Threshold for detectable leak rate (gpm)	1 - 10	E10.3
ALKBIG	0.1	Threshold for defining big leaks (gpm)	11 - 20	E10.3
Line #11 Operating Stresses (Card 6A)				
SGCLD	0.01	Deadweight stress (ksi)	1 - 10	E10.4
SGDWTE	11	Deadweight and thermal expansion stress (ksi)	11 - 20	E10.4
OPPRES	1.25	Normal operating pressure (ksi)	21 - 30	E10.4
PRFPRS	1.5625	Pressure in hydrostatic proof test (ksi)	31 - 40	E10.4
SIGVIB	-1	Vibratory stresses not modeled	41 - 50	E10.4
VBTHLD	0	Not used	51 - 60	E10.4
Line #12 Frequency of Heat-up/Cool-down Transient 1 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.2	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	480	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10

```
                 P     R     A     I     S     E

        PIPING RELIABILITY ANALYSIS INCLUDING SEISMIC EVENTS

                      PC-PRAISE VERSION 2.40

                   EXECUTED ON  12/06/91 AT 10:14p


               ECHO-PRINT OF INPUT DATA IN FILE  SAMPLE7.DAT

LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
    1>PROBLEM 7 : SCC Baseline + Residual                                             <
    2>    1    0    6 5000         0      .500         0    1     688    7225    0    <
    3>   -5    2    1    0   -2    0    0    0    0    0    0    0    1    0    1    4<
    4>  .400E+02  .100E+00    0    0                                                  <
    5>  .340E+00  .173E+01                                                            <
    6>   4.6        4.0     .914E-11  .350E-10                                        <
    7>  .800E+01  .200E+00  .550E+03  .500E+01  .200E+00                              <
    8> .4490E+02 .1900E+01                                                            <
    9>  .000E+00  .000E+00    0                                                       <
   10>  .010E+01  .010E+01                                                            <
   11>  .100E-01  .110E+02  .125E+01 -1.5625   -.100E+01  .000E+00                    <
   12>    1 .200 480.00000                                                     <
LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
 ****** NEW SEED (L,R)         688        7225*****
```

Figure 10-7a. Echo of input file for Sample Problem 7.

```
*** PROBLEM 7 : SCC Baseline + Residual                                          ***

CIRCUMFERENTIAL CRACK ANALYSIS

PARAMETERS THAT DETERMINE NON-DETECTION PROBABILITY
    EPST  =      .000E+00
    ASTAR =      .170
    TRANSDUCER DIAMETER =  1.00000 INCHES
    ANUU  =    1.600

SCC-INITIATED CRACKS ONLY

MAXIMUM NO. OF CRACKS =    6
NO. OF REPLICATIONS   = 5000
A/H BOUNDARY          =     .5000

SCC ONLY

                  MATERIAL SELECTED (FOR SCC) - S304

LEAKERS WILL NOT BE REPAIRED

FAILURE CRITERIA = APPLIED STRESS>FLOW STRESS

TIMESTEP FOR SCC =    .100 YEARS

PIPE DIMENSIONS
    WALL THICKNESS =    .34 INCHES
    INSIDE RADIUS  =   1.73 INCHES
      L/H RATIO    =       .00
      L/R RATIO    =       .00
    AREA OF PIPE          =     4.06 SQ. INCHES
    FLOW AREA OF PIPE     =     9.40 SQ. INCHES

CRACK GROWTH LAW PARAMETERS
    EXPONENT  =   4.000
    GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
         MEDIAN         =   .9140E-11
         90-TH PERCENT  =   .3500E-10
    THRESHOLD =   4.600

SCC PARAMETERS
                 O2 AT STARTUP(PPM) =    8.00
            O2 AT STEADY STATE(PPM) =     .20
     TEMP. AT STEADY STATE(DEG F) =  550.00
     HEATUP (100-550F) TIME (HRS) =    5.00
     COOLANT CONDUCTIVITY (US/CM) =     .20


FLOW STRESS NORMALLY DISTRIBUTED
    MEAN                 =   .4490E+02
    STANDARD DEVIATION =   .1900E+01

DISTRIBUTION PARAMETERS FOR ULTIMATE STRESS IN PIPE
    MEAN                 =   .0000E+00
    STANDARD DEVIATION =   .0000E+00
    STANDARD DEVIATION =  0.0 MEANS THE ULTIMATE STRESS IS CONSTANT
    INTERPOLATION FLAG =   0  ( IULT ) FOR WHOLE PIPE BREAK PROBABILITY
    ABS ( IULT ) IS THE NUMBER OF INTERPOLATION POINTS
    IF  IULT .GT. 0  LINEAR INTERPOLATION
    IF  IULT .EQ. 0  NO INTERPOLATION
    IF  IULT .LT. 0  LOGARITHMIC INTERPOLATION
```

Figure 10-7b. Input summary for Sample Problem 7.

```
PIPE LOADING VALUES
    STRESS (KSI) DUE TO COLD DEADWEIGHT  =       .01
    STRESS (KSI)  DUE TO DWGHT + THERMAL =     11.00
    STRESS (KSI)  DUE TO         THERMAL =     10.99
    OPERATING PRESSURE (KSI)             =      1.25
    STRESS (KSI) DUE TO OPER. PRESSURE   =      2.90
    STRESS (KSI) DUE TO DWGHT + OP PRESR =      2.91
    STRESS (KSI) DUE TO DWT+THML+OP PRES =     13.90

    NO HYDROSTATIC PROOF TEST IS MODELLED

LEAK DETECTION AND DEFINITION PARAMETERS
    DETECTABLE LEAK (GPM) =     .10
    BIG LEAK        (GPM) =     .10

RESIDUAL STRESSES FOR SMALL LINE SELECTED

NO VIBRATORY STRESSES ARE MODELLED

NO PRE-SERVICE ULTRASONIC INSPECTION

TIME INTERVALS
    PLANT LIFETIME =  40.0 YEARS
    ENDPOINTS OF INTERVALS AT     .0   2.0   4.0   6.0   8.0 YEARS
    ENDPOINTS OF INTERVALS AT   10.0  12.0  14.0  16.0  18.0 YEARS
    ENDPOINTS OF INTERVALS AT   20.0  22.0  24.0  26.0  28.0 YEARS
    ENDPOINTS OF INTERVALS AT   30.0  32.0  34.0  36.0  38.0 YEARS
    ENDPOINTS OF INTERVALS AT   40.0

NO IN-SERVICE INSPECTIONS ARE MODELLED

NO SEISMIC EVENTS EVALUATED

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS    1

NORMAL OUTPUT REQUESTED


NUMBER OF TRANSIENT TYPES =  1

TYPE  1
    REGULAR AT        .200 YEARS/EVENT
    MAX DELTA TEMP = 480.0  BLOCKING FACTOR =  1.0
```

Figure 10-7b. (Continued).

```
*** PROBLEM 7 : SCC Baseline + Residual                                        ***


                                              * * * RESULTS WITHOUT EARTHQUAKES * * *

          SEISMIC CLASS INFORMATION
                   CLASS     SIGEQ        SGLCEQ     CYCLES   COV F-BM
                     0     .0000E+00        .000        0        .0000

               PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                  SULTMU           SULTSD     IULT
                .00000E+00      .00000E+00     0
                 STRESS(1)
                .29056E+01
                 PBREAK(1)
                .10000E+01

      TIME     AVG LEAK      AVG BIG LEAK      AVG LOCA       SIGMA LEAK    SIGMA BIG LEAK    SIGMA LOCA
        .0   0.00000E+00    0.00000E+00     0.00000E+00    0.00000E+00    0.00000E+00     0.00000E+00
       2.0   2.00000E-04    2.00000E-04     0.00000E+00    2.00000E-04    2.00000E-04     0.00000E+00
       4.0   2.20000E-03    2.20000E-03     0.00000E+00    6.62661E-04    6.62661E-04     0.00000E+00
       6.0   1.04000E-02    1.04000E-02     0.00000E+00    1.43484E-03    1.43484E-03     0.00000E+00
       8.0   2.42000E-02    2.42000E-02     0.00000E+00    2.17343E-03    2.17343E-03     0.00000E+00
      10.0   4.72000E-02    4.70000E-02     0.00000E+00    2.99937E-03    2.99332E-03     0.00000E+00
      12.0   7.36000E-02    7.32000E-02     0.00000E+00    3.69315E-03    3.68389E-03     0.00000E+00
      14.0   1.07200E-01    1.06800E-01     0.00000E+00    4.37555E-03    4.368836E-03    0.00000E+00
      16.0   1.36200E-01    1.35800E-01     0.00000E+00    4.85125E-03    4.84524E-03     0.00000E+00
      18.0   1.64800E-01    1.64200E-01     0.00000E+00    5.24726E-03    5.23958E-03     0.00000E+00
      20.0   1.99000E-01    1.98400E-01     0.00000E+00    5.64678E-03    5.64038E-03     0.00000E+00
      22.0   2.29200E-01    2.28400E-01     0.00000E+00    5.94479E-03    5.93749E-03     0.00000E+00
      24.0   2.60600E-01    2.60000E-01     0.00000E+00    6.20848E-03    6.20385E-03     0.00000E+00
      26.0   2.91000E-01    2.90400E-01     0.00000E+00    6.42433E-03    6.42042E-03     0.00000E+00
      28.0   3.15800E-01    3.15000E-01     0.00000E+00    6.57440E-03    6.56990E-03     0.00000E+00
      30.0   3.39400E-01    3.38400E-01     0.00000E+00    6.69705E-03    6.69224E-03     0.00000E+00
      32.0   3.59600E-01    3.58600E-01     0.00000E+00    6.78725E-03    6.78310E-03     0.00000E+00
      34.0   3.78800E-01    3.77800E-01     0.00000E+00    6.86087E-03    6.85732E-03     0.00000E+00
      36.0   3.96600E-01    3.95600E-01     0.00000E+00    6.91891E-03    6.91590E-03     0.00000E+00
      38.0   4.14400E-01    4.13400E-01     0.00000E+00    6.96737E-03    6.96490E-03     0.00000E+00
      40.0   4.32200E-01    4.31200E-01     0.00000E+00    7.00646E-03    7.00451E-03     0.00000E+00
```

Figure 10-7c. Failure probabilities for Sample Problem 7.

```
--- PROBLEM 7 : SCC Baseline + Residual                                      ---


                     TOTAL NUMBER OF REPLICATIONS =  5000
NUMBER OF POSSSIBLE INITIATION SITES(USER SPEC.) =     6
NO. OF TIMES     INITIATED CRACKS CAUSED BIG LEAK =  2156
NO. OF TIMES PRE-EXISTING CRACKS CAUSED BIG LEAK =     0

       TIME   TOTAL INITIATED    FIRST INITIATED
      (YRS)       CRACKS              CRACKS

         1          37                 37
         2         307                297
         3         552                486
         4         776                585
         5         867                585
         6         923                511
         7         883                424
         8         879                348
         9         877                319
        10         828                237
        11         728                173
        12         768                174
        13         698                144
        14         656                115
        15         610                 87
        16         588                 72
        17         544                 61
        18         530                 44
        19         511                 38
        20         442                 25
        21         439                 34
        22         406                 28
        23         391                 20
        24         380                 22
        25         336                 16
        26         325                 17
        27         244                  4
        28         270                 10
        29         287                  7
        30         268                  9
        31         246                  7
        32         221                  5
        33         230                  8
        34         187                  5
        35         180                  1
        36         188                  2
        37         170                  0
        38         155                  2
        39         163                  5
        40         157                  2

        81           0                  0


    PRAISE VERSION 2.40
    Execution Start -    12/06/91 at 10:1[illegible]p
    Execution End        12/06/91 at 11:55p
```

Figure 10-7d. Statistics of time to initiation for Sample Problem 7.

10.8 Sample Problem 8: SCC Baseline Case with Residual Stresses and Mid-Life Changes in Operating Conditions

This sample problem illustrates the simulation of SCC-mitigation procedures involving changes in water chemistry, lowering of stresses, and redistribution of residual stresses by IHSI or MSIP treatment. Only the stress corrosion mechanism is considered for initiation and growth of cracks. Built-in stress corrosion properties for 304 are selected in this case. The only load cycle used is the heat-up/cool-down cycle. Failure criteria used is the net-section stress exceeding the flow stress. Pre-service inspection and the proof test are not modeled since pre-existing cracks are not considered in the analysis. The default residual stress distribution for intermediate lines is used. The major inputs related to the geometry of the pipe, the pipe material, and the operating conditions are described below.

Pipe Geometry:
Inside Radius = 10.8 in
Wall Thickness = 1.043 in

Stresses:
Deadweight = 1.0 ksi (for 0 - 10 years)
Deadweight = 0.5 ksi (for 10 - 40 years)
Deadweight + Thermal Expansion = 3.41 ksi (for 0 - 10 years)
Deadweight + Thermal Expansion = 2.91 ksi (for 10 - 40 years)
Operating Pressure = 1330 psi

Water Chemistry and Conditions that Affect SCC:
Oxygen at Plant Start-Up = 8 ppm (for 0 - 10 years)
Oxygen at Plant Start-Up = 0.2 ppm (for 10 - 40 years)
Oxygen at Steady-State Operation = 0.2 ppm (unchanged)
Water Temperature at Steady-State = 550°F
Duration of Plant Heat-Up = 5 hrs
Coolant Conductivity = 0.2 μs/cm (unchanged)

Flow Stress.
Mean = 43.0 ksi
Standard Deviation = 4.2 ksi

SCC Properties:
AISI 304 Stainless Steel

At 10 years, IHSI treatment is applied to redistribute residual stresses. Plant lifetime of 40 years is simulated and results are printed at two year intervals. The maximum time step for stress corrosion crack growth is limited to 0.2 years, meaning that even during long periods of steady-state operation, crack size, stress intensity factors, and other calculations are updated every 0.2 year. The vibratory stresses are not considered in the analysis. The heat-up/cool-down cycles are assumed to occur regularly 10 times a year.

The input file for Sample Problem 8 is shown in Figure 10-8a. Each variable in the input file is described in Table 10-8. The output file is shown in Figures 10-8b through 10-8e. Description of the inputs is summarized in Figure 10-8b. The probabilities of leak, big leak, and LOCA as a function of time are shown in Figure 10-8c. Unlike the case of pre-existing cracks with stratified sampling, the leak and LOCA probabilities are obtained in the same run. Figure 10-8d provides statistics on the initiated cracks as a function of time. The probability of leak as a function of time is shown in Figure 10-8e.

Table 10-8
VARIABLE INPUT FILE FOR SAMPLE PROBLEM 8: SCC BASELINE CASE WITH RESIDUAL STRESSES AND MID-LIFE CHANGES IN OPERATING CONDITIONS

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #1 Title				
TITLE( )		Analysis title		
Line #2 Control Variables (Card 0B)				
INCIAT	1	SCC-initiated cracks only	1 - 5	I5
IFAILC	0	Net-section stress criteria	6 - 10	I5
ICRAKS	35	Number of stress corrosion initiation sites	11 - 15	I5
IREPLS	1000	Number of replications for crack initiation problem	16 - 20	I5
IREPAR	0	Leakers will not be repaired	26 - 30	I5
BNDRY	0.5	Not used	31 - 40	F10.3
ISF	0	Not used	41 - 50	I10
MTTYPE	1	Use 304 properties for SCC	51 - 55	I5
ISEED	688	Random number seed 1	56 - 62	I7
ISEEDR	7225	Random number seed 2	63 - 70	I8
IREMED	2	Number of remedial actions during the plant life	71 - 75	I5
Line #3 Control Variables (Card 1B)				
NTRIES	-5	Not used	1 - 5	I5
ISQARE	2	Not used	6 - 10	I5
KTYPES	1	Number of transients experienced by the plant	11 - 15	I5
KRKDIS	0	Not used	16 - 20	I5
NEVAL	-2	Interval for printing results (years)	21 - 25	I5
NINSPT	0	Number of in-service inspections	26 - 30	I5
NQUAKE	0	No earthquakes to be modeled	31 - 35	I5
IDEBUG	0	Normal output to be printed	36 - 40	I5
KONPRP	0	Not used	41 - 45	I5
NEQINT	0	Number of seismic intensity classes to modeled	46 - 50	I5
MCELLS	0	Not used	51 - 55	I5
KNSFLO	0	Flow stress normally distributed	56 - 60	I5
NSKIP	0	No indicator function printout	61 - 65	I5
NPSI	0	No pre-service inspection to be performed	66 - 70	I5
ISCC	1	Crack growth by SCC only	71 - 75	I5
ISIGRS	3	Residual stresses for intermediate lines modeled	75 - 80	I5

Table 10-8 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #4 Time and NDE Parameters (Card 1D)				
THRIZN	40	Maximum plant lifetime simulated (years)	1 - 10	E10.3
DTSCC	0.2	Maximum time step for SCC growth (years)	11 - 20	E10.3
ICTYPE	0	Crack orientation is circumferential	21 - 25	I5
IPTYPE	0	Default NDE parameters for thick austenitic pipe used	26 - 30	I5
EPST		Not used	31 - 40	E10.0
ASTAR		Not used	41 - 50	E10.0
TRANSD		Not used	51 - 60	E10.0
ANUU		Not used	61 - 70	E10.0
Line #5 Pipe Dimensions (Card 2A)				
THICK	1.043	Wall thickness of the pipe (inches)	1 - 10	E10.3
RIN	10.8	Inside radius (inches)	11 - 20	E10.3
ELOVRR	5	Not used	21 - 30	E10.3
Line #6 Fatigue Crack Growth Characteristics (Card 2B)				
THRHLD	4.6	Not used	1 - 10	E10.3
EMEXP	4	Not used	11 - 20	E10.3
CONSMU	9.14×10^{-12}	Not used	21 - 30	E10.3
CONS90	3.50×10^{-11}	Not used	31 - 40	E10.3
Line #7 SCC Variables (Card 2B-1)				
OSTART	8	Oxygen at plant start-up (ppm)	1 - 10	F10.5
OSTEDY	0.2	Oxygen at steady-state operation (ppm)	11 - 20	F10.5
TFSTDY	560	Steady-state temperature (°F)	21 - 30	F10.5
DURATN	5	Duration of plant heat-up (hrs)	31 - 40	F10.5
CONDUC	0.2	Coolant conductivity (µs/cm)	41 - 50	F10.5
Line #8 Flow Stress (Card 2C)				
SFLOMU	43	Mean value of flow stress (ksi)	1 - 10	E10.4
SFLOSD	4.2	Standard deviation of flow stress (ksi)	11 - 20	E10.4
XJIC	0	Not used	21 - 30	E10.4
DJDAMT	0	Not used	31 - 40	E10.4
SIG0	0	Not used	41 - 50	E10.4
DEE	0	Not used	51 - 60	E10.4

Table 10-8 (Continued)

