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Probabilistic Pipe Fracture Evaluations for Leak-Rate-Detection Applications

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Battelle

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ABSTRACT

Regulatory Guide 1.45, "Reactor Coolant Pressure Boundary Leakage Detection Systems," was published by the U.S. Nuclear Regulatory Commission (NRC) in May 1973, and provides guidance on leak detection methods and system requirements for Light Water Reactors. Additionally, leak detection limits are specified in plant Technical Specifications and are different for Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs). These leak detection limits are also used in leak-before-break evaluations performed in accordance with Draft Standard Review Plan, Section 3.6.3, "Leak Before Break Evaluation Procedures" where a margin of 10 on the leak detection limit is used in determining the crack size considered in subsequent fracture analyses.

This study was requested by the NRC to: (1) evaluate the conditional failure probability for BWR and PWR piping for pipes that were leaking at the allowable leak detection limit, and (2) evaluate the margin of 10 to determine if it was unnecessarily large.

A probabilistic approach was undertaken to conduct fracture evaluations of circumferentially cracked pipes for leak-rate-detection applications. Sixteen nuclear piping systems in BWR and PWR plants were analyzed to evaluate conditional failure probability and effects of crack-morphology variability on the current margins used in leak rate detection for leak-before-break.

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EXECUTIVE SUMMARY

Regulatory Guide 1.45, "Reactor Coolant Pressure Boundary Leakage Detection Systems," was published by the U.S. Nuclear Regulatory Commission (NRC) in May 1973, and provides guidance on leak detection methods and system requirements for Light Water Reactors. Additionally, leak detection limits are specified in plant Technical Specifications and are different for Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs). These leak detection limits are also used in leak-before-break (LBB) evaluations performed in accordance with Draft Standard Review Plan, Section 3.6.3, "Leak Before Break Evaluation Procedures" where a margin of 10 on the leak detection limit is used in determining the crack size considered in subsequent fracture analyses.

This study was requested by the NRC to: (1) evaluate the conditional failure probability for BWR and PWR piping for pipes that were leaking at the allowable leak detection limit, and (2) evaluate the margin of 10 to determine if it was unnecessarily large. It provides a fracture-mechanics evaluation of pipe flaws as related to structural integrity. Few axial cracks occur in piping, but numerous cases of circumferential crack have been reported. Consequently, the fracture evaluation can be focussed on circumferential cracks in piping for evaluation of leak-rate detection.

The objective of this work is to conduct probabilistic pipe fracture evaluations for application to leak-rate detection requirements. This was accomplished in this study in the following four distinct stages.

(1) Review of Deterministic Models. A review was conducted to evaluate the adequacy of current models for various deterministic analyses. The models included: (a) thermal-hydraulic models for estimating leakage, (b) area-of-crack-opening models for determining crack growth (flow area), and (c) elastic-plastic fracture mechanics models for predicting the maximum load-carrying capacity of a piping system. The results predicted from the above deterministic models were compared with those obtained from the experimental data furnished by previous research programs, such as the Degraded Piping Program, International Piping Integrity Research Group, and others. Based on these comparisons, it was concluded that the underlying deterministic models considered in this study provide reasonably accurate estimates of leak rates, area of crack-opening, and maximum load-carrying capacity of pipes.

(2) Statistical Characterization of Input. A statistical analysis was conducted to characterize various input variables for thermal-hydraulic analysis and elastic-plastic fracture mechanics. The statistical characterization was performed for (a) crack morphology variables, (b) material properties of pipe, and (c) the location of cracks found in nuclear piping. A search of NRC's PIFRAC database and data generated in the Degraded Piping and IPIRG Programs as well as by Argonne, David Taylor Research Center, Material Engineering Associates, and various EPRI programs have provided a reasonable wealth of data for statistical characterization of strength (stress-strain curve) and toughness (J-resistance curve) properties of base and weld metals typically used in nuclear piping. From the statistical analyses, mean, covariance, and probability distributions of these random variables were estimated. These statistical properties were used subsequently for probabilistic pipe fracture analyses.

(3) Development of Probabilistic Models. A probabilistic model was developed to evaluate the stochastic performance of piping systems subjected to normal operating loads plus safe shutdown earthquake loads. The model was based on a probabilistic extension of current LBB methodology described in NUREG 1061 Volume 3 and the NRC's draft Standard Review Plan 3.6.3. It involved (a) accurate deterministic models for estimation of leak rates, area-of-crack-opening, and maximum

load-carrying capacity of pipes, (b) a complete statistical characterization of crack morphology parameters, material property variables, and crack location, and (c) standard methods of structural reliability theory. From this model, the conditional probability of failure of a circumferentially cracked pipe based on the exceedance of its maximum load-carrying capacity can be predicted. These probabilities determine the performance of degraded piping systems subject to normal plus safe shutdown earthquake loads considering statistical variability of various input parameters. The model developed here is versatile. It can be easily adapted when additional uncertain parameters are required to be included into the description of any relevant performance criteria.

(4) Applications to BWR and PWR Piping. The probabilistic model was applied to sixteen nuclear piping systems in Boiling Water Reactors and Pressurized Water Reactors for calculating conditional probabilities of failure. Numerical examples highlighting various merits of the proposed models in terms of accuracy and computational effort were provided. The results showed that the reliability methods, such as First-Order Reliability Method, Second-Order Reliability Method, and Importance Sampling, can provide accurate estimates of piping reliability with much less computational effort when compared with those obtained from the direct Monte Carlo simulation. Several pipe sizes, ranging in diameter from 101.6 mm (4 inches) to 812.8 mm (32 inches), and several pipe materials, including stainless steel, carbon steel, and cast stainless steel and welds, were considered for determining the conditional probability of failure. The results showed that:

- For the same leaking crack size, the conditional failure probability of wrought stainless steel pipes was much lower than that for carbon steel pipes in both BWR and PWR plants, particularly when the crack was located in the base metal.

- Due to a significant reduction in the toughness properties of the weld metal compared with the base metal of wrought stainless steel pipes, the conditional probability of failure for cracks in weld metal was much larger than that for cracks in base metal. Also, for the ferritic pipes, the failure probabilities were larger for cracks in weld metal than those for cracks in base metal due to the slightly lower toughness of the weld metal. However, the differences between the base metal and the weld metal failure probabilities were not as large as exhibited for wrought stainless steel pipes.

- Comparisons of the results for the PWR austenitic pipes showed that due to aging, the conditional failure probabilities of cast stainless steel pipes can be much higher than those for wrought stainless steel pipes for base metal cracks, in which cases the fracture toughness of aged cast stainless steel materials was significantly lower than that of wrought stainless steel pipes. It appears that the toughness reduction has more detrimental effects than the beneficial effects due to strength increase in aged cast stainless steel pipes, particularly for larger diameter pipes.

- The conditional failure probability for both BWR and PWR piping systems was found to decrease with increasing pipe diameter. Similar results were reported in the past piping studies. For small diameter austenitic pipes, if the welds were tungsten inert-gas or metal inert-gas rather than flux welds, then the failure probabilities would decrease and perhaps be close to base metal failure probabilities.

- The conditional failure probability of complex-cracked[a] pipes was higher than that for through-wall-cracked pipes. Also, the conditional probability of failure was found to increase with increasing depth of the surface crack. In fact, if the depth of the surface crack is large enough, then failure could occur even under normal operating loads (which is a principal reason that pipes susceptible to an intergranular stress corrosion cracking type mechanism are not permitted for leak-before-break analysis).

- Relative comparisons of the results suggest that the conditional failure probability of BWR and PWR pipe systems would strongly depend on the pipe-specific material properties and geometric characteristics, crack-morphology for determining the size of a leaking crack, and the applied normal operating stresses. However, when the leak rates are different, e.g., 18.925 l/min (5 gpm) for BWRs and 3.785 l/min (1 gpm) for PWRs, the conditional failure probabilities for PWR ferritic pipes were lower than those for BWR ferritic pipes. Further comparisons of permissible leak rates indicate that the PWR leak rates are much higher than BWR leak rates to maintain the same conditional failure probability.

Finally, the adequacy of the current margin of 10 on the leak rate was evaluated by explicitly considering the statistical variability of crack morphology variables. Histograms of the leak rates were developed by Monte Carlo simulation. From these histograms, the margin accounting for crack-morphology variability and the residual margin were calculated [b]. It was found that the calculated margins corresponding to the leak rate that has 2-percent probability of exceedance were 1.85 to 2.25 to account for the crack-morphology variability alone. Hence, with the current margin (total) of 10 being used in leak-before-break applications, a residual margin of 4.44 to 5.39 remains to account for the variability in leak-rate detection equipment, actual stresses, and other factors affecting leak rates.

(a) A complex crack is a long circumferential surface crack that penetrates the thickness over a short length.

(b) The margin accounting for the crack-morphology variability is defined as the ratio of the leak rate that has 2-percent probability of exceedance and the mean value of leak rate. The residual margin is defined as the mean leak rate times current (total) margin of 10 divided by the leak rate that has 2-percent probability of exceedance.

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NOMENCLATURE

1. Symbols

A_b	Coefficient defined in Equation A-1
A_c	Cross-sectional flow area at crack exit plane
A_i	Cross-sectional flow area at plane where $L_a/D_i = 12$
A_o	Cross-sectional flow area at crack entrance plane
A_t	Coefficient defined in Equation A-5
a	Half crack length
a^*	Half crack length at instability
a_e	Effective half crack length
B	Constant in Equation 2-3
B_b	Coefficient defined in Equation A-1
B_t	Coefficient defined in Equation A-5
B_1, B_2	Constants used in Equation 5-1
b	Half of pipe circumference
C	Power-law coefficient for modeling J-resistance Curve in Equation 3-2
$\hat{C}$	Constraint factor
C_b	Coefficient defined in Equation A-1
C_D	Coefficient of discharge
C_F	Correction factor for Importance Sampling estimate
C_t	Coefficient defined in Equation A-5
C_1, C_2	Constants in the friction factor correlation
D_m	Mean diameter of pipe
$\mathcal{D}$	Sample space (domain) of **X**
D	Transformation vector in Equation D-2
D_H	Hydraulic diameter
D_i	Inside diameter of pipe
D_o	Outside diameter of pipe
d	Depth of surface crack in complex-cracked pipe
E	Modulus of elasticity
e	Eccentricity of axial load in a cracked pipe

e_n	Number of velocity heats per unit flow path length
e_v	Total loss coefficient over flow path
F	Ramberg-Osgood parameter in original form
F	Failure set of **X**
$F_B(\theta)$	Geometry function for bending
$F_i(x_i)$	Cumulative probability distribution function of X_i
$F_T(\theta)$	Geometry function for tension
$F_{\mathbf{X}}(\mathbf{x})$	Joint probability distribution function of **X**
$F_{Z_i}(z_i)$	Cumulative probability distribution function of Z_i
f	Friction factor
$f_i(u)$	Probability density function of Y_i
$f_{ij}(u,v)$	Joint probability density function of Y_i and Y_j
$f_{\mathbf{X}}(\mathbf{x})$	Joint probability density function of **X**
f_2	LEFM crack-opening displacement function
$f_{2a}(x)$	Probability density function of 2a
G_c	Mass flux of fluid at crack exit plane
G_o	Mass flux of fluid at crack entrance plane
G_s	Mass flux in single-phase region of crack flow
G_T	Mass flux in two-phase region of crack flow
$\bar{G}$	Average mass flux of fluid
$\bar{G}_T$	Average mass flux in two-phase region of crack flow
$g(\mathbf{x})$	Performance function in x space
$g_{app}(\mathbf{u})$	Approximate performance function (linear or quadratic) of $g_U(\mathbf{u})$
$g_L(\mathbf{u})$	First-order approximation of performance function in **u** space (hyperplane)
$g_Q(\mathbf{u})$	Second-order approximation of performance function in **u** space (hyperparaboloid)
$g_U(\mathbf{u})$	Performance function in **u** space
$g_V(\mathbf{v})$	Mapped limit state in **v** space
H	General Transformation from **x** space to **u** space
$H_B(n,\theta)$	Function defined by the LBB.ENG2 method for bending
H_0	Enthalpy of fluid at crack plane entrance
$h_Q(\mathbf{v}_r)$	Quadratic approximation of $h_V(\mathbf{v}_r)$ in **v** space
$h_V(\mathbf{v}_r)$	Alternative representation of $g_V(\mathbf{v}_r)$ in **v** space

h_2	Fully plastic crack-opening displacement function
I	Moment of inertia of uncracked pipe cross-section
$I_B(\theta)$	Nondimensional LEFM function for a pipe in bending
$I_{b_1}, I_{b_2}, I_{b_3}$	Constants defined in Equation A-4
$I_T(\theta)$	Nondimensional LEFM function for a pipe in tension
$I_{t_1}, I_{t_2}, I_{t_3}$	Constants defined in Equation A-8
J	J-integral (energy release rate)
J_e	Elastic component of J
J_{Ic}	Plane strain J at crack initiation by ASTM E813
J_M^{CC}	Modified J-resistance of complex-cracked pipe
J_M^{TWC}	Modified J-resistance of through-wall-cracked pipe
J_p	Plastic component of J
J_R	J-resistance (toughness)
K	Total number of measurements for random vector, **Y**
K_G	Correction factor for global path deviation
K_{G+L}	Correction factor for global plus local path deviation
K_I^B	Stress-intensity factor for bending
K_I^T	Stress-intensity factor for tension
$\hat{K}$	Function defined by the LBB.ENG2 method
L	Total number of samples in Monte Carlo simulation
L_a	Flow-path length
$L_B(n,\theta)$	Function defined by the LBB.ENG2 method for bending
L_f	Number of samples satisfying failure condition
$L_T(n,\theta)$	Function defined by the LBB.ENG2 method for tension
$\mathscr{L}_2$	Lebesgue space
M	Bending moment
M_{N+SSE}	Applied moment from normal plus safe shutdown earthquake stresses
M_0	Limit moment at reference stress
m	Power-law exponent for modeling J-resistance curve in Equation 3-2
N	Total number of random variables in a performance function
N_{IS}	Total number of samples in Importance Sampling
N_1	Variable defined in Equations 2-1 and 2-3

n	Strain-hardening exponent in Ramberg-Osgood model in Equation 3-1
n_t	Total number of turns in the flow path
n_{tL}	Total local number of turns in the flow path
P	Axial Load on a pipe
Pr	Probability operator
P_F	Conditional probability of failure
$P_{F,IS}$	Importance Sampling estimate of the conditional probability of failure
$P_{F,MCS}$	Monte Carlo estimate of the conditional probability of failure
$P_{F,1}$	First-order estimate of the conditional probability of failure
$P_{F,2}$	Second-order estimate of the conditional probability of failure
P_0	Axial limit load at reference stress
p	Internal pressure
p_a	Pressure loss due to acceleration
p_{aa}	Pressure loss due to area change acceleration
p_c	Absolute pressure at exit plane of crack
p_e	Pressure loss due to entrance effects
p_f	Pressure loss due to friction
p_k	Pressure loss due to protrusions in the crack path
p_o	Absolute pressure at entrance plane at crack
Q	Transformation matrix defined in Equation D-2
R_i	ith component of **R**
R_m	Mean radius of pipe
R	N-dimensional Gaussian random vector
$\Re^N$	N-dimensional real vector space
r	A dummy parameter with a value of unity
S	Applied stress/yield strength
S	Safe set of **X**
S_{gc}	Entropy of saturated vapor at crack exit plane pressure
S_{Lc}	Entropy of saturated liquid at crack exit plane pressure
S_m	Code-specified nominal design stress
S_o	Entropy of the liquid at the crack entrance plane pressure
S_y	Code-specified nominal yield strength
T_o	Temperature at crack plane entrance

t	Pipe wall thickness
U	N-dimensional standard Gaussian random vector
U_i	ith component of **U**
u	Vector space of standard Gaussian image
$\mathbf{u}^*$	Design point (beta point) of performance function in **u** space
V	Coefficient of variation
V_i	Coefficient of variation of ith variable
v	Mapped vector space by rotational transformation of **u** space
$\mathbf{v}_r$	Reduced vector in **v** space
$\mathbf{v}^*$	Design point of performance function in **v** space
W	Mass flow rate through the crack
W	N-1 dimensional standard Gaussian vector
$\bar{X}$	Average fluid quality
X_c	Fluid quality using nonequilibrium vapor generation rate in Equation 2-1
X_E	Equilibrium fluid quality
X_i	ith component of **X**
X_o	Fluid quality at crack plane entrance
X_t	Critical quality
X	N-dimensional input random vector characterizing uncertainty in a performance function
x	Space of original random vector
$\mathbf{x}^{(k)}$	kth realization (sample) of input random vector **X**
Y	A random vector characterizing uncertainty in material properties
Y_i	ith component of **Y**
y_i^a	Lower limit of Y_i
y_i^b	Upper limit of Y_i
$\mathbf{y}^{(k)}$	kth measurement of **Y**
Z_i	Uniformly distributed random variable in the range [0,1].
α	Coefficient of Ramberg-Osgood model in Equation 3-1
α_1	Ramberg-Osgood coefficient when reference stress is σ_{01}
α_2	Ramberg-Osgood coefficient when reference stress is σ_{02}
$\boldsymbol{\alpha}$	Vector of direction cosines
β_{HL}	Hasofer-Lind reliability index

$\Gamma(u)$	Gamma function
γ_{ij}	Covariance between Y_i and Y_j
$\hat{\gamma}_{ij}$	Estimate of γ_{ij}
γ_0	The isentropic expansion coefficient
Δ^c	Load-point displacement due to presence of a crack
Δ^c_e	Elastic component of Δ^c
Δ^c_p	Plastic component of Δ^c
δ	Center-crack-opening displacement
δ_e	Elastic component of δ
δ_p	Plastic component of δ
ϵ	Total Strain
ϵ_p	Plastic strain
ϵ_0	Reference strain in Ramberg-Osgood model
θ	Half crack angle
θ_{ID}	Half crack angle at inside diameter
θ_{OD}	Half crack angle at outside diameter
κ_i	ith component of principal curvatures at the design point
μ	Surface roughness
μ	Mean vector
μ_G	Global surface roughness
μ_i	Mean of Y_i
μ_L	Local surface roughness
$\hat{\mu}$	Estimate of μ_i
$\tilde{\mu}$	Mean of ln X when X is lognormally distributed
ν	Poisson's ratio
ν_{gc}	Specific volume of saturated vapor at exit pressure
$\bar{\nu}_g$	Average volume of saturated vapor at average crack pressure
ν_{Lc}	Specific volume of saturated liquid at exit pressure
ν_{Lo}	Specific volume of saturated liquid at entrance pressure
$\bar{\nu}_L$	Average volume of saturated liquid at average crack pressure
Σ	Covariance matrix
Σ_{ij}	(i,j)-th element of the covariance matrix

Σ_R	Covariance matrix of random vector, **R**
$\Sigma_{R,ij}$	(i,j)-th element of Σ_R
σ	Stress
σ_b	Bending stress
σ_f	Flow stress
σ_t	Axial tension stress
σ_y	Yield strength
σ_u	Ultimate strength
σ_0	Reference stress in Ramberg-Osgood model
σ_{01}, σ_{02}	Two possible values of reference stress in Ramberg-Osgood model
$\tilde{\sigma}$	Standard deviation of ln X when X is lognormally distributed
$\Phi(u)$	Standard Gaussian cumulative probability distribution function
$\phi(u)$	Standard Gaussian probability density function
ϕ^c	Load-point rotation due to presence of a crack
${\phi^c}_e$	Elastic component of ϕ^c
${\phi^c}_p$	Plastic component of ϕ^c
Ψ	Function defined in Equation C-18
$\nabla g_U(\mathbf{u}^*)$	Gradient of scalar field, $g_U(\mathbf{u})$ at $\mathbf{u}^*$

2. Acronyms and Initialisms

ACO	Area of crack opening
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
BWR	Boiling water reactor
CC	Complex crack
COD	Crack-opening displacement
COV	Coefficient of variation
C(T)	Compact (tension) specimen
CPU	Central Processing Unit
DEGB	Double-ended guillotine break
DPP	Degraded Piping Program
DTRC	David Taylor Research Center
EPFM	Elastic-plastic fracture mechanics
EPRI	Electric Power Research Institute
FDACS	Frequency Distribution Analysis of Crack Size
FEA	Finite element analysis
FEM	Finite element method
FORM	First-order reliability method
HRR	Hutchinson-Rice-Rosengren
ID	Inside diameter
IGSCC	Intergranular stress corrosion cracking
IPIRG	International Piping Integrity Research Group
J-R	J-resistance
LBB	Leak-before-break
LLNL	Lawrence Livermore National Laboratory
LEFM	Linear-elastic fracture mechanics
MCS	Monte Carlo simulation
MEA	Material Engineering Associates
MIG	Metal inert-gas
NED	Nuclear Engineering and Design
NRC	Nuclear Regulatory Commission

OD	Outside diameter
PICEP	PIpe Crack Evaluation Program
PROLBB	PRObabilistic Leak-Before-Break
PSQUIRT	Probabilistic Seepage Quantification of Upsets in Reactor Tubes
PWR	Pressurized water reactor
SAW	Submerged-arc weld
SCRAMP	Simulation of CRAck Morphology Parameters
SMAW	Shielded-metal arc weld
SQUIRT	Seepage Quantification of Upsets in Reactor Tubes
SORM	Second-order reliability method
SSE	Safe-shutdown earthquake
TWC	Through-wall-cracked
TIG	Tungsten inert-gas

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"Short Cracks in Piping and Piping Welds," Third Semiannual Report, NUREG/CR-4599, Vol. 2, No. 1, September 1992.

"Short Cracks in Piping and Piping Welds," Fourth Semiannual Report, NUREG/CR-4599, Vol. 2, No. 2, May 1993.

"Short Cracks in Piping and Piping Welds," Fifth Semiannual Report, NUREG/CR-4599, Vol. 3, No. 1, October 1993.

"Short Cracks in Piping and Piping Welds," Sixth Semiannual Report, NUREG/CR-4599, Vol. 3, No. 2, March 1994.

"Dynamic Crack Instabilities in Nuclear Ferritic Piping at LWR Temperatures and the Role of Dynamic Strain Aging", Topical Report, NUREG/CR-6226, October 1994.

Previous Related Documents from NRC's Degraded Piping Program

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 1, October 1984.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 2, June 1985.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 3, March 1986.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 4, July 1986.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 5, December 1986.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 6, April 1988.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 7, March 1989.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 8, March 1989.

"NRC Leak-Before-Break (LBB.NRC) Analysis Method for Circumferentially Through-Wall Cracked Pipes Under Axial Plus Bending Loads," Topical Report, NUREG/CR-4572, March 1986.

"Elastic-Plastic Finite Element Analysis of Crack Growth in Large Compact Tension and Circumferentially Through-Wall-Cracked Pipe Specimen--Results of the First Battelle/NRC Analysis Round Robin," Topical Report, NUREG/CR-4573 September 1986.

"An Experimental and Analytical Assessment of Circumferential Through-Wall Cracked Pipes Under Pure Bending," Topical Report, NUREG/CR-4574, June 1986.

"Predictions of J-R Curves With Large Crack Growth From Small Specimen Data," Topical Report, NUREG/CR-4575, August 1986.

"An Assessment of Circumferentially Complex-Cracked Pipe Subjected to Bending," Topical Report, NUREG/CR-4687, September 1986.

"Analysis of Cracks in Stainless Steel TIG Welds," Topical Report, NUREG/CR4806, November 1986.

"Approximate Methods for Fracture Analyses of Through-Wall Cracked Pipes," Topical Report, NUREG/CR-4853, January 1987.

"Assessment of Design Basis for Load-Carrying Capacity of Weld-Overlay Repair," Topical Report," NUREG/CR-4877, February 1987.

"Analysis of Experiments on Stainless Steel Flux Welds," Topical Report, NUREG/CR-4878, February 1987.

"Experimental and Analytical Assessment of Circumferentially Surface-Cracked Pipes Under Bending," Topical Report, NUREG/CR-4872, April 1987.

Previous Related Documents from NRC's International Piping Integrity Research Group (IPIRG) Program

"Evaluation and Refinement of Leak-Rate Estimation Models," Topical Report, NUREG/CR-5128, Revision 1, June 1994.

"Loading Rate Effects on Strength and Fracture Toughness of Pipe Steels Used in Task 1 of the IPIRG Program", Topical Report, NUREG/CR-6098, October 1993.

"Stability of Cracked Pipe Under Inertial Stresses--Subtask 1.1 Final Report", NUREG/CR-6233, Vol. 1, August 1994.

1.0 INTRODUCTION

1.1 Overview

Regulatory Guide 1.45, "Reactor Coolant Pressure Boundary Leakage Detection Systems," was published by the U.S. Nuclear Regulatory Commission (NRC) in May 1973, and provides guidance on leak detection methods and system requirements for Light Water Reactors. Additionally, leak detection limits are specified in plant Technical Specifications and are different for Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs). These leak detection limits are also used in leak-before-break (LBB) evaluations where a margin of 10 on the leak detection limit is used in determining the crack size considered in subsequent fracture analyses.

This study was requested by the NRC to: (1) evaluate the conditional failure probability for BWR and PWR piping for pipes that were leaking at the allowable leak detection limit, and (2) evaluate the margin of 10 to determine if it was unnecessarily large. It provides a fracture-mechanics evaluation of pipe flaws as related to structural integrity. Few axial cracks occur in piping, but numerous cases of circumferential crack have been reported. Consequently, the fracture evaluation can be focussed on circumferential cracks in piping for evaluation of leak rate detection.

LBB analyses are currently being conducted in the nuclear industry to justify elimination of dynamic effects during pipe rupture. This allows elimination of hardware, such as pipe whip restraints and jet impingement shields, which can impede accessibility to pipes and increase radiation exposure during maintenance operations and in-service inspections. In a leak-before-break analysis for nuclear piping systems, the following approach is frequently employed. First, a fatigue analysis is conducted. This determines the growth of a surface crack from a hypothetical flaw that would be permitted by the acceptance criteria of IWB-3500 of Section XI of the ASME Boiler and Pressure vessel code (Ref. 1). From this, the likelihood of a leak (i.e., a surface crack growing to become a through-wall crack) can be evaluated. Second, as a worst-case assumption, it is assumed that a through-wall crack exists with maximum credible flaw size that can be detected under normal operating loads. It is then desired that this through-wall crack will remain stable at normal operating plus safe shutdown earthquake (N+SSE) loads. Further details of LBB methods are described in NRC publications NUREG/CR-1061 Volume 3 (Ref. 2), and the Draft Standard Review Plan, Section 3.6.3 (Ref. 3).

The application of the LBB methodology requires (1) a knowledge of pipe loads during various operating conditions of a power plant, (2) the details of geometry and material properties of the pipe, (3) crack morphology variables, and (4) methods for thermal-hydraulic and fracture analysis of a flawed pipe. Some of these items mentioned above are subject to inherent statistical variability. Therefore, a rational treatment of these uncertainties and an assessment of their impact on system performance should be based on the theories of probability and structural reliability.

Nevertheless, most LBB analyses have been traditionally based on the principles of deterministic fracture mechanics and thermal-hydraulic analysis. Consequently, various "conservative" assumptions are made by selecting worst-case values of uncertain parameters, which determine initial through-wall-crack (TWC) size and its subsequent growth characteristics. However, fluctuation of loads, variability of crack morphology variables and material properties, and uncertainties in the analytical models all contribute to a probability that the safety margins in LBB methodology may be variable. Quantitative assessment of this failure probability then becomes the essence of structural-reliability analysis. The NRC (Ref. 2) has currently included several safety margins on leak-rate detection, initial TWC flaw size, and N+SSE stresses to envelop these uncertainties qualitatively. These margins were derived from engineering judgement and currently do not include any correlation with the failure probability. Hence, the probability of having a double-ended guillotine break, conditional on the event that the pipe is leaking, needs to be evaluated.

1.2 Objective of the Study

The objective of this study was to conduct probabilistic pipe fracture evaluations for application to leak-rate detection requirements. It was accomplished here in four distinct stages.

(1) Review of Deterministic Models. A review was conducted to evaluate the adequacy of current models for various deterministic analyses. The review included (a) thermal-hydraulic models for estimation of leak rates, (b) area-of-crack-opening models for determination of crack geometry (flow area), and (c) elastic-plastic fracture mechanics analyses for prediction of the maximum load-carrying capacity of a piping system. The results predicted from these deterministic models were compared with the experimental data from previous research programs, such as the NRC's Degraded Piping Program (Ref. 4), International Piping Integrity Research Group (IPIRG) Program (Ref. 5), and others (Ref. 6).

(2) Statistical Characterization of Input. A statistical analysis was conducted to characterize various input variables for thermal-hydraulic analysis and elastic-plastic fracture mechanics analysis. The variables included (a) crack morphology variables, (b) material properties of pipe, and (c) the locations of cracks found in nuclear piping. A search of the NRC's PIFRAC database (Ref. 7) and the data generated by the Degraded Piping and IPIRG (Refs. 4 and 5) Programs provided a reasonable wealth of data for statistical characterization of strength (stress-strain curve) and toughness (J-resistance curve) properties of base and weld metals typically used in nuclear piping. Additional data on aged cast stainless steel were obtained from Argonne National Laboratory (Ref. 8), and other sources of data were also available from past EPRI programs at Westinghouse (Ref. 9) and Babcock & Wilcox (Ref. 10). Data were also collected from Ontario Hydro, General Electric, David Taylor Research Center, and Framatome. From the statistical analyses, mean, covariance, and probability distributions of these random variables were estimated.

(3) Development of a Probabilistic Model. A probabilistic model was developed to evaluate the stochastic performance of cracked piping systems subject to normal operating plus safe shutdown earthquake loads. The model was based on a probabilistic extension of current LBB methodology described in NUREG 1061 Volume 3 (Ref. 2) and the NRC's draft Standard Review Plan, Section 3.6.3 (Ref. 3). It involved (a) accurate deterministic models for estimation of leak rates, area of crack opening, and maximum load-carrying capacity of pipes, (b) statistical characterization of crack morphology parameters, material property variables, and crack location, and (c) standard computational methods of structural reliability theory. From this model, the conditional probability of

2failure of a cracked pipe can be predicted. This probability determines the performance of a piping systems due to statistical variability of various input parameters defined earlier.

(4) Applications to BWR and PWR Piping. The probabilistic model was applied to sixteen nuclear piping systems in Boiling Water Reactors and Pressurized Water Reactors for calculating conditional probabilities of failure. Numerical examples highlighting the merits of the proposed model in terms of accuracy and computational effort were provided. Several pipe sizes, ranging in diameter from 101.6 mm (4 inches) to 812.8 mm (32 inches), and several pipe materials, including stainless steel, carbon steel, and cast stainless steel and welds, were considered. A comparison of the above conditional failure probabilities will provide a technical basis for the evaluation of the maximum allowable unidentified leak rates in Regulatory Guide 1.45 with reference to the NRC's LBB procedures. In addition, the adequacy of the current margin of 10 used for leak rate was evaluated by explicitly considering the statistical variability of crack morphology variables.

1.3 Outline of the Report

Section 2 provides a state-of-the-art review of current deterministic models for thermal-hydraulic analysis and elastic-plastic fracture mechanics.

Section 3 describes the statistical characterization of crack morphology parameters, material property variables, and crack location.

Section 4 contains the new analytical formulation of probabilistic models for structural reliability analysis of cracked piping systems.

Section 5 describes the application of the above probabilistic model for computing the conditional probability of failure of various nuclear piping in BWR and PWR.

Section 6 discusses the results of the previous sections and proposes their potential application in leak-rate detection.

Section 7 identifies known limitations of the current models.

Section 8 summarizes the principal contributions made from this study and draws conclusions regarding piping performance in nuclear power plants.

2.0 DETERMINISTIC MODELS

2.1 Thermal-Hydraulic Model

The two-phase critical flow of water through piping systems is a highly complex physical phenomenon that has been widely studied during the last 40 years. What makes this problem so difficult is the existence of the two phases in the flow system, which can interact in a variety of ways. For instance, a two-phase flow system can exist with either vapor bubbles dispersed in a continuous liquid phase or as liquid droplets dispersed in a continuous vapor phase. The physics of each of these situations is vastly different, yet each represents a two-phase flow.

Simple models of two-phase flow systems (Ref. 11) assume the fluid to be a homogeneous mixture of the gas and liquid phases. Mass, momentum, and energy balances are then written for the homogeneous mixture. The equations are solved for a single fluid having the average properties of the mixture at any point in the system. Although this is a reasonable first approach to modeling two-phase systems, significant errors in the predicted system mass flow rates can occur for systems in which nonequilibrium interactions are taking place, or in systems where large differences in the velocities of the two phases exist. These errors can be larger than a factor of two when comparing flow rates from the models and the experiments (Ref. 12).

To overcome some of the limitations of the homogeneous equilibrium model, many authors have suggested refinements to the model to make it more realistic. This led to the development of the slip-flow models of Zivi (Ref. 13), Henry and Fauske (Ref. 14), and Moody (Ref. 15). In these models, the gas is assumed to have a higher velocity than the liquid; the ratio of gas velocity to liquid velocity is referred to as the slip ratio. By incorporating the slip ratio in the homogeneous equilibrium model equations, good agreement can be obtained between the model and experiment in a number of instances.

However, further complications arise when the two-phase mixture is experiencing critical flow. In this case, the time required for the fluid to reach thermodynamic equilibrium when moving into regions of lower pressure is comparable to the time that the fluid is flowing in the crack. This leads to nonequilibrium vapor generation rates for two-phase critical flows. To account for nonequilibrium effects between the phases, Henry (Ref. 16) and Henry and Fauske (Ref. 14) proposed a simple model for the nonequilibrium vapor generation rate. In this model they assume that the mixture quality relaxes in an exponential manner toward the equilibrium quality that would be obtained in a long tube. The relaxation coefficient was calculated based on their experiments with the critical flow of a two-phase water mixture in long tubes ($L_a/D_i > 100$, where L_a is the flow-path length and D_i is the inside diameter of the pipe). The Henry-Fauske model is the one that has been chosen in this study to model the two-phase critical flow of water through cracks in piping systems.

2.1.1 Henry-Fauske Model

The Henry-Fauske model of two-phase flow through long channels is the basis for the thermal-hydraulic analysis (Refs. 14 and 16). Henry's mass flux equation is written in the following format:

$$\psi(G_c,p_c) = G_c^2 - \frac{1}{\left[\frac{X_c \nu_{gc}}{\gamma_0 p_c} - (\nu_{gc} - \nu_{Lc})\, N_1 \frac{dX_E}{dp}\right]} = 0 \tag{2-1}$$

subject to the constraint

$$\Omega(G_c,p_c) = p_c + p_e + p_a + p_f + p_k + p_{aa} - p_0 = 0 \tag{2-2}$$

where G_c and p_c are the mass flux of the fluid and the absolute pressure at the crack exit plane; p_e, p_a, p_f, p_k, and p_{aa} are pressure losses due to the entrance effects, acceleration, friction, crack-path protrusions, and area change acceleration; p is the internal pressure; p_0 is the absolute pressure at the entrance of the crack plane; γ_0 is the isentropic expansion coefficient; ν_{gc} and ν_{Lc} are specific volumes of saturated vapor and liquid at exit pressure; and X_c and X_E are nonequilibrium vapor generation rate and equilibrium fluid quality. X_c and X_E are given by

$$X_c = N_1 X_E \{1 - \exp\,[-B\,(L_a/D_i - 12)]\} \tag{2-3}$$

and

$$X_E = \left[\frac{S_0 - S_{Lc}}{S_{gc} - S_{Lc}}\right] \tag{2-4}$$

in which L_a is flow-path length, D_i is inside diameter of the pipe, S_0 is the entropy of the liquid at the crack entrance plane pressure, S_{gc} and S_{Lc} are the entropy of saturated vapor and liquid at the crack exit plane pressure, and B is a constant. Also, in Equations 2-1 and 2-3

$$\begin{aligned} N_1 &= 20\,X_E \text{ for } X_E < 0.05 \\ N_1 &= 1.0 \text{ for } X_E \geq 0.05 \end{aligned} \tag{2-5}$$

The constant B was inferred from the data of Henry (Ref. 16) as being equal to 0.523. Each of the pressure loss terms is defined below.

The entrance pressure loss, p_e, is given by

$$p_e = \frac{G_0^2 \, \nu_{L0}}{2 \, C_D^2} \tag{2-6}$$

where G_0 is the mass flux of the fluid at the crack entrance plane, ν_{L0} is the specific volume of the saturated liquid at the entrance pressure, and C_D is the discharge coefficient. A value of $C_D = 0.95$ is recommended for tight cracks, i.e., cracks with center-crack-opening displacement (COD) less than 0.15 mm (0.006 inch). This is in accordance with the *ASME Fluid Metering Handbook* (Ref. 17), which defines a rounded entrance as one having a rounded inlet equal to 1/6 the radius of the tube opening. Since the hydraulic radius of a tight crack is approximately equal to the COD, the entrance edges would only need to have a radius of 1/6 the COD to be considered round. In the case of a crack with a COD of 0.15 mm (0.006 inch), the radius of the entrance edges would have to be about 0.025 mm (0.001 inch) to be considered round. For cracks with a larger COD, a coefficient of discharge between 0.62 and 0.95 should be chosen based on the judgement of the user as to how round the entrance edges are in comparison with the COD.

The pressure loss due to friction, p_f, is calculated over the flow path length using

$$p_f = f \, \frac{L_a}{D_i} \, \frac{\bar{G}^2}{2} \, [(1 - \bar{X}) \, \bar{\nu}_L + \bar{X} \, \bar{\nu}_g] \tag{2-7}$$

where $\bar{G}$ is the average mass flux of the fluid, $\bar{X}$ is the average fluid quality, $\bar{\nu}_g$ and $\bar{\nu}_L$ are the average volume of saturated vapor and liquid at average crack pressure, and f is the friction factor calculated by (Ref. 18)

$$f = \left[C_1 \log \left(\frac{D_i}{\mu} \right) + C_2 \right]^{-2} \tag{2-8}$$

where μ is the surface roughness and the coefficients C_1 and C_2 are equal to 2.00 and 1.74, respectively, for $D_i/\mu > 100$, and 3.39 and -0.866, respectively, for $D_i/\mu < 100$ (Refs. 6 and 14).

The pressure loss due to bends and protrusions in the crack flow path, p_k, is given by

$$p_k = e_v \, \frac{\bar{G}^2}{2} \left[(1 - \bar{X}) \, \bar{\nu}_L + \bar{X} \, \bar{\nu}_g\right] \tag{2-9}$$

where e_v is the total loss coefficient over the crack flow path length. The variable e_v can be determined experimentally by defining

$$e_v = e_n L_a \tag{2-10}$$

where e_n is the number of velocity heads lost per unit flow path length for a given type of crack.

The phase change acceleration pressure loss, p_a, of the fluid as it flows through the crack is given by

$$p_a = \bar{G}_T^2 \left[(1 - X_c)\nu_{Lc} + X_c\, \nu_{gc} - \nu_{Lc}\right] \tag{2-11}$$

where $\bar{G}_T$ is the average mass flux in the two-phase region of crack flow. Likewise, the area change acceleration pressure loss, p_{aa}, of the fluid is given by

$$p_{aa} = \frac{G_c^2\, \nu_{Lo}}{2} \left[\left(\frac{A_c}{A_i}\right)^2 - \left(\frac{A_c}{A_o}\right)^2\right] + \frac{G_c^2}{2} + \left[(1 - \bar{X})\, \nu_{Lc} + \bar{X}\, \bar{\nu}_{gc}\right] \left[1 - \left(\frac{A_c}{A_i}\right)^2\right] \tag{2-12}$$

where G_c is the mass flux of the fluid at a crack-exit plane, A_c is the cross-sectional flow area at a crack-exit plane, and A_i is the cross-sectional flow area at the plane where $L_a/D_i = 12$, and A_0 is the cross-sectional flow area at the crack entrance plane.

The reader is referred to the papers of Henry (Ref. 16), Collier et al. (Ref. 19), Abdollahian and Chexal (Ref. 20), and the book by El-Wakil (Ref. 21) for further information. Equations 2-1 and 2-2 represent two nonlinear algebraic equations with two unknowns, namely G_c and p_c. A Newton-Raphson iteration method (Ref. 22) was used to solve these simultaneous nonlinear equations.

2.1.2 Improved Model for Crack Morphology Variables

The key crack morphology variables considered in past leak-rate analyses were surface roughness, number of turns in the leakage path, and entrance loss coefficients. However, examination of service cracks also shows that cracks frequently do not grow radially through the pipe thickness. Hence, a fourth parameter "actual crack path/thickness" representing deviation from straightness was also considered here. This parameter had been ignored in the past. A brief description of the above crack morphology variables and how they affect the pressure loss terms in Equations 2-1 and 2-2 is given below.

Surface Roughness. This input parameter defines the roughness of the crack face surface to be used in the calculation of the friction factor and pressure loss due to friction for the fluid flow through the crack (see Equations 2-7 and 2-8). In the past, the surface roughness was assumed to be invariant with respect to the COD. For example, the constant numerical values, such as 0.0062 mm and 0.04 mm, were used to quantify surface roughness of intergranular stress-corrosion cracks and fatigue-growth cracks, respectively (Ref. 6). However, a careful examination of Figure 2.1 suggests that the appropriate surface roughness should be large (global) or small (local) depending on whether the COD is large or small, respectively. For this study, the dependence of surface roughness, μ, was achieved by assuming a piecewise linear function given by

$$\mu = \begin{cases} \mu_L, & 0.0 < \dfrac{\delta}{\mu_G} < 0.1 \\ \mu_L + \dfrac{\mu_G - \mu_L}{9.9}\left[\dfrac{\delta}{\mu_G} - 0.1\right], & 0.1 < \dfrac{\delta}{\mu_G} < 10 \\ \mu_G, & \dfrac{\delta}{\mu_G} > 10 \end{cases} \qquad (2\text{-}13)$$

where μ_L is the local surface roughness, μ_G is the global surface roughness, and δ is the center-crack-opening-displacement. Figure 2.2 shows the schematic variation of μ with respect to δ.

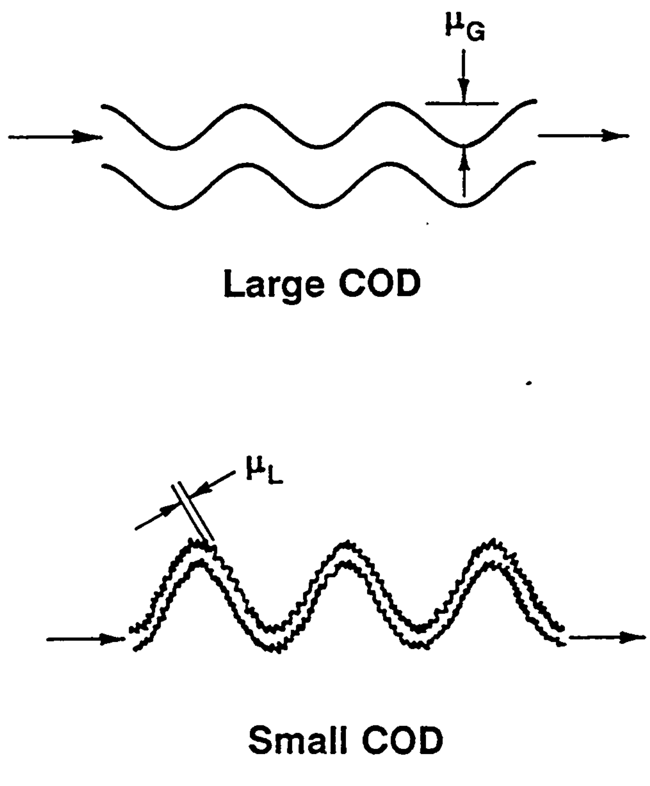

Figure 2.1 Local and global surface roughness and number of turns

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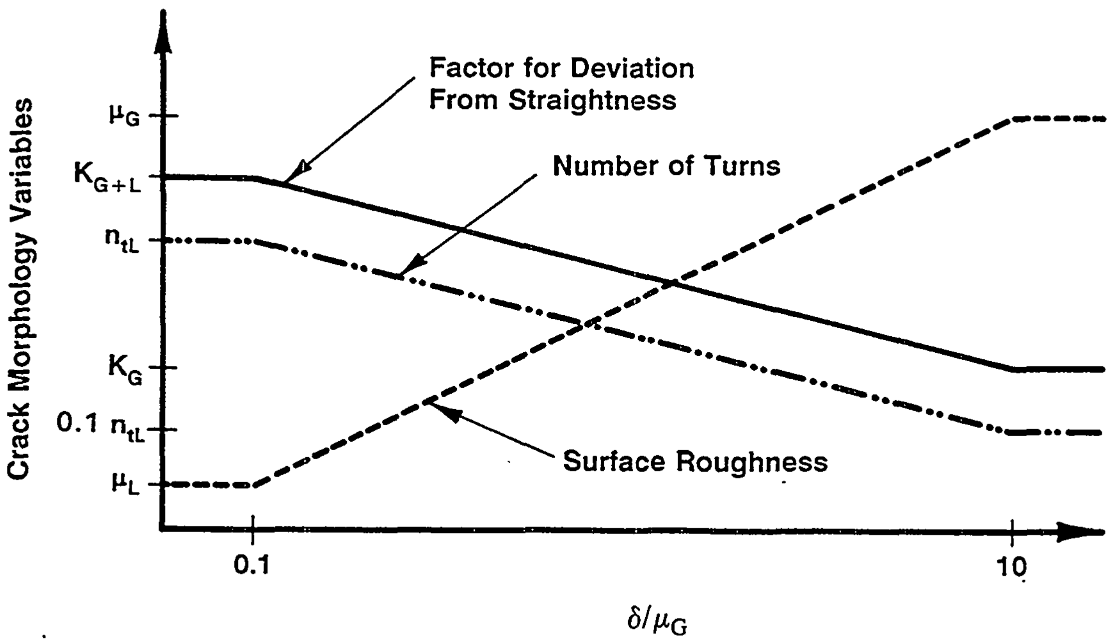

Figure 2.2 Crack morphology variables versus normalized COD

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Number of Turns. This input parameter defines the number of turns that the fluid must make when flowing through the crack. In fatigue and stress-corrosion cracks, the number and severity of the bends can in some circumstances account for upwards of one-half the total pressure loss of the fluid when flowing through the crack. Typically, a 45- or a 90-degree angle change in flow direction results in about a 0.4 and 1.0 velocity head loss, respectively. (See Equations 2-9 and 2-10 on how the velocity head loss affects the pressure loss due to bends and protrusions.) Norris et al. (Ref. 23) have shown this parameter to be of importance for stress-corrosion cracks. In the past, this parameter was thought to be of lesser importance for fatigue cracks because fatigue cracks generally break through in a fairly flat plane. However, the experimental results shown in Reference 6 indicate that the number of bends in the flow path can be significant even for fatigue cracks. This occurs when the variations in the contours of the relatively flat plane of a fatigue crack are large compared with the COD. Therefore, even though the fracture faces of a fatigue crack appear to be fairly flat to the naked eye, the fatigue cracks contain many flow path bends when the crack is tight.

Following similar considerations given above for the surface roughness, the appropriate number of turns, n_t, also depends on the COD. Once again, a piece-wise linear function was assumed, i.e.,

$$n_t = \begin{cases} n_{tL}\,, & 0.0 < \dfrac{\delta}{\mu_G} < 0.1 \\ n_{tL} - \dfrac{n_{tL}}{11}\left[\dfrac{\delta}{\mu_G} - 0.1\right], & 0.1 < \dfrac{\delta}{\mu_G} < 10 \\ 0.1 n_{tL}\,, & \dfrac{\delta}{\mu_G} > 10 \end{cases} \tag{2-14}$$

where n_{tL} is the local number of turns. A schematic plot of Equation 2-14 is also shown in Figure 2.2.

Discharge Coefficient. The discharge coefficient is the ratio of the flow areas associated with the vena contracta to the flow area at the crack entrance. For sharp-edged crack entrances, a typical discharge coefficient would be a value of 0.60. For round or smooth-edged crack entrances, a typical discharge coefficient would be close to 0.95.

Actual Crack Path/Thickness. This parameter represents the deviation of the flow path from straightness. Depending on the COD (see Fig. 2.3), it can be defined as

$$\frac{L_a}{t} = \begin{cases} K_{G+L}\,, & 0.0 < \dfrac{\delta}{\mu_G} < 0.1 \\ K_{G+L} - \dfrac{K_{G+L} - K_G}{9.9}\left[\dfrac{\delta}{\mu_G} - 0.1\right], & 0.1 < \dfrac{\delta}{\mu_G} < 10 \\ K_G\,, & \dfrac{\delta}{\mu_G} > 10 \end{cases} \tag{2-15}$$

where L_a is the actual length of the flow path, K_G is the correction factor for global path deviations for straightness (e.g., a crack following the fusion line of the weld), and K_{G+L} is the correction factor for global plus local path deviations for straightness (e.g., a crack following the grain boundaries for IGSCC). A schematic plot of Equation 2-15 is also shown in Figure 2.2. Note that the piecewise linear variation of the above crack morphology variables is a first attempt to simulate their dependency on COD. The numerical constants in Equations 2-13 to 2-15 are based on a review of cracks found in service and expert opinion at Battelle.

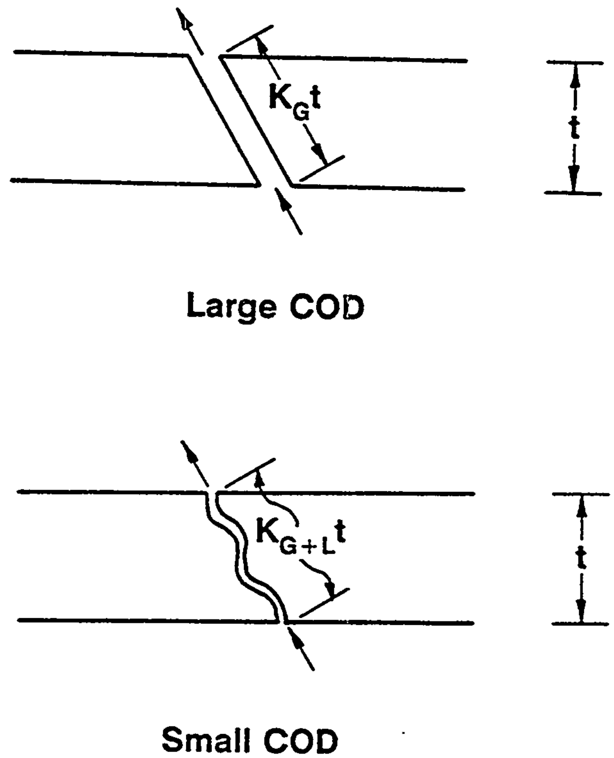

Figure 2.3 Global plus local and global path deviations from straightness

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2.2 Area-of-Crack-Opening (ACO) Model

Generally, leak-rate calculations are performed for one of the following two purposes:

(1) Given a flaw size, pipe dimensions, material stress-strain properties, and loading, it is desired to know the fluid leak rate through the crack. The aim is to estimate whether the given flaw size would result in a reliably detectable leak rate. Therefore, the aim is to underestimate rather than overestimate the ACO.

(2) Given a leak rate, it is desired to know what the ACO must be. Then, knowing the ACO, pipe dimensions, material properties, and loading, the aim is to estimate the flaw size, which is subsequently used to determine the pipe's load-carrying capacity. For this purpose, it is more desirable to have an overestimate than an underestimate of ACO.

For either of the two purposes, it is desirable to have a mathematical model, that is sufficiently accurate but still relatively simple and inexpensive to use. For example, a detailed finite-element analysis model, while generally accurate, would have very limited use because it would be too expensive and time consuming to be used routinely. What is needed is a relatively simple equation (or a set of equations) to estimate flaw sizes and ACOs.

Simple mathematical models, often referred to as estimation models, are almost invariably based on assumptions, which are necessary to minimize the need for elaborate numerical techniques. Typically, such assumptions lead to simpler representations of the material's stress-strain behavior, flaw shape and orientation, loading condition, etc. The available estimation models can be broadly classified as (1) linear-elastic fracture-mechanics (LEFM) models, (2) pseudoplastic fracture-mechanics models, and (3) elastic-plastic fracture-mechanics (EPFM) models. In Reference 6, a detailed review of the above models was conducted. For adaptation in a relatively general LBB analysis, it was concluded that an EPFM model would be most appropriate. For this study, the EPFM model in Reference 6 will be used. A brief description of this model is given below.

2.2.1 Elastic-Plastic Fracture-Mechanics (EPFM) Models

In general, ACO estimates in the elastic-plastic regime are possible only by numerical analysis techniques such as the finite-element method (FEM). For a pipe containing a through-wall crack, either a three dimensional or a shell formulation must be used to compute the ACO. Such computations are too time consuming and expensive to be used for routine LBB assessments. On the other hand, general closed-form solutions, even with simplified representations of the material's nonlinear stress-strain behavior, are difficult to develop.

Consider a TWC pipe under combined bending and tension in Figure 2.4, which has mean radius, R_m, thickness, t, and crack angle, 2θ, with the crack circumferentially located in the pipe. Kumar, German, and Shih, in pioneering work sponsored by EPRI (Ref. 24), developed a method which enables one to generalize selected FEM solutions to be applicable to a wide range of flaw and pipe sizes and materials. This generalization is possible because of the key assumption in their approach that the nonlinear stress-strain behavior can be represented by a power-law function. Specifically, the following equation is used to represent the plastic strain (ϵ_p) as a function of stress σ

$$\frac{\epsilon_p}{\epsilon_0} = \alpha \left[\frac{\sigma}{\sigma_0}\right]^n \tag{2-16}$$

in which n is the hardening exponent and α is a material constant. The constants σ_0 and ϵ_0 are reference values of stress and strain. With plastic strain expressed as in Equation 2-16 and by invoking Ilyushin's theorem (Ref. 25), the plastic component of the center crack-opening displacement δ_p for a circumferential crack in a pipe subjected to remote bending moment, M, can be expressed as (Ref. 24)

$$\delta_p = \alpha\, \epsilon_0\, a\, h_2 \left[\frac{a}{b}, n, \frac{R_m}{t}\right] \left[\frac{M}{M_0}\right]^n \tag{2-17}$$

where $a = R_m\theta$, $b = \pi R_m$, and M_0 is the limit moment of TWC pipe under pure bending with σ_0 as the collapse stress. For the case of a pipe with a circumferential crack subjected to pure tension, M and M_0 would be replaced by the axial force P and the limit load P_0, respectively. In Equation 2-17,

h_2 is a nondimensional function of a/b, R_m/t, and n. In Reference 24, the h_2 values are given separately for pipes with circumferential cracks subjected to axial tension and to bending loads. These values were generated using a number of FEM analyses based on a thin-shell formulation. Reference 24 also provides the equation for the elastic component of the center COD, δ_e, given by

$$\delta_e = \left[\frac{M}{E}\right] f_2 \left[a, \frac{R_m}{t}\right] \tag{2-18}$$

where f_2 is another nondimensional function of the crack length and the radius-to-thickness ratio of the pipe. In Reference 24, f_2 is proposed to be a function of "effective" crack length, a_e, instead of actual crack length, a. The rationale for using a_e instead of a is that for $M \ll M_0$ and $n \gg 1$, the plastic component, δ_p (see Equation 2-17) will tend to be underestimated. Therefore, the attempt is to account for this underestimate by using a plastic-zone correction in the elastic component, δ_e. However, recent work performed by Scott and Brust at Battelle (Ref. 26) indicates that the method in Reference 24 tends to overestimate experimental displacement values even when the actual (rather than effective) crack length is used in the calculations. Therefore, in the present work, it was decided to evaluate the f_2 function using the actual crack length. Both elastic (δ_e) and plastic (δ_p) components of the COD are obtained by adding the contributions from tension and bending, where the bending part includes the induced bending due to axial tension in the presence of a TWC. Using Equations 2-17 and 2-18, together with the tabulated h_2 and f_2 values given in Reference 24, one can then find the total COD, δ, as the sum of δ_e and δ_p. However, this still leaves the problem of determining the ACO. Reference 24 does not provide any information on the crack-opening profiles, which are needed to calculate the ACO.

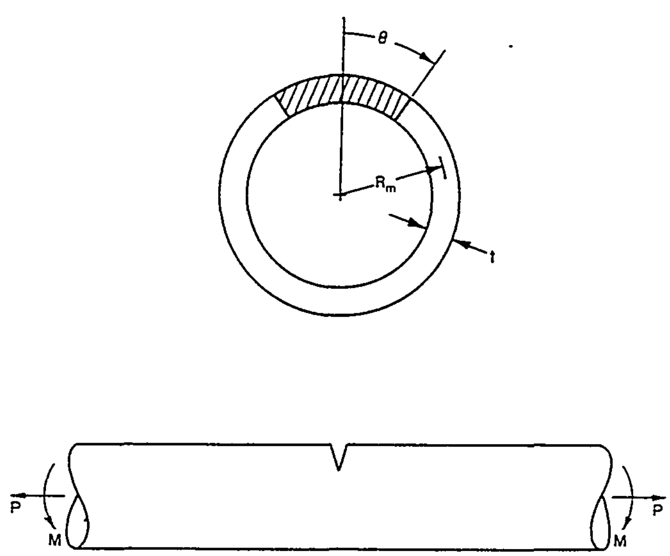

Figure 2.4 Through-wall-cracked pipe under combined bending and tension

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Several options exist in modeling crack-opening profiles. Paul et al. (Ref. 6) and Norris et al. (Ref. 23) investigated several crack shapes, such as elliptical, diamond shaped, and rectangular. Comparisons with the experimental data as well as finite-element results reported in Reference 6 suggest that the ellipse may provide the best representation of the crack-opening shape. This will be evaluated in this study. Nevertheless, knowing the center COD, crack length, and crack-opening profile, the corresponding ACO can be readily found.

2.3 Elastic-Plastic Fracture Model

It is now well established that elastic-plastic fracture mechanics provides more realistic measures of fracture behavior of cracked piping systems than elastic methods. Recent analytical, experimental, and computational studies on this subject indicate that energy release rate (also known as J-integral) and crack-tip opening displacement are the most viable fracture parameters for characterizing crack initiation, stable crack growth, and subsequent instability in ductile materials (Refs. 27 and 28). This clearly suggests that parameters like J and/or CTOD can be conveniently used to assess structural integrity for both leak-before-break and in-service flaw acceptance criteria in degraded piping systems. It is, however, noted that the parameter J still possesses some theoretical limitations. For example, the Hutchinson-Rice-Rosengren (HRR) singular field (Refs. 29 and 30) may not be valid in the case of certain amounts of crack extension where J ceases to act as an amplifier for this singular field. Nevertheless, possible error is considered tolerable if the relative amount of crack extension stays within a certain limit and if elastic unloading and nonproportional plastic loading zones around a crack tip are surrounded by a much larger zone of nearly proportional loading controlled by the HRR field. Under this condition of J-dominance, both the onset and limited amount of crack growth can be correlated to the critical values of J and J-resistance curve, respectively (Ref. 31).

Evaluation of energy release rates in nonlinear elastic bodies is usually performed by numerical analysis and estimation techniques. Traditionally, a comprehensive numerical study is based on FEM for nonlinear stress analysis. Although several general and special purpose computer codes are available for detailed finite-element analysis, they are impractical and inconvenient to use for conducting routine pipe fracture evaluations. The computational effort by FEM is still significant even with the recent development of numerical techniques and industry-standard computational facilities. In addition, the employment of FEM can be time consuming and may require a high degree of expertise for its implementation. These issues become particularly significant when numerous deterministic analyses are required in a full probabilistic analysis.

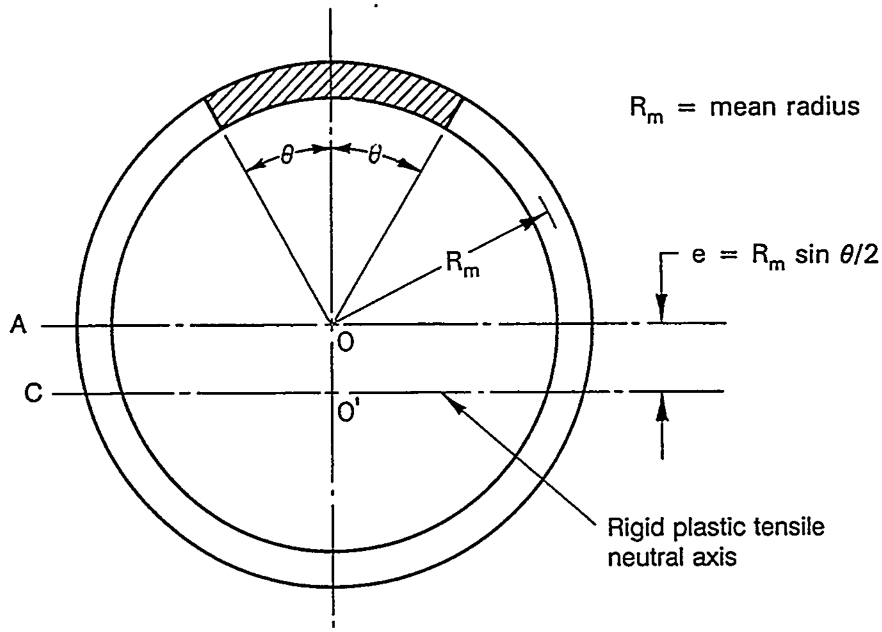
For circumferentially through-wall-cracked pipes, elastic-plastic analysis techniques, which do not require full three-dimensional finite-element analysis (FEA) for combined tension and bending loads, are scarce. Paris and Tada (Ref. 32) have presented a method that interpolates between the known elastic and rigid-plastic solutions by using a pseudo plastic-zone correction to the elastic solution. Klecker et al. (Ref. 33) introduced a method that is very similar to the Paris and Tada approach except it empirically accounts for material strain hardening. Both of these techniques require numerical integration. Recently, Kumar and German (Ref. 34) presented a method, that is based upon interpolation between compiled finite-element solutions. The British R-6 method (Ref. 35) is a method to predict failure loads for pipes subjected to combined tension and bending. However, displacements are not provided. It should be noted that methods for the purely elastic problem have been available for some time now as summarized in Forman et al. (Ref. 36).

Discussions of the conditions for achieving J-dominance and the suitability of J as a fracture parameter for combined bending and tensile loadings have been presented by Shih (Ref. 37) and Shih and Hutchinson (Ref. 38) by studying the single-edge notch specimen. Additional studies based on FEA of the single-edge notch specimen subjected to combined tension and bending have recently appeared (Refs. 39 and 40). An important result obtained by Sonnerlind and Kaiser (Ref. 40) indicates that the value of J is essentially independent of whether tension is applied, then bending; bending then tension; or both tension and bending are applied proportionally. This is not intuitively obvious since such loading clearly violates the hypothesis (necessary for valid J-tearing theory) of proportional loading. Based on this premise, an estimation method is proposed by Brust and Gilles (Ref. 41) for evaluating the J-integral of cracked tubular members subjected to combined tensile and bending loads. The method of analysis is based on (1) classical deformation theory of plasticity, (2) a constitutive law characterized by a Ramberg-Osgood model, and (3) an equivalence criteria incorporating a reduced thickness analogy for simulating system compliance due to the presence of a crack in a pipe (Refs. 42 to 45). The method is general in the sense that it may be applied in the complete range between elastic and fully plastic conditions. Since it is based on J-tearing theory, it is subject to the usual limitations imposed upon this theory, e.g., proportional loading, etc. As explained earlier, this has the implication that the crack growth must be small, although in practice, J-tearing methodology is used far beyond the limits of its theoretical validity with acceptable results (Ref. 4).

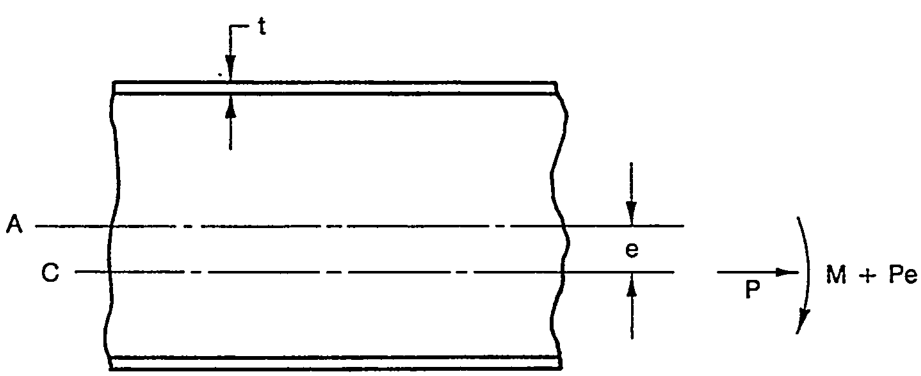
In this study, the above method, known as LBB.ENG2, was used. This method was selected because of its computational efficiency and it was found to be slightly conservative yet reasonably accurate when compared with experimental data (Ref. 46). A brief description of this method is given below.

2.3.1 The LBB.ENG2 Method

Consider a pipe with a TWC under combined bending and tension in Figure 2.5, which has mean radius, R_m, wall thickness, t, and crack angle, 2θ, with the crack circumferentially located in the pipe. It is assumed that the tensile load, P, is applied through the point, O, and the bending moment, M, is applied about the axis A [Fig. 2.5(a)]. As shown in Figure 2.5(b), this can be converted to an equivalent problem with axial force, P, applied through Point, O′, which is a distance, e, below Point O and bending moment, M + Pe. It is assumed that P causes pure stretch, which is precisely true for perfect plasticity and, at worst, gives conservative results for strain hardening materials.



(a) Cracked section of through-wall-cracked pipe



(b) Combined tensile and bending analogy

Figure 2.5 Through-wall-cracked pipe under combined bending and tension

T-6004-F2.5(a)/2.5(b)

In the development of a J-estimation scheme, it is generally assumed that the load-point displacement and rotation due to the presence of a crack, Δ^c and ϕ^c, respectively, and the crack driving force, J, admit additive decomposition into elastic and plastic components given by

$$\phi^c = \phi_e^c + \phi_p^c \tag{2-19}$$

$$J = J_e + J_p \tag{2-20}$$

$$\Delta^c = \Delta_e^c + \Delta_p^c \tag{2-21}$$

where the subscripts "e" and "p" refer to the elastic and plastic contributions, respectively. In the elastic range, $\phi^c{}_e$ and M, and $\Delta^c{}_e$ and P are uniquely related. In addition, if the deformation theory of plasticity holds, a unique relationship also exists between $\phi^c{}_p$ and M, and $\Delta^c{}_p$ and P. They are available in the original paper by Brust and Gilles (Ref. 41) and will not be repeated here. Once these relationships are determined, the elastic component, J_e, and the plastic component, J_p, of the total energy release rate, J, can be readily obtained. In Reference 41, detailed derivations of J_e and J_p are provided. Once again, they will not be repeated here. Only the final expressions will be provided. They are as follows.

Elastic Solution. The elastic component, J_e, is given by

$$J_e = \left[\frac{K_I^T + K_I^B}{E} \right]^2 \tag{2-22}$$

where E is the modulus of elasticity and K_I^T and K_I^B are the tensile and bending stress-intensity factors in which plane stress conditions are assumed. From the theory of linear-elastic fracture mechanics, K_I^T and K_I^B can be obtained from

$$K_I^T = \frac{P}{2\pi R_m t} F_T(\theta)\sqrt{\pi R_m \theta} \tag{2-23}$$

$$K_I^B = \frac{(M + Pe)}{\pi R_m^2 t} F_B(\theta)\sqrt{\pi R_m \theta} \tag{2-24}$$

where $F_T(\theta)$ and $F_B(\theta)$ are the tension and bending geometry functions with explicit definitions given in Appendix A.

Plastic Solution. The plastic component, J_p, is given by

$$J_p = \frac{\alpha}{E\sigma_0^{n-1}} \frac{\pi R_m}{2(n+1)} H_T(n,\theta) L_T(n,\theta) I_T(\theta) \left[\frac{P}{2\pi R_m t} \right]^{n+1} + \frac{\alpha}{E\sigma_0^{n-1}} \frac{\pi R_m}{2(n+1)} H_B(n,\theta) L_B(n,\theta) I_B(\theta) \left[\frac{M + Pe}{\pi R_m^2 t} \right]^{n+1} \quad (2\text{-}25)$$

where σ_0 is the reference stress, α and n are Ramberg-Osgood parameters characterizing the stress-strain curve of the material,

$$H_T(n,\theta) = \frac{4\theta F_T(\theta)^2}{I_T(\theta)} + \frac{1}{L_T(n,\theta)} \frac{\partial L_T(n,\theta)}{\partial \theta} \quad (2\text{-}26)$$

$$L_T(n,\theta) = \left[1 - \left[\frac{\theta}{\pi} \right] - \left[\frac{2}{\pi} \right] \sin^{-1} \left[\frac{1}{2} \sin(\theta) \right] \right]^{1-n} \quad (2\text{-}27)$$

$$I_T(\theta) = 4 \int_0^{\theta} \theta F_T(\theta)^2 \, d\theta \quad (2\text{-}28)$$

and

$$H_B(n,\theta) = \frac{4\theta F_B(\theta)^2}{I_B(\theta)} + \frac{1}{L_B(n,\theta)} \frac{\partial L_B(n,\theta)}{\partial \theta} \quad (2\text{-}29)$$

$$L_B(n,\theta) = \left[\frac{\pi}{4 \left\{ \cos \left[\frac{\theta}{2} \right] - \frac{1}{2} \sin\theta \right\}} \right]^{n-1} \left[\frac{\pi}{4\hat{K}} \right]^{n} \quad (2\text{-}30)$$

$$I_B(\theta) = 4 \int_0^{\theta} \theta F_B(\theta)^2 \, d\theta \quad (2\text{-}31)$$

$$\hat{K} = \frac{\sqrt{\pi}}{2} \frac{\Gamma\left[1+\frac{1}{2}n\right]}{\Gamma\left[\frac{3}{2}+\frac{1}{2}n\right]} \tag{2-32}$$

with

$$\Gamma(u) = \int_0^{\infty} \xi^{u-1} \exp(-\xi)\, d\xi \tag{2-33}$$

as the gamma function. Explicit functional forms of $I_T(\theta)$ and $I_B(\theta)$ are also given in Appendix A.

2.3.2 Maximum Load

In applications of nonlinear fracture mechanics, particularly for nuclear power plants, J-tearing theory is a very prominent concept for calculating the maximum load-carrying capacity of a pipe. It is based on the fact that fracture instability can occur after some amount of stable crack growth in tough and ductile materials with an attendant higher applied load level at fracture. Let J and J_R denote the crack driving force and toughness of a ductile piping material. The fracture instability based on J-tearing theory can be represented by

$$f_1(M_{max}, a^*) = J(M_{max}, a^*) - J_R(a^* - a) = 0 \tag{2-34}$$

and

$$f_2(M_{max}, a^*) = \frac{\partial J}{\partial a}\left(M_{max}, a^*\right) - \frac{dJ_R}{da}\left(a^* - a\right) = 0 \tag{2-35}$$

where M_{max} and a^* represent the moment and half the crack length when crack growth becomes unstable. Equations 2-34 and 2-35 are two nonlinear simultaneous equations with the independent variables M_{max} and a^*. They can be solved by standard numerical methods such as the Newton-Raphson method (Ref. 22).

2.4 Computer Codes NRCPIPE and SQUIRT

2.4.1 The NRCPIPE Computer Code

The NRCPIPE computer code was developed to perform elastic-plastic fracture-mechanics analysis, i.e., to establish the fracture-failure conditions of an engineering structure in terms of sustainable load (or stress) or displacement (Ref. 46). For nuclear applications, engineering elastic-plastic fracture-mechanics techniques are based on the J-integral fracture parameter. To perform a fracture analysis, the user provides the input data describing the pipe and crack geometry, material stress-strain characteristics, and fracture resistance of the material (i.e., a J_R curve) as obtained from a laboratory test specimen. A wide variety of results describing fracture characteristics of the pipe can be obtained.

The engineering treatment of elastic-plastic fracture mechanics is still in a dynamic state of development. Although a number of procedures have been proposed, many have not been validated by experimental data. For this reason, NRCPIPE was written to include numerous analysis procedures. At the user's option, NRCPIPE can perform an analysis using any of these procedures. In addition, the modular structure of NRCPIPE permits inclusion of new procedures as they are developed, because incomplete blocks of code have been reserved for just this purpose.

The NRCPIPE code was originally developed under the past Degraded Piping Program (Ref. 4). A significant amount of development and numerous enhancements were made in the Short Cracks in Piping and Piping Welds program (Ref. 47). Further details on these enhancements can be obtained from Reference 47.

2.4.2 The SQUIRT Computer Code

SQUIRT, which stands for Seepage Quantification of Upsets In Reactor Tubes, is a computer program that predicts the leakage rate and area-of-crack-opening for cracked pipes in nuclear power plants (Ref. 6). In all cases, the fluid in the piping system is assumed to be water at either subcooled or saturated conditions. The development of the SQUIRT computer model enables licensing authorities and industry users to conduct the leak-rate evaluations for leak-before-break applications in an efficient manner. The SQUIRT code also includes technical advances that are not available in other computer codes currently used for leak-rate estimation (Ref. 6).

The SQUIRT computer program is the result of combining two independent computer programs. The fracture-mechanics analysis performed by SQUIRT was derived from a modified version of the NRCPIPE computer program (Ref. 46). The thermal-hydraulic model was derived from programming the Henry-Fauske model for two-phase flow. A user of the SQUIRT program can choose to run the fracture-mechanics (SQUIRT1 subroutine) or thermal-hydraulic (SQUIRT2 subroutine) models independently; a combined analysis is also possible. In the combined fracture and fluid-mechanics analysis, the user first does the fracture-mechanics analysis to yield crack-opening displacements (CODs) and crack lengths as a function of pipe load, and then chooses the specific cases for which leak-rate analyses are performed.

A recent version of the SQUIRT code (SQUIRT4) was developed to compute the approximate crack size by performing iterative calculations between the fracture-mechanics and the thermal-hydraulic parts of the program when an applied load and an allowable leak rate are prescribed. However, there are two limitations in this version. First, the crack morphology variables are required to be constant regardless of the values of crack-opening displacement. Second, only one analysis can be performed at a time. No option is available for conducting multiple analyses, which are required in probabilistic or sensitivity studies.

For this study, the SQUIRT4 program was modified to handle more than one set of crack morphology parameters (SQUIRT5) automatically. Also, additional interface routines were developed to use the output of the NRCPIPE module (crack length and crack-opening displacement) to update the COD-dependent crack morphology parameters before performing thermal-hydraulic calculations. This was done in accordance with the piece-wise linear functional dependence described previously (see Section 2.1.2).

The SQUIRT code was developed under the past IPIRG program (Ref. 5). Further development and enhancements are also being pursued in the Short Cracks in Piping and Piping Welds program (Ref. 47).

2.5 Evaluation of Deterministic Models

2.5.1 Thermal-Hydraulic Model in SQUIRT

A literature search for leakage-flow-rate data for high-temperature and high-pressure water flowing through tight cracks (i.e., cracks with a wall thickness much larger than the COD) was conducted in Ref. 6. The data can be divided into three categories: pipe flows, flows through artificially produced slits, and flows through naturally occurring pipe cracks.

Although the literature abounds with data on two-phase flow through long pipes, this particular geometry is not of great interest for flow through tight cracks. However, it is worthwhile determining that the thermal-hydraulic model agrees reasonably well with this well-defined flow situation. For this reason, we limited ourselves to the pipe flow data of Sozzi and Sutherland (Ref. 48). Figure 2.6 compares the SQUIRT thermal-hydraulic predictions to the pipe flow data of Sozzi and Sutherland. In this figure, the calculation error, defined as the predicted flow rate minus measured flow rate divided by measured flow rate times 100, is plotted against the measured flow rate. The agreement between the model and the experiment is excellent.

The next level of difficulty involves comparing the thermal-hydraulic model with the experimental data obtained on artificially produced slits with known surface roughness and spacing. Figures 2.7, 2.8, and 2.9 show the comparison of the results from the SQUIRT thermal-hydraulic model to the slit flow data of Collier et al. (Ref. 19), Amos and Schrock (Ref. 49), Matsushima, et al. (Ref. 50), and Yano, et al. (Ref. 51). In some cases, the agreement is not quite as good as that for pipe flows. In general, the SQUIRT program predicts leakage flow rates that are lower than those measured with artificial slits. Since the geometry is well defined, this suggests that the nonequilibrium vapor generation rate may be different for flow through tight slits than for flow through long tubes. Allowing less vapor to be formed in the slit would increase the net flow through the artificial slits. Jones (Ref. 52) and Jones and Zuber (Ref. 53) have information that support this hypothesis. Some additional work is needed in this area.

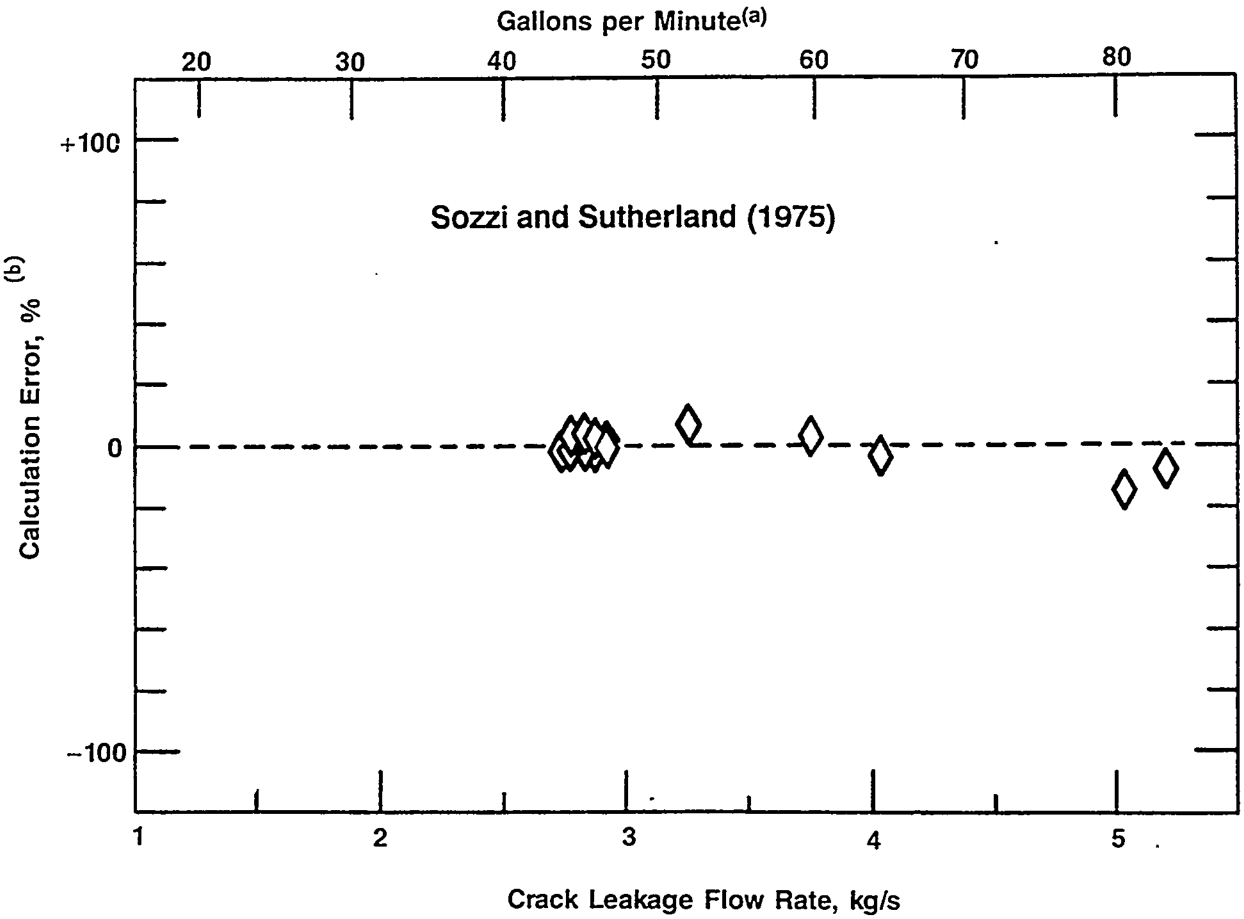


Figure 2.6 Comparison of SQUIRT thermal-hydraulic model predictions with the experimental data of Sozzi and Sutherland (Ref. 48) for flows through pipes

(a) Gallons per minute for water at ambient conditions

(b) Calculation error, % = predicted minus measured flow rate divided by measured flow rate times 100

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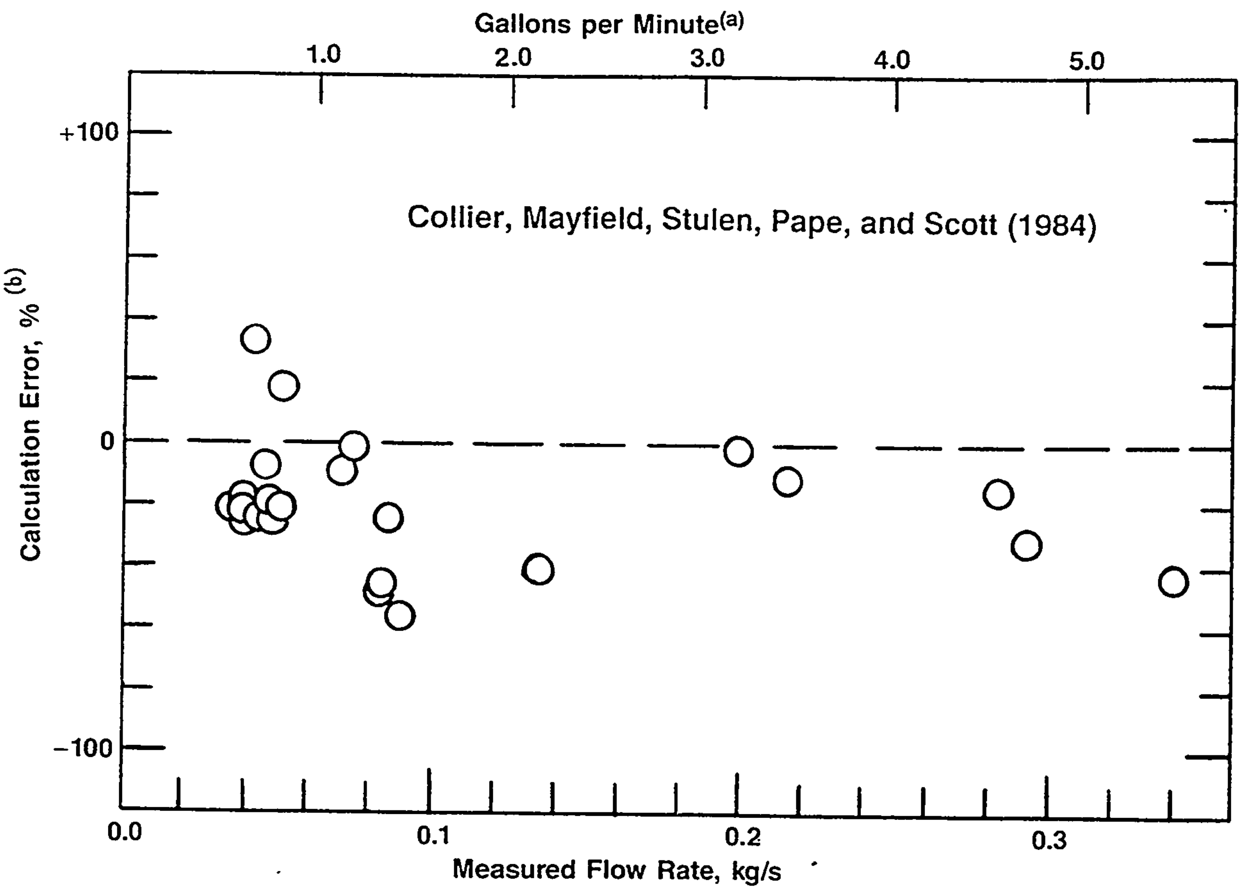


Figure 2.7 Comparison of SQUIRT thermal-hydraulic model predictions with the experimental data of Collier et al. (Ref. 19) for flows through artificially produced tight slits

(a) Gallons per minute for water at 1 atm and 20 C

(b) Calculation error, % = predicted minus measured flow rate divided by measured flow rate times 100

T-6004-F2.7

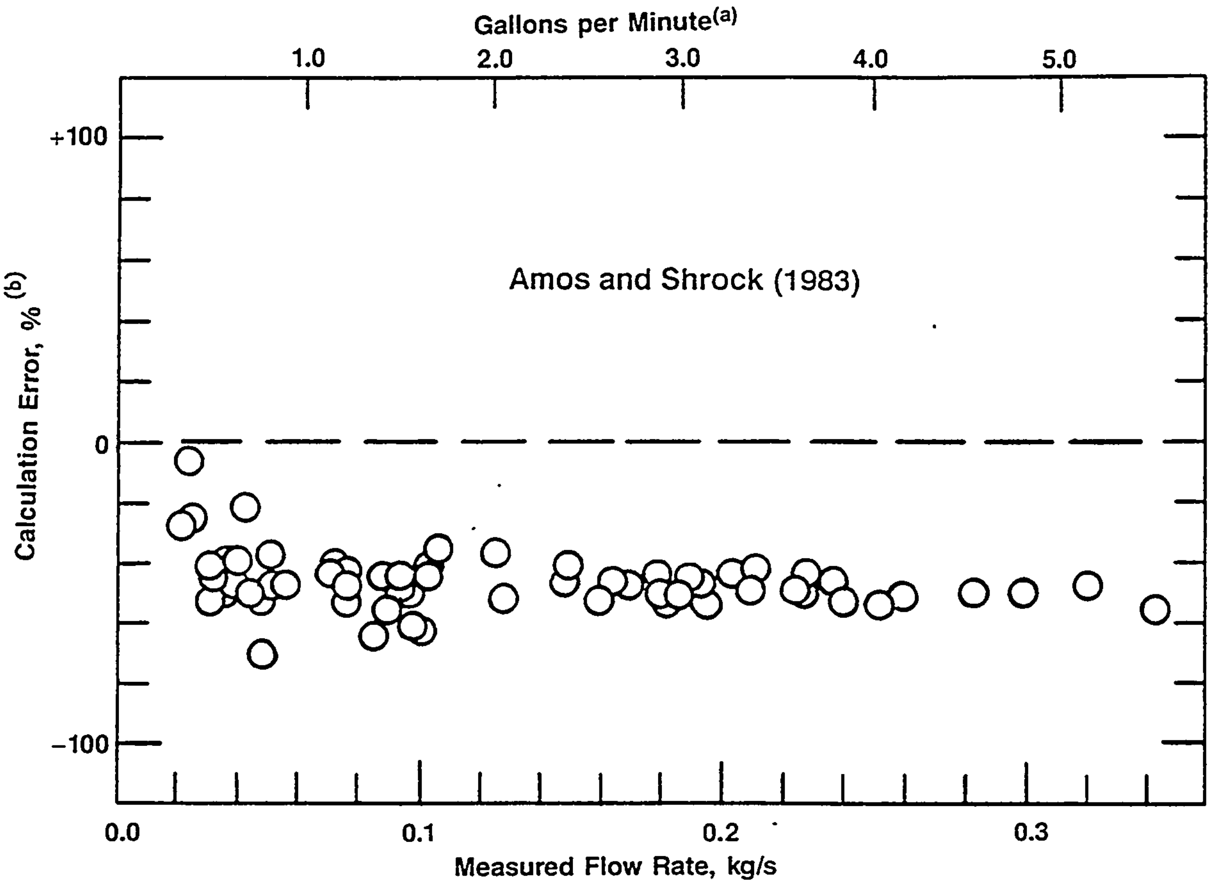


Figure 2.8 **Comparison of SQUIRT thermal-hydraulic model predictions with the experimental data of Amos and Schrock (Ref. 49) for flows through artificially produced tight slits**

(a) Gallons per minute for water at 1 atm and 20 C

(b) Calculation error, % = predicted minus measured flow rate divided by measured flow rate times 100

T-6004-F2.8

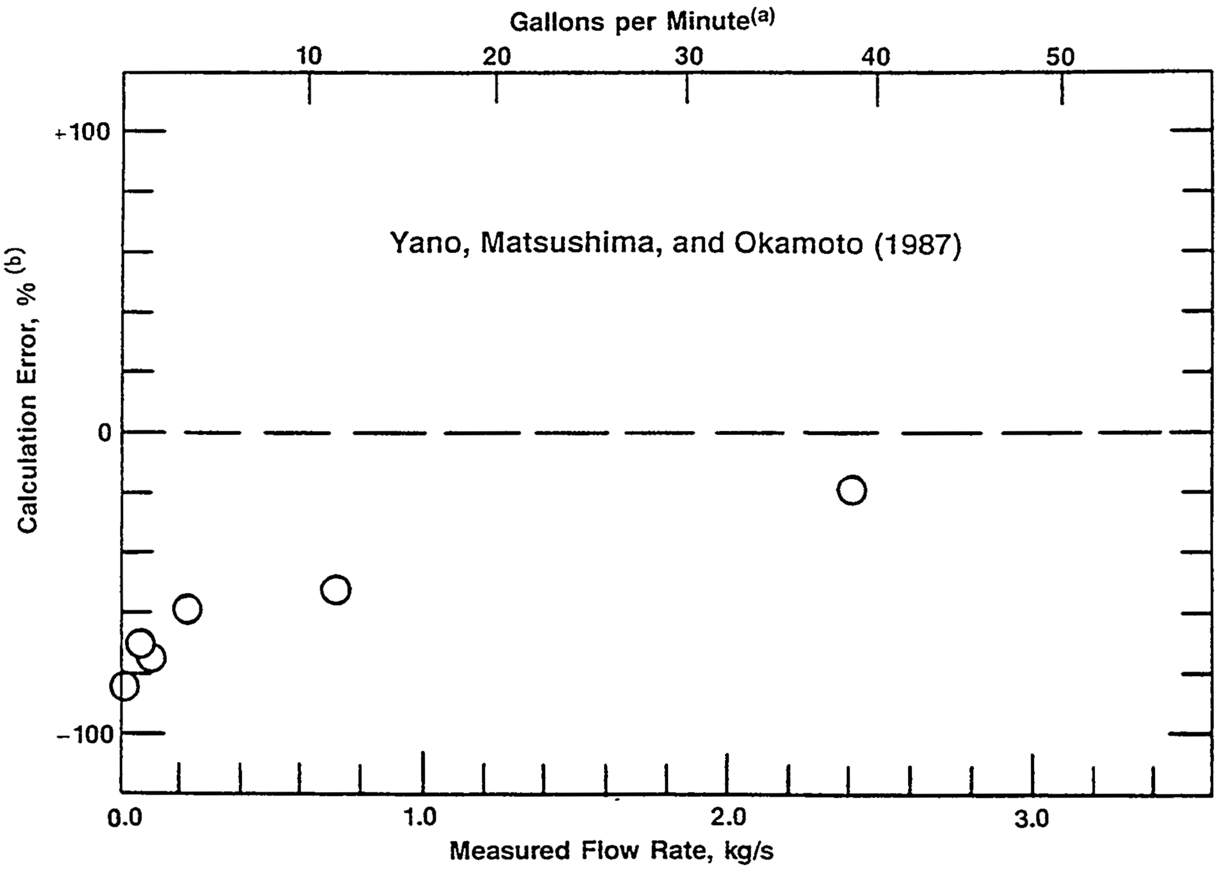


Figure 2.9 Comparison of SQUIRT thermal-hydraulic model predictions with the experimental data of Yano et al. (Ref. 51) for flows through artificially produced tight slits

(a) Gallons per minute for water at 1 atm and 20 C

(b) Calculation error, % = predicted minus measured flow rate divided by measured flow rate times 100

T-6004-F2.9

The final level of difficulty involves the comparison between the thermal-hydraulic models and the leakage-flow-rate data obtained in naturally occurring pipe cracks. Figures 2.10 through 2.13 compare the SQUIRT (original version of SQUIRT, Ref. 6) thermal-hydraulic model predictions with the experimental data for intergranular stress-corrosion cracks obtained by Collier et al. (Ref. 19). In general, the mean values of model error are very close to zero, but there is a much greater scatter in the data than previously seen in either the pipe or slit flow tests. Collier et al. have attributed this larger uncertainty to the possibility that the cracks could have become partially plugged by particles in the water. For the larger CODs, the SQUIRT program tends to agree reasonably well with the measured data points, although there is more scatter in the data than those observed for the artificial slit experiments.

