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Probability of Pipe Fracture in the Primary Coolant Loop of a PWR Plant

Volume 9: PRAISE Computer Code User's Manual Load Combination Program Project I Final Report

E. Y. Lim

Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

The PRAISE (Piping Reliability Analysis Including Seismic Events) computer code estimates the influence of earthquakes on the probability of failure at a weld joint in the primary coolant system of a pressurized water reactor. Failure, either a through-wall defect (leak) or a complete pipe severance (a large-LOCA), is assumed to be caused by fatigue crack growth of an as-fabricated interior surface circumferential defect. These defects are assumed to be two-dimensional and semi-elliptical in shape. The distribution of initial crack sizes is a function of crack depth and aspect ratio. Crack propagation rates are governed by a Paris-type relationship with separate RMS cyclic stress intensity factors for the depth and length. Both uniform through the wall and radial gradient thermal stresses are included in the calculation of the stress intensity factors. The failure probabilities are estimated by applying Monte Carlo methods to simulate the life histories of the selected weld joint. In order to maximize computational efficiency, a stratified sampling procedure is used to select the initial crack size. Hydrostatic proof test, pre-service inspection, and in-service inspection can be simulated. PRAISE treats the inter-arrival times of operating transients either as a constant or exponentially distributed according to observed or postulated rates. Leak rate and leak detection models are also included. The criterion for complete pipe severance is exceedance of a net section critical stress. Earthquakes of various intensity and arbitrary occurrence times can be modeled. PRAISE presently assumes that exactly one initial defect exists in the weld and that the earthquake of interest is the first earthquake experienced at the reactor.

PRAISE has a very modular structure and can be tailored to a variety of crack growth and piping reliability problems. Although PRAISE was developed on a CDC-7600 computer, it was, however, coded in standard FORTRAN IV and is readily transportable to other machines.

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NOTATION Lower Case

a	crack depth
a^*	crack depth which has a 50-50 chance of being detected in an ultrasonic inspection
a_{new}	new value of the crack depth
a_{old}	old value of the crack depth
b	one-half the crack length
g_{max}	normalized increase in the stress intensity factor during the i -th transient
g_{min}	normalized reduction in the stress intensity factor during the i -th transient
h	thickness of the pipe wall
m	exponent in the Paris-type crack growth relationship
p_m	probability of obtaining an initial crack with dimensions corresponding to the m -th stratum
$p(x)$	a generalized probability density function for the random variable x
$s^2(t)$	unbiased estimator for the variance of $F(t)$
$s_m^2(t)$	unbiased estimator for the variance of $F_m(t)$
$s_m^2(g,t)$	unbiased estimator for the variance of $F_m(g,t)$
$s_{st}^2(t)$	unbiased estimator for the variance of $F_{st}(t)$
$s_{st}^2(g,t)$	unbiased estimator for the variance of $F_{st}(g,t)$

Upper Case

A	crack area
A^*	area of crack that has a 50-50 chance of being detected in an ultrasonic inspection
A_{crack}	idealized cross-sectional area of the crack surface
A_{pipe}	cross-sectional area of the pipe wall
C	parameter in the Paris-type crack growth relationship
C^*	normalization constant used to ensure that probability density functions integrate to unity
E	Young's modulus
$F(t)$	proportion of samples that has failed at or before time t when no earthquakes are modeled
$F_m(t)$	proportion of samples drawn from the m -th stratum that has failed at or before time t when no earthquakes are modeled
$F_m(g,t)$	proportion of samples drawn from the m -th stratum that have failed at or before time t given that an earthquake of intensity g occurs at time t
$F_{\text{st}}(t)$	unbiased estimator for the failure probability at time t when stratified sampling is used and no earthquakes are modeled
$F_{\text{st}}(g,t)$	unbiased estimator for the failure probability at time t when an earthquake of intensity g occurs at time t and stratified sampling is used
$I_n(t)$	Bernoulli random variable that indicates the state of the n -th sample (either failed or not failed) at time t - also referred to as an indicator function
$I_{m,n}(t)$	Bernoulli random variable that indicates the state of the n -th sample drawn from the m -th stratum at time t
$I_{m,n}(g,t)$	Bernoulli random variable that indicates the state of the n -th sample drawn from the m -th stratum at time t given that the first earthquake occurs at time t and is of intensity g

N	total number of samples to be simulated, or total number of cycles during a single earthquake
N_{eq}	equivalent number of cycles used to model an earthquake with N actual cycles
$N_F(t)$	number of samples which have failed at or before time t when earthquakes are not included in the stress history
$N_F^*(t)$	number of samples which have failed at or before time t when earthquakes are included in the stress history
$N_F(g,t)$	number of samples which have failed at or before time t given that it is subjected to an earthquake of intensity g at time t
$N_{F,m}(t)$	number of samples from the m -th stratum that have failed at or before time t when earthquakes are not included in the stress history
$N_{F,m}(g,t)$	number of samples from the m -th stratum that have failed at or before time t given that it is subjected to an earthquake of intensity g at time t
N_m	total number of samples to be taken from the m -th stratum
P_{ND}	non-detection probability in an ultrasonic inspection
$P(t_F \leq t)$	probability that the weld has failed at or before time t ; stress history includes random occurrence of earthquakes
$P(t_F \leq t n)$	probability that the weld has failed at or before time t given that the weld contained n initial defects; stress history includes occurrence of earthquakes
$P(t_F \leq t \overline{EQ})$	probability that the weld has failed at or before time t ; stress history does not include earthquakes
$P(t_F \leq t EQ(g,t))$	probability that the weld has failed at or before time t ; stress history includes a single earthquake of intensity g at time t
$\dot{Q}$	flow rate
R_i	inside radius of the pipe
S	standard deviation of the logarithm of a random variable when that variable is log-normally distributed, or parameter which defines crack during an earthquake
S_{eq}	an equivalent S -factor when crack growth during an earthquake is modeled with N_{eq} cycles

Greek Symbols

α	normalized crack depth, defined as a/h or crack depth divided by the wall thickness
β	aspect ratio, defined as b/a or one-half the crack length divided by the crack depth
β^*	reciprocal of the aspect ratio, $\beta^* = 1/\beta$
δ	crack opening displacement
ΔT	maximum temperature excursion during a transient
$\Delta \bar{K}_a$	cyclic value of the RMS stress intensity factor for crack growth in the a-direction
$\Delta \bar{K}_b$	cyclic value of the RMS stress intensity factor for crack growth in the b-direction
$(\Delta \bar{K}_a)_{\text{eff}}$	effective cyclic value of the RMS stress intensity factor for crack growth in the a-direction
$(\Delta \bar{K}_b)_{\text{eff}}$	effective cyclic value of the RMS stress intensity factor for crack growth in the b-direction
K	local stress intensity factor
$\bar{K}_a$	RMS stress intensity factor for crack growth in the a-direction
$\bar{K}_{a,\text{max}}$	maximum value of the RMS stress intensity factor for crack growth in the a-direction during a cycle
$\bar{K}_{a,\text{min}}$	minimum value of the RMS stress intensity factor for crack growth in the a-direction during a cycle
$\bar{K}_b$	RMS stress intensity factor for crack growth in the b-direction
$\bar{K}_{b,\text{max}}$	maximum value of the RMS stress intensity factor for crack growth in the b-direction during a cycle
$\bar{K}_{b,\text{min}}$	minimum value of the RMS stress intensity factor for crack growth in the b-direction during a cycle
K_0	threshold value of the stress intensity factor
$\bar{K}_{\text{op}}$	RMS stress intensity factor during normal operating conditions

λ	parameter defining the intensity of an exponential distribution ,
σ_i	parameter that defines the intensity of the exponential distribution for the i-th transient
σ_{flo}	material flow stress
σ_{LC}	load-controlled stress
σ_{TE}	restraint of thermal expansion stress
σ_{DW}	deadweight stress
σ_p	pressure stress
σ_{EQ}	earthquake stress
σ_{RG}	radial gradient thermal stress
σ_R	welding residual stress
σ_{max}	maximum stress during a fatigue cycle
σ_{min}	minimum stress during a fatigue cycle
σ	stress or standard deviation

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The PRAISE computer code was developed for the Load Combination Program at the Lawrence Livermore National Laboratory (LLNL) by Science Applications, Inc. (SAI) under contract 3323809. Dr. David O. Harris had overall responsibility for the SAI activities and was primarily responsible for the fracture mechanics model. Mr. Stanley Basin (SAI), Dr. Laurence L. George (LLNL), and Dr. Donald Inglehart (Professor of Operations Research at Stanford University) made many valuable suggestions to the PRAISE calculational algorithm. Dr. Dilip Dedhia (SAI) exercised the code extensively. Mr. Fred Leverenz suggested the techniques used to generate random numbers. Key contributors to the programming and testing of the code were Richard Northrup and Douglas Smith.

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EXECUTIVE SUMMARY

The Code of Federal Regulations requires that structures, systems, and components that affect the safe operation of nuclear power plants be designed to withstand combinations of loads that can be expected to result from natural phenomena, normal operating conditions, and postulated accidents. One load combinations requirement--the combination of the most severe LOCA (loss-of-coolant accident) load and SSE (safe shutdown earthquake) loads--has been controversial because both events occur with very low probabilities. This issue became more controversial in recent years because postulated large LOCA and SSE loads were each increased by a factor of 2 or more to account for such phenomena as asymmetric blowdown and because better techniques for defining loading have been developed.

The original objective of Load Combinations Project I was to estimate the joint probability of simultaneous occurrence of both events and to develop a technical basis for the NRC (Nuclear Regulatory Commission) to use in determining whether it could relax its requirement on the combination of SSE and large LOCA for nuclear power plants. However, in the process of probability estimation we have not only estimated the probability of simultaneous occurrence of a large LOCA and an earthquake, but also estimated the probability of a large LOCA caused by normal and abnormal loading conditions without an earthquake. The estimates provide very useful information on the likelihood of asymmetric blowdown, which is a subset of large LOCA. Also, the probabilistic fracture mechanics model that we developed can be used to estimate the probability of pipe rupture with or without prior leak. That is, we can estimate the proportion of pipes that will leak detectably before rupture under normal operation, accident, or upset conditions. We can also evaluate the piping reliability in general. After a sufficient parametric study is done, we will be able to recommend a more rational basis for postulating pipe rupture locations.

If earthquakes and large LOCAs are independent events, the probability of their simultaneous occurrence is small. However, this probability is expected to be greater if an earthquake can induce pipe failure that leads to a LOCA. This LOCA could result directly (i.e., ground motion causes a pipe break in the primary cooling system) or indirectly (e.g., an earthquake causes a structural, mechanical, or electrical failure that in turn causes a pipe break in the primary cooling system).

In the first-phase study reported in these nine volumes, we concentrated on determining the probability of a large LOCA in a PWR plant directly induced by an earthquake. The expert consensus is that such a directly induced LOCA is most likely to result from the growth of cracks formed in the pipes during fabrication. Therefore, we selected a demonstration plant for study (Unit 1 of the Zion Nuclear Power Plant), modeled its primary cooling loop (Vol. 2), analyzed the best estimated responses of that piping system to nonseismic and seismic stresses (Vols. 3 and 4), developed a probabilistic fracture mechanics model of that piping system (Vols. 5, 6, and 7), analyzed the failure modes (Vol. 6) and developed a computer code, PRAISE, to simulate the life history of a primary coolant system (Vol. 9 is a PRAISE user's manual). Finally, we examined the probability with which an earthquake can indirectly induce a LOCA (Vol. 8).

Volume 9 is a computer code user's manual for PRAISE. The relation between this volume and the rest of the report is shown in the following schematic:

A basic issue in the safety evaluation of a nuclear reactor is its structural-mechanical response to various combinations of loads imposed by accidents and/or natural phenomena. The Load Combination Program sponsored by the Nuclear Regulatory Commission (NRC) and carried out at the Lawrence Livermore National Laboratory was designed to study various load combinations issues. The emphasis of Project I in the Load Combination Program was directed toward evaluating the probability that an earthquake could directly induce a complete pipe severance at one of the girth butt welds in the primary coolant system of the Zion-1 pressurized water reactor (PWR). Detailed discussions of the overall methodology and results from this program are given in Harris 81 and Streit 81.

The main ingredients of the evaluation performed in Project I are:

- (1) the stresses to which each weld is subjected under normal operating conditions, anticipated transients, and seismic events of various magnitudes,
- (2) the observed and anticipated frequency of transient events as well as the frequency and magnitude of the seismic events that may occur at the plant site,
- (3) a fracture mechanics model that translates the stresses calculated in (a) at the occurrence rates obtained in (b) to evaluate crack growth and pipe failure.

The flow of these ingredients in the Project I effort is shown in Figure 1.1. Science Applications, Inc. (SAI) was responsible for developing both the fracture mechanics models and a calculational tool which combines the above ingredients to produce numerical estimates for the distribution of time to first failure for individual joints in the Zion-1 primary coolant system. The resultant computer code is called PRAISE (Piping Reliability Analysis Including Seismic Events).

Figure 1.1. Information Flow in the Load Combinations Program

The objectives of this manual are:

- (1) present the assumptions in the PRAISE code,
- (2) summarize the fracture mechanics model implemented in PRAISE,
- (3) provide directions for constructing inputs to execute PRAISE,
- (4) give details of the structure and coding of PRAISE.

The PRAISE code is written in Standard FORTRAN IV. Although it was developed on a CDC-7600 computer, the amount of machine-dependent coding has been kept to an absolute minimum. Hence, conversion to other computers should be relatively straight forward. The PRAISE input was designed with the flexibility to handle a variety of piping reliability problems in which fatigue crack growth is the failure mechanism. Furthermore, the modular structure of PRACE facilitates tailoring of the algorithm by the analyst to suit his particular needs.

1.1 Objectives of the PRAISE Code

The goal of Project I was to develop and demonstrate a methodology for estimating the probability that a seismic event would induce a large-LOCA in the primary coolant system of a PWR. The girth butt welds have been identified as the principal locations in the primary coolant system where a large-LOCA can occur. Since the coolant system contains several dozen welds, an overall estimate of system reliability would be a function of the reliabilities of the individual welds. The approach adopted in the Load Cominations Program is to analyze each weld joint separately and then combine these results in an appropriate manner to estimate the probability of system failure. Although the procedure for analyzing individual welds is straightforward, the complexity of the fracture mechanics models, the variety of anticipated transients, the stochastic nature of the transient occurrence times, and the uncertainty in the effects of an earthquake would make a closed-form evaluation of the weld failure probability exceedingly difficult.

An alternative to a direct evaluation is a Monte Carlo simulation (Naylor 66, Schreider 66, Hammersley 64), which can be illustrated by the following situation. Suppose that an estimate for the failure probability of a specific weld in the primary coolant system is required. In theory, a simple experiment could be performed. A set of N weld joints, each of which is representative of the joint that is actually in the system is fabricated. These welds would be produced to the same specifications as the joint actually in the system. But, they will not be identical to that joint or amongst themselves because of manufacturing tolerances, variations between batches of materials, and differences in welding conditions. Suppose that each joint is subjected to a stress history typical of the actual joint. Normal operations, anticipated transients, and earthquakes are included. The stress histories are not identical but are equally likely to occur during the plant lifetime. Two pieces of data are recorded for each of the samples:

- (1) the time the joint failed, and
- (2) whether the failure was induced by an earthquake.

In this discussion, failure denotes either a through-wall defect or a complete pipe severance, i.e., a large-LOCA.

The probability that the joint has failed at or before time t is estimated by dividing the number of samples $N_F^*(t)$ that have failed at or before time t , or

$$P(t_F \leq t) \sim \frac{N_F^*(t)}{N} \quad (1.1)$$

where t_F is the failure time.

An estimate for the probability of an earthquake and failure occurring simultaneously is the number of failure induced by an earthquake divided by the number of samples, or

$$p(\text{FAIL} \cap \text{EQ}) \sim \frac{N_{\text{EQ-FAIL}}}{N} \quad (1.2)$$

where $N_{\text{EQ-FAIL}}$ is the number of times the failure of the weld was induced by the earthquake. Although this experiment may never be performed with real joints and real stresses, an equivalent numerical experiment can be performed by modeling joints and stress histories on a computer. PRAISE is the computer code that performs that numerical experiment.

In order to increase the computational efficiency, PRAISE employs several simplifying assumptions. The basis for the first assumption can be seen by expanding $P(t_F \leq t)$ in terms of conditional probabilities on the number of cracks in the weld joint, or

$$P(t_F \leq t) = \sum_{n=0}^{\infty} P(t_F \leq t|n)p(n) \quad (1.3)$$

where $P(t_F \leq t|n)$ is the probability that a weld joint with n as-fabricated defects will fail at or before time t ,
and $p(n)$ is the probability that n cracks exist in the weld initially.

If crack initiation is ignored, i.e., no cracks will form during the plant lifetime, and the operating stresses are below the material flow stress, Equation (1.3) then becomes

$$P(t_F \leq t) = \sum_{n=1}^{\infty} P(t_F \leq t|n)p(n) \quad (1.4)$$

where the summation index begins with $n=1$ rather than $n=0$, because

$$P(t_F \leq t|0) = 0^* \quad (1.5)$$

It can be shown (Harris 81) that if multiple cracks exist in the weld but do not interact, i.e., the growth rate of one crack is not affected by the presence of other cracks and the cracks do not coalesce to form a single larger crack, the results obtained assuming a single crack can be used to approximate the result when several cracks are present. Thus the present version of PRAISE assumes that only one as-fabricated defect exists in the weld joint. Unless otherwise noted, all future references to failure probabilities as calculated by PRAISE implicitly assume that one as-fabricated defect exists in the weld.

In addition to estimating the probability of a simultaneous earthquake and piping failure as in Equation (1.2), PRAISE also estimates some idea of how the failure probability varies with the intensity of the earthquake, or

$$p(\text{FAIL} \cap \text{EQ}|g) \sim \frac{N_{\text{EQ-FAIL}}(g)}{N} \quad (1.6)$$

where g is the intensity of the seismic event. Since earthquakes of moderate to large intensity occur infrequently, attempts to simulate Equation (1.6) by placing intensity g earthquakes into the stress histories according to their observed or forecasted rates of occurrence may require a large number of samples. Therefore, rather than estimating $P(t_F \leq t)$ and $p(\text{FAIL} \cap \text{EQ}|g)$, PRAISE estimates

*In reality, the probability of failure given no as-fabricated cracks is equal to the probability that the load-controlled stress σ_{LC} exceeds the material flow stress σ_{f10} . For the present problem, this probability is negligible (See Section 3.0 of Harris 81).

- (1) $P(t_F \leq t | \overline{EQ})$, the probability that a weld joint with one as-fabricated defect will have failed by time t if it experiences no earthquakes during the plant lifetime. $\overline{EQ}$ indicates that no earthquakes occur during the lifetime of the plant.
- (2) $P(t_F \leq t | EQ(g,t))$, the probability that a weld joint with one as-fabricated defect will fail at or before time t when it is subjected to its first earthquake at time t .

The present analysis assumes that the earthquake at t is the first earthquake. For example, consider two times t_1 and t_2 with $t_2 > t_1 > 0$ and the values $P(t_F \leq t_1 | EQ(g,t_1))$ and $P(t_F \leq t_2 | EQ(g,t_2))$. The earthquake at the earlier time t_1 has no effect on the results for $t > t_1$. In other words, the earthquake at t_2 is treated as the first earthquake in the evaluation of $P(t_F \leq t_2 | EQ(g,t_2))$.

Typical plots of $P(t_F \leq t | \overline{EQ})$ and $P(t_F \leq t | EQ(g,t))$ are shown in Figure 1.2. The difference between $p(t_F \leq t | EQ(g,t))$ and $p(t_F \leq t | \overline{EQ})$ is the influence of an earthquake of intensity g at time t on the failure probability of a given weld joint.

In terms of simulation, these quantities are estimated by the proportions

$$P(t_F \leq t | \overline{EQ}) \sim \frac{N_F(t)}{N} \quad (1.7)$$

and

$$P(t_F \leq t | EQ(g,t)) \sim \frac{N_F(g,t)}{N} \quad (1.8)$$

In Equation (1.7) the samples are subjected to stress histories which have no seismic events. $N_F(t)$ is the number of those samples which fail at or before time t . In Equation (1.8), the samples are subjected to an earthquake of intensity g at time t . $N_F(g,t)$ is the number of those samples which fail at or before time t .

Figure 1.2 Typical PRAISE Results ($g_2 > g_1$)

The probabilities calculated by Equation (1.7) and (1.8) can be used to estimate various other probabilities. For example, the probability that an earthquake at time t will lead to failure of a weld is given by

$$p(\text{FAIL} \cap \text{EQ at } t | \text{EQ}(t)) = \int_0^{\infty} \{P(t_F \leq t | \text{EQ}(g, t)) - P(t_F \leq t | \overline{\text{EQ}})\} G(g) dg \quad (1.9)$$

where $G(g)$ is the density function for earthquakes of intensity g . Again, Equation (1.9) assumes that no earthquakes have occurred prior to time t . The conditional probability of an earthquake induced failure given that exactly one earthquake occurs within the plant lifetime of T years is approximately

$$p(\text{FAIL} \cap \text{EQ} | \text{EQ}) = \int_0^T \frac{dt}{T} \int_0^{\infty} dg \{P(t_F \leq t | \text{EQ}(g, t)) - P(t_F \leq t | \overline{\text{EQ}})\} G(g) \quad (1.10)$$

Equation (1.10) implicitly assumes that the earthquake arrival times can be modeled as a Poisson process. When exactly one event is observed in time T , the arrival time can be shown to be uniformly distributed within the interval T (see Blake 79).

1.2 Overview of the PRAISE Algorithm

The basic steps of the Monte Carlo simulation algorithm implemented in PRAISE are shown pictorially in Figure 1.3. Each replication of the simulation starts with an as-fabricated interior surface circumferential defect. The initial size of this defect is randomly selected according to user-supplied probability density function (pdfs). Each defect is then checked to determine whether a pre-service ultrasonic test or a hydrostatic proof test would detect the defect. If the defect goes undetected, it is subjected to a typical stress history consisting of normal operations, anticipated transients, and postulated earthquakes. The user supplies the frequency of these events. A crack growth model translates this stress history into stress intensity factors and ultimately into increases in the crack size. For cracks which become through-wall defects, leak rate calculations are used in conjunction with leak detection models to determine whether the leak is detected and repaired. A LOCA failure criterion based on exceeding a critical net section stress is also included. Tabular results for Equations (1.7) and (1.8) and their variance estimates are output.

Figure 1.3 Basic PRAISE Flowchart

1.3 Assumptions in the PRAISE Code

The simplifying assumptions upon which the PRAISE code is constructed can be categorized as either

- (1) fracture mechanics, or
- (2) simulation.

The principal fracture mechanics assumptions are summarized in Chapter 2 of Vol. 5 of the final report. They are:

- The axial component of the stress is taken to be applied normal to the crack in cases where torsional stresses are small.
- The initial crack size distributions are defined in terms of the crack depth and the aspect ratio.
- The subcritical growth of a crack-like defect is as a fatigue crack, and the growth rate can be predicted from laboratory linear-elastic fracture mechanics tests [$da/dn = F(\Delta K, R, \text{environment, etc.})$].
- Stress corrosion cracking is not included
- The cyclic stress history controls fatigue crack growth, and is estimated from plant operating history regarding frequency and types of transients. Stresses for unanticipated transients such as water hammer are therefore omitted from consideration.
- The influence of seismic events enters through their contribution to the cyclic stress history and influence on maximum stresses.
- The unstable final growth of a crack is determined by a net section instability (exceedance of a critical net section stress).
- The applied stress to be used in the failure criterion is stress that cannot be relaxed by crack extension. These load-controlled stresses consist of pressure, deadweight, and seismic stresses.

- Axial pipe stresses induced by bending moments are taken to be uniformly distributed over the pipe cross-section at a value equal to the maximum bending stress at the inside pipe wall.
- The maximum principal stress, including the contributions of torsion and transverse shear, is assumed to act normal to the plane of the crack. Since torsional contributions are small, especially in the highly stressed joints, the value of the maximum principal stress and axial stress are usually quite close.
- Cracks are initially elliptical in shape and remain elliptical as they grow, unless they develop into a through-wall crack.
- The growth of an elliptical (or semi-elliptical surface) crack in the directions of its axes is controlled by an averaged (RMS) stress intensity factor associated with each axis.
- The growth rates for each axis of a crack at a given cyclic stress intensity factor can be determined from corresponding results on a planar specimen.
- Once a crack grows through the pipe wall, its outside surface length is equal to its inside surface length.

Assumptions inherent in the mechanics of the simulation include:

- Only circumferential welds are analyzed.
- Each weld joint has exactly one as-fabricated defect.
- The defect is located on the interior surface of the pipe and is oriented perpendicular to the axis of the pipe.
- Earthquakes are included only to evaluate their influence on the failure probability at user-specified points in time. They do not affect the crack growth at subsequent times.
- Temporal variation of coolant temperature during a plant transient can be treated as a random process.
- Leak rates are calculated for all through-wall cracks. For leaks that develop during an earthquake, the leak rate calculation is performed at the end of the earthquake. If the calculated leak rate exceeds a user specified value, the leak is assumed to be detected.

- The probability of detecting a part-through crack during an in-service inspection is a function only of its current crack size. It does not depend on the results of the pre-service inspection or previous in-service inspections.
- Part-through defects detected during a pre-service or in-service inspection are assumed to be removed and the weld repaired.
- Defects are not introduced during the repair process.
- Welding residual stresses are not included.

1.4 Outline of the User's Manual

The User's Manual consists of five chapters. Chapters 2 and 3 summarize the fracture mechanics and simulation algorithm. They are intended to help the analyst determine whether PRAISE is a suitable tool for his particular problem. Detailed discussions of the fracture mechanics models are given in the SAI final report for the Load Cominations Program (Harris 81). Chapter 4 is intended for the PRAISE user who must prepare input and execute the code. Data input formats and sample problems are provided. Suggestions are provided for setting up and executing specific problems. Chapter 5 contains a detailed description of the code itself and is directed to programmers and analysts who must modify or extend PRAISE to handle new or specialized problems. An effort was made to have each chapter stand alone. Hence, the reader may encounter instances where the same information appears in several chapters.

1.5 Comments on Notation

PRAISE was designed to be a very flexible computer code which brings together concepts from a variety of disciplines such as fracture mechanics, probability theory, statistics, and stress analysis. Since the PRAISE algorithm uses a large number of variables from each of these different disciplines, two notational problems arise when preparing the code description. First, there are only a limited number of symbols available to represent the various mathematical functions and variables. Second, the same symbol has often become well established in the different disciplines to represent different things. For example, the stress and standard deviation are both commonly represented by σ . In the following description different symbols are used to represent different concepts whenever that is possible. However, in those cases where the same symbol represents several different things, it is judged that the reader can distinguish the meaning by the context.

2.0 FRACTURE MECHANICS MODEL

The PRAISE computer code is a calculational tool designed to estimate the time to first failure (leak or LOCA) of girth butt weld in the primary coolant system of a nuclear reactor. The current version of PRAISE analyzes fatigue growth of an as-fabricated circumferential interior surface defect subjected to normal operations, anticipated transients, and various seismic events. The fracture mechanics model which is the basis of the PRAISE algorithm is closely related to earlier models. A detailed description of this model is given in Vol.5 of this report. For completeness, a summary of the major fracture mechanics models in the PRAISE code is presented in this section.

2.1 Initial Crack Size Distribution

The PRAISE model assumes that failure of a weld joint stems from fatigue growth of an as-fabricated defect. Crack initiation during plant operation is not included in the PRAISE model. Even though as-fabricated defects in piping welds are either sub-surface or surface, surface cracks pose a greater safety hazard than sub-surface cracks because for a given size the surface crack will have a larger stress intensity factor. Since stresses tend to be higher at the inner pipe wall, interior surface cracks are of greater concern than exterior surface cracks. This effect will be especially true of radial gradient thermal stresses. A circumferential orientation is more severe than a longitudinal (or axial) orientation because the maximum principal stresses are normal to the circumferential orientation. Hence, the starting point of the PRAISE model is an interior surface circumferential as-fabricated defect.

The major extension of the PRAISE algorithm beyond previous efforts lies in its two degree-of-freedom model of the crack. The as-fabricated surface cracks are assumed to be semi-elliptical and to remain semi-elliptical throughout the plant lifetime. The crack geometry is shown in Figure 2.1. The crack depth is denoted by a , while the crack half-length is indicated by b . The ratio of half-length to depth is known as the aspect ratio and denoted by $\beta (=b/a)$. Note that PRAISE does not assume a constant aspect ratio during the plant lifetime; i.e., the crack depth and the crack length can vary independently.

Since the defect is two-dimensional, two independent parameters are needed to define its size. PRAISE uses crack depth and aspect ratio as the parameters which describe the crack size. PRAISE furthermore assumes that crack depth and crack aspect ratio are independent random variables. This assumption allows the joint probability density function to be calculated as the product of the crack depth pdf and the aspect ratio pdf.

The PRAISE code can model the crack depth with either an exponential or log-normal pdf. The aspect ratio is modeled either as

- (1) a shifted exponential pdf in which
$$p(\beta)=0 \text{ for } \beta < 1,$$
- or
- (2) a truncated log-normal pdf which satisfies
 - (a) $p(\beta)=0$ for $\beta < 1$,
 - (b) $p(\beta=1)= \max p(\beta)$, and
 - (c) $p(>\beta_0)= P_0$

Condition (b) requires that the most likely crack shape is semi-circular, while condition (c) defines the fraction of defects which exceed the aspect ratio β_0 .

Published literature on crack depth and aspect ratio distributions that have been used in previous studies are given in Wilson 74, Nilsson 77, and Harris 79.

Figure 2.1. Crack Geometry

2.2 Crack Detection Probability

Pre-service and in-service inspections of piping weldments are performed using ultrasonic testing (UT). Considerable information exists in the literature on the probability of detecting a crack by such procedures as a function of defect size. Harris 76, Harris 77 suggests that the probability of not detecting a crack of depth a can be approximated as:

$$P_{ND}(a) = \frac{1}{2} \text{erfc}\left(\nu \ln \frac{a}{a^*}\right) \quad (2.1)$$

where $\nu = 1.60$
 a^* is the crack depth which has a 50-50 chance of being detected, and
 erfc is the complementary error function.

This is for a crack that is several times longer than it is deep. The above equation can be generalized to include both crack length and depth. If the crack area A is the relevant measure of crack size, then

$$P_{ND}(A) = \frac{1}{2} \text{erfc}\left(\nu \ln \frac{A}{A^*}\right). \quad (2.2)$$

where A^* is defined by

$$A^* = \frac{\pi}{4} D_B a^* \quad (2.3)$$

and D_B is the diameter of the ultrasonic beam. The current PRAISE model assumes that D_B is 1 inch. The crack area is defined by

$$A = \begin{cases} \frac{\pi}{2} ab & \text{if } 2b < D_b \\ \frac{\pi}{2} a \frac{D_b}{2} & \text{if } 2b \geq D_b \end{cases} \quad (2.4)$$

where a and $2b$ are the crack depth and crack length, respectively.