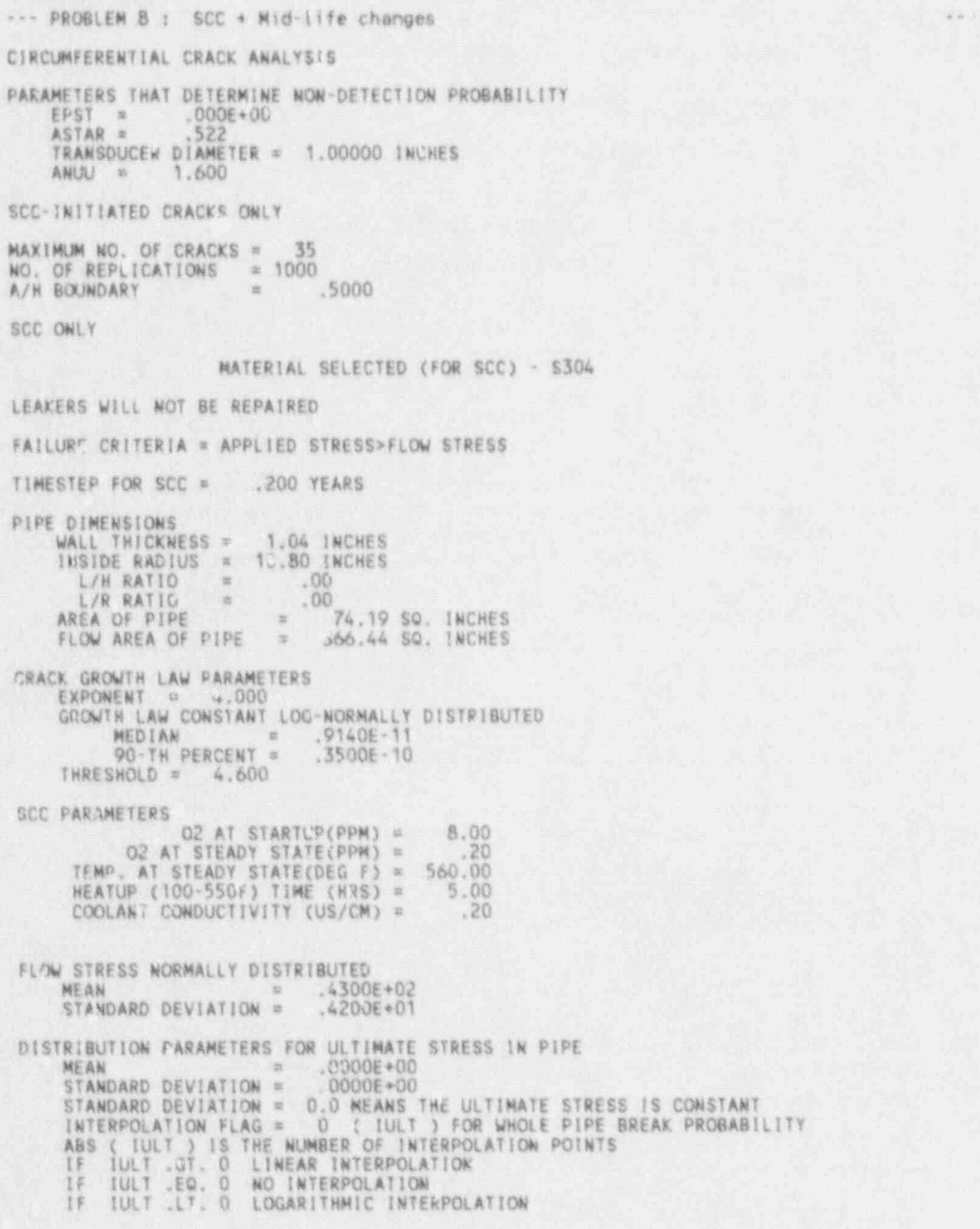
VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #8 Flow Stress (Card 2C) [Continued]				
YOUNGS	0	Not used	61 - 70	E10.4
XN	0	Not used	71 - 80	E10.4
Line #9 Ultimate Stress Definition (Card 2D)				
SULTMU	0	Not used	1 - 10	E10.0
SULTSD	0	Not used	11 - 20	E10.0
IULT	0	Not used	21 - 25	I5
Line #10 Leak Rate and Detection Parameters (Card 4C)				
FNDLEK	3	Threshold for detectable leak rate (gpm)	1 - 10	E10.3
ALKBIG	3	Threshold for defining big leaks (gpm)	11 - 20	E10.3
Line #11 Operating Stresses (Card 6A)				
SGCLD	1	Deadweight stress (ksi)	1 - 10	E10.4
SGDWTE	3.41	Deadweight and thermal expansion stress (ksi)	11 - 20	E10.4
OPPRES	1.33	Normal operating pressure (ksi)	21 - 30	E10.4
PRFPRS	-1.5625	Pressure in hydrostatic proof test (ksi)	31 - 40	E10.4
SIGVIB	-1	Vibratory stresses not modeled	41 - 50	E10.4
VBTHLD	0	Not used	51 - 60	E10.4
Line #12 Frequency of Heat-up/Cool-down Transient 1 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.1	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	460	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10
Line #13 Mid-Life Changes (Card 8A)				
RTIMES(1)	10	Time at which mid-life changes made (years)	1 - 10	E10.4
THICKS(1)	1.043	Wall thickness of pipe (in)	11 - 20	E10.4
OSTARS(1)	0.2	Oxygen at start-up (ppm)	21 - 30	E10.4
OSTDYS(1)	0.2	Oxygen at steady-state (ppm)	31 - 40	E10.4
CONDUS(1)	0.2	Coolant conductivity (μs/cm)	41 - 50	E10.4
SGCLDS(1)	0.5	Deadweight stress (ksi)	51 - 60	E10.4
SDWTES(1)	2.91	Deadweight and thermal expansion stress (ksi)	61 - 70	E10.4
SGVIBS(1)	-1	Vibratory stresses not modeled	71 - 80	E10.4

Table 10-8 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #14 Mid-Life Changes (Card 8B)				
ISIGRX(1)	7	No change in the residual stresses	1 - 10	I10
RSINMS(1)		Not used	11 - 20	E10.4
RSISDS(1)		Not used	21 - 30	E10.4
Line #15 Mid-Life Changes (Card 8A)				
RTIMES(1)	20	Time at which mid-life changes made (years)	1 - 10	E10.4
THICKS(1)	1.043	Wall thickness of pipe (in)	11 - 20	E10.4
OSTARS(1)	0.2	Oxygen at start-up (ppm)	21 - 30	E10.4
OSTDYS(1)	0.2	Oxygen at steady-state (ppm)	31 - 40	E10.4
CONDUS(1)	0.2	Coolant conductivity (µs/cm)	41 - 50	E10.4
SGCLDS(1)	0.5	Deadweight stress (ksi)	51 - 60	E10.4
SDWTES(1)	2.91	Deadweight and thermal expansion stress (ksi)	61 - 70	E10.4
SGVIBS(1)	-1	Vibratory stresses not modeled	71 - 80	E10.4
Line #16 Mid-Life Changes (Card 8B)				
ISIGRX(1)	6	IHSI treatment performed at this time	1 - 10	I10
RSINMS(1)	-44.7	Mean of value of post-IHSI residual stress at ID (ksi)	11 - 20	E10.4
RSISDS(1)	11.6	Standard deviation of value of post-IHSI residual stress at ID (ksi)	21 - 30	E10.4

```
                    P     R     A     I     S     E

                    PIPING RELIABILITY ANALYSIS INCLUDING SEISMIC EVENTS

                                PC-PRAISE VERSION 2.4U

                             EXECUTED ON  12/06/91 AT 11:55p


                          ECHO-PRINT OF INPUT DATA IN FILE  SAMPLE8.DAT

LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5- -(7)---5---(8
    1>PROBLEM 8 :  SCC + Mid-life changes                                             <
    2>    1    0   35 1000         0      .500         0    1  688      7225    2     <
    3>   -5    2    1    0   -2    0    0    0    0    0    0    0    0    0    1    3<
    4>  .400E+02  .200E+00    0    0                                                  <
    5>     1.043      10.8                                                            <
    6>  .460E+01  .400E+01  .914E-11  .350E-10                                        <
    7>  .800E+01  .200E+00  .560E+03  .500E+01  .200E+00                              <
    8> .4300E+02 .4200E+01                                                            <
    9>  .000E+00  .000E+00    0                                                       <
   10>  .300E+01  .300E+01                                                            <
   11>      1.00      3.41  .133E+01 -.156E+01 -.100E+01  .000E+00                    <
   12>    1   .1 460.00000                                                       <
   13>      10.0     1.043  .200E+00  .200E+00  .200E+00       0.5      2.91 -.100E+01<
   14>         7  .000E+00  .000E+00                                                  <
   15>      20.0     1.043  .200E+00  .200E+00  .200E+00       0.5      2.91 -.100E+01<
   16>         6    -44.70      11.6                                                  <
LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
 ****** NEW SEED (L,R)           688         7225*****
```

Figure 10-8a. Echo of input file for Sample Problem 8.



```
--- PROBLEM 8 :  SCC + Mid-life changes                                             ---

CIRCUMFERENTIAL CRACK ANALYSIS

PARAMETERS THAT DETERMINE NON-DETECTION PROBABILITY
    EPST  =       .000E+00
    ASTAR =       .522
    TRANSDUCER DIAMETER =  1.00000 INCHES
    ANUU  =     1.600

SCC-INITIATED CRACKS ONLY

MAXIMUM NO. OF CRACKS =   35
NO. OF REPLICATIONS   = 1000
A/H BOUNDARY          =       .5000

SCC ONLY

                    MATERIAL SELECTED (FOR SCC) - S304

LEAKERS WILL NOT BE REPAIRED

FAILURE CRITERIA = APPLIED STRESS>FLOW STRESS

TIMESTEP FOR SCC =     .200 YEARS

PIPE DIMENSIONS
    WALL THICKNESS =    1.04 INCHES
    INSIDE RADIUS  =  10.80 INCHES
      L/H RATIO    =        .00
      L/R RATIO    =        .00
    AREA OF PIPE         =    74.19 SQ. INCHES
    FLOW AREA OF PIPE    =   366.44 SQ. INCHES

CRACK GROWTH LAW PARAMETERS
    EXPONENT  =   4.000
    GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
         MEDIAN         =   .9140E-11
         90-TH PERCENT =   .3500E-10
    THRESHOLD =   4.600

SCC PARAMETERS
               O2 AT STARTUP(PPM) =     8.00
          O2 AT STEADY STATE(PPM) =      .20
     TEMP. AT STEADY STATE(DEG F) =  560.00
     HEATUP (100-550F) TIME (HRS) =     5.00
     COOLANT CONDUCTIVITY (US/CM) =      .20


FLOW STRESS NORMALLY DISTRIBUTED
    MEAN                  =   .4300E+02
    STANDARD DEVIATION =   .4200E+01

DISTRIBUTION PARAMETERS FOR ULTIMATE STRESS IN PIPE
    MEAN                  =   .0000E+00
    STANDARD DEVIATION =   .0000E+00
    STANDARD DEVIATION =  0.0 MEANS THE ULTIMATE STRESS IS CONSTANT
    INTERPOLATION FLAG =    0  ( IULT ) FOR WHOLE PIPE BREAK PROBABILITY
    ABS ( IULT ) IS THE NUMBER OF INTERPOLATION POINTS
    IF  IULT .GT. 0  LINEAR INTERPOLATION
    IF  IULT .EQ. 0  NO INTERPOLATION
    IF  IULT .LT. 0  LOGARITHMIC INTERPOLATION
```

Figure 10-8b. Input summary for Sample Problem 8.

```
PIPE LOADING VALUES
    STRESS (KSI) DUE TO COLD DEADWEIGHT  =      1.00
    STRESS (KSI)  DUE TO DWGHT + THERMAL =      3.41
    STRESS (KSI)  DUE TO         THERMAL =      2.41
    OPERATING PRESSURE (KSI)             =      1.33
    STRESS (KSI) DUE TO OPER. PRESSURE   =      6.57
    STRESS (KSI) DUE TO DWGHT + OP PRESR =      7.57
    STRESS (KSI) DUE TO DWT+THML+OP PRES =      9.98

    NO HYDROSTATIC PROOF TEST IS MODELLED

LEAK DETECTION AND DEFINITION PARAMETERS
    DETECTABLE LEAK (GPM) =    3.00
    BIG LEAK        (GPM) =    3.00

RESIDUAL STRESSES FOR INTERMEDIATE LINE SELECTED

NO VIBRATORY STRESSES ARE MODELLED

NO PRE-SERVICE ULTRASONIC INSPECTION

TIME INTERVALS
    PLANT LIFETIME =  40.0 YEARS
    ENDPOINTS OF INTERVALS AT     .0   2.0   4.0   6.0   8.0 YEARS
    ENDPOINTS OF INTERVALS AT   10.0  12.0  14.0  16.0  18.0 YEARS
    ENDPOINTS OF INTERVALS AT   20.0  22.0  24.0  26.0  28.0 YEARS
    ENDPOINTS OF INTERVALS AT   30.0  32.0  34.0  36.0  38.0 YEARS
    ENDPOINTS OF INTERVALS AT   40.0

NO IN-SERVICE INSPECTIONS ARE MODELLED

NO SEISMIC EVENTS EVALUATED

Number of remedial actions =  2
Details of the remedial actions are as follows :

Action Time  Thick-  Oxygen        Cond.  Dead Wt DW+TE Vib.   Res.      Mean    Std.
       (yrs) -ness  Start S.State         Stress  Str.  Stress Stress            Dev.

   1  10.00   1.04    .20    .20    .20     .50   2.91  -1.00No change
   2  20.00   1.04    .20    .20    .20     .50   2.91  -1.00 IHSI/MSIP-44.70 11.60

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS   0

 NORMAL OUTPUT REQUESTED


 NUMBER OF TRANSIENT TYPES =  1

 TYPE  1
     REGULAR AT        .100 YEARS/EVENT
     MAX DELTA TEMP = 460.0  BLOCKING FACTOR =  1.0
```

Figure 10-8b. (Continued).

```
--- PROBLEM 8 :  SCC + Mid-life changes                                                 ---


                                              - - - RESULTS WITHOUT EARTHQUAKES - - -

            SEISMIC CLASS INFORMATION
                   CLASS      SIGEQ        SGLCEQ     CYCLES   COV F-BM
                     0     .0000E+00        .000        0        .0000

                 PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                   SULTMU          SULTSD     IULT
                .00000E+00     .90000E+00     0
                  STRESS(1)
                .70687E+01
                  PBREAK(1)
                .10000E+01

          TIME      AVG LEAK      AVG BIG LEAK      AVG LOCA        SIGMA LEAK     SIGMA BIG LEAK     SIGMA LOCA
            .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
           4.0    1.00000E-03    1.00000E-03     0.00000E+00     1.00000E-03     1.00000E-03     0.00000E+00
           6.0    1.10000E-02    1.10000E-02     0.00000E+00     3.29998E-03     3.29998E-03     0.00000E+00
           8.0    2.00000E-02    2.00000E-02     0.00000E+00     4.42940E-03     4.42940E-03     0.00000E+00
          10.0    3.90000E-02    3.90000E-02     0.00000E+00     6.12507E-03     6.12507E-03     0.00000E+00
          12.0    5.60000E-02    5.40000E-02     0.00000E+00     7.27440E-03     7.15088E-03     0.00000E+00
          14.0    7.90000E-02    7.80000E-02     0.00000E+00     8.53416E-03     8.48457E-03     0.00000E+00
          16.0    1.02000E-01    1.01000E-01     0.00000E+00     9.57537E-03     9.53362E-03     0.00000E+00
          18.0    1.24000E-01    1.22000E-01     0.00000E+00     1.04275E-02     1.03569E-02     0.00000E+00
          20.0    1.43000E-01    1.40000E-01     0.00000E+00     1.10758E-02     1.09782E-02     0.00000E+00
          22.0    1.47000E-01    1.47000E-01     0.00000E+00     1.12034E-02     1.12034E-02     0.00000E+00
          24.0    1.54000E-01    1.54000E-01     0.00000E+00     1.14199E-02     1.14199E-02     0.00000E+00
          26.0    1.63000E-01    1.63000E-01     0.00000E+00     1.16862E-02     1.16862E-02     0.00000E+00
          28.0    1.65000E-01    1.65000E-01     0.00000E+00     1.17436E-02     1.17436E-02     0.00000E+00
          30.0    1.68000E-01    1.67000E-01     0.00000E+00     1.18286E-02     1.18004E-02     0.00000E+00
          32.0    1.73000E-01    1.71000E-01     0.00000E+00     1.19672E-02     1.19122E-02     0.00000E+00
          34.0    1.75000E-01    1.73000E-01     0.00000E+00     1.20216E-02     1.19672E-02     0.00000E+00
          36.0    1.76000E-01    1.75000E-01     0.00000E+00     1.20486E-02     1.20216E-02     0.00000E+00
          38.0    1.79000E-01    1.78000E-01     0.00000E+00     1.21287E-02     1.21022E-02     0.00000E+00
          40.0    1.83000E-01    1.82000E-01     0.00000E+00     1.22336E-02     1.22076E-02     0.00000E+00
```

Figure 10-8c. Failure Probabilities for Sample Problem 8.

```
--- PROBLEM 8 :  SCC + Mid-life changes                                          ---


                   TOTAL NUMBER OF REPLICATIONS =  1000
NUMBER OF POSSSIBLE INITIATION SITES(USER SPEC.) =    35
NO. OF TIMES     INITIATED CRACKS CAUSED BIG LEAK =   182
NO. OF TIMES PRE-EXISTING CRACKS CAUSED BIG LEAK =     0

       TIME   TOTAL INITIATED    FIRST INITIATED
      (YRS)       CRACKS             CRACKS

          1         459                368
          2        2018                510
          3        2707                 98
          4        2752                 17
          5        2660                  5
          6        2359                  0
          7        2128                  2
          8        1911                  0
          9        1691                  0
         10        1465                  0
         11         873                  0
         12         743                  0
         13         709                  0
         14         649                  0
         15         552                  0
         16         538                  0
         17         501                  0
         18         469                  0
         19         455                  0
         20         406                  0
         21          32                  0
         22           1                  0
         23           2                  0
         24           0                  0
         25           1                  0
         26           0                  0
         27           0                  0
         28           0                  0
         29           0                  0
         30           0                  0
         31           0                  0
         32           0                  0
         33           0                  0
         34           0                  0
         35           0                  0
         36           1                  0
         37           0                  0
         38           0                  0
         39           0                  0
         40           0                  0

         81           0                  0


   PC-PRAISE VERSION 2.40
   Execution Start -    12/06/91 at 11:55p
   Execution End   -    12/07/91 at  3:23a
```

Figure 10-8d. Statistics of time to initiation for Sample Problem 8.

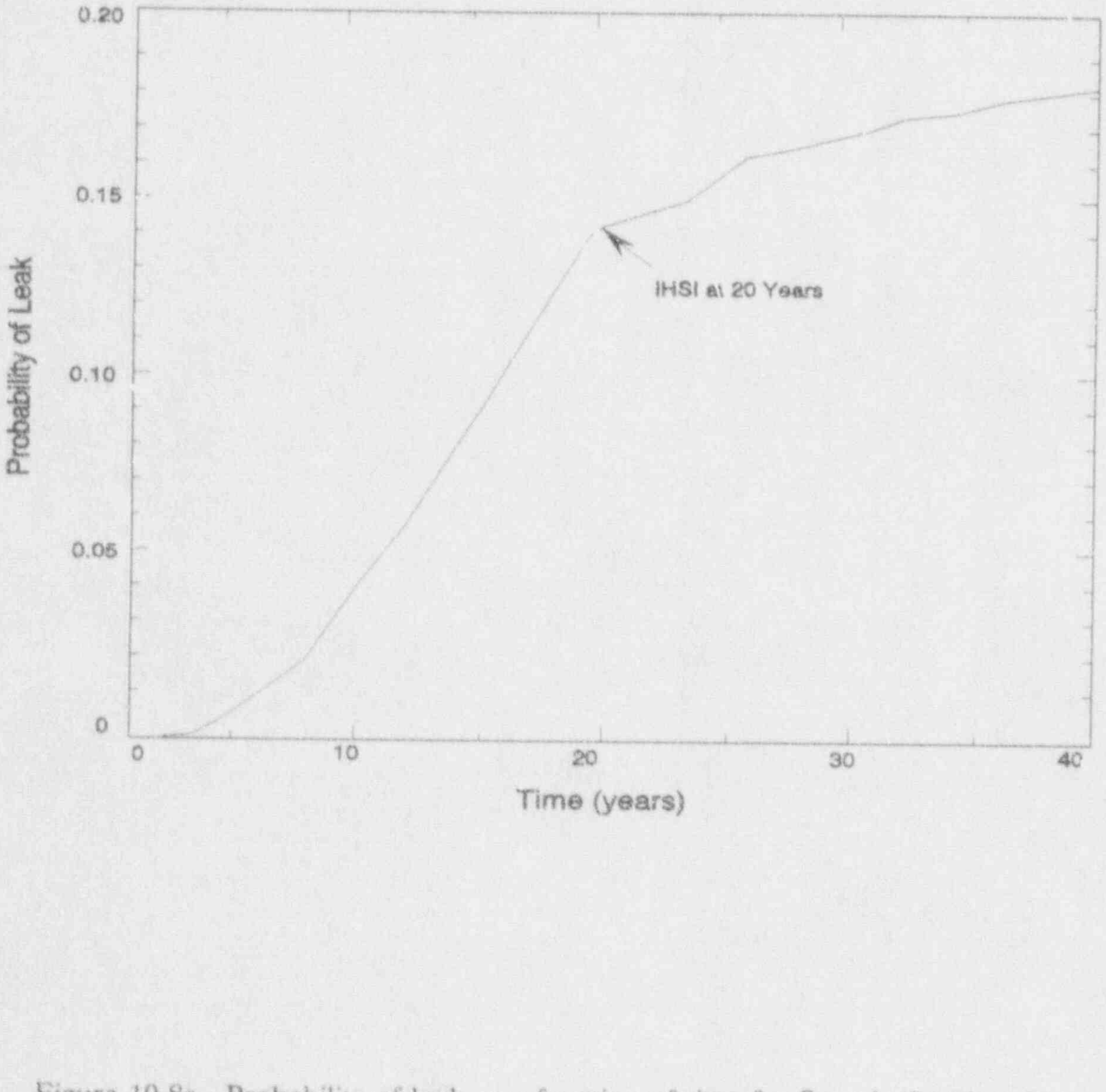


Figure 10-8e. Probability of leak as a function of time for Sample Problem 8.

