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Fracture Mechanics Models Developed for Piping Reliability Assessment in Light Water Reactors

Piping Reliability Project

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Prepared for
U.S. Nuclear Regulatory Commission

MASTER

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EXECUTIVE SUMMARY

The FY 81 scope of work for the Piping Reliability Project sponsored by the U.S. Nuclear Regulatory Commission at the Lawrence Livermore National Laboratory consists of two major tasks: (1) the development of fracture mechanics models for assessing the piping reliability in light water reactor plants; and (2) the validation of the models developed in task (1) by comparing the results with real piping failure data observed. The results of task (2) impact the confidence level for the models developed in task (1). This report is only concerned with task (1). Task (2) results are reported in another NUREG report, "Piping Reliability Model Validation and Potential Use for Licensing Regulation Development." The ultimate objective of this project is to provide guidance for nuclear power plant piping design so that high-reliability piping systems can result.

The piping reliability model presented in this report covers two major failure modes, namely, fatigue failure and stress corrosion cracking failure. Both have been observed in the piping systems of light water reactor plants. Various failure mechanisms such as vibratory stresses, residual stresses, seismic stresses, assembly stresses, and operating stresses, attributed to these two failure modes are considered in the model. Initial interior surface flaws are assumed to exist along either the pipe circumferential direction or the longitudinal direction. In-service inspection is also included in the model. In summary, this piping reliability model has wide application to piping systems in nuclear power plants.

ABSTRACT

This report summarizes the work performed during fiscal year 1981 by Science Applications, Inc. on the Piping Reliability Project for Lawrence Livermore National Laboratory. The efforts concentrated on modifications of the stratified Monte Carlo code called PRAISE (Piping Reliability Analysis Including Seismic Events) to make it more widely applicable to probabilistic fracture mechanics analysis of nuclear reactor piping. Pipe failures are considered to occur as the result of crack-like defects introduced during fabrication, that escape detection during inspections. The code modifications allow the following factors in addition to those considered in earlier work to be treated: other materials, failure criteria and subcritical crack growth characteristic; welding residual and vibratory stresses; and longitudinal welds (the original version considered only circumferential welds). The fracture mechanics background for the code modifications is included, and details of the modifications themselves provided. Additionally, an updated version of the PRAISE user's manual is included. The revised code, known as PRAISE-B was then applied to a variety of piping problems, including various size lines subject to stress corrosion cracking and vibratory stresses. Analyses including residual stresses and longitudinal welds were also performed. The result of these analyses indicate that lines subject to stress corrosion cracking (SCC) are more failure prone than ones subject only to fatigue. This is in agreement with field observations, and is an expected result. Additionally, residual stresses were observed to have a strong influence in lines subject to SCC. The influence was beneficial or detrimental depending on the nature of the residual stress. Vibratory stresses could be influential in the case of fatigue — depending on the vibratory cyclic stress magnitude. The probability of a sudden and complete pipe severance was invariably much smaller than the corresponding probability of a leak. This supports the "leak-before-break" concept for primary piping in light water reactors.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
LIST OF FIGURES.....	viii
LIST OF TABLES.....	xii
ACKNOWLEDGEMENTS.....	xiii
1.0 INTRODUCTION.....	1
1.1 Purpose of Investigation.....	1
1.2 Review of Methodology.....	2
2.0 ADDITIONAL FACTORS FOR FRACTURE MECHANICS MODEL.....	5
2.1 Subcritical Crack Growth Characteristics.....	5
2.1.1 Fatigue Crack Growth.....	5
2.1.2 Stress Corrosion Cracking.....	5
2.1.3 Combined Fatigue-Stress Corrosion Cracking.....	7
2.2 Failure Criteria.....	7
2.3 Review of Relevant Operating Stresses.....	8
2.4 Vibratory Stresses.....	8
2.4.1 Stress Ranges.....	8
2.4.2 Threshold Conditions.....	10
2.4.3 Approximate Treatment of Crack Growth..	13
2.5 Residual Stresses.....	15
2.5.1 Review of Relevant Residual Stresses...	15
2.5.2 General Discussion of Stress Intensity Factors Due to Residual Stresses.....	17
2.5.3 Stress Intensity Factors Due to Relevant Residual Stresses.....	23
2.5.4 Regimes of Crack Growth Behavior.....	31

2.6	Longitudinal Welds.....	37
2.6.1	Review of Relevant Stresses.....	37
2.6.2	Failure Criteria.....	40
2.6.3	Stress Intensity Factors.....	42
3.0	PRAISE-B COMPUTER CODE.....	47
3.1	Review of PRAISE Code.....	47
3.2	Overview of PRAISE-B Code.....	48
3.3	Logical Structure.....	52
3.4	Fatigue Crack Growth Calculations.....	57
3.5	Leaks and LOCAs.....	60
3.6	Stress Intensity Factors.....	61
3.7	Welding Residual Stresses.....	63
3.8	Stress Corrosion Cracking Model.....	63
3.9	Vibratory Stress Model.....	66
4.0	SAMPLE PROBLEMS.....	69
4.1	Sample Problem 1: Verification.....	71
4.2	Sample Problem 2: Fatigue with Deterministic Material Properties.....	79
4.3	Sample Problem 3: Fatigue with Random Material Problems.....	90
4.4	Sample Problem 4: Fatigue with In-Service Inspection.....	103
4.5	Sample Problem 5: Fatigue with Residual and Vibratory Stresses.....	114
4.6	Sample Problem 6: Fatigue of Longitudinal Weld...	122
4.7	Sample Problem 7: SCC - LOCA.....	131
4.8	Sample Problem 8: SCC - Leak.....	140

5.0	RESULTS AND DISCUSSION.....	147
5.1	Fatigue Crack Growth.....	147
5.2	Stress Corrosion Cracking.....	152
5.3	Fatigue of Longitudinal Welds.....	158
5.4	Additional Discussions.....	162
6.0	CONCLUDING REMARKS.....	165
7.0	MAJOR NOTATION.....	167
8.0	REFERENCES.....	171
	APPENDIX A.....	A-1
A.0	INPUT DESCRIPTIONS FOR PRAISE-B CODE.....	A-2
A.1	Problem Content Variables.....	A-2
A.2	Geometry and Material Properties.....	A-8
A.3	Initial Crack Size Distribution.....	A-10
A.4	Inspection Times, Earthquake Evaluation Times, and Leak Detection.....	A-12
A.5	Stratified Sample Space.....	A-13
A.6	Stresses, Stress Intensity Factors and Frequency of Transients.....	A-17
A.7	Seismic Crack Growth Parameters.....	A-21
A.8	Detailed Formula for the Input Cards.....	A-21
A.9	Output Description.....	A-49

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1-1 Schematic Diagram of Steps in Analysis of Reliability of a Given Weld Location.....	3
2-1 Crack Growth Kinetic Relation of Equation 2-1 Along With Some Selected Experimental Data.....	6
2-2 Summary of Experimental Results on the Influence of R on Fatigue Crack Growth Threshold for Steel.....	14
2-3 Axial and Circumferential Stresses Due to Welding a 34 Inch Hot Leg at Cross Sections on Weld Centerline and 0.5 Inch Away.....	16
2-4 Thickness Variation of Axial Component of As-Welded Residual Stress in a 24 Inch Line.....	18
2-5 Planar "Analog" of a Pipe With a Complete Circumferential Crack.....	22
2-6 A crack Approaching A Free Surface in a Body Without Rotational Constraint.....	24
2-7 Stress Intensity Factors for a Flat Plate and Pipe with Complete Interior Surface Circumferential Crack for Uniform Stress and Through-Wall Bending Stress Showing Marked Difference in Behavior of Pipe and Plate When Force Equilibrium is Satisfied, But Not Moment Equilibrium.....	25
2-8 RMS-Averaged Stress Intensity Factors for Part-Circumferential Interior Surface Cracks in Pipes With Residual Stresses at Weld Center Line in 34 Inch Hot Leg.....	27
2-9 Polynomial Curve Fit to RMS Stress Intensity Factors Due to Residual Stresses in Hot Leg.....	28
2-10 RMS-Averaged Stress Intensity Factors for Part-Circumferential Interior Surface Cracks in 26 Inch Pipe With Residual Stresses Shown in Figure 2-4.....	29
2-11 Polynomial Curve Fit to RMS Stress Intensity Factors Due to Stresses in 24 Inch Line.....	30
2-12 RMS-Averaged Stress Intensity Factors Due to Residual Stresses for Part-Circumferential Cracks at Angular Location Resulting in Maximum Values; 16 Inch Line Heat Affected Zone.....	32
2-13 Polynomial Curve Fit to RMS Stress Intensity Factors Due to Residual Stresses in 16 Inch Line.....	33
2-14 Regimes of Crack Growth Behavior in a-b Plane for a 24 Inch Pipe With Applied Stress of 9.86 ksi and Residual Stress Pattern Shown in Figure 2-4.....	35

List of Figures (cont'd)

<u>Figure</u>		<u>Page</u>
2-15	Regimes of Crack Growth Behavior in a-b Plane for a 24 Inch Pipe With Applied Stress of 9.86 ksi and Residual Stress Pattern Shown in Figure 2-4.....	43
2-16	Regions On a/h-a/b Plane That Include Cracks That Will Produce Leaks and Large Slot Failure in Longitudinal Welds According to the Two Criteria Employed.....	44
2-17	Least Squares Polynomial Curve Fit to Results of Figure 2-16 ($s = \sigma_B$).....	45
3-1	Hierarchy of Routines in PRAISE-B.....	53
3-2	Calculational Flow in PRAISE.....	54
3-3	Flowchart for Subroutine CRKGRO.....	58
3-4	Flowchart of the KBARS Subroutine.....	62
3-5	Flowchart of the SCC Subroutine.....	65
3-6	Flowchart for VIBES Subroutine.....	67
4-1	Input Cards for Sample Problem 1.....	73
4-2	Input Summary for Sample Problem 1.....	74
4-3	Stratification Description for Sample Problem 1.....	76
4-4	Stratification Scheme for Sample Problem 1.....	77
4-5	Results for Sample Problem 1.....	78
4-6	Card Images for Input to Sample Problem 2.....	81
4-7	Input Summary for Sample Problem 2.....	82
4-8	Stratification System for Sample Problem 2.....	84
4-9	Results of the No Earthquake Case in Sample Problem 2.....	85
4-10a	Results for Earthquake Category 1 in Sample Problem 2.....	86
4-10b	Results for Earthquake Category 2 in Sample Problem 2.....	87
4-10c	Results for Earthquake Category 3 in Sample Problem 2.....	88
4-10d	Results for Earthquake Category 4 in Sample Problem 2.....	89
4-11	Card Images for Input to Sample Problem 3.....	93
4-12	Input Summary for Sample Problem 3.....	94
4-13	Stratification Description for Sample Problem 3.....	96
4-14	Stratification Scheme for Sample Problem 3.....	97
4-15	Results for the No Earthquake Case for Sample Problem 3....	98
4-16a	Results for Earthquake Category 1 for Sample Problem 3.....	99
4-16b	Results for Earthquake Category 2 for Sample Problem 3.....	100
4-16c	Results for Earthquake Category 3 for Sample Problem 3.....	101

List of Figures (cont'd)

<u>Figure</u>	<u>Page</u>
4-16d Results for Earthquake Category 4 for Sample Problem 3.....	102
4-17 Card Images for Input to Sample Problem 4.....	105
4-18 Input Summary for Sample Problem 4.....	106
4-19 Stratification Description for Sample Problem 4.....	108
4-20 Results for No Earthquake Case in Sample Problem 4.....	109
4-21a Results for Earthquake Category 1 in Sample Problem 4.....	110
4-21b Results for Earthquake Category 2 in Sample Problem 4.....	111
4-21c Results for Earthquake Category 3 in Sample Problem 4.....	112
4-21d Results for Earthquake Category 4 in Sample Problem 4.....	113
4-22 Input Cards for Sample Problem 5.....	117
4-23 Input Summary for Sample Problem 5.....	118
4-24 Stratification Description for Sample Problem 5.....	120
4-25 Results of the No Earthquake Case in Sample Problem 5.....	121
4-26 Card Images for Input to Sample Problem 6.....	125
4-27 Input Summary for Sample Problem 6.....	126
4-28 Stratification Description for Sample Problem 6.....	128
4-29 Results of the No Earthquake Case in Sample Problem 6.....	130
4-30 Card Images to Sample Problem 7.....	134
4-31 Input Summary for Sample Problem 7.....	135
4-32 Stratification Description for Sample Problem 7.....	137
4-33 Results of the No Earthquake Case in Sample Problem 7.....	139
4-34 Card Images for Input to Sample Problem 8.....	141
4-35 Input Summary for Sample Problem 8.....	142
4-36 Stratification Description for Sample Problem 8.....	144
4-37 Results of the No Earthquake Case in Sample Problem 8.....	145
5-1 Cumulative Leak Probability for 34 Inch Line Under Various Conditions. Results are Conditional on a Crack Being Initially Present.....	150
5-2 Cumulative Probability of a Sudden and Complete Pipe Severance for the 34 Inch Weld Joint Under Various Conditions. Results are Conditional on a Crack Being Initially Present.....	151
5-3 Cumulative Leak Probability in Various Size Lines with Cracks Growing due to Stress Corrosion Cracking. Results are Conditional on a Crack Being Initially Present.....	155

List of Figures (cont'd)

<u>Figure</u>		<u>Page</u>
5-4	Cumulative Probability of a Sudden and Complete Pipe Severance in Various Size Lines with Cracks Growing due to Stress Corrosion Cracking. Results are Conditional on a Crack Being Initially Present.....	157
5-5	Cumulative Leak Probability for a Circumferential and a Longitudinal Weld in Hot Leg Subjected to Fatigue. Longitudinal Results for the Two Failure Criteria Depicted in Figure 2-15 are Included. Results are Conditional on a Crack Being Initially Present.....	159
5-6	Cumulative Probability of a LOCA or Large Slot Failure in a Circumferential and a Longitudinal Weld in Hot Leg Subjected to Fatigue. Longitudinal Results for the Two Failure Criteria Depicted in Figure 2-15 are Included. Results are Conditional on a Crack Being Initially Present.....	160
A-1	PRAISE-B Input Data Categories.....	A-3
A-2	Number of Samples Assigned to the M-th Cell.....	A-5
A-3	Specification of the Stratification Scheme by the PRAISE-B User.....	A-14
A-4	PRAISE-B Generated Stratification of the Sample Space...	A-15
A-5	Input Sequence for the Normalized Stress Intensity Factors.....	A-20
A-6	Organization of PRAISE-B Output.....	A-50

LIST OF TABLES

<u>Table</u>	<u>Page</u>
2-1 Summary of Circumferential Welds Considered.....	9
2-2 Values of m and Mean and Standard Deviation of C for Various Growth Laws and Sets of Data.....	12
2-3 Experimental Values of Axial Residual Stress in 16 in. Welded Pipe at 0.63 in. From Weld Fusion Line.....	19
2-4 Regimes of Crack Growth Behavior Shown in Figure 2-14.....	36
3-1 Summary of Routines in PRAISE-B.....	49
4-1 Comparison of Sample Problem Inputs.....	70
5-1 Summary of Cumulative Leak and LOCA Probabilities for a PWR Hot Leg Weld for Various Times. Results are Conditional on a Crack Being Initially Present.....	148
5-2 Summary of Cumulative Leak and LOCA Probabilities for Stress Corrosion Cracking in Various Pipe Sizes. Results are Conditional on a Crack Being Initially Present.....	154

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1.0 INTRODUCTION

This is the final report of work performed during the 1981 fiscal year by Science Applications, Inc. (SAI) under subcontract to Lawrence Livermore National Laboratory (LLNL) on the Piping Reliability Project. The work reported herein is a direct continuation of earlier efforts which were summarized in references 1 and 2. In that work, attention was specifically concentrated on the analysis of the influence of seismic events on the probability of failure in the large primary piping of a commercial pressurized water reactor. As a result, a probabilistic fracture mechanics model of piping reliability was developed (1). The PRAISE (Piping Reliability Analysis Including Seismic Events) Computer Code (2) was written to analyze the specific materials and crack growth mechanisms applicable to the piping system considered. Therefore, the PRAISE code, as described in reference 2, is applicable only to the case of fatigue crack growth in circumferential welds in austenitic stainless steel piping. The general methodology described in Reference 1 and implemented in reference 2 is of much wider applicability than the specific case considered in earlier work. The primary purpose of the work reported here was to alter the PRAISE code to make it more generally applicable, and to apply it to new and additional problems of interest.

1.1 Purpose of Investigation

The primary purpose of the work reported here was to alter the PRAISE code to make it more applicable to other piping systems composed of a variety of materials. The modified PRAISE code (PRAISE-B) was then applied to other piping systems, including ones that are subjected to other mechanisms of subcritical crack growth — such as stress corrosion cracking. The results of such efforts provide additional insights into the many factors that influence the reliability of piping systems.

Specifically the work reported herein consists of the following items:

- Modifications to PRAISE to allow consideration of
 - other materials
 - other failure criteria

- other subcritical crack growth characteristics
- Analysis of factors not previously considered, such as
 - welding residual stresses
 - assembly stresses
 - vibratory stresses
 - longitudinal welds

The fracture mechanics considerations that enter into the expanded items considered will be discussed in Section 2. This will be followed in Section 3 by discussions of modifications of the PRAISE code to allow these additional factors to be considered. Section 4 will provide the results of sample problems obtained by use of the modified PRAISE code, and is intended primarily for users of the code. Section 5 provides results obtained for various examples of piping that incorporate the new capabilities of PRAISE-B and is intended primarily for those interested in piping reliability. Section 6 then provides concluding remarks. For users' convenience, input descriptions for PRAISE-B code are contained in the Appendix.

Before proceeding with discussion of the expanded fracture mechanics model of piping reliability, the following brief review of the model will be presented.

1.2 Review of Methodology

A brief review of the methodology employed in reference 1 will be presented for completeness and to provide the background information for later discussion. Basically, the components of the model are shown in Figure 1-1, and it is assumed that failure results from the growth of crack-like defects introduced during fabrication. Part-circumferential semi-elliptical surface cracks are considered. The development of a leak or a complete pipe severance is considered to be a failure. Cracks are generally concentrated in welds, and attention is therefore focused on these locations. Each weld location can be considered discretely, and the procedures shown schematically in Figure 1-1 applied individually to each weld location considered. Initial populations of crack-like defects at a given weld are considered to be randomly distributed in size. These initial cracks will be found with a certain probability during pre-service and in-service inspection. The probability of detection depends on the crack size. Those cracks that escape detection and repair can then grow due to subcritical crack growth. Fatigue crack growth and stress corrosion cracking will be considered in this

Figure 1-1: Schematic Diagram of Steps in Analysis of Reliability of a Given Weld Location.

investigation. The crack growth is analyzed by fracture mechanics procedures, which requires knowledge of the stress history at the location of interest. The critical sizes of cracks for leaks and complete pipe severance (LOCA) can be obtained from appropriate failure criteria. The probability of a leak or LOCA within a given time is equal to the probability of a crack growing to the corresponding critical size within that time. Other factors, such as the influence of leak detection systems and proof tests, can be included in the analysis.

Details of the procedures involved and inputs to the model are included in reference 1. The numerical scheme used to provide results from the model is presented in reference 2. These references should be referred to for details, and this report will contain only the additional information required for the more recent studies.

2.0 ADDITIONAL FACTORS FOR FRACTURE MECHANICS MODEL

The various fracture mechanics inputs to this current study that are in addition to those utilized in reference 1 will be discussed in this section.

2.1 Subcritical Crack Growth Characteristics

Reference 1 considered only fatigue crack growth in austenitic stainless steel. In the current work it is desired to make the model more general by allowing other materials and crack growth mechanisms to be considered.

2.1.1 Fatigue Crack Growth

The fatigue crack growth characteristics of the piping material play a very important role in the model of piping reliability. In order to make PRAISE more generally applicable to other materials, the fatigue crack growth characteristics are now input into PRAISE as a self-contained subroutine supplied by the user. The growth per cycle is defined as a function of cyclic stress intensity factor (ΔK), load ratio (R) and other pertinent variables. Section 3.4 provides additional details. The current efforts did not include analysis of fatigue crack growth in materials in addition to austenitic stainless steel, so no additional fatigue crack growth characteristics were considered.

2.1.2 Stress Corrosion Cracking

Stress corrosion cracking has been observed to occur in sensitized weldments in austenitic stainless steel piping in boiling water reactors (3-5). Such crack growth can occur under constant loading conditions, and is therefore much different than the crack growth due to cyclic loading considered in references 1 and 2. The crack growth velocity, da/dt , is generally considered to be controlled by the current value of the stress intensity factor K (for a given material and environment). The crack growth kinetics for relevant environments are currently a topic of investigation. Reference 6 provides a summary of data available at that time along with a convenient curve fit. Figure 2-1 provides a summary and a plot of the following curve fit

Figure 2-1: Crack Growth Kinetic Relation of Equation 2-1 Along With Some Selected Experimental Data. (from Ref. 6)

$$\log \frac{da}{dt} = \begin{cases} -39.90 + 64.32(\log K) - 38.17(\log K)^2 + 7.81(\log K)^3 & K < 100 \text{ ksi-in}^{\frac{1}{2}} \\ -1.46 & K > 100 \text{ ksi-in}^{\frac{1}{2}} \end{cases}$$

$$\frac{da}{dt} - \text{inches/day} \quad K - \text{ksi-in}^{\frac{1}{2}} \quad (2-1)$$

This relationship will be used in analysis of subcritical crack growth in sensitized welds in boiling water reactor (BWR) lines. It is considered to be applicable to intergranular stress corrosion crack growth under operating reactor conditions in the presence of water with 0.1 - 0.3 ppm oxygen.

2.1.3 Combined Fatigue-Stress Corrosion Cracking

The crack growth kinetics of equation 2-1 are used to estimate crack growth velocities under constant load conditions. In actual operating reactors long times are spent at constant load with intermittent short-term load cycling. Hence, the real conditions are some combination of fatigue and stress corrosion cracking. Current knowledge is insufficient to allow an accurate treatment of such conditions. In order for PRAISE to be applicable to this situation the code has been set up to treat crack growth due to fatigue and SCC to be "uncoupled". That is, crack extension during a load cycle is governed by the fatigue relation, and crack growth while at load is governed by the $da/dt - K$ relation. Hence, synergistic effects are ignored — which is not conservative. Section 3 provides details of the PRAISE modifications.

2.2 Failure Criteria

The failure criterion used in previous work was that failure would occur if the net section stress due to load controlled contributors exceeds a critical value called the flow stress. This criterion is usually applicable to circumferential welds in relatively short runs of the tougher materials used in construction of reactor piping. However, in longer piping runs different failure criteria, such as a tearing instability criterion, might be more applicable. Therefore, PRAISE was modified to allow a user-defined criterion to be employed. This makes PRAISE more generally applicable, and details are presented in Sections 2.6.2 and 3.5.

Earlier work concentrated on circumferential welds. It is desired to also treat longitudinal welds, which may inherently involve a different failure criterion. Hence, the capability of easily altering the failure criterion will make the analysis of longitudinal welds easier. Specific criteria for longitudinal welds are included in Section 2.6.2.

2.3 Review of Relevant Operating Stresses

Analyses of various piping sizes were performed as a part of this investigation in order to exercise the modified PRAISE code and to give perspectives on its use. Radial gradient thermal stresses were found in reference 1 to have a minimal influence on crack growth. Therefore, they will not be considered here. Circumferential welds were again concentrated on, and the representative pipe sizes listed in Table 2-1 were selected for analysis. These lines were selected because representative applied stress values and residual stress information were available. Additionally, a range of pipe sizes, plant type and crack growth mechanisms are covered. All lines are austenitic stainless steel - the 34 in. line is centrifugally cast and the smaller lines are wrought. Assembly stresses can be treated simply by adding the proper components onto the deadweight stresses of Table 2-1. No attempt is made here to define and determine the assembly stresses since it is beyond the scope of the current work. Stresses for longitudinal welds are discussed in Section 2.6.1, and residual stresses are covered in Section 2.5.1.

2.4 Vibratory Stresses

Vibratory stresses could have a strong influence on crack growth in reactor piping. Such stresses are generally very small, but occur at high cyclic rates. Therefore, threshold conditions for fatigue and/or stress corrosion cracking are a very important aspect of the problem, and the cyclic stress amplitude is also important.

2.4.1 Stress Ranges

The cyclic stress range ($\sigma_{\max} - \sigma_{\min}$) in reactor piping due to vibrations is not well known, but is generally considered to be small. Reference 8 includes a discussion of such stresses which indicates that such values are typically

TABLE 2-1
Summary of Circumferential Welds Considered

Description	nominal OD, in	h, in	R _i , in	σ_{DW} , ksi	σ_p , ksi	σ_{NO} , ksi	source ref.
PWR, Hot Leg-Pressure Vessel	34	2.50	14.5	2.08	6.49	15.07	1
BWR Recirculation Line Nozzle	24	1.043	10.8	0.51	5.96	9.86	7
BWR 16in. Line	16	0.843	7.16	0.5	5.31	12.0	6

on the order of 500 psi. This is consistent with the conservative estimate of 1000 psi employed in reference 9. A cyclic frequency of 1000 per minute will be assumed, which is close to the operating speed of the reactor coolant pump. For illustration purposes, both values of 500 and 1000 psi for the cyclic stress range will be considered here.

2.4.2 Threshold Conditions

The threshold condition for fatigue crack growth has a very important influence on the calculated influence of vibratory stresses. The threshold employed in reference 1 was suitable for the analysis reported there, but additional care should be used in applying it to the case of vibratory stresses.

The fatigue crack growth relation employed in reference 1 was

$$\frac{da}{dn} = \begin{cases} 0 & \Delta K/(1-R)^{\frac{1}{2}} < 4.60 \text{ ksi-in}^{\frac{1}{2}} \\ C \left[\frac{\Delta K}{(1-R)^{\frac{1}{2}}} \right]^m & \Delta K/(1-R)^{\frac{1}{2}} > 4.60 \text{ ksi-in}^{\frac{1}{2}} \end{cases} \quad (2-2)$$

$m = 4$

Thus, the threshold condition, which gives ΔK_{th} as a function of load ratio, is the following

$$\Delta K_{th} = 4.60 (1-R)^{\frac{1}{2}} \quad (2-3)$$

The behavior of this relation as R approaches unity is not what would be expected; nor does it agree with experimental observations (10).

An alternative crack growth law that exhibits much of the behavior of that exhibited by equation 2-2 is

$$\frac{da}{dn} = \begin{cases} 0 & \Delta K(1+\frac{1}{2}R) < 4.60 \text{ ksi-in}^{\frac{1}{2}} \\ C [\Delta K (1+\frac{1}{2}R)]^m & \Delta K(1+\frac{1}{2}R) > 4.60 \text{ ksi-in}^{\frac{1}{2}} \end{cases} \quad (2-4)$$

This relation has the same behavior as equation 2-2 for small R and is better

behaved as R approaches unity. The corresponding threshold relation is

$$\Delta K_{th} = 4.60 / (1 + \frac{1}{2}R) \quad (2-5)$$

In order to assess which of the above growth and threshold conditions is most appropriate for austenitic piping steels, a least-square curve fit to experimental data was performed for C and m for the two cases. The procedures and data used were the same as described in Section 2.5.1 of reference 1, except for the treatment of Bamford's data. Reference 1 used data points drawn from the literature (11). In order to improve the use of Bamford's data, a listing of the experimental data points was obtained (12). Some data was included in reference 12 that was not obtainable from reference 11. The expanded set of data was then least squares curve fitted to determine C and m for the two crack growth laws. Once m was determined, the statistical distribution of C was obtained for the two cases by procedures described in reference 1. The growth law that gave the smallest variance of C would be the one that provides the better fit to the experimental results. Hence, the better of the two "laws" could be ascertained, thereby also given the preferable threshold condition. Due to the inclusion of additional data points from reference 12, as well as some corrections to the original data set, the updated least squares fit to equation 2-2 did not provide the same results as given in reference 1. The results are summarized in Table 2-2, which shows that the updated data set gave a different value of m than the original data (4.31 vs. 4). Additionally, the parameter C for the new data is not as nearly lognormally distributed as it was for the original data set. However, the differences between the old and new sets of results using $\Delta K / (1-R)^{\frac{1}{2}}$ are small enough that the older results will be employed in the current work.

The main conclusion to be drawn from the results of Table 2-2 is that the $\Delta K(1 + \frac{1}{2}R)$ results have a larger "spread", and therefore provide a less accurate representation of the data. Therefore, the original crack growth relation (equation 2-2) will be used along with the related threshold condition (equation 2-3). However, the threshold condition will be altered somewhat to provide a more accurate representation of threshold conditions as R approaches unity.