Becker 1980 suggests that a crack would have to be half way through the wall thickness before it would have a 50% chance of being found. Using a typical wall thickness of 2.50 in. this results in a value of a^* of 1.25 in. Since $\nu = 1.60$ will be assumed, a through-wall crack has a 95% chance of being detected by the ultrasonic inspection. Figure 2.2 plots the estimated P_{ND} for welds in cast austenitic materials and summarizes the parameters used.

Figure 2.2 Two Dimensional Log-Normal Model for Probability of Non-Detection of a Crack in Cast Austenitic Material.

2.3 Crack Growth Characteristics

PRAISE assumes that the semi-elliptical as-fabricated defects continue to grow as semi-elliptical defects. However, PRAISE does not assume that the initial aspect ratio is constant throughout the plant lifetime. The crack depth and crack length may vary independently during the plant lifetime. Various assumptions are made in the literature regarding the measure of the stress intensity factor controlling the a and b growth rate. PRAISE assumes that the growth rate for each dimension is controlled by an RMS-averaged stress intensity factor associated with that growth direction ("degree of freedom"). This is consistent with analyses in the literature and experimental evidence (Cruse 75a, Besuner 76, Besuner 78). It has the added advantage of allowing the RMS-averaged stress intensities to be evaluated by use of influence functions (Cruse 75b, Besuner 76, Besuner 78, Rice 72).

Suppose that the local stress intensity factor is denoted by $K(\phi)$ where ϕ is the elliptical angle along the crack front, then the RMS values of the stress intensity factor in the a and b directions are defined by

$$\bar{K}_a^2 = \frac{1}{\Delta A_a} \int_0^{\pi/2} K^2(\phi) d[\Delta A_a(\phi)] \quad (2.5a)$$

and
$$\bar{K}_b^2 = \frac{1}{\Delta A_b} \int_0^{\pi/2} K^2(\phi) d[\Delta A_b(\phi)] \quad (2.5b)$$

where ϕ is the elliptical angle measured along the crack front,

ΔA_a and ΔA_b are the incremental crack areas growing in the a and b directions, respectively.

In PRAISE, the relationship for estimating subcritical crack growth is

$$\frac{da}{dn} = \begin{cases} 0 & \text{if } (\Delta \bar{K}_a)_{\text{eff}} < K_0 \\ C(\Delta \bar{K}_a)_{\text{eff}}^m & \text{if } (\Delta \bar{K}_a)_{\text{eff}} \geq K_0 \end{cases} \quad (2.6)$$

$$\text{and } \frac{db}{dn} = \begin{cases} 0 & \text{if } (\Delta \bar{K}_b)_{\text{eff}} < K_0 \\ C(\Delta \bar{K}_b)_{\text{eff}}^m & \text{if } (\Delta \bar{K}_b)_{\text{eff}} \geq K_0 \end{cases} \quad (2.7)$$

C is the fatigue crack growth parameter and K_0 is a threshold value of the stress intensity factor. $(\Delta \bar{K}_a)_{\text{eff}}$ and $(\Delta \bar{K}_b)_{\text{eff}}$ are effective cyclic stress intensity factors which are defined by

$$(\Delta \bar{K}_a)_{\text{eff}} = \frac{\bar{K}_{a,\text{max}} - \bar{K}_{a,\text{min}}}{\sqrt{1 - \frac{\bar{K}_{a,\text{min}}}{\bar{K}_{a,\text{max}}}}} \quad (2.8)$$

$$\text{and } (\Delta \bar{K}_b)_{\text{eff}} = \frac{\bar{K}_{b,\text{max}} - \bar{K}_{b,\text{min}}}{\sqrt{1 - \frac{\bar{K}_{b,\text{min}}}{\bar{K}_{b,\text{max}}}}} \quad (2.9)$$

The subscripts min and max refer to the minimum and maximum values of the RMS stress intensity factor experienced during the cyclic loading. Experimental evidence suggests that the parameter C may be treated as a log normally distributed random variable. PRAISE has an option for treating C as a constant or as a log-normal random variable. The crack growth formulation in PRAISE also has a threshold value K_0 below which crack propagation is not calculated.

2.4 Stresses on the Crack Surface

The stresses to which a crack are subjected can be classified in several ways. For purposes of calculating the stress intensity factors, a logical distinction is between stresses distributed uniformly throughout the pipe wall and stresses which vary through the thickness of the pipe. Uniformly distributed through the wall stresses are:

- (1) the restraint of thermal expansion σ_{TE} ,
- (2) deadweight σ_{DW} ,
- (3) pressure σ_p , and
- (4) seismically-induced σ_{EQ} .

Circumferential variation of these stresses is currently ignored. Examples of stresses with non-uniform through the wall distributions are

- (1) radial gradient thermal stress σ_{RG} which are due to thermal fluctuations of the coolant during plant operation and
- (2) welding residual stresses σ_R .

In the shutdown condition, the relevant stresses are σ_{DW} and σ_R . In the hot operating condition, the relevant stresses are σ_{TE} , σ_{DW} , σ_p , and σ_R . During a transient, the σ_{RG} will be superimposed upon the hot operating condition stresses. The present version of PRAISE does not model welding residual stresses.

A second classification scheme separates the stresses into load-controlled and displacement-controlled components. The load-controlled components are σ_p , σ_{DW} , and σ_{EQ} . The displacement-controlled components are σ_{TE} , σ_{RG} , and σ_R . Even though all stresses contribute to crack growth, only the load-controlled components contribute to final crack instability.

2.5 Leak Quantification and Detection

Cracks which develop into part-through defects are assumed to result in a leak. PRAISE has a simple model for estimating the flow rate of collant through this crack. In this calculation, the crack is idealized as a rectangular opening rather than a semi-elliptical opening. The width of the rectangle is equal to the thickness of the pipe wall. The length of the opening is equal to the length of the semi-ellipse at the moment the crack breaks through the pipe wall. Since the as-fabricated cracks have aspect ratios greater than unity ($b/a > 1$), the smallest possible opening length is $2h$. A lower bound for the crack opening displacement can be estimated by using elasticity theory. This results in

$$\delta = \frac{4b\sigma(1 - \nu^2)}{E} \quad (2.10)$$

where δ is the crack opening displacement,
 b is the crack half length,
 σ is the axial stress,
 ν is Poisson's ratio, and
 E is Young's modulus.

A two-phase fluid mechanics calculation uses the opening displacement in Equation (2.10) to obtain a flow rate $\dot{Q}$ as

$$\dot{Q} = 0.294 \frac{b^2 \sigma}{h} - 3.5 \quad (2.11)$$

where $\dot{Q}$ is the flow rate in gpm and the other symbols have their previous definitions.

PRAISE also has a simple zero-one leak detection model. The user specifies a threshold flow rate for leak detection. PRAISE assumes that any leak with a calculated flow rate greater than this threshold value will be detected with probability one. Leaks with flow rates below this threshold value are

assumed to be undetected. Cracks that are detected are assumed to be repaired. For normal operations and anticipated transients, the leak calculation is performed after each cycle. For earthquakes, the leak calculation uses the crack geometry that is calculated after the final cycle.

2.6 Failure Criterion for Double-Ended Guillotine Break

Very tough and ductile materials fail either by a tearing instability or by exceeding a critical net stress on the uncracked portion of the pipe cross-section. The dimensions of piping in the primary coolant loop and the tearing resistance of the material indicate that a tearing instability will not occur in these pipes. Failure will, however, occur if a critical net section stress is exceeded (Harris 81) because of the inability of the remaining cross-section to transmit the applied loads. Only load-controlled stresses are included in the failure criterion. For a crack of area A_{crack} , the failure criterion for a complete pipe severance is

$$(A_{\text{pipe}} - A_{\text{crack}})\sigma_{\text{f10}} \leq A_{\text{pipe}}\sigma_{\text{LC}} \quad (2.12)$$

where σ_{f10} is the material flow stress,
 σ_{LC} is the load-controlled stress associated with a given operating condition, transient, or seismic event,
 A_{pipe} is the cross-sectional area of the pipe wall, and
 A_{crack} is an idealized cross-sectional area of the crack surface.

Simple rearrangement of Equation (2.12) gives

$$A_{\text{crack}} \geq A_{\text{pipe}} \left[1 - \frac{\sigma_{\text{LC}}}{\sigma_{\text{f10}}} \right] \quad (2.13)$$

The cross-sectional area of the pipe wall is the annular region between R_i and $(R_i + h)$, or

$$A_{\text{pipe}} = \pi[R_i + h]^2 - \pi R_i^2 = \pi h[2R_i + h] \quad (2.14)$$

where R_i is the inner pipe radius and h is the pipe thickness.

The area of the crack surface is approximated as a portion of the annular region between $(R_i + a)$ and R_i , or

$$A_{\text{crack}} = \frac{2b}{\pi 2R_i} \left[\pi(R_i + a)^2 - \pi R_i^2 \right] = ab \left[2 + \frac{a}{R_i} \right] \quad (2.15)$$

These definitions for A_{crack} and A_{pipe} are shown in Figure 2.3. Substitution of A_{pipe} and A_{crack} into Equation (2.13) and solving for b gives

$$b \geq \left[1 - \frac{\sigma_{\text{LC}}}{\sigma_{\text{f10}}} \right] \left[A_{\text{pipe}} \right] \left[\frac{1}{a(2 + \frac{a}{R_i})} \right] \quad (2.16)$$

For a given pipe geometry, material property, transient event, and crack depth, the right-hand side of Equation (2.16) represents a critical value of the half-crack length. When b exceeds this critical value, a complete severance is assumed to occur.

Figure 2.3 Geometry of Crack Used in the Failure Criterion

3.0 MONTE CARLO SIMULATION

The PRAISE computer code uses Monte Carlo simulation techniques to estimate the cdf 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. As discussed in Chapter 1, PRAISE is presently limited to analyzing welds having a single as-fabricated defect. The basic equations in the PRAISE simulation were presented as Equations (1.7) and (1.8) or

$$P(t_F \leq t) \sim \frac{N_F(t)}{N} \quad (3.1)$$

and

$$P(t_F \leq t | EQ(g,t)) \sim \frac{N_F(g,t)}{N} \quad (3.2)$$

where N is the sample size,
 $N_F(t)$ is the number of samples which have failed at or before time t , and
 $N_F(g,t)$ is the number of samples which have failed at or before time t if it is subjected to an earthquake of intensity g .

A simplified flowchart of the PRAISE algorithm is shown in Figure 3.1. As shown on the right side of the chart, the six basic steps are:

- (1) sample space definition and stratification,
- (2) initial crack size selection,
- (3) next event simulation,
- (4) crack growth calculation,
- (5) leak detection or LOCA event, and
- (6) estimate of failure probabilities and associated statistical variations.

Corresponding to each of these steps are various user-supplied inputs. The calculational steps and inputs are described in the following sections.

Figure 3.1. Simplified PRAISE Flowchart

3.1 Sample Space Definition

A key ingredient in the PRAISE algorithm is the sample space representation of the Monte Carlo simulation. Several possibilities exist. The final choice was motivated largely by computational convenience. From a physical standpoint, the most natural choice for the sample space is a two-dimensional representation with crack depth and crack length as the coordinates. Another possibility is to use crack depth and aspect ratio as the coordinates. These are also the variables that define the initial crack size distribution. The crack depth would lie between zero and the pipe wall thickness, while the aspect ratio is permitted to take values between one and infinity. Unfortunately, it is likely that the large values of aspect ratio could lead to some troublesome computational problems. A reasonable compromise is to use the reciprocal of the aspect ratio or $\beta^* = a/b$ as one coordinate. The limits on β^* become zero and one. The crack depth coordinate can be normalized by dividing by the wall thickness so that it also lies between zero and one. This representation of the sample space is displayed in Figure 3.2. Any crack with an (a/h) coordinate equal to one would be a through-wall defect and result in a leak. Cracks with $(a/b)=1$ are semi-circular defects. A small wedged-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

$$(a/b) < \frac{h}{2\pi R_i}(a/h) \quad . \quad (3.3)$$

The loci of all cracks that would cause a double-ended guillotine break are also shown in Figure 3.2. As shown in Section 2.6, the points in the LOCA failure have dimensions that satisfy

$$b \geq \left[1 - \frac{\sigma_{LC}}{\sigma_{f10}} \right] \left[A_{pipe} \right] \left[\frac{1}{a(2 + \frac{a}{R_i})} \right] \quad . \quad (3.4)$$

As suggested by intuition, the cracks are both deep and long.

Figure 3.2 Sample Space Representation

Typical crack growth trajectories are also displayed on Figure 3.2. 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. Many of the previous models either assumed a complete circumferential defect (crack depth equals wall thickness) or a constant aspect ratio (vertical lines in the (a/h) vs. (a/b) space).

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 through-wall leak or a catastrophic complete pipe severance. Figure 3.2 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.

3.2 Stratified Sampling

A direct evaluation of Equations (3.1) and (3.2) 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 methods, 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 (3.1) and (3.2) become

$$P(t_F \leq t | \overline{EQ}) = \sum_{m=1}^M \frac{N_{F,m}(t)}{N_m} p_m \quad (3.5)$$

and

$$P(t_F \leq t | EQ(g,t)) = \sum_{m=1}^M \frac{N_{F,m}(g,t)}{N_m} p_m \quad (3.6)$$

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

A typical stratification of the sample space is illustrated in Figure 3.3. 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 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 (3.5) and (3.6) 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.

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

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

N_m = Number of replications from m-th cell

p_m = Probability of initial crack lying in cell m

Figure 3.3 Stratification of the Sample Space

3.3 Transformation of Variables

The initial crack size distribution postulated by Harris 81 is defined in terms of the crack depth and the crack aspect ratio. Coordinates of the PRAISE sample space are normalized crack depth and inverse aspect ratio. This section describes the transformation of variables required to obtain the PRAISE formulation. The algorithm used to select initial crack sizes from their respective cells is also discussed.

Suppose that a two-dimensional joint probability density function is defined as $f(x_1, x_2)$ where x_1 and x_2 are the random variables. If new variables are defined by the functions g_1 and g_2 such that

$$y_1 = g_1(x_1, x_2) \quad (3.7)$$

$$y_2 = g_2(x_1, x_2) \quad (3.8)$$

or

$$\underline{y} = G(x_1, x_2) = G(\underline{x}) \quad (3.9)$$

where $\underline{x}$ and $\underline{y}$ are vectors

$$\underline{x} = \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} \quad (3.10)$$

$$\underline{y} = \begin{Bmatrix} y_1 \\ y_2 \end{Bmatrix} \quad (3.11)$$

and G is a generalized function

$$G = \begin{pmatrix} g_1(x_1, x_2) \\ g_2(x_1, x_2) \end{pmatrix} , \quad (3.12)$$

how does one obtain the joint probability density function $p(y_1, y_2)$ for the transformed variables y_1 and y_2 ? Elegant formulations and solutions for this problem are presented in several intermediate probability texts (Hahn 67, Hogg 70, Walpole 72). Only the results are presented here.

Suppose that Equations (3.7) and (3.8) can be solved for the original variables x_1 and x_2 , i.e., an inverse function to $G(\underline{x})$ exists. If this inverse function is denoted by H , or

$$\underline{x} = H(\underline{y}) = \begin{pmatrix} h_1(y_1, y_2) \\ h_2(y_1, y_2) \end{pmatrix} \quad (3.13)$$

the transformed pdf is given by

$$p(\underline{y}) = f(H(\underline{y})) \left| \frac{\partial H}{\partial \underline{y}} \right| \quad (3.14)$$

where $\frac{\partial H}{\partial \underline{y}}$ is the Jacobian of the inverse transformation

or

$$\frac{\partial H}{\partial \underline{y}} = \begin{bmatrix} \frac{\partial h_1}{\partial y_1} & \frac{\partial h_1}{\partial y_2} \\ \frac{\partial h_2}{\partial y_1} & \frac{\partial h_2}{\partial y_2} \end{bmatrix} \quad (3.15)$$

and $\left| \frac{\partial H}{\partial \underline{y}} \right|$ is the absolute value of the determinant of that Jacobian.

For the PRAISE algorithm, the following associations can be made:

$$\begin{aligned} x_1 &= a = \text{crack depth} \\ x_2 &= b/a = \text{aspect ratio} \\ y_1 &= a/h = \text{normalized crack depth} \\ y_2 &= a/b = \text{inverse aspect ratio} \\ y_1 &= x_1/h = g_1(x_1, x_2) \end{aligned} \quad (3.16)$$

$$y_2 = 1/x_2 = g_2(x_1, x_2) \quad (3.17)$$

$$x_1 = hy_1 = h_1(x_1, x_2) \quad (3.18)$$

$$x_2 = 1/y_2 = h_2(x_1, x_2) \quad (3.19)$$

Note that h is the crack depth and is not directly related to the inverse functions h_1 and h_2 . By taking the derivatives of h_1 and h_2 as defined in Equations (3.18) and (3.19), the Jacobian is

$$\frac{\partial H}{\partial \underline{y}} = \begin{bmatrix} h & 0 \\ 0 & -\frac{1}{y_2^2} \end{bmatrix} \quad (3.20)$$

and

$$\left| \frac{\partial H}{\partial \underline{y}} \right| = h/y_2^2 \quad (3.21)$$

Equation (3.14) can now be written as

$$p(\underline{y}) = f(hy_1, 1/y_2)(h/y_2^2) \quad (3.22)$$

Recall from Section 2.1 that the original random variables were assumed to be independent. Therefore the joint pdf is simply the product of the marginal density functions $f_1(x_1)$ and $f_2(x_2)$, or

$$f(x_1, x_2) = f_1(x_1)f_2(x_2). \quad (3.23)$$

Under the assumption of independence, Equation (3.22) becomes

$$p(\underline{y}) = f_1(hy_1)f_2(1/y_2)(h/y_2^2) \quad (3.24)$$

$$p(\underline{y}) = p_1(y_1)p_2(y_2) \quad (3.25)$$

where

$$p_1(y_1) = hf_1(hy_1) = hf_1(h(a/h)) \quad (3.26)$$

$$p_2(y_2) = f_2(1/y_2)(1/y_2^2) = f_2\left(\frac{1}{a/b}\right) \frac{1}{(a/b)^2} \quad (3.27)$$

Hence, the joint pdf for the new variables (a/h) and (a/b) is the product of the marginal density functions of these variables.

PRAISE is capable of modeling crack depth and aspect ratio either as exponential or log-normal distributions. PRAISE then transforms these inputs according to the procedure described above. The formulas used by PRAISE are given below:

(1) Crack depth is exponentially distributed

$$f_1(a) = \lambda \exp(-\lambda a) \quad a \geq 0 \quad (3.28)$$

$$\begin{aligned} p_1(a/h) &= h f_1(h(a/h)) \\ &= h \lambda \exp(-\lambda h(a/h)) \end{aligned}$$

$$p_1(a/h) = \mu \exp[-\mu(a/h)] \quad (3.29)$$

where $\mu = \lambda h$. (3.30)

(2) Crack depth is log-normally distributed

$$f_1(a) = \frac{1}{S\sqrt{2\pi}a} \exp\left[-\frac{1}{2}\left\{\frac{\ln(a/a_{50})}{S}\right\}^2\right] \quad a \geq 0 \quad (3.31)$$

$$\begin{aligned} p_1(a/h) &= h f_1(h(a/h)) \\ &= \frac{h}{S\sqrt{2\pi}(a/h)} \exp\left[-\frac{1}{2}\left\{\frac{\ln((a/h)/(a_{50}/h))}{S}\right\}^2\right] \end{aligned} \quad (3.32)$$

$$p_1(a/h) = \frac{1}{S\sqrt{2\pi}(a/h)} \exp\left[-\frac{1}{2}\left\{\frac{\ln(a/h) - \ln a'_{50}}{S}\right\}^2\right] \quad (3.33)$$

where

$$a'_{50} = a_{50}/h \quad .$$

The value a_{50} denotes the median of the distribution while S is the standard deviation of the distribution on $\ln a$. In these expressions, the initial distribution $f_1(a)$ is defined on $0 \leq a < \infty$. In reality, the crack depth must be less than the pipe wall thickness, i.e., the $f_1(a)$ functions should be restricted to the range $0 \leq a \leq h$. In order for these functions to integrate to one, normalization constants should be introduced into Equation (3.28) and (3.31). These constants would pass through the transformation unaltered so that

for both the exponential and log-normal distributions, the new pdf has the same form as the old pdf but with slightly modified parameters. The new rate parameter in the exponential is h times the old rate parameter, while the median in the new log-normal is $1/h$ times the old median.

(3) Aspect ratio is distributed as a shifted exponential

$$f_2(b/a) = \lambda \exp(-\lambda(b/a - 1)) \quad b/a \geq 1 \quad (3.34)$$

$$\begin{aligned} p_2(a/b) &= f_2\left(\frac{1}{a/b}\right) \frac{1}{(a/b)^2} \\ &= \frac{\lambda \exp(-\lambda(\frac{1}{a/b} - 1))}{(a/b)^2} \end{aligned} \quad (3.35)$$

(4) Aspect ratio is modeled as a truncated log-normal distribution

$$f_2(b/a) = \frac{1}{S\sqrt{2\pi}(b/a)} \exp \left[-\frac{1}{2} \left\{ \frac{\ln(b/a) - M}{S} \right\}^2 \right] \quad b/a > 1 \quad (3.36)$$

$$\begin{aligned} p_2(a/b) &= f_2\left(\frac{1}{a/b}\right) \frac{1}{(a/b)^2} \\ &= \frac{1}{S\sqrt{2\pi} \left(\frac{1}{a/b}\right)} \exp \left[-\frac{1}{2} \left\{ \frac{\ln(\frac{1}{a/b}) - M}{S} \right\}^2 \right] \frac{1}{(a/b)^2} \\ &= \frac{1}{S\sqrt{2\pi}(a/b)} \exp \left[-\frac{1}{2} \left\{ \frac{\ln(\frac{1}{a/b}) - M}{S} \right\}^2 \right] \end{aligned} \quad (3.37)$$

Typical plots of the distributions given in Equations (3.34) and (3.36) are shown in Figure 3.4. Equation (3.34) is a shifted exponential in which $f_2(b/a) = 0$ when $(b/a) < 1$. Equation (3.36) is a truncated log-normal distribution in which the portion $b/a < 1$ has been eliminated. The parameters M and S are the median and the standard deviation of the logarithm of b/a in the original (prior to truncation) function, respectively. A normalization constant should be introduced into Equation (3.36) so that $f_2(b/a)$ will integrate to unity.

$$\text{LOG-NORMAL: } f_2\left(\frac{b}{a}\right) = \frac{1.419}{.538\sqrt{2\pi}(b/a)} \exp \left[-\frac{1}{2} \left(\frac{\ln \frac{b}{a} - \ln 1.336}{.538} \right)^2 \right]$$

$$\text{EXPONENTIAL: } f_2\left(\frac{b}{a}\right) = 1.15 \exp \left[-1.15 \left(\frac{b}{a} - 1 \right) \right]$$

Figure 3.4 Typical Plots of $f_2(b/a)$

3.4 Pre-Service Inspection and Hydrostatic Proof Test

Prior to its first startup, the primary coolant system of a nuclear reactor undergoes several pre-service inspections designed to locate as-fabricated defects. PRAISE is capable of simulating the influence of both ultrasonic testing and a hydrostatic proof test on the failure probability. The PRAISE model for the ultrasonic test is described in Section 2.2. The hydrostatic proof test failure criterion is analogous to the LOCA failure criterion described in Section 2.6, or

$$(A_{\text{pipe}} - A_{\text{crack}}) \sigma_{\text{flo}} < A_{\text{pipe}} \sigma_{\text{LC}} \quad (3.38)$$

where the load-controlled stress consists of the deadweight and hydrostatic pressure stress contributions,

$$\sigma_{\text{LC}} = \sigma_{\text{DW}} + \sigma_{\text{p}} \quad (3.39)$$

A force balance for a closed cylinder shows that

$$\sigma_{\text{p}} \pi h (2R_i + h) = \text{Pressure} (\pi R_i^2) \quad (3.40)$$

For a thin-walled cylinder ($h \ll R_i$), the following approximation can be made:

$$\sigma_{\text{p}} \sim \frac{(\text{Pressure}) R_i}{2h} \quad (3.41)$$

Two general approaches exist for incorporating the influence of pre-service inspections on the estimates of failure probability. Suppose that the non-detection probability is given by $P_{\text{ND}}(a,b)$. One approach is to

simulate the test explicitly. For example, an initial defect is selected according to the postulated crack size distributions. A random number r that is uniformly distributed between 0 and 1 is then selected and compared to $P_{ND}(a,b)$. If $r > P_{ND}(a,b)$, the crack is assumed to be detected and corrective action is taken. Otherwise crack growth is simulated. Each selection of an initial crack size is treated as one of the samples included in the N and N_m that appear in the denominator of Equations (3.1), (3.2), (3.5), and (3.6). Cracks that are detected do not contribute to the samples which fail. Although this scheme is straightforward it may in fact be computationally inefficient. When the probability of non-detection is small, the majority of the defects that lead to failure will be rejected. Hence, only a relatively small number of cracks is actually simulated through the lifetime of the plant. This would result in large variances and large confidence intervals.

Another approach is to grow each crack that is sampled, and to correct the summation in Equations (3.1), (3.2), (3.5), and (3.6) to reflect the influence of non-detection. Rather than adding the number of failures that are observed, this approach would add the P_{ND} associated with the cracks that failed. This procedure can be illustrated by referring to Table 3.1. For simplicity consider first the case of simple random sampling. Suppose that N as-fabricated defects have been selected. The P_{ND} column gives the probability that the crack was not detected. The E_n column presents results from a hypothetical simulation in which random numbers are selected and compared with P_{ND} . A zero indicates that the crack was detected (failed to escape detection; i.e., $r > P_{ND}$). Otherwise $r \leq P_{ND}$ and a one is recorded. If N_E is the number of samples that escape detection, the ratio $\frac{N_E}{N}$ asymptotically approaches P_{ND} . The failed column gives results from a simulation in which crack growth is simulated regardless of whether it is detected. A one in the F_n column indicates that the n -th sample would lead to failure if not detected, while a zero indicates no failure over the lifetime of the plant. N_F is the number of failures in N samples without crack detection. In the direct approach, the only failures would be cracks that escaped the detection in the pre-service

inspection ($E_n = 1$) and then grew to failure within the plant lifetime ($F_n = 1$). N_{FE} is the number of cracks in N samples that escape detection and also fail. The failure probability is estimated by the ratio

$$P_F \sim \frac{N_{FE}}{N} \quad (3.42)$$

In the second approach, each failure is weighted by the probability of non-detection or

$$P_F \sim \frac{1}{N} \sum_{n=1}^N P_{ND,n} F_n \quad (3.43)$$

Since $F_n = 0$ when there is no failure, Equation (3.43) is equivalent to adding the P_{ND} of the cracks that fail.

A third and more sophisticated approach is to combine the postulated crack size distribution with the non-detection probability and hydrostatic proof test to create a post-inspection joint pdf. The initial crack sizes would then be drawn from this post-inspection joint pdf.

The second approach is presently being used in PRAISE. Computationally speaking, it is more efficient than the direct approach. It requires a minimal change in coding. On the other hand, an application of the third approach requires either that the post-inspection pdf be input by the user or that a specialized procedure be developed to combine the initial crack size distribution with the non-detection probabilities. These requirements would impose unnecessary additional calculations.

The analysis of a hydrostatic proof test is slightly less involved than the ultrasonic tests. All three approaches are identical because the hydrostatic test is assumed to give perfect results. P_{ND} is exactly one, if the conditions of Equation (3.38) are satisfied. Hence, cracks in the failure region have absolutely no chance of growing to a failure. The present assumption is that cracks in the failure region would be removed and a new initial crack size selected.

The welds may be periodically subjected to in-service inspections. The PRAISE procedure for modelling in-service inspections is similar to its treatment of pre-service inspections. At each in-service inspection time, a non-detection probability based on the crack size at that time is calculated. Suppose that $P_{ND}(t_i)$ denotes the non-detection probability corresponding to time t_i and that the individual inspections are independent. The overall non-detection probability for the n -th weld after the I -th in-service inspection is given

$$P_{ND,n} = \prod_{i=0}^I P_{ND,n}(t_i) \quad (3.44)$$

where $P_{ND,n}$ is the pre-service inspection. When in-service inspections are to be modelled, $P_{ND,n}$ as defined in Equation (3.44) should be used in Equation (3.43).

Table 3.1
PRAISE TREATMENT OF PRE-SERVICE INSPECTION AND HYDROSTATIC PROOF TEST

<u>Sample Number</u>	<u>Probability Non-Detection</u>	<u>Escaped Detection</u>	<u>Piping Failure</u>	<u>Escaped and Failed</u>	
n	$P_{ND,n}$	E_n	F_n	FE	$F_n \times P_{ND,n}$
1	.02	0	1	0	.02
2	.05	0	1	0	.05
3	.12	1	1	1	.12
4	.07	0	0	0	0
5	.10	1	0	0	0
<u>N</u>	<u>.05</u>	<u>0</u>	<u>1</u>	<u>0</u>	<u>.05</u>
		N_E	N_F	N_{FE}	

$$P_F = \frac{1}{N} N_{FE} \quad \text{or} \quad P_F = \frac{1}{N} \sum_{n=1}^N F_n P_{ND,n}$$

3.5 Arrival Time For Events

The PRAISE algorithm may be broadly classified as a next event simulation in which the calculation proceeds from event to event during the reactor lifetime. Thus, it is necessary for the simulation to model the arrival of various events. From an operational point of view, each point in time at which some calculation is performed is signaled by an event. According to this definition, events include the following:

- (1) startup or shutdown,
- (2) occurrence of anticipated transients,
- (3) pre-service and in-service inspection time, and
- (4) earthquake evaluation times.

The frequency of arrival for these events is controlled by the user.

The times at which startup/shutdown and anticipated transients occur can be uniformly spaced throughout the plant lifetime or appear randomly in the plant lifetime. In the stochastic case, the events are assumed to be part of a Poisson process. Each transient type will be governed by a separate intensity λ_i . The distribution of inter-arrival times is exponential or for the i -th transient type

$$f(t) = \lambda_i \exp(-\lambda_i t) \quad . \quad (3.45)$$

The intensity λ_i represents the average number of events in a unit time. The reciprocal ($= \lambda_i^{-1}$) is the mean time between arrivals of the i -th transient.

If the user desires to model pre-service inspections, they will naturally occur at the beginning of each replication. In-service inspections and earthquake evaluation times are deterministic inputs supplied by the user. These

can occur either uniformly spaced (with input time interval) or arbitrarily specified (though still deterministic) throughout the plant lifetime.