10.9 Sample Problem 9: Fatigue and SCC

Sample Problems 1-8 considered either pre-existing cracks or SCC-initiated cracks, but not both. This sample problem illustrates the use of pc-PRAISE when both pre-existing and initiated cracks are important. This sample problem is set up to calculate probability of leak. Seismic events are not modeled. The only load cycle used is the heat-up/cool-down cycle. The weld location is subjected to pre-service and in-service inspections and a proof-test. Failure criteria used is the net-section stress exceeding the flow stress. The major inputs related to the geometry of the pipe, the pipe material, the welding process used, and the operating history are described below.

Pipe Geometry:
- Inside Radius = 5.0 in
- Wall Thickness = 0.5 in

Stresses:
- Deadweight = 2.08 ksi
- Deadweight + Thermal Expansion = 8.58 ksi
- Operating Pressure = 2400 psi
- Proof Pressure = 3000 psi

Water Chemistry and Conditions that Affect SCC:
- Oxygen at Plant Start-Up = 8 ppm
- Oxygen at Plant Start-Up = 0.2 ppm
- Oxygen at Steady-State Operation = 0.2 ppm
- Water Temperature at Steady-State = 550°F
- Duration of Plant Heat-Up = 5 hrs
- Coolant Conductivity = 0.2 μs/cm

Fatigue Crack Growth Properties:
- C (median) = $9.14\text{x}10^{-12}$
- C (90th percentile) = $3.5\text{x}10^{-11}$
- Fatigue Exponent = 4.0
- Fatigue Threshold = 4.6 ksi-in$^{1/2}$

Flow Stress:
- Mean = 43.2 ksi
- Standard Deviation = 4.2 ksi

Initial Crack Size Distribution:
Depth Distribution -- Exponential
- Parameter = 4.07

Aspect Ratio Distribution -- Lognormal

Median = 1.34
Shape Parameter = 0.538

SCC Properties:
AISI 304 Stainless Steel

The a/h - a/b sample space is divided into 100 cells and 100 samples are taken from each cell. The SCC-initiated cracks are always included in the analysis (BNDRY = 1.1). Plant lifetime of 40 years is simulated and results are printed at two year intervals. The heat-up/cool-down cycles are assumed to occur regularly five times a year. Post-IHSI residual stresses are also modeled.

The input file for Sample Problem 9 is shown in Figure 10-9a. Each variable in the input file is described in Table 10-9. The output file is shown in Figures 10-9b through 10-9e. Description of the inputs is summarized in Figure 10-9b. The stratification scheme used is shown in Figure 10-9c. Coordinates of each cell are shown along with the number of samples and the conditional probability of crack from that cell. The last three columns of that table show the number of cracks that resulted in leak, big-leak, and LOCA, respectively. The probabilities of leak as a function of time are shown in Figure 10-9d. Leak and big-leak probabilities are the same at any given time because the same threshold leak rate is used for identifying big and small leaks. The LOCA probability calculations for this case may not be accurate because the stratification used is not optimized for the estimation of LOCA probabilities. Figure 10-9e provides statistics on initiated cracks as a function of time.

Table 10-9
VARIABLE INPUT FILE FOR SAMPLE PROBLEM 9: FATIGUE AND SCC

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #1 Title				
TITLE( )		Analysis title		
Line #2 Control Variables (Card 0B)				
INCIAT	2	Pre-existing and initiated cracks included	1 - 5	I5
IFAILC	0	Net-section stress failure criteria	6 - 10	I5
ICRAKS	5	Number of stress corrosion initiation sites	11 - 15	I5
IREPLS	0	Not used	16 - 20	I5
IREPAR	0	Leakers will not be repaired	26 - 30	I5
BNDRY	1.1	Initiated cracks will always be included	31 - 40	F10.3
ISF	0	Fatigue crack growth data input by the user	41 - 50	I10
MTTYPE	1	Use 304 properties for SCC	51 - 55	I5
ISEED	688	Random number seed 1	56 - 62	I7
ISEEDR	7225	Random number seed 2	63 - 70	I8
IREMED	0	Number of remedial actions during the plant life	71 - 75	I5
Line #3 Control Variables (Card 1B)				
NTRIES	-50	Number of replications from each cell = abs (NTRIES)	1 - 5	I5
ISQARE	1	Rectangular grid to be set up	6 - 10	I5
KTYPES	1	Number of transients experienced by the plant	11 - 15	I5
KRKDIS	3	Crack depth exponential, aspect ratio lognormal	16 - 20	I5
NEVAL	-2	Interval for printing results (years)	21 - 25	I5
NINSPT	3	Number of in-service inspections	26 - 30	I5
NQUAKE	0	No earthquakes to be modeled	31 - 35	I5
IDEBUG	0	Normal output to be printed	36 - 40	I5
KONPRP	0	C lognormally distributed	41 - 45	I5
NEQINT	0	Number of seismic intensity classes to modeled	46 - 50	I5
MCELLS	0	Not used	51 - 55	I5
KNSFLO	0	Flow stress normally distributed	56 - 60	I5
NSKIP	0	No indicator function printout	61 - 65	I5
NPSI	1	A pre-service inspection is modeled	66 - 70	I5
ISCC	-1	Crack growth by fatigue and SCC	71 - 75	I5
ISIGRS	5	Residual stress at ID and OD input by the user	75 - 80	I5

Table 10-9 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #4 Constant IHSI Residual Stresses (Card 1C0)				
RSIN	30	Residual stress at ID (ksi)	1 - 10	E10.3
RSOUT	-30	Residual stress at OD (ksi)	11 - 20	E10.3
Line #5 Time and NDE Parameters (Card 1D)				
THRIZN	40	Maximum plant lifetime simulated (years)	1 - 10	E10.3
DTSCC	0.2	Maximum time step for SCC growth (years)	11 - 20	E10.3
ICTYPE	0	Crack orientation is circumferential	21 - 25	I5
IPTYPE	0	Default NDE parameters for thick austenitic pipe used	26 - 30	I5
EPST		Not used	31 - 40	E10.0
ASTAR		Not used	41 - 50	E10.0
TRANSD		Not used	51 - 60	E10.0
ANUU		Not used	61 - 70	E10.0
Line #6 Pipe Dimensions (Card 2A)				
THICK	0.5	Wall thickness of the pipe (inches)	1 - 10	E10.3
RIN	5	Inside radius (inches)	11 - 20	E10.3
ELOVRR		Not used	21 - 30	E10.3
Line #7 Fatigue Crack Growth Characteristics (Card 2B)				
THRHLD	4.6	Threshold for fatigue crack growth (ksi-in$^{1/2}$)	1 - 10	E10.3
EMEXP	4	Exponent for fatigue crack growth equation	11 - 20	E10.3
CONSMU	9.14×10^{-12}	50th percentile of C	21 - 30	E10.3
CONS90	3.50×10^{-11}	90th percentile of C	31 - 40	E10.3
Line #8 SCC Variables (Card 2B-1)				
OSTART	8	Oxygen at plant start-up (ppm)	1 - 10	F10.5
OSTEDY	0.2	Oxygen at steady-state operation (ppm)	11 - 20	F10.5
TFSTDY	550	Steady-state temperature (°F)	21 - 30	F10.5
DURATN	5	Duration of plant heat-up (hrs)	31 - 40	F10.5
CONDUC	0.2	Coolant conductivity (µs/cm)	41 - 50	F10.5
Line #9 Flow Stress (Card 2C)				
SFLOMU	43.2	Mean value of flow stress (ksi)	1 - 10	E10.4
SFLOSD	4.2	Standard deviation of flow stress (ksi)	11 - 20	E10.4
XJIC		Not used	21 - 30	E10.4
DJDAMT		Not used	31 - 40	E10.4

Table 10-9 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #9 Flow Stress (Card 2C) [Continued]				
SIG0		Not used	41 - 50	E10.4
DEE		Not used	51 - 60	E10.4
YOUNGS		Not used	61 - 70	E10.4
XN		Not used	71 - 80	E10.4
Line #10 Ultimate Stress Definition (Card 2D)				
SULTMU	0	Not used	1 - 10	E10.0
SULTSD	0	Not used	11 - 20	E10.0
IULT	0	Not used	21 - 25	I5
Line #11 Initial Crack Depth Distribution (Card 3A)				
AMEDIAN	4.07	Rate parameter for exponential distribution of depth (1/in)	1 - 10	E10.3
ASIGMA		Not used	11 - 20	E10.3
ALAMDA		Not used	21 - 30	E10.3
Line #12 Initial Aspect Ratio Distribution (Card 3B)				
BOAMED	1.34	Median of truncated lognormal distribution of b/a	1 - 10	E10.3
BOASIG	0.538	Shape factor of truncated lognormal distribution of b/a	11 - 20	E10.3
BOALDA		Not used	1 - 10	E10.3
Line #13 In-service Inspection Times (Card 4B)				
TINSPT	10, 20, ..	In-service inspection times (years)	1 - 80	8E10.3
Line #14 Leak Rate and Detection Parameters (Card 4C)				
FNDLEK	3	Threshold for detectable leak rate (gpm)	1 - 10	E10.3
ALKBIG	3	Threshold for defining big leaks (gpm)	11 - 20	E10.3
Line #15 Stratified Sample Space (Card 5A)				
NAOH	10	Number of divisions in a/h direction	1 - 5	I5
NAOB	10	Number of divisions in a/b direction	6 - 10	I5
AOHLOW	0	Lower limit of a/h	11 - 20	E10.3
AOHUP	1	Upper limit of a/h	21 - 30	E10.3
AOBLFT	0	Lower limit of a/b	31 - 40	E10.3
AOBRGT	1	Upper limit of a/b	41 - 50	E10.3

Table 10-9 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #16 Operating Stresses (Card 6A)				
SGCLD	2.08	Deadweight stress (ksi)	1 - 10	E10.4
SGDWTE	8.58	Deadweight and thermal expansion stress (ksi)	11 - 20	E10.4
OPPRES	2.4	Normal operating pressure (ksi)	21 - 30	E10.4
PRFPRS	3	Pressure in hydrostatic proof test (ksi)	31 - 40	E10.4
SIGVIB	-1	Vibratory stresses not modeled	41 - 50	E10.4
VBTHLD	0	Not used	51 - 60	E10.4
Line #17 Frequency of Heat-up/Cool-down Transient 1 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.2	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	460	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10

```
                  P     R         A       I       S     E

                  PIPING RELIABILITY ANALYSIS INCLUDING SEISMIC EVENTS

                               PC-PRAISE VERSION 2.40

                            EXECUTED ON  12/07/91 AT  3:23a


                          ECHO-PRINT OF INPUT DATA IN FILE  SAMPLE9.DAT

LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
   1> PROBLEM 9 : Fatigue + SCC initiated                                        <
   2>    2   0    5   0        0     1.100        0    1   688    7225    0    <
   3>  -50   1    1   3   -2   3    0   0    0    0    0    0   0    1   -1   5<
   4>   30.0       -30.0                                                         <
   5>  .400E+02  .200E+00    0    0                                              <
   6>  .500E+00  .500E+01                                                        <
   7>  .460E+01  .400E+01  .914E-11  .350E-10                                    <
   8>  .800E+01  .200E+00  .550E+03  .500E+01  .200E+00                          <
   9> .4300E+02 .4200E+01                                                        <
  10>  .000E+00  .000E+00    0                                                   <
  11>  .407E+01                                                                  <
  12>  .134E+01  .538E+00                                                        <
  13>      10.0      20.0      30.0                                              <
  14>  .300E+01  .300E+01                                                        <
  15>   10   10      .000     1.000      .000     1.000                          <
  16> 2.08       8.58      2.400     3.00      -.100E+01  .000E+00               <
  17>    1 .2   460.00000Heat-up and Cool-down                                   <
LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
 ****** NEW SEED (L,R)           688        7225*****
```

Figure 10-9a. Echo of input file for Sample Problem 9.

```
---  PROBLEM 9 : Fatigue + SCC initiated                                                    ---

CIRCUMFERENTIAL CRACK ANALYSIS

PARAMETERS THAT DETERMINE NON-DETECTION PROBABILITY
    EPST  =      .000E+00
    ASTAR =      .250
    TRANSDUCER DIAMETER =  1.00000 INCHES
    ANUU  =     1.600

PRE-EXISTING CRACKS + INITIATED CRACKS WILL BE
INCLUDED WHENEVER (SAMPLED A/H)<BNDRY

MAXIMUM NO. OF CRACKS =     5
NO. OF REPLICATIONS   =     0
A/H BOUNDARY          =     1.1000

SCC AND FATIGUE CRACK GROWTH

                   MATERIAL SELECTED (FOR SCC) - S304

LEAKERS WILL NOT BE REPAIRED

FAILURE CRITERIA = APPLIED STRESS>FLOW STRESS

TIMESTEP FOR SCC =     .200 YEARS

PIPE DIMENSIONS
    WALL THICKNESS       .50 INCHES
    INSIDE RADIUS  =   5.00 INCHES
      L/H RATIO    =       .00
      L/P RATIO    =       .00
    AREA OF PIPE          =     16.49 SQ. INCHES
    FLOW AREA OF PIPE   =     78.54 SQ. INCHES

INITIAL CRACK SIZE DISTRIBUTION
CRACK DEPTH IS EXPONENTIAL
    PARAMETER =    4.0700
ASPECT RATIO IS LOG-NORMAL
    MEDIAN                  =     1.3400
    SHAPE PARAMETER         =      .5380
    NORMALIZATION CONSTANT =     1.4149

CRACK GROWTH LAW PARAMETERS
    EXPONENT  =   4.000
    GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
         MEDIAN         =   .9140E-11
         90-TH PERCENT =   .3500E-10
    THRESHOLD =   4.600

SCC PARAMETERS
               O2 AT STARTUP(PPM) =     8.00
          O2 AT STEADY STATE(PPM) =      .20
     TEMP. AT STEADY STATE(DEG F) =  550.00
     HEATUP (100-550F) TIME (HRS) =     5.00
     COOLANT CONDUCTIVITY (US/CM) =      .20


FLOW STRESS NORMALLY DISTRIBUTED
    MEAN                 =   .4300E+02
    STANDARD DEVIATION =   .4200E+01
```

Figure 10-9b. Input summary for Sample Problem 9.

```
DISTRIBUTION PARAMETERS FOR ULTIMATE STRESS IN PIPE
    MEAN                =    .0000E+00
    STANDARD DEVIATION =    .0000E+00
    STANDARD DEVIATION =  0.0 MEANS THE ULTIMATE STRESS IS CONSTANT
    INTERPOLATION FLAG =    0  ( IULT ) FOR WHOLE PIPE BREAK PROBABILITY
    ABS ( IULT ) IS THE NUMBER OF INTERPOLATION POINTS
    IF  IULT .GT. 0  LINEAR INTERPOLATION
    IF  IULT .EQ. 0  NO INTERPOLATION
    IF  IULT .LT. 0  LOGARITHMIC INTERPOLATION

PIPE LOADING VALUES
    STRESS (KSI) DUE TO COLD DEADWEIGHT  =     2.08
    STRESS (KSI)  DUE TO DWGHT + THERMAL =     8.58
    STRESS (KSI)  DUE TO         THERMAL =     6.50
    OPERATING PRESSURE (KSI)             =     2.40
    STRESS (KSI) DUE TO OPER. PRESSURE   =    11.43
    STRESS (KSI) DUE TO DWGHT + OP PRESR =    13.51
    STRESS (KSI) DUE TO DWT+THML+OP PRES =    20.01
    PROOF PRESSURE (KSI)                 =     3.00
    STRESS (KSI) DUE TO DWGHT + PRF PRES =    16.37

    HYDROSTATIC PROOF TEST IS MODELLED

LEAK DETECTION AND DEFINITION PARAMETERS
    DETECTABLE LEAK (GPM) =    3.00
    BIG LEAK        (GPM) =    3.00

IHSI-RESIDUAL STRESSES SELECTED
     INSIDE  STRESS (KSI) =   30.000
     OUTSIDE STRESS (KSI) =  -30.000

NO VIBRATORY STRESSES ARE MODELLED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELLED

TIME INTERVALS
    PLANT LIFETIME =  40.0 YEARS
    ENDPOINTS OF INTERVALS AT      .0   2.0   4.0   6.0   8.0 YEARS
    ENDPOINTS OF INTERVALS AT    10.0  12.0  14.0  16.0  18.0 YEARS
    ENDPOINTS OF INTERVALS AT    20.0  22.0  24.0  26.0  28.0 YEARS
    ENDPOINTS OF INTERVALS AT    30.0  32.0  34.0  36.0  38.0 YEARS
    ENDPOINTS OF INTERVALS AT    40.0
    IN-SERVICE INSPECTIONS AT    10.0  20.0  30.0

NO SEISMIC EVENTS EVALUATED

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS   0

NORMAL OUTPUT REQUESTED


NUMBER OF TRANSIENT TYPES =  1

TYPE  1    Heat-up and Cool-down
    REGULAR AT         .200 YEARS/EVENT
    MAX DELTA TEMP = 460.0  BLOCKING FACTOR =  1.0
```

Figure 10-9b. (Continued).

```
                    - - - SUMMARY OF CELLS IN SAMPLE SPACE - - -

                              - - - UNIFORM MESH - - -

CELL     AOH1      AOH2      AOB1      AOB2        PROBABILITY       SAMPLES    LEAKS    B-LEAKS    LOCAS
  1     .9000    1.0000     .0000     .1000       .4490496E-05        50         50        50         0
  2     .9000    1.0000     .1000     .2000       .3407369E-03        50         50        50         0
  3     .9000    1.0000     .2000     .3000       .1821773E-02        50         50        50         0
  4     .9000    1.0000     .3000     .4000       .3746652E-02        50         50        50         0
  5     .9000    1.0000     .4000     .5000       .5046091E-02        50         50        50         0
  6     .9000    1.0000     .5000     .6000       .5483384E-02        50         50        50         1
  7     .9000    1.0000     .6000     .7000       .5284579E-02        50         50        50         0
  8     .9000    1.0000     .7000     .8000       .4740713E-02        50         50        50         0
  9     .9000    1.0000     .8000     .9000       .4066781E-02        50         50        49         0
 10      9000    1.0000     .9000    1.0000       .3390729E-02        50         50        50         0
 11     .8000     .9000     .0000     .1000       .5503934E-05        50         50        50         0
 12     .8000     .9000     .1000     .2000       .4176361E-03        50         50        50         0
 13     .8000     .9000     .2000     .3000       .2232920E-02        50         50        50         0
 14     .8000     .9000     .3000     .4000       .4592216E-02        50         50        50         0
 15     .8000     .9000     .4000     .5000       .6184919E-02        50         50        50         0
 16     .8000     .9000     .5000     .6000       .6720903E-02        50         50        50         0
 17     .8000     .9000     .6000     .7000       .6477230E-02        50         50        49         1
 18     .8000     .9000     .7000     .8000       .5810621E-02        50         50        49         0
 19     .8000     .9000     .8000     .9000       .4984839E-02        50         50        49         0
 20     .8000     .9000     .9000    1.0000       .4155966E-02        50         50        50         0
 21     .7000     .8000     .0000     .1000       .6746091E-05        50         50        50         0
 22     .7000     .8000     .1000     .2000       .5118904E-03        50         50        50         0
 23     .7000     .8000     .2000     .3000       .2736856E-02        50         50        50         0
 24     .7000     .8000     .3000     .4000       .5628611E-02        50         50        50         0
 25     .7000     .8000     .4000     .5000       .7580763E-02        50         50        50         0
 26     .7000     .8000     .5000     .6000       .8237711E-02        50         50        49         0
 27     .7000     .8000     .6000     .7000       .7939044E-02        50         50        50         0
 28     .7000     .8000     .7000     .8000       .7121992E-02        50         50        50         0
 29     .7000     .8000     .8000     .9000       .6109843E-02        50         50        50         0
 30     .7000     .8000     .9000    1.0000       .5093906E-02        50         50        49         0
 31     .6000     .7000     .0000     .1000       .8268583E-05        50         50        50         0
 32     .6000     .7000     .1000     .2000       .6274164E-03        50         50        50         0
 33     .6000     .7000     .2000     .3000       .3354524E-02        50         50        50         0
 34     .6000     .7000     .3000     .4000       .6898904E-02        50         50        50         0
 35     .6000     .7000     .4000     .5000       .9291629E-02        50         50        49         0
 36     .6000     .7000     .5000     .6000       .1009684E-01        50         47        47         0
 37     .6000     .7000     .6000     .7000       .9730769E-02        50         50        49         0
 38     .6000     .7000     .7000     .8000       .8729320E-02        50         50        50         0
 39     .6000     .7000     .8000     .9000       .7488744E-02        50         48        47         0
 40     .6000     .7000     .9000    1.0000       .6243525E-02        50         47        47         1
 41     .5000     .6000     .0000     .1000       .1013468E-04        50         50        50         0
 42     .5000     .6000     .1000     .2000       .7690150E-03        50         50        50         0
 43     .5000     .6000     .2000     .3000       .4111590E-02        50         50        50         0
 44     .5000     .6000     .3000     .4000       .8455885E-02        50         50        50         1
 45     .5000     .6000     .4000     .5000       .1138861E-01        50         49        49         0
 46     .5000     .6000     .5000     .6000       .1237555E-01        50         46        46         0
 47     .5000     .6000     .6000     .7000       .1192686E-01        50         50        50         0
 48     .5000     .6000     .7000     .8000       .1069940E-01        50         48        48         0
 49     .5000     .6000     .8000     .9000       .9178842E-02        50         46        46         0
 50     .5000     .6000     .9000    1.0000       .7652595E-02        50         45        45         0
 51     .4000     .5000     .0000     .1000       .1242193E-04        50         50        50         0
 52     .4000     .5000     .1000     .2000       .9425703E-03        50         50        50         0
 53     .4000     .5000     .2000     .3000       .5039515E-02        50         50        50         0
 54     .4000     .5000     .3000     .4000       .1036425E-01        50         48        48         0
 55     .4000     .5000     .4000     .5000       .1395885E-01        50         50        50         0
 56     .4000     .5000     .5000     .6000       .1516852E-01        50         48        48         0
 57     .4000     .5000     .6000     .7000       .1461857E-01        50         42        42         0
 58     .4000     .5000     .7000     .8000       .1311409E-01        50         46        46         0
 59     .4000     .5000     .8000     .9000       .1125037E-01        50         42        42         0
```