TABLE 2-2
Values of m and Mean and Standard Deviation of C
for Various Growth Laws and Sets of Data

	m	mean C,	Std. dev. of C	$\frac{C_{sd}}{\bar{C}}$
$\Delta K/(1-R)^{\frac{1}{2}}$ ref. 1	4	1.57×10^{-11}	2.20×10^{-11}	1.40
$\Delta K/(1-R)^{\frac{1}{2}}$ updated	4.31	6.80×10^{-11}	3.76×10^{-11}	1.87
$\Delta K(1+\frac{1}{2}R)$ updated	3.96	3.76×10^{-11}	1.51×10^{-10}	4.02

The alteration to the threshold condition will be based on experimental results for steels reported in references 10, 13 and 14. The relevant results are presented in Figure 2-2, which presents $\Delta K_{th}/\Delta K_0$ as a function of R . ΔK_0 is the value of ΔK_{th} at $R = 0$. The linear variation suggested by Schmidt and Paris (10) is shown along with the relation of equation 2-3. It is seen that ΔK_{th} becomes independent of R as R exceeds 0.7 - 0.8, and that equation 2-3 provides a reasonable fit to the data. Based on these observations the following threshold condition will be employed.

$$\Delta K_{th} = \begin{cases} 4.60 (1-R)^{\frac{1}{2}} & R < R^* \\ 4.60 (1-R^*)^{\frac{1}{2}} & R > R^* \end{cases} \quad (2-6)$$

$$R^* = 0.9$$

This condition has the desirable feature of being easily incorporated into the PRAISE code.

2.4.3 Approximate Treatment of Crack Growth

The growth of fatigue cracks due to vibratory stresses once the threshold has been exceeded will be quite rapid because of the cyclic frequency assumed (1000/min, see Section 2.4.1). For example, Figure 2-14 of reference 1 shows that the median crack growth rate just above the threshold is 3.5×10^{-9} in/cycle. The upper bound time to failure (existence of a through-wall crack) for a typical LWR pipe once the threshold is exceeded is given by

$$t_{f(max)} = \frac{\Delta a_{max}}{(da/dn)_{min} (dn/dt)} = \frac{h_{max}}{(da/dn)_{min} (dn/dt)}$$

$$= \frac{4 \text{ in}}{(3.5 \times 10^{-9} \frac{\text{in}}{\text{cycle}}) (10^3 \frac{\text{cycle}}{\text{min}})} = 1.14 \times 10^6 \text{ min} = 2.2 \text{ yrs.}$$

Hence, once the fatigue threshold is exceeded, failure will occur in less than 2.2 years. On the time scale of a reactor lifetime, this is virtually immediate failure. Therefore, vibratory stresses can be treated by incorporating these into the failure criterion by saying failure occurs once ΔK_{th} is exceeded. This circumvents the need to follow the crack growth in detail.

Figure 2-2: Summary of Experimental Results on the Influence of R on Fatigue Crack Growth Threshold for Steel.

For semi-elliptical surface cracks subjected to vibratory stresses, the threshold conditions will be exceeded in the "a" direction before being exceeded in the "b" direction (except for half-penny shaped cracks, which have low K values). Therefore, if $\Delta a = h - a_{th}$ is the amount of growth in the depth direction between the first exceedance of the threshold, then the growth in the "b" direction will be less than this. In order to conservatively (but reasonably) account for growth in the "b" direction, the corresponding change in b will be taken to be

$$\Delta b = h - a_{th} \quad (2-7)$$

The depth at which ΔK_{th} is first exceeded due to vibratory stresses is a_{th} .

This treatment of vibratory stresses is consistent with the PRAISE code, and is sufficient for current needs.

2.5 Residual Stresses

Residual stresses in piping systems can result from welding and assembly. As-welded residual stresses will be discussed in this section. Methods of treating assembly stresses are discussed in Section 2.3. As-welded residual stresses in representative weld joints will first be reviewed, followed by a discussion of some general features of stress intensity factors due to axisymmetric residual stresses. Stress intensity factors due to the residual stresses of interest will then be presented.

2.5.1 Review of Relevant Residual Stresses

The welding residual stresses in the three pipe sizes included in Table 2-1 will be summarized here. The welding residual stresses in representative pipes in a PWR primary system were calculated and are reported in reference 8. The hot leg results are of interest here which are summarized in Figure 2-3. The axial component of the stress at the weld centerline will be used in subsequent analyses. The calculated stresses are axisymmetric; this is built in to the finite element code. However, experimental results (15) suggest that this is a realistic assumption for this large line.

Figure 2-3: Axial and Circumferential Stresses Due to Welding a 34 Inch Hot Leg at Cross Sections on Weld Centerline and 0.5 Inch Away (from Ref. 8).

The welding residual stresses in a 24 inch BWR recirculation line have been calculated (16) and experimentally determined (15). They have been found to be axisymmetric. The values of the stress in the heat affected zone is of interest here, because the dominant mode of crack growth in BWR lines has been observed to be stress corrosion cracking (3 - 5). Such cracking occurs in the heat affected zone rather than at the weld fusion line. Figure 2-4 summarizes the axial component of the residual stresses in a 24 inch line. Also shown is a plot of a cosine relation which is seen to provide a good approximation to the calculated and measured values.

Experimental results reported in reference 6 for the axial component of the residual stress in the heat affected zone of a 16 in. line reveal that these stresses are not axisymmetric. Table 2-3 summarizes such results which includes information on the thickness distribution at various angular positions around the pipe circumference. It is seen that at certain angular positions the stresses are tensile all the way across the thickness. This is in marked contrast to the results for the larger lines shown in Figures 2-3 and 2-4.

These residual stress results serve as inputs to the analysis of stress intensity factors resulting from them. Before proceeding to the stress intensity factors themselves, the following discussion of general properties of stress intensity factors due to residual stresses will be provided.

2.5.2 General Discussion of Stress Intensity Factors Due to Residual Stresses

The stress intensity factors due to complex stresses that vary through the thickness of a body are most easily calculated by use of weight functions or influence functions. This was the approach used to treat radial gradient thermal stresses in reference 1. Such techniques employ the superposition principle along with the stresses on the plane of the crack before the crack was present in order to calculate the resulting K . In the case of residual stresses, two questions immediately come to mind:

- (i) What is the influence of residual stress redistribution when the crack is introduced, and what is the effect of the steep axial gradients of the residual stresses on the resulting K ?,

Figure 2-4: Thickness Variation of Axial Component of As-Welded Residual Stress in a 24 Inch Line.

TABLE 2-3

Experimental Values of Axial Residual Stress in
16 in. Welded Pipe at 0.63 in. From Weld Fusion Line

depth, x/h	$\theta = 0$		90°		180°		270°	
	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
0	22.6	3.28	-84.95	-12.32	39.2	5.69	18.1	2.63
1/8	76.12	11.04	25.	3.6	29.	4.2	--	--
1/4	68.1	9.88	-5.2	-0.75	6.9	1.0	-6.	-0.8
3/8	40.4	5.86	-62.	-9.0	-42.9	-6.22	--	--
1/2	17.	2.5	-78.6	-11.4	-75.8	-11.0	-34.	-4.9
5/8	64.	9.3	-53.	-7.7	-26.	-3.8	--	--
3/4	66.	9.6	-48.	-7.0	0.0	0.0	-18.1	-2.62
7/8	66.	9.5	-146.5	-21.25	-6.9	-1.0	--	--
1	75.02	10.88	-65.8	-9.55	37.	5.3	9.0	1.3

- (ii) What is the behavior of K as a approaches h ? Most generally, K approaches infinity as a approaches h . Is this also true for self-equilibrating residual stresses?

The first question is the topic of current research, and a detailed discussion is beyond the scope of this work. It will be assumed herein that the axial gradient is not influential on K , and that the standard application of influence functions (and superposition) is adequate. This will certainly be true for shallow cracks. It has yet to be demonstrated that it is not also applicable to deep cracks.

The second question is of some importance for very deep cracks. The influence functions developed in reference 1, and also reported in reference 17 are strictly applicable only for $a \leq 0.8 h$. In many cases, deeper cracks are of interest, and information on the general behavior of K due to residual stresses for deep cracks is of interest. This is the major topic of this section. Parker (18 - 20) has published some closely related results.

The axial component of axisymmetric residual stresses must be self-equilibrating through the wall thickness in order for the body to remain in equilibrium. For a pipe this means

$$\int_{R_i}^{R_i + h} \sigma_z(r) 2\pi r dr = 0 \quad (2-8a)$$

For pipes with $R_i \gg h$ the following approximation is applicable.

$$\int_0^h \sigma_z(x) dx = 0 \quad (2-8b)$$

This is the only equilibrium requirement for pipes, because pipes can support a bending moment that is distributed around the pipe circumference. This is not true for flat plates, in which case the following moment equilibrium requirement is also necessary

$$\int_0^h x \sigma_z(x) dx = 0 \quad (2-9)$$

(moment equilibrium)

The planar body shown in Figure 2-5 provides an approximation to a pipe because the rotation constraints imposed by the cylindrical nature of a pipe are present (in an approximate manner). The advantage of the planar body of Figure 2-5 is that an exact closed form solution for K is available (21) — when symmetry conditions for a periodic array of coplanar cracks are considered. The K solution for a point load $\bar{P}$ (force per unit thickness of the body) is given by

$$K = \bar{P} \left(\frac{2}{h} \tan \frac{\pi a}{2h} \right)^{\frac{1}{2}} \frac{\cos \frac{\pi x}{2h}}{(\sin^2 \frac{\pi a}{2h} - \sin^2 \frac{\pi x}{2h})^{\frac{1}{2}}} \quad (2-10)$$

This can be used as the Green's function to provide the following relation for a stress $\sigma(x)$ on the crack plane

$$K = \left(\frac{2}{h} \tan \frac{\pi a}{2h} \right)^{\frac{1}{2}} \int_0^a \frac{\sigma(x) \cos \frac{\pi x}{2h}}{(\sin^2 \frac{\pi a}{2h} - \sin^2 \frac{\pi x}{2h})^{\frac{1}{2}}} dx \quad (2-11)$$

Using the definitions shown in Figure 2-5 along with trigonometrical identities, this can be rewritten as

$$K = \left(\frac{2}{h} \cot \frac{\pi \epsilon}{2} \right)^{\frac{1}{2}} \int_0^{h-b} \frac{\sigma(x) \cos \frac{\pi x}{2h}}{(\cos^2 \frac{\pi \epsilon}{2} - \sin^2 \frac{\pi x}{2h})^{\frac{1}{2}}} dx \quad (2-12)$$

For deep cracks, ϵ is small and $\cos(\pi \epsilon/2) \sim 1$. The above equation then reduces to

$$K \sim \left(\frac{2}{h} \cot \frac{\pi \epsilon}{2} \right)^{\frac{1}{2}} \int_0^h \sigma(x) dx$$

$$\sim \left(\frac{4}{h \pi \epsilon} \right)^{\frac{1}{2}} \int_0^h \sigma(x) dx \quad (2-13)$$

Therefore, if $\int_0^h \sigma(x) dx \neq 0$, K will be infinite as $\epsilon \rightarrow 0$. If $\int_0^h \sigma(x) dx = 0$, then K can approach zero as ϵ approaches 0. Note that no moment equilibrium (equation 2-9) is required for K to be zero as $a \rightarrow h$.

Figure 2-5: Planar "Analog" of a Pipe With a Complete Circumferential Crack.

Consider now the case of a planar strip without constraint of rotation. A closed form solution for an edge-cracked strip of finite width is not available. The geometry shown in Figure 2-6 will be used to check conditions on K as a crack approaches a free surface in a body without rotational constraint. The solution for this body is in reference 21. Retaining only dominant terms as $b \rightarrow 0$, the following result is applicable

$$K = 3.97 \frac{b+x}{b^{3/2}} \bar{P} \quad (2-14)$$

For a stress $\sigma(x)$ on the crack plane

$$K = \frac{3.97}{b^{3/2}} \left[b \int_0^{\infty} \sigma(x) dx + \int_0^{\infty} x \sigma(x) dx \right] \quad (2-15)$$

From this results it is seen that for K to remain finite as $b \rightarrow 0$, both force equilibrium and moment equilibrium must be satisfied.

In retrospect, the above results are not surprising and are a consequence of the different ways that pipes and flat plates can support loads. These differences result in marked differences between stress intensity factor results for deep cracks for pipes and plates for self-equilibrating stress systems. These differences are not observed for more common loading conditions, such as uniform stress. This is vividly demonstrated by the results presented in Figure 2-7, which is drawn primarily from previously published results (such as summarized in references 7 and 22). The result for uniform bending around the pipe circumference was obtained by use of Labben's weight functions (7,23).

2.5.3 Stress Intensity Factors Due to Relevant Residual Stresses

The stress intensity factors due to the residual stress distributions discussed in Section 2.5.1 will now be presented. The values of $\bar{K}_i$ due to the residual stresses can be calculated from the influence functions developed earlier in this project (1, 17) by procedures detailed in reference 1. Basically, this consists of numerical integration of the equation.

$$\bar{K}_i = \int_{A_{\text{crack}}} h_i(x,y,a,b) \sigma(x,y) dA \quad (2-16)$$

Figure 2-7: Stress Intensity Factors for a Flat Plate and Pipe with Complete Interior Surface Circumferential Crack for Uniform Stress and Through-Wall Bending Stress Showing Marked Difference in Behavior of Pipe and Plate When Force Equilibrium is Satisfied, But Not Moment Equilibrium.

where h_i is the influence function. In the case of complete circumferential cracks, the Labbens weight function is employed (23).

The residual stresses for the 34 inch pipe at the weld centerline were used in equation 2-16 to produce the results shown in Figure 2-8. In order to perform the numerical integration, the stress values were tabulated and linear interpolation employed.

The results of Figure 2-8 were fitted to a polynomial in a/h and a/b to provide a functional representation for use in subsequent PRAISE runs. The order of the polynomial was adjusted to provide an adequate fit. The fact that $\bar{K}_a$ goes to zero at $a = h$ was used as a data point in the least squares fit. This is in accordance with the discussion in Section 2.5.2. Section 3.7 provides additional details of the assumed polynomial form. Figure 2-9 presents results generated by a least squares polynomial fit of order 3 in a/h and 1 in a/b . The functional representation is felt to be adequate for current purposes.

Corresponding results for the 24 inch BWR line are included in Figure 2-10. In this case the cosine relation shown in Figure 2-4 was used to represent the stress. A polynomial fit to $\bar{K}_a$ of order 5 in a/h and 2 in a/b is shown in Figure 2-11. The fit for $\bar{K}_b$ was order 4 in a/h and 3 in a/b . The values of $\bar{K}_a$ going positive for large α is not reasonable, but the values are so low that they will not have a noticable influence when added onto the K due to applied stresses for such deep cracks.

The case of the 16 inch line is considerably more complex. Due to the lack of axisymmetry and sparseness of data, a mathematical representation of the stresses on the crack plane is more difficult. A bi-cubic spline was employed to interpolate between the data points of Table 2-3. Another difficulty is that the stress intensity factors are now dependent on where around the circumference the crack is located. Additionally, there is no longer symmetry about the point of maximum crack penetration, and the two degree-of-freedom model built into PRAISE is no longer strictly applicable. A three degree-of-freedom (DOF) model would be necessary to accurately treat these more complex residual stresses.

In order to be able to use the existing procedures, two sets of stress intensity factors were calculated for each crack size at each circumferential

Figure 2-8: RMS-Averaged Stress Intensity Factors for Part-Circumferential Interior Surface Cracks in Pipes With Residual Stresses at Weld Center Line in 34 Inch Hot Leg (see Figure 2-3).

Figure 2-9: Polynomial Curve Fit to RMS Stress Intensity Factors Due to Residual Stresses in Hot Leg (Figure 2-8).

Figure 2-10: RMS-Averaged Stress Intensity Factors for Part-Circumferential Interior Surface Cracks in 26 Inch Pipe With Residual Stresses Shown in Figure 2-4.

Figure 2-11: Polynomial Curve Fit to RMS Stress Intensity Factors Due to Residual Stresses in 24 Inch Line (Figure 2-10).

location; one set used the stresses on one half the crack and assumed them to be applicable to both halves; the second set then used the same procedure but used the stresses on the crack half not utilized the first time. The actual $\bar{K}_a$ for a three DOF model will be the average of the two values of $\bar{K}_a$ generated in this manner. The three DOF model would have two values of $\bar{K}_b$, but each would be smaller than the larger of the two values generated by the above procedure. Therefore, the largest set of values of $\bar{K}_b$ found will be utilized as an approximation to the three DOF values.

The above procedure was followed for numerous circumferential locations of the crack. It was found that a crack centered at $\theta = 0$ generally had the highest stress intensity factors, and the value of $\bar{K}_a$ and largest value of $\bar{K}_b$ are shown in Figure 2-12. Also shown in Figure 2-12 is the maximum local value of K due to the residual stresses for a complete circumferential crack. These results are from reference 6, and use the approximate solution for a concentrated point load on a complete circumferential crack (7, 22). It is seen that the local maximum for a complete circumferential crack is much larger than the RMS values for a part-circumferential crack, which is an expected result. The two sets of $\bar{K}_b$ are very similar, so that the two values will be close to the ones shown here. The near equality of the two values in this case is because this angular location is close to a maximum of the stresses. Therefore, the circumferential gradients of stresses are relatively small, and the symmetry with respect to the point of maximum crack penetration is nearly satisfied. Figure 2-13 presents results generated by a least squares curve fit of order 3 in a/h and 1 in a/b (order 3 in a/b for $\bar{K}_b$). It is seen that $\bar{K}_a$ does not approach zero as a approaches h . This is because the residual stresses at a given angular location are not self-equilibrating through the thickness. For non-axisymmetric stresses this is not required.

2.5.4 Regimes of Crack Growth Behavior

Residual stresses can have markedly different influences on subcritical crack growth depending on whether or not they produce negative calculated values of stress intensity factors. The purpose of this section is to present a qualitative discussion of the influence of residual stresses on subcritical crack growth. Much information can be obtained simply by observing the signs of $\bar{K}_a$ and $\bar{K}_b$ due to the combination of applied and residual stresses.

The results presented in Figure 2-12 are in marked contrast to the corresponding

Figure 2-12: RMS-Averaged Stress Intensity Factors Due to Residual Stresses for Part-Circumferential Cracks at Angular Location Resulting in Maximum Values; 16 Inch Line Heat Affected Zone.

Figure 2-13: Polynomial Curve Fit to RMS Stress Intensity Factors Due to Residual Stresses in 16 Inch Line (see Figure 2-12).

earlier results presented in Figures 2-8 and 2-10, in that the results in Figure 2-12 have positive stress intensity factors for all crack depths. Hence, these residual stresses will obviously accelerate crack growth. In marked contrast to this, the corresponding axisymmetric stress results shown in Figures 2-8 and 2-10 have negative stress intensity factors for some crack depths. Although negative values of K are physically meaningless, this means that these residual stresses are going to retard crack growth, and are therefore going to be beneficial. Thus, it is already apparent that residual stresses can be beneficial or harmful — depending on their sign and spatial distribution.

The beneficial nature of residual stresses can be easily visualized simply by considering the sign of $\bar{K}_a$ and $\bar{K}_b$ due to the combination of applied and residual stresses. This is discussed more thoroughly in reference 24. For the residual stresses in Figure 2-4 (corresponding $\bar{K}_i$ in Figure 2-10) and an applied stress of 9.86 ksi (see Table 2-1), the crack sizes with various signs of $\bar{K}_a$ and $\bar{K}_b$ are conveniently summarized in Figure 2-14. For shallow cracks, both $\bar{K}_a$ and $\bar{K}_b$ are positive. Therefore cracks will grow in both the depth and length directions (Region A). As the crack grows it will approach a point where $\bar{K}_a$ is zero, and further growth in the depth direction will be arrested (Region B). The various regions of crack growth behavior are summarized in Table 2-4. The main feature of these results is that a region exists (C) through which a crack would never grow at the applied stress level considered. Therefore, any crack that would result in failure must initially be deep enough to put it into Region D, i.e., $a/h > \sim 0.8$. This means that very deep initial cracks will be required to cause failure in the case under consideration. Additionally, these results indicate that growth in the depth direction will dominate — which means that if failure does occur it will most probably be a leak.

These qualitative observations are independent of the crack growth mechanism (as long as $da/dn = 0$ for $K_{\max} \leq 0$) and are based only on the sign of the stress intensity factors. The influence of residual stresses on piping reliability will be quantified in Section 5 by calculating their effect on the pipe failure probabilities.

Results analogous to those shown in Figure 2-14 could be drawn for the 34 inch line. The general features would be very similar.

Figure 2-14: Regimes of Crack Growth Behavior in a - b Plane for a 24 Inch Pipe With Applied Stress of 9.86 ksi and Residual Stress Pattern Shown in Figure 2-4.

TABLE 2-4
Regimes of Crack Growth Behavior Shown in Figure 2-14

	$\bar{K}_a$	$\bar{K}_b$	Comment
A	+	+	Growth in depth and circumferential direction
B	-	+	No growth in depth direction
C	-	-	No growth whatever in this region
D	+	-	No growth in circumferential direction
E	+	?	Possible growth in circumferential direction. Uncertainty in $\bar{K}_b$ for very deep cracks.

2.6 Longitudinal Welds

The analysis performed in the first phase of this work, as was reported in reference 1, concentrated on circumferential welds and omitted longitudinal piping welds from consideration. This was justified for three reasons: (i) there are more circumferential than longitudinal welds in the piping considered in reference 1 (14 vs 6 at Zion 1, 14 vs 0 at Zion 2), (ii) failure of circumferential welds is more likely to produce a large loss-of-coolant accident (LOCA) than failure of a longitudinal weld, and (iii) stresses were expected to be larger in circumferential welds than in longitudinal ones. The first two reasons are still valid. However, the stress analysis reported in reference 8 was less conservative than conventionally employed, which resulted in lower values of restraint of thermal expansion bending moments. It turned out that the overall axial and hoop stress components were of the same order. The load controlled portion of the stress (pressure plus deadweight) is actually considerably higher in the hoop direction. In order to provide estimates of the influence of longitudinal welds on calculated piping reliability, it is therefore desirable to incorporate capabilities for handling longitudinal welds into PRAISE. The only difference between circumferential and longitudinal welds from a fracture mechanics standpoint is differences in the stresses and failure criterion. Results presented in references 1 and 17 indicate that the RMS stress intensity factors for part-circumferential and semi-elliptical longitudinal cracks are very similar. Hence, the influence functions developed for circumferential cracks will be applied here to the longitudinal cracks.

2.6.1 Review of Relevant Stresses

The only longitudinal welds in the large primary piping at Zion 1 are located in elbows. The stresses in elbows resulting from applied bending moments are considerably more complex than in straight piping runs (25). Not only are the longitudinal stresses no longer given simply by My/I , but appreciable hoop stresses are also generated. The results of Rodabaugh and George (25) will be applied to estimation of the stresses induced in elbows by bending. The results will be closely comparable to those obtained by use of Section III of the ASME Boiler and Pressure Vessel Code (26).

Maximum stresses due to in-plane and out-of-plane bending are very similar (25), and the largest of these two will be employed here. In regions of

maximum hoop stress, the hoop stresses due to bending are nearly equal but of opposite sign on the inside and outside of the pipe. As a reasonable but conservative approach, the maximum hoop stresses will be taken to be applied across the longitudinal weld and to be tensile on the inside surface.

The 90° elbows in the cross-over leg will be concentrated upon. These elbows have the following dimensions

$$\begin{aligned}\text{inside radius} &= R_i = 15.5 \text{ in} \\ \text{thickness} &= h = 3.312 \text{ in} \\ \text{bend radius} &= R_B = 51.25 \text{ in} \\ \text{mean radius} &= \bar{R} = R_i + \frac{1}{2}h = 17.16 \text{ in}\end{aligned}$$

$$R_B/\bar{R} = 2.99$$

$$\lambda = \frac{hR_B}{\bar{R}^2 (1-\nu^2)^{\frac{1}{2}}} = 0.60$$

For $\lambda > 0.5$, the results of reference 25 are particularly simple, because only one term of the infinite series solution is required for reasonable accuracy. The stresses can be evaluated quite easily, including the angular variation of both the hoop and axial components. The internal pressure has an influence on the stresses due to bending moments. For an internal pressure of 2500 psi, the following results due solely to an applied bending moment M are obtained

$$\frac{\sigma_z(\max)}{MR_o/I} = 1.25$$

$$\frac{\sigma_\theta(\max)}{MR_o/I} = \begin{cases} + 2.4 \text{ inside} \\ - 2.4 \text{ outside} \end{cases}$$

These results show that the maximum axial bending stress is higher than the nominal value of $M\bar{R}/I$ by 25%, and that the peak hoop stresses are actually nearly twice as large as the maximum axial stress. The above results can be transformed into actual stress values from information in reference 1. The elbow between joints 7 and 8 in the cross-over leg (see Figure 1-2 of reference 1) will be concentrated upon here, because the axial stresses from reference 1

indicates that this will have higher hoop stresses than the other elbow in the cross-over leg. Additionally, the other elbow is attached to the pump, and therefore would tend to have lower stresses than the elbow that is attached to straight piping runs (27).

The stresses due to bending in the longitudinal weld can be estimated from results in reference 1. The axial component of the bending stresses under normal operation conditions at joint 7 can be estimated from

$$\sigma_{B(nom)} = \sigma_{NO} - \sigma_p = 2.11 \text{ ksi}$$

This is equal to MR_o/I — the denominator in the above results. This value of bending stress was calculated using the thinner value of h at the joint (according to procedures described in reference 1). It must therefore be compensated to allow for the thicker elbow. This is accomplished by multiplying by

$$\frac{(MR_o/I)_{thick}}{(MR_o/I)_{thin}} \sim \frac{(D_o^4 - D_i^4)_{thin}}{(D_o^4 - D_i^4)_{thick}} = 0.756$$

The following results are obtained for the bending induced stresses under normal operating conditions.

$$\sigma_{z(max)} = 1.25 (0.756) (2.11) = 2.00 \text{ ksi}$$

$$\sigma_{\theta(max)} = \frac{2.4}{1.25} \sigma_{z(max)} = 3.84 \text{ ksi} \left\{ \begin{array}{l} + \text{ on inside} \\ - \text{ on outside} \end{array} \right.$$

Results for the deadweight stresses are obtained in a similar manner, and the hoop pressure stress is twice the axial value given in reference 1 (neglecting differences in wall thickness). Using results from Table 1-2, the following stress values are obtained for the hoop stresses on the longitudinal weld. These stresses will be assumed to be constant along the weld length. Positive values refer to the inner pipe wall; negative to the outer wall

$$\sigma_{dw} = \pm 0.58 \text{ ksi}$$

$$\sigma_p = 13.0 \text{ ksi}$$

$$\sigma_{NO} = 13.0 \pm 3.84 \text{ ksi}$$

$$\sigma_{LC} = \sigma_p + \sigma_{dw} = 13.0 \pm 0.58 \sim 13.6 \text{ ksi}$$

The hoop component of the radial gradient thermal stresses and the resulting stress intensity factor could be evaluated by procedures analogous to those employed in reference 1. However, results presented in reference 1 indicated that radial gradient thermal stresses have a minimal influence on the calculated failure probabilities, so these stress contributors will not be considered in this work. Also, the influence of residual and vibratory stresses on longitudinal welds will not be considered. Therefore, the stress history utilized for the longitudinal welds will consist of a pre-service proof test followed by 200 heatup-cooldown cycles in 40 years.

2.6.2 Failure Criteria

The failure criterion employed in reference 1 for circumferential welds was the exceedance of a critical net section stress. This criterion is not applicable to longitudinal welds, because the load controlled stresses can be redistributed to uncracked areas of the pipe. This is not true in the case of circumferential welds. Therefore, a revised failure criterion for axial part-through and through-wall cracks must be devised. Failure conditions for axial cracks have been more thoroughly studied than for circumferential cracks. A comprehensive review of such criteria will not be included here, but references 9 and 28 - 30 are of particular relevance to the current discussion.

Consistent with the spirit of the failure criterion utilized in earlier work, the following discussion of applications of tearing instability to longitudinal cracks will be included. Paris, et al. (31) provides an estimate of T_{app1} for long and deep longitudinal cracks. For a crack of length ℓ in a body of thickness h , $T_{app1} \sim 2\ell/h$. Taking ℓ to conservatively be equal to the arc length at the outer surface of the 90° elbow under consideration, and using the appropriate value of h

$$T_{app1} \sim 2(107)/3.312 = 65$$

This is considerably below T_{mat} for austenitic stainless steel (see Section 2.9 of reference 1). Therefore, it appears that a part-through crack (PTC) will never go unstable. Therefore, a PTC will grow as a fatigue crack until it becomes through-wall — at which time it may or may not grow axially, depending on the failure criterion for through-wall cracks. This will be one of the approaches used for longitudinal PTC, and is consistent with the approach used

in reference 1.