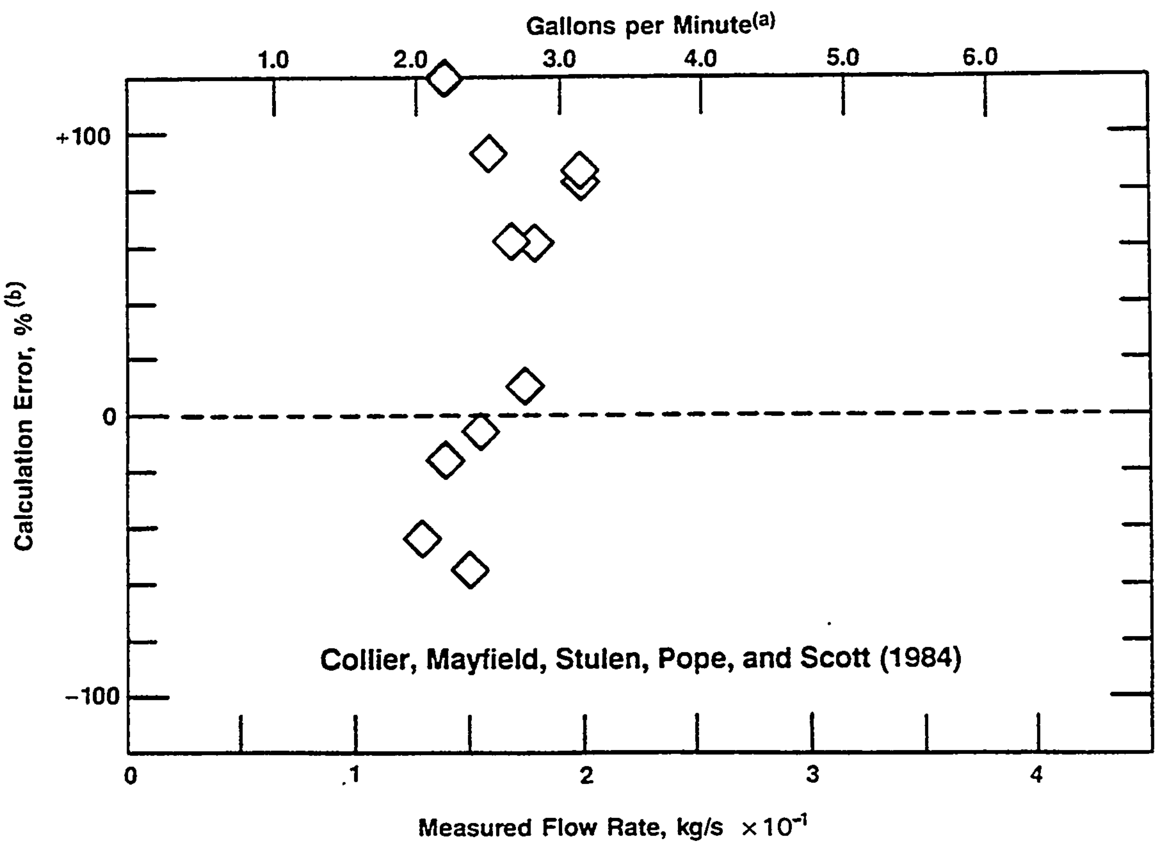


Figure 2.10 Comparison of SQUIRT thermal-hydraulic model predictions with the experimental data of Collier et al. (Ref. 19) for cracks with a COD of 220 μm

(a) Gallons per minute for water at 1 atm and 20 C

(b) Calculation error, % = predicted minus measured flow rate divided by measured flow rate times 100

T-6004-F2.10

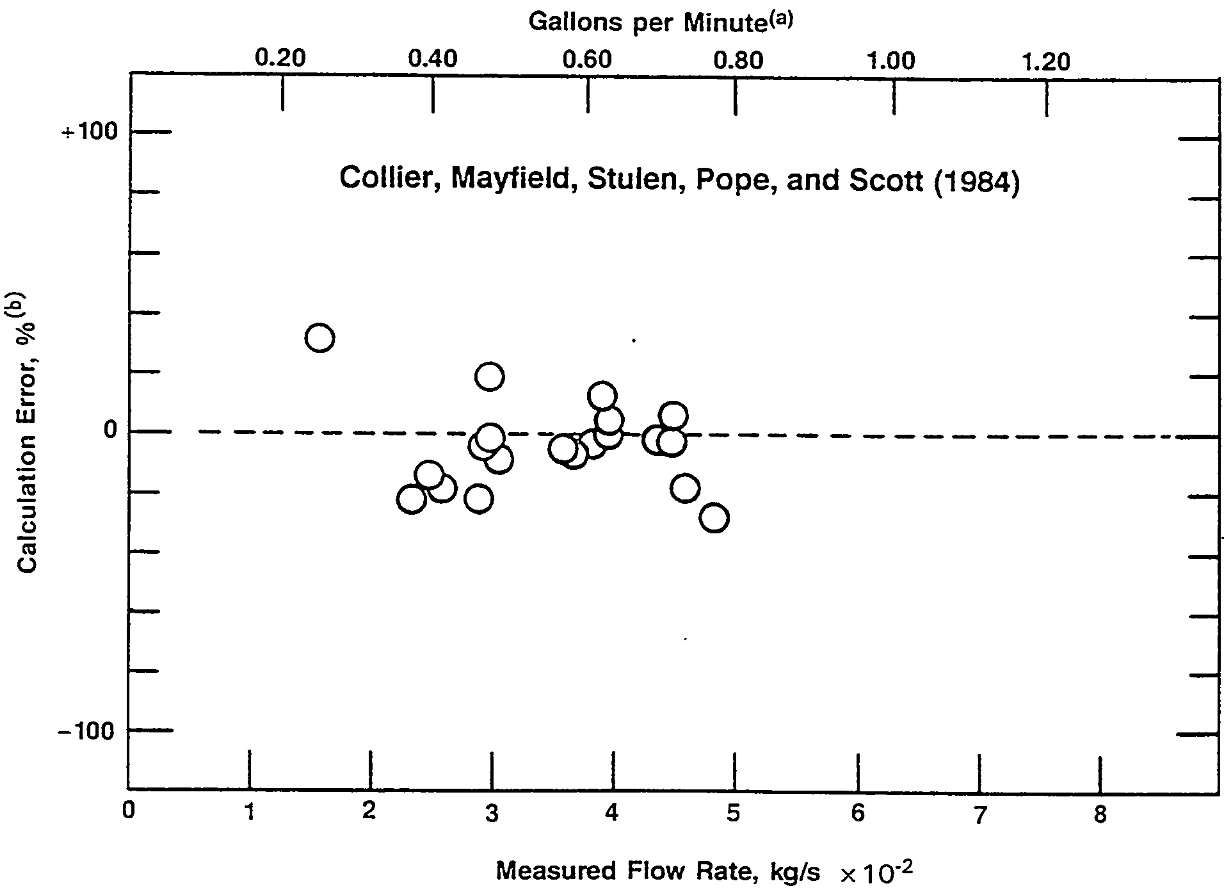


Figure 2.11 Comparison of SQUIRT thermal-hydraulic model predictions with the experimental data of Collier et al. (Ref. 19) for cracks with a COD of 108 μm

(a) Gallons per minute for water at 1 atm and 20 C

(b) Calculation error, % = predicted minus measured flow rate divided by measured flow rate times 100

T-6004-F2.11

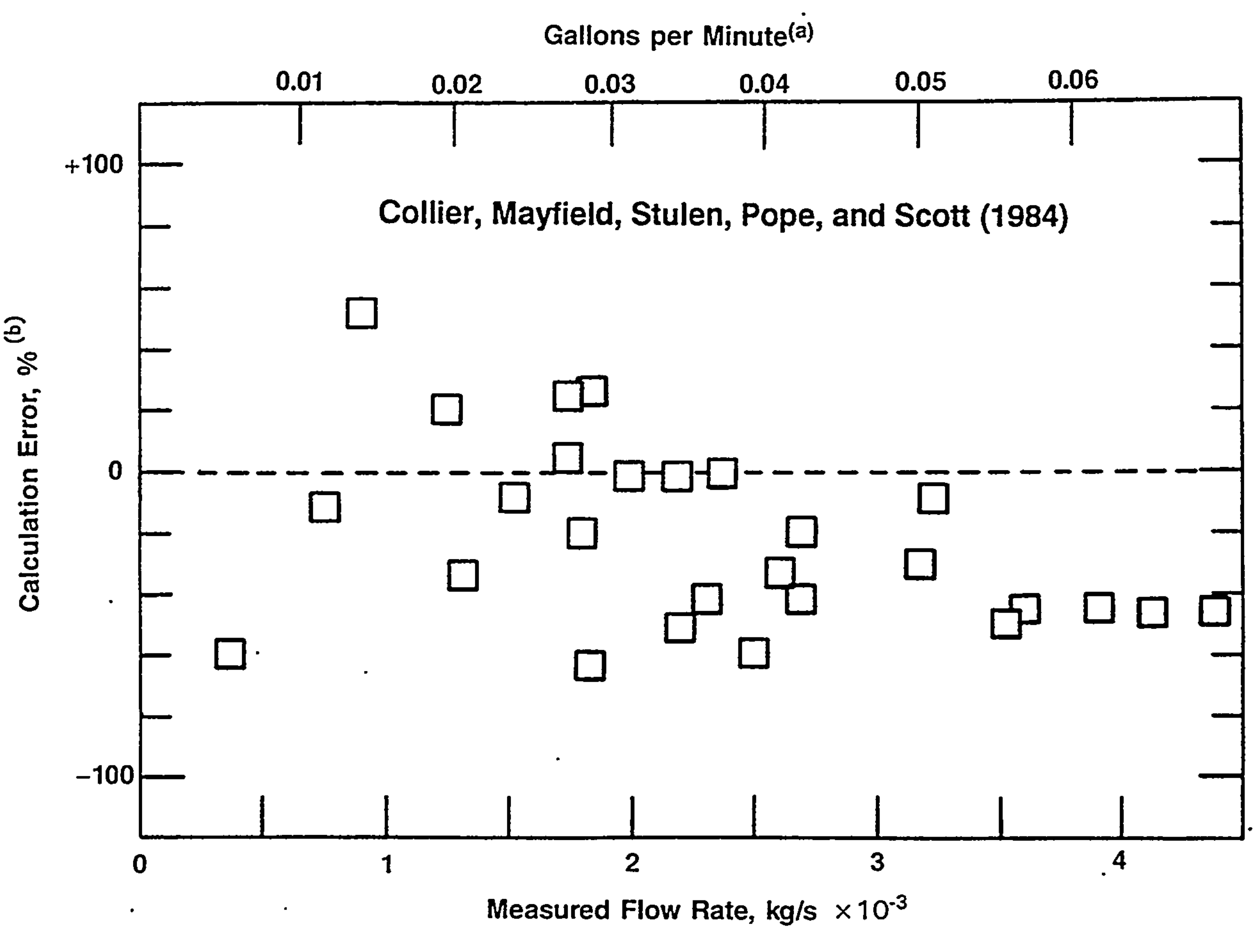


Figure 2.12 Comparison of SQUIRT thermal-hydraulic model predictions with the experimental data of Collier et al. (Ref. 19) for cracks with a COD of 50 μm

(a) Gallons per minute for water at 1 atm and 20 C

(b) Calculation error, % = predicted minus measured flow rate divided by measured flow rate times 100

T-6004-F2.12

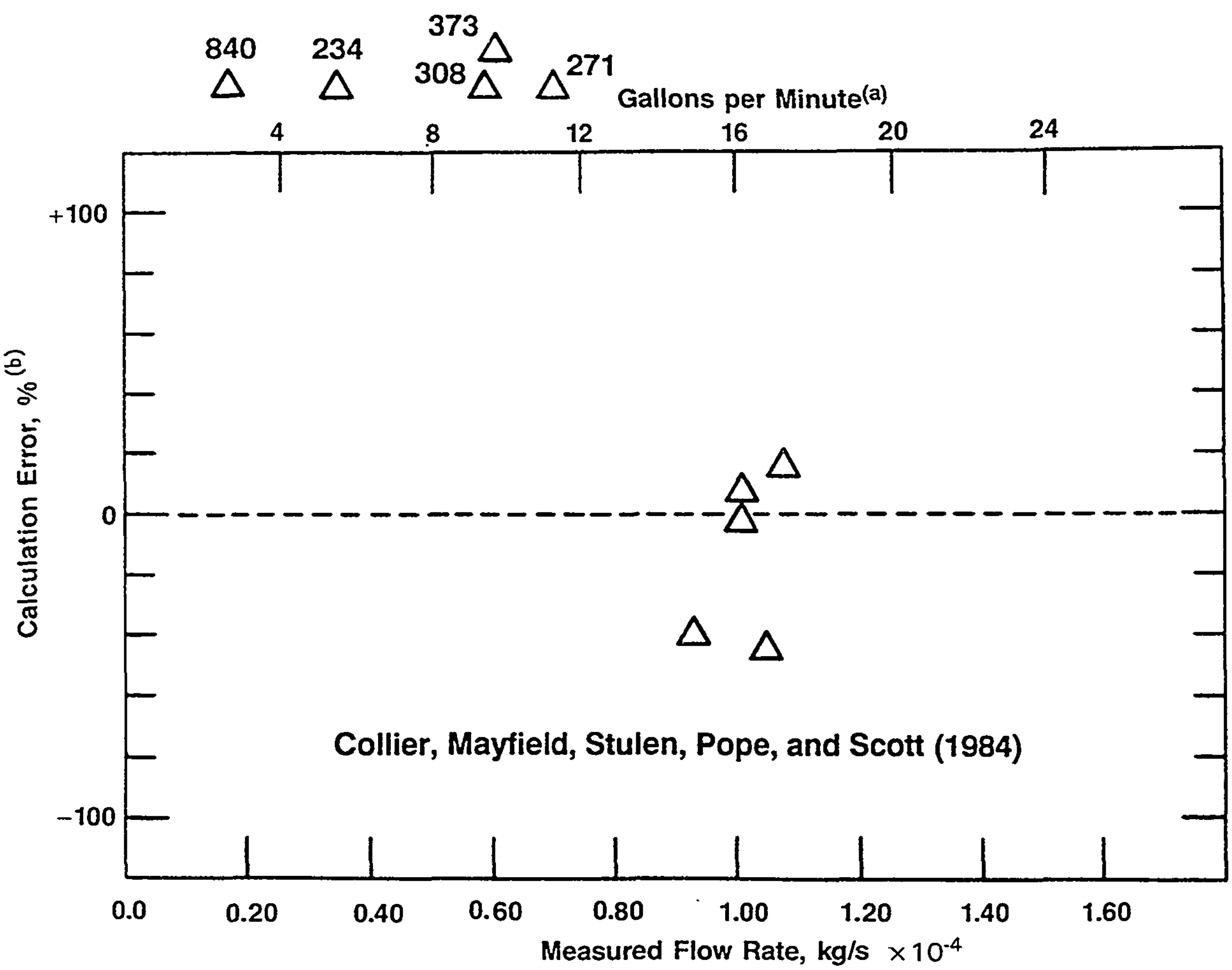


Figure 2.13 Comparison of SQUIRT thermal-hydraulic model predictions with the experimental data of Collier et al. (Ref. 19) for cracks with a COD of 20 μm

(a) Gallons per minute for water at 1 atm and 20 C

(b) Calculation error, % = predicted minus measured flow rate divided by measured flow rate times 100

T-6004-F2.13

2.5.2 Area-of-Crack-Opening Model in SQUIRT

The area-of-crack-opening model in SQUIRT was evaluated by comparing its estimates with the available experimental measurements. The experimental data used for comparisons were in the form of center COD measurements made during pipe fracture experiments previously conducted at Battelle during the Degraded Piping Program (Ref. 4).

Through-Wall-Cracked Pipes. Figure 2.14 shows the results of the ACO estimation model for Experiment 4111-1 reported in Reference 4. The experiment in this case was performed on 114.3-mm (4.5-inch) outer diameter, SA-333, Grade 6, carbon steel pipe, which is subjected to four-point bending. The solid line in this figure represents the measured COD as a function of applied load up to the load at crack initiation. It is seen that in this case, the linear regression fit of the stress-strain data over the whole strain range leads to the best estimate of COD. The same trend was also found to be true for Experiment 4111-3, the results of which are shown in Figure 2.15. However, in this case, the results using the low-strain region and the total strain range were virtually the same. Experiment 4111-3 was conducted on 1066.8-mm (42-inch) nominal diameter, SA358 Type 304, stainless steel pipe under pure bending. Reviewing the results of the estimation method shown in Figures 2.14 and 2.15, it would appear that the use of a linear regression curve fit of the entire stress-strain curve may serve as the method for prescribing the Ramberg-Osgood constants in SQUIRT. Figure 2.16 shows the result of the estimation analysis using SQUIRT for Experiment 4111-2. This experiment was performed on a 711.2-mm (28-inch) nominal diameter, A155 CK70 CL1, carbon steel pipe under pure bending. Again, the calculated COD is in reasonably good agreement with the experimental data up to the load at initiation of crack growth. Similar types of comparisons between predicted and experimental COD for other pipe experiments conducted at Battelle are available in Reference 6, including cracks in weld metal.

Complex-Cracked Pipes. A complex or compound crack is a long surface crack that penetrates the thickness over a short length. This could happen with a thermal fatigue or IGSCC crack. Exact J-estimation formulas to calculate COD for a circumferentially complex-cracked pipe have not yet been developed, primarily because the problem is so complicated to analyze. Here it is assumed that the J-estimation formulas for simple through-wall circumferentially cracked pipes in bending can be applied to analyze complex-cracked pipes by adjusting the pipe radius and the thickness in the crack plane to account for the presence of the surface crack. A 360-degree surface crack of constant depth was assumed. Thus, any radial crack driving force contribution was ignored. Only growth of the through-wall crack in the circumferential direction was considered. Also, possible closure of the surface crack in the compressively stressed region of the crack plane was not included in the analysis. Further details are available in References 54 and 55.

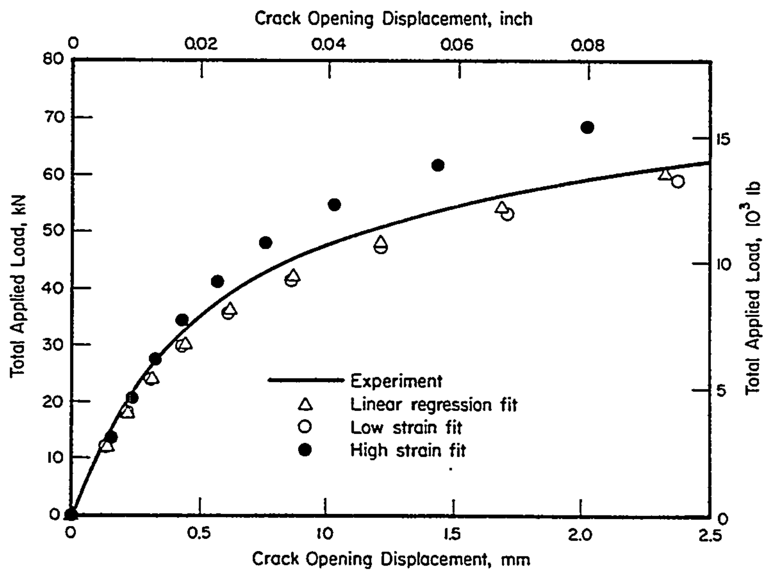


Figure 2.14 Center-crack-opening displacement in Experiment 4111-1 up to load at initiation of crack growth

T-6005-F2.14

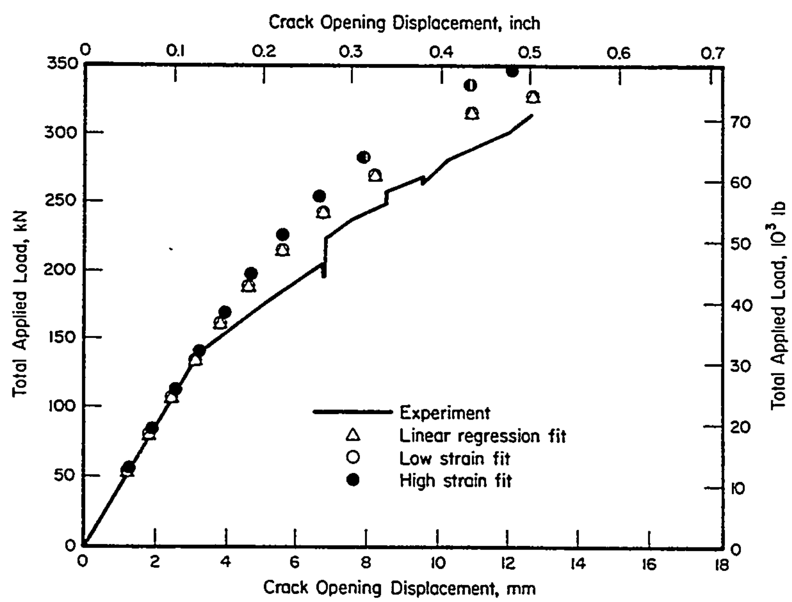


Figure 2.15 Center-crack-opening displacement in Experiment 4111-3 up to load at initiation of crack growth

T-6004-F2.15

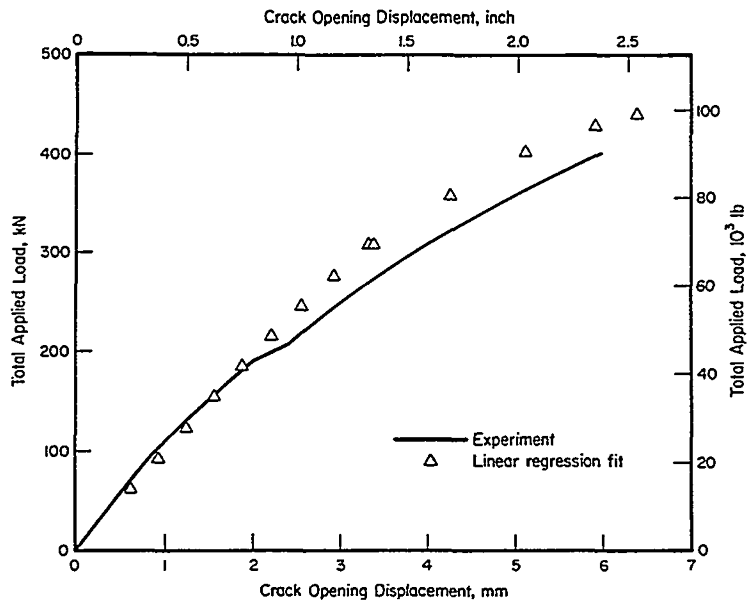


Figure 2.16 Center-crack-opening displacement in Experiment 4111-2 up to load at initiation of crack growth

T-6004-F2.16

Figures 2.17 and 2.18 show the plots of applied load versus center COD up to a maximum load for two complex-cracked pipes under four-point bending in Experiments 4114-3 and 4114-4 from the past Degraded Piping Program (Ref. 4). Both of these experiments were conducted on 406.4-mm (16-inch) nominal diameter, SA358, Type 304, stainless steel pipes. The results were obtained from both J-estimation formulas (LBB.ENG2) and the experimental data. Theoretical results were obtained for two cases of J-resistance curves. One was based on a J-resistance curve from C(T) specimen data ($\hat{C} = 1$) and the other was based on a J-resistance curve from C(T) specimen data multiplied with a relevant reduction factor, $\hat{C}$, which has a value less than 1. The parameter $\hat{C}$ varies as a function of d/t where d and t represent depth of surface crack and pipe thickness of a complex-cracked pipe, respectively. The reduction factor $\hat{C}$ was developed from the comparisons of J-resistance curves from simple through-wall-cracked pipes and complex-cracked pipes (Ref. 54). See Reference 54 for explicit details on how $\hat{C}$ can be related to the d/t ratio. The results show that in both pipe fracture tests, the experimental COD is well-predicted by the J-estimation method in the linear-elastic range using either J-resistance curve. Since the normal operating stresses are close to linear-elastic, predicted COD with either J-resistance curve is adequate. Hence, for the sake of simplicity, the J-resistance curve from C(T) specimen data without any reduction factor will be used in this study.

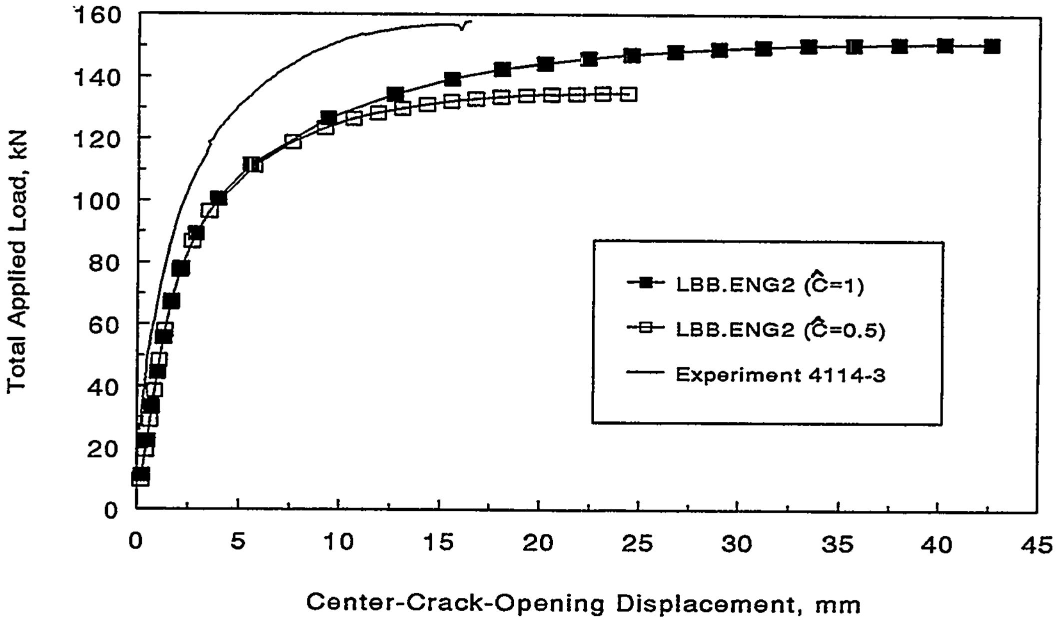


Figure 2.17 Center-crack-opening displacement in Experiment 4114-3

T-6004-F2.17

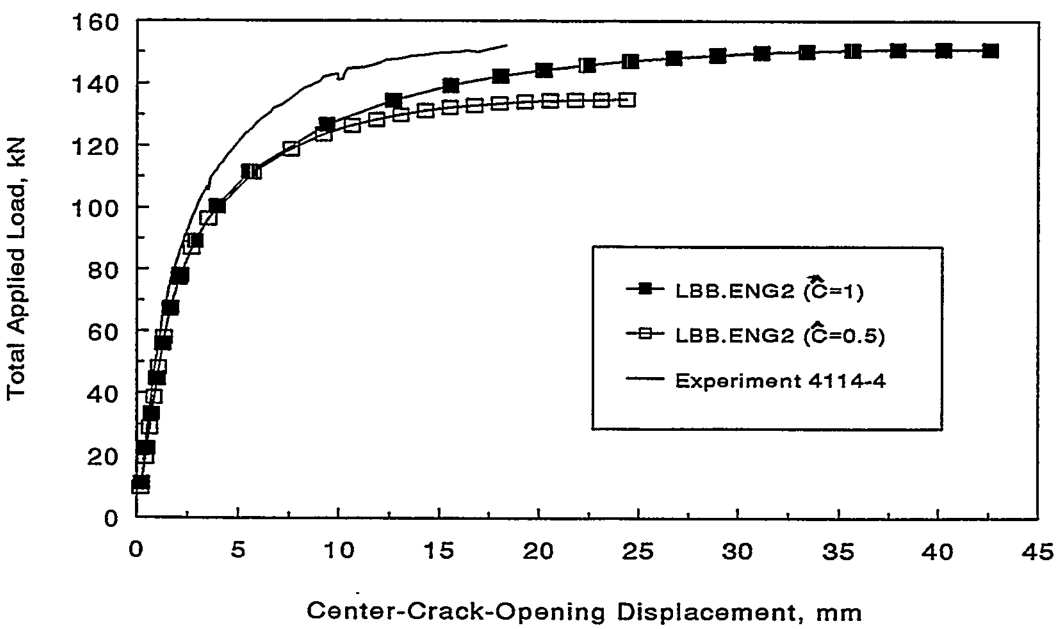


Figure 2.18 Center-crack-opening displacement in Experiment 4114-4

T-6004-F2.18

Restraint of Induced Bending. Current analyses assume that for axial stresses (generally pressure induced), the pipe is free to rotate. The restraint of the rotation increases the failure stresses (Ref. 56), but decreases the crack opening at a given load. If the pipe system restrains the bending (i.e., from cracks being close to a nozzle or restraint from the rest of the pipeline system), then the leak rate will be less than that calculated by using analyses that assume that the pipe is free to rotate. This will cause the actual crack length to be larger than the crack length calculated by the current analyses methods for the same leak rate. Since under normal operating conditions a large component of the total stress is the pressure-induced stress, this may have some effect on LBB analyses.

As part of this program, the following investigation was undertaken. For a numerical example, consider a TWC pipe with mean radius R_m = 355.6 mm (14 inch), wall thickness t = 35.56 mm (1.4 inch), R_m/t = 10, and two distinct cases of initial crack angle, 2θ, with $\theta/\pi = 1/8$ and $\theta/\pi = 1/4$. For material properties, it was assumed that the modulus of elasticity E = 200 GPa (29,000 ksi) and the Poisson's ratio $\nu = 0.3$. The pipe was subjected to remote pressure with the resultant force applied at the centroid of the uncracked pipe cross section. Linear-elastic analyses by FEM were preformed to examine the effects of restraint due to induced bending in a piping system when the pressure load was applied. Figure 2.19 shows a mesh representing finite-element discretization of the pipe under consideration.

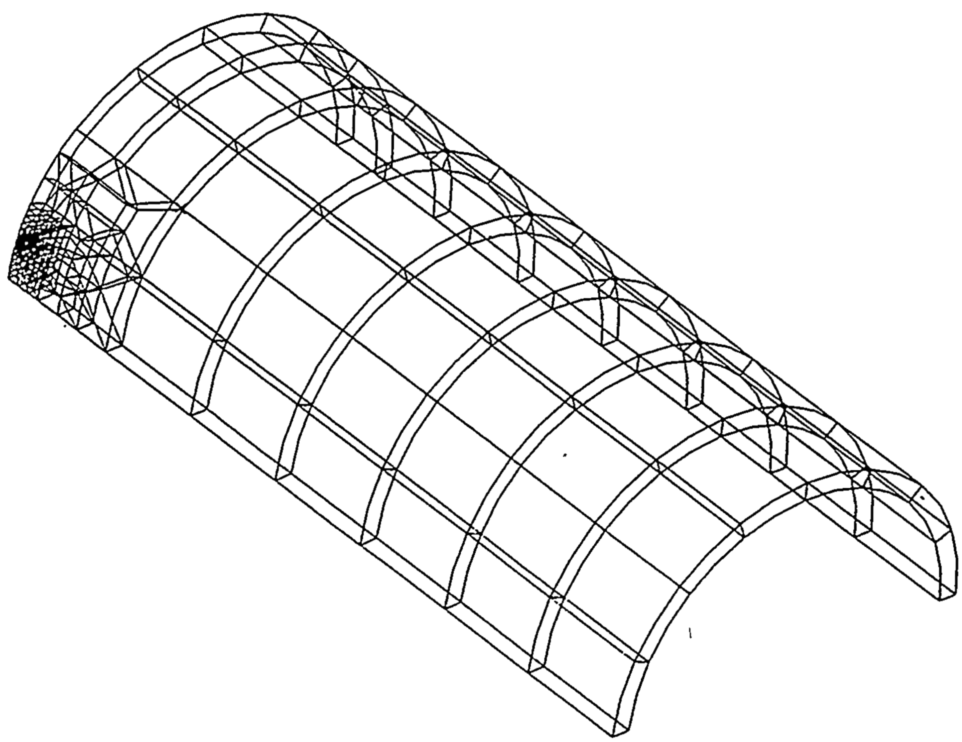


Figure 2.19 Finite-element mesh for linear-elastic restraint of crack-opening displacement

T-6004-F2.19

Figure 2.20 presents the results of center COD as a function of "restraint length" normalized with respect to the mean pipe diameter $D_m = 2R_m$. The restraint length defined here simply represents the location of the restrained pipe cross section from the cracked plane. The COD values were also normalized with reference to the COD when no external constraints were present in the pipe (i.e., when the restraint length becomes infinity) allowing free rotation and ovalization. The results show that when the crack angle is "small" ($\theta/\pi = 1/8$), the restraint effects may be neglected. However, for larger crack angles ($\theta/\pi = 1/4$), the restrained COD can be smaller than the unrestrained COD and hence, may become important in the crack-opening-area analysis for leak-rate quantification. It is interesting to note that the "restraint length" is not currently considered in the thermal-hydraulic codes SQUIRT (Refs. 5 and 6) or PICEP (Ref. 23) or in any other leak-rate analyses. This is because the appropriate reduction factor for unrestrained COD has not been evaluated. Also, due to restraint of bending the failure load of the pipe may increase and it is not clear how this compensates the effects of reduction of COD. Hence, the evaluation of COD in this study will be based on unrestrained conditions, which may be sufficient for short crack lengths typical of leaking cracks, but some margin on the calculated leak rate for restraint considerations is needed. Nevertheless, more studies are needed in this area.

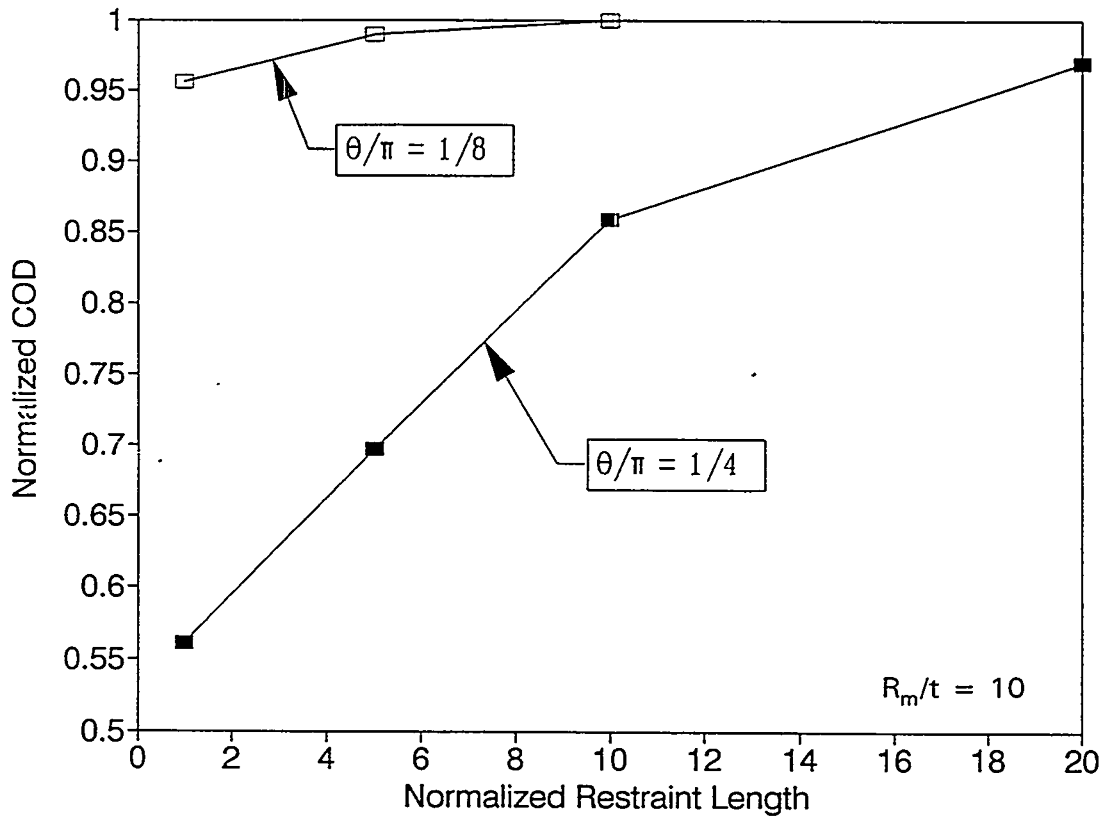


Figure 2.20 Effect of fully restrained bending conditions from crack location on COD normalized by unrestrained COD

T-6004-F2.20

Crack-Opening Profile. In order to determine the crack-opening profile, Reference 8 reported comparisons of predicted results with experimental data. Figure 2.21 shows the detailed plots of COD (at mean surface) for a through-wall-cracked pipe experiment (Experiment 8T) at crack initiation load as a function of crack-tip distance. This experiment was conducted on a 406.4-mm (16-inch) nominal diameter, Type 304, stainless steel pipe containing a through-wall crack with length 37 percent of the pipe circumference. Also shown in Figure 2.21 are the predicted COD by FEM and estimation models of SQUIRT with several assumptions of crack-opening shapes, such as diamond, ellipse, and rectangle. Compared with the test data as well as with the finite-element results, the elliptical profile was found to best represent the crack-opening shape of a stationary circumferential crack in a pipe. Note that in the FEM analysis, the stress-strain curve of the material was described by a multi-linear representation of the experimental data.

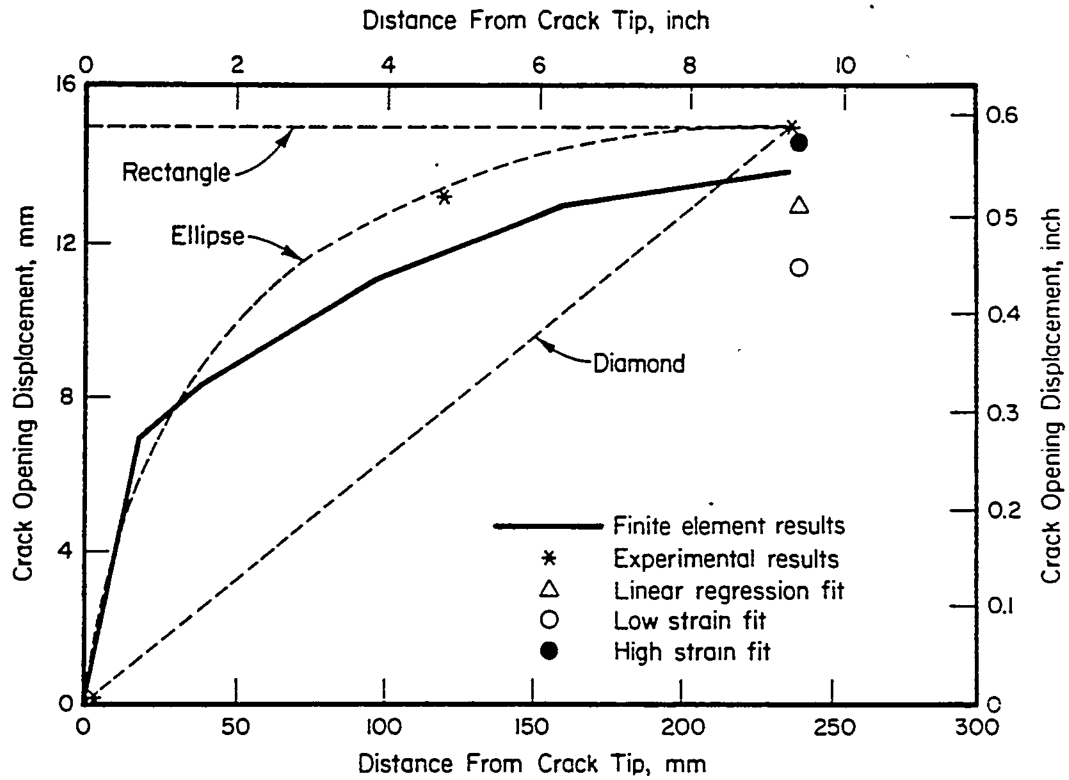


Figure 2.21 Crack-opening displacement in Experiment 8T during load at crack initiation

T-6004-F2.21

During the course of the NRC's Short Cracks in Piping and Piping Welds program, a separate finite-element study was performed to evaluate the adequacy of an elliptical representation of the crack-opening profile. In this regard, a through-wall-cracked pipe under pure bending was analyzed. The pipe had outer diameter D_0 = 406.4 mm (16 inch), wall thickness t = 26.19 mm (1.031 inch), crack size θ/π = 12 percent, and applied bending moment M = 522.61 kN-m (4,626 kip-inch). The elastic modulus, E, was 193.06 MPa (28,000 ksi) and the Poisson's ratio, ν, was 0.3. The loading was assumed to be linear-elastic with no plasticity or crack growth. The finite element analysis was performed by the ABAQUS code (Version 5.3) with 20-noded 3D solid elements. The total number of elements and nodal points were 1,260 and 9,030, respectively. Only one element through the thickness was used. Figure 2.22 shows the results of the FEM analysis in terms of COD plotted as a function of angle from the crack tip. In Figure 2.22, two plots are shown, one for the crack-opening profile at the outer surface, and the other for the crack-opening profile at the inner surface of the pipe. For each case, the continuous line indicates the crack-opening shape assuming an elliptical representation with the center COD estimated by FEM analysis. The solid points indicate explicit calculations by FEM as a function of the angle from the crack tip. It appears that both outer and inner crack-opening profiles can be accurately modeled by elliptical shapes.

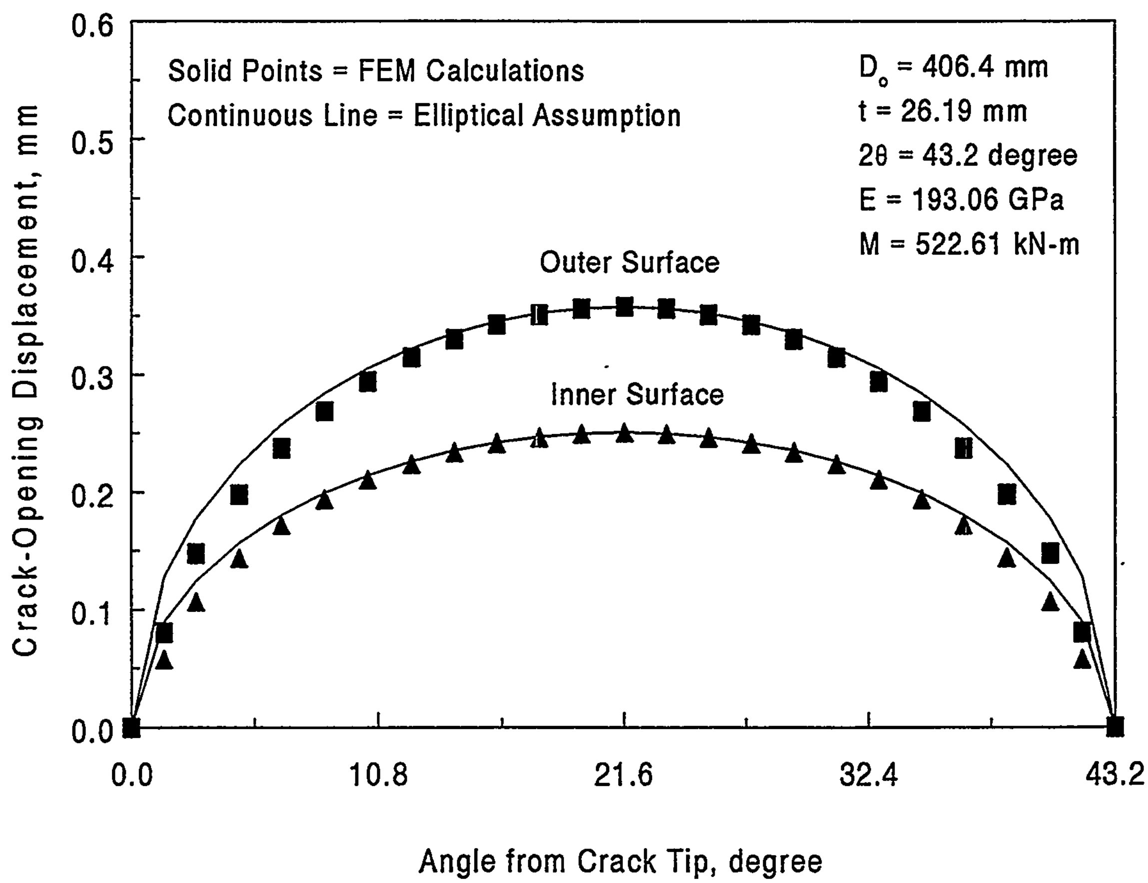


Figure 2.22 Crack-opening displacement as a function crack-tip angle

T-6004-F2.22

Note that the results presented in Figures 2.21 and 2.22 are based on stationary cracks. If there is significant crack growth, which is highly unlikely under normal operating conditions, the initial elliptical shape may perhaps change to more of a diamond shape. From the studies reported in References 4 to 6, it has been suggested that the elliptical profile is a good assumption of crack-opening shape up to crack initiation, but following severe crack growth, the crack-opening approaches the diamond shape.

2.5.3 Maximum Load Calculation by the LBB.ENG2 Method

Through-Wall-Cracked Pipes. Twelve full-scale pipe fracture experiments were analyzed to determine the predictive capability of the LBB.ENG2 method. In all experiments, the pipes had circumferential through-wall cracks and were subjected to pure bending without internal pressure. The experiments were: Experiments 1T to 4T, 4111-2, 4111-5, 4141-1, 4141-5, 1.1.1.21, 1.1.1.23, 1.1.1.24, and 1.1.1.26. They were selected from the Degraded Piping program (Ref. 4) and the Short Cracks in Piping and Piping Welds program (Ref. 47). The experiments involved both austenitic and ferritic steel piping with cracks located either in the base or weld metals. The initial crack lengths were both short and long and ranged between 5.3 and 38.3 percent of the mean pipe circumference. There were five experiments conducted at room temperature while the rest of the tests were performed at 288 C (550 F). Table 2.1 provides the test matrix of circumferential through-wall-cracked pipes considered in this study.

The pipe fracture experiments in Table 2.1 were analyzed by the LBB.ENG2 method using the computer program NRCPIPE (Version 1.4G) described earlier. Using this program, the maximum loads were computed and then compared with the corresponding test data. The predictions were based on using a power-law extrapolation of the J_D-R curves and best fit of the engineering stress-strain curves from 1-percent strain to 80-percent of ultimate strain. Table 2.2 shows the maximum load predictions by the LBB.ENG2 method and their comparisons with the pipe fracture data. From Table 2.2, standard statistical analysis of maximum load ratio, defined as the ratio of experimental maximum load to predicted maximum load, revealed that the LBB.ENG2 method can provide fairly accurate results when compared with the experimental data. The mean and standard deviation of the maximum load ratio was calculated to be 1.03 and 0.13, respectively.

Figure 2.23 shows the plots of applied load versus load-line displacement of a 152.4-mm (6-inch) diameter (nominal) stainless steel pipe with a 37 percent circumferential TWC subject to four-point bending and tension due to internal pressure of 17.24 MPa (2.50 ksi) at 288 C (550 F). They were obtained from several J-estimation methods including LBB.ENG2 and laboratory data from the Degraded Piping Program Experiment 4131-1 (Ref. 4). These plots clearly show that the LBB.ENG2 method gives reasonable predictions of load when compared with the test data. Note that the load-line displacement from the experiment contained machine compliance and, for this reason, the elastic slope was underestimated by the test when compared with the results of the analysis..

Table 2.1 Test matrix of through-wall-cracked pipe experiments

Experiment No.	Pipe Material	Outside Pipe Diameter, mm (inch)	Wall Thickness, mm (inch)	$2a/\pi D_m$ (a)	Test Temperature, C (F)
1T	SA-312 TP304	114.3 (4.50)	9.00 (0.354	0.371	20 (68)
2T	SA-312 TP304	114.3 (4.50)	8.94 (0.352)	0.229	20 (68)
3T	SA-312 TP304	114.3 (4.50)	8.89 (0.350)	0.290	20 (68)
4T	SA-312 TP304	114.3 (4.50)	8.89 (0.350)	0.053	20 (68)
4111-2	SA-515 Gr 60	711.2 (28.0)	23.6 (0.930)	0.370	288 (550)
4111-5	SA-240 TP316 SMAW(b)	719.6 (28.33)	30.2 (1.190)	0.370	288 (550)
4141-1	SA-376 TP304 SAW(c)	168.3 (6.625)	14.3 (0.562)	0.371	288 (550)
4141-5	SA-376 TP304 SA-SAW(d)	167.8 (6.605)	14.1 (0.555)	0.383	288 (550)
1.1.1.21	SA-515 Gr 60	711.2 (28.00)	22.7 (0.890)	0.063	288 (550)
1.1.1.23	SA-240 TP316L SAW(c)	711.2 (28.00)	30.2 (1.190)	0.063	288 (550)
1.1.1.24	SA-333 Gr 6 SAW(c)	612.0 (24.10)	31.3 (1.230)	0.079	288 (550)
1.1.1.26	TP316LN	106.2 (4.18)	8.31 (0.327)	0.244	21 (70)

(a) 2a is through-wall crack length at mean radius; D_m is mean pipe diameter
(b) Shielded-metal arc weld
(c) Submerged-arc weld
(d) Solution-annealed submerged-arc weld

Table 2.2 Comparisons of maximum loads by LBB.ENG2 method with experimental data for 12 through-wall-cracked pipe experiments

Experiment No.	$2a/\pi D_m$ (a)	Maximum Load, kN (predicted)	Maximum Load, kN (experiment)	Maximum Load Ratio, Experimental/Predicted
1T	0.371	59.00	64.81	1.10
2T	0.229	86.29	97.86	1.13
3T	0.290	89.85	98.39	1.10
4T	0.053	180.19	139.52	0.77
4111-2	0.370	698.72	585.00	0.84
4111-5	0.370	636.82	611.00	0.96
4141-1	0.371	62.54	73.80	1.18
4141-5	0.383	57.08	60.50	1.06
1.1.1.21	0.063	1435.87	1466.00	1.02
1.1.1.23	0.063	1321.32	1489.00	1.13
1.1.1.24	0.079	1423.33	1660.00	1.16
1.1.1.26	0.244	83.70	74.84	0.90
			Mean	1.03
			Standard Deviation	0.13

(a) 2a is mean length of through-wall crack; D_m is mean pipe diameter

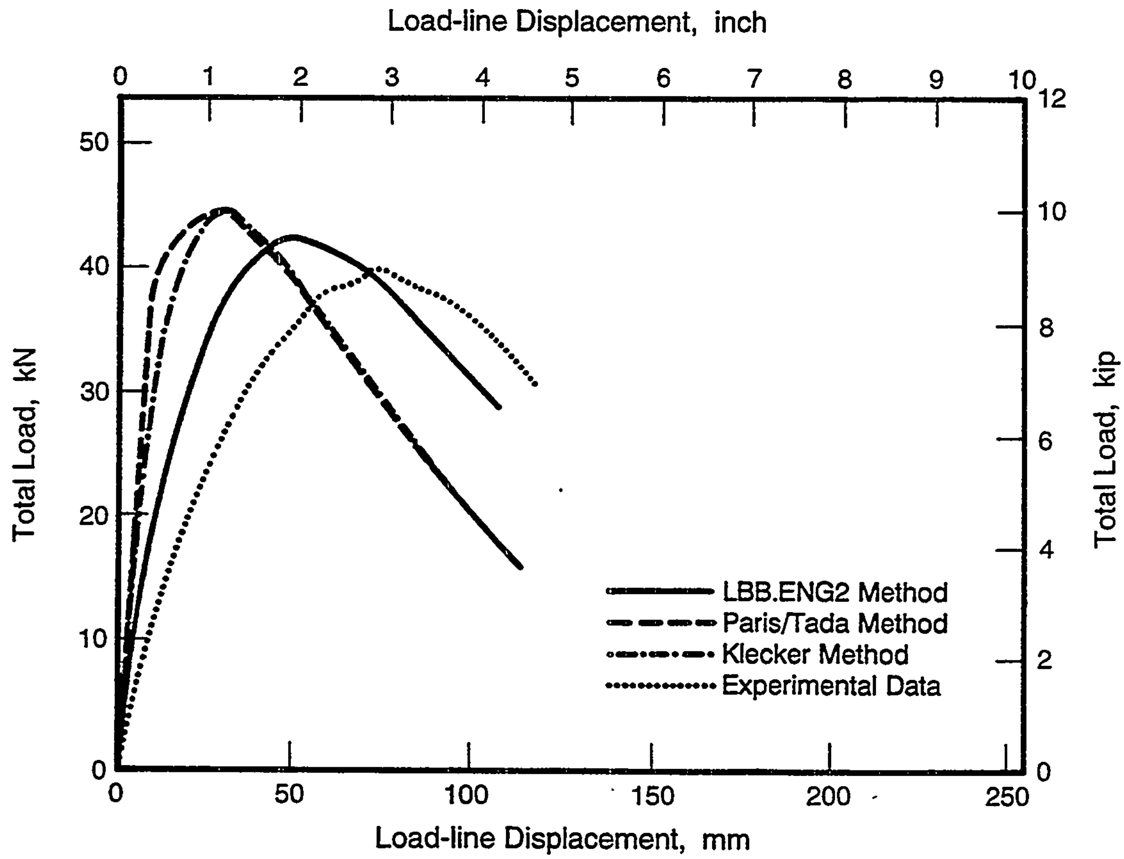


Figure 2.23 Comparisons of load-displacement of through-wall-cracked pipe under combined bending and tension (Experiment 4131-1)

T6004-F2.23

Complex-Cracked Pipes. In order to evaluate the adequacy of the LBB.ENG2 method for complex-cracked pipes, results of ten pipe experiments conducted under the Degraded Piping Program (Ref. 4) were also examined. These were Experiments 4113-1 to 4113-6, and 4114-1 to 4114-4. Table 2.3 shows the test matrix of complex-cracked pipe experiments considered in this study.

Table 2.3 Test matrix of complex-cracked pipe experiments

Experiment No.	Pipe Material	Outside Pipe Diameter, mm (inch)	Wall Thickness, mm (inch)	$2a/\pi D_m$ (a)	d/t (b)	Test Temperature, C (F)
4113-1	SA-376 TP304	168 (6.625)	14.5 (0.570)	0.37	0.31	288 (550)
4113-2	SA-376 TP304	168 (6.625)	14.5 (0.570)	0.37	0.63	288 (550)
4113-3	Inconel 600	168 (6.625)	11.0 (0.435)	0.37	0.34	288 (550)
4113-4	Inconel 600	168 (6.625)	11.0 (0.435)	0.37	0.61	288 (550)
4113-5	A106 Grade B	168 (6.625)	14.2 (0.560)	0.37	0.31	288 (550)
4113-6	A106 Grade B	168 (6.625)	14.2 (0.560)	0.37	0.64	288 (550)
4114-1	A106 Grade B	165 (6.500)	12.7 (0.501)	0.37	0.47	288 (550)
4114-2	SA-376 TP304	167 (6.560)	13.5 (0.530)	0.37	0.32	288 (550)
4114-3	SA-358 TP304	414 (16.30)	26.2 (1.030)	0.37	0.33	288 (550)
4114-4	SA-358 TP304	414 (16.30)	26.2 (1.030)	0.37	0.33	288 (550)

(a) 2a is the mean length of through-wall crack; D_m is the mean pipe diameter
(b) d is the depth of internal surface crack; t is the thickness of pipe

Table 2.4 provides the maximum loads for the above complex-cracked pipes subjected to four-point bending that were obtained from both LBB.ENG2 formulas and experimental data. Predictions by LBB.ENG2 method were based on a simple TWC formula by adjusting the pipe radius and the thickness of complex-cracked pipes in the crack plane to account for the presence of the surface crack. A 360-degree surface crack of constant depth was assumed. The results showed that:

(1) The predicted maximum loads for the pipes in Test Series 4113 with shallow surface cracks ($d/t \simeq 0.3$) compared well with those obtained from experimental observations. They also indicated that the use of J_M^{TWC} (i.e., $\hat{C} = 1$) for Experiments 4113-1 and 4113-3 resulted in better predictions than those based on the use of J_M^{CC} (i.e., $\hat{C} < 1$) while the reverse was true for Experiment 4113-5.

(2) The predicted maximum loads for the pipes in Test Series 4114, estimated with a reduced J_M-resistance curve (J_M^{CC}), were closer to experimentally observed values for the smaller pipe diameters (e.g., Experiment 4114-1 and 4114-2). They also indicated, however, that the use of J_M^{TWC} for the larger diameter TP304 pipe (e.g., Experiments 4114-3 and 4114-4) resulted in better predictions than those based on the use of J_M^{CC}.

Table 2.4 Comparisons of maximum loads by LBB.ENG2 method with experimental data for ten complex-cracked pipes

Experiment No.	d/t	Constraint Factor, $\hat{C}$	Maximum Load, kN (predicted)		Maximum Load, kN (experiment)	Maximum Load Ratio, Experimental/Predicted	
			C(T) J-R	Using $\hat{C}$		C(T) J-R	Using $\hat{C}$
4113-1	0.31	0.50	115.44	99.59	124.10	1.08	1.24
4113-2	0.63	0.32	61.22	47.92	80.95	1.32	1.68
4113-3	0.34	0.50	115.88	100.21	117.87	1.02	1.16
4113-4(a)	0.61	0.32	66.85	52.52	86.74	1.30	1.65
4113-5	0.31	0.50	169.20	148.93	147.23	0.87	0.99
4113-6	0.64	0.32	88.14	69.94	88.52	1.00	1.26
4114-1	0.47	0.40	92.87	77.81	82.96	0.89	1.06
4114-2	0.32	0.50	32.18	27.76	29.09	0.90	1.04
4114-3	0.33	0.50	150.94	134.87	157.80	1.05	1.17
4114-4	0.33	0.50	150.94	134.87	152.08	1.01	1.13
					Mean	1.04	1.24
					Standard Deviation	0.16	0.24

(a) Shim used in crack to allow for crack closure on compression side, but closure not accounted for in analysis.

Results from Table 2.4 also showed that the estimation method underpredicted maximum loads for the pipes with deeper surface cracks (d/t ≈ 0.6), irrespective of the use of any J_M-resistance curves with the exception of Experiment 4113-6 with J_M^{TWC}. One plausible reason for the general loss of accuracy in the case of deeper surface cracks may be attributed to the oversimplification of using the simple through-wall-cracked pipe J-estimation formula. Finally, the mean and standard deviation of maximum load ratio (using the C(T) J-R curve) was calculated to be 1.04 and 0.16, respectively.

2.6 Summary of Review

The following summary can be drawn from the review of the deterministic models for conducting leak-rate and pipe fracture evaluations:

- The thermal-hydraulic model in SQUIRT provided reasonably good predictions of leak-rates for flows through naturally occurring pipe cracks, except when the cracks were very tight. There was greater scatter in the data for flow through tight cracks. This uncertainty is due to the fact that cracks, when especially tight, can be partially plugged by particles in the water.

- The area-of-crack-opening model in SQUIRT yielded accurate estimates of crack opening displacement for through-wall-cracked pipe. Results for crack opening displacement were found to be closer to experimental values when the Ramberg-Osgood fit was based on an entire range of actual stress-strain data. The crack opening displacement for complex-cracked pipe was also well-predicted by the estimation method in the linear elastic range irrespective of the J-resistance curve from C(T) specimen data with and without a toughness reduction factor. Also, the crack opening profile (flow area) was found to be best approximated by an elliptical shape with the crack length and crack opening displacement defining the lengths of the major and minor axes.

- The restraint of induced bending from axial loads for cracks close to terminal ends can reduce the crack opening relative to the unrestrained condition assumed in all crack-opening models; however, it can also increase failure loads. A margin of up to a factor of 2 on leak rate appears to be needed to account for this effect. More studies are needed in this area to better quantify the restraint effect.

- The elastic-plastic fracture mechanics model in LBB.ENG2 method provided a satisfactory prediction of the load-displacement curve for through-wall-cracked pipes subjected to bending and combined bending and tension. From analyses of 12 experiments on through-wall-cracked pipes, the mean and standard deviation of the maximum load ratio by the LBB.ENG2 method were 1.03 and 0.13, respectively.

- For complex-cracked pipes, the maximum loads predicted by the LBB.ENG2 method were consistently lower when the toughness reduction factor was used. Compared with the experimental data, results also indicated that the LBB.ENG2 method underpredicted maximum loads for the pipes with deeper surface cracks, irrespective of the use of any J-resistance curves with or without the reduction factor. The general loss of accuracy in the case of very deep surface cracks may be due to the oversimplification of using the simple through-wall-cracked pipe J-estimation formula for complex-cracked pipes.

- The elastic-plastic fracture mechanics model in the LBB.ENG2 method provided satisfactory prediction of loads for complex-cracked pipes subjected to bending. From analyses of 10 experiments on complex-cracked pipes, the mean and standard deviation of the maximum load ratio [using a C(T) J-R curve without any reduction factor] obtained using the LBB.ENG2 method were 1.04 and 0.16, respectively.

Thus, in general, it can be concluded that the underlying deterministic models considered in this study provided reasonably accurate estimates of leak rates, crack-opening area, and maximum load-carrying capacity of circumferentially cracked pipes. These validated deterministic models will be used for subsequent development of novel probabilistic models to evaluate the conditional failure probability of cracked piping systems.

3.0 STATISTICAL CHARACTERIZATION OF INPUT

3.1 Statistical Characterization of Material Properties

The material properties of base and weld metals used in typical nuclear piping are available in the NRC's PIFRAC database (Ref. 7), reports of the Degraded Piping Program (Ref. 4) and the IPIRG-1 Program (Ref. 5), and others (Refs. 8, 9, and 10). The PIFRAC database, which was originally developed at Material Engineering Associates, was updated significantly by adding more data from other sources. Data were collected from Ontario Hydro, General Electric, Westinghouse, Argonne National Laboratory, Babcock and Wilcox, David Taylor Research Center, and Framatome. Additional data from Battelle's Degraded Piping program, Short Cracks in Piping and Piping Welds program, and IPIRG-1 and IPIRG-2 programs were also included. A search of the above database from these research programs has provided a reasonable amount of data for characterizing strength (stress-strain curve) and toughness (J-resistance) properties of typical pipe materials. From the analysis of these data, it was observed that the parameters controlling stress-strain and J-resistance curves show substantial amounts of statistical variability. Hence, these parameters should be modeled as random variables with possible correlations. In this section, a statistical analysis is conducted from which the mean, covariance, and probability distribution of these random variables can be estimated.

3.1.1 Analytical Idealizations

In conducting numerical calculations, several analytical idealizations were considered. For example, it was assumed that the constitutive law characterizing a material's stress-strain response can be represented by the normalized Ramberg-Osgood model

$$\frac{\epsilon}{\epsilon_0} = \frac{\sigma}{\sigma_0} + \alpha \left[\frac{\sigma}{\sigma_0}\right]^n \tag{3-1}$$

in which σ_0 is a reference stress usually assumed to be the yield stress, E is the modulus of elasticity, $\epsilon_0 = \sigma_0/E$ is the associated reference strain, and α and n are strain-hardening parameters usually chosen from a best fit of laboratory data. The use of Equation 3-1 can lead to confusion, since it appears that there are three parameters (in addition to the elastic modulus). In reality, the original Ramberg-Osgood model has only two parameters along with the elastic modulus. The original equation is

$$\epsilon = \frac{\sigma}{E} + \left[\frac{\sigma}{F}\right]^n \tag{3-2}$$

where F and n are the power-law parameters of the model. Note that Equations 3-1 and 3-2 are equivalent if

$$\alpha = \frac{\sigma_0^{n-1} E}{F^n} \tag{3-3}$$

Hence, contrary to many opinions, σ_0 need not be equal to the material yield strength, but can be equal to any arbitrary value as long as α is appropriately adjusted as per Equation 3-3. Nevertheless, the computations of α conducted in this study were based on σ_0 being equal to the yield stress. The J-resistance curve from the C(T) specimen was deemed to be adequately characterized by a power-law equation of the form

$$J_R(\Delta a) = J_{Ic} + C\left[\frac{\Delta a}{r}\right]^m \tag{3-4}$$

in which $\Delta a = R\,\Delta\theta$ is the crack length extension during crack growth, J_{Ic} is the fracture toughness at crack initiation, and C and m are power-law parameters from a best fit of experimental data. In Equation 3-4, r is a dummy parameter with a value of unity introduced here to dimensionalize C. For example, if J and J_R are expressed in kJ/m^2 and Δa is expressed in mm, then the dimension of C is the same as that of the J-integral when r = 1 mm. Note that "Δa" here is the physical crack extension, i.e., without blunting. This is because blunting is automatically accounted for in the pipe estimation schemes (as well as finite-element analysis).

3.1.2 Statistical Analysis

Consider the random parameters that determine the strength and toughness properties of a pipe material. The parameters are: yield stress, σ_y, ultimate stress, σ_u, Ramberg-Osgood coefficients, F and n (stress-strain curve), crack initiation toughness, J_{Ic}, and power-law coefficients, C and m (J-resistance curve). It is assumed that the elastic modulus, E, is deterministic and is equal to 182,700 MPa (26,500 ksi) and 193,100 MPa (28,000 ksi) for austenitic and ferritic materials, respectively. Define an M-dimensional random vector, $\mathbf{Y} = \{Y_1, Y_2, \cdots, Y_M\}$, with its components representing random material property variables defined earlier. For example, $\mathbf{Y} = \{\sigma_y, \sigma_u\}$ or $\mathbf{Y} = \{F, n\}$ when representing the parameters of the stress-strain curve and $\mathbf{Y} = \{J_{Ic}, C, m\}$ when representing the parameters of the J-R curve. In all cases, this input vector, $\mathbf{Y}$, characterizes the uncertainty in the material properties of piping systems. The mean and covariance of $\mathbf{Y}$ can be obtained from

$$\mu_i = \int_{y_i^a}^{y_i^b} u f_i(u)\,du, \quad i=1,2,\cdots,M \tag{3-5}$$

and

$$\gamma_{ij} = \int_{y_i^a}^{y_i^b}\int_{y_j^a}^{y_j^b} (u-\mu_i)(v-\mu_j) f_{ij}(u,v)\,du\,dv, \quad i,j=1,2,\cdots,M \tag{3-6}$$

when the marginal probability density function

$$f_i(u) = \frac{d}{du} \Pr[Y_i \leq u] \quad (3\text{-}7)$$

of Y_i and the joint probability density function

$$f_{ij}(u,v) = \frac{\partial^2}{\partial u \partial v} \Pr[Y_i \leq u, Y_j \leq v] \quad (3\text{-}8)$$

of Y_i and Y_j are available. The limits of integration in Equations 3-5 and 3-6 correspond to the range of possible values of the components of **Y**. Estimates of μ_i and γ_{ij} can also be obtained when the probability density function of **Y** is not known, but K measurements $\{y^{(1)}, y^{(2)}, \cdots, y^{(K)}\}$ ($y^{(k)}$ is the kth measurement of the random vector **Y**) are available for all components of this vector. The estimates are

$$\hat{\mu}_i = \frac{1}{K} \sum_{k=1}^{K} y_i^{(k)}, \quad i=1,2,\cdots,M \quad (3\text{-}9)$$

and

$$\hat{\gamma}_{ij} = \frac{1}{K-1} \sum_{k=1}^{K} \left(y_i^{(k)} - \hat{\mu}_i\right)\left(y_j^{(k)} - \hat{\mu}_j\right), \quad i,j=1,2,\cdots,M \quad (3\text{-}10)$$

respectively. They approach the exact values μ_i and γ_{ij} as the sample size, K, increases indefinitely.

Samples of raw data for stress-strain and J-R curves of a specific pipe material were obtained from References 4, 5, and 7 to 10. Round-bar tensile specimens, machined from actual pipes and plates, were used to determine the uniaxial stress-strain curves of the material. The tests were conducted mostly at 288 C (550 F). The stress-strain data ranging between 1-percent strain and 80-percent of ultimate strain were used to fit Equation 3-2. Compact-tension [C(T)] specimens, machined from actual pipes and plates, were used to determine the fracture toughness curves of the material. The specimens were oriented such that crack growth would be in the circumferential direction (L-C or L-T orientation). The tests were also performed mostly at 288 C (550 F). The J_D-R data, with crack growth below 30 percent of the uncracked ligament, were used to fit Equation 3-4. Using these equations, the constitutive model parameters, F and n, and fracture toughness parameters, J_{Ic}, C, and m, were calculated. The basic strength parameters, such as yield strength, σ_y (0.2% offset), and ultimate strength, σ_u, were determined as well. The parameters representing tensile and fracture toughness properties were calculated for four different base metals: TP304 stainless steel, A106B carbon steel, CF8M cast stainless steel, and A516 Gr70 carbon steel. The parameters representing fracture toughness properties of two generic flux welds, such as stainless steel welds and carbon steel welds, were also evaluated. These provided the independent measurements of the random vectors, $\{\sigma_y, \sigma_u\}$, $\{F, n\}$, and $\{J_{Ic}, C, m\}$. Further details of these material properties are presented in Appendix B.

Using Equations 3-9 and 3-10, the data in Appendix B were analyzed to determine the statistical characteristics of random material properties. In computing the statistical properties, multiple specimens from a given pipe or heat were lumped together (i.e., average values from several specimens) so that the statistics would not be biased for a given pipe. For J-R curves, the specimens with large differences in net-thickness were treated as if they were from different pipes or heats. Past studies from the Degraded Piping program (Ref. 4) at Battelle showed that for stainless steel base metal, the statistical variability of tensile properties within a pipe or a heat was not significant. For example, Figures 3.1 and 3.2 from Reference 4 show the quasi-static stress-strain curves of TP304 stainless steel base metal from 8 different specimens of A23 pipe at room temperature and 288 C (550 F), respectively[(a)]. Clearly, the variability of stress-strain curves for this specific pipe material is not substantial. Unfortunately, similar data for J-R curves of this material and tensile and J-R curves of other materials were not available to study their variability within a pipe.

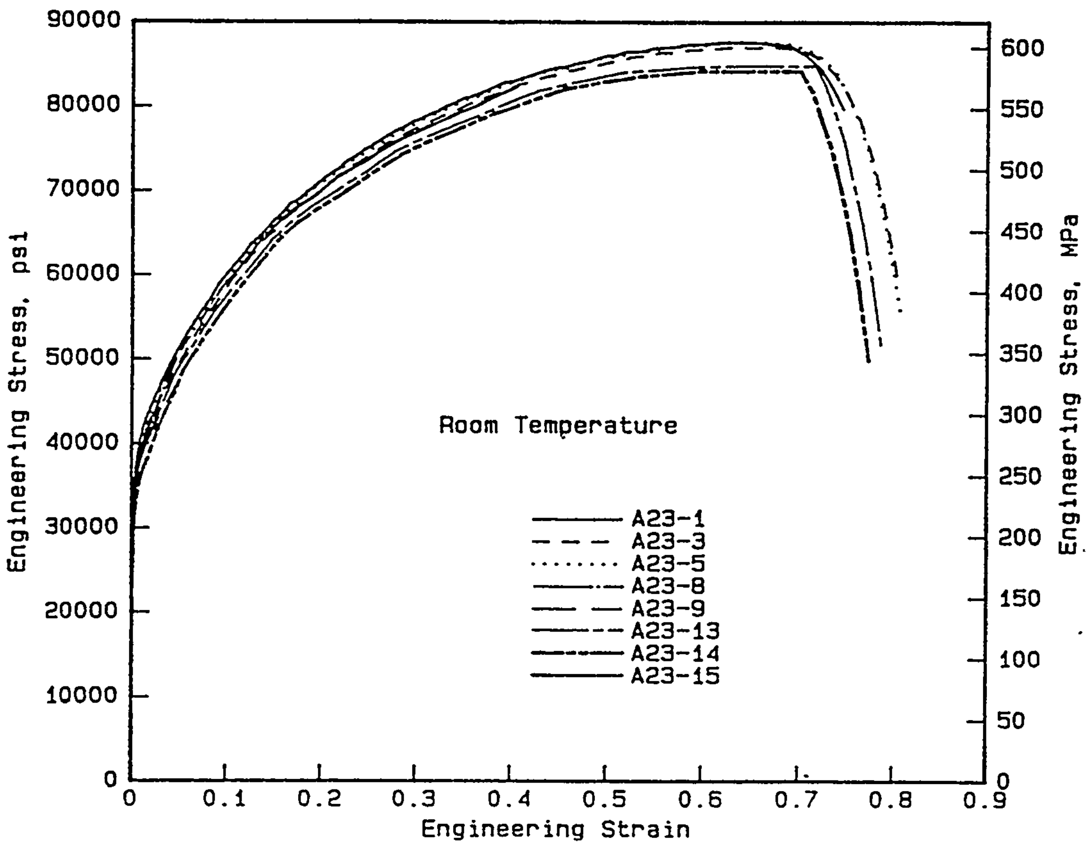


Figure 3.1 Stress-strain curves for TP304 stainless steel at room temperature

SA-6/86-F3.1.4

(a) Further details can be found in "Degraded Piping Program--Phase II," by G. Wilkowski and others, NUREG/CR-4082, Vol. 6, April 1988.

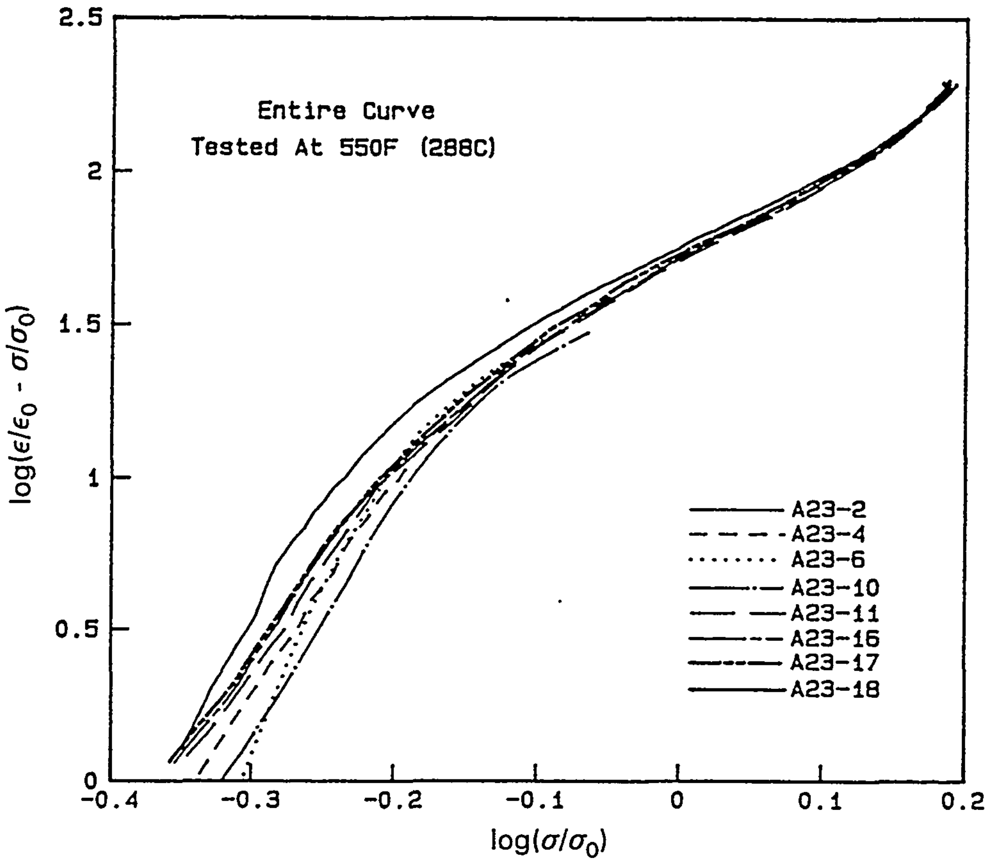


Figure 3.2 Plot of logarithms of stress-strain curves for TP304 stainless steel at 288 C (550 F)

T-6004-F3.2

Table 3.1 shows the estimated mean and standard deviation of σ_y, σ_u, F, n, J_{Ic}, C, and m for TP304 stainless steel, A106B carbon steel, CF8M cast stainless steel, and A516 Gr70 carbon steel base metals at 288 C (550 F). Table 3.2 shows similar statistics of J-R curve parameters for stainless steel and carbon steel flux-welds, also at 288 C (550 F). Since the fracture behavior of cracked pipe welds is primarily governed by the base-metal stress-strain curve and weld-metal J-R curve, no such statistics were developed for the tensile properties of weld metal. Estimates of covariance (see Equation 3-10) for these random material properties were also calculated. They are given in Appendix B for each of the pipe materials considered in this study.

Table 3.1 Mean and standard deviation of base metal properties at 288 C (550 F)

Random Variable	A106B		TP304		CF8M		A516 Gr70	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev
σ_y, MPa	245.10	31.11	154.78	11.15	201.05	25.77	295.25	70.15
σ_u, MPa	557.43	63.58	442.40	24.26	529.20	66.48	562.85	33.13
F	938.58	199.22	605.32	52.89	720.47	114.60	892.33	120.79
n	4.90	1.31	3.80	0.56	4.84	0.81	5.83	0.99
J_{Ic}, kJ/m^2	183.40	107.06	1242.71	583.44	300.64	255.96	216.20	72.03
C, kJ/m^2	133.14	51.67	344.19	113.25	202.07	51.40	204.32	70.89
m	0.71	0.07	0.74	0.15	0.72	0.09	0.67	0.07

Table 3.2 Mean and standard deviation of weld metal properties at 288 C (550 F)

Random Variable	CS Flux[(a)]		SS Flux[(b)]	
	Mean	Std. Dev.	Mean	Std. Dev.
J_{Ic}, kJ/m^2	170.68	116.91	194.65	166.01
C, kJ/m^2	137.17	69.00	119.31	42.50
m	0.67	0.09	0.73	0.13

(a) CS Flux = Carbon steel flux weld (SAW or SMAW)
(b) SS Flux = Stainless steel flux weld (SAW or SMAW)

The statistical analyses also involved the calculation of the cumulative frequency distribution for each of the random parameters defined above. The cumulative frequency distribution of a random variable, Y_i, is defined as the ratio of the number of samples equal to or less than a particular value to the total number of samples. When the sample size increases indefinitely, this ratio approaches the cumulative probability of Y_i. For example, Figures 3.3, 3.4, and 3.5 show the cumulative probability distribution of σ_y, σ_u, F, n, J_{Ic}, C, and m for TP304 stainless steel base metal at 288 C (550 F). From comparisons between actual data and theoretical distributions, it appears that the marginal probabilities of material property variables follow a lognormal distribution reasonably well. A Gaussian (normal) distribution also seems to be a good choice, but there are some concerns about the possible negative realizations of some of these positive random variables that have large coefficients of variation. Hence, **Y** was modeled with lognormal probability in this study although no mathematically rigorous proof was provided by comparing multi-variate joint probability distributions. No correlations were permitted between the strength and toughness properties because each set of laboratory data did not always include simultaneous measurement of all properties. However, the components within each vector were correlated and their correlation characteristics are defined in the covariance matrices provided in Appendix B.

3.2 Statistical Characterization of Crack Morphology Variables

The key crack morphology variables, which were considered in the leak-rate quantification study, are: (1) surface roughness, (2) number of turns in the leakage path, (3) entrance loss coefficients, and (4) actual crack path/thickness.

3.2.1 Surface Roughness

Some roughness values for cracks found in pipes removed from service are summarized below. The statistics are listed in Tables 3.3 and 3.4 for stainless steel and carbon steel pipes with various cracking mechanisms.

<u>Stainless Steel - IGSCC</u>

- Surface roughness values for an IGSCC crack from the Phase II pipe leak rate experiments (Ref. 19) were measured to be 5.105 μm (201 microinches). (Note: The authors of Reference 19 are not sure about the accuracy of this measurement, but the data were used due to the scarcity of these types of data.) Furthermore, the crack was thought to grow at a 10 to 15 degree angle from the straight crack through the thickness, which would increase the global flow path by 1.5 to 3.5 percent.

- From a typical stainless steel used in Ref. 57 (see Figure I-1 of Ref. 57), the global surface roughness that includes the peak-to-peak heights for intergranular crack growth was 101.346 μm (3,990 microinches). The roughness along the grain boundary was estimated to be 2.032 μm (80 microinches).

  Using Figure H-9 in Reference 57, a global roughness for IGSCC cracks was estimated to be 107.442 μm (4,230 microinches).

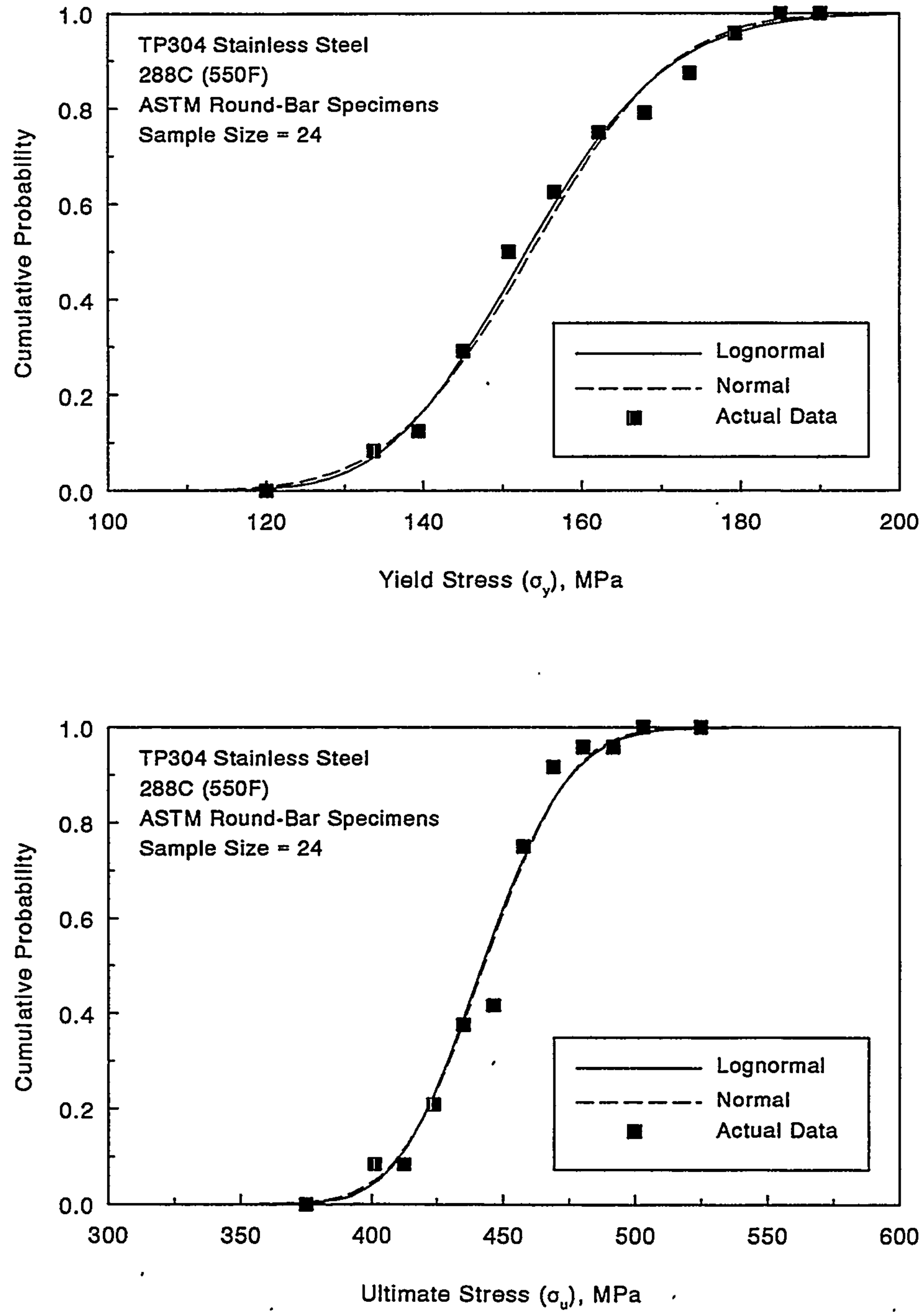
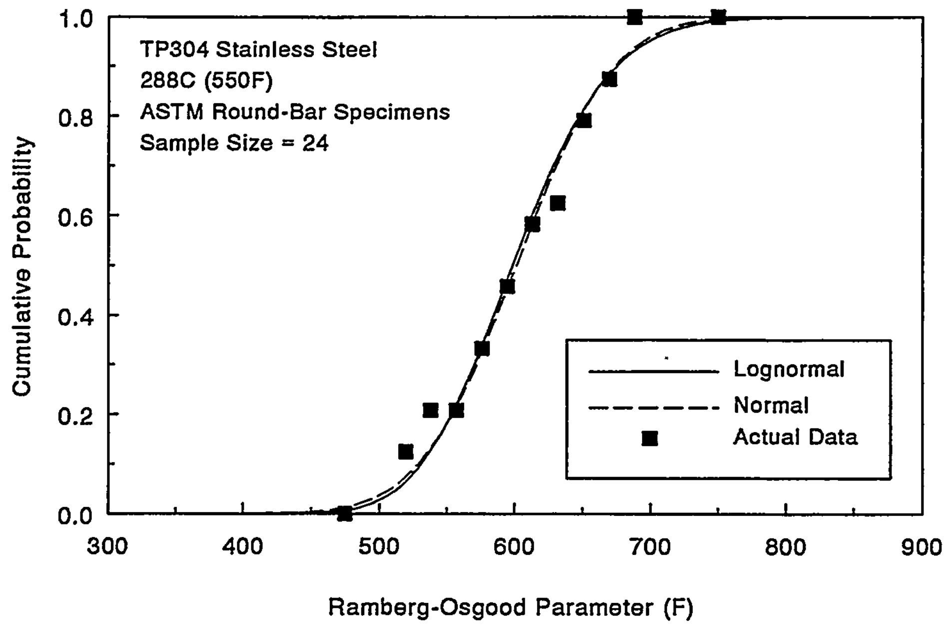


Figure 3.3 Probability distribution of σ_y and σ_u for TP304 stainless steel base metal at 288 C (550 F)

T-6004-F3.3



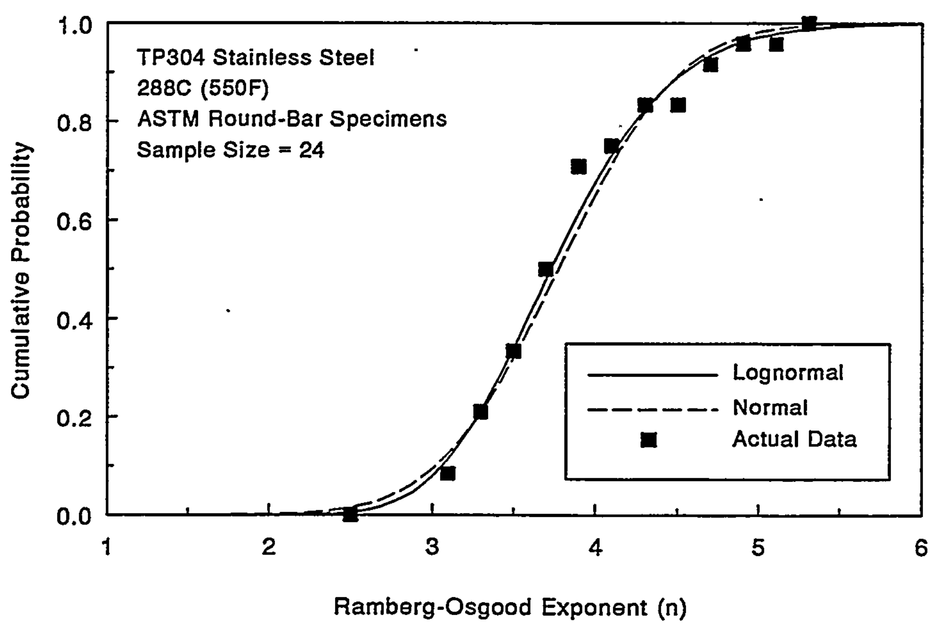


Figure 3.4 Probability distribution of F and n for TP304 stainless steel base metal at 288 C (550 F)

T-6004-F3.4

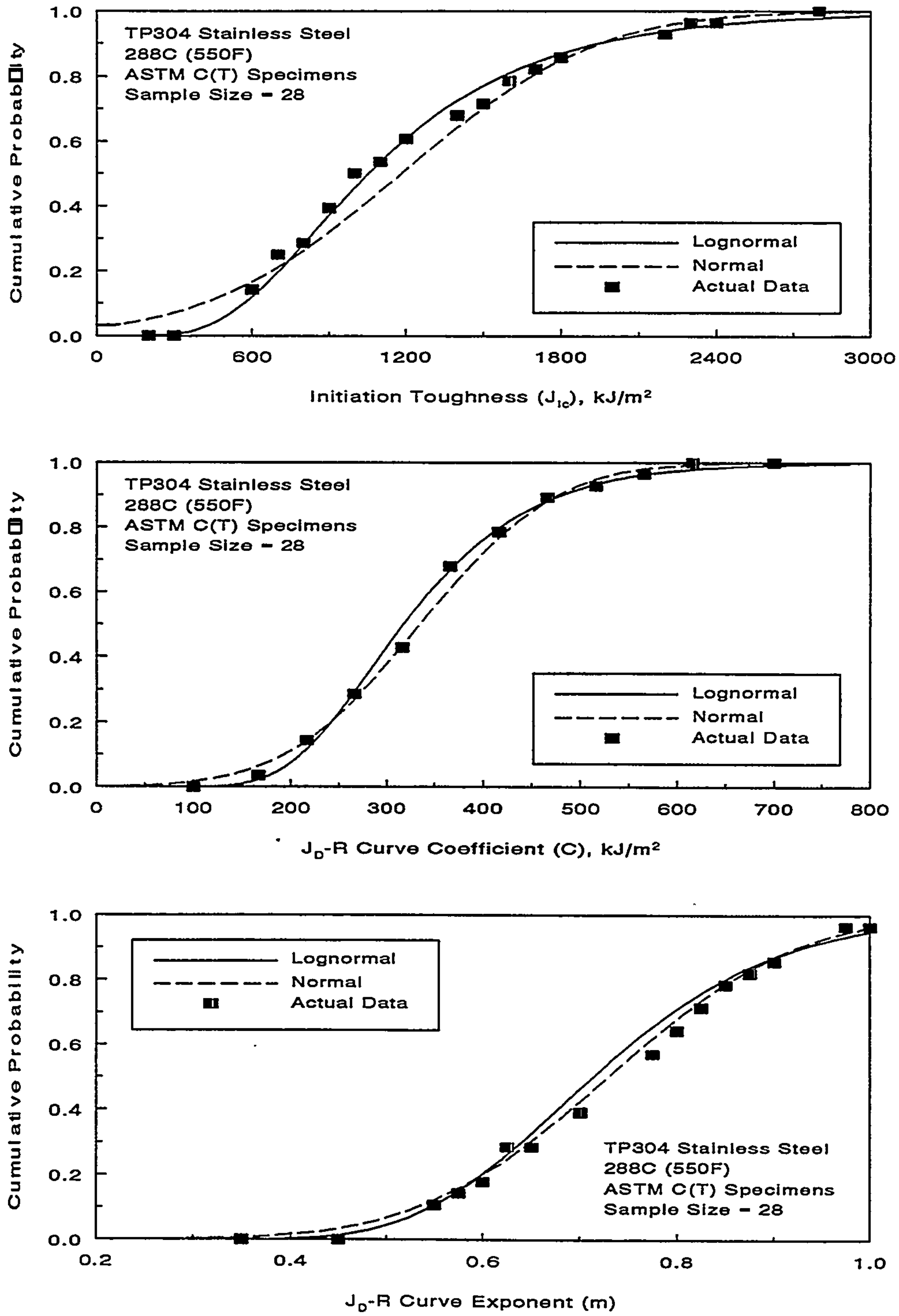


Figure 3.5 Probability distribution of J_{Ic}, C, and m for TP304 stainless steel base metal at 288 C (550 F)

T6004-F3.5

Table 3.3 Summary of surface roughness measurements in stainless steel pipes

Mechanism	Source	Roughness, μm (μinch)	
		Local	Global
	(a) Stainless steel pipes - IGSCC		
IGSCC	NP-2472 Vol. 2 (see Figure I-1)	2.032 (80)	101.346 (3,990)
IGSCC	NP-2472 Vol. 2 (see Figure H-9)	--	107.442 (4,230)
IGSCC	NP-3684SR, Vol. 3 (Paper 4, Figure 11)	7.366 (290)	74.498 (2,933)
IGSCC	NP-3684SR, Vol. 3 (Paper 4, Figure 5)	10.465 (412)	41.910 (1,650)
IGSCC	NP-3684SR, Vol. 2 (Paper 5, Figure 21)	0.635 to 6.35 (25 to 250)	127.0 (5,000)
IGSCC	NP-3684SR, Vol. 2 (Paper 19, Figure 12)	1.397 (55)	27.94 (1,100)
Average		4.699 (185)	80.010 (3,150)
Standard Deviation		3.937 (155)	39.014 (1,536)
Range		0.635 to 10.465 (25 to 412)	27.940 to 127.0 (1,100 to 5,000)
Number of Samples		6	6
	(b) Stainless steel pipes - fatigue in air		
Fatigue (air)	Hitachi, (NED, Vol. 128, 1991, pp 24)	8.052 (317)	33.655 (1,325)

Table 3.4 Summary of surface roughness measurements in carbon steel pipes

Mechanism	Source	Roughness, μm (μinch) Local	Roughness, μm (μinch) Global
	(a) Ferritic Steels - fatigue in air		
Fatigue (air)	NUREG/CR-5128 (girth weld)	3.023 (119)	--
Fatigue (air)	NUREG/CP-0051 Mayfield, pp 365 (A106B)	8.534 (336)	--
Fatigue (air)	Hitachi, NED, Vol. 128 1991, pp. 24 (STS 42)	8.052 (317)	33.655 (1,325)
Average		6.528 (257)	33.655 (1,325)
Standard Deviation		3.048 (120)	--
Range		3.023 to 8.534 (119 to 336)	--
Number of Samples		3	1
	(b) Ferritic Steels - corrosion fatigue in feedwater line		
Corrosion fatigue (Point Beach plant feedwater line)	NUREG/CR-1603, Figure 3.13	8.636 (340)	44.45 (1,750)
Corrosion fatigue (D.C. Cook plant feedwater line)	NUREG/CR-1603, Figure 3.17	3.048 (120)	20.066 (790)
Corrosion fatigue (Beaver Valley plant feedwater line)	NUREG/CR-1603, Figure 3.15	9.144 (360)	38.10 (1,500)
Corrosion fatigue (Palisades plant feedwater line)	NUREG/CR-1603, Figure 3.11	10.668 (420)	60.96 (2,400)
Corrosion fatigue (Ginna plant feedwater line)	NUREG/CR-1603, Figure 3.8	10.414 (410)	58.42 (2,300)
Corrosion fatigue (Salem plant feedwater line)	NUREG/CR-1603, Figure 3.16	10.922 (430)	21.082 (830)
Average		8.814 (347)	40.513 (1,595)
Standard Deviation		2.972 (117)	17.653 (695)
Range		3.048 to 10.922 (120 to 430)	(20.66 to 60.96) (790 to 2,400)
Number of Samples		6	6

- From a paper by Christer Jansson on Swedish IGSCC studies (Ref. 58), Figure 11 of Reference 58 shows the typical global surface roughness for an IGSCC crack to be 74.498 μm (2,933 microinches), and Figure 5 of Reference 58 shows a global roughness of 41.91 μm mm (1,650 microinches). The roughness along a grain boundary could be up to 7.366 μm (290 microinches) in Figure 11 of Reference 58 and 10.465 μm (412 microinches) in Figure 5 of Reference 58.

- From the paper by Olson et al. (Ref. 59) on large pipe IGSCC experiments at Battelle Pacific Northwest Laboratory (PNL), Figure 21 of Reference 59 shows that the typical global surface roughness of IGSCC cracks was 127.0 μm (5,000 microinches). The roughness along a grain boundary could be up to 6.35 μm (250 microinches) in some areas and perhaps a factor of 10 less in other areas (0.635 μm [25 microinches]).

- From the paper by Kurtz (Ref. 60) on effects of sulfides on IGSCC at PNL, Figure 12 of Reference 60 shows the typical global surface roughness for an IGSCC crack to be 27.94 μm (1,100 microinches). The roughness along a grain boundary was 1.397 μm (55 microinches) in some relatively smooth areas.

Stainless Steel - Fatigue (Air)

- Hitachi fatigue cracked pipe results showed a smaller or local surface roughness superimposed on a larger or global surface roughness (Ref. 61). The average value of the global roughness may correspond to the waviness of the fatigue crack, 33.655 μm (1,325 microinches). The average value of the local roughness was 8.052 μm (317 microinches). The results were very similar for their ferritic and stainless steel pipes.

Carbon Steel - Corrosion Fatigue

- From an investigation on thermal fatigue cracks in a feedwater line from the Point Beach plant in the 1978 time period (Ref. 62), Figure 3.13 of Reference 62 showed a local surface roughness of 8.636 μm (340 microinches) and a global surface roughness of 44.45 μm (1,750 microinches).

- From the same investigation (Ref. 62), a thermal fatigue crack in a feedwater line from the D.C. Cook plant in the 1978 time period, Figure 3.17 of Reference 62 showed a local surface roughness of 3.048 μm (120 microinches) and a global surface roughness of 20.066 μm (790 microinches).

- From the same investigation (Ref. 62), a thermal fatigue crack in a feedwater line from the Beaver Valley plant in the 1978 time period, Figure 3.15 of Reference 62 showed a local surface roughness of 9.144 μm (360 microinches) and a global surface roughness of 38.10 μm (1500 microinches).

- From the same investigation (Ref. 62), a thermal fatigue crack in a feedwater line from the Palisades plant in the 1978 time period, Figure 3.11 of Reference 62 showed a local surface roughness of 10.668 μm (420 microinches) and a global surface roughness of 60.96 μm (2,400 microinches).

- From the same investigation (Ref. 62), a thermal fatigue crack in a feedwater line from the Ginna plant in the 1978 time period, Figure 3.8 of Reference 62 showed a local surface roughness of 10.414 μm (410 microinches) and a global surface roughness of 58.42 μm (2,300 microinches).

Carbon Steel - Fatigue (Air)

- In Reference 6, results on a carbon steel weld fatigue crack showed a roughness of 3.023 μm (119 microinches).

- Measurements of a carbon steel base metal fatigue crack in air from the NRC Cold-Leg program showed a roughness of 8.534 μm (336 microinches). These were obtained from a technical paper authored by Mayfield and Collier (Ref. 63).

- Hitachi fatigue-cracked-pipe results showed a local surface roughness superimposed on a global surface roughness (Ref. 61). The average value of the global roughness may correspond to the waviness of the fatigue crack, 33.655 μm (1,325 microinches). The average value of the local roughness was 8.052 μm (317 microinches). The results were very similar for their ferritic and stainless steel pipes.

3.2.2 Number of Turns per Unit Thickness

From the examinations of photomicrographs in References 60 to 64, Tables 3.5 and 3.6 show the number of 90-degree turns per inch of thickness. For IGSCC cracks in stainless steels this can be a much larger number than for a corrosion fatigue crack and can also vary significantly since the grain size may vary.

3.2.3 Entrance Loss Coefficient (C_D)

If entrance edges have a radius of 1/6 of the COD or larger, then they are considered as rounded and $C_D = 0.62$. Consequently,

- IGSCC produces sharp edges (no pitting corrosion to smooth the edges). $C_D = 0.95$ for small COD values, i.e., COD < 0.006 inch.

- Fatigue and corrosion fatigue typically initiate at small pits with some surface corrosion to round the edges. $C_D = 0.62$ for all COD values of interest.

These values were obtained from Reference 6 and were assumed to be deterministic.

Table 3.5 Summary of measurements of the number of 90-degree turns in stainless steel pipes

Mechanism	Source	Number of 90-degree Turns, mm^{-1} ($inch^{-1}$)
	(a) Stainless steel pipes - IGSCC	
IGSCC	NP-2472, Vol. 2 (see Figure I-1)	57.09 (1,450)
IGSCC	NP-3684SR, Vol. 3 (Paper 4, Figure 11)	13.86 (352)
IGSCC	NP-3684SR, Vol. 3 (Paper 4, Figure 5)	34.37 (873)
IGSCC	NP-3684SR, Vol. 2 (Paper 5, Figure 21)	9.45 (240)
IGSCC	NP-3684SR, Vol. 2 (Paper 19, Figure 12)	26.38 (670)
Average		28.23 (717)
Standard Deviation		18.94 (481)
Range		9.45 to 57.09 (240 to 1,450)
Number of Samples		5
	(b) Stainless steel pipes - fatigue in air	
Fatigue (air)	Hitachi (NED, Vol. 128, 1991, pp. 24)	2.52 (64)

Table 3.6 Summary of measurements of the number of 90-degree turns in carbon steel pipes

Mechanism	Source	Number of 90-degree Turns, mm^{-1} ($inch^{-1}$)
	(a) Ferritic steels -- fatigue in air	
Fatigue (air)	Hitachi, NED, Vol. 128 1991, pp. 24 (STS 42)	2.01 (51)
	(b) Ferritic steels - corrosion fatigue in feedwater lines	
Corrosion fatigue (Point Beach plant feedwater line)	NUREG/CR-1603, Figure 3.13	2.40 (61)
Corrosion fatigue (D.C. Cook plant feedwater line)	NUREG/CR-1603, Figure 3.17c	19.96 (507)
Corrosion fatigue (Beaver Valley plant feedwater line)	NUREG/CR-1603, Figure 3.15	2.28 (58)
Corrosion fatigue (Palisades plant feedwater line)	NUREG/CR-1603, Figure 3.11	13.74 (349)
Corrosion fatigue (Ginna plant feedwater line)	NUREG/CR-1603, Figure 3.8	1.42 (36)
Corrosion fatigue (Salem plant feedwater line)	NUREG/CR-1603, Figure 3.16	0.63 (16)
Average		6.73 (171)
Standard deviation		8.07 (205)
Range		1.42 to 19.96 (16 to 507)
Number of Samples		6

3.2.4 Actual Crack Path/Thickness

- Global path deviations from straight through the pipe thickness, K_G.