A simplified sequence of events modeled in a PRAISE replication is shown in Figure 3.5. The time begins at the top of the figure with a pre-service inspection and proof-test. An earthquake evaluation is inserted immediately before the plant startup. The time of occurrence of in-service inspections and earthquakes is shown on the left-hand side of the time line. Earthquake evaluations were defined to be twice as frequent as in-service inspections in this example. An earthquake evaluation is always present at the end of the plant lifetime if the crack survives until then. The time of occurrence of various anticipated transients is shown on the right-hand side of the time line.

Figure 3.5 Transient Event Sequence in PRAISE

3.6 Crack Growth Calculation

The two-degree-of-freedom fatigue crack growth model in PRAISE consists of the following four basic steps:

- (1) identify the condition causing the crack growth (heatup/cooldown or anticipated transient),
- (2) calculate the corresponding values of the effective RMS cyclic stress intensity factor,
- (3) evaluate the increase in crack depth and crack length,
- and (4) determine whether the expanded crack will lead to pipe failure.

A flowchart of the PRAISE crack growth algorithm is shown in Figure 3.6.

The equations representing the crack growth characteristics were presented in Section 2.3 and are repeated here:

$$\frac{da}{dn} = \begin{cases} 0 & \text{if } (\Delta \bar{K}_a)_{\text{eff}} \leq K_0 \\ C(\Delta \bar{K}_a)_{\text{eff}}^m & \text{otherwise} \end{cases} \quad (3.46a)$$

$$\frac{db}{dn} = \begin{cases} 0 & \text{if } (\Delta \bar{K}_b)_{\text{eff}} \leq K_0 \\ C(\Delta \bar{K}_b)_{\text{eff}}^m & \text{otherwise} \end{cases} \quad (3.46b)$$

$(\Delta \bar{K}_a)_{\text{eff}}$ and $(\Delta \bar{K}_b)_{\text{eff}}$ are the effective RMS cyclic stress intensity factors associated with crack depth and crack length, respectively. The general form of $(\Delta \bar{K})_{\text{eff}}$ is

$$(\Delta \bar{K})_{\text{eff}} = \frac{\bar{K}_{\text{max}} - \bar{K}_{\text{min}}}{\sqrt{1 - \frac{\bar{K}_{\text{min}}}{\bar{K}_{\text{max}}}}} \quad (3.47)$$

Figure 3.6. Crack Growth Algorithm

where $\bar{K}_{\max}$ and $\bar{K}_{\min}$ are the maximum and minimum values of the RMS stress intensity factor during the cyclic loading. PRAISE also has an option to treat the crack growth parameter C either as a user input constant or as a log normally distributed random variable which changes from replication to replication. For the stochastic case, the user provides the median and the 90-th percentile values of C .

For purposes of calculating $\bar{K}_{\min}$ and $\bar{K}_{\max}$, the loading conditions may be classified either as

- (1) uniform through the wall stresses, or
- (2) non-uniformly distributed through the wall stresses, such as radial gradient thermal stresses and welding residual stresses.

For uniform through the wall stresses, the present model assumes that

$$\bar{K}_{\max} = \sigma_{\max} \sqrt{a} f(a/h, a/b) \quad (3.48a)$$

$$\bar{K}_{\min} = \sigma_{\min} \sqrt{a} f(a/h, a/b) \quad (3.48b)$$

where $\sigma_{\min}$ and $\sigma_{\max}$ are the minimum and maximum values of the uniform through the wall stresses, a is the crack depth, and $f(a/h, a/b)$ is a normalized stress intensity factor for uniform through the wall stresses.

Equations (3.48a) and (3.48b) are equally applicable to growth in either the a or b directions. However, the function $f(a/h, a/b)$ is different for the a and b directions. In the cold shutdown condition, the only contribution to the uniform stress is the deadweight. On the other hand, in the hot operating condition there are contributions from the deadweight, pressure, and thermal expansion. For the specific case of a heatup/cooldown cycle,

$$\sigma_{\min} = \sigma_{DW} \quad (3.49)$$

$$\sigma_{\max} = \sigma_{DW} + \sigma_P + \sigma_{TE} \quad (3.50)$$

PRAISE currently assumes that radial gradient thermal stresses are the only contributors to non-uniform through the wall stresses. Since these stresses are associated with temperature transients, they will be superimposed onto the normal operating stresses. Hence $\bar{K}_{\min}$ and $\bar{K}_{\max}$ may be written as

$$\bar{K}_{\min} = \bar{K}_{op} + \Delta\bar{K}_{\min}(i, a/h, a/b, \Delta T) \quad (3.51a)$$

$$\bar{K}_{\max} = \bar{K}_{op} + \Delta\bar{K}_{\max}(i, a/h, a/b, \Delta T) \quad (3.51b)$$

where $\bar{K}_{op}$ is the stress intensity factor corresponding to the normal operating condition prior to the transient,
 $\Delta\bar{K}_{\min}$ is the largest decrease in the stress intensity factor during the transient,
 $\Delta\bar{K}_{\max}$ is the largest increase in the stress intensity factor during the transient, and
 ΔT is the temperature variation during the transient.

The temperature variation is displayed explicitly in $\Delta\bar{K}_{\min}$ and $\Delta\bar{K}_{\max}$ because it might vary between occurrences of a particular transient type. PRAISE accommodates these differences in temperature variation by treating ΔT as a random variable. The PRAISE formulations for $\Delta\bar{K}_{\min}$ and $\Delta\bar{K}_{\max}$ are

$$\Delta\bar{K}_{\min} = \Delta T \sqrt{a} g_{\min}(i, a/h, a/b) \quad (3.52a)$$

$$\Delta\bar{K}_{\max} = \Delta T \sqrt{a} g_{\max}(i, a/h, a/b) \quad (3.52b)$$

where the functions $g_{\min}$ and $g_{\max}$ are different for the a and b directions. In general, a pdf will be supplied by the user to describe the distribution of ΔT for each transient type. A complete description of the procedure used to generate the functions f , $g_{\min}$, and $g_{\max}$ is given in Harris 81. The coding used by PRAISE to evaluate these functions is shown in Chapter 5 of this manual.

If the crack grows through the pipe wall, the increase in crack length for the heatup-cooldown event is given by

$$\frac{db}{dn} = C\sqrt{\pi b} (\sigma_{DW} + \sigma_P + \sigma_{TE}), \quad (3.53a)$$

while for transients with radial gradient thermal stresses it is assumed to be

$$\frac{db}{dn} = 0. \quad (3.53b)$$

The basis for the approximation in Equation (3.53b) is that radial gradient thermal stresses are self-equilibrating through the wall; i.e., there are both tensile and compressive stresses along the crack front. Therefore, only a portion of the crack will actually grow. Furthermore, the intensity of these stresses are expected to be small. The approximation given by Equation (3.53b) is judged to be adequate for the present purposes.

After each increment of crack growth, the crack is examined to determine whether it will lead to a double-ended guillotine break. As shown in Section 2.6, this failure criterion is based on the exceedance of a critical net section stress, or

$$(A_{\text{pipe}} - A_{\text{crack}})\sigma_{f10} \leq A_{\text{pipe}} \sigma_{LC} \quad (3.54)$$

The user has the option of treating σ_{f10} either as a constant to be used throughout the calculation or a normally distributed random variable that varies from replication to replication. In the latter case, the user specifies the mean and standard deviation of the normal distribution. The load-controlled stress is defined by

$$\sigma_{LC} = \sigma_{DW} + \sigma_P \quad (3.55)$$

If the crack is a through wall defect (but does not produce a large LOCA), a leak rate calculation is performed. PRAISE is designed to maintain statistics on the number of leaks and the number of "big" leaks. The user is expected to provide a value of leak rate which is the threshold for the big leak definition.

The leak rate is also used in conjunction with a leak detection model to determine whether a given leak can be detected. The current leak detection model has a user-specified leak detection threshold. Any leak with a rate greater than this threshold is assumed to be detected and leads to a plant shutdown with subsequent corrective maintenance.

3.6.1 Approximations for High Frequency Low Amplitude Fatigue Cycles

For transients with high frequency but low amplitude stress cycles, the amount of crack growth per cycle may be quite small. Hence, a cycle-by-cycle simulation is inefficient. An approximation can be made that significantly reduces computer requirements but still retains much of the accuracy associated with a cycle-by-cycle analysis. Since the crack size increases very little during an individual cycle, the same stress intensity factor can be applied over several cycles. For example, suppose that Δa_{TOT} represents the total change in crack depth after N occurrences of a high frequency low amplitude transient. In terms of the crack growth relationship in Equation (3.46a), the depth increases by

$$\Delta a_{TOT} = \sum_{n=1}^N C \left(\Delta \bar{K}_a(a_n, b_n) \right)_{eff}^m \quad (3.56)$$

where the dependence of $\Delta \bar{K}_a$ on the current crack dimensions (a_n and b_n) is shown explicitly. If $\Delta \bar{K}_a$ is constant over the N cycles, or

$$\left(\Delta \bar{K}_a(a_n, b_n) \right)_{eff} = \left(\Delta \bar{K}_a(a_1, b_1) \right)_{eff} \quad (3.57)$$

then

$$\Delta a_{TOT} = C N \left(\Delta \bar{K}_a(a_1, b_1) \right)_{eff}^m$$

and

$$\Delta a_{TOT} = C \left[N^{\frac{1}{m}} \left(\Delta \bar{K}_a(a_1, b_1) \right)_{eff} \right]^m \quad (3.58)$$

Equation (3.58) shows that the equivalent stress intensity factor is $N^{\frac{1}{m}}$ times the stress intensity factor present at the first cycle in the block. An analogous result is applicable for the stress intensity factor for increase of the crack length.

3.7 Influence of Earthquakes on Crack Growth

Seismic events occur at random times and with random intensities. It would be inefficient to simulate earthquakes as stochastic processes in the PRAISE code. The probability of a significant earthquake within a 40 year period is generally low, so that many lifetimes would have to be simulated in order to generate a sufficiently large sample to confidently estimate the influence of seismic events on piping reliability. This is somewhat analogous to the problem discussed earlier associated with randomly sampling the crack size distribution. That problem was circumvented by using stratified sampling. In the case of seismic events another approach will be taken. In this case, the influence of specified earthquakes of a given intensity and time of occurrence will be evaluated. For example, the influence of a safe shutdown earthquake (SSE) occurring 20 years into the plant lifetime can be considered. Such results can then be used in conjunction with information on the probability of such an event occurring at that time to provide estimates of the probability of a seismically induced piping failure.

Within each replication, PRAISE periodically evaluates the instantaneous effect of seismic events on the crack growth. The times at which these evaluations occur are known as evaluation times and are provided by the user. These times may be placed either at regularly spaced intervals or be arbitrarily specified throughout the plant lifetime. Since earthquakes have a continuum of intensities and stress-time histories, the evaluation earthquake is actually a series of earthquakes. It is envisioned that several earthquake intensity categories spanning the credible values at a given site will be included. Within each intensity category, several earthquakes will be examined. These will be treated as representative and equally likely to occur at that intensity. At each evaluation time, the current crack is subjected to each of the postulated earthquakes. The earthquake evaluation algorithm is shown schematically in Figure 3.7. A flowchart of the algorithm is shown in Figure 3.8.

Figure 3.7 Crack Growth at an Earthquake Evaluation Time

Figure 3.8 Algorithm for Evaluation Earthquakes

The treatment of crack growth during seismic events is somewhat different than crack growth under normal operations or anticipated transients. Fatigue crack growth due to non-seismic events can be characterized by a single loading cycle of known amplitude. Relationships of the form

$$a_{\text{new}} = a_{\text{old}} + C(\Delta \bar{K}_a)_{\text{eff}}^m \quad (3.59)$$

are very convenient for predicting the crack growth under single cycle loadings. Seismic events characteristically have many cycles, each of which may have a different amplitude. A cycle-by-cycle crack growth analysis would require repeated applications of Equation (3.59) and consequently repeated evaluation of $(\Delta \bar{K})_{\text{eff}}$. This approach is not only time consuming but is questionable in accuracy because the amplitude of each cycle is unknown. A reasonable compromise to derive a value (which is denoted the S-factor) such that

$$a_{\text{new}} = a_{\text{old}} + C[S(\Delta \bar{K}_a)_{\text{eff}}]^m \quad (3.60)$$

where a_{old} and a_{new} are the crack sizes before and after the seismic events. The basis for this approximation is given in Section 2.6 of Harris 81. After each evaluation earthquake and corresponding increment of crack growth, the crack is examined for leak or LOCA. The appropriate load-controlled stress to be used in the failure criterion is

$$\sigma_{\text{LC}} = \sigma_{\text{DW}} + \sigma_{\text{P}} + \sigma_{\text{EQ}} \quad (3.61)$$

where σ_{EQ} is the maximum stress experienced by the joint during the earthquake. This is a conservative approach because the worst load-controlled stress is applied to the maximum crack size. Within a single seismic event, it is conceivable that a crack can proceed from a safe condition to a leak and ultimately a LOCA. Since the temporal extent of the earthquake is very short, leak detection will be ineffective in shutting down the plant if a leak should occur during the earthquake. Hence all comparisons for leak and LOCA are performed after the earthquake has occurred.

The effects of the evaluation earthquake are removed, i.e., the crack dimensions are reset to their pre-evaluation values, after each application of the evaluation earthquake. In order to further clarify this point, consider the sample space shown in Figure 3.9. Let a_0 represent the initial crack. The line a_0 - a_1 - a_2 - a_3 is the so-called crack trajectory in the absence of the earthquake. Suppose that evaluation earthquakes are desired at times corresponding to points a_0 , a_1 , a_2 , and a_3 . The resulting crack dimensions are schematically represented by the points a'_0 , a'_1 , a'_2 , and a'_3 . Since a'_0 , a'_1 , and a'_2 have a/h values less than 1.0 and are not in the LOCA region, earthquakes at times t_0 , t_1 , and t_2 would not lead to failure. On the other hand, an earthquake at time t_3 would cause a through the wall defect. PRAISE records at each evaluation time the number of leaks and LOCAs that result from a single earthquake at that time. It is important to recognize that once the evaluation is performed, the crack size is returned to its pre-evaluation value and the simulation proceeds. In other words, points on the crack trajectory are not influenced by the evaluation earthquakes.

Figure 3.9 Crack Growth Trajectories During the Evaluation of Earthquakes.

3.7.1 The S-Factor for Crack Growth During Earthquakes

As shown in Equations (3.60) and (3.61), PRAISE models crack growth during seismic events by using an S-factor which incorporates the variation in amplitude and number of cycles during the earthquake. A derivation for the S-factor is presented in this section. Suppose that an earthquake has the stress history shown in Figure 3.10. Each of the N identical cycles has an amplitude $(\sigma_{\max} - \sigma_{\min})$. If these stresses are assumed to be uniform-through the wall and the crack growth relationship has an exponent of four (4), then as derived later in Equation (5.76), the effective stress intensity factor is

$$(\Delta \bar{K})_{\text{eff}} = \sqrt{(\sigma_{\max} - \sigma_{\min}) \sigma_{\max}} \sqrt{a} f(a/h, a/b) . \quad (3.63)$$

In an exact calculation, the value of $\sqrt{a} f(a/h, a/b)$ should be updated after each of the N cycles. However, as a first approximation and if the amount of crack growth is small, the product $\sqrt{a} f(a/h, a/b)$ can be treated as a constant. The total crack growth is then approximated by

$$\Delta a_{\text{TOT}} = C N \left\{ \sqrt{(\sigma_{\max} - \sigma_{\min}) \sigma_{\max}} \sqrt{a} f(a/h, a/b) \right\}^4 \quad (3.64)$$

$$= C \left\{ S \sqrt{a} f(a/h, a/b) \right\}^4 . \quad (3.65)$$

The quantity

$$\sqrt[4]{N} \sqrt{(\sigma_{\max} - \sigma_{\min}) \sigma_{\max}}$$

is the S factor. A slightly more accurate result could be obtained by re-evaluating $\sqrt{a} f(a/h, a/b)$ periodically. For example, if an additional evaluation is performed, the total crack growth is then approximated by

$$\begin{aligned} \Delta a_{\text{TOT}} = & C \frac{N}{2} \left\{ \sqrt{(\sigma_{\max} - \sigma_{\min}) \sigma_{\max}} \sqrt{a_0} f((a/h)_0, (a/b)_0) \right\}^4 \\ & + C \frac{N}{2} \left\{ \sqrt{(\sigma_{\max} - \sigma_{\min}) \sigma_{\max}} \sqrt{a_1} f((a/h)_1, (a/b)_1) \right\}^4 \end{aligned} \quad (3.66)$$

Figure 3.10 Simplified Earthquake Stress History

where the subscript 0 denotes the pre-earthquake state and the subscript 1 denotes the crack dimensions after $N/2$ cycles. Equation (3.65) can be written as

$$\Delta a_{TOT} = C \left\{ \frac{S}{2^{1/4}} \right\}^4 \sum_{n=0}^1 \left\{ \sqrt{a_n} f((a/h)_n, (a/b)_n) \right\}^4 \quad (3.67)$$

and generalized to obtain

$$\Delta a_{TOT} = C \left\{ \frac{S}{\sqrt[4]{N_{eq}}} \right\}^4 \sum_{n=0}^{N_{eq}-1} \left\{ \sqrt{a_n} f((a/h)_n, (a/b)_n) \right\}^4 \quad (3.68)$$

where N_{eq} is an equivalent number of earthquake cycles.

Hence if the earthquake is modeled with N_{eq} (equivalent) cycles rather than a single cycle, the equivalent S-factor is

$$S_{eq} = \frac{S}{\sqrt[4]{N_{eq}}} \quad (3.69)$$

The PRAISE user models earthquakes by specifying the value of S^4 and, if desired, the equivalent number of cycles.

Realistically speaking, earthquakes do not have identical stress cycles. Hence, the S factor definition is not as simple as Equation (3.65). Nevertheless, if an S is defined, Equations (3.68) and (3.69) are assumed to be applicable even in the more realistic case.

3.8 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. It was shown in Chapter 1 that $F(t)$, the estimator for the probability of failure at or before time t , is given by

$$F(t) = \frac{N_F(t)}{N} \sim P(t_F \leq t) \quad (3.70)$$

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 , and

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

$$I_n(t) = \begin{cases} 1 & \text{if the weld is failed at time } t, \\ 0 & \text{if the weld is not failed at time } t. \end{cases} \quad (3.71)$$

The subscript n indicates the particular replication.

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

$$N_F(t) = \sum_{n=1}^N I_n(t), \quad (3.72)$$

while the proportion of failures is estimated by

$$F(t) = \frac{1}{N} \sum_{n=1}^N I_n(t) \quad (3.73)$$

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

$$\begin{aligned} s^2(t) &= \frac{1}{N-1} F(t) [1-F(t)] \\ &= \frac{1}{N-1} [F(t) - F^2(t)] \end{aligned} \quad (3.74)$$

$$s^2(t) = \frac{1}{N(N-1)} \left[\left(\sum_{n=1}^N I_n(t) \right) - \frac{1}{N} \left(\sum_{n=1}^N I_n(t) \right)^2 \right] \quad (3.75)$$

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

$$F_m(t) = \frac{N_{F,m}(t)}{N_m} \quad (3.76)$$

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

If, in analogy to Equation (3.71), Bernoulli random variables for initial cracks drawn from the m -th cell are defined as

$$I_{m,n}(t) = \begin{cases} 1 & \text{if the weld with an initial defect from the} \\ & \text{m-th cell is failed at time } t, \text{ and} \\ 0 & \text{if the weld with an initial defect from the} \\ & \text{m-th cell is not failed at time } t \end{cases} \quad (3.77)$$

then

$$N_{F,m}(t) = \sum_{n=1}^{N_m} I_{m,n}(t) \quad (3.78)$$

and

$$F_m(t) = \frac{1}{N_m} \sum_{n=1}^{N_m} I_{m,n}(t) \quad (3.79)$$

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 (3.74), an unbiased estimator for the variance of $F_m(t)$ is

$$s_m^2 = \frac{1}{N_m - 1} F_m(t) [1 - F_m(t)] \quad (3.80)$$

$$s_m^2 = \frac{1}{N_m(N_m - 1)} \left[\sum_{n=1}^{N_m} I_{m,n}(t) - \frac{1}{N_m} \left(\sum_{n=1}^{N_m} I_{m,n}(t) \right)^2 \right] \quad (3.81)$$

It can be shown (see Section 6.9 of Yamane 67) 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

$$F_{st}(t) = \sum_{m=1}^M F_m(t) p_m \quad (3.82)$$

and

$$s_{st}^2(t) = \sum_{m=1}^M s_m^2(t) p_m \quad (3.83)$$

Additional considerations with regard to computational efficiency suggest that Equation (3.77) should be modified to accommodate the pre-service and in-service inspection test. The random variables are redefined so that

$$I_{m,n}(t) = \begin{cases} P_{ND,n} & \text{if the weld has failed by time } t, \\ 0 & \text{if the weld has not failed by time } t \end{cases} \quad (3.84)$$

Equations (3.78) and (3.79) are then evaluated using $I_{m,n}(t)$ as defined in Equation (3.84).

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

$$I_{m,n}(g,t) = \begin{cases} P_{ND,n} & \text{if a category } g \text{ earthquake occurs at} \\ & \text{time } t \text{ and the weld with a crack from} \\ & \text{the } m\text{-th stratum has failed at or before} \\ & \text{time } t \\ 0 & \text{if a category } g \text{ earthquake occurs at} \\ & \text{time } t \text{ and the weld with a crack from} \\ & \text{the } m\text{-th stratum has not failed at or} \\ & \text{before time } t. \end{cases} \quad (3.85)$$

The corresponding estimators are:

(1) stratum proportion

$$F_m(g,t) = \frac{1}{N_m} \sum_{n=1}^{N_m} I_{m,n}(g,t) \quad (3.86)$$

(2) variance of the stratum proportion

$$s_m^2(g,t) = \frac{1}{N_m-1} F_m(g,t) [1 - F_m(g,t)] \quad (3.87)$$

(3) overall failure probability

$$F_{st}(g,t) = \sum_{m=1}^M p_m F_m(g,t) \quad (3.88)$$

(4) variance of the overall failure probability

$$s_{st}^2(g,t) = \sum_{m=1}^M p_m^2 s_m^2(g,t) \quad (3.89)$$

4.0 INPUT DESCRIPTION

This chapter is intended for the PRAISE user; i.e. the person who must construct the input deck to execute the code. The input can be roughly divided into the following seven categories, as shown in Figure 4.1:

- (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 and frequency of transients, and
- (7) seismic intensity and stresses.

These data are all read in through the subroutine INITIAL. A brief description of each input variable is given in this chapter. A detailed card-by-card description of the format is also given in Section 4.8. Each card is identified by a sequence number indicating its order in each of the above categories.

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
 - 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 PRAISE
 - user-specified
6. Transient Data
 - frequency of occurrence
 - maximum temperature excursion
 - normalized variation of stress intensity factor during transients
7. Earthquake Definitions
 - S-factor
 - load controlled stresses

Figure 4.1 PRAISE Input Data Categories

4.1 Problem Control Variables

The first card read by 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 card of the input deck.

- 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-M cell). If the user defines the cells and $NTRIES < 0$, all 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. This is illustrated in Figure 4.2.
- ISQARE - option for definition of the cells in the stratification scheme. If $ISQARE = 1$ then PRAISE generates the set of cells based on the values of NAOH and 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.
- KTYPES - total number of types of operating conditions and transient events that are to be modeled. PRAISE assumes that the heatup/cool-down cycle is the first transient event type. This does not 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, 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 into at user specified intervals.
- IDEBUG - option for additional debugging output. IDEBUG = 0 yields the normal output, while IDEBUG = 1 gives the additional output. The user is cautioned that this option not only generates a large volume of output, but it also is presently not well formatted.
- KONPRP - option for the constant in the crack growth relationship. If KONPRP = 1, the same value is used throughout the simulation for the constant. When KONPRP = 0, the constant is assumed to be log-normally distributed and is changed at the beginning of each replication.

- NEQINT - number of earthquake intensity categories
- MCELLS - number of cells in the stratified sample space when it is input by the user. If PRAISE constructs the sample space, the value of MCELLS is ignored.
- 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.
- THRIZN - plant lifetime (years). If no failures occur, this is the maximum length of time that a particular simulation runs.
- ISKIP - 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 ISKIP. For example, if ISKIP = 5, then every 5th evaluation time is printed out.
- NPSI - option for modelling an ultrasonic pre-service inspection. If NPSI = 0, then no inspection is performed. If NPSI = 1, a pre-service inspection is performed.

4.2 Geometry and Material Properties

The variables that define the pipe geometry are:

THICK - wall thickness of the pipe.

RIN - inside radius of the pipe.

As shown in Section 2.3, the crack growth relationships in PRAISE are:

$$\frac{da}{dn} = \begin{cases} 0 & \text{if } (\Delta \bar{K}_a)_{\text{eff}} \leq K_0 \\ C(\Delta \bar{K}_a)_{\text{eff}}^m & \text{otherwise} \end{cases} \quad (4.1)$$

and

$$\frac{db}{dn} = \begin{cases} 0 & \text{if } (\Delta \bar{K}_b)_{\text{eff}} \leq K_0 \\ C(\Delta \bar{K}_b)_{\text{eff}}^m & \text{otherwise} \end{cases} \quad (4.2)$$

The inputs for Equations (4.1) and (4.2) are:

THRHL D - the threshold value for crack propagation ($\text{KSI-IN}^{\frac{1}{2}}$). This corresponds to K_0 in Equations (4.1) and (4.2)

EMEXP - value of the exponent denoted by m in Equations (4.1) and (4.2). Experimental evidence suggests that m is in the range of 2-4. For the piping materials considered in the Load Combination project, a value of $m = 4.0$ was judged appropriate. Since exponentiation to an integer power is computationally more efficient than exponentiation to a real power, PRAISE presently equates EMEXP to MEXP and raises the stress intensity factor to the MEXP power.

CONSMU - parameter for the constant in the crack growth law. If the constant is the same in each replication ($\text{KONPRP} = 1$), then CONSMU is the value of the constant. If C is log normally

Figure 4.2 Number of Samples Assigned to the M-th Cell

distributed (KONPRP = 0), then CONSMU is the median of the distribution.

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

The failure criterion for complete pipe severance is based on the exceedance of a critical net section stress. The material flow stress becomes the relevant parameter. PRAISE has the option of treating σ_{f10} either 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_{f10} . 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.

4.3 Initial Crack Size Distribution

In 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 log-normally distributed, the pdf is given by

$$p(a) = \frac{1}{Sa\sqrt{2\pi}} \exp \left[-\frac{1}{2} \left\{ \frac{\ln a - \ln a_{50}}{S} \right\}^2 \right] \quad (4.3)$$

The relevant input parameters are:

AMEDIN - the median value of the log-normal distribution. It is equal to a_{50} in Equation (4.3).

ASIGMA - the shape factor in the log-normal distribution. It is also the standard deviation of $\ln a$ and corresponds to S in Equation (4.3).

Both AMEDIN and ASIGMA have units of inches.

If the crack depth is exponentially distributed, the pdf is

$$p(a) = \lambda \exp(-\lambda h) \quad (4.4)$$

and the required input is

ALAMDA - the intensity or rate parameter λ (in^{-1}) for exponential distribution.

For both Equations (4.3) and (4.4), PRAISE computes normalization factors such that the integrals of $p(a)$ over the range $0 \leq a \leq h$ are unity.

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

$$p(b/a) = \frac{C}{S\sqrt{2\pi}(b/a)} \exp \left[-\frac{1}{2} \left\{ \frac{\ln(b/a) - \ln M}{S} \right\}^2 \right] \quad (4.5)$$

$$(b/a) \geq 1$$

and the input parameters are:

BOAMED - parameter analogous to the median in a log-normal distribution. It is equal to M in Equation (4.5).

BOASIG - parameter analogous to the shape parameter in a log-normal distribution. It is equal to S in Equation (4.5).

BOANRM - the normalization factor C in Equation (4.5).

PRAISE assumes that the integral of Equation (4.5) 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

$$p(b/a > \beta_0) = p \quad (4.6)$$

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

$$p(b/a) = \lambda \exp [-\lambda(b/a - 1)] \quad (4.7)$$

$$(b/a) \geq 1$$

the relevant input parameter is:

BOALDA - the rate parameter λ in the shifted exponential distribution on b/a . PRAISE automatically calculates a normalization constant to ensure that the integral of Equation (4.7) between one and infinity is unity.

4.4 Inspection Times, Earthquake Evaluation Times, and Leak Detection

The 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

$$\text{NEVAL} = -\text{YY} \quad . \quad (4.8)$$

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 supplied NINSPT values into the vector TINSPT(I), I = 1, NINSPT. If no in-service are desired, PRAISE must be fooled by setting TINSPT(1) = XX, where XX is a number greater than the lifetime of the plant, or

$$\text{TINSPT}(1) = \text{XX} > \text{THRIZN} \quad . \quad (4.9)$$

The 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. 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.

4.5 Stratified Sample Space

The PRAISE user can either request that the code automatically generate the stratification cells in the sample space or he can specify both the location and the number of samples to be taken from each stratification cell. In the first case, the user specifies ISQARE = 1 in the card 1B, the problem specification. Then he must input

NAOH - the number of divisions in the a/h coordinate direction, and
NAOB - the number of divisions in the a/b coordinate direction.

PRAISE then creates MCELLS = (NAOH) (NAOB) cells, each of which has an a/h length of $1/\text{NAOH}$ and an a/b length of $1/\text{NAOB}$. Cells which fall entirely within the infeasible region (i.e. have lengths greater than the pipe circumference) are deleted and the value of MCELLS is reduced accordingly. A typical PRAISE generation of the sample space is shown in Figure 4.3.

Alternately, the PRAISE user can specify the attributes of each of the MCELLS individually. In this case he must input 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,
NUMTRY(M)	the number of replications to be taken from the m-M cell.

The values of AOHSIZ and AOBSIZ for two typical cells are illustrated in Figure 4.4.

If the value of NTRIES in card 1B is negative, PRAISE will internally reset the value of NUMTRY(M) to ABS(NTRIES). If a positive value of

NTRIES is input, then NUMTRY(M) is reset to NTRIES times the input value, or

$$\text{NUMTRY}(M) = \text{NTRIES} * \text{NUMTRY}(M) \quad . \quad (4.10)$$

If the user specified NTRIES = 1, the number of replications as input through NUMTRY(M) will be used by PRAISE. The present formulation of the initial crack size distributions restrict the stratification to rectangular cells.

When the user has obtained some measure of experience with a particular problem, it is recommended that he develop a stratification scheme which is most efficient for the problem at hand.

NAOH = 2

NAOB = 4

Figure 4.3 PRAISE Generated Stratification of the Sample Space

For the $m=1$ cell

$$AOHSIZ (1,1) = .50$$

$$AOHSIZ (1,2) = .80$$

$$AOBSIZ (1,1) = .25$$

$$AOBSIZ (1,2) = .45$$

For the $m=2$ cell

$$AOHSIZ (2,1) = .20$$

$$AOHSIZ (2,2) = .40$$

$$AOBSIZ (2,1) = .60$$

$$AOBSIZ (2,2) = .75$$

Figure 4.4. Specification of the Stratification Scheme by the PRAISE User

4.6 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 input:

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 any negative value can be used.