However, there is considerable experimental evidence that part-through cracks in stainless steel pipes can go unstable and produce a through-wall crack (9, 28, 30). The approach of Kiefner, et al. (28) will be followed here. This approach is based on a large amount of experimental data, was used in the cold leg integrity evaluation (9) and is not inconsistent with references 29 and 30. The results of reference 28 for tough materials that are flow stress controlled will be utilized. In this case, the results readily reduce to the following. Let

$$M_T = \left(1 + 1.255 \frac{b^2}{Rh} - 0.0135 \frac{b^4}{R^2 h^2} \right)^{\frac{1}{2}} \quad (2-17)$$

For through-wall cracks, $M_T = \sigma_{f10}/\sigma_{LC}$. Setting this equal to the expression for M_T in equation 2-17 defines a quadratic equation for the critical length of a through-wall crack. Denote this value as b_c . Then, if $b > b_c$ crack instability in the length direction will occur — which would lead to a large slot failure. For part-through cracks denote the critical depth as $a_c (= h\alpha_c)$. The critical value of α_c for a given stress and crack length b is then provided by the expression

$$\frac{\alpha_c (\sigma_{LC}/\sigma_{f10})}{\alpha_c + (\sigma_{LC}/\sigma_{f10}) - 1} = M_T \quad (2-18)$$

where M_T for the corresponding b is defined in equation 2-17. If $\alpha > \alpha_c$, a crack instability in the depth direction will occur. If an instability in the depth direction is predicted, then the stability of a through-wall crack of the same length is then checked by comparison with b_c . If $b < b_c$ no instability will occur in the length direction, and the failure will be called a leak. If an instability is predicted, then the crack can run axially. Such a failure will be called a "large slot" failure. This is a second set of failure criteria that will be employed. The following table summarizes the two failure criteria that will be considered for longitudinal cracks.

name	instability of part-through-cracks	instability of through-wall cracks
Tearing	no instability	eq. 2-17
Kiefner	eq. 2-18	eq. 2-17

The sizes of cracks that can result in a failure (leak or large slot) according to these two criteria can be conveniently summarized on an a/h , a/b plane. Such plots are presented in Figure 2-15 for $\sigma_{LC}/\sigma_{f10} = 0.3$. This value of the ratio of stresses corresponds closely to the above value for the longitudinal weld considered here, and the mean value of the flow stress. Figure 2-15 shows that the two criteria predict considerably different behavior for part-through cracks. The degree to which this influences the calculated failure probabilities will be discussed in Section 5.3.

2.6.3 Stress Intensity Factors

Stress intensity factors for semi-elliptical longitudinal cracks in pipes will be nearly the same as corresponding part-circumferential cracks (1, 17). This was mentioned at the beginning of Section 2.6, and eliminates the need to calculate a new set of stress intensity factors for longitudinal cracks. However, stress intensity factors for the case where the stresses vary linearly through the wall thickness are of interest for longitudinal cracks so that the "bending" stresses in elbows discussed in Section 2.6.1 can be conveniently incorporated into PRAISE. Figure 2-16 presents results for semi-elliptical longitudinal cracks with stress σ_B at the inside surface and $-\sigma_B$ on the outside surface. Also shown is the corresponding result for a complete circumferential crack which was also included in Figure 2-7. Note that $\bar{K}_a$ is small as a approaches h . This is expected behavior that is in accordance with the discussion of Section 2.5.2. The results of Figure 2-16 were fitted to a polynomial by least squares procedures in the same manner as discussed earlier for residual stresses. For $\bar{K}_a$ a first order polynomial in a/h and third in a/b was used. A third order polynomial was employed in both a/h and a/b for $\bar{K}_b$. Figure 2-17 presents a plot of the results obtained by use of the polynomial representation. These results will be used in the analysis of longitudinal welds which is discussed in Section 5.3.

This concludes the discussion of the fracture mechanics aspect of the work reported here. Descriptions of the corresponding modifications to PRAISE are presented in Sections 3 and 4. Failure probability results generated by the the expanded code are presented and discussed in Section 5.

Figure 2-15: Regions On a/h - a/b Plane That Include Cracks That Will Produce Leaks And Large Slot Failures In Longitudinal Welds According To The Two Criteria Employed.

Figure 2-16: RMS-Averaged Stress Intensity Factors For Semi-Elliptical Cracks In Pipes With Linearly Varying Stress Through The Thickness. $\sigma = \sigma_B$ At Inside Surface and $-\sigma_B$ At Outside Surface.

Figure 2-17: Least Squares Polynomial Curve Fit to Results of Figure 2-16 ($s = \sigma_B$)

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3.0 PRAISE-B COMPUTER CODE

The PRAISE (Piping Reliability Analysis Including Seismic Events) computer code has been modified to incorporate the features described in Section 2. The resulting new code, designated as PRAISE-B (PRAISE-version B), is described in this chapter. A brief summary of the PRAISE code is given in Section 3.1. Subsequent sections provide specific details on how these new features were implemented in PRAISE-B. The interested reader is referred to Ref. 2 for a description of the models which have not been changed. Details of the input and sample problems are given in Section 4.

3.1 Review of the PRAISE Code

The objective of the PRAISE computer code was to estimate 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 cyclic RMS 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 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.

3.2 Overview of PRAISE-B Code

The PRAISE-B code extends the capabilities of the PRAISE code to include:

- (1) crack propagation due to stress corrosion cracking,
- (2) contribution of welding residual stresses to the stress intensity factors, and
- (3) influence of high-cycle low-amplitude vibratory stresses.

Furthermore, PRAISE-B is coded so that it can be readily modified by the user to accommodate a wide range of crack growth relationships, failure criteria, stress intensity factor formulations, and longitudinal welds.

Changes in the PRAISE code which resulted in PRAISE-B can be divided into two categories:

- (1) significant modification of existing subroutines (the main routine PRAISE, KBARS, and CRKGRO)
- (2) addition of new routines (FAILS, SCC, SIFRSA, SIFRSB, and VIBES)

Changes to correct coding errors or to accommodate the major modifications have also been incorporated. A summary of these changes is given in Table 3-1.

No changes have been made in the subroutines which evaluate the influence of earthquakes. It is judged that neither stress corrosion cracking nor vibratory stresses are important failure mechanisms within the duration of the earthquake. The formulation for representing earthquake stress history which was used in the PRAISE code has been retained in PRAISE-B.

Table 3-1 Summary of Routines in PRAISE-B

ROUTINE	MODIFICATIONS			COMMENTS
	Small/None	Large	New	
MAIN		•		Restructured to put more calculations in the subroutines; added call to SCC
INITAL	•			Added inputs for selecting and defining new models - more flexible definition of the strata
VERIFY	•			Verifies the input options or values for the new models
ALOC	•			Added storage locations for the coefficients of the polynomial that defines the contribution of the residual stresses to the stress intensity factors
MATPRO	•			No changes
PROBAB	•			Added a normalization to the log normal distribution of aspect ratio
RESET	•			No changes
INSPCT	•			No changes
FTIME	•			Routine itself was not changed, but its role in the computational scheme was changed
KBARS		•		Calculates the parameters needed to evaluate the effective cyclic stress intensity factor for fatigue crack growth. These are: (1) maximum "RMS-averaged" stress intensity factor during the cycle (2) minimum "RMS-averaged" stress intensity factor during the cycle

Table 3-1 (Cont'd.)

ROUTINE	MODIFICATIONS			COMMENTS
	Small/None	Large	New	
				(3) "RMS-averaged" stress intensity factor corresponding to the operating stress prior to the transient
				(4) Load ratio
				These are calculated for both the length and depth directions.
SIFBARA	•			No changes
SIFBARB	•			No changes
CRKGRO		•		Based on parameters supplied from KBARS, CRKGRO calculates
				(1) the effective cyclic stress intensity factor,
				(2) the amount of crack growth during this cycle
				Calls VIBES to evaluate influence of vibratory stresses
				Calls FAILS to evaluate failure
TABLAR	•			No changes
ERFINT	•			Evaluation of probabilities is now done in double precision arithmetic. Also corrected a small coding error.
SHAKER	•			No changes
EQSIZE	•			No changes
EQCRK	•			No changes
OUTS	•			No changes

Table 3-1 (Cont'd.)

ROUTINE	MODIFICATIONS			COMMENTS
	Small/None	Large	New	
FAILS			•	Evaluates failure (leak or LOCA) based on the current crack size
SCC			•	Evaluates crack propagation due to stress corrosion cracking
SIFRSA			•	Calculates contribution of residual stresses to the RMS-averaged stress intensity factor in the depth direction
SIFRSB			•	Calculate contribution of residual stresses to the RMS-averaged stress intensity factor in the length direction
VIBES			•	Evaluates influence of vibratory stresses
INTERP	•			No change
LOCATE	•			No change
FINDI	•			No change
FINDJ	•			No change
YEQ	•			No change
XEQ	•			No change
XSWEEP	•			No change
YSWEEP	•			No change
DSWEEP	•			No change
LAGINT	•			No change

3.3 Logical Structure

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 3-1. The PRAISE-B algorithm can be divided into two 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, calculates the failure probabilities, and presents the results. The calculational flow of the PRAISE-B code is shown in Figure 3-2.

Before initiating the simulation, PRAISE-B 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 the tabular functions needed to evaluate the stress intensity factors,
- (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 being properly transferred in the DATA arrays and the COMMON blocks.
- (5) MAIN calls subroutine PROBAB to calculate the individual cell probabilities.

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

Figure 3-1. Hierarchy of Routines in PRAISE-B

Figure 3-2. Computational Flow in PRAISE

ranges 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.
- (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) If SCC is modeled, evaluate the SCC growth in the interval between the present time and the time of the next event. If the present replication is to be terminated, MAIN returns to step (1); otherwise, the next event is then modeled.
- (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 (12).
- (10) If an evaluation earthquake 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 (12).
- (11) If an operating condition or anticipated transient is the next event, MAIN calls subroutine CRKGRO to increase the crack dimensions and check for leak or LOCA. If the present replication is to be terminated, MAIN returns to step (1); otherwise, go to step (12).

- (12) Subroutine FTIME is called to update the time and type of the next event. If the next event occurs before the plant lifetime is reached, go to step (8).
- (13) If the next event occurs after the plant lifetime has been reached and only fatigue growth is modeled, MAIN returns to step (1). If the next event occurs after the plant lifetime has been reached and SCC is modeled, call subroutine SCC to evaluate the growth in the interval from now to the plant lifetime.

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

When compared with the MAIN routine in PRAISE, the MAIN routine in PRAISE-B has the following major differences:

- (1) A call to the new SCC subroutine to evaluate stress corrosion cracking has been added to the MAIN routine.
- (2) The call to the KBARS subroutine has been moved into the CRKGRO subroutine.
- (3) The check for leak or LOCA has been placed in the new FAILS subroutine.
- (4) The call to FTIME to determine the time and type of next event is made after the current event has been evaluated, rather than before the current event is evaluated.

These changes reduce the number of calculations which are actually performed in the MAIN routine. In other words, the function of the MAIN routine shifts toward a control, rather than a computing capacity.

3.4 Fatigue Crack Growth Calculation

PRAISE-B has been reorganized so that if a non-seismic fatigue crack growth calculation is needed, the MAIN routine issues a call to the CRKGRO sub-routine. As shown in Figure 3-3, CRKGRO performs the following functions:

- (1) select the temperature variation corresponding to this transient,
- (2) calls KBARS to obtain the parameters needed to evaluate the cyclic RMS stress intensity factor,
- (3) evaluates the effective cyclic stress intensity factors using the relationships

$$(\Delta \bar{K}_a)_{\text{eff}} = \frac{\bar{K}_{a,\text{max}} - \bar{K}_{a,\text{min}}}{\sqrt{1 - \bar{K}_{a,\text{min}}/\bar{K}_{a,\text{max}}}} \quad (3-1)$$

and

$$(\Delta \bar{K}_b)_{\text{eff}} = \frac{\bar{K}_{b,\text{max}} - \bar{K}_{b,\text{min}}}{\sqrt{1 - \bar{K}_{b,\text{min}}/\bar{K}_{b,\text{max}}}} \quad (3-2)$$

- (4) If the effective stress intensity factors exceed the threshold, the effective stress intensity factor is multiplied by the multi-cycle blocking factor, BLKFTR.
- (5) If prior to the transient, the crack is only a part-through defect and $(\Delta \bar{K}_a)_{\text{eff}} \geq \bar{K}_0$, then the post-transient crack depth is estimated from

$$a_{\text{new}} = a_{\text{old}} + C(\Delta \bar{K}_a)_{\text{eff}}^m \quad (3-3)$$

Figure 3-3. Flowchart for Subroutine CRKGRO

If a_{new} exceeds the wall thickness, a is reset to h . If the transient is the heatup-cooldown event, subroutine KBARS is called to re-evaluate $\bar{K}_{b,\text{min}}$ and $\bar{K}_{b,\text{max}}$ before calculating growth in the b direction. For transients with non-uniform through-wall stresses, through-wall cracks do not grow in the b -direction because the stresses are self-equilibrating through the wall.

- (6) The new value of b is calculated from

$$b_{\text{new}} = b_{\text{old}} + C(\Delta \bar{K}_b)_{\text{eff}}^m \quad (3-4)$$

- (7) If vibratory stresses are present, the VIBES subroutine is called to evaluate the influence of those vibratory stresses.
- (8) The FAILS subroutine is called to determine whether the new crack size would cause a failure (leak or LOCA).

The PRAISE-B version of CRKGRO is designed to permit the user to easily modify either the definition of the effective stress intensity factors, $(\Delta \bar{K}_a)_{\text{eff}}$ and $(\Delta \bar{K}_b)_{\text{eff}}$, in Equations (3-1) and (3-2) and/or the crack growth relationships defined in Equations (3-3) and (3-4).

3.5 Leaks and LOCAs

In PRAISE-B, the calculation of crack growth is performed in the subroutines SCC (for stress corrosion cracking) and CRKGRO (for fatigue cracks). After each increment of crack growth, both SCC and CRKGRO call subroutine FAILS to determine whether a leak or LOCA has occurred. If a leak is predicted, FAILS also estimates the coolant flow rate through the leak. The PRAISE-B version of FAILS predicts a double-ended guillotine break (LOCA) when a critical net section stress is exceeded. As shown in Section 2.6 of Ref. 1, a LOCA occurs when the crack length exceeds a critical crack length, or

$$b > b_{crit} = \left[1 - \frac{\sigma_{LC}}{\sigma_{flo}} \right] \left[\pi h (2R_i + h) \right] \left[\frac{1}{a(2 + a/R_i)} \right] \quad (3-5)$$

where a = depth of the crack,
 b = one-half the crack length,
 σ_{LC} = load controlled stress,
 σ_{flo} = flow stress,
 h = pipe wall thickness, and
 R_i = inside pipe radius

If a LOCA is predicted, flags are updated and statistics accumulated before control is returned to the MAIN program.

If a through-wall defect is present, FAILS performs a leak rate calculation and categorizes the defect as a big leak if

$$RATE > ALKBIG \quad (3-6)$$

where RATE is the leak rate calculated as

$$RATE = 0.294 b^2 \sigma_{op} / h - 3.5 \quad (3-7)$$

σ_{op} = stress due to operating pressure

and ALKBIG is a user-supplied threshold level.

In PRAISE-B, 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, the leak is not detected.

3.6 Stress Intensity Factors

The stress intensity factors used to calculate crack propagation are evaluated in the subroutine KBARS. As shown in the flowchart in Figure 3-4, KBARS evaluates the following parameters for both the length and the depth direction:

- (1) $\bar{K}_{op,i}$ the "RMS-averaged" stress intensity factor in the i-th direction under normal operating conditions,
- (2) $\bar{K}_{min,i}$ the minimum "RMS-averaged" stress intensity factor in the i-th direction during a fatigue cycle,
- (3) $\bar{K}_{max,i}$ the maximum "RMS-averaged" stress intensity factor in the i-th direction during a fatigue cycle, and
- (4) $R_i = (\bar{K}_{min,i}/\bar{K}_{max,i})$, the load ratio.

The subscript i is an index to denote either a or b.

If welding residual stresses are modeled, their contributions to the stress intensity factors are included in $\bar{K}_{op}$, or

$$\bar{K}_{op,i} = \sigma_H \sqrt{a} f_i(a/h, a/b) + \bar{K}_{RES,i} \quad (3-8)$$

where f_i is a geometric correction factor to account for the finite wall thickness, σ_H is the hot uniform through the wall stresses, and $\bar{K}_{RES,i}$ is the residual stress contribution. The minimum and maximum stress intensity factor values during a transient are given by

$$\bar{K}_{min,i} = \bar{K}_{op,i} + \delta\bar{K}_{min,i} \quad (3-9)$$

$$\bar{K}_{max,i} = \bar{K}_{op,i} + \delta\bar{K}_{max,i} \quad (3-10)$$

where $\delta\bar{K}_{min,i}$ and $\delta\bar{K}_{max,i}$ are the minimum and maximum change from the nor-

Figure 3-4. Flowchart of the KBARS Subroutine

mal operating level in the i -th direction. The evaluation of $\bar{K}_{\min,i}$ and $\bar{K}_{\max,i}$ is discussed in Sections 5.6 and 5.8 of Reference (1). Since negative values of the stress intensity factor do not result in crack propagation, PRAISE-B sets $\bar{K}_{\min,i}$, $\bar{K}_{\max,i}$, and R_i to zero if $\bar{K}_{\max,i} < 0$.

After these values have been calculated, they are transferred to the CRKGRO subroutine where the effective cyclic stress intensity is calculated. This particular approach increases the flexibility of the code because it provides the user with the parameters needed to define his own effective stress intensity factor.

3.7 Welding Residual Stresses

The contribution of welding residual stresses to the "RMS-averaged" stress intensity factor was discussed in Section 2.5.3. The numerical evaluation of this contribution is performed in the function subprograms SIFRSA and SIFRSB for the depth and length directions, respectively. In both function subprograms, two dimensional polynomial expressions of the form

$$\bar{K}_{\text{RES},i} = \sum_{k=1}^K \left\{ \sum_{l=1}^L b_{lk} (a/h)^{l-1} \right\} (a/b)^{k-1} \quad (3-11)$$

are used. The user inputs the limits K and L as well as the coefficients b_{lk} . Various polynomials which fit the residual stress patterns of interest are provided in Figures 2-9, 2-11 and 2-13.

3.8 Stress Corrosion Cracking Model

The PRAISE-B model for crack propagation due to stress corrosion cracking is coded in the subroutine SCC. The basic assumption in this model is that SCC growth can be described by relationships of the form

$$\frac{da}{dt} = F(\bar{K}_{\text{op},a}) \quad (3-12)$$

$$\text{and} \quad \frac{db}{dt} = F(\bar{K}_{op,b}) \quad (3-13)$$

where $\bar{K}_{op,a}$ and $\bar{K}_{op,b}$ are the stress intensity factors in the a and b directions under normal operating conditions and F is an arbitrary function which defines the relationship between $\bar{K}_{op,a}$ and $\bar{K}_{op,b}$ and the crack growth velocity. The function F shown in Equation 2-1 is presently coded in SCC.

The subroutine SCC employs a first-order approximation to estimate the growth that results from Equations (3-12) and (3-13), or

$$a(t + \Delta t) = a(t) + \left(\frac{da}{dt}\right)_t \Delta t \quad (3-14)$$

$$\text{and} \quad b(t + \Delta t) = b(t) + \left(\frac{db}{dt}\right)_t \Delta t \quad (3-15)$$

The magnitude of the timestep Δt is specified by the user.

A flowchart of the SCC subroutine is shown in Figure 3-5. The arguments to SCC are:

- (1) TSTART, the initial time of the interval over which the SCC growth is to be computed,
- (2) TEND, the final time of the interval over which the SCC growth is to be computed,
- (3) MM, the stratum from which the initial crack size was chosen, and
- (4) PRB, the probability of obtaining an initial crack from the MM-th stratum

The calculation marches from time TSTART to time TEND in steps of magnitude Δt . Since the interval TEND - TSTART is generally not an integral multiple of the interval TEND - TSTART, the final time step in the interval will generally be less than length Δt . PRAISE-B assumes that Δt , TSTART, and TEND have units of years. The stress intensity factor from normal operating stresses, including welding residual stresses, is calculated by SCC at each time step.

Figure 3-5 Flowchart of SCC Subroutine

After each increment of crack growth, the subroutine VIBES is called to model the effects of any existing vibratory stresses. Finally the FAILS subroutine is called to determine whether the new crack size would cause a leak or a LOCA.

3.9 Vibratory Stress Model

In PRAISE-B, the influence of low amplitude high cycle fatigue crack growth is calculated in the subroutine VIBES. Since it is computationally impractical to perform a cycle-by-cycle analysis for these vibratory stresses, PRAISE-B assumes that once the effective cyclic stress intensity factor due to vibratory stresses exceeds the threshold value, growth to a through wall defect occurs instantaneously. As shown in Section 2.4.3, this assumption slightly overestimates the number of failures in a given length of time, i.e., the result is conservative. A flowchart of the VIBES subroutine is shown in Figure 3-6. After each increment of crack growth, the subroutine VIBES is called from the subroutine CRKGRO in the fatigue growth case or from subroutine SCC in the stress corrosion case. Upon entering VIBES, $\bar{K}_{op,a}$, the RMS-averaged stress intensity factor in the depth direction under the normal operating stress is evaluated. The contribution of the vibratory stresses is then added to $\bar{K}_{op,a}$ to obtain the minimum and maximum values of $\bar{K}_a$ during a cycle of vibratory stress, or

$$\bar{K}_{min,a} = \bar{K}_{op,a} - \frac{1}{2} \Delta\sigma_v \sqrt{a} f_a(a/h, a/b) \quad (3-16)$$

$$\bar{K}_{max,a} = \bar{K}_{op,a} + \frac{1}{2} \Delta\sigma_v \sqrt{a} f_a(a/h, a/b) \quad (3-17)$$

where $\Delta\sigma_v$ is the peak-to-peak amplitude of the vibratory stresses, and $f_a(a/h, a/b)$ is the normalized RMS-averaged stress intensity factor in the depth direction for uniform through the wall stress.

If $\bar{K}_{max,a}$ is less than or equal to zero, control is returned to the calling subroutine. If $\bar{K}_{max,a}$ is greater than zero, VIBES proceeds to calculate the load ratio $R = \bar{K}_{min,a} / \bar{K}_{max,a}$. The effective cyclic stress intensity factor due to vibratory stresses is assumed to depend on the load ratio R according to the relationship

Figure 3-6 Flowchart for VIBES Subroutine

$$\bar{K}_{\text{eff},a} = \begin{cases} \frac{\Delta \bar{K}a}{\sqrt{1-R}} & \text{if } R < R^* \\ \frac{\Delta \bar{K}a}{\sqrt{1-R^*}} & \text{if } R > R^* \end{cases} \quad (3-18)$$

$$\begin{aligned} \text{where } \bar{K}_a &= \bar{K}_{\text{max},a} - \bar{K}_{\text{min},a} \\ &= \Delta \sigma_v \sqrt{a} f_a(a/h, a/b) \end{aligned} \quad (3-20)$$

and R^* is a user-defined plateau value for the load ratio.

Growth to a through-wall defect is assumed to occur when the effective stress intensity factor exceeds a threshold value, or

$$\bar{K}_{\text{eff},a} \geq \bar{K}_{\text{th}} \quad (3-21)$$

By combining Equations 3-18, 3-19, 3-20, and 3-21, the condition for vibratory stresses to cause a through-wall defect is

$$\begin{aligned} \Delta \sigma_v \sqrt{a} f_a(a/h, a/b) &\geq \bar{K}_{\text{th}} \sqrt{1-R^*} & \text{if } R > R^* \\ &\geq \bar{K}_{\text{th}} \sqrt{1-R} & \text{if } R < R^* \end{aligned} \quad (3-22)$$

The magnitude of crack growth in the depth direction $\Delta a = h - a$ is also assumed to occur in the length direction, or

$$b_{\text{new}} + b_{\text{old}} + \Delta a \quad (3-23)$$

The subroutine FAILS is then called from either CRKGRO or SCC to evaluate the failure mode using the latest values of a and b , or h and $b_{\text{old}} + \Delta a$, respectively.

4.0 SAMPLE PROBLEMS

The eight sample problems included in the PRAISE-B package are discussed in this section. These sample problems and the related discussion are intended for the reader interested in using the PRAISE-B code. Results for additional problems intended for the reader interested in the influence of various factors on piping reliability without details of the coding are presented in Section 5, which also includes discussion of some of the ramifications of the results.

Input decks and results for the eight sample problems are discussed in this section. The inputs for the first four problems are identical to the four sample problems described in the original PRAISE manual (ref. 2). These four problems are repeated because the calculational algorithm in PRAISE-B is slightly different. The last four problems are designed to demonstrate the new features incorporated in the PRAISE-B code. The following are the brief descriptions for eight sample problems.

- Sample problem 1 (verification problem): The most basic problem, only random parameter considered is initial crack size distribution.
- Sample problems 2, 3, and 4: failure probability due to fatigue crack growth for weld joints in the primary coolant system.
- Sample problem 5: failure probability for weld joints under fatigue with residual and vibratory stresses included.
- Sample problem 6: failure probability due to fatigue crack growth for longitudinal weld joints in the primary coolant system.
- Sample problem 7: LOCA probability due to SCC.
- Sample problem 8: leak probability due to SCC.

Since all sample problems presented here are for demonstrating the capabilities of PRAISE-B computer code, some input data are hypothetical. Readers are advised not to interpret the results as final failure probabilities for any specific piping systems in either PWR or BWR plants. A summary of the various input options used in these sample problems is given in Table 4-1.

TABLE 4-1. COMPARISON OF SAMPLE PROBLEM INPUTS

	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4	SAMPLE 5	SAMPLE 6	SAMPLE 7	SAMPLE 8
FATIGUE	YES	YES	YES	YES	YES	YES	NO	YES
STRESS CORROSION	NO	NO	NO	NO	NO	NO	YES	YES
RESIDUAL STRESSES	NO	NO	NO	NO	YES	NO	NO	NO
VIBRATORY STRESSES	NO	NO	NO	NO	YES	NO	YES	YES
PLANT LIFETIME (YRS)	10	40	40	40	40	40	40	40
WALL THICKNESS (IN)	1.0	2.5	2.5	2.5	2.5	3.31	1.04	1.04
PIPE INSIDE RADIUS	5.0	14.5	14.5	14.5	14.5	15.5	10.80	10.80
CRACK GROWTH CONSTANT C	CONSTANT	CONSTANT	LOG NORMAL	LOG-NORMAL	LOG-NORMAL	LOG-NORMAL	LOG-NORMAL	LOG-NORMAL
FLOW STRESS	CONSTANT	CONSTANT	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL
CRACK DEPTH DISTRIBUTION	EXPONENTIAL	LOG NORMAL	LOG NORMAL	EXPONENTIAL	EXPONENTIAL	EXPONENTIAL	EXPONENTIAL	EXPONENTIAL
CRACK ASPECT RATIO DISTRIBUTION	EXPONENTIAL	LOG NORMAL	EXPONENTIAL	LOG-NORMAL	LOG-NORMAL	LOG-NORMAL	LOG-NORMAL	LOG-NORMAL
HYDROSTATIC PROOF TEST	NONE	NONE	NONE	YES (3.1)	YES (3.125)	YES (3.125)	YES (1.563)	YES (1.563)
PRE-SERVICE INSPECTION	NONE	NONE	YES	YES	YES	YES	YES	YES
EVALUATION TIME	UNIFORM	UNIFORM	VARIABLE	UNIFORM	UNIFORM	UNIFORM	YES	YES
IN-SERVICE INSPECTION	NONE	NONE	NONE	YES	NONE	NONE	NONE	NONE
LEAK DETECTION (GPM)	10 ⁵	2.0	10 ⁵	2.0	2.0	2.0	2.0	2.0
BIG LEAK (GPM)	2.0	5.0	2.0	2.0	2.0	2.0	2.0	2.0
STRATIFICATION	UNIFORM (ENTIRE)	VARIABLE	VARIABLE	VARIABLE	UNIFORM (PARTIAL)	UNIFORM (PARTIAL)	UNIFORM (PARTIAL)	UNIFORM (PARTIAL)
NUMBER OF SAMPLES	50	50-100	50-100	50-250	200	50	25	
TRANSIENTS (TYPE/FREQUENCY)	HEATUP-COOLDOWN	HEATUP-COOLDOWN	HEATUP-COOLDOWN	HEATUP-COOLDOWN	HEATUP-COOLDOWN	HEATUP-COOLDOWN	N/A	HEATUP-COOLDOWN
BLOCKING FACTOR IS SHOWN IN PARENTHESIS-	REGULAR (1)	STOCHASTIC (1)	STOCHASTIC (1)	REGULAR (1)	REGULAR (1)	REGULAR (1)		REGULAR (1)
			PLANT LOADING STOCHASTIC(100)	PLANT LOADING REGULAR (100)				
COLD SHUTDOWN STRESS (KSI)	2	2.0	2.0	2.0	2.0	.58		
DEADWGT.& THERMAL EXP.(KSI)	10	8.8	8.8	8.8	8.75	4.47	.51	.51
OPERATING PRESSURE (KSI)	2	2.25	2.25	2.25	2.25	2.25	3.90	3.90
VIBRATORY STRESSES (KSI)	N/A	N/A	N/A	N/A	1.0	N/A	1.05	1.05
R-STAR	N/A	N/A	N/A	N/A	0.9	N/A	1.0	1.0
							0.9	0.9
EARTHQUAKES	NONE	4 CATEGORIES 1 PER CATEGORY	4 CATEGORIES VARIABLE IN EACH CATEGORY	4 CATEGORIES 1 PER CATEGORY	NONE	NONE	NONE	NONE
EXECUTION TIME CPU SECONDS	4	15	40	190	50	76	24	41

4.1 Sample Problem 1: Verification

This problem illustrates the most basic analysis that can be performed with the PRAISE-B 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
$$da/dn = 1.0 \times 10^{-10} (\Delta \bar{K})^4_{eff} \text{ in/cycle}$$
$$\bar{K}_0 = 4.7 \text{ KSI-in}$$
$$(\text{KONPRP} = 1, \text{CONSMU} = 1.0\text{E-}10, \text{EMEXP} = 4.0, \text{THRHL D} = 4.7)$$
- Constant flow stress (KNSFLO = 1, SIGFLO = 40)
- Exponential distributions for both the crack depth and aspect ratio in the initial crack size distribution
$$(\text{KRKDIS} = 4, \text{ALAMDA} = 4.07, \text{BOALDA} = 1.15).$$
- 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

(KTYPES = 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 4-1 and 4-2, respectively. The summary of the stratification scheme is given in Figure 4-3 and graphically illustrated in Figure 4-4. Since the entire sample is used, the total probability sums to unity. The estimated failure probabilities are shown in Figure 4-5.