  (a) If a crack follows the fusion line of the weld, then $K_G = L_a/t = 1/[\cos(37 \text{ degrees})] = 1.25$ (Ref. 64).

  (b) Angular crack growth of thermal fatigue cracks in feedwater piping showed $K_G = L_a/t = 1.05$. (Ref. 62).

- Local waviness causing the flow path to be longer, K_{G+L}.

  If the COD is small compared with the global roughness, then the local waviness will cause an increase in the flow path length. If the COD is small compared with the global roughness, then the local surface roughness should be used with this local plus global waviness flow-path multiplication factor, K_{G+L}, as well as the pressure drop from the number of turns.

Measured values of K_G and K_{G+L} from typical cracks for stainless steel and carbon steel are presented in Tables 3.7 and 3.8. In general, these values are larger for IGSCC cracks in stainless steels than for corrosion fatigue cracks in carbon steels.

Table 3.7 Crack flow-path-length to pipe-thickness ratios for stainless steel pipes

Mechanism	Source	K_{G+L}	K_G
	(a) Stainless steel pipes - IGSCC		
IGSCC	NP-2472, Vol. 2 (See Figure G-14)	1.47	1.25
IGSCC	NP-3684SR, Vol. 3 (Paper 4, Figure 11, 75x)	1.35	1.02
IGSCC	NP-3684SR, Vol. 3 (Paper 4, Figure 5, 100x)	1.53	1.06
IGSCC	NP-3684SR, Vol. 2 (Paper 5, Figure 21)	1.15	1.02
IGSCC	NP-3684SR, Vol. 2 (Paper 19, Figure 12, 200x)	1.15	1.01
Average		1.33	1.07
Standard Deviation		0.17	0.10
Range		1.15 to 1.53	1.01 to 1.25
Number of Samples		5	5

Table 3.8 Crack flow-path-length to pipe-thickness ratios for carbon steel pipes

Mechanism	Source	K_{G+L}	K_G
	(a) Ferritic Steels - Corrosion fatigue in feedwater lines		
Corrosion fatigue (Point Beach plant feedwater line)	NUREG/CR-1603, Figure 3.13	1.10	1.035
Corrosion fatigue (D.C. Cook plant feedwater line)	NUREG/CR-1603, Figure 3.17c	1.03	1.001
Corrosion fatigue (Beaver Valley plant feedwater line)	NUREG/CR-1603, Figure 3.15	1.08	1.03
Corrosion fatigue (Palisades plant feedwater line	NUREG/CR-1603, Figure 3.11	1.04	1.004
Corrosion fatigue (Ginna plant feedwater line)	NUREG/CR-1603, Figure 3.8	1.07	1.03
Corrosion fatigue (Salem plant feedwater line)	NUREG/CR-1603, Figure 3.16	1.02	1.001
Average		1.06	1.017
Standard Deviation		0.03	0.0163
Range		1.02 to 1.10	1.001 to 1.035
Number of Samples		6	6

A separate evaluation was also made to assess the crack morphology parameters for a thermal fatigue crack in cast stainless steel. Photographs of fracture surfaces from Reference 65 were examined. Only a few cases were sufficiently documented for the level of detail needed in this work. Of these, the crack morphology parameters fell in the range of the carbon steel corrosion-fatigue cracks. Hence, the carbon steel crack morphology variables were used for the cast stainless steel thermal fatigue-crack morphology.

Table 3.9 shows the summary of results in terms of statistics of crack morphology variables considered in this study. In general, it was found that the global surface roughness, local number of turns, and the path deviation factors for IGSCC in stainless steel are larger than those for corrosion fatigue in carbon steel. But, when the local surface roughness is considered, it was found to be larger for the corrosion fatigue type of cracking mechanism. The statistical properties of the crack morphology variables, presented in Table 3.9, were based on a small number of samples. Hence, these results should be viewed as preliminary estimates. Also, the sample sizes were not large enough to determine accurately their probability distribution. Here, was assumed that each of the crack morphology parameters followed a lognormal probability distribution and that they were statistically independent. The assumption was somewhat arbitrary and was not verified simply because no additional data were available. Finally, the entrance loss coefficient was assumed to be deterministic and the values of 0.95 and 0.62 were used for IGSCC and corrosion fatigue cracks, respectively.

Table 3.9 Mean and standard deviation of crack morphology parameters

Crack Morphology Variable	IGSCC		Corrosion Fatigue	
	Mean	Standard Deviation	Mean	Standard Deviation
μ_L, μm	4.699	3.937	8.814	2.972
μ_G, μm	80.010	39.014	40.513	17.653
n_{tL}, mm^{-1}	28.2	18.9	6.73	8.07
K_G	1.07	0.10	1.017	0.0163
K_{G+L}	1.33	0.17	1.06	0.03

3.3 Statistical Characterization of Crack Location

Cracks in nuclear power plants can occur in various locations of piping systems, such as the base metal, weld metal, fusion line, and heat-affected zone. It is difficult to quantify the location of cracks in a pipe purely on a deterministic basis. This problem can be circumvented by modeling the crack location to be a discrete random variable. The probabilistic characteristics of this variable can be obtained from some limited amount of information available in the existing literature (Refs. 62 and 64). Tables 3.10 and 3.11 show the statistics of the number of cracks in the base metal versus the weld metal or fusion line, obtained for several types of cracking mechanisms considered in this study. If a crack was along the fusion line, then it was counted as a weld crack. This was done since there are few data for stainless steel welds suggesting that the fusion line has lower toughness than the weld metal. Also, any possible differences in these statistics for stainless steel and carbon steel materials were not determined since no data were available.

Table 3.10 Summary of crack location in piping systems (IGSCC)

Figure Number in Reference 62	Number of Cracks in Weld Metal or Fusion Line	Number of Cracks in Base Metal
3.2	0	1
3.3	2	8
3.4(a)	2	3
3.5(a)	1	1
3.5(c)	2	1
Total	7 (33 percent)	14 (67 percent)

Table 3.11 Summary of crack location in piping systems (corrosion fatigue)

Figure Number in Reference 64	Number of Cracks in Weld Metal or Fusion Line	Number of Cracks in Base Metal
B-1	0	1
B-2	0	1
B-3	0	1
B-4	0	2
B-6	0	2
B-8	0	2
B-9	0	2
B-10	0	1
B-12	0	1
B-13	0	1
B-16	1	0
B-17	1	0
B-18	1	0
B-19	1	0
B-20	1	0
B-23	1	0
B-24	1	0
B-25	1	0
B-26	1	0
B-27	2	0
B-28	0	2
B-29	0	2
B-30	0	2
B-31	0	1
B-32	1	1
B-33	0	2
B-34	0	1
B-35	1	0
Total	13 (34 percent)	25 (66 percent)

3.4 Statistical Properties of Maximum Load Ratio

Any error or uncertainty in the deterministic prediction of maximum loads for cracked pipes can also be modeled statistically if sufficient experimental data are available. In Section 2.5.3, the predicted maximum loads by the LBB.ENG2 method were evaluated by 12 through-wall-cracked pipes and 10 complex-cracked pipes. From the results of this evaluation, the mean and standard deviation of the maximum load ratio, defined as the ratio of the experimental to the predicted maximum loads, were 1.03 and 0.13, respectively, for through-wall-cracked pipes and 1.04 and 0.16, respectively, for complex-cracked pipes. Hence, on average, the LBB.ENG2 method underpredicts the maximum loads slightly. In principle, the above statistics with the assumption of a probability distribution can be applied to account for the uncertainty in the predicted loads. However, the number of experiments that were analyzed was not large enough to provide complete information on the probability distribution. Also, these statistics may change slightly in the future when more experimental data are available. For these reasons, the results of analyses presented in this study were based on predicted loads directly from the LBB.ENG2 method without applying these statistics.

4.0 DEVELOPMENT OF PROBABILISTIC MODELS

The application of the LBB methodology requires (1) knowledge of the pipe loads during various operating conditions of power plants, (2) details of geometry and material properties of the pipe, (3) knowledge of the anticipated cracking mechanisms and the resulting crack morphology variables for leak-rate analyses, and (4) methods for thermal-hydraulic and fracture mechanics analyses of a flawed pipe. Some of the items mentioned above are subject to inherent statistical variability. Therefore, a rational treatment of these uncertainties and an assessment of their impact on system performance should be based on theories of probability and structural reliability.

4.1 Probabilistic LBB Methodology

A probabilistic LBB methodology was developed based on the general guidelines proposed in Reference 2. The steps of the probabilistic evaluation are very similar to the steps of the deterministic LBB methodology. These are summarized below.

- Specify a piping system to be evaluated.
- Identify the pipe materials and determine their statistical properties and probability distribution.
- Identify the crack morphology variables used in leak-rate analyses and determine their statistical properties and probability distribution.
- Postulate a probability distribution function for a TWC flaw in a pipe. The size of the flaw should be large enough so that detection of leakage is ensured using the installed leak-detection equipment when the pipe is subjected to normal operating loads.
- Perform an elastic-plastic fracture mechanics analysis using the above crack size to determine the maximum bending moment, M_{max}, the pipe can carry.
- Determine the extreme moment, M_{N+SSE}, from the normal plus SSE stresses.
- Conduct a probabilistic fracture-mechanics evaluation to compute the conditional probability of failure, $P_F = Pr[M_{max} < M_{N+SSE}]$. The probability of failure is conditional on (1) the pipe is leaking with an LBB detectable flaw size and (2) an earthquake occurring with N+SSE stresses, resulting in an applied bending moment equal to M_{N+SSE}, also during leakage.

4.2 Probabilistic Characteristics of Leakage Size Flaws

Consider a TWC pipe shown in Figure 2.4 with mean radius, R_m, thickness, t, and a circumferential through-wall-crack with length, 2a. The pipe is subjected to combined bending and tension stresses under normal operating conditions. The tension load, P, can be computed from the known internal pipe pressure, p; and the bending moment, M, can be calculated from the normal operating bending stresses. The crack length, 2a, is defined as the LBB detectable flaw size for a given leak rate. Following iterative calculations between thermal-hydraulic and fracture-mechanics analyses (e.g., see SQUIRT code of Reference 6), 2a can be easily calculated when the leak rate, pipe geometry, material properties, and normal operating loads (e.g., P and M) are specified.

Due to statistical variability of the crack morphology parameters, the flaw size, 2a, will also be a random variable. Hence, to conduct a probabilistic analysis, the probability distribution of this crack size needs to be specified as well. In this study, a Monte Carlo method was developed to determine the probabilistic characteristics of leakage size flaws. A three-phase approach was undertaken. It involved:

- generation of independent samples of random crack-morphology parameters according to their probability distribution,

- iterative thermal-hydraulic and fracture-mechanics analyses to determine LBB detectable flaw sizes corresponding to each sample set of crack-morphology parameters and to simulate such samples of flaw size by performing repeated deterministic analyses, and

- standard statistical analyses of replicated samples of LBB detectable flaw size.

During the calculation of flaw size, the material property variables were assigned their mean values (deterministic). This is justified since no significant plasticity and crack growth are expected during normal operating loads. Hence, any variability in the plastic component of the nonlinear stress-strain curve or J-R curve characteristics would have little effect on the leakage flaw size. Note that the elastic properties, such as modulus of elasticity and Poisson's ratio, were also deterministic.

4.3 Structural Reliability Analysis

Structural reliability analysis requires a mathematical model derived from the principles of mechanics and experimental data that relate various input random parameters for a specific performance criterion of interest. For example, consider a TWC pipe under combined stresses due to tension and bending. Let M_{max} denote the maximum moment-carrying capacity of the pipe with the constant applied tension P (due to constant internal pressure, p). M_{max} can be obtained from the solution of two nonlinear equations based on J-tearing theory (see Section 2). In a generic implicit form, the solution of M_{max} can be represented by

$$M_{max} = f(\sigma_y,\sigma_u,F,n,J_{Ic},C,m,2a) \quad (4\text{-}1)$$

where f is a function of various input variables (only the random arguments are shown in the functional dependence of M_{max}). The fracture stability of the leakage size flaw in a pipe can be evaluated by comparing the maximum load-carrying capacity of the pipe (see Equation 4-1) with the applied load from N+SSE stresses. Mathematically, this can be represented by

$$M_{max} < M_{N+SSE} \quad (4\text{-}2)$$

where M_{N+SSE} is the applied bending moment due to normal plus safe-shutdown earthquake stresses. M_{N+SSE} can be estimated from the knowledge of actual N+SSE stresses in nuclear power plants or from the Service Levels B, C, or D stress limits in Reference 1. This fail-safe condition can be conveniently expressed in the traditional form

$$\begin{aligned} g(\mathbf{X}) &< 0 \quad \text{(failure)} \\ g(\mathbf{X}) &= 0 \quad \text{(limit state)} \\ g(\mathbf{X}) &> 0 \quad \text{(survival)} \end{aligned} \quad (4\text{-}3)$$

where the performance function,

$$\begin{aligned} g(\mathbf{X}) &= M_{max} - M_{N+SSE} \\ &= f\left(\sigma_y,\sigma_u,F,n,J_{Ic},C,m,2a\right) - M_{N+SSE} \end{aligned} \quad (4\text{-}4)$$

in which $\mathbf{X} = \{\sigma_y, \sigma_u, F, n, J_{Ic}, C, m, 2a, M_{N+SSE}\}$ is an augmented vector of input random parameters characterizing uncertainty in all load and system parameters. Note that the performance function, $g(\mathbf{X})$, itself is random, because it depends on the input vector, $\mathbf{X}$, which is random. In the x space, the equation $g(x) = 0$, also known as limit state, separates the domain D of $\mathbf{X}$ into the safe set $S = \{x: g(x) > 0\}$ and the failure set $F = \{x: g(x) < 0\}$. These sets are schematically shown in Figure 4.1 for $x \in \Re^N$ where $\Re^N$ is an N-dimensional real vector space. The reliability, P_S, is the complement of the conditional probability of failure, P_F, i.e., $P_S = 1 - P_F$. P_F is defined as the probability that the failure event represented by Inequality 4-2 is true, i.e.,

$$P_F \overset{\text{def}}{=} \Pr\left[g(\mathbf{X}) < 0\right] \overset{\text{def}}{=} \int_{g(x)<0} f_{\mathbf{X}}(x)\, dx \quad (4\text{-}5)$$

where $f_{\mathbf{X}}(x)$ is the joint probability density of the random vector, $\mathbf{X}$, which is assumed to be known. In general, the multi-dimensional integral in Equation 4-5 cannot be determined analytically. As an alternative, numerical integration can be performed; however, it becomes impractical and the computational effort becomes prohibitive when the dimension of $\mathbf{X}$ becomes greater than two and, in this case, one may have a maximum of nine dimensions according to Equation 4-4.

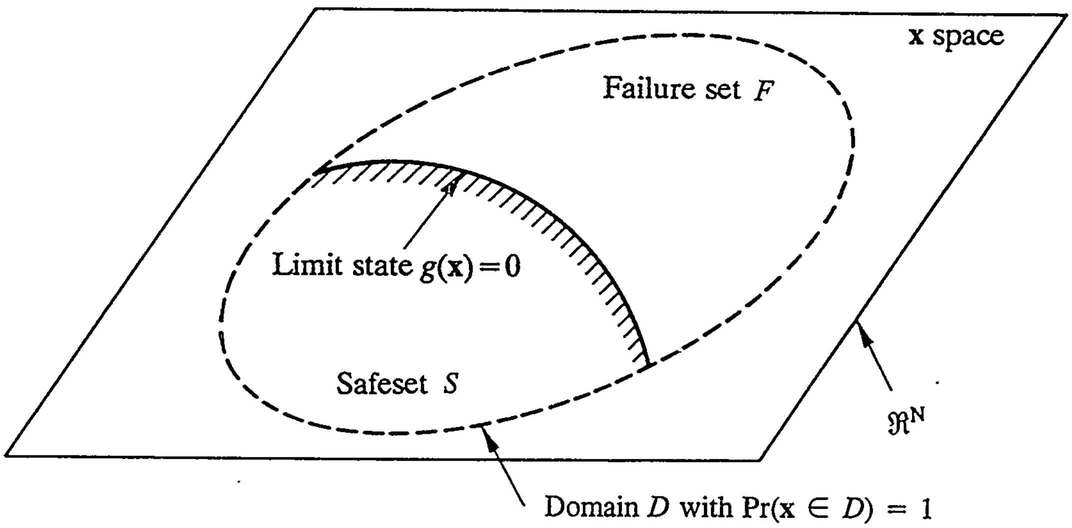


Figure 4.1 Definition of limit state in the original space

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Note that P_F is defined here as a conditional probability of failure. The principal conditions are that (1) the pipe is leaking with an LBB detectable flaw size and (2) an earthquake occurs with induced stresses that give rise to the applied bending moment M_{N+SSE} during leakage.

4.4 Methods of Structural Reliability Analysis

Several approximate methods exist for performing the multi-dimensional probability integration in Equation 4-5. Among them, First- and Second-Order Reliability Methods (FORM/SORM) (Refs. 66 to 71), Importance Sampling (Refs. 71 to 76), Directional Simulation (Refs. 77 to 79), Monte Carlo Simulation (MCS) (Refs. 68, 71, and 80), and others can be applied to estimate P_F in Equation 4-5. In this section, a few of them will be presented for their use in the reliability analysis.

4.4.1 First- and Second-Order Reliability Methods (FORM/SORM)

First- and Second-Order Reliability Methods (FORM/SORM) are standard methods of structural reliability theory. They are based on linear (first-order) and quadratic (second-order) approximations of the limit state surface $g(\mathbf{x}) = 0$ tangent to the closest point of the surface to the origin of the space. The determination of this point involves nonlinear constrained optimization and is usually performed in the standard Gaussian image of the original space.

The algorithms implementing these methods involve several steps. They will be described here briefly assuming a generic N-dimensional random vector, **X**. First, the space of uncertain parameters, **x**, is transformed into a new N-dimensional space, **u**, consisting of independent standard Gaussian variables. The original limit state, $g(\mathbf{x}) = 0$, then becomes mapped into the new limit state, $g_U(\mathbf{u}) = 0$, in the **u** space. Second, the point on the limit state, $g_U(\mathbf{u}) = 0$, having the shortest distance to the origin of the **u** space is determined by using an appropriate nonlinear optimization algorithm. This point is referred to as the design point or β-point and has a distance, β_{HL}, to the origin of the **u** space. Third, the limit state, $g_U(\mathbf{u}) = 0$, is approximated by a surface tangent to it at the design point. Let such limit states be $g_L(\mathbf{u}) = 0$ and $g_Q(\mathbf{u}) = 0$, which correspond to two approximating surfaces: a hyperplane (linear or first-order) and a hyperparaboloid (quadratic or second-order), respectively. These approximations are schematically shown in Figure 4.2. The probability of failure, P_F, (Equation 4-5) is thus approximated by $\Pr[g_L(\mathbf{u}) < 0]$ in FORM and $\Pr[g_Q(\mathbf{u}) < 0]$ in SORM. These first-order and second-order estimates, $P_{F,1}$ and $P_{F,2}$, are given by (Refs. 66 to 71)

$$P_{F,1} = \Phi(-\beta_{HL}) \tag{4-6}$$

and

$$P_{F,2} \simeq \Phi(-\beta_{HL}) \prod_{i=1}^{N-1} \left(1 - \kappa_i \beta_{HL}\right)^{-\frac{1}{2}} \tag{4-7}$$

where

$$\Phi(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} \exp\left[-\frac{1}{2} \xi^2\right] d\xi \tag{4-8}$$

is the cumulative distribution function of a standard Gaussian random variable, and the κ_i's are the principal curvatures of the limit state surface at the design point. Further details of the derivation of Equations 4-6 and 4-7 are provided in Appendix C.

In FORM/SORM analysis, each input random variable and the performance function $g(\mathbf{x})$ must be continuous. Depending on the solver used for nonlinear optimization, an additional requirement regarding smoothness (differentiability) of $g(\mathbf{x})$ may be required.

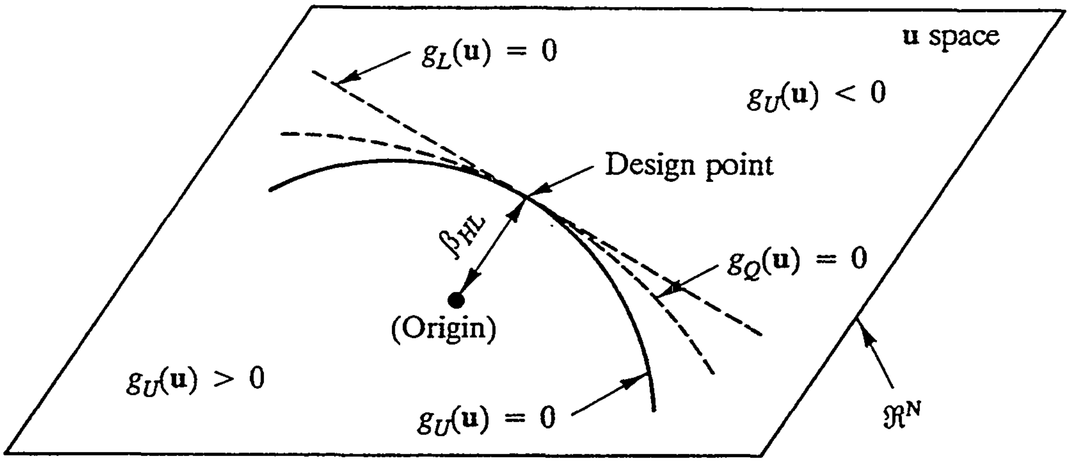

Figure 4.2 Linear and quadratic approximations to the limit state in the Gaussian image

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4.4.2 Monte Carlo Simulation (MCS)

Consider a generic N-dimensional random vector, **X**, which characterizes uncertainty in all load and system parameters with the known joint distribution function, $F_X(x)$. Suppose, $x^{(1)}, x^{(2)},\ldots, x^{(L)}$ are L realizations of the input random vector, **X**, which can be generated independently. Methods of generating samples of **X** are described in Appendix D. This usually involves probability preserving transformations when **X** has a generic probability distribution. However, for special cases when **X** is either a correlated normal (Gaussian) or a correlated lognormal vector (which is the case for the present study as determined from the statistical characterization effort in Section 3), the above transformations can be sidestepped by using a much simpler Cholesky decomposition (Ref. 22) of the covariance matrix. They are also explained in Appendix D. Nevertheless, let $g^{(1)}, g^{(2)},\ldots, g^{(L)}$ be the output samples of g(**X**) corresponding to the input $x^{(1)}, x^{(2)},\ldots, x^{(L)}$ that can be obtained by conducting repeated deterministic evaluation of the performance function in Equation 4-4. Define L_f as the number of trials (analyses) which are associated with negative values of the performance function. Then, the estimate, $P_{F,MCS}$, of the actual probability of failure, P_F, by simulation is given by

$$P_{F,MCS} = \frac{L_f}{L} \tag{4-9}$$

which approaches the exact value of P_F when L approaches infinity. When L is finite, a statistical estimate on the probability estimator may be needed. In general, the required sample size must be at least $10/\mathrm{Min}(P_F,P_S)$, where $\mathrm{Min}(P_F,P_S)$ is the minimum of P_F and P_S for a 30-percent coefficient of variation of the estimator (Ref. 80).

4.4.3 Experience with FORM/SORM and MCS

Practical experience with FORM/SORM algorithms indicates that their estimates usually provide satisfactory reliability measures. A wide variety of example problems with applications in stochastic mechanics are available in References 66 to 71 demonstrating the accuracy of FORM/SORM analysis. In general, the SORM reliability is more accurate and may differ from FORM reliability when the design conditions are highly nonlinear. Besides, the SORM reliability has the property of approaching exact reliability, P_S, when P_S approaches 1 asymptotically. When the reliability is large (small probability of failure), FORM/SORM are extremely efficient when compared with the Monte Carlo method regarding the requirement of computer time, such as the Central Processing Unit (CPU). The CPU time for FORM is approximately linear in N (N = number of basic input variables) and the additional CPU time for SORM grows approximately with N^2. However, if SORM is based on the diagonal of the matrix of second-order derivatives at the β point (in **u** space) it has a CPU time which is linear in N. Obviously, the absolute CPU time depends on the CPU time required to evaluate the performance function, g(**x**). The CPU time may be invariant with the actual reliability level if the calculation of g(**x**) does not depend on different combinations of input variables. This has a bearing in that when P_S approaches 1, the computational effort by FORM/SORM may remain relatively unchanged, and hence it becomes a much faster method when compared with simulations.

Direct Monte Carlo Simulation (MCS) is a very general method and is based on repeated deterministic evaluation of the g(**x**) function due to random sampling of the input random vector, **X** according to their joint distribution function. This method can be applied to any type of problem without requiring any continuity in the random variables or the limit state function. For a sample size, L, approaching infinity, the estimated reliability converges to the exact result. For a finite sample size, uncertainty estimates on the results may need to be evaluated. As a rule of thumb, the CPU time grows linearly with N and $1/\text{Min}(P_F,P_S)$ for a given coefficient of variation on the estimator. The absolute value of the CPU time depends on the time necessary to evaluate the g(**x**) function. When P_S approaches 1 or P_F approaches 0, the Monte Carlo simulation may be inefficient and expensive and, hence, may become computationally prohibitive.

4.5 The Computer Code PSQUIRT

In this study, a new computer code titled PSQUIRT was developed to estimate the probability density of the LBB detectable flaw size. It is based on direct Monte Carlo simulation as explained earlier. PSQUIRT, which stands for **P**robabilistic **S**eepage **Q**uantification of **U**psets **i**n **R**eactor **T**ubes, is essentially a combination of three independent programs entitled SCRAMP (**S**imulation of **CRA**ack **M**orphology **P**arameters), SQUIRT5 (A modified version of **S**eepage **Qu**antification of **U**psets **i**n **R**eactor **T**ubes), and FDACS (**F**requency **D**istribution **A**nalysis of **C**rack **S**ize). SCRAMP generates independent samples of various crack-morphology parameters according to their probability distribution. SQUIRT5 conducts iterative thermal-hydraulic and fracture-mechanics calculations to solve for the leakage flaw size when the pipe loads, material properties, and leak rate are specified. FDACS performs standard statistical analysis, such as computing the mean, standard deviation, and histogram of the simulated flaw size from SCRAMP and SQUIRT5 analyses. When the sample size becomes large, the histogram, if normalized appropriately, approaches the probability density function of the flaw size. Analytical models for this density function are discussed in the next section.

Appendix E provides further details of the PSQUIRT (SCRAMP, SQUIRT5, and FDACS) program. It also contains some results from a typical run of PSQUIRT and its source listing.

4.6 The Computer Code PROLBB

A new computer program titled PROLBB, which is an acronym for **PRO**babilistic **L**eak-**B**efore-**B**reak, was developed to evaluate failure probability of flawed nuclear piping subjected to combined stresses due to tension and bending. Various failure criteria based on the exceedance of (1) Net-Section-Collapse load, (2) crack initiation load, and (3) maximum load from elastic-plastic fracture mechanics can be used to obtain the corresponding probability of failure. In this study, the calculation of conditional probability of failures was based on the maximum load-carrying capacity of pipes from elastic-plastic fracture mechanics analyses.

The deterministic part of PROLBB is based on the LBB.ENG2 method. The fracture-mechanics equations for this method used to calculate the J-integral and its applications for computing maximum loads were defined in Section 2 of this report. The probabilistic part of PROLBB is based on (1) First-Order Reliability Method, (2) Second-Order Reliability Method, (3) Importance Sampling, and (4) Monte Carlo Simulation. In addition to the calculation of piping reliability, PROLBB can also perform automatic sensitivity study to determine importance and sensitivity factors to identify important and unimportant random variables, and important parameters of a given random variable.

As noted above, besides FORM and SORM, PROLBB includes the Importance Sampling method which can update the second-order results from SORM to an arbitrary degree of precision. This is also a simulation method, but it differs from direct Monte Carlo with respect to the techniques of sample generation. In Importance Sampling, the input random variables are sampled from a different probability density, known as the sampling density, to generate more outcomes from the region of interest. Good sampling densities can be constructed using information from FORM/SORM analyses. See Appendix C for further details of this method.

The PROLBB code also includes the direct Monte Carlo simulation for performing a generic probability integration. Results of Monte Carlo and Importance Sampling methods provide a means for evaluating the adequacy of analytical probability computation methods. Further details on the validation of FORM and SORM results are given in the next section.

Appendix F provides further details of the PROLBB program. To verify the results of PROLBB, sample calculations were made to compare its deterministic predictions with the NRCPIPE results. The NRCPIPE (Version 1.4G) code was previously tested (both alpha and beta tests) and was released to the NRC as part of the Short Cracks in Piping and Piping Welds program[(a)]. Typical probabilistic results from this code, such as computation of conditional failure probability of cracked pipes, are also presented. Finally, a source listing of PROLBB is provided in Appendix F.

(a) Further details can be found in "Short Cracks in Piping and Piping Welds," NUREG/CR-4599, Vol. 3, No. 2, March 1994.

5.0 APPLICATIONS TO BWR AND PWR PIPING

5.1 Selection of Piping Systems

The probabilistic model developed in this study was applied to various nuclear piping systems in Boiling Water Reactors (BWR) and Pressurized Water Reactors (PWR) for calculating the conditional probability of failure. Pipe sizes were selected with large, intermediate, and small diameters typically used. Two pipes of each size were considered with austenitic and ferritic materials. The BWR piping systems included side riser, main steam, recirculation branch line, feedwater, bypass line, and reactor water clean-up. The PWR piping systems included main coolant, surge line, feedwater, spray line, and steam generator blowdown lines. Various types of cracking mechanisms, such as intergranular stress corrosion cracking, corrosion fatigue, and thermal fatigue, were also considered. Both simple circumferential through-wall-cracked (TWC) pipes and complex-cracked (CC) pipes were analyzed. A complex crack is a long circumferential surface crack that penetrates the pipe thickness for a shorter length, such as the Duane-Arnold safe-end IGSCC's in 1978 (Ref. 81). Crack location was defined in both a deterministic sense (either base metal or weld metal) and a probabilistic sense (random location). Tables 5.1 and 5.2 show the BWR and PWR piping systems used for probabilistic pipe fracture evaluations in this study.

5.2 Estimation of Applied Stresses

For the various piping systems being evaluated, the normal operating (N) stresses are needed to determine the crack size for a given leak rate, and the normal plus safe shutdown earthquake (N+SSE) stresses are needed to evaluate the stability of the cracked pipe.

5.2.1 Normal Operating Stresses

The actual normal operating stresses and their probabilities of occurring for all plants in the U.S. are difficult to quantify. To simplify this effort, it is assumed that the ASME Section III Code stress level limits apply, even though actual stresses may be lower. For the normal operating stresses, the Class 1 piping, Service Level A limits will be used, which is $1.5S_m$ by Equation 9 of Article NB-3652 in the ASME Boiler and Pressure Vessel Code (Ref. 1) given by

$$B_1 \frac{pD_o}{2t} + B_2 \frac{D_o}{2I} M \leq 1.5 S_m \quad (5\text{-}1)$$

where, for a circumferential crack evaluation, $B_1 = 0.5$, $B_2 = 1.0$, p = internal pressure, t = pipe wall thickness, $I = 0.0491(D_o^4 - D_i^4)$, D_o = outside diameter, D_i = inside diameter, M = applied moment, and S_m = material design stress intensity from ASME Section III, Appendix I (Ref. 1).

Table 5.1 BWR piping systems for probabilistic fracture evaluations

Cases	Piping System	Nominal Diameter, mm (inches)	Thickness, mm (inches)	Base Metal	Weld[(a)] Metal	Assumed[(b)] Cracking Mechanism
		(a) Through-wall-cracked pipes				
BWR-1	Side Riser	711.2 (28)	35.8 (1.41)	TP304	SS Flux	IGSCC
BWR-2	Main Steam	711.2 (28)	35.8 (1.41)	A516 Gr70	CS Flux	Corrosion Fatigue
BWR-3	Recirculation Branch Line	457.2 (18)	23.9 (0.94)	TP304	SS Flux	IGSCC
BWR-4	Feedwater	457.2 (18)	39.4 (1.55)	A106B	CS Flux	Corrosion Fatigue
BWR-5	Bypass Line	101.6 (4)	8.51 (0.34)	TP304	SS Flux	IGSCC
BWR-6	Reactor Water Clean-up	101.6 (4)	8.51 (0.34)	A106B	CS Flux	Corrosion Fatigue
		(b) Complex-cracked pipes				
BWR-7	Side Riser (d/t=0.25)[(c)]	711.2 (28)	35.8 (1.41)	TP304	SS Flux	IGSCC
BWR-8	Main Steam (d/t=0.50)[(c)]	711.2 (28)	35.8 (1.41)	TP304	SS Flux	IGSCC
BWR-9	Side Riser (d/t=0.25)[(c)]	457.2 (18)	23.9 (0.94)	TP304	SS Flux	IGSCC
BWR-10	Main Steam (d/t=0.50)[(c)]	457.2 (18)	23.9 (0.94)	TP304	SS Flux	IGSCC

(a) SS = stainless steel; CS = carbon steel; Flux = submerged arc weld (SAW) or shielded metal arc weld (SMAW)
(b) IGSCC = intergranular stress-corrosion cracking
(c) Complex cracks; through-wall crack with surface crack in same plane and 360-degrees around the circumference; d/t = depth of surface crack/pipe thickness

Table 5.2 PWR piping systems for probabilistic fracture evaluations

Cases	Piping System	Nominal Diameter, mm (inches)	Thickness, mm (inches)	Base Metal	Weld[a] Metal	Assumed[b] Cracking Mechanism
			Through-wall-cracked pipes			
PWR-1	Main Coolant	812.8 (32)	76.2 (3.00)	CF8M	SS Flux	Thermal Fatigue
PWR-2	Main Coolant	812.8 (32)	76.2 (3.00)	A516 Gr70	CS Flux	Corrosion Fatigue
PWR-3	Surge Line	355.6 (14)	35.8 (1.41)	CF8M	SS Flux	Thermal Fatigue
PWR-4	Feedwater	355.6 (14)	35.8 (1.41)	A106B	CS Flux	Corrosion Fatigue
PWR-5	Spray Line	101.6 (4)	13.5 (0.53)	TP304	SS Flux	IGSCC
PWR-6	Steam Generator Blowdown Line	101.6 (4)	13.5 (0.53)	A106B	CS Flux	Corrosion Fatigue

(a) SS = stainless steel; CS = carbon steel; Flux = submerged arc weld or shielded metal arc weld
(b) IGSCC = intergranular stress-corrosion cracking

Actual normal operating stresses, however, may be considerably less than this maximum limit. Hence, two stress intensities that are 50 and 100 percent of the Service Level A limits were used. The lower the normal operating stresses, the more conservative is the LBB detectable flaw size. Table 5.3 shows the ASME Service Level A stresses for various through-wall-cracked and complex-cracked pipes considered in this study.

5.2.2 Normal Plus Safe-Shutdown Earthquake Stresses

One of the most difficult aspects of this analysis was the selection of normal plus safe-shutdown earthquake stresses. Obviously for application to a generic document, such as the NRC Regulatory Guide 1.45, there are large numbers of piping systems and plant locations. It was beyond the scope of this effort to analyze all plants and piping systems. Instead, the ASME Section III service level stresses were used in this study. In this regard, some actual N+SSE stresses were obtained from References 82 to 86 and private communications with NRC personnel and then compared with the limit stresses from the ASME service levels. Table 5.4 shows 29 values of such actual N+SSE stresses for several piping materials and nuclear power plants. In all cases, the N+SSE stresses included pressure, dead weight, thermal expansion, and earthquake loads. These stresses were normalized with respect to S_y (S_y is the code-specified yield stress) and S_m, and are also shown in Table 5.4. Following statistical analysis of these data, the histograms of the actual N+SSE stresses were developed. They are shown in Figure 5.1, which clearly indicates that the actual N+SSE stresses may be significantly lower than the Service Level B, C, or D stress limits. Thus, actual

Table 5.3 ASME Service Level A and B stresses for through-wall-cracked and complex-cracked pipes

Cases	Internal Pressure, MPa	Temperature, °C	Service Level A Stress, MPa	Service Level B Stress, MPa
		(a) BWR Piping Systems		
BWR-1	7.239	288	175.325	194.42
BWR-2	7.239	288	218.208	261.85
BWR-3	7.239	288	175.325	194.42
BWR-4	7.239	288	187.183	224.62
BWR-5	7.239	288	175.325	194.42
BWR-6	7.239	288	187.183	224.62
BWR-7	7.239	288	175.325	194.42
BWR-8	7.239	288	175.325	194.42
BWR-9	7.239	288	175.325	194.42
BWR-10	7.239	288	175.325	194.42
		(b) PWR Piping Systems		
PWR-1	15.512	288	180.978	200.15
PWR-2	15.512	288	218.208	261.85
PWR-3	15.512	288	180.978	200.15
PWR-4	15.512	288	187.183	224.62
PWR-5	15.512	288	175.325	194.42
PWR-6	15.512	288	187.183	224.62

Table 5.4 Actual normal plus safe-shutdown earthquake (N+SSE) stresses

Pipe Material	Plant	σ_{N+SSE}[a] MPa	σ_{N+SSE}/S_y[b]	σ_{N+SSE}/S_m[c]	Source
TP316	PWR	70.88	0.53	0.59	NRC
		160.93	1.20	1.33	
		250.91	1.88	2.08	
		89.64	0.67	0.74	
		108.94	0.82	0.90	
		128.25	0.96	1.06	
TP316	PWR (Zion)	166.38	1.25	1.38	Reference 82
		98.74	0.74	0.82	
		92.19	0.69	0.76	
		103.98	0.78	0.86	
		90.95	0.68	0.75	
		101.22	0.76	0.84	
		108.11	0.81	0.90	
		96.32	0.72	0.80	
		101.70	0.76	0.84	
		97.43	0.73	0.81	
		67.16	0.50	0.56	
		103.29	0.77	0.86	
		104.53	0.78	0.87	
		81.50	0.61	0.68	
TP304	BWR (Unknown)	86.19	0.66	0.74	Reference 83
		87.57	0.68	0.75	
		80.67	0.62	0.69	
		97.08	0.75	0.83	
TP316	PWR (Unknown)	50.54	0.37	0.42	Reference 84
		73.78	0.55	0.61	
		66.61	0.50	0.55	
		83.84	0.63	0.69	
TP304	PWR (Unknown)	144.11	1.11	1.23	Reference 85

(a) σ_{N+SSE} = actual normal plus safe-shutdown earthquake (N+SSE) stress
(b) S_y = Code-specified yield stress (S_y = 133.42 MPa for TP316; S_y = 129.63 MPa for TP304)
(c) S_m = material design stress (S_m = 120.66 MPa for TP316; S_m = 116.87 MPa for TP304)

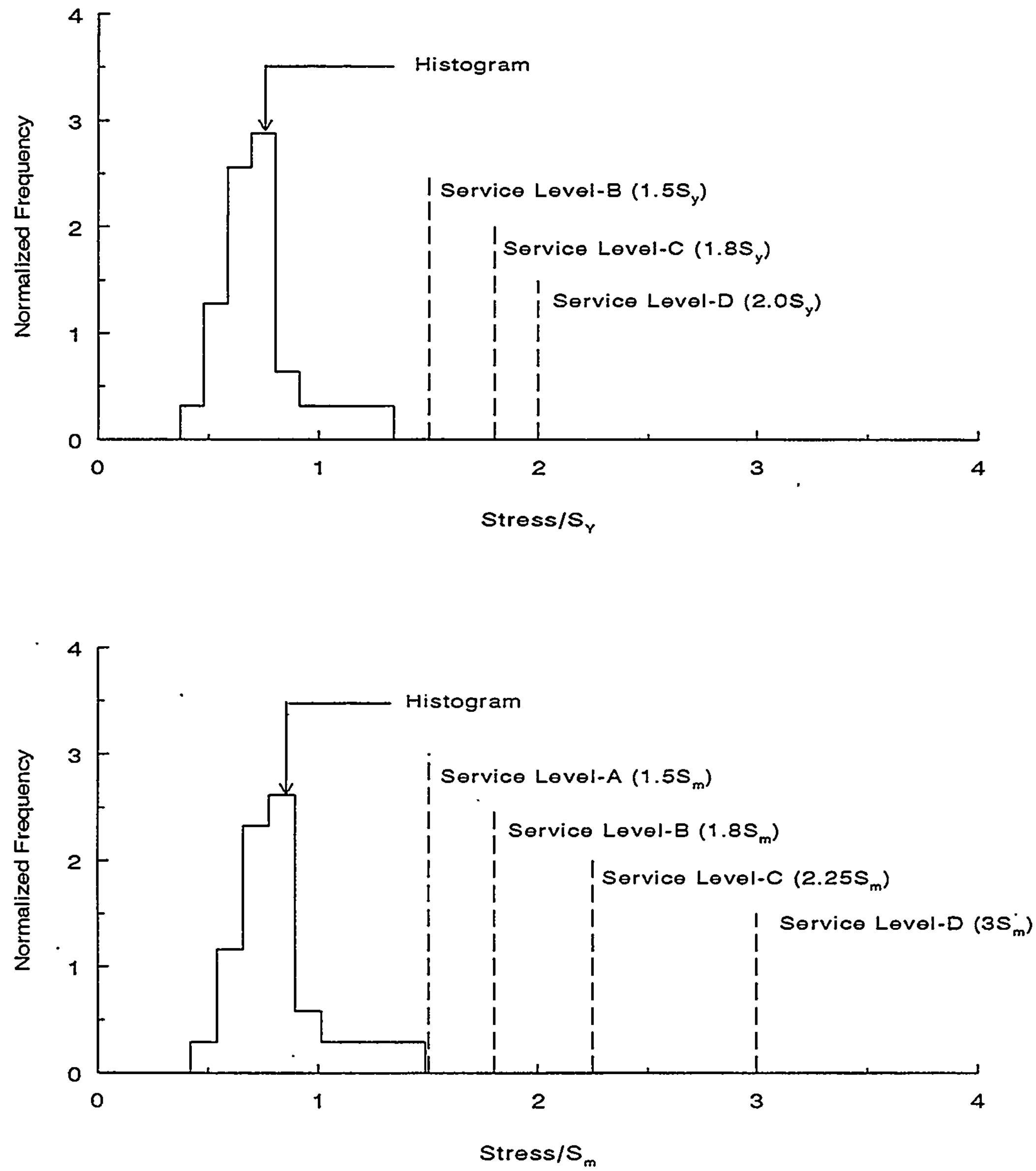


Figure 5.1 Comparisons of actual N+SSE stresses with various service limits

normal plus SSE stresses may be below these service level stress limits, but these possible combinations were not investigated here. T-6004-F 5.1

Based on the values shown in Table 5.4 and Figure 5.1 for N+SSE stresses, the maximum stress limit in Service Level B was used. It was felt that since the N+SSE stress values given were mainly from LBB applications, there may be other piping systems or cases with higher stresses that might preclude them from LBB acceptance. Hence, there was concern that our N+SSE stress distribution may be biased to lower stresses. Consequently, the Service Level B limit was used to add some conservatism to account for this concern. By ASME Section III, this maximum stress limit is the lower of either $1.8S_m$ or $1.5S_y$ when using Equation 9 in Article NB-3652. The above stresses are also shown in Table 5.3 for ten BWR pipes and six PWR pipes considered in this study.

One point of difficulty is that these stress values are elastically calculated. The actual bending stresses may be much lower due to plastic action during seismic loading on pipes. Hence, there is an inherent margin in the use of the elastic stresses to determine the bending moment in the pipe system of interest. Thus, some plasticity corrections may be necessary for the Service Level B stresses. Figure 5.2 shows the correction factor as a function of elastically calculated Service Level B stresses. It is based on the assumptions that (1) no correction is required for elastically calculated stresses smaller than the yield stress, σ_y, (2) a correction factor of $\pi/4$ is applied (based on the equivalence of Net-Section Collapse loads) when stresses calculated under elastic assumptions are larger than the flow stress, σ_f, where the flow stress is defined as the average of yield and ultimate stresses, and (3) a linear variation is adequate for the range of stresses between the above two limits. There are other alternative means for defining the plasticity correction factor which may be available in the literature. They were not explored here.

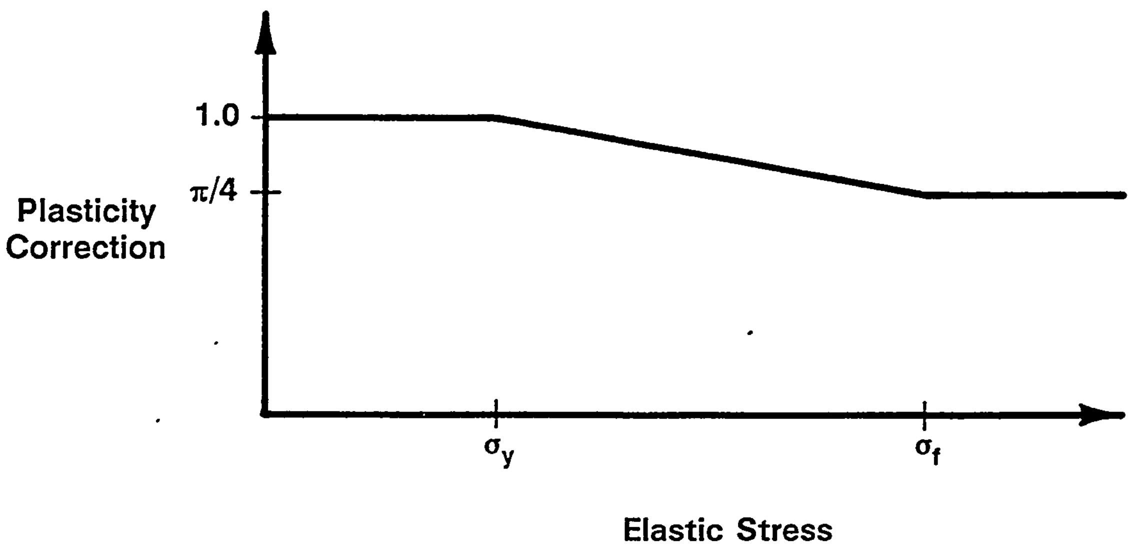


Figure 5.2 Plasticity correction for stresses calculated under elastic assumptions

T-6004-F5.2

In addition, the above characterization of system loads in both Service Level A and B were purely deterministic. A more realistic representation would require exploration of existing databases to randomize these stresses. This is particularly important for N+SSE stresses, since ground motion parameters during potentially damaging earthquakes can exhibit significant amount of scatter. These factors were beyond the scope of this study.

In the following analysis, it was assumed that the N+SSE stress at Service Level B occurred with absolute certainty (i.e., a probability of 1). Considerable time was spent assessing if a more realistic probability of the N+SSE stresses could be used in a generic sense. To do so would involve the following considerations.

(1) Determine the frequency of earthquakes occurring at a specific site

(2) Determine the probability distribution of the magnitude of an earthquake

(3) Compare the frequency of occurrence relative to the time from leakage at the specific rate of interest to plant shutdown

(4) Conduct the assessment for all U.S. plants either accounting for plant-to-plant variations by using variability or use the worst-case plant.

These were not considered in this study.

5.3 Probabilistic Characteristics of a Leakage Size Flaw

The computer code PSQUIRT was used to determine the probability density function of the LBB detectable flaw size, 2a. Figure 5.3 shows the histogram of 2a from PSQUIRT generated by simulating 1000 samples. It was obtained for the piping system BWR-1 with a 3.785 l/min (1 gpm) leak rate and 100 percent of Service Level A stresses under normal operating conditions. It appears that the histogram fits the lognormal probability density function,

$$f_{2a}(x) = \frac{1}{\sqrt{2\pi}\, x\tilde{\sigma}} \exp\left[-\frac{1}{2} \left\{ \frac{\ln x - \tilde{\mu}}{\tilde{\sigma}} \right\}^2 \right] \qquad (5\text{-}2)$$

with

$$\begin{aligned} \tilde{\sigma} &= \sqrt{\ln(1+V^2)} \\ \tilde{\mu} &= \ln\mu - \frac{1}{2}\tilde{\sigma}^2 \end{aligned} \qquad (5\text{-}3)$$

where μ and V denote the mean and coefficient of variation of 2a. Results obtained by varying leak rates, normal operating stresses, and piping systems, which are not shown here, also indicated that the density of LBB detectable flaw sizes could be fairly approximated by the lognormal probability. According to Equations 5-2 and 5-3, two parameters, such as the mean and coefficient of variation (COV), are needed to define a lognormal probability density function. Tables 5.5 to 5.8 provide the values of these parameters for various piping systems considered in this study. For each piping system, they are further broken down for various combinations of normal operating stresses and leak rates.

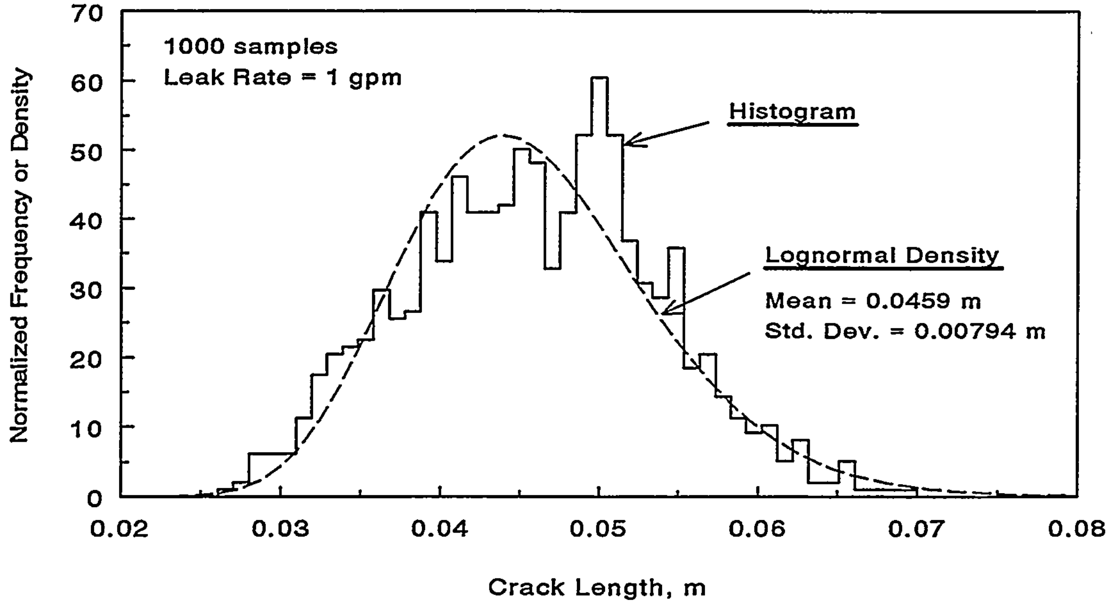


Figure 5.3 Histogram of LBB detectable flaw size for BWR-1 (3.785 l/min [1 gpm] leak rate and 100 percent of Service Level-A limit)

T-6004-F5.3

Table 5.5 Mean values of LBB detectable crack length for BWR pipes under normal operating stresses[a]

Cases	Mean Crack Length with 100 Percent of Service Level-A, m				Mean Crack Length with 50 Percent of Service Level-A, m			
	0.1 (gpm)	1 (gpm)	10 (gpm)	100 (gpm)	0.1 (gpm)	1 (gpm)	10 (gpm)	100 (gpm)
BWR-1	0.0195	0.0459	0.1010	0.1300	0.0740	0.1790	0.3210	0.4520
BWR-2	0.0276	0.0647	0.1462	0.3090	0.0562	0.1305	0.2715	0.5333
BWR-3	0.0207	0.0488	0.0942	0.1097	0.0724	0.1642	0.2711	0.3235
BWR-4	0.0341	0.0815	0.1669	0.2813	0.0642	0.1493	0.2794	0.4608
BWR-5	0.0149	0.0305	0.0343	0.0538	0.0429	0.0780	0.0897	0.1056
BWR-6	0.0234	0.0490	0.0710	0.0905	0.0434	0.0815	0.1084	0.1340
BWR-7	0.0245	0.0376	0.0703	0.0820	0.0606	0.1526	0.2792	0.4075
BWR-8	0.0197	0.0368	0.0512	0.0675	0.0372	0.0938	0.1797	0.2514
BWR-9	0.0154	0.0293	0.0491	0.0631	0.0535	0.1276	0.2186	0.2692
BWR-10	0.0124	0.0287	0.0674	0.0767	0.0545	0.1278	0.2187	0.2980

(a) 1 gpm = 3.785 l/min

Table 5.6 Mean values of LBB detectable crack length for PWR pipes under normal operating stresses(a)

Cases	Mean Crack Length with 100 Percent of Service Level-A, m				Mean Crack Length with 50 Percent of Service Level-A, m			
	0.1 (gpm)	1 (gpm)	10 (gpm)	100 (gpm)	0.1 (gpm)	1 (gpm)	10 (gpm)	100 (gpm)
PWR-1	0.0188	0.0436	0.0988	0.2225	0.0518	0.1158	0.2520	0.4729
PWR-2	0.0219	0.0516	0.1177	0.2640	0.0454	0.1020	0.2304	0.4553
PWR-3	0.0166	0.0385	0.0819	0.1596	0.0453	0.0971	0.1891	0.2905
PWR-4	0.0237	0.0578	0.1209	0.2160	0.0483	0.1085	0.2145	0.3266
PWR-5	0.0097	0.0229	0.0384	0.0475	0.0337	0.0622	0.0845	0.0939
PWR-6	0.0191	0.0408	0.0673	0.0866	0.0366	0.0697	0.1046	0.1254

(a) 1 gpm = 3.785 l/min

Table 5.7 Coefficient of variation of LBB detectable crack length for BWR pipes under normal operating stresses(a)

Cases	COV of Crack Length with 100 Percent of Service Level-A, m				COV of Crack Length with 50 Percent of Service Level-A, m			
	0.1 (gpm)	1 (gpm)	10 (gpm)	100 (gpm)	0.1 (gpm)	1 (gpm)	10 (gpm)	100 (gpm)
BWR-1	0.1420	0.1730	0.1040	0.0850	0.0990	0.1150	0.0940	0.0300
BWR-2	0.0790	0.1099	0.0777	0.0006	0.0731	0.0885	0.0822	0.0471
BWR-3	0.1315	0.1563	0.0948	0.0713	0.1020	0.0991	0.0775	0.0013
BWR-4	0.1309	0.1573	0.1069	0.0031	0.1029	0.1312	0.0976	0.0205
BWR-5	0.1163	0.0832	0.0357	0.0104	0.0832	0.0649	0.0017	0.0017
BWR-6	0.0926	0.0647	0.0247	0.0036	0.0588	0.0588	0.0778	0.0019
BWR-7	0.1959	0.2275	0.1464	0.0839	0.1132	0.1087	0.0955	0.0447
BWR-8	0.1864	0.1312	0.1127	0.0724	0.1181	0.1754	0.0936	0.0371
BWR-9	0.1526	0.1772	0.1573	0.0169	0.1097	0.1039	0.0798	0.0418
BWR-10	0.1452	0.1686	0.0815	0.0455	0.1032	0.1021	0.0821	0.0381

(a) 1 gpm = 3.785 l/min

Table 5.8 Coefficient of variation of LBB detectable crack length for PWR pipes under normal operating stresses[a]

Cases	COV of Crack Length with 100 Percent of Service Level-A, m				COV of Crack Length with 50 Percent of Service Level-A, m			
	0.1 (gpm)	1 (gpm)	10 (gpm)	100 (gpm)	0.1 (gpm)	1 (gpm)	10 (gpm)	100 (gpm)
PWR-1	0.0674	0.0870	0.0909	0.0835	0.0841	0.0646	0.0820	0.0510
PWR-2	0.0674	0.0799	0.0905	0.0776	0.0806	0.0700	0.0883	0.0595
PWR-3	0.0752	0.0990	0.0928	0.0555	0.0856	0.0705	0.0763	0.0340
PWR-4	0.0936	0.1280	0.1104	0.0614	0.0879	0.1011	0.1039	0.0500
PWR-5	0.0923	0.1031	0.0473	0.0073	0.0936	0.0630	0.0240	0.0012
PWR-6	0.0726	0.0926	0.0473	0.0006	0.0736	0.0756	0.0436	0.0027

(a) 1 gpm = 3.785 l/min

5.4 Evaluation of FORM/SORM Methods in Piping Reliability Analysis

The first- and second-order reliability methods were used to compute the conditional probability of failure by code PROLBB. These methods were evaluated by comparing their failure probability estimates with those obtained from reference solutions, such as the Monte Carlo simulation and Importance Sampling.

Figure 5.4 shows the plots of conditional failure probability (P_F) versus leak rate obtained by several methods: FORM, SORM, Monte Carlo simulation, and Importance Sampling, for 100- and 50-percent of Service Level A stress representing a normal operating condition. They were calculated for a large diameter BWR pipe (side riser) with a crack in the base metal with no margins on flaw size and N+SSE stresses. There are several interesting features that can be observed from this figure. First, it indicates that as the leak rate increases the failure probability increases because of larger crack size for a given normal operating stress. Second, for a given leak rate, the probability of failure decreases with the intensity of normal operating stress. This may appear counter-intuitive, but further thought on the definition of LBB detectable flaw size will clarify the matter. According to LBB methodology, the leakage flaw size in a pipe decreases with an increase in the normal operating stress when the leak-rate detection is the same. Naturally with the smaller flaw size, the failure probability should also decrease, and hence, the trend exhibited in Figure 5.4. Third, the reliability methods FORM and SORM provide accurate probability estimates when compared with those obtained by the simulation methods. No meaningful differences were found between the results of FORM and SORM and their probability estimates were practically identical. During the calculation of probability of failure by the Monte Carlo method, the sample size was varied according to the level of probability being estimated. In all cases, the sample size was targeted to be at least $10/\text{Min}(P_F,P_S)$ (with a minimum of 500) for obtaining a 30-percent coefficient of variation of the estimator. All of the above failure probabilities by FORM and SORM, including the estimates by Monte Carlo and Importance Sampling methods, were obtained by using the PROLBB program.

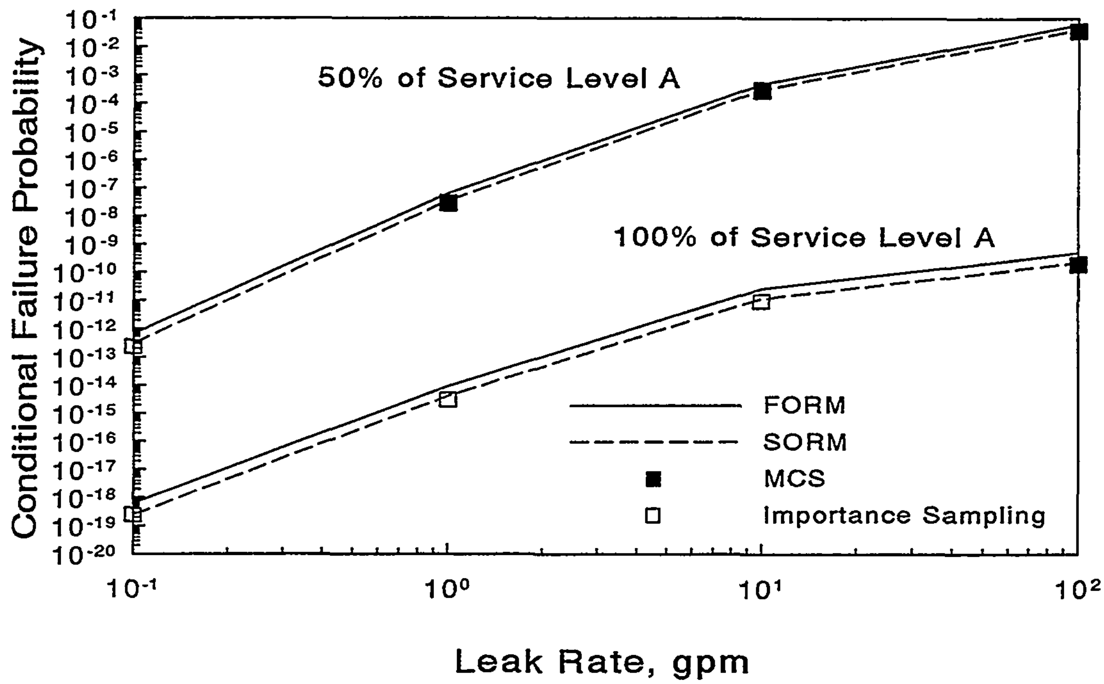


Figure 5.4 Conditional probability of failure by various methods (BWR-1)
Note: 1 gpm = 3.785 l/min

T-6004-F5.4

Figure 5.5 exhibits the relative effort and computational expense required to determine the above solutions by FORM, SORM, Importance Sampling, and Monte Carlo simulation. They were measured in terms of Central Processing Units (CPU) by executing the PROLBB code for each of these methods on a Personal Computer. The plots in this figure show how the CPU ratios required by FORM, SORM, and Importance Sampling (CPU ratio are defined as the CPU by Monte Carlo simulation divided by the CPU required by each of these methods) vary with the range of the probability estimates made in this study for the BWR-1 pipe when the normal operating stress is 50-percent of Service Level A stress. It appears that for values of failure probability approaching 1, all three CPU ratios also approach 1 implying that the computational effort by each of the above four methods are very similar. However, when the failure probabilities are smaller, a significant amount of CPU time can be saved by using FORM, SORM, and Importance Sampling instead of direct Monte Carlo simulation. The computational time decreased by a factor of 10^{11} times the CPU time required by the Monte Carlo method. Clearly, FORM, SORM, and Importance Sampling methods are more efficient than Monte Carlo simulation and become much faster methods, particularly when the failure probabilities are in the lower range ("tail" of the distribution). Hence, the rest of pipe fracture evaluations conducted in this study, were based on SORM estimates using the PROLLB program. This was essential to completing the large number of probabilistic analyses that follow within the time frame of this project.

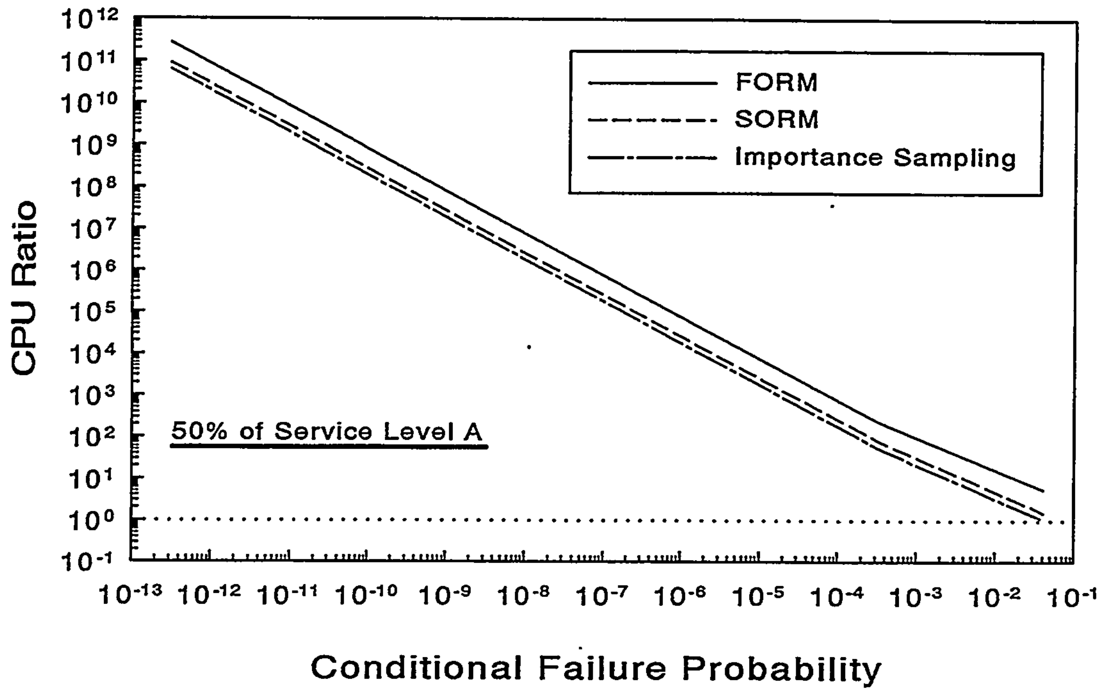


Figure 5.5 Computational efficiency of FORM, SORM, and Importance Sampling (BWR-1)

T-6004-F5.5

5.5 Results for BWR Piping

Figures 5.6 to 5.17 show the variation of the conditional failure probability of six through-wall-cracked pipe cases, BWR-1 to BWR-6, for various leak rates and normal operating stresses. The above probabilities were calculated separately when the crack was assumed to be located either in the base metal or in the weld metal. Due to the significant reduction in the toughness properties of the weld metal compared with the base metal of stainless steel (TP304) pipes, the conditional probability of failure for cracks in the weld metal showed much larger values than those obtained for cracks in the base metal. These were observed for BWR-1, BWR-3, and BWR-5 pipes that are made of austenitic materials (see Figs. 5.6, 5.7, 5.10, 5.11, 5.14, and 5.15).

For the ferritic pipes; the failure probabilities were also found to be larger for cracks in the weld metal than those for cracks in the base metal due to the slightly lower toughness of the weld metal. These were observed for BWR-2, BWR-4, and BWR-6 pipes that are made of ferritic materials (see Figs. 5.8, 5.9, 5.12, 5.13, 5.16, and 5.17). However, these differences in probability of failure are not as significant as those exhibited for austenitic materials.

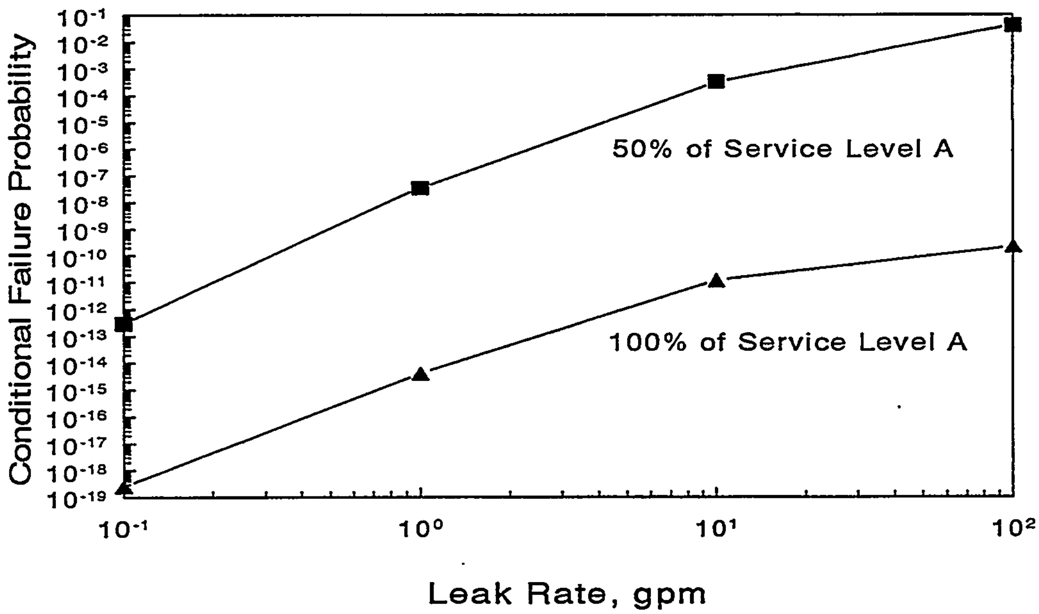


Figure 5.6 Conditional failure probability for BWR-1 (base metal)

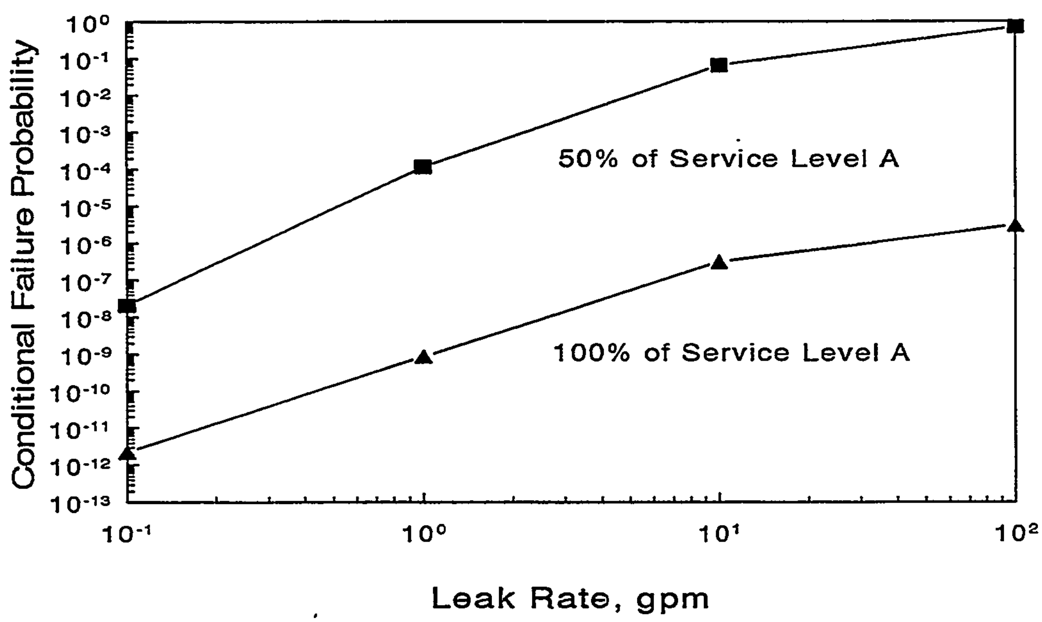


Figure 5.7 Conditional failure probability for BWR-1 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.6/F5.7

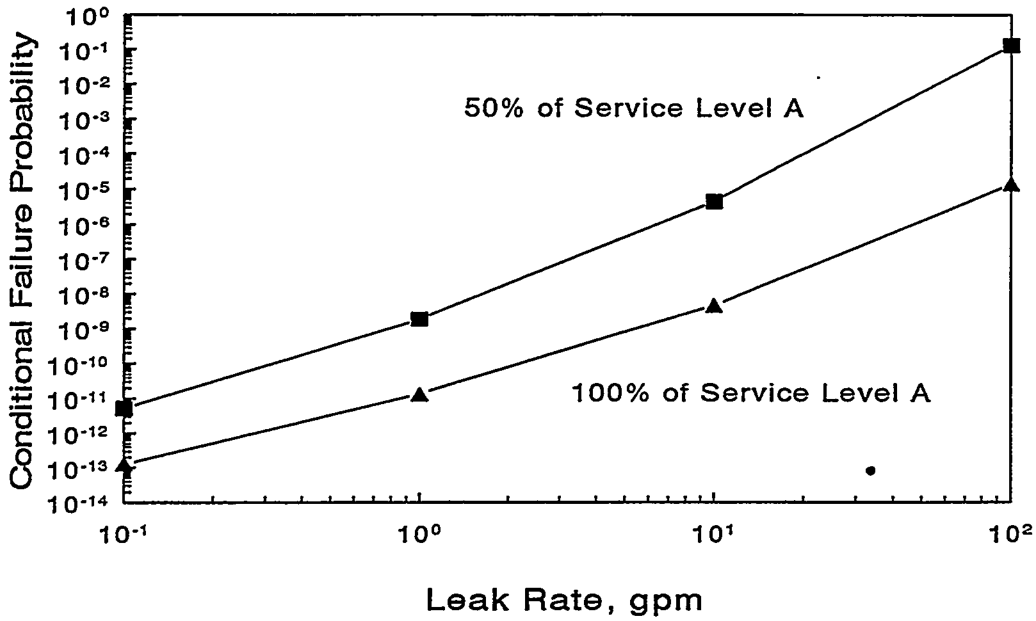


Figure 5.8 Conditional failure probability for BWR-2 (base metal)

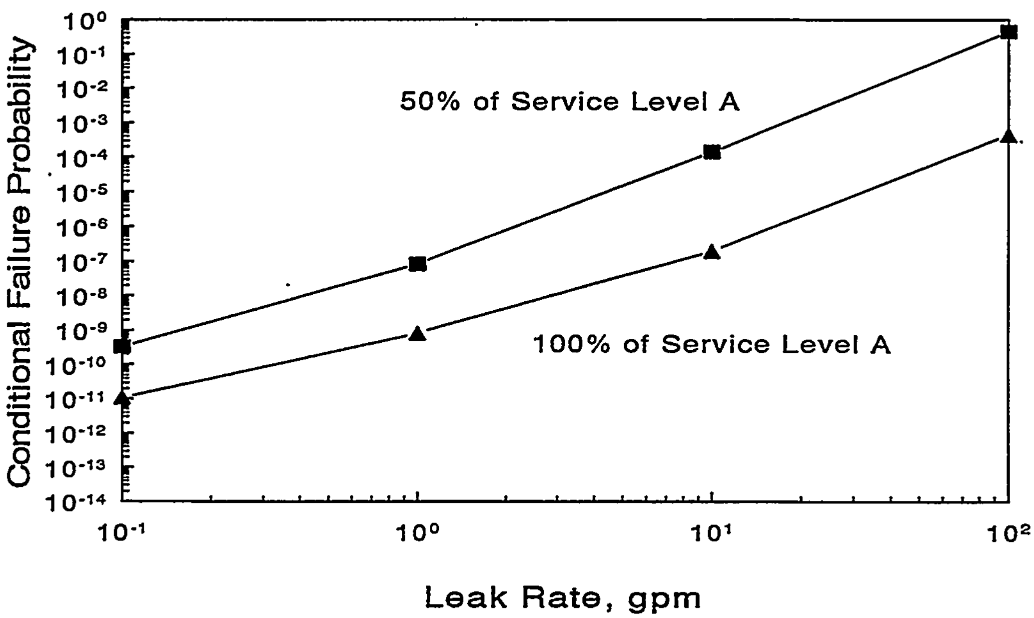


Figure 5.9 Conditional failure probability for BWR-2 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.8/F5.9

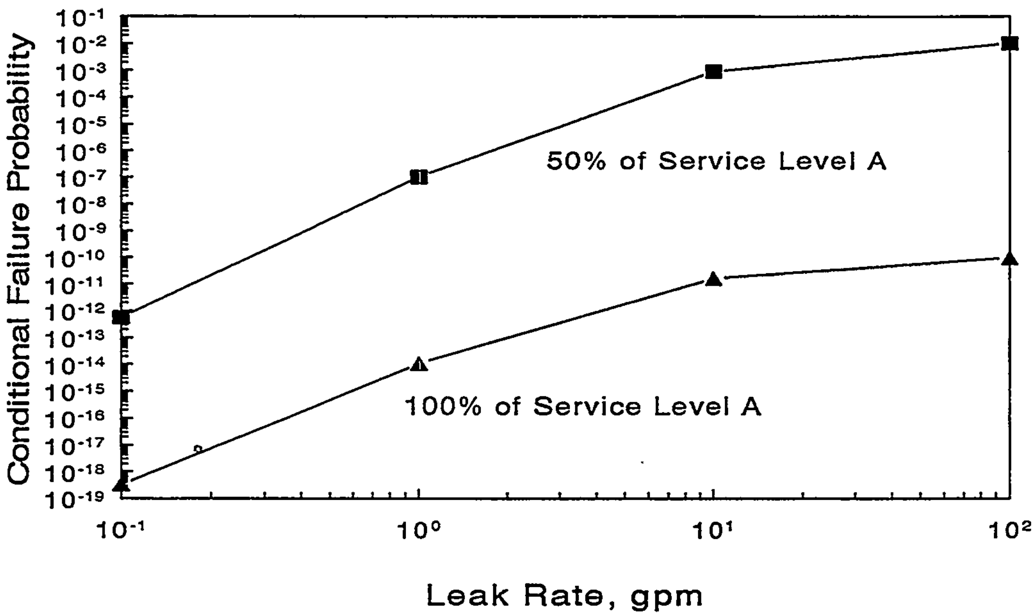


Figure 5.10 Conditional failure probability for BWR-3 (base metal)

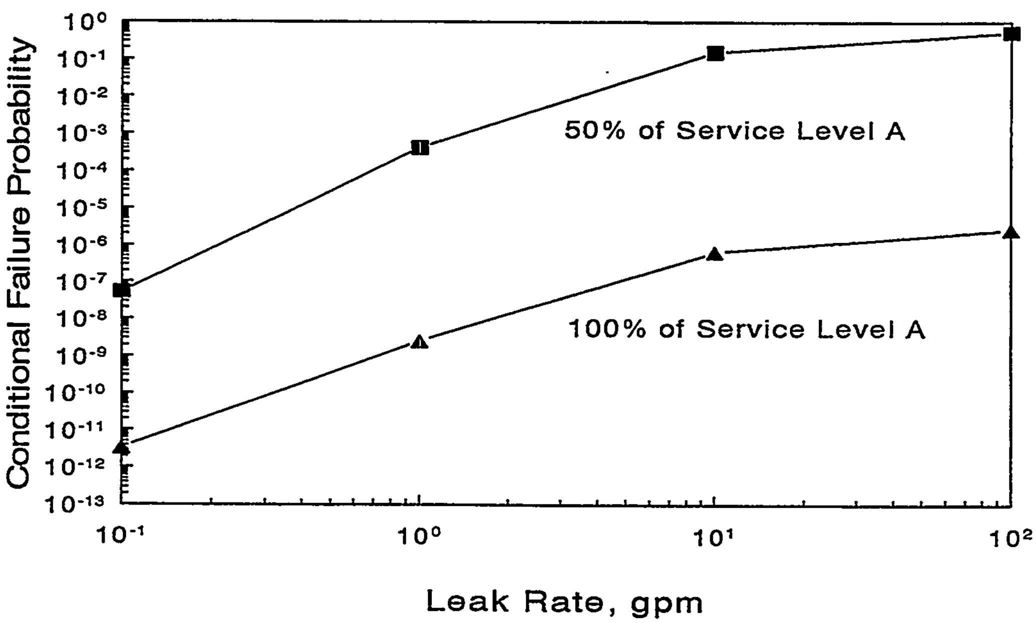


Figure 5.11 Conditional failure probability for BWR-3 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.10/F5.11

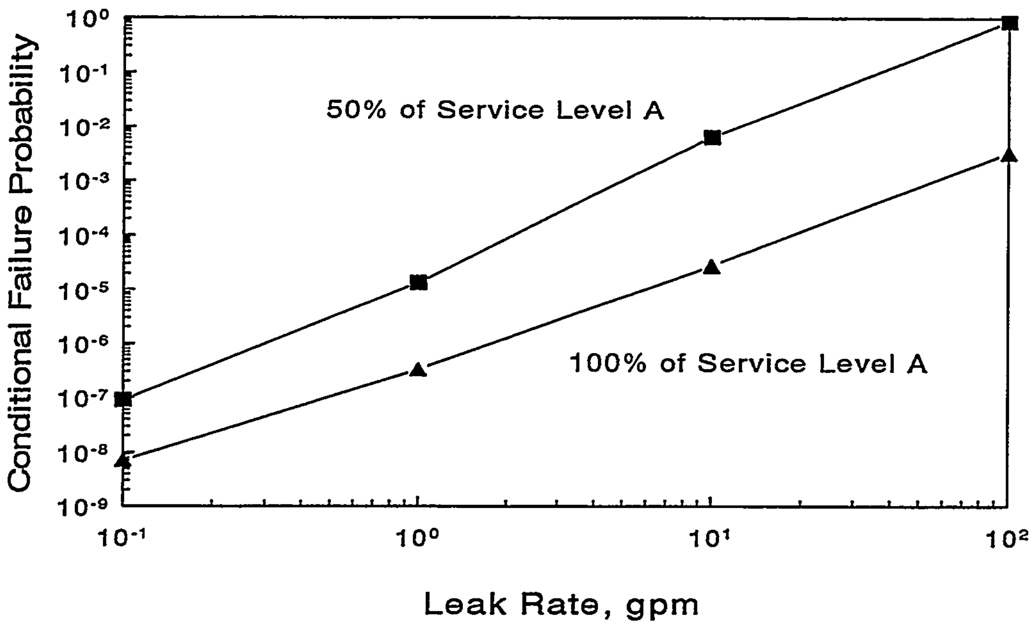


Figure 5.12 Conditional failure probability for BWR-4 (base metal)

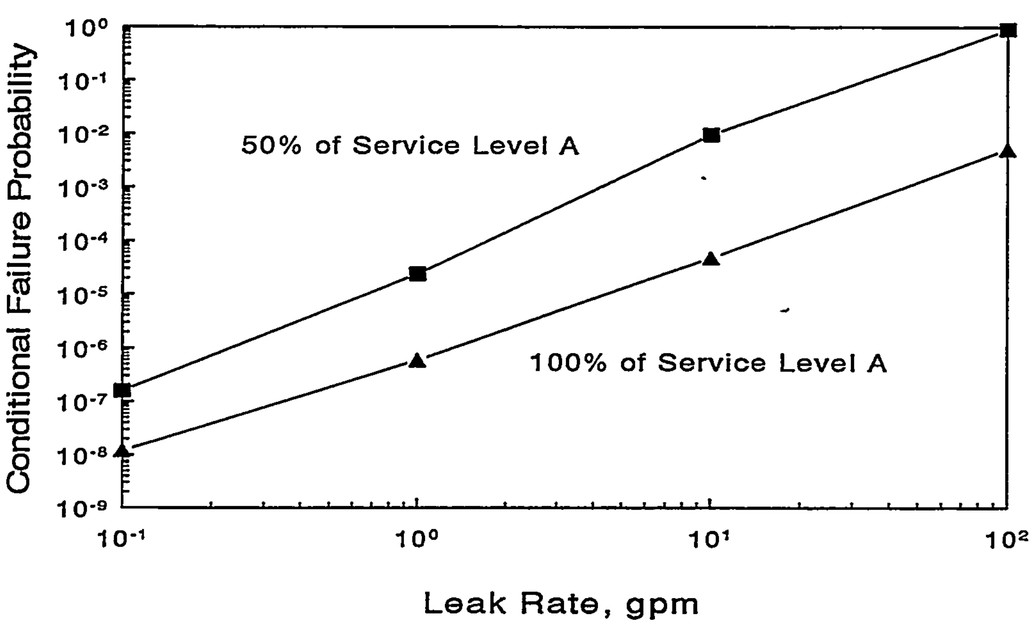


Figure 5.13 Conditional failure probability for BWR-4 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.12/F5.13

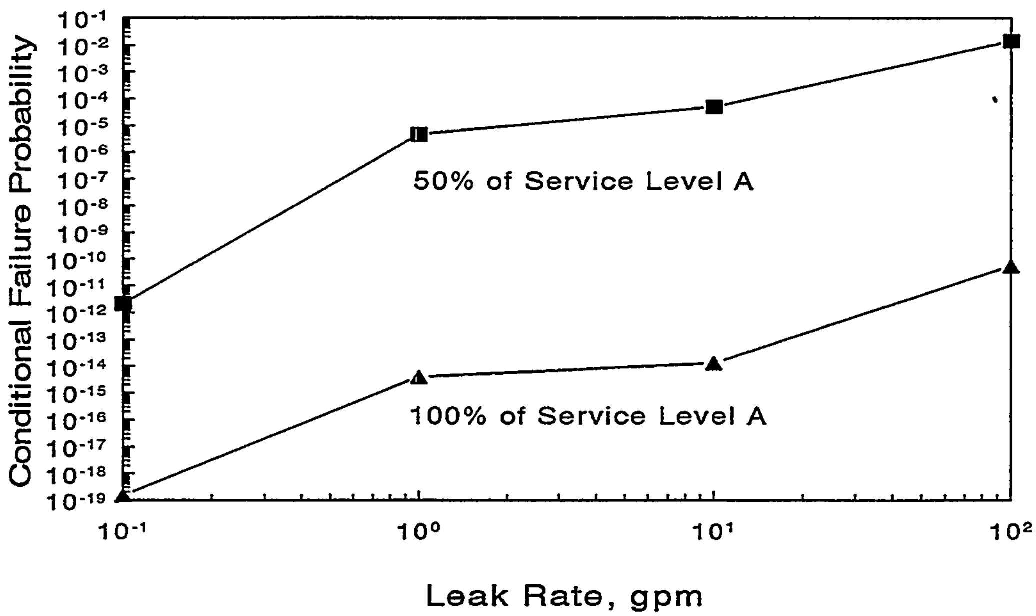


Figure 5.14 Conditional failure probability for BWR-5 (base metal)

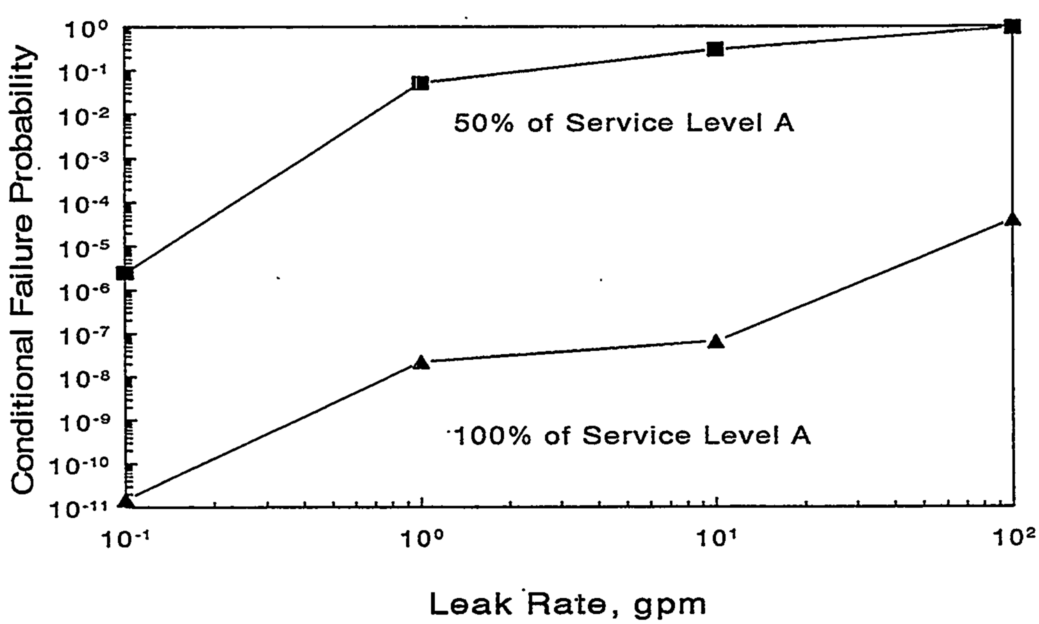


Figure 5.15 Conditional failure probability for BWR-5 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.14/F5.15

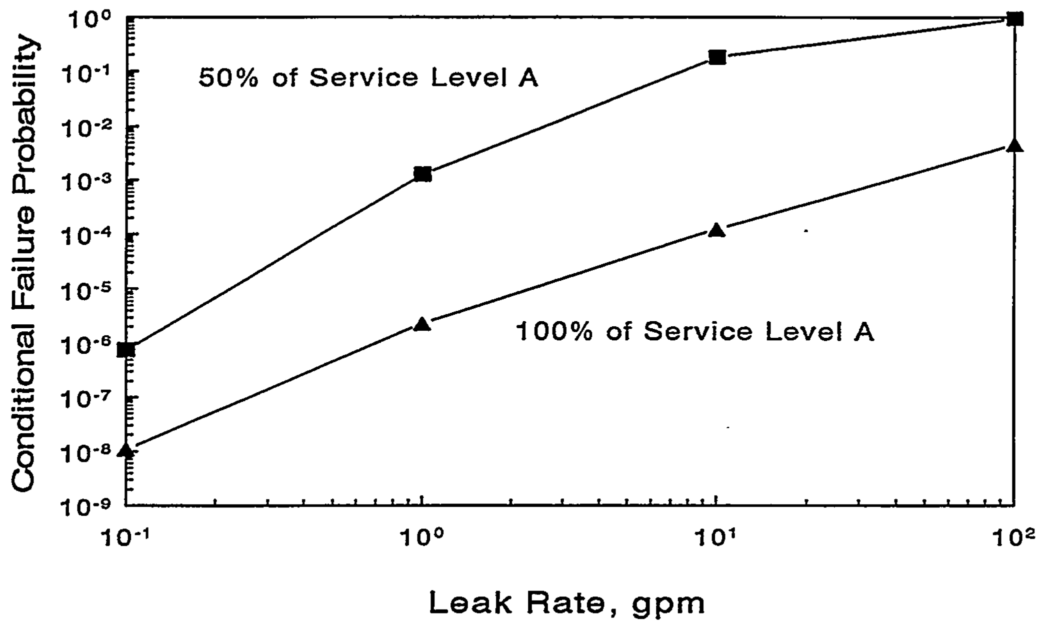


Figure 5.16 Conditional failure probability for BWR-6 (base metal)

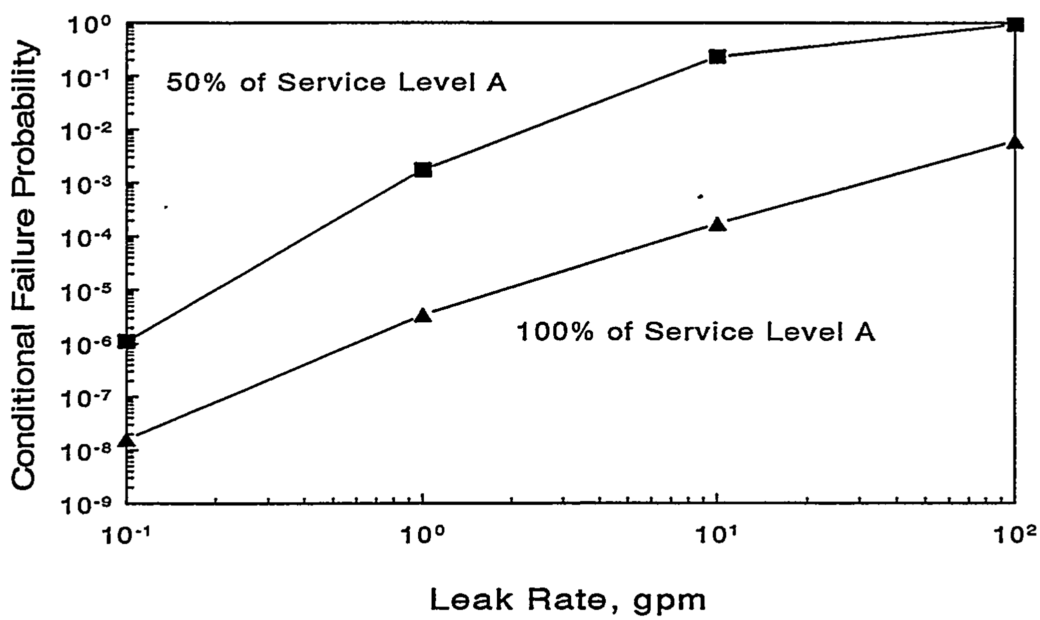


Figure 5.17 Conditional failure probability for BWR-6 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.16/F5.17

Comparisons between the results for austenitic and ferritic materials suggest that the conditional failure probabilities for austenitic materials are much lower than those for ferritic materials with the same leaking crack size when the crack is located in the high-toughness base metal. However, when the crack is located in the low-toughness weld metal, the failure probabilities for ferritic materials can also be lower than those for austenitic materials in some cases. This is due to similar toughness properties of ferritic and austenitic welds but significantly higher tensile properties of ferritic base metals. See Appendix B for further details on the material properties of austenitic and ferritic steels.

Figures 5.18 to 5.25 show the conditional failure probability of the four complex-cracked pipes BWR-7 to BWR-10 for various leak rates and normal operating stresses. As expected, the failure probability of complex-cracked pipes were much higher than those for through-wall-cracked pipes.

As mentioned previously, the conditional failure probabilities were obtained separately for deterministic locations of cracks in the base or weld metals. However, when a random crack location is considered, with the probability being 2/3 for cracks in base metal and 1/3 for cracks in either weld metal or the fusion line (see the statistics in Tables 3.10 and 3.11), the weighted combination (the probabilities are the weights) of the failure probabilities given in the above figures can be easily obtained. The conditional failure probability calculated as a function of leak rates for random crack locations are provided in Figures 5.26 to 5.31 and Figures 5.32 to 5.35 for six through-wall-cracked and four complex-cracked BWR pipes, respectively. From the results of these figures, it appears that the conditional failure probabilities for random crack locations are closer to those obtained for weld-metal cracks in austenitic materials. This is due to failure probabilities for weld-metal cracks being 5 to 7 orders higher than those for base-metal cracks. Since the above differences were not as large for ferritic materials (differences in 1 or 2 orders of magnitude), the conditional failure probabilities for random crack location were similar to those for either base-metal or weld-metal cracks.

Figure 5.36 shows several plots of conditional probability of failure (random crack location) for a given leak rate of 3.785 l/min (1 gpm) as a function of diameter of BWR austenitic pipes with LBB detectable crack size obtained for both 100 and 50 percent of Service Level A stresses. They indicate that the conditional failure probability decreases with an increase in pipe diameter for both through-wall-cracked and complex-cracked pipes. Similar results were also obtained by Harris et al. (Ref. 82) and Wilson (Ref. 87). Also, comparisons between the failure probabilities of through-wall-cracked and complex-cracked pipes indicate that the through-wall-cracked pipes are far more reliable than complex-cracked pipes. In particular, when the depth-to-thickness (d/t) ratio of the complex-cracked pipe is 50 percent, the failure probability is significantly higher than it is for through-wall-cracked pipes. For a d/t ratio larger than 0.5, some difficulty was experienced in obtaining the LBB detectable crack size. This was mainly due to the pipe failure (maximum load being reached) even under normal operating conditions.

For austenitic pipe, it was assumed that flux welds were used even for small diameter pipe. It may be that TIG or MIG welds may be used instead for the small-diameter pipe. These welds have comparable toughness to the base metal, so the failure probability for small diameter austenitic pipe (e.g., 4-inch-diameter BWR-5 pipe) may be lower than indicated in Figure 5.15. For small diameter ferritic pipe (e.g., 4-inch-diameter BWR-6 pipe), the welding procedure is typically SMAW, so the failure probabilities are correctly reflected in Figure 5.17.