As shown in Section 3.6, the variation in the stress intensity factor during a transient where radial gradient thermal stresses are important can be modeled as

$$\Delta \bar{K}_{\min} = \Delta T \sqrt{a} g_{\min} (k, a/h, a/b) \quad (4.11)$$

and

$$\Delta \bar{K}_{\max} = \Delta T \sqrt{a} g_{\max} (k, a/h, a/b) \quad (4.12)$$

where

ΔT is the temperature variation during the transient,

a is the current crack depth,

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

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

Tabulated values of $g_{\min}^*(k, a/h, a/b)$ and $g_{\max}^*(k, a/h, a/b)$ must be supplied by the user for each transient in both the a/h and the b/a (or $1/a$) directions. The asterisk indicates that one of the coordinates in $g_{\min}^*$ and $g_{\max}^*$ is b/a rather than the a/b which is used in the PRAISE calculation. The coordinates of the tables are the same for all transients.

The number of entries in the b/a and a/h directions is input on card 6B as NX and NY respectively. The names NX and NY correspond to using a/h as the vertical (or Y axis), while the b/a axis is the horizontal or X axis. Section 5.5 later describes how the PRAISE code uses these normalized stress intensity factor values. It is shown in Section 5.5 that the user must also define the degree of accuracy desired when using $g_{\min}$ and $g_{\max}$. The relevant input are IX and IY . The greater the value of IX and IY , the greater the accuracy of the resultant calculation of the stress intensity factors. These values are also input on card 6B. The coordinate points in the a/h direction are read into the vector $(AAOH(I), I=1, \dots, NY)$ through card 6C. The coordinate points in the b/a direction are read into the vector $(ABOA(I), I=1, \dots, NX)$ through card 6D. PRAISE converts the values into corresponding a/b values.

For each transient, PRAISE then reads in card 6E and a sequence of 6F cards. In the present version of PRAISE, the first transient type ($k = 1$)

is assumed to be the heatup-cooldown cycle in which only uniform through the wall stresses exist. Hence when $k = 1$, no 6F cards are input. The inputs on the 6E card are:

NCYBLK -number of actual events of 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.

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 sequence of inputs is shown in Figure 4.5.

Figure 4.5. Input Sequence for the Normalized Stress Intensity Factors

4.7 Seismic Crack Growth Model

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. As shown in Section 3.7.1, the seismic crack growth in PRAISE is modeled as

$$\Delta a = C \left\{ \frac{S}{\sqrt{N_{eq}}} \right\}^4 \sum_{n=0}^{N_{eq}-1} \left\{ \sqrt{a} f((a/h)_n, (a/b)_n) \right\}^4 \quad (4.13)$$

$$= C \frac{S^4}{N_{eq}} \sum_{n=0}^{N_{eq}-1} \left\{ \sqrt{a} f((a/h)_n, (a/b)_n) \right\}^4 . \quad (4.14)$$

In addition to S (or S^4) and N_{eq} , the model also needs the load controlled stress which determines whether crack growth will lead to catastrophic failure. As a matter of convenience, PRAISE is written to use S^4 . The units of S^4 are (cycle - KSI⁴).

4.8 Detailed Formats for the Input Cards

Detailed descriptions of the input cards read by PRAISE are given in this section. Each input card is shown on a separate table. The name, position on the card, format, and description of each variable are given.

CARD TITLE CARD

ID 1A

VARIABLE

COLUMNS

FORMAT

DESCRIPTION

TITLE

1-80

10A8

Problem description

CARD PROBLEM SPECIFICATION

ID 1B

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
NTRIES	1-5	I5	Option for number of replications to be drawn from each cell When NTRIES < 0, then ABS(NTRIES) replications will be taken from each and every cell If NTRIES = 0, not used If NTRIES > 0, then user inputs a number for each cell. This number is then multiplied by NTRIES to obtain the number of samples for each cell.
ISQARE	6-10	I5	Cell definition option ISQARE = 0, User inputs coordinates of each cell in the state space ISQARE = 1, PRAISE internally sets up a regular grid of rectangular cells
KTYPES	11-15	I5	Number of transient types experienced by plant

CARD PROBLEM SPECIFICATION (Cont'd)

ID 1B (Cont'd)

VARIABLE COLUMNS FORMATDESCRIPTION

KRKDIS

16-20

I5

Initial crack size distributions

KRKDIS = 1, Crack depth is log-normal
Aspect ratio is log-normalKRKDIS = 2, Crack depth is log-normal
Aspect ratio is exponentialKRKDIS = 3, Crack depth is exponential
Aspect ratio of log-normalKRKDIS = 4, Crack depth is exponential
Aspect ratio is exponential

NEVAL

21-25

I5

Option for times during plant lifetime when the reliability is
to be evaluated

NEVAL < 0, Evaluation is performed for every ABS(NEVAL) years

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

= 1, Earthquakes at each evaluation time

CARD PROBLEM SPECIFICATION (Cont'd)

ID 1B (Cont'd)

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
IDEBUG	36-40	I5	Debugging output option IDEBUG = 0, Normal output is printed IDEBUG = 1, Additional debugging output will be supplied
KONPRP	41-45	I5	Option for material constant (C) in the fatigue crack growth relationship KONPRP = 0, C is log-normally distributed KONPRP = 1, C is constant; i.e. the crack growth relationship is deterministic
NEQINT	46-50	I5	Number of seismic intensity classes to be simulated If NQUAKE = 0, set NEQINT = 0. PRAISE, as presently dimensioned, can handle up to 10 classes.
MCELLS	51-55	I5	Number of cells in the calculational grid If ISQARE = 1, value of MCELLS is ignored
KNSFLO	56-60	I5	Option for flow stress definition KNSFLO = 0, Flow stress is normally distributed KNSFLO = 1, Flow stress is constant

CARD PROBLEM SPECIFICATION (Continued)

ID 1B (Continued)

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
NSKIP	61-65	I5	Parameter to specify the number of evaluation times which are skipped in the printout of the indicator functions. Subroutine OUTS prints every NSKIP-th evaluation time.
NPSI	66-70	I5	Option for pre-service ultrasonic inspection NPSI = 0, no pre-service inspection = 1, a pre-service inspection is modeled

CARD

PLANT LIFETIME

ID 1C

VARIABLE

COLUMNS

FORMAT

DESCRIPTION

THRIZN

1-10

E10.3

Maximum plant lifetime for the simulation

CARD PIPE DIMENSIONS

ID 2A

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
THICK	1-10	E10.3	Wall thickness of the pipe (inches)
RIN	11-20	E10.3	Inside radius of the pipe (inches)

CARD FATIGUE CRACK GROWTH CHARACTERISTICS

ID 2B

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

4-30

CARD FLOW STRESS

ID 2C

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
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)

CARD INITIAL CRACK DEPTH DISTRIBUTION

ID 3A

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
AMEDIN	1-10	E10.3	Median of the log-normal distribution on crack depth (Read if KRKDIS = 1,2)
ASIGMA	11-20	E10.3	Shape factor (= standard deviation of logarithm of A) of the log-normal distribution on crack depth (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

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

CARD EARTHQUAKE EVALUATION TIMES

ID 4A

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>
-----------------	----------------	---------------

<u>DESCRIPTION</u>

TEVAL

1-80

8E10.3

Evaluation times (yrs)

(Used only if NEVAL > 0)

CARD IN-SERVICE INSPECTION TIMES

ID 4B

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
TINSPT	1-80	8E10.3	In-service inspection time (yrs) (Used only if NINSPT > 0)

CARD LEAK RATE AND DETECTION DEFINITIONS

ID 4C

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
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

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
NAOH	1-5	I5	Number of divisions of the a/h coordinate in the sample space definition (Read if ISQARE = 1)
NAOB	6-10	I5	Number of divisions of the a/b coordinate in the sample space definition (Read if ISQARE = 1) If (ISQARE = 0), repeat following card MCELLS times
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(M)	41-50	I10	Number of replications to be taken from the m-th cell

CARD STRESS VALUES

ID 6A

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
SIGCLD	1-10	E10.3	Load controlled stress in the cold shutdown condition (KSI) This is equal to the deadweight stress
SGDWTE	11-20	E10.3	Load controlled stress in pipe in the hot normal operating condition (KSI). This consists of the deadweight and restraint of thermal expansion components.
OPPRES	21-30	E10.3	Normal operating pressure of the system (KSI)
PRFPRS	31-40	E10.3	Pressure in the hydrostatic proof test (KSI) If no proof test is to be modeled, set this value to any arbitrary negative number.

CARD SPECIFICATIONS FOR THE TABLES IN THE $g_{\min}$ AND $g_{\max}$ FUNCTIONS

ID 6B

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
NX	1-5	I5	Number of entries in the b/a coordinate for the input of the $g_{\min}^*$ and $g_{\max}^*$ functions
NY	6-10	I5	Number of entries in the a/h coordinate for the input of the $g_{\min}^*$ and $g_{\max}^*$ functions
IX	11-15	I5	Number of entries in the a/b coordinate for the internal tables on $g_{\min}$ and $g_{\max}$
IY	16-20	I5	Number of entries in the a/h coordinate for the internal tables on $g_{\min}$ and $g_{\max}$ This card read only if KTYPE5 > 1

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

ID 6C

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
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) Read only if KTYPES > 1

B/A COORDINATE FOR TABULAR INPUT OF CONTRIBUTION FROM RADIAL
GRADIENT THERMAL STRESSES TO STRESS INTENSITY FACTORS

ID 6D

CARD

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
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, NX) Read only if KTYPES > 1

CARD FREQUENCY OF HEATUP/COOLDOWN AND TRANSIENTS

ID 6E

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
NCYBLK	1-5	I5	Number of cycles in the equivalent event
BLAMDA(K)	6-10	F5.2	Arrival time parameter for transients If BLAMDA(K) > 0.0, then k-th transient arrives at uniformly spaced intervals of BLAMDA(K) years If BLAMDA(K) < 0.0, then k-th transient is treated as a Poisson process with ABS (BLAMDA(K)) as the average number of arrivals per unit time
TEMP(K)	11-20	F10.5	Temperature excursion (⁰ F) during the K-th transient
TITLE(K)	21-80	6A10	Description for the k-th transient type

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
The following sequence of cards is required for all transients except the heatup/cool-down cycle. The 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)
GDBMIN(I,J,K)	1-72	9F8.5	$g_{\min,b}^*$ (J=1,...NY)
GDBMAX(I,J,K)	1-72	9F8.5	$g_{\max,b}^*$ (J=1,...NY)

CARD EARTHQUAKES PER MAGNITUDE CATEGORY

ID 7A

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
NEQCLS(N)	1-80	16 I5	Number of earthquakes in the N-th intensity category A maximum of ten earthquakes can be modeled in each category Read only if NQUAKE = 1 on card 1B

CARD SEISMIC CRACK GROWTH PARAMETERS

ID 7B

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

4.9 Output Description

The output from a PRAISE calculation consists of four basic parts:

- (a) input summary,
- (b) description of the stratification scheme and the number of samples taken from each cell,
- (c) listing of the indicator functions used in the calculation of the failure probabilities, and
- (d) tabular summary of the failure probabilities (leak and LOCA) and their sampling standard deviation.

Figure 4.6 provides an overview of the organization of the PRAISE output. Specific examples are given with the sample problems in the following section.

The input summary is intended to verify the user's problem specification. The user should note that the hot uniform stress shown in the summary represents

$$\sigma_{HOT} = \sigma_{DW} + \sigma_{TE} + \sigma_P \quad (4.15)$$

and is computed from

$$SIGHOT = SGNWTE + OPPRES * RIN * 0.5 / THICK \quad (4.16)$$

the stress under hydrostatic proof test is given by

$$\sigma_{PRF} = \sigma_P + \sigma_{DW} \quad (4.17)$$

or

$$SIGPRF = PRFPRS * RIN * 0.5 / THICK + SIGCLD \quad (4.18)$$

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

1. INPUT SUMMARY
2. STRATIFICATION DESCRIPTION
3. FAILURES OBSERVED AT EACH EVALUATION INTERVAL
FOR EVERY STRATIFICATION CELL
4. FOR THE NO EARTHQUAKE CASE AND EACH EARTHQUAKE
MAGNITUDE CATEGORY, OUTPUT
 - a. Indicator Functions
 - b. Tabulation of Estimated Failure Probabilities
and their Sampling Standard Deviation

Figure 4.6 Organization of PRAISE Output

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 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 from only selected evaluation times. PRAISE permits the user to output data at each NSKIP evaluation time. The first set of output is the number of failures obtained during the interval. For the case of no pre-service and no in-service inspections, these are integer values. When pre-service and in-service inspections are modeled, the numbers are weighted by the non-detection 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 value of the total number of failures observed 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 magnitude 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 categories.

4.10 Sample Problems

Four sample problems are described in this section. The first problem is a simple test problem which can be used to verify the operational status of the PRAISE code. The remaining problems are designed to demonstrate the flexibility of PRAISE. Even though "reasonable" values of the inputs have been used, these problems were not actually used in the load combinations project. A summary of the various input options used in these sample problems is given in Table 4.2. The user is cautioned that exact duplication of these results should not be expected. Generally speaking, the sequence of uniformly distributed random numbers is generated by an in-line function which may vary from computer to computer and from facility to facility even for the same type of computer.

Table 4.2
COMPARISON OF SAMPLE PROBLEM INPUTS

	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4
PLANT LIFETIME (YRS)	10	40	40	40
WALL THICKNESS (IN)	1.0	2.5	2.5	2.5
PIPE INSIDE RADIUS	5.0	14.5	14.5	14.5
CRACK GROWTH CONSTANT C	CONSTANT	CONSTANT	LOG NORMAL	LOG NORMAL
FLOW STRESS	CONSTANT	CONSTANT	NORMAL	NORMAL
CRACK DEPTH DISTRIBUTION	EXPONENTIAL	LOG NORMAL	LOG NORMAL	EXPONENTIAL
CRACK ASPECT RATIO DISTRIBUTION	EXPONENTIAL	LOG NORMAL	EXPONENTIAL	LOG NORMAL
HYDROSTATIC PROOF TEST	NONE	NONE	NONE	YES (3.1 KSI)
PRE-SERVICE INSPECTION	NONE	NONE	YES	YES
EVALUATION TIME	UNIFORM	UNIFORM	VARIABLE	UNIFORM
IN-SERVICE INSPECTION	NONE	NONE	NONE	YES
LEAK DETECTION	10^5	2.0	10^5	2.0
SMALL/BIG LEAK	2.0	5.0	2.0	2.0
STRATIFICATION	UNIFORM	VARIABLE	VARIABLE	VARIABLE
NUMBER OF SAMPLES	50	50-100	50-100	50-250
TRANSIENTS (TYPE/FREQUENCY)	HEATUP-COOLDOWN	HEATUP-COOLDOWN	HEATUP-COOLDOWN	HEATUP-COOLDOWN
BLOCKING FACTOR IS SHOWN	REGULAR (1)	STOCHASTIC (1)	STOCHASTIC (1)	REGULAR (1)
IN PARATHENSIS			PLANT LOADING	PLANT LOADING
			STOCHASTIC (100)	REGULAR (100)

Table 4.2 (Continued)

	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4
COLD SHUTDOWN STRESS DEADWEIGHT AND THERMAL EXP. OPERATING PRESSURE	2 KSI 10 KSI 2 KSI	2.0 KSI 8.8 KSI 2.25 KSI	2.0 KSI 8.8 KSI 2.25 KSI	2.0 KSI 8.8 KSI 2.25 KSI
EARTHQUAKES	NONE	4 CATEGORIES 1 PER CATEGORY	4 CATEGORIES VARIABLE IN EACH CATEGORY	4 CATEGORIES 1 PER CATEGORY
EXECUTION TIME CPU SECONDS	4	15	40	190

4.10.1 Verification Problem

This problem illustrates the most basic analysis that can be performed with the PRAISE computer code. The only random variables are the parameters describing the initial crack size distribution. Specific inputs include:

- Ten year plant lifetime (THRIZN = 10),
- One inch pipe wall thickness (THICK = 1.0),
- Five inch pipe inside radius (RIN = 5.0),
- Crack growth relationship with constant C
$$\frac{da}{dn} = 1.0 \times 10^{-10} (\Delta \bar{K})_{eff}^4 \text{ in/cycle}$$
$$K_0 = 4.7 \text{ KSI} \sqrt{\text{in}}$$
(KONPRP = 1, CONSMU = 1.0E-10, EMEXP = 4.0, THRHLD = 4.7)
- Constant flow stress (KNSFLO = 1, SIGFLO = 40)
- Exponential distributions for both the crack depth and aspect ratio in the initial crack size distribution (KRKDIS = 4, ALAMDA = 4.07, BOALDA = 1.15).
- Evaluations of the failure probabilities occur every 2 years during the plant lifetime (NEVAL = -2).
- No in-service inspections during the plant lifetime (NINSPT = 0)
- Neither leak detection nor differentiation between large and small leaks is modeled. Elimination of leak detection is performed by setting the threshold for leak detection to a large number (FNDLEK = 1.0E05). The discrimination between small and big leak is bypassed by setting the threshold between big and small leaks at 0.0 (ALKBIG = 0.0).
- The code internally stratifies the sample into a 5x5 grid of rectangular regions. (ISQUARE = 1, NAOH = 5, NAOB = 5).
- Fifty samples are selected from each of the cells (NTRIES = -50).

- Load controlled stresses in the cold shutdown (deadweight) normal operating (deadweight and restraint of thermal expansion) condition are 2 KSI and 10 KSI respectively. (SIGCLD = 2.0, SGDWTE = 10.0).
- Operating pressure of 2000 psia (OPPRES = 2 KSI)
- No hydrostatic proof test is modeled (PRFPRS = - 3.0)
- The only transient modeled is the heatup/cooldown cycle which is assumed to occur five times per year (KTYPE = 1, BLAMDA(1) = - 0.2).
- No earthquakes are included (NQUAKE = 0, NEQINT = 0).

The card images and input summary for this sample problem are given in Figures 4.7 and 4.8, respectively. The summary of the stratification scheme is given in Figure 4.9 and graphically demonstrated in Figure 4.10. Since the stratification is generated internally by PRAISE, rather than specified by the user, the entire sample space is used. Hence, the total probability sums to unity. The estimated failure possibilities are shown in Figure 4.11.

```

SAMPLE-1,NO PSI,HU-CD,C=1.E-10,SIGFLO=40,A EXP,B/A EXP,NO PROOF,NO EGS,NO LEAK
-50 1 1 4 -2 0 0 0 1 0 0 1 1 0
10.0
1.0 5.0
4.6 4.0 1.0E-10
40.0
4.07
1.15
1.0E05 0.0
5 5
2.0 10.0 2.0 -3.0
1-0.2 480.0 HEATUP FROM COLD SHUTDOWN TO HOT STANDBY

```

Figure 4.7 Input Cards for Sample Problem 1

```

      --- SAMPLE-1,NO PSI,HU-CD,C=1.E-10,SIGFLO=40,A EXP,B/A EXP,NO PROOF,NO EGS,NO LEAK ---

PIPE DIMENSIONS
  INSIDE RADIUS =      5.00  INCHES
  WALL THICKNESS  1.00  INCHES

INITIAL CRACK SIZE DISTRIBUTION
CRACK DEPTH IS EXPONENTIAL
  PARAMETER =      4.0700
ASPECT RATIO IS EXPONENTIAL
  PARAMETER =      1.1500

CRACK GROWTH LAW PARAMETERS
  EXPONENT =      4.00
  GROWTH LAW CONSTANT IS CONSTANT
  CONSTANT =      .1000E-09
  THRESHOLD =      4.60
  FLOW STRESS IS CONSTANT
  CONSTANT=      .4000E+02

PIPE STRESS VALUES
  CSD DEADWT STRESS (KSI)  2.00
  HOT UNIFORM STRESS (KSI) 15.00
  PRESSURE STRESS (KSI)   5.00

NO HYDROSTATIC PROOF TEST IS MODELED

LEAK DETECTION AND DEFINITION PARAMETERS
  DETECTABLE LEAK (GPM) 100000.0
  BIG LEAK (GPM)       0.

NO PRE-SERVICE ULTRASONIC INSPECTION

TIME INTERVALS
  PLANT LIFETIME      10.0  YEARS
  ENDPNTS OF INTERVALS AT  0.    2.0    4.0    6.0    8.0    10.0

NO IN-SERVICE INSPECTIONS ARE MODELED

      - - - NO SEISMIC EVENTS EVALUATED - - -

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS  1

      - - - NORMAL OUTPUT REQUESTED - - -

```

Figure 4.8 Input Summary for Sample Problem 1

- - NUMBER OF TRANSIENT TYPES = 1 - -

TYPE 1 HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
STOCHASTIC WITH MEAN TIME .200 YRS/EVENT
MAX DELTA TEMP =480.0 BLOCKING FACTOR = 1.

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

\$\$\$ UNIFORM MESH \$\$\$

CELL	AOH1	AOH2	AOR1	AOR2	PROBABILITY	SAMPLES
1	0.	.2000	0.	.2000	.5695307E-02	50
2	0.	.2000	.2000	.4000	.9525643E-01	50
3	0.	.2000	.4000	.6000	.1622645E+00	50
4	0.	.2000	.6000	.6000	.1618065E+00	50
5	0.	.2000	.8000	1.0000	.1415711E+00	50
6	.2000	.4000	0.	.2000	.2523489E-02	50
7	.2000	.4000	.2000	.4000	.4220643E-01	50
8	.2000	.4000	.4000	.6000	.7189651E-01	50
9	.2000	.4000	.6000	.8000	.7169356E-01	50
10	.2000	.4000	.8000	1.0000	.6272762E-01	50
11	.4000	.6000	0.	.2000	.1118113E-02	50
12	.4000	.6000	.2000	.4000	.1870092E-01	50
13	.4000	.6000	.4000	.6000	.3185606E-01	50
14	.4000	.6000	.6000	.8000	.3176614E-01	50
15	.4000	.6000	.8000	1.0000	.2779349E-01	50
16	.6000	.8000	0.	.2000	.4954160E-03	50
17	.6000	.8000	.2000	.4000	.8286043E-02	50
18	.6000	.8000	.4000	.6000	.1411485E-01	50
19	.6000	.8000	.6000	.8000	.1407501E-01	50
20	.6000	.8000	.8000	1.0000	.1231460E-01	50
21	.8000	1.0000	0.	.2000	.2195100E-03	50
22	.8000	1.0000	.2000	.4000	.3671398E-02	50
23	.8000	1.0000	.4000	.6000	.6254040E-02	50
24	.8000	1.0000	.6000	.8000	.6236386E-02	50
25	.8000	1.0000	.8000	1.0000	.5456468E-02	50

SUM OF CELL PROBABILITIES = .1000000000E+01

Figure 4.9 Stratification Description for Sample Problem 1

Figure 4.10 Stratification Scheme for Sample Problem 1

- - - SAMPLE-1,NO PSI,HU-CD,C=1.E-10,SIGFLO=40,A EXP,B/A EXP,NO PROOF,NO EGS,NO LEAK - - -

- - RESULTS WITHOUT EARTHQUAKES - - -

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	4.53061E-04	4.53061E-04	0.	2.24568E-04	2.24568E-04	0.
2.0	1.67869E-03	1.67869E-03	0.	4.18444E-04	4.18444E-04	0.
4.0	1.95467E-03	1.95467E-03	0.	4.45691E-04	4.45691E-04	0.
6.0	2.32678E-03	2.32678E-03	0.	4.83852E-04	4.83852E-04	0.
8.0	2.64319E-03	2.64319E-03	0.	5.09000E-04	5.09000E-04	0.
10.0	2.88179E-03	2.88179E-03	0.	5.27846E-04	5.27846E-04	0.

Figure 4.11 Results for Sample Problem 1

4.10.2 Sample Problem 2

Sample problem 2 presents additional PRAISE capabilities for analyzing weld joints in the primary coolant system of a PWR. The card images for the input are shown in Figure 4.12. Specific inputs include:

- Forty year plant lifetime (THRIZN = 40).
- Two and one-half inch pipe wall thickness (THICK = 2.5).
- Fourteen and one-half inch inside pipe radius (RIN = 14.5).
- Crack growth relationship with constant C
$$\frac{da}{dn} = 9 \times 10^{-12} (\Delta \bar{K})_{\text{eff}}^4 \text{ in/cycle}$$
$$K_0 = 4.7 \text{ KSI} \cdot \sqrt{\text{in}}$$
$$(\text{KOIIPRP} = 1, \text{CONSMU} = 9.0\text{E-}12, \text{EMEXP} = 4.0, \text{THRHL} = 4.7).$$
- Constant flow stress (KNSFLO = 1, SIGFLO = 45).
- Log normal distributions for the crack depth and aspect ratio in the initial crack size distribution (KRKDIS = 1, AMEDIN = .05 in, ASIGMA = .82, BOAMED = 1.336, BOASIG = .538, BOANRM = 1.1419).
- Evaluation of failure probabilities is performed every ten years (NEVAL = -10).
- No in-service inspection (NINSPT = 0).
- The leak detection threshold is 2 gpm (FNDLEK = 2.0). The discrimination level between small and big leaks is 5 gpm (ALKBIG = 5.0).
- The user specifies 25 stratification cells (MCELLS = 25).
- The multiplier for the number of samples is ten (NTRIES = 10).
- Contributions to the load controlled stresses in the cold shutdown (deadweight) and normal operating (deadweight and restraint of thermal expansion) condition are 2 KSI and 10 KSI respectively. (SIGCLD = 2.0, SGDWTE = 10.0).

- Operating pressure of 2000 psia (OPRES = 2 KSI).
- No hydrostatic proof test is modeled (PRFPRS = 3.1).
- No pre-service inspection is modeled (NPSI = 0).
- The only transient modeled is the heatup/cool-down cycle. The arrival times of this transient are assumed to be exponentially distributed with a rate of 5 per year, i.e., a mean inter-arrival time of 0.2 years.
- Four categories of earthquakes are modeled. A typical earthquake is placed into each category.

(NQUAKE = 1, NEQINT = 4, NEQCLS(1) = 1,
 NEQCLS(2) = 1,
 NEQCLS(3) = 1,
 NEQCLS(4) = 1).

The specific parameters describing the number of equivalent cycles, the value of S^4 , and the load-controlled stress are shown in input summary given in Figure 4.13.

The stratification scheme and the number of samples to be taken from each cell are shown in Figure 4.14. Since only a portion of the sample space is being investigated, the total probability is 5.265×10^{-7} .

The failure probabilities and the sampling standard deviation for the no earthquake case are given in Figure 4.15. The failure probabilities and sampling standard deviation for the four earthquake categories are shown in Figures 4.16a through 4.16d.

```

SAMPLE-2 HU-CD DETERM,C=9.E-12,SIGFLO=45,NO PROOF,4 EQ,A LGNRM,B/A LGNRM,NO PSI
10 0 1 1 -10 0 1 0 1 4 25 1 2 0
40.0
2.5 14.5
4.6 4.0 9.0E-12
45.0
0.05 0.62
1.336 0.538 1.1419
2.0 5.0
0.98 1.0 0.05 0.07 10
0.98 1.0 0.07 0.1 10
0.98 1.0 0.1 0.2 10
0.98 1.0 0.2 0.4 10
0.98 1.0 0.4 0.7 10
0.98 1.0 0.7 1.0 10
0.92 0.98 0.05 0.07 5
0.92 0.98 0.07 0.1 5
0.92 0.98 0.1 0.2 5
0.92 0.98 0.2 0.4 5
0.92 0.98 0.4 0.7 5
0.92 0.98 0.7 1.0 5
0.85 0.92 0.04 0.07 5
0.85 0.92 0.07 0.1 5
0.85 0.92 0.1 0.2 5
0.8 0.85 0.04 0.07 5
0.8 0.85 0.07 0.1 5
0.8 0.85 0.1 0.2 5
0.75 0.8 0.04 0.07 5
0.75 0.8 0.08 0.2 5
0.7 0.75 0.03 0.08 5
0.7 0.75 0.08 0.2 5
0.65 0.7 0.03 0.06 5
0.6 0.65 0.03 0.06 5
0.6 0.7 0.06 0.1 5
2.0 8.8 2.25 -3.1
1 0.2 480.0 HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
1 1 1 1
1 521.6 8.757 1 OBE TH 1 JOINT 1 LLNL DATA
2 2958.3 9.059 1 SSE TH 1 JOINT 1 LLNL DATA
2 63430.0 10.557 3 SSE TH 2 JOINT 1 LLNL DATA
4 162000.0 10.617 5 SSE TH 4 JOINT 1 LLNL DATA

```

Figure 4.12 Card Images for Input to Sample Problem 2

```

--- SAMPLE-2 HU-CD DETERM,C=9.E-12,SIGFLO=45,NO PROOF,4 EQ,A LGARM,B/A LGARM,NO PSI ---

PIPE DIMENSIONS
  INSIDE RADIUS =      14.50  INCHES
  WALL THICKNESS   2.50  INCHES

INITIAL CRACK SIZE DISTRIEUTION
CRACK DEPTH IS LOG-NORMAL
  MEDIAN =          .0500
  SHAPE PARAMETER   .8200
ASPECT RATIO IS LOG-NORMAL
  MEDIAN =          1.3360
  SHAPE PARAMETER   .5380
  NORMALIZATION CONSTANT =      1.1419

CRACK GROWTH LAW PARAMETERS
  EXPONENT =          4.00
  GROWTH LAW CONSTANT IS CONSTANT
  CONSTANT =          .9000E-11
  THRESHOLD =          4.60
  FLOW STRESS IS CONSTANT
  CONSTANT=          .4500E+02

PIPE STRESS VALUES
  CSD DEADWT STRESS (KSI)  2.00
  HOT UNIFORM STRESS (KSI) 15.33
  PRESSURE STRESS (KSI)   6.53

NO HYDROSTATIC PROGF TEST IS MODELED

LEAK DETECTION AND DEFINITION PARAMETERS
  DETECTABLE LEAK(GPM)    2.0
  BIG LEAK(GPM)           5.0

SEISMIC CLASS INFORMATION
  CLASS      S4-EQ      SGLCEQ      CYCLES
  1          .5216E+03    8.757      1          1 OBE TH 1 JOINT 1 LLNL DATA
  2          .2958E+04    9.059      2          1 SSE TH 1 JOINT 1 LLNL DATA
  3          .6343E+05   10.557      2          3 SSE TH 2 JOINT 1 LLNL CATA
  4          .1620E+06   10.617      4          5 SSE TH 4 JOINT 1 LLNL DATA

NO PRE-SERVICE ULTRASONIC INSPECTION

TIME INTERVALS
  PLANT LIFETIME      40.0  YEARS
  ENDPPOINTS OF INTERVALS AT  0.  10.0  20.0  30.0  40.0

NO IN-SERVICE INSPECTIONS ARE MODELED

- - - EARTHQUAKES AT EACH EVALUATION INTERVAL -

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS      2

- - - NORMAL OUTPUT REQUESTED - - -

```

Figure 4.13 Input Summary for Sample Problem 2

- - NUMBER OF TRANSIENT TYPES = 1 - -
TYPE 1 HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
REGULAR AT .200 YRS/EVENT
MAX DELTA TEMP =480.0 BLOCKING FACTOR = 1.