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 4-1. 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+C2

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
  ENDPOINTS 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 4-2. 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.

Figure 4-2. (continued)

---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	.8000	.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 4-3. Stratification Description for Sample Problem 1

Figure 4-4. 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,NC EQS,NO LEAK - - -

- - RESULTS WITHOUT EARTHQUAKES - - -

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	5.45532E-04	5.45532E-04	0.	2.43356E-04	2.43356E-04	0.
2.0	1.40031E-03	1.40031E-03	0.	3.71754E-04	3.71754E-04	0.
4.0	2.00224E-03	2.00224E-03	0.	4.46539E-04	4.46539E-04	0.
6.0	2.38626E-03	2.38626E-03	0.	4.90521E-04	4.90521E-04	0.
8.0	2.58881E-03	2.58881E-03	0.	5.07677E-04	5.07677E-04	0.
10.0	2.66663E-03	2.66663E-03	0.	5.12111E-04	5.12111E-04	0.

Figure 45. Results for Sample Problem 1

4.2 Sample Problem 2: Fatigue with Deterministic Material Properties

Sample problem 2 presents additional PRAISE-B capabilities for analyzing weld joints in the primary coolant system of a PWR. 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

$$da/dn = 9 \times 10^{-12} (\Delta \bar{K})_{\text{eff}}^4 \text{ in/cycle}$$

$$\bar{K}_0 = 4.7 \text{ KSI} \cdot \sqrt{\text{in}}$$

$$(\text{KONPRP} = 1, \text{CONSMU} = 9.0\text{E-}12, \text{EMEXP} = 4.0, \text{THRHL D} = 4.7).$$

- 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 (FNKLEK = 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 (OPPRES = 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/cooldown 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 card images for the input are shown in Figure 4-6. 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 4-7. The stratification scheme and the number of samples to be taken from each cell are shown in Figure 4-8. 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 4-9. The failure probabilities and sampling standard deviation for the four earthquake categories are shown in Figures 4-10a through 4-10d.

```

SAMPLE-2 HU-CD DETERM,C=9.E-12,SIGFLO=45,NO PROOF,4 EG,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 8.6 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 09E 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 4-6. 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 DISTRIBUTION

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 PROOF 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 DATA
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
ENDPOINTS 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 47. 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.

Figure 4-7. (continued)

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

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

CELL	AOH1	AOH2	AOB1	AOB2	PROBABILITY	SAMPLES
1	.9800	1.0000	.0538	.0700	.8127579E-12	100
2	.9800	1.0000	.0700	.1000	.1456141E-10	100
3	.9800	1.0000	.1000	.2000	.1181219E-08	100
4	.9800	1.0000	.2000	.4000	.1943018E-07	100
5	.9800	1.0000	.4000	.7000	.5548848E-07	100
6	.9800	1.0000	.7000	1.0000	.4298987E-07	100
7	.9200	.9800	.0505	.0700	.3399378E-11	50
8	.9200	.9800	.0700	.1000	.5819774E-10	50
9	.9200	.9800	.1000	.2000	.4720991E-08	50
10	.9200	.9800	.2000	.4000	.7765684E-07	50
11	.9200	.9800	.4000	.7000	.2217715E-06	50
12	.9200	.9800	.7000	1.0000	.1718181E-06	50
13	.8500	.9200	.0466	.0700	.6584429E-11	50
14	.8500	.9200	.0700	.1000	.1095594E-09	50
15	.8500	.9200	.1000	.2000	.8887443E-08	50
16	.8000	.8500	.0439	.0700	.7506911E-11	50
17	.8000	.8500	.0700	.1000	.1235582E-09	50
18	.8000	.8500	.1000	.2000	.1002302E-07	50
19	.7500	.8000	.0412	.0800	.3474441E-10	50
20	.7500	.8000	.0800	.2000	.1520791E-07	50
21	.7000	.7500	.0384	.0800	.5330987E-10	50
22	.7000	.7500	.0800	.2000	.2330822E-07	50
23	.6500	.7000	.0357	.0600	.6996593E-11	50
24	.6000	.6500	.0329	.0600	.1130581E-10	50
25	.6000	.7000	.0600	.1000	.1217439E-08	50

SUM OF CELL PROBABILITIES = .6541317365E-06

Figure 4-8. Stratification System 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 - - -

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	1.59477E-08	1.59477E-08	1.75975E-12	2.33744E-09	2.33744E-09	2.88088E-13
10.0	8.25149E-08	8.25149E-08	2.12407E-12	3.42324E-09	3.42324E-09	3.01561E-13
20.0	1.13538E-07	1.13538E-07	2.53200E-12	3.88905E-09	3.88905E-09	3.07140E-13
30.0	1.46816E-07	1.46816E-07	2.79966E-12	8.79111E-09	8.79111E-09	3.31488E-13
40.0	1.57001E-07	1.57001E-07	3.06304E-12	1.03735E-08	1.03735E-08	3.73648E-13

Figure 4-9. 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,E/A LGNRM,NO PSI - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

88

SEISMIC CLASS INFORMATION

	CLASS	S4-EG	SGLCEG	CYCLES	1 OBE TH 1 JOINT 1 LLNL DATA		
	1	.5216E+03	8.757	1			
TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA	
0.	1.67568E-08	1.67568E-08	1.78413E-12	2.39838E-09	2.39838E-09	2.87960E-13	
10.0	8.25150E-08	8.25150E-08	2.19206E-12	3.42324E-09	3.42324E-09	3.03277E-13	
20.0	1.13539E-07	1.13539E-07	2.66369E-12	3.88905E-09	3.88905E-09	3.32056E-13	
30.0	1.46816E-07	1.46816E-07	2.79966E-12	8.79111E-09	8.79111E-09	3.31488E-13	
40.0	1.57001E-07	1.57001E-07	3.06304E-12	1.03735E-08	1.03735E-08	3.73648E-13	

Figure 4-10a. 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 - -

SEISMIC CLASS INFORMATION

CLASS S4-EQ SGLCEG 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
G.	1.77783E-08	1.77783E-08	1.88463E-12	2.47474E-09	2.47474E-09	2.91178E-13
10.0	8.25151E-08	8.25151E-08	2.26005E-12	3.42324E-09	3.42324E-09	3.04673E-13
20.0	1.13539E-07	1.13539E-07	2.73167E-12	3.88905E-09	3.88905E-09	3.31914E-13
30.0	1.46818E-07	1.46818E-07	2.79966E-12	8.79111E-09	8.79111E-09	3.31488E-13
40.0	1.57001E-07	1.57001E-07	3.06304E-12	1.03735E-08	1.03735E-08	3.73648E-13

Figure 4-10b. Results for Earthquake Category 2 in Sample Problem 2

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

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

CLASS S4-EQ SGLCEG 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.	2.32381E-08	2.32381E-08	2.71552E-12	2.79598E-09	2.79598E-09	3.62621E-13
10.0	8.47059E-08	8.47059E-08	2.94980E-12	3.38730E-09	3.38730E-09	3.63903E-13
20.0	1.17975E-07	1.17975E-07	3.14947E-12	5.89896E-09	5.89896E-09	3.83630E-13
30.0	1.46820E-07	1.46820E-07	4.03975E-12	8.79111E-09	8.79111E-09	8.11682E-13
40.0	1.57001E-07	1.57001E-07	3.06304E-12	1.03735E-08	1.03735E-08	3.73648E-13

Figure 4-10c. 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 - - -

68

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

	CLASS	S4-EQ	SGLCEG	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.	3.16680E-08	3.16680E-08	2.85149E-12	3.16444E-09	3.16444E-09	3.63660E-13	
10.0	8.71596E-08	8.71596E-08	2.94980E-12	3.33013E-09	3.33013E-09	3.63903E-13	
20.0	1.18625E-07	1.18625E-07	3.97605E-12	5.88203E-09	5.88203E-09	8.02840E-13	
30.0	1.50258E-07	1.50258E-07	4.03975E-12	9.38766E-09	9.38766E-09	8.11682E-13	
40.0	1.57001E-07	1.57001E-07	3.06304E-12	1.03735E-08	1.03735E-08	3.73648E-13	

Figure 4-10d. Results for Earthquake Category 4 in Sample Problem 2

4.3 Sample Problem 3: Fatigue with Random Material Properties

Sample problem 3 is another example of an analysis for weld joints in the primary coolant system of a PWR. 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

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

$$\bar{K}_0 = 4.6 \text{ KSI} \cdot \sqrt{\text{in}}$$

(KONPRP = 0, CONSMU = $9.0\text{E-}12$, CONS90 = $3.5\text{E-}11$, EXEMP = 4.0, THRHLD = 4.6).

- The flow stress normally distributed with mean = 45 KSI and standard deviation = 1.4 KSI. (SFLOMU = 45, SFLSO = 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 455 events per year (or 1/.0022 per year). A blocking factor of 100 is assumed.
- (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 card images and input summary are given in Figures 4-11 and 4-12, respectively.

The stratification description is shown in Figure 4-13 and illustrated in Figure 4-14. The results for the no earthquake case are tabulated in Figure 4-15. Results for each of the four earthquake classes are given in Figures 4-16a through 4-16d.

Figure 4-11. Card Images for Input to Sample Problem 3

--- SAMPLE-3 HU-CO,PLANT LOADING,C=LGARM,SIGFLO=NRM,PROOF TEST,A LOGNRM,2/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 4-12. 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 4-12 (continued)

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

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

CELL	AOM1	AOM2	AOP1	AOP2	PROBABILITY	SAMPLES
1	.9800	1.0000	.0538	.0700	.2738137E-13	100
2	.9800	1.0000	.0700	.1000	.3782932E-11	100
3	.9800	1.0000	.1000	.2000	.1193416E-06	100
4	.9800	1.0000	.2000	.4000	.2002411E-07	100
5	.9800	1.0000	.4000	.7000	.5153748E-07	100
6	.9800	1.0000	.7000	1.0000	.4634640E-07	100
7	.9200	.9800	.0505	.0700	.1100205E-12	50
8	.9200	.9800	.0700	.1000	.1511929E-10	50
9	.9200	.9800	.1000	.2000	.4769738E-08	50
10	.9200	.9800	.2000	.4000	.8003061E-07	50
11	.9200	.9800	.4000	.7000	.2059804E-06	50
12	.9200	.9800	.7000	1.0000	.1852332E-06	50
13	.8500	.9200	.0466	.0700	.2074252E-12	50
14	.8500	.9200	.0700	.1000	.2846263E-10	50
15	.8500	.9200	.1000	.2000	.8579211E-08	50
16	.8000	.8500	.0439	.0700	.2339779E-12	50
17	.8000	.8500	.0700	.1000	.3209939E-10	50
18	.8000	.8500	.1000	.2000	.1012651E-07	50
19	.7500	.8000	.0412	.0800	.2738242E-11	50
20	.7500	.8000	.0800	.2000	.1524699E-07	50
21	.7000	.7500	.0384	.0800	.4196737E-11	50
22	.7000	.7500	.0800	.2000	.2336812E-07	50
23	.6500	.7000	.0357	.0600	.5463469E-13	50
24	.6000	.6500	.0329	.0600	.8799243E-13	50
25	.6000	.7000	.0600	.1000	.3045020E-09	50

SUM OF CELL PROBABILITIES = .6532278301E-06

Figure 4-13. Stratification Description for Sample Problem 3

Figure 4-14. 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.	8.22670E-10	8.22670E-10	1.62972E-15	1.33021E-10	1.33021E-10	3.57784E-16
1.0	2.39092E-09	2.39092E-09	2.15920E-15	2.01366E-10	2.01366E-10	4.23877E-16
2.0	3.06243E-09	3.06243E-09	2.47655E-15	2.13210E-10	2.13210E-10	4.55439E-16
5.0	4.82736E-09	4.82736E-09	2.85067E-15	3.71620E-10	3.71620E-10	4.82263E-16
10.0	6.61578E-09	6.61578E-09	2.90089E-15	5.61564E-10	5.61564E-10	4.82188E-16
20.0	9.56826E-09	9.56826E-09	4.25455E-15	8.08751E-10	8.08751E-10	6.82559E-16
40.0	1.28436E-08	1.28436E-08	3.11075E-14	1.06196E-09	1.06196E-09	2.13834E-14

Figure 4-15. 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-EG	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

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	1.01354E-09	1.01354E-09	1.82982E-15	1.47388E-10	1.47388E-10	3.66621E-16
1.0	2.39092E-09	2.39092E-09	2.19270E-15	2.01366E-10	2.01366E-10	4.23560E-16
2.0	3.07519E-09	3.07519E-09	2.58273E-15	2.13235E-10	2.13235E-10	4.55473E-16
5.0	4.82736E-09	4.82736E-09	2.94749E-15	3.71620E-10	3.71620E-10	4.81400E-16
10.0	6.61578E-09	6.61578E-09	3.15472E-15	5.61564E-10	5.61564E-10	4.79601E-16
20.0	9.56826E-09	9.56826E-09	4.66317E-15	8.08751E-10	8.08751E-10	6.99983E-16
40.0	1.28436E-08	1.28436E-08	3.11075E-14	1.06196E-09	1.06196E-09	2.13834E-14

Figure 4-16a. 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.	1.16907E-09	1.16907E-09	2.18028E-15	1.56715E-10	1.56715E-10	4.07065E-16
1.0	2.39169E-09	2.39169E-09	2.50288E-15	2.01365E-10	2.01365E-10	4.38401E-16
2.0	3.12938E-09	3.12938E-09	3.25494E-15	2.13476E-10	2.13476E-10	5.00016E-16
5.0	4.83368E-09	4.83368E-09	3.60340E-15	3.71659E-10	3.71659E-10	5.15558E-16
10.0	6.61578E-09	6.61578E-09	3.70473E-15	5.61564E-10	5.61564E-10	5.15051E-16
20.0	9.56826E-09	9.56826E-09	5.31057E-15	8.08751E-10	8.08751E-10	7.82761E-16
40.0	1.28436E-08	1.28436E-08	3.11075E-14	1.06196E-09	1.06196E-09	2.13834E-14

Figure 4-16b. Results for Earthquake Category 2 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 - -

101

SEISMIC CLASS INFORMATION

CLASS	S4-EG	SGLCEG	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.	1.76961E-09	1.76961E-09	5.18158E-15	1.84537E-10	1.84537E-10	7.87577E-16
1.0	2.69018E-09	2.69018E-09	5.92769E-15	2.07936E-10	2.07936E-10	7.92485E-16
2.0	3.32614E-09	3.32614E-09	6.28985E-15	2.15526E-10	2.15526E-10	7.93908E-16
5.0	4.94798E-09	4.94798E-09	6.64149E-15	3.70897E-10	3.70897E-10	7.91619E-16
10.0	7.14557E-09	7.14557E-09	8.24310E-15	6.53322E-10	6.53322E-10	9.53940E-16
20.0	9.61033E-09	9.61033E-09	1.16332E-14	8.08316E-10	8.08316E-10	2.55778E-15
40.0	1.28436E-08	1.28436E-08	3.11075E-14	1.06196E-09	1.06196E-09	2.13834E-14

Figure 4-16c. Results for Earthquake Category 3 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 - -

102

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.	2.39665E-09	2.39665E-09	5.53853E-15	2.03062E-10	2.03062E-10	7.85097E-16
1.0	3.01841E-09	3.01841E-09	6.03906E-15	2.12608E-10	2.12608E-10	7.88466E-16
2.0	3.72004E-09	3.72004E-09	6.29847E-15	2.39888E-10	2.39888E-10	7.93775E-16
5.0	5.07722E-09	5.07722E-09	6.70680E-15	3.70045E-10	3.70045E-10	7.86740E-16
10.0	7.24567E-09	7.24567E-09	8.57994E-15	6.52407E-10	6.52407E-10	9.39134E-16
20.0	9.63082E-09	9.63082E-09	1.17092E-14	8.08244E-10	8.08244E-10	2.55515E-15
40.0	1.28436E-08	1.28436E-08	3.11075E-14	1.06196E-09	1.06196E-09	2.13834E-14

Figure 4-16d. Results for Earthquake Category 4 in Sample Problem 3

4.4 Sample Problem 4: Fatigue with In-Service Inspection

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. 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

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

$$\bar{K}_0 = 4.6 \text{ KSI} \cdot \sqrt{\text{in}}$$

(KONPRP = 0, CONSMU = $9.0\text{E-}12$, CONS90 = $3.5\text{E-}11$, 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. (KRKDIS = 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).
- As 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 480⁰F. Plant loadings at greater than 5% per minute are assumed to occur at regular intervals of 0.002 years. A blocking factor of 100 is assumed.
- 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)

The card images are shown in Figure 4-17. These input are summarized in Figure 4-18. The stratification scheme is tabulated in Figure 4-19. Results for the no earthquake case are presented in Figure 4-20. Results for each of the four earthquake cases are given in Figures 4-21a through 4-21d, respectively.

```

SAMPLE-4 HL-PV,SIGFLO NRM,C LGNRM,B/A LGNRM,A EXP,PSI,ISI-20,PROOF,LEAK DETECT
50 0 2 3 -2 1 1 0 0 4 48 0 5 1
40.0
2.5 14.5
4.6 4.0 9.14-12 3.50-11
44.9 1.373
4.665
1.336 0.538 1.419
20.01
2.0 2.0
.96 1.0 .052 .06 5
.96 1.0 .06 .07 4
.96 1.0 .07 .1 4
.96 1.0 .1 .2 3
.96 1.0 .2 .4 3
.96 1.0 .4 .7 1
.96 1.0 .7 1.0 1
.96 .96 .052 .06 5
.96 .96 .06 .07 4
.96 .96 .07 .1 4
.96 .96 .1 .2 3
.96 .96 .2 .4 3
.96 .96 .4 .7 1
.96 .96 .7 1.0 1
.96 .96 .05 .06 5
.96 .96 .06 .07 4
.96 .96 .05 .06 5
.96 .96 .06 .07 4
0.92 0.96 0.070 0.100 3
0.92 0.96 0.10 0.200 3
0.92 0.96 0.20 0.400 3
0.92 0.96 0.40 0.70 1
0.92 0.96 0.70 1.00 1
0.90 0.92 0.046 0.060 5
0.88 0.90 0.046 0.060 5
0.85 0.88 0.046 0.060 5
0.85 0.92 0.060 0.075 5
0.85 0.92 0.075 0.100 5
0.85 0.92 0.100 0.200 3
0.85 0.92 0.200 0.400 3
0.85 0.85 0.043 0.050 5
0.85 0.85 0.050 0.075 5
0.85 0.85 0.075 0.100 3
0.85 0.85 0.100 0.200 3
0.75 0.80 0.041 0.050 5
0.75 0.80 0.050 0.075 5
0.75 0.80 0.075 0.100 3
0.75 0.80 0.100 0.200 3
0.75 0.75 0.038 0.045 5
0.75 0.75 0.045 0.060 5
0.75 0.75 0.060 0.10 4
0.75 0.75 0.10 0.20 3
0.65 0.70 0.032 0.040 5
0.65 0.70 0.040 0.060 5
0.65 0.70 0.060 0.10 4
0.60 0.65 0.032 0.040 5
0.60 0.65 0.040 0.060 5
0.60 0.65 0.060 0.100 4
2.0 8.75 2.25 3.137
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 -.2 478.5 HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
100-102 39.5 PLANT LOADING .GT. 5 PERCENT PER MINUTE
-.16460 -.11884 -.08442 -.06174 -.04481 -.03040 -.01809 -.00624 -.00002
-.20431 -.15301 -.11518 -.08577 -.07266 -.05772 -.04072 -.02260 -.00619
-.21584 -.16405 -.12631 -.10161 -.08451 -.07031 -.05250 -.03211 -.01303
-.21920 -.16856 -.13107 -.10784 -.09261 -.07749 -.05972 -.03852 -.01774
-.22250 -.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. 0.00539
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
-.17864 -.14238 -.12205 -.11220 -.10549 -.09890 -.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.
0. 0. 0. 0. 0. 0. 0. 0. 0.
1 1 1
1 521.6 8.757 1 ONE TH 1 JOINT 1 LLNL DATA
2 2458.3 9.059 1 SSC TH 1 JOINT 1 LLNL DATA
2 63430.0 10.557 3 SSC TH 2 JOINT 1 LLNL DATA
4 162000.0 10.617 5 SSC TH 4 JOINT 1 LLNL DATA

```

Figure 4-17. Card Images for Input to Sample Problem 4

```

--- 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-EG      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 4-18. 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.

Figure 4-18. (continued)

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

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

CELL	AOM1	AOM2	AOM3	AGE2	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	.9600	.0520	.0600	.1514874E-10	250
9	.9600	.9600	.0600	.0700	.5954219E-10	200
10	.9600	.9600	.0700	.1000	.1303293E-08	200
11	.9600	.9600	.1000	.2000	.1057229E-06	150
12	.9600	.9600	.2000	.4000	.1739064E-05	150
13	.9600	.9600	.4000	.7000	.4966399E-05	50
14	.9600	.9600	.7000	1.0000	.3647733E-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	.2852991E-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	.3422288E-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	.5665040E-10	250
36	.7500	.8000	.0500	.0750	.2563313E-08	250
37	.7500	.8000	.0750	.1000	.2262910E-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 4-19. Stratification Description for Sample Problem 4

- - - SAMPLE-4 HL-FV,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.	6.07665E-08	6.07665E-08	0.	1.32331E-08	1.32331E-08	0.
2.0	2.32968E-07	2.32968E-07	3.54033E-14	2.24299E-08	2.24299E-08	3.54033E-14
4.0	3.11192E-07	3.11192E-07	6.22138E-14	2.43126E-08	2.43126E-08	4.02843E-14
6.0	3.62723E-07	3.62723E-07	4.29589E-13	2.68755E-08	2.68755E-08	3.54685E-13
8.0	4.15910E-07	4.15910E-07	5.55534E-13	2.69855E-08	2.69855E-08	3.59320E-13
10.0	4.45893E-07	4.45893E-07	1.06275E-12	2.74820E-08	2.74820E-08	5.08932E-13
12.0	4.93503E-07	4.93503E-07	1.14575E-12	2.84938E-08	2.84938E-08	5.10897E-13
14.0	5.14629E-07	5.14629E-07	1.19697E-12	2.81286E-08	2.81286E-08	5.12297E-13
16.0	5.82062E-07	5.82062E-07	1.31126E-12	3.67597E-08	3.67597E-08	5.15289E-13
18.0	6.08917E-07	6.08917E-07	1.81476E-12	3.70382E-08	3.70382E-08	6.31707E-13
20.0	6.29459E-07	6.29459E-07	1.93393E-12	3.65542E-08	3.65542E-08	6.34686E-13
22.0	6.30923E-07	6.30923E-07	1.94582E-12	3.64859E-08	3.64859E-08	6.34687E-13
24.0	6.32098E-07	6.32098E-07	1.95523E-12	3.64772E-08	3.64772E-08	6.34686E-13
26.0	6.33334E-07	6.33334E-07	1.95897E-12	3.64214E-08	3.64214E-08	6.34683E-13
28.0	6.35009E-07	6.35009E-07	1.96315E-12	3.63728E-08	3.63728E-08	6.34683E-13
30.0	6.36594E-07	6.36594E-07	1.97371E-12	3.62898E-08	3.62898E-08	6.34688E-13
32.0	6.38100E-07	6.38100E-07	1.99024E-12	3.62656E-08	3.62656E-08	6.34692E-13
34.0	6.39453E-07	6.39453E-07	1.99329E-12	3.62714E-08	3.62714E-08	6.34694E-13
36.0	6.41322E-07	6.41322E-07	2.01372E-12	3.62616E-08	3.62616E-08	6.34701E-13
38.0	6.43150E-07	6.43150E-07	2.03093E-12	3.62669E-08	3.62669E-08	6.34735E-13
40.0	6.44956E-07	6.44956E-07	2.04604E-12	3.62060E-08	3.62060E-08	6.34736E-13

Figure 4-20. 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,PRCCF,LEAK DETECT - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

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

1 ORE TH 1 JOINT 1 LLNL DATA

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	6.57426E-08	6.57426E-08	0.	1.36677E-08	1.36677E-08	0.
2.0	2.37959E-07	2.37959E-07	3.54033E-14	2.26035E-08	2.26035E-08	3.54033E-14
4.0	3.11228E-07	3.11228E-07	4.14274E-13	2.43126E-08	2.43126E-08	3.54357E-13
6.0	3.62770E-07	3.62770E-07	4.29589E-13	2.68755E-08	2.68755E-08	3.54685E-13
8.0	4.16052E-07	4.16052E-07	5.91600E-13	2.69858E-08	2.69858E-08	3.61112E-13
10.0	4.45893E-07	4.45893E-07	1.07764E-12	2.74820E-08	2.74820E-08	5.09137E-13
12.0	4.93503E-07	4.93503E-07	1.14575E-12	2.84938E-08	2.84938E-08	5.10897E-13
14.0	5.14633E-07	5.14633E-07	1.23256E-12	2.81286E-08	2.81286E-08	5.13482E-13
16.0	5.82062E-07	5.82062E-07	1.31126E-12	3.67597E-08	3.67597E-08	5.15289E-13
18.0	6.08963E-07	6.08963E-07	1.82640E-12	3.70382E-08	3.70382E-08	6.31810E-13
20.0	6.29460E-07	6.29460E-07	1.99806E-12	3.65542E-08	3.65542E-08	6.35831E-13
22.0	6.30923E-07	6.30923E-07	1.94827E-12	3.64859E-08	3.64859E-08	6.34688E-13
24.0	6.32098E-07	6.32098E-07	1.95771E-12	3.64772E-08	3.64772E-08	6.34684E-13
26.0	6.33334E-07	6.33334E-07	1.96192E-12	3.64214E-08	3.64214E-08	6.34684E-13
28.0	6.35048E-07	6.35048E-07	1.96315E-12	3.63728E-08	3.63728E-08	6.34683E-13
30.0	6.36594E-07	6.36594E-07	2.01672E-12	3.62898E-08	3.62898E-08	6.35173E-13
32.0	6.38100E-07	6.38100E-07	1.99152E-12	3.62656E-08	3.62656E-08	6.34691E-13
34.0	6.39453E-07	6.39453E-07	2.00250E-12	3.62714E-08	3.62714E-08	6.34699E-13
36.0	6.41332E-07	6.41332E-07	2.02264E-12	3.62616E-08	3.62616E-08	6.34716E-13
38.0	6.43150E-07	6.43150E-07	2.03656E-12	3.62669E-08	3.62669E-08	6.34737E-13
40.0	6.44956E-07	6.44956E-07	2.04604E-12	3.62060E-08	3.62060E-08	6.34736E-13

Figure 4-21a. 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,PRCCF,LEAK DETECT - - -