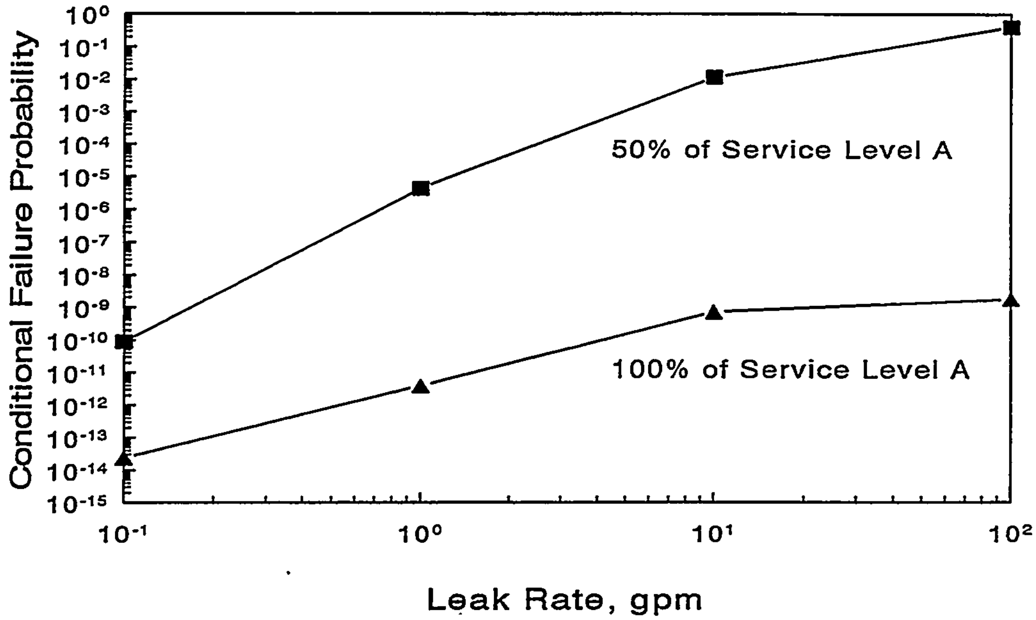


Figure 5.18 Conditional failure probability for BWR-7 (base metal)

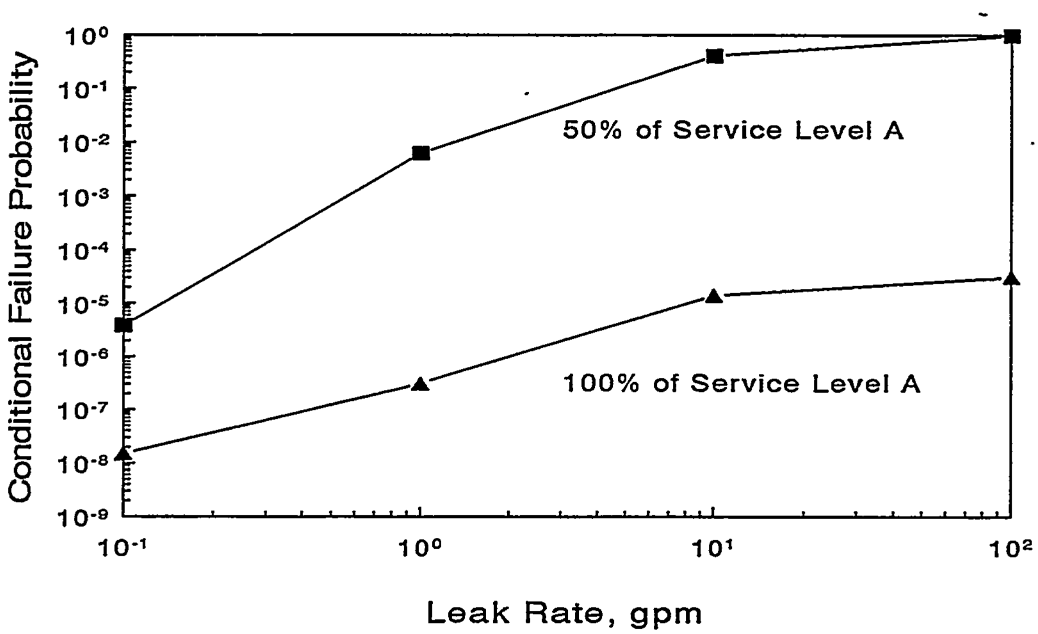


Figure 5.19 Conditional failure probability for BWR-7 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.18/F5.19

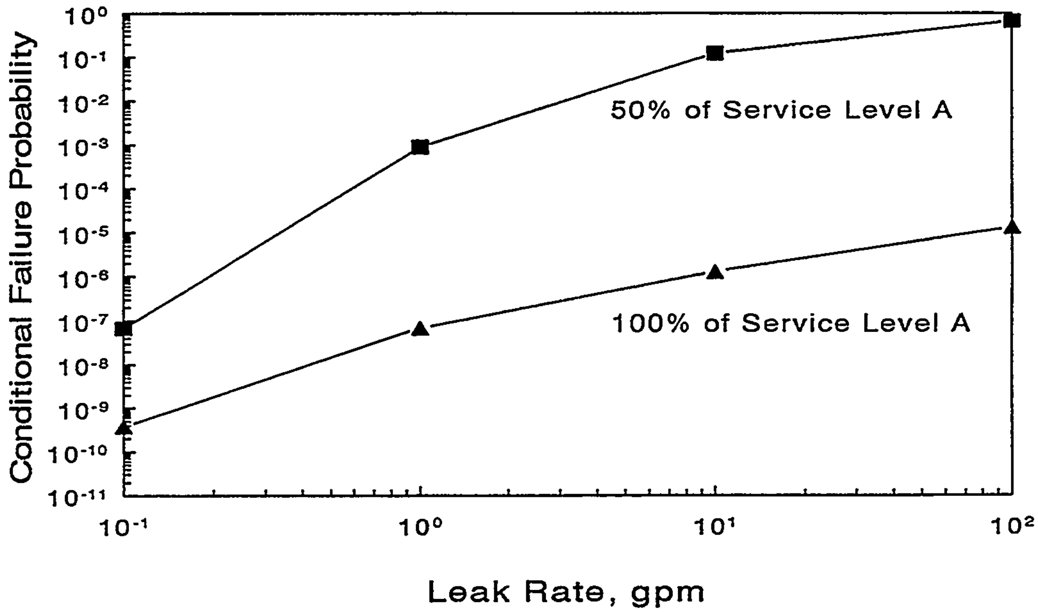


Figure 5.20 Conditional failure probability for BWR-8 (base metal)

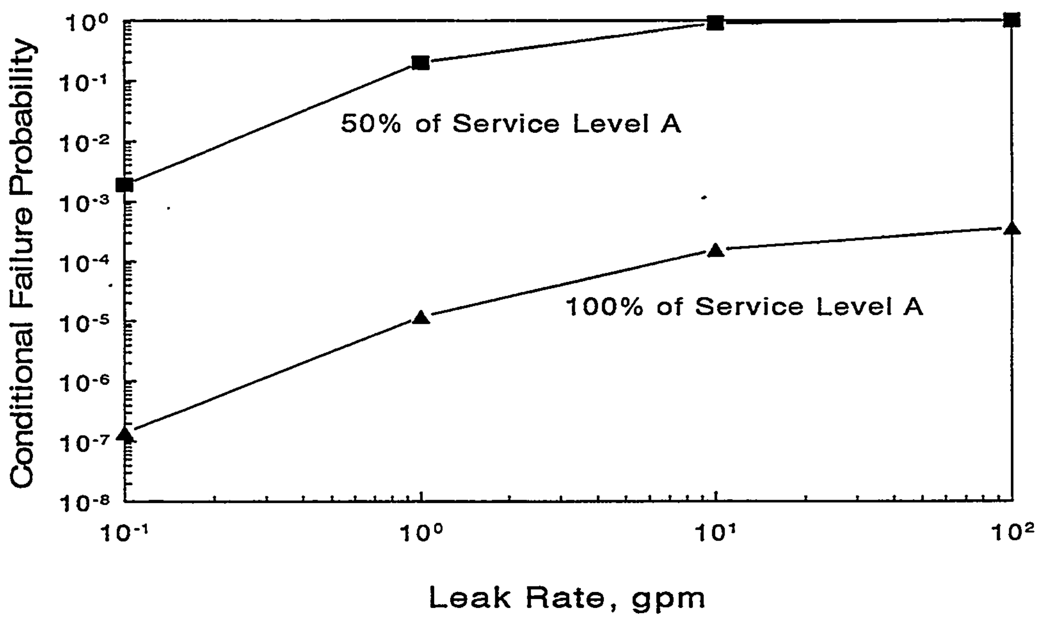


Figure 5.21 Conditional failure probability for BWR-8 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.20/F5.21

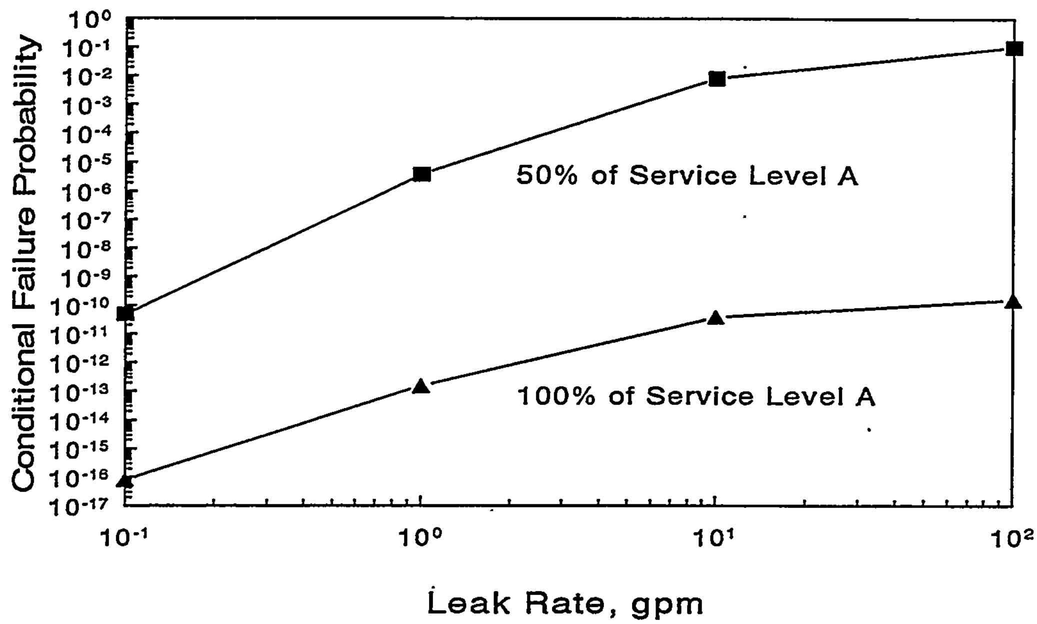


Figure 5.22 Conditional failure probability for BWR-9 (base metal)

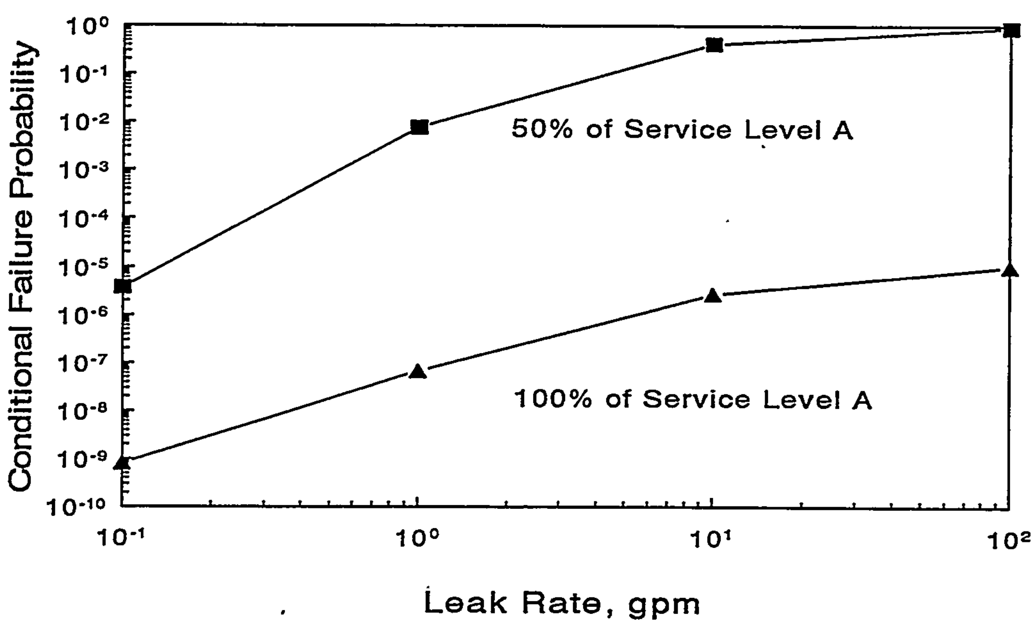


Figure 5.23 Conditional failure probability for BWR-9 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.22/F5.23

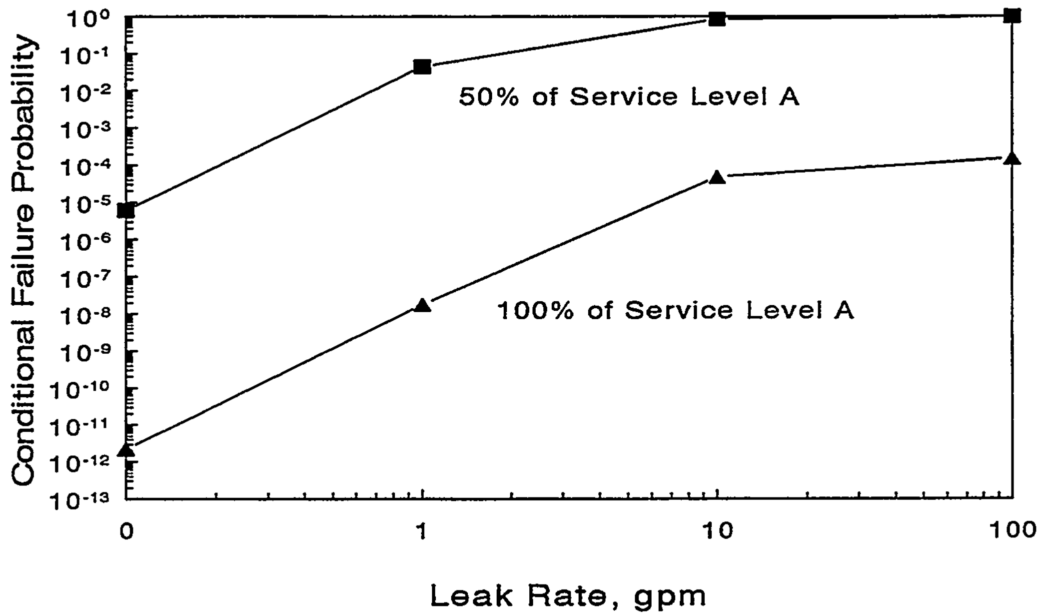


Figure 5.24 Conditional failure probability for BWR-10 (base metal)

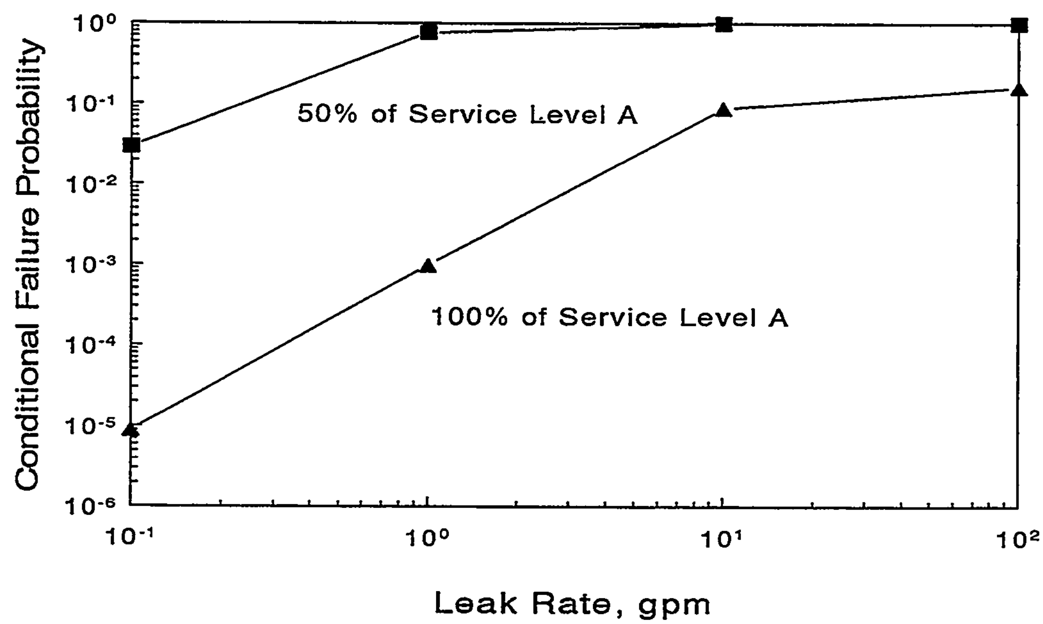


Figure 5.25 Conditional failure probability for BWR-10 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.24/F5.25

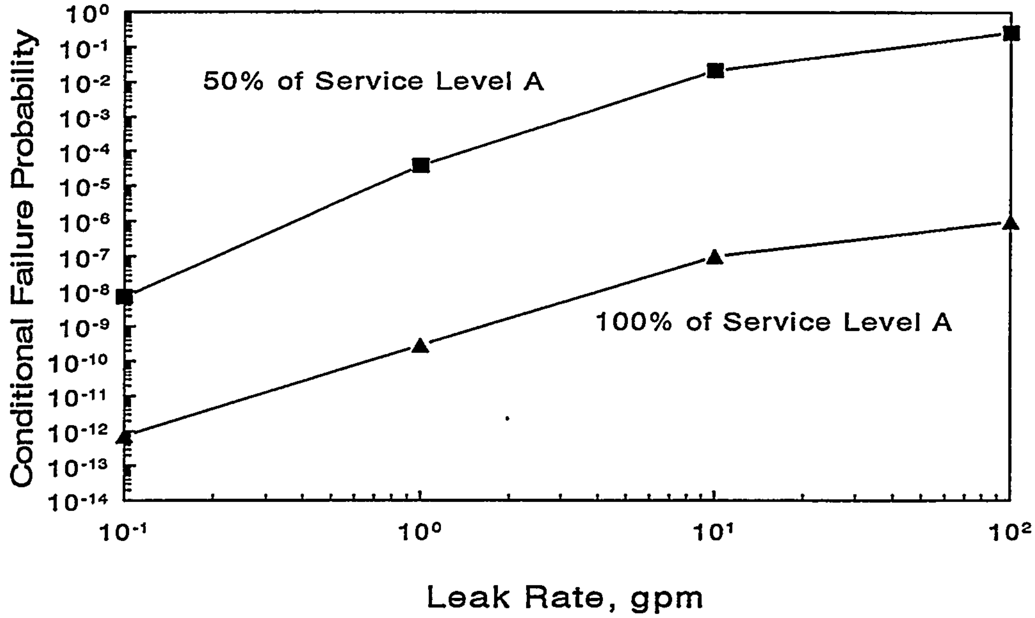


Figure 5.26 Conditional failure probability for BWR-1 (random crack location)

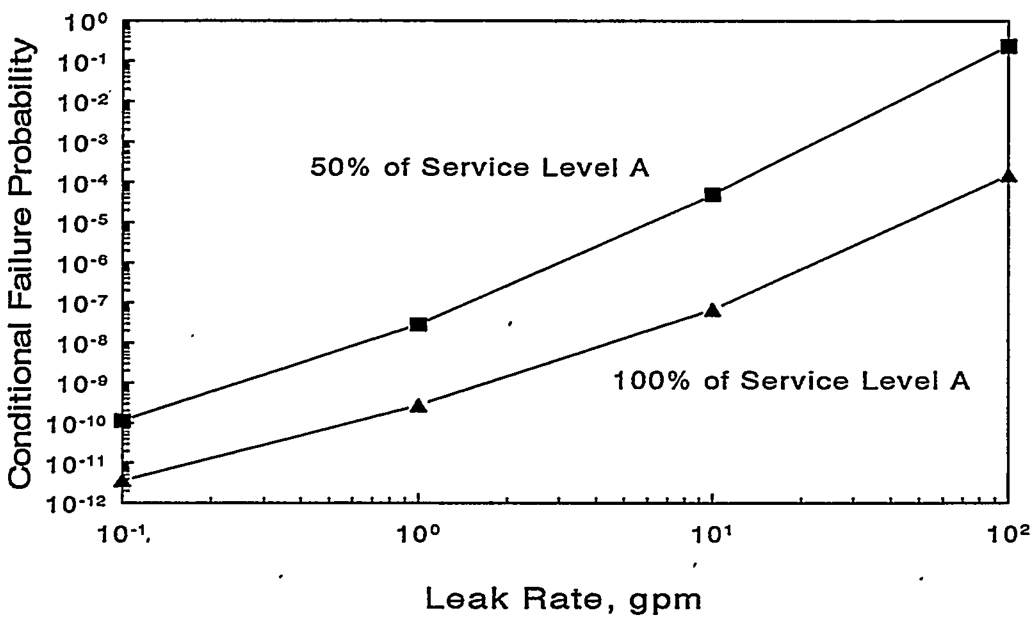


Figure 5.27 Conditional failure probability for BWR-2 (random crack location)
Note: 1 gpm = 3.785 l/min

T-6004-F5.26/F5.27

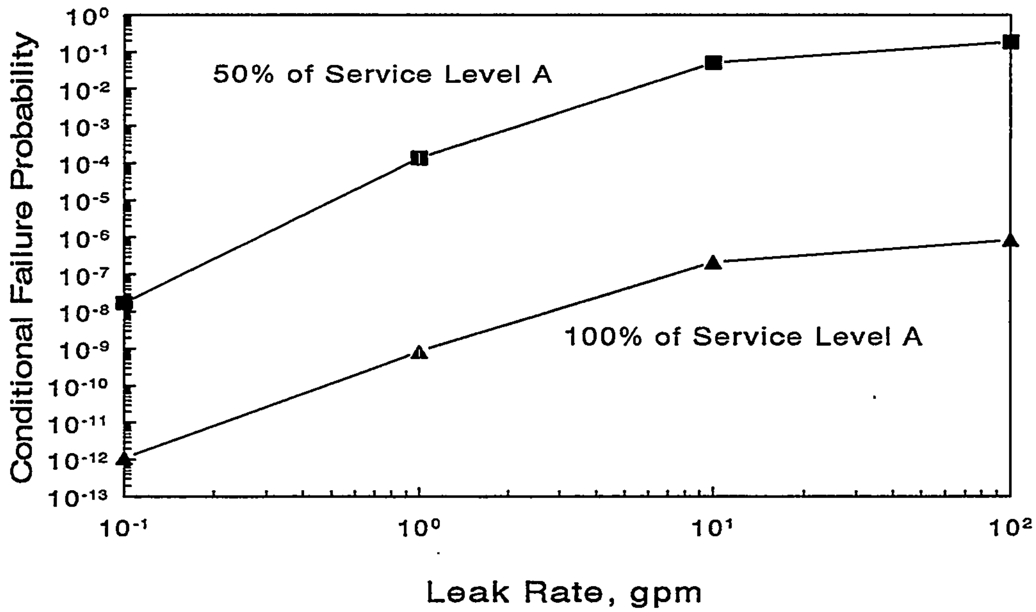


Figure 5.28 Conditional failure probability for BWR-3 (random crack location)

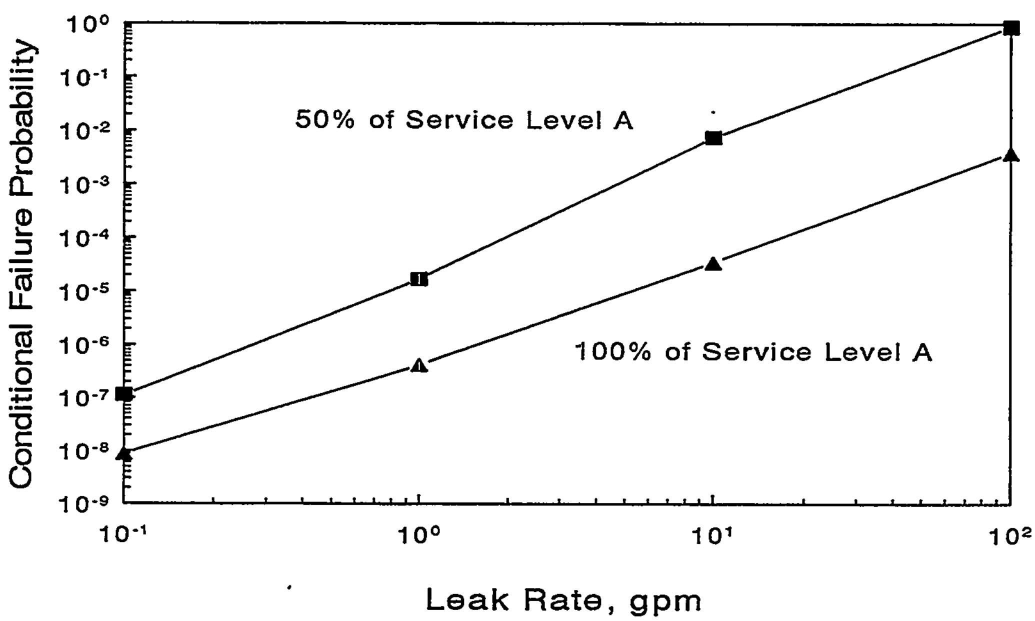


Figure 5.29 Conditional failure probability for BWR-4 (random crack location)
Note: 1 gpm = 3.785 l/min

T-6004-F5.28/F5.29

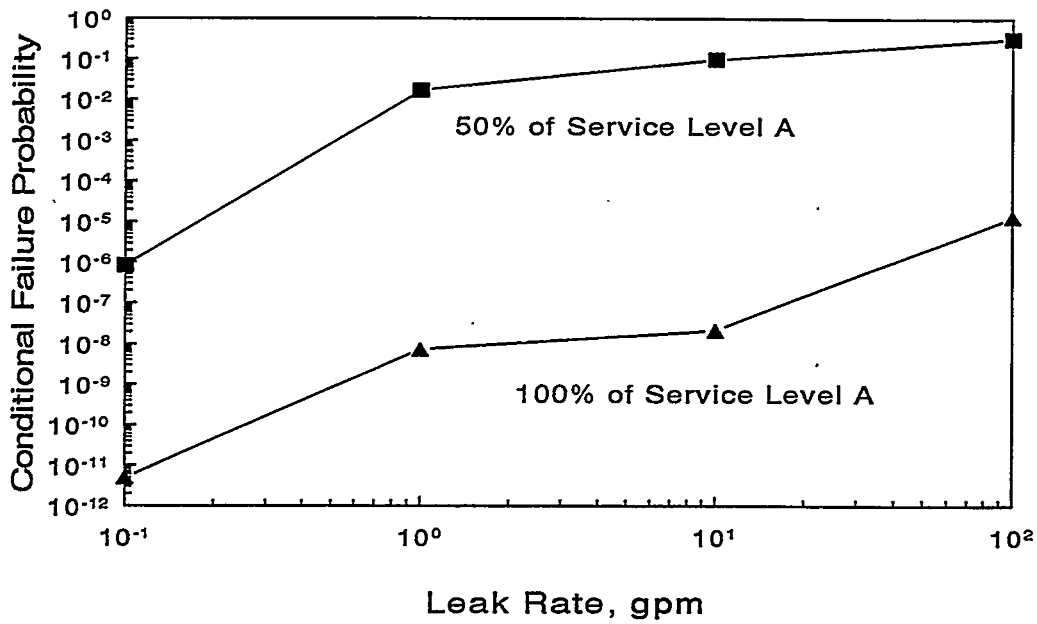


Figure 5.30 Conditional failure probability for BWR-5 (random crack location)

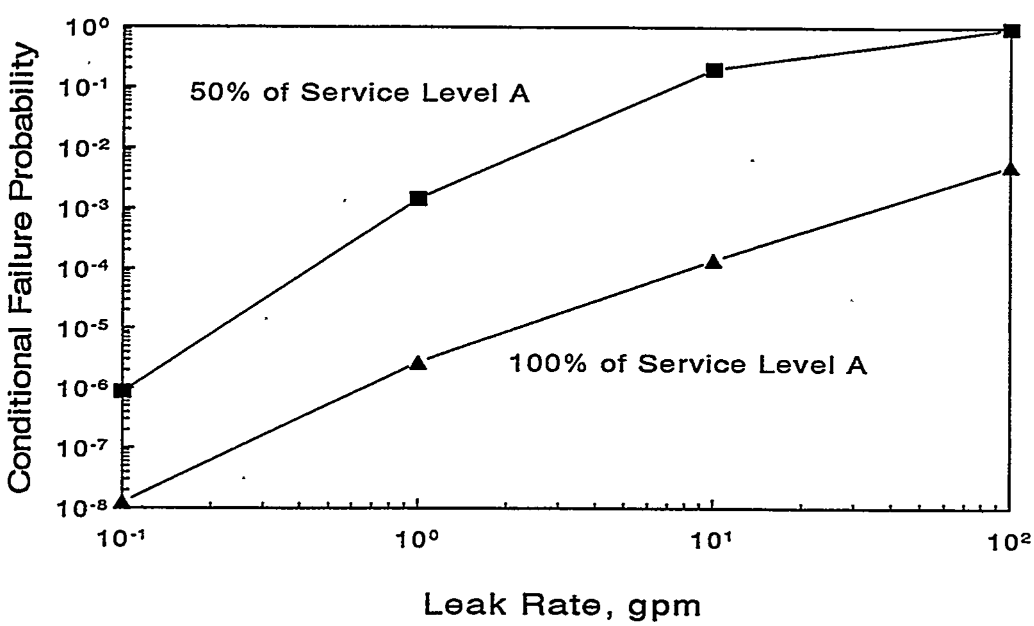


Figure 5.31 Conditional failure probability for BWR-6 (random crack location)
Note: 1 gpm = 3.785 l/min

T-6004-F5.30/F5.31

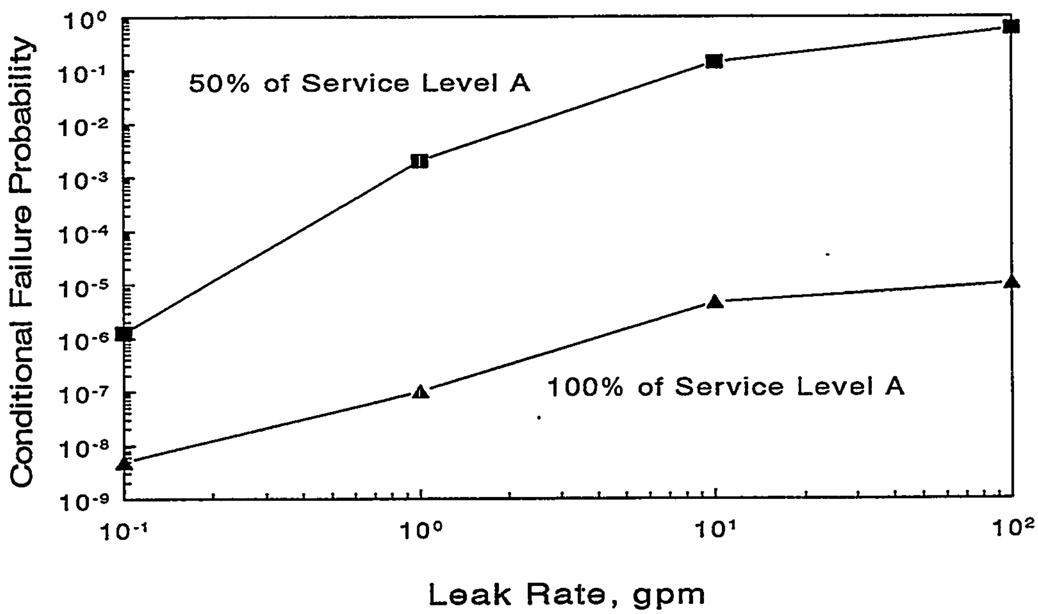


Figure 5.32 Conditional failure probability for BWR-7 (random crack location)

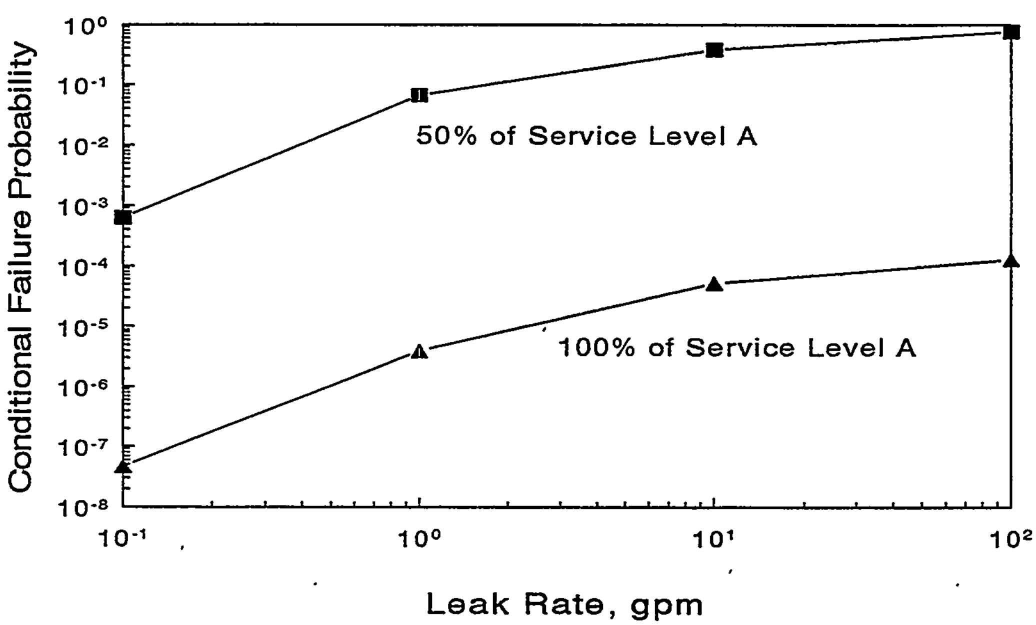


Figure 5.33 Conditional failure probability for BWR-8 (random crack location)
Note: 1 gpm = 3.785 l/min

T-6004-F5.32/F5.33

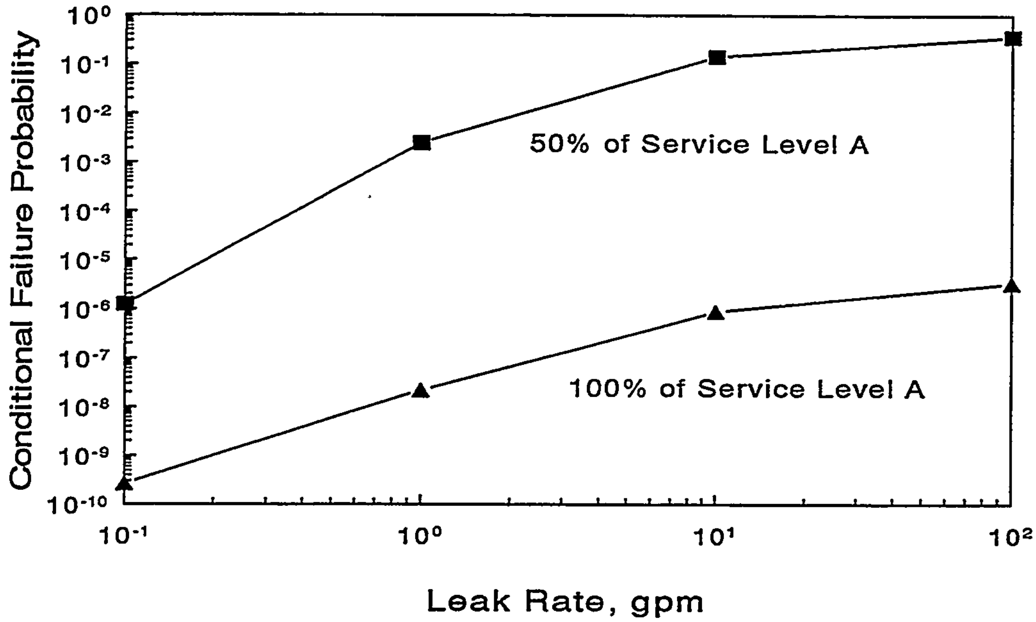


Figure 5.34 Conditional failure probability for BWR-9 (random crack location)

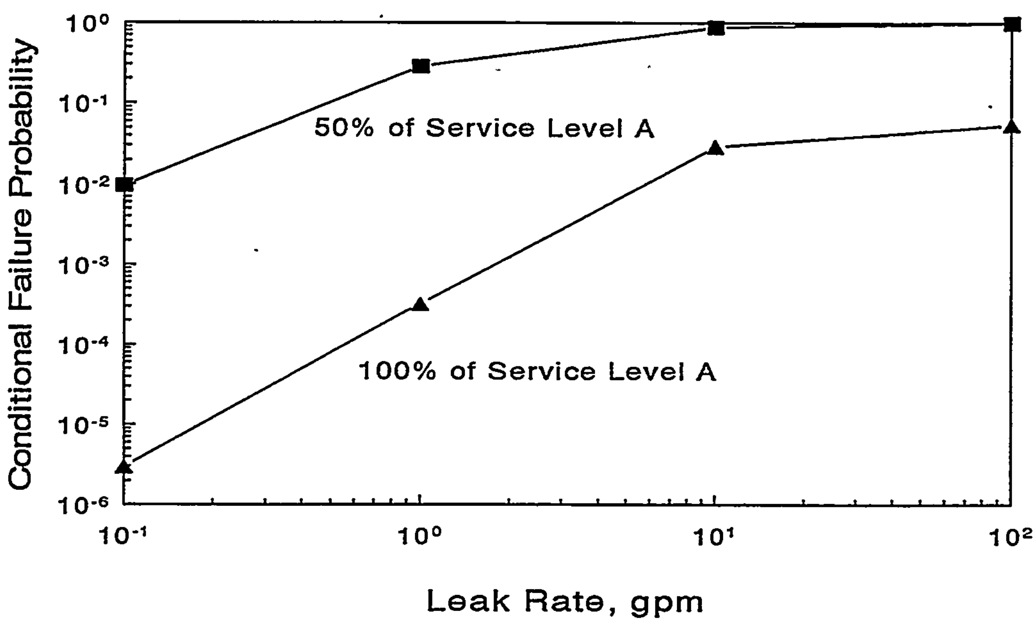
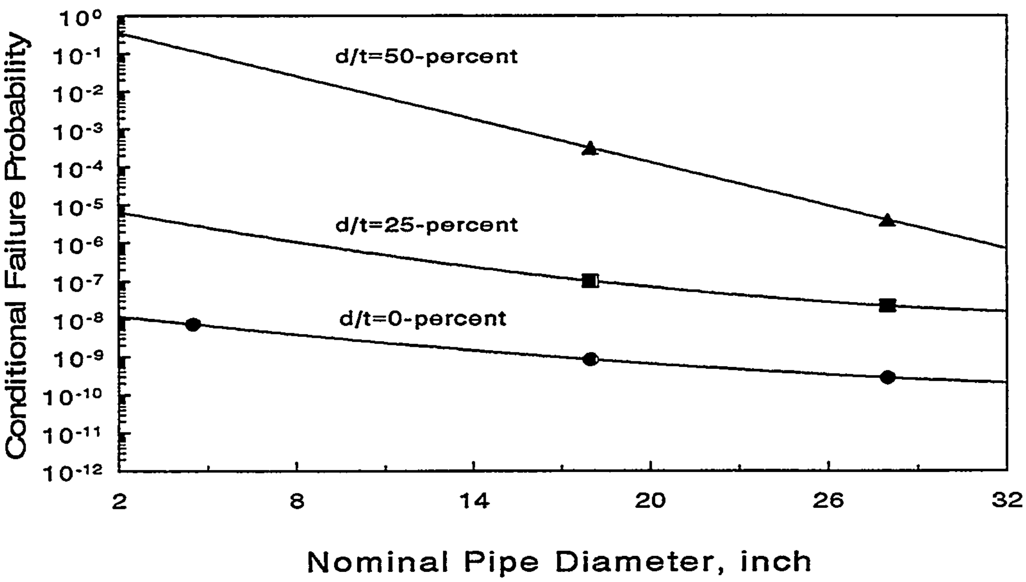
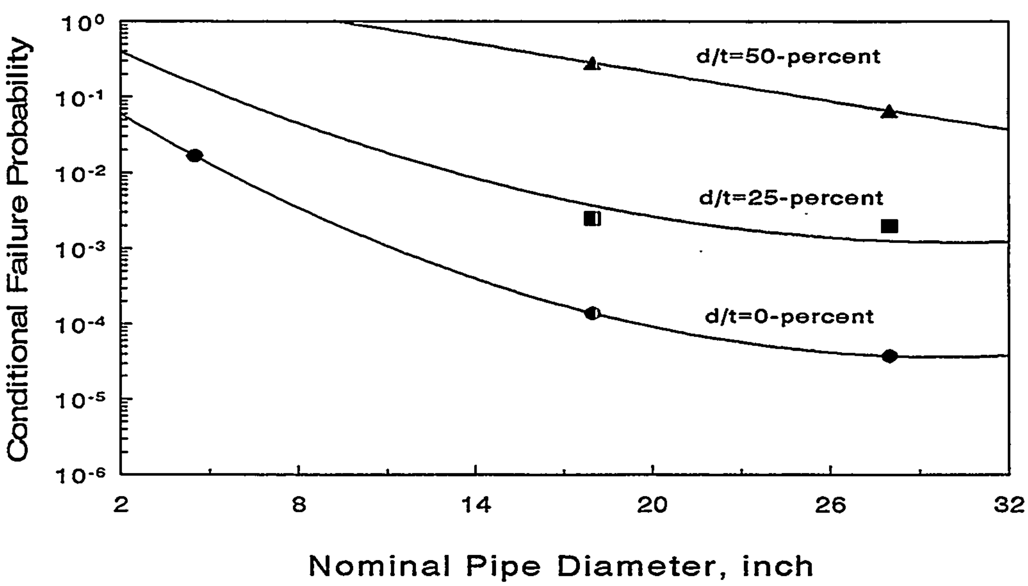


Figure 5.35 Conditional failure probability for BWR-10 (random crack location)
Note: 1 gpm = 3.785 l/min

T-6004-F5.34/F5.35



(a) 100 percent of Service Level A



(b) 50 percent of Service Level A

Figure 5.36 Conditional failure probability versus diameter in through-wall-cracked BWR pipes with austenitic materials at 3.785 l/min (1 gpm) leak rate

T-6004-F5.36

5.6 Results for PWR Piping

Figures 5.37 to 5.48 show the variation of conditional failure probability of six through-wall-cracked PWR pipe cases, PWR-1 to PWR-6, for various leak rates and normal operating stresses. As before, the probabilities were calculated separately when the crack was assumed to be located either in the base metal or in the weld metal. Due to a reduction in the toughness properties of the weld metal compared with the base metal of stainless and cast stainless steel (TP304 and CF8M) pipes, the conditional probability of failure for cracks in weld metal showed larger values than those obtained for cracks in base metal. These were observed for PWR-1, PWR-3, and PWR-5 pipes that are made of austenitic materials (see Figs. 5.37, 5.38, 5.41, 5.42, 5.45, and 5.46).

In the PWR austenitic pipe cases considered in this study, PWR-1 and PWR-3 are aged cast stainless steel (CF8M) pipes, whereas PWR-5 is a wrought stainless steel (TP304) pipe. Comparisons of the results in Figures 5.37, 5.38, 5.41, 5.42, 5.45, and 5.46 suggest that, due to aging, the reliability of cast stainless steel pipes can be much lower than for wrought stainless steel pipes. This was especially true for pipes with base metal cracks, in which cases the fracture toughness of aged cast stainless steel materials was significantly lower than that of wrought stainless steel pipes. It appears that the toughness reduction has more detrimental effects than the beneficial effects due to strength increase in aged cast stainless steel pipes. Also, in these pipe cases, the differences between toughness properties of base and weld metals for wrought stainless steel pipes were much larger than those for aged cast stainless steel pipes. Consequently, the increases in failure probability due to low-toughness weld-metal cracks were more significant in wrought stainless steel pipes than for aged cast stainless steel pipes.

For the ferritic pipes, the failure probabilities were also found to be larger for cracks in weld metal than those for cracks in base metal due to the slightly lower toughness of the weld metal. These were observed for PWR-2, PWR-4, and PWR-6 pipes that are made of ferritic materials (see Figs. 5.39, 5.40, 5.43, 5.44, 5.47, and 5.48). Similar observations were also made based on the BWR pipe system analysis.

As before, when a random crack location is considered, with the probability being 2/3 for cracks in base metal and 1/3 for cracks in weld metal or fusion line, the weighted average of the failure probabilities given in the referenced figures was obtained. The conditional failure probability calculated as a function of leak rate for random crack locations is provided in Figures 5.49 to 5.54 for six through-wall-cracked PWR pipes considered in this study. Comparisons of the conditional failure probabilities indicate that the wrought stainless steel pipes are more reliable than either the aged cast stainless steel or the ferritic pipes for the same size leaking crack.

Figure 5.55 shows several plots of conditional probability of failure (random crack location) for a given leak rate of 3.785 l/min (1 gpm) as a function of diameter of PWR pipes with LBB detectable flaw size obtained for both 100 and 50 percent of Service Level A stresses. They also indicate that the conditional failure probability decreases with increase in pipe diameter for both austenitic (cast stainless steel) and ferritic materials. However, it appears that the effects of pipe diameter are more pronounced when the normal operating stresses are low and the pipe material is ferritic.

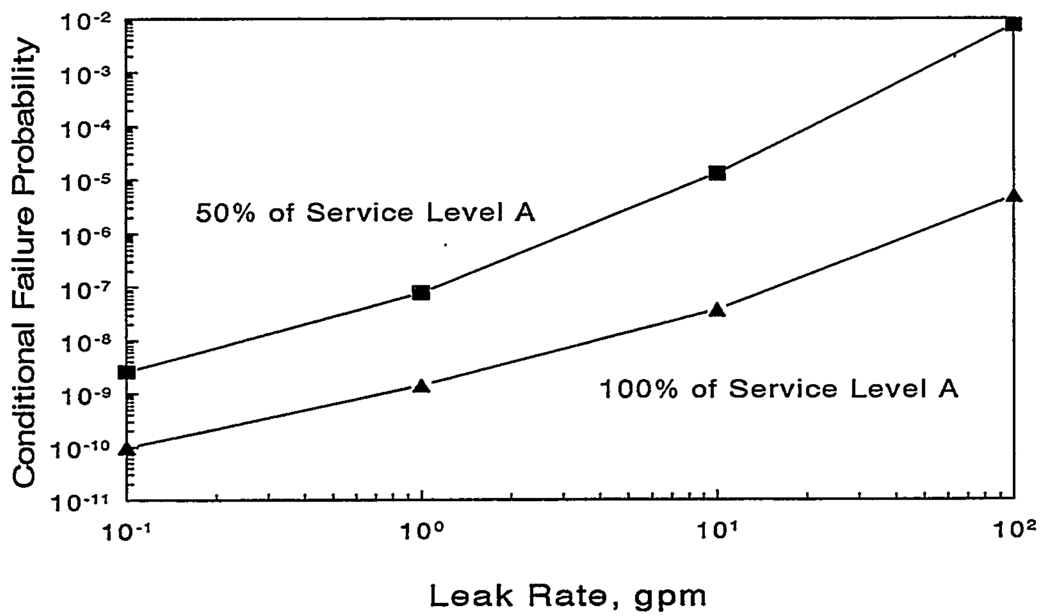


Figure 5.37 Conditional failure probability for PWR-1 (base metal)

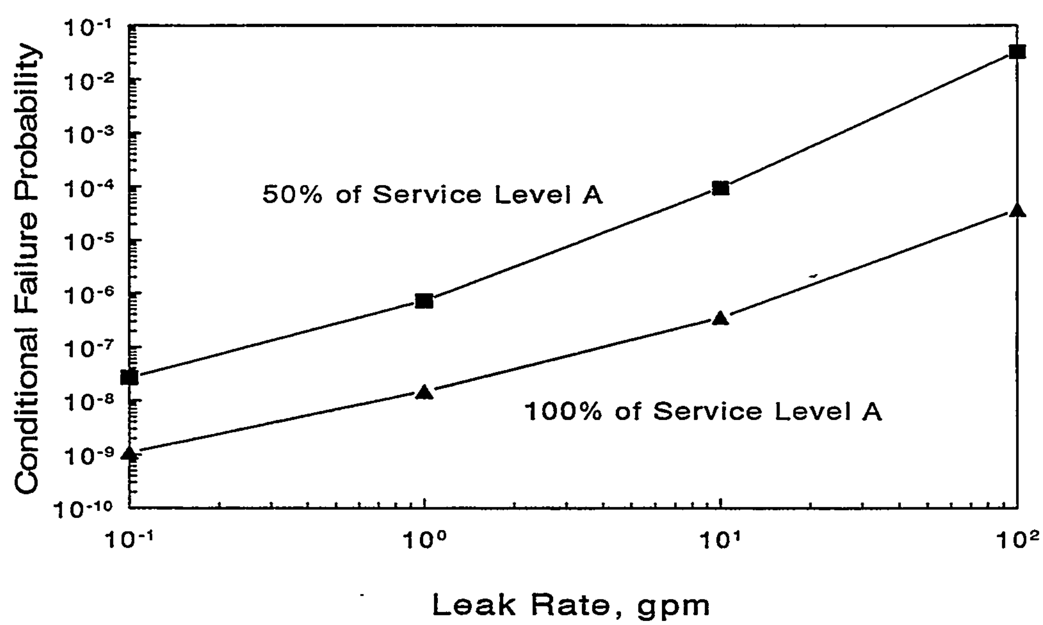


Figure 5.38 Conditional failure probability for PWR-1 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.37/F5.38

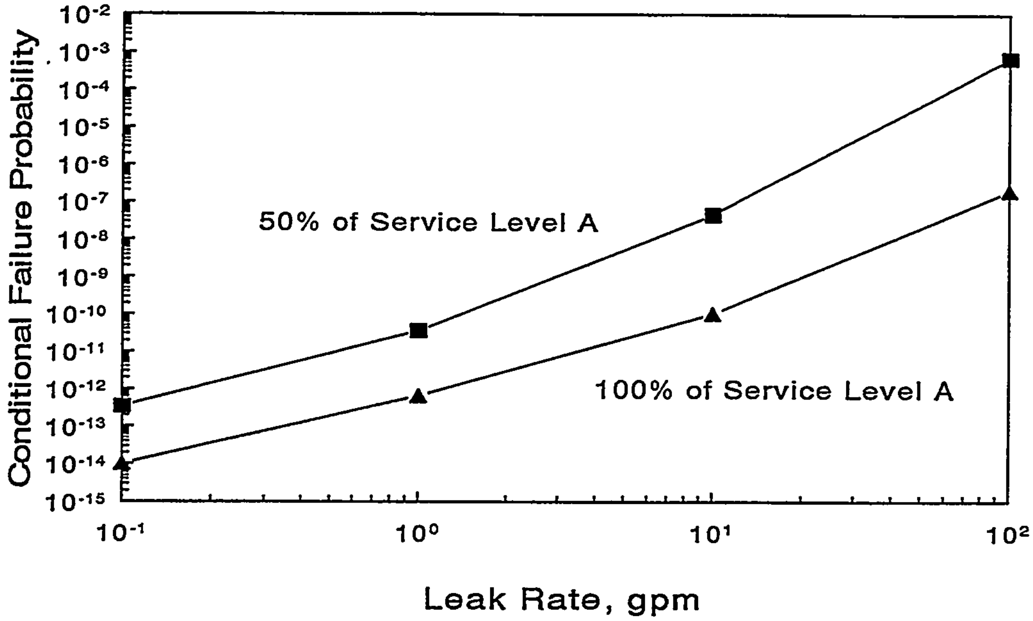


Figure 5.39 Conditional failure probability for PWR-2 (base metal)

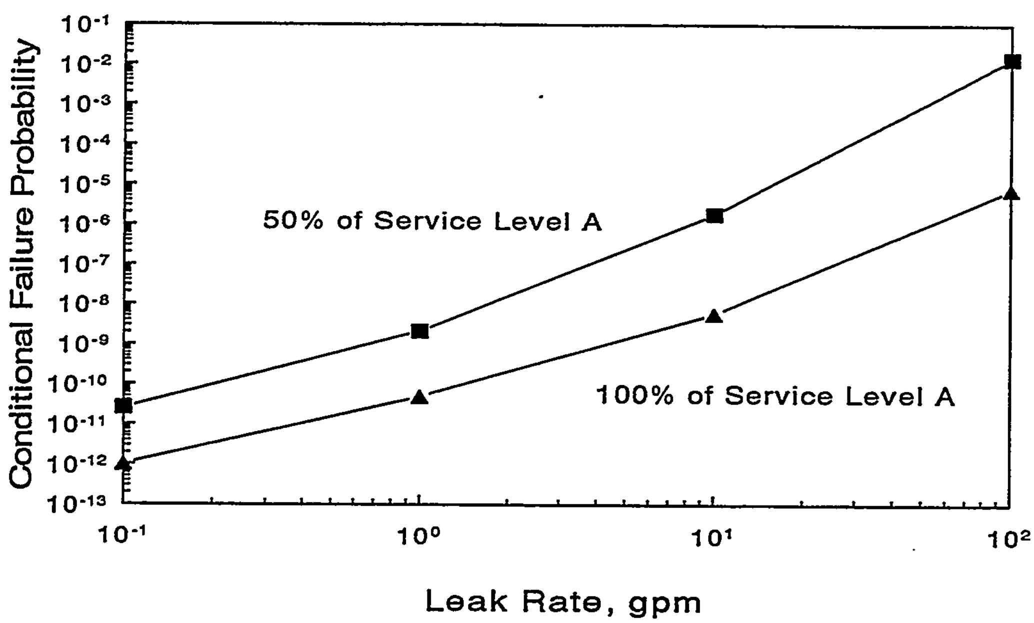


Figure 5.40 Conditional failure probability for PWR-2 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.39/F5.40

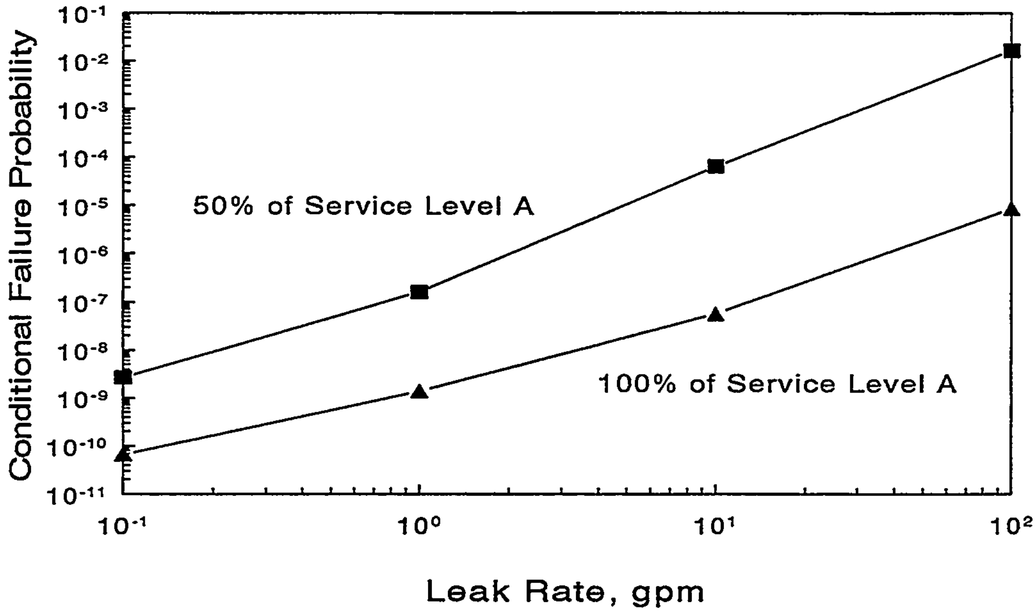


Figure 5.41 Conditional failure probability for PWR-3 (base metal)

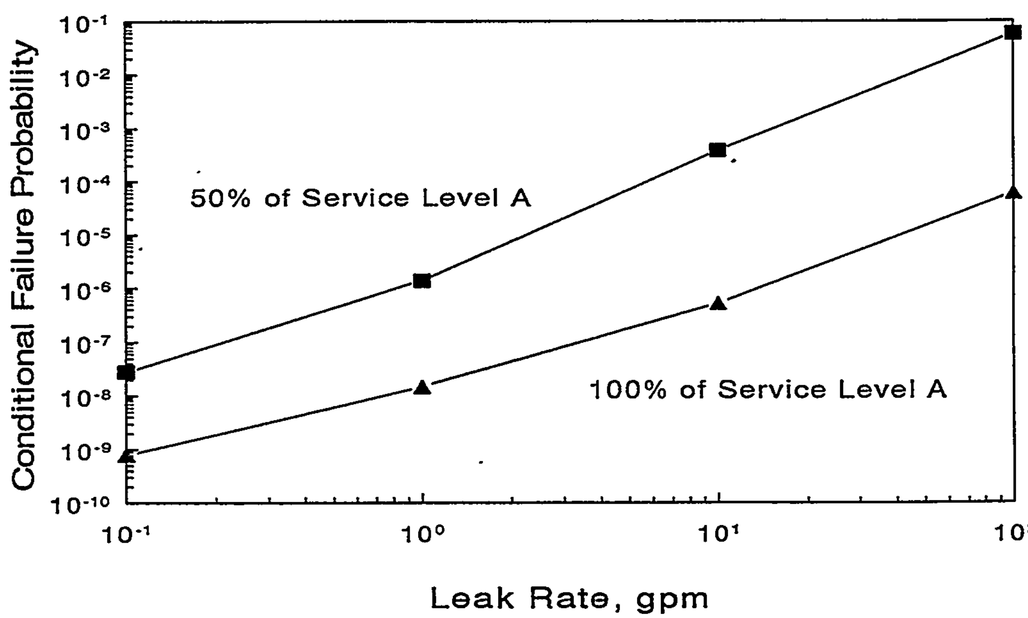


Figure 5.42 Conditional failure probability for PWR-3 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.41/F5.42

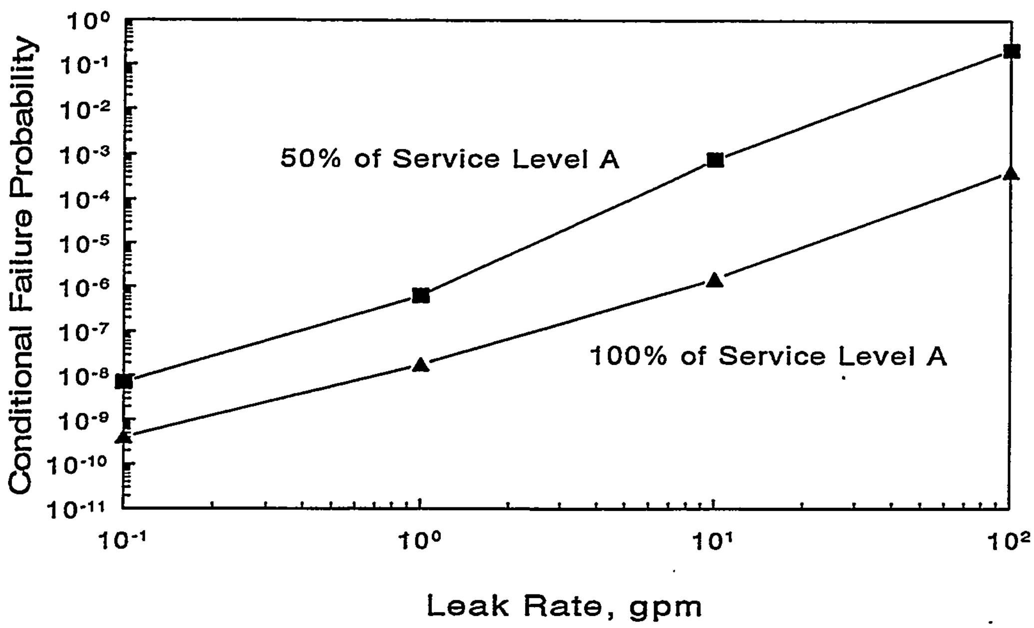


Figure 5.43 Conditional failure probability for PWR-4 (base metal)

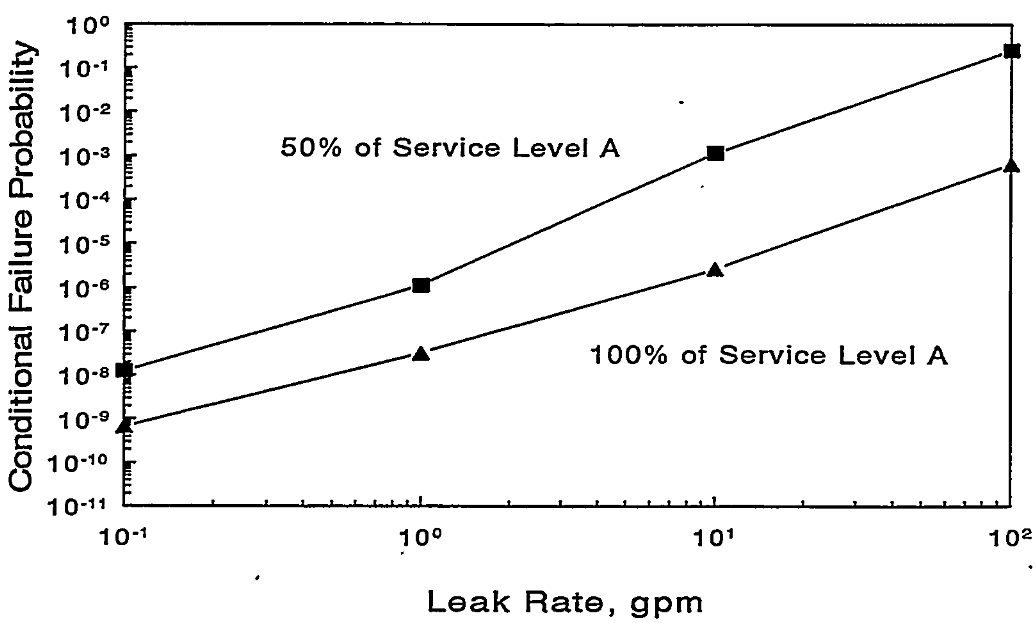


Figure 5.44 Conditional failure probability for PWR-4 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.43/F5.44

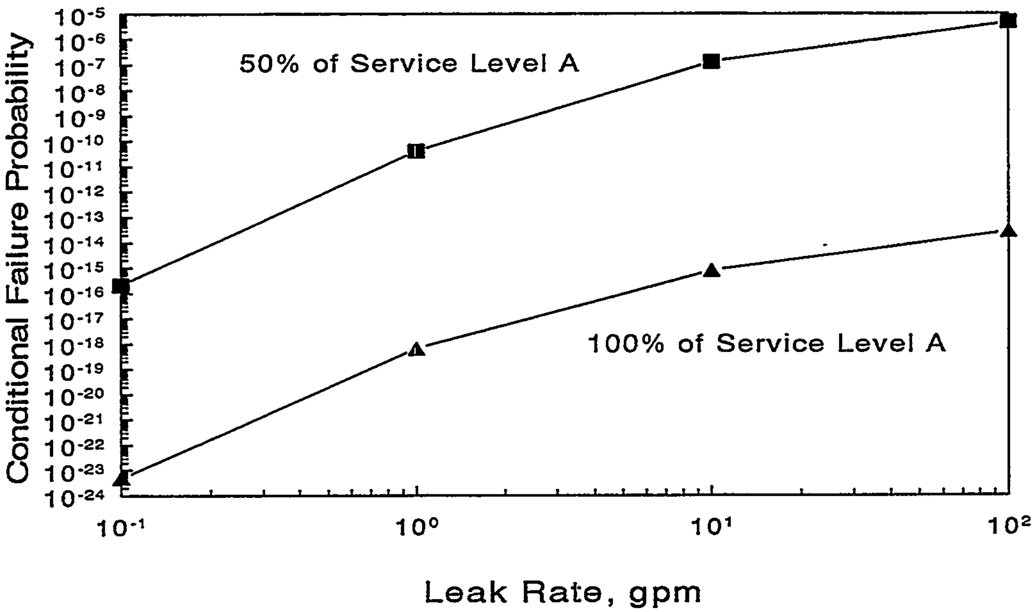


Figure 5.45 Conditional failure probability for PWR-5 (base metal)

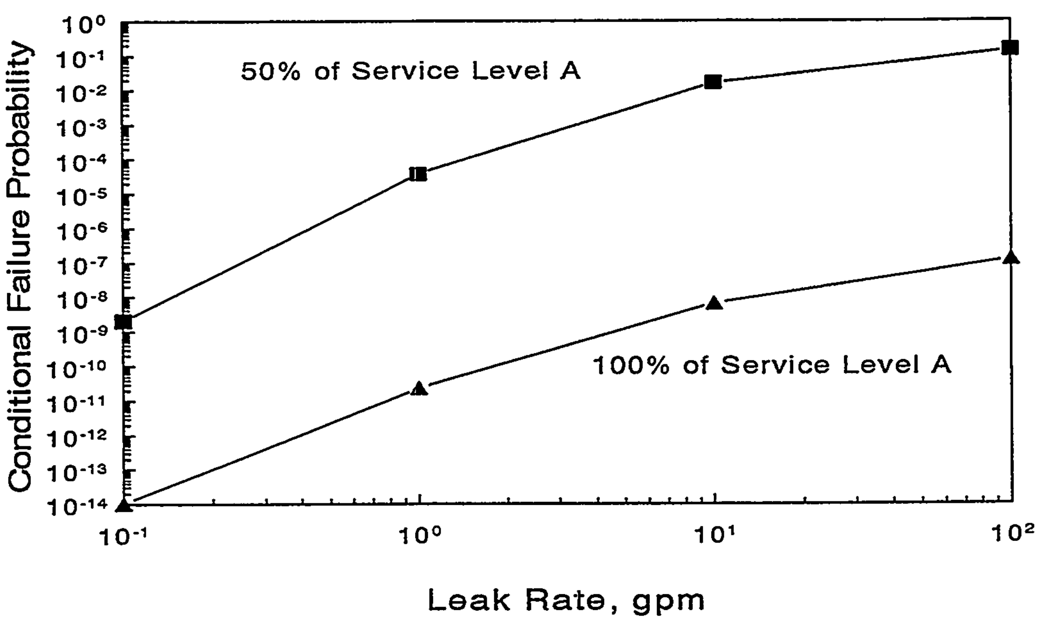


Figure 5.46 Conditional failure probability for PWR-5 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.45/F5.46

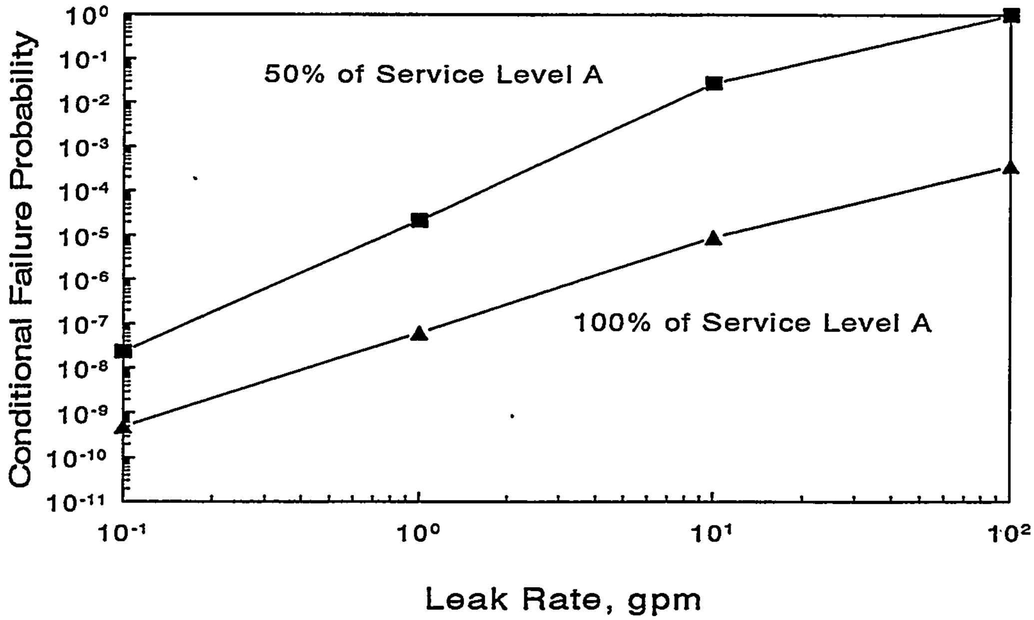


Figure 5.47 Conditional failure probability for PWR-6 (base metal)

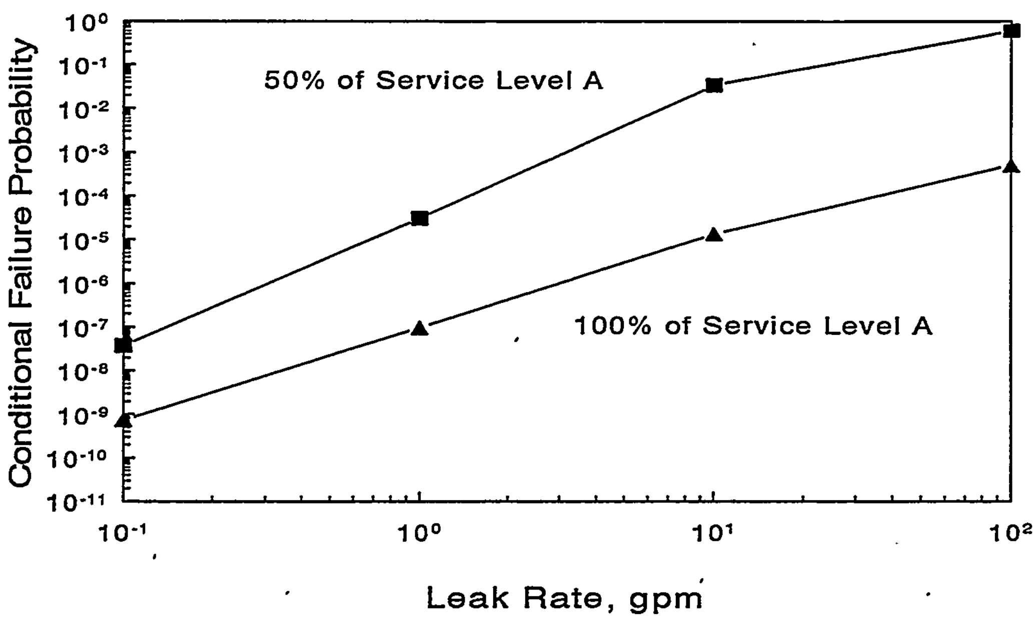


Figure 5.48 Conditional failure probability for PWR-6 (weld metal)
Note: 1 gpm = 3.785 l/min

T-6004-F5.47/F5.48

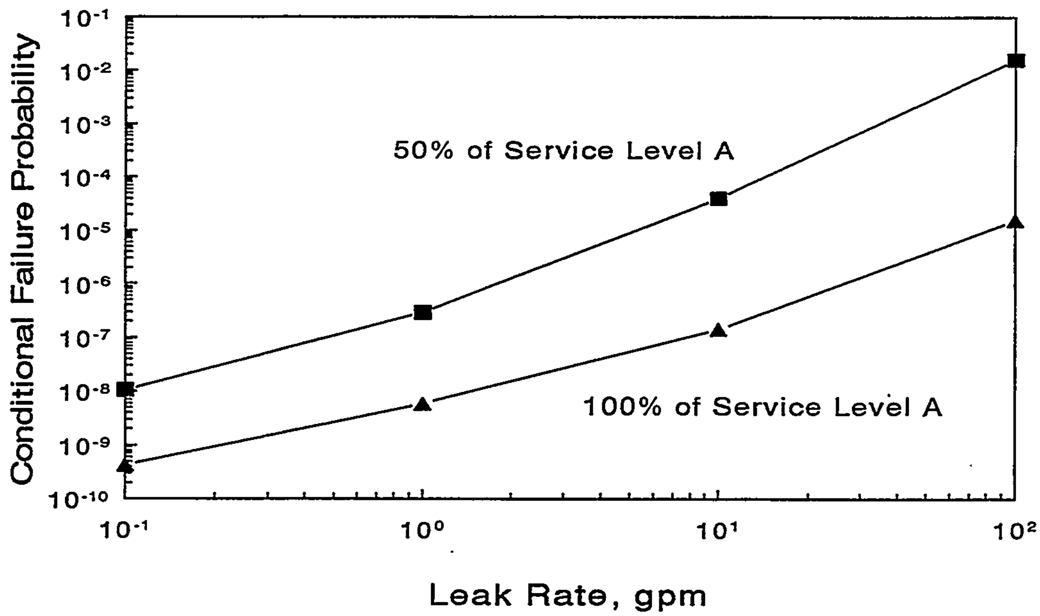


Figure 5.49 Conditional failure probability for PWR-1 (random crack location)

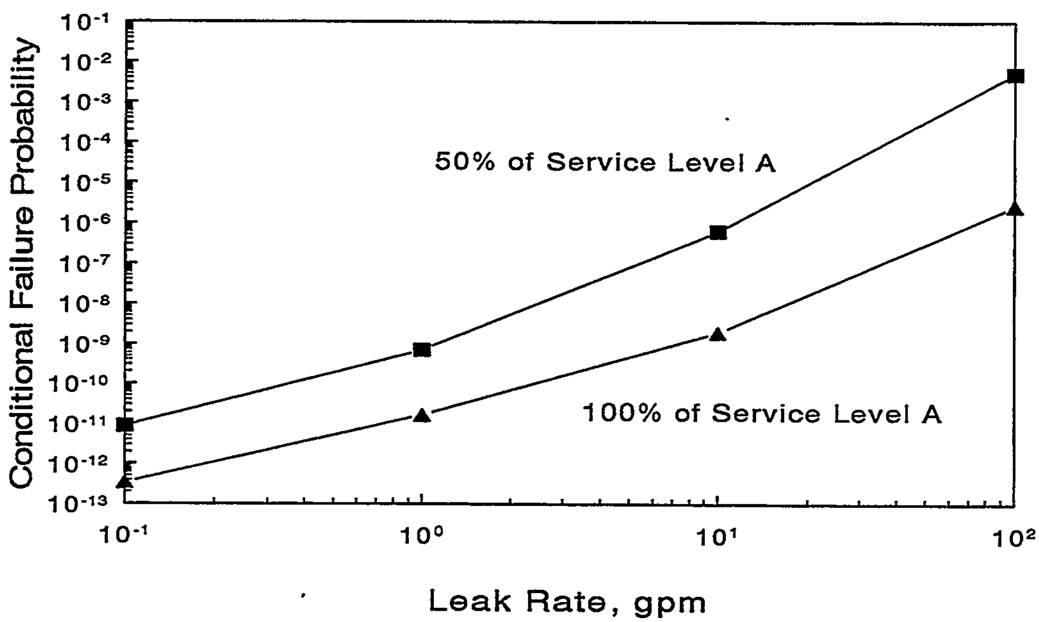


Figure 5.50 Conditional failure probability for PWR-2 (random crack location)
Note: 1 gpm = 3.785 l/min

T-6004-F5.49/F5.50

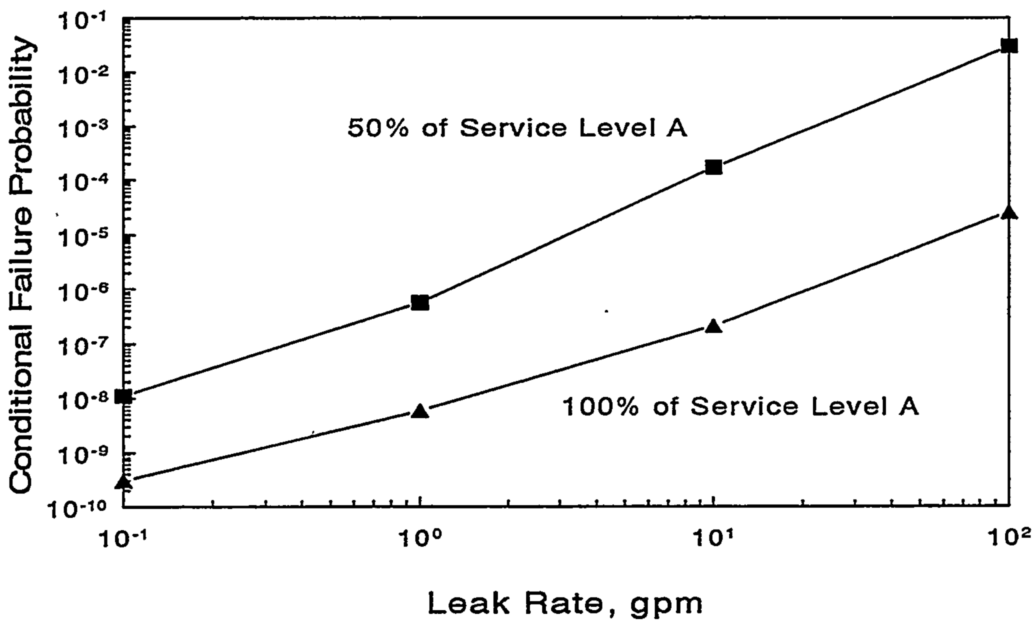


Figure 5.51 Conditional failure probability for PWR-3 (random crack location)

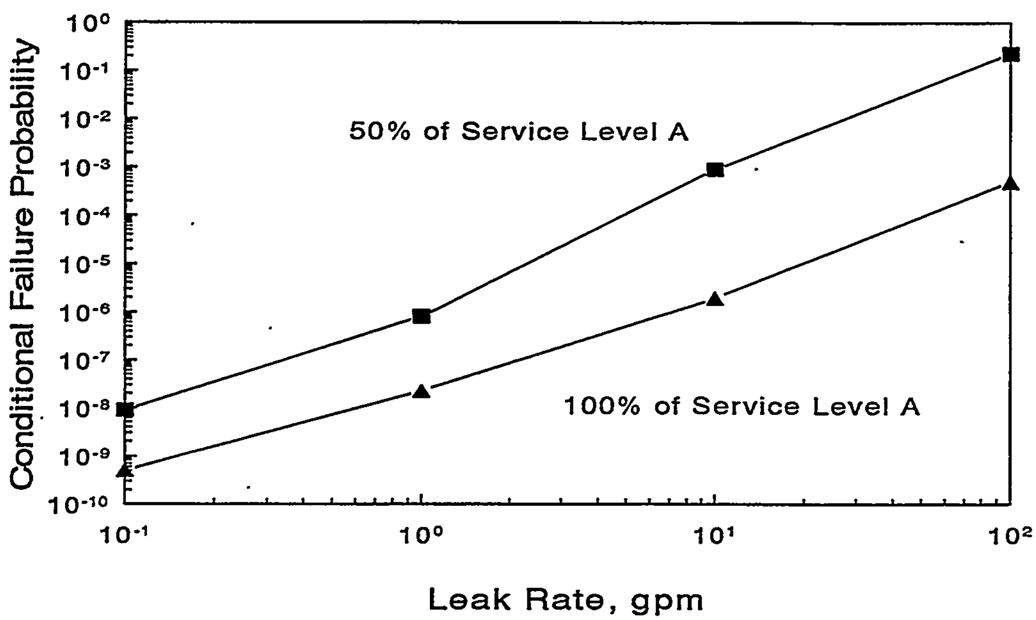


Figure 5.52 Conditional failure probability for PWR-4 (random crack location)
Note: 1 gpm = 3.785 l/min

T-6004-F5.51/F5.52

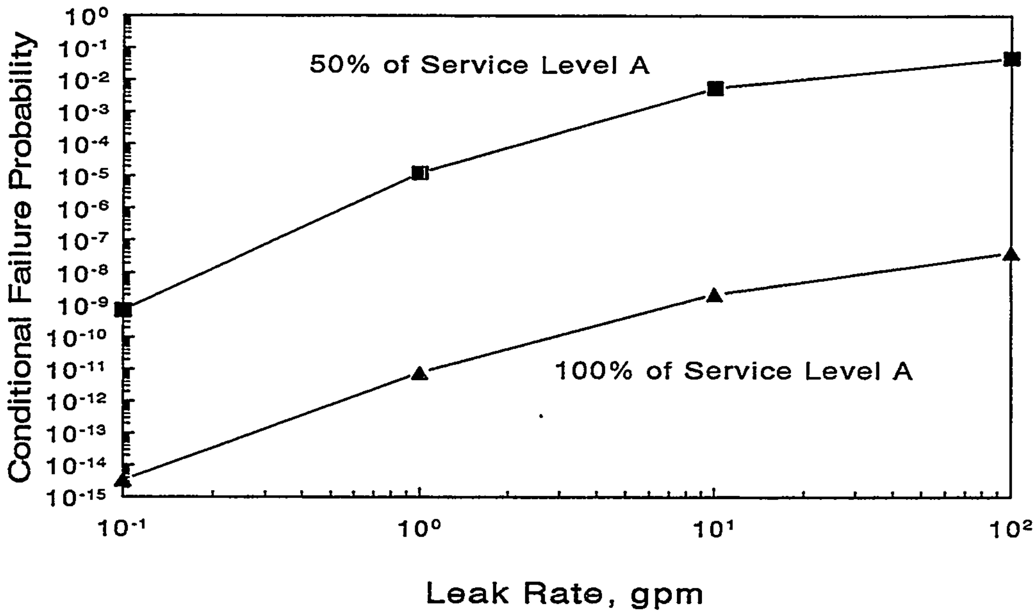


Figure 5.53 Conditional failure probability for PWR-5 (random crack location)

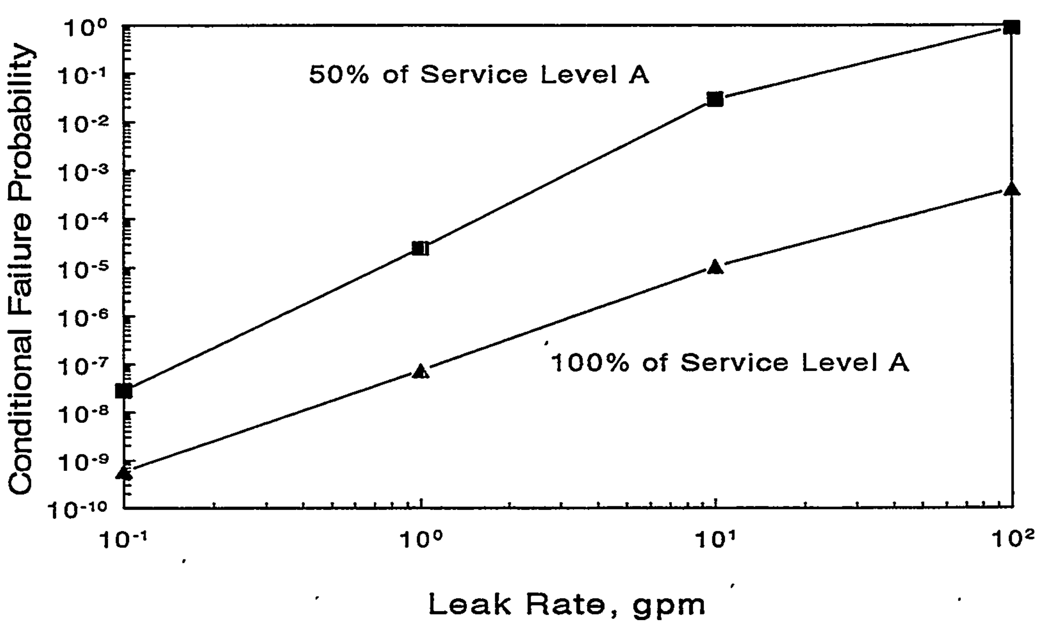
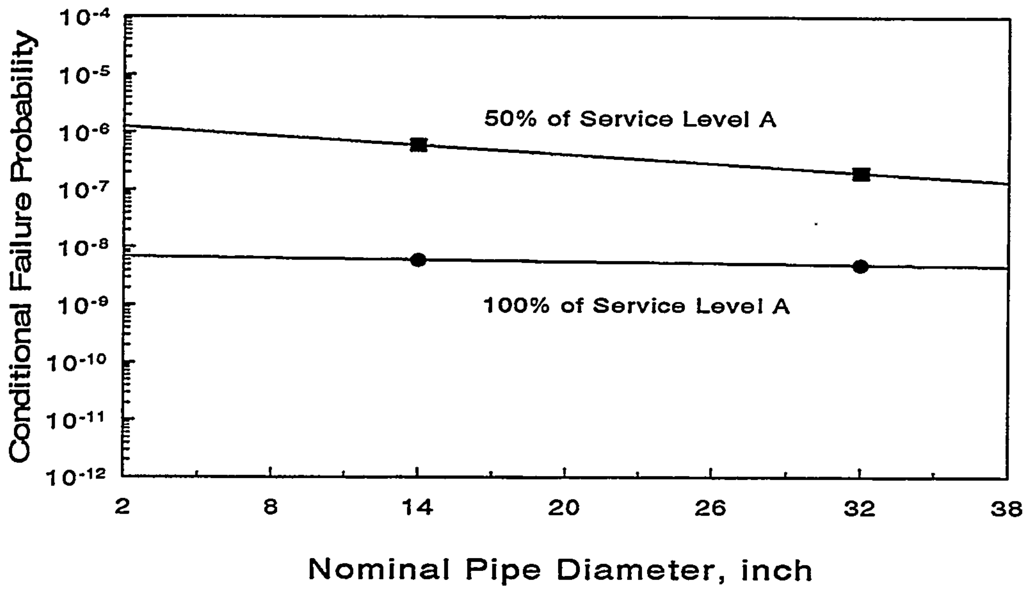
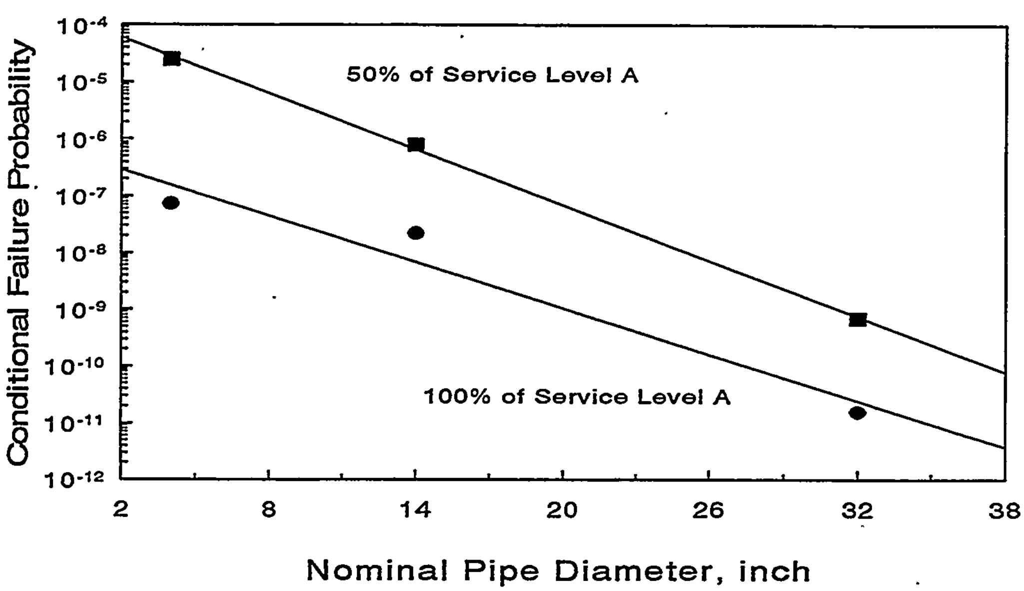


Figure 5.54 Conditional failure probability for PWR-6 (random crack location)
Note: 1 gpm = 3.785 l/min

T-6004-F5.53/F5.54



(a) Aged Cast Stainless Steel Pipes



(b) Ferritic Pipes

Figure 5.55 Conditional failure probability at 3.785 l/min (1 gpm) leak rate versus diameter in through-wall-cracked PWR pipes

T-6004-F5.55

As noted for the BWR calculations, it was assumed that the small diameter austenitic pipe had flux welds. If they have TIG welds, then the failure probability would decrease, i.e., the TIG weld failure probability would be closer to the base metal failure probability for Case PWR-5.

6.0 DISCUSSIONS ON THE APPLICATIONS OF RESULTS

6.1 Introduction

In Section 4 of this report, a new probabilistic model was developed to determine the conditional failure probability of nuclear piping subjected to normal plus safe-shutdown earthquake loads. The model was applied to compute the failure probability for six through-wall-cracked and four complex-cracked BWR pipes and six through-wall-cracked PWR pipes. In Section 5, plots of conditional probability of failure versus leak rate were developed for several cases of normal operating loads (percentages of Service Level A stresses). In this section, examples illustrating potential applications of these results are discussed. The specific procedure for regulatory evaluations will be determined by the NRC and is not in this report.

6.2 Calculation of Leak Rate

When the actual normal operating stress in a pipe and the leak-rate detection capability of existing equipment are known, the results generated in Section 5 can be used to calculate the conditional probability of failure of that pipe. This probability is conditional on (1) the pipe leaking with absolute certainty, and (2) at the same time, an earthquake occurring at least once during the plant lifetime with the N+SSE stresses close to the Service Level B stress limits. An inverse problem is to determine the leak-rate detection capability that will correspond to an acceptable (target) value of the conditional probability of failure. Figure 6.1 shows a schematic for calculating such a leak rate for a generic target conditional probability of failure, p_0.

For a quantitative assessment of the required leak rates, it is required to know what acceptable values of probability of failure, p_0, one should use. In a risk-based approach, there are several methods to determine p_0. For example, p_0 can be obtained from expert opinion and experience from historical failure rates of piping systems in existing power plants (Refs. 88 to 95). Another method is performing probabilistic analyses of NRC-approved actual pipes that were found to be LBB acceptable. If such pipes exist (BWR and/or PWR), the probabilistic model developed in this study can be applied to determine the conditional failure probability of this pipe. This failure probability can then be defined as the acceptable conditional probability of failure from which the leak-rate requirements for any given pipe can be determined.

Nevertheless, the actual evaluation of target failure probability is not an easy task. Currently, various opinions exist in piping reliability studies for assigning acceptable values of conditional failure probability and they may also vary considerably. This report is focussed on developing methodologies to conduct probabilistic pipe fracture evaluations that can potentially be used for leak-rate detection applications. The specific procedure and guideline for regulatory evaluations will be determined by NRC and are not discussed in this report.

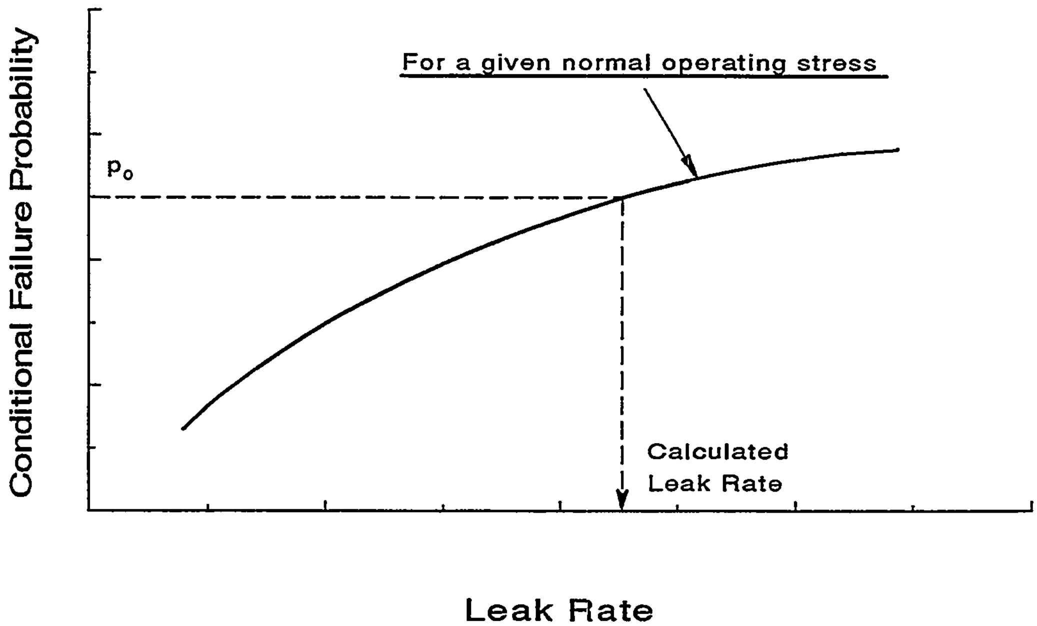


Figure 6.1 Schematic calculation of a leak rate for an acceptable conditional probability of failure

F6004-F6.1

6.3 Comparisons of Results for BWR and PWR Piping

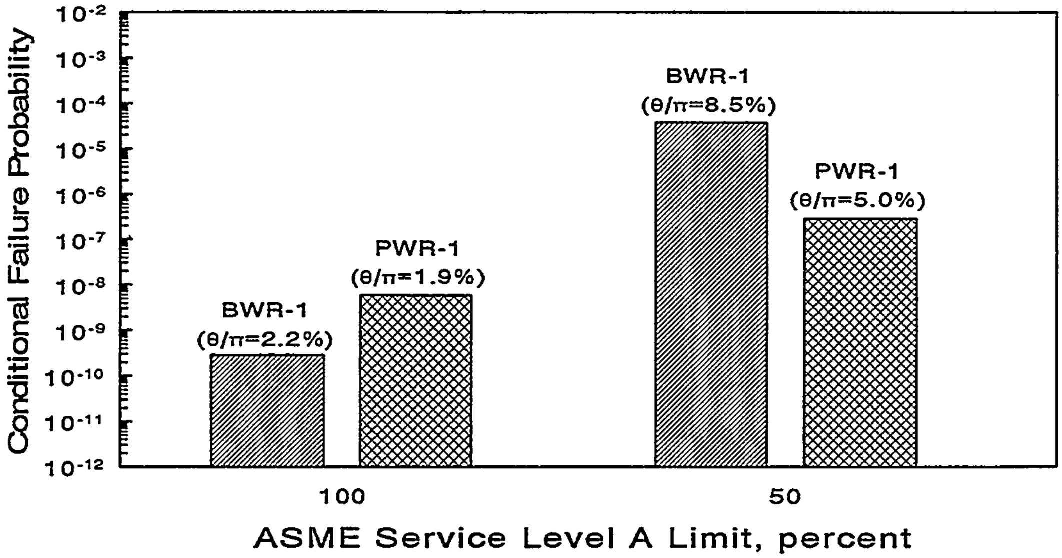
The conditional failure probabilities presented in Section 5 were analyzed to determine any differences in the results for the BWR and the PWR pipe systems considered in this study. The failure probabilities were compared for two large-diameter austenitic pipe cases, BWR-1 and PWR-1, and two large-diameter ferritic pipe cases, BWR-2 and PWR-2. Figure 6.2 shows the comparisons of conditional failure probabilities for these pipes as a function of normal operating stresses measured in terms of a percentage of the ASME Service Level A stress limit. These plots are made for random crack locations at 3.785 l/min (1 gpm) leak rate and are shown in Figures 6.2(a) and 6.2(b) for austenitic and ferritic pipes, respectively. From Figure 6.2(a), it appears that the failure probability of the PWR-1 pipe is larger than that of the BWR-1 pipe when the normal operating stress is 100 percent of the ASME Service Level A stress limit. This is mainly due to the reduction of the fracture toughness in aged cast stainless steel pipe (PWR-1) when compared with the toughness of wrought stainless steel (BWR-1) pipe. Note that this was observed in spite of the smaller value of mean crack size (of an initially leaking crack) in PWR-1 pipe also shown in Figure 6.2(a). However, when the normal operating stress is 50 percent of the ASME Service Level A stress limit, the opposite trend was observed. One reason may be due to the large difference in the mean values of the initial flaw size shown in Figure 6.2(a). Also, the outer diameter of the PWR-1 pipe (D_0 = 812.8 mm [32 inches]) is slightly larger than that of the BWR-1 pipe (D_0 = 711.2 mm [28 inches]) and hence, some diameter effects, which were discussed earlier, may also contribute to lowering conditional failure probability of the PWR-1 pipe.

Figure 6.2(b) shows similar plots comparing the conditional failure probabilities of two ferritic pipes, BWR-2 and PWR-2. In this case, the failure probabilities for PWR-2 pipe were consistently lower than those for BWR-2 pipe, regardless of the magnitude of the normal operating stress. Since the material properties of both BWR-2 and PWR-2 are identical (for both base and weld metals), the lower failure probabilities for PWR-2 pipe are due to the smaller values of mean crack size and diameter effects discussed earlier.

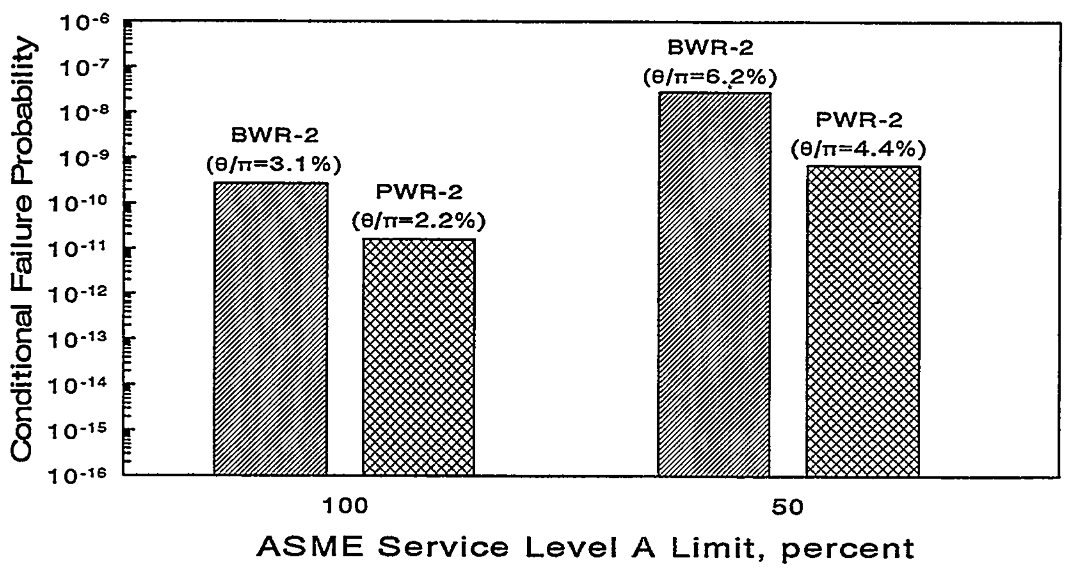
Figure 6.3 shows the comparisons of conditional failure probabilities of BWR ferritic pipes at 18.925 l/min (5 gpm) and PWR ferritic pipes at 3.785 l/min (1 gpm), for random crack locations. These are the current unidentified maximum leak rates for BWR and PWR plants. The failure probabilities at 18.925 l/min (5 gpm) were estimated by linear interpolation of results at 3.785 l/min (1 gpm) and 37.85 l/min (10 gpm) leak rates presented earlier. The conditional failure probabilities are plotted as functions of nominal pipe diameter for both 100-percent and 50-percent of Service Level A stress limits and are shown in Figures 6.3(a) and 6.3(b), respectively. It appears that the PWR failure probabilities are lower than the BWR failure probabilities regardless of the pipe diameter and the magnitude of the normal operating stress. This was expected, since the leaking flaw sizes for PWR pipes were much smaller than those for BWR pipes due to the lower value of allowable unidentified leak rates for PWR pipes.