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Figure 4.13 (continued)

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

\$\$\$ USER-SPECIFIED MESH \$\$\$

CELL	AOH1	AOH2	AOB1	AOB2	PROBABILITY	SAMPLES
1	.9800	1.0000	.0500	.0700	.6878804E-12	100
2	.9800	1.0000	.0700	.1000	.1172000E-10	100
3	.9800	1.0000	.1000	.2000	.9507241E-09	100
4	.9800	1.0000	.2000	.4000	.1563871E-07	100
5	.9800	1.0000	.4000	.7000	.4466086E-07	100
6	.9800	1.0000	.7000	1.0000	.3460113E-07	100
7	.9200	.9800	.0500	.0700	.2749330E-11	50
8	.9200	.9800	.0700	.1000	.4684264E-10	50
9	.9200	.9800	.1000	.2000	.3799867E-08	50
10	.9200	.9800	.2000	.4000	.6250502E-07	50
11	.9200	.9800	.4000	.7000	.1785011E-06	50
12	.9200	.9800	.7000	1.0000	.1382943E-06	50
13	.8500	.9200	.0400	.0700	.5400295E-11	50
14	.8500	.9200	.0700	.1000	.8818264E-10	50
15	.8500	.9200	.1000	.2000	.7153361E-08	50
16	.8000	.8500	.0400	.0700	.6090331E-11	50
17	.8000	.8500	.0700	.1000	.9945041E-10	50
18	.8000	.8500	.1000	.2000	.8067400E-08	50
19	.7500	.8000	.0400	.0800	.2798056E-10	50
20	.7500	.8000	.0800	.2000	.1224051E-07	50
21	.7000	.7500	.0300	.0800	.4295036E-10	50
22	.7000	.7500	.0800	.2000	.1876040E-07	50
23	.6500	.7000	.0300	.0600	.5658778E-11	50
24	.6000	.6500	.0300	.0600	.9113779E-11	50
25	.6000	.7000	.0600	.1000	.9798961E-09	50
SUM OF CELL PROBABILITIES =			.5265000778E-06			

Figure 4.14 Stratification Description for Sample Problem 2

- - - SAMPLE-2 HU-CD DETERM,C=9.E-12,SIGFLO=45,NO PROOF,4 EQ,A LGNRM,B/A LGNRM,NO PSI - - -

- - RESULTS WITHOUT EARTHQUAKES - - -

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TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	1.42869E-08	1.42869E-08	1.38292E-12	2.03715E-09	2.03715E-09	2.43246E-13
10.0	7.52057E-08	7.52057E-08	2.21754E-12	2.51322E-09	2.51322E-09	3.03340E-13
20.0	1.02081E-07	1.02081E-07	2.21754E-12	3.33491E-09	3.33491E-09	3.03340E-13
30.0	1.11215E-07	1.11215E-07	2.21754E-12	4.44175E-09	4.44175E-09	3.03340E-13
40.0	1.28187E-07	1.28187E-07	2.32554E-12	8.40511E-09	8.40511E-09	3.18276E-13

Figure 4.15 Results of the No Earthquake Case in Sample Problem 2

- - - SAMPLE-2 HU-CD DETERM,C=9.E-12,SIGFLO=45,NO PROOF,4 EQ,A LGNRM,B/A LGNRM,NO PSI - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

CLASS S4-EQ SGLCEQ CYCLES
1 .5216E+03 8.757 1

1 OBE TH 1 JOINT 1 LLNL DATA

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	1.62191E-08	1.62191E-08	1.72266E-12	2.16425E-09	2.16425E-09	2.87357E-13
10.0	7.52057E-08	7.52057E-08	2.21754E-12	2.51322E-09	2.51322E-09	3.03340E-13
20.0	1.02081E-07	1.02081E-07	2.21754E-12	3.33491E-09	3.33491E-09	3.03340E-13
30.0	1.11215E-07	1.11215E-07	2.32554E-12	4.44175E-09	4.44175E-09	3.18276E-13
40.0	1.28187E-07	1.28187E-07	2.32554E-12	8.40511E-09	8.40511E-09	3.18276E-13

Figure 4.16a Results for Earthquake Category 1 in Sample Problem 2

- - - SAMPLE-2 HU-CD DETERM,C=9.E-12,SIGFLO=45,NO PROOF,4 EQ,A LGNRM,B/A LGNRM,NO PSI - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

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SEISMIC CLASS INFORMATION

CLASS	S4-EQ	SGLCEQ	CYCLES
2	.2958E+04	9.059	2

1 SSE TH 1 JOINT 1 LLNL DATA

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	1.84451E-08	1.84451E-08	1.99759E-12	2.26275E-09	2.26275E-09	2.98418E-13
10.0	7.52057E-08	7.52057E-08	2.21754E-12	2.51322E-09	2.51322E-09	3.03340E-13
20.0	1.02427E-07	1.02427E-07	2.21754E-12	3.31873E-09	3.31873E-09	3.03340E-13
30.0	1.11215E-07	1.11215E-07	2.43355E-12	4.44175E-09	4.44175E-09	3.31825E-13
40.0	1.28187E-07	1.28187E-07	2.44735E-12	8.40511E-09	8.40511E-09	3.40788E-13

Figure 4.16b Results for Earthquake Category 2 in Sample Problem 2

- - - SAMPLE-2 HU-CD DETERM,C=9.E-12,SIGFLO=45,NO PROOF,4 EQ,A LGNRM,B/A LGNRM,NO PSI - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

CLASS S4-EQ SGLCEQ CYCLES
3 .6343E+05 10.557 2

3 SSE TH 2 JOINT 1 LLNL DATA

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	2.36013E-08	2.36013E-08	2.72233E-12	2.46218E-09	2.46218E-09	3.41898E-13
10.0	7.61322E-08	7.61322E-08	2.44735E-12	2.48581E-09	2.48581E-09	3.40788E-13
20.0	1.02428E-07	1.02428E-07	2.66336E-12	3.31873E-09	3.31873E-09	3.65071E-13
30.0	1.11215E-07	1.11215E-07	2.87937E-12	4.44175E-09	4.44175E-09	3.85374E-13
40.0	1.28187E-07	1.28187E-07	2.89317E-12	8.40511E-09	8.40511E-09	3.94163E-13

Figure 4.16c Results for Earthquake Category 3 in Sample Problem 2

- - - SAMPLE-2 HU-CD DETERM,C=9.E-12,SIGFLO=45,NO PROOF,4 EQ,A LGNRM,B/A LGNRM,NO PSI - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

CLASS S4-EQ SGLCEQ CYCLES
4 .1620E+06 10.617 4

5 SSE TH 4 JOINT 1 LLNL DATA

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	2.93506E-08	2.93506E-08	2.77731E-12	2.65796E-09	2.65796E-09	3.41808E-13
10.0	7.86994E-08	7.86994E-08	2.44735E-12	2.73186E-09	2.73186E-09	3.40788E-13
20.0	1.02775E-07	1.02775E-07	2.66336E-12	3.30211E-09	3.30211E-09	3.65071E-13
30.0	1.11216E-07	1.11216E-07	3.10919E-12	4.44175E-09	4.44175E-09	4.11884E-13
40.0	1.28187E-07	1.28187E-07	2.89317E-12	8.40511E-09	8.40511E-09	3.94163E-13

Figure 4.16d Results for Earthquake Category 4 in Sample Problem 2

4.10.3 Sample Problem 3

Sample problem 3 is another example of an analysis for weld joints in the primary coolant system of a PWR. The card images are shown in Figure 4.17. Specific inputs include:

- Forty year plant lifetime (THRIZN = 40).
- Two and one-half inch pipe wall thickness (THICK = 2.5).
- Fourteen and one-half inch inside pipe radius (RIN = 14.5).
- Crack growth relationship with a log-normally distributed C, with median = 9×10^{-12} and 90-th percentile = 3.5×10^{-11} , or
$$\frac{da}{dn} = C(\Delta \bar{K})_{eff}^4 \text{ in/cycle}$$
$$K_0 = 4.6 \text{ KSI} \cdot \sqrt{\text{in}}$$
(KONPRP = 0, CONSMU = 9.0E-12, CONS90 = 3.5E-11, EXEMP = 4.0, THRHLN = 4.6).
- The flow stress normally distributed with mean = 45 KSI and standard deviation = 1.4 KSI. (SFLOMU = 45, SFLOS0 = 1.4).
- The crack depth distribution is log normally distributed, while the aspect ratio is exponentially distributed (KRKDIS = 2, AMEDIN = .05, ASIGMA = .82, BOALDA = 1.15).
- Evaluation of failure probabilities is performed at six user specified points in time
(NEVAL = 6, TEVAL(1) = 1.0
TEVAL(2) = 2.0
TEVAL(3) = 5.0
TEVAL(4) = 10.0
TEVAL(5) = 20.0
TEVAL(6) = 40.0).
- No in-service inspections are performed (NINSPT = 0).
- No leak detection is modeled (FNDLEK = 1.0E05, see sample problem 1 for explanation).
- The discrimination level between small and big leak rates is 2 gpm (ALKBIG = 2.0).
- A pre-service inspection is modeled (NPSI = 1).

- The multiplier on the number of samples to be taken from each cell is ten (NTRIES = 10).
- The contributions to the load controlled stresses in the cold shutdown (deadweight) and normal operating (deadweight and restraint of thermal expansion) condition are 2 KSI 8.8 KSI respectively. (SIGCLD = 2.0, SGDWTE = 8.8).
- Operating pressure of 2250 psia (OPPRES = 2.25).
- No hydrostatic proof test is modeled (PRFPRS = -3.1).
- Two types of transients are modeled. The first transient is the heatup/cooldown cycle with exponentially distributed arrival times and a rate of 5 events per year, i.e., a mean time between events of 0.2 years. The temperature variation is 480°F. The second transient is the plant loading at a rate greater than 5% per minute. Its inter-arrival times are also exponentially distributed with an intensity of 4.55 events per year.
(KTYPES = 2, BLAMDA(1) = 2.0, DTEMP(1) = 480,
BLAMDA(2) = .22, DTEMP(2) = 40).
- Four categories of earthquake are modeled. In the first and fourth categories, two representative earthquakes have been identified. In the second and third categories, one representative earthquake is used.
(NEQINT = 4, NEQCLS(1) = 1,
NEQCLS(2) = 2,
NEQCLS(3) = 2,
NEQCLS(4) = 1)

The parameters describing the number of equivalent cycles, the value of S^4 , and the load-controlled stress are shown in the input summary given in Figure 4.18.

The stratification description is shown in Figure 4.19 and illustrated in Figure 4.20.

SAMPLE-3 HU-CD,PLANT LOADING,C=LGNRM,SIGFLO=NRN,PROOF TEST,A LOGNRM,B/A EXP,4 EQ

```

10 0 2 2 6 0 1 0 0 4 25 0 1 1
40.0
2.5      14.5
4.6      4.0      9.0E-12  3.5E-11
45.0     1.4
0.05     0.82
1.15
1.0      2.0      5.0      10.0      20.0      40.0
1.0E05  2.0
0.98     1.0     0.05     0.07     10
0.98     1.0     0.07     0.1      10
0.98     1.0     0.1      0.2      10
0.98     1.0     0.2      0.4      10
0.98     1.0     0.4      0.7      10
0.98     1.0     0.7      1.0      10
0.92     0.98     0.05     0.07     5
0.92     0.98     0.07     0.1      5
0.92     0.98     0.1      0.2      5
0.92     0.98     0.2      0.4      5
0.92     0.98     0.4      0.7      5
0.92     0.98     0.7      1.0      5
0.85     0.92     0.04     0.07     5
0.85     0.92     0.07     0.1      5
0.85     0.92     0.1      0.2      5
0.8      0.85     0.04     0.07     5
0.8      0.85     0.07     0.1      5
0.8      0.85     0.1      0.2      5
0.75     0.8      0.04     0.08     5
0.75     0.8      0.08     0.2      5
0.7      0.75     0.03     0.08     5
0.7      0.75     0.08     0.2      5
0.65     0.7      0.03     0.06     5
0.6      0.65     0.03     0.06     5
0.6      0.7      0.06     0.1      5
2.0      8.8      2.25     -3.1
6 9 20 20
0.01     0.1      0.2      0.3      0.4      0.5      0.6      0.7
0.8
1.0      2.0      3.0      4.0      5.0      6.0
1.0.2 480.0 HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
100.0022 40.0 PLANT LOADING .GT. 5 PERCENT PER MINUTE
-.16460 -.11864 -.08482 -.06174 -.04481 -.03080 -.01809 -.00624 -.00002
-.20431 -.15301 -.11518 -.08977 -.07266 -.05772 -.04072 -.02260 -.00619
-.21584 -.16405 -.12631 -.10161 -.08451 -.07031 -.05250 -.03211 -.01303
-.21920 -.16856 -.13107 -.10784 -.09261 -.07749 -.05972 -.03852 -.01774
-.22256 -.16987 -.13269 -.11129 -.09686 -.08220 -.06458 -.04302 -.02154
-.22480 -.17271 -.13616 -.11570 -.10177 -.08745 -.06978 -.04771 -.02485
0. 0. 0. 0. 0. 0. 0. 0. 0.0539
0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0. 0. 0. 0. 0. 0. 0. 0.
-.17004 -.13813 -.11679 -.10185 -.09046 -.08066 -.07117 -.06128 -.05073
-.17757 -.13742 -.11693 -.10348 -.09342 -.08476 -.07617 -.06696 -.05675
-.17405 -.13554 -.11532 -.10357 -.09506 -.08770 -.08024 -.07188 -.06217
-.16972 -.13473 -.11571 -.10553 -.09803 -.09144 -.08454 -.07649 -.06666
-.17869 -.14238 -.12205 -.11228 -.10549 -.09990 -.09413 -.08686 -.07707
-.17853 -.14365 -.12359 -.11471 -.10889 -.10439 -.10013 -.09395 -.08378
0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0. 0. 0. 0. 0. 0. 0. 0.
2 1 1 2
1 521.6 8.757 1 OBE TH 1 JOINT 1 LLNL DATA
1 550. 8.500 1 OBE TH 1 JOINT 1 LLNL DATA
2 2958.3 9.059 1 SSE TH 1 JOINT 1 LLNL DATA
2 63430.0 10.557 3 SSE TH 2 JOINT 1 LLNL DATA
4 162000.0 10.617 5 SSE TH 4 JOINT 1 LLNL DATA
4 170000.0 10.50 5 SSE TH 4 JOINT 1 LLNL DATA

```

Figure 4.17 Card Images for Input to Sample Problem 3

--- SAMPLE-3 HU-CD,PLANT LOADING,C=LGCRM,SIGFLO=NRM,PROOF TEST,A LOGCRM,B/A EXP,4 EQ---

PIPE DIMENSIONS

INSIDE RADIUS = 14.50 INCHES
WALL THICKNESS 2.50 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 = 4.00
GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
MEDIAN = .9000E-11
90-TH PERCENT = .3500E-10
THRESHOLD = 4.60
FLOW STRESS NORMALLY DISTRIBUTED
MEAN= .4500E+02
STANDARD DEVIAT .1400E+01

PIPE STRESS VALUES

CSD DEADWT STRESS (KSI) 2.00
HOT UNIFORM STRESS (KSI) 15.33
PRESSURE STRESS (KSI) 6.53

NO HYDROSTATIC PROOF TEST IS MODELED

LEAK DETECTION AND DEFINITION PARAMETERS

DETECTABLE LEAK(GPM) 100000.0
BIG LEAK(GPM) 2.0

SEISMIC CLASS INFORMATION

CLASS	S4-EQ	SGLCEG	CYCLES	
1	.5216E+03	8.757	1	1 OBE TH 1 JOINT 1 LLNL DATA
1	.5500E+03	8.500	1	1 OBE TH 1 JOINT 1 LLNL DATA
2	.2958E+04	9.059	2	1 SSE TH 1 JOINT 1 LLNL DATA
3	.6343E+05	10.557	2	3 SSE TH 2 JOINT 1 LLNL DATA
4	.1620E+06	10.617	4	5 SSE TH 4 JOINT 1 LLNL DATA
4	.1700E+06	10.500	4	5 SSE TH 4 JOINT 1 LLNL DATA

PRE-SERVICE ULTRASONIC INSPECTION IS MODELED

TIME INTERVALS

PLANT LIFETIME 40.0 YEARS
ENDPOINTS OF INTERVALS AT 0. 1.0 2.0 5.0 10.0 20.0 40.0

NO IN-SERVICE INSPECTIONS ARE MODELED

- - - EARTHQUAKES AT EACH EVALUATION INTERVAL -

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS 1

- - - NORMAL OUTPUT REQUESTED - - -

Figure 4.18 Input Summary for Sample Problem 3

- - NUMBER OF TRANSIENT TYPES = 2 - -

TYPE 1 HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
STOCHASTIC WITH MEAN TIME .200 YRS/EVENT
MAX DELTA TEMP = 480.0 BLOCKING FACTOR = 1.

TYPE 2 PLANT LOADING .GT. 5 PERCENT PER MINUTE
STOCHASTIC WITH MEAN TIME .002 YRS/EVENT
MAX DELTA TEMP = 40.0 BLOCKING FACTOR = 100.

Figure 4.18 (continued)

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

\$\$\$ USER-SPECIFIED MESH \$\$\$

CELL	A0H1	A0H2	A0B1	A0B2	PROBABILITY	SAMPLES
1	.9800	1.0000	.0500	.0700	.2753687E-13	100
2	.9800	1.0000	.0700	.1000	.3782857E-11	100
3	.9800	1.0000	.1000	.2000	.1193392E-08	100
4	.9800	1.0000	.2000	.4000	.2002372E-07	100
5	.9800	1.0000	.4000	.7000	.5153646E-07	100
6	.9800	1.0000	.7000	1.0000	.4634548E-07	100
7	.9200	.9800	.0500	.0700	.1100597E-12	50
8	.9200	.9800	.0700	.1000	.1511937E-10	50
9	.9200	.9800	.1000	.2000	.4769765E-08	50
10	.9200	.9800	.2000	.4000	.8003106E-07	50
11	.9200	.9800	.4000	.7000	.2059816E-06	50
12	.9200	.9800	.7000	1.0000	.1852342E-06	50
13	.8500	.9200	.0400	.0700	.2074802E-12	50
14	.8500	.9200	.0700	.1000	.2846267E-10	50
15	.8500	.9200	.1000	.2000	.8979223E-08	50
16	.8000	.8500	.0400	.0700	.2339915E-12	50
17	.8000	.8500	.0700	.1000	.3209956E-10	50
18	.8000	.8500	.1000	.2000	.1012657E-07	50
19	.7500	.8000	.0400	.0600	.2738226E-11	50
20	.7500	.8000	.0800	.2000	.1524689E-07	50
21	.7000	.7500	.0300	.0800	.4196742E-11	50
22	.7000	.7500	.0800	.2000	.2336814E-07	50
23	.6500	.7000	.0300	.0600	.5463484E-13	50
24	.6000	.6500	.0300	.0600	.8799247E-13	50
25	.6000	.7000	.0600	.1000	.3045021E-09	50
SUM OF CELL PROBABILITIES =					.6532261824E-06	

Figure 4.19 Stratification Description for Sample Problem 3

Figure 4.20 Stratification Scheme for Sample Problem 3

- - - SAMPLE-3 HU-CD, PLANT LOADING, C=LGNRM, SIGFLO=NRM, PROOF TEST, A LOGNRM, B/A EXP, 4 EQ - - -

- - RESULTS WITHOUT EARTHQUAKES - - -

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	1.04303E-09	1.04303E-09	8.48248E-16	1.47080E-10	1.47080E-10	1.67004E-16
1.0	2.66150E-09	2.66150E-09	1.38917E-15	2.05922E-10	2.05922E-10	3.18858E-16
2.0	3.16898E-09	3.16898E-09	1.57453E-15	2.12050E-10	2.12050E-10	3.54296E-16
5.0	4.40526E-09	4.40526E-09	2.65676E-15	2.38477E-10	2.38477E-10	6.02142E-16
10.0	6.53153E-09	6.53153E-09	3.39410E-15	5.20656E-10	5.20656E-10	6.45769E-16
20.0	7.94332E-09	7.94332E-09	5.10802E-15	5.89020E-10	5.89020E-10	8.47443E-16
40.0	1.04986E-08	1.04986E-08	3.43262E-14	8.31964E-10	8.31964E-10	2.34634E-14

Figure 4.21 Results for the No Earthquake Case for Sample Problem 3

- - - SAMPLE-3 HU-CD, PLANT LOADING, C=LGNRM, SIGFLO=NRM, PROOF TEST, A LOGNRM, B/A EXP, 4 EQ - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

CLASS	S4-EQ	SGLCEQ	CYCLES	1 OBE TH 1 JOINT 1 LLNL DATA
1	.5216E+03	8.757	1	1 OBE TH 1 JOINT 1 LLNL DATA
1	.5500E+03	8.500	1	1 OBE TH 1 JOINT 1 LLNL DATA

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	1.11431E-09	1.11431E-09	9.83968E-16	1.51472E-10	1.51472E-10	1.85404E-16
1.0	2.66223E-09	2.66223E-09	1.51466E-15	2.05921E-10	2.05921E-10	3.25940E-16
2.0	3.16898E-09	3.16898E-09	1.75582E-15	2.12050E-10	2.12050E-10	3.62269E-16
5.0	4.40526E-09	4.40526E-09	2.71529E-15	2.38477E-10	2.38477E-10	6.01716E-16
10.0	6.53153E-09	6.53153E-09	3.68878E-15	5.20656E-10	5.20656E-10	6.44955E-16
20.0	7.94332E-09	7.94332E-09	5.11611E-15	5.89020E-10	5.89020E-10	8.47375E-16
40.0	1.04986E-08	1.04986E-08	3.46090E-14	8.31964E-10	8.31964E-10	2.34629E-14

Figure 4.22a Results for Earthquake Category 1 in Sample Problem 3

- - - SAMPLE-3 HU-CD, PLANT LOADING, C=LGNRM, SIGFLO=NRM, PROOF TEST, A LOGNRM, B/A EXP, 4 EQ - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

	CLASS	S4-EQ	SGLCEQ	CYCLES	1 SSE TH 1 JOINT 1 LLNL DATA		
	2	.2958E+04	9.059	2			
TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA	
0.	1.22298E-09	1.22298E-09	1.42218E-15	1.56379E-10	1.56379E-10	2.86670E-16	
1.0	2.70590E-09	2.70590E-09	2.47603E-15	2.06883E-10	2.06883E-10	5.68808E-16	
2.0	3.16898E-09	3.16898E-09	2.49233E-15	2.12050E-10	2.12050E-10	5.68761E-16	
5.0	4.41736E-09	4.41736E-09	3.32378E-15	2.38337E-10	2.38337E-10	6.33091E-16	
10.0	6.56094E-09	6.56094E-09	4.30582E-15	5.20235E-10	5.20235E-10	6.80969E-16	
20.0	7.94332E-09	7.94332E-09	6.44084E-15	5.89020E-10	5.89020E-10	9.33057E-16	
40.0	1.08114E-08	1.08114E-08	3.59809E-14	8.78884E-10	8.78884E-10	2.34648E-14	

Figure 4.22b Results for Earthquake Category 2 in Sample Problem 3

- - - SAMPLE-3 HU-CD, PLANT LOADING, C=LGNRM, SIGFLO=NRM, PROOF TEST, A LOGNRM, B/A EXP, 4 EQ - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

	CLASS	S4-EQ	SGLCEQ	CYCLES	3 SSE TH 2 JOINT 1 LLNL DATA		
	3	.6343E+05	10.557	2			
TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA	
0.	1.75331E-09	1.75331E-09	4.54299E-15	1.81731E-10	1.81731E-10	6.66349E-16	
1.0	2.83536E-09	2.83536E-09	5.05868E-15	2.08999E-10	2.08999E-10	6.78668E-16	
2.0	3.41501E-09	3.41501E-09	5.71813E-15	2.13497E-10	2.13497E-10	6.95054E-16	
5.0	4.54150E-09	4.54150E-09	7.68787E-15	2.37711E-10	2.37711E-10	7.60074E-16	
10.0	6.57324E-09	6.57324E-09	2.83110E-14	5.20152E-10	5.20152E-10	1.95985E-14	
20.0	8.07079E-09	8.07079E-09	3.01181E-14	5.97830E-10	5.97830E-10	1.96088E-14	
40.0	1.08265E-08	1.08265E-08	1.04824E-13	8.79004E-10	8.79004E-10	4.19900E-14	

Figure 4.22c Results for Earthquake Category 3 in Sample Problem 3

- - - SAMPLE-3 HU-CD,PLANT LOADING,C=LGNRM,SIGFLO=NRM,PROOF TEST,A LOGNRM,B/A EXP,4 EQ - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

CLASS	S4-EQ	SGLCEQ	CYCLES
4	.1620E+06	10.617	4
4	.1700E+06	10.500	4

5 SSE TH 4 JOINT 1 LLNL DATA
5 SSE TH 4 JOINT 1 LLNL DATA

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	2.54478E-09	2.54478E-09	4.58083E-15	2.03806E-10	2.03806E-10	6.55417E-16
1.0	3.07162E-09	3.07162E-09	5.29036E-15	2.10904E-10	2.10904E-10	6.79246E-16
2.0	3.63015E-09	3.63015E-09	6.01775E-15	2.36951E-10	2.36951E-10	6.86061E-16
5.0	4.83131E-09	4.83131E-09	1.74786E-14	2.34671E-10	2.34671E-10	9.82021E-15
10.0	6.58591E-09	6.58591E-09	1.85931E-14	5.20067E-10	5.20067E-10	9.82406E-15
20.0	8.13608E-09	8.13608E-09	3.12956E-14	5.96858E-10	5.96858E-10	1.96441E-14
40.0	1.12076E-08	1.12076E-08	1.05121E-13	9.09432E-10	9.09432E-10	4.19898E-14

Figure 4.22d Results for Earthquake Category 4 in Sample Problem 3

4.10.4 Sample Problem 4

The input for this problem closely resembles the input for the hot leg to pressure vessel weld joint that was analyzed in the load combinations project. The card images for the input are shown in Figure 4.23. Specific inputs include:

- Forty year plant lifetime (THRIZN = 40).
- Two and one-half inch pipe wall thickness (THICK = 2.5).
- Fourteen and one-half inch pipe inside radius (RIN = 14.5).
- Crack growth relationship with a log-normally distributed C whose median = 9.0×10^{-12} and 90-th percentile value = 3.5×10^{-11} , or

$$\frac{da}{dn} = C(\Delta K)_{eff}^4 \text{ in/cycle}$$

$$K_0 = 4.6 \text{ KSI} \cdot \sqrt{\text{in}}$$

(KONPRP = 0, CONSMU = 9.0×10^{-12} , CONS90 = 3.5×10^{-11} , EXEMP = 4.0, THRHLD = 4.6).

- The flow stress is normally distributed with mean = 44.9 KSI and a standard deviation = 1.373 KSI. (SFLOMU = 44.9, SFLOSD = 1.373).
- The crack depth is exponentially distributed, while the aspect ratio is log normally distributed. (KRRDIS = 3, ALAMDA = 4.065, BOAMED = 1.336, BOASIG = 0.538, and BOANRM = 1.419).
- Evaluation of the failure probabilities is carried out at 2 year intervals (NEVAL = -2).
- An in-service inspection is performed at 20.01 years into the life of the plant, (NINSPT = 1, TINSPT(1) = 20.01).
- A detectable leak is 2 gpm (FNDLEK = 2.0).
- The discrimination level for a big leak is 2 gpm (ALKBIG = 2.0).
- The multiplier for the number of samples from each cell is fifty (NTRIES = 50).
- A pre-service inspection is modeled (NSPI = 1.0).

- The contribution to the load controlled stresses in the cold shutdown (deadweight) and normal operating (deadweight and restraint of thermal expansion) condition are 2 KSI and 8.75 KSI, respectively. (SIGCLD = 2.0, SGDWTE = 8.75).
- Operating pressure is 2250 psia (OPPRES = 2.25).
- A hydrostatic proof test with pressure of 3107 psia is modeled (PRFPRS = 3.107).
- Two types of transients are modeled. The heatup/cooldown cycle occurs regularly five (5) times per year. The temperature variation is 480°F. Plant loadings at greater than 5% per minute are assumed to occur at regular intervals of 0.2186 years.
- Four earthquake categories are modeled. Each category has one representative earthquake
 (NQUAKE = 1, NEQINT = 4, NEQCLS(1) = 1,
 NEQCLS(2) = 1,
 NEQCLS(3) = 1,
 NEQCLS(4) = 1)


```

--- SAMPLE-4 HL-PV,SIGFLO NRM,C LGNRM,B/A LGNRM,A EXP,PSI,ISI-20,PROOF,LEAK DETECT ---

PIPE DIMENSIONS
  INSIDE RADIUS =      14.50  INCHES
  WALL THICKNESS  =      2.50  INCHES

INITIAL CRACK SIZE DISTRIBUTION
CRACK DEPTH IS EXPONENTIAL
  PARAMETER =      4.0650
ASPECT RATIO IS LOG-NORMAL
  MEDIAN =      1.3360
  SHAPE PARAMETER =      .5380
  NORMALIZATION CONSTANT =      1.4190

CRACK GROWTH LAW PARAMETERS
  EXPONENT =      4.00
  GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
    MEDIAN =      .9140E-11
    90-TH PERCENT =      .3500E-10
  THRESHOLD =      4.60
  FLOW STRESS NORMALLY DISTRIBUTED
    MEAN=      .4490E+02
    STANDARD DEVIAT =      .1373E+01

PIPE STRESS VALUES
  CSD DEADWT STRESS (KSI)  2.00
  HOT UNIFORM STRESS (KSI) 15.28
  PRESSURE STRESS (KSI)   6.53
  PROOF TEST STRESS(KSI)  11.01

LEAK DETECTION AND DEFINITION PARAMETERS
  DETECTABLE LEAK(GPM)    2.0
  BIG LEAK(GPM)           2.0

SEISMIC CLASS INFORMATION
  CLASS   S4-EQ   SGLCEQ   CYCLES
  1       .5216E+03  8.757   1       1 OBE TH 1 JOINT 1 LLNL DATA
  2       .2958E+04  9.059   2       1 SSE TH 1 JOINT 1 LLNL DATA
  3       .6343E+05  10.557  2       3 SSE TH 2 JOINT 1 LLNL DATA
  4       .1620E+06  10.617  4       5 SSE TH 4 JOINT 1 LLNL DATA

PRE-SERVICE ULTRASONIC INSPECTION IS MODELED

TIME INTERVALS
  PLANT LIFETIME      40.0  YEARS
  ENDPOINTS OF INTERVALS AT  0.    2.0  4.0  6.0  8.0  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  30.0  32.0  34.0  36.0  38.0  YEARS
  ENDPOINTS OF INTERVALS AT 40.0
  IN-SERVICE INSPECTIONS AT 20.0

- - - EARTHQUAKES AT EACH EVALUATION INTERVAL -

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS 5

- - - NORMAL OUTPUT REQUESTED - - -

```

Figure 4.24 Input Summary for Sample Problem 4

- - NUMBER OF TRANSIENT TYPES = 2 - -

TYPE 1 HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
REGULAR AT .200 YRS/EVENT
MAX DELTA TEMP = 478.5 BLOCKING FACTOR = 1.