Figure 10-9c. Stratification description for Sample Problem 9.

```
 60    .4000    .5000    .9000   1.0000      .9379673E-02      50       49       47       0
 61    .3000    .4000    .0000    .1000      .1522537E-04      50       49       49       0
 62    .3000    .4000    .1000    .2000      .1155294E-02      50       50       50       0
 63    .3000    .4000    .2000    .3000      .6176859E-02      50       48       47       0
 64    .3000    .4000    .3000    .4000      .1270331E-01      50       49       49       0
 65    .3000    .4000    .4000    .5000      .1710916E-01      50       46       46       0
 66    .3000    .4000    .5000    .6000      .1859183E-01      50       46       46       0
 67    .3000    .4000    .6000    .7000      .1791777E-01      50       45       45       0
 68    .3000    .4000    .7000    .8000      .1607375E-01      50       43       43       0
 69    .3000    .4000    .8000    .9000      .1378941E-01      50       47       46       0
 70    .3000    .4000    .9000   1.0000      .1149653E-01      50       45       44       0
 71    .2000    .3000    .0000    .1000      .1866151E-04      50       49       49       0
 72    .2000    .3000    .1000    .2000      .1416027E-02      50       45       45       0
 73    .2000    .3000    .2000    .3000      .7570885E-02      50       47       47       0
 74    .2000    .3000    .3000    .4000      .1557026E-01      50       48       48       0
 75    .2000    .3000    .4000    .5000      .2097044E-01      50       46       46       0
 76    .2000    .3000    .5000    .6000      .2278774E-01      50       46       46       0
 77    .2000    .3000    .6000    .7000      .2196154E-01      50       45       45       0
 78    .2000    .3000    .7000    .8000      .1970136E-01      50       41       41       0
 79    .2000    .3000    .8000    .9000      .1690148E-01      50       46       45       0
 80    .2000    .3000    .9000   1.0000      .1409112E-01      50       42       42       0
 81    .1000    .2000    .0000    .1000      .2287314E-04      50       46       46       0
 82    .1000    .2000    .1000    .2000      .1735604E-02      50       44       44       0
 83    .1000    .2000    .2000    .3000      .9279521E-02      50       41       41       0
 84    .1000    .2000    .3000    .4000      .1908424E-01      50       36       36       0
 85    .1000    .2000    .4000    .5000      .2570316E-01      50       36       36       0
 86    .1000    .2000    .5000    .6000      .2793059E-01      50       32       31       0
 87    .1000    .2000    .6000    .7000      .2691794E-01      50       40       39       0
 88    .1000    .2000    .7000    .8000      .2414766E-01      50       35       35       0
 89    .1000    .2000    .8000    .9000      .2071589E-01      50       33       32       0
 90    .1000    .2000    .9000   1.0000      .1727128E-01      50       33       32       0
 91    .0000    .1000    .0000    .1000      .2803527E-04      50       25       25       0
 92    .0000    .1000    .1000    .2000      .2127303E-02      50       26       25       0
 93    .0000    .1000    .2000    .3000      .1137377E-01      50       23       23       0
 94    .0000    .1000    .3000    .4000      .2339126E-01      50       20       20       0
 95    .0000    .1000    .4000    .5000      .3150398E-01      50       30       30       0
 96    .0000    .1000    .5000    .6000      .3423411E-01      50       26       25       0
 97    .0000    .1000    .6000    .7000      .3299292E-01      50       24       24       0
 98    .0000    .1000    .7000    .8000      .2959743E-01      50       27       27       0
 99    .0000    .1000    .8000    .9000      .2539116E-01      50       23       23       0
100    .0000    .1000    .9000   1.0000      .2116915E-01      50       26       26       0
                                          ---------------
                SUM OF CELL PROBABILITIES =  .1000000E+01
```

Figure 10-9c. (Continued).

```
---  PROBLEM 9 : Fatigue + SCC initiated                                              ---


                                           - - - RESULTS WITHOUT EARTHQUAKES - - -

                SEISMIC CLASS INFORMATION
                          CLASS     SIGEQ       SGLCEQ     CYCLES  COV F-BM
                            0     .0000E+00       .000        0       .0000

                     PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                        SULTMU           SULTSD     IULT
                     .00000E+00      .00000E+00     0
                      STRESS(1)
                     .13509E+02
                      PBREAK(1)
                     .10000E+01

            TIME     AVG LEAK      AVG BIG LEAK     AVG LOCA        SIGMA LEAK    SIGMA BIG LEAK   SIGMA LOCA
              .0   3.95496E-04    2.45185E-04    0.00000E+00    3.99341E-05    2.83085E-05    0.00000E+00
             2.0   1.59151E-01    1.42459E-01    1.62792E-04    5.31564E-03    5.07336E-03    1.01702E-04
             4.0   2.42649E-01    2.27206E-01    1.62792E-04    6.16817E-03    6.10646E-03    1.01702E-04
             6.0   2.97784E-01    2.86847E-01    1.62792E-04    6.57631E-03    6.55354E-03    1.01702E-04
             8.0   3.36719E-01    3.26843E-01    1.62792E-04    6.76151E-03    6.73132E-03    1.01702E-04
            10.0   3.66254E-01    3.54607E-01    1.62792E-04    6.91371E-03    6.93060E-03    1.01702E-04
            12.0   3.90179E-01    3.81011E-01    1.62792E-04    7.01532E-03    7.05529E-03    1.01702E-04
            14.0   4.13551E-01    4.02281E-01    1.62792E-04    7.20466E-03    7.19449E-03    1.01702E-04
            16.0   4.31364E-01    4.20669E-01    1.62792E-04    7.26531E-03    7.26462E-03    1.01702E-04
            18.0   4.54726E-01    4.45028E-01    1.62792E-04    7.47444E-03    7.49196E-03    1.01702E-04
            20.0   4.71040E-01    4.61809E-01    1.62792E-04    7.57127E-03    7.55496E-03    1.01702E-04
            22.0   4.86107E-01    4.75904E-01    1.62792E-04    7.57601E-03    7.56317E-03    1.01702E-04
            24.0   4.98013E-01    4.89356E-01    1.62792E-04    7.61640E-03    7.60743E-03    1.01702E-04
            26.0   5.11597E-01    5.00846E-01    1.62792E-04    7.54127E-03    7.57626E-03    1.01702E-04
            28.0   5.27096E-01    5.15792E-01    1.62792E-04    7.58868E-03    7.61860E-03    1.01702E-04
            30.0   5.39329E-01    5.28097E-01    1.62792E-04    7.57422E-03    7.60781E-03    1.01702E-04
            32.0   5.50517E-01    5.39792E-01    1.62792E-04    7.51951E-03    7.56912E-03    1.01702E-04
            34.0   5.62437E-01    5.50807E-01    1.62792E-04    7.45018E-03    7.52584E-03    1.01702E-04
            36.0   5.70731E-01    5.58323E-01    1.62792E-04    7.42423E-03    7.47915E-03    1.01702E-04
            38.0   5.81207E-01    5.68409E-01    1.62792E-04     .36099E-03    7.43270E-03    1.01702E-04
            40.0   5.97364E-01    5.78041E-01    1.62792E-04     .32412E-03    7.37635E-03    1.01702E-04
```

Figure 10-9d. Failure probabilities for Sample Problem 9.

```
---  PROBLEM 9 : Fatigue + SCC initiated                                              ---


                   TOTAL NUMBER OF REPLICATIONS =  5000
NUMBER OF POSSSIBLE INITIATION SITES(USER SPEC.) =     5
NO. OF TIMES    INITIATED CRACKS CAUSED BIG LEAK =   172
NO. OF TIMES PRE-EXISTING CRACKS CAUSED BIG LEAK =  4303

       TIME   TOTAL INITIATED    FIRST INITIATED
      (YRS)       CRACKS              CRACKS

          1            47                 47
          2           398                379
          3           809                678
          4          1012                719
          5          1121                662
          6          1184                562
          7          1193                444
          8          1090                317
          9          1060                269
         10          1049                200
         11           917                145
         12  [illegible]74               119
         13  [illegible]1                 76
         14                               68
         15           679                 72
         16           600                 42
         17           614                 32
         18           564                 24
         19           548                 23
         20           508                 17
         21           447                  8
         22           450                 18
         23           431                  9
         24           369                  3
         25           380                  5
         26           337                  8
         27           317                  5
         28           277                  4
         29           254                  3
         30           264                  2
         31           228                  7
         32           229                  3
         33           228                  2
         34           193                  0
         35           182                  6
         36           191                  2
         37           172                  1
         38           163                  3
         39           149                  1
         40           129                  4

         81             0                  0


       PC-PRAISE VERSION 2.40
       Execution Start  -    12/07/91 at   3:23a
       Execution End    -    12/07/91 at   4:27a
```

Figure 10-9e. Statistics of time to initiation for Sample Problem 9.

10.10 Sample Problem 10: Fatigue and SCC With Mid-Life Changes

This sample problem illustrates the use of pc-PRAISE when both pre-existing and initiated cracks are important. The operating conditions are changed twice during the plant lifetime. This sample problem is set up to calculate probability of leak. Seismic events are not modeled. The only load cycle used is the heat-up/cool-down cycle. The weld location is subjected to pre-service and in-service inspections and a proof-test. Failure criteria used is the net-section stress exceeding the flow stress. The major inputs related to the geometry of the pipe, the pipe material, the welding process used, and the operating history are described below.

Pipe Geometry:
Inside Radius = 5.0 in
Wall Thickness = 0.8 in (for 0 - 5 years)
Wall Thickness = 1.0 in (for 5 - 40 years)

Stresses:
Deadweight = 2.08 ksi (for 0 - 5 years)
Deadweight = 0.5 ksi (for 5 - 40 years)
Deadweight + Thermal Expansion = 8.58 ksi (for 0 - 5 years)
Deadweight + Thermal Expansion = 2.91 ksi (for 5 - 40 years)
Operating Pressure = 2400 psi

Water Chemistry and Conditions that Affect SCC:
Oxygen at Plant Start-Up = 8 ppm (for 0 - 5 years)
Oxygen at Plant Start-Up = 0.2 ppm (for 5 - 40 years)
Oxygen at Steady-State Operation = 0.2 ppm (unchanged)
Water Temperature at Steady-State = 550°F
Duration of Plant Heat-Up = 5 hrs
Coolant Conductivity = 0.2 μs/cm (unchanged)

Fatigue Crack Growth Properties:
C (median) = 9.14×10^{-12}
C (90th percentile) = 3.5×10^{-11}
Fatigue Exponent = 4.0
Fatigue Threshold = 4.6 ksi-in$^{1/2}$

Flow Stress:
Mean = 43.2 ksi
Standard Deviation = 4.2 ksi

Initial Crack Size Distribution:
Depth Distribution -- Exponential
Parameter = 4.07
Aspect Ratio Distribution -- Lognormal
Median = 1.34
Shape Parameter = 0.538

SCC Properties:
AISI 304 Stainless Steel

The a/h - a/b sample space is divided into 100 cells and 100 samples are taken from each cell. The SCC-initiated cracks are always included in the analysis (BNDRY = 1.1). Plant lifetime of 40 years is simulated and results are printed at two year intervals. The heat-up/cool-down cycles are assumed to occur regularly five times a year. The first remedial action is taken at 5 years, at which time the thickness at the weld is increased and oxygen concentration and applied stresses are lowered. Default residual stresses for small lines are assumed to exist during the first 10 years of operation. At the age of 10 years, IHSI treatment is applied which results in the new distribution of residual stresses.

The input file for Sample Problem 10 is shown in Figure 10-10a. Each variable in the input file is described in Table 10-10. The output file is shown in Figures 10-10b through 10-10e. Description of the inputs is summarized in Figure 10-10b. The stratification scheme used is shown in Figure 10-10c. Coordinates of each cell are shown along with the number of samples and the conditional probability of crack from that cell. The last three columns of that table show the number of cracks that resulted in leak, big-leak, and LOCA, respectively. The probabilities of leak as a function of time are shown in Figure 10-10d. Leak and big-leak probabilities are the same at any given time because the same threshold leak rate is used for identifying big and small leaks. The LOCA probability calculations for this case may not be accurate because the stratification used is not optimized for the estimation of LOCA probabilities. Figure 10-10e provides statistics on initiated cracks as a function of time.

Table 10-10
VARIABLE INPUT FILE FOR
SAMPLE PROBLEM 10: FATIGUE AND SCC WITH MID-LIFE CHANGES

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line # 1 Title				
TITLE( )		Analysis title		
Line #2 Control Variables (Card 0B)				
INCIAT	2	Pre-existing and initiated cracks included	1 - 5	I5
IFAILC	0	Net-section stress & tearing modulus criteria	6 - 10	I5
ICRAKS	8	Number of stress corrosion initiation sites	11 - 15	I5
IREPLS	0	Not used	16 - 20	I5
IREPAR	0	Leakers will not be repaired	26 - 30	I5
BNDRY	1.1	Initiated cracks will always be included	31 - 40	F10.3
ISF	0	Fatigue crack growth data input by the user	41 - 50	I10
MTTYPE	1	Use 304 properties for SCC	51 - 55	I5
ISEED	688	Random number seed 1	56 - 62	I7
ISEEDR	7225	Random number seed 2	63 - 70	I8
IREMED	2	Number of remedial actions during the plant life	71 - 75	I5
Line #3 Control Variables (Card 1B)				
NTRIES	-50	Number of replications from each cell = abs (NTRIES)	1 - 5	I5
ISQARE	1	Rectangular grid to be set up	6 - 10	I5
KTYPES	1	Number of transients experienced by the plant	11 - 15	I5
KRKDIS	3	Crack depth exponential, aspect ratio lognormal	16 - 20	I5
NEVAL	-2	Interval for printing results (years)	21 - 25	I5
NINSPT	3	Number of in-service inspections	26 - 30	I5
NQUAKE	0	Earthquakes to be modeled	31 - 35	I5
IDEBUG	0	Normal output to be printed	36 - 40	I5
KONPRP	0	C lognormally distributed	41 - 45	I5
NEQINT	0	Number of seismic intensity classes to modeled	46 - 50	I5
MCELLS	0	Not used	51 - 55	I5
KNSFLO	0	Flow stress normally distributed	56 - 60	I5
NSKIP	0	No indicator function printout	61 - 65	I5
NPSI	1	A pre-service inspection is modeled	66 - 70	I5
ISCC	-1	Crack growth by fatigue and SCC	71 - 75	I5
ISIGRS	4	Residual stresses for small lines used	75 - 80	I5

Table 10-10 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #4 Time and NDE Parameters (Card 1D)				
THRIZN	20	Maximum plant life time simulated (years)	1 - 10	E10.3
DTSCC	0.2	Maximum time step for SCC growth (years)	11 - 20	E10.3
ICTYPE	0	Crack orientation is circumferential	21 - 25	I5
IPTYPE	0	Default NDE parameters for thick austenitic pipe used	26 - 30	I5
EPST		Not used	31 - 40	E10.0
ASTAR		Not used	41 - 50	E10.0
TRANSD		Not used	51 - 60	E10.0
ANUU		Not used	61 - 70	E10.0
Line #5 Pipe Dimensions (Card 2A)				
THICK	0.8	Wall thickness of the pipe (inches)	1 - 10	E10.3
RIN	5	Inside radius (inches)	11 - 20	E10.3
ELOVRR		Not used	21 - 30	E10.3
Line #6 Fatigue Crack Growth Characteristics (Card 2B)				
THRHLD	4.6	Threshold for fatigue crack growth (ksi-in$^{1/2}$)	1 - 10	E10.3
EMEXP	4	Exponent for fatigue crack growth equation	11 - 20	E10.3
CONSMU	9.14×10^{-12}	50th percentile of C	21 - 30	E10.3
CONS90	3.50×10^{-11}	90th percentile of C	31 - 40	E10.3
Line #7 SCC Variables (Card 2B-1)				
OSTART	8	Oxygen at plant start-up (ppm)	1 - 10	F10.5
OSTEDY	0.2	Oxygen at steady-state operation (ppm)	11 - 20	F10.5
TFSTDY	550	Steady-state temperature (°F)	21 - 30	F10.5
DURATN	5	Duration of plant heat-up (hrs)	31 - 40	F10.5
CONDUC	0.2	Coolant conductivity (μs/cm)	41 - 50	F10.5
Line #8 Flow Stress (Card 2C)				
SFLOMU	43.2	Mean value of flow stress (ksi)	1 - 10	E10.4
SFLOSD	4.2	Standard deviation of flow stress (ksi)	11 - 20	E10.4
XJIC		Not used	21 - 30	E10.4
DJDAMT		Not used	31 - 40	E10.4
SIG0		Not used	41 - 50	E10.4
DEE		Not used	51 - 60	E10.4

Table 10-10 (Continued)