With the information in the various graphs in this report, the PWR leak rate that would give the same failure probability as BWR piping at 18.925 l/min (5 gpm) was determined, and the BWR leak rate that gave the same failure probability as the PWR piping at 3.785 l/min (1 gpm) was determined. Tables 6.1 and 6.2 show the calculated leak rates for ferritic PWR and BWR piping, respectively, at 50-percent and 100-percent of Service Level A stresses for random crack locations. Results from Tables 6.1 and 6.2 suggest that the PWR leak rates are much higher than the BWR leak rates to maintain the same values of conditional failure probability.

From the above results, it appears that the reliability would strongly depend on the pipe-specific material properties and geometric characteristics, crack-morphology for determining the size of the leaking crack, and the applied normal operating stresses. For a specific case, when the detectable leak rate is 18.925 l/min (5 gpm) for BWR and 3.785 l/min (1 gpm) for PWR, the conditional failure probabilities for PWR ferritic pipes were lower than those of BWR ferritic pipes. Also, comparisons of the calculated leak rates suggest that PWR allowable leak rates could be much higher than BWR leak rates for the same conditional failure probability.



(a) Austenitic pipe cases BWR-1 and PWR-1



(b) Ferritic pipe cases BWR-2 and PWR-2

Figure 6.2 Comparisons of conditional failure probabilities (total) of BWR and PWR pipes for random crack location and 3.785 l/min (1 gpm) leak rate (θ/π values are mean crack lengths)

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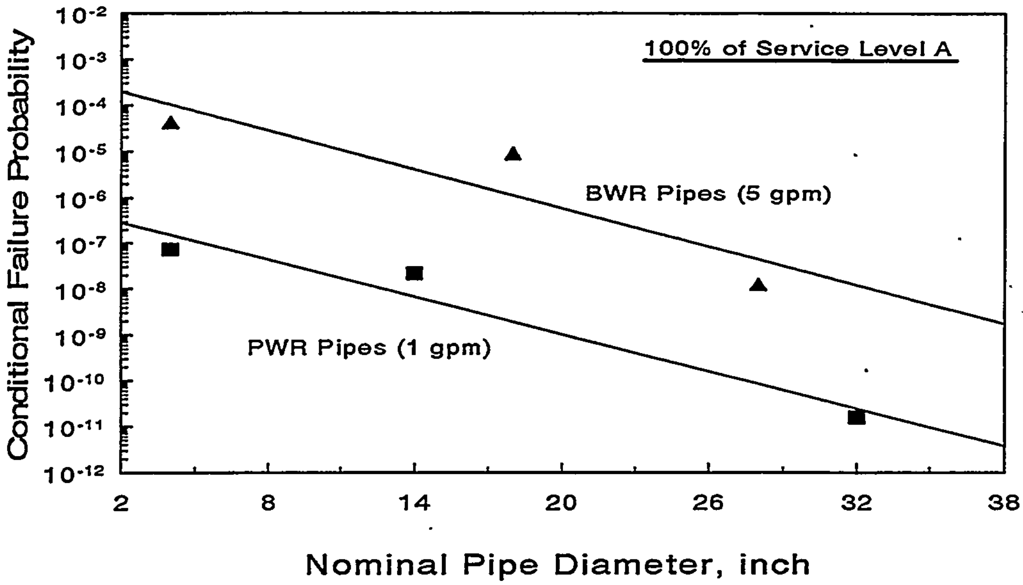
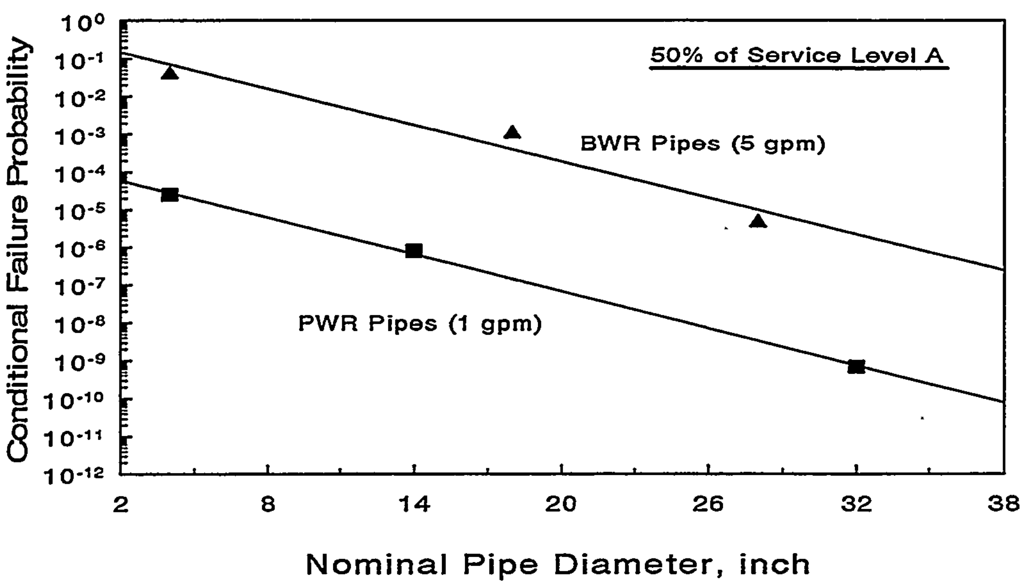


(a) 100-percent of Service Level A



(b) 50-percent of Service Level A

Figure 6.3 Comparisons of conditional failure probabilities (total) of BWR ferritic pipes at 18.925 l/min (5 gpm) and PWR ferritic pipes at 3 .785 l/min (1 gpm) with random crack locations

T-6004-F6.3

Table 6.1 Calculated leak rates for PWR ferritic pipes corresponding to the same conditional failure probabilities as BWR ferritic pipes at 18.925 l/min (5 gpm) (random crack location)[(a)]

PWR pipes	Conditional failure probability of corresponding BWR pipes	Calculated Leak Rate, gpm
	(a) 50-percent of ASME Service Level A stress	
PWR-2	5.17×10^{-6}	17.11
PWR-4	1.19×10^{-3}	11.23
PWR-6	4.50×10^{-2}	13.37
	(b) 100-percent of ASME Service Level A stress	
PWR-2	1.28×10^{-8}	18.24
PWR-4	9.11×10^{-6}	19.15
PWR-6	4.24×10^{-5}	24.05

(a) 1 gpm = 3.785 l/min

Table 6.2 Calculated leak rates for BWR ferritic pipes corresponding to the same conditional failure probabilities as PWR ferritic pipes at 3.785 l/min (1 gpm) (random crack location)[(a)]

BWR pipes	Conditional failure probability of corresponding PWR pipes	Calculated Leak Rate, gpm
	(a) 50-percent of ASME Service Level A stress	
BWR-2	7.02×10^{-10}	0.21
BWR-4	7.97×10^{-7}	0.25
BWR-6	2.45×10^{-5}	0.28
	(b) 100-percent of ASME Service Level A stress	
BWR-2	1.63×10^{-11}	0.22
BWR-4	2.25×10^{-8}	0.18
BWR-6	7.32×10^{-8}	0.21

(a) 1 gpm = 3.785 l/min

6.4 Assessment of Current Margins for Leak Rates Due to Crack Morphology Variability

Current deterministic methods for incorporating conservatism into LBB methodology are based on several safety margins. For example, safety margins of 2, $\sqrt{2}$, and 10 are being used on the LBB detectable flaw size, N+SSE stresses, and leak-rate detection, respectively. These margins, which are established based on engineering judgement, do not currently have any explicit correlation with failure probabilities of piping systems. In this study, the adequacy of the current margin of 10 used for leak rates was evaluated by explicitly considering the statistical variability of crack morphology variables.

Consider the stainless steel pipe BWR-1 with IGSCC under normal operating stresses. The probabilistic characteristics of the crack morphology variables for this cracking mechanism can be obtained from Section 3. Using the program PSQUIRT, the above crack morphology variables were randomly generated according to their probability distribution functions, and the corresponding leak rates were calculated under a given normal operating stress. Figure 6.4 shows the histogram of the leak rate obtained from 1000 calculations when the normal operating stress is 50 percent of the Service Level A limit. The mean and standard deviation of the leak rate were estimated to be 4.58 l/min (1.21 gpm) and 1.55 l/min (0.41 gpm), respectively. Figure 6.5 shows the histogram of leak rates from 1000 samples when the normal operating stress is 100 percent of the Service Level A limit. Similar histograms were also generated for another carbon steel pipe BWR-2 with the cracking mechanism governed by corrosion fatigue. The histograms shown in Figures 6.6 and 6.7 correspond to the normal operating stress being 50 percent and 100 percent of the Service Level A limit, respectively.

Using the histograms shown in Figures 6.4 to 6.7, one can determine various upper fractiles (percentiles) of leak rate corresponding to any desired probability level. These fractiles provide convenient descriptions of leak rate, which can be used to define safety margins in a deterministic analysis. From probability theory, the X-percent upper fractile of the leak rate is defined as the value of leak rate that has X/100 probability of exceedance. As an example, the 2-percent upper fractile of the leak rate determined from the above histograms are shown in Figures 6.4 to 6.7. Using those leak rates that have 2-percent probability of exceedance, the margin accounting for crack-morphology variability and the residual margin were calculated [(a)]. It appears that the calculated margins, corresponding to a leak rate that has a 2-percent probability of exceedance, were 1.85 to 2.25 to account for the crack-morphology variability alone. This means that with the current safety margin (total) of 10 being used in LBB applications, a residual margin of 4.44 to 5.39 remains to account for the variability in leak rate detection equipment, actual stresses, and other factors (e.g., restraint of pressure-induced bending at nozzles, see Section 2 of this report).

(a) The margin accounting for the crack-morphology variability is defined as the ratio of the leak rate that has 2-percent probability of exceedance (known as the 2-percent upper fractile) and the mean value of the leak rate. The residual margin is defined as the mean leak rate times current (total) margin of 10 divided by the leak rate that has 2-percent probability of exceedance (2-percent upper fractile).

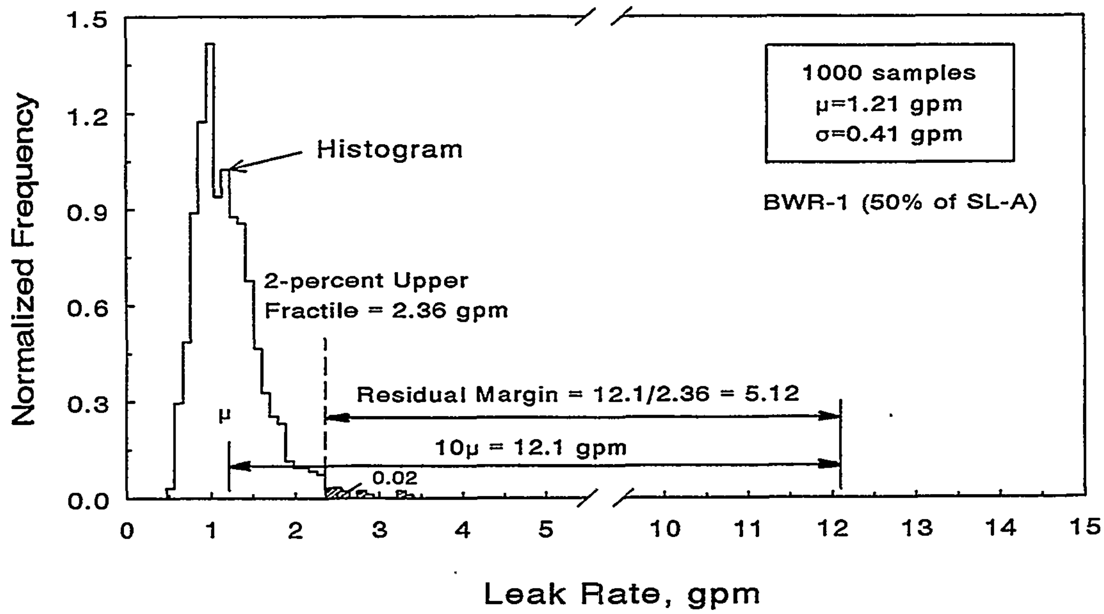


Figure 6.4 Histogram of leak rate under 50 percent of Service Level-A limit for BWR-1

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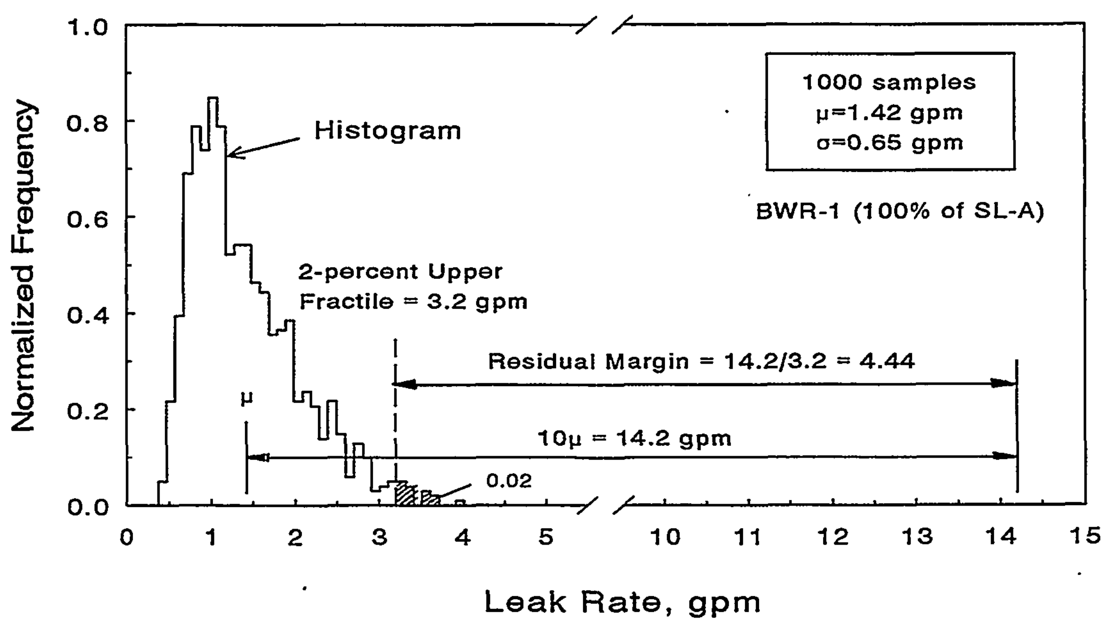


Figure 6.5 Histogram of leak rate under 100 percent of Service Level-A limit for BWR-1
Note: 1 gpm = 3.785 l/min

T-6004-F6.5

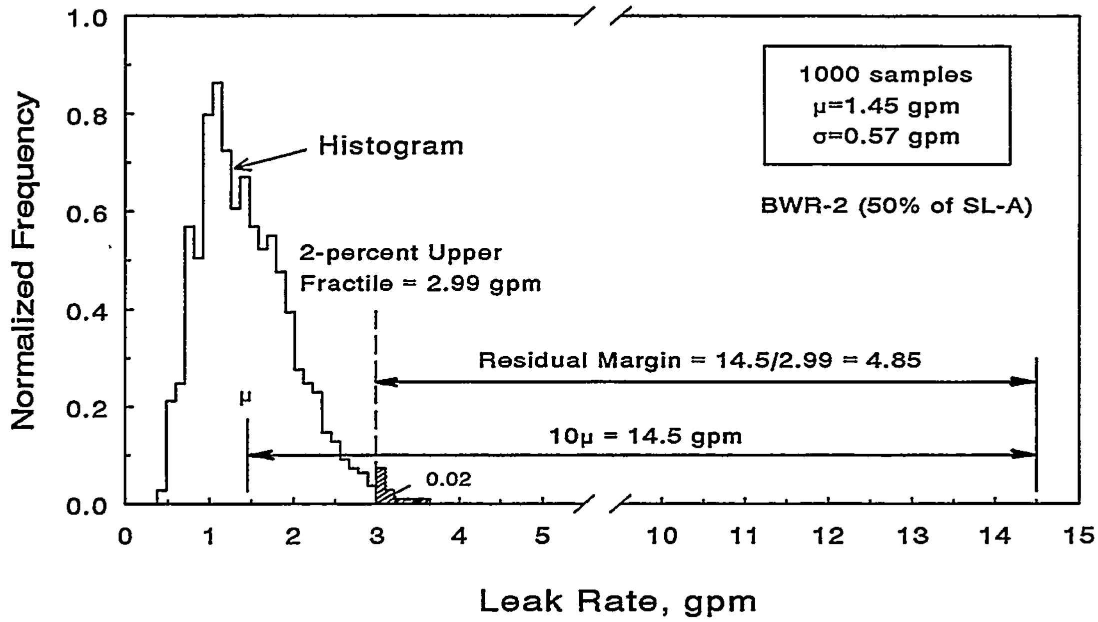


Figure 6.6 Histogram of leak rate under 50 percent of Service Level-A limit for BWR-2

T-6004-F6.6

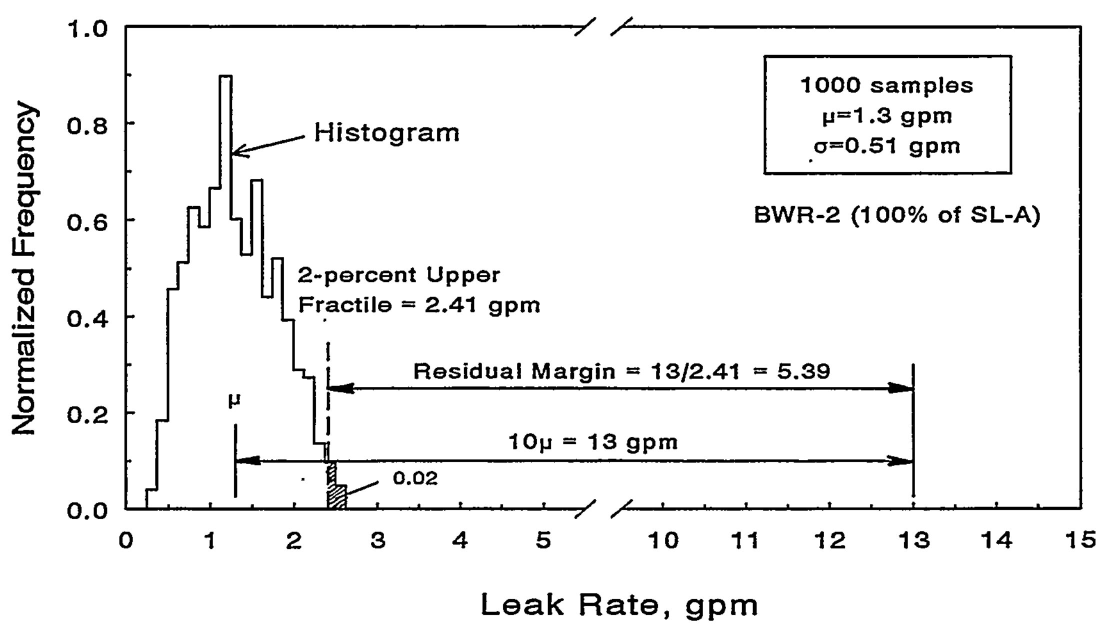


Figure 6.7 Histogram of leak rate under 100 percent of Service Level-A limit for BWR-2
Note: 1 gpm = 3.785 l/min

T-6004-F6.7

7.0 LIMITATIONS TO THE CURRENT MODELS

During the development of the models and the calculations of results presented in this study, we received comments and recommendations from various reviewers of this work. We have already incorporated some of their constructive suggestions. However, there were some areas that were not incorporated into this study. As a result, the following key areas were identified where further improvement could be made in the current deterministic and probabilistic models.

Expansion of Database. The statistical characteristics of material properties, crack morphology variables, and crack location require a substantial amount of data to determine their probabilistic characteristics accurately. If additional data are available or developed, they should be used to verify the statistical properties of input used in this study. In particular, having more service data for crack morphology variables are desired. Thus, more effort should be expended to expand the above databases. These databases should also contain information regarding (1) effects of dynamic and/or cyclic load on quasi-static material properties, and (2) effects of aging on material properties, e.g., statistical properties as a function of aging time. Some of these efforts are underway in other, current, NRC research programs.

Normal Operating Stresses. In this report, we considered normal operating stresses of 50 and 100 percent of the ASME Service Level A limits. Many pipe systems may have lower operating stresses. Hence, it may be desirable to conduct analyses at 25 percent of the Service Level A stress limits, so that graphs of failure probability versus normal operating stress at a given leak rate can be developed.

Normal Plus Safe-Shutdown Earthquake Stresses. The selection of applied N+SSE stresses should be based on actual stresses in nuclear power plants. Obviously, this will require additional effort in conducting explicit linear or nonlinear dynamic analyses of piping configurations subjected to seismic ground acceleration. As an alternative, however, the actual stresses can be compiled from extensive literature surveys from which the N+SSE stresses can be obtained. The data base of N+SSE stresses should be expanded, since it was based on pipe applications for LBB. Other piping may have higher stresses. Also, due to uncertainty in seismic loads, the actual stresses should be treated as random variables or random processes. Thus, more realistic results could be obtained if accurate probabilistic representations of normal and seismically induced stresses are known.

Additionally, if the proposed ASME Section III design stress limits are increased, then there will be a significant change in the failure probabilities. Such analyses would require a more sophisticated nonlinear correction than the one used in this report when stresses calculated under elastic assumptions are above yield.

Restraint of Induced Bending. Current structural analyses of flawed piping systems subjected to axial tension loads (generally pressure induced) assume that the pipe is free to rotate. The restraint of the rotation increases the failure stresses, but can decrease the crack opening at a given load. If the pipe system restrains the bending (i.e., from cracks being close to a nozzle or restraint from the rest of the piping system) then the leak rate will be less than that calculated by using analyses that assume that the pipe is free to rotate. This will cause the actual crack to be larger than that calculated by the current analyses methods for the same leak rate. Since normal operating stresses have a large component of the total stress being the pressure stress, this can have a significant effect on LBB analyses. Results from Section 2 suggest that when the crack angle is small ($\theta/\pi=1/8$), the restraint effects are also small and may be neglected. However, for larger crack angles ($\theta/\pi=1/4$), the restrained COD can be significantly different from the unrestrained COD, and hence, should not be ignored in the crack-opening-area analysis for leak-rate quantification. The mean LBB detectable crack size reported in this study varies from $\theta/\pi = 0.01$ (large diameter pipe) to $\theta/\pi = 0.40$ (small diameter pipe). Thus, the effect of restraint due to induced bending can be important, particularly for small diameter pipes. To use the current deterministic COD analyses, a generalized pipe system restraint function would have to be developed. Also, any effects of restraint on increased load-carrying capacity of pipes should be evaluated and determined if and how this compensates for the COD effect.

Through-Thickness Crack Opening Angle. There are several crack morphology variables not considered in this study. For example, due to an angle of crack opening through the thickness, the interior crack-opening displacement may be significantly larger than the exterior crack-opening displacement possibly from weld residual stresses as shown in Figure 7.1. Another factor that may contribute to larger ID crack-opening is a higher rate of erosion and corrosion damage at the interior surface along the flow path. In the past, Battelle conducted a sensitivity study using the SQUIRT program to determine the effects of crack-opening angle on the leak rate predictions. For a specific crack size with given crack-morphology parameters as base line conditions, the results suggest that for $\pm$10-percent change in the crack-opening angle, the predicted leakage rate would change by $\pm$1.3 percent and $\pm$1.4 percent for a pipe with a wavy and a straight crack, respectively. Parameter ranking based on leak-rate sensitivity for eleven input parameters showed that crack-opening angle could be moderately important for leak-rate analysis, although more studies are needed to make a generic conclusion. The current versions of SQUIRT and PSQUIRT have the option of assigning different values for interior COD and exterior COD. The effects of crack-opening angle through the thickness were not considered in this study.

ID Versus OD Crack Lengths. Another parameter that may be important in leak-rate analysis is the ratio of ID crack length and OD crack length as exhibited in Figure 7.2. The current versions of the SQUIRT and PSQUIRT programs can account for this ratio. Some amount of data may exist in the literature for quantifying this ratio of ID and OD crack lengths. However, we were not able to consider them in this study. A thorough review of cracks found in service would be needed.

Also, when performing fracture calculations, it is difficult to consider the difference in ID and OD crack lengths. The maximum load may be conservatively bounded by using ID crack length, but the leak rate is probably more dependent on the OD crack length. Unless a detailed investigation is conducted, it is difficult to incorporate their resultant effects on the leak rate and the maximum load-carrying capacity of the pipe.

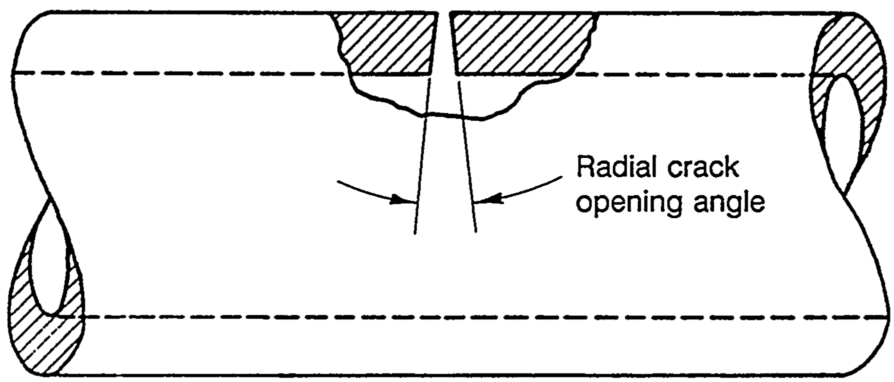
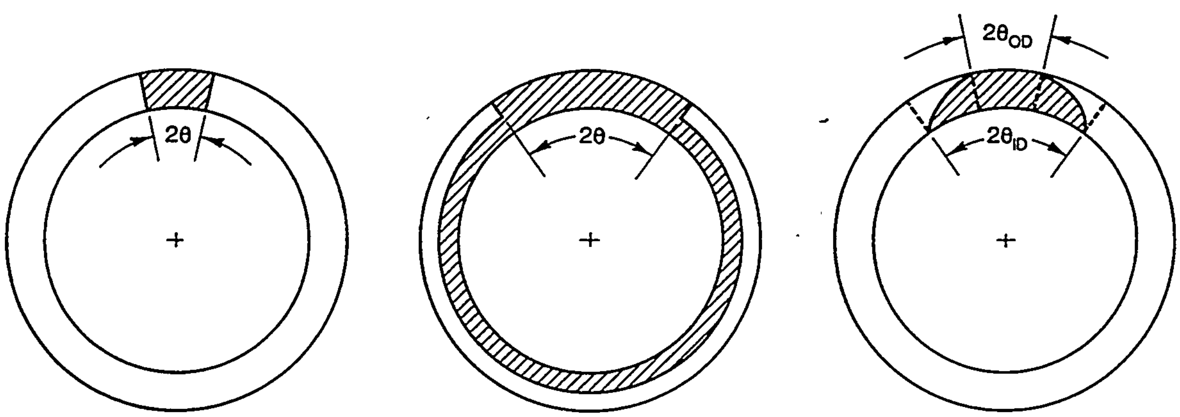


Figure 7.1 Angle of crack opening through the pipe thickness



(a) Through-wall crack (b) Complex crack (c) Real crack

Figure 7.2 ID versus OD crack lengths

T-6004-F7.1/7.2

Off-Center Cracks. According to current pipe fracture evaluations, a through-wall crack is often placed symmetrically with respect to the bending plane of the pipe, see Figure 7.3(a). This is usually justified with the reasoning that the tensile stress due to bending is largest at the center of this symmetrical crack. However, fabrication imperfections will occur randomly around the pipe circumference. Additionally, in the normal operating condition, the pressure component is more significant than the bending component. As such, the postulated leakage flaw may be off-centered and can thus be located anywhere around the pipe circumference, see Figure 7.3(b). Furthermore, the symmetric bending plane under normal operating stresses may be different from that under N+SSE loading. Consequently, there are two major effects on pipe fracture evaluations:

(1) For a given leak rate and identically applied load, the detectable flaw size for the off-centered crack will be larger (due to smaller crack-opening area) than that for the symmetrically centered crack (detrimental effects); and

(2) For the same crack length, the load-carrying capacity of the pipe with an off-centered crack will be higher than that with a symmetrically centered crack (beneficial effects).

Since these are two opposing effects, analytical efforts are needed to determine the resultant effect on the failure probabilities. Currently, the effects of an off-centered crack on the crack-opening area are being evaluated for a TWC pipe under pure bending and will be in another report (NUREG/CR-6300) from the Short Cracks in Piping and Piping Welds program. However, no work is being done on the failure loads of an off-centered crack.

Low-Cycle Fatigue Crack Growth Considerations. Current analyses for pipe flaw evaluations consider seismic loading, but assume the seismic load as a one-time applied load for static analysis. They do not include the potential adverse effects of low-cycle fatigue crack growth during the seismic excitation. Recent results from an ORNL pipe fracture experiment under simulated seismic loading showed that low-cycle fatigue can contribute to significant crack growth and reduction of load-carrying capacity in through-wall-cracked pipes. These findings were also verified by analysis methods developed recently at Battelle for predicting low-cycle fatigue crack growth in a pipe, see Reference 96. Hence, improvements to the accuracy of the conditional failure probabilities could include possible effects due to low-cycle fatigue from the seismic event.

Effects of Residual Stresses on Crack-Opening. One of the frequently asked questions with respect to determination of the crack-opening-displacement for leak-rate analyses is, what is the effect of residual stresses on the crack-opening displacement? Currently, there are no simple estimation analyses to account for the residual stress effects; therefore, they are typically neglected. In this study, no residual stress effects were considered in performing crack-opening-area analyses.

Both simple and computational methods can be applied to evaluate effects of residual stresses on crack-opening area and leak-rate estimations. A computational model usually involves thermo-elastic or thermo-plastic analysis following temperature analysis. On the other hand, a simple model involves simulation of residual stress field prescribed from a suitable database. In both models, however, finite-element analysis is essential for performing crack-opening-area calculations.

Currently, a preliminary study is underway at Battelle to determine the effects of residual stresses on crack-opening in conjunction with the Short Cracks in Piping and Piping Welds program and will be in a separate topical report (NUREG/CR-6300).

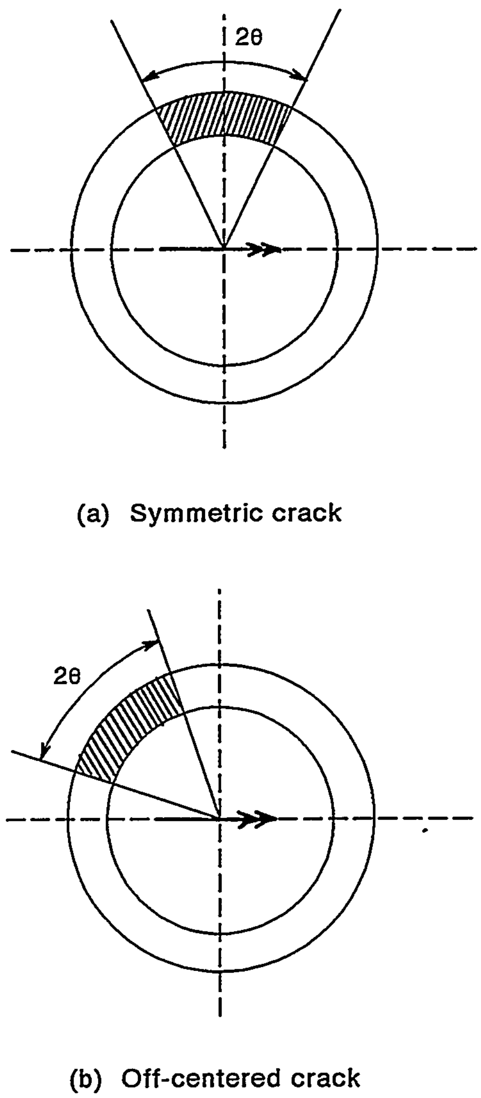


Figure 7.3 Symmetric and off-centered cracks in through-wall-cracked pipes
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8.0 SUMMARY AND CONCLUSIONS

The objective of this study was to conduct probabilistic pipe fracture evaluations for applications to leak-rate detection. It has been accomplished in four distinct stages.

(1) Review of Deterministic Models. A review was conducted to evaluate the adequacy of current models for various deterministic analyses. They included (a) thermal-hydraulic models for estimating leakage, (b) area-of-crack-opening models for determining crack growth (flow area), and (c) elastic-plastic fracture mechanics models for predicting the maximum load-carrying capacity of a piping system. The results predicted from the above deterministic models were compared with those obtained from the experimental data furnished by previous research programs, such as the Degraded Piping Program, International Piping Integrity Research Group Programs, and others. Based on these comparisons, it was concluded that the underlying deterministic models considered in this study provide reasonably accurate estimates of leak rates, area of crack opening, and maximum load-carrying capacity of pipes.

(2) Statistical Characterization of Input. A statistical analysis was conducted to characterize various input variables for thermal-hydraulic analysis and elastic-plastic fracture mechanics. The statistical characterization was performed for (a) crack morphology variables, (b) material properties of pipe, and (c) the location of cracks found in nuclear piping. Searches of NRC's PIFRAC database and data generated by the Degraded Piping and IPIRG Programs have provided a reasonable wealth of data for statistical characterization of strength (stress-strain curves) and toughness (J-resistance curve) properties of base and weld metals typically used in nuclear piping.

The PIFRAC database, which was originally developed at Material Engineering Associates, was updated significantly at Battelle by adding data from other sources. Data were collected from Ontario Hydro, General Electric, Westinghouse, Argonne National Laboratory, Babcock and Wilcox, David Taylor Research Center, and Framatome. Additional data from Battelle's Degraded Piping Program, Short Cracks in Piping and Piping Welds Program, and the IPIRG-1 and IPIRG-2 Programs were also included. From the statistical analyses, mean, covariance, and probability distributions of these random variables were estimated. These statistical properties were used subsequently for probabilistic pipe fracture analyses.

(3) Development of Probabilistic Models. A probabilistic model was developed to evaluate the stochastic performance of piping systems subject to normal operating loads plus safe shutdown earthquake loads. The model was based on a probabilistic extension of current LBB methodology described in NUREG/CR-1061 Volume 3 and the NRC's draft Standard Review Plan, Section 3.6.3. It involved (a) accurate deterministic models for estimation of leak rates, area of crack opening, and maximum load-carrying capacity of pipes, (b) a complete statistical characterization of crack morphology parameters, material property variables, and crack location, and (c) standard methods of structural reliability theory. From this model, the conditional probability of failure of a circumferentially cracked pipe based on the exceedance of its maximum load-carrying capacity can be predicted. These probabilities determine the performance of degraded piping systems subject to N+SSE loads considering statistical variability of various input parameters. The model developed

here is versatile. It can be easily adapted when additional uncertain parameters are required to be included in the description of any relevant performance criteria.

(4) Applications to BWR and PWR Piping. The probabilistic model was applied to sixteen nuclear piping systems in Boiling Water Reactors and Pressurized Water Reactors for calculating conditional probabilities of failure. Numerical examples highlighting various merits of the proposed models in terms of accuracy and computational effort were provided. The results showed that reliability methods, such as FORM, SORM, and Importance Sampling, can provide accurate estimates of piping reliability with much less computational effort when compared with those obtained from the direct Monte Carlo simulation. Several pipe sizes, ranging in diameter from 101.2 mm (4 inches) to 812.8 mm (32 inches), and several pipe materials, including wrought stainless steel, carbon steel, and cast stainless steel and their respective welds, were considered for determining the conditional probability of failure. The results showed that:

- For the same leaking crack size, the conditional failure probability of wrought stainless steel pipes was much lower than that for carbon steel pipes in both BWR and PWR plants, particularly when the crack was located in the base metal.

- Due to a significant reduction in the toughness properties of the weld metal compared with the base metal of wrought stainless steel pipes, the conditional probability of failure for cracks in weld metal was much larger than that for cracks in base metal. Also, for the ferritic pipes, the failure probabilities were larger for cracks in weld metal than those for cracks in base metal due to the slightly lower toughness of the weld metal. However, the differences between the base metal and the weld metal failure probabilities were not as large as exhibited for wrought stainless steel pipes.

- Comparisons of the results for the PWR austenitic pipes showed that due to aging, the conditional failure probabilities of cast stainless steel pipes can be much higher than those for wrought stainless steel pipes for base metal cracks, in which cases the fracture toughness of aged cast stainless steel materials was significantly lower than that of wrought stainless steel pipes. It appears that the toughness reduction has more detrimental effects than the beneficial effects due to strength increase in aged cast stainless steel pipes, particularly for larger diameter pipes.

- The conditional failure probability for both BWR and PWR piping systems was found to decrease with increasing pipe diameter. Similar results were reported in the past piping studies. For small diameter austenitic pipes, if the welds were TIG or MIG rather than flux welds, then the failure probabilities would decrease and perhaps be close to base metal failure probabilities.

- The conditional failure probability of complex-cracked[a] pipes was higher than that for through-wall-cracked pipes. Also, the conditional probability of failure was found to increase with increasing depth of the surface crack. In fact, if the depth of the surface

(a) A complex crack is a long circumferential surface crack that penetrates the thickness over a short length.

crack is large enough, then failure could occur even under normal operating loads (which is a principal reason that pipe susceptible to IGSCC type mechanisms are not permitted for LBB).

- Relative comparisons of the results suggest that the conditional failure probabilities of BWR and PWR pipe systems would strongly depend on the pipe-specific material properties and geometric characteristics, crack-morphology for determining the size of a leaking crack, and the applied normal operating stresses. However, when the leak rates are different, e.g., 18.925 l/min (5 gpm) for BWR and 3.785 l/min (1 gpm) for PWR, the conditional failure probabilities for PWR ferritic pipes were lower than those for BWR ferritic pipes. Further comparisons of permissible leak rates indicate that PWR leak rates are much higher than BWR leak rates to maintain the same conditional failure probability.

Finally, the adequacy of the current margin of 10 used for leak rate was evaluated by explicitly considering the statistical variability of crack morphology variables. Histograms of the leak rates were developed by Monte Carlo simulation. From these histograms, the margin accounting for crack-morphology variability and the residual margin were calculated [a]. It was found that the calculated margins, corresponding to a leak rate that has a 2-percent probability of exceedance, were 1.85 to 2.25 to account for the crack-morphology variability alone. Hence, with the current safety margin (total) of 10 being used in leak-before-break applications, a residual margin of 4.44 to 5.39 remains to account for the variability in leak-rate detection equipment, actual stresses, and other factors affecting leak rates.

During this study, several key areas were also identified where further refinement could be made in the current deterministic and probabilistic models. They involved: (1) the expansion of the database for material properties, crack morphology parameters, and actual stresses in a pipe, (2) the evaluation of the effects of restraint of pressure-induced bending and off-centered cracks on the crack-opening-area analysis, (3) the determination of the effects of through-thickness crack-opening angle on leak rate and fracture-mechanics analysis, (4) low-cycle fatigue crack growth considerations for seismic loading on pipes, and (5) the evaluation of the effects of residual stresses on crack-opening calculations.

(a) The margin accounting for the crack-morphology variability is defined as the ratio of the leak rate that has 2-percent probability of exceedance and the mean value of leak rate. The residual margin is defined as the mean leak rate times current (total) margin of 10 divided by the leak rate that has 2-percent probability of exceedance.

9.0 REFERENCES

1 1989 Addenda ASME Boiler & Pressure Vessel Code - Section III, Article NB-3652.

2 "Report to the U.S. Nuclear Regulatory Commission Piping Review Committee," Prepared by the Pipe Break Task Group, NUREG/CR-1061, Vol. 3, November 1984.

3 Published for public comment on "Standard Review Plan, Section 3.6.3 Leak-Before-Break Evaluation," Federal Register, Vol. 52, No. 167, Notices, pp. 32626 to 32633, Friday, August 28, 1987.

4 Wilkowski, G. M. and others, "Degraded Piping Program-Phase II," NUREG/CR-4082, Final and Semiannual Reports, 1985-1989.

5 Schmidt, R. A., Wilkowski, G. M., and Mayfield, M. E., "The International Piping Integrity Research Group (IPIRG) Program - An Overview," SMiRT-11, Paper G12/1, August 1991.

6 Paul, D. D., and others, "Evaluation and Refinement of Leak-Rate Estimation Models," NUREG/CR-5128, Rev. 1, June 1994.

7 Hiser, A. L., and Callahan, G. M., "A User's Guide to the NRC's Piping Fracture Mechanics Database (PIFRAC)," NUREG/CR-4894, May 1987.

8 Chopra, O., "Long-Term Embrittlement of Cast Duplex Stainless Steels in LWR Systems," Semiannual Report NUREG/CR-4744, Vols. 1 to 7, Nos. 1 and 2, January 1987 to May 1993.

9 Landes, J. D. and McCabe, D. E., "Elastic-Plastic Methodology to Establish R-Curves and Instability Criteria," Topical Report on Toughness Characterization of Austenitic Stainless Steel Pipe Weldments, AWI CP-86-003, February 1986.

10 Van Der Sluys, W. A., "Toughness of Ferritic Piping Steels," Final Report, EPRI NP-6264, October 1988.

11 Wallis, G. B., One-Dimensional Two-Phase Flow, McGraw-Hill, 1969.

12 Isbin, H. S., Moy, J. E., and Dacruz, J. R., "Two-Phase, Steam-Water Critical Flow," AI. Ch.E. Journal, Vol. 3, pp. 361-365, (1957).

13 Zivi, S. M., "Estimation of Steady-State Steam Void Fraction by Means of the Principle of Minimum Entropy Production," Trans. ASME J. Heat Transfer, Vol. 64, pp. 247-252, 1964.

14 Henry, R. E., and Fauske, H. K., "Two-Phase Critical Flow at Low Qualities, Part I: Experimental," Nuclear Science and Engineering, Vol. 41, pp. 79-91, 1970.

15 Moody, F. J., "Maximum Flow Rate of a Single Component, Two-Phase Mixture," Trans. ASME J. Heat Transfer, Vol. 86, pp. 132-142, 1965.

16 Henry, R. E., "The Two-Phase Critical Discharge of Initially Saturated or Subcooled Liquid," Nuclear Science and Engineering, Vol. 41, pp. 336-342, 1970.

17 Fluid Meters: Their Theory and Application, American Society of Mechanical Engineering, 6th edition, 1971.

18 Schlichting, H., Boundary Layer Theory, McGraw-Hill, 1968.

19 Collier, R. P., Stulen, F. B., Mayfield, M. E., Pape, D. B., and Scott, P. M., "Two-Phase Flow Through Intergranular Stress Corrosion Cracks and Resulting Acoustic Emission," EPRI Report No. NP-3540-LD, 1984.

20 Abdollahian, D. and Chexal, B., "Calculation of Leak Rates Through Cracks in Pipes and Tubes," EPRI Report No. NP-3395, 1983.

21 El-Wakil, M. M., Nuclear Heat Transport, International Textbook Company, 1971.

22 Press, W. H., Flannery, B. P., Teukolsky, S. A., and Vetterling, W. T., Numerical Recipes, Cambridge University Press, New York, New York, 1990.

23 Norris, D. et al., "PICEP: Pipe Crack Evaluation Program," Electric Power Research Institute Report, NP-3596-SR, 1984.

24 Kumar, V., German, M. D., and Shih, C. F., "An Engineering Approach to Elastic-Plastic Fracture Analysis," Electric Power Research Institute Report, NP-1931, 1981.

25 Ilyushin, A. A., "The Theory of Small Elastic Plastic Deformations," Prikadnaia Matematika i Mekhanika, P.M.M., Vol. 10, 1946.

26 Scott, P. and Brust, F., "An Experimental and Analytical Assessment of Circumferential Through-Wall Cracked Pipes Under Pure Bending," Battelle Columbus Division report to NRC, NUREG/CR-4574, 1986.

27 Rice, J. R., "A Path-Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks," Trans. ASME, Journal of Applied Mechanics, 35, pp. 376-386, 1968.

28 Hutchinson, J. W., "Fundamentals of the Phenomenological Theory of Nonlinear Fracture Mechanics," Journal of Applied Mechanics, 49, pp. 103-107, 1982.

29 Rice, J. R. and Rosengren, G. F., "Plane Strain Deformation near a Crack-Tip in a Power-Law Hardening Material," Journal of the Mechanics and the Physics of Solids, 16, pp. 1-12, 1968.

30 Hutchinson, J. W., "Singular Behavior at the End of a Tensile Crack in a Hardening Material," Journal of the Mechanics and the Physics of the Solids, 16, pp. 13-31, 1968.

31 Paris, P. C., Tada, H., Zahoor, A., and Ernst, H., "The Theory of Instability of the Tearing Mode of Elastic-Plastic Crack Growth," ASTM STP 668, Elastic-Plastic Fracture, pp. 5-36, 1979.

32 Paris, P. C., and Tada, H., "The Application of Fracture Proof Design Methods Using Tearing Instability Theory to Nuclear Piping Postulating Circumferential Through-Wall Cracks," NUREG/CR-3464, September 1983.

33 Klecker, R., Brust, F. W., and Wilkowski, G. M., "NRC Leak-Before-Break (LBB.NRC) Analysis Method for Circumferentially Through-Wall Cracked Pipes Under Axial Plus Bending Loads," NUREG/CR-4572, May 1986.

34 Kumar, V., and German, M. D., "Elastic-Plastic Fracture Analysis of Through-Wall and Surface Flaws in Cylinders," EPRI Topical Report, EPRI NP-5596, January 1988.

35 Milne, I., Ainsworth, R. A., Dowling, A. R., and Stewart, A. T., "Assessment of the Integrity of Structures Containing Defects," CEGB Report R/H/R6, Rev. 3, 1986.

36 Forman, R. G., Hickman, J. C., and Shivakumer, V., "Stress Intensity Factors for Circumferential Through Cracks in Hollow Cylinders Subjected to Combined Tension and Bending Loads," Engineering Fracture Mechanics, Vol. 21, No. 3, pp. 563-571, 1985.

37 Shih, C. F., "J-Dominance Under Plane Strain Fully Plastic Conditions: The Edge Crack Panel Subject to Combined Tension and Bending," International Journal of Fracture, Vol. 29, pp. 73-84, 1985.

38 Shih, C. F., and Hutchinson, J. W., "Combined Loading of a Fully Plastic Ligament Ahead of an Edge Crack," Journal of Applied Mechanics, Vol. 53/271, June 1986.

39 Kaiser, S., "An Extension of Tearing Instability Theory to Multiple Loading Parameters," International Journal of Fracture, Vol. 29, pp. 85-99, 1985.

40 Sonnerlind, H., and Kaiser, S., "The J-Integral for a SEN Specimen Under Nonproportionally Applied Bending and Tension," Engineering Fracture Mechanics, Vol. 24, No. 5, pp. 637-646, 1986.

41 Gilles, P., and Brust, F. W., "Approximate Methods for Fracture Analysis of Tubular Members Subjected to Combined Tensile and Bending Loads," Proceedings of the 8th OMAE Conference, Hague, The Netherlands, 1989.

42 Brust, F. W., "Approximate Methods for Fracture Analyses of Through-Wall Cracked Pipe," NUREG/CR-4853, February 1987.

43 Rahman, S., Brust, F., Nakagaki, M., and Gilles, P., "An Approximate Method for Estimating Energy Release Rates of Through-Wall Cracked Pipe Weldments," Proceedings of the 1991 ASME Pressure Vessels and Piping Conference, Vol. 215, pp 87-92, San Diego, California, 1991.

44 Gilles, P., and Brust, F., "Approximate Fracture Methods for Pipes - Part I: Theory," Nuclear Engineering and Design, Vol. 127, pp. 1-27, 1992.

45 Gilles, P., Chao, K. S., and Brust, F., "Approximate Fracture Methods for Pipes - Part II: Applications," Nuclear Engineering and Design, Vol. 127, pp. 13-31, 1991.

46 Wilkowski, G. M., and Others, "Degraded Piping Program - Phase II," NUREG/CR-4082, Vol. 8, 1989.

47 Wilkowski, G. M., and others, "Short Cracks in Piping and Piping Welds," Semiannual reports by Battelle, NUREG/CR-4599, Vols. 1 to 3, Nos. 1 and 2, May 1991 to March 1994.

48 Sozzi, G. L., and Sutherland, W. A., "Critical Flow of Saturated and Subcooled Water at High Pressure," NEDO-13418, 1975.

49 Amos, C., and Shrock, V., "Critical Discharge of Initially Subcooled Water Through Slits," NUREG/CR-3476, 1983.

50 Matsushima, E., Yano, T., and Okamoto, A., "Experimental Study of Leak Flow Rate Through Artificial Slits," SMiRT-9, Vol. G, pp. 287-292, 1987.

51 Yano, T., Matsushima, E., and Okamoto, A., "Leak Flow Rate From Through-Wall Crack In Pipe," Proceedings of 1987 ASME/JSME Thermal Engineering Joint Conference, Honolulu, Hawaii, pp. 301-308, 1987.

52 Jones, O. C., "Flashing Inception in Flowing Liquids, Nonequilibrium Interfacial Transport Processes, pp. 29-34, 1979.

53 Jones, O. C., Jr., and Zuber, N., "Bubble Growth in Variable Pressure Fields," Trans. ASME, Journal of Heat Transfer, Vol. 100, pp. 453-459, 1978.

54 Kramer, G., and Papaspyropaulos, V., "An Assessment of Circumferentially Complex-Cracked Pipe Subjected to Bending," NUREG/CR-4687, October 1986.

55 Wilkowski, G. M., and others, "Short Cracks in Piping and Piping Welds," Second semiannual report by Battelle, NUREG/CR-4599, Vol. 1, No. 2, April 1992

56 Wilkowski, G. M., and others, "Degraded Piping Program - Phase II," Semiannual Report, October 1984-March 1985, NUREG/CR-4082, Vol. 2., July 1985.

57 Hale, D. A., and others, "The Growth and Stability of Stress Corrosion Cracks in Large-Diameter BWR Piping," EPRI NP-2472, Vol. 2., Final Report, July 1982.

58 Jansson, C., and others, "BWR Pipe Repairs in Sweden," Paper 4 in Proceedings: Second Seminar on Countermeasures for Piping Cracks in BWRs, EPRI NP-3684-SR, Vol. 3, Special Report, September 1984.

59 Olson, N. H., and others, "Crack Growth Rates and Effectiveness of LPHSW Remedy in Large-Diameter Type 304 Stainless Steel BWR Pipe," Paper 5 in Proceedings: Second Seminar on Countermeasures for Piping Cracks in BWRs, EPRI NP-3684-SR, Vol. 2, Special Report, September 1984.

60 Kurtz, R. J., "Effect of Sulfate and Chloride Intrusions on Cracking of Stainless Steel at 288°C," Paper 19 in Proceedings: Second Seminar on Countermeasures for Piping Cracks in BWRs, EPRI NP-3684-SR, Vol. 2, Special Report, September 1984.

61 Matsumoto, K., Nakamura, S., Gotoh, N., Narabayashi, T., Tanaka, Y., and Horimizu, Y., "Study on Coolant Leak Rates Through Pipe Cracks," ASME PVP - Vol. 165, pp. 121-127, 1989.

62 Goldberg, A., Streit, R. D., and Scott, R. G., "Evaluation of Cracking in Feedwater Piping Adjacent to the Steam Generators in Nine Pressurized Water Reactor Plants," NUREG/CR-1603, October 1980.

63 Mayfield, M. E. and Collier, R. P., "Leak-Before-Break Due to Fatigue in the Cold Leg Piping System," Proceedings of the CSNI Specialist Meeting on Leak-Before-Break in Nuclear Reactor Piping, NUREG/CP-0051, September 1983.

64 "Ultrasonic Sizing Capability of IGSCC and Its Relation to Flaw Evaluation Procedures," prepared by EPRI NDE Center and EPRI Staff, August 4, 1983.

65 Bates, D. J., Doctor, S. R., Heasler, P. G., and Burck, E., "Stainless Steel Round Robin Test Centrifugally Cast Stainless Steel Screening Phase," NUREG/CR-4970, October 1987.

66 Fiessler, B., Neumann, H. J., and Rackwitz, R. "Quadratic Limit States in Structural Reliability," Journal of Engineering Mechanics, ASCE, Vol. 105, No. EM4, pp. 661-676, 1979.

67 Rackwitz, R. and Fiessler, B., "Structural Reliability under Combined Random Load Sequences," Computer and Structures, Vol. 9, pp. 484-494, 1978.

68 Madsen, H. O., Krenk, S., and Lind, N. C., Methods of Structural Safety, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1986.

69 Hohenbichler, M., "New Light on First- and Second-Order Reliability Methods," Structural Safety, 4, pp. 267-284, 1987.

70 Breitung, K., "Asymptotic Approximation for Multinormal Integrals," Journal of Engineering Mechanics, ASCE, Vol. 110, No. 3, pp. 357-366, March 1984.

71 Rahman, S. and Grigoriu, M., "A Markov Model for Local and Global Damage Indices in Seismic Analysis," Technical Report NCEER-94-0003, National Center for Earthquake Engineering Research, Buffalo, New York, February 1994.

72 Fu, G., and Moses, F., "A Sampling Distribution for System Reliability Applications," Proceedings of the First IFIP WG 7.5 Working Conference on Reliability and Optimization of Structural Systems, Aalborg, Denmark, pp. 141-155, May 1987.

73 Harbitz, A., "An Efficient Sampling Method for Probability of Failure Calculation," Structural Safety, Vol. 3, No. 1., pp. 109-115, October 1986.

74 Harbitz, A., "Efficient and Accurate Probability of Failure Calculation by use of the Importance Sampling Technique," Proceedings of the 4th International Conference on Applications of Statistics and Probability in Soil and Structural Engineering, Florence, Italy, 1983.

75 Ibrahim, Y. and Rahman, S., "Reliability Analysis of Uncertain Dynamic Systems Using Importance Sampling," Proceedings of the Sixth International Conference on Applications of Statistics and Probability in Civil Engineering, Mexico City, Mexico, 1991.

76 Melchers, R. E., "Efficient Monte Carlo Probability Integration," Report No. 7, Dept. of Civil Engineering, Monash University, Australia, 1984.

77 Bjerager, P., "Probability Integration by Directional Simulation," Journal of Engineering Mechanics, ASCE, Vol. 114, No. 8, pp. 1285-1302, August 1988.

78 Deak I., "Three Digit Accurate Multiple Normal Probabilities," Numerische Mathematik, 35, pp. 369-380, 1980.

79 Ditlevson, O., Olesen, R., and Mohr, G., "Solution of a Class of Load Combination Problems by Directional Simulation," Structural Safety, 4, pp. 95-109, 1986.

80 Rubinstein, R. Y., Simulation and the Monte Carlo Method, John Wiley & Sons, New York, New York, 1981.

81 "Investigation and Evaluation of Stress-Corrosion Cracking in Piping of Light Water Reactor Plants," NUREG-0531, Pipe Crack Study Group, U.S. Nuclear Regulatory Commission, February 1979.

82 Harris, D. O., Lim, E. Y., and Dedhia, D. D., "Probability of Pipe Fracture in the Primary Coolant Loop of a PWR Plant," NUREG/CR-2189, Vol. 5, August 1981.

83 Mehta, H. S., Patel, N. T., and Ranganath, S., "Application of the Leak-Before-Break Approach to BWR Piping," EPRI NP-4991, Final Report, December 1986.

84 Maxham, W. D., and Yoon, K. K., "Application of Leak-Before-Break Approach to PWR Piping Designed by Babcock and Wilcox," EPRI NP-4972, Final Report, January 1987.

85 Swamy, S. A., and Others, "Application of the Leak-Before-Break Approach to Westinghouse PWR Piping," EPRI NP-4971, Final Report, December 1986.

86 Ayres, D. J., LaRussa, J. J., Ganta, B. R., and Austin, S. C., "Application of Leak-Before-. Break Analysis to PWR Piping Design by Combustion Engineeirng," EPRI NP-5010, Final Report, February 1987.

87 Wilson, S. A., "Estimating the Relative Probability of Pipe Severance by Fault Cause," General Electric Company Report GYP-20615, Boiling Water Reactor Systems Department, San Jose, California, September 1974.

88 Lawrence Livermore National Laboratory, "Probability of Pipe Failure in the Reactor Coolant Loops of Westinghouse PWR Plants," Report UCID-19988, NUREG/CR-3660, Vols. 1, 2, 3, and 4, U.S. Nuclear Regulatory Commission, Washington, D.C., 1984.

89 Reactor Safety Study, An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, WASH-1400 (NUREG-75/014), Appendices III and IV, "Failure Data and Common Mode Failures Bounding Techniques and Special Techniques," Nuclear Regulatory Commission, Washington, D.C., October 1975.

90 Bush, S. H., "Pressure Vessel Reliability," Journal of Pressure Vessel Technology, Vol. 97, Series H, No. 1, pp. 54-70, February 1975.

91 Bush, S. H., "The Impact of In-service Inspection ont he Reliability of Pressure Vessels and Piping," Reliability Engineering in Pressure Vessels and Piping, pp. 1-13, American Society of Mechanical Engineers, New York, 1975.

92 Bush, S. H., "Reliability of Piping in Light-Water Reactors," Nuclear Safety, Vol. 17, No. 5, pp. 568-579, September-October 1976.

93 Report on the Integrity of Reactor Vessels for Light Water Power Reactors, The Advisory Committee on Reactor Safeguards, U.S. A.E.C. Report WASH-1285, Washington, D.C., January 1974, also published in Nuclear Engineering and Design, Vol. 28, pp. 147-195, 1974.

94 Burns, E. T., Harris, D. O., and Erdmann, R. C., "Reliability of Nuclear Piping Systems with Consideration of Cases where Design Points have been Exceeded," Science Applications, Inc., Report SAI-091-79-PA, Palo Alto, California, presented at ASME/CSME Pressure Vessels and Piping Conference, Montreal, June 1978.

95 Basin, S. L., and Burns, E. T., "Characteristics of Pipe System Failures in Light Water Reactors," EPRI NP-438, Electric Power Research Institute, Palo Alto, California, August 1977.

96 Wilkowski, G. M., Rahman, S., and Mohan, R., "Low-Cycle Fatigue Crack Growth Consideration in Pipe Fracture Analysis," PVP-Vol. 280, Fatigue, Flaw Evaluation, and Leak-Before-Break Assessments, edited by G. M. Wilkowski, pp 281-297, June 1994.

APPENDIX A $F_B(\theta)$, $I_B(\theta)$, $F_T(\theta)$ AND $I_T(\theta)$ FUNCTIONS

Using Sanders' solutions (Refs. A.1 and A.2) by shell theory and energy integral technique, Klecker et al. (Ref. A.3) have developed the following approximations for $F_B(\theta)$, $I_B(\theta)$, $F_T(\theta)$ and $I_T(\theta)$:

A.1 Bending Case

$$F_B(\theta) \simeq 1 + A_b \left[\frac{\theta}{\pi}\right]^{1.5} + B_b \left[\frac{\theta}{\pi}\right]^{2.5} + C_b \left[\frac{\theta}{\pi}\right]^{3.5} \tag{A-1}$$

where

$$\begin{aligned} A_b &= -3.2654 + 1.5278 \left[\frac{R_m}{t}\right] - 0.0727 \left[\frac{R_m}{t}\right]^2 + 0.0016 \left[\frac{R_m}{t}\right]^3 \\ B_b &= 11.3632 - 3.9141 \left[\frac{R_m}{t}\right] + 0.1862 \left[\frac{R_m}{t}\right]^2 - 0.0041 \left[\frac{R_m}{t}\right]^3 \\ C_b &= -3.1861 + 3.8476 \left[\frac{R_m}{t}\right] - 0.1830 \left[\frac{R_m}{t}\right]^2 + 0.0040 \left[\frac{R_m}{t}\right]^3 \end{aligned} \tag{A-2}$$

and

$$\begin{aligned} I_B(\theta) &= 4\int_0^\theta \xi F_B(\xi)^2 d\xi \\ &\simeq 2\theta^2 \left[1 + 8 \left[\frac{\theta}{\pi}\right]^{1.5} I_{b_1} + \left[\frac{\theta}{\pi}\right]^3 \left(I_{b_2} + I_{b_3}\right)\right] \end{aligned} \tag{A-3}$$

where

$$\begin{aligned} I_{b_1} &= \frac{A_b}{7} + \frac{B_b}{9}\left[\frac{\theta}{\pi}\right] + \frac{C_b}{11}\left[\frac{\theta}{\pi}\right]^2 \\ I_{b_2} &= \frac{A_b^2}{2.5} + \frac{A_b B_b}{1.5}\left[\frac{\theta}{\pi}\right] + \frac{2A_b C_b + B_b^2}{3.5}\left[\frac{\theta}{\pi}\right]^2 \\ I_{b_3} &= \frac{B_b C_b}{2}\left[\frac{\theta}{\pi}\right]^3 + \frac{C_b^2}{4.5}\left[\frac{\theta}{\pi}\right]^4 \end{aligned} \tag{A-4}$$

A.2 Tension Case

$$F_T(\theta) \simeq 1 + A_t \left[\frac{\theta}{\pi}\right]^{1.5} + B_t \left[\frac{\theta}{\pi}\right]^{2.5} + C_t \left[\frac{\theta}{\pi}\right]^{3.5} \quad \text{(A-5)}$$

where

$$A_t = -2.0292 + 1.6776 \left[\frac{R_m}{t}\right] - 0.0799 \left[\frac{R_m}{t}\right]^2 + 0.0018 \left[\frac{R_m}{t}\right]^3$$

$$B_t = 7.0999 - 4.4239 \left[\frac{R_m}{t}\right] + 0.2104 \left[\frac{R_m}{t}\right]^2 - 0.0046 \left[\frac{R_m}{t}\right]^3$$

$$C_t = 7.7966 + 5.1668 \left[\frac{R_m}{t}\right] - 0.2458 \left[\frac{R_m}{t}\right]^2 + 0.0054 \left[\frac{R_m}{t}\right]^3 \quad \text{(A-6)}$$

and

$$I_T(\theta) = \int_0^\theta \xi F_T(\xi)^2 \, d\xi$$

$$\simeq 2\theta^2 \left[1 + 8 \left[\frac{\theta}{\pi}\right]^{1.5} I_{t_1} + \left[\frac{\theta}{\pi}\right]^3 \left(I_{t_2} + I_{t_3}\right)\right] \quad \text{(A-7)}$$

where

$$I_{t_1} = \frac{A_t}{7} + \frac{B_t}{9} \left[\frac{\theta}{\pi}\right] + \frac{C_t}{11} \left[\frac{\theta}{\pi}\right]^2$$

$$I_{t_2} = \frac{A_t^2}{2.5} + \frac{A_t B_t}{1.5} \left[\frac{\theta}{\pi}\right] + \frac{2A_t C_t + B_t^2}{3.5} \left[\frac{\theta}{\pi}\right]^2$$

$$I_{t_3} = \frac{B_t C_t}{2} \left[\frac{\theta}{\pi}\right]^3 + \frac{C_t^2}{4.5} \left[\frac{\theta}{\pi}\right]^4 \quad \text{(A-8)}$$

Further details of derivation for the above empirical coefficients are described in the References A.4 to A.6.

A.3 References

A.1 Sanders, J. L., "Circumferential Through-Cracks in Cylindrical Shells Under Tension," ASME Journal of Applied Mechanics, Vol. 49. No. 103, March 1982.

A.2 Sanders, J. L., "Circumferential Through-Crack in a Cylindrical Shell Under Combined Bending and Tension," Journal of Applied Mechanics, Vol. 50, No. 221, March 1983.

A.3 Klecker, R., Brust, F. W., and Wilkowski, G. M., "NRC Leak-Before-Break (LBB.NRC) Analysis Method for Circumferentially Through-Wall Cracked Pipes Under Axial Plus Bending Loads," NUREG/CR-4572, May 1986.

A.4 Gilles, P., and Brust, F. W., "Approximate Methods for Fracture Analysis of Tubular Members Subjected to Combined Tensile and Bending Loads," Proceedings of the 8th OMAE Conference, Hague, The Netherlands, 1989.

A.5 Brust, F. W., "Approximate Methods for Fracture Analyses of Through-Wall Cracked Pipe," NUREG/CR-4853, February 1987.

A.6 Rahman, S., Brust, F., Nakagaki, M., and Gilles, P., "An Approximate Method for Estimating Energy Release Rates of Through-Wall Cracked Pipe Weldments," Proceedings of the 1991 ASME Pressure Vessels and Piping Conference, Vol. 215, pp. 87-92, San Diego, California, 1991.

APPENDIX B PIPE MATERIAL PROPERTIES

B.1 Experimental Evaluation of Stress-Strain and J-R Curves

Round-bar tensile specimens, machined from actual pipes and plates, were used to determine the uniaxial stress-strain curves of the material. The tests were conducted at 288 C (550 F). The stress-strain data ranging between 1-percent strain and 80-percent of ultimate strain were fitted with a power-law equation shown in Equation 3-1 or Equation 3-2 and the corresponding Ramberg-Osgood parameters, F (or α) and n, were calculated. The basic strength parameters, e.g., yield stress, σ_y (0.2- percent offset) and ultimate stress, σ_u, were calculated as well. Tables B.1 to B.4 show the experimental values of σ_y, σ_u, F (or α), and n for TP304, A106B, CF8M, and A516 Gr70 base metals, respectively, mostly at 288 C (550 F). The values of α listed in these tables correspond to reference stress values equal to the respective yield strength of the specimens. The elastic modulus, E, was assumed to be 182.7 GPa (26,500 ksi) for stainless steel and 193.1 GPa (28,000 ksi) for carbon steel.

Compact-tension [C(T)] specimens, machined from actual pipes and plates, were also used to determine the fracture toughness curves of the material. The specimens were oriented such that crack growth would be in the circumferential or transverse direction (L-C or L-T orientation). Specimen thicknesses were the maximum achievable from the nominal wall thickness. Two different types of starting notches were employed: (1) a fatigue precrack, and (2) a machined notch having a radius of about 0.13 mm (0.005 inch). Both side-grooved and non-side-grooved specimens were considered. The tests were performed at 288 C (550 F) at a displacement rate to cause crack initiation in about 5 to 15 minutes. From the load and displacement data from the C(T) specimens, the deformation J (J_D) was calculated according to the manner specified in ASTM E1152. Then, the J_D-R data with crack growth below 30 percent of the uncracked ligament were fitted with a power-law equation yielding fracture toughness parameters J_{Ic}, C, and m defined in Equation 3-4. Tables B.5 to B.8 show the experimental values of these parameters for TP304, A106B, CF8M, and A516 Gr70 base metals, respectively, mostly at 288 C (550 F). The weld metal J_D-R curve parameters were determined as well. They are shown in Tables B.9 and B.10 for stainless steel flux weld and carbon steel flux weld, respectively.

B.2 Statistical Analysis of Stress-Strain and J-R Curves

Using Equations 3-9 and 3-10, the data in Tables B.1 to B.10 were analyzed to determine the statistical characteristics of random material properties. Tables B.11 to B.14 show the mean and covariance properties of $\{\sigma_y, \sigma_u\}$, {F, n} (or $\{\alpha, n\}$), and $\{J_{Ic}, C, m\}$ for TP304, A106B, CF8M, and A516 Gr70 base metals, respectively, mostly at 288 C (550 F). During the computations of statistical properties, multiple specimens from a given pipe or heat were lumped together (i.e., average values from several specimens) so that the statistics would not be biased for a given pipe. For J-R curves, the specimens with large differences in net-thickness were treated as if they were from different pipes or heats. In computing the statistics of α, its sample values listed in Tables B.1 to B.4 were modified so that the reference stress (σ_0) used in the statistical analysis corresponds to the mean value of all yield stresses. This was done according to

$$\alpha_2 = \alpha_1 \left[\frac{\sigma_{02}}{\sigma_{01}} \right]^{n-1} \tag{B-1}$$

in which α_1 and α_2 are two values of α that correspond to the reference stresses, σ_{01} and σ_{02}, respectively. If a value of α is known for a given reference stress, the corresponding value of α for another reference stress can be easily calculated from Equation B-1. This modification was necessary since in a Ramberg-Osgood equation, which is a two-parameter model, if α and n are modeled as random variables, σ_0 must remain deterministic (i.e., both α and σ_0 must not be random and vary independently). Finally, Table B.15 shows the mean and covariance properties of $\{J_{Ic}$, C, m$\}$ for both stainless steel flux welds and carbon steel flux welds mostly at 288 C (550 F).

B.3 References

B.1 Wilkowski, G. M. and others, "Degraded Piping Program-Phase II," NUREG/CR-4082, Final and Semiannual Reports, 1985-1989.

B.2 Hiser, A. L., and Callahan, G. M., "A User's Guide to the NRC's Piping Fracture Mechanics Database (PIFRAC)," NUREG/CR-4894, May 1987.

B.3 Wilkowski, G. M., and others, "Short Cracks in Piping and Piping Welds," Semiannual reports by Battelle, NUREG/CR-4599, Vols. 1 to 3, Nos. 1 and 2, May 1991 to March 1994.

B.4 Landes, J. D. and McCabe, D. E., "Elastic-Plastic Methodology to Establish R-Curves and Instability Criteria," Topical Report on Toughness Characterization of Austenitic Stainless Steel Pipe Weldments, AWI CP-86-003, February 1986.

B.5 Chopra, O., "Long-Term Embrittlement of Cast Duplex Stainless Steels in LWR Systems," Semiannual Reports, NUREG/CR-4744, Vols. 1 to 7, January 1987 to May 1993.

B.6 Van Der Sluys, W. A., "Toughness of Ferritic Piping Steels," Final Report, EPRI NP-6264, October 1988.

Table B.1 Quasi-static tensile properties of TP304 stainless steel base metal at 288 C (550 F) (24 specimens)[(a)]

Specimen Code	σ_y, MPa	σ_u, MPa	F, MPa	n	α[(b)]	Test Temperature, C (F)	Reference
A8-39	185	460	567.64	4.895	4.085	288 (550)	B.1, B.2
A8-40	174	456	576.22	4.162	7.191	288 (550)	B.1, B.2
A23-1	133	450	665.34	3.054	10.059	288 (550)	B.1, B.2
A23-2	128	446	679.27	2.895	11.38	288 (550)	B.1, B.2
A23-105	139	450	528.68	3.565	11.23	288 (550)	B.1, B.2
A45-1	168	475	596.12	3.72	9.78	288 (550)	B.1, B.2
A45-2	145	466	599.89	3.693	6.651	288 (550)	B.1., B.2
ZP6-4L	140	391	518.38	3.842	8.538	288 (550)	B.2[(c)]
ZP6-6L	141	390	518.76	3.942	7.627	288 (550)	B.2[(c)]
ZP12-11L	146	453	633.57	3.442	8.004	288 (550)	B.2[(c)]
ZP12-12L	147	426	649.43	3.294	9.313	288 (550)	B.2[(c)]
ZP12-16L	179	447	629.17	3.639	10.527	288 (550)	B.2[(c)]
ZP17-13L	145	452	641.35	3.328	8.941	288 (550)	B.2[(c)]
ZP17-16L	147	448	688.31	3.237	8.397	288 (550)	B.2[(c)]
A35-5	150	503	600.01	4.114	4.062	288 (550)	B.2
A35-6	151	469	590.83	3.606	8.836	288 (550)	B.2
A52-5T	171	432	501.02	5.31	3.546	288 (550)	B.2, B.3
A52-6T	155	431	527.42	4.645	3.991	288 (550)	B.2, B.3
GGKX00	159	461	688.37	3.270	9.533	288 (550)	B.2[(d)]
A7	147	449	642.33	3.368	8.658	288 (550)	B.1, B.2
Heat B[(e)]	159	423	568.75	3.556	12.36	288 (550)	B.2, B.4
Heat C[(e)]	163	427	667.99	4.662	1.562	288 (550)	B.2, B.4
F33SS-T1	161	414	583.44	3.68	9.935	288 (550)	B.2[(f)]
F33SS-T2	154	414	570.31	3.66	9.844	288 (550)	B.2[(f)]

(a) Stress-strain curve is represented by: $\epsilon = \sigma/E + (\sigma/F)^n$, where E = 182.7 GPa.

(b) For a normalized Ramberg-Osgood model given by: $\epsilon/\epsilon_0 = \sigma/\sigma_0 + \alpha(\sigma/\sigma_0)^n$, $\alpha = (\sigma_0)^{n-1}E/F^n$, where $\epsilon_0 = \sigma_0/E$, $\sigma_0 = \sigma_y$, and E = 182.7 GPa.

(c) Further details can be found in "Fracture Toughness Characterization of Nuclear Piping Steels," NUREG/CR-5188, November 1989.

(d) Data were originally developed at DTRC.

(e) Engineering stress-strain (σ-ϵ) curve is calculated from true stress-strain (σ'-ϵ') curve based on constant volume deformation, i.e., $\epsilon = \exp(\epsilon') - 1$; $\sigma = \sigma' \exp(-\epsilon')$.

(f) Data were originally developed in the Short Cracks in Piping and Piping Welds program at Battelle.

Table B.2 Quasi-static tensile properties of A106B carbon steel base metal at 250 C (482 F) to 316 C (600 F) (30 specimens)[(a)]

Specimen Code	σ_y, MPa	σ_u, MPa	F, MPa	n	α[(b)]	Test Temperature, C (F)	Reference
F29-5	240	618	1169.91	3.729	2.189	288 (550)	B.1, B.2
F29-6	233	601	981.23	4.249	1.842	288 (550)	B.1, B.2
F45-5	268	639	881.91	5.578	0.938	288 (550)	B.1, B.2
F45-6	285	734	864.23	5.790	1.1	288 (550)	B.1, B.2
F30-5	342	647	800.24	7.835	0.723	288 (550)	B.1, B.2
F30-6	360	650	804.59	8.063	0.819	288 (550)	B.1, B.2
F30-104	294	599	868.01	5.366	1.97	288 (550)	B.1, B.2
F13-5	262	609	1040.42	3.998	2.972	288 (550)	B.1, B.2
F13-6	260	613	947.74	4.489	2.235	288 (550)	B.1, B.2
ZP13-4L	212	426	599.85	7.220	0.499	288 (550)	B.2[(c)]
ZP14-4L	262	568	715.61	8.395	0.16	288 (550)	B.2[(c)]
ZP14-9L	254	571	707.76	8.131	0.183	288 (550)	B.2[(c)]
ZP15-4L	319	620	922.48	5.734	1.373	288 (550)	B.2[(c)]
ZP15-13L	145	452	652.11	3.328	8.941	288 (550)	B.2[(c)]
F22-T1	224	588	918.43	4.858	0.909	288 (550)	B.2[(d)]
F22-T2	225	588	908.85	5.096	0.698	288 (550)	B.2[(d)]
F23-3T	221	514	777.95	5.142	1.352	288 (550)	B.2[(d)]
F23-4T	210	499	777.09	4.951	1.413	288 (550)	B.2[(d)]
OH-T1	219	506	1040.66	3.736	2.611	250 (482)	B.2[(e)]
OH-T3	220	528	881.45	5.210	0.635	250 (482)	B.2[(e)]
OH-T13	221	511	1020.09	3.881	2.311	250 (482)	B.2[(e)]
OH-T34	267	564	1369.68	3.251	3.556	250 (482)	B.2[(e)]
OH-T45	231	535	1118.55	3.659	2.602	250 (482)	B.2[(e)]
OH-T65	250	451	923.17	3.618	6.841	250 (482)	B.2[(e)]
OH-T71	250	531	1122.69	3.653	3.2	250 (482)	B.2[(e)]
Heat 1	203	577	634.68	5.477	1.848	288 (550)	B.2[(f)]
Heat 2	229	622	677.37	5.743	1.663	288 (550)	B.2[(f)]
Heat 5	238	630	1043.38	4.320	1.369	288 (550)	B.2[(f)]
Heat 7	305	483	1027.39	5.513	0.783	288 (550)	B.2[(f)]
A106B	266	603	1294.15	3.810	1.75	316 (600)	B.2[(f)]

(a) Stress-strain curve is represented by: $\epsilon = \sigma/E + (\sigma/F)^n$, where E = 193.1 GPa.

(b) For a normalized Ramberg-Osgood model given by: $\epsilon/\epsilon_0 = \sigma/\sigma_0 + \alpha(\sigma/\sigma_0)^n$, $\alpha = (\sigma_0)^{n-1}E/F^n$, where $\epsilon_0 = \sigma_0/E$, $\sigma_0 = \sigma_y$, and E = 193.1 GPa.

(c) Further details can be found in "Fracture Toughness Characterization of Nuclear Piping Steels," NUREG/CR-5188, November 1989.

(d) Data were originally developed in the IPIRG-2 program at Battelle.

(e) Further details can be found in "Observations on the effect of post-weld heat treatment on J-resistance curves of SA-106B seamless piping welds," by B. Mukherjee, Nuclear Engineering and Design, Vol. 111, pp. 63-75, 1989.

(f) Further details can be found in "Evaluation of Flaws in Ferritic Piping," EPRI Report, NP-4824M, October 1986.

Table B.3 Quasi-static tensile properties of CF8M cast stainless steel base metal at 290 C (554 F) to 320 C (608 F) (45 specimens)[a]

Specimen Code	σ_y, MPa	σ_u, MPa	F, MPa	n	$\alpha^{(b)}$	Aging Temperature, C	Aging Time, h	Test Temperature, C (F)	Reference
205-25	179	506	712.3029	4.763	1.419	400	18,000	290 (554)	B.2, B.5[c]
205-28	177	508	702.8734	4.712	1.555	400	18,000	290 (554)	B.2, B.5[c]
205-29	168	495	745.3123	4.261	1.903	400	18,000	290 (554)	B.2, B.5[c]
744-40	172	412	454.1063	7.154	1.023	Unaged	Unaged	290 (554)	B.2, B.5[c]
743-42	165	443	601.0027	4.198	4.87	Unaged	Unaged	290 (554)	B.2, B.5[c]
744-35	194	425	567.087	3.915	14.13	290	30,000	290 (554)	B.2, B.5[c]
744-36	165	424	570.8533	3.797	9.943	290	30,000	290 (554)	B.2, B.5[c]
744-26	193	440	615.2082	3.994	9.233	320	10,000	290 (554)	B.2, B.5[c]
744-27	181	421	566.8787	4.002	10.467	320	10,000	290 (554)	B.2, B.5[c]
742-40	154	453	628.5183	4.144	3.492	320	30,000	290 (554)	B.2, B.5[c]
742-41	190	483	616.0921	5.115	2.343	320	30,000	290 (554)	B.2, B.5[c]
742-28	204	473	642.2563	4.62	4.477	320	50,000	290 (554)	B.2, B.5[c]
742-29	215	474	603.3907	5.744	2.265	320	50,000	290 (554)	B.2, B.5[c]
742-27	175	454	619.8871	4.624	3.012	350	2,570	290 (554)	B.2, B.5[c]
744-06	185	448	617.8331	4.138	6.722	350	10,000	290 (554)	B.2, B.5[c]
744-09	198	507	704.947	4.028	5.542	350	10,000	290 (554)	B.2, B.5[c]
744-18	229	511	743.1856	3.961	7.53	350	30,000	290 (554)	B.2, B.5[c]
743-15	180	504	731.2368	3.745	5.328	350	30,000	290 (554)	B.2, B.5[c]
74-270	182	495	711.0458	3.873	5.123	350	30,000	290 (554)	B.2, B.5[c]
742-18	166	485	644.9755	4.778	1.68	400	2,570	290 (554)	B.2, B.5[c]
742-15	179	516	703.3696	4.044	4.031	400	10,000	290 (554)	B.2, B.5[c]
742-24	184	509	505.9555	6.311	1.677	400	10,000	290 (554)	B.2, B.5[c]
741-06	172	501	678.204	5.279	0.76	450	2,570	290 (554)	B.2, B.5[c]
742-09	170	485	655.2724	5.252	0.899	450	2,570	290 (554)	B.2, B.5[c]
754-40	197	471	560.8929	6.425	1.116	Unaged	Unaged	290 (554)	B.2, B.5[c]
753-42	192	475	636.8825	4.801	3.008	Unaged	Unaged	290 (554)	B.2, B.5[c]
754-29	193	528	856.7427	2.999	10.838	290	30,000	290 (554)	B.2, B.5[c]
754-30	203	495	716.5527	4.02	5.653	290	30,000	290 (554)	B.2, B.5[c]
754-26	206	538	684.9527	5.652	0.997	320	10,000	290 (554)	B.2, B.5[c]
754-27	212	534	679.7296	5.639	1.208	320	10,000	290 (554)	B.2, B.5[c]
752-40	232	589	769.9699	5.356	1.276	320	30,000	290 (554)	B.2, B.5[c]
752-42	269	576	804.6752	5.024	2.762	320	30,000	290 (554)	B.2, B.5[c]
752-28	259	588	768.8569	5.716	1.404	320	30,000	290 (554)	B.2, B.5[c]
752-29	264	582	769.6842	5.744	1.482	320	30,000	290 (554)	B.2, B.5[c]
752-27	205	529	668.6488	6.021	0.722	350	30,000	290 (554)	B.2, B.5[c]
754-09	220	614	825.2955	5.098	0.982	350	30,000	290 (554)	B.2, B.5[c]
753-12	264	616	797.7809	5.711	1.251	350	30,000	290 (554)	B.2, B.5[c]
754-12	227	614	865.7759	4.645	1.604	350	30,000	290 (554)	B.2, B.5[c]
752-18	203	591	743.897	5.601	0.624	400	2,570	290 (554)	B.2, B.5[c]
752-24	208	630	859.9204	5.033	0.694	400	10,000	290 (554)	B.2, B.5[c]
751-06	219	598	819.5628	5.268	0.798	450	2,570	290 (554)	B.2, B.5[c]
752-09	198	606	849.6533	4.85	0.789	450	2,570	290 (554)	B.2, B.5[c]
B3	207	619	957.6485	4.145	1.543	400	700	320 (608)	B.1, B.2
B4	204	586	870.3858	4.252	1.875	400	700	320 (608)	B.1, B.2
A40-G002	231	610	860.4665	4.478	2.191	400	700	320 (608)	B.1, B.2[d]

(a) Stress-strain curve is represented by: $\epsilon = \sigma/E + (\sigma/F)^n$, where E = 182.7 GPa.
(b) For a normalized Ramberg-Osgood model given by: $\epsilon/\epsilon_0 = \sigma/\sigma_0 + \alpha(\sigma/\sigma_0)^n$, $\alpha = (\sigma_0)^{n-1}E/F^n$, where $\epsilon_0 = \sigma_0/E$, $\sigma_0 = \sigma_y$, and E = 182.7 GPa.
(c) Further details can be found in "Tensile-Property Characterization of Thermally Aged Cast Stainless Steel," NUREG/CR-6142, February 1994.
(d) Data were developed from tests conducted at DTRC

Table B.4 Quasi-static tensile properties of A516 Gr70 carbon steel base metal at 288 C (550 F) (16 specimens)(a)

Specimen Code	σ_y, MPa	σ_u, MPa	F, MPa	n	$\alpha^{(b)}$	Test Temperature, C (F)	Reference
F26-5	231	541	718.56	5.644	1.382	288 (550)	B.1, B.2
F26-6	230	545	726.60	5.488	1.522	288 (550)	B.1, B.2
BL-I2	236	482	670.50	6.035	1.5	288 (550)	B.1, B.2
BL-M2	236	508	798.26	4.695	2.68	288 (550)	B.1, B.2
BL-O2	254	491	690.84	6.253	1.458	288 (550)	B.1, B.2
B34	421	601	947.53	6.353	2.651	288 (550)	B.2, B.6
B36	293	583	1008.58	5.025	1.322	288 (550)	B.2, B.6
B37	379	590	924.36	6.429	1.651	288 (550)	B.2, B.6
A65	297	574	1036.14	4.565	2.166	288 (550)	B.2, B.6
A66	258	522	910.48	4.751	1.872	288 (550)	B.2, B.6
A67	429	529	779.63	8.065	3.64	288 (550)	B.2, B.6
JUB4	241	587	1047.66	4.535	1.022	288 (550)	B.2, B.6
JUB5	241	595	921.05	6.465	0.138	288 (550)	B.2, B.6
JUB6	277	588	979.24	6.683	0.151	288 (550)	B.2, B.6
F40-1	234	547	703.60	6.174	0.922	288 (550)	B.1, B.2
F40-2	235	550	719.30	5.661	1.46	288 (550)	B.1, B.2

(a) Stress-strain curve is represented by: $\epsilon = \sigma/E + (\sigma/F)^n$, where E = 193.1 GPa.

(b) For a normalized Ramberg-Osgood model given by: $\epsilon/\epsilon_0 = \sigma/\sigma_0 + \alpha(\sigma/\sigma_0)^n$, $\alpha = (\sigma_0)^{n-1}E/F^n$, where $\epsilon_0 = \sigma_0/E$, $\sigma_0 = \sigma_y$, and E = 193.1 GPa.

Table B.5 Quasi-static fracture toughness properties of TP304 stainless steel base metal at 288 C (550 F) (28 specimens)[(a)]

Specimen Code	Specimen Size	Net Thickness, mm	Notch[(b)] Type (SG%)	J_{Ic}, kJ/m²	C, kJ/m²	m	Test Temperature, C (F)	Reference
A23-10	1T	10.414	FC (20%)	1090	213.3	0.6144	288 (550)	B.1, B.2
A35-9	1T	13.030	FC (20%)	573	353.6	0.7667	288 (550)	B.1, B.2
A8-43	1T	18.212	FC (20%)	623	459.3	0.7953	288 (550)	B.1, B.2
A8-54	1T	4.064	FC (20%)	910	232.2	0.3121	288 (550)	B.1, B.2
A8-55	1T	8.636	FC (20%)	924	272.8	0.6720	288 (550)	B.1, B.2
A8-56	1T	8.255	FC (20%)	962	287.8	0.6104	288 (550)	B.1, B.2
A8-57	1T	16.256	FC (20%)	2230	284.0	0.4907	288 (550)	B.1, B.2
A8-71	1T	18.288	FC (20%)	1500	374.7	0.7236	288 (550)	B.1, B.2
A8-12A	1T	15.519	FC (20%)	854	451.5	0.7691	288 (550)	B.1, B.2
A23-113	0.5T	9.639	FC (20%)	646	232.6	0.8345	288 (550)	B.1, B.2
A23-9	0.5T	12.0	FC (0%)	1420	336.7	0.6185	288 (550)	B.1, B.2
A35-7	0.5T	16.0	FC (0%)	695	439.5	0.8089	288 (550)	B.1, B.2
A52-5	0.5T	7.0	FC (20%)	377	207.9	0.8190	288 (550)	B.2, B.3
A52-6	0.5T	6.9	FC (20%)	303	247.0	0.7726	288 (550)	B.2, B.3
A8-41	1T	22.8	FC (0%)	710	492.1	0.9207	288 (550)	B.1, B.2
A8-47	0.4T	5.0	FC (0%)	816	343.0	0.6907	288 (550)	B.1, B.2
A8-48	0.4T	5.0	FC (0%)	1160	246.8	0.4607	288 (550)	B.1, B.2
A8-49	1T	5.0	FC (0%)	1570	342.1	0.7787	288 (550)	B.1, B.2
A8-52	1.375T	5.0	FC (0%)	1690	539.2	0.6871	288 (550)	B.1, B.2
A45-37	1T	25.0	FC (0%)	2190	363.8	0.7225	288 (550)	B.1, B.2
A45-38	1T	19.0	FC (24%)	1370	415.7	0.9153	288 (550)	B.1, B.2
A45-39	3T	19.0	FC (24%)	1320	367.5	0.8616	288 (550)	B.1, B.2
A45-40	3T	25.0	FC (0%)	2480	194.9	0.8750	288 (550)	B.1, B.2
A45-41	10T	25.0	FC (0%)	2050	615.9	0.5798	288 (550)	B.1, B.2
A45-42	10T	20.0	FC (20%)	2190	318.1	0.5600	288 (550)	B.1, B.2
A23-2C	0.5T	12.7	FC (0%)	1124	117.0	0.9661	288 (550)	B.1, B.2
4B-J2	1T	–[(c)]	–[(c)]	473	360.3	0.8454	288 (550)	B.2, B.4
4CB-J2	1T	–[(c)]	–[(c)]	832	273.2	0.9187	288 (550)	B.2, B.4

(a) J-R curve is represented by: $J = J_{Ic} + C(\Delta a/r)^m$, where r = 1 mm and Δa is in mm.
(b) FC = fatigue pre-cracked; SG% = percent side-grooved.
(c) Not determined due to inadequate information.

Table B.6 Quasi-static fracture toughness properties of A106B carbon steel base metal at 200 C (392 F) to 300 C (572 F) (43 specimens)[(a)]

Specimen Code	Specimen Size	Net Thickness, mm	Notch[(b)] Type (SG%)	J_{Ic}, kJ/m^2	C, kJ/m^2	m	Test Temperature, C (F)	Reference
F13-19	1T	9.0	FC (0%)	193	119.22	0.795	288 (550)	B.1, B.2
F13-20	1T	7.2	FC (20%)	138	109.76	0.602	288 (550)	B.1, B.2
F29-17	1T	21.0	FC (0%)	111	123.86	0.71	288 (550)	B.1, B.2
F29-18	1T	16.8	FC (20%)	149	101.52	0.542	288 (550)	B.1, B.2
ZP13-3LC	0.5T	5.8	FC (0%)	455	285.76	0.822	288 (550)	B.2[(c)]
ZP13-4LC	0.5T	5.8	FC (0%)	388	187.21	0.702	288 (550)	B.2[(c)]
ZP13-7LC	0.5T	4.64	FC (20%)	274	76.68	0.826	288 (550)	B.2[(c)]
ZP13-8LC	0.5T	4.64	FC (20%)	244	140.52	0.72	288 (550)	B.2[(c)]
ZP14-3LC	0.8T	15.2	FC (0%)	322	187.83	0.801	288 (550)	B.2[(c)]
ZP14-3LC (SG)	0.8T	12.2	FC (20%)	183	126.16	0.779	288 (550)	B.2[(c)]
ZP14-4LC (SG)	0.8T	12.2	FC (20%)	197	119.5	0.761	288 (550)	B.2[(c)]
ZP14-5LC	0.8T	15.2	FC (0%)	246	196.5	0.828	288 (550)	B.2[(c)]
ZP15-3LC	0.5T	9.1	FC (0%)	125	123.3	0.694	288 (550)	B.2[(c)]
ZP15-4LC	0.5T	9.1	FC (0%)	126	113.89	0.658	288 (550)	B.2[(c)]
ZP15-5LC	0.5T	7.3	FC (20%)	104	98.62	0.764	288 (550)	B.2[(c)]
ZP15-6LC	0.5T	7.3	FC (20%)	111	92.99	0.74	288 (550)	B.2[(c)]
F22-3	0.5T	7.32	FC (20%)	79	106.64	0.7915	288 (550)	B.2[(d)]
F22-5	0.5T	7.29	FC (20%)	44	114.49	0.7007	288 (550)	B.2[(d)]
F23-1	1T	20.27	FC (20%)	74	118.45	0.7107	288 (550)	B.2[(d)]
F23-2	1T	20.35	FC (20%)	69	160.44	0.7089	288 (550)	B.2[(d)]
FE17-3	1T	20.32	FC (20%)	533	239.83	0.7976	288 (550)	B.2[(d)]
FE17-4	1T	20.32	FC (20%)	434	340.15	0.7362	288 (550)	B.2[(d)]
2F30F1	0.5T	10.36	FC (20%)	125	99.4	0.608	288 (550)	B.2, B.6
2F30F2	0.5T	10.41	FC (20%)	131	84.11	0.6913	288 (550)	B.2, B.6
2F29F1	1T	17.78	FC (20%)	139	105.64	0.4913	288 (550)	B.2, B.6
2F29F2	1T	17.78	FC (20%)	112	91.3	0.8009	288 (550)	B.2, B.6
OH-J01	0.75T	25.47	FC (20%)	185	118.82	0.6484	250 (482)	B.2[(e)]
OH-J02	0.75T	25.47	FC (20%)	160	117.62	0.6732	250 (482)	B.2[(e)]
OH-J03	0.75T	25.52	FC (20%)	265	131.96	0.708	250 (482)	B.2[(e)]
OH-J17	0.75T	24.46	FC (20%)	131	117.73	0.8783	250 (482)	B.2[(e)]
OH-J18	0.75T	24.59	FC (20%)	160	130.15	0.6304	250 (482)	B.2[(e)]
OH-J19	0.75T	24.55	FC (20%)	138	137.77	0.6108	250 (482)	B.2[(e)]
OH-J45	0.75T	15.21	FC (20%)	131	137.98	0.5721	250 (482)	B.2[(e)]
OH-J46	0.75T	15.05	FC (20%)	158	103.59	0.8468	250 (482)	B.2[(e)]
OH-J47	0.75T	15.20	FC (20%)	112	131.78	0.4062	250 (482)	B.2[(e)]
OH-J56	0.75T	20.12	FC (20%)	139	91.8	0.7528	250 (482)	B.2[(e)]
OH-J57	0.75T	19.95	FC (20%)	131	123.1	0.6434	250 (482)	B.2[(e)]
OH-J58	0.75T	20.05	FC (20%)	150	113.04	0.6947	250 (482)	B.2[(e)]
OH-TD13	0.75T	25.31	FC (20%)	113	86.05	0.4724	200 (392)	B.2[(e)]
OH-TD14	0.75T	25.43	FC (20%)	100	51.69	0.8237	200 (392)	B.2[(e)]
OH-TD15	0.75T	25.51	FC (20%)	98	43.88	0.9452	250 (482)	B.2[(e)]
OH-TD17	0.75T	25.41	FC (20%)	104	53.3	0.7883	300 (572)	B.2[(e)]
OH-TD18	0.75T	25.35	FC (20%)	79	63.01	0.5997	250 (482)	B.2[(e)]

(a) J-R curve is represented by: $J = J_{Ic} + C(\Delta a/r)^m$, where r = 1 mm and Δa is in mm.
(b) FC = fatigue pre-cracked; SG% = percent side-grooved.
(c) Further details can be found in "Fracture Toughness Characterization of Nuclear Piping Steels," NUREG/CR-5188, November 1989.
(d) Data were originally developed in the IPIRG-2 program at Battelle.
(e) Further details can be found in "Observations on the Effect of Post-Weld Heat Treatment on J-Resistance Curves of SA-106B Seamless Piping Welds," by B. Mukherjee, Nuclear Engineering and Design, Vol. 111, pp. 63-75, 1989.

Table B.7 Quasi-static fracture toughness properties of CF8M cast stainless steel base metal at 288 C (550 F) to 320 C (608 F) (25 specimens)[a]

Specimen Code	Specimen Size	Net Thickness, mm	Notch[b] Type (SG%)	J_{Ic}, kJ/m²	C, kJ/m²	m	Aging Tempera-ture, C	Aging Time, h	Test Tempera-ture, C (F)	Reference
207-10C	1T	20.3	FC (20%)	474	316.86	0.6957	Unaged	Unaged	290 (554)	B.2, B.5
207-09C	1T	20.4	FC (20%)	615	251.97	0.8063	Unaged	Unaged	290 (554)	B.2, B.5
205-24C	1T	20.2	FC (20%)	207	175.03	0.6373	400	18,000	290 (554)	B.2, B.5
743-07T	1T	20.3	FC (20%)	285	252.91	0.7694	Unaged	Unaged	290 (554)	B.2, B.5
743-03T	1T	20.3	FC (20%)	233	170.28	0.7221	320	50,000	290 (554)	B.2, B.5
741-05T	1T	20.0	FC (20%)	309	184.99	0.8018	400	2,570	290 (554)	B.2, B.5
741-02T	1T	20.0	FC (20%)	195	193.34	0.7307	400	10,000	290 (554)	B.2, B.5
741-04T	1T	20.3	FC (20%)	101	154.67	0.7165	450	3,000	290 (554)	B.2, B.5
752-08B	1T	20.0	FC (20%)	437	230.76	0.7896	Unaged	Unaged	290 (554)	B.2, B.5
753-05B	1T	20.3	FC (20%)	330	305.37	0.7621	Annealed	Annealed	290 (554)	B.2, B.5
752-07T	1T	20.0	FC (20%)	210	198.72	0.5976	320	30,000	290 (554)	B.2, B.5
753-02T	1T	20.3	FC (20%)	234	156.69	0.6475	320	50,000	290 (554)	B.2, B.5
752-03T	1T	20.0	FC (20%)	130	184	0.76	350	10,000	290 (554)	B.2, B.5
752-05T	1T	20.0	FC (20%)	108	191.17	0.6173	350	30,000	290 (554)	B.2, B.5
751-05T	1T	20.0	FC (20%)	150	200.15	0.4804	400	2,570	290 (554)	B.2, B.5
751-02T	1T	20.0	FC (20%)	156	140.46	0.7235	400	10,000	290 (554)	B.2, B.5
751-03T	1T	20.4	FC (20%)	107	141.62	0.5979	450	2,570	290 (554)	B.2, B.5
758-01C	1T	20.0	FC (20%)	167	132.85	0.712	400	18,000	290 (554)	B.2, B.5
6PB26	1T	20.0	FC (20%)	116	139.59	0.749	400	700	320 (608)	B.1, B.2[c]
3PA26	2T	40.0	FC (20%)	115	154.72	0.9069	400	700	320 (608)	B.1, B.2[c]
1PA26	2T	40.0	FC (20%)	99	167.32	0.8987	400	700	320 (608)	B.1, B.2[c]
A40-G00	1T	20.5	SMN	113	234.05	0.694	400	700	300 (572)	B.1, B.2[d]
A37-10	1.5T	24.0	FC (0%)	776	230.98	0.6964	400	18,000	288 (550)	B.1, B.2
A37-11	1.5T	23.0	SMN	1040	301.83	0.6334	400	18,000	288 (550)	B.1, B.2
A37-12	1.5T	22.0	SMN	1050	272.35	0.58	400	18,000	288 (550)	B.1, B.2

(a) J-R curve is represented by: $J = J_{Ic} + C(\Delta a/r)^m$, where r = 1 mm and Δa is in mm.
(b) FC = fatigue pre-cracked; SMN = sharp machine notch with radius of 0.127 mm; SG% = percent side-grooved.
(c) Data were developed from tests conducted at Framatome.
(d) Data were developed from tests conducted at DTRC.