TYPE 2 PLANT LOADING .GT. 5 PERCENT PER MINUTE
REGULAR AT .002 YRS/EVENT
MAX DELTA TEMP = 39.5 BLOCKING FACTOR = 100.

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

\$\$\$ USER-SPECIFIED MESH \$\$\$

CELL	AOH1	AOH2	AOB1	AOB2	PROBABILITY	SAMPLES
1	.9800	1.0000	.0520	.0600	.1236250E-10	250
2	.9800	1.0000	.0600	.0700	.4867245E-10	200
3	.9800	1.0000	.0700	.1000	.1063584E-08	200
4	.9800	1.0000	.1000	.2000	.8627773E-07	150
5	.9800	1.0000	.2000	.4000	.1419205E-05	150
6	.9800	1.0000	.4000	.7000	.4052950E-05	50
7	.9800	1.0000	.7000	1.0000	.3140035E-05	50
8	.9600	.9800	.0520	.0600	.1514874E-10	250
9	.9600	.9800	.0600	.0700	.5964219E-10	200
10	.9600	.9800	.0700	.1000	.1303293E-08	200
11	.9600	.9800	.1000	.2000	.1057229E-06	150
12	.9600	.9800	.2000	.4000	.1739064E-05	150
13	.9600	.9800	.4000	.7000	.4966399E-05	50
14	.9600	.9800	.7000	1.0000	.3847733E-05	50
15	.9400	.9600	.0500	.0600	.2064938E-10	250
16	.9400	.9600	.0600	.0700	.7308427E-10	200
17	.9200	.9400	.0500	.0600	.2530393E-10	250
18	.9200	.9400	.0600	.0700	.8955592E-10	200
19	.9200	.9600	.0700	.1000	.3553991E-08	150
20	.9200	.9600	.1000	.2000	.2892991E-06	150
21	.9200	.9600	.2000	.4000	.4742310E-05	150
22	.9200	.9600	.4000	.7000	.1354303E-04	50
23	.9200	.9600	.7000	1.0000	.1049250E-04	50
24	.9000	.9200	.0460	.0600	.3422868E-10	250
25	.8800	.9000	.0460	.0600	.4267857E-10	250
26	.8500	.8800	.0460	.0600	.8271275E-10	250
27	.8500	.9200	.0600	.0750	.1042857E-08	250
28	.8500	.9200	.0750	.1000	.1049338E-07	250
29	.8500	.9200	.1000	.2000	.8942657E-06	150
30	.8500	.9200	.2000	.4000	.1471989E-04	150
31	.8000	.8500	.0430	.0500	.3175522E-10	250
32	.8000	.8500	.0500	.0750	.1542147E-08	250
33	.8000	.8500	.0750	.1000	.1365027E-07	150
34	.8000	.8500	.1000	.2000	.1164083E-05	150
35	.7500	.8000	.0410	.0500	.5865040E-10	250
36	.7500	.8000	.0500	.0750	.2563313E-08	250
37	.7500	.8000	.0750	.1000	.2268910E-07	150
38	.7500	.8000	.1000	.2000	.1934906E-05	150
39	.7000	.7500	.0380	.0450	.3295482E-10	250
40	.7000	.7500	.0450	.0600	.5856511E-09	250
41	.7000	.7500	.0600	.1000	.4146120E-07	200
42	.7000	.7500	.1000	.2000	.3216146E-05	150
43	.6500	.7000	.0320	.0400	.1808450E-10	250
44	.6500	.7000	.0400	.0600	.1019945E-08	250
45	.6500	.7000	.0600	.1000	.6891563E-07	200
46	.6000	.6500	.0320	.0400	.3005954E-10	250
47	.6000	.6500	.0400	.0600	.1695324E-08	250
48	.6000	.6500	.0600	.1000	.1145496E-06	200

SUM OF CELL PROBABILITIES = .7064022475E-04

Figure 4.25 Stratification Description for Sample Problem 4

- - - SAMPLE-4 HL-PV,SIGFLO NRM,C LGNRM,B/A LGNRM,A EXP,PSI,ISI-20,PROOF,LEAK DETECT - - -

- - RESULTS WITHOUT EARTHQUAKES - - -

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	6.31309E-08	6.31309E-08	0.	1.40995E-08	1.40995E-08	0.
2.0	2.34161E-07	2.34161E-07	3.54103E-14	2.19799E-08	2.19799E-08	3.54103E-14
4.0	3.02411E-07	3.02411E-07	4.25308E-13	2.24159E-08	2.24159E-08	3.57737E-13
6.0	3.68824E-07	3.68824E-07	8.19421E-13	2.27089E-08	2.27089E-08	5.01564E-13
8.0	4.15929E-07	4.15929E-07	8.98573E-13	2.33941E-08	2.33941E-08	5.03512E-13
10.0	4.52255E-07	4.52255E-07	1.45424E-12	2.26194E-08	2.26194E-08	6.19090E-13
12.0	4.95907E-07	4.95907E-07	1.57321E-12	2.36870E-08	2.36870E-08	6.21660E-13
14.0	5.26038E-07	5.26038E-07	1.65452E-12	2.50466E-08	2.50466E-08	6.23182E-13
16.0	5.67718E-07	5.67718E-07	1.81548E-12	3.29665E-08	3.29665E-08	6.26894E-13
18.0	6.00147E-07	6.00147E-07	2.23086E-12	3.36264E-08	3.36264E-08	7.23681E-13
20.0	6.10146E-07	6.10146E-07	2.39223E-12	3.37362E-08	3.37362E-08	7.25696E-13
22.0	6.12100E-07	6.12100E-07	2.40010E-12	3.36814E-08	3.36814E-08	7.25704E-13
24.0	6.13801E-07	6.13801E-07	2.41102E-12	3.36458E-08	3.36458E-08	7.25704E-13
26.0	6.15420E-07	6.15420E-07	2.41102E-12	3.35879E-08	3.35879E-08	7.25704E-13
28.0	6.15865E-07	6.15865E-07	2.41982E-12	3.35642E-08	3.35642E-08	7.25716E-13
30.0	6.16895E-07	6.16895E-07	2.43269E-12	3.35162E-08	3.35162E-08	7.25713E-13
32.0	6.18649E-07	6.18649E-07	2.45801E-12	3.34446E-08	3.34446E-08	7.25733E-13
34.0	6.21085E-07	6.21085E-07	2.45801E-12	3.34318E-08	3.34318E-08	7.25733E-13
36.0	6.23416E-07	6.23416E-07	2.48271E-12	3.34305E-08	3.34305E-08	7.25748E-13
38.0	6.25343E-07	6.25343E-07	2.49923E-12	3.34057E-08	3.34057E-08	7.25766E-13
40.0	6.26594E-07	6.26594E-07	2.50886E-12	3.34011E-08	3.34011E-08	7.25765E-13

Figure 4.26 Results for No Earthquake Case in Sample Problem 4

- - - SAMPLE-4 HL-PV,SIGFLO NRM,C LGNRM,B/A LGNRM,A EXP,PSI,ISI-20,PROOF,LEAK DETECT - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

CLASS S4-EQ SGLCEQ CYCLES
1 .5216E+03 8.757 1

1 OBE TH 1 JOINT 1 LLNL DATA

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	6.43568E-08	6.43568E-08	0.	1.41148E-08	1.41148E-08	0.
2.0	2.34197E-07	2.34197E-07	3.54103E-14	2.19798E-08	2.19798E-08	3.54103E-14
4.0	3.03009E-07	3.03009E-07	7.77439E-13	2.24139E-08	2.24139E-08	5.00969E-13
6.0	3.68824E-07	3.68824E-07	8.19421E-13	2.27089E-08	2.27089E-08	5.01564E-13
8.0	4.16821E-07	4.16821E-07	9.35119E-13	2.34035E-08	2.34035E-08	5.04826E-13
10.0	4.52255E-07	4.52255E-07	1.47045E-12	2.26194E-08	2.26194E-08	6.19290E-13
12.0	4.95943E-07	4.95943E-07	1.57321E-12	2.36870E-08	2.36870E-08	6.21660E-13
14.0	5.26042E-07	5.26042E-07	1.69058E-12	2.50466E-08	2.50466E-08	6.24175E-13
16.0	5.67718E-07	5.67718E-07	1.83373E-12	3.29665E-08	3.29665E-08	6.27158E-13
18.0	6.00148E-07	6.00148E-07	2.25999E-12	3.36264E-08	3.36264E-08	7.23954E-13
20.0	6.10146E-07	6.10146E-07	2.39223E-12	3.37362E-08	3.37362E-08	7.25696E-13
22.0	6.12148E-07	6.12148E-07	2.40255E-12	3.36810E-08	3.36810E-08	7.25706E-13
24.0	6.13801E-07	6.13801E-07	2.41102E-12	3.36458E-08	3.36458E-08	7.25704E-13
26.0	6.15420E-07	6.15420E-07	2.41232E-12	3.35879E-08	3.35879E-08	7.25703E-13
28.0	6.15903E-07	6.15903E-07	2.42347E-12	3.35642E-08	3.35642E-08	7.25718E-13
30.0	6.16895E-07	6.16895E-07	2.46867E-12	3.35162E-08	3.35162E-08	7.26080E-13
32.0	6.18975E-07	6.18975E-07	2.45801E-12	3.34438E-08	3.34438E-08	7.25733E-13
34.0	6.21085E-07	6.21085E-07	2.46644E-12	3.34318E-08	3.34318E-08	7.25739E-13
36.0	6.23426E-07	6.23426E-07	2.49032E-12	3.34305E-08	3.34305E-08	7.25750E-13
38.0	6.25343E-07	6.25343E-07	2.50939E-12	3.34057E-08	3.34057E-08	7.25785E-13
40.0	6.26594E-07	6.26594E-07	2.52702E-12	3.34011E-08	3.34011E-08	7.25815E-13

Figure 4.27a Results for Earthquake Category 1 in Sample Problem 4

- - - SAMPLE-4 HL-PV,SIGFLO NRM,C LGNRM,B/A LGNRM,A EXP,PSI,ISI-20,PROOF,LEAK DETECT - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

	CLASS	S4-EQ	SGLCEQ	CYCLES	1 SSE TH 1 JOINT 1 LLNL DATA		
	2	.2958E+04	9.059	2			
TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA	
0.	6.94084E-08	6.94084E-08	0.	1.45532E-08	1.45532E-08	0.	
2.0	2.34784E-07	2.34784E-07	3.54103E-14	2.19796E-08	2.19796E-08	3.54103E-14	
4.0	3.03009E-07	3.03009E-07	7.77439E-13	2.24139E-08	2.24139E-08	5.00969E-13	
6.0	3.69410E-07	3.69410E-07	8.31950E-13	2.27054E-08	2.27054E-08	5.01718E-13	
8.0	4.16821E-07	4.16821E-07	9.51131E-13	2.34035E-08	2.34035E-08	5.05076E-13	
10.0	4.52255E-07	4.52255E-07	1.52019E-12	2.26194E-08	2.26194E-08	6.20388E-13	
12.0	4.95943E-07	4.95943E-07	1.60158E-12	2.36870E-08	2.36870E-08	6.21971E-13	
14.0	5.26042E-07	5.26042E-07	1.70756E-12	2.50466E-08	2.50466E-08	6.24387E-13	
16.0	5.68232E-07	5.68232E-07	1.86616E-12	3.29704E-08	3.29704E-08	6.27549E-13	
18.0	6.00148E-07	6.00148E-07	2.29187E-12	3.36264E-08	3.36264E-08	7.24294E-13	
20.0	6.10146E-07	6.10146E-07	2.39223E-12	3.37362E-08	3.37362E-08	7.25696E-13	
22.0	6.12199E-07	6.12199E-07	2.40698E-12	3.36806E-08	3.36806E-08	7.25705E-13	
24.0	6.13801E-07	6.13801E-07	2.41102E-12	3.36458E-08	3.36458E-08	7.25704E-13	
26.0	6.15420E-07	6.15420E-07	2.42013E-12	3.35879E-08	3.35879E-08	7.25718E-13	
28.0	6.15903E-07	6.15903E-07	2.43130E-12	3.35642E-08	3.35642E-08	7.25719E-13	
30.0	6.16895E-07	6.16895E-07	2.47899E-12	3.35162E-08	3.35162E-08	7.26084E-13	
32.0	6.18987E-07	6.18987E-07	2.46359E-12	3.34437E-08	3.34437E-08	7.25737E-13	
34.0	6.21095E-07	6.21095E-07	2.48016E-12	3.34318E-08	3.34318E-08	7.25768E-13	
36.0	6.23426E-07	6.23426E-07	2.50048E-12	3.34305E-08	3.34305E-08	7.25770E-13	
38.0	6.25343E-07	6.25343E-07	2.51633E-12	3.34057E-08	3.34057E-08	7.25787E-13	
40.0	6.26595E-07	6.26595E-07	2.53462E-12	3.34011E-08	3.34011E-08	7.25813E-13	

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Figure 4.27b Results for Earthquake Category 2 in Sample Problem 4

- - - SAMPLE-4 HL-PV,SIGFLO NRM,C LGNRM,B/A LGNRM,A EXP,PSI,ISI-20,PROOF,LEAK DETECT - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

CLASS S4-EQ SGLCEQ CYCLES
3 .6343E+05 10.557 2

3 SSE TH 2 JOINT 1 LLNL DATA

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TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	1.33515E-07	1.33515E-07	9.02551E-14	1.92072E-08	1.92072E-08	4.04813E-14
2.0	2.42713E-07	2.42713E-07	4.11309E-13	2.21000E-08	2.21000E-08	1.03409E-13
4.0	3.14745E-07	3.14745E-07	1.55657E-12	2.23734E-08	2.23734E-08	5.20162E-13
6.0	3.76199E-07	3.76199E-07	1.97032E-12	2.33073E-08	2.33073E-08	6.30120E-13
8.0	4.25624E-07	4.25624E-07	2.45531E-12	2.32483E-08	2.32483E-08	7.25876E-13
10.0	4.53832E-07	4.53832E-07	2.19955E-12	2.26107E-08	2.26107E-08	6.35557E-13
12.0	4.97445E-07	4.97445E-07	2.87603E-12	2.36892E-08	2.36892E-08	7.35745E-13
14.0	5.26092E-07	5.26092E-07	3.47861E-12	2.50466E-08	2.50466E-08	8.21439E-13
16.0	5.72899E-07	5.72899E-07	3.14707E-12	3.28452E-08	3.28452E-08	7.40140E-13
18.0	6.00959E-07	6.00959E-07	3.30778E-12	3.36300E-08	3.36300E-08	7.41669E-13
20.0	6.15800E-07	6.15800E-07	3.42112E-12	3.40595E-08	3.40595E-08	7.43914E-13
22.0	6.12209E-07	6.12209E-07	2.51779E-12	3.36806E-08	3.36806E-08	7.26022E-13
24.0	6.14679E-07	6.14679E-07	2.55699E-12	3.35980E-08	3.35980E-08	7.26356E-13
26.0	6.15668E-07	6.15668E-07	2.57999E-12	3.35652E-08	3.35652E-08	7.26499E-13
28.0	6.15904E-07	6.15904E-07	2.57716E-12	3.35642E-08	3.35642E-08	7.26152E-13
30.0	6.17469E-07	6.17469E-07	2.61065E-12	3.34926E-08	3.34926E-08	7.26214E-13
32.0	6.18990E-07	6.18990E-07	2.61416E-12	3.34437E-08	3.34437E-08	7.25904E-13
34.0	6.21107E-07	6.21107E-07	2.64732E-12	3.34318E-08	3.34318E-08	7.25922E-13
36.0	6.23849E-07	6.23849E-07	2.73857E-12	3.34205E-08	3.34205E-08	7.26917E-13
38.0	6.25682E-07	6.25682E-07	2.73359E-12	3.34045E-08	3.34045E-08	7.26600E-13
40.0	6.26595E-07	6.26595E-07	2.71533E-12	3.34011E-08	3.34011E-08	7.26011E-13

Figure 4.27c Results for Earthquake Category 3 in Sample Problem 4

- - - SAMPLE-4 HL-PV,SIGFLO NRM,C LGNRM,B/A LGNRM,A EXP,PSI,ISI-20,PROOF,LEAK DETECT - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

	CLASS	S4-EQ	SGLCEQ	CYCLES	5 SSE TH 4 JOINT 1 LLNL DATA		
	4	.1620E+06	10.617	4			
TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA	
0.	1.53361E-07	1.53361E-07	2.52137E-13	1.99124E-08	1.99124E-08	7.45784E-14	
2.0	2.57050E-07	2.57050E-07	1.36377E-12	2.22347E-08	2.22347E-08	5.15184E-13	
4.0	3.38519E-07	3.38519E-07	2.55073E-12	2.31502E-08	2.31502E-08	7.24564E-13	
6.0	3.93559E-07	3.93559E-07	2.27868E-12	2.39241E-08	2.39241E-08	6.36380E-13	
8.0	4.37682E-07	4.37682E-07	2.69293E-12	2.29946E-08	2.29946E-08	7.30556E-13	
10.0	4.60116E-07	4.60116E-07	2.82780E-12	2.28486E-08	2.28486E-08	7.43725E-13	
12.0	5.07015E-07	5.07015E-07	3.47952E-12	2.33729E-08	2.33729E-08	8.22050E-13	
14.0	5.31763E-07	5.31763E-07	3.66098E-12	2.49016E-08	2.49016E-08	8.24672E-13	
16.0	5.88810E-07	5.88810E-07	3.48009E-12	3.30688E-08	3.30688E-08	7.45212E-13	
18.0	6.01625E-07	6.01625E-07	3.43977E-12	3.36338E-08	3.36338E-08	7.43966E-13	
20.0	6.22257E-07	6.22257E-07	3.91670E-12	3.44846E-08	3.44846E-08	8.27104E-13	
22.0	6.12793E-07	6.12793E-07	2.52855E-12	3.36576E-08	3.36576E-08	7.26030E-13	
24.0	6.14783E-07	6.14783E-07	2.57709E-12	3.35980E-08	3.35980E-08	7.26366E-13	
26.0	6.15686E-07	6.15686E-07	2.60623E-12	3.35652E-08	3.35652E-08	7.26512E-13	
28.0	6.16100E-07	6.16100E-07	2.60816E-12	3.35633E-08	3.35633E-08	7.26224E-13	
30.0	6.17854E-07	6.17854E-07	2.63702E-12	3.34688E-08	3.34688E-08	7.26247E-13	
32.0	6.19935E-07	6.19935E-07	2.64560E-12	3.34519E-08	3.34519E-08	7.25922E-13	
34.0	6.21578E-07	6.21578E-07	2.66669E-12	3.34216E-08	3.34216E-08	7.25916E-13	
36.0	6.24312E-07	6.24312E-07	2.82776E-12	3.34098E-08	3.34098E-08	7.30236E-13	
38.0	6.26010E-07	6.26010E-07	2.75867E-12	3.34033E-08	3.34033E-08	7.26643E-13	
40.0	6.27096E-07	6.27096E-07	2.72605E-12	3.33612E-08	3.33612E-08	7.26008E-13	

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Figure 4.27d Results for Earthquake Category 4 in Sample Problem 4

5.0 ORGANIZATION OF THE PRAISE CODE

This chapter presents a detailed description of the PRAISE coding and is intended primarily for the analyst or programmer who wishes to understand or modify PRAISE. A working knowledge of the objectives and theory behind the PRAISE simulation, as discussed in Chapters 2 and 3, is assumed. Section 5.1 presents the logical structure of the PRAISE coding. Subroutine INPUT, which reads and subsequently transforms the input data into the appropriate PRAISE format, is described in Section 5.2. Since many of the PRAISE subroutines require random numbers generated according to prescribed probability density functions, Section 5.3 briefly summarizes the techniques used in PRAISE. Detailed descriptions of the other major calculational units are given in Sections 5.4 through 5.11. The data management scheme developed for PRAISE is discussed in Sections 5.12 and 5.13.

5.1 Logical Structure and Description of Subroutines

Overall program control is exercised by the routine MAIN. From MAIN, calls are issued to the calculational subroutines and subprograms. The hierarchy of subroutine calls is illustrated in Figure 5.1. The algorithm can be divided into three sections. The first section includes overhead activities such as reading input and calculating program constants. The second or main section carries out the actual simulations, while the final section calculates and presents the results. The calculational flow of the PRAISE code is shown in Figure 5.2.

Before initiating the simulation, PRAISE performs the following sequence of overhead functions:

- (1) MAIN calls INITIAL to read the user inputs and to initialize program variables,
- (2) INITIAL calls subroutine ALOC to allocate locations within the data arrays where the program variables are to be stored,
- (3) If transients with radial gradient thermal stresses are to be included in the simulation, MAIN calls INTERP to construct tabular functions for
$$g_{\min,a}(i,a/h,a/b), g_{\max,a}(i,a/h,a/b), g_{\min,b}(i,a/h,a/b),$$
$$g_{\max,b}(i,a/h,a/b)$$
as described in Equations (3.52a) and (3.52b).
- (4) MAIN calls subroutine VERIFY to print a summary of the problem specifications so that the user can verify his input. The use of separate routines for input and verification helps to insure that the data are begin properly transferred in the DATA arrays and the COMMON blocks.
- (5) MAIN calls subroutine PROBAB to calculate the individual cell probabilities; i.e., the p_m indicated in Equations (3.5) and (3.6).

The replication of crack histories is performed within two loops of the MAIN routine. The outer loop ranges over the M cells, while the inner loop ranges

Figure 5.1 Hierarchy of Routines in PRAISE

Figure 5.2 Computational Flow in PRAISE

over the number of replications from each cell. For each replication the MAIN routine performs the following functions:

- (1) If C , the fatigue crack growth parameter, is to be modeled as a random variable, MAIN calls subroutine MATPRO to select a value of C from the user defined log-normal distribution; otherwise, the constant value of C is assumed.
- (2) If σ_{f10} , the material flow stress, is treated as a normally distributed variable, a value of σ_{f10} is selected; otherwise, the constant value is assumed.
- (3) MAIN calls subroutine CRKSIZ to select random values of a/h and a/b conditional on their frequency of occurrence within the m -th cell.
- (4) If a hydrostatic proof test is modeled, MAIN calculates the critical values of the crack dimension using the LOCA failure criterion. If the crack satisfies the criterion for failure, MAIN terminates this replication.
- (5) MAIN calls subroutine INSPCT to evaluate the non-detection probability for the chosen initial crack size. This probability is denoted by PRB.
- (6) MAIN calls subroutine RESET to reset the indicator flags.
- (7) MAIN calls subroutine FTIME to generate and chronologically order the first occurrence of each event.
- (8) The simulation time is moved to the time of the next event to occur. The event type is also identified. If this time is greater than the plant lifetime this replication is terminated. Otherwise, subroutine FTIME is called again to replace the next arrival time for the event type that just occurred.
- (9) If an in-service inspection is the next event, subroutine ISI is called to simulate an in-service inspection. The simulation then returns to step (8).
- (10) If evaluation earthquakes is the next event, subroutine SHAKER is called to perform the next earthquake evaluation. When control is returned from SHAKER to MAIN, the simulation returns to step (8).

(11) If an operating condition or anticipated transient is the next event, MAIN does the following:

- (a) evaluates the temperature
- (b) calls subroutine KBARS to calculate the effective RMS stress intensity factors
- (c) calls subroutine CRKGRO to increase the crack dimensions and check for leak or LOCA
- (d) if failure has occurred statistics on the failures are accumulated.

If the present replication is to be terminated, MAIN returns to step (1). Otherwise, control returns to step (8) to determine the next transient event.

After all of the requested replications have been completed, MAIN calls subroutine OUTS to evaluate the probability distribution functions and prints out the results.

5.2 Input Data

All of the input data required by the PRAISE program is read from the subroutine INITIAL. The seven major categories are:

- (1) problem control variables,
- (2) geometry and material properties,
- (3) initial crack size distribution,
- (4) inspection times, seismic evaluation times, and leak detection,
- (5) stratified sample space,
- (6) stresses and frequency of transients, and
- (7) seismic magnitude and stresses.

Some of the mechanics for transforming the input quantities into the form suitable for use in PRAISE is also carried out in INITIAL. This section briefly reviews the organization and functions of INITIAL. A detailed input description including a list of variables and formats is given in Chapter 4.

5.2.1 Problem Control Variables

The PRAISE user has considerable flexibility in adapting the code to his specific application. The choice of the various options is determined by the problem control variables.

5.2.2 Initial Crack Size Distribution

PRAISE permits the user to choose either an exponential or log-normal distribution on crack depth and either a shifted exponential or a truncated log-normal distribution for the aspect ratio. This results in four combinations

of crack depth and aspect ratio definitions. The indicator KRKDIS (for crack distributions) controls the distributions that are to be used. The definitions of KRKDIS are shown in Table 5.1.

Table 5.1
COMBINATIONS OF CRACK DEPTH AND ASPECT RATIO DISTRIBUTIONS

		b/a	
		LOG-NORMAL	EXPONENTIAL
a	LOG-NORMAL	1	2
	EXPONENTIAL	3	4

The input for the exponential distribution on the crack depth is the rate parameter ALAMDA which corresponds to λ in Equation (3.28). INITIAL converts ALAMDA to the new rate parameter

$$\mu = \text{AOHLDH} = \text{ALAMDA} * \text{THICK} = \lambda h \quad (5.1)$$

as required by Equation (3.30). INITIAL also computes a normalization constant C for Equation (3.29). By direct integration of Equation (3.29) between the limits zero and one and equating the result to one, C* is given by

$$C^* = \frac{1}{1 - e^{-\mu}} \quad (5.2)$$

For the log-normal distribution on crack depth, the input variables are AMEDIN and ASIGMA which correspond to a_{50} and S, respectively in Equation (3.31) or

$$f_1(a) = \frac{C^*}{(\text{ASIGMA})a \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left\{ \frac{\ln(a/\text{AMEDIN})}{\text{ASIGMA}} \right\}^2 \right] \quad (5.3)$$

INITIAL then transforms to the form of Equation (3.33) by setting

$$\ln a'_{50} = \text{AOHMU} = \ln(a_{50}/h) = \text{ALOG}(\text{AMEDIN}/\text{THICK}) \quad (5.4)$$

so that the new pdf on a/h becomes

$$P_1(a/h) = \frac{C^*}{(ASIGMA) \sqrt{2\pi}(a/h)} \exp \left[-\frac{1}{2} \left\{ \frac{\ln(a/h) - AOHMU}{ASIGMA} \right\}^2 \right] \cdot \quad (5.5)$$

The normalization constant C^* is given by

$$C^* \int_0^1 P_1(a/h) d(a/h) = 1 \quad (5.6)$$

or

$$C^* \int_{-\infty}^0 \frac{1}{S \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left\{ \frac{\ln(a/h) - \ln(a_{50}/h)}{S} \right\}^2 \right] d(\ln(a/h)) = 1 \quad (5.7)$$

Equation (5.7) is expressible as an error function. INITIAL calls the function ERFINT to evaluate the integral in Equation (5.7). The constant then follows directly.

For the shifted exponential distribution on aspect ratio, INITIAL reads in the λ of Equation (3.34) as BOALDA. For the truncated log-normal distribution on the aspect ratio, INITIAL reads in BOAMED, BOASIG, and BOANRM which correspond to the median, shape factor, and normalization constant in Equation (3.37). The logarithm of the median is then formed as

$$BOAMU = ALOG(BOAMED) \quad (5.8)$$

5.2.3 Stratified Sampling Plan

The PRAISE code partitions the sample space into a set of disjoint cells. A user-specified number of initial crack sizes is then selected from each cell. PRAISE has two options for defining the location of the individual cells. In the first, the code generates a regular array of rectangular cells. The user sets ISQUARE = 1 and then specifies the number of subdivisions in each coordiante direction using the variables NAOH and NAOB for the a/h

and a/b dimensions respectively. Each point in the sample space is included within one of these cells. The same number of samples is taken from each cell. This is specified by the input variable NTRIES. In the second option, ISQUARE = 0 and the user specifies that MCELLS cells are to be included. He then inputs the location and the number of samples to be selected from each of the required cells. The cells are assumed to be rectangular. For the m-th cell (m=1,2,...,MCELLS), the location is

$$AOHSIZ(M,1) \leq (a/h) \leq AOHSIZ(M,2)$$

$$AOBSIZ(M,1) \leq (a/b) \leq AOBSIZ(M,2),$$

while the number of samples to be taken from the m-th cell is read in through NUMTRY(M). For purposes of variance reduction the number of samples from each cell may differ from cell to cell. In some cases, it may be necessary to uniformly change the number of samples to be taken from each of the user-specified cells. Suppose that it is desired to increase the number of samples taken from each cell by a factor of 3. One brute force approach would be to increase each value of NUMTRY(M) by 3. For problems where there are a large number of cells, this could become quite tedious. PRAISE has an option for reducing this effort by using the variable NTRIES as a multiplier on the value NUMTRY(M) input by the user. When NTRIES > 0 is input, the actual number of samples drawn from the m-th cell is then NTRIES*NUMTRY(M). Thus, if the user actually intends for the NUMTRY(M) to be used, he should set NTRIES = 1. Another option allows the user-specified to reset the number of samples to a constant value. When NTRIES < 0 is input, NUMTRY(M) = ABS(NTRIES) for M = 1,...,MCELLS regardless of the input for NUMTRY(M). These options are summarized in Table 5.2.

PRAISE currently checks for cells which lie totally within the infeasible portion of the sample space. These are automatically eliminated from the calculation. PRAISE does not check for overlapping cells.