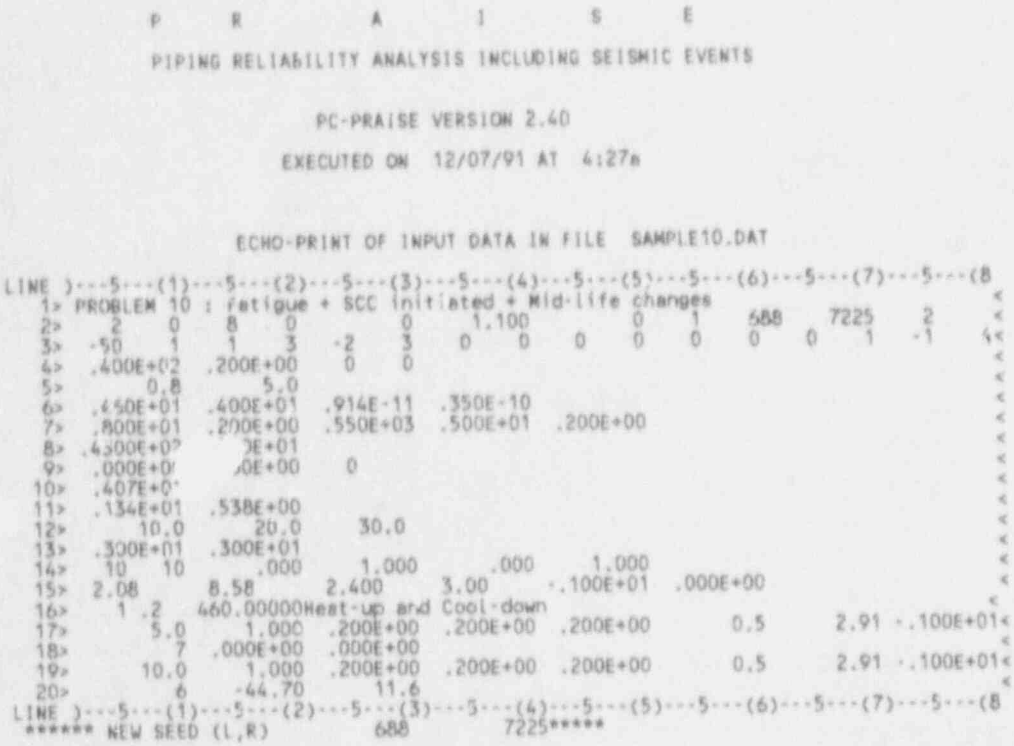
VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #8 Flow Stress (Card 2C) [Continued]				
YOUNGS		Not used	61 - 70	E10.4
XN		Not used	71 - 80	E10.4
Line #9 Ultimate Stress Definition (Card 2D)				
SULTMU	0	Not used	1 - 10	E10.0
SULTSD	0	Not used	11 - 20	E10.0
IULT	0	Not used	21 - 25	I5
Line #10 Initial Crack Depth Distribution (Card 3A)				
AMEDIAN	4.07	Rate parameter for exponential distribution of depth (1/in)	1 - 10	E10.3
ASIGMA		Not used	11 - 20	E10.3
ALAMDA		Not used	21 - 30	E10.3
Line #11 Initial Aspect Ratio Distribution (Card 3B)				
BOAMED	1.34	Median of truncated lognormal distribution of b/a	1 - 10	E10.3
BOASIG	0.538	Shape factor of truncated lognormal distribution of b/a	11 - 20	E10.3
BOALDA		Not used	1 - 10	E10.3
Line #12 In-Service Inspection Times (Card 4B)				
TINSPT	10, 20, ..	In-service inspection times (years)	1 - 80	8E10.3
Line #13 Leak Rate and Detection Parameters (Card 4C)				
FNDLEK	3	Threshold for detectable leak rate (gpm)	1 - 10	E10.3
ALKBIG	3	Threshold for defining big leaks (gpm)	11 - 20	E10.3
Line #14 Stratified Sample Space (Card 5A)				
NAOH	10	Number of divisions in a/h direction	1 - 5	I5
NAOB	10	Number of divisions in a/b direction	6 - 10	I5
AOHLOW	0	Lower limit of a/h	11 - 20	E10.3
AOHUP	1	Upper limit of a/h	21 - 30	E10.3
AOBLFT	0	Lower limit of a/b	31 - 40	E10.3
AOBRGT	1	Upper limit of a/b	41 - 50	E10.3
Line #15 Operating Stresses (Card 6A)				
SGCLD	2.08	Deadweight stress (ksi)	1 - 10	E10.4
SGDWTE	8.58	Deadweight and thermal expansion stress (ksi)	11 - 20	E10.4
OPPRES	2.4	Normal operating pressure (ksi)	21 - 30	E10.4

Table 10-10 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #15 Operating Stresses (Card 6A) [Continued]				
PRFPRS	3	Pressure in hydrostatic proof test (ksi)	31 - 40	E10.4
SIGVIB	-1	Vibratory stresses not modeled	41 - 50	E10.4
VBTHLD	0	Not used	51 - 60	E10.4
Line #16 Frequency of Heat-up/Cool-down Transient 1 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.2	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	460	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10
Line #17 Mid-Life Changes (Card 8A)				
RTIMES(1)	5	Time at which mid-life changes made (years)	1 - 10	E10.4
THICKS(1)	1	Wall thickness of pipe (in)	11 - 20	E10.4
OSTARS(1)	0.2	Oxygen at start-up (ppm)	21 - 30	E10.4
OSTDYS(1)	0.2	Oxygen at steady-state (ppm)	31 - 40	E10.4
CONDUS(1)	0.2	Coolant conductivity (µs/cm)	41 - 50	E10.4
SGCLDS(1)	0.5	Deadweight stress (ksi)	51 - 60	E10.4
SDWTES(1)	2.91	Deadweight and thermal expansion stress (ksi)	61 - 70	E10.4
SGVIBS(1)	-1	Vibratory stresses not modeled	71 - 80	E10.4
Line #18 Mid-Life Changes (Card 8B)				
ISIGRX(1)	7	No change in the residual stresses	1 - 10	I10
RSINMS(1)		Not used	11 - 20	E10.4
RSISDS(1)		Not used	21 - 30	E10.4
Line #19 Mid-Life Changes (Card 8A)				
RTIMES(2)	10	Time at which mid-life changes made (years)	1 - 10	E10.4
THICKS(2)	1	Wall thickness of pipe (in)	11 - 20	E10.4
OSTARS(2)	0.2	Oxygen at start-up (ppm)	21 - 30	E10.4
OSTDYS(2)	0.2	Oxygen at steady-state (ppm)	31 - 40	E10.4
CONDUS(2)	0.2	Coolant conductivity (µs/cm)	41 - 50	E10.4
SGCLDS(2)	0.5	Deadweight stress (ksi)	51 - 60	E10.4
SDWTES(2)	2.91	Deadweight and thermal expansion stress (ksi)	61 - 70	E10.4
SGVIBS(2)	-1	Vibratory stresses not modeled	71 - 80	E10.4

Table 10-10 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #20 Mid-Life Changes (Card 8B)				
ISIGRX(2)	6	IHSI treatment performed at this time	1 - 10	I10
RSINMS(2)	-44.7	Mean of value of post-IHSI residual stress at ID (ksi)	11 - 20	E10.4
RSISDS(2)	11.6	Standard deviation of value of post-IHSI residual stress at ID (ksi)	21 - 30	E10.4



```
                 P     R         A       I       S       E

                 PIPING RELIABILITY ANALYSIS INCLUDING SEISMIC EVENTS

                              PC-PRAISE VERSION 2.40

                          EXECUTED ON  12/07/91 AT  4:27a


                         ECHO-PRINT OF INPUT DATA IN FILE  SAMPLE10.DAT

LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
   1> PROBLEM 10 : fatigue + SCC initiated + Mid-life changes                        <
   2>    2   0   8   0          0     1.100          0    1    688    7225     2     <
   3>  -50   1   1   3  -2   3   0    0    0    0    0    0    0    1   -1         4<
   4>  .400E+02  .200E+00    0    0                                                   <
   5>       0.8       5.0                                                             <
   6>  .450E+01  .400E+01  .914E-11  .350E-10                                         <
   7>  .800E+01  .200E+00  .550E+03  .500E+01  .200E+00                               <
   8> .4300E+02       0E+01                                                           <
   9>  .000E+0       0E+00    0                                                       <
  10>  .407E+0                                                                        <
  11>  .134E+01  .538E+00                                                             <
  12>      10.0      20.0      30.0                                                   <
  13>  .300E+01  .300E+01                                                             <
  14>   10   10      .000     1.000      .000     1.000                               <
  15>  2.08      8.58      2.400     3.00     -.100E+01  .000E+00                     <
  16>    1  .2   460.00000Heat-up and Cool-down                                       <
  17>       5.0     1.000  .200E+00  .200E+00  .200E+00       0.5      2.91 -.100E+01<
  18>         7  .000E+00  .000E+00                                                   <
  19>      10.0     1.000  .200E+00  .200E+00  .200E+00       0.5      2.91 -.100E+01<
  20>         6    -44.70      11.6                                                   <
LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
 ****** NEW SEED (L,R)          688         7225*****
```

Figure 10-10a. Echo of input file for Sample Problem 10.

```
***  PROBLEM 10 : Fatigue + SCC initiated + Mid-life changes                                ***

CIRCUMFERENTIAL CRACK ANALYSIS

PARAMETERS THAT DETERMINE NON-DETECTION PROBABILITY
    EPST  =      .000E+00
    ASTAR =      .400
    TRANSDUCER DIAMETER =  1.00000 INCHES
    ANUU  =    1.600

PRE-EXISTING CRACKS + INITIATED CRACKS WILL BE
INCLUDED WHENEVER (SAMPLED A/H)<BNDRY

MAXIMUM NO. OF CRACKS =     8
NO. OF REPLICATIONS   =     0
A/H BOUNDARY          =     1.1000

SCC AND FATIGUE CRACK GROWTH

                   MATERIAL SELECTED (FOR SCC) - S304

LEAKERS WILL NOT BE REPAIRED

FAILURE CRITERIA = APPLIED STRESS>FLOW STRESS

TIMESTEP FOR SCC =    .200 YEARS

PIPE DIMENSIONS
    WALL THICKNESS =    .80 INCHES
    INSIDE RADIUS  =   5.00 INCHES
      L/H RATIO    =       .00
      L/R RATIO    =       .00
    AREA OF PIPE          =    27.14 SQ. INCHES
    FLOW AREA OF PIPE     =    78.54 SQ. INCHES

INITIAL CRACK SIZE DISTRIBUTION
CRACK DEPTH IS EXPONENTIAL
    PARAMETER =    4.0700
ASPECT RATIO IS LOG-NORMAL
    MEDIAN                  =    1.3400
    SHAPE PARAMETER         =     .5380
    NORMALIZATION CONSTANT  =    1. 149

CRACK GROWTH LAW PARAMETERS
    EXPONENT  =   4.000
    GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
         MEDIAN         =   .9140E-11
         90-TH PERCENT  =   .3500E-10
    THRESHOLD =   4.600

SCC PARAMETERS
                   O2 AT STARTUP(PPM) =     8.00
              O2 AT STEADY STATE(PPM) =      .20
      TEMP. AT STEADY STATE(DEG F) =  550.00
      HEATUP (100-550F) TIME (HRS) =     5.00
      COOLANT CONDUCTIVITY (US/CM) =      .20


FLOW STRESS NORMALLY DISTRIBUTED
    MEAN                 =   .4300E+02
    STANDARD DEVIATION   =   .4200E+01
```

Figure 10-10b. Input summary for Sample Problem 10.

```
DISTRIBUTION PARAMETERS FOR ULTIMATE STRESS IN PIPE
     MEAN                  =    .0000E+00
     STANDARD DEVIATION =    .0000E+00
     STANDARD DEVIATION =  0.0 MEANS THE ULTIMATE STRESS IS CONSTANT
     INTERPOLATION FLAG =    0  ( IULT ) FOR WHOLE PIPE BREAK PROBABILITY
     ABS ( IULT ) IS THE NUMBER OF INTERPOLATION POINTS
     IF  IULT .GT. 0  LINEAR INTERPOLATION
     IF  IULT .EQ. 0  NO INTERPOLATION
     IF  IULT .LT. 0  LOGARITHMIC INTERPOLATION

PIPE LOADING VALUES
     STRESS (KSI) DUE TO COLD DEADWEIGHT  =      2.08
     STRESS (KSI)  DUE TO DWGHT + THERMAL =      8.58
     STRESS (KSI)  DUE TO          THERMAL =      6.50
     OPERATING PRESSURE (KSI)             =      2.40
     STRESS (KSI) DUE TO OPER. PRESSURE   =      6.94
     STRESS (KSI) DUE TO DWGHT + OP PRESR =      9.02
     STRESS (KSI) DUE TO DWT+THML+OP PRES =     15.52
     PROOF PRESSURE (KSI)                 =      3.00
     STRESS (KSI) DUE TO DWGHT + PRF PRES =     10.76

     HYDROSTATIC PROOF TEST IS MODELLED

LEAK DETECTION AND DEFINITION PARAMETERS
     DETECTABLE LEAK (GPM) =    3.00
     BIG LEAK        (GPM) =    3.00

RESIDUAL STRESSES FOR SMALL LINE SELECTED

NO VIBRATORY STRESSES ARE MODELLED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELLED

TIME INTERVALS
     PLANT LIFETIME =  40.0 YEARS
     ENDPOINTS OF INTERVALS AT     .0   2.0   4.0   6.0   8.0 YEARS
     ENDPOINTS OF INTERVALS AT   10.0  12.0  14.0  16.0  18.0 YEARS
     ENDPOINTS OF INTERVALS AT   20.0  22.0  24.0  26.0  28.0 YEARS
     ENDPOINTS OF INTERVALS AT   30.0  32.0  34.0  36.0  38.0 YEARS
     ENDPOINTS OF INTERVALS AT   40.0
     IN-SERVICE INSPECTIONS AT   10.0  20.0  30.0

NO SEISMIC EVENTS EVALUATED

Number of remedial actions =  2
Details of the remedial actions are as follows :

Action Time  Thick-  Oxygen        Cond.  Dead Wt DW+TE Vib.   Res.      Mean     Std.
       (yrs) -ness  Start S.State         Stress  Str.  Stress Stress             Dev.

    1   5.00   1.00    .20    .20    .20    .50   2.91  -1.00No change
    2  10.00   1.00    .20    .20    .20    .50   2.91  -1.00 IHSI/MSIP-44.70 11.60

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS   0

NORMAL OUTPUT REQUESTED


NUMBER OF TRANSIENT TYPES =  1

TYPE  1    Heat-up and Cool-down
     REGULAR AT        .200 YEARS/EVENT
     MAX DELTA TEMP = 460.0  BLOCKING FACTOR =  1.0
```

Figure 10-10b. (Continued).

```
                    - - - SUMMARY OF CELLS IN SAMPLE SPACE - - -

                               - - - UNIFORM MESH - - -

CELL        AOH1        AOH2        AOB1        AOB2          PROBABILITY          SAMPLES     LEAKS     B-LEAKS     LOCAS
   1       .9000      1.0000       .0000       .1000        .2042073[illegible] 05          50        48         48          0
   2       .9000      1.0000       .1000       .2000        .1549516E-03          50        50         50          0
   3       .9000      1.0000       .2000       .3000        .8284591E-03          50        50         50          0
   4       .9000      1.0000       .3000       .4000        .1703807E-02          50        50         50          0
   5       .9000      1.0000       .4000       .5000        .2294732E-02          50        50         50          0
   6       .9000      1.0000       .5000       .6000        .2493593E-02          50        50         50          0
   7       .9000      1.0000       .6000       .7000        .2403185E-02          50        50         50          1
   8       .9000      1.0000       .7000       .8000        .2155860E-02          50        49         48         13
[illegible]       .9000      1.0000       .8000       .9000        .1849478E-02          50        50         49         32
  10       .9000      1.0000       .9000      1.0000        .1541949E-02          50        49         49         31
  11       .[illegible]000       .9000       .0000       .1000        .2827988E-05          50        50         50          1
  12       .80[illegible]       .9000       .1000       .2000        .2145865E-03          50        50         50          0
  13       .8000       [illegible]000       .2000       .3000        .1147301E-02          50        50         50          0
  14       .8000       .9000       .3000       .4000        .2359536E-02          50        50         50          0
  15       .800[illegible]       .9000       .4000       .5000        .3177886E-02          50        50         50          0
  16       .8000       .9000       .5000       .6000        .345[illegible]E-02          50        49         49          0
  17       .8000       .9000       .6000       .7000        .3328[illegible]E-02          50        48         48          0
  18       .80[illegible]       .9000       .7000       .8000        .2985[illegible]E-02          50        46         46          5
  19       .80[illegible]       .9000       .80[illegible]       .9000        .2561270E-02          50        45         45         24
  20       .8[illegible]       .9000       .9000      1.0000        .2135385E-02          50        46         43         24
  21       [illegible]       .8000       .0000       .1000        .3916371E-05          50        50         50          0
  22       [illegible]       .8000       .1000       .2000        .2971725E-03          50        50         50          0
  23       .[illegible]00       .8000       .2000       .3000        .1588853E-02          50        49         49          0
  24       .7000       .8000       .3000       .4000        .3267630E-02          50        47         47          0
  25       .7000       .8000       .4000       .5000        .4400931E-02          50        48         48          0
  26       .7000       .8000       .5000       .6000        .4782315E-02          50        45         45          0
  27       .7000       .8000       .6000       .7000        .4608927E-02          50        46         46          0
  28       .7000       .8000       .7000       .8000        .4134596E-02          50        44         44          5
  29       .7000       .8000       .8000       .9000        .3547004E-02          50        45         44         16
  30       .7000       .8000       .9000      1.0000        .2957213E-02          50        47         44         19
  31       .6000       .7000       .0000       .1000        .5423631E-05          50        50         50          0
  32       .6000       .7000       .1000       .2000        .4115427E-03          50        49         49          0
  33       .6000       .7000       .2000       .3000        .2200341E-02          50        49         49          0
  34       .6000       .7000       .3000        4000        .4525214E-02          50        46         46          0
  35       .6000       .7000       .4000       .5000        .6094679E-02          50        43         43          0
  36       .6000       .7000       .5000       .6000        .6622843E-02          50        45         43          0
  37       .6000       .7000       .6000       .7000        .6382725E-02          50        43         43          0
  38       .6000       .7000       .7000       .8000        .5725843E-02          50        42         42          4
  39       .6000       .7000       .8000       .9000        .4912109E-02          50        40         40          9
  40       .6000       .7000       .9000      1.0000        .4095329E-02          50        42         37         16
  41       .5000       .6000       .0000       .1000        .7510976E-05          50        47         47          0
  42       .5000       .6000       .1000       .2000        .5699295E-03          50        49         49          0
  43       .5000       .6000       .2000       .3000        .3047167E-02          50        46         46          0
  44       .5000       .6000       .3000       .4000        .6266794E-02          50        44         44          0
  45       .5000       .6000       .4000       .5000        .8440285E-02          50        44         43          0
  46       .5000       .6000       .5000       .6000        .9171719E-02          50        39         39          0
  47       .5000       .6000       .6000       .7000        .8839189E-02          50        41         41          0
  48       .5000       .6000       .7000       .8000        .7929498E-02          50        38         36          3
  49       .5000       .6000       .8000       .9000        .6802589E-02          50        37         32         13
  50       .5000       .6000       .9000      1.0000        .5671463E-02          50        40         37         15
  51       .4000       .5000       .0000       .1000        .1040166E-04          50        47         47          0
  52       .4000       .5000       .1000       .2000        .7892734E-03          50        46         46          0
  53       .4000       .5000       .2000       .3000        .4219903E-02          50        42         42          0
  54       .4000       .5000       .3000       .4000        .8678640E-02          50        43         43          0
  55       .4000       .5000       .4000       .5000        .1168862E-01          50        38         38          0
  56       .4000       .5000       .5000       .6000        .1270156E-01          50        36         36          0
  57       .4000       .5000       .6000       .7000        .1224105E-01          50        39         38          1
  58       .4000       .5000       .7000       .8000        .1098125E-01          50        44         41          8
  59       .4000       .5000       .8000       .9000        .9420642E-02          50        37         36         12
```

Figure 10-10c. Stratification description for Sample Problem 10.

```
 60    .4000    .5000    .9000   1.0000      .7854190E-02      50       36       34       15
 61    .3000    .4000    .0000    .1000      .1440486E-04      50       39       39        0
 62    .3000    .4000    .1000    .2000      .1093034E-02      50       41       41        0
 63    .3000    .4000    .2000    .3000      .5843981E-02      50       39       39        0
 64    .3000    .4000    .3000    .4000      .1201871E-01      50       36       36        0
 65    .3000    .4000    .4000    .5000      .1618712E-01      50       40       38        0
 66    .3000    .4000    .5000    .6000      .1758990E-01      50       36       35        0
 67    .3000    .4000    .6000    .7000      .1695216E-01      50       28       28        2
 68    .3000    .4000    .7000    .8000      .1520752E-01      50       30       30        3
 69    .3000    .4000    .8000    .9000      .1304628E-01      50       33       33        6
 70    .3000    .4000    .9000   1.0000      .1087696E-01      50       35       35       14
 71    .2000    .3000    .0000    .1000      .1994873E-04      50       37       37        0
 72    .2000    .3000    .1000    .2000      .1513701E-02      50       36       36        0
 73    .2000    .3000    .2000    .3000      .8093103E-02      50       36       35        0
 74    .2000    .3000    .3000    .4000      .1664425E-01      50       31       31        0
 75    .2000    .3000    .4000    .5000      .2241692E-01      50       34       32        1
 76    .2000    .3000    .5000    .6000      .2435957E-01      50       31       29        2
 77    .2000    .3000    .6000    .7000      .2347639E-01      50       31       28        6
 78    .2000    .3000    .7000    .8000      .2106030E-01      50       27       25        9
 79    .2000    .3000    .8000    .9000      .1806729E-01      50       20       19        6
 80    .2000    .3000    .9000   1.0000      .1506309E-01      50       28       28        7
 81    .1000    .2000    .0000    .1000      .2762622E-04      50       32       32        0
 82    .1000    .2000    .1000    .2000      .2096266E-02      50       30       30        0
 83    .1000    .2000    .2000    .3000      .1120782E-01      50       26       26        1
 84    .1000    .2000    .3000    .4000      .2304998E-01      50       39       37        7
 85    .1000    .2000    .4000    .5000      .3104433E-01      50       25       25        3
 86    .1000    .2000    .5000    .6000      .3373462E-01      50       30       29        9
 87    .1000    .2000    .6000    .7000      .3251154E-01      50       20       20        6
 88    .1000    .2000    .7000    .8000      .2916559E-01      50       28       28        5
 89    .1000    .2000    .8000    .9000      .2502070E-01      50       22       21        5
 90    .1000    .2000    .9000   1.0000      .2086028E-01      50       17       17        4
 91    .0000    .1000    .0000    .1000      .3825849E-04      50        9        9        0
 92    .0000    .1000    .1000    .2000      .2903037E-02      50       18       18        0
 93    .0000    .1000    .2000    .3000      .1552128E-01      50        6        6        0
 94    .0000    .1000    .3000    .4000      .3192102E-01      50        6        6        1
 95    .0000    .1000    .4000    .5000      .4299209E-01      50        7        7        3
 96    .0000    .1000    .5000    .6000      .4671778E-01      50        5        5        1
 97    .0000    .1000    .6000    .7000      .4502398E-01      50        7        7        1
 98    .0000    .1000    .7000    .8000      .4039030E-01      50        4        4        0
 99    .0000    .1000    .8000    .9000      .3465019E-01      50        3        3        1
100    .0000    .1000    .9000   1.0000      .2888860E-01      50        2        2        1
                                           ...............
                 SUM OF CELL PROBABILITIES =  .1000000E+01
```