- - RESULTS INCLUDING SEISMIC EVENTS - -

SEISMIC CLASS INFORMATION

	CLASS	S4-EQ	SGLCEG	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 LCCA	
0.	6.99920E-08	6.99920E-08	0.	1.40442E-08	1.40442E-08	0.	
2.0	2.38560E-07	2.38560E-07	3.54033E-14	2.26029E-08	2.26029E-08	3.54033E-14	
4.0	3.11265E-07	3.11265E-07	4.14274E-13	2.43126E-08	2.43126E-08	3.54357E-13	
6.0	3.62821E-07	3.62821E-07	4.40917E-13	2.68755E-08	2.68755E-08	3.54865E-13	
8.0	4.20662E-07	4.20662E-07	5.91600E-13	2.69146E-08	2.69146E-08	3.61112E-13	
10.0	4.46482E-07	4.46482E-07	1.11475E-12	2.74773E-08	2.74773E-08	5.10457E-13	
12.0	4.93503E-07	4.93503E-07	1.18086E-12	2.84938E-08	2.84938E-08	5.12063E-13	
14.0	5.19836E-07	5.19836E-07	1.23256E-12	2.85119E-08	2.85119E-08	5.13482E-13	
16.0	5.82576E-07	5.82576E-07	1.37251E-12	3.67633E-08	3.67633E-08	5.16121E-13	
18.0	6.14013E-07	6.14013E-07	1.86102E-12	3.68611E-08	3.68611E-08	6.32711E-13	
20.0	6.29460E-07	6.29460E-07	1.99806E-12	3.65542E-08	3.65542E-08	6.35831E-13	
22.0	6.30923E-07	6.30923E-07	1.95198E-12	3.64859E-08	3.64859E-08	6.34687E-13	
24.0	6.32098E-07	6.32098E-07	1.96074E-12	3.64772E-08	3.64772E-08	6.34685E-13	
26.0	6.33334E-07	6.33334E-07	1.96192E-12	3.64214E-08	3.64214E-08	6.34684E-13	
28.0	6.35048E-07	6.35048E-07	1.98186E-12	3.63728E-08	3.63728E-08	6.34691E-13	
30.0	6.36594E-07	6.36594E-07	2.01966E-12	3.62898E-08	3.62898E-08	6.35174E-13	
32.0	6.38111E-07	6.38111E-07	1.99669E-12	3.62656E-08	3.62656E-08	6.34695E-13	
34.0	6.39462E-07	6.39462E-07	2.01676E-12	3.62714E-08	3.62714E-08	6.34717E-13	
36.0	6.41332E-07	6.41332E-07	2.03949E-12	3.62616E-08	3.62616E-08	6.34762E-13	
38.0	6.43150E-07	6.43150E-07	2.05347E-12	3.62669E-08	3.62669E-08	6.34763E-13	
40.0	6.44956E-07	6.44956E-07	2.04604E-12	3.62060E-08	3.62060E-08	6.34736E-13	

Figure 4-21b. Results for Earthquake Category 2 in Sample Problem 4

- - - SAMPLE-4 FL-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

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	1.03836E-07	1.03836E-07	1.24466E-13	1.62219E-08	1.62219E-08	5.07195E-14
2.0	2.47941E-07	2.47941E-07	1.21101E-13	2.31763E-08	2.31763E-08	5.39467E-14
4.0	3.12089E-07	3.12089E-07	8.60591E-13	2.43098E-08	2.43098E-08	3.71678E-13
6.0	3.73376E-07	3.73376E-07	1.51539E-12	2.68263E-08	2.68263E-08	5.21302E-13
8.0	4.26572E-07	4.26572E-07	2.08560E-12	2.68162E-08	2.68162E-08	6.36341E-13
10.0	4.62232E-07	4.62232E-07	1.74144E-12	2.79090E-08	2.79090E-08	5.26149E-13
12.0	4.98285E-07	4.98285E-07	2.43463E-12	2.83756E-08	2.83756E-08	6.44507E-13
14.0	5.21368E-07	5.21368E-07	2.84402E-12	2.85242E-08	2.85242E-08	7.38489E-13
16.0	5.82739E-07	5.82739E-07	2.77360E-12	3.67635E-08	3.67635E-08	6.51378E-13
18.0	6.14064E-07	6.14064E-07	2.93768E-12	3.68611E-08	3.68611E-08	6.54373E-13
20.0	6.34697E-07	6.34697E-07	3.00264E-12	3.68080E-08	3.68080E-08	6.55362E-13
22.0	6.31068E-07	6.31068E-07	2.07729E-12	3.64848E-08	3.64848E-08	6.35135E-13
24.0	6.32497E-07	6.32497E-07	2.10530E-12	3.64571E-08	3.64571E-08	6.35576E-13
26.0	6.33372E-07	6.33372E-07	2.11278E-12	3.64209E-08	3.64209E-08	6.35253E-13
28.0	6.35447E-07	6.35447E-07	2.13270E-12	3.63616E-08	3.63616E-08	6.35272E-13
30.0	6.36916E-07	6.36916E-07	2.15246E-12	3.62847E-08	3.62847E-08	6.35288E-13
32.0	6.38112E-07	6.38112E-07	2.21311E-12	3.62656E-08	3.62656E-08	6.39515E-13
34.0	6.39571E-07	6.39571E-07	2.33847E-12	3.62708E-08	3.62708E-08	6.46007E-13
36.0	6.41334E-07	6.41334E-07	2.32537E-12	3.62616E-08	3.62616E-08	6.40817E-13
38.0	6.43151E-07	6.43151E-07	2.38211E-12	3.62669E-08	3.62669E-08	6.43669E-13
40.0	6.44956E-07	6.44956E-07	2.04604E-12	3.62060E-08	3.62060E-08	6.34736E-13

Figure 4-21c. Results for Earthquake Category 3 in Sample Problem 4.

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

- - 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.	1.45210E-07	1.45210E-07	3.50094E-13	1.86275E-08	1.86275E-08	8.78986E-14
2.0	2.82207E-07	2.82207E-07	6.34426E-13	2.41812E-08	2.41812E-08	3.61681E-13
4.0	3.18157E-07	3.18157E-07	1.89324E-12	2.43090E-08	2.43090E-08	6.29210E-13
6.0	3.82179E-07	3.82179E-07	1.81448E-12	2.68157E-08	2.68157E-08	5.29049E-13
8.0	4.30220E-07	4.30220E-07	2.20217E-12	2.69082E-08	2.69082E-08	6.38667E-13
10.0	4.68042E-07	4.68042E-07	2.27702E-12	2.81045E-08	2.81045E-08	6.51138E-13
12.0	4.99526E-07	4.99526E-07	3.02929E-12	2.83660E-08	2.83660E-08	7.42386E-13
14.0	5.27940E-07	5.27940E-07	3.07256E-12	2.83445E-08	2.83445E-08	7.42233E-13
16.0	5.85321E-07	5.85321E-07	2.94582E-12	3.67773E-08	3.67773E-08	6.54693E-13
18.0	6.15494E-07	6.15494E-07	3.05055E-12	3.68682E-08	3.68682E-08	6.56714E-13
20.0	6.35498E-07	6.35498E-07	3.54682E-12	3.68112E-08	3.68112E-08	7.49815E-13
22.0	6.31199E-07	6.31199E-07	2.08567E-12	3.64846E-08	3.64846E-08	6.35140E-13
24.0	6.32652E-07	6.32652E-07	2.12694E-12	3.64569E-08	3.64569E-08	6.35587E-13
26.0	6.33823E-07	6.33823E-07	2.12838E-12	3.64149E-08	3.64149E-08	6.35253E-13
28.0	6.35642E-07	6.35642E-07	2.14732E-12	3.63608E-08	3.63608E-08	6.35292E-13
30.0	6.37033E-07	6.37033E-07	2.24577E-12	3.62845E-08	3.62845E-08	6.40002E-13
32.0	6.39054E-07	6.39054E-07	2.23946E-12	3.62730E-08	3.62730E-08	6.39542E-13
34.0	6.39618E-07	6.39618E-07	2.35016E-12	3.62706E-08	3.62706E-08	6.46017E-13
36.0	6.41537E-07	6.41537E-07	2.35074E-12	3.62602E-08	3.62602E-08	6.40848E-13
38.0	6.43248E-07	6.43248E-07	2.40420E-12	3.62660E-08	3.62660E-08	6.43714E-13
40.0	6.44956E-07	6.44956E-07	2.04604E-12	3.62060E-08	3.62060E-08	6.34736E-13

Figure 4-21d. Results for Earthquake Category 4 in Sample Problem 4.

4.5 Sample Problem 5: Fatigue with Residual and Vibratory Stresses

Sample problem 5 shows how residual stresses and vibratory stresses can be added to the analysis for fatigue growth of cracks in the circumferential welds of a pressurized water reactor. The stratification scheme for this problem is designed to capture all LOCA events; however, it does not cover all cracks which can eventually leak. Therefore, only the LOCA results should be considered valid for this weld. The LOCA results for this sample problem are further discussed in Section 5.1 and plotted as part of Figure 5-2. The leak results are conditional on the crack initially being in the part of the sample space that is modeled. Specific inputs include:

- Fatigue crack growth only (ISCC=0)
- Residual stress contribution to the stress intensity factors (ISIGRS=1). These residual stresses correspond to those discussed in Section 2.5.3 for a 34 in. line, and shown in Figures 2-8 and 2-9.

$$\bar{K}_{RES,a} = (1.77308 - 79.62676 (a/h) - 265.12729 (a/h)^2 + 344.08357 (a/h)^3)$$

$$+ (1.57272 - 45.57625 (a/h) + 378.51393 (a/h)^2 - 333.86294 (a/h)^3) (a/b)$$

$$\bar{K}_{RES,b} = (.88570 - 25.23307 (a/h) - 183.67743 (a/h)^2 + 156.02632 (a/h)^3)$$

$$+ (.60779 - 22.10977 (a/h) - 95.13838 (a/h)^2 - 58.06677 (a/h)^3) (a/b)$$

- 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

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

$$\bar{K}_0 = 4.6 \text{ KSI} - \sqrt{\text{in}}$$

(KONPRP = 0, CONSMU = $9.0\text{E-}12$, CONS90 = $3.5\text{E-}11$, EXEMP = 4.0, THRHLD = 4.6).

- The flow stress is normally distributed, while the aspect ratio is log-normally distributed. (KRKDIS = 3, ALAMDA = 4.065, BOAMED = 1.336, BOASIG = 0.538, and BOANRM = 1.419).
- Evaluation of the failure probabilities is carried out at 1 hour intervals (NEVAL = -1).
- No in-service inspection is performed (NINSPT=0).
- A detectable leak is 2 gpm (FNDLEK = 2.0).
- The discrimination level for a big leak is 2 gpm (ALKBIG = 2.0).
- Two hundred samples are drawn from each cell (NTRIES = 200).
- 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).
- Vibratory stresses are modeled, peak-to-peak amplitude is 1.0 KSI (SIGVIB = 1.0). Plateau value of load ratio is 0.9 (RSTAR = 0.9).
- Stratification over a part of the sample space is generated internally by the code (NAOH = -7, NAOB = -8, AOHLOW = 0.72, AOHUP = 1.00, AOBLFT = 0.0, AOBRGT = 0.08).

A maximum of 56 cells is requested. Each cell will have an a/h interval of length 0.04 and an a/b interval of length 0.01. Since some of these cells lie entirely within the infeasible region, they have been eliminated. Several others have been redefined to minimize their coverage of the infeasible region.

- Only the heatup-cooldown transient is modeled. These are specified to occur 5 times per year throughout the lifetime of the plant.
- No earthquakes are modeled.

The card images for this problem are shown in Figure 4-22. These input are summarized in Figure 4-23. The stratification scheme is tabulated in Figure 4-24. The total probability of finding an initial defect in this region is 1.43×10^{-8} . The results are tabulated in Figure 4-25.

117

SAMPLE	5	HU-CD	ONLY	FATIGUE	ONLY	RESIDUAL	VIBRATORY	PSI	HYDRO	NO	ISI			
-200	1	1	3	-1	0	0	0	0	48	0	10	1	0	1
2	4	2	4											
40.		0.10												
2.5		14.5												
4.6		4.0		9.14-12		3.50-11								
44.9		1.373												
4.065														
1.336		0.538		1.419										
2.0		2.0												
-7	-8	0.72		1.0		0.0		0.08						
2.0		0.75		2.25		3.125		1.00		0.9				
1	-.2	478.5		HEATUP FROM COLD SHUTDOWN TO HOT STANDBY										
1.77308		-79.62676		-265.12729		344.08357								
1.57272		-45.57625		378.51393		-333.86294								
.88570		-25.23307		-183.67743		156.02632								
.60779		-22.10977		95.13838		-58.06677								

Figure 4-22. Input Cards for Sample Problem 5

```

---      SAMPLE5,NO-CC ONLY,FATIGUE ONLY,RESIDUAL,VIBRATORY,FSI,HYDRO,NO ISI      ---

FATIGUE CRACK GROWTH ONLY

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 =      1.4187

CRACK GROWTH LAW PARAMETERS
  EXPONENT =      4.00
  GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED
    MEDIAN =      .5140E-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
  VIBRATORY STRESSES (KSI)      1.00
  R-RATIO LIMIT (=R-STAR)      .90
  PROOF TEST STRESS (KSI) 11.06

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

RESIDUAL STRESSES ARE MODELED

VIBRATORY STRESSES ARE MODELED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELED

TIME INTERVALS
  PLANT LIFETIME      40.0  YEARS
  ENDPOINTS OF INTERVALS AT 0.  1.0  2.0  3.0  4.0  5.0  6.0  7.0  8.0  9.0  YEARS
  ENDPOINTS OF INTERVALS AT 10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 YEARS
  ENDPOINTS OF INTERVALS AT 20.0 21.0 22.0 23.0 24.0 25.0 26.0 27.0 28.0 29.0 YEARS
  ENDPOINTS OF INTERVALS AT 30.0 31.0 32.0 33.0 34.0 35.0 36.0 37.0 38.0 39.0 YEARS
  ENDPOINTS OF INTERVALS AT 40.0

NO IN-SERVICE INSPECTIONS ARE MODELED

- - - NO SEISMIC EVENTS EVALUATED - - -

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS 10

- - - NORMAL OUTPUT REQUESTED - - -

```

Figure 4-23. Input Summary for Sample Problem 5

- - NUMBER OF TRANSIENT TYPES = 1 - -

TYPE 1 HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
REGULAR AT .200 YRS/EVENT
MAX DELTA TEMP =474.5 BLOCKING FACTOR = 1.

--- CONTRIBUTION OF RESIDUAL STRESSES TO THE STRESS INTENSITY FACTORS ---

DEPTH DIRECTION

1.77308 -75.62676 -265.12729 344.08357
1.57272 -45.57625 378.51393 -333.86294

.110E+01	.110E+01	.117E+01	.123E+01	.130E+01	.136E+01	.143E+01	.149E+01	.156E+01	.162E+01	.169E+01	.175E+01
.900E+00	-.338E+02	-.314E+02	-.291E+02	-.267E+02	-.243E+02	-.219E+02	-.195E+02	-.172E+02	-.148E+02	-.124E+02	-.100E+02
.800E+00	-.554E+02	-.518E+02	-.482E+02	-.445E+02	-.409E+02	-.372E+02	-.336E+02	-.299E+02	-.263E+02	-.227E+02	-.190E+02
.700E+00	-.659E+02	-.618E+02	-.577E+02	-.537E+02	-.496E+02	-.455E+02	-.415E+02	-.374E+02	-.334E+02	-.293E+02	-.252E+02
.600E+00	-.671E+02	-.633E+02	-.595E+02	-.556E+02	-.518E+02	-.479E+02	-.441E+02	-.403E+02	-.364E+02	-.326E+02	-.287E+02
.500E+00	-.613E+02	-.581E+02	-.550E+02	-.518E+02	-.486E+02	-.455E+02	-.423E+02	-.391E+02	-.360E+02	-.328E+02	-.296E+02
.400E+00	-.505E+02	-.482E+02	-.460E+02	-.437E+02	-.415E+02	-.392E+02	-.370E+02	-.347E+02	-.324E+02	-.302E+02	-.279E+02
.300E+00	-.367E+02	-.354E+02	-.341E+02	-.328E+02	-.315E+02	-.302E+02	-.289E+02	-.276E+02	-.263E+02	-.250E+02	-.237E+02
.200E+00	-.220E+02	-.215E+02	-.210E+02	-.205E+02	-.200E+02	-.195E+02	-.190E+02	-.186E+02	-.181E+02	-.176E+02	-.171E+02
.100E+00	-.850E+01	-.845E+01	-.840E+01	-.835E+01	-.831E+01	-.826E+01	-.822E+01	-.817E+01	-.812E+01	-.808E+01	-.803E+01
0.	.177E+01	.193E+01	.209E+01	.224E+01	.240E+01	.256E+01	.272E+01	.287E+01	.303E+01	.319E+01	.335E+01

LENGTH DIRECTION

.88570 -25.23307 -163.67743 156.02632
.60779 -22.10977 95.13638 -58.06677

.100E+01	-.520E+02	-.504E+02	-.489E+02	-.473E+02	-.458E+02	-.442E+02	-.427E+02	-.411E+02	-.395E+02	-.380E+02	-.364E+02
.900E+00	-.565E+02	-.553E+02	-.538E+02	-.522E+02	-.507E+02	-.491E+02	-.476E+02	-.461E+02	-.445E+02	-.430E+02	-.414E+02
.800E+00	-.570E+02	-.556E+02	-.542E+02	-.527E+02	-.513E+02	-.499E+02	-.485E+02	-.471E+02	-.457E+02	-.443E+02	-.429E+02
.700E+00	-.533E+02	-.521E+02	-.509E+02	-.497E+02	-.485E+02	-.473E+02	-.462E+02	-.450E+02	-.438E+02	-.426E+02	-.414E+02
.600E+00	-.467E+02	-.458E+02	-.449E+02	-.440E+02	-.431E+02	-.422E+02	-.412E+02	-.403E+02	-.394E+02	-.385E+02	-.376E+02
.500E+00	-.381E+02	-.375E+02	-.369E+02	-.363E+02	-.357E+02	-.351E+02	-.345E+02	-.339E+02	-.333E+02	-.327E+02	-.321E+02
.400E+00	-.286E+02	-.283E+02	-.280E+02	-.276E+02	-.273E+02	-.270E+02	-.266E+02	-.263E+02	-.260E+02	-.257E+02	-.253E+02
.300E+00	-.190E+02	-.189E+02	-.188E+02	-.187E+02	-.186E+02	-.185E+02	-.184E+02	-.183E+02	-.182E+02	-.181E+02	-.180E+02
.200E+00	-.103E+02	-.103E+02	-.104E+02	-.104E+02	-.105E+02	-.105E+02	-.106E+02	-.106E+02	-.107E+02	-.107E+02	-.107E+02
.100E+00	-.332E+01	-.339E+01	-.346E+01	-.353E+01	-.360E+01	-.367E+01	-.374E+01	-.382E+01	-.389E+01	-.396E+01	-.403E+01
0.	.885E+00	.946E+00	.101E+01	.107E+01	.113E+01	.119E+01	.125E+01	.131E+01	.137E+01	.143E+01	.149E+01

Figure 4-23. (continued)

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

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

CELL	AOH1	AOH2	AOB1	AOB2	PROBABILITY	SAMPLES
1	.9600	1.0000	.0527	.0600	.2619642E-10	200
2	.9600	1.0000	.0600	.0700	.1082931E-09	200
3	.9600	1.0000	.0700	.0800	.2586144E-09	200
4	.9200	.9600	.0505	.0600	.4494205E-10	200
5	.9200	.9600	.0600	.0700	.1626079E-09	200
6	.9200	.9600	.0700	.0800	.4483853E-09	200
7	.8800	.9111	.0483	.0500	.3534914E-11	200
8	.8800	.9200	.0500	.0600	.6890855E-10	200
9	.8800	.9200	.0600	.0700	.2441644E-09	200
10	.8800	.9200	.0700	.0800	.6732744E-09	200
11	.8400	.8800	.0461	.0500	.1254804E-10	200
12	.8400	.8800	.0500	.0600	.1035900E-09	200
13	.8400	.8800	.0600	.0700	.3666258E-09	200
14	.8400	.8800	.0700	.0800	.1016957E-08	200
15	.8000	.8400	.0439	.0500	.2481773E-10	200
16	.8000	.8400	.0500	.0600	.1555458E-09	200
17	.8000	.8400	.0600	.0700	.5505081E-09	200
18	.8000	.8400	.0700	.0800	.1518006E-08	200
19	.7600	.8000	.0417	.0500	.4304974E-10	200
20	.7600	.8000	.0500	.0600	.2335604E-09	200
21	.7600	.8000	.0600	.0700	.8266172E-09	200
22	.7600	.8000	.0700	.0800	.2279367E-08	200
23	.7200	.7289	.0395	.0400	.2524622E-12	200
24	.7200	.7600	.0400	.0500	.6908225E-10	200
25	.7200	.7600	.0500	.0600	.3507033E-09	200
26	.7200	.7600	.0600	.0700	.1241210E-08	200
27	.7200	.7600	.0700	.0800	.3422591E-08	200
SUM OF CELL PROBABILITIES =			.1428803297E-07			

Figure 4-24. Stratification Description for Sample Problem 5

- - - SAMPLE 5, FC-CD ONLY, FATIGUE ONLY, RESIDUAL, VIBRATORY, FSI, HYCRC, AC ISI

- - RESULTS WITHOUT EARTHQUAKES - - -

TIME	AVG LEAK	AVG EIG LEAK	AVG LCCA	SIGMA LEAK	SIGMA EIG LEAK	SIGMA LOCA
0.	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
1.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
2.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
3.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
4.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
5.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
6.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
7.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
8.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
9.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
10.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
11.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
12.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
13.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
14.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
15.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
16.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
17.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
18.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
19.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
20.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
21.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
22.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
23.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
24.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
25.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
26.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
27.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
28.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
29.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
30.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
31.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
32.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
33.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
34.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
35.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
36.0	6.75467E-10	6.75467E-10	2.41753E-11	8.81775E-12	8.81775E-12	1.16226E-12
37.0	6.75641E-10	6.75641E-10	2.41753E-11	8.81882E-12	8.81882E-12	1.16226E-12
38.0	6.75641E-10	6.75641E-10	2.41753E-11	8.81882E-12	8.81882E-12	1.16226E-12
39.0	6.75641E-10	6.75641E-10	2.41753E-11	8.81882E-12	8.81882E-12	1.16226E-12
40.0	6.75641E-10	6.75641E-10	2.41753E-11	8.81882E-12	8.81882E-12	1.16226E-12

Figure 4-25. Results of the No Earthquake Case in Sample Problem 5

4.6 Sample Problem 6: Fatigue of Longitudinal Weld

Sample problem 6 illustrates an analysis of fatigue crack growth in a longitudinal weld in the primary coolant system of a pressurized water reactor. This problem corresponds to the longitudinal weld results with the Kiefner failure criteria that are presented and extensively discussed in Section 5.3. In addition to constructing inputs which describe the geometry and environment of the longitudinal weld, the user must also modify the failure criterion in accordance with the discussion given in Section 2.6. The principal features of the geometry and environment are:

- Fatigue crack growth only (ISCC=0)
- No residual stresses (SIGRS=0)
- No vibratory stresses (SIGVIB=-1.0)
- A portion of the sample was partitioned internally by PRAISE-B (NAOH = -10, NAOB = -10, AOHUP = 0.65, AOHLOW = 1.00, AOBLFT = 0.0, AOBRTG = 1.0). This stratification is designed to accurately determine the leak probabilities. (Therefore the results generated here are also in Figure 5-5, but only approximate those of Figure 5-6).
- Only the heatup-cooldown transient is modeled. These occur uniform intervals of 0.2 years through the lifetime of the plant.
- No earthquakes are modeled.
- Forty year plant lifetime (THRIZN=40).
- Pipe wall thickness is 3.31 in (THICK=3.31).
- Pipe inside radius is 15.50 in (RIN=15.5).

- Crack growth relationship with a log-normally distributed C whose median = 9.14×10^{-12} and 90-th percentile value = 3.5×10^{-11} , or

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

$$\bar{K}_0 = 4.6 \text{ KSI} \cdot \sqrt{\text{in}}$$

(KONPRP = 0, CONSMU = 9.14×10^{-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 (KRKDIS = 3, ALAMDA = 4.065, BOAMED = 1.336, BOASIG = 0.538, and BOANRM = 1.4187).
- Evaluation of the failure probabilities is carried out at 1 year intervals (NEVAL = -1).
- No in-service inspection is performed.
- A detectable leak is 2 gpm (FNDLEK = 2.0).
- The discrimination level for a big leak is 2 gpm (ALKBIG = 2.0).
- Fifty samples are drawn from each cell (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 0.58 KSI and 4.47 KSI respectively. (SIGCLD = .58, SGDWTE = 4.47).

- Operating pressure is 2250 psia (OPPRES = 2.25).
- A hydrostatic proof test with pressure of 3125 psia is modeled (PRFPRS = 3.125).

The card images, input summary, and stratification scheme are shown in Figures 4-26, 4-27, and 4-28, respectively. The probability of having an initial defect in this region of the sample space is 1.5×10^{-4} .

Coding modifications must be made in the INITIAL, KBARS, and FAILS subroutines. The end results of the calculations are tabulated in Figure 4-29.

```

SAMPLE6, HU-CD ONLY, FATIGUE ONLY, LONGITUDINAL, NO RESIDUAL, NO VIBRATORY
-50      1      1      3      -1      0      0      0      0      0      48      0      10      1      0      0
40.      0.10
3.312    15.5
4.6      4.0      9.14-12      3.50-11
44.9     1.373
4.065
1.336    0.538      1.419
2.0      2.0
-10     -10      .65      1.      0.      1.
.58      4.47      2.25      3.125      -1.00      0.9
1  -.2  478.5      HEATUP FROM COLD SHUTDOWN TO HOT STANDBY

```

Figure 4-26. Card Images for Input to Sample Problem 6

```

---      SAMPLE6,HU-CC ONLY,FATIGUE ONLY, LONGITUDINAL, NO RESIDUAL, NO VIBRATION ---

FATIGUE CRACK GROWTH ONLY

PIPE DIMENSIONS
  INSIDE RADIUS =      15.50  INCHES
  WALL THICKNESS   3.31  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 =      1.4187

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

PIPE STRESS VALUES
  CSC DEADWT STRESS (KSI)   .50
  HOT UNIFORM STRESS (KSI) 15.00
  PRESSURE STRESS (KSI)    10.53
  PROOF TEST STRESS(KSI)    7.89

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

NO RESIDUAL STRESSES ARE MODELED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELED

TIME INTERVALS
  PLANT LIFETIME      40.0  YEARS
  ENDCPOINTS OF INTERVALS AT  0.    1.0    2.0    3.0    4.0    5.0    6.0    7.0    8.0    9.0  YEARS
  ENDCPOINTS OF INTERVALS AT 10.0   11.0   12.0   13.0   14.0   15.0   16.0   17.0   18.0   19.0  YEARS
  ENDCPOINTS OF INTERVALS AT 20.0   21.0   22.0   23.0   24.0   25.0   26.0   27.0   28.0   29.0  YEARS
  ENDCPOINTS OF INTERVALS AT 30.0   31.0   32.0   33.0   34.0   35.0   36.0   37.0   38.0   39.0  YEARS
  ENDCPOINTS OF INTERVALS AT 40.0

NO IN-SERVICE INSPECTIONS ARE MODELED

- - - NO SEISMIC EVENTS EVALUATED - - -

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS  10

- - - NORMAL OUTPUT REQUESTED - - -

```

Figure 4-27. Input Summary for Sample Problem 6

- - NUMBER OF TRANSIENT TYPES = 1 - -
TYPE 1 HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
REGULAR AT .200 YRS/EVENT
MAX DELTA TEMP = 474.5 BLOCKING FACTOR = 1.