Table B.8 Quasi-static fracture toughness properties of A516 Gr70 carbon steel base metal at 288 C (550 F) (13 specimens)[(a)]

Specimen Code	Specimen Size	Net Thickness, mm	Notch[(b)] Type (SG%)	J_{Ic}, kJ/m^2	C, kJ/m^2	m	Test Temperature, C (F)	Reference
F26-17	1T	19.0	FC (0%)	182	349.41	0.6	288 (550)	B.1, B.2
F26-19	1T	15.2	FC (20%)	217	121.85	0.727	288 (550)	B.1, B.2
F26-21	1T	21.0	SMN (0%)	260	246.4	0.625	288 (550)	B.1, B.2
F26-22	1T	16.8	SMN (20%)	211	141.84	0.543	288 (550)	B.1, B.2
B1	4T	52.8	FC (20%)	190	172.12	0.689	288 (550)	B.1, B.2
B2	4T	66.0	FC (0%)	97	231.1	0.829	288 (550)	B.1, B.2
F34-17	1T	20.0	FC (20%)	97	94.73	0.704	288 (550)	B.1, B.2
F34-18	1T	20.0	FC (20%)	125	233.13	0.525	288 (550)	B.1, B.2
F34-19	1T	20.0	FC (20%)	179	158.55	0.744	288 (550)	B.1, B.2
F34-20	1T	20.0	FC (20%)	190	156.73	0.708	288 (550)	B.1, B.2
F40-37	1T	25.0	FC (0%)	287	271.11	0.713	288 (550)	B.1, B.2
F40-38	1T	20.0	FC (20%)	228	131.87	0.752	288 (550)	B.1, B.2
F40-39	3T	20.0	FC (20%)	480	156.81	0.583	288 (550)	B.1, B.2

(a) J-R curve is represented by: $J = J_{Ic} + C(\Delta a/r)^m$, where r = 1 mm and Δa is in mm.

(b) FC = fatigue pre-cracked; SMN = sharp machine notch with radius of 0.127 mm; SG% = percent side-grooved.

Table B.9 Quasi-static fracture toughness properties of stainless steel flux-weld at 288 C (550 F) to 290 C (554 F) (28 specimens)[a]

Specimen Code	Specimen Size	Weld Type[b]	Net Thickness, mm	Notch[c] Type (SG%)	J_{Ic}, kJ/m^2	C, kJ/m^2	m	Test Temperature, C (F)	Reference
A45W2-2	1T	SAW	19.79	FC (20%)	58	148.1	0.7932	288 (550)	B.2
A45W2-3	1T	SAW	19.99	FC (20%)	61	146.8	0.7444	288 (550)	B.2
A8W-110	1T	SAW	17.65	FC (20%)	55	122.3	0.7618	288 (550)	B.1, B.2
A45W-1	1T	SAW	25.50	FC (0%)	96	102.2	0.8229	288 (550)	B.1, B.2
A45W-2	1T	SAW	25.50	FC (0%)	120	144.4	0.7052	288 (550)	B.1, B.2
A45W-7	1T	SAW	21.70	SMN (0%)	128	177.3	0.6070	288 (550)	B.1, B.2
A45W-8	1T	SAW	24.90	SMN (0%)	69	122.9	0.7980	288 (550)	B.1, B.2
A45WA-3	1T	SAW-SA	25.20	SMN (0%)	186	160.1	0.8020	288 (550)	B.1, B.2
A45WA-4	1T	SAW-SA	25.30	SMN (0%)	154	169.6	0.7530	288 (550)	B.1, B.2
2-1re	2T	SAW	25.40	FC (0%)	210	184.9	0.4448	288 (550)	B.2[d]
2-2re	2T	SAW-SA	25.40	FC (0%)	221	65.7	0.6102	288 (550)	B.2[d]
3re	2T	SAW	25.40	FC (0%)	170	70.1	0.6279	288 (550)	B.2[d]
5g1	2T	SMAW	25.40	FC (0%)	194	103.1	0.6649	288 (550)	B.2[d]
5g3	2T	SMAW	25.40	FC (0%)	215	96.3	0.7160	288 (550)	B.2[d]
5g4	2T	SMAW-SA	25.40	FC (0%)	169	37.8	0.9776	288 (550)	B.2[d]
FUC-10	1T	SAW	18.10	FC (20%)	213	94.2	0.9189	288 (550)	B.2[e]
FUC-12	1T	SAW	18.10	FC (20%)	174	89.0	0.8048	288 (550)	B.2[e]
6WSW-J2	1T	SMAW	20.32	FC (20%)	109	95.7	0.7370	288 (550)	B.2, B.4
4SMAW-J2	1T	SMAW	–[f]	–[f]	168	124.9	0.8171	288 (550)	B.2, B.4
4WSA-J2	1T	SAW	–[f]	–[f]	47	101.7	0.9459	288 (550)	B.2, B.4
A45W2-5	1T	SAW	24.36	FC (0%)	38	165.6	0.7494	288 (550)	B.2
A45W2-6	1T	SAW	24.33	FC (0%)	57	204.4	0.7159	288 (550)	B.2
A53W1-FL-1	1T	SAW	17.80	FC (0%)	475	148.3	0.7212	288 (550)	B.2[g]
A53W1-FL-2	1T	SAW	17.80	FC (0%)	510	193.0	0.7306	288 (550)	B.2[g]
A8W4-FL-1	1T	SAW	17.10	FC (0%)	600	220.5	0.6359	288 (550)	B.2[g]
A8W4-FL-2	1T	SAW	17.10	FC (0%)	899	122.4	0.4849	288 (550)	B.2[g]
A8W4-FL-3	1T	SAW	17.10	FC (0%)	803	54.9	0.5524	288 (550)	B.2[g]
205-23C	1T	–[f]	20.32	FC (20%)	187	71.9	0.8174	290 (554)	B.2, B.5

(a) J-R curve is represented by: $J = J_{Ic} + C(\Delta a/r)^m$, where r = 1 mm and Δa is in mm.
(b) SAW = submerged-arc weld; SMAW = shielded-metal arc weld; SA = solution-annealed.
(c) FC = fatigue pre-cracked; SMN = sharp machine notch with radius of 0.127 mm; SG% = percent side-grooved.
(d) Further details can be found in "Evaluation of the toughness of austenitic stainless steel pipe weldments," EPRI NP-4668, June 1986.
(e) Further details can be found in "J-integral Tearing Instability Analyses for 8-inch Diameter ASTM A106 Steel Pipe," NUREG/CR-3740, R5, April 1984.
(f) Not determined due to inadequate information.
(g) Data were originally developed in the Short Cracks in Piping and Piping Welds program of Battelle.

Table B.10 Quasi-static fracture toughness properties of carbon steel flux-weld at 250 C (482 F) to 288 C (550 F) (45 specimens)[(a)]

Specimen Code	Specimen Size	Weld Type[(b)]	Net Thickness, mm	Notch[(c)] Type (SG%)	J_{Ic}, kJ/m^2	C, kJ/m^2	m	Test Temperature, C (F)	Reference
F86W-13	0.5T	SMAW	9.65	FC (0%)	100	364.92	0.4972	288 (550)	B.1, B.2
F86W-14	0.5T	SMAW	9.65	FC (0%)	110	202.02	0.7149	288 (550)	B.1, B.2
F86W-15	0.5T	SMAW	7.72	FC (20%)	160	194.21	0.624	288 (550)	B.1, B.2
F86W-16	0.5T	SMAW	7.72	FC (20%)	170	179.98	0.7825	288 (550)	B.1, B.2
F34W-30	1.375T	SW	26.0	SMN (20%)	390	419.56	0.3744	288 (550)	B.1, B.2
F34W-31	1.375T	SW	26.2	SMN (20%)	170	265.11	0.448	288 (550)	B.1, B.2
F34W-32	1.375T	SW	26.2	SMN (20%)	580	211.41	0.545	288 (550)	B.1, B.2
F40W2-54	1T	SAW	18.8	FC (20%)	60	57.3	0.575	288 (550)	B.1, B.2
F40W2-55	1T	SAW	23.5	FC (0%)	60	64.19	0.7106	288 (550)	B.1, B.2
F29W-12	1T	SAW	17.1	FC (20%)	82	79.58	0.637	288 (550)	B.1, B.2
F49W-3	1.25T	SAW	25.2	FC (20%)	53	85.93	0.698	288 (550)	B.1, B.2
F49W-4	1.25T	SAW	25.0	FC (20%)	59	85.97	0.68	288 (550)	B.1, B.2
F49W-5	1.25T	SAW	31.0	FC (0%)	55	120.57	0.742	288 (550)	B.1, B.2
F49W-6	1.25T	SAW	31.0	FC (0%)	62	107.94	0.83	288 (550)	B.1, B.2
OH-J04	0.75T	SMAW	24.0	FC (20%)	419	151.94	0.5788	250 (482)	B.2[(d)]
OH-J05	0.75T	SMAW	24.0	FC (21%)	495	172.95	0.7356	250 (482)	B.2[(d)]
OH-J06	0.75T	SMAW	24.1	FC (21%)	378	166.77	0.704	250 (482)	B.2[(d)]
OH-J09	0.75T	SMAW	24.0	FC (21%)	246	98.56	0.9242	250 (482)	B.2[(d)]
OH-J10	0.75T	SMAW	24.1	FC (21%)	243	104.29	0.8642	250 (482)	B.2[(d)]
OH-J11	0.75T	SMAW	24.0	FC (21%)	223	150.19	0.6293	250 (482)	B.2[(d)]
OH-J12	0.75T	SMAW	24.2	FC (20%)	214	105.78	0.681	250 (482)	B.2[(d)]
OH-J23	0.75T	SMAW	20.1	FC (20%)	134	99.88	0.7389	250 (482)	B.2[(d)]
OH-J24	0.75T	SMAW	20.2	FC (20%)	110	103.24	0.5251	250 (482)	B.2[(d)]
OH-J25	0.75T	SMAW	20.2	FC (20%)	135	90.73	0.762	250 (482)	B.2[(d)]
OH-J33	0.75T	SAW	20.1	FC (20%)	86	78.77	0.5589	250 (482)	B.2[(d)]
OH-J34	0.75T	SAW	20.2	FC (20%)	63	69.21	0.679	250 (482)	B.2[(d)]
OH-J35	0.75T	SAW	20.2	FC (20%)	74	76.86	0.6021	250 (482)	B.2[(d)]
OH-J40	0.75T	SMAW	20.0	FC (21%)	346	154.88	0.6437	250 (482)	B.2[(d)]
OH-J41	0.75T	SMAW	20.0	FC (21%)	236	139.07	0.62	250 (482)	B.2[(d)]
OH-J42	0.75T	SMAW	20.0	FC (21%)	323	150.45	0.7061	250 (482)	B.2[(d)]
OH-J48	0.75T	SMAW	12.6	FC (20%)	54	87.47	0.7777	250 (482)	B.2[(d)]
OH-J49	0.75T	SMAW	13.0	FC (20%)	121	96.98	0.5577	250 (482)	B.2[(d)]
OH-J50	0.75T	SMAW	13.2	FC (19%)	95	122.78	0.6166	250 (482)	B.2[(d)]
OH-J84	0.75T	SAW	20.0	FC (21%)	162	150.39	0.7438	250 (482)	B.2[(d)]
OH-J85	0.75T	SAW	20.0	FC (21%)	132	174.94	0.6694	250 (482)	B.2[(d)]
473JW1	1T	SAW	20.4	(20%)[(e)]	175	134.69	0.8107	288 (550)	B.2, B.6
473JW2	1T	SAW	20.6	(20%)[(e)]	168	131.64	0.7651	288 (550)	B.2, B.6
BBM871	1T	SMAW	20.4	(20%)[(e)]	273	277.45	0.8479	288 (550)	B.2, B.6
BBM872	1T	SMAW	20.4	(20%)[(e)]	263	203.94	0.7307	288 (550)	B.2, B.6
018AW1	1T	SMAW	20.4	(20%)[(e)]	139	96.81	0.8338	288 (550)	B.2, B.6
018AW2	1T	SMAW	20.4	(20%)[(e)]	184	133.56	0.5459	288 (550)	B.2, B.6
181SR1	1T	SMAW	20.4	(20%)[(e)]	420	149.44	0.7352	288 (550)	B.2, B.6
181SR2	1T	SMAW	20.4	(20%)[(e)]	326	176.62	0.6445	288 (550)	B.2, B.6
F40W21	1T	SAW	20.4	(20%)[(e)]	91	49.39	0.4361	288 (550)	B.2, B.6
F40W22	1T	SAW	20.4	(20%)[(e)]	52	62.81	0.6015	288 (550)	B.2, B.6

(a) J-R curve is represented by: $J = J_{Ic} + C(\Delta a/r)^m$, where r = 1 mm and Δa is in mm.
(b) SAW = submerged-arc weld; SMAW = shielded-metal arc weld; SW = shop weld (girth).
(c) FC = fatigue pre-cracked; SMN = sharp machine notch with radius of 0.127 mm; SG% = percent side-grooved.
(d) Further details can be found in "Observations on the effect of post-weld heat treatment on J-resistance curves of SA-106B seamless piping welds," by B. Mukherjee, Nuclear Engineering and Design, Vol. 111, pp. 63-75, 1989.
(e) Notch type could not be determined due to inadequate information.

Table B.11 Mean and covariance of quasi-static material properties for TP304 stainless steel base metal at 288 C (550 F)

Random Vector	Mean Vector	Covariance Matrix
$\begin{Bmatrix} \sigma_y \\ \sigma_u \end{Bmatrix}^{(a)}$	$\begin{Bmatrix} 154.782 \\ 442.397 \end{Bmatrix}$	$\begin{bmatrix} 124.502 & 33.706 \\ 33.706 & 588.703 \end{bmatrix}$
$\begin{Bmatrix} \alpha \\ n \end{Bmatrix}^{(b)}$	$\begin{Bmatrix} 8.073 \\ 3.800 \end{Bmatrix}$	$\begin{bmatrix} 12.538 & -1.727 \\ -1.727 & 0.308 \end{bmatrix}$
$\begin{Bmatrix} F \\ n \end{Bmatrix}^{(c)}$	$\begin{Bmatrix} 605.32 \\ 3.800 \end{Bmatrix}$	$\begin{bmatrix} 2.798\times10^3 & -14.355 \\ -14.355 & 0.308 \end{bmatrix}$
$\begin{Bmatrix} J_{Ic} \\ C \\ m \end{Bmatrix}^{(d)}$	$\begin{Bmatrix} 1242.70 \\ 344.189 \\ 0.7393 \end{Bmatrix}$	$\begin{bmatrix} 3.404\times10^5 & 1.112\times10^4 & -15.938 \\ 1.112\times10^4 & 1.282\times10^4 & -1.170 \\ -15.938 & -1.170 & 0.0231 \end{bmatrix}$

(a) Both σ_y and σ_u are in MPa unit.
(b) α and n are dimensionless; σ_0 = 154.78 MPa; E = 182.7 GPa (see Equation 3-1).
(c) F is in MPa unit; n is dimensionless; E = 182.7 GPa (see Equation 3-2).
(d) Both J_{Ic} and C are in kJ/m^2 unit with r = 1 mm (see Equation 3-4); m is dimensionless; Δa is to be expressed in mm unit.

Table B.12 Mean and covariance of quasi-static material properties for A106B carbon steel base metal at 288 C (550 F)

Random Vector	Mean Vector	Covariance Matrix
$\begin{Bmatrix} \sigma_y \\ \sigma_u \end{Bmatrix}^{(a)}$	$\begin{Bmatrix} 245.095 \\ 557.429 \end{Bmatrix}$	$\begin{bmatrix} 967.800 & 653.614 \\ 653.614 & 4042.01 \end{bmatrix}$
$\begin{Bmatrix} \alpha \\ n \end{Bmatrix}^{(b)}$	$\begin{Bmatrix} 2.223 \\ 4.901 \end{Bmatrix}$	$\begin{bmatrix} 2.389 & -1.234 \\ -1.234 & 1.734 \end{bmatrix}$
$\begin{Bmatrix} F \\ n \end{Bmatrix}^{(c)}$	$\begin{Bmatrix} 938.58 \\ 4.901 \end{Bmatrix}$	$\begin{bmatrix} 3.969\times10^4 & -196.895 \\ -196.895 & 1.734 \end{bmatrix}$
$\begin{Bmatrix} J_{Ic} \\ C \\ m \end{Bmatrix}^{(d)}$	$\begin{Bmatrix} 183.395 \\ 133.139 \\ 0.7116 \end{Bmatrix}$	$\begin{bmatrix} 1.146\times10^4 & 4.842\times10^3 & 3.396 \\ 4.842\times10^3 & 2.670\times10^3 & 1.641 \\ 3.396 & 1.641 & 0.0051 \end{bmatrix}$

(a) Both σ_y and σ_u are in MPa unit.
(b) α and n are dimensionless; $\sigma_0 = 245.10$ MPa; E = 193.1 GPa (see Equation 3-1).
(c) F is in MPa unit; n is dimensionless; E = 193.1 GPa (see Equation 3-2).
(d) Both J_{Ic} and C are in kJ/m^2 unit with r = 1 mm (see Equation 3-4); m is dimensionless; Δa is to be expressed in mm unit.

Table B.13 Mean and covariance of quasi-static material properties for CF8M cast stainless steel base metal at 288 C (550 F)

Random Vector	Mean Vector	Covariance Matrix
$\begin{Bmatrix} \sigma_y \\ \sigma_u \end{Bmatrix}^{(a)}$	$\begin{Bmatrix} 201.051 \\ 529.197 \end{Bmatrix}$	$\begin{bmatrix} 663.905 & 1199.76 \\ 1199.76 & 4419.50 \end{bmatrix}$
$\begin{Bmatrix} \alpha \\ n \end{Bmatrix}^{(b)}$	$\begin{Bmatrix} 3.524 \\ 4.839 \end{Bmatrix}$	$\begin{bmatrix} 13.619 & -1.806 \\ -1.806 & 0.661 \end{bmatrix}$
$\begin{Bmatrix} F \\ n \end{Bmatrix}^{(c)}$	$\begin{Bmatrix} 720.47 \\ 4.839 \end{Bmatrix}$	$\begin{bmatrix} 1.313\times10^4 & -27.886 \\ -27.886 & 0.6611 \end{bmatrix}$
$\begin{Bmatrix} J_{Ic} \\ C \\ m \end{Bmatrix}^{(d)}$	$\begin{Bmatrix} 300.637 \\ 202.069 \\ 0.7196 \end{Bmatrix}$	$\begin{bmatrix} 6.551\times10^4 & 8.934\times10^3 & -6.035 \\ 8.934\times10^3 & 2.642\times10^3 & -0.454 \\ -6.035 & -0.454 & 0.0078 \end{bmatrix}$

(a) Both σ_y and σ_u are in MPa unit.
(b) α and n are dimensionless; σ_0 = 201.05 MPa; E = 182.7 GPa (see Equation 3-1).
(c) F is in MPa unit; n is dimensionless; E = 182.7 GPa (see Equation 3-2).
(d) Both J_{Ic} and C are in kJ/m^2 unit with r = 1 mm (see Equation 3-4); m is dimensionless; Δa is to be expressed in mm unit.

Table B.14 Mean and covariance of quasi-static material properties for A516 Gr70 carbon steel base metal at 288 C (550 F)

Random Vector	Mean Vector	Covariance Matrix
$\begin{Bmatrix} \sigma_y \\ \sigma_u \end{Bmatrix}^{(a)}$	$\begin{Bmatrix} 295.250 \\ 562.847 \end{Bmatrix}$	$\begin{bmatrix} 4920.81 & 530.614 \\ 530.614 & 1097.76 \end{bmatrix}$
$\begin{Bmatrix} \alpha \\ n \end{Bmatrix}^{(b)}$	$\begin{Bmatrix} 1.891 \\ 5.835 \end{Bmatrix}$	$\begin{bmatrix} 2.407 & -0.837 \\ -0.837 & 0.996 \end{bmatrix}$
$\begin{Bmatrix} F \\ n \end{Bmatrix}^{(c)}$	$\begin{Bmatrix} 892.38 \\ 5.835 \end{Bmatrix}$	$\begin{bmatrix} 1.459\times10^4 & -45.789 \\ -45.789 & 0.9960 \end{bmatrix}$
$\begin{Bmatrix} J_{Ic} \\ C \\ m \end{Bmatrix}^{(d)}$	$\begin{Bmatrix} 216.194 \\ 204.328 \\ 0.6738 \end{Bmatrix}$	$\begin{bmatrix} 5.189\times10^3 & -6.406\times10^2 & -1.738 \\ -6.406\times10^2 & 5.026\times10^3 & -0.240 \\ -1.738 & -0.240 & 0.0060 \end{bmatrix}$

(a) Both σ_y and σ_u are in MPa unit.
(b) α and n are dimensionless; σ_0 = 295.25 MPa; E = 193.1 GPa (see Equation 3-1).
(c) F is in MPa unit; n is dimensionless; E = 193.1 GPa (see Equation 3-2).
(d) Both J_{Ic} and C are in kJ/m^2 unit with r = 1 mm (see Equation 3-4); m is dimensionless; Δa is to be expressed in mm unit.

Table B.15 Mean and covariance of quasi-static material properties for stainless steel and carbon steel flux-welds at 288 C (550 F)

Random Vector	Mean Vector	Covariance Matrix
(a) Stainless Steel Flux-Weld		
$\begin{Bmatrix} J_{Ic} \\ C \\ m \end{Bmatrix}^{(a)}$	$\begin{Bmatrix} 194.649 \\ 119.314 \\ 0.733 \end{Bmatrix}$	$\begin{bmatrix} 2.756\times10^4 & 5.754\times10^2 & -8.141 \\ 5.754\times10^2 & 1.807\times10^3 & -2.278 \\ -8.141 & -2.278 & 0.0159 \end{bmatrix}$
(b) Carbon Steel Flux-Weld		
$\begin{Bmatrix} J_{Ic} \\ C \\ m \end{Bmatrix}^{(a)}$	$\begin{Bmatrix} 170.675 \\ 137.170 \\ 0.6694 \end{Bmatrix}$	$\begin{bmatrix} 1.367\times10^4 & 4.744\times10^3 & -0.2639 \\ 4.744\times10^3 & 4.761\times10^3 & -0.6344 \\ -0.2639 & -0.6344 & 0.0072 \end{bmatrix}$

(a) Both J_{Ic} and C are in kJ/m^2 unit with $r = 1$ mm (see Equation 3-4); m is dimensionless; Δa is to be expressed in mm unit.

APPENDIX C FORM/SORM AND IMPORTANCE SAMPLING

C.1 First- and Second-Order Reliability Methods (FORM/SORM)

Consider a transformation $H : \mathbf{X} \rightarrow \mathbf{U}$ where $\mathbf{U} \in \Re^N$ denotes an N-dimensional independent standard Gaussian random vector and $\Re^N$ represents an N-dimensional real vector space. The transformation H is necessary if originally the basic uncertainty vector, $\mathbf{X}$, has an arbitrary joint distribution function, $F_{\mathbf{X}}(\mathbf{x})$. For example, when the Rosenblatt transformation (Ref. C.1) is used, the explicit form of the above mapping from the original $\mathbf{x}$ space to $\mathbf{u}$ space becomes

$$H : \begin{cases} u_1 = \Phi^{-1}[F_1(x_1)] \\ u_2 = \Phi^{-1}[F_2(x_2 \mid x_1)] \\ \cdot \quad \cdot \\ \cdot \quad \cdot \\ u_n = \Phi^{-1}[F_n(x_n \mid x_1, x_2, \cdots, x_{n-1})] \end{cases} \tag{C-1}$$

in which $F_i(x_i \mid x_1, x_2, \cdots, x_{i-1})$ is the cumulative distribution function of component X_i, conditional on $X_1 = x_1$, $X_2 = x_2, \cdots, X_{i-1} = x_{i-1}$, and $\Phi(\cdot)$ is the cumulative distribution function of a standard Gaussian random variable. $F_i(x_i \mid x_1, x_2, \cdots, x_{i-1})$ can be obtained from

$$F_i(x_i \mid x_1, x_2, \cdots, x_{i-1}) = \frac{\int_{-\infty}^{x_i} f_{1,2,\cdots,i}(x_1, x_2, \cdots, x_{i-1}, s)\, ds}{f_{1,2,\cdots,i-1}(x_1, x_2, \cdots, x_{i-1})} \tag{C-2}$$

where $f_{1,2,\cdots,i-1}(x_1, x_2, \cdots, x_{i-1})$ is the joint probability density function of $\{X_1, X_2, \cdots, X_{i-1}\}^T$. The inverse transformation can be obtained in a stepwise manner as

$$H^{-1} : \begin{cases} x_1 = F_1^{-1}[\Phi(u_1)] \\ x_2 = F_2^{-1}[\Phi(u_2) \mid x_1] \\ \cdot \quad \cdot \\ \cdot \quad \cdot \\ x_n = F_n^{-1}[\Phi(u_n) \mid x_1, x_2, \cdots, x_{n-1}] \end{cases} \tag{C-3}$$

which when substituted into Equation 4-5 yields

$$P_F = \Pr[g_U(\mathbf{U}) < 0] = \int_{g_U(\mathbf{U})<0} \phi(\mathbf{u})\, d\mathbf{u} \tag{C-4}$$

where $\phi(\mathbf{u})$ is the standard multivariate Gaussian probability density function defined as

$$\phi(\mathbf{u}) = (2\pi)^{-\frac{N}{2}} \exp\left[-\frac{1}{2}\mathbf{u}^T\mathbf{u}\right] \tag{C-5}$$

and $g_U(\mathbf{u})$ is the new limit state surface in the Gaussian image, $\mathbf{u}$, of the original space, $\mathbf{x}$. Note that Equation C-4 represents the same N-dimensional integral as Equation 4-5 but in a different space from the original space due to a change of variables, described earlier. The integral is still difficult to compute unless some approximations are sought for the domain of the integral.

C.1.1 First-Order Reliability Method (FORM)

Consider a tangential linearization at the point $\mathbf{u}^*$ of the limit state surface $g_U(\mathbf{u}) = 0$, which is given by

$$g_L(\mathbf{u}) = \alpha^T(\mathbf{u} - \mathbf{u}^*) = 0 \tag{C-6}$$

where $\mathbf{u}^*$ is the closest point (known as the design point, beta point etc.) of $g_U(\mathbf{u}) = 0$ to the origin of $\mathbf{u}$ space, and $\alpha \in \Re^N$ is the vector of direction cosines. α can be obtained from

$$\alpha = \frac{\nabla g_U(\mathbf{u}^*)}{\|\nabla g_U(\mathbf{u}^*)\|} \tag{C-7}$$

in which

$$\nabla = \left\{ \frac{\partial}{\partial u_1} \quad \frac{\partial}{\partial u_2} \quad \cdots \quad \frac{\partial}{\partial u_N} \right\}^T \tag{C-8}$$

$\nabla g_U(\mathbf{u}^*)$ is the gradient of scalar field $g_U(\mathbf{u})$ at $\mathbf{u}^*$, and

$$\| \nabla g_U(\mathbf{u}^*)\| = \sqrt{\sum_{i=1}^{N} \left|\frac{\partial g_U}{\partial u_i}(\mathbf{u}^*)\right|^2} \tag{C-9}$$

is the Euclidean $\mathcal{L}_2$-norm of an N-dimensional vector, $\nabla g_U(\mathbf{u}^*)$. The distance β_{HL} of this point $\mathbf{u}^*$ to the origin of $\mathbf{u}$ space is referred to as Hasofer-Lind Reliability Index (Ref. C.2). β_{HL} can be obtained from a nonlinear optimization scheme, which can be mathematically formulated as

$$\begin{aligned} \beta_{HL} &= \underset{g_U(\mathbf{u})=0}{\text{Minimum}} \ \| \mathbf{u} \| \\ &= \| \mathbf{u}^* \| \\ &= \alpha^T \mathbf{u}^* \end{aligned} \tag{C-10}$$

which requires the determination of the design point, $\mathbf{u}^*$. When the linear approximation of the limit state in Equation C-6 is substituted into Equation C-4, the estimate of P_F by FORM becomes (Ref. C.3)

$$\begin{aligned} P_{F,1} &= \int_{\alpha^T(\mathbf{u}-\mathbf{u}^*)<0} \phi(\mathbf{u})\ d\mathbf{u} \\ &= \int_{\alpha^T\mathbf{u}-\beta_{HL}<0} \phi(\mathbf{u})\ d\mathbf{u} \\ &= \Phi(-\beta_{HL}) \end{aligned} \tag{C-11}$$

C.1.2 Second-Order Reliability Method (SORM)

Consider a suitable rotational transformation from the $\mathbf{u}$ space to the $\mathbf{v}$ space so that the mapped design point, $\mathbf{v}^*$, in $\mathbf{v}$ space has the coordinates $(0,0,\cdots,-\beta_{HL})$. Suppose that the transformed vector $\mathbf{v} = \{v_1,v_2,\cdots,v_N\} = \{\mathbf{v}_r,v_N\}^T$ where $\mathbf{v}_r = \{v_1,v_2,\cdots,v_{N-1}\}$ is the reduced vector and $v_N = h_V(\mathbf{v}_r)$ is the root of the mapped limit state surface, $g_V(\mathbf{v}_r,v_n) = 0$, in $\mathbf{v}$ space. In this way, the limit state surface, $g_V(\mathbf{v}) = g_V(\mathbf{v}_r,v_n) = 0$, can be alternatively represented by $v_N = h_V(\mathbf{v}_r)$ in the $\mathbf{v}$ space. Consider now a second-order approximation, $g_Q(\mathbf{v}) = 0$, or rather an approximation, $v_N = h_Q(\mathbf{v}_r)$ to $v_N = h_V(\mathbf{v}_r)$, of the limit state surface. If the quadratic approximant is of special form such as the rotational hyperparaboloid, it can be shown that

$$h_Q(\mathbf{v}_r) = -\beta_{HL} + \frac{1}{2}\sum_{i=1}^{N-1} \kappa_i v_i^2 \tag{C-12}$$

where κ_i is the ith principal curvature of the limit-state surface at the design point. The above quadratic is equivalent to the actual $v_n = h_V(\mathbf{v}_r)$ in the sense that

$$h_Q(v_r^*) = h_V(v_r^*) \tag{C-13}$$

$$\frac{\partial h_Q}{\partial v_i}(v_r^*) = \frac{\partial h_V}{\partial v_i}(v_r^*) \tag{C-14}$$

$$\frac{\partial^2 h_Q}{\partial v_i \partial v_j}(v_r^*) = \frac{\partial^2 h_V}{\partial v_i \partial v_j}(v_r^*) \tag{C-15}$$

for i,j = 1,2, · · ·,N-1. When the actual limit state surface is approximated by the hyperparaboloid in Equation C-12, the estimate of P_F by SORM becomes (Ref. C.4)

$$P_{F,2} \simeq \Phi(-\beta_{HL}) \prod_{i=1}^{N-1} (1 - \kappa_i \beta_{HL})^{-\frac{1}{2}} \tag{C-16}$$

which is asymptotically exact when β_{HL} approaches infinity. An improvement over the above probability estimate has also been proposed by Hohenbichler (Ref. C.5), who gives

$$P_{F,2} \simeq \Phi(-\beta_{HL}) \prod_{i=1}^{N-1} \left[1 - \kappa_i \Psi(-\beta_{HL})\right]^{-\frac{1}{2}} \tag{C-17}$$

where

$$\Psi(-\beta_{HL}) = \frac{\phi(-\beta_{HL})}{\Phi(-\beta_{HL})} \tag{C-18}$$

Note that when β_{HL} approaches infinity, $\Psi(\beta_{HL})$ approaches β_{HL} and Equation C-17 degenerates to Equation C-16 as expected.

C.2 Importance Sampling

In Importance Sampling, the input random variables are sampled from a different probability density, known as the sampling density. The purpose is to generate more outcomes from the region of interest, e.g., the failure set $F = \{x: g(x) < 0\}$. Using information from FORM/SORM analyses, good sampling densities can be constructed.

Consider Equation C-4 which can be rewritten in the form

$$\begin{aligned} P_F &= \Pr\left[g_{app}(\mathbf{U}) < 0\right] \times \frac{\Pr\left[g_U(\mathbf{U}) < 0\right]}{\Pr\left[g_{app}(\mathbf{U}) < 0\right]} \\ &= \Pr\left[g_{app}(\mathbf{U}) < 0\right] \times C_F \end{aligned} \qquad \text{(C-19)}$$

where $g_{app}(\mathbf{U})$ is either a linear or quadratic approximation to the limit state surface, $g_U(\mathbf{U})$, and $C_F = \Pr[g_U(\mathbf{U}) < 0]/\Pr[g_{app}(\mathbf{U}) < 0]$ is the correction factor improving the reliability estimate by $g_{app}(\mathbf{U})$. When the quadratic approximation in Equation C-12 is used, C_F can be approximated by simulation with importance sampling. According to Hohenbichler (Ref. 100), it is given by

$$C_F \simeq \frac{1}{N_{IS}} \sum_{j=1}^{N_{IS}} C_{F,j} \qquad \text{(C-20)}$$

in which

$$C_{F,j} = \frac{\Phi\left(h_Q(\mathbf{w}_j)\right)}{\Phi(\beta_{HL})} \exp\left[-\frac{1}{2}\Psi(\beta_{HL}) \sum_{k=1}^{N-1} \kappa_k w_{k,j}^2\right] \qquad \text{(C-21)}$$

where $\mathbf{w}_j = \{w_{1,j}, w_{2,j}, \cdots, w_{N-1,j}\}^T$ is the jth realization of the independent Gaussian random vector $\mathbf{W} \in \Re^{N-1}$ with mean zero and variance, $\mathrm{Var}[W_i]$, of the ith component given by

$$\mathrm{Var}\left[W_i\right] = \frac{1}{\left[1 - \Psi(-\beta_{HL})\right]} \qquad \text{(C-22)}$$

and N_{IS} is the total number of samples for this simulation. Thus, the estimates of $P_{F,IS}$ by simulation with importance sampling becomes

$$P_{F,IS} \simeq \Phi(-\beta_{HL}) \prod_{i=1}^{N-1} \left[1 - \kappa_i \Psi(-\beta_{HL})\right]^{-\frac{1}{2}} \frac{1}{N_{IS}} \sum_{j=1}^{N_{IS}} \frac{\Phi\left(h_Q(\mathbf{w}_j)\right)}{\Phi(\beta_{HL})} \exp\left[-\frac{1}{2}\Psi(\beta_{HL}) \sum_{k=1}^{N-1} \kappa_k w_{k,j}^2\right] \qquad \text{(C-23)}$$

C.3 References

C.1 Rosenblatt, M., "Remarks on a Multivariate Transformation," Ann. Math. Statistics, Vol. 23, pp. 470-472, 1952.

C.2 Hasofer, A. M. and Lind, N. C., "An Exact and Invariant First-Order Reliability Format," Journal of Engineering Mechanics, ASCE, Vol. 100, No. EM1, pp. 111-121, February 1974.

C.3 Rackwitz, R. and Fiessler, B., "Structural Reliability under Combined Random Load Sequences," Computer and Structures, Vol. 9, pp. 484-494, 1978.

C.4 Breitung, K., "Asymptotic Approximation for Multinormal Integrals," Journal of Engineering Mechanics, ASCE, Vol. 110 No. 3, pp. 357-366, March 1984.

C.5 Hohenbichler, M., "Improvement of Second-Order Reliability Estimates by Importance Sampling," Journal of Engineering Mechanics, ASCE, Vol. 114, No. 12, pp. 2195-2199, December 1988.

APPENDIX D SAMPLE GENERATION OF RANDOM VECTOR

A simple method is presented for generating samples of the N-dimensional generic random vector, $\mathbf{X} = \{X_1, X_2, \cdots, X_N\}$, with arbitrary joint distribution function, $F_{\mathbf{X}}(\mathbf{x})$. The vector **X** may have independent and correlated components.

D.1 Independent Random Parameters

Consider a random component, X_i, with the cumulative probability distribution function, $F_i(x_i)$. Let Z_i be a random variable uniformly distributed in the interval [0,1]. It has the distribution function, $F_{Z_i}(z_i) = z_i$. For a probability preserving transformation with the distribution functions of X_i and Z_i being equal, the realization, x_i, of random variable, X_i, can be obtained as

$$x_i = F_i^{-1}(z_i) \tag{D-1}$$

A two-step simulation technique can be developed based on this transformation. First, a sample, z_i, of Z_i is generated, e.g., by using a standard random number generator available in any computer. Second, a sample of X_i can be obtained from Equation D-1. Thus, by generating independent samples of Z_i, one can obtain from Equation D-1 independent samples of X_i.

Alternative simulation techniques are available and can be found in Reference D.1. They are based on the characteristics of various probability distributions.

D.2 Dependent Random Parameters

Consider an N-dimensional random vector, **X**, with a generic joint distribution function, $F_{\mathbf{X}}(\mathbf{x})$. A three-phase method can be applied to generate samples, **x**, of **X**. First, generate N independent uniformly distributed samples, $z_1, z_2, \cdots, z_N$, in the interval [0,1]. Second, map each of these samples into a sample, u_i, of a standard Gaussian random variable, U_i. For example, u_i can be obtained from $u_i = \Phi^{-1}(z_i)$, $i = 1,2,\cdots,N$ where $\Phi(\cdot)$ is the cumulative distribution function of a standard Gaussian random variable. Third, use the Rosenblatt transformation described in Appendix C to map the samples of the standard Gaussian vector, $\mathbf{U} = \{U_1, U_2, \cdots, U_N\}$, into the corresponding samples of $\mathbf{X} = \{X_1, X_2, \cdots, X_N\}$. For special cases, when the random vector, **X**, is correlated Gaussian or correlated lognormal, the Rosenblatt transformation can be sidestepped by using a Cholesky decomposition of the covariance matrix. They are described below.

D.2.1 Multivariate Normal Distribution

Let **X** be an N-dimensional normal vector with mean vector, μ, and covariance matrix, Σ. Consider a linear transformation of the form

$$\mathbf{X} = \mathbf{D} + \mathbf{Q}\,\mathbf{U} \tag{D-2}$$

where **U** is a standard Gaussian random vector, **D** is an N-dimensional transformation vector, and **Q** is an N×N transformation matrix. Using the expectation operator on **X** and $(\mathbf{X} - \mu)(\mathbf{X} - \mu)^T$, it is elementary to show that

$$\begin{aligned} \mu &= \mathbf{D} \\ \Sigma &= \mathbf{Q}\,\mathbf{Q}^T \end{aligned} \tag{D-3}$$

From Equation D-3, **D** is equal to μ, and **Q** is a lower triangular matrix representing the Cholesky decomposition of Σ. Standard methods of linear algebra can be used to determine **Q** (Ref. D.2).

D.2.2 Multivariate Lognormal Distribution

Let **X** be an N-dimensional lognormal vector with mean vector, μ, and covariance matrix, Σ. Suppose that **R** is an N-dimensional Gaussian random vector with component, $R_i = \ln X_i$, $i = 1,2,\cdots,N$. Let μ_R and Σ_R denote the mean and covariance matrix of **R**. From moment generating function of **R**, it can be shown that the mean and covariance properties of **R** are (Refs. D.1 and D.3)

$$\mu_{R,i} = \ln \mu_i - \frac{1}{2}\ln\left(1 + V_i^2\right) \tag{D-4}$$

and

$$\begin{aligned} \Sigma_{R,ii} &= \ln\left(1 + V_i^2\right) \\ \Sigma_{R,ij} &= \ln\left[1 + \rho_{ij} V_i V_j\right] \end{aligned} \tag{D-5}$$

where μ_i is the ith component of μ, $\mu_{R,i}$ is the ith component of μ_R, Σ_{ij} is the (i,j)th element of Σ, $\Sigma_{R,ij}$ is the (i,j)th element of Σ_R, $V_i = \sqrt{\Sigma_{ii}}/\mu_i$ is the coefficient of variation of X_i, and $\rho_{ij} = \Sigma_{ij}/(\sqrt{\Sigma_{ii}}\sqrt{\Sigma_{jj}})$ is the correlation coefficient between random variables, X_i and X_j. Following calculations of the statistics of the Gaussian vector, **R**, from Equations D-4 and D-5, the same type of linear mapping described in Section D.2.1 (e.g., Equation D-2) can be applied for transforming **R** into the standard Gaussian random vector, **U**.

D.3 References

D.1 Rubinstein, R. Y., Simulation and the Monte Carlo Method, John Wiley & Sons, New York, New York, 1981.

D.2 Press, W. H., Flannery, B. P., Teukolsky, S. A., and Vetterling, W. T., Numerical Recipes, Cambridge University Press, New York, New York, 1990.

D.3 Madsen, H. O., Krenk, S., and Lind, N. C., Methods of Structural Safety, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1986.

APPENDIX E THE PSQUIRT COMPUTER CODE

E.1 The PSQUIRT Computer Code

PSQUIRT, which stands for Probabilistic Seepage Quantification of Upsets In Reactor Tubes, is a computer program for determining the probability distribution of leakage size flaws in through-wall-cracked pipes for LBB applications. It is a combination of three independent programs, SCRAMP, SQUIRT5, and FDACS for conducting pre-processing of input, thermal-hydraulic and fracture-mechanics analyses, and post-processing of the output. Figure E.1 shows a flow chart describing various modules of the PSQUIRT code. Further details of these modules are given below.

- SCRAMP (Simulation of CRAck Morphology Parameters). SCRAMP generates samples of various crack-morphology parameters according to their probability distribution for subsequent thermal-hydraulic analysis. The random crack-morphology variables are: (1) local surface roughness, μ_L, (2) global surface roughness, μ_G, (3) local number of turns per unit thickness, n_{tL}, (4) global path deviation factor, K_G, and (5) global plus local path deviation factor, K_{G+L}. SCRAMP can generate samples from both normal and lognormal distribution functions.

- SQUIRT5 (Seepage Quantification of Upsets In Reactor Tubes). SQUIRT5 is a modified version of the SQUIRT4 program that is available in the SQUIRT code (Version 2.2). SQUIRT was released to the NRC during the Short Cracks in Piping and Piping Welds program (Ref. E.1). Both SQUIRT4 and SQUIRT5 can compute crack length and center-crack-opening displacement in a pipe when the pipe loads and leakage rate are specified. This usually involves numerical iteration between thermal-hydraulic and fracture-mechanics parts of the code to solve for an unknown crack size. In this study, SQUIRT5 has been enhanced to:

  (1) read the crack-morphology parameters generated from a SCRAMP analysis as input,

  (2) conduct deterministic thermal-hydraulic and fracture-mechanics analyses for each input set (sample set) of crack-morphology parameters and perform multiple such analyses

  (3) generate output samples of leakage flaw size.

  In conducting a SQUIRT5 analysis, several interface routines have been developed to update the crack-morphology variables as a function of center-crack-opening displacement. This updating procedure is automated and continued as many times as needed during the iteration from which the leakage flaw (LBB detectable flaw) size is determined.

- FDACS (Frequency Distribution Analysis of Crack Size). FDACS is a program to conduct standard statistical analysis, such as computing the mean, standard deviation, and histogram, of the simulated or actual samples of a variable of interest. Following SCRAMP and SQUIRT5 analyses, many samples of LBB detectable flaw sizes are generated for a given normal operating load and a specified leak rate. FDACS can be used to determine their statistical properties and develop a frequency distribution or histogram of the flaw size. It can compute both relative and cumulative frequency distribution functions.

E.2 Typical Results from PSQUIRT Analysis

In this section, typical results are presented to illustrate the PSQUIRT code. Table E.1 shows the output results from a SCRAMP analysis representing 100 samples of various crack morphology parameters. The samples in Table E.1 were generated for the BWR-1 pipe (defined in Section 5 of this report) with an IGSCC type of cracking mechanism. It is assumed that the crack-morphology variables follow a lognormal probability distribution with the mean and standard deviation given in Section 3 of this report. Using these sample values, 100 analyses were conducted by the SQUIRT5 program to determine the corresponding realizations of leakage crack size for the BWR-1 pipe when the leak rate is 3.785 l/min (1 gpm) and the normal operating stress is 50-percent of the ASME Service Level A stress limit. Table E.1 also shows the computed samples of crack length at mean pipe diameter for the BWR-1 pipe. Finally, using the FDACS program, statistics of crack lengths, such as mean, standard deviation, and histograms, were calculated. The statistical properties of crack size are shown in Figures E.2 and E.3.

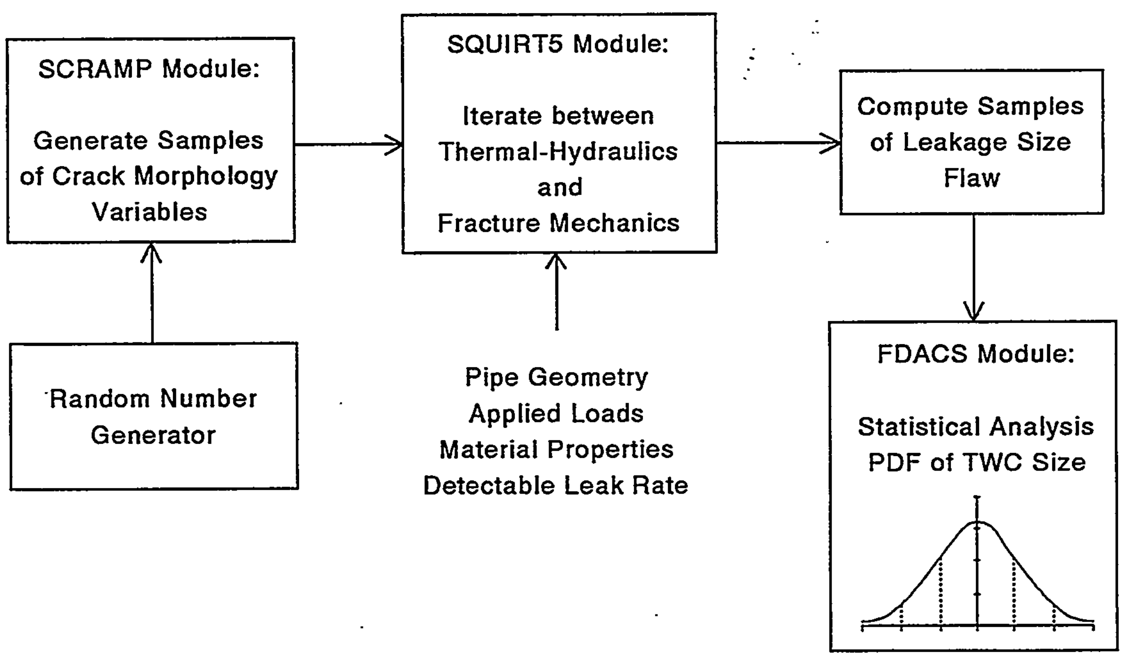

Figure E.1 Flow chart of PSQUIRT code

F6004-FE.1

Table E.1 Detailed simulation results for BWR-1 pipe (SCRAMP and SQUIRT5 analyses)

Sample No.	μ_L, μm	μ_G, μm	n_{tL}, mm^{-1}	K_G	K_{G+L}	Crack Length, mm
1	2.257	167.300	43.447	1.083	1.447	0.212
2	18.340	32.750	19.557	1.198	1.363	0.159
3	4.229	26.710	14.511	0.974	1.315	0.147
4	1.352	48.490	12.286	1.027	1.275	0.155
5	9.123	77.650	14.896	1.200	1.229	0.167
6	5.387	33.040	48.947	0.897	1.526	0.182
7	5.101	70.170	22.153	1.163	1.390	0.177
8	4.863	108.400	28.117	1.066	1.168	0.191
9	5.400	89.220	24.546	0.915	1.313	0.184
10	5.599	79.040	8.301	1.247	1.229	0.152
11	2.616	44.190	37.248	0.976	1.575	0.185
12	15.340	70.220	10.440	0.948	1.631	0.155
13	8.580	99.190	47.188	1.173	1.511	0.209
14	3.008	123.600	42.860	0.960	1.367	0.208
15	0.980	105.400	7.092	0.971	1.404	0.149
16	4.037	38.520	12.305	1.005	1.195	0.152
17	2.118	113.900	13.690	1.098	1.708	0.168
18	1.227	75.480	22.106	0.929	1.179	0.178
19	4.129	75.340	11.163	0.995	1.229	0.158
20	2.231	59.850	19.314	0.947	1.269	0.171
21	5.010	145.700	39.733	1.154	1.268	0.207
22	4.364	104.000	45.206	1.084	1.419	0.208
23	13.600	175.600	6.685	1.144	1.215	0.153
24	3.103	89.770	12.819	1.240	1.392	0.164
25	7.201	63.520	9.449	1.041	1.244	0.152
26	18.220	48.550	22.745	1.181	1.394	0.173
27	1.996	49.250	24.440	1.254	1.572	0.175
28	3.796	64.510	15.148	1.014	1.723	0.165
29	9.469	31.810	50.623	1.027	1.146	0.180
30	4.710	40.780	24.999	1.141	1.409	0.171
31	10.180	109.200	27.699	1.047	1.271	0.190
32	3.622	89.520	84.688	0.930	1.492	0.226
33	7.463	106.100	11.350	1.112	1.345	0.162
34	1.362	131.800	6.453	1.186	1.315	0.150
35	3.543	43.890	16.943	1.077	1.311	0.162
36	5.312	87.060	46.658	1.131	1.184	0.207
37	4.518	48.940	16.125	1.127	1.524	0.163
38	3.196	137.500	13.271	1.136	1.449	0.169
39	6.560	84.170	13.341	1.115	1.475	0.165
40	14.400	62.330	30.435	1.041	1.020	0.186
41	2.594	73.310	14.098	0.985	1.021	0.164
42	14.160	40.860	33.116	1.102	1.345	0.179
43	1.817	92.390	31.915	1.055	1.508	0.194
44	3.801	34.480	10.468	0.879	1.438	0.146
45	2.828	97.300	80.946	1.102	1.292	0.226
46	4.812	68.310	46.602	1.048	1.431	0.202
47	0.971	54.690	25.105	1.090	1.199	0.177
48	10.680	94.930	17.482	1.035	1.418	0.174
49	1.944	117.000	17.661	1.085	1.094	0.176
50	11.530	71.580	36.550	0.982	1.340	0.195

Table E.1 (Continued)

Sample No.	μ_L, μm	μ_G, μm	n_{tL}, mm^{-1}	K_G	K_{G+L}	Crack Length, mm
51	3.727	68.830	32.697	1.090	1.421	0.190
52	5.176	136.300	49.254	0.872	1.150	0.214
53	6.613	49.700	35.154	0.935	1.416	0.186
54	3.935	33.670	63.830	1.071	1.503	0.189
55	1.232	102.100	11.024	1.052	1.159	0.161
56	3.762	41.170	11.504	1.097	1.384	0.151
57	1.210	85.110	14.271	1.026	1.840	0.167
58	2.547	139.500	11.523	1.204	1.374	0.165
59	0.784	47.810	21.963	1.006	1.431	0.171
60	6.326	115.100	50.511	1.277	1.239	0.213
61	6.094	33.470	111.297	1.029	0.981	0.203
62	5.196	30.430	20.528	1.056	1.261	0.158
63	4.344	90.850	28.425	1.027	1.202	0.189
64	11.100	164.900	48.417	1.149	1.311	0.216
65	2.330	59.820	32.808	1.019	1.236	0.188
66	8.748	192.500	13.369	0.910	1.287	0.171
67	0.866	153.900	33.451	1.128	1.452	0.201
68	5.085	70.170	22.904	0.997	1.150	0.179
69	1.856	68.340	42.162	1.153	1.060	0.200
70	2.516	60.140	41.073	1.171	1.420	0.195
71	13.570	49.510	30.184	1.056	1.108	0.182
72	2.657	46.990	16.267	1.209	1.402	0.162
73	5.923	58.170	19.727	0.999	1.129	0.171
74	2.359	94.890	30.519	1.226	1.779	0.193
75	5.570	37.550	26.487	1.037	1.531	0.171
76	1.482	137.700	46.881	1.260	1.096	0.213
77	3.354	90.850	15.231	1.100	1.401	0.169
78	3.827	46.840	44.508	1.065	1.234	0.191
79	6.136	114.800	9.759	1.219	1.472	0.159
80	1.238	104.500	14.637	0.929	1.282	0.169
81	3.133	145.700	23.742	1.065	1.436	0.188
82	3.857	83.790	24.468	0.913	1.509	0.184
83	3.611	27.010	11.752	1.177	1.167	0.142
84	2.824	76.540	22.067	1.118	1.603	0.179
85	2.394	52.240	16.024	0.991	1.494	0.164
86	4.245	24.960	23.184	1.016	1.548	0.154
87	8.091	73.720	15.053	1.094	1.423	0.167
88	14.550	82.770	57.519	0.998	1.149	0.214
89	4.567	79.440	25.392	1.192	1.241	0.184
90	4.077	58.960	10.599	1.137	1.662	0.154
91	2.395	126.400	48.919	1.064	1.411	0.213
92	2.307	73.100	15.145	1.170	1.132	0.167
93	6.619	69.320	49.254	1.073	1.533	0.204
94	6.099	48.540	58.413	1.068	1.082	0.202
95	8.258	34.670	10.895	1.002	1.337	0.147
96	0.658	39.880	25.479	1.106	1.143	0.171
97	3.007	129.700	67.320	0.967	1.402	0.224
98	4.333	66.330	24.007	1.008	1.286	0.179
99	2.756	196.700	26.381	1.044	1.178	0.194
100	5.429	113.200	34.986	0.971	1.270	0.200

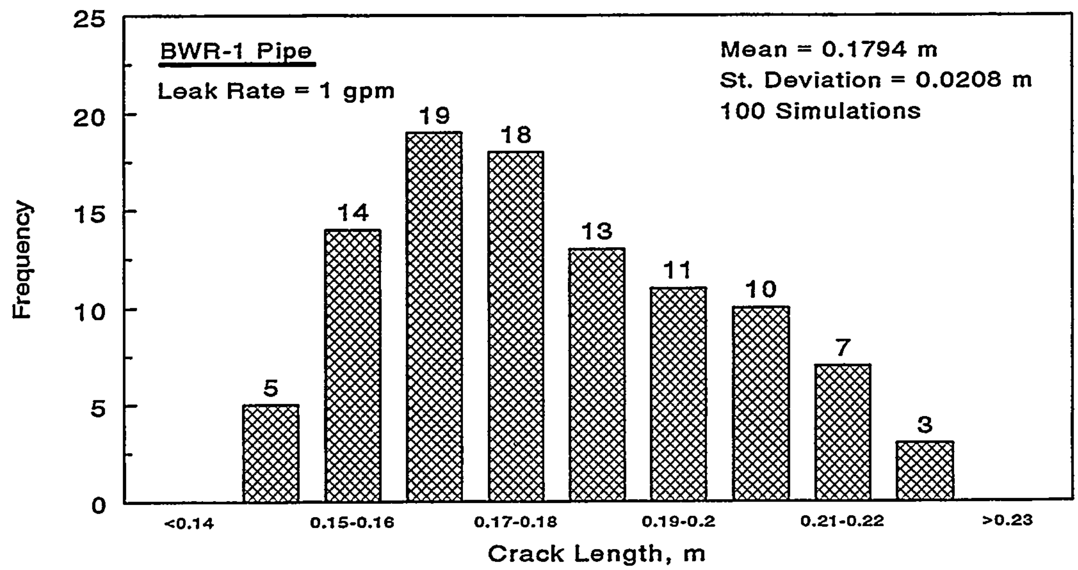

Figure E.2 Histogram of leakage flaw size in BWR-1 pipe for 3.785 l/min (1 gpm) leak rate and 50-percent of ASME Service Level A stress limit (FDACS Analysis)

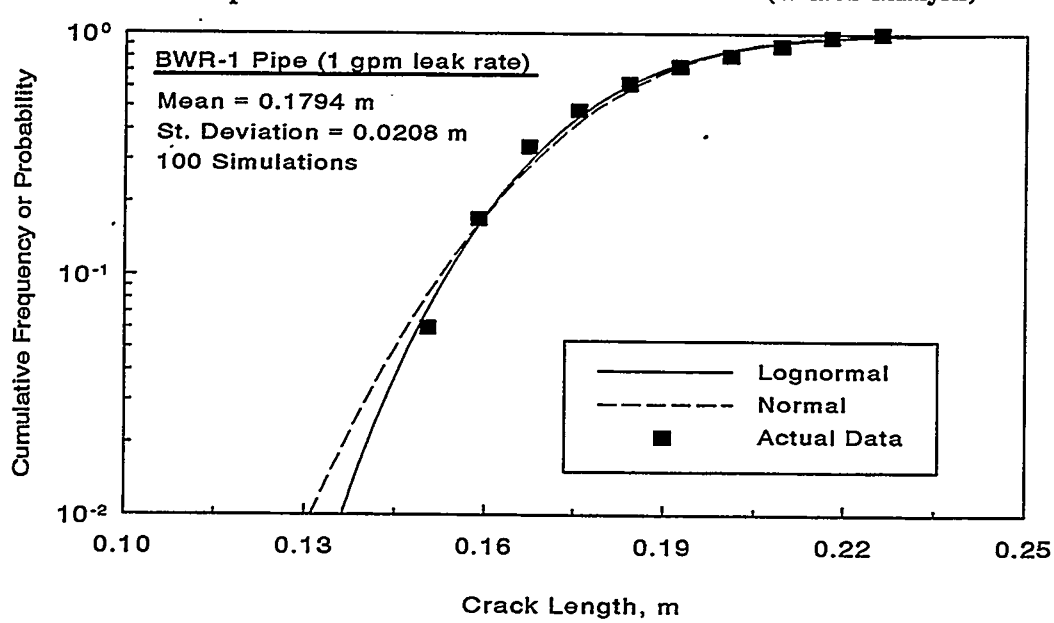

Figure E.3 Probability distribution of leakage flaw size in BWR-1 pipe for 3.785 l/min (1 gpm) leak rate and 50-percent of ASME Service Level A stress limit (FDACS Analysis)

T-6004-FE.2/E.3

E.3 Listing of PSQUIRT Code

The following pages contain the computer listing for the source codes of SCRAMP, SQUIRT5, and FDACS. The SCRAMP and FDACS codes were written in ANSI Standard Fortran. SQUIRT5 was written as an MS DOS batch program that executes the independent programs, INTFACE, NRCP3M, and SQUIRT4A.

E.4 References

E.1 Wilkowski, G. M., and others, "Short Cracks in Piping and Piping Welds," Semiannual reports by Battelle, NUREG/CR-4599, Vols. 1 to 3, Nos. 1 and 2, May 1991 to March 1994.

LISTING OF SCRAMP.FOR

```
C     ================================================================
C     PROGRAM TO GENERATE SAMPLES OF CRACK MORPHOLOGY VARIABLES
C     FOR LBB APPLICATIONS - WRITTEN BY S. RAHMAN, JUNE 1992.
C
C     THE RANDOM (CRACK MORPHOLOGY) VARIABLES ARE:
C
C          SRUFFL, SRUFFG, KGL, KG, NTURN
C
C     WHERE:     SRUFFL = LOCAL SURFACE ROUGHNESS
C          SRUFFG = GLOBAL SURFACE ROUGHNESS
C          KGL = GLOBAL+LOCAL DEVIATION FROM STRAIGHTNESS
C          KG  = GLOBAL DEVIATION FROM STRAIGHTNESS
C          NTURN = LOCAL NUMBER OF TURNS PER UNIT LENGTH
C
C          {X1} = {SRUFFL,SRUFFG,KGL,KG,NTURN}
C               = A RANDOM VECTOR WITH INDEPENDENT COMPONENTS
C
C          COMPONENT OF {X1} IS EITHER NORMAL OR LOGNORMAL R.V.
C
C     NOTE:      INPUT WILL BE THE DISTRIBUTION PARAMETERS OF THESE RVS;
C          OUTPUT WILL BE THEIR DETERMINISTIC REALIZATIONS
C
C     ----------------------------------------------------------------
C     DECLARE VARIABLES
C
      IMPLICIT REAL*8 (A-H, O-Z)
      PARAMETER (MBV1=5)
      REAL*8 M1(MBV1),STD1(MBV1),U1(MBV1),X1(MBV1)
      REAL*8 UM1(MBV1), USTD1(MBV1)
      REAL*8 FMOM(MBV1),SMOM(MBV1)
      REAL*8 XL1(MBV1),XR1(MBV1)
      DIMENSION ITYPE1(MBV1)
      CHARACTER*20 INPUT,OUTPUT
C
C     ----------------------------------------------------------------
C     OPEN INPUT/OUTPUT FILES AND READ INPUT PARAMETERS
C
      PRINT*, 'ENTER NAME OF INPUT FILE                    [SCRAMP.DAT]'
      PRINT*,'--> '
      READ(5,'(A)') INPUT
      IF (INPUT .EQ. ' ') INPUT = 'SCRAMP.DAT'
      OPEN(1,FILE=INPUT,STATUS='OLD')
      PRINT*, 'ENTER NAME OF OUTPUT FILE                    [SCRAMP.OUT]'
      PRINT*,'--> '
      READ(5,'(A)') OUTPUT
      IF (OUTPUT .EQ. ' ') OUTPUT = 'SCRAMP.OUT'
      OPEN(2,FILE=OUTPUT,STATUS='UNKNOWN')
C
      READ(1,*) NBV1, IOPT
      DO 10 I = 1,NBV1
10    READ(1,*) ITYPE1(I),M1(I),STD1(I),XL1(I),XR1(I)
      READ(1,*) NSAMP
      READ(1,*) ISEED
C
C     ----------------------------------------------------------------
C     START OF SIMULATION
C
C     (1)  GENERATE STANDARD NORMAL VARIATES      --------->
C
      DO 800 I = 1,NBV1
      FMOM(I) = 0.
800   SMOM(I) = 0.
C
C
      DO 1000 ISAMP = 1, NSAMP
C
```

```
      DO 100 I = 1,NBV1
      RNUNIF = RANGEN(ISEED)
      U1(I) = YNINVP(RNUNIF)
100   CONTINUE
C
C
C     (2)  TRANSFORM NORMAL TO ORIGINAL VARIABLES  ---------->
C
      DO 300 I = 1,NBV1
      IF (ITYPE1(I) .EQ. 1) GO TO 311
      IF (ITYPE1(I) .EQ. 2) GO TO 322
      PRINT*, 'DISTRIBUTION TYPE NOT ENTERED PROPERLY ! STOP CALC !'
      STOP
C
C     (A)  X1(I) IS NORMAL (GAUSSIAN)
C
311   IF (IOPT .EQ. 0) GO TO 3811
      X1(I) = YNINVP(     YPHIN( U1(I) ) *
     &           (  YPHIN( (XR1(I)-M1(I))/STD1(I) ) -
     &              YPHIN( (XL1(I)-M1(I))/STD1(I) )    ) +
     &          YPHIN( (XL1(I)-M1(I))/STD1(I) )      )*STD1(I) + M1(I)
      GO TO 3812
3811    X1(I) =  STD1(I)*U1(I) + M1(I)
3812  FMOM(I) = FMOM(I) + X1(I)
      SMOM(I) = SMOM(I) + X1(I)**2
      GO TO 300
C
C     (B)  X1(I) IS LOGNORMAL
C
322   USTD1(I) = DSQRT(    DLOG( 1. + ( STD1(I)/M1(I) )**2 )     )
      UM1(I) = DLOG( M1(I) ) - 0.5 * USTD1(I)**2
      IF (IOPT .EQ. 0) GO TO 3822
      X1(I) = YNINVP(     YPHIN( U1(I) ) *
     &           (  YPHIN( (DLOG(XR1(I))-UM1(I))/USTD1(I) ) -
     &              YPHIN( (DLOG(XL1(I))-UM1(I))/USTD1(I) )    ) +
     &          YPHIN( (DLOG(XL1(I))-UM1(I))/USTD1(I) )      )*USTD1(I)
     &          + UM1(I)
      X1(I) = DEXP( X1(I) )
        GO TO 3823
3822  X1(I) = DEXP(  USTD1(I)*U1(I) + UM1(I)   )
3823  FMOM(I) = FMOM(I) + X1(I)
      SMOM(I) = SMOM(I) + X1(I)**2
C
C
300   CONTINUE
C
C     ----------------------------------------------------------------
C     WRITE OUT SAMPLES OF {X1}
C
      WRITE (2,111) (X1(I), I=1,NBV1)
111   FORMAT(5(3X,E12.4))
C
C
1000  CONTINUE
C
C     ----------------------------------------------------------------
C     CHECK STATISTICS OF SIMULATED SAMPLES
C
      PRINT*
      PRINT*, 'SAMPLE SIZE = ', NSAMP
      PRINT*
      PRINT*
      DO 900 I = 1,NBV1
      PRINT*, 'MEAN(',I,') =  ', FMOM(I)/DFLOAT(NSAMP)
      PRINT*, 'STD(',I,') =  ', DSQRT(  SMOM(I)/DFLOAT(NSAMP) -
     &                          ( FMOM(I)/DFLOAT(NSAMP) )**2  )
```

```
      PRINT*
900   CONTINUE
C
C      PRINT*, 'Note: {X1} = {SRUFFL,SRUFFG,KGL,KG,NTURN} '
      PRINT*
C
      STOP
      END
C
C
C
C     ================================================================
      FUNCTION RANGEN(IX)
C
C     RANDOM NUMBER GENERATOR FOR STANDARD UNIFORM VARIABLE
C
C     ----------------------------------------------------------------
      IMPLICIT REAL*8 (A-H,O-Z)
      INTEGER A, P, IX, B15, B16, XHI, XALO, LEFTLO, FHI, K
      DATA A/16807/,B15/32768/,B16/65536/,P/2147483647/
C
      XHI = IX/B16
      XALO = (IX - XHI*B16)*A
      LEFTLO = XALO/B16
      FHI = XHI*A + LEFTLO
      K = FHI/B15
      IX = (((XALO - LEFTLO*B16) - P) + (FHI - K*B15)*B16) + K
      IF (IX.LT.0) IX = IX + P
      RANGEN = IX*4.656612875E - 10
C
      RETURN
      END
C.
C
C     ================================================================
      DOUBLE PRECISION FUNCTION YPHIN (X0)
C
C     INTEGRAL OF THE STANDARD-NORMAL DISTRIBUTION FUNCTION
C
C     YPHIN(X0) = P (X < X0)
C     FOLLOWING ABRAMOWITZ/STEGUN"S FORMULA 26.2.17
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C     ----------------------------------------------------------------
      COMMON /YCMACH/ CEMIN,CEMAX,CLMIN,CLMAX,CNORM,
     1 COGEN,COGE2,COGE3,COGE4,COGE8,COG10,
     2 CONE1,COMPI,COLGPI,CDELT1,CDELT2
C     ----------------------------------------------------------------
C
C     ZERO=0.
C     ONE=1.
C     A= .2316419
      ZERO=0.D0
      ONE=1.D0
      A= .2316419D0
      R = ABS(X0)
      IF (R.GT.CNORM) THEN
        T = ZERO
        GOTO 4
      ENDIF
      R = EXP(-R*R/2.0)/2.506628274631
      T = ONE/2.
      IF (X0) 1, 4, 2
 1    T = ONE/(ONE-A*X0)
      GOTO 3
```

```
2     T = ONE/(ONE+A*X0)
3     T = ((((1.330274429*T-1.821255978)*T+1.781477937)*T
     1    -0.356563782)*T+0.31938153)*T
      T = R*T
4     R = T
      IF (X0.GT.ZERO) R = ONE-T
      YPHIN = R
      RETURN
      END
C
C
C
C     ===============================================================
      DOUBLE PRECISION FUNCTION YNINVP (P)
C
C     INVERSE INTEGRAL OF THE STANDARD-NORMAL DISTRIBUTION
C     *YNINVP* IS THE INVERSE OF *YPHIN*
C     METHOD:
C     YNINVG FURNISHES THE STARTING SOLUTION WHICH IS IMPROVED
C     WITH THE NEWTON METHOD. PRECISION DOWN TO COG10, AS *YLINVP*.
C
C     IT USES: YNINVG, YPHIN.
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C     ---------------------------------------------------------------
      COMMON /YCMACH/ CEMIN,CEMAX,CLMIN,CLMAX,CNORM,
     1 COGEN,COGE2,COGE3,COGE4,COGE8,COG10,
     2 CONE1,COMPI,COLGPI,CDELT1,CDELT2
C     ---------------------------------------------------------------
C
C     ZERO=0.
C     ONE=1.
      ZERO=0.D0
      ONE=1.D0
      IF (P.EQ.ONE/2.) THEN
        H=ZERO
      ELSE IF (P.LE.ZERO) THEN
        H=-CNORM
      ELSE
C
      EPS = COGE3
      H = YNINVG (P)
      FXS = YPHIN (H+EPS)
1     FX = YPHIN (H)
      IF (ABS(FX/P-ONE).LT.COG10 .OR. (FX-FXS).EQ.ZERO) GOTO 2
      EPS = (FX-P)*EPS/(FXS-FX)
      H = H-EPS
      FXS = FX
      GOTO 1
2     CONTINUE
C
      ENDIF
C
      YNINVP = H
C
      RETURN
      END
C
C
C     ===============================================================
      DOUBLE PRECISION FUNCTION YNINVG  (P)
C
C     INVERSE INTEGRAL OF THE STANDARD-NORMAL DISTRIBUTION
C       X = YNINVG (P) = INVERSE (PHI (X))
C      METHOD:  FORMULA 26.2.23 (ABRAMOWITZ/SEGUN)
```

```
C       REMARK:  SMALL PRECISION
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C     ---------------------------------------------------------------
      COMMON /YCMACH/ CEMIN,CEMAX,CLMIN,CLMAX,CNORM,
     1 COGEN,COGE2,COGE3,COGE4,COGE8,COG10,
     2 CONE1,COMPI,COLGPI,CDELT1,CDELT2
C     ---------------------------------------------------------------
C
C     ZERO=0.
C     ONE=1.
      ZERO=0.D0
      ONE=1.D0
      IF (P.LE.ONE/2.) THEN
        A = P
        ISIG = 1
      ELSE
        A = ONE-P
        ISIG = 0
      ENDIF
      IF (A.GT.ZERO) GOTO 1
      A = CEMIN
1     A = SQRT(-2.0*LOG(A))
      A = A-((0.010328*A+0.802853)*A+2.515517)/
     1    (((0.001308*A+0.189269)*A+1.432788)*A+ONE)
      IF (ISIG.EQ.1) A = -A
      YNINVG = A
      RETURN
      END
C
C
C
C     ================================================================
      BLOCK DATA DSODAT
C
C     !! DOUBLE PRECISION !!
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C     ---------------------------------------------------------------
      COMMON /YCMACH/ CEMIN,CEMAX,CLMIN,CLMAX,CNORM,
     1 COGEN,COGE2,COGE3,COGE4,COGE8,COG10,
     2 CONE1,COMPI,COLGPI,CDELT1,CDELT2
C     ---------------------------------------------------------------
C
C     THE FOLLOWING DATA ARE VALID FOR OLIVETTI (32 BIT PROCESSOR).
C            (MS-FORTRAN, REAL*8)
C     DATA CEMIN/.873D-291/,CEMAX/.648D+293/,CLMIN/-670.D0/,
C    2 CLMAX/674.D0/,CNORM/36.6D0/,COGEN/1.D-16/,COGE2/1.D-8/,
C    3 COGE4/1.D-4/,COGE8/.158D-12/,COG10/1.D-15/,COGE3/.464D-05/,
C    4 CONE1/8.45D0/,COMPI/3.141592653589793/,
C    5 COLGPI/-0.918938533204673/,CDELT1/5.D-4/,CDELT2/5.D-3/
C
C     THE FOLLOWING DATA ARE VALID FOR OLIVETTI (32 BIT PROCESSOR).
C            (RM-FORTRAN, REAL*8),(COGEN IS A CONSERVATIVE ESTIMATE)
      DATA CEMIN/.538D-292/,CEMAX/.692D+293/,CLMIN/-673.D0/,
     2 CLMAX/674.D0/,CNORM/36.7D0/,COGEN/1.D-16/,COGE2/1.D-8/,
     3 COGE4/1.D-4/,COGE8/.158D-12/,COG10/1.D-15/,COGE3/.464D-05/,
     4 CONE1/8.45D0/,COMPI/3.141592653589793/,
     5 COLGPI/-0.918938533204673/,CDELT1/5.D-4/,CDELT2/5.D-3/
C
C
      END
```

LISTING OF SQUIRT5.BAT

```
ECHO OFF
CLS
ECHO
ECHO This procedure runs NRCP3M & SQUIRT4A
ECHO
ECHO Loops till leakage flow criteria is met in SQUIRT4A
ECHO for a given load and allowable leak rate
ECHO Crack Size is modified in SQUIRT4A
ECHO and Load, Cod etc. is re-calculated IN NRCP3M
ECHO
ECHO  Please Wait Calculations in Progress
REM
REM   LOOP ON PROBLEM NUMBER BEGINS HERE
REM
     DIR >CURDI.LOC
     COPY CURDI.LOC DIRECT.LOC
     COPY START.200 INTFACE1.NDG
     COPY bwr-1.SMP CRMOR.OUT
     COPY %1 BWR-1.INP
     INTFACE1.EXE
REM
REM   Create INTFACE.NDG TO DEFAULT
REM
:NextProb
      INTFACE.EXE
      NRCP3M.EXE < BWR-1.INP >bwr-1.out
      INTFACE2.EXE
      SQUIRT4A.EXE
      IF EXIST INTFACE.NDG GOTO DoNext
      GOTO End
:DoNext
      NRCP3M.EXE
      INTFACE2.EXE
      SQUIRT4A.EXE
      IF EXIST INTFACE.NDG GOTO DoNext
:End
rem
rem   clean the disk
rem
      CHKDSK /F <NO.INP
      INTFACE1.EXE
      IF EXIST INTFACE1.NDG GOTO NextProb
:RealEnd
      copy FINAL.OUT %2
      DEL CRMOR.OUT
      DEL BWR-1.INP
      del final.out
```

LISTING OF INTFACE1.BAS

```
REM
REM  READ  FILE BWR-1.INP AND MODIFY IT USING CRMOR.OUT
REM
     DIM A$(35)
     OPEN "INTFACE1.NDG" FOR INPUT AS #1
     INPUT #1, NPROB, MAXPROB
     CLOSE #1
     NPROB = NPROB + 1
     IF (NPROB <= MAXPROB) THEN
      OPEN "BWR-1.INP" FOR INPUT AS #1
      FOR I = 1 TO 35
      INPUT #1, A$(I)
      NEXT I
      CLOSE #1
      OPEN "CRMOR.OUT" FOR INPUT AS #3
      FOR J = 1 TO NPROB
       INPUT #3, A1, A2, A3, A4, A5
      NEXT J
      CLOSE #3
      OPEN "BWR-1.INP" FOR OUTPUT AS #2
      FOR I = 1 TO 15
      PRINT #2, A$(I)
      NEXT I
      PRINT #2, A1
      PRINT #2, A2
      PRINT #2, A3
      PRINT #2, A4
      PRINT #2, A5
      FOR I = 21 TO 35
      PRINT #2, A$(I)
      NEXT I
      CLOSE #2
      OPEN "INTFACE1.NDG" FOR OUTPUT AS #1
      PRINT #1, NPROB, MAXPROB
      CLOSE #1
     ELSE
     SHELL "DEL " + "INTFACE1.NDG"
     END IF
     SYSTEM
```

LISTING OF INTFACE.BAS

```
REM
REM  CREATE A FILE INTFACE.NDG
REM     WITH KITER = 0
REM
     DIM CRK(20), CFLOW(20), CRITER(20)
     KITER = 0
     JFLAG1 = 0
     JFLAG2 = 0
     OPEN "INTFACE.NDG" FOR OUTPUT AS #3
     WRITE #3, KITER, JFLAG1, JFLAG2
     FOR I = 1 TO 20
     CRK(I) = 0
     CFLOW(I) = 0
     CRITER(I) = 0
     WRITE #3, CRK(I), CFLOW(I), CRITER(I)
     NEXT I
     CLOSE #3
     SYSTEM
```