Table 5.2

DEFINITION OF CELLS FOR STRATIFIED SAMPLING

1. ISQARE = 0 User inputs cell definitions

MCELLS = Number of cells to be defined

NTRIES $\left\{ \begin{array}{l} < 0: \text{ABS(NTRIES) samples from each cell} \\ > 0: \text{Multiplier for number of samples from each cell} \end{array} \right.$

For M = 1, ..., MCELLS

READ (AOHSIZ(M,I),I=1,2),(AOBSIZ(M,I),I=1,2),NUMTRY(M)

2. ISQARE = 1 Code generates cell definitions

NAOH = Number of subdivisions along a/h coordinate

NOAB = Number of subdivisions along a/b coordinate

NTRIES = Number of samples from each cell

5.2.4 Pipe Geometry, Material Properties, and Fatigue Crack Growth Characteristics

The pipe geometry is defined by THICK, the wall thickness of the pipe, and RIN, the inside radius of the pipe. The relevant material properties are:

- (1) The flow stress SIGFLO, which can be treated either as a constant throughout the calculation or as a normally distributed random variable which changes at each replication. For the stochastic case, the inputs for the mean and standard deviation are denoted by SFLOMU and SFLOSD, respectively.
- (2) The threshold stress intensity value THRHLD for the crack growth law.
- (3) The constant C in the crack growth law can be treated either as a constant throughout the entire simulation or as a log-normally distributed random variable which is changed at the beginning of each replication.
- (4) The exponent m in the crack growth relationship.

5.2.5 Transient Frequencies and Stress Intensity Factors

The data that characterizes the transient events which are to be modeled in PRAISE are the frequency of the event and the radial gradient thermal stress contributions to the RMS stress intensity factors. The inter-arrival time can either be regular (a deterministic arrival time) or exponentially distributed. INITAL reads in a value BLAMDA(K), $K = 1 \dots KTYPES$ where KTYPES is the number of operating conditions and transients that PRAISE is to model. The heatup/cooldown cycle must always be designated as $K = 1$. If the inter-arrival time is constant, then BLAMDA(K) is set equal to that time. If the inter-arrival time is exponential, the negative of the mean time between arrivals is input as BLAMDA(K). INITAL also reads in the maximum temperature variation and a short identifier associated with each transient.

As discussed in Section 3.6, PRAISE models the contribution of the radial gradient thermal stresses on the RMS-stress intensity factor using functions of the form

$$(1) \quad g_{\min,a}(i,a/h,a/b) = \frac{\Delta \bar{K}_{\min,a}}{\Delta T \sqrt{a}} \quad (5.9)$$

$$(2) \quad g_{\max,a}(i,a/h,a/b) = \frac{\Delta \bar{K}_{\max,a}}{\Delta T \sqrt{a}} \quad (5.10)$$

$$(3) \quad g_{\min,b}(i,a/h,a/b) = \frac{\Delta \bar{K}_{\min,b}}{\Delta T \sqrt{a}} \quad (5.11)$$

$$(4) \quad g_{\max,b}(i,a/h,a/b) = \frac{\Delta \bar{K}_{\max,b}}{\Delta T \sqrt{a}} \quad (5.12)$$

Instead of developing analytical expressions for the functions $g_{\min}$ and $g_{\max}$, PRAISE uses a tabular representation. However, in order to be consistent with the crack size definitions, the input to PRAISE for these functions is in terms of the crack depth and the aspect ratio.

In other words, the user constructs tabular functions for $g_{\min,a}^*(i,a/h,b/a)$, $g_{\max,a}^*(i,a/h,b/a)$, $g_{\min,b}^*(i,a/h,b/a)$, and $g_{\max,b}^*(i,a/h,b/a)$ such that

$$(a) \quad g_{\min,a}^*(i,a/h,b/a) = g_{\min,a}(i,a/h,a/b)$$

$$(b) \quad g_{\max,a}^*(i,a/h,b/a) = g_{\max,a}(i,a/h,a/b)$$

$$(c) \quad g_{\min,b}^*(i,a/h,b/a) = g_{\min,b}(i,a/h,a/b)$$

$$(d) \quad g_{\max,b}^*(i,a/h,b/a) = g_{\max,b}(i,a/h,a/b)$$

The asterisks on the $g_{\min}^*$ and $g_{\max}^*$ indicate that the coordinates are a/h and b/a rather than a/h and a/b . As described in Section 4.6, the input is controlled by two DO loops. The outer loop is on b/a and proceeds from the smallest to the largest values for b/a . However, rather than storing these values of $g_{\min}^*$ and $g_{\max}^*$, PRAISE stores them directly as $g_{\min}$ and $g_{\max}$. Since the smallest value

of a/b corresponds to the largest value of b/a and vice versa, the $g_{\min}$ and $g_{\max}$ arrays can be filled in reverse order as the $g_{\min}^*$ and $g_{\max}^*$ values are input in ascending order of b/a .

5.3 Generation of Random Variables

A common method for generating random variates from a given pdf is the inverse transformation method. Suppose the density function $f(x)$ has a cumulative distribution $F(x)$. Since $F(x)$ is defined over the range 0 to 1 we can generate uniformly distributed random numbers and set $F(x) = r$. The desired random variate is then given by

$$x = F^{-1}(r) \quad (5.13)$$

where $F^{-1}(r)$ is the inverse transformation (or mapping) of r on the unit interval into the domain of x . We can summarize this method mathematically by saying that if we generate uniform random numbers corresponding to a given $F(x)$,

$$r = F(x) = \int_{-\infty}^x f(t)dt \quad (5.14)$$

then

$$P(X \geq x) = F(x) = P[r \leq F(x)] = P[F^{-1}(r) \leq x], \quad (5.15)$$

and consequently $F^{-1}(r)$ is a variable that has $f(x)$ as its probability density function. This technique can be applied whenever the cumulative distribution function is available either analytically or in tabular form.

A random variable is said to have an exponential distribution if its density function is defined as,

$$f(x) = \alpha e^{-\alpha x} \quad (5.16)$$

for $\alpha > 0$ and $x \geq 0$.

The cumulative distribution function of x is

$$F(x) = \int_0^x \alpha e^{-\alpha t} dt = 1 - e^{-\alpha x}, \quad (5.17)$$

when $F(x)$ exists in explicit form, the inverse transformation technique can be used in a straightforward manner. Because of the symmetry of the uniform distribution, $F(x)$ and $1-F(x)$ are interchangeable. Therefore,

$$r = e^{-\alpha x} \quad (5.18)$$

and consequently,

$$x = -\left(\frac{1}{\alpha}\right) \ln r \quad (5.19)$$

Thus, for each value of the random number r , a unique value of x is determined which will take only non-negative values (since $\ln r \leq 0$ for $0 \leq r \leq 1$) and will follow the exponential density function.

In many instances, an analytical form of the cumulative distribution function is not available. An alternate approach is to construct a tabular representation of the cdf and then interpolate the cumulative distribution. For example, let $F(x_1) < r < F(x_2)$, then $x_1 < x < x_2$. Linear interpolation gives

$$x = x_1 + \frac{x_2 - x_1}{F(x_2) - F(x_1)} (r - F(x_1)) \quad (5.20)$$

The generation of random variates from a standard normal distribution (with a mean of zero and a standard deviation of one) is due to (Box) and is given by

$$x = \sqrt{-2 \ln r_1} \cos(2\pi r_2) \quad (5.21)$$

where r_1 and r_2 are two uniformly distributed independent random numbers defined on the interval $(0,1)$. For a Gaussian with mean μ and standard deviation σ the random variate is defined as

$$y = \mu + x\sigma \quad (5.22)$$

where x is defined as above.

In a log-normal distribution, it is the logarithm of the random variable that is randomly distributed. Thus, if Equation (5.22) is used to generate $y = \ln Z$, Z will have a log-normal distribution, or

$$\ln Z = \mu + x\sigma \quad (5.23)$$

and $Z = \exp (\mu + x\sigma)$

Random variates Z from a log normal are generated using Equation (5.23).

A certain amount of caution must be exercised in defining the parameters which determine the log-normal distribution. As mentioned above, a log-normal distribution on x is equivalent to a normal distribution on the logarithm of x , or

$$f(x) = \frac{1}{S \sqrt{2\pi} x} \exp \left[-\frac{1}{2} \left\{ \frac{\ln x - \ln x_{50}}{S} \right\}^2 \right] \quad (5.24)$$

$$g(\ln x) = \frac{1}{S \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left\{ \frac{\ln x - \ln x_{50}}{S} \right\}^2 \right] \quad (5.25)$$

where x_{50} is the median value of the log-normal and S is the shape parameter that is identical to the standard deviation of $\ln x$. A common way to define S is to give the values of x_{50} and x_{90} , the median and 90-th percentiles of x . Since $\ln x$ is normally distributed,

$$\ln x_{90} - \ln x_{50} = \ln \left(\frac{x_{90}}{x_{50}} \right) = 1.282 \quad (5.26)$$

or

$$S = \frac{1}{1.282} \ln \left(\frac{x_{90}}{x_{50}} \right) \quad (5.27)$$

5.4 Selection of Initial Crack Size

A key step in the PRAISE algorithm is the selection of initial crack sizes for the simulation. In most applications of PRAISE, the procedure is complicated by the need to select these cracks from individual cells according to their frequency within that cell. In other words, PRAISE must be able to select cracks sizes conditional on their presence in a particular cell. Symbolically, PRAISE needs knowledge of

$$p(a/h, a/b \mid \alpha_1 \leq a/h \leq \alpha_2, \beta_1^* \leq a/b \leq \beta_2^*) \quad (5.28)$$

where

α_1 and α_2 are the a/h limits for the m -th cell, and

β_1^* and β_2^* are the a/b limits for the m -th cell.

Fortunately, the random variables a/h and a/b have been assumed to be independent. This permits the joint conditional pdf to be written as the product of two marginal distribution functions or

$$p_1(a/h \mid \alpha_1 \leq a/h \leq \alpha_2) p_2(a/b \mid \beta_1^* \leq a/b \leq \beta_2^*) . \quad (5.29)$$

Random variates can be selected from these conditional marginal distributions by first forming the conditional cumulative distribution function and then applying the inverse transformation method. For example, the conditional cdf for $p_1(a/h)$ over the interval $(\alpha_1 \leq a/h \leq \alpha_2)$ is given by

$$p_1(\alpha_1 \leq a/h \leq \alpha) = \frac{\int_{\alpha_1}^{\alpha} p_1(a/h) d(a/h)}{\int_{\alpha_1}^{\alpha_2} p_1(a/h) d(a/h)} \quad (5.30)$$

A similar formulation exists for $p_2(\beta_1^* \leq a/b \leq \beta_2^*)$. The denominator in Equation (5.30) acts as a normalization constant.

For the exponential distribution on (a/h) given in Equation (3.29), direct substitution gives

$$\begin{aligned}
 p_1(\alpha_1 \leq a/h \leq \alpha) &= \frac{\int_{\alpha_1}^{\alpha} \mu \exp(-\mu a/h) d(a/h)}{\int_{\alpha_1}^{\alpha_2} \mu \exp(-\mu a/h) d(a/h)} \\
 &= \frac{\exp(-\mu\alpha_1) - \exp(-\mu\alpha)}{\exp(-\mu\alpha_1) - \exp(-\mu\alpha_2)} \quad (5.31)
 \end{aligned}$$

If the random number r distributed uniformly between 0 and 1 is set equal to $p_1(\alpha_1 \leq a/h < \alpha)$, then

$$r = \frac{\exp(-\mu\alpha_1) - \exp(-\mu\alpha)}{\exp(-\mu\alpha_1) - \exp(-\mu\alpha_2)} \quad (5.32)$$

which can be solved for α , simply as

$$\alpha = -\frac{1}{\mu} \ln \left[(1-r)\exp(-\mu\alpha_1) + r(\exp(-\mu\alpha_2)) \right] \quad (5.33)$$

A direct application of the inverse transformation method for the log-normal distribution of (a/h) is not quite as straightforward because the integrations in Equation (5.30) do not have closed-form analytical representations. Hence, a closed-form solution for the random variate in terms of the uniformly distributed random number is not possible. Instead, a tabular representation of the cdf is use in Equation (5.15). For a table with J entries $\alpha_1, \alpha_2, \dots, \alpha_j, \dots, \alpha_J$, the individual points are given by

$$p_1(\alpha_1 \leq \alpha \leq \alpha_j) = \frac{\int_{\alpha_1}^{\alpha_j} \frac{1}{\sqrt{2\pi}S(a/h)} \exp \left[-\frac{1}{2} \left\{ \frac{\ln[(a/h)/(a_{50}/h)]}{S} \right\}^2 \right] d(a/h)}{\int_{\alpha_1}^{\alpha_J} \frac{1}{\sqrt{2\pi}S(a/h)} \exp \left[-\frac{1}{2} \left\{ \frac{\ln[(a/h)/(a_{50}/h)]}{S} \right\}^2 \right] d(a/h)} \quad (5.34)$$

Integrals of the type shown in Equation (5.34) can be evaluated with a simple change of variables. Suppose that

$$\Phi(\alpha_j) = \int_{\alpha_1}^{\alpha_j} \frac{1}{\sqrt{2\pi}\sigma x} \exp \left[-\frac{1}{2} \left\{ \frac{\ln x - \mu}{\sigma} \right\}^2 \right] dx \quad (5.35)$$

The change of variable

$$y = \ln x \quad (5.36)$$

$$\text{with } dy = \frac{1}{x} dx \quad (5.37)$$

and limits

$$y_1 = \ln \alpha_1 \quad (5.38)$$

$$y_2 = \ln \alpha_j$$

can be substituted into Equation (5.35) to give

$$\Phi(\alpha_j) = \int_{\ln \alpha_1}^{\ln \alpha_j} \frac{1}{\sqrt{2\pi}\sigma} \exp \left[-\frac{1}{2} \left(\frac{y - \mu}{\sigma} \right)^2 \right] dy \quad (5.39)$$

$$= \text{erf}(\ln \alpha_j, \mu, \sigma) - \text{erf}(\ln \alpha_1, \mu, \sigma) \quad (5.40)$$

where $\text{erf}(\alpha, \mu, \sigma)$ is the error function defined by

$$\text{erf}(\alpha, \mu, \sigma) = \int_{-\infty}^{\alpha} \frac{1}{\sqrt{2\pi}\sigma} \exp \left[-\frac{1}{2} \left(\frac{x - \mu}{\sigma} \right)^2 \right] dx \quad (5.41)$$

Substitution of Equation (5.40) into Equation (5.34) gives

$$p(\alpha_1 \leq \alpha \leq \alpha_j) = \frac{\text{erf}(\ln \alpha_j, \ln(a_{50}/h), S) - \text{erf}(\ln \alpha_1, \ln(a_{50}/h), S)}{\text{erf}(\ln \alpha_j, \ln(a_{50}/h), S) - \text{erf}(\ln \alpha_1, \ln(a_{50}/h), S)} \quad (5.42)$$

After the table of α_j and $p_1(\alpha_1 \leq \alpha \leq \alpha_j)$ has been constructed according to Equation (5.42), linear interpolation is used to determine the random variate $\alpha = a/h$.

The conditional cumulative distribution function when $(b/a = \beta)$ is exponential can be obtained by combining Equation (3.34) with Equation (5.30), or

$$p_2(\beta_1^* \leq a/b \leq \beta^*) = \frac{\int_{\beta_1^*}^{\beta^*} \lambda \exp \left[-\lambda \left(\frac{1}{(a/b)} - 1 \right) \right] \frac{1}{(a/b)^2} d(a/b)}{\int_{\beta_1^*}^{\beta_2^*} \lambda \exp \left[-\lambda \left(\frac{1}{(a/b)} - 1 \right) \right] \frac{1}{(a/b)^2} d(a/b)} \quad (5.43)$$

The change of variables

$$y = -\frac{\lambda}{(a/b)} \quad (5.44)$$

$$dy = \frac{\lambda}{(a/b)^2} d(a/b) \quad (5.45)$$

can be used to evaluate these integrals, or

$$p_2(\beta_1^* \leq a/b \leq \beta^*) = \frac{\int_{-\lambda/\beta_1^*}^{-\lambda/\beta^*} e^y dy}{\int_{-\lambda/\beta_1^*}^{-\lambda/\beta_2^*} e^y dy} \quad (5.46)$$

$$= \frac{\exp(-\lambda/\beta^*) - \exp(-\lambda/\beta_1^*)}{\exp(-\lambda/\beta_2^*) - \exp(-\lambda/\beta_1^*)} \quad (5.47)$$

For the uniformly distributed random number r , the inverse transformation gives

$$\beta^* = \frac{-\lambda}{\ln \left[\exp(-\lambda/\beta_1^*) + r \{ \exp(-\lambda/\beta_2^*) - \exp(-\lambda/\beta_1^*) \} \right]} \quad (5.48)$$

When the aspect ratio is log-normally distributed, the integrals in Equation (5.30) are not amenable to a closed-form evaluation. Hence, in a manner similar to the log-normal distribution on (a/h) , tabular conditional cumulative

distribution functions must be constructed and linear interpolation used. The integral of $p_2(a/b)$ shown in Equation (3.37) or

$$\Phi(\beta^*) = \int_{\beta_1^*}^{\beta^*} \frac{1}{S \sqrt{2\pi(a/b)}} \exp \left[-\frac{1}{2} \left(\frac{\ln(\frac{1}{a/b}) - M}{S} \right)^2 \right] d(a/b) \quad (5.49)$$

can be evaluated by making the change of variable

$$y = \ln(\frac{1}{a/b}) = \ln(b/a) = \ln \beta \quad (5.50)$$

$$dy = -\frac{1}{a/b} d(a/b) \quad (5.51)$$

so that

$$\Phi(\beta^*) = \int_{\ln \beta}^{\ln \beta_1} \frac{1}{S \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left\{ \frac{y - M}{S} \right\}^2 \right] dy \quad (5.52)$$

$$= \text{erf}(\ln \beta_1, M, S) - \text{erf}(\ln \beta, M, S) \quad (5.53)$$

The conditional cumulative distribution function is then given by

$$p_2(\beta_1^* \leq \beta \leq \beta_j^*) = \frac{\text{erf}(\ln \beta_1, M, S) - \text{erf}(\ln \beta_j, M, S)}{\text{erf}(\ln \beta_1, M, S) - \text{erf}(\ln \beta_2, M, S)} \quad (5.54)$$

The preceding derivations can also be used to estimate the probability that a crack will be found in a particular cell. Suppose that the m -th cell is bounded by

$$\alpha_1 \leq a/h \leq \alpha_2 \quad (5.55)$$

$$\text{and} \quad \beta_1^* \leq a/b \leq \beta_2^* \quad (5.56)$$

then the probability of a crack in the m-th cell is given by

$$p_m = \int_{\alpha_1}^{\alpha_2} d(a/h) \int_{\beta_1^*}^{\beta_2^*} d(a/h) p(a/b, a/h) . \quad (5.57)$$

Since the variables a/h and a/b are shown in Equation (3.25) to be independent, Equation (5.57) can be written as

$$p_m = \int_{\alpha_1}^{\alpha_2} d(a/h) p_1(a/h) \int_{\beta_1^*}^{\beta_2^*} d(a/h) p_2(a/b) . \quad (5.58)$$

When $p_1(a/h)$ has an exponential distribution,

$$\int_{\alpha_1}^{\alpha_2} d(a/h) p_1(a/h) = \exp(-\mu\alpha_1) - \exp(-\mu\alpha_2) . \quad (5.59)$$

For a log-normal distribution on a ,

$$\int_{\alpha_1}^{\alpha_2} d(a/h) p_2(a/h) = \text{erf}(\ln \alpha_2, \mu, \sigma) - \text{erf}(\ln \alpha_1, \mu, \sigma) . \quad (5.60)$$

For an exponential distribution on b/a ,

$$\int_{\beta_1^*}^{\beta_2^*} d(a/b) p_2(a/b) = \exp(-\lambda/\beta_2^*) - \exp(-\lambda/\beta_1^*) . \quad (5.61)$$

If the aspect ratio is log-normally distributed, then

$$\int_{\beta_1^*}^{\beta_2^*} d(a/b) p_2(a/b) = \text{erf}(\ln \beta_2, \mu, \sigma) - \text{erf}(\ln \beta_1, \mu, \sigma) . \quad (5.62)$$

In some cases, the distributions input by the user may need to be renormalized so that the integrals of the marginal density functions are equal to one. In other words if C_1 and C_2 are the normalization constants for (a/h) and (a/b) respectively, they satisfy

$$\int_0^1 C_1 p_1(a/h) d(a/h) = 1 \quad (5.63)$$

and

$$\int_0^1 C_2 p_2(a/b) d(a/b) = 1 . \quad (5.64)$$

For Equations (5.59) through (5.62), one may deduce that the normalization constants are:

- (1) exponential pdf on a ,

$$C_1 = \frac{1}{1 - \exp(-\mu)} \quad (5.65)$$

- (2) log-normal pdf on a ,

$$C_1 = \frac{1}{\text{erf}(0, \mu, \sigma)} \quad (5.66)$$

The generation of initial crack sizes is carried out as a two-step process involving the subroutines PROBAB and CRKSIZ. The functions of PROBAB are:

- (1) normalize the a/h distributions according to Equations (5.65) and (5.66)
- (2) calculate the probability P_m of obtaining an initial crack size within the m -th cell
- (3) if the crack depth or aspect ratio have a log-normal distribution, construct and save the tabular representation for the conditional cumulative distribution function

- (4) form the sum of the cell probabilities

$$P_{\text{TOTAL}} = \sum_{m=1}^M p_m \quad (5.67)$$

and output the result,

- (5) if a debug option is selected, print out the tabular functions representing the conditional cumulative distributions.

The subroutine CRKSIZ performs the actual generation of the initial crack sizes. For the exponential distributions on a and (b/a) , CRKSIZ evaluates Equations (5.33) and (5.48), respectively. For log-normal distributions on a and (b/a) , CRKSIZ calls the funtions subprogram TABLAR to interpolate the tabulated conditional cumulative distribution functions defined in Equations (5.42) and (5.54).

5.5 Time and Type of Event to Occur Next

Subroutine FTIME generates the time and type of event which is to be simulated next. FTIME has two calculational options. The first option is exercised the first time FTIME is called in each replication. The time of first arrival of each event is determined. The values are stored in the vector TFAIL(KTYPE) where the counter KTYPE ranges from one to (KTYPES + 2). The first event is always the heatup/cool-down cycle. The next (KTYPES - 1) events correspond to anticipated transients. The last two event types are earthquake evaluation and in-service inspection. If earthquakes are requested, an earthquake evaluation is always performed at $t=0$. After the vector TFAIL is filled out, the arrival times are sorted into ascending order and stored in the vector TORDER(K). The event type which corresponds to the time in TORDER(K) is stored in the vector KORDER(K). Hence there is a one-to-one correspondence of time and event type in the component of the TORDER and KORDER vectors. The time and type of event to occur first is simply TORDER(1) and KORDER(1).

The MAIN routine has a variable named TIME which is advanced to the arrival time of the next event when that event is selected. After the selection of each event, FTIME is called again. In these calls, the second calculational option is exercised. The objective is to update the next arrival time for the type of event that has just occurred. It also updates the vectors TORDER and KORDER to account for this update. The time and type of event to occur next is given by TORDER(1) and KORDER(1). For example, suppose that the K-th event type has just occurred. FTIME then changes TFAIL(K) to the next time the K-th event is anticipated to occur. The straightforward manner of reordering the TORDER vector is to simply determine the value of KK such that

$$TORDER(KK) \leq TFAIL \leq TORDER(KK+1) \quad (5.68)$$

All entries in TORDER up to KK are then advanced by one, i.e.,

$$TORDER(K-1) = TORDER(K) \quad K=2, KK \quad (5.69)$$

and

$$TORDER(KK) = TFAIL(K) \quad (5.70)$$

KORDER is also updated accordingly. In order to determine the value of KK which satisfies Equation (5.55), a DO loop is used in which TFAIL(K) is compared with each component of TORDER in sequence until Equation (5.55) is satisfied.

A flowchart of FTIME is given in Figure 5.3. The arguments of FTIME are TIME and KTYPE which denote the time and the type of event that has just occurred. The first call to FTIME in each replication has values of zero for both KTYPE and TIME. PRAISE has an option for treating the arrival time of the anticipated transients as random variables which are governed by a Poisson process. In this case, the inter-arrival times are exponentially distributed with a mean value of λ_K for the k-th transient type, or

$$f_K(\Delta t) = \lambda_K \exp(-\lambda_K \Delta t) \quad . \quad (5.71)$$

Equation (5.19) which gives the recipe for selecting random variates from an exponential distribution can be applied to give

$$\Delta t = - \frac{1}{\lambda_K} \ln r \quad (5.72)$$

where r is the ubiquitous uniformly distributed random number between 0 and 1.

Figure 5.3 Flowchart of the FTIME Subroutine

5.6 Effective Stress Intensity Factor Calculation

The evaluation of the effective RMS stress intensity factor for the heatup/cooldown cycle and anticipated transients is performed in the subroutine KBARS. The relationships for $(\Delta \bar{K})_{\text{eff}}$ and $(\Delta \bar{K})_{\text{eff}}$ were shown to be

$$\Delta \bar{K}_{\text{eff}} = \frac{\bar{K}_{\text{max}} - \bar{K}_{\text{min}}}{\sqrt{1 - \frac{\bar{K}_{\text{min}}}{\bar{K}_{\text{max}}}}} \quad (5.73)$$

For a part through defect subjected to uniform through the wall stresses such as during the heatup/cooldown cycle,

$$\bar{K}_{\text{min}} = \sigma_{\text{min}} \sqrt{a} f(a/h, a/b) \quad (5.74)$$

$$\bar{K}_{\text{max}} = \sigma_{\text{max}} \sqrt{a} f(a/h, a/b) \quad (5.75)$$

Direct substitution of Equations (5.74) and (5.75) into Equation (5.73) gives

$$\begin{aligned} (\Delta \bar{K})_{\text{eff}} &= \frac{(\sigma_{\text{max}} - \sigma_{\text{min}}) \sqrt{a} f(a/h, a/b)}{\sqrt{1 - \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}}}} \\ (\Delta \bar{K})_{\text{eff}} &= \sqrt{(\sigma_{\text{max}} - \sigma_{\text{min}}) \sigma_{\text{max}}} a f(a/h, a/b) \quad (5.76) \end{aligned}$$

This must be evaluated for both the a and b directions. The quantity in the square root is the same in both directions and needs to be evaluated only once. The function $f(a/h, a/b)$ is different for the a and b directions.

For transients in which the cyclic loading includes non-uniform through-the-wall thermal gradient radial stresses, the minimum and maximum values of the RMS stress intensity factor values are:

$$\bar{K}_{\min} = \bar{K}_{\text{op}} + \Delta\bar{K}_{\min} \quad (5.77)$$

$$\bar{K}_{\max} = \bar{K}_{\text{op}} + \Delta\bar{K}_{\max} \quad (5.78)$$

Substitution of Equations (5.77) and (5.78) into Equation (5.73) gives

$$(\Delta\bar{K})_{\text{eff}} = \frac{(\bar{K}_{\text{op}} + \Delta\bar{K}_{\max}) - (\bar{K}_{\text{op}} + \Delta\bar{K}_{\min})}{\sqrt{1 - \frac{\bar{K}_{\text{op}} + \Delta\bar{K}_{\min}}{\bar{K}_{\text{op}} + \Delta\bar{K}_{\max}}}}$$

$$(\Delta\bar{K})_{\text{eff}} = \sqrt{(\Delta\bar{K}_{\max} - \Delta\bar{K}_{\min})(\bar{K}_{\text{op}} + \Delta\bar{K}_{\max})} \quad (5.79)$$

If one applies the relationship for $\Delta\bar{K}_{\min}$ and $\Delta\bar{K}_{\max}$ developed in Equations (3.53) and (3.54), i.e.,

$$\Delta\bar{K}_{\min} = \sqrt{a} \Delta T g_{\min}(i, a/h, a/b) \quad (5.80)$$

$$\Delta\bar{K}_{\max} = \sqrt{a} \Delta T g_{\max}(i, a/h, a/b) \quad (5.81)$$

then Equation (5.79) becomes

$$(\Delta\bar{K})_{\text{eff}} = \sqrt{\sqrt{a} \Delta T (g_{\max} - g_{\min}) (\sigma_{\text{HOT}} \sqrt{a} f(a/h, a/b) + \sqrt{a} \Delta T g_{\max})}$$

$$= \sqrt{\Delta T a (g_{\max} - g_{\min}) (\sigma_{\text{HOT}} f(a/h, a/b) + \Delta T g_{\max})} \quad (5.82)$$

This is evaluated in both the a and b directions.

5.7 Normalized Stress Intensity Factors Function Subprograms: SIFBARA and SIFBARB

It was shown in the preceding section that PRAISE represents the stress intensity factor to which a part through crack subjected uniformly distributed through the wall stresses as

$$K = \sigma \sqrt{a} f(a/h, a/b) \quad (5.83)$$

where $f(a/h, a/b)$ is a normalized stress intensity factor. The evaluation of $f(a/h, a/b)$ is carried out in the function subprograms SIFBARA and SIFBARB for the a and b directions, respectively. The functions $f(a/h, a/b)$ are expressed as two-dimensional 3rd order polynomials which can be written as the double product

$$f_i(a/h, a/b) = \frac{1.15 \left[\sum_{i=0}^3 \left\{ \sum_{j=0}^3 c_{ij} (a/b)^j \right\} (a/h)^i \right]}{\sqrt{1 - (a/h)}} \quad (5.84)$$

where the constant C_{ij} depends on whether the a or b direction is being evaluated. The derivation of these constants is described in Chapter 2 of Harris 81. A compilation of these constants is given in Table 5.3. For computational efficiency and accuracy, the product in Equation (5.84) is evaluated using Horner's rule or nested multiplication.

Table 5.3

CONSTANTS FOR THE NORMALIZED STRESS INTENSITY FACTORS UNDER
UNIFORM THROUGH-THE-WALL STRESSES

I. Constants C_{ij} in $f_a(a/h, a/b)$

		j			
		0	1	2	3
i	0	1.4401	-.34296	-.40410	.29273
	1	-.68159	-.42330	-.49695	.96951
	2	.036574	11.798	-20.734	9.6933
	3	.42562	-15.827	29.538	-15.044

II. Constants C_{ij} in $f_b(a/h, a/b)$

		j			
		0	1	2	3
i	0	.97917	.20174	-.24769	.05483
	1	1.0621	-6.6880	9.2182	-4.2890
	2	-2.7479	21.818	-36.218	18.605
	3	1.4344	-17.705	31.190	-16.477

5.8 Contribution of Radial Gradient Thermal Stresses to the RMS - Stress Intensity Factors

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. In principle, it is possible to represent the functions $g_{\min}$ and $g_{\max}$ analytically. However, it is likely that the analytical representation will not be simple. The expressions may involve higher order polynomial fits or transcendental functions. 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, instead of analytic expressions for $g_{\min}$ and $g_{\max}$, 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 N_Y and N_X , 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 (Gerald 78) 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 5.4. The data storage strategy is discussed in Section 5.13. The procedure for $g_{\max}$ is identical to the $g_{\min}$ procedure.

$g_{\min}^*$ as input
by user to
subroutine INITIAL

direct transformation
of $g_{\min}^*$ into $g_{\min}$

interpolation to
obtain regular
in the a/h and a/b
spaces.