Figure 10-10c. (Continued).

```
---  PROBLEM 10 : Fatigue + SCC initiatad + Mid-life changes                                    ---

                                                   - - - RESULTS WITHOUT EARTHQUAKES - - -

              SEISMIC CLASS INFORMATION
                       CLASS      SIGEQ        SGLCEQ     CYCLES   COV F-BM
                         0      .0000E+00        .000        0        .0000

                    PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                       SULTMU            SULTSD     IULT
                    .00000E+00       .00000E+00     0
                       STRESS(1)
                    .59545E+01
                       PBREAK(1)
                    .10000E+01

          TIME       AVG LEAK       AVG BIG LEAK       AVG LOCA        SIGMA LEAK    SIGMA BIG LEAK    SIGMA LOCA
            .0     3.04209E-04      2.26304E-04      6.22889E-09      2.56539E-05      2.23180E-05     6.22889E-09
           2.0     1.31118E-01      1.30548E-01      3.21917E-02      5.71002E-03      5.89973E-03     3.67105E-03
           4.0     2.10225E-01      2.08655E-01      4.53303E-02      7.18719E-03      7.15460E-03     4.34110E-03
           6.0     2.40694E-01      2.39351E-01      4.94009E-02      7.56654E-03      7.55599E-03     4.57706E-03
           8.0     2.46008E-01      2.45286E-01      5.03314E-02      7.66384E-03      7.66338E-03     4.61470E-03
          10.0     2.59402E-01      2.58089E-01      5.27064E-02      7.82202E-03      7.82060E-03     4.70947E-03
          12.0     2.66449E-01      2.62179E-01      5.27064E-02      7.86069E-03      7.84140E-03     4.70947E-03
          14.0     2.72945E-01      2.66124E-01      5.27064E-02      7.94121E-03      7.85446E-03     4.70947E-03
          16.0     2.79075E-01      2.72295E-01      5.27064E-02      8.00482E-03      7.93819E-03     4.70947E-03
          18.0     2.86309E-01      2.77752E-01      5.27064E-02      8.03271E-03      7.99435E-03     4.70947E-03
          20.0     2.92672E-01      2.83754E-01      5.27064E-02      8.11127E-03      8.03367E-03     4.70947E-03
          22.0     2.99573E-01      2.88218E-01      5.27064E-02      8.16432E-03      8.06445E-03     4.70947E-03
          24.0     3.04762E-01      2.93080E-01      5.27064E-02      8.17163E-03      8.07888E-03     4.70947E-03
          26.0     3.07950E-01      2.97692E-01      5.27064E-02      8.20004E-03      8.17055E-03     4.70947E-03
          28.0     3.11380E-01      3.01150E-01      5.27064E-02      8.19578E-03      8.17847E-03     4.70947E-03
          30.0     3.14661E-01      3.05265E-01      5.27064E-02      8.18639E-03      8.17485E-03     4.70947E-03
          32.0     3.17849E-01      3.08727E-01      5.27064E-02      8.18139E-03      8.17246E-03     4.70947E-03
          34.0     3.19464E-01      3.12345E-01      5.27064E-02      8.18413E-03      8.20140E-03     4.70947E-03
          36.0     3.21940E-01      3.16269E-01      5.27064E-02      8.17427E-03      8.19997E-03     4.70947E-03
          38.0     3.25078E-01      3.18381E-01      5.27064E-02      8.17258E-03      8.19724E-03     4.70947E-03
          40.0     3.25970E-01      3.19369E-01      5.27064E-02      8.16835E-03      8.19531E-03     4.70947E-03
```

Figure 10-10d. Failure probabilities for Sample Problem 10.

```
---  PROBLEM 10 : Fatigue + SCC initiated + Mid-life changes                                  ---


                           TOTAL NUMBER OF REPLICATIONS =  4998
NUMBER OF POSSSIBLE INITIATION SITES(USER SPEC.) =     8
NO. OF TIMES    INITIATED CRACKS CAUSED BIG LEAK =     1
NO. OF TIMES PRE-EXISTING CRACKS CAUSED BIG LEAK =  3313

      TIME   TOTAL INITIATED    FIRST INITIATED
     (YRS)      CRACKS              CRACKS

         1          69                68
         2         431               404
         3         912               748
         4        1227               809
         5        1458               727
         6        1139               477
         7        1001               332
         8        1010               276
         9        1072               240
        10        1001               188
        11         179                31
        12           0                 0
        13           1                 0
        14           2                 0
        15           2                 0
        16           1                 0
        17           0                 0
        18           0                 0
        19           0                 0
        20           1                 0
        21           1                 0
        22           0                 0
        23           0                 0
        24           0                 0
        25           1                 0
        26           1                 1
        27           0                 0
        28           0                 0
        29           0                 0
        30           0                 0
        31           0                 0
        32           0                 0
        33           1                 0
        34           0                 0
        35           1                 0
        36           2                 1
        37           0                 0
        38           0                 0
        39           0                 0
        40           0                 0

        81           0                 0


PC-PRAISE VERSION 2.40
Execution Start -    12/07/91 at  4:27a
Execution End   -    12/07/91 at  5:11a
```

Figure 10-10e. Statistics of time to initiation for Sample Problem 10.

10.11 Sample Problem 11: A Complex Analysis

This sample problem illustrates the use of pc-PRAISE to carry out a very complex analysis. All the features of the code are activated. Both pre-existing and initiated cracks are considered. Fatigue and SCC are considered for the growth of cracks. Proof test, pre-service and in-service inspections, and seismic events are modeled. The net-section stress and the tearing modulus based criteria are applied. Two mid-life remedial actions are modeled. One transient involving radial gradient thermal stresses is included, in addition to the heat-up and cool-down transient. The sample problem is set up to calculate probability of leak. The major inputs related to the geometry of the pipe, the pipe material, the welding process used, and the operating history are described below.

Pipe Geometry:
    Inside Radius = 14.5 in
    Wall Thickness = 2.5 in

Stresses:
    Deadweight = 2.08 ksi (for 0 - 20 years)
    Deadweight = 1.08 ksi (for 20 - 40 years)
    Deadweight + Thermal Expansion = 8.58 ksi (for 0 - 20 years)
    Deadweight + Thermal Expansion = 4.58 ksi (for 20 - 40 years)
    Operating Pressure = 2400 psi

Water Chemistry and Conditions that Affect SCC:
    Oxygen at Plant Start-Up = 8 ppm (for 0 - 20 years)
    Oxygen at Plant Start-Up = 0.2 ppm (for 20 - 40 years)
    Oxygen at Steady-State Operation = 0.2 ppm (0 - 20 years)
    Oxygen at Steady-State Operation = 0.1 ppm (20 - 40 years)
    Water Temperature at Steady-State = 550°F
    Duration of Plant Heat-Up = 5 hrs
    Coolant Conductivity = 0.2 μs/cm (0 - 20 years)
    Coolant Conductivity = 0.1 μs/cm (20 - 40 years)

Fatigue Crack Growth Properties:
    C (median) = 9.14×10^{-12}
    C (90th percentile) = 3.5×10^{-11}
    Fatigue Exponent = 4.0
    Fatigue Threshold = 4.6 ksi-in$^{1/2}$

Flow Stress:
    Mean = 43.2 ksi
    Standard Deviation = 4.2 ksi

Initial Crack Size Distribution:
Depth Distribution -- Exponential
Parameter = 4.07
Aspect Ratio Distribution -- Lognormal
Median = 1.34
Shape Parameter = 0.538

SCC Properties:
AISI 304 Stainless Steel

The a/h - a/b sample space is divided into 100 cells and 100 samples are taken from each cell. The SCC-initiated cracks are always included in the analysis (BNDRY = 1.1). Plant lifetime of 40 years is simulated and results are printed at two year intervals. The heat-up/cool-down cycles are assumed to occur regularly five times a year. The first remedial action is taken at 20 years, at which time the oxygen concentration and applied stresses are lowered. Default residual stresses for intermediate lines are assumed to exist during the first 30 years of operation. At the age of 30 years, IHSI treatment is applied which results in the new distribution of residual stresses.

The input file for Sample Problem 11 is shown in Figure 10-11a. Each variable in the input file is described in Table 10-11. The output file is shown in Figures 10-11b through 10-11g. Description of the inputs is summarized in Figure 10-11b. The stratification scheme used is shown in Figure 10-11c. Coordinates of each cell are shown along with the number of samples and the conditional probability of crack from that cell. The last three columns of that table show the number of cracks that resulted in leak, big-leak, and LOCA, respectively. The probabilities of leak as a function of time are shown in Figure 10-11d for the case without the earthquakes, and in Figures 10-11e and 10-11f for the four intensities of earthquakes. Leak and big-leak probabilities are the same at any given time because the same threshold leak rate is used for identifying big and small leaks. The LOCA probability calculations for this case may not be accurate because the stratification used is not optimized for the estimation of LOCA probabilities. Figure 10-11g provides statistics on initiated cracks as a function of time.

Table 10-11
VARIABLE INPUT FILE FOR SAMPLE PROBLEM 11: A COMPLEX ANALYSIS

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #1 Title				
TITLE( )		Analysis title		
Line #2 Control Variables (Card 0B)				
INCIAT	2	Pre-existing and initiated cracks included	1 - 5	I5
IFAILC	2	Net-section stress & tearing modulus criteria	6 - 10	I5
ICRAKS	25	Number of stress corrosion initiation sites	11 - 15	I5
IREPLS	0	Not used	16 - 20	I5
IREPAR	0	Leakers will not be repaired	26 - 30	I5
BNDRY	1.1	Initiated cracks will always be included	31 - 40	F10.3
ISF	0	Fatigue crack growth data input by the user	41 - 50	I10
MTTYPE	1	Use 304 properties for SCC	51 - 55	I5
ISEED	688	Random number seed 1	56 - 62	I7
ISEEDR	7225	Random number seed 2	63 - 70	I8
IREMED	2	Number of remedial actions during the plant life	71 - 75	I5
Line #3 Control Variables (Card 1B)				
NTRIES	-50	Number of replications from each cell = abs (NTRIES)	1 - 5	I5
ISQARE	1	Rectangular grid to be set up	6 - 10	I5
KTYPES	2	Number of transients experienced by the plant	11 - 15	I5
KRKDIS	3	Crack depth exponential, aspect ratio lognormal	16 - 20	I5
NEVAL	-2	Interval for printing results (years)	21 - 25	I5
NINSPT	3	Number of inservice inspections	26 - 30	I5
NQUAKE	1	Earthquakes to be modeled	31 - 35	I5
IDEBUG	0	Normal output to be printed	36 - 40	I5
KONPRP	0	C lognormally distributed	41 - 45	I5

Table 10-11 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #3 Control Variables (Card 1B) [Continued]				
NEQINT	4	Number of seismic intensity classes to modeled	46 - 50	I5
MCELLS	0	Not used	51 - 55	I5
KNSFLO	0	Flow stress normally distributed	56 - 60	I5
NSKIP	0	No indicator function printout	61 - 65	I5
NPSI	1	A pre-service inspection is modeled	66 - 70	I5
ISCC	-1	Crack growth by fatigue and SCC	71 - 75	I5
ISIGRS	3	Residual stresses for intermediate lines used	75 - 80	I5
Line #4 Time and NDE Parameters (Card 1D)				
THRIZN	40	Maximum plant lifetime simulated (years)	1 - 10	E10.3
DTSCC	0.2	Maximum time step for SCC growth (years)	11 - 20	E10.3
ICTYPE	0	Crack orientation is circumferential	21 - 25	I5
IPTYPE	0	Default NDE parameters for thick austenitic pipe used	26 - 30	I5
EPST		Not used	31 - 40	E10.0
ASTAR		Not used	41 - 50	E10.0
TRANSD		Not used	51 - 60	E10.0
ANUU		Not used	61 - 70	E10.0
Line #5 Pipe Dimensions (Card 2A)				
THICK	2.5	Wall thickness of the pipe (inches)	1 - 10	E10.3
RIN	14.5	Inside radius (inches)	11 - 20	E10.3
ELOVRR	5	Pipe length/radius ratio	21 - 30	E10.3
Line #6 Fatigue Crack Growth Characteristics (Card 2B)				
THRHLD	4.6	Threshold for fatigue crack growth (ksi-in$^{1/2}$)	1 - 10	E10.3
EMEXP	4	Exponent for fatigue crack growth equation	11 - 20	E10.3

Table 10-11 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #6 Fatigue Crack Growth Characteristics (Card 2B) [Continued]				
CONS50	9.14×10^{-12}	50th percentile of C	21 - 30	E10.3
CONS90	3.50×10^{-11}	90th percentile of C	31 - 40	E10.3
Line #7 SCC Variables (Card 2B-1)				
OSTART	8	Oxygen at plant start-up (ppm)	1 - 10	F10.5
OSTEDY	0.2	Oxygen at steady-state operation (ppm)	11 - 20	F10.5
TFSTDY	550	Steady-state temperature (°F)	21 - 30	F10.5
DURATN	5	Duration of plant heat-up (hrs)	31 - 40	F10.5
CONDUC	0.2	Coolant conductivity (µs/cm)	41 - 50	F10.5
Line #8 Flow Stress (Card 2C)				
SFLOMU	43.2	Mean value of flow stress (ksi)	1 - 10	E10.4
SFLOSD	4.2	Standard deviation of flow stress (ksi)	11 - 20	E10.4
XJIC	10	J_{Ic} (in-kips/in^2)	21 - 30	E10.4
DJDAMT	25	dJ/da (ksi)	31 - 40	E10.4
SIG0	30.6	Yield strength (ksi)	41 - 50	E10.4
DEF	106	Constant D in the power-law hardening equation (ksi)	51 - 60	E10.4
YOUNGS	25000	Elastic modulus (ksi)	61 - 70	E10.4
XN	5	Exponent n in the power-law hardening equation	71 - 80	E10.4
Line #9 Ultimate Stress Definition (Card 2D)				
SULTMU	0	Not used	1 - 10	E10.0
SULTSD	0	Not used	11 - 20	E10.0
IULT	0	Not used	21 - 25	I5

Table 10-11 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #10 Initial Crack Depth Distribution (Card 3A)				
AMEDIAN	4.07	Rate parameter for exponential distribution of depth (1/in)	1 - 10	E10.3
ASIGMA		Not used	11 - 20	E10.3
ALAMDA		Not used	21 - 30	E10.3
Line #11 Initial Aspect Ratio Distribution (Card 3B)				
BOAMED	1.34	Median of truncated lognormal distribution of b/a	1 - 10	E10.3
BOASIG	0.538	Shape factor of truncated lognormal distribution of b/a	11 - 20	E10.3
BOALDA		Not used	1 - 10	E10.3
Line #12 In-service Inspection Times (Card 4B)				
TINSPT	10, 20, ...	In-service inspection times (years)	1 - 80	8E10.3
Line #13 Leak Rate and Detection Parameters (Card 4C)				
FNDLEK	3	Threshold for detectable leak rate (gpm)	1 - 10	E10.3
ALKBIG	3	Threshold for defining big leaks (gpm)	11 - 20	E10.3
Line #14 Stratified Sample Space (Card 5A)				
NAOH	10	Number of divisions in a/h direction	1 - 5	I5
NAOB	10	Number of divisions in a/b direction	6 - 10	I5
AOHLOW	0	Lower limit of a/h	11 - 20	E10.3
AOHUP	1	Upper limit of a/h	21 - 30	E10.3
AOBLFT	0	Lower limit of a/b	31 - 40	E10.3
AOBRGT	1	Upper limit of a/b	41 - 50	E10.3
Line #15 Operating Stresses (Card 6A)				
SGCLD	2.08	Deadweight stress (ksi)	1 - 10	E10.4
SGDWTE	8.58	Deadweight and thermal expansion stress (ksi)	11 - 20	E10.4
OPPRES	2.4	Normal operating pressure (ksi)	21 - 30	E10.4

Table 10-11 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #15 Operating Stresses (Card 6A) [Continued]				
PRFPRS	3	Pressure in hydrostatic proof test (ksi)	31 - 40	E10.4
SIGVIB	-1	Vibratory stresses not modeled	41 - 50	E10.4
VBTHLD	0	Not used	51 - 60	E10.4
Line #16 Specifications for g_{min} and g_{max} Tables (Card 6B)				
NX	6	Number of entries in a/b direction for the input table	1 - 5	I5
NY	9	Number of entries in a/h direction for the input table	6 - 10	I5
IX	10	Number of entries in a/b direction for the internal table	11 - 15	I5
IY	10	Number of entries in a/h direction for the internal table	16 - 20	I5
Line #17-18 (Card 6C)				
AAOH( )	.01, .1, ..	a/h coordinates for g_{min}, g_{max} tables	1 - 80	8F10.3
Line #19 (Card 6D)				
AAOB( )	1, 2, ..	b/a coordinates for g_{min}, g_{max} tables	1 - 80	8F10.3
Line #20 Frequency of Heat-up/Cool-down Transient 1 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.2	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	460	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10
Line #21 Frequency of Transient 2 (Card 6E)				
NCYBLK	1	Blocking factor for fatigue crack growth calculations	1 - 5	I5
BLAMDA	0.5	Inter-arrival time of this transient (deterministic)	6 - 10	F5.2
TEMP	73	Maximum temperature excursion during this transient (°F)	11 - 20	F10.5
TITLE		Transient title	21 - 80	6A10

Table 10-11 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #22-45 g_{min} and g_{max} Tables (Card 6F)				
Line #46 Earthquakes per Magnitude Category (Card 7A)				
NEQCLS( )	1, 1, ..	Number of earthquakes in each category	1 - 80	10I5
Line #47 Seismic Stresses and Cycles (Card 7B)				
NCYCEQ( )	1	Number of equivalent cycles in Category 1	1 - 10	I10
SIGEQ( )	8.757	Equivalent cyclic stress (ksi)	11 - 20	F10.3
SGEQMX( )	8.757	Maximum cyclic stress during this category (ksi)	21 - 30	F10.3
TITLE( )		Earthquake title	31 - 80	5A10
Line #48-50 Seismic Stresses for Other Categories (Card 7B)				
Line #51 Mid-Life Changes (Card 8A)				
RTIMES(1)	20	Time at which mid-life changes made (years)	1 - 10	E10.4
THICKS(1)	2.5	Wall thickness of pipe (in)	11 - 20	E10.4
OSTARS(1)	0.2	Oxygen at start-up (ppm)	21 - 30	E10.4
OSTDYS(1)	0.1	Oxygen at steady-state (ppm)	31 - 40	E10.4
CONDUS(1)	0.1	Coolant conductivity (μs/cm)	41 - 50	E10.4
SGCLDS(1)	1.08	Deadweight stress (ksi)	51 - 60	E10.4
SDWTES(1)	4.58	Deadweight and thermal expansion stress (ksi)	61 - 70	E10.4
SGVIBS(1)	-1	Vibratory stresses not modeled	71 - 80	E10.4
Line #52 Mid-Life Changes (Card 8B)				
ISIGRX(1)	7	No change in the residual stresses	1 - 10	I10
RSINMS(1)		Not used	11 - 20	E10.4
RSISDS(1)		Not used	21 - 30	E10.4

Table 10-11 (Continued)