LISTING OF NRCP3M.BAS

```
REM
REM    SUBROUTINE FOR FRACTURE MECHANICS CALCULATION
REM
REM    USED IN CONJUNCTION WITH HYDRO CODE SQUIRT
REM    (LEAK RATE COMPUTATION)
REM
DECLARE SUB CHECKJR (IN%, KCHECK%, A!, B!, IJ%, LP%)
DECLARE SUB COPFIL (GFIL$, LFIL$, IPRC%)
DECLARE SUB DEFILE (XSTR$, YSTR$, NPLM, NTASK, KSAVIN%, R$, PM$, AP$, DA$, DELX$, TM$, TA$,
MATJ(), PDELX$, JR$, FDR$, FPA$, DIREF$, FINEX$, LFIL$, GFIL$, NINFIL, INFIL$, INOF%, MDJ, MDP,
PDELTA(), LPDELXT, LMATJ, XAR(), TIT$(), TSTR$())
DECLARE SUB DOYOUWANT (XSTR$, C$, NCHAN!)
DECLARE SUB ENDCO (KSAVIN$, LINEP$, INFILTYP$, RESU$, PDELX$, JR$, LINFIL$, GINFIL$, WORK$,
GWORK$)
DECLARE SUB FILENAME (KDIR%, KFIL%)
DECLARE SUB FILINDIR (FIL$, DIR$, INOF%, OOTR$, CUDI$, SPOT$)
DECLARE SUB HEADTAB (NHEAD!, NOUT!, KPRINT)
DECLARE SUB LOADARR (KLD%, NTASK)
DECLARE SUB MAKEMENU (SEL$, COM$, MENU$(), LMENU!, LSMENU!, LXSM%, NCHOIC!, OOTR$, TSTR$())
DECLARE SUB MOUT ()
DECLARE SUB MUNIT ()
DECLARE SUB OKNAME (XSTR$, KN!, IER%, OOTR$)
DECLARE SUB PAUSE ()
DECLARE SUB PRINTSC (NAR!, LAR!, NPLM, MXAR, XAR(), TIT$())
DECLARE SUB STRINGSPLITTING (XSTR$, LXSM%, IL%, TSTR$())
DECLARE SUB DISPLAYMENU (MENU$(), SEL$, LMENU, LSMENU, NCHOIC)
DECLARE SUB STORDIR (CUDI$, LCUDI%)
DECLARE SUB Pipedim (MENU$(), SEL$, LMENU, LSMENU, NCHOIC, NCRACK, NSIZE, UC$, UL$, NLODE, NBEND,
PM$, UM$, UP$, TWOL, TWOS, TWOA, DIA, THICK, RADIUS, PI, AC, CA, US$, SIGTEN)
170    REM ---------------------- INITIALIZE --------------------- REM 10120
175 OPTION BASE 1
     DIM RESUL(50, 10), MATJ(50, 2), PDELTA(60, 6)
     DIM RPINIT(12, 12)
     DIM MENU$(12), TSTR$(5)
     DIM HFUNC(10, 10)
     DIM H1(10, 2), H2(10, 2), H3(10, 2), H1B(10, 2), H2B(10, 2), H3B(10, 2)
     DIM FAB(10, 5), FAT(10, 5), HCA(10), HCA2(10)
     DIM H1RT1(10, 10), H2RT1(10, 10), H3RT1(10, 10)
     DIM H1RT2(10, 10), H2RT2(10, 10), H3RT2(10, 10)
     DIM HF(20, 2), FAL(10, 5), FAU(10, 5)
     DIM TA(50), TB(50), TC(50), XAR(600), TIT$(10), GOUTFIL$(20)
     COMMON SHARED INOF%, KSAVIN%, MXAR, NPLM, NOUF
     COMMON SHARED MDJ, MDP, MATJ(), PDELTA(), LPDELXT, LMATJ
     COMMON SHARED CUDI$, LCUDI%, CUDR$, DADI$
     COMMON SHARED DAT$, BSLA$, COLU$, SPOT$, DIREC$, FILTR$, FILCOM$
     COMMON SHARED LINEP$, OOPS$, OOTR$, JREC$, PDCT$, RESU$, INFILTYP$
     COMMON SHARED UNIT$, U0$, UD$, UJ$, UK$, UL$, UM$, UP$, US$
     COMMON SHARED JA$, UZ$, R$, PM$, AP$, DA$, DELX$, TM$, TA$, PI$, PMAX$
     COMMON SHARED TMN, TSE, TIMIO, DDATE$
     COMMON SHARED PI, PIS3, PIS4, SQPI, TRUNKA, ATRUNKA
     COMMON SHARED MENU$(), SEL$, LMENU, LSMENU, NCHOIC
     COMMON SHARED STA$, GEOM$, CRACK$, LODE$, PROC$, TASK$
     COMMON SHARED NUNIT, NGEOM, NCRACK, NLODE, NBEND, NTASK, NREND, NALERT
     COMMON SHARED DIA, THICK, TWOL, TWOS, TWOC, CC, TWOA, AC, ARMLENGTH, WIDE
     COMMON SHARED YIELD, UTS, SCOLL, SOX, EO, ALPHA, AN
     COMMON SHARED SIGTEN, RPINIT(), RESUL(), JTABLE, LRES
     COMMON SHARED CO$, S$, SI$, SMAX$
     COMMON SHARED GO$, G$, P$, KO$, K$, R6$, COL$
     COMMON SHARED PDELX$, PA$, JR$, FFI$, FDR$, FPA$, DIREF$, FINEX$
     COMMON SHARED LFIL$, GFIL$, LINFIL$, GINFIL$, WORK$, GWORK$, GOUTFIL$()
     COMMON SHARED TA(), TB(), TC(), XAR(), TIT$(), TSTR$()
     COMMON SHARED NSCREEN
     COMMON SHARED KITER
     COMMON SHARED NFUNIT, PFLOW, FLOW
     CLEAR , , 5000
     SCREEN 9: COLOR 10, 1
REM
REM  OPEN INTERFACE FILE TO SQUIRT2
REM
     OPEN "INTFACE.NDG" FOR INPUT AS #3
     INPUT #3, KITER
     CLOSE #3
REM
REM  KITER = 0 THEN ALL SCREENS ARE DISPLAYED AND DATA IS PROVIDED BY USER
REM
```

```
REM  KITER > 0 THEN CRACK SIZE HAS BEEN CHANGED BY SQUIRT2 AND ALL INPUT
REM            TO NRCPIPE IS PROVIDED FROM A FILE
REM
     IF (KITER = 0) THEN
      CLS : LOCATE 2, 32: PRINT "SCREEN #0"
      LOCATE 4, 18: PRINT "INTERNATIONAL PIPING INTEGRITY RESEARCH GROUP"
      LOCATE 8, 30: PRINT "S  Q  U  I  R  T"
      LOCATE 10, 15: PRINT "Seepage Quantification of Upsets In Reactor Tubes"
      LOCATE 12, 32: PRINT "VERSION 2.1"
      LOCATE 14, 32: PRINT "MARCH 1991"
      LOCATE 18, 31: PRINT "Developed by"
      LOCATE 20, 33: PRINT "BATTELLE"
      LOCATE 21, 28: PRINT "Columbus, Ohio  U.S.A."
      LOCATE 23, 15: PRINT "Please read disclaimer in User's Manual before proceding"
      LOCATE 25, 28: PRINT "Press ENTER to continue";
      INPUT " ", DUMMY
      CLS :
      LOCATE 2, 35: PRINT "SCREEN #1"
      PRINT
      PRINT "                                LEGAL NOTICE"
      PRINT
      PRINT " The SQUIRT program was created by Battelle as an account of work sponsored"
      PRINT " by IPIRG and the USNRC."
      PRINT
      PRINT " Neither IPIRG, members of IPIRG, Battelle, officers, trustees, or staff of "
      PRINT " Battelle, nor any person acting on behalf of either:"
      PRINT
      PRINT "     a.  Makes any warranty or representation, expressed or implied, with"
      PRINT "         respect to the accuracy, completeness, or usefulness of the infor-"
      PRINT "         mation contained in this report, or that the use of any information,"
      PRINT "         apparatus, software, method, or process disclosed in this report"
      PRINT "         may not infringe privately owned rights; or"
      PRINT
      PRINT "     b.  Assumes any liability with respect to the use of, or for damages"
      PRINT "         resulting from the use of, any information, apparatus, software, "
      PRINT "         method, or process disclosed in this report."
      PRINT
      PRINT " Reference to trade names or specific commercial products, commodities, or ser-"
      PRINT " vices in this report does not represent nor constitute an endorsement, recom-"
      PRINT " mendation, or favoring by IPIRG or Battelle of the specific commercial pro-"
      PRINT " duct, commodity, or service."
      LOCATE 25, 28: PRINT "Press ENTER to continue";
      INPUT " ", DUMMY
      OPEN "INTFACE.DAT" FOR OUTPUT AS #3
      CLS :
     ELSE
     OPEN "INTFACE.DAT" FOR INPUT AS #3
     END IF
224    REM ------------ MAXIMUM SIZE FOR J-R AND P-DELTA FILES-------------
     MDJ = 45: MDP = 45: MRES = 50
     NPLM = 25
     MXAR = 600
     TRUNKA = 1000000!: ATRUNKA = .000001
     PI = 4! * ATN(1!): PIS3 = PI / 3!: PIS4 = PI / 4!: SQPI = SQR(PI)
     V$ = TIME$
     A$ = MID$(V$, 7, 1): B$ = MID$(V$, 8, 2)
     DDATE$ = DATE$
     LINEP$ = "------------------------------------------------------------------------------"
     OOPS$ = "PRESS F1<ENTER> TO STOP; PRESS <ENTER> TO CONTINUE "
     OOPS$ = OOPS$ + " FOR NEW SELECTION"
350 WDR$ = "IN WHICH DRIVE A OR B ?  DEFAULT IS A "
360    REM ------------------- INTRODUCTION ---------------------- REM 10500
     DAT$ = "DAT"
     OOTR$ = " TRY AGAIN"
     BSLA$ = "\"
     COLU$ = ":"
     SPOT$ = "."
     XSTR$ = SPACE$(8) + "The terms enclosed in [] denote optional information " + CHR$(13)
     XSTR$ = XSTR$ + SPACE$(8) + "DRIVE 'DR:' = ONE LATIN CHARACTER IMMEDIATELY FOLLOWED BY A ':'
." + CHR$(13) + SPACE$(8) + "PATH 'PA' MAY CONTAIN SEVERAL '\' (ONE AT LEAST FOR A DIRECTORY
NAME)" + CHR$(13)
     YSTR$ = SPACE$(8) + "IF DIRECTORY 'DR:\PA\' IS OMITTED , THE CURRENT OR THE PREVIOUSLY" +
SPACE$(51) + "CHOSEN DIRECTORY IS SELECTED ."
     YSTR$ = YSTR$ + CHR$(13) + SPACE$(8) + "IF THERE IS NO '\' IN THE DIRECTORY NAME , THE
DIRECTORY IS REDUCED" + SPACE$(49) + "TO THE DRIVE ."
```

```
     YSTR$ = YSTR$ + CHR$(13) + SPACE$(8) + "IF EXTENSION '.EX' IS OMITTED , 'EX' = 'DAT' ."
     FILTR$ = "* FILE NAME STRUCTURE : FFI$ = [DR:][\PA\]FINA[.EX] " + CHR$(13) + CHR$(13) +
XSTR$ + SPACE$(8)
     FILTR$ = FILTR$ + "NUMBER OF CHARACTERS FOR FILENAME 'FINA' IS < 9" + CHR$(13) + SPACE$(29)
+ "FOR EXTENSION NAME 'EX' IS = 3" + CHR$(13) + YSTR$
     YSTR$ = SPACE$(8) + "PRESS RETURN FOR CURRENT DIRECTORY ."
     DIREC$ = "* DIRECTORY NAME STRUCTURE : [DR:][\PA\]" + CHR$(13) + CHR$(13) + XSTR$ + YSTR$
     JREC$ = "    J-RESISTANCE CURVE     "
     PDCT$ = " P-DELTA-CRACK SIZE TABLE "
     RESU$ = " OUTPUT / RESULTS          "
     NCHAN = 5
REM ------------------- INTRODUCTION ---------------------- REM 10500
REM *** CALL OF SUBROUTINE STORDIR ( FILES OF CURRENT DIRECTORY )***
       CALL STORDIR(CUDI$, LCUDI%)
       NOUF = 1
660 CLOSE 8: CLS
REM *** CALL OF SUBROUTINE FILENAME  FOR OUTPUT (KDIR%=0, KFIL% = 2).
665   ON NCHAN GOTO 1270, 700, 1870, 670, 670
670 FILCOM$ = RESU$
    IF (KITER = 0) THEN
     NSCREEN = 2
     CALL FILENAME(0, 2)
     WORK$ = LFIL$
     WRITE #3, WORK$, GWORK$
    ELSE
     INPUT #3, WORK$, GWORK$
    END IF
    IPR = 1
    GOUTFIL$(NOUF) = GWORK$
    CLOSE 8: CLS
    OPEN WORK$ FOR OUTPUT AS 8
    NHEAD = 0
690 ON NCHAN GOTO 1270, 700, 1870, 2360, 700
700 REM ------------------- UNITS SELECTION ---------------------- REM 10720
    NSCREEN = 3
    CALL MUNIT
1270 REM --------------- GEOMETRY SELECTION --------------------- REM 11000
1280 NBEND = 0
1290 ON NCHAN GOTO 1300, 2390, 1870, 2360, 1300
1300 SEL$ = " THE GEOMETRY": NBEND = 0: UP$ = UZ$: NCRACK = 0
1310 MENU$(1) = "PIPE OR PIPING"
1320 NCHOIC = 1
1380 GEOM$ = MENU$(NCHOIC)
1390 GE$ = LEFT$(MENU$(NCHOIC), 2)
1400 IF NCHOIC = 1 THEN GE$ = "P"
1410 NGEOM = NCHOIC
1480 REM ------------ TYPE OF CRACK SELECTION -------------------- REM 11590
1490 SEL$ = " THE TYPE OF CRACK": UP$ = UZ$
1500 MENU$(1) = "THROUGH CRACK ;CIRCUMFERENTIAL "
1510 NCHOIC = 1
1570 NCRACK = NCHOIC
1580 CRACK$ = MENU$(NCHOIC)
1590 FGE$ = "F" + LEFT$(MENU$(NCHOIC), 2)
1630 GE$ = GE$ + LEFT$(MENU$(NCHOIC), 2)
1640 REM ------------------ TYPE OF LOADING SELECTION ------------- REM 11790
1650 SEL$ = " THE TYPE OF LOADING"
1660 SIGTEN = 0!
1670 MENU$(1) = "BENDING"
1680 MENU$(2) = "PRESSURE"
1690 MENU$(3) = "AXIAL LOADING"
1700 MENU$(4) = "PRESSURE AND BENDING "
1750 LMENU = 4: LSMENU = 4
     NSCREEN = 4
     IF (KITER = 0) THEN
       CALL DISPLAYMENU(MENU$(), SEL$, LMENU, LSMENU, NCHOIC)
       WRITE #3, NCHOIC
     ELSE
      INPUT #3, NCHOIC
     END IF
1760 NLODE = NCHOIC
1810 LODE$ = MENU$(NCHOIC)
1820 IF NLODE = 3 THEN FGE$ = FGE$ + "PR"
1830 IF NLODE = 3 THEN GE$ = GE$ + "PR"
1840 IF NLODE = 3 THEN GOTO 1870
1850 FGE$ = FGE$ + LEFT$(MENU$(NCHOIC), 2)
```

```
1860 GE$ = GE$ + LEFT$(MENU$(NCHOIC), 2)
1870 REM ------------------ TASK SELECTION ---------------------- REM 13000
1880 ON NCHAN GOTO 2280, 2390, 1890, 2360, 1890
1890 SEL$ = " THE WORK TO BE DONE"
1900 MENU$(1) = " CALCULATION OF J-R CURVE FROM TEST RECORD"
1910 MENU$(2) = " CALCULATION OF INITIATION AND INSTABILITY IN LOAD CONTROL"
1920 MENU$(3) = " CALCULATION OF INITIATION AND INSTABILITY IN DISP CONTROL"
1930 LMENU = 3: LSMENU = 3
     NSCREEN = 5
     IF (KITER = 0) THEN
      CALL DISPLAYMENU(MENU$(), SEL$, LMENU, LSMENU, NCHOIC)
      WRITE #3, NCHOIC
     ELSE
      INPUT #3, NCHOIC
     END IF
1940 TASK$ = MENU$(NCHOIC)
1950 NTASK = NCHOIC
1960 NSUPP = 1
1970 REM
1980 REM
1990 REM ------------- ESTIMATION SCHEME SELECTION --------------- REM 13400
2000 SEL$ = " THE J - ESTIMATION SCHEME"
2010 MENU$(1) = "GE/EPRI ORIGINAL  "
2011 MENU$(2) = "GE/EPRI MODIFIED  "
2012 NCHOIC = 1
2013 NPROCX = 1: NEPRI = 1
2063 PROC$ = MENU$(NCHOIC)
2065 NPROC = 1
2067 IF NPROCX = 2 THEN NEPRI = 2
2090 IF NPROC = 1 THEN GOTO 2100
2100 IF NPROC > 3 THEN NSUPP = 0
2270 REM ---------------------- INPUT ---------------------------- REM 14055
2280 ON NCHAN GOTO 2290, 2390, 2390, 2360, 2290
2290 CLS
2310 REM GET PIPE DIMENSIONS
2320 CALL Pipedim(MENU$(), SEL$, LMENU, LSMENU, NCHOIC, NCRACK, NSIZE, UC$, UL$, NLODE, NBEND,
PM$, UM$, UP$, TWOL, TWOS, TWOA, DIA, THICK, RADIUS, PI, AC, CA, US$, SIGTEN)
2360 ON NCHAN GOTO 2390, 2390, 2390, 2370, 2370
2370 REM GET INPUT - OUTPUT FORMAT
2380 GOSUB 9140
     CLOSE #3
2390 REM -------------------- INPUT ECHO ------------------------ REM 15000
     IF (KITER = 0) THEN
     CLS
2420 GOSUB 8110
     NSCREEN = 12
     LOCATE 1, 30
     PRINT "Screen #"; NSCREEN
     LOCATE 2, 1
2430 PRINT "    INPUT ECHO"
2440 GOSUB 8110
2450 PRINT DATE$; "         "; GWORK$
2460 GOSUB 8110
2461 PRINT
2465 PRINT "J-ESTIMATION SCHEME : "; PROC$
2470 PRINT "GEOMETRY            : "; GEOM$
2480 IF NGEOM > 1 THEN GOTO 2500
2490 PRINT "LOADING             : "; LODE$
2491 PRINT "CRACK TYPE          : "; CRACK$
2492 PRINT
2500 PRINT "TASK  : "; TASK$
2501 IF NGEOM > 1 THEN PRINT "STATE OF STRESS : "; STA$
2502 PRINT
2510 PRINT "YIELD STRESS = "; YIELD; " "; US$; "; ULTIMATE TENS STRENGTH = "; UTS; " "; US$
2520 PRINT "COLLAPSE STR = "; SCOLL; " "; US$
2530 PRINT "SIGMA - ZERO = "; SOX; " "; US$; " ; EPSILON - ZERO = "; EO
2540 PRINT "ALPHA        = "; ALPHA; "         ; EXPONENT       = "; AN
2550 IF NGEOM > 1 THEN GOTO 2710
2560 PRINT "OUTER DIAMETER = "; DIA; " "; UL$; "      ; WALL THICKNESS = "; THICK; UL$
2570 PRINT "CRACK SIZE 2A = "; TWOA; " "; UL$; "       ; ";
2620 PRINT
2630 IF NLODE = 3 THEN GOTO 2700
2640 IF NLODE = 2 THEN GOTO 2700
2650 IF NLODE = 5 THEN GOTO 2700
2660 IF NLODE = 6 THEN GOTO 2700
```

```
2670 IF NBEND = 1 THEN GOTO 2700
2680 PRINT "LENGTH BETWEEN OUTER LOAD POINTS = "; TWOL; " "; UL$
2690 PRINT "LENGTH BETWEEN INNER LOAD POINTS = "; TWOS; " "; UL$: PRINT
2700 GOTO 2780
2710 REM
2780 PRINT "FILENAMES :"
2790 IF NTASK = 1 THEN
      XSTR$ = PDELX$: IF KSAVIN% = 1 THEN XSTR$ = GINFIL$
      PRINT "P - DELTA CURVE AS     : "; XSTR$
      ELSE
      XSTR$ = JR$: IF KSAVIN% = 1 THEN XSTR$ = GINFIL$
      PRINT "J - R CURVE AS         : "; XSTR$
      END IF
2810 PRINT "OUTPUT AND RESULTS AS : "; GWORK$
2820 GOSUB 8110
2830 REM ------------------- CHANGES IN INPUT ---------------------- REM 15525
2840 PRINT "DO YOU WANT TO MAKE ANY CHANGES? Y OR N"; : INPUT C$
     ELSE
     C$ = "N"
     END IF
2850 IF LEFT$(C$, 1) = "Y" THEN NCHAN = 1
2860 IF LEFT$(C$, 1) = "y" THEN NCHAN = 1
2870 IF LEFT$(C$, 1) = "n" THEN NCHAN = 5
2880 IF LEFT$(C$, 1) = "N" THEN NCHAN = 5
2890 IF NCHAN = 5 THEN GOTO 3020
2900 IF NCHAN = 1 THEN GOTO 2930
2910 PRINT "ANSWER  Y OR N, PLEASE": BEEP: GOTO 2840
2920 IF NCHAN = 5 THEN GOTO 3020
2930 SEL$ = " WHAT YOU WANT TO CHANGE"
2940 MENU$(1) = "GEOMETRY, CRACK SIZE AND/OR LOADING"
2950 MENU$(2) = "UNITS"
2960 MENU$(3) = "TASK AND/OR ESTIMATION SCHEME"
2970 MENU$(4) = "MATERIAL DATA OR FILE NAMES"
2980 MENU$(5) = "NO FURTHER CHANGES"
2990 LMENU = 5: LSMENU = 5
     CALL DISPLAYMENU(MENU$(), SEL$, LMENU, LSMENU, NCHOIC)
3000 NCHAN = NCHOIC
3010 REM
3020 IF NCHAN <> 5 THEN GOTO 690
3030 CLS
3040 PRINT
REM ----------------- READ INPUT FILES ----------------------- REM 16000
3120 H$ = "CE11" + ".DAT"
3130 OPEN H$ FOR INPUT AS 1: CLOSE 1
3140 IF NTASK = 1 THEN GOTO 3230
3150 OPEN JR$ FOR INPUT AS 1
3160 FOR LD = 1 TO 30
3165 IF EOF(1) THEN GOTO 3210
3180 INPUT #1, MATJ(LD, 1), MATJ(LD, 2)
3190 LMATJ = LD
3200 NEXT LD
3210 CLOSE 1
3220 GOTO 3300
3225 PDELX$ = PDELX$ + ".DAT"
3230 OPEN PDELX$ FOR INPUT AS 1
3240 FOR LD = 1 TO 40
3245 IF EOF(1) THEN GOTO 3290
3260 INPUT #1, PDELTA(LD, 1), PDELTA(LD, 2), PDELTA(LD, 3)
3270 LPDELXT = LD
3280 NEXT LD
3290 CLOSE 1
3300 ON ERROR GOTO 0
3690 CLS
3700 GOSUB 8110: PRINT "       PLEASE WAIT CALCULATION IN PROGRESS": PRINT : GOSUB 8110
3750 REM ------------------- EXECUTION ----------------------------- REM 17400
3760 REM -------------------- GENERAL ------------------------------ REM 17410
3770 FOR I = 1 TO MDP: FOR J = 1 TO 10: RESUL(I, J) = 0!: NEXT J: NEXT I
3780 FOR I = 1 TO MDP: FOR J = 4 TO 6: PDELTA(I, J) = 0!: NEXT J: NEXT I
3790 FOR I = 1 TO 12: FOR J = 1 TO 12: RPINIT(I, J) = 0!: NEXT J: NEXT I
3800 NALERT = 0: ROVERT = 0!: NFIRST = 1: NTURN = 1:
REM
REM 7/23/93
REM
     GPLO = 2 * PI * RADIUS * THICK
     FTWO = 0
```

```
    HTWO = 0
REM
REM 7/22/93
REM
3810 GE1$ = GE$ + "1"
3820 GE2$ = GE$ + "2"
3830 GE3$ = GE$ + "3"
3840 IF NGEOM = 1 THEN GOTO 3890
3870 REM ALL GEOMETRIES EXCEPT PIPE
3875 REM GET H FOR N
3880 GOSUB 15030
3885 GOTO 4690
3890 ROVERT = RADIUS / THICK
3895 RT5$ = "5"
3900 RT1$ = "10"
3905 RT2$ = "20"
3910 ROT = ROVERT
3915 ROT5 = 5!
3920 ROT1 = 10!
3925 ROT2 = 20!
3935 IF NLODE <> 4 THEN GOTO 4005
3940 HULP$ = GE$
3945 GE$ = "PTHBE"
3950 REM GET H FOR R/T
3955 GOSUB 19500
3960 FOR IA = 1 TO LTABLE
3965 FOR JA = 1 TO 2
3970 H1B(IA, JA) = H1(IA, JA)
3975 H2B(IA, JA) = H2(IA, JA)
3980 H3B(IA, JA) = H3(IA, JA)
3985 NEXT JA
3990 NEXT IA
3995 NFIRST = 1
4000 GE$ = HULP$
4005 REM GET H FOR R/T
4010 GOSUB 19500
4015 GOTO 4640
4640 REM GET F FUNCTIONS
4660 GOSUB 15830
4690 REM CONTINUE
4700 ON NTASK GOTO 4710, 5030, 5030
4710 REM ---------------- CALCULATE J-R CURVE FROM TEST ----------- REM 19200
4720 LMATJ = 1: DELXA = 0!: DA = 0!: MATJ(1, 1) = 0!: AREA = 0!: OPP = 0!
4721 NPARIS = 0
4730 FOR IE = 2 TO LPDELXT
4740 DA = PDELTA(IE, 3) - PDELTA(IE - 1, 3)
4750 IF NPROC <> 5 THEN GOTO 4800
4760 P1 = PDELTA(IE - 1, 1): P2 = PDELTA(IE, 1)
4770 DELTA1 = PDELTA(IE - 1, 2): DELTA2 = PDELTA(IE, 2)
4780 AI = PDELTA(IE, 3)
4785 REM GET J
4790 GOSUB 14340
4800 IF DA < 0 THEN GOTO 4980
4810 IF NPROC <> 5 THEN GOTO 4850
4811 LMATJ = LMATJ + 1
4820 DELXA = DELXA + DA: MATJ(LMATJ, 1) = DELXA: MATJ(LMATJ, 2) = TOTALJ
4840 GOTO 4980
4850 REM
4860 DELXA = DELXA + DA
4870 MATJ(LMATJ, 1) = DELXA
4880 AI = PDELTA(IE, 3)
4890 P = PDELTA(IE, 1)
4900 IF NBEND = 2 THEN P = P * (TWOL - TWOS) / 4!
4910 REM GET J,DELTA,COD
4920 GOSUB 14340
4921 REM NPARIS = 1
4930 PDELTA(IE, 5) = DELXA
4940 PDELTA(IE, 4) = TCOD
4950 PDELTA(IE, 6) = TOTALJ
4960 MATJ(LMATJ, 2) = TOTALJ
4970 MATJ(LMATJ, 1) = DELXA
4971 LMATJ = LMATJ + 1
4980 NEXT IE
4985 LMATJ = LMATJ - 1
4990 REM IF NPROC = 5 THEN GOTO 5020
```

```
5020 REM CONTINUE
5030 REM -- RESIDUAL STRENGTH  TASKS 1 & 2 EXIT AT 21410 & 21680 --REM 21000
5040 IF NSUPP = 0 THEN GOTO 5370
5070 AI = AC
5080 IB = 1
5090 JTABLE = 0
5150 TOUGH = MATJ(1, 2)
5160 NSUBP = NPROC
5165 NPARIS = 0
5170 NPROC = 1
5180 JOU = 5
5190 REM
5200 REM
5210 REM
5220 FOR JB = 2 TO JOU
5230 REM GET P
5240 GOSUB 14530
5250 RPINIT(IB, JB) = P
5260 IF NBEND = 2 THEN RPINIT(IB, JB) = 4! * P / (TWOL - TWOS)
5270 RPINIT(IB, JB + 6) = P / PF: IF NGEOM = 3 THEN RPINIT(IB, JB + 6) = 0!
5280 NPROC = NPROC + 1
5290 NEXT JB
5300 RPINIT(IB, 1) = 2 * AI
5310 RPINIT(IB, 7) = 2 * AI
5320 RPINIT(IB, 6) = SCOLL * POF
5330 IF NBEND = 2 THEN RPINIT(IB, 6) = 4! * RPINIT(IB, 6) / (TWOL - TWOS)
5340 RPINIT(IB, 12) = SCOLL * POF / PF: IF NGEOM = 3 THEN RPINIT(IB, 12) = 0!
5350 NPROC = NSUBP
5370 IF NTASK = 1 THEN GOTO CGEND
5460 FOR JB = 1 TO 6
5470 PDELTA(1, JB) = 0
5480 NEXT JB
5481 PDELTA(1, 3) = AC
   REM ----- INITIATION LOAD .
5485 P = RPINIT(JTABLE + 1, NPROC + 1)
       IF NBEND = 2 THEN P = P * ARMLENGTH
5487 PINIT = P
5490 FOR IB = 1 TO 10
5500 DEEL = IB
5530 PDELTA(IB, 1) = (.1 * DEEL) * PINIT
5540 P = PDELTA(IB, 1): IF NBEND = 2 THEN PDELTA(IB, 1) = 4! * P / (TWOL - TWOS)
5560 AI = AC
   REM -----  GET J,DELTA,COD
5580   GOSUB 14340
5590 PDELTA(IB, 2) = DELTA
5600 PDELTA(IB, 3) = AC
5610 PDELTA(IB, 4) = TCOD
5620 PDELTA(IB, 5) = 0!
5630 PDELTA(IB, 6) = TOTALJ
       NEXT IB
    REM ---------- LOAD OR DISPLACEMENT CONTROL ( TASK 2 OR 3 ) .
    REM ----- CRACK LENGTH LIMIT .
     WHALT = .9000001 * WIDE
       IF NGEOM = 2 THEN WHALT = WHALT / 2!
       IF NGEOM = 5 THEN WHALT = .9000001 * WIDE
       IF NGEOM = 1 OR NGEOM = 6 AND NCRACK < 5 THEN
     WHALT = .9000001 * PI * RADIUS
       IF NCRACK = 3 THEN WHALT = .9000001 * THICK
       IF NCRACK = 4 THEN WHALT = .979999 * THICK
    END IF
REM 6770 IF NCRACK = 6 THEN WHALT = .7000001 * THICK
    REM ----- STABLE CRACK GROWTH COMPUTATIONS  .
       IF MATJ(2, 2) < MATJ(1, 2) THEN
     PRINT #8, "***** INITIAL SLOPE OF J-R CURVE IS NEGATIVE "
       GOTO CGEND
       END IF
     BFACT = .005
       IF NGEOM = 1 OR NGEOM = 6 THEN
     CHECK = AI / (PI * RADIUS)
     BFACT = 1! / (500 * CHECK)
       END IF
     NTELL = 0
CGRST:   REM  ---  RESTARTING POINT WITH A SMALLER CRACK INCREMENT .
     NCOUNT = 10
     LCOUNT = 0
```

```
      ISTOP = 0
      NREND = 0
      KREND = 0
 REM  ---  INITIALISATIONS .
      P = RPINIT(JTABLE + 1, NPROC + 1)
      IF NBEND = 2 THEN P = P * ARMLENGTH
      AI = AC
      DELXA = 0!
      DELTA = PDELTA(10, 2)
      ANEWJ = PDELTA(10, 6)
      TOUGH = MATJ(1, 2)
      DJDA = 0!
      DJRDA = 0!
 CGITE:  REM  ---  CRACK GROWTH LOOP .
      NKLPA = 0
      OAI = AI
      OP = P
      IF NBEND = 2 THEN OP = OP / ARMLENGTH
      ODELTA = DELTA
      OLDJ = ANEWJ
      OTOUGH = TOUGH
      DA = BFACT * AI
      DELXA = DELXA + DA
      AI = AI + DA
      IF AI > WHALT THEN GOTO CGSTO2
      IF NREND = 1 THEN GOTO CGSTO2
      IF KREND = 1 THEN GOTO CGSTO2
 REM -----  GET J, DELTA, COD  FOR A = AI + DA  AND  P = PI .
      GOSUB 14340
      APDAJ = TOTALJ
 REM -----  GET TOUGH  FOR A = AI + DA .
      GOSUB 14160
      DJRDA = (TOUGH - OTOUGH) / DA
      DJDA = (APDAJ - OLDJ) / DA
      IF NKLPA = 1 THEN DJDA = 1.1 * DJRDA
 REM -----  GET P  FOR A = AI + DA  AND  JRI+1 .
      GOSUB 14530
 REM -----  GET J,DELTA,COD  FOR A = AI + DA AND P = PI+1 .
      IF P <= 0! THEN GOTO CGSTO2
      GOSUB 14340
      ANEWJ = TOTALJ
      NCOUNT = NCOUNT + 1
      LCOUNT = LCOUNT + 1
      PDELTA(NCOUNT, 1) = P
      IF NBEND = 2 THEN PDELTA(NCOUNT, 1) = P / ARMLENGTH
      PDELTA(NCOUNT, 2) = DELTA
      PDELTA(NCOUNT, 3) = AI
      PDELTA(NCOUNT, 4) = TCOD
      PDELTA(NCOUNT, 5) = DELXA
      PDELTA(NCOUNT, 6) = ANEWJ
      RESUL(LCOUNT, 1) = 2! * OAI
      RESUL(LCOUNT, 2) = OAI
      RESUL(LCOUNT, 3) = OP
      RESUL(LCOUNT, 4) = OP / PF
      RESUL(LCOUNT, 5) = OLDJ
      RESUL(LCOUNT, 6) = OTOUGH
      RESUL(LCOUNT, 7) = DJDA
      RESUL(LCOUNT, 8) = DJRDA
      RESUL(LCOUNT, 9) = ODELTA
      RESUL(LCOUNT + 1, 10) = DELXA
 REM  PRINT #8, LCOUNT, PDELTA(LCOUNT, 1), PDELTA(LCOUNT, 2)
      IF LCOUNT >= (MRES - 1) THEN GOTO CGEND
      IF NPROC = 2 AND P > PO THEN GOTO CGSTO1
      ON NTASK GOTO CGERR, CGNT2, CGNT3
 CGERR: PRINT #8, "***** ERROR IN CRACK GROWTH SCHEME "
        GOTO CGEND
 CGNT2: LCOMA = 5
        IF DJDA <= 0! THEN GOTO CGSTO2
        IF DJDA >= DJRDA THEN
 CGSTO1: ISTOP = ISTOP + 1
        IF ISTOP < 2 THEN GOTO CGITE ELSE GOTO CGSTO2
        END IF
 CGNT3: LCOMA = 10
        IF DJDA <= 0! THEN GOTO CGSTO2
        IF DJDA >= DJRDA THEN BFACT = 1.25 * BFACT
```

```
        IF NREND = 0 THEN GOTO CGITE
REM --- CHECK ON NUMBER OF LOAD-DISPLACEMENT POINTS .
CGSTO2: LRES = LCOUNT
    LPDELXT = NCOUNT
    IF DJDA <= 0! THEN
    LRES = LRES - 1
    LPDELXT = LPDELXT - 1
    END IF
    NTELL = NTELL + 1
        IF NTELL > 5 THEN GOTO CGEND
        IF LCOUNT < LCOMA THEN
    BFACT = .5 * BFACT
    GOTO CGRST
        END IF
CGEND: REM  ----- END OF CRACK GROWTH COMPUTATION .
     CALL MOUT
7975 CLOSE 8
7980 CLS
8100 GOTO 19800
8110 REM ********************************************************** REM 30000
8120 REM
8130 REM     SUB ROUTINE PRINT LINE ON SCREEN
8140 REM
8150 REM ********************************************************** REM 30040
8160 RETURN
8170 FOR LA = 1 TO 73: PRINT #8, "-"; : NEXT LA: PRINT #8, : RETURN
9140 REM ********************************************************** REM 36000
9150 REM
9160 REM        SUB ROUTINE MATERIAL INPUT AND FILE NAMES
9170 REM
9180 REM ********************************************************** REM 36040
9190 CLS
     LOCATE 1, 30
     NSCREEN = 9
     IF (KITER = 0) THEN
     PRINT "Screen #"; NSCREEN
     LOCATE 3, 1
9200 PRINT "GIVE YIELD STRESS IN "; US$; : INPUT YIELD
9210 PRINT "GIVE ULT.TENS.STR IN "; US$; : INPUT UTS
9220 PRINT "IF YOU GIVE THE COLLAPSE STRESS AS ZERO THEN THIS PROGRAM WILL"
9230 PRINT "AUTOMATICALLY TAKE COLLAPSE STRESS AS (YIELD + ULT)/2"
9240 PRINT "GIVE COLLAPSE STR.IN "; US$; : INPUT SCOLL
9250 IF SCOLL <= 0 THEN SCOLL = (YIELD + UTS) / 2!
9260 PRINT "SIGMA ZERO IS REFERENCE STRESS; EPSILON ZERO IS REFERENCE STRAIN"
9270 PRINT "GIVE SIGMA ZERO   IN "; US$; : INPUT SOX
9280 PRINT "GIVE EPSILON ZERO              "; : INPUT EO
9290 PRINT "GIVE ALPHA                     "; : INPUT ALPHA
9300 PRINT "GIVE EXPONENT STRAIN HARDENING "; : INPUT AN
9310 E = SOX / EO
9320 CLS
     WRITE #3, YIELD, UTS, SCOLL, SOX, EO, ALPHA, AN, E
     ELSE
     INPUT #3, YIELD, UTS, SCOLL, SOX, EO, ALPHA, AN, E
     END IF
REM ***** CALL SUBROUTINE DEFILE ******
REM  MENU FOR J-R CURVE OR P-DELTA-CRACK SIZE TABLE
       ON NTASK GOTO MA940, MA950, MA950
MA940: XSTR$ = PDCT$
     YSTR$ = PM$ + "(" + UM$ + ") ," + DELX$ + "(" + UL$ + ") ," + AP$ + "(" + UL$ + ")  TRIPLETS
"
     INFILTYP$ = PDCT$
     FILCOM$ = PDCT$
       CALL DEFILE(XSTR$, YSTR$, NPLM, NTASK, KSAVIN%, R$, PM$, AP$, DA$, DELX$, TM$, TA$,
MATJ(), PDELX$, JR$, FDR$, FPA$, DIREF$, FINEX$, LFIL$, GFIL$, NINFIL, INFIL$, INOF%, MDJ, MDP,
PDELTA(), LPDELXT, LMATJ, XAR(), TIT$(), TSTR$())
     LINFIL$ = PDELX$
     GOTO 9590
MA950: XSTR$ = JREC$
     YSTR$ = DA$ + "(" + UL$ + ") ," + R$ + "(" + UJ$ + ")   PAIRS "
     INFILTYP$ = JREC$
     FILCOM$ = JREC$
     IF (KITER = 0) THEN
     CALL DEFILE(XSTR$, YSTR$, NPLM, NTASK, KSAVIN%, R$, PM$, AP$, DA$, DELX$, TM$, TA$, MATJ(),
PDELX$, JR$, FDR$, FPA$, DIREF$, FINEX$, LFIL$, GFIL$, NINFIL, INFIL$, INOF%, MDJ, MDP, PDELTA(),
LPDELXT, LMATJ, XAR(), TIT$(), TSTR$())
```

```
     WRITE #3, JR$, GFIL$
     ELSE
     INPUT #3, JR$, GFIL$
     COPYFILE$ = "COPY " + GFIL$ + " " + JR$
     SHELL COPYFILE$
     END IF
     LINFIL$ = JR$
9590 RETURN
9600 REM ********************************************************** REM 37000
9610 REM
9620 REM         SUBROUTINE ALL H, F, AND BETA
9630 REM
9640 REM ********************************************************** REM 37040
9650 REM GET BETA
9660 GOSUB 10440
9680 IF NGEOM = 1 THEN GOTO 9880
9690 A = AI / WIDE
9700 FOR MC = 1 TO 3
9710 FOR MA = 1 TO LTABLE
9720 FOR MB = 1 TO 2
9730 ON MC GOTO 9740, 9760, 9780
9740 HF(MA, MB) = H1(MA, MB)
9750 GOTO 9790
9760 HF(MA, MB) = H2(MA, MB)
9770 GOTO 9790
9780 HF(MA, MB) = H3(MA, MB)
9790 NEXT MB
9800 NEXT MA
9810 REM GET H
9820 GOSUB 15600
9830 IF MC = 1 THEN HONE = HV
9840 IF MC = 2 THEN HTWO = HV
9850 IF MC = 3 THEN HTHREE = HV
9860 NEXT MC
9870 GOTO 10430
9880 REM PIPE
9890 A = AI / (PI * RADIUS)
9900 MD = 3
9910 IF NLODE = 4 THEN MD = 6
9920 FOR MC = 1 TO MD
9930 FOR MA = 1 TO LTABLE
9940 FOR MB = 1 TO 2
9950 ON MC GOTO 9960, 9970, 9980, 9990, 10000, 10010
9960 HF(MA, MB) = H1(MA, MB): GOTO 10020
9970 HF(MA, MB) = H2(MA, MB): GOTO 10020
9980 HF(MA, MB) = H3(MA, MB): GOTO 10020
9990 HF(MA, MB) = H1B(MA, MB): GOTO 10020
10000 HF(MA, MB) = H2B(MA, MB): GOTO 10020
10010 HF(MA, MB) = H3B(MA, MB)
10020 NEXT MB
10030 NEXT MA
10040 REM GET H
10050 GOSUB 15600
10060 ON MC GOTO 10070, 10080, 10090, 10100, 10110, 10120
10070 HONE = HV: GOTO 10130
10080 HTWO = HV: GOTO 10130
10090 HTHREE = HV: GOTO 10130
10100 HONEB = HV: GOTO 10130
10110 HTWOB = HV: GOTO 10130
10120 HTHREEB = HV
10130 NEXT MC
10140 IF NCRACK < 3 THEN GOTO 10180
10150 REM GET BETA
10160 GOSUB 10440
10170 GOTO 10430
10180 FOR MC = 1 TO 6
10190 FOR MA = 1 TO LTABLE
10200 HF(MA, 1) = FAT(MA, 1)
10210 ON MC GOTO 10220, 10230, 10240, 10270, 10280, 10290
10220 HF(MA, 2) = FAT(MA, 2): GOTO 10310
10230 HF(MA, 2) = FAT(MA, 3): GOTO 10310
10240 REM HF(MA,2) = FAT(MA,4)
10250 HF(MA, 2) = FAT(MA, 5)
10260 GOTO 10310
10270 HF(MA, 2) = FAB(MA, 2): GOTO 10310
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```
10280 HF(MA, 2) = FAB(MA, 3): GOTO 10310
10290 REM HF(MA,2) = FAB(MA,4)
10300 HF(MA, 2) = FAB(MA, 5)
10310 NEXT MA
10320 REM GET F
10330 GOSUB 15600
10340 ON MC GOTO 10350, 10360, 10370, 10380, 10390, 10400
10350 FONE = HV: GOTO 10410
10360 FTWO = HV: GOTO 10410
10370 FTHREE = HV: GOTO 10410
10380 FONEB = HV: GOTO 10410
10390 FTWOB = HV: GOTO 10410
10400 FTHREEB = HV
10410 NEXT MC
10411 IF NLODE <> 1 THEN GOTO 10430
10412 FONE = FONEB: FTWO = FTWOB: FTHREE = FTHREEB
10430 REM ERASE HF
10431 RETURN
10440 REM ************************************************************ REM 38000
10450 REM
10460 REM                    SUBROUTINE BETA
10470 REM
10480 REM ************************************************************ REM 38040
10490 REM              PIPE  CC    CT    BEND  SEN    NA
10500 ON NGEOM GOTO 10660, 10770, 10770, 10770, 10770, 10770
10660 REM PIPE
10670 REM               TH C  COMC  SU C  TH A  COMA  SU A
10680 ON NCRACK GOTO 10770, 10770, 10690, 10710, 10730, 10750
10690 REM CIRCUMFERENTIAL SURFACE FLAW
10691 REM FOR TIME BEING:
10692 BETA = 1!
10700 GOTO 10770
10710 REM AXIAL SURFACE CRACK
10720 GOTO 10770
10730 REM AXIAL THROUGH CRACK
10740 GOTO 10770
10750 REM AXIAL COMPLETE CRACK
10760 GOTO 10770
10770 REM
10780 RETURN
11380 REM ************************************************************ REM 40000
11390 REM
11400 REM               FIGURE CASE
11410 REM
11420 REM ************************************************************ REM 40040
11430 IF NGEOM <> 1 THEN GOTO 11630
11435 IF NLODE <> 4 THEN GOTO 11620
11510 REM NLODE = 4 COMBINED
11520 BSX = 1!
11530 REM IF SIGMA <= 0 THEN BSX = 0!
11540 REM IF SIGMA = 0 THEN SIGMA = SIGTEN
11550 SIGPOF = (POF * SOX) / PF
REM
REM 7/23/93
REM
      FTWOTEN = FTWO
      HTWOTEN = HTWO
REM
REM 7/23/93
REM
11560 FONE = FONEB * BSX + SIGTEN * FONE / SIGPOF
11570 FTWO = FTWOB * BSX + SIGTEN * FTWO / SIGPOF
11580 FTHREE = FTHREEB * BSX + SIGTEN * FTHREE / SIGPOF
11590 HONE = HONEB * BSX + SIGTEN * HONE / SIGPOF
11600 HTWO = HTWOB * BSX + SIGTEN * HTWO / SIGPOF
11610 HTHREE = HTHREEB * BSX + HTHREE * SIGTEN / SIGPOF
11620 BETA = FONE
11630 RETURN
11640 REM ************************************************************ REM 41000
11650 REM
11660 REM          SUBROUTINE C, POF, PF
11670 REM
11680 REM ************************************************************ REM 41040
11690 REM              PIPE   CC    CT    BEND  SEN    NA
11700 ON NGEOM GOTO 12060, 12580, 12580, 12580, 12580, 12580
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```
12060 REM PIPE
12070 REM            BEND    PR     AX    BE+PR TORS     OTHERS
12080 ON NLODE GOTO 12100, 12340, 12340, 12510, 12510, 12560, 12560, 12560
12090 REM                TH     COM         AXIAL
12100 ON NCRACK GOTO 12110, 12110, 12300, 12300
12110 REM THROUGH CRACK AND COMPLEX CIRCUMFERENTIAL BENDING
12115 CS = PI * RADIUS - AI
12120 POF = 4 * THICK * RADIUS ^ 2!
12130 GAM = AI / RADIUS
12140 POF = POF * (COS(GAM / 2!) - .5 * SIN(GAM))
12150 C = (PI * RADIUS - AI) / (PI * RADIUS)
12160 PF = (PI * ((DIA ^ 4!) - (DIA - 2! * THICK) ^ 4!)) / (32! * (DIA - THICK))
12190 GOTO 12580
12300 REM AXIAL CRACKS
12310 GOTO 12580
12320 REM
12330 REM                TH     COM    SUR     AXIAL
12340 ON NCRACK GOTO 12350, 12350, 12440, 12470, 12470, 12470
12350 REM THROUGH AND COMPLEX CRACKS CIRCUMFERENTIAL IN TENSION AND PRESSURE
12360 GAM = AI / RADIUS
12361 SIGAM = SIN(GAM)
12362 HSIGAM = SIGAM / 2!
12363 ASIN = ATN(HSIGAM / SQR(1! - HSIGAM ^ 2!))
12364 REM
12380 POF = 2! * RADIUS * THICK * (PI - GAM - 2! * ASIN)
12390 C = 1 - AI / (PI * RADIUS)
12400 PF = 2! * PI * RADIUS * THICK
12430 GOTO 12580
12440 REM SURFACE FLAW TENSION
12450 REM LIGAMENT INSTABILITY
12460 GOTO 12580
12470 REM AXIAL CRACKS
12480 GOTO 12580
12490 REM OTHERS
12500 GOTO 12580
12510 REM BENDING AND PRESSURE ONLY THROUGH AND COMPLEX CRACKS
12520 IF NLODE = 1 THEN SIGTEN = 0!
12530 IF NLODE = 2 THEN SIGTEN = P / (2! * PI * RADIUS * THICK)
12531 THE = AI / RADIUS
      SOX1 = SCOLL
12532 MB = COS(THE / 2! + PI * SIGTEN / (2! * SOX1)) - .5 * SIN(THE)
      IF (MB <= 0) THEN KREND = 1
12533 POF = 4! * MB * THICK * RADIUS ^ 2!
12534 C = 1! - AI / (PI * RADIUS)
12535 PF = (PI * ((DIA ^ 4!) - (DIA - 2! * THICK) ^ 4!)) / (32! * (DIA - THICK))
12550 GOTO 12580
12560 REM OTHER CASES
12570 GOTO 12580
12580 RETURN
12590 REM ********************************************************** REM 45000
12600 REM
12610 REM                    J BY GE-SCHEME
12620 REM
12630 REM ********************************************************** REM 45040
12640 REM
12650 ELJ = (BETA ^ 2!) * PI * ((P / PF) ^ 2!) * AI / E
12653 ALPH1 = ALPHA
12655 IF NEPRI = 2 THEN ALPH1 = ALPHA ^ (1 / (AN + 1))
12660 PLJ = ALPH1 * EO * SOX * C * AI * HONE * (P / (SOX * POF)) ^ (AN + 1)
12670 TOTALJ = ELJ + PLJ
12680 ELCOD = 4 * P * AI * FTWO / (E * PF)
12690 PLCOD = ALPH1 * EO * AI * HTWO * (P / (SOX * POF)) ^ AN
REM
REM 7/23/93
REM
      IF NLODE <> 4 GOTO 12700
      GAM = AI / RADIUS
      SIGAM = SIN(GAM)
      HSIGAM = SIGAM / 2!
      ASIN = ATN(HSIGAM / SQR(1! - HSIGAM ^ 2!))
      POFT = (PI - GAM - 2! * ASIN)
      ELCOD = ELCOD + 4! * AI * FTWOTEN * (SIGTEN) / E
      PLCOD = PLCOD + ALPH1 * EO * AI * HTWOTEN * ((SIGTEN) / (SOX * POFT)) ^ AN
REM
REM 7/23/93
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REM
12700 TCOD = ELCOD + PLCOD
12710 DELEC = 4 * FTHREE * P / (E * PF)
12720 DELPC = ALPH1 * EO * HTHREE * (P / (SOX * POF)) ^ AN
12730 DELTA = DELEC + DELPC
12740 IF NGEOM <> 1 THEN DELTA = DELTA * AI
12750 RETURN
14010 REM ********************************************************** REM 53000
14020 REM
14030 REM   SUBROUTINE  MU AND LAMBDA ITERATION SIGMA P
14040 REM
14050 REM ********************************************************** REM 53040
14052 REM *****CERTAIN QUANTITIES HERE ARE CONVERTED TO KSI
14053 REM *****LOCALLY TO AVOID ERROR OCCURING IN CALCULATING
14054 REM ***** AMU UNDER SOME COMBINATION OF VALUES IN THE
14055 REM *****INVOLVED PARAMETERS.THIS HAPPENS WHEN UNITS ARE
14056 REM *****ARE GIVEN IN PSI******************************
14057 IF NUNIT = 2 THEN SOX = SOX / 1000!
14058 ALPH1 = ALPHA
14059 IF NEPRI = 2 THEN ALPH1 = ALPHA ^ (1 / (AN + 1))
14060 ALAMB = (BETA ^ 2!) * PI * AI / (SOX / EO)
14070 AMU = ALPH1 * EO * SOX * C * AI * HONE * (PF / (POF * SOX)) ^ (AN + 1)
14080 AMUN = AMU
14089 IF NUNIT = 2 THEN TOUGH = TOUGH / 1000!
14090 SIGMA = (TOUGH / AMUN) ^ (1 / (AN + 1))
14100 TOUGHI = (ALAMB * SIGMA ^ 2!) + AMU * SIGMA ^ (AN + 1)
14110 IF ABS(TOUGH - TOUGHI) <= .001 * TOUGH THEN GOTO 14136
14120 AMUN = TOUGHI / (SIGMA ^ (AN + 1))
14130 GOTO 14090
14136 IF NUNIT = 2 THEN TOUGHI = TOUGHI * 1000!
14137 IF NUNIT = 2 THEN SOX = SOX * 1000!
14138 IF NUNIT = 2 THEN SIGMA = SIGMA * 1000!
14139 IF NUNIT = 2 THEN TOUGH = TOUGH * 1000!
14140 P = PF * SIGMA
14141 TOTALJ = TOUGHI
14150 RETURN
14160 REM ********************************************************** REM 55000
14170 REM
14180 REM           SUBROUTINE J-R FROM CURVE
14190 REM
14200 REM ********************************************************** REM 55040
14210 NREND = 0
14220 IF DELXA > MATJ(LMATJ, 1) GOTO 14320
14230 FOR IJ = 1 TO LMATJ
14240 IF DELXA < MATJ(IJ, 1) GOTO 14260
14250 NTEL = IJ
14260 NEXT IJ
14270 AJR2 = (DELXA - MATJ(NTEL, 1)) * (MATJ(NTEL + 1, 2) - MATJ(NTEL, 2))
14280 AJR2 = AJR2 / (MATJ(NTEL + 1, 1) - MATJ(NTEL, 1))
14290 AJR2 = AJR2 + MATJ(NTEL, 2)
14300 TOUGH = AJR2
14310 GOTO 14330
14320 NREND = 1
14330 RETURN
14340 REM ********************************************************** REM 56000
14350 REM
14360 REM     SUBROUTINE GET J, COD, DELTA
14370 REM
14380 REM ********************************************************** REM 56040
14390 REM GET C,POF,PF
14400 GOSUB 11640
      IF (KREND = 1) THEN GOTO 14520
14410 REM GET H,F,BETA
14420 GOSUB 9600
14430 REM FIGURE CASE
14440 GOSUB 11380
14470 NWHAT = 1
14480 REM  GET J ETC.  FOR GE/EPRI METHOD
14490 GOSUB 12590
14500 REM GET DELTA
14510 GOSUB 14700
14511 IF NPROC <> 1 THEN TCOD = 0!
14520 RETURN
14530 REM ********************************************************** REM 57000
14540 REM
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14550 REM      SUBROUTINE GET P AND SIGMA
14560 REM
14570 REM ************************************************************ REM 57040
14580 REM GET C,POF,PF
14590 GOSUB 11640
      IF (KREND = 1) THEN GOTO 14690
14600 REM GET H,F,BETA
14610 GOSUB 9600
14620 REM FIGURE CASE
14630 GOSUB 11380
14660 NWHAT = 2
14670 REM GET LAMBDA,MU,ITERATE SIGMA,P
14680 GOSUB 14010
14690 RETURN
14700 REM ************************************************************ REM 58000
14710 REM
14720 REM                 DISPLACEMENT OR ROTATION
14730 REM
14740 REM ************************************************************ REM 58040
14750 IF NBEND <> 1 THEN GOTO 14790
14760 DELTA = DELTA + 2 * P * ARMLENGTH / (E * PI * THICK * RADIUS ^ 3!)
14770 REM  DELTA = DELTA + TCOD/(RADIUS*(1.5+COS(AI/RADIUS)))
14771 IF NPROC > 1 THEN DELTA = DELEC + DELPC + 2 * P * ARMLENGTH / (E * PI * THICK * RADIUS ^ 3)
14780 GOTO 15020
14790 IF NGEOM = 1 THEN GOTO 14950
14800 IF NGEOM <> 2 THEN GOTO 14840
14810 EPS = (P / (PF * SOX))
14820 DELTA = DELTA + EO * EPS * ARMLENGTH
14830 GOTO 15020
14840 IF NGEOM = 3 THEN GOTO 15020
14850 IF NGEOM <> 4 THEN GOTO 14890
14860 DELTA = DELTA + 2 * P * (ARMLENGTH ^ 3!) / (E * THICK * WIDE ^ 3!)
14870 GOTO 15020
14880 REM SEN
14890 IF NGEOM <> 5 THEN GOTO 14930
14900 EPS = (P / (PF * SOX))
14910 DELTA = DELTA + EO * EPS * ARMLENGTH
14920 GOTO 15020
14930 REM NGEOM = 6 OTHER
14940 GOTO 15020
14950 REM PIPE OTHER THAN NBEND = 1
14960 IF NLODE = 1 THEN GOTO 14990
14970 IF NLODE = 4 THEN GOTO 14990
14980 GOTO 14810
14990 TW = TWOL ^ 3! + 2! * TWOS ^ 3! - 3! * TWOL * TWOS ^ 2!
14999 DELENC = P * TW / (48! * (E * (TWOL - TWOS) * PI * THICK * RADIUS ^ 3!))
15000 IF NPROC = 1 THEN GOTO 15013
15010 DELTA = DELENC + DELEC + DELPC
15012 GOTO 15020
15013 DELTA = DELENC + DELTA * (TWOL - TWOS) / 4
15020 RETURN
15030  REM ************************************************************ REM 60000
15040 REM
15050  REM     SUBROUTINE GET H FOR N
15060 REM
15070  REM ************************************************************ REM 60040
15080 H$ = GE1$ + ".DAT"
15090 H = 1
15100 OPEN H$ FOR INPUT AS 2
15110 INPUT #2, LTABLE, WTABLE
15120 FOR IK = 1 TO LTABLE
15130 FOR JIJ = 1 TO WTABLE
15140 INPUT #2, HFUNC(IK, JIJ)
15143 NEXT JIJ
15160 NEXT IK
15170 CLOSE 2
15180 NTEL = 0
15190 FOR JIJ = 2 TO WTABLE
15200 IF HFUNC(1, JIJ) > AN GOTO 15220
15210 NTEL = JIJ
15220 NEXT JIJ
15230 FOR IK = 1 TO LTABLE - 1
15240 IF NTEL > 0 GOTO 15280
15250 H3(IK, 2) = HFUNC(IK + 1, 2)
15260 H3(IK, 1) = HFUNC(IK + 1, 1)
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15270 GOTO 15380
15280 IF NTEL < WTABLE GOTO 15330
15290 H3(IK, 2) = HFUNC(IK + 1, WTABLE)
15300 H3(IK, 1) = HFUNC(IK + 1, 1)
15310 IF AN > HFUNC(1, WTABLE) THEN NALERT = 1
15320 GOTO 15380
15330 H3(IK, 1) = HFUNC(IK + 1, 1)
15340 H3(IK, 2) = HFUNC(IK + 1, NTEL)
15350 DELX = (AN - HFUNC(1, NTEL)) / (HFUNC(1, NTEL + 1) - HFUNC(1, NTEL))
15360 DELX = DELX * (HFUNC(IK + 1, NTEL + 1) - HFUNC(IK + 1, NTEL))
15370 H3(IK, 2) = H3(IK, 2) + DELX
15380 NEXT IK
15390 IF H > 1 GOTO 15480
15400 FOR IK = 1 TO LTABLE - 1
15410 FOR JIJ = 1 TO 2
15420 H1(IK, JIJ) = H3(IK, JIJ)
15430 NEXT JIJ
15440 NEXT IK
15450 H = H + 1
15460 H$ = GE2$ + ".DAT"
15470 GOTO 15100
15480 IF H > 2 GOTO 15570
15490 FOR IK = 1 TO LTABLE - 1
15500 FOR JIJ = 1 TO 2
15510 H2(IK, JIJ) = H3(IK, JIJ)
15520 NEXT JIJ
15530 NEXT IK
15540 H$ = GE3$ + ".DAT"
15550 H = H + 1
15560 GOTO 15100
15570 REM
15580 LTABLE = LTABLE - 1
15590 RETURN
15600  REM ************************************************************ REM 61000
15610 REM
15620  REM    SUBROUTINE  H  FOR A = AO/W
15630 REM
15640  REM ************************************************************ REM 61040
15650 NTEL = 0
15660 IF A > HF(LTABLE, 1) THEN HV = HF(LTABLE, 2)
15670 IF A > HF(LTABLE, 1) GOTO 15820
15680 FOR II = 1 TO LTABLE
15690 IF HF(II, 1) > A GOTO 15710
15700 NTEL = II
15710 NEXT II
15720 IF NTEL > 0 GOTO 15750
15730 HV = HF(1, 2)
15740 GOTO 15820
15750 IF NTEL < LTABLE GOTO 15780
15760 HV = HF(LTABLE, 2)
15770 GOTO 15820
15780 HV = HF(NTEL, 2)
15790 DELX = (A - HF(NTEL, 1)) / (HF(NTEL + 1, 1) - HF(NTEL, 1))
15800 DELX = DELX * (HF(NTEL + 1, 2) - HF(NTEL, 2))
15810 HV = HV + DELX
15820 RETURN
15830 REM ************************************************************ REM 62000
15840 REM
15850 REM          SUBROUTINE F FUNCTIONS
15860 REM
15870 REM ************************************************************ REM 62040
15890 H = 0
15900 IF NCRACK <> 1 THEN GOTO 16430
15910 H$ = FGE$
15912 IF NLODE = 4 THEN H$ = LEFT$(H$, 3) + "PR"
15920 OPEN H$ + ".DAT" FOR INPUT AS 1
15930 INPUT #1, FAKE
15940 FOR IB = 1 TO LTABLE
15960 INPUT #1, FAL(IB, 1), FAL(IB, 2), FAL(IB, 3), FAL(IB, 4), FAL(IB, 5)
15980 NEXT IB
15990 IF ROVERT <= 5 THEN GOTO 16230
16000 INPUT #1, FAKE
16010 FOR IB = 1 TO LTABLE
16030 INPUT #1, FAU(IB, 1), FAU(IB, 2), FAU(IB, 3), FAU(IB, 4), FAU(IB, 5)
16035 FOR JB = 1 TO 5
```

```
16040 IF ROVERT > 10 THEN FAL(IB, JB) = FAU(IB, JB)
16050 NEXT JB
16060 NEXT IB
16070 IF ROVERT <= 10 THEN GOTO 16150
16080 INPUT #1, FAKE
16090 FOR IB = 1 TO LTABLE
16110 INPUT #1, FAU(IB, 1), FAU(IB, 2), FAU(IB, 3), FAU(IB, 4), FAU(IB, 5)
16115 FOR JB = 1 TO 5
16120 IF ROVERT >= 20 THEN FAL(IB, JB) = FAU(IB, JB)
16130 NEXT JB
16140 NEXT IB
16150 IF ROVERT >= 20 THEN GOTO 16230
16160 IF ROVERT > 5 THEN D = 5
16170 IF ROVERT > 10 THEN D = 10
16180 FOR IB = 1 TO LTABLE
16190 FOR JB = 2 TO 5
16200 FAL(IB, JB) = FAL(IB, JB) + (ROVERT - D) * (FAU(IB, JB) - FAL(IB, JB)) / D
16210 NEXT JB
16220 NEXT IB
16230 CLOSE 1
16240 REM
16250 FOR IB = 1 TO LTABLE
16260 FOR JB = 1 TO 5
16270 REM
16280 IF H > 0 THEN GOTO 16310
16290 FAB(IB, JB) = FAL(IB, JB)
16300 GOTO 16320
16310 FAT(IB, JB) = FAL(IB, JB)
16320 NEXT JB
16330 NEXT IB
16340 IF H > 0 THEN GOTO 16420
16360 IF NLODE > 4 THEN GOTO 16420
16370 H$ = LEFT$(H$, 3)
16380 IF NLODE = 1 THEN H$ = H$ + "PR"
16390 IF NLODE <> 1 THEN H$ = H$ + "BE"
16400 H = H + 1
16410 GOTO 15920
16420 REM CONTINUE
16430 RETURN
16440 REM ********************************************************* REM 63000
16450 REM
16460 REM      SUBROUTINE DUMP OUTPUT ON FILE
16470 REM
16480 REM ********************************************************* REM 63040
16860 RETURN
16870 REM ********************************************************* REM 64000
16880 REM
16890 REM      SUBROUTINE READ PREVIOUS OUTPUT FROM FILE
16900 REM
17320 RETURN
18000 REM
18010 REM TRAP ERRORS ON LCONT
18020 REM
18050 PRINT "ERROR ICONT > 300 "
18051 STOP
19500 REM ********************************************************* REM 59000
19505 REM
19510 REM           SUBROUTINE H FOR R/T
19515 REM
19520 REM ********************************************************* REM 59040
19525 IF ROT < ROT2 THEN GOTO 19550
19530 IF ROT > ROT2 THEN NALERT = 1
19535 RT$ = RT2$
19540 NFIRST = 2
19545 GOTO 19610
19550 IF ROT <= ROT1 THEN GOTO 19570
19555 IF NFIRST = 2 THEN RT$ = RT2$
19560 IF NFIRST = 1 THEN RT$ = RT1$
19565 GOTO 19610
19570 IF ROT <= ROT5 THEN GOTO 19590
19575 IF NFIRST = 2 THEN RT$ = RT1$
19580 IF NFIRST = 1 THEN RT$ = RT5$
19585 GOTO 19610
19590 IF ROT < ROT5 THEN NALERT = 1
19595 NFIRST = 2
```

```
19600 RT$ = RT5$
19605 GOTO 19610
19610 GE1$ = GE$ + "1" + RT$
19615 GE2$ = GE$ + "2" + RT$
19620 GE3$ = GE$ + "4" + RT$
19625 IF NLODE = 2 THEN GE3$ = GE$ + "3" + RT$
19626 IF NLODE = 3 THEN GE3$ = GE$ + "3" + RT$
19635 REM GET H FOR N, R/T, SINGLE OR COMBINED LOADING
19640 GOSUB 15030
19645 IF ROT <= ROT5 THEN GOTO 19790
19650 IF ROT >= ROT2 THEN GOTO 19790
19655 IF NFIRST > 1 THEN GOTO 19705
19660 FOR IA = 1 TO LTABLE
19665 FOR JA = 1 TO 2
19670 H1RT1(IA, JA) = H1(IA, JA)
19675 H2RT1(IA, JA) = H2(IA, JA)
19680 H3RT1(IA, JA) = H3(IA, JA)
19685 NEXT JA
19690 NEXT IA
19695 NFIRST = 2
19700 GOTO 19520
19705 FOR IA = 1 TO LTABLE
19710 FOR JA = 1 TO 2
19715 H1RT2(IA, JA) = H1(IA, JA)
19720 H2RT2(IA, JA) = H2(IA, JA)
19725 H3RT2(IA, JA) = H3(IA, JA)
19730 NEXT JA
19735 NEXT IA
19740 REM
19745 IF ROT > ROT2 THEN GOTO 19790
19750 IF ROT < ROT5 THEN GOTO 19790
19755 D = ROT2 - ROT1
19760 IF ROT <= ROT1 THEN D = ROT1 - ROT5
19761 TEM1 = (ROT - D) / D
19765 FOR IA = 1 TO LTABLE
19770 H1(IA, 2) = H1RT1(IA, 2) + TEM1 * (H1RT2(IA, 2) - H1RT1(IA, 2))
19775 H2(IA, 2) = H2RT1(IA, 2) + TEM1 * (H2RT2(IA, 2) - H2RT1(IA, 2))
19780 H3(IA, 2) = H3RT1(IA, 2) + TEM1 * (H3RT2(IA, 2) - H3RT1(IA, 2))
19785 NEXT IA
19790 RETURN
19795 STOP
19800 CALL ENDCO(KSAVIN$, LINEP$, INFILTYP$, RESU$, PDELX$, JR$, LINFIL$, GINFIL$, WORK$, GWORK$)
      MINUS = 1
      IF NTASK = 2 THEN MINUS = 2
      LPDELXT = LPDELXT - MINUS
      OPEN "MNBVCXZ.TRN" FOR OUTPUT AS 6
      WRITE #6, NUNIT, NBEND, LPDELXT, THICK, GWORK$
      FOR LJ = 1 TO LPDELXT
      FOR LK = 1 TO 5
      WRITE #6, PDELTA(LJ, LK)
      NEXT LK
      NEXT LJ
      CLOSE #6
      SYSTEM
END

SUB CHECKJR (IN%, KCHECK%, A, B, IJ%, LP%) STATIC
        REM ******************************
        REM *** SUBROUTINE CHECKJR
        REM     CHECKS THE VALIDITY OF THE J-R  CURVE .
        REM     INPUT  : IN% = 1 FOR INITIALISATION
        REM                KCHECK% = 1 IF THE CUVE IS CHECKED AND MODIFIED
        REM                A,B = DA  AND JMAT  VALUES FOR THE POINT BEING ENTERED .
        REM     OUTPUT : IJ% = INDEX VALUE IN INPUT TABLE
        REM                LP% = EDITED LINES NUMBER .
        REM ******************************
     DEFINT I-L
        REM ******************************
     WARN1JR$ = "THE J-R CURVE IS NO MORE INCREASING !, DJ = "
     WARN2JR$ = "THE J-R CURVE IS INCREASING TOO QUICKLY !, DJ/DA1 > DJ/DA2 : "
     IF IN% <> 1 THEN GOTO CH110
CH105:  REM INITIALISATION .
     AM1 = -1: BM1 = 0: AM2 = 0: BM2 = 0
     PRINT "     DA AND J HAVE TO BE >= 0 !"
     PRINT "     DA     SHOULD NEVER DECREASE !"
```

```
     PRINT "     J     SHOULD NEVER DECREASE !"
     PRINT "     DJ/DA SHOULD NEVER INCREASE !"
     LP% = 4
       EXIT SUB
CH110:  REM CHECKING A,B PAIRS .
     LP% = 0
     DA1 = A - AM1: DB1 = B - BM1
     IF A < 0 OR B < 0 THEN GOTO CH180
     IF DB1 <= 0 THEN LP% = LP% + 1: PRINT WARN1JR$; DB1
     IF DA1 <= 0 THEN GOTO CH180
     DA2 = AM1 - AM2: DB2 = BM1 - BM2
     AM2 = AM1: BM2 = BM1
     AM1 = A: BM1 = B
     IF IJ% < 3 OR DB1 <= 0 THEN GOTO CHEND
     DBA1 = DB1 / DA1: DBA2 = DB2 / DA2
     IF DBA1 > DBA2 THEN LP% = LP% + 2: PRINT WARN2JR$, TAB(44); DBA1; " > "; DBA2
       GOTO CHEND
CH180: IF KCHECK = 1 THEN GOTO CH184
CH182: LP% = LP% + 1
     PRINT "THE LAST PAIR ( DA,J = "; A, B; " ) IS NOT VALID ! "
       GOTO CHEND
CH184: LP% = LP% + 1
     PRINT "THE LAST PAIR ( DA,J = "; A, B; " ) IS NOT VALID ! ,TRY AGAIN "
     IJ% = IJ% - 1
CHEND: END SUB

DEFSNG I-L
SUB COPFIL (GFIL$, LFIL$, IPRC%)
        REM ******************************
        REM *** SUBROUTINE COPFIL
        REM     COPIES THE GLOBAL FILE GFIL$ ON THE LOCAL FILE .
        REM     LFIL$ LOCATED IN THE CURRENT DIRECTORY .
        REM     INPUT  : GFIL$  AND LFIL$ .
        REM     OUTPUT : FILE "LFIL$" .
        REM ******************************
     IF IPRC% <> 1 THEN IPRC% = 0: GOTO CO110
     PRINT
     PRINT "THE FILE  '"; GFIL$; "'  IS BEING COPIED ON THE FILE  ' "; LFIL$; " '"
     PRINT
CO110: COPYFILE$ = "COPY " + GFIL$ + " " + LFIL$
       SHELL COPYFILE$ + " >DUMMY.OUT"
       PRINT
COEND: END SUB

SUB DEFILE (XSTR$, YSTR$, NPLM, NTASK, KSAVIN%, R$, PM$, AP$, DA$, DELX$, TM$, TA$, MATJ(),
PDELX$, JR$, FDR$, FPA$, DIREF$, FINEX$, LFIL$, GFIL$, NINFIL, INFIL$, INOF%, MDJ, MDP, PDELTA(),
LPDELXT, LMATJ, XAR(), TIT$(), TSTR$())
        REM ******************************
        REM *** SUBROUTINE DEFILE
        REM     DEFINES INPUT CURVE OR TABLE .
        REM     INPUT  : XSTR$ IS THE NAME OF INPUT CURVE OR TABLE
        REM              YSTR$ DEFINES THE TYPE OF INPUT POINTS .
        REM     OUTPUT : LOCAL FILE PDELX$ OR JR$ ( NTASK = 1/2 OR 3 ) .
        REM
        REM ******************************
        REM ******************************
        REM  SELECTION OF INPUT CURVE OR TABLE
     CLS
     LOCATE 1, 30
     NSCREEN = 10
     PRINT "Screen #"; NSCREEN
     LOCATE 4, 1
     SEL$ = XSTR$ + " INPUT"
     COM$ = "CAUTION : THE " + XSTR$ + " IS DEFINED BY A FILE CONTAINING " + CHR$(13) + YSTR$ +
CHR$(13) + " ONLY THE 40 FIRST PAIRS/TRIPLETS WILL BE CONSIDERED ! J must be > 0."
     MENU$(1) = "ENTER A FILENAME"
     MENU$(2) = "LIST FILE NAMES IN A SPECIFIED DIRECTORY & RETURN TO THIS MENU"
     MENU$(3) = "ENTER THE " + XSTR$ + " POINT BY POINT" + SPACE$(15) + " ( EACH POINT IS
AUTOMATICALLY CHECKED )"
     MENU$(4) = MENU$(1) + ", CHECK IT AND MODIFY IT WITH EDLIN "
     MENU$(5) = MENU$(1) + ", THE POINTS WILL BE FITTED AND CHECKED " + SPACE$(12) +
"AUTOMATICALLY ( ONLY FOR J-RESISTANCE CURVE )    ---INACTIVE---"
     LMENU = 4: LSMENU = 4: IF NTASK = 1 THEN LSMENU = 2
     LXSM% = 65
     KDIR% = 0
```

```
DE105: CALL MAKEMENU(SEL$, COM$, MENU$(), LMENU, LSMENU, LXSM%, NCHOIC, OOTR$, TSTR$())
REM P       CALL PAUSE
     NINFIL = NCHOIC
     INFIL$ = MENU$(NINFIL)
        REM ******************************
        REM  DEFINITION OF INPUT CURVE OR TABLE    ( KFIL% = 1 )
       ON NINFIL GOTO DE110, DE120, DE130, DE140, DE110
DE110:  REM ******************************
REM LOADING AN INPUT FILE ( KDIR% <> 1 ) .
     NSCREEN = 11
     CALL FILENAME(KDIR%, 1)
     IF INOF% = 1 THEN GOTO DE105
       CALL LOADARR(1, NTASK)
       ON NINFIL GOTO DESAV1, DESAV1, DE190, DE142, DE140
DE120:  REM ******************************
        REM SEARCHING THE FILE NAME IN A DIRECTORY AND GOING BACK TO THE MENU .
     KDIR% = 1
       CALL FILENAME(KDIR%, 1)
       CALL PAUSE
     SHELL "DIR " + DIREF$ + "\*.* /P "
       CALL PAUSE
       GOTO DE105
DE130:  REM ******************************
        REM FILE ENTERED POINT BY POINT , EACH POINT IS CHECKED AUTOMATICALLY
        REM              AND MODIFYED IF NEEDED .
     CLS : LOCATE 2, 8
     PRINT "ENTERING THE J-R CURVE POINT BY POINT , EACH POINT BEING CHECKED" + CHR$(13)
     PRINT ">> YOU WILL HAVE TO GIVE A FILE NAME ,"
     PRINT "   THEN NRCPIPE WILL ASK YOU TO ENTER THE DA-J PAIRS AND WILL CHECK THEM ,"
     PRINT "   THE CREATED ARRAY WILL BE PRINTED ON THE SCREEN  ,"
     PRINT "   FINALLY THIS ARRAY WILL BE PRINTED ON THE FILE PREVIOUSLY SPECIFIED ."
       CALL FILENAME(KDIR%, -1)
       CALL PAUSE
DE131: CLS : LOCATE 2, 8
     PRINT "ENTERING THE J-R CURVE POINT BY POINT , EACH POINT BEING CHECKED" + CHR$(13)
     PRINT " >> GIVE THE DA - J PAIRS ( A1,J1 'ENTER'·) : "
     PRINT "      ( THE FILE IS ENDED WHEN J = 0 )"; CHR$(10)
     IJ% = 0
       CALL CHECKJR(1, 1, A, B, IJ%, LP%)
DE132: IJ% = IJ% + 1
     INPUT A, B
     IF B = 0 THEN GOTO DE138
     TA(IJ%) = A: TB(IJ%) = B
       CALL CHECKJR(2, 1, A, B, IJ%, LP%)
       GOTO DE132
DE138:  REM ******************************
     NJ = IJ% - 1
     PRINT NJ; " PAIRS OF DA,J VALUES ARE RECORDED ON THE J-R FILE"
       FOR I = 1 TO NJ
     XAR(I) = TA(I): XAR(NJ + I) = TB(I)
     MATJ(I, 1) = TA(I): MATJ(I, 2) = TB(I)
       NEXT I
     TIT$(1) = DA$: TIT$(2) = R$
       CALL PRINTSC(2, NJ, NPLM, MXAR, XAR(), TIT$())
     XSTR$ = "USE THE STORED DATA (Y) OR START ALL OVER (N)": NCHAN = 1
       CALL DOYOUWANT(XSTR$, C$, NCHAN)
     IF NCHAN = 5 THEN GOTO DE131
     LMATJ = NJ: KDIR% = 0
     PRINT
REM     PRINT "* THESE CREATED 'DA,J-MAT' ARRAYS WILL BE STORED ON A LOCAL FILE ,"; TAB(3); "THEN
COPIED ON A GLOBAL FILE .  PLEASE SPECIFY THIS GLOBAL NAME ."; TAB(3); "THE LOCAL ONE WILL BE :
'FILENAME.LOC'  ."
       CALL LOADARR(2, NTASK)
       CALL COPFIL(LFIL$, GFIL$, 0)
     GINFIL$ = GFIL$
       GOTO DEEND
DE140:  REM ******************************
        REM  CHECKING A FILE AND MODIFYING IT WITH EDLIN .
     CLS : LOCATE 2, 12
     PRINT "CHECKING THE J-R CURVE FILE AND MODIFYING IT WITH EDLIN" + CHR$(13)
     PRINT ">> YOU WILL HAVE TO GIVE A FILE NAME ,"
     PRINT "   THIS FILE WILL BE COPIED ON TH CURRENT DIRECTORY WITH A NEW EXTENSION '.LOC'"
     PRINT "   THEN THE NEW FILE WILL BE CHECKED ,"
     PRINT "    FINALLY THI CREATED FILE WILL BE USED BY EDLIN ."
     CALL PAUSE
```

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     GOTO DE110
DE142: CALL PAUSE
     PRINT "* THE FILE : "; LFIL$; " IS CHECKED BEFORE BEING MODIFYED WITH EDLIN ."
     PRINT
       CALL CHECKJR(1, 2, A, B, IJ%, LP%)
     NLP = CSRLIN: NJ = LMATJ
       FOR IJ% = 1 TO NJ
     A = MATJ(IJ%, 1): B = MATJ(IJ%, 2)
     TA(IJ%) = A: TB(IJ%) = B
     PRINT "* CHECKED LINE : "; IJ%; DA$; "="; A; R$; "="; B: LP% = LP% + 1
       CALL CHECKJR(2, 2, A, B, IJ%, LP%)
     NLP = NLP + LP% + 1
     IF NLP >= NPLM - 2 THEN NLP = 0: CALL PAUSE
       NEXT IJ%
        REM ****************************** MODIFYING THE FILE WITH EDLIN .
CLS : PRINT
     PRINT "* THE FILE : "; LFIL$; " IS HANDLED BY  EDLIN .": PRINT
     SHELL "EDLIN " + LFIL$
       CALL PAUSE
       CALL LOADARR(1, NTASK)
     IF LMATJ < NJ THEN GOTO DE144
     NJM = LMATJ: I = NJ + 1
       FOR I = I TO NJM: TA(I) = 0: TB(I) = 0: NEXT I
       GOTO DE145
DE144: NJM = NJ: I = LMATJ + 1
       FOR I = I TO NJM: MATJ(I, 1) = 0: MATJ(I, 2) = 0: NEXT I
DE145: N1 = NJM: N2 = 2 * NJM: N3 = 3 * NJM
       FOR I = 1 TO NJM
     XAR(I) = TA(I): XAR(N1 + I) = MATJ(I, 1)
     XAR(N2 + I) = TB(I): XAR(N3 + I) = MATJ(I, 2)
       NEXT I
     TIT$(1) = "  OLD DA  ": TIT$(2) = DA$: TIT$(3) = " OLD J-MAT": TIT$(4) = R$
       CALL PRINTSC(4, NJM, NPLM, MXAR, XAR(), TIT$())
     PRINT "* THE MODIFYED FILE IS STORED ON THE LOCAL FILE "; LFIL$; TAB(3); "AND WILL NOT BE
COPIED ON THE GLOBAL FILE "; GFIL$; "  ."
     PRINT
     XSTR$ = "USE THE MODIFIED FILE (Y) OR EDIT OLD FILE AGAIN (N)": NCHAN = 1
       CALL DOYOUWANT(XSTR$, C$, NCHAN)
     IF NCHAN = 5 THEN GOTO DE140
       ON NINFIL GOTO DESAV, DESAV, DE190, DESAV, DE150
DE150:  REM ******************************
        REM LOADING A FILE , FITTING THE POINTS AND CHECKING THEM
        REM                 AUTOMATICALLY ( ONLY FOR J-RESISTANCE CURVE ) .
     PRINT "***** OPTION INACTIVE"
       GOTO DESAV
DE190: PRINT "***** ERROR IN SUBROUTINE INFIL "
DESAV:  REM ******* LOCAL INPUT FILES SAVED/DELETED IN THE MAIN ROUTINE  *******  DESAV
     CLS : KSAVIN% = 2
     XSTR$ = "OVERWRITE THE FILE " + GINFIL$ + " (IF NO A NEW FILE IS CREATED)": NCHAN = 0
       CALL DOYOUWANT(XSTR$, C$, NCHAN)
     IF NCHAN <> 1 THEN GOTO DEEND
     KSAVIN% = 1
       CALL COPFIL(LFIL$, GFIL$, 0)
DESAV1: IF KSAVIN% <> 2 THEN KSAVIN% = 1
DEEND: END SUB

SUB DISPLAYMENU (MENU$(), SEL$, LMENU, LSMENU, NCHOIC)
REM ****************************************************** REM 32000
REM
REM              SUB ROUTINE MENU SELECTION
REM
REM ****************************************************** REM 32040
     CLS
     LOCATE 1, 30
     PRINT "Screen #"; NSCREEN
     LOCATE 3, 1
     PRINT TAB(10); "SELECT FROM MENU "; SEL$
     PRINT
     IF LMENU < 10 THEN PRINT
     FOR LC = 1 TO LMENU
     XSTR$ = MENU$(LC): XR = LEN(XSTR$): YSTR$ = XSTR$
     IF XR < 65 THEN
        IF LC < 10 THEN
        PRINT TAB(10); LC; ". "; YSTR$
        ELSE
```

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        PRINT TAB(9); LC; ". "; YSTR$
        END IF
     ELSE
     YSTR$ = LEFT$(XSTR$, 64): ZSTR$ = MID$(XSTR$, 65)
        IF LC < 10 THEN
        PRINT TAB(10); LC; ". "; YSTR$
        PRINT TAB(14); ZSTR$
        ELSE
        PRINT TAB(9); LC; ". "; YSTR$
        PRINT TAB(15); ZSTR$
        END IF
     END IF
     PRINT : NEXT LC:
     PRINT TAB(10); "ENTER YOUR SELECTION";
8310 INPUT NCHOIC
     IF NCHOIC <> INT(NCHOIC) THEN GOTO 8380
8330 IF NCHOIC < 1 THEN GOTO 8380
8340 IF NCHOIC > LSMENU THEN GOTO 8360
8350   GOTO 8400
8360 PRINT
8370 IF NCHOIC <= LMENU THEN PRINT TAB(10); "THIS SELECTION IS NOT YET ACTIVE"
8380 PRINT
8390 PRINT TAB(10); "TRY AGAIN FOR A VALID MENU SELECTION"; : BEEP: GOTO 8310
8400 REM
END SUB

SUB DOYOUWANT (XSTR$, C$, NCHAN)
        REM ******************************
        REM *** SUBROUTINE DOYOUWANT
        REM     ASKS A Y/N ANSWER TO XSTR$ QUESTION .
        REM     INPUT  : XSTR$ (1 LINE ,LENGTH < 53 )
        REM              DEFAULT VALUE FOR NCHAN .
        REM     OUTPUT : C$ = ONE LETTER ANSWER
        REM              NCHAN = 1 FOR YES
        REM              NCHAN = 5 FOR NO
        REM              NCHAN = INPUT FOR A WRONG ANSWER .
        REM ******************************
REM USE AFTER LINES 2830 ( CHANGES IN INPUT ) ,...
     YSTR$ = "MAKE ANY CHANGES "
     IF XSTR$ = "" THEN XSTR$ = YSTR$
        REM ******************************
     PRINT ">> DO YOU WANT TO " + XSTR$ + "? Y OR N "; : INPUT C$
     PRINT
     IF LEFT$(C$, 1) = "Y" THEN NCHAN = 1
     IF LEFT$(C$, 1) = "y" THEN NCHAN = 1
     IF LEFT$(C$, 1) = "n" THEN NCHAN = 5
     IF LEFT$(C$, 1) = "N" THEN NCHAN = 5
DYEND: END SUB

SUB ENDCO (KSAVIN$, LINEP$, INFILTYP$, RESU$, PDELX$, JR$, LINFIL$, GINFIL$, WORK$, GWORK$)
REM ******************************
REM ****************************** CLEANING THE FILES
      IF (KITER = 0) THEN
       CLS
REM       SHELL "DEL " + "CURDI.LOC"
REM       SHELL "DEL " + "DIRECT.LOC"
      END IF
      IF KSAVIN% <> 1 THEN GOTO EN150
REM      SHELL "DEL " + LINFIL$
EN150: CLOSE 8
      CALL COPFIL(WORK$, GWORK$, 0): CLS
      SHELL "DEL " + WORK$
REM ************************************************ END OF COMPUTATION
ENEND: END SUB

SUB FILENAME (KDIR%, KFIL%)
        REM ******************************
        REM *** SUBROUTINE FILENAME
        REM     READS AND CHECKS A FILE NAME OR A DIRECTORY NAME .
        REM     INPUTS  : KDIR% = 1 FOR READING A DIRECTORY NAME
        REM               IF KFIL% < O THEN SIGN IS CHANGED BUT NO FILE COPY IS MADE
        REM               KFIL% = 1 FOR AN INPUT FILE
        REM               KFIL% = 2 FOR AN OUTPUT FILE .
        REM     OUTPUTS : FDR$ CONTAINS THE DRIVE NAME
        REM               FPA$ CONTAINS THE PATH  NAME
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        REM                 LFIL$ CONTAINS THE LOCAL  FILE NAME
        REM                  ( THE EXTENSION OF THIS FILE IS ".LOC" )
        REM                 FINEX$ CONTAINS THE FILE.EXT NAME
        REM                 GFIL$ CONTAINS THE GLOBAL FILE NAME
        REM                 GWORK$ CONTAINS THE GLOBAL OUTPUT FILE NAME
        REM                 INOF% = 1 IF INPUT FILE NOT FOUND .
        REM     REMARK  : ALL LETTERS ARE CONVERTED TO UPPERCASE .
        REM ******************************
     DEFINT I-L
        REM ******************************
     CLS : LIP = 2
     KCOPY = 2
       GOTO FI110
FI105: PAUSE: CLS : LIP = 4
     PRINT "******  "; FFI$; " IS A WRONG NAME "
FI110: IF KFIL% < 0 THEN KCOPY = 1: KFIL% = -KFIL%
     LOCATE LIP, 20
     IF KDIR <> 1 THEN GOTO FI120
     PRINT "READING AND CHECKING A DIRECTORY NAME" + CHR$(13)
     PRINT DIREC$: PRINT
     PRINT ">> GIVE DIRECTORY NAME  "; : INPUT FFI$
       GOTO FI125
FI120:
     LOCATE 1, 30
     PRINT "Screen #"; NSCREEN
     LOCATE 3, 20
     PRINT "DEFINE FILE NAME FOR " + FILCOM$ + CHR$(13)
     PRINT FILTR$: PRINT
     PRINT ">> GIVE FILE NAME FOR "; FILCOM$; : INPUT FFI$
FI125: PCOLU% = INSTR(FFI$, COLU$)
     PBSI% = INSTR(FFI$, BSLA$)
     PSPOT% = INSTR(FFI$, SPOT$)
     LNFI = LEN(FFI$)
REM PRINT "FI125"; PCOLU%, PBSI%, PSPOT%, LNFI
REM PRINT "FI125"; CUDI$, FDR$, FPA$, KDIR
     IF LNFI > 0 THEN GOTO FI130
     IF KDIR = 1 THEN LDR = 2: FDR$ = LEFT$(CUDI$, 2): GOTO FI140
     PRINT "FILE NAME OMITTED , "; OOTR$: GOTO FI110
FI130:  REM  ***************************** DRIVE NAME IDENTIFICATION
     PNAI% = 1: PBSF% = 0
     IF KDIR > 1 AND PCOLU% = 0 THEN GOTO FI150
     FPA$ = "": LPA = 0: NBS = 0
     IF PCOLU% = 0 THEN LDR = 2: FDR$ = LEFT$(CUDI$, 2): GOTO FI140
     FDR$ = "": LDR = 0
     IF PCOLU% <> 2 THEN GOTO FI139
       CALL OKNAME(FFI$, 1, IER%, OOTR$)
     IF IER% = 1 THEN GOTO FI139
     LDR = 2: FDR$ = LEFT$(FFI$, 2)
     FDR$ = UCASE$(FDR$): DIREF$ = FDR$
       GOTO FI141
FI139: PRINT "WRONG DRIVE NAME , "; OOTR$
       GOTO FI105
FI140:  REM  ***************************** PATH NAME IDENTIFICATION
     IF KFIL% = 2 AND KCOPY = 2 GOTO FI1402
     PRINT : PRINT "** YOU HAVE SELECTED THE CURRENT DIRECTORY : "; CUDI$
     PRINT
FI1402: LPA = LCUDI% - 1: FPA$ = MID$(CUDI$, 3) + BSLA$
     DIREF$ = CUDI$
     IF KDIR = 1 THEN GOTO FI198 ELSE GOTO FI150
FI141: IF PBSI% > 0 THEN GOTO FI142
     PRINT : PRINT "** YOU HAVE SELECTED THE ROOT  DIRECTORY : "; DIREF$
     LPA = 0
     IF KDIR = 1 THEN GOTO FI198
       GOTO FI150
FI142: NBS = 1
     PBSF% = PBSI%
FI144: PBS% = INSTR(PBSF% + 1, FFI$, BSLA$)
     IF PBS% = 0 THEN GOTO FI145
     PBSF% = PBS%: NBS = NBS + 1
       GOTO FI144
FI145: IF KDIR = 1 THEN : LPA = LNFI - PBSI% + 1: GOTO FI147
     IF NBS = 1 THEN GOTO FI150
     LPA = PBSF% - PBSI% + 1
FI147: IF LPA < 3 THEN GOTO FI149
     FPA$ = MID$(FFI$, PBSI%, LPA)
```

```
        CALL OKNAME(FPA$, 2, IER%, OOTR$)
      IF IER% = 1 THEN GOTO FI149
      FPA$ = UCASE$(FPA$): DIREF$ = FPA$
      IF NBS > 1 THEN DIREF$ = LEFT$(FPA$, LPA - 1)
      DIREF$ = FDR$ + DIREF$
      IF NBS = 1 THEN FPA$ = FPA$ + BSLA$
      PRINT : PRINT "* YOU HAVE SELECTED THE FOLLOWING DIRECTORY : "; DIREF$
      IF KDIR = 1 THEN GOTO FI198
        GOTO FI150
FI149: PRINT "WRONG PATH NAME , "; OOTR$: GOTO FI105
FI150:  REM  ***************************** FILE EXTENSION NAME IDENTIFICATION
      XR = PCOLU% + 1: YR = PBSF% + 1
      IF XR > YR THEN PNAI% = XR ELSE PNAI% = YR
      IF PSPOT% > 0 THEN PNAF% = PSPOT% - 1: LNF = LNFI: GOTO FI152
      PNAF% = LNFI
      EX$ = DAT$
        GOTO FI156
FI152: IF (LNF - PSPOT%) <> 3 THEN GOTO FI159
      EX$ = RIGHT$(FFI$, 3)
        CALL OKNAME(EX$, 4, IER%, OOTR$)
      IF IER% = 1 THEN GOTO FI159
FI156: LEX = 4
        EX$ = UCASE$(EX$): FEX$ = SPOT$ + EX$
        GOTO FI160
FI159: PRINT "WRONG EXTENSION NAME , "; OOTR$: GOTO FI105
FI160:  REM  ***************************** FILE NAME IDENTIFICATION
      LNA = PNAF% - PNAI% + 1
REM PRINT "FI160 "; PNAI%, PNAF%, LDR, LPA, LNA, LEX, LNFI
      IF LNA < 1 OR LNA > 8 THEN GOTO FI169
      FINA$ = MID$(FFI$, PNAI%, LNA)
        CALL OKNAME(FINA$, 3, IER%, OOTR$)
      IF IER% = 1 THEN GOTO FI169
      FINA$ = UCASE$(FINA$)
      FINEX$ = FINA$ + FEX$
      GFIL$ = DIREF$ + BSLA$ + FINEX$
      LFIL$ = FINA$ + ".LOC"
        GOTO FI170
FI169: PRINT "WRONG FILE NAME , "; OOTR$: GOTO FI105
FI170:  REM  *****************************
        REM IF THE FILE IS AN INPUT  FILE  THEN  THIS FILE WILL BE COPIED
        REM         ON THE LOCAL FILE LFIL$ IMMEDIATELY .
        REM IF THE FILE IS AN OUTPUT FILE  THEN  THE RESULTS  WILL BE RECORDED
        REM         ON THE LOCAL FILE LFIL$ AND THE LOCAL FILE WILL BE COPIED
        REM         ON THE GLOBAL FILE AFTER RETURNING TO THE CALLING ROUTINE .
REM PRINT "FI170 "; FDR$, FPA$, FINA$, FEX$
REM PRINT "FI170 "; FINEX$,DIREF$
REM PRINT "FI170 "; LDR, LPA, LNA, LEX, LNFI : PAUSE
      IF KCOPY = 1 THEN GOTO FIEND
        ON KFIL% GOTO FI172, FI174
FI172: CALL FILINDIR(FINEX$, DIREF$, INOF%, OOTR$, CUDI$, SPOT$)
      IF INOF% = 1 THEN GOTO FIEND
        CALL COPFIL(GFIL$, LFIL$, 0)
      GINFIL$ = GFIL$
        GOTO FIEND
FI174: GWORK$ = GFIL$
        GOTO FIEND
FI198: KDIR% = KDIR% + 1
FIEND:
REM PRINT "FIEND "; DIREF$, FINEX$, LFIL$, GFIL$
REM  PAUSE
END SUB

DEFSNG I-L
SUB FILINDIR (FIL$, DIR$, INOF%, OOTR$, CUDI$, SPOT$)
        REM ******************************
        REM *** SUBROUTINE FILINDIR
        REM     CHEKS IF FILENAME 'FIL$' IS IN DIRECTORY 'DIR$' .
        REM     INPUT NAMES DIR$ AND DIREF$ .
        REM     OUTPUT : INOF% = 1 AND ERROR MESSAGE IF FIL$ IS NOT FOUND .
        REM ******************************
      DEFINT I-L
        REM ******************************
      INOF% = 0: L = 0
      PSPOT% = INSTR(FIL$, SPOT$): LNF = LEN(FIL$)
      IF PSPOT% < 1 OR LNF < 1 THEN GOTO FDERR
```

```
     FI = ASC(FIL$)
     SHELL "DIR " + DIR$ + " > DIRECT.LOC "
     OPEN "DIRECT.LOC" FOR INPUT AS 2
FD110: L = L + 1
     IF EOF(2) THEN GOTO FD140
     INPUT #2, XR$
     XF = ASC(XR$ + ":")
     IF FI <> XF THEN GOTO FD110
     YR$ = LEFT$(XR$, 12)
     ZR$ = RIGHT$(YR$, 3)
     YR$ = LEFT$(YR$, 8): XR$ = RTRIM$(YR$)
     IF FIL$ = XR$ + "." + ZR$ THEN GOTO FD150
       GOTO FD110
FD140: INOF% = 1
     PRINT
     PRINT "*** FILENAME ' "; FIL$; " ' NOT FOUND IN DIRECTORY ' "; DIR$; " '! "; OOTR$
       GOTO FDPAU
FDERR: INOF% = 1: PRINT
     PRINT "*** WRONG FILENAME ' "; FIL$; OOTR$
FDPAU: CALL PAUSE
FD150: CLOSE 2
FDEND: END SUB

DEFSNG I-L
SUB HEADTAB (NHEAD, NOUT, KPRINT)
         REM *****************************************************************
         REM
         REM     SUB ROUTINE HEAD TABLES
         REM
         REM *****************************************************************
      SHARED DDATE$, KSAVIN%
REM      SHARED MENU$(), SEL$, LMENU, LSMENU, NCHOIC
REM      SHARED STA$, GEOM$, CRACK$, LODE$, PROC$, TASK$
REM      SHARED NGEOM, NCRACK, NLODE, NBEND, NTASK, NREND, NALERT
REM      SHARED DIA, THICK, TWOL, TWOS, TWOC, CC, TWOA, AC, ARMLENGTH, WIDE
REM      SHARED YIELD, UTS, SCOLL, SOX, EO, ALPHA, AN
REM      SHARED SIGTEN, RPINIT()
      SHARED LINEP$, US$, UL$
         REM ******************************
      PRINT #8, LINEP$: PRINT #8,
      PRINT #8, DDATE$; "    "; GWORK$
      PRINT #8, " TABLE OF "; MENU$(NOUT)
      PRINT #8, LINEP$: PRINT #8,
      PRINT #8, "  "
        IF NHEAD <> 1 THEN EXIT SUB
         REM ****************************** TASK
      XSTR$ = PROC$: LXSM% = 58
        CALL STRINGSPLITTING(XSTR$, LXSM%, IL%, TSTR$())
      PRINT #8, "J-ESTIMATION SCHEME : "; TSTR$(1)
        FOR I = 2 TO IL%: PRINT #8, TAB(22); TSTR$(I): NEXT
      PRINT #8, "                         -------------------------"
      PRINT #8, "  "
      PRINT #8, "GEOMETRY             : "; GEOM$
        IF NGEOM = 1 THEN
      PRINT #8, "LOADING              : "; LODE$
      PRINT #8, "CRACK TYPE           : "; CRACK$
      PRINT #8, "  "
        END IF
      XSTR$ = TASK$: LXSM% = 60
        CALL STRINGSPLITTING(XSTR$, LXSM%, IL%, TSTR$())
      PRINT #8, "TASK : "; TSTR$(1)
        FOR I = 2 TO IL%: PRINT #8, TAB(7); TSTR$(I): NEXT
         REM ****************************** MATERIAL CHARACTERISTICS
      IF NGEOM > 1 THEN PRINT #8, "STATE OF STRESS : "; STA$
      PRINT #8, "  "
      PRINT #8, " YIELD STRESS      = "; YIELD; " "; US$;
      PRINT #8, " ULT. TENS. ST.= "; UTS; " "; US$
      PRINT #8, " COLLAPSE STRESS   = "; SCOLL; " "; US$
      PRINT #8, " SIGMA - ZERO      = "; SOX; " "; US$;
      PRINT #8, " EPSILON -ZERO = "; EO
      PRINT #8, " ALPHA             = "; ALPHA; "    ";
      PRINT #8, " EXPONENT      = "; AN: PRINT #8,
      IF NLODE = 4 THEN PRINT #8, "TENSILE STRESS =  "; SIGTEN; " "; US$;
REM ****************************** GEOMETRY
      PRINT #8, " OUT. DIAMETER = "; DIA; " "; UL$;
```

```
      PRINT #8, " WALL THICKNESS= "; THICK; " "; UL$
      PRINT #8, " CRACK SIZE 2A = "; TWOA; " "; UL$
HE10:   IF NLODE <> 1 OR NLODE <> 4 THEN
        IF NBEND = 1 THEN
      PRINT #8, " MOMENT ARM LENGTH  = "; ARMLENGTH; " "; UL$
        ELSE
      PRINT #8, " LENGTH BETWEEN OUTER LOAD POINTS = "; TWOL; " "; UL$
      PRINT #8, " LENGTH BETWEEN INNER LOAD POINTS = "; TWOS; " "; UL$
        END IF
        END IF
        GOTO HE30
HE30: IF NBEND = 1 THEN
      PRINT #8, " CALCULATED COLLAPSE MOMENT        = "; RPINIT(JTABLE + 1, 6); ""; UP$
      END IF
      IF NBEND = 2 THEN
      PRINT #8, " CALCULATED COLLAPSE LOAD          = "; RPINIT(JTABLE + 1, 6); ""; UP$
      END IF
      PRINT #8, " NOMINAL REMOTE STRESS AT COLLAPSE = "; RPINIT(JTABLE + 1, 12); ""; US$
      PRINT #8, " "
         REM ****************************** MESSAGES AND FILENAMES
        IF NREND <> 0 THEN
      PRINT #8, "  *WARNING : CALCULATION WAS STOPPED BECAUSE CRACK GROWTH "
      PRINT #8, "   WAS BEYOND THE LIMITS OF THE GIVEN J-R CURVE"; CHR$(10)
        END IF
      PRINT #8, " FILENAMES:"
      XSTR$ = PDELX$: IF KSAVIN% = 1 THEN XSTR$ = GINFIL$
        IF NTASK = 1 THEN
      PRINT #8, " P - DELTA CURVE AS    : "; XSTR$
      PRINT #8, " P - A CURVE AS        : "; PA$
        END IF
      XSTR$ = JR$: IF KSAVIN% = 1 THEN XSTR$ = GINFIL$
      IF NTASK <> 1 THEN PRINT #8, " J - R CURVE AS       : "; XSTR$
        IF NALERT = 1 THEN
      PRINT #8, " H AND F FUNCTIONS BEYOND LIMIT OF TABLE"
      PRINT #8, " RESULTS MAY NOT BE RELIABLE FOR GE/EPRI METHODS"
        END IF
      PRINT #8, "  "
HEEND: END SUB

SUB LOADARR (KLD%, NTASK)
        REM ******************************
        REM *** SUBROUTINE LOADARR
        REM      LOADS ARRAYS FROM INPUT FILE ( KLD% = 1 )
        REM            OR ARRAYS ON OUTPUT FILE ( KLD% = 2 ) .
        REM      INPUT  : KLD% DEFINES THE TYPE OF LOADING ( 1 OR 2 )
        REM               LFIL$ IS THE LOCAL  NAME OF THE FILE
        REM               GFIL$ IS THE GLOBAL NAME OF THE FILE
        REM               NTASK = 1 FOR A P-DELTA-CRACK SIZE TABLE
        REM               NTASK = 2 OR 3 FOR A J-R CURVE .
        REM      OUTPUT : ARRAYS PDELTA() / MATJ() ( NTASK = 1/2 OR 3 )
        REM               NUMBER OF POINTS LPDELXT/LMATJ .
        REM ******************************
        REM ******************************
     IF KLD% <> 2 THEN KLD% = 1
     IF NTASK > 1 THEN GOTO LO120
     L1 = 1
        REM ******************************
     PDELX$ = LFIL$
     ON KLD% GOTO LO112, LO114
LO112: OPEN PDELX$ FOR INPUT AS 1
       FOR LD = 1 TO MDP
     IF EOF(1) THEN GOTO LO150
     INPUT #1, PDELTA(LD, 1), PDELTA(LD, 2), PDELTA(LD, 3)
     LPDELXT = LD
       NEXT LD
       GOTO LO150
LO114: OPEN PDELX$ FOR OUTPUT AS 1
       FOR LD = 1 TO LPDELXT
     PRINT #1, PDELTA(LD, 1), PDELTA(LD, 2), PDELTA(LD, 3)
     LPDELXT = LD
       NEXT LD
       GOTO LO150
        REM ******************************
LO120: JR$ = LFIL$
       ON KLD% GOTO LO122, LO124
```

```
LO122: OPEN JR$ FOR INPUT AS 1: L1 = 2
     INPUT #1, MATJ(1, 1), MATJ(1, 2)
     IF MATJ(1, 2) = 0! THEN L1 = 1
       FOR LD = L1 TO MDJ
     IF EOF(1) THEN GOTO LO150
     INPUT #1, MATJ(LD, 1), MATJ(LD, 2)
     LMATJ = LD
       NEXT LD
       GOTO LO150
LO124: OPEN JR$ FOR OUTPUT AS 1: L1 = 1
     IF MATJ(1, 2) = 0! THEN L1 = 2
     IF LMATJ <= MDJ THEN GOTO LO125
     PRINT "*** THE NUMBER OF POINTS IN J-R CURVE IS TOO LARGE"; TAB(4); "THIS NUMBER : "; LMATJ;
" IS REDUCED TO : "; MDJ
     PRINT
     PRINT "    A NEW INPUT FILE 'FILENAME.LOC' WILL BE CREATED ON THE CURRENT DIRECTORY"
     PAUSE
     LMATJ = MDJ: KSAVIN% = 2
LO125: FOR LD = L1 TO LMATJ
     PRINT #1, MATJ(LD, 1), MATJ(LD, 2)
       NEXT LD
       GOTO LO150
        REM ******************************
LO150: CLOSE 1
        REM ******************************
LO190: ON ERROR GOTO 0
LOEND: END SUB

SUB MAKEMENU (SEL$, COM$, MENU$(), LMENU, LSMENU, LXSM%, NCHOIC, OOTR$, TSTR$()) STATIC
        REM ******************************
        REM *** SUBROUTINE MAKEMENU SELECTION
        REM     PRINTS ON THE SCREEN THE MENU AND ASK FOR SELECTION .
        REM     INPUT  : SEL$ = PART OF THE TITLE TELLING WHAT IS TO BE SELECTED
        REM              COM$ = COMMENT INSERTED BETWEEN TITLE AND MENU
        REM              LMENU  = NUMBER OF OPTIONS
        REM              LSMENU = NUMBER OF ACTIVE OPTIONS
        REM              MENU$(LC) = NAME OF THE LC OPTION
        REM              LXSM%  = MAXIMAL LENGTH FOR THE LINES IN WHICH
        REM                      EACH NAME MAY BE SPLITTED .
        REM     OUTPUT : NCHOIC .
        REM ******************************
        REM ******************************
     IF LXSM% > 65 THEN LXSM% = 65
     PRINT CHR$(10), TAB(10); "SELECT FROM MENU "; SEL$
     PRINT
     PRINT COM$
     PRINT
       FOR LC = 1 TO LMENU
     XSTR$ = MENU$(LC)
       CALL STRINGSPLITTING(XSTR$, LXSM%, IL%, TSTR$())
     PRINT TAB(10); LC; ".  "; TSTR$(1)
     M = IL% - 1: N = 2
ME120: M = M - 1
     IF M < 0 THEN GOTO ME140
     PRINT TAB(14); TSTR$(N)
     N = N + 1
       GOTO ME120
ME140: PRINT
       NEXT LC
     PRINT : PRINT TAB(10); "ENTER YOUR SELECTION ";
ME150: INPUT XR
     NCHOIC = INT(XR)
     IF XR <> NCHOIC THEN GOTO ME180
     IF NCHOIC < 1 THEN GOTO ME180
     IF NCHOIC > LSMENU THEN GOTO ME160
       GOTO MEEND
ME160: PRINT
     IF NCHOIC <= LMENU THEN PRINT TAB(10); "THIS SELECTION IS NOT YET ACTIVE"
     PRINT
ME180: PRINT OOTR$; " FOR A VALID MENU SELECTION"; : BEEP: GOTO ME150
MEEND: END SUB

SUB MOUT
        REM ****************************************************************
        REM
```

```
        REM     SUB ROUTINE STORED OUTPUT ON TAPE #8 .
        REM
        REM *****************************************************************
REM    SHARED MENU$(), SEL$, LMENU, LSMENU, NCHOIC
      SHARED UO$, UL$, US$, UM$, UP$, UJ$
      SHARED MDJ, MDP, MATJ(), PDELTA(), LMATJ, LPDELXT
      SHARED LINEP$, OOTR$
REM ******************************
REM      SEL$ = "THE OUTPUT OPTION "
REM      MENU$(1) = "Print "
REM      MENU$(2) = "Store on file  " + GWORK$
REM      MENU$(3) = "Print and Store on file  " + GWORK$
REM      LMENU = 3
REM      LSMENU = LMENU
REM      CALL DISPLAYMENU(MENU$(), SEL$, LMENU, LSMENU, NCHOIC)
REM      NPRINT = NCHOIC
     CLOSE 8
REM
REM   STORE ONLY FIRST
REM
      NPRINT = 2
     IF NPRINT = 1 OR NPRINT = 3 THEN
REM       CLS
REM       PRINT " GIVE PRINTER DEVICE (normally LPT1) "; : INPUT PRDEV$
REM       IF PRDEV$ = " " THEN PRDEV$ = "LPT1"
      PRDEV$ = "LPT1:"
     END IF
REM ---------------- STORED  OUTPUT --------------------- REM 28000
MO1:
     NSCREEN = 13
      SEL$ = "THE OUTPUT TABLES YOU WANT  ; WE WILL RETURN TO THIS MENU"
      SEL$ = SEL$ + " FOR FURTHER SELECTIONS"
      MENU$(1) = "J-R CURVE  DELTA-A VS J"
      MENU$(2) = "SCREENING CRITERIA  ---------(NOT ACTIVE)"
      MENU$(3) = "LOADING AT INITIATION FOR FOUR APPROACHES "
      MENU$(4) = "P-DELTA-CRACK SIZE-COD-DELTA A-J"
      MENU$(5) = "CRACK SIZE-LOAD-J-JR-DJ/DA-DJR/DA"
      MENU$(6) = "ALL OUTPUT"
      MENU$(7) = "EXIT -NO MORE OUTPUT"
      LMENU = 7
        IF NTASK = 1 THEN
      MENU$(5) = MENU$(6)
      MENU$(6) = MENU$(7)
      LMENU = 6
        END IF
      LSMENU = LMENU
REM       CALL DISPLAYMENU(MENU$(), SEL$, LMENU, LSMENU, NCHOIC)
      NOUTP = 6: NALL = 0
      IF NOUTP = LMENU - 1 THEN NALL = 1: NOUTP = 1
      IF NOUTP = 7 THEN GOTO MO100
      IF NTASK = 1 AND NOUTP = 6 THEN GOTO MO100
REM ****************************** HEAD TABLES  OUTPUT  -
      NHEAD = 1
      JPRINT = 1
      IF NPRINT = 3 THEN JPRINT = 2
      FOR KPRINT = 1 TO JPRINT
      IF KPRINT = 1 AND NPRINT = 1 THEN OPEN PRDEV$ FOR OUTPUT AS 8
      IF KPRINT = 1 AND NPRINT = 2 THEN OPEN WORK$ FOR APPEND AS 8
      IF KPRINT = 1 AND NPRINT = 3 THEN OPEN PRDEV$ FOR OUTPUT AS 8
      IF KPRINT = 2 AND NPRINT = 3 THEN OPEN WORK$ FOR APPEND AS 8
      CALL HEADTAB(NHEAD, NOUTP, KPRINT)
     CLOSE 8
     NEXT KPRINT
     NHEAD = 2
MO5:     REM ----------------- OUTPUT SELECTIONS --------------------------
         REM      JR / SCR. CRIT. / INITIATION  /PDELX /  RESUL / ALL  DONE
       ON NOUTP GOTO MO10, MO20, MO30, MO40, MO50, MO100, MO100
MO10:    REM ****************************** OUTPUT SELECTION #1 ( J-R CURVE )
      FOR KPRINT = 1 TO JPRINT
      IF KPRINT = 1 AND NPRINT = 1 THEN OPEN PRDEV$ FOR OUTPUT AS 8
      IF KPRINT = 1 AND NPRINT = 2 THEN OPEN WORK$ FOR APPEND AS 8
      IF KPRINT = 1 AND NPRINT = 3 THEN OPEN PRDEV$ FOR OUTPUT AS 8
      IF KPRINT = 2 AND NPRINT = 3 THEN OPEN WORK$ FOR APPEND AS 8
      LMAX = 15: LIMA = LMAX: LK = 1
      NCOL = FIX((LMATJ - 1) / LMAX) + 1
```

```
      LIMI = LMATJ MOD LMAX
        ON NCOL GOTO MO11, MO14, MO16
      PRINT "ERROR IN J-R CURVE OUTPUT LIST": REM----------GOTO DUMP
MO11: LIMA = LMATJ: PRINT #8, DA$, R$: PRINT #8, UL$, UJ$: PRINT #8, LINEP$
MO12:   FOR LK = LK TO LIMA
      AA = MATJ(LK, 1) * TRUNKA
      BB = INT(AA) * ATRUNKA
      PRINT #8, BB, MATJ(LK, 2)
        NEXT LK
        GOTO MO18
MO14: LIMA = LIMI: PRINT #8, DA$, R$, DA$, R$: PRINT #8, UL$, UJ$, UL$, UJ$: PRINT #8, LINEP$
MO15:   FOR LK = LK TO LIMA
      LK1 = LK + LMAX
      AA = MATJ(LK, 1) * TRUNKA: AA1 = MATJ(LK1, 1) * TRUNKA
      BB = INT(AA) * ATRUNKA: BB1 = INT(AA1) * ATRUNKA
      PRINT #8, BB, MATJ(LK, 2), BB1, MATJ(LK1, 2)
        NEXT LK
        IF LIMI = LMAX THEN GOTO MO18
        LIMA = LMAX:   GOTO MO12
MO16: PRINT #8, DA$, R$, DA$, R$, DA$, R$: PRINT #8, UL$, UJ$, UL$, UJ$, UL$, UJ$: PRINT #8,
LINEP$
MO17:   FOR LK = LK TO LIMI
      LK1 = LK + LMAX: LK2 = LK1 + LMAX
      AA = MATJ(LK, 1) * TRUNKA: AA1 = MATJ(LK1, 1) * TRUNKA: AA2 = MATJ(LK2, 1) * TRUNKA
      BB = INT(AA) * ATRUNKA: BB1 = INT(AA1) * ATRUNKA: BB2 = INT(AA2) * ATRUNKA
      PRINT #8, BB, MATJ(LK, 2), BB1, MATJ(LK1, 2), BB2, MATJ(LK2, 2)
        NEXT LK
        IF LIMI = LMAX THEN GOTO MO18
        GOTO MO15
MO18: PRINT #8, LINEP$: PRINT #8,
      PRINT #8, CHR$(12)
      CLOSE 8
   NEXT KPRINT
      GOTO MO80
MO20:   REM ******************************** OUTPUT SELECTION #2 ( SCR. CRIT.)
      IF NALL = 1 THEN GOTO MO80
      BEEP
      PRINT "SELECTION NON ACTIVE " + OOTR$
      PRINT
        GOTO MO1
MO30:   REM ******************************** OUTPUT SELECTION #3 ( LOADING AT INITIATION )
      FOR KPRINT = 1 TO JPRINT
      IF KPRINT = 1 AND NPRINT = 1 THEN OPEN PRDEV$ FOR OUTPUT AS 8
      IF KPRINT = 1 AND NPRINT = 2 THEN OPEN WORK$ FOR APPEND AS 8
      IF KPRINT = 1 AND NPRINT = 3 THEN OPEN PRDEV$ FOR OUTPUT AS 8
      IF KPRINT = 2 AND NPRINT = 3 THEN OPEN WORK$ FOR APPEND AS 8
      CALL HEADTAB(NHEAD, NOUTP, KPRINT)
      IF NBEND = 1 THEN PRINT #8, TAB(33); "MOMENT AT INITIATION"
      IF NBEND = 2 THEN PRINT #8, TAB(33); "LOAD   AT INITIATION"
      PRINT #8, " "
      PRINT #8, UO$, G$, P$, K$, R6$, COL$
      PRINT #8, "2*" + AP$
      PRINT #8, UL$, UP$, UP$, UP$, UP$, UP$
      PRINT #8, LINEP$: PRINT #8,
        FOR LK = 1 TO JTABLE + 1
        FOR LJ = 1 TO 6
      AA = RPINIT(LK, LJ) * TRUNKA
      BB = INT(AA) * ATRUNKA
         IF (BB >= 10000000) THEN
          PRINT #8, USING "#.####^^^^    "; BB;
         ELSE
          PRINT #8, BB,
         END IF
        NEXT LJ
      PRINT #8,
        NEXT LK
      PRINT #8, LINEP$: PRINT #8,
      PRINT #8, " "
      PRINT #8, TAB(26); "NOMINAL STRESS AT INITIATION": PRINT #8, " "
      PRINT #8, UO$, G$, P$, K$, R6$, COL$
      PRINT #8, "2*" + AP$
      PRINT #8, UL$, US$, US$, US$, US$, US$
      PRINT #8, LINEP$: PRINT #8,
        FOR LK = 1 TO JTABLE + 1
        FOR LJ = 7 TO 12
```

```
      AA = RPINIT(LK, LJ) * TRUNKA
      BB = INT(AA) * ATRUNKA
         IF (BB >= 10000000) THEN
          PRINT #8, USING "#.####^^^^    "; BB;
         ELSE
          PRINT #8, BB,
         END IF
        NEXT LJ
      PRINT #8,
        NEXT LK
      PRINT #8, LINEP$: PRINT #8,
      PRINT #8, CHR$(12)
      CLOSE 8
   NEXT KPRINT
   GOTO M080
M040:   REM ****************************** OUTPUT SELECTION #4 ( P-DELTA CURVE )
      FOR KPRINT = 1 TO JPRINT
      IF KPRINT = 1 AND NPRINT = 1 THEN OPEN PRDEV$ FOR OUTPUT AS 8
      IF KPRINT = 1 AND NPRINT = 2 THEN OPEN WORK$ FOR APPEND AS 8
      IF KPRINT = 1 AND NPRINT = 3 THEN OPEN PRDEV$ FOR OUTPUT AS 8
      IF KPRINT = 2 AND NPRINT = 3 THEN OPEN WORK$ FOR APPEND AS 8
      CALL HEADTAB(NHEAD, NOUTP, KPRINT)
      PRINT #8, PM$, DELX$, AP$, CO$, DA$, JA$
      PRINT #8, UP$, UD$, UL$, UL$, UL$, UJ$
      PRINT #8, LINEP$: PRINT #8,
      MINUS = 1
      IF NTASK = 2 THEN MINUS = 2
      FOR LK = 1 TO LPDELXT - MINUS
        FOR LJ = 1 TO 6
      AA = PDELTA(LK, LJ) * TRUNKA
      BB = INT(AA) * ATRUNKA
         IF (BB >= 10000000) THEN
          PRINT #8, USING "#.####^^^^    "; BB;
         ELSE
          PRINT #8, BB,
         END IF
      NEXT LJ
      PRINT #8,
        NEXT LK
      PRINT #8, LINEP$: PRINT #8,
      PRINT #8, CHR$(12)
      CLOSE 8
      NEXT KPRINT
      GOTO M080
M050:   REM ****************************** OUTPUT SELECTION #5 ( STABLE CRAK GROWTH ... )
      IF LMENU = 5 THEN GOTO MOEND
      FOR KPRINT = 1 TO JPRINT
      IF KPRINT = 1 AND NPRINT = 1 THEN OPEN PRDEV$ FOR OUTPUT AS 8
      IF KPRINT = 1 AND NPRINT = 2 THEN OPEN WORK$ FOR APPEND AS 8
      IF KPRINT = 1 AND NPRINT = 3 THEN OPEN PRDEV$ FOR OUTPUT AS 8
      IF KPRINT = 2 AND NPRINT = 3 THEN OPEN WORK$ FOR APPEND AS 8
      CALL HEADTAB(NHEAD, NOUTP, KPRINT)
      PRINT #8, TAB(26); "STABLE CRACK GROWTH AND INSTABILITY"
      PRINT #8, AP$, PM$, JA$, R$, TA$, TM$
      PRINT #8, UL$, UP$, UJ$, UJ$, UO$, UO$
      PRINT #8, LINEP$: PRINT #8,
      MINUS = 0
      IF NTASK = 2 THEN MINUS = 1
      FOR LK = 1 TO LRES - MINUS
        FOR LJ = 2 TO 3
      AA = RESUL(LK, LJ) * TRUNKA
      BB = INT(AA) * ATRUNKA
         IF (BB >= 10000000) THEN
          PRINT #8, USING "#.####^^^^    "; BB;
         ELSE
          PRINT #8, BB,
         END IF
        NEXT LJ
        FOR LJ = 5 TO 8
      AA = RESUL(LK, LJ) * TRUNKA
      BB = INT(AA) * ATRUNKA
         IF (BB >= 10000000) THEN
          PRINT #8, USING "#.####^^^^    "; BB
         ELSE
          PRINT #8, BB,
```

```
          END IF
        NEXT LJ
      PRINT #8,
        NEXT LK
      PRINT #8, LINEP$: PRINT #8,
      CLOSE 8
      NEXT KPRINT
MO80:     REM *******************************
        IF NALL = 1 THEN
      NOUTP = NOUTP + 1
        IF NOUTP = LMENU - 1 THEN GOTO MO100
        GOTO MO5
        END IF
        GOTO MO1
MO100:    REM *******************************
MOEND: CLS
       A$ = "N"
       IF (UCASE$(A$) = "Y" OR UCASE$(A$) = "YES") THEN
       PRINT
       PRINT
       PRINT " Please set up the printer and press any key."
       PRINT
ANYKEY:
      A$ = INKEY$
      IF (A$ = "") GOTO ANYKEY
        CLOSE 8
        CLOSE 1
        OPEN WORK$ FOR INPUT AS #8
        OPEN "LPT1:" FOR OUTPUT AS #1
        CLS
        PRINT
        PRINT "Output tables being printed."
        PRINT
        DO UNTIL EOF(8)
        LINE INPUT #8, Line$
        PRINT #1, LEFT$(Line$, 80)
        LOOP
        CLS
       END IF
END SUB

SUB MUNIT
    IF (KITER = 0) THEN
710 SEL$ = " THE UNITS YOU WANT TO USE"
720 MENU$(1) = "ENGLISH, ksi, ksi " + CHR$(251) + "in, kips/in, in-kips, in"
730 MENU$(2) = "ENGLISH, psi, psi " + CHR$(251) + "in, lbs/in, in-lbs , in"
740 MENU$(3) = "METRIC , MPa, MPa " + CHR$(251) + "m , MN/m , MN-m  ,  m"
750 MENU$(4) = "METRIC , N/mm" + CHR$(253) + ", N/mm" + CHR$(253) + " " + CHR$(251) + "mm, N/mm,
N-mm,  mm"
760 LMENU = 4: LSMENU = 4
    CALL DISPLAYMENU(MENU$(), SEL$, LMENU, LSMENU, NCHOIC)
    WRITE #3, NCHOIC
    ELSE
    INPUT #3, NCHOIC
    END IF
770 NUNIT = NCHOIC
780 UNIT$ = MENU$(NCHOIC)
790 SI$ = " IN.STRESS"
800 SMAX$ = "MAX STRESS"
810 S$ = "  STRESS  "
820 CO$ = "   COD    "
830 UO$ = "          "
840 GO$ = "   GE."
850 P$ = "PARIS/TADA"
860 KO$ = " LBB."
    R6$ = " R6-REV3."
870 COL$ = " COLLAPSE "
880 ON NUNIT GOTO 890, 960, 1030, 1100
890 US$ = "    ksi   "
900 UK$ = "ksi RT in "
910 UJ$ = "  kips/in "
920 UL$ = "  inches  "
930 UM$ = " in-kips  "
940 UP$ = "   kips   "
950   GOTO 1170
```

```
960 US$ = "    psi    "
970 UK$ = "psi RT in "
980 UJ$ = "  lbs/in   "
990 UL$ = "  inches   "
1000 UM$ = "  in-lbs  "
1010 UP$ = "   lbs    "
1020   GOTO 1170
1030 US$ = "    MPa   "
1040 UK$ = "MPa RT m  "
1050 UJ$ = "   MN/m   "
1060 UL$ = "  meters  "
1070 UM$ = "   m-MN   "
1080 UP$ = "   MN     "
1090   GOTO 1170
1100 US$ = " N/SQ mm  "
1110 UK$ = "N/mm RT mm"
1120 UJ$ = "   N/mm   "
1130 UL$ = "    mm    "
1140 UM$ = "   mm-N   "
1150 UP$ = "  Newton  "
1160   GOTO 1170
1170 UZ$ = UP$
     UD$ = UL$
     JA$ = "  J-APPL  ": UZ$ = UP$
1180 R$ = "   J-MAT  "
1190 PM$ = " LOAD "
1200 AP$ = " CRACK.L  "
1210 DA$ = " DELTA-a  "
1220 DELX$ = "  DISPL   "
1230 TM$ = "  dJR/da  "
1240 TA$ = "  dJ/da   "
1250 PI$ = " INIT P/M "
1260 PMAX$ = " MAX P/M  "
REM
END SUB

SUB OKNAME (XSTR$, KN, IER%, OOTR$)
REM ******************************
REM *** SUBROUTINE OKNAME
REM     CHECKS THE VALIDITY OF A NAME USED IN FILE SPECIFICATION .
REM     INPUT  : XSTR$ IS THE NAME
REM              KN = 1 FOR ANY ALLOWED CHARACTERS FOR DRIVE NAME
REM               ( ONLY LATIN CHARACTERS )
REM              KN = 2 FOR ANY ALLOWED CHARACTERS FOR PATH NAME
REM               ( ONLY LATIN CHARACTERS , NUMBERS AND \ )
REM              KN = 3 FOR ANY ALLOWED CHARACTERS FOR FILE NAME
REM               ( SEE MS-DOS MANUAL )
REM              KN = 4 FOR ANY ALLOWED CHARACTERS FOR EXTENSION NAME
REM               ( SEE MS-DOS MANUAL ) .
REM     OUTPUT : IER% = ERROR INDEX ( 0 IF NAME IS OK ) .
REM ******************************
     IER% = 0
     KN = INT(KN): IF KN < 1 OR KN > 4 THEN KN = 5
     LX = LEN(XSTR$)
       ON KN GOTO OK110, OK120, OK130, OK140, OK150
OK110:  REM ****************************** DRIVE NAME TESTING
     NAM$ = XSTR$: XR = ASC(XSTR$)
     IF (XR < 65 OR XR > 90) AND (XR < 97 OR XR > 122) THEN
     IER% = 1
     GOTO OKERR
     ELSE
     GOTO OKEND
     END IF
OK120:  REM ****************************** PATH NAME TESTING
     IF LX > 64 THEN IER% = 1: GOTO OKERR
       FOR I = 1 TO LX
     NAM$ = MID$(XSTR$, I): XR = ASC(NAM$)
     IF XR = 92 THEN GOTO OK125
     IF (XR > 47 AND XR < 58) THEN GOTO OK125
     IF (XR < 65 OR XR > 90) AND (XR < 97 OR XR > 122) THEN
     IER% = 1
     GOTO OKERR
     END IF
OK125: NEXT I
       GOTO OKEND
```

```
OK130:  REM ****************************** FILE NAME TESTING
        FOR I = 1 TO LX
      NAM$ = MID$(XSTR$, I): XR = ASC(NAM$)
      IF XR = 33 THEN GOTO OK135
      IF (XR < 35 OR XR > 126) THEN IER% = 1: GOTO OKERR
      IF XR = 45 THEN GOTO OK135
      IF (XR > 41 AND XR < 48) THEN IER% = 1: GOTO OKERR
      IF (XR > 57 AND XR < 64) THEN IER% = 1: GOTO OKERR
      IF (XR > 90 AND XR < 94) OR XR = 124 THEN
      IER% = 1
      GOTO OKERR
      END IF
OK135: NEXT I
      IF LX <> 3 GOTO OKEND
      IF XSTR$ = "AUX" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "COM" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "CON" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "LTP" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "PRN" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "NUL" THEN IER% = 1: GOTO OKERR
        GOTO OKEND
OK140:  REM ****************************** EXTENSION NAME TESTING
      FOR I = 1 TO LX
       NAM$ = MID$(XSTR$, I): XR = ASC(NAM$)
       IF (XR < 65 OR XR > 90) AND (XR < 97 OR XR > 122) THEN
        IER% = 1
        GOTO OKERR
       END IF
      NEXT I
OK145: IF XSTR$ = "ASM" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "BAT" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "CHK" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "COM" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "EXE" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "LIB" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "MAP" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "OBJ" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "REC" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "SYS" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "BAK" THEN IER% = 1: GOTO OKERR
        GOTO OKEND
OK150:  REM ****************************** MOST SEVERE TESTING
      FOR I = 1 TO LX
      NAM$ = MID$(XSTR$, I): XR = ASC(NAM$)
      IF (XR < 65 OR XR > 90) AND (XR < 97 OR XR > 122) THEN
      IER% = 1
      GOTO OKERR
      END IF
      NEXT I
      IF LX <> 3 GOTO OKEND
      IF XSTR$ = "AUX" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "CON" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "LTP" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "PRN" THEN IER% = 1: GOTO OKERR
      IF XSTR$ = "NUL" THEN IER% = 1: GOTO OKERR
        GOTO OK145
         REM ******************************
OKERR: PRINT "*** oKname ERROR , CHECKED NAME : "; XSTR$; "  , INVALID PART : "; NAM$
        CALL PAUSE
OKEND: END SUB

SUB PAUSE
         REM ******************************
         REM *** SUBROUTINE PAUSE
         REM ******************************
      LOCATE 25, 50
      SHELL "PAUSE"
      CLS
PAEND: END SUB

SUB Pipedim (MENU$(), SEL$, LMENU, LSMENU, NCHOIC, NCRACK, NSIZE, UC$, UL$, NLODE, NBEND, PM$,
UM$, UP$, TWOL, TWOS, TWOA, DIA, THICK, RADIUS, PI, AC, CA, US$, SIGTEN)
8410     REM ***************************************************** REM 33000
8415     REM
8420     REM             SUB ROUTINE INPUT PIPE DIMENSIONS
```

```
8425    REM
8430    REM ***************************************************** REM 33040
8440 SEL$ = "CRACK DIMENSION INPUT"
8445 MENU$(1) = "CRACK LENGTH IN  degrees, " + CHR$(224)
8450 MENU$(2) = "CRACK LENGTH IN  radians, " + CHR$(224)
8455 MENU$(3) = "CRACK LENGTH IN" + UL$ + ", 21"
8460 MENU$(4) = "CRACK LENGTH IN  PERCENT OF CIRCUMFERENCE"
8465 LMENU = 4: LSMENU = 4:
     NSCREEN = 6
     IF (KITER = 0) THEN
     CALL DISPLAYMENU(MENU$(), SEL$, LMENU, LSMENU, NCHOIC)
     WRITE #3, NCHOIC
     ELSE
     INPUT #3, NCHOIC
     END IF
8470 NSIZE = NCHOIC
8475 UC$ = UL$
8480 IF NSIZE = 1 THEN UC$ = " degrees  "
8485 IF NSIZE = 2 THEN UC$ = " radians  "
8490 IF NSIZE = 4 THEN UC$ = " % CIRC   "
8495 IF NLODE = 2 THEN GOTO 8550
8500 IF NLODE = 3 THEN GOTO 8550
8505 IF NLODE = 5 THEN GOTO 8550
8510 IF NLODE = 6 THEN GOTO 8550
8515 SEL$ = "BENDING MOMENT REPRESENTATION"
8520 MENU$(1) = "IN TERMS OF BENDING MOMENT IN " + UM$
8525 MENU$(2) = "IN TERMS OF TOTAL LOAD FOR FOUR-POINT BENDING IN " + UP$
8530 LMENU = 2: LSMENU = 2
     NSCREEN = 7
     IF (KITER = 0) THEN
      CALL DISPLAYMENU(MENU$(), SEL$, LMENU, LSMENU, NCHOIC)
      WRITE #3, NCHOIC
     ELSE
      INPUT #3, NCHOIC
     END IF
8535 NBEND = NCHOIC
8540 IF NBEND = 1 THEN
     PM$ = " MOMENT   ": UP$ = UM$
     DELX$ = " ROTATION ": UD$ = "radians"
       END IF
8550 CLS
8605 LOCATE 1, 30
     NSCREEN = 8
     IF (KITER = 0) THEN
     PRINT "Screen #"; NSCREEN
     LOCATE 3, 1
PRINT "     GIVE DIMENSIONS"
8610 PRINT "OUTER DIAMETER IN                             "; UL$; : INPUT DIA
8615 PRINT "WALL THICKNESS IN                             "; UL$; : INPUT THICK
8620 IF NBEND > 1 THEN GOTO 8640
8625 PRINT "GIVE PIPE LENGTH; ANY LENGTH IF LENGTH UNKNOWN IN "; UL$;
8630 INPUT ARMLENGTH
8635   GOTO 8655
8640 PRINT "GIVE DISTANCE BETWEEN OUTER LOADING POINTS IN "; UL$; : INPUT TWOL
8645 PRINT "GIVE DISTANCE BETWEEN INNER LOADING POINTS IN "; UL$; : INPUT TWOS
     ARMLENGTH = (TWOL - TWOS) / 4!
8655    REM
     CLS
8660 PRINT "GIVE AN ESTIMATE OF TOTAL LENGTH (2A) OF THROUGH CRACK IN    "; UC$; : INPUT TWOA
     PRINT "GIVE LOAD IN "; UP$; : INPUT PFLOW
     SEL$ = "FLOW RATE REPRESENTATION"
     IF (NUNIT = 1 OR NUNIT = 2) THEN
      MENU$(1) = "IN TERMS OF MASS FLOW (Lbs/Sec) "
      MENU$(2) = "IN TERMS OF VOLUME FLOW (Gallons/Min)"
     ELSE
      MENU$(1) = "IN TERMS OF MASS FLOW (Kg/Sec) "
      MENU$(2) = "IN TERMS OF VOLUME FLOW (Litter/Min)"
     END IF
     LMENU = 2: LSMENU = 2
     CALL DISPLAYMENU(MENU$(), SEL$, LMENU, LSMENU, NCHOIC)
     NFUNIT = NCHOIC
     PRINT
     PRINT
     IF (NUNIT = 1 OR NUNIT = 2) THEN
      IF (NFUNIT = 1) THEN PRINT "GIVE REQUIRED FLOW RATE IN Lbs/Sec", : INPUT FLOW
```

```
     IF (NFUNIT = 2) THEN PRINT "GIVE REQUIRED FLOW RATE IN Gallons/Min", : INPUT FLOW
    ELSE
     IF (NFUNIT = 1) THEN PRINT "GIVE REQUIRED FLOW RATE IN Kg/Sec", : INPUT FLOW
     IF (NFUNIT = 2) THEN PRINT "GIVE REQUIRED FLOW RATE IN Litter/Min", : INPUT FLOW
    END IF
REM
REM  CRACK MORPHOLOGY PARAMETERS USED BY INTFACE2 AND PASSED ON TO SQUIRT4A
REM
    PRINT "Enter Global Roughness         in "; UL$; : INPUT GROUGH
    PRINT "Enter Local  Roughness         in "; UL$; : INPUT LROUGH
    PRINT "Enter Global Depth(Thick) Factor "; : INPUT GLFACT
    PRINT "Enter Local  Depth(Thick) Factor "; : INPUT LLFACT
    PRINT "Enter Number of 90 degree turns  "; : INPUT N90TURN
    PRINT "Enter Fluid Pressure           in "; US$; : INPUT FPRESS
    IF (NUNIT = 1 OR NUNIT = 2) THEN
    PRINT "Enter Fluid Temperature        (F)"; : INPUT FTEMP
    ELSE
    PRINT "Enter Fluid Temperature        (C)"; : INPUT FTEMP
    END IF
    PRINT "Enter Ambient Pressure         in "; US$; : INPUT EXTPRESS
    PRINT "Enter Discharge Coeff             "; : INPUT DCOEFF
8705 IF NSIZE = 1 THEN TWOA = (DIA - THICK) * PI * TWOA / 360!
8710 IF NSIZE = 2 THEN TWOA = (DIA - THICK) * TWOA / 2!
8715 IF NSIZE = 4 THEN TWOA = (DIA - THICK) * PI * TWOA / 100!
8720 RADIUS = (DIA - THICK) / 2!: CA = TWOA / 2!
8735 AC = TWOA / 2!
8740 IF NLODE <> 4 THEN GOTO 8750
8745 PRINT "GIVE TENSION STRESS IN "; US$; : INPUT SIGTEN
8750 REM
    WRITE #3, DIA, THICK, ARMLENGTH, TWOL, TWOS, TWOA, RADIUS, AC, CA
    WRITE #3, NFUNIT, PFLOW, FLOW, SIGTEN
    WRITE #3, GROUGH, LROUGH, GLFACT, LLFACT, N90TURN
    WRITE #3, FPRESS, FTEMP, EXTPRESS, DCOEFF
    ELSE
    INPUT #3, DIA, THICK, ARMLENGTH, TWOL, TWOS, TWOA, RADIUS, AC, CA
    INPUT #3, NFUNIT, PFLOW, FLOW, SIGTEN
    INPUT #3, GROUGH, LROUGH, GLFACT, LLFACT, N90TURN
    INPUT #3, FPRESS, FTEMP, EXTPRESS, DCOEFF
    END IF
END SUB

SUB PRINTSC (NAR, LAR, NPLM, MXAR, XAR(), TIT$())
        REM ******************************
        REM *** SUBROUTINE PRINTSC
        REM       PRINTS ON SCREEN ARRAY XAR ON NAR COLUMNS .
        REM       INPUT  : NAR  = NUMBER OF COLUMNS
        REM                LAR  = NUMBER OF LINES
        REM                XAR  = ARRAY (MXAR) .
        REM                TIT$ = ARRAY FOR TITLES RELATED TO XAR() .
        REM       OUTPUT : PRINTOUT .
        REM ******************************
        REM ******************************
    NPL = NPLM - 3
    IF NAR < 1 THEN NBAR = 1
    IF NAR > 6 THEN NBAR = 6
    NBAR = INT(NAR)
      FOR I = 1 TO NBAR
    TIT$(I) = LEFT$(TIT$(I), 10)
      NEXT I
    LPAR = LAR
    IF NAR * LAR < MXAR THEN GOTO PR105
    LPAR = INT(MXAR / NAR)
    PRINT "****** LENGTH OF THE ARRAYS EXCEEDS THE MAXIMUM VALUE !", CHR$(13), SPACE$(6), "NUMBER
OF LINES BEING EDITED : "; LPAR
PR105:  REM ******************************
    NP1 = -CSRLIN - 1
    IF LPAR <= NPL OR NP1 > INT(NPL / 2) THEN CLS : NP1 = 0
    PRINT "PRINTOUT OF "; NBAR; " ARRAYS OF "; LPAR; " LINES :"
    ON NBAR GOTO PR110, PR120, PR130, PR140, PR150, PR160
PR110:  REM ******************************
    PRINT " N"; TIT$(1)
      FOR I = 1 TO LPAR
    IF I - NP1 > NPL THEN CALL PAUSE: NP1 = I
    PRINT I; XAR(I)
      NEXT I
```

```
        GOTO PRAUS:
PR120:  REM ******************************
      N2 = LPAR
      PRINT " N"; TIT$(1), TIT$(2)
        FOR I = 1 TO LPAR
      IF I - NP1 > NPL THEN CALL PAUSE: NP1 = I
      PRINT I; XAR(I), XAR(N2 + I)
        NEXT I
        GOTO PRAUS:
PR130:  REM ******************************
      N2 = LPAR: N3 = 2 * LPAR
      PRINT " N"; TIT$(1), TIT$(2), TIT$(3)
        FOR I = 1 TO LPAR
      IF I - NP1 > NPL THEN CALL PAUSE: NP1 = I
      PRINT I; XAR(I), XAR(N2 + I), XAR(N3 + I)
        NEXT I
        GOTO PRAUS:
PR140:  REM ******************************
      N2 = LPAR: N3 = 2 * LPAR: N4 = 3 * LPAR
      PRINT " N"; TIT$(1), TIT$(2), TIT$(3), TIT$(4)
        FOR I = 1 TO LPAR
      IF I - NP1 > NPL THEN CALL PAUSE: NP1 = I
      PRINT I; XAR(I), XAR(N2 + I), XAR(N3 + I), XAR(N4 + I)
        NEXT I
        GOTO PRAUS:
PR150:  REM ******************************
      N2 = LPAR: N3 = 2 * LPAR: N4 = 3 * LPAR: N5 = 4 * LPAR
      PRINT " N"; TIT$(1); TIT$(2); TIT$(3); TIT$(4); TIT$(5)
        FOR I = 1 TO LPAR
      IF I - NP1 > NPL THEN CALL PAUSE: NP1 = I
      PRINT I; XAR(I); XAR(N2 + I); XAR(N3 + I); XAR(N4 + I); XAR(N5 + I)
        NEXT I
        GOTO PRAUS:
PR160:  REM ******************************
      N2 = LPAR: N3 = 2 * LPAR: N4 = 3 * LPAR: N5 = 4 * LPAR: N6 = 5 * LPAR
      PRINT " N"; TIT$(1); TIT$(2); TIT$(3); TIT$(4); TIT$(5); TIT$(6)
        FOR I = 1 TO LPAR
      IF I - NP1 > NPL THEN CALL PAUSE: NP1 = I
      PRINT I; XAR(I); XAR(N2 + I); XAR(N3 + I); XAR(N4 + I); XAR(N5 + I); XAR(N6 + I)
        NEXT I
        GOTO PRAUS:
PR190:  REM ******************************
PRAUS: CALL PAUSE
PREND: END SUB

SUB STORDIR (CUDI$, LCUDI%) STATIC
        REM ******************************
        REM *** SUBROUTINE STORDIR
        REM     STORES FILENAMES AND NAME OF CURRENT DIRECTORY .
        REM     OUTPUT : CURDI.LOC
        REM              CUDI$,CUDR$ (NAMES OF CURRENT DIRECTORY AND DRIVE )
        REM              LCUDI% = LENGTH OF CUDI$
        REM              DADI$ = CUDR$ + "\NPDAT\" (DATA FILE DIRECTORY ) .
        REM ******************************
      DEFINT I-L
        REM ******************************
      SHELL "DIR > CURDI.LOC "
      OPEN "CURDI.LOC" FOR INPUT AS 2
      FOR LD = 1 TO 7
      IF EOF(2) THEN GOTO ST150
      INPUT #2, XR$
      LCUDI = LEN(XR$)
      FOR I = 2 TO LCUDI
      IF (MID$(XR$, I - 1, 1) = ":" AND MID$(XR$, I, 1) = "\") THEN
      GOTO ST150
      END IF
      NEXT I
      NEXT LD
ST150: CLOSE 2
       FOR J = I + 1 TO LCUDI
       IF (MID$(XR$, J) = " ") THEN
       GOTO ST151
       END IF
       NEXT J
ST151: CUDI$ = MID$(XR$, I - 2, J - I + 2)
```

```
       CUDI$ = UCASE$(CUDI$)
       LCUDI = LEN(CUDI$)
       CUDR$ = MID$(XR$, I - 2, 2)
       IF LCUDI = 3 THEN CUDI$ = CUDR$: LCUDI% = 2
       DADI$ = CUDR$ + "\NPDAT\"
STEND: END SUB

DEFSNG I-L
SUB STRINGSPLITTING (XSTR$, LXSM%, IL%, TSTR$())
        REM ******************************
        REM *** SUBROUTINE STRING SPLITTING
        REM     SPLITS THE STRING XSTR$ IN IL% LINES OF LXSM% CHARACTERS .
        REM            THESE IL% LINES ARE STORED IN TSTR$(I) .
        REM     INPUT  : XSTR$ , LXSM% .
        REM     OUTPUT : IL% , TSTR$(I) .
        REM ******************************
     DEFINT I-L
     LXST = LEN(XSTR$)
     IF LXST <= 0 THEN IL = 1: TSTR$(1) = "": EXIT SUB
     LXI = 1
     IL = 0
SR120: IL = IL + 1
     TSTR$(IL) = ""
     TSTR$(IL) = MID$(XSTR$, LXI, LXSM%)
     LX = LXST - (IL - 1) * LXSM%
     IF LX <= LXSM% THEN EXIT SUB
     LXI = LXI + LXSM%
     IF IL > 4 THEN PRINT "***** STRING EXCEEDS 5 LINES !": EXIT SUB
       GOTO SR120
SREND: END SUB
```