Figure 4-27 (continued)

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

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

CELL	AGE1	AGE2	AGE3	AGE4	FRCDAEILITY	SAMPLES
1	.5650	1.0000	.0656	.1000	.1074218E-05	50
2	.9650	1.0000	.1000	.2000	.8490328E-06	50
3	.9650	1.0000	.2000	.3000	.4559143E-07	50
4	.9650	1.0000	.3000	.4000	.9406825E-07	50
5	.9650	1.0000	.4000	.5000	.1270146E-06	50
6	.9650	1.0000	.5000	.6000	.1383045E-06	50
7	.9650	1.0000	.6000	.7000	.1335194E-06	50
8	.9650	1.0000	.7000	.8000	.1199548E-06	50
9	.9650	1.0000	.8000	.9000	.1030407E-06	50
10	.9650	1.0000	.9000	1.0000	.8660579E-07	50
11	.9300	.9650	.0633	.1000	.1737286E-05	50
12	.9300	.9650	.1000	.2000	.1360099E-07	50
13	.9300	.9650	.2000	.3000	.7303469E-07	50
14	.9300	.9650	.3000	.4000	.1506916E-06	50
15	.9300	.9650	.4000	.5000	.2034696E-06	50
16	.9300	.9650	.5000	.6000	.2215553E-06	50
17	.9300	.9650	.6000	.7000	.2138699E-06	50
18	.9300	.9650	.7000	.8000	.1921603E-06	50
19	.9300	.9650	.8000	.9000	.1650648E-06	50
20	.9300	.9650	.9000	1.0000	.1377760E-06	50
21	.8950	.9300	.0609	.1000	.2802678E-05	50
22	.8950	.9300	.1000	.2000	.2178795E-07	50
23	.8950	.9300	.2000	.3000	.1169971E-06	50
24	.8950	.9300	.3000	.4000	.2413988E-06	50
25	.8950	.9300	.4000	.5000	.3259459E-06	50
26	.8950	.9300	.5000	.6000	.3549181E-06	50
27	.8950	.9300	.6000	.7000	.3426387E-06	50
28	.8950	.9300	.7000	.8000	.3076292E-06	50
29	.8950	.9300	.8000	.9000	.2644238E-06	50
30	.8950	.9300	.9000	1.0000	.2207088E-06	50
31	.8600	.8950	.0565	.1000	.4513609E-05	50
32	.8600	.8950	.1000	.2000	.3490297E-07	50
33	.8600	.8950	.2000	.3000	.1674222E-06	50
34	.8600	.8950	.3000	.4000	.3867061E-06	50
35	.8600	.8950	.4000	.5000	.5221455E-06	50
36	.8600	.8950	.5000	.6000	.5685572E-06	50
37	.8600	.8950	.6000	.7000	.5488862E-06	50
38	.8600	.8950	.7000	.8000	.4931236E-06	50
39	.8600	.8950	.8000	.9000	.4235908E-06	50
40	.8600	.8950	.9000	1.0000	.3535621E-06	50
41	.8250	.8600	.0561	.1000	.7258015E-05	50
42	.8250	.8600	.1000	.2000	.5591244E-07	50
43	.8250	.8600	.2000	.3000	.3002390E-06	50
44	.8250	.8600	.3000	.4000	.6194796E-06	50
45	.8250	.8600	.4000	.5000	.8364453E-06	50
46	.8250	.8600	.5000	.6000	.9107939E-06	50
47	.8250	.8600	.6000	.7000	.8792823E-06	50
48	.8250	.8600	.7000	.8000	.7699539E-06	50
49	.8250	.8600	.8000	.9000	.6785667E-06	50
50	.8250	.8600	.9000	1.0000	.5663849E-06	50
51	.7900	.8250	.0537	.1000	.1165834E-05	50
52	.7900	.8250	.1000	.2000	.8956831E-07	50
53	.7900	.8250	.2000	.3000	.4809646E-06	50
54	.7900	.8250	.3000	.4000	.9923686E-06	50
55	.7900	.8250	.4000	.5000	.1339934E-05	50
56	.7900	.8250	.5000	.6000	.1459036E-05	50
57	.7900	.8250	.6000	.7000	.1408557E-05	50
58	.7900	.8250	.7000	.8000	.1265458E-05	50

Figure 4-28. Stratification Description for Sample Problem 6

59	.7400	.8250	.8000	.5000	.1087023E-05	50
60	.7500	.8250	.9000	1.0000	.9073141E-06	50
61	.7550	.7900	.0514	.1000	.1871114E-08	50
62	.7550	.7900	.1000	.2000	.1434830E-06	50
63	.7550	.7900	.2000	.3000	.7704760E-06	50
64	.7550	.7900	.3000	.4000	.1589714E-05	50
65	.7550	.7900	.4000	.5000	.2146493E-05	50
66	.7550	.7900	.5000	.6000	.2337287E-05	50
67	.7550	.7900	.6000	.7000	.2256422E-05	50
68	.7550	.7900	.7000	.8000	.2027187E-05	50
69	.7550	.7900	.8000	.9000	.1741344E-05	50
70	.7550	.7900	.9000	1.0000	.1453462E-05	50
71	.7200	.7550	.0490	.1000	.3001258E-08	50
72	.7200	.7550	.1000	.2000	.2298510E-06	50
73	.7200	.7550	.2000	.3000	.1234256E-05	50
74	.7200	.7550	.3000	.4000	.2546625E-05	50
75	.7200	.7550	.4000	.5000	.3438551E-05	50
76	.7200	.7550	.5000	.6000	.3744192E-05	50
77	.7200	.7550	.6000	.7000	.3614650E-05	50
78	.7200	.7550	.7000	.8000	.3247429E-05	50
79	.7200	.7550	.8000	.9000	.2789527E-05	50
80	.7200	.7550	.9000	1.0000	.2328357E-05	50
81	.6850	.7200	.0466	.1000	.4811928E-08	50
82	.6850	.7200	.1000	.2000	.3682073E-06	50
83	.6850	.7200	.2000	.3000	.1977202E-05	50
84	.6850	.7200	.3000	.4000	.4079538E-05	50
85	.6850	.7200	.4000	.5000	.5508349E-05	50
86	.6850	.7200	.5000	.6000	.5997967E-05	50
87	.6850	.7200	.6000	.7000	.5790450E-05	50
88	.6850	.7200	.7000	.8000	.5202184E-05	50
89	.6850	.7200	.8000	.9000	.4468652E-05	50
90	.6850	.7200	.9000	1.0000	.3729986E-05	50
91	.6500	.6850	.0442	.1000	.7712648E-08	50
92	.6500	.6850	.1000	.2000	.5898456E-06	50
93	.6500	.6850	.2000	.3000	.3167357E-05	50
94	.6500	.6850	.3000	.4000	.6535171E-05	50
95	.6500	.6850	.4000	.5000	.8824040E-05	50
96	.6500	.6850	.5000	.6000	.9608377E-05	50
97	.6500	.6850	.6000	.7000	.9275947E-05	50
98	.6500	.6850	.7000	.8000	.8333581E-05	50
99	.6500	.6850	.8000	.9000	.7158507E-05	50
100	.6500	.6850	.9000	1.0000	.5975951E-05	50

SUM OF CELL PROBABILITIES = .1568599792E-03

Figure 4-28. (continued)

- - - SAMPLE 6, PL-CC ONLY, FATIGUE ONLY, LONGITUDINAL, NO RESIDUAL, NO VIBRATORY - - -

- - RESULTS WITHOUT EARTHQUAKES - - -

TIME	AVG LEAK	AVG PIC LEAK	AVG LOCA	SIGMA LEAK	SIGMA PIC LEAK	SIGMA LOCA
0.0	5.10057E-06	5.00057E-06	6.79578E-11	1.03401E-09	1.03401E-09	5.41386E-12
1.0	5.10952E-06	5.00952E-06	6.50106E-11	1.03491E-09	1.03491E-09	5.43736E-12
2.0	5.16772E-06	5.06772E-06	7.00687E-11	1.06636E-09	1.06636E-09	5.45740E-12
3.0	5.18933E-06	5.08933E-06	7.00687E-11	1.07706E-09	1.07706E-09	5.45740E-12
4.0	5.14657E-06	5.14657E-06	7.00687E-11	1.07165E-09	1.07165E-09	5.45740E-12
5.0	5.16527E-06	5.16527E-06	7.00687E-11	1.07203E-09	1.07203E-09	5.45740E-12
6.0	5.21213E-06	5.21213E-06	7.00687E-11	1.08869E-09	1.08869E-09	5.45740E-12
7.0	5.23474E-06	5.23474E-06	7.00687E-11	1.09067E-09	1.09067E-09	5.45740E-12
8.0	5.10684E-06	5.10684E-06	7.00687E-11	1.10212E-09	1.10212E-09	5.45740E-12
9.0	5.14653E-06	5.14653E-06	7.00687E-11	1.11464E-09	1.11464E-09	5.45740E-12
10.0	5.126411E-06	5.126411E-06	7.00687E-11	1.12547E-09	1.12547E-09	5.45740E-12
11.0	5.40706E-06	5.40706E-06	7.00687E-11	1.13311E-09	1.13311E-09	5.45740E-12
12.0	5.41421E-06	5.41421E-06	7.00687E-11	1.13352E-09	1.13352E-09	5.45740E-12
13.0	5.41421E-06	5.41421E-06	7.00687E-11	1.13352E-09	1.13352E-09	5.45740E-12
14.0	5.44262E-06	5.44262E-06	7.00687E-11	1.14656E-09	1.14656E-09	5.45740E-12
15.0	5.46794E-06	5.46794E-06	7.00687E-11	1.14383E-09	1.14383E-09	5.45740E-12
16.0	5.47604E-06	5.47604E-06	7.00687E-11	1.14261E-09	1.14261E-09	5.45740E-12
17.0	5.57306E-06	5.57306E-06	7.00687E-11	1.22656E-09	1.22656E-09	5.45740E-12
18.0	5.59617E-06	5.59617E-06	7.00687E-11	1.23527E-09	1.23527E-09	5.45740E-12
19.0	5.52359E-06	5.52359E-06	7.11683E-11	1.27987E-09	1.27987E-09	5.47790E-12
20.0	5.72773E-06	5.72773E-06	7.11683E-11	1.29775E-09	1.29775E-09	5.47750E-12
21.0	5.75862E-06	5.75862E-06	7.11683E-11	1.29032E-09	1.29032E-09	5.47790E-12
22.0	5.52304E-06	5.52304E-06	7.11683E-11	1.30695E-09	1.30695E-09	5.47790E-12
23.0	5.16878E-06	5.16878E-06	7.22630E-11	1.31371E-09	1.31371E-09	5.49327E-12
24.0	5.57167E-06	5.57167E-06	7.22630E-11	1.31345E-09	1.31345E-09	5.49327E-12
25.0	5.18014E-06	5.18014E-06	7.22630E-11	1.31549E-09	1.31549E-09	5.49327E-12
26.0	5.48506E-06	5.48506E-06	7.22630E-11	1.31620E-09	1.31620E-09	5.49327E-12
27.0	5.51897E-06	5.51897E-06	7.22630E-11	1.32633E-09	1.32633E-09	5.49327E-12
28.0	5.93735E-06	5.93735E-06	7.22630E-11	1.32536E-09	1.32536E-09	5.49327E-12
29.0	5.48647E-06	5.48647E-06	7.22630E-11	1.32556E-09	1.32556E-09	5.49327E-12
30.0	6.00652E-06	6.00652E-06	7.40377E-11	1.33348E-09	1.33348E-09	5.77281E-12
31.0	6.10669E-06	6.10669E-06	7.40377E-11	1.33348E-09	1.33348E-09	5.77281E-12
32.0	6.00669E-06	6.00669E-06	7.40377E-11	1.33348E-09	1.33348E-09	5.77281E-12
33.0	6.02562E-06	6.02562E-06	7.40377E-11	1.33455E-09	1.33455E-09	5.77281E-12
34.0	6.14115E-06	6.14115E-06	7.77953E-11	1.33298E-09	1.33298E-09	6.31527E-12
35.0	6.05846E-06	6.05846E-06	7.77953E-11	1.32928E-09	1.32928E-09	6.31527E-12
36.0	6.05867E-06	6.05867E-06	7.98514E-11	1.32928E-09	1.32928E-09	6.61333E-12
37.0	6.06759E-06	6.06759E-06	8.16855E-11	1.32669E-09	1.32669E-09	6.82142E-12
38.0	6.08106E-06	6.08106E-06	8.16855E-11	1.32760E-09	1.32760E-09	6.82142E-12
39.0	6.17771E-06	6.17771E-06	8.16855E-11	1.44895E-09	1.44895E-09	6.82142E-12
40.0	6.21554E-06	6.21554E-06	8.36399E-11	1.46144E-09	1.46144E-09	7.09540E-12

Figure 4-29. Results of the No Earthquake Case in Sample Problem 6

4.7 Sample Problem 7: SCC-LOCA

Sample problem 7 shows how PRAISE-B can be used to estimate the LOCA probabilities for a weld in BWR piping. The crack propagation mechanism is assumed to be stress corrosion cracking. In addition to constructing inputs which describe the geometry and environment of the crack, the user must also modify subroutine INSPCT, which calculates the non-detection probabilities during an in-service inspection. Specific inputs are:

- Stress corrosion cracking only (ISCC = 1)
Time-step is 0.1 years (DTSCC = 0.1)
- No residual stresses (SIGRS = 0)
- Vibratory stresses are modeled
Peak-to-peak amplitude is 1.0 KSI (SIGVIB = 1.0)
R* = 0.9
- A portion of the sample space is internally partitioned by the PRAISE-B code (NAOH = -20, NAOB = -9, AOHUP = 1.0, AOHLOW = 0.36, AOBLFT = 0.0, AOBRTG = 0.045)

This partition will yield accurate results for the LOCA probabilities; it will give only a small fraction of the overall leak probability.

- Forty year plant lifetime (THRIZN = 40).
- Pipe wall thickness is 1.04 inches (THICK = 1.04).
- Inside radius of the pipe is 10.8 in (RIN = 10.8).

- Crack growth relationship with a log-normally distributed C whose median = 9.0×10^{-12} and 90-th percentile value = 3.5×10^{-11} ,

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

$$\bar{K}_0 = 4.6 \text{ KSI} \cdot \sqrt{\text{in}}$$

(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. (KRKDIS = 3, ALAMDA = 4.065, BOAMED = 1.336, BOASIG = 0.538, and BOANRM = 1.4187).
- Evaluation of the failure probabilities is carried out at 1 year intervals (NEVAL = -1).
- No in-service inspection is performed.
- A detectable leak is 2 gpm (FNDLEK = 2.0).
- The discrimination level for a big leak is 2 gpm (ALKBIG = 2.0).
- Twenty-five samples are taken from each cell (NTRIES = -25).
- A pre-service inspection is modeled (NSPI = 1.0). Equation (5-1) is used except $v = 1.6$.
- The contribution to the load controlled stresses in the cold shutdown (deadweight) and normal operating (deadweight and

restraint of thermal expansion) condition are 0.51 KSI and 3.90 KSI, respectively. (SIGCLD = 0.51, SGDWTE = 3.90).

- Operating pressure is 1050 psia (OPPRES = 1.05).
- A hydrostatic proof test with pressure of 1563 psia is modeled (PRFPRS = 1.563).

The card images, input summary, and stratification scheme are shown in Figures 4-30, 4-31. and 4-32. respectively. The probability of having a crack in this part of the sample space is 2.53×10^{-8} . The results are tabulated in Figure 4-33.

```

SAMPLE7, SCC ONLY, NO RESIDUAL, VIBRATORY, PSI, HYDRO, NO ISI
-25      1      1      3      -1      0      0      0      0      0      48      0      10      1      1      0
40.      0.10
1.043      10.8
4.6      4.0      9.14-12      3.50-11
44.9      1.373
4.065
1.336      0.538      1.419
2.0      2.0
-20      -9      0.36      1.0      0.0      0.045
0.51      3.90      1.05      1.563      1.0      0.9
1 -0.2 478.5      HEATUP FROM COLD SHUTDOWN TO HOT STANDBY

```

Figure 4-30. Card Images to Sample Problem 7

--- SAMPLE7, SCC ONLY, NO RESIDUAL, VIBRATORY, PSI, HYCRO, NO ISI

SCC ONLY

TIMESTEP FOR SCC = .100 YEARS

PIPE DIMENSIONS

INSIDE DIAMETER = 10.60 INCHES
WALL THICKNESS = 1.04 INCHES

INITIAL CRACK SIZE DISTRIBUTION

CRACK DEPTH IS EXPONENTIAL

PARAMETER = 4.0650

ASPECT RATIO IS LOG-NORMAL

MEAN = 1.3360

SHAPE PARAMETER = .5300

NORMALIZATION CONSTANT = 1.41E7

CRACK GROWTH LAW PARAMETERS

EXPONENT = 4.00

GROWTH LAW CONSTANT LOG-NORMALLY DISTRIBUTED

MEDIAN = .9140E-11

50-TH PERCENT = .3500E-10

THRESHOLD = 4.60

FLOW STRESS NORMALLY DISTRIBUTED

MEAN = .4490E+02

STANDARD DEVIAT = .1373E+01

PIPE STRESS VALUES

CSU DEADWT STRESS (KSI) .51

HOT UNIFORM STRESS (KSI) 5.34

PRESSURE STRESS (KSI) 5.44

VIBRATORY STRESSES (KSI) 1.00

R-RATIO LIMIT (K-SIG) .90

PROOF TEST STRESS (KSI) 4.60

LEAK DETECTION AND DEFINITION PARAMETERS

DETECTABLE LEAK (GPM) 2.0

RTG LEAK (GPM) 2.0

NO RESIDUAL STRESSES ARE MODELED

VIBRATORY STRESSES ARE MODELED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELED

TIME INTERVALS

PLANT LIFETIME 40.0 YEARS

ENDPOINTS OF INTERVALS AT 0. 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 YEARS

ENDPOINTS OF INTERVALS AT 10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 YEARS

ENDPOINTS OF INTERVALS AT 20.0 21.0 22.0 23.0 24.0 25.0 26.0 27.0 28.0 29.0 YEARS

ENDPOINTS OF INTERVALS AT 30.0 31.0 32.0 33.0 34.0 35.0 36.0 37.0 38.0 39.0 YEARS

ENDPOINTS OF INTERVALS AT 40.0

NO IN-SERVICE INSPECTIONS ARE MODELED

- - - NO SEISMIC EVENTS EVALUATED - - -

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS 10

- - - NORMAL OUTPUT REQUESTED - - -

Figure 4-31. Input Summary for Sample Problem 7

- - NUMBER OF TRANSIENT TYPES = 1 - -
TYPE 1 HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
REGULAR AT 20.000 YRS/EVENT
MAX DELTA TEMP = 474.5 DEGREE C PLUCKING FACTOR = 1.

Figure 4-31. (Continued)

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

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

CELL	AOB1	AOB2	AOB1	AOB2	PRCBABILITY	SAMPLES
1	.9680	.9759	.0298	.0300	.7798151E-13	25
2	.9680	1.0000	.0300	.0350	.1545754E-10	25
3	.9680	1.0000	.0350	.0400	.5941581E-10	25
4	.9680	1.0000	.0400	.0450	.1832623E-09	25
5	.9360	.9680	.0288	.0300	.1472854E-11	25
6	.9360	.9680	.0300	.0350	.1770364E-10	25
7	.9360	.9680	.0350	.0400	.6804939E-10	25
8	.9360	.9680	.0400	.0450	.2094918E-09	25
9	.9040	.9360	.0278	.0300	.2598079E-11	25
10	.9040	.9360	.0300	.0350	.2027612E-10	25
11	.9040	.9360	.0350	.0400	.7793750E-10	25
12	.9040	.9360	.0400	.0450	.2403907E-09	25
13	.8720	.9040	.0268	.0300	.3698651E-11	25
14	.8720	.9040	.0300	.0350	.2322239E-10	25
15	.8720	.9040	.0350	.0400	.8926243E-10	25
16	.8720	.9040	.0400	.0450	.2753213E-09	25
17	.8400	.8720	.0258	.0300	.4799611E-11	25
18	.8400	.8720	.0300	.0350	.2659679E-10	25
19	.8400	.8720	.0350	.0400	.1022330E-09	25
20	.8400	.8720	.0400	.0450	.3153277E-09	25
21	.8080	.8133	.0248	.0250	.1026552E-13	25
22	.8080	.8400	.0250	.0300	.5868671E-11	25
23	.8080	.8400	.0300	.0350	.3046151E-10	25
24	.8080	.8400	.0350	.0400	.1170882E-09	25
25	.8080	.8400	.0400	.0450	.3611473E-09	25
26	.7760	.8080	.0239	.0250	.3898640E-12	25
27	.7760	.8080	.0250	.0300	.6721435E-11	25
28	.7760	.8080	.0300	.0350	.3488781E-10	25
29	.7760	.8080	.0350	.0400	.1341320E-09	25
30	.7760	.8080	.0400	.0450	.4136248E-09	25
31	.7440	.7760	.0229	.0250	.6820726E-12	25
32	.7440	.7760	.0250	.0300	.7698112E-11	25
33	.7440	.7760	.0300	.0350	.3595728E-10	25
34	.7440	.7760	.0350	.0400	.1535881E-09	25
35	.7440	.7760	.0400	.0450	.4737277E-09	25
36	.7120	.7440	.0219	.0250	.9490456E-12	25
37	.7120	.7440	.0250	.0300	.8816708E-11	25
38	.7120	.7440	.0300	.0350	.4576338E-10	25
39	.7120	.7440	.0350	.0400	.1759057E-09	25
40	.7120	.7440	.0400	.0450	.5425641E-09	25
41	.6800	.7120	.0209	.0250	.1203263E-11	25
42	.6800	.7120	.0250	.0300	.1009785E-10	25
43	.6800	.7120	.0300	.0350	.5241316E-10	25
44	.6800	.7120	.0350	.0400	.2014661E-09	25
45	.6800	.7120	.0400	.0450	.6214029E-09	25
46	.6480	.6800	.0199	.0200	.4223042E-15	25
47	.6480	.6800	.0200	.0250	.1451370E-11	25
48	.6480	.6800	.0250	.0300	.1156514E-10	25
49	.6480	.6800	.0300	.0350	.6002920E-10	25
50	.6480	.6800	.0350	.0400	.2307407E-09	25
51	.6480	.6800	.0400	.0450	.7116976E-09	25
52	.6160	.6480	.0189	.0200	.5629170E-13	25
53	.6160	.6480	.0200	.0250	.1652265E-11	25
54	.6160	.6480	.0250	.0300	.1324565E-10	25
55	.6160	.6480	.0300	.0350	.6875191E-10	25
56	.6160	.6480	.0350	.0400	.2642692E-09	25
57	.6160	.6480	.0400	.0450	.8151128E-09	25
58	.5840	.6160	.0180	.0200	.9614576E-13	25

Figure 4-32. Stratification Description for Sample Problem 7

59	.5840	.6160	.0200	.0250	.1903803E-11	25
60	.5840	.6160	.0250	.0300	.1517034E-10	25
61	.5840	.6160	.0300	.0350	.7874211E-10	25
62	.5840	.6160	.0350	.0400	.3026696E-09	25
63	.5840	.6160	.0400	.0450	.9335550E-09	25
64	.5520	.5540	.0170	.0200	.1290690E-12	25
65	.5520	.5840	.0200	.0250	.2180443E-11	25
66	.5520	.5840	.0250	.0300	.1737471E-10	25
67	.5520	.5840	.0300	.0350	.9018395E-10	25
68	.5520	.5840	.0350	.0400	.3466498E-09	25
69	.5520	.5840	.0400	.0450	.1069208E-08	25
70	.5200	.5520	.0160	.0200	.1586221E-12	25
71	.5200	.5520	.0200	.0250	.2497278E-11	25
72	.5200	.5520	.0250	.0300	.1589939E-10	25
73	.5200	.5520	.0300	.0350	.1032884E-09	25
74	.5200	.5520	.0350	.0400	.3970207E-09	25
75	.5200	.5520	.0400	.0450	.1224572E-08	25
76	.4880	.5200	.0150	.0200	.1874967E-12	25
77	.4880	.5200	.0200	.0250	.2860153E-11	25
78	.4880	.5200	.0250	.0300	.2279093E-10	25
79	.4880	.5200	.0300	.0350	.1182970E-09	25
80	.4880	.5200	.0350	.0400	.4547110E-09	25
81	.4880	.5200	.0400	.0450	.1402512E-08	25
82	.4560	.4880	.0140	.0150	.2935832E-14	25
83	.4560	.4880	.0150	.0200	.2147473E-12	25
84	.4560	.4880	.0200	.0250	.3275755E-11	25
85	.4560	.4880	.0250	.0300	.2610263E-10	25
86	.4560	.4880	.0300	.0350	.1354865E-09	25
87	.4560	.4880	.0350	.0400	.5207840E-09	25
88	.4560	.4880	.0400	.0450	.1606308E-08	25
89	.4240	.4560	.0130	.0150	.4755487E-14	25
90	.4240	.4560	.0150	.0200	.2459518E-12	25
91	.4240	.4560	.0200	.0250	.3751748E-11	25
92	.4240	.4560	.0250	.0300	.2989555E-10	25
93	.4240	.4560	.0300	.0350	.1551737E-09	25
94	.4240	.4560	.0350	.0400	.5964580E-09	25
95	.4240	.4560	.0400	.0450	.1839717E-08	25
96	.3920	.4240	.0121	.0150	.6046488E-14	25
97	.3920	.4240	.0150	.0200	.2816905E-12	25
98	.3920	.4240	.0200	.0250	.4296906E-11	25
99	.3920	.4240	.0250	.0300	.3423960E-10	25
100	.3920	.4240	.0300	.0350	.1777217E-09	25
101	.3920	.4240	.0350	.0400	.6831280E-09	25
102	.3920	.4240	.0400	.0450	.2107042E-08	25
103	.3600	.3920	.0111	.0150	.7158538E-14	25
104	.3600	.3920	.0150	.0200	.3226224E-12	25
105	.3600	.3920	.0200	.0250	.4921280E-11	25
106	.3600	.3920	.0250	.0300	.3921469E-10	25
107	.3600	.3920	.0300	.0350	.2035460E-09	25
108	.3600	.3920	.0350	.0400	.7823919E-09	25
109	.3600	.3920	.0400	.0450	.2413212E-08	25

SUM OF CELL PROBABILITIES = .2533052746E-07

--CELL-- 46HAS PROBABILITY LESS THAN .100E-14

Figure 4-32. (continued)

- - - SAMPLE7, SCC ONLY, NO RESIDUAL, VIERATORY, PSI, HYDRO, NO ISI

- - RESULTS WITHOUT EARTHQUAKES - - -

TIME	AVG LEAK	AVG BIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	0.	0.	0.	0.	0.	0.
1.0	2.10542E-10	2.10542E-10	2.23911E-13	4.38612E-12	4.38612E-12	1.86679E-14
2.0	2.27911E-10	2.27911E-10	2.24962E-13	1.45909E-12	1.45909E-12	1.86675E-14
3.0	2.36037E-10	2.36037E-10	2.26542E-13	2.99231E-12	2.99231E-12	1.86750E-14
4.0	2.67707E-10	2.67707E-10	2.26892E-13	7.16567E-12	7.16567E-12	1.86775E-14
5.0	2.89348E-10	2.89348E-10	2.27253E-13	7.20343E-12	7.20343E-12	1.86799E-14
6.0	2.99475E-10	2.99475E-10	2.27253E-13	6.83928E-12	6.83928E-12	1.86799E-14
7.0	3.14148E-10	3.14148E-10	2.28055E-13	5.75351E-12	5.75351E-12	1.86851E-14
8.0	3.33100E-10	3.33100E-10	2.28471E-13	1.48132E-12	1.48132E-12	1.86873E-14
9.0	3.45138E-10	3.45138E-10	2.28895E-13	5.86606E-12	5.86606E-12	1.86894E-14
10.0	3.63732E-10	3.63732E-10	2.28895E-13	8.08548E-12	8.08548E-12	1.86894E-14
11.0	3.72293E-10	3.72293E-10	2.29451E-13	9.30586E-12	9.30586E-12	1.86968E-14
12.0	3.89307E-10	3.89307E-10	2.30010E-13	1.05455E-11	1.05455E-11	1.87041E-14
13.0	4.18708E-10	4.18708E-10	2.30055E-13	1.10757E-11	1.10757E-11	1.87041E-14
14.0	4.32661E-10	4.32661E-10	2.30087E-13	1.07391E-11	1.07391E-11	1.87041E-14
15.0	4.49426E-10	4.49426E-10	2.30684E-13	9.77198E-12	9.77198E-12	1.87119E-14
16.0	4.59414E-10	4.59414E-10	2.31300E-13	8.64949E-12	8.64949E-12	1.87193E-14
17.0	4.68065E-10	4.68065E-10	2.31941E-13	7.68892E-12	7.68892E-12	1.87266E-14
18.0	4.84651E-10	4.84651E-10	2.32595E-13	2.94533E-12	2.94533E-12	1.87331E-14
19.0	4.94255E-10	4.94255E-10	2.32595E-13	6.25305E-12	6.25305E-12	1.87331E-14
20.0	5.08161E-10	5.08161E-10	2.32604E-13	1.01831E-11	1.01831E-11	1.87331E-14
21.0	5.20131E-10	5.20131E-10	2.32619E-13	1.17594E-11	1.17594E-11	1.87331E-14
22.0	5.35705E-10	5.35705E-10	2.33425E-13	1.37734E-11	1.37734E-11	1.87498E-14
23.0	5.41822E-10	5.41822E-10	2.34265E-13	1.39730E-11	1.39730E-11	1.87658E-14
24.0	5.59060E-10	5.59060E-10	2.34329E-13	1.49459E-11	1.49459E-11	1.87658E-14
25.0	5.75730E-10	5.75730E-10	2.34361E-13	1.56026E-11	1.56026E-11	1.87658E-14
26.0	5.98439E-10	5.98439E-10	2.34378E-13	1.67773E-11	1.67773E-11	1.87658E-14
27.0	6.16905E-10	6.16905E-10	2.34378E-13	1.70096E-11	1.70096E-11	1.87658E-14
28.0	6.30746E-10	6.30746E-10	2.34378E-13	1.68867E-11	1.68867E-11	1.87658E-14
29.0	6.33581E-10	6.33581E-10	2.34412E-13	1.68373E-11	1.68373E-11	1.87658E-14
30.0	6.38032E-10	6.38032E-10	2.34430E-13	1.67624E-11	1.67624E-11	1.87658E-14
31.0	6.59289E-10	6.59289E-10	2.34448E-13	1.60421E-11	1.60421E-11	1.87658E-14
32.0	6.83528E-10	6.83528E-10	2.34484E-13	1.41258E-11	1.41258E-11	1.87658E-14
33.0	7.13002E-10	7.13002E-10	2.34539E-13	8.15233E-12	8.15233E-12	1.87658E-14
34.0	7.15445E-10	7.15445E-10	2.34539E-13	7.90596E-12	7.90596E-12	1.87658E-14
35.0	7.25447E-10	7.25447E-10	2.34558E-13	3.71098E-12	3.71098E-12	1.87658E-14
36.0	7.26351E-10	7.26351E-10	2.34596E-13	3.67543E-12	3.67543E-12	1.87658E-14
37.0	7.36193E-10	7.36193E-10	2.34635E-13	9.68964E-12	9.68964E-12	1.87658E-14
38.0	7.57871E-10	7.57871E-10	2.34635E-13	1.56456E-11	1.56456E-11	1.87658E-14
39.0	7.76984E-10	7.76984E-10	2.34635E-13	1.90605E-11	1.90605E-11	1.87658E-14
40.0	7.98063E-10	7.98063E-10	2.34660E-13	2.14072E-11	2.14072E-11	1.87658E-14

Figure 4-33 Results of the No Earthquake Case in Sample Problem 7

4.3 Sample Problem 8: SCC-Leak

Sample problem 8 presents an analysis in which leak probabilities for a weld in BWR piping are calculated. The inputs used to describe the environment and geometry are very similar to those used in sample problem 7. The primary differences are:

- Fatigue crack growth and stress corrosion cracking are modeled (ISCC = -1).
- The heatup-cooldown transient has been added. These are assumed to occur at 0.2 year intervals throughout the lifetime of the plant.
- The stratification scheme has been expanded to include all cracks which can lead to leaks during the lifetime of the plant (NAOH = -3, NAOB = -20, ANHOP = 0.30, ANHLEW = 1.00, AOBLEFT = 0.0, and AOBRIGHT = 1.0). The probability of finding an initial crack in this region is 0.270.
- Fifty samples are taken from each cell (HTKIES = - 50).