Storage in one-
dimensional arrays
for easy retrieval

Figure 5.4 Derivation and Storage of the $g_{\min}$ functions

5.9 Crack Growth Calculation

Simulation of crack growth, when earthquakes are not included, is carried out in subroutine CRKGRO. A flowchart is shown in Figure 5.5. CRKGRO is called from the MAIN routine with the current values of a , b , $(\Delta \bar{K}_a)_{\text{eff}}$ and $(\Delta \bar{K}_b)_{\text{eff}}$. If prior to the transient, the crack is only a part-through defect and $(\Delta \bar{K}_a)_{\text{eff}} > K_0$, then the post-transient crack depth is estimated to be

$$a_{\text{new}} = a_{\text{old}} + C(\Delta \bar{K}_a)_{\text{eff}}^m \quad (5.85)$$

If a_{new} exceeds the wall thickness, then a_{new} is reset to the wall thickness and a new $(\Delta \bar{K}_b)_{\text{eff}}$ is obtained by calling the KBARS subroutine. If $(\Delta \bar{K}_b)_{\text{eff}} > K_0$, the dimension in the b direction is increased as

$$b_{\text{new}} = b_{\text{old}} + C(\Delta \bar{K}_b)_{\text{eff}}^m \quad (5.86)$$

After a_{new} and b_{new} are obtained, the value of b_{new} is compared with the b_{crit} value given by the failure criterion. If a LOCA has been obtained, flags are updated and control is returned to the MAIN routine. If there is no LOCA and no through wall defect, control is also returned to the MAIN routine.

When a through-wall defect is present, CRKGRO performs a leak rate calculation and categorizes the defect is then classified as a big leak if

$$\text{RATE} > \text{ALKBIG} \quad (5.87)$$

where RATE is the leak rate calculated as

$$\text{RATE} = 0.294 b^2 \sigma_{\text{op}} / h^{-3.5} \quad (5.88)$$

σ_{op} = operating pressure

and ALKBIG is a user-supplied threshold level big leak.

Figure 5.5 Flowchart for Subroutine CRKGRO

In PRAISE, a leak is detected with probability one if the leak rate exceeds a user supplied level defined by the input FNDLEK. If the rate is less than FNDLEK, there is zero probability of finding the leak.

5.10 Influence of Earthquakes on the Failure Probability

The influence of earthquakes on the failure probability is simulated in subroutines SHAKER and EQCRK. When an earthquake evaluation is required, SHAKER is called from the MAIN routine. A flowchart of SHAKER is shown in Figure 5.6. Since the crack is returned to its original state after each evaluation, the initial step in SHAKER is to save the current dimensions of the crack. The functions of SHAKER are contained within two DO loops. The outer loop goes through the categories of earthquakes, while the inner loop goes through the number of earthquakes within each intensity category. Subroutine EQCRK is called to do the actual crack growth. The number of earthquakes in a given category differ amongst the categories. Hence, it is convenient to combine the results of the earthquakes within a given category and treat them as a single equivalent earthquake. It is presently assumed that earthquakes in a given category are equally likely. Hence, the weighting factor is

$$\text{PROBEQ} = \frac{1}{\text{NEQCLS}(N)} \quad (5.89)$$

where $\text{NEQCLS}(N)$ is the number of earthquakes in the N-th intensity class.

For example, if 3 of 5 evaluation earthquakes of intensity g lead to a LOCA, then 0.6 is added to the number of samples that fail. Correspondingly only one (not five) additional replication is added. After each earthquake, the crack size and calculational flags are reset to their pre-earthquake values. When the inner loop is completed, the statistics are updated and SHAKER proceeds to the next earthquake category.

The subroutine EQCRK is outlined in Figure 5.7. The calculational flow is very similar to that in the subroutine CRKGRO. The principal differences are:

- (1) EQCRK can simulate multiple cycle loadings
- (2) EQCRK assumes explicitly that the exponent (m) in the fatigue crack growth relationship is 4.0.

- (3) leak rate calculations are performed to estimate the category of leak due to earthquake but leak detection is not performed because the effect of the earthquake is not carried back into the simulation of the remainder of the stress history.

For each earthquake evaluation, inputs to EQCRK are:

- (1) the S-factor for earthquake crack growth
- (2) the load controlled stress for each evaluation earthquake, and
- (3) the number of equivalent cycles used to model crack growth during the earthquake.

Figure 5.6 Flowchart for Subroutine Shaker

Figure 5.7. Flowchart for Subroutine EQCRK

5.11 Probability Estimates

PRAISE estimates the failure probabilities (leak, big leak, and LOCA) and their corresponding statistical variances at discrete user-specified points in time. The appropriate equations have been derived in Section 3.7. The evaluation is performed in the subroutine OUTF which is called from the MAIN routine after all the requested replications have been performed.

Although the indicator function is a convenient mechanism for deriving the equations in Section 3.8, it is extremely wasteful in the data storage aspect. Individual elements of the indicator function are never needed. Only the sum or sum of squared elements is ever used. Thus it is more convenient to construct alternate representations of those quantities. For example, define an NEVAL-component vector denoted by $\underline{v}_m(g)$ by

$$\sum_{j=1}^i v_{m,j}(g) = \sum_{n=1}^{N_m} I_{m,n}(g, t_i) \quad (5.90)$$

where NEVAL corresponds to the number of evaluation points requested by the user, m indicates the m -th stratification call, g is the earthquake magnitude category and j is the component of $\underline{v}_m(g)$.

The j -th element of $\underline{v}_m(g)$ represents the total number initial defects from cell m which fail in the interval $[t_{j-1} \leq t \leq t_j]$ due to a magnitude g earthquake. Consistent with the formulations in Sections 3.4 and 3.7, the individual failures are weighted by the non-detection probabilities. In other words, each time a crack is predicted to fail between t_{j-1} and t_j , the P_{ND} of that crack is added to j -th component of $\underline{v}_m(g)$. A cumulative function $\underline{v}_m(g)$ can be defined by setting

$$v_{m,i}(g) = \sum_{j=1}^i v_{m,j}(g) = \sum_{n=1}^{N_m} I_{m,n}(g, t_i) \quad (5.91)$$

The i -th component of $\underline{v}_m(g)$ is the sum of the first i -terms of the vector $\underline{v}_m(g)$.

In a completely analogous manner the sum of the squared elements of the indicator function is retained in an NEVAL-component vector $\underline{w}_m(g)$ and defined by

$$\sum_{j=1}^i w_{m,j}(g) = \sum_{n=1}^{N_m} I_{m,n}^2(g, t_i) \quad (5.92)$$

where NEVAL, m , g , and j are defined as above. The j -th element of $\underline{w}_m(g)$ is the sum of squared non-detection probabilities for cracks from the m -th cell which fail in the time interval t_{j-1} to t_j due to intensity g earthquakes. Each time a crack is predicted to fail between t_{j-1} and t_j , P_{ND}^2 for that crack is added to the j -th component of $\underline{w}_m(g)$. A cumulative function $\underline{W}_m(g)$ can be defined by setting

$$\underline{W}_{m,i}(g) = \sum_{j=1}^i w_{m,j}(g) = \sum_{n=1}^{N_m} I_{m,n}(g, t_i) \quad (5.93)$$

$$F_m(g, t_i) = \frac{1}{N_m} \sum_{j=1}^i v_{m,i}(g) \quad (5.94)$$

$$F(g, t_i) = \sum_{m=1}^M P_m F_m(g, t_i) \quad (5.95)$$

$$s_m^2(g, t_i) = \frac{1}{N_m - 1} \left[\sum_{j=1}^i w_{m,j}(g) - N_m \left\{ \frac{1}{N_m} \sum_{j=1}^i v_{m,j}(g) \right\}^2 \right] \quad (5.96)$$

$$s_m^2(g, t_i) = \frac{1}{N_m - 1} \left[\sum_{j=1}^i w_{m,j}(g) - \frac{1}{N_m} \left\{ \sum_{j=1}^i v_{m,j}(g) \right\}^2 \right] \quad (5.97)$$

$$s^2(g, t_i) = \sum_{m=1}^M s_m^2(g, t_i) P_m^2 \quad (5.98)$$

The vectors $\underline{w}_m(g)$ and $\underline{v}_m(g)$ are constructed in the MAIN routine when the failure is not induced by an earthquake and in subroutine SHAKER when the failure is induced by the earthquake. These vectors are then input to subroutine OUTS when OUTS is called from the MAIN routine. For a problem with G earthquake intensities, three failure modes (leak, big leak, and LOCA), and MCELLS cells, a total of 3(G+1)MCELLS vectors are needed for $\underline{w}_m(g)$ and $\underline{v}_m(g)$ each.

The principal steps in subroutine OUTS are:

- (1) form the cumulative functions $\underline{W}_m(g)$ and $\underline{V}_m(g)$
- (2) print out various values of $\underline{W}_m(g)$ and $\underline{V}_m(g)$
- (3) form the means $F_m(g, t_i)$ and variances $s_m^2(g, t_i)$ conditional on cracks being taken from the m-th cell.
- (4) form the overall mean $F(g, t_i)$ and variances $s_{st}^2(g, t_i)$.

A flowchart of the OUTS subroutine is shown in Figure 5.8. In order to conserve storage locations, the vectors $\underline{w}_m(g)$ and $\underline{v}_m(g)$ are overwritten in the process of forming $\underline{W}_m(g)$ and $\underline{V}_m(g)$. The coding is:

$$v_{m,i}(g) = \begin{cases} v_{m,i}(g) & \text{if } i=1 \\ v_{m,i}(g) + v_{m,i-1}(g) & \text{if } i>1 \end{cases} \quad (5.99)$$

and similarly for $w_{m,i}(g)$ and $W_{m,i}(g)$. For each earthquake intensity class, PRAISE prints out the values of $\underline{v}_m(g)$ and $\underline{w}_m(g)$ categorized by cell and listed by the requested evaluation times. OUTS then enters a loop on the MCELLS cells to form the means $F_m(g, t_i)$ and variances $s_m^2(g, t_i)$. Finally, these means and variances are combined according to Equations (5.95) and (5.98) to yield the desired results.

Figure 5.8 Flowchart of Subroutine Outs

5.12 Data Management in PRAISE

A common characteristic of Monte Carlo simulations is the need for a large number of replications in order to obtain accurate solutions. This normally translates into long execution times and a major financial commitment. This problem is particularly acute when the probability of occurrence is extremely low. Strategies to alleviate this problem fall into two general categories:

- (1) more efficient algorithms such as including stratified sampling, and
- (2) more efficient coding of the selected algorithm. Most of the documentation from this project has been addressed to aspects from the first area.

This section will document some features implemented in PRAISE to address the second aspect of this problem.

A modularized computer code is very convenient because it enhances readability and facilitates modification. On the other hand, a code in which subroutines are repeatedly being called can also increase the execution times. As a compromise, PRAISE is organized so that logical sequences of related calculations are performed in the same subroutine, even at the expense of more complicated subroutines. Data transfers to subroutines are usually accomplished through named COMMON blocks rather than argument lists.

Well-known programming practices to reduce the cost of individual operations have also been used. These include:

- (1) avoidance of exponentiation to evaluate squared quantities, i.e., use
 $A \cdot A$ instead of A^{**2}
- (2) avoidance of exponentiation to evaluate the square root, i.e., use
 $\text{SQRT}(A)$ instead of $A^{**0.5}$

- (3) avoidance of real powers when exponentiating, use
 A^{**4} rather than $A^{**4.0}$
- (4) multiply by the reciprocal rather than divide by the constant,
e.g.
 $0.5*A$ is better than $A/2$.
- (5) evaluation of polynomials is carried out using Horner's
rule which is also known as nested multiplication.

Another source of considerable inefficiency is the use (or perhaps misuse) of multiple-dimensional arrays. The computer treats all arrays as one-dimensional arrays. Hence, a multiple-dimensional array is transformed into a one-dimensional array. When a particular value is needed the computer calculates the appropriate location in core and then retrieves that piece of data. This calculation is transparent to the casual programmer. In cases where the data are accessed sequentially the programmer may be able to produce more efficient coding by storing and retrieving the data from one-dimensional arrays or by designing DO loops such that the innermost loops are on the first subscripts.

In PRAISE, a majority of the data is stored in one-dimensional data arrays. The basic idea is to divide these data arrays into "data blocks". The location of the data blocks within the data array is identified by a pointer, which normally has a value one less than the first piece of data in the data block. For example, suppose that an array called DATA(I) has been declared and that DATA is to be subdivided into data blocks DAT1, DAT2, and DAT3. Pointers LDAT1, LDAT2, LDAT3 can be defined so that the I-th piece of data in the DAT1 block is DATA(LDAT1 + I). Similarly, the J-th piece of data in the DAT2 block becomes DATA(LDAT2 + J). The pointers would reside in COMMON blocks which appear in all subroutines where these data blocks are used. This technique is illustrated graphically in Figure 5.9. PRAISE presently has three data arrays, known as DATA, ADATA, and DSUM. The data blocks, pointers, and descriptions are given in Section 5.13.

Figure 5.9 Data Blocks and Pointers

An additional advantage of using one-dimensional data storage arrays as described above is that it reduces the need to specify the dimension for a large number of arrays. This can become a problem if storage costs are assessed to the user and a large amount of the declared storage is unused. An equally frustrating problem is to exceed the amount of storage declared. Although dynamic allocation of storage space is possible, the necessary software is often machine-dependent (and in machine language) and would severely limit the ability to transport PRAISE to other machines. The use of data storage arrays means that compensation can occur, i.e., some data blocks are long, while others are short; but, the total is roughly the same. In any case, if changes have to be made, only a few dimensions need to be modified.

5.13 Data Storage Arrays

Three one-dimensional data storage arrays are currently built into the PRAISE program. These arrays are referenced as DATA, ADATA, and DSUM. The assignment of pointers and the allocation of space within these arrays is performed in the subroutine ALOC. The DATA array contains the following data:

- (a) the cell definition parameters,
- (b) tabulations of the conditional cdfs used to select random variates when the crack depth or aspect ratio are log-normally distributed,
- (c) the cell probabilities, and
- (d) the information used to calculate the contribution of the radial gradient thermal stresses to the stress intensity factors.

Table 5.4 gives the pointers, the length, and a brief description of each data block within the DATA array. The coding needed to calculate the location of a given data item is also shown in the description. Note that the coding uses the index MM when referring to the m-th cell. This avoids possible confusion with using M as a DO loop index. NPTSPI is the number of tabulated points in the cumulation cdfs. The total space requirement for the DATA array is $[9+4NPTSPI](MCELLS)+4(IX)(IY)(KTYPES)$ locations. IX and IY are the number of entries in the g_{min} and g_{max} tables as described in Section 5.8.

The ADATA arrays stores the alphanumeric descriptions of the transient events and the earthquakes that are to be modeled. Each of the KTYPES descriptions is stored under the format 6A10. Hence the first $60 \times KTYPES$ locations in ADATA are used for transient descriptors. The earthquake descriptors are of length 5A10 and fill the remainder of the ADATA array.

The DSUM array contains the data needed to estimate the failure probabilities and the statistical fluctuation in these estimates. Figure 5.10 graphically displays the structure of the DSUM array. The array is divided into $2(G + 1)$ data blocks. The first two blocks are used to store the failure data in the

Table 5.4
DESCRIPTION OF THE DATA ARRAY

POINTER	LENGTH	DESCRIPTION
LABSIZ	2MCELLS	<p>The a/b limit of the cells in the stratified sampling scheme</p> <p>The left boundary on the m-th cell is stored in</p> $\alpha_1 = \text{AOBSIZ}(\text{MM}, 1) = \text{DATA}(\text{LABSIZ} + 2 * (\text{MM} - 1) + 1)$ <p>The right boundary on the m-th cell is denoted by</p> $\alpha_2 = \text{AOBSIZ}(\text{MM}, 2) = \text{DATA}(\text{LABSIZ} + 2 * (\text{MM} - 1) + 2)$
LAHSIZ	2MCELLS	<p>The a/h limits of the cells in the stratified sampling scheme</p> <p>The lower boundary on the m-th cell is stored in</p> $\beta_1^* = \text{AOHSIZ}(\text{MM}, 1) = \text{DATA}(\text{LAHSIZ} + 2 * (\text{MM} - 1) + 1)$ <p>The upper boundary on the m-th cell is stored in</p> $\beta_2^* = \text{AOHSIZ}(\text{MM}, 2) = \text{DATA}(\text{LAHSIZ} + 2 * (\text{MM} - 1) + 1)$
LLNAH	(NPTS + 1)(MCELLS)	<p>The abscissa values of α_j in the tabulated conditional cdf when the crack depth has a log-normal distribution. The j-th value from the m-th cell is given by</p> $\alpha_j = \text{DATA}(\text{LLNAH} + (\text{MM} - 1) * (\text{NPTS} + 1) + \text{J})$
LLNTAH	(NPTS + 1)(MCELLS)	<p>The ordinate values $p(>\alpha_j)$ in the tabulated conditional cdf when the crack depth has a log-normal distribution. The j-th value from the m-th cell is given by</p> $p(>\alpha_j) = \text{DATA}(\text{LLNTAH} + (\text{MM} - 1) * (\text{NPTS} + 1) + \text{J})$

Table 5.4 (continued)
DESCRIPTION OF THE DATA ARRAY

POINTER	LENGTH	DESCRIPTION
LLNAB	(NPTS + 1)(MCELLS)	<p>The abscissa values β_j^* in the tabulated conditional cdfs when the crack aspect ratio has a log-normal distribution. The j-th value from the m-th cell is given by</p> $\beta_j^* = \text{DATA}(\text{LLNAB} + (\text{MM}-1) * (\text{NPTS} + 1) + \text{J})$
LLNTAB	(NPTS + 1)(MCELLS)	<p>The ordinate values $p(>\beta_j^*)$ in the tabulated conditional cdf when the crack aspect ratio has a log-normal distribution. The j-th value from the m-th cell is given by</p> $p(>\beta_j^*) = \text{DATA}(\text{LLNTAB} + (\text{MM}-1) * (\text{NPTS} + 1) + \text{J})$
LEXPAB	2MCELLS	<p>The values of the unconditional cdf at the a/b boundaries of the m-th cell when the crack aspect ratio distribution is exponential. The value at the lower boundary is $\exp(-\lambda/\beta_1^*)$ and is stored in</p> $\text{DATA}(\text{LEXPAB} + (\text{MM}-1) * \text{MCELLS} + 1)$ <p>The upper value is given by $\exp(-\lambda/\beta_2^*)$ and is stored in</p> $\text{DATA}(\text{LEXPAB} + (\text{MM}-1) * \text{MCELLS} + 2)$
LEXPAH	2MCELLS	<p>The values of the unconditional cdf at the a/h boundaries of the m-th cell when the crack depth distribution is exponential. The value at the lower boundary is $\exp(-\mu\lambda_1)$ and is stored in</p> $\text{DATA}(\text{LEXPAH} + (\text{MM}-1) * \text{MCELLS} + 1)$ <p>The upper value is given by $\exp(-\mu\alpha_2)$ and is stored in</p> $\text{DATA}(\text{LEXPAH} + (\text{MM}-1) * \text{MCELLS} + 2)$

Table 5.4 (continued)
DESCRIPTION OF THE DATA ARRAY

POINTER	LENGTH	DESCRIPTION										
LPROBS	MCELLS	The probability P_m that an initial defect will be found in the m-th cell is stored in $DATA(LPROBS + MM)$										
LDKTAB	4(IX)(IY)KYPES	<p>The tabulated values of the contributions of the radial gradient thermal stresses to the stress intensity factors. The four functions are identified by</p> <table><tr><td>ITYPE</td><td>FUNCTION</td></tr><tr><td>= 1</td><td>$g_{min,a}$</td></tr><tr><td>= 2</td><td>$g_{max,a}$</td></tr><tr><td>= 3</td><td>$g_{min,b}$</td></tr><tr><td>= 4</td><td>$g_{max,b}$</td></tr></table> <p>The indices for the a/b and a/h values are I and J, respectively. KTYPE indicates the type of transient. For the KTYPE transient, the data for the ITYPE function at $(a/b)_i$ and $(a/h)_j$ are stored in the location</p> $DATA(LDKTAB + 4*(IX*((KTYPE - 2)*IY + (J - 1)) + (I - 1)) + ITYPE)$ <p>A graphical display of the sequence of data storage is shown in Figure 5.11 The data locations are divided into (KYPES-1) blocks. The first transient type is reserved for the heatup/cooldown cycle in which there is no radial gradient thermal stress contribution to the stress intensity factor.(continued on following page)</p>	ITYPE	FUNCTION	= 1	$g_{min,a}$	= 2	$g_{max,a}$	= 3	$g_{min,b}$	= 4	$g_{max,b}$
ITYPE	FUNCTION											
= 1	$g_{min,a}$											
= 2	$g_{max,a}$											
= 3	$g_{min,b}$											
= 4	$g_{max,b}$											

Table 5.4 (continued)
DESCRIPTION OF THE DATA ARRAY

<u>POINTER</u>	<u>LENGTH</u>	<u>DESCRIPTION</u>
LDKTAB (continued)		<p>Within each transient block, the data are further divided into sub-blocks according to the value of the (a/b) coordinates. The sub-blocks are then categorized by the (a/h) coordinate. For a given value of (a/h) and (a/b) in a particular transient, the four function values of $g_{\min}$ and $g_{\max}$ are stored sequentially. Once, the location of the first function is determined, the locations of the other functions can be determined by simple addition. Since these functions are used at each increment of crack growth, this formulation considerably reduces the cost associated with retrieving these data from core.</p>

Figure 5.10 Structure of the DSU4 Data Array

Figure 5.11 Structure of the Storage Scheme for the Contribution of Radial Gradient Thermal Stresses to the Stress Intensity Factor

non-seismic cases. Block one is the vector $\underline{v}_m(0)$, i.e., the sum of the indicator function, while block two is the vector $\underline{w}_m(0)$, i.e., the sum of the squared indicator functions. The next G blocks (3,4...G+2) are used to store $\underline{v}_m(g)$ for $g=1,\dots,G$. The final G blocks (G+3,...,26+2) are used to store $\underline{w}_m(g)$ for $g=1,\dots,G$. The functions $\underline{v}_m(g)$ and $\underline{w}_m(g)$ are defined in Section 3.7. The data structure in these individual blocks is identical. Each block is subdivided into MCELLS sub-blocks. These sub-blocks are then further subdivided into the total number of evaluations requested by the user. Leak, big leak, and LOCA values are stored for each evaluation time. For failures not directly attributable to seismic events, the core locations for data in the m-th cell and the n-th evaluation time are

$$\text{DATA}(\text{LSUM} + (\text{MM}-1)*\text{NEVAL3} + (\text{INTER}-1)*3 + \text{K})$$

and

$$\text{DATA}(\text{LSUM2} + (\text{MM}-1)*\text{NEVAL3} + (\text{INTER}-1)*3 + \text{K})$$

where INTER is the index on the time interval (=1)
 NEVAL3 is 3*NEVAL
 NEVAL is the number of times at which an evaluation is requested
 K = 1 is leak data
 K = 2 is big leak data
 K = 3 is LOCA data
 LSUM is the pointer for the sum of the indicator functions,
 LSUM2 is the pointer for the sum of the squared indicator functions.

For failure induced by seismic events, the core locations are

$$\text{DATA}(\text{LSUMEQ} + ((\text{N}-1)*\text{MCELLS} + (\text{M}-1))*\text{NEVAL3} + (\text{INTER}-1)*3 + \text{K})$$

$$\text{DATA}(\text{LSMEQ2} + ((\text{N}-1)*\text{MCELLS} + (\text{M}-1))*\text{NEVAL3} + (\text{INTER}-1)*3 + \text{K})$$

where N is the index on the earthquake magnitude (N=1,...G)
 LSUMEQ is the pointer for the sum of the indicator function
 LSMEQ2 is the pointer for the sum of the squared indicator function.

The other symbols are identical to their representation above.

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7.0 GLOSSARY

Artificial accelerogram

A numerically simulated acceleration time-history plot of an earthquake's ground motion.

Aspect ratio

Half-length-to-depth ratio of a semi-elliptical surface crack, $b/a = \beta$. The half length is measured along the surface of the pipe.

Availability

The percent of time that the reactor plant is actually in operation during its 40-yr life. For Zion, the estimated availability is 70%.

Boundary integral equation (BIE) technique

A mathematical solution of three-dimensional elasticity problems which divides a body's surface into elements and provides displacements and tractions at surface nodal points. Results are a set of simultaneous linear equations that are solved for the unknown nodal displacements or tractions.

BWR

Boiling water reactor.

Cold leg

Portion of the primary coolant loop piping which connects reactor coolant pump to reactor pressure vessel.

Conditional probability

If A and B are any two events, the conditional probability of A relative to B is the probability that A will occur given that B has occurred or will occur.

Confidence interval (estimator)

An interval estimator with a given probability (the confidence coefficient) that it will contain the parameter it is intended to estimate.

Containment

A concrete shell designed to house the NSSS, the polar crane, and other internal systems and components of a nuclear power plant.

Correlation

The relation between two or more variables.

Couple

To combine, to connect for consideration together.

Covariance

The expected value of the product of the deviations of two random variables from their respective means. The covariance of two independent random variables is zero, but a zero covariance does not imply independence.

Crossover leg

Portion of the primary coolant loop piping which connects the steam generator to the reactor coolant pump.

Cumulative distribution function (cdf)

A function that gives the probability that a random variable, X , is less than or equal to a real value, x .

DEPB

Double-ended pipe break.

Decouple

The opposite of couple; disconnecting two events.

EPFM

Elastic-plastic fracture mechanics.

Estimate

A number or an interval, based on a sample, that is intended to approximate a parameter of a mathematical model.

Estimator

A real-valued function of a sample used to estimate a parameter.

Fatigue crack growth

Growth of cracks due to cyclic stresses.

Flow stress

The average of the yield strength and ultimate tensile strength of a material. Approximate stress at which gross plastic flow occurs.

Fracture

See pipe fracture.

Girth butt weld

Circumferential weld connecting adjacent pipe ends. The girth butt welds referred to in this report are in the primary coolant loop piping.

Hazard curve (seismic)

The probability that one earthquake will generate a specified value of the peak ground acceleration in a time interval of specified length, usually one year.

- Hot leg

Portion of the primary coolant loop piping which connects the reactor pressure vessel to steam generator.

Independent events

Two events are independent if, and only if, the probability that they will both occur equals the product of the probabilities that each one, individually, will occur. If two events are not independent, they are dependent.

Independent random variables

Two or more random variables are independent if, and only if, the values of their joint distribution function are given by the products of the corresponding values of their individual (marginal) distribution functions. If random variables are not independent, they are dependent.

LEFM

Linear-elastic fracture mechanics.

Large LOCA

Large loss-of-coolant accident. For the purpose of this report the large LOCA is equivalent to a pipe fracture in the primary coolant loop pipe. (See pipe fracture).

Leak-before-break situation

A pipe defect that grows to become a through-wall crack but is of insufficient length to result immediately in a complete pipe severance.

Load-controlled stress

Stress upon a pipe that cannot be relaxed by displacement. As such, the load is not relieved by crack extension. In this analysis pressure, dead weight, and seismic stresses are assumed to be load controlled.

Mean

(1). A measure of the center of a set of data. The sample mean of n numbers is their sum divided by n . (2). A population mean is a measure of the center of the probability density function. This is also called the mathematical expectation.

NSSS

Nuclear steam supply system.

OBE

Operating basis earthquake.

Operating stress

Stress in the piping due to normal operating loads, e. g., dead weight, pressure, start ups, etc.

Pipe fracture

A double-ended guillotine pipe break; also referred to in this report as a LOCA and a large LOCA. Refers to a circumferential pipe fracture in which pipe sections on either side of the fracture are completely severed from each other.

Pipe severance

See pipe fracture.

Poisson process

A random process, continuous in time, for which the probability of the occurrence of a certain kind of event during a small time interval t is approximately λt , the probability of occurrence of more than one such event during the same time interval is negligible, and the probability of what happened during such a small time interval does not depend on what happened before.

PRAISE

A computer code, Piping Reliability Analysis Including Seismic Events, developed to estimate the time to first failure for individual joints in a piping system. It is used to analyze the Zion 1 primary coolant loop. PRAISE is written in FORTRAN.

Primary cooling loop

Cold leg, hot leg, and crossover leg.

Probability density function (pdf)

A non-negative, real-valued function whose integral from a to b (a less than or equal to b) gives the probability that a corresponding random variable assumes a value on the interval from a to b .

PWR

Pressurized water reactor.

Radial gradient thermal stress

Axisymmetric stress in the pipe arising from temperature variations through the pipe wall thickness. In this report, the radial gradient thermal stress is a result of temperature transients in the reactor coolant.

Random variable

A real-valued function defined over a sample space.

Response spectrum analysis

A response analysis that estimates the maximum response from response spectra.

RCL

Reactor coolant loop.

RCP

Reactor coolant pump.

Risk

Expected loss.

RPV

Reactor pressure vessel.

Sample space

A set of points that represent all possible outcomes of an experiment.

S factor

Stress factor used for fatigue analysis to account for multiple stress cycles.

Seismic hazard curve

See hazard curve.

SG

Steam generator.

Simulation

Numerical technique employed to simulate a random event, artificial generation of a random process. The PRAISE computer code uses Monte Carlo Simulation to estimate the probability of failure in nuclear reactor piping.

Soil impedance functions

Forces required to oscillate the foundation through unit displacements in different directions.

SSE

Safe shutdown earthquake.

Standard deviation

(1). A measure of the variation of a set of data. The sample standard deviation of a sample of size n is given by the square root of the sum of the deviations from the mean divided by $(n-1)$. (2). A measure of the variability of a random variable. The population standard deviation is the square root of the variance; the mean of the square of the random variable minus its mean.

Statistically dependent

Two events are statistically dependent if they do not fit the criterion for statistical independence.

Statistically independent

See independent events.

Stratified random sampling

A method of sampling in which portions of the total sample are allocated to individual subpopulations and randomly selected from these strata.

The principal purpose of this kind of sampling is to guarantee that population subdivisions of interest are represented in the sample, and to improve the precision of whatever estimates are to be made from the sample data.

Stress corrosion cracking

Cracking due to the combined effects of stress and corrosion.

Stress intensity factor

A fracture mechanics parameter that describes the state of stress at the tip of a crack.

Surge line

Piping that connects pressurizers to the reactor coolant loop. In the Zion I PWR the surge line is a branch from the hot leg in Loop 4.

Time-history response analysis

A response analysis that estimates the maximum response from response spectra.

Transient

An event in the operation of the PWR that gives rise to a load in the piping over a specified length of time.

Uncertainty

Absence of certainty due to randomness of a random variable or lack of knowledge of the pdf of a random variable.

Uniform hazard method (uhm)

A procedure for estimating frequency of occurrence distributions for various ground motion parameters.

UT

Ultrasonic testing.

Variance

The mean of the squares of the deviations from the mean of a random variable.

ZPGA

Zero period ground acceleration; defines the size of an earthquake.

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