VARIABLE	VALUE	DESCRIPTION	POSITION	FORMAT
Line #53 Mid-Life Changes (Card 8A)				
RTIMES(2)	30	Time at which mid-life changes made (years)	1 - 10	E10.4
THICKS(2)	2.5	Wall thickness of pipe (in)	11 - 20	E10.4
OSTARS(2)	0.2	Oxygen at start-up (ppm)	21 - 30	E10.4
OSTDYS(2)	0.1	Oxygen at steady-state (ppm)	31 - 40	E10.4
CONDUS(2)	0.1	Coolant conductivity (μs/cm)	41 - 50	E10.4
SGCLDS(2)	1.08	Deadweight stress (ksi)	51 - 60	E10.4
SDWTES(2)	4.58	Deadweight and thermal expansion stress (ksi)	61 - 70	E10.4
SGVIBS(2)	-1	Vibratory stresses not modeled	71 - 80	E10.4
Line #54 Mid-Life Changes (Card 8B)				
ISIGRX(2)	6	IHSI treatment performed at this time	1 - 10	I10
RSINMS(2)	-44.7	Mean of value of post-IHSI residual stress at ID (ksi)	11 - 20	E10.4
RSISDS(2)	11.6	Standard deviation of value of post-IHSI residual stress at ID (ksi)	21 - 30	E10.4

```
              P     R        A     I       S    E

              PIPING RELIABILITY ANALYSIS INCLUDING SEISMIC EVENTS

                         PC-PRAISE VERSION 2.40

                       EXECUTED ON  12/07/91 AT  5:11a


                 ECHO-PRINT OF INPUT DATA IN FILE  SAMPLE11.DAT

LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
   1> PROBLEM 11 : Fatigue + SCC initiated + Mid-life changes + Tearing Mod. + ...   <
   2>    2    2   25    0         0     1.100         0    1   688     7225    2     <
   3>  -50    1    2    3   -2    3    1    0    0    4    0    0    0    1   -1    3<
   4>  .400E+02  .200E+00    0    0  .000E+00  .000E+00  .000E+00  .000E+00          <
   5>  .250E+01  .145E+02  .500E+01                                                  <
   6>  .460E+01  .400E+01  .914E-11  .350E-10                                        <
   7>  .800E+01  .200E+00  .550E+03  .500E+01  .200E+00                              <
   8> .4300E+02 .4200E+01      10.0      25.0      30.6     106.0   25000.0      5.00<
   9>  .000E+00  .000E+00    0                                                       <
  10>  .407E+01                                                                      <
  11>  .134E+01  .538E+00                                                            <
  12>      10.0      20.0      30.0                                                  <
  13>  .300E+01  .300E+01                                                            <
  14>   10   10      .000     1.000      .000     1.000                              <
  15>  2.08      8.58      2.400     3.00      -.100E+01  .000E+00                   <
  16>    6    9   10   10                                                            <
  17>       .010      .100      .200      .300      .400      .500      .600      .700<
  18>       .800                                                                     <
  19>      1.000     2.000     3.000     4.000     5.000     6.000                   <
  20>    1 .2   460.00000Heat-up and Cool-down                                      <
  21>    1 .5    73.00000 Reactor Trip from Full Power                               <
  22>    .0190    .0084    .0038    .0020    .0013    .0009    .0007    .0006    .0004 <
  23>    .0241    .0116    .0060    .0038    .0026    .0019    .0013    .0009    .0005 <
  24>    .0258    .0127    .0069    .0045    .0031    .0023    .0016    .0010    .0005 <
  25>    .0268    .0133    .0072    .0046    .0032    .0022    .0014    .0008    .0001 <
  26>    .0281    .0140    .0074    .0045    .0029    .0019    .0011    .0003   -.0007 <
  27>    .0293    .0143    .0073    .0042    .0026    .0015    .0006   -.0002   -.0036 <
  28>    .3283    .2513    .1926    .1482    .1146    .0882    .0667    .0486    .0337 <
  29>    .4151    .3290    .2641    .2137    .1723    .1370    .1060    .0783    .0537 <
  30>    .4437    .3516    .2839    .2365    .1995    .1684    .1403    .1139    .0891 <
  31>    .4598    .3614    .2948    .2510    .2183    .1909    .1655    .1402    .1143 <
  32>    .4814    .3792    .3109    .2665    .2335    .2054    .1783    .1503    .1204 <
  33>    .5023    .3945    .3233    .2776    .2434    .2136    .1837    .1518    .1167 <
  34>    .0210    .0135    .0090    .0064    .0048    .0037    .0029    .0023    .0018 <
  35>    .0218    .0138    .0090    .0063    .0046    .0033    .0023    .0015    .0009 <
  36>    .0226    .0139    .0085    .0053    .0032    .0018    .0009    .0001   -.0006 <
  37>    .0235    .0136    .0074    .0039    .0018    .0006   -.0002   -.0029   -.0095 <
  38>    .0234    .0124    .0059    .0021    .0007   -.0003   -.0035   -.0126   -.0236 <
  39>    .0224    .0109    .0046    .0015    .0000   -.0026   -.0109   -.0222   -.0362 <
  40>    .3536    .3064    .2642    .2295    .1998    .1736    .1505    .1298    .1114 <
  41>    .3679    .3134    .2669    .2365    .2143    .1967    .1814    .1673    .1536 <
  42>    .3802    .3190    .2742    .2444    .2233    .2067    .1919    .1772    .1620 <
  43>    .3973    .3300    .2809    .2472    .2208    .1986    .1775    .1558    .1327 <
  44>    .3969    .3224    .2689    .2324    .2043    .1796    .1555    .1293    .1005 <
  45>    .3819    .3035    .2476    .2090    .1781    .1503    .1223    .0922    .0591 <
  46>    1    1    1    1                                                            <
  47>         1  8.757     8.757      ONE OBE                                        <
  48>         2  9.059     9.059      ONE SSE                                        <
  49>         3  10.557    10.557     THREE SSE                                      <
  50>         4  10.617    10.617     FIVE SSE                                       <
  51>      20.0     2.500  .200E+00  .100E+00  .100E+00      1.08      4.58 -.100E+01<
  52>         7  .000E+00  .000E+00                                                  <
  53>      30.0     2.500  .200E+00  .100E+00  .100E+00      1.08      4.58 -.100E+01<
  54>         6    -44.70      11.6                                                  <
LINE )---5---(1)---5---(2)---5---(3)---5---(4)---5---(5)---5---(6)---5---(7)---5---(8
 ****** NEW SEED (L,R)          688          7225*****
```

Figure 10-11a. Echo of input file for Sample Problem 11.

```
--- PROBLEM 11 : Fatigue + SCC initiated + Mid-life changes + Tearing Mod. + ...    ---

CIRCUMFERENTIAL CRACK ANALYSIS

PARAMETERS THAT DETERMINE NON-DETECTION PROBABILITY
          EPST  =      .000E+00
          ASTAR =    1.250
          TRANSDUCER DIAMETER =  1.00000 INCHES
          ANUU  =    1.600

PRE-EXISTING CRACKS + INITIATED CRACKS WILL BE
INCLUDED WHENEVER (SAMPLED A/H)<BNDRY

MAXIMUM NO. OF CRACKS =   25
NO. OF REPLICATIONS   =    0
A/H BOUNDARY          =    1.1000

SCC AND FATIGUE CRACK GROWTH

               MATERIAL SELECTED (FOR SCC) - S304

LEAKERS WILL NOT BE REPAIRED

FAILURE CRITERIA = APPLIED STRESS>FLOW STRESS OR JIC OR DJDA EXCEEDENCE

TIMESTEP FOR SCC =    .200 YEARS

PIPE DIMENSIONS
          WALL THICKNESS =   2.50 INCHES
          INSIDE RADIUS  =  14.50 INCHES
                 L/H RATIO    =    29.00
                 L/R RATIO    =     5.00
          AREA OF PIPE        =   247.40 SQ. INCHES
          FLOW AREA OF PIPE   =   660.52 SQ. INCHES

INITIAL CRACK SIZE DISTRIBUTION
CRACK DEPTH IS EXPONENTIAL
          PARAMETER =    4.0700
ASPECT RATIO IS LOG-NORMAL
          MEDIAN                  =    1.3400
          SHAPE PARAMETER         =     .5380
          NORMALIZATION CONSTANT  =    1.4149

CRACK GROWTH LAW PARAMETERS
          EXPONENT  =   4.000
          GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
                 MEDIAN        =   .9140E-11
                 90-TH PERCENT =   .3500E-10
          THRESHOLD =   4.600

SCC PARAMETERS
          O2 AT STARTUP(PPM) =     8.00
          O2 AT STEADY STATE(PPM) =      .20
          TEMP. AT STEADY STATE(DEG F) =  550.00
          HEATUP (100-550F) TIME (HRS) =    5.00
          COOLANT CONDUCTIVITY (US/CM) =     .20

FLOW STRESS NORMALLY DISTRIBUTED
          MEAN                =   .4300E+02
          STANDARD DEVIATION =   .4200E+01
```

Figure 10-11b. Input summary for Sample Problem 11.

```
DISTRIBUTION PARAMETERS FOR ULTIMATE STRESS IN PIPE
         MEAN                 =   .0000E+00
         STANDARD DEVIATION =   .0000E+00
         STANDARD DEVIATION =  0.0 MEANS THE ULTIMATE STRESS IS CONSTANT
         INTERPOLATION FLAG =   0  ( IULT ) FOR WHOLE PIPE BREAK PROBABILITY
         ABS ( IULT ) IS THE NUMBER OF INTERPOLATION POINTS
         IF  IULT .GT. 0  LINEAR INTERPOLATION
         IF  IULT .EQ. 0  NO INTERPOLATION
         IF  IULT .LT. 0  LOGARITHMIC INTERPOLATION

         JIC (IN-KIPS/IN.IN) =     10.0000
         DJDA      (KSI) =      5.0000
         YIELD STRESS  (KSI) =     30.6000
         D      (KSI) =    106.0000
         YOUNGS MODULUS(KSI) =  25000.0000
         EXPONENT, N          =      5.0000

 PIPE LOADING VALUES
         STRESS (KSI) DUE TO COLD DEADWEIGHT  =      2.08
         STRESS (KSI)  DUE TO DWGHT + THERMAL =      8.58
         STRESS (KSI)  DUE TO         THERMAL =      6.50
         OPERATING PRESSURE (KSI)             =      2.40
         STRESS (KSI) DUE TO OPER. PRESSURE   =      6.41
         STRESS (KSI) DUE TO DWGHT + OP PRESR =      8.49
         STRESS (KSI) DUE TO DWT+THML+OP PRES =     14.99
         PROOF PRESSURE (KSI)                 =      3.00
         STRESS (KSI) DUE TO DWGHT + PRF PRES =     10.09

 HYDROSTATIC PROOF TEST IS MODELLED

 LEAK DETECTION AND DEFINITION PARAMETERS
         DETECTABLE LEAK (GPM) =    3.00
         BIG LEAK        (GPM) =    3.00

 RESIDUAL STRESSES FOR INTERMEDIATE LINE SELECTED

 NO VIBRATORY STRESSES ARE MODELLED

 SEISMIC CLASS INFORMATION
     CLASS      AMPL.      MAX.AMPL  CYCLES
       1        8.757      8.757       1     ONE OBE
       2        9.059      9.059       2     ONE SSE
       3       10.557     10.557       3     THREE SSE
       4       10.617     10.617       4     FIVE SSE

 PRE-SERVICE ULTRASONIC INSPECTION IS MODELLED

 TIME INTERVALS
         PLANT LIFETIME =  40.0 YEARS
         ENDPOINTS OF INTERVALS AT     .0   2.0   4.0   6.0   8.0 YEARS
         ENDPOINTS OF INTERVALS AT   10.0  12.0  14.0  16.0  18.0 YEARS
         ENDPOINTS OF INTERVALS AT   20.0  22.0  24.0  26.0  28.0 YEARS
         ENDPOINTS OF INTERVALS AT   30.0  32.0  34.0  36.0  38.0 YEARS
         ENDPOINTS OF INTERVALS AT   40.0
         IN-SERVICE INSPECTIONS AT   10.0  20.0  30.0

 EARTHQUAKES AT EACH EVALUATION INTERVAL

 Number of remedial actions =  2
 Details of the remedial actions are as follows :

     Action Time  Thick-  Oxygen         Cond.  Dead Wt DW+TE Vib.   Res.       Mean    Std.
            (yrs)  ness  Start S.State          Stress  Str.  Stress Stress             Dev.

        1  20.00   2.50    .20     .10     .10    1.08   4.58  -1.00No change
        2  30.00   2.50    .20     .10     .10    1.08   4.58  -1.00 IHSI/MSIP-44.70 11.60
```

Figure 10-11b. (Continued).

```
SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS   0

NORMAL OUTPUT REQUESTED

NUMBER OF TRANSIENT TYPES =  2

TYPE  1    Heat-up and Cool-down
         REGULAR AT        .200 YEARS/EVENT
         MAX DELTA TEMP = 460.0  BLOCKING FACTOR =  1.0

TYPE  2     Reactor Trip from Full Power
         REGULAR AT        .500 YEARS/EVENT
         MAX DELTA TEMP =  73.0  BLOCKING FACTOR =  1.0
```

Figure 10-11b. (Continued).

```
                    - - - SUMMARY OF CELLS IN SAMPLE SPACE - - -

                             - - - UNIFORM MESH - - -

CELL     AOH1      AOH2      AOB1      AOB2        PROBABILITY       SAMPLES   LEAKS    B-LEAKS    LOCAS
  1      .9000    1.0000     .0000     .1000      .8910199E-08         50        0         0         0
  2      .9000    1.0000     .1000     .2000      .6761020E-06         50        0         0         0
  3      .9000    1.0000     .2000     .3000      .3614825E-05         50        0         0         0
  4      .9000    1.0000     .3000     .4000      .7434238E-05         50        0         0         0
  5      .9000    1.0000     .4000     .5000      .1001263E-04         50        0         0         0
  6      .9000    1.0000     .5000     .6000      .1088032E-04         50        0         0         0
  7      .9000    1.0000     .6000     .7000      .1048585E-04         50        0         0         0
  8      .9000    1.0000     .7000     .8000      .9406688E-05         50        0         0         0
  9      .9000    1.0000     .8000     .9000      .8069847E-05         50        0         0         0
 10      .9000    1.0000     .9000    1.0000      .6728002E-05         50        0         0         0
 11      .8000     .9000     .0000     .1000      .2464802E-07         50       36        36        35
 12      .8000     .9000     .1000     .2000      .1870281E-05         50       25        25         0
 13      .8000     .9000     .2000     .3000      .9999583E-05         50       32        32         0
 14      .8000     .9000     .3000     .4000      .2056511E-04         50       30        30         0
 15      .8000     .9000     .4000     .5000      .2769764E-04         50       33        33         0
 16      .8000     .9000     .5000     .6000      .3009792E-04         50       32        32         0
 17      .8000     .9000     .6000     .7000      .2900669E-04         50       31        31         0
 18      .8000     .9000     .7000     .8000      .2602144E-04         50       33        33         0
 19      .8000     .9000     .8000     .9000      .2232338E-04         50       34        34         0
 20      .8000     .9000     .9000    1.0000      .1861147E-04         50       34        34         0
 21      .7000     .8000     .0000     .1000      .6818309E-07         50       50        50        28
 22      .7000     .8000     .1000     .2000      .5173703E-05         50       50        50         0
 23      .7000     .8000     .2000     .3000      .2766155E-04         50       50        50         0
 24      .7000     .8000     .3000     .4000      .5688866E-04         50       50        50         0
 25      .7000     .8000     .4000     .5000      .76[illegible]1917E-04         50       50        50         0
 26      .7000     .8000     .5000     .6000      .8325897E-04         50       50        50         0
 27      .7000     .8000     .6000     .7000      .8024034E-04         50       50        50         0
 28      .7000     .8000     .7000     .8000      .7198235E-04         50       50        50         0
 29      .7000     .8000     .8000     .9000      .6175250E-04         50       50        50         0
 30      .7000     .8000     .9000    1.0000      .5148437E-04         50       50        50         0
 31      .6000     .7000     .0000     .1000      .1886129E-06         50       50        50         4
 32      .6000     .7000     .1000     .2000      .1431186E-04         50       50        50         0
 33      .6000     .7000     .2000     .3000      .7651933E-04         50       50        50         0
 34      .6000     .7000     .3000     .4000      .1573694E-03         50       50        50         0
 35      .6000     .7000     .4000     .5000      .2119493E-03         50       50        50         0
 36      .6000     .7000     .5000     .6000      .2303168E-03         50       49        49         0
 37      .6000     .7000     .6000     .7000      .2219665E-03         50       50        50         0
 38      .6000     .7000     .7000     .8000      .1991226E-03         50       50        50         0
 39      .6000     .7000     .8000     .9000      .1708241E-03         50       48        48         0
 40      .6000     .7000     .9000    1.0000      .1424197E-03         50       48        48         0
 41      .5000     .6000     .0000     .1000      .5217542E-06         50       50        50         2
 42      .5000     .6000     .1000     .2000      .3959048E-04         50       50        50         0
 43      .5000     .6000     .2000     .3000      .2116732E-03         50       50        50         0
 44      .5000     .6000     .3000     .4000      .4353264E-03         50       50        50         0
 45      .5000     .6000     .4000     .5000      .5863092E-03         50       50        50         0
 46      .5000     .6000     .5000     .6000      .6371187E-03         50       49        49         0
 47      .5000     .6000     .6000     .7000      .6140193E-03         50       48        48         0
 48      .5000     .6000     .7000     .8000      .5508271E-03         50       49        49         0
 49      .5000     .6000     .8000     .9000      .4725457E-03         50       47        47         0
 50      .5000     .6000     .9000    1.0000      .3939714E-03         50       48        48         0
 51      .4000     .5000     .0000     .1000      .1443313E-05         50       50        50         1
 52      .4000     .5000     .1000     .2000      .1095180E-03         50       50        50         0
 53      .4000     .5000     .2000     .3000      .5855452E-03         50       49        49         0
 54      .4000     .5000     .3000     .4000      .1204231E-02         50       49        49         0
 55      .4000     .5000     .4000     .5000      .1621890E-02         50                 49         0
 56      .4000     .5000     .5000     .6000      .1762442E-02         50                 49         0
 57      .4000     .5000     .6000     .7000      .1698543E-02         50       4[illegible]        48         0
 58      .4000     .5000     .7000     .8000      .1523737E-02         50       48        48         0
 59      .4000     .5000     .8000     .9000      .1307189E-02         50       48        48         0
```

Figure 10-11c. Stratification description for Sample Problem 11.

```
 60     .4000     .5000     .9000    1.0000       .1089831E-02      50      48      48      0
 61     .3000     .4000     .0000     .1000       .3992595E-05      50      50      50      1
 62     .3000     .4000     .1000     .2000       .3029563E-03      50      49      49      0
 63     .3000     .4000     .2000     .3000       .1619776E-02      50      48      48      0
 64     .3000     .4000     .3000     .4000       .3331227E-02      50      48      48      0
 65     .3000     .4000     .4000     .5000       .4486586E-02      50      50      50      0
 66     .3000     .4000     .5000     .6000       .4875393E-02      50      46      46      0
 67     .3000     .4000     .6000     .7000       .4698630E-02      50      44      44      0
 68     .3000     .4000     .7000     .8000       .4215068E-02      50      43      43      0
 69     .3000     .4000     .8000     .9000       .3616039E-02      50      46      46      0
 70     .3000     .4000     .9000    1.0000       .3014768E-02      50      43      43      0
 71     .2000     .3000     .0000     .1000       .1104460E-04      50      49      49      0
 72     .2000     .3000     .1000     .2000       .8380591E-03      50      46      46      0
 73     .2000     .3000     .2000     .3000       .4480739E-02      50      42      42      0
 74     .2000     .3000     .3000     .4000       .9215076E-02      50      46      46      0
 75     .2000     .3000     .4000     .5000       .1241111E-01      50      45      45      0
 76     .2000     .3000     .5000     .6000       .1348665E-01      50      43      43      0
 77     .2000     .3000     .6000     .7000       .1299768E-01      50      39      39      0
 78     .2000     .3000     .7000     .8000       .1166002E-01      50      30      30      0
 79     .2000     .3000     .8000     .9000       .1000294E-01      50      43      43      0
 80     .2000     .3000     .9000    1.0000       .8339665E-02      50      36      36      0
 81     .1000     .2000     .0000     .1000       .3055234E-04      50      43      43      0
 82     .1000     .2000     .1000     .2000       .2318298E-02      50      41      41      0
 83     .1000     .2000     .2000     .3000       .1239494E-01      50      41      41      0
 84     .1000     .2000     .3000     .4000       .2549139E-01      50      42      42      0
 85     .1000     .2000     .4000     .5000       .3433249E-01      50      38      38      0
 86     .1000     .2000     .5000     .6000       .3730773E-01      50      40      40      0
 87     .1000     .2000     .6000     .7000       .3595510E-01      50      36      36      0
 88     .1000     .2000     .7000     .8000       .3225476E-01      50      36      36      0
 89     .1000     .2000     .8000     .9000       .2767084E-01      50      35      35      0
 90     .1000     .2000     .9000    1.0000       .2306977E-01      50      34      34      0
 91     .0000     .1000     .0000     .1000       .8451604E-04      50      22      22      0
 92     .0000     .1000     .1000     .2000       .6413040E-02      50      24      24      0
 93     .0000     .1000     .2000     .3000       .3428775E-01      50      28      28      0
 94     .0000     .1000     .3000     .4000       .7051608E-01      50      23      23      0
 95     .0000     .1000     .4000     .5000       .9497294E-01      50      28      28      0
 96     .0000     .1000     .5000     .6000       .1032033E+00      50      26      26      0
 97     .0000     .1000     .6000     .7000       .9946154E-01      50      21      21      0
 98     .0000     .1000     .7000     .8000       .8922539E-01      50      24      24      0
 99     .0000     .1000     .8000     .9000       .7654503E-01      50      17      17      0
100     .0000     .1000     .9000    1.0000       .6381722E-01      50      24      24      0
                                                ---------------
                SUM OF CELL PROBABILITIES =       .1000000E+01
```