As in sample problem 7, the LESPCT subroutine in PRAISE-B must be modified to accommodate BWR piping materials. The card images, input summary, and stratification scheme are shown in Figures 4-34, 4-35, and 4-36. The results are tabulated in Figure 4-37.

SAMPLE 8, LEAK, SCC AND FATIGUE, NO RESIDUAL, VIBRATION, PSI, PTDRO, NO ISI															
-50	1	1	3	-1	0	0	0	0	0	48	0	10	1	-1	0
40.		0.10													
1.043		10.8													
4.6		4.9		9.14-12		3.50-11									
44.9		1.373													
4.065															
1.336		0.538		1.419											
2.0		2.0													
-3	-20	0.36		1.00		0.0		1.0							
0.51		3.90		1.05		1.563		1.0		0.9					
1	-0.2	478.5		HEATUP FROM COLD SHUTDOWN TO HOT STANDBY											

Figure 4-34 Card Images for Input to Sample Problem 8

```

--- SAMPLE LEAK, SCC AND FATIGUE, NO RESIDUAL VIBRATORY, PSI, MICRO, NO ISI ---

SCC AND FATIGUE CRACK GROWTH
TIMESCALE FOR SCC = 100 YEARS

PIPE DIMENSIONS
  INSIDE RADIUS = 11.40 INCHES
  WALL THICKNESS = 1.04 INCHES

INITIAL CRACK SIZE DISTRIBUTION
CRACK LENGTH IS EXPONENTIAL
  PARAMETER = 4.0000
ASPECT RATIO IS LOG-NORMAL
  MEDIAN = 1.3300
  SHAPE PARAMETER = .0000
  NORMALIZATION CONSTANT = 1.4167

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

PIPE STRESS VALUES
  CSD CLADDT STRESS (KSI) = .51
  HOT UNIFORM STRESS (KSI) = 9.34
  PRESSURE STRESS (KSI) = 5.44
  VIBRATORY STRESSES (KSI) = 1.00
  R-RATIO LIMIT (R-STAR) = .90
  PROOF TEST STRESS (KSI) = 8.60

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

NO RESIDUAL STRESSES ARE MODELED

VIBRATORY STRESSES ARE MODELED

PRE-SERVICE ULTRASONIC INSPECTION IS MODELED

TIME INTERVALS
  PLANT LIFETIME = 40.0 YEARS
  ENDPOINTS OF INTERVALS AT 0. 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 YEARS
  ENDPOINTS OF INTERVALS AT 10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 YEARS
  ENDPOINTS OF INTERVALS AT 20.0 21.0 22.0 23.0 24.0 25.0 26.0 27.0 28.0 29.0 YEARS
  ENDPOINTS OF INTERVALS AT 30.0 31.0 32.0 33.0 34.0 35.0 36.0 37.0 38.0 39.0 YEARS
  ENDPOINTS OF INTERVALS AT 40.0

NO IN-SERVICE INSPECTIONS ARE MODELED

--- NO SEISMIC EVENTS EVALUATED ---

SKIP PARAMETER FOR INDICATOR FUNCTION PRINTOUT IS 10

--- NORMAL OUTPUT REQUESTED ---

```

Figure 4-35 Input Summary for Sample Problem 8

..... - - NUMBER OF TRANSIENT TYPES = 1 - -
TYPE 1 HEATUP FROM COLD SHUTDOWN TO HOT STANDBY
REGULATED AT 200 YRS/EVENT
MAX DELTA TEMP = 478.5 BLOCKING FACTOR = 1.

Figure 4-35 (continued)

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

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

CELL	AGP1	AGP2	AGP1	AGP2	PROBABILITY	SAMPLES
1	.7667	1.0000	.0236	.0500	.8598763E-06	50
2	.7667	1.0000	.0500	.1000	.3196568E-05	50
3	.7667	1.0000	.1000	.1500	.4602632E-04	50
4	.7667	1.0000	.1500	.2000	.1529329E-03	50
5	.7667	1.0000	.2000	.2500	.4792784E-03	50
6	.7667	1.0000	.2500	.3000	.6361057E-03	50
7	.7667	1.0000	.3000	.3500	.1199239E-02	50
8	.7667	1.0000	.3500	.4000	.1514777E-02	50
9	.7667	1.0000	.4000	.4500	.1754273E-02	50
10	.7667	1.0000	.4500	.5000	.1910297E-02	50
11	.7667	1.0000	.5000	.5500	.1963646E-02	50
12	.7667	1.0000	.5500	.6000	.2001654E-02	50
13	.7667	1.0000	.6000	.6500	.1963688E-02	50
14	.7667	1.0000	.6500	.7000	.1888556E-02	50
15	.7667	1.0000	.7000	.7500	.1796269E-02	50
16	.7667	1.0000	.7500	.8000	.1672616E-02	50
17	.7667	1.0000	.8000	.8500	.1545195E-02	50
18	.7667	1.0000	.8500	.9000	.1423685E-02	50
19	.7667	1.0000	.9000	.9500	.1300123E-02	50
20	.7667	1.0000	.9500	1.0000	.1181279E-02	50
21	.5333	.7667	.0164	.0500	.2313080E-07	50
22	.5333	.7667	.0500	.1000	.8597618E-05	50
23	.5333	.7667	.1000	.1500	.1237792E-03	50
24	.5333	.7667	.1500	.2000	.5345928E-03	50
25	.5333	.7667	.2000	.2500	.1268929E-02	50
26	.5333	.7667	.2500	.3000	.2246549E-02	50
27	.5333	.7667	.3000	.3500	.3225129E-02	50
28	.5333	.7667	.3500	.4000	.4073708E-02	50
29	.5333	.7667	.4000	.4500	.4717787E-02	50
30	.5333	.7667	.4500	.5000	.5137395E-02	50
31	.5333	.7667	.5000	.5500	.5348090E-02	50
32	.5333	.7667	.5500	.6000	.5383073E-02	50
33	.5333	.7667	.6000	.6500	.5280969E-02	50
34	.5333	.7667	.6500	.7000	.5078918E-02	50
35	.5333	.7667	.7000	.7500	.4805214E-02	50
36	.5333	.7667	.7500	.8000	.4498186E-02	50
37	.5333	.7667	.8000	.8500	.4166281E-02	50
38	.5333	.7667	.8500	.9000	.3826733E-02	50
39	.5333	.7667	.9000	.9500	.3496437E-02	50
40	.5333	.7667	.9500	1.0000	.3176828E-02	50
41	.3000	.5333	.6092	.6500	.6220609E-07	50
42	.3000	.5333	.6500	.1000	.2312168E-04	50
43	.3000	.5333	.1000	.1500	.3328808E-03	50
44	.3000	.5333	.1500	.2000	.1438763E-02	50
45	.3000	.5333	.2000	.2500	.3466333E-02	50
46	.3000	.5333	.2500	.3000	.6047051E-02	50
47	.3000	.5333	.3000	.3500	.8673380E-02	50
48	.3000	.5333	.3500	.4000	.1095547E-01	50
49	.3000	.5333	.4000	.4500	.1268760E-01	50
50	.3000	.5333	.4500	.5000	.1391603E-01	50
51	.3000	.5333	.5000	.5500	.1438262E-01	50
52	.3000	.5333	.5500	.6000	.1447676E-01	50
53	.3000	.5333	.6000	.6500	.1420218E-01	50
54	.3000	.5333	.6500	.7000	.1365880E-01	50
55	.3000	.5333	.7000	.7500	.1293348E-01	50
56	.3000	.5333	.7500	.8000	.1209702E-01	50
57	.3000	.5333	.8000	.8500	.1120443E-01	50
58	.3000	.5333	.8500	.9000	.1029666E-01	50
59	.3000	.5333	.9000	.9500	.9403110E-02	50
60	.3000	.5333	.9500	1.0000	.8543482E-02	50

SUM OF CELL PROBABILITIES = .2697646675E+00

Figure 4-36 Stratification Description for Sample Problem 8

- - - SAMPLE, LEAK, SCC AND FATIGUE, I.D. RESIDUAL, VIBRATORY, PSI, HYDRO, NO ISI - - -

- - RESULTS WITHOUT EARTHQUAKES - - -

TIME	AVG LEAK	AVG FIG LEAK	AVG LOCA	SIGMA LEAK	SIGMA BIG LEAK	SIGMA LOCA
0.	3.06369E-04	3.59740E-04	0.	1.16634E-05	1.16112E-05	0.
1.0	4.22530E-04	3.95869E-04	0.	1.19613E-05	1.18947E-05	0.
2.0	4.48973E-04	4.29101E-04	0.	1.24770E-05	1.24251E-05	0.
3.0	4.69466E-04	4.54986E-04	0.	1.27035E-05	1.26659E-05	0.
4.0	4.87534E-04	4.75819E-04	0.	1.30210E-05	1.29569E-05	0.
5.0	5.11200E-04	5.00406E-04	0.	1.33799E-05	1.33404E-05	0.
6.0	5.30906E-04	5.21796E-04	0.	1.36856E-05	1.36548E-05	0.
7.0	5.50429E-04	5.42951E-04	0.	1.55276E-05	1.55283E-05	0.
8.0	5.77247E-04	5.69493E-04	0.	1.74626E-05	1.74673E-05	0.
9.0	5.93483E-04	5.83515E-04	0.	1.76971E-05	1.76319E-05	0.
10.0	6.13407E-04	6.02439E-04	0.	1.78764E-05	1.77529E-05	0.
11.0	6.25677E-04	6.19650E-04	0.	1.83546E-05	1.84002E-05	0.
12.0	6.06591E-04	6.53173E-04	0.	2.28582E-05	2.28153E-05	0.
13.0	6.97156E-04	6.50281E-04	0.	2.47923E-05	2.47513E-05	0.
14.0	7.37140E-04	7.29275E-04	0.	2.71343E-05	2.70839E-05	0.
15.0	7.51232E-04	7.54766E-04	0.	2.90060E-05	2.89695E-05	0.
16.0	7.76418E-04	7.64669E-04	0.	2.90692E-05	2.90575E-05	0.
17.0	7.93126E-04	7.84416E-04	0.	3.00831E-05	3.00245E-05	0.
18.0	8.15154E-04	8.07674E-04	0.	3.16955E-05	3.16826E-05	0.
19.0	8.38460E-04	8.31442E-04	0.	3.33123E-05	3.33001E-05	0.
20.0	8.61185E-04	8.52205E-04	0.	3.44110E-05	3.43652E-05	0.
21.0	9.10797E-04	8.99902E-04	0.	3.74203E-05	3.73516E-05	0.
22.0	9.26152E-04	9.11750E-04	0.	3.75383E-05	3.74247E-05	0.
23.0	9.46158E-04	9.32421E-04	0.	3.77125E-05	3.75946E-05	0.
24.0	9.50266E-04	9.41641E-04	0.	3.77449E-05	3.76505E-05	0.
25.0	9.64915E-04	9.55078E-04	0.	3.81046E-05	3.80387E-05	0.
26.0	9.72127E-04	9.65846E-04	0.	3.80895E-05	3.80510E-05	0.
27.0	9.95110E-04	9.87603E-04	0.	3.93703E-05	3.93088E-05	0.
28.0	1.01370E-03	1.00546E-03	0.	4.05014E-05	4.04425E-05	0.
29.0	1.04764E-03	1.03809E-03	0.	4.31084E-05	4.30367E-05	0.
30.0	1.05706E-03	1.05219E-03	0.	4.31447E-05	4.31135E-05	0.
31.0	1.06204E-03	1.07459E-03	0.	4.48567E-05	4.48063E-05	0.
32.0	1.10101E-03	1.08963E-03	0.	4.54965E-05	4.54093E-05	0.
33.0	1.12290E-03	1.11603E-03	0.	4.65142E-05	4.64664E-05	0.
34.0	1.14045E-03	1.13135E-03	0.	4.68363E-05	4.67743E-05	0.
35.0	1.16142E-03	1.15166E-03	0.	4.85215E-05	4.84550E-05	0.
36.0	1.17725E-03	1.17117E-03	0.	4.92620E-05	4.92201E-05	0.
37.0	1.19603E-03	1.19201E-03	0.	5.06055E-05	5.05827E-05	0.
38.0	1.21449E-03	1.20716E-03	0.	5.16413E-05	5.15994E-05	0.
39.0	1.24313E-03	1.23762E-03	0.	5.33755E-05	5.33470E-05	0.
40.0	1.25559E-03	1.24693E-03	0.	5.33943E-05	5.33490E-05	0.

Figure 4-37 Results of the No Earthquake Case in Sample Problem 8

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5.0 RESULTS AND DISCUSSION

The series of sample problems presented in Section 4 were intended to illustrate the use of the PRAISE-B code for a variety of conditions and was included for the use of the PRAISE-B code user. In Section 6 attention is turned to the presentation and discussion of results for the various line sizes and conditions discussed in Section 2. The emphasis in this section is on the significance of the results, with minimal consideration of the mechanics involved in generating the results by use of the PRAISE-B computer code.

Unless otherwise stated, all results presented in this section are conditional on a crack being initially present and are for the following set of conditions

- pre-service ultrasonic inspection (no in-service inspection)
- pre-service proof test
- heatup-cooldown only operating transient
- exponentially distributed crack depth (eq. A-4)
- lognormally distributed aspect ratio (eq. A-5)

These correspond closely to the base case set of conditions employed for the Zion primary piping in reference 1.

5.1 Fatigue Crack Growth

Analyses of fatigue crack growth in circumferential welds were limited to the 34 inch hot leg to pressure vessel joint of a PWR. This corresponds to joint number 1 in reference 1. The stresses in Table 2-1 were employed, and the fatigue crack growth relation was the same as utilized in reference 1. The parameter C in the fatigue crack growth equation (see eq. 2-2) was taken to be lognormally distributed. The detection probability was the same as employed in reference 1; for the cast austenitic materials a crack must be half way through the thickness before it has a 50% chance of being detected.

The various combinations of residual and vibratory stresses considered are summarized in Table 5-1, which also provides the cumulative leak and LOCA probabilities at times of 2, 10 and 40 years. The LOCA results with residual stress and $\Delta\sigma_v = 1$ correspond to sample problem 5 which was discussed in Section 4.5. All results are conditional on a crack being initially present.

TABLE 5-1

Summary of Cumulative Leak and LOCA Probabilities for a
PWR Hot Leg Weld for Various Times. Results
are Conditional on a Crack Being Initially Present.

	σ_{res}	$\Delta\sigma_v$, ksi	leak			LOCA		
			t = 2 yrs	10	40	2	10	40
fatigue	no	0	2.3×10^{-7}	4.5×10^{-7}	8.6×10^{-7}	0	3.6×10^{-13}	2.3×10^{-12}
		$\frac{1}{2}$	1.4×10^{-5}	1.5×10^{-5}	1.5×10^{-5}	7.3×10^{-11}	7.3×10^{-11}	7.5×10^{-11}
		1	1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	1.6×10^{-10}	1.6×10^{-10}	1.6×10^{-10}
	yes*	0	2.3×10^{-7}	4.3×10^{-7}	7.9×10^{-7}	0	0	4.7×10^{-13}
		$\frac{1}{2}$	2.3×10^{-5}	2.3×10^{-5}	2.3×10^{-5}	2.4×10^{-11}	2.4×10^{-11}	2.4×10^{-11}
		1	2.3×10^{-5}	2.3×10^{-5}	2.3×10^{-5}	2.4×10^{-11}	2.4×10^{-11}	2.4×10^{-11}
SCC	no	0	1.1×10^{-3}	4.4×10^{-2}	1.7×10^{-1}	1.5×10^{-10}	1.6×10^{-10}	1.6×10^{-10}

* Figure 2-3 for stresses, Figure 2-9 for stress intensity factors

Results for stress corrosion crack growth (SCC) (with kinetics given by equation 2-1) for the 34 inch line are also given in order to provide a direct comparison between predictions for fatigue and SCC. Consideration of stress corrosion cracking for a PWR hot leg is not consistent with field experience; such analyses are included here only to provide perspective on the expected behavior due to the two different crack growth mechanisms.

Figure 5-1 summarizes results for the conditional leak probabilities for the 34 inch line. The following observations are drawn from this figure:

- Residual stresses have a minimal but beneficial influence on the leak probabilities in the absence of vibratory stresses. This is expected; residual stresses have a minimal influence on fatigue crack growth because they affect only the load ratio (R) and not the cyclic stress intensity factor (ΔK).
- Residual stresses have much more of a beneficial influence when vibratory stresses are present (for the 34 in. line). This is because the residual stresses result in negative K_{max} due to vibratory stresses, in which case vibration will have no influence.
- Vibratory stresses have a strong influence on the calculated leak probabilities, and the influence is a strong function of the vibratory stress amplitude ($\Delta\sigma_v$).
- Stress corrosion cracking results in a much higher leak probability than fatigue crack growth. This is expected, and is consistent with field observations.
- The time dependence of the leak probabilities are quite strong in the absence of vibratory stresses. The time dependencies are virtually eliminated when vibratory stresses are considered. The absence of time effects in the presence of vibratory stress is not surprising, and is partially due to the simplification discussed in Section 2.4.3. Any crack with ΔK due to vibratory stresses above the threshold is taken to fail immediately. Any crack small enough that the vibratory threshold is not exceeded, is also small enough that it will not grow significantly due to the normal operating stress. Therefore, cracks will either grow to failure very rapidly — or not at all.

Corresponding results for the LOCA probabilities are presented in Figure 5-2. Once again, residual stresses are beneficial with the benefit being

Figure 5-1: Cumulative Leak Probability for 34 Inch Line Under Various Conditions. Results are Conditional on a Crack Being Initially Present.

Figure 5-2: Cumulative Probability of a Sudden and Complete Pipe Severance for the 34 Inch Line Weld Joint Under Various Conditions. Results are Conditional on a Crack Being Initially Present.

more pronounced than in the leak results. Vibratory stresses and stress corrosion cracking are observed to be detrimental, and to produce results that are virtually independent of time. The time independence of the vibratory stress results is observed for the same reason as in the case of leaks. The time independence of the SCC LOCA results is in marked contrast to the SCC leak results. These observations are not surprising. As discussed in Section 2.5.4, and summarized in Figure 2-14 and Table 2-4, cracks that cause failure when the residual stresses are present are either very deep and long to begin with (in which case they cause failure in a very short time), or will grow primarily in the depth direction (to produce a leak rather than a LOCA). This topic is discussed more fully in reference 24.

5.2 Stress Corrosion Cracking

Analyses of stress corrosion crack growth were performed using the crack growth kinetics of equation 2-1. The various pipe sizes summarized in Table 2-1 were considered. Calculations were performed for the base case set of conditions discussed at the beginning of Section 5. The detection probabilities were altered for the lines other than the 34 inch line. The 34 inch line is cast austenitic with a 2.5 inch wall thickness. Cracks are difficult to detect in thick cast materials. The smaller lines considered here are considerably thinner, and fabricated from wrought material. These two factors make it easier to detect cracks. Therefore, the nondetection probability employed was altered to the following:

$$P_{ND}(A) = \frac{1}{2}(1-\epsilon) \operatorname{erfc}(\nu \ln A/A^*) + \epsilon \quad (5.1)$$

$$\nu = 1.33$$

$$\epsilon = 0.005$$

$$A^* = \frac{\pi}{4} D_B a^*$$

$$D_B = 1 \text{ in.}$$

$$a^* = 1/4 \text{ in.}$$

$$A = \begin{cases} \frac{\pi}{2} a b & 2b < D_B \\ \frac{\pi}{2} a D_B & 2b > D_B \end{cases}$$

This is very close to the same form used in reference 1 (eq. 2-29, p. 56; ref. 1), but has been altered to provide a higher probability of detection (lower P_{ND}). The detection probability of equation 5-1 is very similar to results presented in Figures 2-10 and 2-11 of reference 1. The major difference is $a^* = 0.35$ in. in those figures. The values of crack depth shown in those figures are less than 1 in. At these depths the value of ϵ is not influential (if ϵ is less than about 0.01). A comparison of Figures 2-10 and 2-13 provides a comparison of the two nondetection probabilities employed. Considerable differences exist.

The value of a^* used in reference 1 was 1.25 in., with $\nu = 1.60$. The parameter ϵ in equation 4-1 is the value of P_{ND} for very large a . The detection probability used in reference 1 gave a value of 0.05 for a 2.5 in. deep crack. A lower limit value of P_{ND} had not yet been reached and the use of ϵ was not needed. In equation 1, ϵ is employed to produce a lower limit on nondetection probability as crack size gets larger. For $\epsilon = 0.005$ and the values of ν and a^* employed, ϵ does not have a strong influence for $a < \sim 1$ in. The use of a lower limit ϵ on P_{ND} is similar to procedures employed in the Marshall report (32, 33) and utilized in reference 7. The above values of ν and a^* are similar to those used in previous investigations (7, 34) and are based on experimental evidence. The nondetection probabilities of equation 5-1 are considerably more favorable than those employed for the thick cast austenitic piping considered in reference 1 and Section 5.1.

The various pipe sizes and combinations of residual and vibratory stresses employed are summarized in Table 5-2, which also provides the cumulative leak and LOCA probabilities at times 2, 10 and 40 years. These results are conditional on a crack being initially present. Figure 5-3 summarizes the results for the conditional leak probabilities. The following observations are drawn from this figure:

- Of the three size lines considered the 34 in. line has the highest failure probability in the absence of residual stresses. This is due to the larger line having higher applied stresses (see Table 2-1), and a less favorable detection probability.

TABLE 5-2

Summary of Cumulative Leak and LOCA Probabilities for
Stress Corrosion Cracking in Various Pipe Sizes. Results are
Conditional on a Crack Being Initially Present.

line size	σ_{res}	$\Delta\sigma_v$	leak			LOCA		
			t = 2 yrs.	10	40	2	10	40
34	no	0	1.1×10^{-3}	4.4×10^{-2}	1.7×10^{-1}	1.5×10^{-10}	1.6×10^{-10}	1.6×10^{-10}
24	no	0	5.6×10^{-5}	2.5×10^{-4}	9.4×10^{-4}	2.0×10^{-13}	2.3×10^{-13}	2.3×10^{-13}
	yes ¹	0	5.0×10^{-5}	6.3×10^{-5}	6.7×10^{-5}	5.1×10^{-14}	6.3×10^{-14}	7.0×10^{-14}
	no	1	4.3×10^{-4}	6.0×10^{-4}	1.2×10^{-3}	2.2×10^{-13}	2.3×10^{-13}	2.3×10^{-13}
16	no	0	2.7×10^{-4}	1.6×10^{-3}	5.9×10^{-3}	5.5×10^{-12}	6.1×10^{-12}	6.2×10^{-12}
	yes ²	0	1.1×10^{-2}	3.9×10^{-1}	6.1×10^{-1}	6.7×10^{-12}	6.7×10^{-12}	6.7×10^{-12}

1. Figure 2-3 for stresses, Figure 2-11 for stress intensity factors.

2. Table 2-3 for stresses, Figure 2-13 for stress intensity factors.

Figure 5-3: Cumulative Leak Probability in Various Size Lines With Cracks Growing due to Stress Corrosion Cracking. Results are Conditional on a Crack Being Initially Present.

- Vibratory stresses are not as influential as in the case of fatigue. This is due to the higher crack growth rates in the case of SCC (as contrasted to fatigue) due to normal plant operation.
- Residual stresses have a considerable influence that is either beneficial (24 in. line) or detrimental (16 in. line). The larger influence of residual stresses in SCC than in fatigue is expected, because the residual stresses strongly influence K_{max} which is the controlling parameter in the SCC model. As discussed above, in the case of fatigue residual stresses do not effect ΔK — the primary controlling factor in fatigue crack growth. The beneficial influence of residual stresses in the 24 in. line is expected and is due to the negative K values calculated for this line (see Figure 2-10) The detrimental influence of residual stresses for the 16 in. line are also as expected and is due to the positive K values for this line (see Figure 2-12).

Corresponding results for the LOCA probabilities are presented in Figure 5-4. In this case, vibratory stresses have virtually no influence (see Table 5-2). This is not surprising. Once again, residual stresses have a beneficial (24 in.) or detrimental (16 in.) influence, which is not as strong as in the case of leaks. Time dependencies are seen to be very weak. The reasons for this are the same as discussed for the case of fatigue.

The high failure probabilities predicted for the 34 in. line in the case of stress corrosion cracking are somewhat surprising. It was expected that the thicker wall pipe would have a lower failure probability. Two factors can be contributing to the high calculated failure probability: the applied stress is higher in this line than the smaller lines; and the detection probabilities are much less favorable for this thick cast line. In order to assess the influence of the nondetection probability, calculations were performed for the 34 in. line using the more favorable nondetection probabilities that were utilized for the smaller lines (eq.5-1). The following leak probabilities resulted. Also shown are the corresponding values from Table 5-2.

	$t = 2$	10	40 yrs
more favorable P_{ND}	1.7×10^{-5}	7.3×10^{-4}	1.1×10^{-2}
original P_{ND}	1.1×10^{-3}	4.4×10^{-2}	1.7×10^{-1}

Figure 5-4: Cumulative Probability of a Sudden and Complete Pipe Severance in Various Size Lines with Cracks Growing due to Stress Corrosion Cracking. Results are Conditional on a Crack Being Initially Present.

These results show a 1 - 2 order of magnitude decrease when the more favorable nondetection probabilities are employed. Such differences are easily attributed to the different nondetection probabilities. The leak probabilities for the more favorable P_{ND} for the 34 in. line are still higher than the corresponding results for smaller lines shown in Table 6-2. However, the results are now roughly comparable and the remaining differences attributed to the different applied stresses.

5.3 Fatigue of Longitudinal Welds

Analyses of fatigue crack growth in a longitudinal weld were performed using the stresses discussed in Section 2.6.1. Results were generated for the two different failure criteria discussed in Section 2.6.2. Sample problem 6 (Section 4.6) corresponds to the leak results that employ the Kiefner failure criterion. Once again the results consider only a pre-service inspection in conjunction with an initial hydrostatic proof test. Nondetection probabilities for cast austenitic materials were employed ($a^* = h/2$). Results for the conditional cumulative leak probabilities are presented in Figure 5-5 for the two failure criteria considered (Kiefner and tearing). Also shown are the corresponding results for the hot leg to pressure vessel joint. Figure 5-5 reveals that the leak probabilities for the circumferential weld are higher than corresponding values for the longitudinal weld. Also the use of the Kiefner criterion results in a higher predicted leak probability than the tearing criterion. However, the results for the two criteria are generally within an order of magnitude of each other, except for small times. Hence, the failure criterion employed does not have a strong influence on the calculated leak probabilities.

Corresponding results for a large slot failure are presented in Figure 5-6. Once again, it is seen that the Kiefner criterion predicts higher failure probabilities, but that the two sets of longitudinal results differ by less than an order of magnitude (for times greater than 5 years). However, in contrast to the leak probability results, the probability of a large failure in the longitudinal weld is higher than in the circumferential weld. The reason for this is related to the predicted lengths of critical through-wall cracks for the two weld geometries - values of which are given below

circumferential:	$b_{LOCA} = 36.8$	$(\sigma_{LC} = 8.57 \text{ ksi})$
longitudinal:	$b_{\text{large slot}} = 14.2 \text{ in.}$	$(\sigma_{LC} = 13.6 \text{ ksi})$

Figure 5-5. Cumulative Leak Probability for a Circumferential and a Longitudinal Weld in Hot Leg Subjected to Fatigue. Longitudinal Results for the Two Failure Criteria Depicted in Figure 2-15 are Included. Results are Conditional on a Crack Being Initially Present.

Figure 5-6: Cumulative Probability of a LOCA or Large Slot Failure in a Circumferential and a Longitudinal Weld in Hot Leg Subjected to Fatigue. Longitudinal Results for the Two Failure Criteria Depicted in Figure 2-15 are Included. Results are Conditional on a Crack Being Initially Present.