Figure 10-11c. (Continued).

```
---  PROBLEM 11 : Fatigue + SCC initiated + Mid-life changes + Tearing Mod. + ...     ---

                                                 - - - RESULTS WITHOUT EARTHQUAKES - - -

           SEISMIC CLASS INFORMATION
                    CLASS     SIGEQ        SGLCEQ     CYCLES  COV F-BM
                      0     .0000E+00       .000        0       .0000

                   PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                     SULTMU          SULTSD     IULT
                   .00000E+00      .00000E+00     0
                    STRESS(1)
                   .74876E+01
                    PBREAK(1)
                   .10000E+01

   TIME      AVG LEAK      AVG BIG LEAK     AVG LOCA      SIGMA LEAK    SIGMA BIG LEAK   SIGMA LOCA
     .0    4.62811E-07    4.62811E-07    6.54923E-10    1.52708E-07    1.52708E-07    1.76279E-10
    2.0    8.57537E-02    8.57537E-02    1.01195E-07    7.19876E-03    7.19876E-03    6.33787E-08
    4.0    1.81467E-01    1.81467E-01    1.01195E-07    1.15641E-02    1.15641E-02    6.33787E-08
    6.0    2.47329E-01    2.47329E-01    1.01195E-07    1.33080E-02    1.33080E-02    6.33787E-08
    8.0    2.95107E-01    2.95107E-01    1.01195E-07    1.42318E-02    1.42318E-02    6.33787E-08
   10.0    3.33420E-01    3.33420E-01    1.01195E-07    1.48004E-02    1.48004E-02    6.33787E-08
   12.0    3.67418E-01    3.67418E-01    1.01195E-07    1.53373E-02    1.53373E-02    6.33787E-08
   14.0    4.00518E-01    4.00518E-01    1.01195E-07    1.58174E-02    1.58174E-02    6.33787E-08
   16.0    4.39808E-01    4.39808E-01    1.01195E-07    1.63584E-02    1.63584E-02    6.33787E-08
   18.0    4.73555E-01    4.73555E-01    1.01195E-07    1.66332E-02    1.66332E-02    6.33787E-08
   20.0    5.05889E-01    5.05889E-01    1.01195E-07    1.69295E-02    1.69295E-02    6.33787E-08
   22.0    5.18674E-01    5.18674E-01    1.01195E-07    1.69573E-02    1.69573E-02    6.33787E-08
   24.0    5.23331E-01    5.23331E-01    1.01195E-07    1.69859E-02    1.69859E-02    6.33787E-08
   26.0    5.31255E-01    5.31255E-01    1.01195E-07    1.70656E-02    1.70656E-02    6.33787E-08
   28.0    5.37689E-01    5.37689E-01    1.01195E-07    1.71122E-02    1.71122E-02    6.33787E-08
   30.0    5.45593E-01    5.45593E-01    1.01195E-07    1.71005E-02    1.71005E-02    6.33787E-08
   32.0    5.47889E-01    5.47889E-01    1.01195E-07    1.70645E-02    1.70645E-02    6.33787E-08
   34.0    5.50675E-01    5.50675E-01    1.01195E-07    1.70505E-02    1.70505E-02    6.33787E-08
   36.0    5.56447E-01    5.56447E-01    1.01195E-07    1.70549E-02    1.70549E-02    6.33787E-08
   38.0    5.60162E-01    5.60162E-01    1.01195E-07    1.70422E-02    1.70422E-02    6.33787E-08
   40.0    5.63683E-01    5.63683E-01    1.01195E-07    1.70732E-02    1.70732E-02    6.33787E-08
```

Figure 10-11d. Failure probabilities for no earthquake case for Sample Problem 11.

```
...  PROBLEM 11 : Fatigue + SCC initiated + Mid-life changes + Tearing Mod. + ...      ..

                                                  - - RESULTS INCLUDING SEISMIC EVENTS - - -

            SEISMIC CLASS INFORMATION
                     CLASS      SIGEQ        PGLCEQ     CYCLES  COV F LF
                       1     .87570E+01      8.757          1       .000  ONE OBE

                     PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                        SULTMU          SULTSD      SULT
                    .00000E+00      .00000E+00      0
                     STRESS(1)
                    .87570E+01
                     PBREAK(1)
                    .10000E+01

     TIME      AVG LEAK      AVG BIG LEAK      AVG LOCA       SIGMA LEAK    SIGMA BIG LEAK   SIGMA LOCA
       .0    5.72709E-05     5.72709E-05     3.89245E-08     2.33427E-06     2.33427E-06     1.73575E-08
      2.0    9.69270E-02     9.52965E-02     1.01195E-07     7.72355E-03     7.69135E-03     6.33787E-08
      4.0    1.89040E-01     1.82294E-01     1.01195E-07     1.17341E-02     1.15644E-02     6.33787E-08
      6.0    2.52407E-01     2.47332E-01     1.01195E-07     1.33843E-02     1.33080E-02     6.33787E-08
      8.0    2.97426E-01     2.95208E-01     1.01195E-07     1.42371E-02     1.42317E-02     6.33787E-08
     10.0    3.36103E-01     3.33567E-01     1.01195E-07     1.48496E-02     1.48003E-02     6.33787E-08
     12.0    3.75769E-01     3.68949E-01     1.01195E-07     1.55361E-02     1.53918E-02     6.33787E-08
     14.0    4.06076E-01     4.00518E-01     1.01195E-07     1.58806E-02     1.58174E-02     6.33787E-08
     16.0    4.46396E-01     4.39808E-01     1.01195E-07     1.64113E-02     1.63584E-02     6.33787E-08
     18.0    4.77127E-01     4.73555E-01     1.01195E-07     1.66790E-02     1.66332E-02     6.33787E-08
     20.0    5.10459E-01     5.05889E-01     1.01195E-07     1.69643E-02     1.69295E-02     6.33787E-08
     22.0    5.19001E-01     5.18674E-01     1.01195E-07     1.69564E-02     1.69573E-02     6.33787E-08
     24.0    5.23753E-01     5.23331E-01     1.01195E-07     1.69850E-02     1.69859E-02     6.33787E-08
     26.0    5.34063E-01     5.31255E-01     1.01195E-07     1.70797E-02     1.70656E-02     6.33787E-08
     28.0    5.40157E-01     5.37689E-01     1.01195E-07     1.71220E-02     1.71122E-02     6.33787E-08
     30.0    5.46300E-01     5.45593E-01     1.01195E-07     1.70158E-02     1.71005E-02     6.33787E-08
     32.0    5.50339E-01     5.47889E-01     1.01195E-07     1.70518E-02     1.70545E-02     6.33787E-08
[illegible]  [illegible]     5.50675E-01     1.01195E-07     1.70543E-02     1.70505E-02     6.33787E-08
[illegible]  5.59853E-01     5.56447E-01     1.01195E-07     1.70441E-02     1.70549E-02     6.33787E-08
[illegible]  5.62668E-01     5.60167E-01     1.01195E-07     1.70379E-02     1.70422E-02     6.33787E-08
     40.0    5.64713E-01     5.63683E-01     1.01195E-07     1.70628E-02     1.70732E-02     6.33787E-08
```

Figure 10-11e. Failure probabilities for Earthquake Classes 1 and 2 for Sample Problem 11.

```
SEISMIC CLASS INFORMATION
        CLASS     SIGEQ         SGLCEQ     CYCLES   COV F-BM
          2     .9059E+01       9.059        2          .0000 ONE SSE

         PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
            SULTMU           SULTSD     IULT
         .00000E+00      .00000E+00      0
          STRESS(1)
         .90590E+01
          PBREAK(1)
         .10000E+01

  TIME     AVG LEAK      AVG BIG LEAK      AVG LOCA        S      LEAK    SIGMA BIG LEAK    SIGMA LOCA
    .0   5.72709E-05    5.72709E-05    3.89245E-08    2.33427E-06    2.33427E-06    1.73575E-08
   2.0   9.69270E-02    9.52965E-02    1.01195E-07    7.72355E-03    7.69135E-03    6.33787E-08
   4.0   1.89048E-01    1.82294E-01    1.01195E-07    1.17341E-02    1.15644E-02    6.33787E-08
   6.0   2.52407E-01    2.47332E-01    1.01195E-07    1.33843E-02    1.33080E-02    6.33787E-08
   8.0   2.97426E-01    2 95208E-01    1.01195E-07    1.42371E-02    1.42317E-02    6.33787E-08
  10.0   3.36103E-01    3.33567E-01    1.01195E-07    1.48496E-02    1.48003E-02    6.33787E-08
  12.0   3.75769E-01    3.68949E 01    1 01195E-07    1.55361E-02    1.53918E-02    6.33787E-08
  14.0   4.06076E-01    4.00518E-01    1.01195E-07    1.58806E-02    1.58174E-02    6.33787E-08
  16.0   4.46396E-01    4.39808E-01    1.01195E-07    1.64113E-02    1.63584E-02    6.33787E-08
  18.0   4.77127E-01    4.73555E-01    1.01195E-07    1.66790E-02    1.66332E-02    6.33787E-08
  20.0   5.10481E-01    5.05889E-01    1.01195E-07    1.69643E-02    1.69295E-02    6.33787E-08
  22.0   5.19001E-01    5.18674E-01    1.01195E-07    1.69564E-02    1.69573E-02    6.33787E-08
  24.0   5.23753E-01    5.23331E-01    1.01195E-07    1.69850E-02    1.69859E-02    6.33787E-08
  26.0   5.34063E-01    5.31255E-01    1.01195E-07    1.70797E-02    1.706[illegible]-02    6.33787E-08
  28.0   5.40157E-01    5.37689E-01    1.01195E-07    1.71220E-02    1.71122E-02    6.33787E-08
  30.0   5.46366E-01    5.45593E-01    1.01195E-07    1.70966E-02    1.71005E-02    6.33787E-06
  32.0   5.50340E-01    5.47889E-01    1.01195E-07    1.70518E-02    1.70645E-02    6.33787E-08
  34.0   5.53515E-01    5.50675E-01    1.01195E-07    1.70543E-02    1.70505E-02    3.33787E-08
  36.0   5.59910E-01    5.56447E-01    1.01195F-07    1.70440E-02    1.70549E-02    6.33787E-08
  38.0   5.62668E-01    5.60162E-01    1.01195E-07    1.70379E-02    1.70422E-02    6.33787E-08
  40.0   5.64722E-01    5.63683E-01    1.01195E-07    1.70628E-02    1.70732F-02    6.33787E-08
```

Figure 10-11e. (Continued).

```
***  PROBLEM 11 : Fatigue + SCC initiated + Mid-life changes + Tearing Mod. + ...     ***


                                                        - - - RESULTS INCLUDING SEISMIC EVENTS - - -

              SEISMIC CLASS INFORMATION
                       CLASS      SIGEQ        SGLCEQ     CYCLES  COV F-BM
                         3     .1056E+02      10.557        3         0000 THREE SSE

                   PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
                      SULTMU           SULTSD     IULT
                  .00000E+00        .00000E+00    0
                   STRESS(1)
                  .10557E+02
                   PBREAK(1)
                  .10000E+01

          TIME     AVG LEAK     AVG BIG LEAK      AVG LOCA      SIGMA LEAK    SIGMA BIG LEAK    SIGMA LOCA
            .0    1.00623E-04    1.00623E-04    1.85048E-07    2.74844E-06    2.74844E-06     8.08086E-08
           2.0    9.96328E-02    9.[illegible]7E-02    1.01195E-07    7.77748E-03    7.74188E-03     6.33787E-08
           4.0    1.92452E-01    1.82462E-01    1.01195E-07    1.19046E-02    1.15643E-02     6.33787E-08
           6.0    2.54267E-01    2.47356E-01    1.01195E-07    1.33943E-02    1.33080E-02     6.33787E-08
           8.0    2.98546E-01    2.95718E-01    1.01195E-07    1.42349E-02    1.42297E-02     6.33787E-08
          10.0    3.36454E-01    3.33567E-01    1.01195E-07    1.48483E-02    1.48003E-02     6.33787E-08
          12.0    3.79641E-01    3.70938E-01    1.01195E-07    1.56050E-02    1.54729E-02     6.33787E-08
          14.0    4.09642E-01    4.00518E-01    1.01195E-07    1.59077E-02    1.58174E-02     6.33787E-08
          16.0    4.48423E-01    4.39809E-01    1.01195E-07    1.64295E-02    1.63584E-02     6.33787E-08
          18.0    4.77893E-01    4.73555E-01    1.01195E-07    1.66751E-02    1.66332E-02     6.33787E-08
          20.0    5.12857E-01    5.05889E-01    1.01195E-07    1.69655E-02    1.69295E-02     6.33787E-08
          22.0    5.19068E-01    5.18674E-01    1.01195E-07    1.69564E-02    1.69573E-02     6.33787E-08
          24.0    5.24085E-01    5.23331E-01    1.01195E-0T    1.69840E-02    1.69859E-02     6.33787E-08
          26.0    5.34067E-01    5.31255E-01    1.01195E-07    1.70797E-02    1.70656E-02     6.33787E-08
          28.0    5.40248E-01    5.37689E-01    1.01195E-07    1.71218E-02    1.71122E-02     6.33787E-08
          30.0    5.46856E-01    5.45593E-01    1.01195E-07    1.70945E-02    1.71005E-02     6.33787E-08
          32.0    5.50513E-01    5.47889E-01    1.01195E-07    1.70515E-02    1.70645E-02     6.33787E-08
          34.0    5.54300E-01    5.50675E-01    1.01195E-07    1.70533E-02    1.70505E-02     6.33787E-08
          36.0    5.60268E-01    5.56447E-01    1.01195E-07    1.70428E-02    1.70549E-02     6.33787E-08
          38.0    5.62733E-01    5.60162E-01    1.01195E-07    1.70378E-02    1.70422E-02     6.33787E-08
          40.0    5.64795E-01    5.63683E-01    1.01195E-07    1.70627E-02    1.70732E-02     6.33787E-08
```

Figure 10-11f. Failure probabilities for Earthquake Classes 3 and 4 for Sample Problem 11.

```
SEISMIC CLASS INFORMATION
            CLASS     SIGEQ       SGLCEQ     CYCLES  COV F-BM
              4     .1062E+02     10.617       4        .0000 FIVE SSE

            PROBABILITY OF FAILURE FOR UNCRACKED PIPE AND INTERPOLATED VALUES
               SULTMU          SULTSD      IULT
            .00000E+00      .00000E+00     0
             STRESS(1)
            .10617E+02
             PBREAK(1)
            .10000E+01

 TIME       AVG L AK      AVG BIG LEAK      AVG LOCA        SIGMA LEAK     SIGMA BIG LEAK    SIGMA LOCA
   .0     1.01007E-04     1.01007E-04     1.85906E-07     2.74282E-06     2.74282E-06     8.08117E-08
  2.0     9.96328E-02     9.74027E-02     1.01195E-07     7.77748E-03     7.74188E-03     6.33787E-08
  4.0     1.92452E-01     1.82462E-01     1.01195E-07     1.19046E-02     1.15643E-02     6.33787E-08
  6.0     2.54267E-01     2.47356E-01     1.01195E-07     1.33943E-02     1.33080E-02     6.33787E-08
  8.0     2.98546E-01     2.95718E-01     1.01195E-07     1.42349E-02     1.42297E-02     6.33787E-08
 10.0     3.36454E-01     3.33567E-01     1.01195E-07     1.48488E-02     1.48007E-02     6.33787E-08
 12.0     3.79641E-01     3.70938E-01     1.01195E-07     1.56050E-02     1.547[illegible]-02     6.33787E-08
 14.0     4.09642E-01     4.00518E-01     1.01195E-07     1.59077E-02     1.58174E-02     6.33787E-08
 16.0     4.48423E-01     4.39809E-01     1.01195E-07     1.64295E-02     1.63584E-02     6.33787E-08
 18.0     4.77893E-01     4.73555E-01     1.01195E-07     1.66751E-02     1.66332E-02     6.3378/E-08
 20.0     5.12857E-01     5.05889E-01     1.01195E-07     1.69655E-02     1.69295E-02     6.33787E-08
 22.0     5.19068E-01     5.18674E-01     1.01195E-07     1.69564E-02     1.69573E-02     6.33787E-08
 24.0     5.24085E-01     5.23331E-01     1.01195E-07     1.69840E-02     1.69859E-02     6.33787E-08
 26.0     5.34067E-01     5.31255E-01     1.01195E-07     1.70797E-02     1.70656E-02     6.33787E-08
 28.0     5.40248E-01     5.37689E-01     1.01195E-07     1.71218E-02     1.71122E-02     6.33787E-08
 30.0     5.46856E-01     5.45593E-01     1.01195E-07     1.70945E-02     1.71005E-02     6.33787E-08
 32.0     5.50513E-01     5.47889E-01     1.01195E-07     1.70515E-02     1.70645E-02     6.33787E-08
 34.0     5.54300E-01     5.50675E-01     1.01195E-07     1.70533E-02     1.70505E-02     6.33787E-08
 36.0     5.60268E-01     5.56447E-01     1.01195E-07     1.70428E-02     1.70549E-02     6.33787E-08
 38.0     5.62733E-01     5.60162E-C1     1.01195E-07     1.70378E-02     1.70422E-02     6.33787E-08
 40.0     5.64795E-01     5.63683E-01     1.01195E-07     1.70627E-02     1.70732E-02     6.33787E-08
```

Figure 10-11f. (Continued).

```
---  PROBLEM 11 : Fatigue + SCC initiated + Mid-life changes + Tearing Mod. + ...     ---


                     TOTAL NUMBER OF REPLICATIONS =  4320
NUMBER OF POSSSIBLE INITIATION SITES(USER SPEC.) =    25
NO. OF TIMES     INITIATED CRACKS CAUSED BIG LEAK =    18
NO. OF TIMES PRE-EXISTING CRACKS CAUSED BIG LEAK =  3714

        TIME    TOTAL INITIATED     FIRST INITIATED
       (YRS)        CRACKS               CRACKS

          1          150                145
          2         1279               1038
          3         2436               1257
          4         3324                903
          5         3775                483
          6         3800                244
          7         3871                127
          8         3709                 47
          9         3578                 32
         10         3364                 14
         11         3265                 10
         12         2969                  6
         13         2883                  3
         14         2568                  3
         15         2562                  2
         16         2342                  2
         17         2164                  1
         18         2133                  0
         19         1961                  1
         20         1898                  1
         21         1235                  0
         22         1156                  0
         23         1171                  0
         24         1144                  1
         25         1149                  0
         26         1138                  0
         27         1106                  0
         28         1087                  0
         29         1059                  0
         30         1018                  0
         31          208                  0
         32            0                  0
         33            0                  0
         34            1                  0
         35            0                  0
         36            1                  0
         37            0                  0
         38                               0
         39            0                  0
         40            0                  0

         81            0                  0


   PC-PRAISE VERSION 2.40
   Execution Start -    12/07/91 at  5:11a
   Execution End   -    12/07/91 at  [illegible]:13a
```

Figure 10-11g. Statistics of time to initiation for Sample Problem 11.

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D. O. Harris, D. D. Dedhia, Failure Analysis Associates, Inc.
S. C. Lu, Lawrence Livermore National Laboratory

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Menlo Park, CA 94025

Under Contract to:
Lawrence Livermore National Laboratory
7000 East Avenue
Livermore, CA 94550

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

This document consolidates and updates the earlier reports which provide the theoretical background as well as information needed for the execution of the computer code pc-PRAISE. pc-PRAISE is a probabilistic fracture mechanics computer code written for the IBM personal computers or their compatibles to evaluate the reliability of welds in nuclear power plant piping systems. pc-PRAISE was adapted from the PRAISE computer code which was originally developed for CDC 7600 computers in 1981 by Lawrence Livermore National Laboratory (LLNL) under funding from the U.S. Nuclear Regulatory Commission, and has been considerably expanded and updated over the years.

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