These values are calculated using the mean value of the flow stress. This large difference in the critical length of through-wall cracks is due to differences in the failure criteria employed for the two weld geometries, rather than the different stresses the welds are subjected to. The use of failure criteria that predicted about the same critical length of through-wall cracks in circumferential and longitudinal welds for the same stress levels would provide a more realistic comparison and would result in the circumferential and longitudinal results for a large failure to be closer to one another. The results presented in Figure 5-6 show that longitudinal welds should be considered when estimating pipe failure probabilities because longitudinal welds have comparable or higher predicted failure probabilities. It is important to note, however, that the failure criteria used for longitudinal welds are different from those for circumferential welds. As shown, longitudinal welds were not included in reference 1. Some interesting pieces of information regarding longitudinal welds may be worth mentioning in the following: longitudinal welds are shop welds and are therefore fabricated under better conditions than field welds. Additionally, they are usually subjected to a shop inspection and shop proof test. This would tend to reduce the failure probability of longitudinal welds, but it is not possible to accurately quantify the influence of such factors at the present time. Another factor that would reduce the influence of longitudinal welds in estimates of pipe-system reliability is that there are many more circumferential welds - at least in the primary piping at Zion 1.

The calculated probabilities for a large slot fracture are still very low, and these results would not appreciably change earlier conclusions regarding the applicability of "leak-before-break", the very low probability of a sudden and large piping failure, or the small influence of seismic events on primary piping reliability.

5.4 Additional Discussions

The end results of this investigation are summarized in Figures 5-1 through 5-6. Generally speaking, the SCC results predict a higher probability of failure than corresponding fatigue results. This is in accordance with field experience. The very low LOCA probabilities observed in reference 1 are again present. The largest LOCA probability observed is about 10^{-10} (cumulative value) which is a very small value. This result is applicable to a given joint and is conditional on a crack being initially present. Including the probability of a crack being present ($\sim 10^{-1}$, see reference 1) and considering a piping system of many weld joints ($\sim 10^2$) would still result in a very low probability of a sudden and complete pipe severance in the cases considered.

The results for the leak probabilities are in marked contrast to the LOCA results in that calculated failure probabilities cover a very wide range, with actual values depending on the conditions. Figures 5-1, 5-3 and 5-5 show values ranging from 10^{-8} to 0.6. Hence, certain cases are predicted to have high failure probabilities.

The 16 in. line with residual stress is seen to be particularly prone to leaks. The average failure rate for such a joint, including the probability of having a crack present is approximately given by the following

$$\bar{p}_{\text{leak}} \sim (8 \times 10^{-1}) V p_V^*/40 \text{ yrs.} \sim 1.3 \times 10^{-4} \text{ yr}^{-1}$$

where $p_V^* = 10^{-4}/\text{in}^3$ and $V = 2\pi D_i h^2 = 64 \text{ in}^3$ (1). This result is applicable to a sensitized weldment and is therefore conditional on the weld being sensitized. The probability of a leak having occurred in a 16 in. line in a 10 year old plant with 10 sensitized welds would be approximately 10^{-2} .

Hence, it would not be surprising to have seen a leak in a 16 in. line in operating BWRs. Numerous leaks in BWR piping have been observed (3 - 5) but not necessarily in 16 in. lines. However, these results indicate that the predicted failure probabilities are not in strong disagreement with field observations.

The LOCA probabilities in Figures 5-2 and 5-4 are invariably very low. This

was also observed in reference 1 and further emphasizes that leaks are much more likely to occur than sudden and complete pipe severances. Hence, the "leak-before-break" concept is further justified — at least for the relatively large lines considered to date. Field observations agree with this prediction, even for lines as small as 4 in.

The LOCA results for stress corrosion cracking (Figure 5-4), and leak and LOCA results when vibratory stresses are present (Figures 5-1, 5-2 and Table 5-1) all show very weak time dependencies for time beyond 5 years. Hence, any failure that occurs in these instances will be concentrated at short times. This means the maximum failure rates are predicted to be at short times. This is in agreement with results in references 6 and 7, and suggests that pipe failure due to these causes will be very unlikely once a plant has survived its first few years of service.

The large influence of residual stresses for the 16 in. line subject to stress corrosion cracking indicates that assembly stresses could be influential for this crack growth mechanism. Conversely, the lack of influence of residual stresses in the case of fatigue crack growth indicates that assembly stresses will not be influential for this crack growth mechanism. This is an expected result, as has been discussed above.

As discussed in reference 1 (page 199 and Figure 4-11), in-service inspections (ISI) have more of an influence on reducing the failure probability if the failure probability varies strongly with time. This is true up to a certain point. If the crack growth rates are very high, then the failure probabilities will show strong time variations, but inspection may not be influential because the time for a crack to grow from an easily detectable size to a critical size could be very short (much less than the time between inspections). Based on these observations, it appears that ISI would not significantly reduce LOCAs in the case of SCC or fatigue with vibratory stress. However, it could be very effective in the case of leaks due to SCC. The PRAISE code is capable of easily incorporating the influences of ISI, but this is beyond the scope of the current work. Reference 35 provides some related results in this area. Analysis of the influence of ISI in one of the more powerful uses of probabilistic fracture mechanics, because the relative benefit of ISI (when

expressed as the ratio of failure rates with and without inspection) is virtually independent of the initial crack size distribution (7, 35). Hence, this source of major uncertainty is eliminated from the problem.

The very low failure probabilities predicted in earlier work (1) suggested that important factors influencing pipe failure may have been omitted from the model. Factors such as design and construction errors and operator errors could occur with much higher probabilities than the low numbers obtained in reference 1. Hence, these factors could dominate the failure probability, thereby invalidating predictions based on the fracture mechanics model. However, results of this investigation show considerably higher failure probabilities — especially for leaks in lines subject to SCC and/or vibratory stresses. Thus, in these cases the piping reliability appears to be dominated by aspects considered in the current fracture mechanics model. In such cases, the model should provide a powerful tool for assessing the factors which influence piping reliability under a wide variety of conditions.

6.0 CONCLUDING REMARKS

The PRAISE computer code developed in earlier work to provide a means of obtaining results from a fracture mechanics model of structural reliability was modified to provide capabilities beyond those provided by the original version. Modifications were made to allow applications to materials other than the austenitic stainless steel considered earlier. This was accomplished by allowing the subcritical crack growth characteristics and failure criterion to be easily specified by the user. The ability to treat time dependent crack growth (such as stress corrosion cracking) in addition to cyclic dependent growth (such as fatigue) was also provided. Additionally, the code was modified to allow consideration of welding residual stresses and vibratory stresses. Provisions for treating longitudinal welds were also implemented. Details of the fracture mechanics considerations that enter into these modifications are provided, and details on the use of the code are included in the form of a user's manual. Sample problems are also included.

The expanded version of PRAISE, known as PRAISE-B, was then applied to a variety of problems. In addition to exercising the code, and demonstrating its capabilities, the results of such efforts provide additional perspectives on how useful and reasonable the code predictions are. Line sizes varying from 16 to 34 in. nominal diameters were considered, including various vibratory and residual stresses. Stress corrosion cracking growth and fatigue crack growth were considered.

The results obtained indicated that the probability of a sudden and complete pipe severance was invariably very low, but that the probability of developing a leak varied widely — depending on various factors considered. Invariably it was observed that the leak probabilities were much higher than the corresponding probability of a sudden and complete pipe severance. This supports the leak-before-break concept. It was found that stress corrosion cracking had a strong influence on the leak probabilities; increasing them considerably over predicted values based on fatigue crack growth considerations. This is as expected and agrees with field observations of failures in primary piping of light water reactors. Vibratory stresses of 1 ksi were found to result in a marked increase in the failure probabilities in the case of fatigue.

Residual stresses were found to have a strong influence in the case of stress corrosion cracking. In some cases the residual stresses were beneficial, and in others detrimental — depending on the nature of the spatial distribution of the residual stresses. In some instances, the predicted failure probabilities were quite high. This indicates that the factors considered in the model dominate the failure probability in some cases. In such instances, the fracture mechanics model of structural reliability should provide a powerful tool for the assessment of the influence of various factors on piping reliability.

7.0 MAJOR NOTATION

A	area of crack
A*	crack area having a 50% chance of being found during inspection
a	maximum depth of a semi-elliptical surface crack
a ₅₀	median value of a
a*	crack depth having a 50% chance of being found during inspection
da/dn	fatigue crack growth rate
da/dt	crack growth velocity
b	half surface length of a semi-elliptical surface crack (or remaining ligament depth in Section 2.5.2)
C	parameter in fatigue crack growth relation or normalization constant in distribution of a and β
D _B	diameter of beam of ultrasonic probe used in inspection
g	parameter in expression for $\bar{K}_i$ due to a transient (Section A.6)
h	pipe wall thickness
h _i	influence function associated with $\bar{K}_i$
K	stress intensity factor
K' = K _{eff}	equals $K_{\max}/(1-R)^{\frac{1}{2}}$
K' ₀	threshold value of K'
$\bar{K}_i$	RMS averaged stress intensity factor associated with crack extension in the "i" degree-of-freedom direction
K _{max}	maximum K during a stress cycle
K _{min}	minimum K during a stress cycle
ΔK	cyclic stress intensity factor (equals $K_{\max} - K_{\min}$)
ΔK_{th}	threshold value of cyclic stress intensity factor
$\delta \bar{K}_i$	stress intensity factor ($\bar{K}_i$) due only to radial gradient thermal stress
M _T	parameter in failure criterion for longitudinal weld (Section 2.6.2)

m	exponent in fatigue crack growth relation
n	number of stress cycles
$P(t_F < t \text{crack})$	probability of failure at or before time t given that a crack is initially present
$P_{ND}(a)$	probability of nondetection of a crack of depth a during inspection
p	pressure
p^*	frequency of cracks in a weld of volume V
p_V^*	frequency of cracks in a unit volume of weld
R	load ratio (equals K_{min}/K_{max})(or radial distance in a polar coordinate system)
R^*	value of R above which ΔK_{th} is constant
R_i	inside radius of pipe
r	radial coordinate
S	parameter in lognormal distribution of crack depth (Eq. A -3) or aspect ratio (Eq. A -4). Also parameter in seismic crack growth relation (Eq. A -13)
T	temperature [or tearing modulus $E(dJ/da)/\sigma_{f10}^2$]
T_{appl}	applied value of tearing modulus
T_{mat}	value of material tearing modulus
t	time
t_f	time to failure
V	weld volume
α	equals a/h
β	aspect ratio (equals b/a)
ϵ	parameter in expression for P_{ND}
θ	a polar coordinate
λ	parameter in marginal distribution of initial crack aspect ratio (Eq. A-4) or geometrical parameter for elbows
ν	parameter in expression for P_{ND}

σ	axial stress (or occasionally standard deviation)
σ_{DW}	stress due to dead weight loads
σ_{EQ}	maximum stress due to an earthquake
σ_{flo}	flow stress [equals $(\sigma_{ys} + \sigma_{ult})/2$]
σ_{LC}	load controlled portion of applied stress
σ_{max}	maximum stress during a stress cycle
σ_{min}	minimum stress during a stress cycle
σ_{NO}	normal operating stress
σ_p	axial stress due to pressure
σ_{res}	residual stress
σ_z	axial component of normal stress in pipe
$\Delta\sigma_v$	vibratory cyclic stress

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APPENDIX A

A.0 INPUT DESCRIPTIONS FOR PRAISE-B CODE

This appendix is intended for the PRAISE-B user; i.e. the person who must construct the input deck to execute the problem. For the sake of completeness, the entire input description is given in this chapter. This eliminates potential confusion that may arise if only the new PRAISE-B inputs are described. The PRAISE-B data inputs have been organized so that an input deck which was developed for the original version of PRAISE can be used in PRAISE-B with no modification. Eight sample problems are also presented. The first four problems were included with the original PRAISE code package. These have been repeated because the modifications in PRAISE-B lead to slightly different results.

As shown in Figure A-1, PRAISE-B input can be roughly divided into the following seven categories:

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

A.1 Problem Control Variables

The first card read by PRAISE-B 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.

1. Problem Control Variables
2. Geometry and Material Properties
 - pipe wall thickness
 - pipe inside radius
 - fatigue crack growth parameters
 - flow stress
3. Initial Crack Size Distribution
 - crack depth ratio
 - crack aspect ratio
4. Evaluation and Inspection
 - earthquake evaluation time
 - in-service inspection time
 - leak detection threshold
 - big/small leak discrimination
5. Sample Space Definition
 - internally generated by PRAISE-B
 - user-specified
6. Stress and Transient Data
 - frequency of occurrence
 - maximum temperature excursion
 - normalized variation of stress intensity factor during transients
 - contribution of residual stresses to the stress intensity factor
 - vibratory stress parameters
7. Earthquake Definitions
 - S-factor
 - load controlled stresses

Figure A-1 PRAISE-B Input Data Categories

NTRIES - parameter to determine the number of replications to be taken from each cell. If the stratified sampling mesh is to be generated internally by the code, then NTRIES samples are to be taken from each cell. When the user defines the cells and $NTRIES > 0$, NTRIES is a multiplier on NUMTRY(M) (the user-defined number of replications in the M-th cell). If the user defines the cells and $NTRIES < 0$, 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 A-2.

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

- (1) $AOHLOW \leq a/h \leq AOHUP$
- (2) $AOBLFT \leq a/b \leq AOBRT$

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

$(AOHUP-AOHLOW)/NAOH$ by $(AOBRT-AOBLFT)/NAOB$

If $ISQARE = 0$, the user must supply the a/h and a/b boundaries of each cell along with the number of replications to be performed in each cell.

KTYPES - total number of types of transient events that are to be modeled. PRAISE-B assumes that the heatup/cool-down cycle is the first transient event type. This does not include inspection events or evaluation earthquakes.

Figure A-2. Number of Samples Assigned to the M-th Cell

- 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-B 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 also the output 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-B 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.

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

ISCC - option for modeling stress corrosion cracking (SCC). If ISCC = 0 then no stress corrosion cracking is modeling, i.e., only fatigue crack growth is analyzed.

If ISCC = 1, only stress corrosion cracking is modeled. If ISCC = -1, both fatigue and stress corrosion cracking are modeled simultaneously.

ISIGRS - option for adding the contribution of residual welding stresses to the stress intensity factors. If ISIGRS = 1, residual stresses are modeled. If ISIGRS = 0, the contribution of welding residual stress to the stress intensity factor is not modeled.

Additional variables in the problem definition are:

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

DTSCC - the timestep (years) to be used in the stress corrosion cracking calculations.

A.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 3.2, the fatigue crack growth relationships in PRAISE-B are:

$$\frac{da}{dn} = \begin{cases} 0 & \text{if } (\Delta \bar{K}_a)_{\text{eff}} \leq K_0 \\ C(\Delta \bar{K}_a)_{\text{eff}}^m & \text{otherwise} \end{cases} \quad (\text{A-1})$$

and

$$\frac{db}{dn} = \begin{cases} 0 & \text{if } (\Delta \bar{K}_b)_{\text{eff}} \leq K_0 \\ C(\Delta \bar{K}_b)_{\text{eff}}^m & \text{otherwise} \end{cases} \quad (\text{A-2})$$

The inputs for Equations (A-1) and (A-2) are:

THRHL D - the threshold value for crack propagation (KSI-in^{1/2}).
This corresponds to K_0 in Equations (A-1) and (A-2)

EMEXP - value of the exponent denoted by m in Equations (A-1) and (A-2) Experimental evidence suggests that m is in the range of 2-4. For the piping materials considered in the Load Combination project (Ref. 1), 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-B 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 (KONPRP = 1), then CONSMU is the value of the constant. If C is log-normally distributed (KONPRP = 0), then CONSMU is the median of the distribution.

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

If the user modifies the code to accommodate an alternate fatigue crack growth calculation, these inputs should be modified accordingly. Complete pipe severance is assumed to occur when a critical net section stress is exceeded. The material flow stress becomes the relevant parameter. PRAISE-B 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.

A.3 Initial Crack Size Distribution

In PRAISE-B, 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

$$p(a) = \frac{1}{Sa\sqrt{2\pi}} \exp \left[-\frac{1}{2} \left\{ \frac{\ln a - \ln a_{50}}{S} \right\}^2 \right] \quad (A-3)$$

The relevant input parameters are:

- AMEDIN - the median value of the log-normal distribution. It is equal to a_{50} in Equation (A-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 (A-3).

Both AMEDIN and ASIGMA have units of inches.

If the crack depth is exponentially distributed, the pdf is

$$p(a) = \lambda \exp(-\lambda a) \quad (A-4)$$

and the required input is

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

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

PRAISE-B 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

$$p(b/a) = \frac{C}{S\sqrt{2\pi}(b/a)} \exp \left[-\frac{1}{2} \left\{ \frac{\ln(b/a) - \ln M}{S} \right\}^2 \right] \quad (A-5)$$

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

and the input parameters are:

- BOAMED - parameter analogous to the median in a log-normal distribution. It is equal to M in Equation (A-5).
- BOASIG - parameter analogous to the shape parameter in a log-normal distribution. It is equal to S in Equation (A-5).
- BOANRM - the normalization factor C in Equation (A-5).

PRAISE-B assumes that the integral of Equation (A-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,

$$p(b/a > \beta_0) = p \quad (A-6)$$

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

$$p(b/a) = \lambda \exp [-\lambda(b/a - 1)] \quad (A-7)$$

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

the relevant input parameter is:

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

A.4 Inspection Times, Earthquake Evaluation Times, and Leak Detection

The PRAISE-B 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

$$\text{NEVAL} = -\text{YY}. \quad (\text{A-8})$$

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), $I = 1, \dots, \text{NEVAL}$. 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), $I = 1, \dots, \text{NINSPT}$. If no in-service inspections are desired, PRAISE-B must be fooled by setting $\text{TINSPT}(1) = \text{XX}$, where XX is a number greater than the lifetime of the plant, or

$$\text{TINSPT}(1) = \text{XX} > \text{THRIZN}. \quad (\text{A-9})$$

The PRAISE-B 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-B also maintains statistics on the fraction of leaks which are classified as big leaks. The threshold value for big leaks is defined by ALKBIG.

A.5 Stratified Sample Space

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

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

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

For option (1), the user specifies ISQARE=0 on card 1B and inputs for the M-th cell:

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

The values of AOHSIZ and AOBSIZ for two typical cells are illustrated in Figure A-3.

For option (2) the user specifies ISQARE=1 on card 1B then inputs:

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

PRAISE-B then creates MCELLS = (NAOH) (NAOB) cells, each of which has an incremental a/h length of $1/NAOH$ and an incremental a/b length of $1/NAOB$. 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. Cells which cover feasible and infeasible regions of the sample space are redefined, if necessary, to give the minimum amount of infeasible regions. A typical partition of the sample space for this option is shown in Figure A-4.

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 A-3. Specification of the Stratification Scheme by the PRAISE-B User

NAOH = 2

NAOB = 4

Figure A-4. PRAISE-B Generated Stratification of the Sample Space

In option (3), only a portion of the sample space is partitioned. The boundaries of this subspace are defined by:

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

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

$$(AOHUP - AOHLOW)/(-NAOH) \text{ by } (AOBRGT - AOBLFT)/(-NAOB)$$

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

Options (2) and (3) are particularly convenient methods of partitioning the sample space for an initial scoping of the problem. However, after the user has obtained some measure of experience with a particular problem, it is recommended that he exercise option (1) and develop a stratification scheme which is most efficient for the problem at hand.

In options (2) and (3), the same number of replications are drawn from each cell. The negative of this number is input as NTRIES on card 1B. For example, if 25 samples are to be drawn from each cell, the user must input $NTRIES = -25$. In option (1), the user must indicate the number of samples to be taken from each cell. These values are specified as NUMTRY(M) and are entered along with the coordinates of each cell. However, in this case, the user has an additional option. He can multiply the input values by a constant integer value or indicate that the same number of samples

are to be taken from each cell. Specifically, if the value of NTRIES on card 1B is negative, PRAISE-B 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

$$\text{NUMTRY}(M) = \text{NTRIES} * \text{NUMTRY}(M). \quad (4-10)$$

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

A.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 an arbitrary negative value is supplied.
- SIGVIB - peak-to-peak amplitude of the vibratory stresses (KSI). If SIGVIB is positive, PRAISE-B models vibratory stresses. If SIGVIB is negative or zero PRAISE-B does not model vibratory stresses.
- VBTHLD - threshold for the load ratio in the calculation of stress intensity factors under vibratory stresses. This corresponds to R^* in Equations 3-16 and 3-17.

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

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

and
$$\Delta \bar{K}_{\max} = \Delta T \sqrt{a} g_{\max} (k, a/h, a/b) \quad (A-12)$$

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 $g_{\min}^* (k, a/h, b/a)$ and $g_{\max}^* (k, a/h, b/a)$ 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-B 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 of Ref. 2 describes how the PRAISE-B code uses these normalized stress intensity factor values. It is shown in Section 5.5 of Ref. 2 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,...NX) through card 6D. PRAISE-B converts the values into corresponding a/b values.

For each transient, PRAISE-B then reads in card 6E and a sequence of 6F cards. In the present version of PRAISE-B, the first transient type (k = 1) is assumed to be the heatup-cooldown cycle in which only uniform through-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 the k-th transient that is to be treated as a single equivalent event,

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

- 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 A-5. Input Sequence for the Normalized Stress Intensity Factors

A.7 Seismic Crack Growth Parameters

PRAISE-B 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 of Ref. 2, the seismic crack growth in PRAISE-B is modeled as

$$\Delta a = C \left\{ \frac{S}{4 \sqrt{N_{eq}}} \right\}^4 \sum_{n=0}^{N_{eq}-1} \left\{ \sqrt{a} f((a/h)_n, (a/b)_n) \right\}^4 \quad (A-13)$$

$$= C \frac{S^4}{N_{eq}} \sum_{n=0}^{N_{eq}-1} \left\{ \sqrt{a} f((a/h)_n, (a/b)_n) \right\}^4 \quad (A-14)$$

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-B is written to use S^4 . The units of S^4 are (cycle - KSI⁴).

A.8 Detailed Formats for the Input Card

Detailed descriptions of the input cards read by PRAISE-B 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

READ Always

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
TITLE	1-80	10A8	Problem description

CARD PROBLEM SPECIFICATION

ID 18

READ Always

<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-B 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)

READ Always

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
KRKDIS	16-20	I5	Initial crack size distributions
			KRKDIS = 1, Crack depth is log-normal Aspect ratio is log-normal
			KRKDIS = 2, Crack depth is log-normal Aspect ratio is exponential
			KRKDIS = 3, Crack depth is exponential Aspect ratio of log-normal
NEVAL	21-25	I5	KRKDIS = 4, Crack depth is exponential Aspect ratio is exponential
			Option for times during plant lifetime when the reliability is to be evaluated
			NEVAL<0, Evaluation is performed for every ABS(NEVAL) years
NINSPT	26-30	I5	NEVAL>0, Number of user supplied times that an evaluation is performed
			Number of user specified in-service inspection times
NQUAKE	31-35	I5	Seismic evaluation option
			NQUAKE = 0, No earthquakes are modeled
			NQUAKE = 1, Earthquakes at each evaluation time

CARD PROBLEM SPECIFICATION (Cont'd)

ID 1B (Cont'd)

READ Always

<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 distri- buted KONPRP = 1, C is constant; i.e., the crack growth relationship is deterministic
NEQINT	46-50	I5	Number of seismic intensity classes to be simulated If NQUAKE = 0, set NEQINT = 0. PRAISE-B, as presently dimensioned, can handle up to 10 classes.
MCELLS	51-55	I5	Number of cells in the calculational grid If ISQARE = 1, the value of MCELLS is ignored
KNSFLO	56-60	I5	Option for flow stress definition KNSFLO = 0, Flow stress is normally distributed KNSFLO = 1, Flow stress is constant

CARD PROBLEM SPECIFICATION (Cont'd)

ID 1B (Cont'd)

READ Always

<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 NPSI = 1, a pre-service inspection is modeled
ISCC	71-75	I5	Option for modeling stress corrosion cracking (SCC) ISCC = 1, stress corrosion cracking only, ISCC = 0, fatigue only (no SCC), ISCC = -1, both SCC and fatigue
ISIGRS	76-80	I5	Option for modeling contribution of welding residual stresses to the stress intensity factor ISIGRS = 1, contribution of residual stresses is modeled ISIGRS = 0, residual stresses are not modeled

CARD RESIDUAL STRESSES MODEL DEFINITION

ID 1C

READ only if ISIGRS = 1 on card 1B

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

Read only if ISIGRS = 1

CARD TIME PARAMETERS

ID 1D

READ Always

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

CARD PIPE DIMENSIONS

ID 2A

READ Always

<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

READ Always

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

CARD FLOW STRESS

ID 2C

READ Always

<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

READ Always

<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

READ Always

<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

READ only if NEVAL>0

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
TEVAL	1-80	8E10.3	Evaluation times (yrs)

CARD IN-SERVICE INSPECTION TIMES

ID 48

READ only if NINSPT>0

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

CARD LEAK RATE AND DETECTION DEFINITIONS

ID 4C

READ Always

<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

READ only if ISQARE = 1

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

CARD STRATIFIED SAMPLE SPACE (cont'd)

ID 5A (cont'd)

READ only if ISQARE = 0

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

READ Always

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
SIGCLD	1-10	E10.3	Deadweight stress (KSI). This is the load controlled stress in the cold shutdown condition
SGDWTE	11-20	E10.3	Deadweight and restraint of thermal expansion components of stress in the hot normal operating condition.
OPPRES	21-30	E10.3	Normal operating pressure of the system (KSI)
PRFPRS	31-40	E10.3	Pressure in the hydrostatic proof test (KSI) If no proof test is to be modeled, set this value to any arbitrary negative number.
SIGVIB	41-50	E10.3	Peak-to-peak amplitude of the high cycle vibratory stresses (KSI). If SIGVIB<0, no vibratory stresses are modeled
VBTHLD	51-60	E10.3	Threshold value of the load ratio (R* in Section 3.7) which is used in the vibratory stress model.

CARD SPECIFICATIONS FOR THE TABLES IN THE $g_{\min}$ AND $g_{\max}$ FUNCTIONS ID 6B
READ only if KTYPES>1

<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 $g_{\max}$

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

READ only if KTYPES>1

<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)

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

READ only if KTYPES>1

<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)

CARD FREQUENCY OF HEATUP/COOLDOWN AND TRANSIENTS ID 6E

READ Always

<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

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

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

<u>VARIABLE</u>	<u>COLUMNS</u>	<u>FORMAT</u>	<u>DESCRIPTION</u>
			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 COEFFICIENTS FOR THE POLYNOMIAL THAT DEFINES ID 6G
THE CONTRIBUTION OF WELDING RESIDUAL STRESSES
TO THE STRESS INTENSITY FACTOR IN THE DEPTH DIRECTION

READ Only if ISIGRS = 1 on card 1B

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

CARD COEFFICIENTS FOR THE POLYNOMIAL THAT DEFINES THE
CONTRIBUTION OF WELDING RESIDUAL STRESSES TO THE
STRESS INTENSITY FACTOR IN THE LENGTH DIRECTION

ID 6H

READ Only if ISIGRS = 1 on card 1B

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

CARD EARTHQUAKES PER MAGNITUDE CATEGORY

ID 7A

READ Only if NQUAKE = 1 on card 1B

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

CARD SEISMIC CRACK GROWTH PARAMETERS

ID 7B

READ Only if NQUAKE = 1 on card 1B

<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.
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

A.9 Output Description

The output from a PRAISE-B 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-B 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

$$\sigma_{\text{HOT}} = \sigma_{\text{DW}} + \sigma_{\text{TE}} + \sigma_{\text{p}} \quad (\text{A-15})$$

and is computed from

$$\text{SIGHOT} = \text{SGDWTE} + \text{OPPRES} * \text{RIN} * 0.5 / \text{THICK}. \quad (\text{A-16})$$

The stress under hydrostatic proof test is given by

$$\sigma_{\text{PRF}} = \sigma_{\text{p}} + \sigma_{\text{DW}} \quad (\text{A-17})$$

or

$$\text{SIGPRF} = \text{PRFPRS} * \text{RIN} * 0.5 / \text{THICK} + \text{SIGCLD}. \quad (\text{A-18})$$

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 A-6 Organization of PRAISE-B Output

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

The description of the stratification cells includes the lower and upper boundaries for both the a/h and a/b coordinates, the conditional probability of occurrence, and the number of samples to be taken from each cell. The sum of the individual cell probabilities is also given.

The listing of the indicator function is intended to give the analyst a more detailed breakdown of the failures calculated for each cell. PRAISE-B is capable of showing every evaluation interval for all the cells. The user can reduce the volume of output by printing data at each NSKIP evaluation time. The first set of output is the number of failures obtained during an evaluation interval. For the cases of pre-service and/or in-service inspections, the numbers are weighted by the 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 number of observed failures that have occurred prior to the evaluation time. This second set of data is given for the no earthquake case and for each of the earthquake intensity categories. Finally, a tabular summary of the failure probabilities (leak, big leak, and LOCA) and estimated sampling standard deviation are given for the no earthquake case and for each of the earthquake intensity categories.

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