LISTING OF INTFACE2.BAS

```
REM
REM    This program interfaces between NRCP3M  &  SQUIRT4A
REM
REM    The  COD/Global Roughness ratios is used to modify some crack
REM    morphology parameters before running squirt
REM
       DIM PDELTA(60, 5)
REM
REM   OPEN FILES CREATED BY NRCPIPE
REM
      OPEN "INTFACE.DAT" FOR INPUT AS #3
      INPUT #3, WORK$, GWORK$
      INPUT #3, NUNIT
      INPUT #3, NLODE
      INPUT #3, NTASK
      INPUT #3, NSIZE
      INPUT #3, NBEND
      INPUT #3, DIA, THICK, ARMLENGTH, TWOL, TWOS, TWOA, RADIUS, AC, CA
      INPUT #3, NFUNIT, PFLOW, AFLOW, SIGTEN
      INPUT #3, GROUGH, LROUGH, GLFACT, LLFACT, N90TURN
      INPUT #3, PRESS, TEMP, EXTPRESS, DCOEFF
      INPUT #3, YIELD, UTS, SCOLL, SOX, EO, ALPHA, ANNN, E
      INPUT #3, JR$, GFIL$
      CLOSE #3
      OPEN "MNBVCXZ.TRN" FOR INPUT AS #5
      INPUT #5, NUNITS, NBEND, LPDELXT, NRCDEPTH, GWORK$
      MAXLOAD = 0
      FOR LJ = 1 TO LPDELXT
      FOR LK = 1 TO 5
      INPUT #5, PDELTA(LJ, LK)
      NEXT LK
      IF (PDELTA(LJ, 1) > MAXLOAD) THEN
      MAXLOAD = PDELTA(LJ, 1)
      END IF
      NEXT LJ
      CLOSE #5
REM
REM   CHECK IF USER SUPPLIED LOAD IS WITHIN NRCPIPE TABLE
REM
CHECK:
      IF (PFLOW > MAXLOAD) THEN
      CLS
      PRINT
      PRINT
      PRINT "The desired load is outside the load table calculated by NRCP#M"
      PRINT "The maximum load in the table is "; MAXLOAD
      PRINT "Please re-enter the load value"
REM      INPUT PFLOW
REM      GOTO CHECK
REM
REM    SET FOR EXTRAPOLATE
REM
       IHI = LPDELXT
       ILO = LPDELXT - 1
       GOTO INTERPOL
       END IF
REM
REM   INTERPOLATE IN NRCPIPE TABLE TO GET VALUES AT PFLOW
REM
      IHI = 1
      ILO = 1
      FOR LJ = 1 TO LPDELXT
      IF PDELTA(LJ, 1) < PFLOW THEN
      ILO = LJ
      ELSE
      IHI = LJ
      GOTO INTERPOL
      END IF
      NEXT LJ
INTERPOL:
      PRATIO = (PFLOW - PDELTA(ILO, 1)) / (PDELTA(IHI, 1) - PDELTA(ILO, 1))
      AL1 = 2! * PDELTA(ILO, 3)
      AL2 = 2! * PDELTA(IHI, 3)
      AG1 = PDELTA(ILO, 4)
      AG2 = PDELTA(IHI, 4)
```

```
      ZEGAP = AG1 + (AG2 - AG1) * PRATIO
      ZIGAP = ZEGAP
      ZAL = AL1 + (AL2 - AL1) * PRATIO
REM
REM NOW USE COD/GROUGH
REM
      RATIO = ZEGAP / GROUGH
      IF (RATIO <= .1) THEN
      ROUGH = LROUGH
      TFACT = LLFACT
      VHEAD = .75 * N90TURN
      GOTO DONE
      END IF
      IF (RATIO >= 10!) THEN
      ROUGH = GROUGH
      TFACT = GLFACT
      VHEAD = .75 * .1 * N90TURN
      GOTO DONE
      END IF
REM
REM INTERPOLATE BETWEEN 0.1 AND 10.0
REM
      X1 = .1
      X2 = 10!
      R1 = GROUGH
      R2 = LROUGH
      T1 = LLFACT
      T2 = GLFACT
      V1 = .75 * N90TURN
      V2 = .75 * .1 * N90TURN
      ROUGH = R1 + (RATIO - X1) * (R2 - R1) / (X2 - X1)
      TFACT = T1 + (RATIO - X1) * (T2 - T1) / (X2 - X1)
      VHEAD = V1 + (RATIO - X1) * (V2 - V1) / (X2 - X1)
DONE:
REM
REM  NOW WRITE FILE FOR SQUIRT4A
REM
     UNITS$ = "SI"
REM     UNITS$ = "ENG"
     SHAPE$ = "ELLI"
     TYPE$ = "OTHER"
     STATE$ = "SUBC"
     IGUESS$ = "AUTOM"
     RDEFAU$ = "DEFAULT"
     ZROUGH = ROUGH * 1000
REM     ZROUGH = ROUGH
     EVLOSS = VHEAD
     ZWALL = TFACT * 1000 * NRCDEPTH
REM     ZWALL = TFACT * NRCDEPTH
     ZAL = 1000 * ZAL
     ZEGAP = 1000 * ZEGAP
     ZIGAP = 1000 * ZIGAP
     ZPO = 1000 * PRESS
REM     ZAL = ZAL
REM     ZEGAP = ZEGAP
REM     ZIGAP = ZIGAP
REM     ZPO = PRESS
     ZTTO = TEMP
     ZHLO = -1
     ZQUAL = 0!
     ZPB = 1000 * EXTPRESS
REM     ZPB = EXTPRESS
     CD = DCOEFF
     ALEAK = 0!
     PGUESS = 0
     OPEN "CASE1" FOR OUTPUT AS #1
     WRITE #1, UNITS$, SHAPE$, TYPE$, STATE$, IGUESS$, RDEFAU$
     WRITE #1, ZROUGH, EVLOSS, ZWALL, ZAL, ZEGAP, ZIGAP, ZPO, ZTTO, ZHLO, ZQUAL, ZPB, CD, ALEAK,
PGUESS
     CLOSE #1
     SYSTEM
END
```

LISTING OF SQUIRT4A.BAS

```
DECLARE SUB STEAMSUB ()
COMMON SHARED NUM
COMMON SHARED US$
COMMON SHARED PRESS, TEMP, VF, VG, SF, SG, HF, HG, H, TSAT, PSAT, T
COMMON SHARED ENTH, ENTR, UF, UG, S, V, U
COMMON SHARED PO, TTO, ALD, FF, AR, ISTATE, CD, DH, THETA
COMMON SHARED PTOT, SPTOT, PE, SPE, PA, SPA, PF, SPF, PAA, SPAA, PK, SPK, GA, SGA, AMA, SAMA,
AVA, SAVA
        DIM CRK(20), CFLOW(20), CRITER(20)
REM DISCHARGE COEFFICIENT
        CLEAR , , 4000
        READ XCD, GZ, FZ, ISTEP, B, PE, PI, GAMMA, SPRES, SLEN
        DATA 0.95,32.174,144.,50,0.0523,0.0,3.14159265,1.33,0.14503824,0.00328084
        PFLAG = 0: NAUTO = 1
        MITER = 0
REM
5 GOSUB DEFALT
        GOSUB 4000
REM
REM
REM   INITIAL GUESS FOR P1 AND G1
10 IF NAUTO > 0 THEN
       PC = PSAT - (PSAT - PB) * .25
        ELSE
       PC = PGUESS
        END IF
        P1 = PC
        GOSUB 1000
        G1 = 1! / ((XC * VGC) / (GAMMA * PC * GZ * FZ) - (VGC - VLO) * AN * DXECDP)
        IF PFLAG > 0 THEN
REM      LPRINT "FIRST GUESS P1 ="; P1; "  FIRST GUESS G1 ="; G1
        ELSE
REM      PRINT "FIRST GUESS P1 ="; P1; "  FIRST GUESS G1 ="; G1
        END IF
        ISKP = 0
        GOSUB 2100
REM
REM
        PL = PB
        PH = PSAT
REM   IF PFLAG > 1 THEN  LPRINT "PL =";PL,"PH =";PH
        FOR I = 1 TO ISTEP
        MITER = I
        IF ISKP = 1 THEN GOTO 245
        PC = P1: GOSUB 1000: GOSUB 2100: GOSUB 2200
        GOSUB 3100: GOSUB 3200
        G2 = (A3 * B1 - A1 * B3) / (A2 * B1 - A1 * B2)
        P2 = (B3 - B2 * G2) / B1
REM   IF PFLAG > 1 THEN LPRINT "PL =";PL,"PH =";PH
        IF PFLAG > 0 THEN
REM      LPRINT "0 NEW PRESSURE ="; P2; "   NEW MASS FLUX ^ 2 ="; G2
        ELSE
REM      PRINT "NEW PRESSURE ="; P2; "   NEW MASS FLUX ^ 2 ="; G2
        END IF
        IF PFLAG > 1 THEN
REM      LPRINT
        ELSE
REM      PRINT
        END IF
REM   IF PFLAG > 1 THEN
REM       LPRINT
REM   ELSE
REM       PRINT
REM   END IF
245 GRESID = ABS((G2 - G1) / G1)
        PRESID = ABS((P2 - P1) / P1)
        IF PRESID < .001 AND GRESID < .001 THEN
         GOTO 500
        ELSEIF P2 > PSAT THEN
         P1 = (PH + P1) / 2!
         PC = P1
         GOSUB 1000
         G1 = 1! / ((XC * VGC) / (GAMMA * PC * GZ * FZ) - (VGC - VLO) * AN * DXECDP)
         IF PFLAG > 0 THEN
REM          LPRINT "NEW GUESS AT P1 ="; P1; "   NEW GUESS AT G1 ="; G1
```

```
          ELSE
REM           PRINT "NEW GUESS AT P1 ="; P1; "   NEW GUESS AT G1 ="; G1
          END IF
          GOSUB 2100: GOSUB 2200
          GOSUB 3100: GOSUB 3200
          G2 = (A3 * B1 - A1 * B3) / (A2 * B1 - A1 * B2)
          P2 = (B3 - B2 * G2) / B1
REM    IF PFLAG > 1 THEN LPRINT "PL =";PL,"PH =";PH
          IF PFLAG > 0 THEN
REM           LPRINT "1  NEW PRESSURE ="; P2; "   NEW MASS FLUX ^ 2 ="; G2
          ELSE
REM           PRINT "NEW PRESSURE ="; P2; "   NEW MASS FLUX ^ 2 ="; G2
          END`IF
          IF PFLAG > 1 THEN
REM           LPRINT
          ELSE
REM           PRINT
          END IF
          ISKP = 1
        ELSEIF P2 < PB THEN
          P1 = (P1 + PL) / 2!
          PC = P1
          GOSUB 1000
          G1 = 1! / ((XC * VGC) / (GAMMA * PC * GZ * FZ) - (VGC - VLO) * AN * DXECDP)
          IF PFLAG > 0 THEN
REM           LPRINT "NEW GUESS AT P1 ="; P1, "   NEW GUESS G1 ="; G1
          ELSE
REM           PRINT "NEW GUESS AT P1 ="; P1, "   NEW GUESS G1 ="; G1
          END IF
          GOSUB 2100: GOSUB 2200
          GOSUB 3100: GOSUB 3200
          G2 = (A3 * B1 - A1 * B3) / (A2 * B1 - A1 * B2)
          P2 = (B3 - B2 * G2) / B1
        REM   IF PFLAG > 1 THEN LPRINT "PL =";PL,"PH =";PH
          IF PFLAG > 0 THEN
REM           LPRINT "2 NEW PRESSURE ="; P2; "   NEW MASS FLUX ^ 2 ="; G2
          ELSE
REM           PRINT "NEW PRESSURE ="; P2; "   NEW MASS FLUX ^ 2 ="; G2
          END IF
          IF PFLAG > 1 THEN
REM           LPRINT
          ELSE
REM           PRINT
          END IF
          ISKP = 1
         ELSE
       ISKP = 0
       IF I < 10 THEN
          P1 = P2
          G1 = G2
       ELSEIF I < 25 THEN
          P1 = (P1 + P2) / 2
          G1 = (G1 + G2) / 2
       ELSE
          P1 = P1 + .25 * (P2 - P1)
          G1 = G1 + .25 * (G2 - G1)
       END IF
         END IF
         NEXT I
        SHELL "DEL " + "INTFACE.NDG"
         IF PFLAG > 0 THEN
        LPRINT "FAILED TO CONVERGE AFTER", ISTEP, " ITERATIONS"
         ELSE
        PRINT "FAILED TO CONVERGE AFTER", ISTEP, " ITERATIONS"
         END IF
         GOTO 5500
REM     GOTO 500
REM STOP
300 EN = PCC / PO
        GM = AREA * GC
        AREA = 144! * AREA
        PER = 12! * PER
        WALL = 12! * WALL
        ROUGH = 12! * ROUGH
         PRESS = PCC
```

```
          NUM = 2
          CALL STEAMSUB
          H1 = HF
          PRESS = PCC
          NUM = 10
          CALL STEAMSUB
          H2 = HG
        HHE = XT * H2 * (1! - XT) * H1
        GOTO 500
400  G2 = 3450.7 * (PO - PB) / VLO
        P2 = PB
        GC = SQR(G2)
        GM = AREA * GC
500 REM
      GOSUB 5000
REM
REM
REM
REM   WATER PROPERTIES AT CRACK EXIT PRESSURE
1000 PRESS = PC: TEMP = 1000000!
        NUM = 6: CALL STEAMSUB: VLC = VF
        NUM = 14: CALL STEAMSUB: VGC = VG
        NUM = 4: CALL STEAMSUB: SLC = SF
        NUM = 12: CALL STEAMSUB: SGC = SG
        NUM = 2: CALL STEAMSUB: HLC = HF
        NUM = 10: CALL STEAMSUB: HGC = HG
REM   WATER PROPERTIES AT THE AVERAGE PRESSURE
        PAVG = (PO - PE + PC) / 2!
        PRESS = PAVG
        NUM = 6: CALL STEAMSUB: VLAVG = VF
        NUM = 14: CALL STEAMSUB: VGAVG = VG
        NUM = 2: CALL STEAMSUB: HLAVG = HF
        NUM = 10: CALL STEAMSUB: HGAVG = HG
REM   DERIVATIVES OF WATER PROPERTIES AT EXIT PRESSURE
        PC2 = PC + 1!
        PC1 = PC - 1!
        DPC = (PC2 - PC1) * GZ * FZ
        PRESS = PC2
        NUM = 6: CALL STEAMSUB: VLC2 = VF
        NUM = 14: CALL STEAMSUB: VGC2 = VG
        NUM = 4: CALL STEAMSUB: SLC2 = SF
        NUM = 12: CALL STEAMSUB: SGC2 = SG
        NUM = 2: CALL STEAMSUB: HLC2 = HF
        NUM = 10: CALL STEAMSUB: HGC2 = HG
        PRESS = PC1
        NUM = 6: CALL STEAMSUB: VLC1 = VF
        NUM = 14: CALL STEAMSUB: VGC1 = VG
        NUM = 4: CALL STEAMSUB: SLC1 = SF
        NUM = 12: CALL STEAMSUB: SGC1 = SG
        NUM = 2: CALL STEAMSUB: HLC1 = HF
        NUM = 10: CALL STEAMSUB: HGC1 = HG
        DVLC = (VLC2 - VLC1) / DPC
        DVGC = (VGC2 - VGC1) / DPC
        DSLC = (SLC2 - SLC1) / DPC
        DSGC = (SGC2 - SGC1) / DPC
        DHLC = (HLC2 - HLC1) / DPC
        DHGC = (HGC2 - HGC1) / DPC
        D2SLC = (VLC2 - 2! * VLC + VLC1) / (DPC * DPC / 4!)
        D2SGC = (SGC2 - 2! * SGC + SGC1) / (DPC * DPC / 4!)
REM   DERIVATIVES OF WATER PROPERTIES AT THE AVERAGE PRESSURE
        PAVG2 = PAVG + 1!
        PAVG1 = PAVG - 1!
        DPAVG = (PAVG2 - PAVG1) * GZ * FZ
        PRESS = PAVG2
        NUM = 6: CALL STEAMSUB: VLAVG2 = VF
        NUM = 14: CALL STEAMSUB: VGAVG2 = VG
        NUM = 2: CALL STEAMSUB: HLAVG2 = HF
        NUM = 10: CALL STEAMSUB: HGAVG2 = HG
        PRESS = PAVG1
        NUM = 6: CALL STEAMSUB: VLAVG1 = VF
        NUM = 14: CALL STEAMSUB: VGAVG1 = VG
        NUM = 2: CALL STEAMSUB: HLAVG1 = HF
        NUM = 10: CALL STEAMSUB: HGAVG1 = HG
        DVLAVG = (VLAVG2 - VLAVG1) / DPAVG
        DVGAVG = (VGAVG2 - VGAVG1) / DPAVG
```

```
        DHLAVG = (HLAVG2 - HLAVG1) / DPAVG
        DHGAVG = (HGAVG2 - HGAVG1) / DPAVG
REM   WATER QUALITY AT THE CRACK EXIT PRESSURE
        DSGL = SGC - SLC
        XEC = (SLO - SLC) / DSGL
        IF XEC < 0! THEN
        PRINT "SINGLE PHASE FLOW EXISTS THROUGH THE CRACK"
        SHELL "DEL " + "INTFACE.NDG"
        GOTO 5500
        END IF
        IF XEC < .05 THEN AN = 20! * XEC ELSE AN = 1!
        RELAX = 1! - EXP(-B * (ALD - 12!))
        XC = AN * XEC * RELAX
        DXECDP = -((1! - XEC) * DSLC + XEC * DSGC) / DSGL
        D2XECDP = -(((1! - XEC) * D2SLC - DSLC * DXECDP + XEC * D2SGC + DSGC * DXECDP) / DSGL) -
(DXECDP * (DSGC - DSLC) / DSGL)
        IF XEC < .05 THEN
         DXCDP = AN * RELAX * 2! * DXECDP
        ELSE
         DXCDP = AN * RELAX * DXECDP
        END IF
        XEHC = (HLO - HLC) / (HGC - HLC)
        DXEHCDP = -((1! - XEHC) * DHLC + XEHC * DHGC) / (HGC - HLC)
REM   WATER QUALITY AT THE AVERAGE PRESSURE
        DHGL = HGAVG - HLAVG
        XEH = (HLO - HLAVG) / DHGL
        DXHDP = -.5 * ((1! - XEH) * DHLAVG + XEH * DHGAVG) / DHGL
        IF XEH < 0 THEN
         XEH = 0!
         DXHDP = 0!
        END IF
        IF PFLAG > 1 THEN LPRINT "10", "VLC", VLC, "VGC", VGC, "SLC", SLC, "SGC", SGC, "VLAVG",
VLAVG, "VGAVG", VGAVG, "HLAVG", HLAVG, "HGAVG", HGAVG, "HLC", HLC, "HGC", HGC
        IF PFLAG > 1 THEN LPRINT "11", "VLC2", VLC2, "VLC1", VLC1, "VGC2", VGC2, "VGC1", VGC1,
"SLC2", SLC2, "SLC1", SLC1, "SGC2", SGC2, "SGC1", SGC1
        IF PFLAG > 1 THEN LPRINT "12", "DVLC", DVLC, "DVGC", DVGC, "DSLC", DSLC, "DSGC", DSGC,
"D2SLC", D2SLC, "D2SGC", D2SGC, "DHLC", DHLC, "DHGC", DHGC
        IF PFLAG > 1 THEN LPRINT "13", "VLAVG2", VLAVG2, "VLAVG1", VLAVG1, "VGAVG2", VGAVG2,
"VGAVG1", VGAVG1, "HLAVG2", HLAVG2, "HLAVG1", HLAVG1, "HGAVG2", HGAVG2, "HGAVG1", HGAVG1
        IF PFLAG > 1 THEN LPRINT "14", "XEC", XEC, "XC", XC, "DXECDP", DXECDP, "D2XECDP",
D2XECDP, "DXCDP", DXCDP, "XEH", XEH, "DXHDP", DXHDP, "XEHC", XEHC, "DXEHCDP", DXEHCDP
        RETURN
REM
REM
REM   ENTRANCE PRESSURE DROP
2100 DPEDG = VLO * ACO * ACO / (2! * CD * CD * GZ * FZ)
        PE = G1 * DPEDG
        DPEDP = 0!
        IF PFLAG > 1 THEN LPRINT "21", "DPEDG", DPEDG, "PE", PE, "DPEDP"; DPEDP
        RETURN
REM
REM
REM   OTHER PRESSURE DROP TERMS
REM   ACCELERATION PRESSURE DROP
2200 DPADG = ACI * (VLC + XEHC * (VGC - VLC) - VLO) / (GZ * FZ)
        PA = G1 * DPADG
        DPADP = G1 * ACI * (DVLC + XEHC * (DVGC - DVLC) + (VGC - VLC) * DXEHCDP)
REM
REM   FRICTION PRESSURE DROP
2300 DPFDG = (6! * FF * ACI * ACO * VLO + (ALD - 12!) * FF * ACI * (VLAVG + XEH * (VGAVG -
VLAVG)) / 2!) / (GZ * FZ)
        PF = G1 * DPFDG
        DPFDP = ((ALD - 12!) * FF * G1 * ACI / 4!) * (DVLAVG + XEH * (DVGAVG - DVLAVG) + (VGAVG -
VLAVG) * DXHDP)
REM
REM   FITTINGS PRESSURE DROP
        DPKDG = (EVLOSS * ACI * (VLAVG + XEH * (VGAVG - VLAVG)) / 2!) / (GZ * FZ)
        PK = G1 * DPKDG
        DPKDP = (EVLOSS * G1 * ACI / 4!) * (DVLAVG + XEH * (DVGAVG - DVLAVG) + (VGAVG - VLAVG) *
DXHDP)
REM
REM   AREA CHANGE PRESSURE DROP
2400 DPAADG = ((VLO * (ACI * ACI - ACO * ACO) / 2!) + (VLAVG + XEH * (VGAVG - VLAVG)) * (1! - ACI
* ACI) / 2!) / (GZ * FZ)
        PAA = G1 * DPAADG
```

```
        DPAADP = (G1 * (1! - ACI * ACI) / 4!) * (DVLAVG + XEH * (DVGAVG - DVLAVG) + (VGAVG -
VLAVG) * DXHDP)
        IF PFLAG > 1 THEN LPRINT "22", "DPADG", DPADG, "PA", PA, "DPADP", DPADP
        IF PFLAG > 1 THEN LPRINT "23", "DPFDG", DPFDG, "PF", PF, "DPFDP", DPFDP
        IF PFLAG > 1 THEN LPRINT "24", "DPAADG", DPAADG, "PAA", PAA, "DPAADP", DPAADP
        RETURN
REM
REM
REM   MASS FLUX SQUARED EQUATIONS AT CRACK EXIT
3100 AGC2 = 1! / (XC * VGC / (GAMMA * P1 * GZ * FZ) - (VGC - VLO) * AN * DXECDP)
        F1 = G1 - AGC2
        A2 = 1!
        A1 = ((XC * DVGC * GZ * FZ + VGC * DXCDP * GZ * FZ) / (GAMMA * P1 * GZ * FZ) - XC * VGC /
(GAMMA * PC * PC * GZ * FZ) - (VGC - VLO) * AN * D2XECDP * GZ * FZ - AN * DXECDP * DVGC * GZ *
FZ) * (AGC2 * AGC2)
        IF XEC < .05 THEN A1 = A1 - 20! * DXECDP * DXECDP * (VGC - VLO) * GZ * FZ * AGC2 * AGC2
        A3 = A1 * P1 + A2 * G1 - F1
        IF PFLAG > 1 THEN LPRINT "31", "AGC2", AGC2, "F1", F1, "A1", A1, "A2", A2, "A3", A3
        RETURN
REM
REM
REM   PRESSURE BALANCE EQUATIONS AT CRACK EXIT
3200 F2 = P1 + PE + PA + PF + PK + PAA - PO
        B1 = 1! + DPEDP + DPADP + DPFDP + DPAADP + DPKDP
        B2 = DPEDG + DPADG + DPFDG + DPAADG + DPKDG
        B3 = B1 * P1 + B2 * G1 - F2
        IF PFLAG > 1 THEN LPRINT "32", "F2", F2, "B1", B1, "B2", B2, "B3", B3
        RETURN
4000 CLS :
REM
REM  OPEN INTERFACE FILES TO NRCPIPE AND READ THEM IN
REM
       OPEN "INTFACE.NDG" FOR INPUT AS #3
       INPUT #3, KITER, JFLAG1, JFLAG2
       FOR I = 1 TO 20
       INPUT #3, CRK(I), CFLOW(I), CRITER(I)
       NEXT I
       CLOSE #3
       OPEN "INTFACE.DAT" FOR INPUT AS #3
       INPUT #3, WORK$, GWORK$
       INPUT #3, NUNIT
       NUNITS = NUNIT
       INPUT #3, NLODE
       INPUT #3, NTASK
       INPUT #3, NSIZE
       INPUT #3, NBEND
       INPUT #3, DIA, THICK, ARMLENGTH, TWOL, TWOS, TWOA, RADIUS, AC, CA
       INPUT #3, NFUNIT, PFLOW, AFLOW, SIGTEN
       INPUT #3, GROUGH, LROUGH, GLFACT, LLFACT, N90TURN
       INPUT #3, APRESS, ATEMP, EXTPRESS, DCOEFF
       INPUT #3, YIELD, UTS, SCOLL, SOX, EO, ALPHA, ANNN, E
       INPUT #3, JR$, GFIL$
       CLOSE #3
REM
REM
REM  KITER = 0 THEN ALL SCREENS ARE DISPLAYED AND SOME DATA IS PROVIDED BY USER
REM
REM  KITER > 0 THEN CRACK SIZE HAS BEEN CHANGED BY SQUIRT2 AND ALL INPUT
REM           TO SQUIRT2 IS PROVIDED FROM A FILE
REM
REM       SCREEN 9: COLOR 10, 1
         IF (KITER = 0) THEN
REM   SCREEN 0
REM       SCREEN 9: COLOR 10, 1
         LOCATE 1, 1: FOR I = 1 TO 22: PRINT "|                                                  |
                     |": NEXT I
         LOCATE 2, 18: PRINT "SCREEN #15:  THERMAL HYDRAULICS OPTION SCREEN";
         LOCATE 1, 2: PRINT
"-----------------------------------------------------------------------------";
         LOCATE 3, 2: PRINT
"-----------------------------------------------------------------------------";
         LOCATE 9, 31: PRINT "--------------------------------------------------";
         LOCATE 10, 33: PRINT "5. INITIAL GUESS:EXIT FLUID PRESSURE ";
         LOCATE 11, 33: PRINT "   AUTOMATIC CHOICE BY PROGRAM              [ ]";
         LOCATE 12, 33: PRINT "   USER INPUTS INITIAL GUESS                [ ]";
```

```
        LOCATE 13, 31: PRINT "---------------------------------------------------";
        LOCATE 17, 31: PRINT "---------------------------------------------------";
        LOCATE 4, 3: PRINT "1. CHOOSE UNITS ";
        LOCATE 5, 6: PRINT "ENGLISH UNITS     [ ]";
        LOCATE 6, 6: PRINT "SI UNITS          [ ]";
        LOCATE 7, 2: PRINT "----------------------------";
        LOCATE 8, 3: PRINT "2. CRACK SHAPE  ";
        LOCATE 9, 6: PRINT "DIAMOND           [ ]";
        LOCATE 10, 6: PRINT "RECTANGULAR       [ ]";
        LOCATE 11, 6: PRINT "ELLIPTIC          [ ]";
        LOCATE 12, 2: PRINT "----------------------------";
        LOCATE 13, 3: PRINT "3. TYPE OF CRACK ";
        LOCATE 14, 6: PRINT "STRESS CORROSION [ ]";
        LOCATE 15, 6: PRINT "FATIGUE GROWTH   [ ]";
        LOCATE 16, 6: PRINT "OTHER            [ ]";
        LOCATE 17, 2: PRINT "----------------------------";
        LOCATE 4, 33: PRINT "4. FLUID THERMODYNAMIC STATE INSIDE ";
        LOCATE 5, 33: PRINT "     SUBCOOLED LIQUID (INPUT TEMP AND PRES)[ ]";
        LOCATE 6, 33: PRINT "   SATURATED MIXTURE";
        LOCATE 7, 33: PRINT "     INPUT PRESSURE (PROGRAM FINDS TEMP)    [ ]";
        LOCATE 8, 33: PRINT "     INPUT TEMPERATURE (PROGRAM FINDS PRES)[ ]";
        LOCATE 22, 2: PRINT
"-------------------------------------------------------------------------------";
        GOTO 4009
        END IF
4005 CLS
        IF (KITER = 0) THEN
REM       SCREEN 9: COLOR 15, 4
          LOCATE 1, 1: FOR I = 1 TO 22: PRINT "|
                                  |": NEXT I
          LOCATE 2, 18: PRINT "SCREEN #16:  THERMAL HYDRAULICS INPUT PARAMETERS";
          LOCATE 1, 2: PRINT
"-------------------------------------------------------------------------------";
          LOCATE 3, 2: PRINT
"-------------------------------------------------------------------------------";
        LOCATE 4, 35: PRINT "     NEW        CURRENT";
        LOCATE 5, 35: PRINT "    VALUE       VALUES";
        LOCATE 6, 10: PRINT "CRACK GEOMETRY ";
        LOCATE 7, 13: PRINT "1.SURFACE ROUGHNESS  =";
        LOCATE 8, 13: PRINT "2.PATH LOSS COEFFICNT=";
        LOCATE 9, 13: PRINT "3.CRACK DEPTH        =";
        LOCATE 10, 13: PRINT "4.LENGTH OF CRACK    =";
        LOCATE 11, 13: PRINT "5.EXTERIOR CRACK GAP =";
        LOCATE 12, 13: PRINT "6.INTERIOR CRACK GAP =";
        LOCATE 13, 10: PRINT "STAGNATION FLUID PROPERTIES";
        LOCATE 14, 13: PRINT "7.FLUID PRESSURE     =";
        LOCATE 15, 13: PRINT "8.FLUID TEMP         =";
        LOCATE 16, 13: PRINT "9.FLUID ENTHALPY     =";
        LOCATE 17, 13: PRINT "10.FLUID QUALITY     =";
        LOCATE 18, 13: PRINT "11.EXTERIOR PRESSURE =";
        LOCATE 19, 13: PRINT "12.DISCHARGE COEFFIC.=";
        LOCATE 20, 13: PRINT "13.LEAKAGE FLOW RATE =";
        LOCATE 21, 13: PRINT "14.INIT. GUESS: PRES =";
        LOCATE 22, 2: PRINT
"-------------------------------------------------------------------------------";
        GOSUB NUMERIC
       END IF
4009  XWALL = 0!: XROUGH = 0!: XAL = 0!: XEGAP = 0!: XIGAP = 0!: XPHI = -1!: XPO = 0!: XTTO = 0!:
XQUAL = 0!: XPB = 14.5: IFLAG = 1
       UNITS$ = "ENG": SHAPE$ = "ELLI": TYPE$ = "OTHER": STATE$ = "SUBC": CALC$ = "LEAK"
       FFCOR$ = "JOHN": IGUESS$ = "AUTOM": RDEFAU$ = "DEFAULT"
       KEY(11) ON: KEY(12) ON: KEY(13) ON: KEY(14) ON: KEY(1) ON
REM
REM   READ CRACK MORPHOLOGY PARAMETERS GENERATED BY INTFACE2
REM
        OPEN "CASE1" FOR INPUT AS #2
        INPUT #2, UNITS$, SHAPE$, TYPE$, STATE$, IGUESS$, RDEFAU$
        INPUT #2, ZROUGH, EVLOSS, zwall, ZAL, zegap, ZIGAP, ZPO, ZTTO, ZHLO, ZQUAL, ZPB, CD,
ALEAK, PGUESS
        CLOSE #2
      OPEN GWORK$ FOR APPEND AS 8
       IF (KITER = 0) THEN
REM      GOSUB WINDOW1
REM      GOSUB SETFLAGS
REM      IF UNITS$ = "ENG" THEN GOSUB ENGUNITS ELSE GOSUB SIUNITS
```

```
         GOSUB NEXTPAGE
        END IF
        GOTO 4700
REM
IDLE: RETURN
REM
REM
SIUNITS: GOSUB SETFLAGS: LOCATE 6, 24, 1: PRINT "*"
        KEY(10) ON: KEY(11) ON: KEY(13) ON: KEY(14) ON: KEY(1) ON
4025 III = 0: ON KEY(1) GOSUB SET2
4026 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB DIAMOND
        ON KEY(11) GOSUB ENGUNITS: ON KEY(12) GOSUB IDLE: ON KEY(13) GOSUB PSATURATED: ON KEY(14)
GOSUB DIAMOND
        ON KEY(10) GOSUB NEXTPAGE
        GOSUB IDLE: GOTO 4025
REM
ENGUNITS:
        LOCATE 23, 1: PRINT "USE NUMERIC KEYPAD ARROW KEYS TO MOVE AROUND OPTION LIST";
        LOCATE 24, 1: PRINT "PRESS FUNCTION KEY F1 TO CHOOSE A NEW OPTION";
        LOCATE 25, 1: PRINT "PRESS F10 WHEN FINISHED";
        GOSUB SETFLAGS: LOCATE 5, 24, 1: PRINT "*";
        KEY(10) ON: KEY(11) ON: KEY(13) ON: KEY(14) ON: KEY(1) ON
4035 III = 0: ON KEY(1) GOSUB SET1
4036 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB DIAMOND
        ON KEY(10) GOSUB NEXTPAGE
REM      ON KEY(11) GOSUB RAEINP
        ON KEY(11) GOSUB GMANUAL
        ON KEY(12) GOSUB IDLE: ON KEY(13) GOSUB SUBCOOLED: ON KEY(14) GOSUB SIUNITS
        GOSUB IDLE: GOTO 4035
REM
DIAMOND: GOSUB SETFLAGS: LOCATE 9, 24, 1: PRINT "*"
        KEY(10) ON: KEY(1) ON: KEY(13) ON: KEY(11) ON: KEY(14) ON
4045 III = 0: ON KEY(1) GOSUB SET3
4046 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB CORROSION
        ON KEY(11) GOSUB SIUNITS: ON KEY(12) GOSUB IDLE: ON KEY(13) GOSUB GAUTO: ON KEY(14) GOSUB
RECTANGLE
        ON KEY(10) GOSUB NEXTPAGE
        GOSUB IDLE: GOTO 4045
REM
RECTANGLE: GOSUB SETFLAGS: LOCATE 10, 24, 1: PRINT "*"
        KEY(10) ON: KEY(1) ON: KEY(13) ON: KEY(11) ON: KEY(14) ON
4055 III = 0: ON KEY(1) GOSUB SET4
4056 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB CORROSION
        ON KEY(11) GOSUB DIAMOND: ON KEY(12) GOSUB IDLE: ON KEY(13) GOSUB GAUTO: ON KEY(14) GOSUB
ELLIPTIC
        ON KEY(10) GOSUB NEXTPAGE
        GOSUB IDLE: GOTO 4055
REM
ELLIPTIC: GOSUB SETFLAGS: LOCATE 11, 24, 1: PRINT "*"
        KEY(10) ON: KEY(1) ON: KEY(13) ON: KEY(11) ON: KEY(14) ON
4065 III = 0: ON KEY(1) GOSUB SET5
4066 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB CORROSION
        ON KEY(11) GOSUB RECTANGLE: ON KEY(12) GOSUB IDLE: ON KEY(13) GOSUB GMANUAL: ON KEY(14)
GOSUB CORROSION
        ON KEY(10) GOSUB NEXTPAGE
        GOSUB IDLE: GOTO 4065
REM
CORROSION: GOSUB SETFLAGS: LOCATE 14, 24, 1: PRINT "*"
        KEY(10) ON: KEY(1) ON: KEY(13) ON: KEY(11) ON: KEY(14) ON
4075 III = 0: ON KEY(1) GOSUB SET6
4076 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB SUBCOOLED
        ON KEY(11) GOSUB ELLIPTIC: ON KEY(12) GOSUB IDLE
REM      ON KEY(13) GOSUB RAEDEF
        ON KEY(13) GOSUB GMANUAL
        ON KEY(14) GOSUB FATIGUE
        ON KEY(10) GOSUB NEXTPAGE: GOSUB IDLE: GOTO 4075
REM
FATIGUE: GOSUB SETFLAGS: LOCATE 15, 24, 1: PRINT "*"
        KEY(10) ON: KEY(1) ON: KEY(13) ON: KEY(11) ON: KEY(14) ON
```

```
4085 III = 0: ON KEY(1) GOSUB SET7
4086 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB SUBCOOLED
        ON KEY(11) GOSUB CORROSION: ON KEY(12) GOSUB IDLE
REM      ON KEY(13) GOSUB RAEDEF
        ON KEY(13) GOSUB GMANUAL
        ON KEY(14) GOSUB OTHER
        ON KEY(10) GOSUB NEXTPAGE
        GOSUB IDLE: GOTO 4085
REM
OTHER: GOSUB SETFLAGS: LOCATE 16, 24, 1: PRINT "*"
        KEY(10) ON: KEY(1) ON: KEY(13) ON: KEY(11) ON: KEY(14) ON
4087 III = 0: ON KEY(1) GOSUB SET11
4088 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB SUBCOOLED
        ON KEY(11) GOSUB FATIGUE: ON KEY(12) GOSUB IDLE
REM      ON KEY(13) GOSUB RAEINP
        ON KEY(13) GOSUB GMANUAL
        ON KEY(14) GOSUB SUBCOOLED
        ON KEY(10) GOSUB NEXTPAGE
        GOSUB IDLE: GOTO 4087
REM

SUBCOOLED: GOSUB SETFLAGS: LOCATE 5, 77, 1: PRINT "*"
        KEY(10) ON: KEY(1) ON: KEY(13) ON: KEY(11) ON: KEY(14) ON
4095 III = 0: ON KEY(1) GOSUB SET8
4096 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB GAUTO
        ON KEY(11) GOSUB OTHER: ON KEY(12) GOSUB ENGUNITS: ON KEY(13) GOSUB IDLE: ON KEY(14)
GOSUB PSATURATED
        ON KEY(10) GOSUB NEXTPAGE
        GOSUB IDLE: GOTO 4095
REM
PSATURATED: GOSUB SETFLAGS: LOCATE 7, 77, 1: PRINT "*"
        KEY(10) ON: KEY(1) ON: KEY(11) ON: KEY(14) ON
4105 III = 0: KEY(13) ON: ON KEY(1) GOSUB SET9
4106 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB GAUTO
        ON KEY(11) GOSUB SUBCOOLED: ON KEY(12) GOSUB SIUNITS: ON KEY(13) GOSUB IDLE: ON KEY(14)
GOSUB TSATURATED
        ON KEY(10) GOSUB NEXTPAGE
        GOSUB IDLE: GOTO 4105
REM
TSATURATED: GOSUB SETFLAGS: LOCATE 8, 77, 1: PRINT "*"
        KEY(10) ON: KEY(1) ON: KEY(13) ON: KEY(11) ON: KEY(14) ON
4115 III = 0: ON KEY(1) GOSUB SET10
4116 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB GAUTO
        ON KEY(11) GOSUB PSATURATED: ON KEY(12) GOSUB DIAMOND: ON KEY(13) GOSUB IDLE: ON KEY(14)
GOSUB GAUTO
        ON KEY(10) GOSUB NEXTPAGE
        GOSUB IDLE: GOTO 4115


GAUTO: GOSUB SETFLAGS: LOCATE 11, 77, 1: PRINT "*"
        KEY(10) ON: KEY(1) ON: KEY(11) ON: KEY(12) ON: KEY(14) ON
4165 III = 0: ON KEY(1) GOSUB SET15
4166 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB RAEDEF
        ON KEY(11) GOSUB TSATURATED: ON KEY(12) GOSUB RECTANGLE: ON KEY(14) GOSUB GMANUAL
        ON KEY(10) GOSUB NEXTPAGE
        GOSUB IDLE: GOTO 4165

GMANUAL: GOSUB SETFLAGS: LOCATE 12, 77, 1: PRINT "*"
        KEY(10) ON: KEY(1) ON: KEY(11) ON: KEY(12) ON: KEY(14) ON
4175 III = 0: ON KEY(1) GOSUB SET16
4176 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB RAEDEF
        ON KEY(11) GOSUB GAUTO: ON KEY(12) GOSUB ELLIPTIC
REM      ON KEY(14) GOSUB RAEDEF
        ON KEY(14) GOSUB ENGUNITS
        ON KEY(10) GOSUB NEXTPAGE
        GOSUB IDLE: GOTO 4175

RAEDEF: GOSUB SETFLAGS: LOCATE 15, 77, 1: PRINT "*"
```

```
        KEY(10) ON: KEY(1) ON: KEY(11) ON: KEY(12) ON: KEY(14) ON
4185 III = 0: ON KEY(1) GOSUB SET17
4186 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB ENGUNITS
        ON KEY(11) GOSUB GMANUAL: ON KEY(12) GOSUB FATIGUE: ON KEY(14) GOSUB RAEINP
        ON KEY(10) GOSUB NEXTPAGE
        GOSUB IDLE: GOTO 4185

RAEINP: GOSUB SETFLAGS: LOCATE 16, 77, 1: PRINT "*"
        KEY(10) ON: KEY(1) ON: KEY(11) ON: KEY(12) ON: KEY(14) ON
4195 III = 0: ON KEY(1) GOSUB SET18
4196 FOR I = 1 TO 50: NEXT I
        IF III = 1 THEN GOSUB ENGUNITS
        ON KEY(11) GOSUB RAEDEF: ON KEY(12) GOSUB OTHER: ON KEY(14) GOSUB ENGUNITS
        ON KEY(10) GOSUB NEXTPAGE
        GOSUB IDLE: GOTO 4195

REM
SET1: III = 1: UNITS$ = "ENG"
       LOCATE 6, 24: PRINT " ";
       LOCATE 5, 24: PRINT "X"; : RETURN
SET2: III = 1: UNITS$ = "SI"
       LOCATE 5, 24: PRINT " ";
       LOCATE 6, 24: PRINT "X"; : RETURN
SET3: III = 1: SHAPE$ = "DIAM"
       LOCATE 9, 24: PRINT "X";
       LOCATE 10, 24: PRINT " ";
       LOCATE 11, 24: PRINT " ": RETURN
SET4: III = 1: SHAPE$ = "RECT"
       LOCATE 9, 24: PRINT " ";
       LOCATE 10, 24: PRINT "X";
       LOCATE 11, 24: PRINT " ": RETURN
SET5: III = 1: SHAPE$ = "ELLI"
       LOCATE 9, 24: PRINT " ";
       LOCATE 10, 24: PRINT " ";
       LOCATE 11, 24: PRINT "X": RETURN
SET6: III = 1: TYPE$ = "CORR"
       LOCATE 14, 24: PRINT "X";
       LOCATE 15, 24: PRINT " ";
       LOCATE 16, 24: PRINT " "; : RETURN
SET7: III = 1: TYPE$ = "FATI"
       LOCATE 14, 24: PRINT " ";
       LOCATE 15, 24: PRINT "X";
       LOCATE 16, 24: PRINT " "; : RETURN
SET8: III = 1: STATE$ = "SUBC"
       LOCATE 5, 77: PRINT "X";
       LOCATE 7, 77: PRINT " ";
       LOCATE 8, 77: PRINT " "; : RETURN
SET9: III = 1: STATE$ = "SATP"
       LOCATE 5, 77: PRINT " ";
       LOCATE 7, 77: PRINT "X";
       LOCATE 8, 77: PRINT " "; : RETURN
SET10: III = 1: STATE$ = "SATT"
       LOCATE 5, 77: PRINT " ";
       LOCATE 7, 77: PRINT " ";
       LOCATE 8, 77: PRINT "X"; : RETURN
SET11: III = 1: TYPE$ = "OTHER"
       LOCATE 16, 24: PRINT "X";
       LOCATE 15, 24: PRINT " ";
       LOCATE 14, 24: PRINT " "; : RETURN
SET12: III = 1: CALC$ = "CRACK"
       LOCATE 5, 77: PRINT " ";
       LOCATE 6, 77: PRINT "X"; : RETURN
SET13: III = 1: FFCOR$ = "NIKURA"
       LOCATE 10, 77: PRINT " ";
       LOCATE 9, 77: PRINT "X"; : RETURN
SET14: III = 1: FFCOR$ = "JOHN"
       LOCATE 9, 77: PRINT " ";
       LOCATE 10, 77: PRINT "X"; : RETURN
SET15: III = 1: IGUESS$ = "AUTOM"
       NAUTO = 1
       LOCATE 11, 77: PRINT "X";
       LOCATE 12, 77: PRINT " "; : RETURN
SET16: III = 1: IGUESS$ = "MANUAL"
       NAUTO = -1
```

```
       LOCATE 11, 77: PRINT " ";
       LOCATE 12, 77: PRINT "X"; : RETURN
SET17: III = 1: RDEFAU$ = "DEFAULT"
       LOCATE 15, 77: PRINT "X";
       LOCATE 16, 77: PRINT " "; : RETURN
SET18: III = 1: RDEFAU$ = "RINPUT"
       LOCATE 15, 77: PRINT " ";
       LOCATE 16, 77: PRINT "X"; : RETURN

REM
REM
SETFLAGS: IF UNITS$ = "ENG" THEN GOSUB SET1 ELSE GOSUB SET2
        IF SHAPE$ = "DIAM" THEN
       GOSUB SET3
       ELSEIF SHAPE$ = "RECT" THEN
       GOSUB SET4
       ELSE
       GOSUB SET5
        END IF
        IF TYPE$ = "CORR" THEN
       GOSUB SET6
       ELSEIF TYPE$ = "FATI" THEN
       GOSUB SET7
       ELSE
       GOSUB SET11
        END IF
        IF STATE$ = "SUBC" THEN
       GOSUB SET8
       ELSEIF STATE$ = "SATP" THEN
       GOSUB SET9
       ELSE
       GOSUB SET10
        END IF
        IF IGUESS$ = "AUTOM" THEN GOSUB SET15 ELSE GOSUB SET16
REM      IF RDEFAU$ = "DEFAULT" THEN GOSUB SET17 ELSE GOSUB SET18
        RETURN
REM
NEXTPAGE: GOTO 4005
REM
NUMERIC: IF IFLAG > 0 THEN GOSUB WINDOW1: IFLAG = 1
        LOCATE 23, 2: PRINT "TYPE IN NEW VALUE AND PRESS ENTER TO CONTINUE";
        LOCATE 24, 2: PRINT "TO RETAIN CURRENT VALUE, JUST HIT THE ENTER KEY";
        LOCATE 25, 2: PRINT "DO NOT USE THE ARROW.KEYS ON THIS SCREEN";
        KEY(1) OFF: KEY(11) OFF: KEY(12) OFF: KEY(13) OFF: KEY(14) OFF: KEY(10) OFF
        IF UNITS$ = "ENG" THEN GOSUB ENGLABELS ELSE GOSUB SILABELS
        GOSUB SETNUM
        IF ZPO < 0! THEN
       LOCATE 14, 46: PRINT "              "
        END IF
        IF ZTTO < 0! THEN
       LOCATE 15, 46: PRINT "              "
        END IF
REM
       IF TYPE$ <> "OTHER" THEN
        IF TYPE$ = "CORR" THEN
             ROUGH = .0002441
             SROUGH = .0062
             REM EVLOSS = 100. * WALL IS RECOMMENDED BY EPRI
             IF UNITS$ = "ENG" THEN
               ZROUGH = ROUGH
               EVLOSS = 3! * 25.4 * zwall
             ELSE
               ZROUGH = SROUGH
               EVLOSS = 3! * zwall
             END IF
        ELSEIF TYPE$ = "FATI" THEN
             ROUGH = .0015748
             SROUGH = .04
             IF UNITS$ = "ENG" THEN
               ZROUGH = ROUGH
               EVLOSS = 6! * 25.4 * zwall
             ELSE
               ZROUGH = SROUGH
               EVLOSS = 6! * zwall
             END IF
```

```
        END IF
       ELSE
REM      LOCATE 7, 39, 1: INPUT ; "", ZROUGH
        LOCATE 7, 39:  PRINT "          ";
        LOCATE 7, 49: PRINT USING "##.###^^^^"; ZROUGH;
REM      LOCATE 8, 39, 1: INPUT ; "", EVLOSS
        LOCATE 8, 39:  PRINT "          ";
        LOCATE 8, 49: PRINT USING "###.#"; EVLOSS
       END IF
REM
REM      IF RDEFAU$ = "DEFAULT" THEN
REM         EVLOSS = 0.0
REM      ELSE
REM         LOCATE 8,39,1: INPUT; "", EVLOSS
REM         LOCATE 8,39:   PRINT "          ";
REM      END IF
        LOCATE 7, 49: PRINT USING "##.###^^^^"; ZROUGH;
        LOCATE 8, 49: PRINT USING "####.#"; EVLOSS;
REM
        IF UNITS$ = "ENG" THEN
         IF zwall < 1E-20 THEN zwall = XWALL
        XWALL = zwall: LOCATE 9, 49, 0: PRINT USING "##.###"; zwall;
        ELSE
         IF zwall < 1E-20 THEN zwall = XWALL
        XWALL = zwall: LOCATE 9, 46, 0: PRINT USING "####.#"; zwall;
        END IF
       IF TYPE$ = "CORR" THEN
REM EVLOSS = 100. * WALL IS RECOMMENDED BY EPRI
             IF UNITS$ = "ENG" THEN
            EVLOSS = 3! * 25.4 * zwall
             ELSE
            EVLOSS = 3! * zwall
             END IF
       ELSEIF TYPE$ = "FATI" THEN
             IF UNITS$ = "ENG" THEN
            EVLOSS = 6! * 25.4 * zwall
             ELSE
            EVLOSS = 6! * zwall
             END IF
REM      ELSEIF TYPE$ = "OTHER" THEN
       END IF
       LOCATE 8, 39:  PRINT "          ";
       LOCATE 8, 49: PRINT USING "###.#"; EVLOSS
REM
        IF CALC$ = "LEAK" THEN
       IF UNITS$ = "ENG" THEN
            IF ZAL = 0! THEN ZAL = XAL
            XAL = ZAL: LOCATE 10, 49, 0: PRINT USING "##.###^^^^"; ZAL;
       ELSE
            IF ZAL = 0! THEN ZAL = XAL
            XAL = ZAL: LOCATE 10, 48, 0: PRINT USING "##.###^^^^"; ZAL;
       END IF
REM
       IF UNITS$ = "ENG" THEN
            IF zegap = 0! THEN zegap = XEGAP
            XEGAP = zegap: LOCATE 11, 50, 0: PRINT USING "#.###^^^^"; zegap;
       ELSE
            IF zegap = 0! THEN zegap = XEGAP
            XEGAP = zegap: LOCATE 11, 49, 0: PRINT USING "#.###^^^^"; zegap;
       END IF
REM
       IF UNITS$ = "ENG" THEN
            IF ZIGAP = 0! THEN ZIGAP = XIGAP
            XIGAP = ZIGAP: LOCATE 12, 50, 0: PRINT USING "#.###^^^^"; ZIGAP;
       ELSE
            IF ZIGAP = 0! THEN ZIGAP = XIGAP
            XIGAP = ZIGAP: LOCATE 12, 49, 0: PRINT USING "#.###^^^^"; ZIGAP;
       END IF
REM
       LOCATE 20, 45: PRINT "...TO BE CALCULATED....";
        ELSE
       LOCATE 10, 45:  PRINT "...TO BE CALCULATED...";
       LOCATE 11, 45: PRINT "...TO BE CALCULATED...";
       LOCATE 12, 45: PRINT "...TO BE CALCULATED...";
       ZAL = 1!: zegap = .005: ZIGAP = .005
```

```
       END IF
REM
4205 IF STATE$ = "SUBC" THEN
REM     LOCATE 14, 39, 1: INPUT ; "", ZPO
       LOCATE 14, 39: PRINT "           ";
       IF UNITS$ = "ENG" THEN
            IF ZPO = 0! THEN ZPO = XPO
            XPO = ZPO: LOCATE 14, 50, 0: PRINT USING "#####.#"; ZPO;
       ELSE
            IF ZPO = 0! THEN ZPO = XPO
            XPO = ZPO: LOCATE 14, 48, 0: PRINT USING "#######."; ZPO;
       END IF
REM
4208 LOCATE 15, 45: PRINT "    RE-ENTER   ";
       LOCATE 16, 45: PRINT "    RE-ENTER   ";
REM     LOCATE 15, 39, 1: INPUT ; "", ZTTO
       LOCATE 15, 39: PRINT "            ";
       IF ZTTO > 1! THEN
            LOCATE 15, 45: PRINT "              ";
            LOCATE 15, 51, 0: PRINT USING "####.#"; ZTTO;
            LOCATE 16, 45: PRINT "(NOT REQUIRED)";
            ZHLO = -1!
            GOTO 4211
       END IF
REM     LOCATE 16, 39, 1: INPUT ; "", ZHLO
       IF ZHLO > 1! THEN
            LOCATE 16, 45: PRINT "              ";
            LOCATE 16, 51, 0: PRINT USING "####.#"; ZHLO;
            LOCATE 15, 45: PRINT "(NOT REQUIRED)";
            ZTTO = -1!
            GOTO 4211
       ELSE
            GOTO 4208
       END IF
4211 ZQUAL = 0!: LOCATE 17, 52: PRINT USING "###.#"; ZQUAL;
       GOTO 4215
        ELSEIF STATE$ = "SATP" THEN
REM     LOCATE 14, 39, 1: INPUT ; "", ZPO
       LOCATE 14, 39: PRINT "            ";
       IF UNITS$ = "ENG" THEN
            IF ZPO = 0! THEN ZPO = XPO
               XPO = ZPO: LOCATE 14, 50, 0: PRINT USING "#####.#"; ZPO;
       ELSE
            IF ZPO = 0! THEN ZPO = XPO
            XPO = ZPO: LOCATE 14, 48, 0: PRINT USING "#######."; ZPO;
       END IF
       LOCATE 15, 46, 1: PRINT "(NOT REQUIRED)"
       LOCATE 16, 46, 1: PRINT "(NOT REQUIRED)"
       ZTTO = -1!
       ZHLO = -1!
REM          LOCATE 17,49: PRINT "RE-ENTER";
REM          LOCATE 17,39,1: INPUT;"", ZQUAL
REM          LOCATE 17,39: PRINT "             ";
       LOCATE 17, 52, 0: PRINT USING "###.#"; ZQUAL;
       GOTO 4215
        ELSEIF STATE$ = "SATT" THEN
       LOCATE 14, 46, 1: PRINT "(NOT REQUIRED)"
REM     LOCATE 15, 49, 1: INPUT ; "", ZTTO
       LOCATE 15, 49: PRINT "            ";
       IF UNITS$ = "ENG" THEN
            IF ZTTO = 0! THEN ZTTO = XTTO
            XTTO = ZTTO: LOCATE 15, 52, 0: PRINT USING "###.#"; ZTTO;
       ELSE
            IF ZTTO = 0! THEN ZTTO = XTTO
            XTTO = ZTTO: LOCATE 15, 51, 0: PRINT USING "####.#"; ZTTO;
       END IF
       LOCATE 16, 46, 1: PRINT "(NOT REQUIRED)"
       ZPO = -1!
       ZHLO = -1!
REM          LOCATE 17,49: PRINT "RE-ENTER";
REM          LOCATE 17,49,1: INPUT;"", ZQUAL
REM          LOCATE 17,39: PRINT "             ";
       LOCATE 17, 52, 0: PRINT USING "###.#"; ZQUAL;
        END IF
4215 LOCATE 18, 39, 1
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REM     INPUT ; "", ZPB
        LOCATE 18, 39: PRINT "          ";
        IF UNITS$ = "ENG" THEN
       IF ZPB = 0! THEN ZPB = XPB
       XPB = ZPB: LOCATE 18, 52, 0: PRINT USING "###.#"; ZPB;
        ELSE
       IF ZPB = 0! THEN ZPB = XPB
       XPB = ZPB: LOCATE 18, 48, 0: PRINT USING "#######."; ZPB;
        END IF
REM
REM      LOCATE 19, 39, 1: INPUT ; "", CD
        LOCATE 19, 39: PRINT "          ";
        IF UNITS$ = "ENG" THEN
       IF CD = 0! THEN CD = XCD
       XCD = CD: LOCATE 19, 54, 0: PRINT USING "#.###"; CD;
        ELSE
       IF CD = 0! THEN CD = XCD
            XCD = CD: LOCATE 19, 54, 0: PRINT USING "#.###"; CD;
        END IF
REM
        IF CALC$ = "CRACK" THEN
REM     LOCATE 20, 39: INPUT ; "", ALEAK
        END IF
        IF IGUESS$ = "AUTOM" THEN
       LOCATE 21, 46: PRINT "(NOT REQUIRED)"
        ELSE
REM     LOCATE 21, 39, 1: INPUT ; "", PGUESS
       LOCATE 21, 39: PRINT "          ";
       IF UNITS$ = "ENG" THEN
            IF PGUESS = 0! THEN PGUESS = XPGUESS
            XPGUESS = PGUESS: LOCATE 21, 52, 0: PRINT USING "#####.#"; PGUESS;
       ELSE
            IF PGUESS = 0! THEN PGUESS = XPGUESS
            XPGUESS = PGUESS: LOCATE 21, 51, 0: PRINT USING "######."; PGUESS;
       END IF
        END IF
        GOSUB SETNUM
4255 LOCATE 23, 1, 0
REM   INPUT ; "IS THE ABOVE DATA CORRECT (Y = YES OR N =NO)?  ", A$
        A$ = "y"
       IF A$ = "Y" OR A$ = "y" THEN
        GOSUB WINDOW1
        GOTO 4410
       END IF
        IF A$ = "N" OR A$ = "n" THEN
       GOSUB WINDOW1
       GOSUB NUMERIC
        ELSE
       GOTO 4255
        END IF
4410 GOSUB WINDOW1
       GOTO 4700
REM
REM   WINDOW1
WINDOW1:
        LOCATE 23, 1: PRINT "
        ";
        LOCATE 24, 1: PRINT "
        ";
        LOCATE 25, 1: PRINT "
        ";
        RETURN
REM
ENGLABELS:
        LOCATE 7, 60: PRINT " INCHES";
        LOCATE 8, 60: PRINT " VEL. HEADS";
        LOCATE 9, 60: PRINT " INCHES";
        LOCATE 10, 60: PRINT " INCHES";
        LOCATE 11, 60: PRINT " INCHES";
        LOCATE 12, 60: PRINT " INCHES";
        LOCATE 14, 60: PRINT " PSIA";
        LOCATE 15, 60: PRINT " DEG. F";
        LOCATE 16, 60: PRINT " BTU/LBM"
        LOCATE 17, 60: PRINT " PERCENT"
        LOCATE 18, 60: PRINT " PSIA";
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        LOCATE 20, 60: PRINT " GAL/MIN";
        LOCATE 21, 60: PRINT " PSIA";
        RETURN
REM
SILABELS:
        LOCATE 7, 60: PRINT " MM      ";
        LOCATE 8, 60: PRINT " VEL. HEADS";
        LOCATE 9, 60: PRINT " MM      ";
        LOCATE 10, 60: PRINT " MM      ";
        LOCATE 11, 60: PRINT " MM      ";
        LOCATE 12, 60: PRINT " MM      ";
        LOCATE 14, 60: PRINT " KPA     ";
        LOCATE 15, 60: PRINT " DEG. C ";
        LOCATE 16, 60: PRINT " KJ/KG ";
        LOCATE 17, 60: PRINT " PERCENT"
        LOCATE 18, 60: PRINT " KPA     ";
        LOCATE 20, 60: PRINT " LIT/MIN";
        LOCATE 21, 60: PRINT " KPA     ";
        RETURN
REM
SETNUM:
        LOCATE 9, 45: PRINT "                    ";
        LOCATE 10, 45: PRINT "                    ";
        LOCATE 11, 45: PRINT "                    ";
        LOCATE 12, 45: PRINT "                    ";
        LOCATE 14, 45: PRINT "                    ";
        LOCATE 15, 45: PRINT "                    ";
        LOCATE 16, 45: PRINT "                    ";
        LOCATE 17, 45: PRINT "                    ";
        LOCATE 18, 45: PRINT "                    ";
        LOCATE 19, 45: PRINT "                    ";
        LOCATE 20, 45: PRINT "                    ";
        IF UNITS$ = "SI" THEN GOTO 4500
        IF zwall < 1E-20 THEN zwall = XWALL
        XWALL = zwall: LOCATE 9, 49, 0: PRINT USING "##.###"; zwall;
        IF CALC$ = "LEAK" THEN
       IF ZAL = 0! THEN ZAL = XAL
       XAL = ZAL: LOCATE 10, 49, 0: PRINT USING "##.###^^^^"; ZAL;
       IF zegap = 0! THEN zegap = XEGAP
       XEGAP = zegap: LOCATE 11, 50, 0: PRINT USING "#.###^^^^"; zegap;
       IF ZIGAP = 0! THEN ZIGAP = XIGAP
       XIGAP = ZIGAP: LOCATE 12, 50, 0: PRINT USING "#.###^^^^"; ZIGAP;
       LOCATE 20, 45: PRINT "...TO BE CALCULATED....";
        ELSE
       LOCATE 10, 45:  PRINT "...TO BE CALCULATED...";
       LOCATE 11, 45: PRINT "...TO BE CALCULATED...";
       LOCATE 12, 45: PRINT "...TO BE CALCULATED...";
       LOCATE 20, 39: PRINT USING "##.###^^^^"; ALEAK;
        END IF
        IF ZPO = 0! THEN ZPO = XPO
        IF ZPO < 0! THEN
       LOCATE 14, 46, 0: PRINT "(NOT REQUIRED)"
       ELSE
       XPO = ZPO: LOCATE 14, 50, 0: PRINT USING "#####.#"; ZPO;
        END IF
        IF ZTTO = 0! THEN ZTTO = XTTO
        IF ZTTO < 0! THEN
       LOCATE 15, 46, 0: PRINT "(NOT REQUIRED)";
       ELSE
       XTTO = ZTTO: LOCATE 15, 52, 0: PRINT USING "###.#"; ZTTO;
       END IF
        IF ZHLO = 0! THEN ZHLO = XHLO
        IF ZHLO < 0! THEN
       LOCATE 16, 46, 0: PRINT "(NOT REQUIRED)";
       ELSE
       XHLO = ZHLO: LOCATE 16, 52, 0: PRINT USING "###.#"; ZHLO;
       END IF
        LOCATE 17, 52, 0: PRINT USING "###.#"; ZQUAL;
        IF ZPB = 0! THEN ZPB = XPB
        XPB = ZPB: LOCATE 18, 52, 0: PRINT USING "###.#"; ZPB;
        IF CD = 0! THEN CD = XCD
        XCD = CD: LOCATE 19, 54, 0: PRINT USING "#.###"; CD;
        IF IGUESS$ = "AUTOM" THEN
       LOCATE 21, 46: PRINT "(NOT REQUIRED)"
        ELSE
```

```
       IF PGUESS = 0! THEN PGUESS = XPGUESS
       XPGUESS = PGUESS: LOCATE 21, 52, 0: PRINT USING "#####.#"; PGUESS;
        END IF
        RETURN
4500 IF zwall < 1E-20 THEN zwall = XWALL
        XWALL = zwall: LOCATE 9, 46, 0: PRINT USING "####.#"; zwall;
        IF CALC$ = "LEAK" THEN
       IF ZAL = 0! THEN ZAL = XAL
       XAL = ZAL: LOCATE 10, 48, 0: PRINT USING "##.###^^^^"; ZAL;
       IF zegap = 0! THEN zegap = XEGAP
       XEGAP = zegap: LOCATE 11, 49, 0: PRINT USING "#.###^^^^"; zegap;
       IF ZIGAP = 0! THEN ZIGAP = XIGAP
       XIGAP = ZIGAP: LOCATE 12, 49, 0: PRINT USING "#.###^^^^"; ZIGAP;
       LOCATE 20, 45: PRINT "...TO BE CALCULATED....";
        ELSE
       LOCATE 10, 45:  PRINT "...TO BE CALCULATED...";
       LOCATE 11, 45: PRINT "...TO BE CALCULATED...";
       LOCATE 12, 45: PRINT "...TO BE CALCULATED...";
       LOCATE 20, 49: PRINT USING "##.##^^^^"; ALEAK;
        END IF
        IF ZPO = 0! THEN ZPO = XPO
        IF ZPO < 0! THEN
       LOCATE 14, 46, 0: PRINT "(NOT REQUIRED)"
       ELSE
       XPO = ZPO: LOCATE 14, 48, 0: PRINT USING "#######."; ZPO;
        END IF
        IF ZTTO = 0! THEN ZTTO = XTTO
        IF ZTTO < 0! THEN
       LOCATE 15, 46, 0: PRINT "(NOT REQUIRED)";
       ELSE
       XTTO = ZTTO: LOCATE 15, 51, 0: PRINT USING "####.#"; ZTTO;
        END IF
        IF ZHLO = 0! THEN ZHLO = XHLO
        IF ZHLO < 0! THEN
       LOCATE 16, 46, 0: PRINT "(NOT REQUIRED)";
       ELSE
       XHLO = ZHLO: LOCATE 16, 51, 0: PRINT USING "####.#"; ZHLO;
       END IF
        LOCATE 17, 52, 0: PRINT USING "###.#"; ZQUAL;
        IF ZPB = 0! THEN ZPB = XPB
        XPB = ZPB: LOCATE 18, 48, 0: PRINT USING "#######."; ZPB;
        IF CD = 0! THEN CD = XCD
        XCD = CD: LOCATE 19, 54, 0: PRINT USING "#.###"; CD;
        IF IGUESS$ = "AUTOM" THEN
       LOCATE 21, 46: PRINT "(NOT REQUIRED)"
        ELSE
       IF PGUESS = 0! THEN PGUESS = XPGUESS
       XPGUESS = PGUESS: LOCATE 21, 51, 0: PRINT USING "######."; PGUESS;
        END IF
        RETURN
REM
4700 IF UNITS$ = "ENG" THEN GOTO 4750
        IF UNITS$ = "SI" THEN GOTO 4705
        PRINT "ERROR: UNITS HAVE NOT BEEN PROPERLY SPECIFIED": STOP
4705 WALL = zwall * SLEN
        ROUGH = ZROUGH * SLEN
        AL = ZAL * SLEN
        EGAP = zegap * SLEN
        IGAP = ZIGAP * SLEN
        PO = ZPO * SPRES
        TTO = 1.8 * ZTTO + 32!
        HLO = ZHLO * .429874
        PB = ZPB * SPRES
        GOTO 4800
4750 WALL = zwall / 12!
        ROUGH = ZROUGH / 12!
        AL = ZAL / 12!
        EGAP = zegap / 12!
        IGAP = ZIGAP / 12!
        TTO = ZTTO
        HLO = ZHLO
        PO = ZPO
        PB = ZPB
4800 XO = ZQUAL / 100!
        XR1 = (EGAP - IGAP) / WALL
```

```
        XR3 = XR1 ^ 3
        XR5 = XR1 ^ 5
        XR7 = XR1 ^ 7
        XR9 = XR1 ^ 9
        RPHI = XR1 - XR3 / 3! + XR5 / 5! - XR7 / 7! + XR9 / 9!
        PHI = RPHI * 360! / (2! * PI)
        IF SHAPE$ = "RECT" THEN
       AREA = EGAP * AL
       PER = 2! * (EGAP + AL)
        ELSEIF SHAPE$ = "DIAM" THEN
       AREA = .5 * EGAP * AL
       PER = 4! * SQR((AL * AL / 4!) + (EGAP * EGAP / 4!))
        ELSEIF SHAPE$ = "ELLI" THEN
       AREA = PI * EGAP * AL / 4!
       MELPS = (AL - EGAP) / (AL + EGAP)
       KELPS = 1! + MELPS ^ 2 / 4! + MELPS ^ 4 / 64! + MELPS ^ 6 / 128!
       PER = PI * (AL + EGAP) * KELPS / 2!
        ELSE
       PRINT "ERROR:  SHAPE OF CRACK HAS NOT BEEN SPECIFIED": STOP
        END IF
        DH = 4! * AREA / PER
        ALD = WALL / DH
        IF RDEFAU$ = "DEFAULT" THEN
        END IF
        IF STATE$ = "SUBC" THEN
       ISTATE = 3
        ELSEIF STATE$ = "SATP" THEN
       ISTATE = 2
        ELSEIF STATE$ = "SATT" THEN
       ISTATE = 1
        ELSE
       PRINT "ERROR:  STATE OF FLUID HAS NOT BEEN SPECIFIED": STOP
        END IF
4850 ACO = EGAP / IGAP
        IF ALD > 12! THEN
       ACI = EGAP / (IGAP + (12! / ALD) * (EGAP - IGAP))
        ELSE
       ACI = 1!
        END IF
        XR1 = (EGAP - IGAP) / WALL
        XR3 = XR1 ^ 3
        XR5 = XR1 ^ 5
        XR7 = XR1 ^ 7
        XR9 = XR1 ^ 9
        RPHI = XR1 - XR3 / 3! + XR5 / 5! - XR7 / 7! + XR9 / 9!
        PHI = RPHI * 360! / (2! * PI)
REM   LPRINT "WALL ="; WALL; "ROUGH ="; ROUGH; "AL ="; AL; "EGAP ="; EGAP; "DH ="; DH;
REM   LPRINT "IGAP ="; IGAP; "PHI ="; PHI; "PO ="; PO; "TTO ="; TTO; "PB ="; PB
REM   LPRINT "AREA ="; AREA; "PER ="; PER; "ALD ="; ALD; "ISTATE ="; ISTATE; "ACO ="; ACO; "ACI
="; ACI;
        DRK = DH / ROUGH
        IF DRK < 27.74 THEN
REM     FF = 1! / (3.39 * LOG(DRK) / 2.30259 - .866) ^ 2
      FF = 1! / (2! * LOG(DRK) / 2.30259 + 1.14) ^ 2
        ELSE
      FF = 1! / (2! * LOG(DRK) / 2.30259 + 1.14) ^ 2
        END IF
        IF ISTATE = 1 THEN
         TEMP = TTO: TSAT = TTO
         NUM = 5: CALL STEAMSUB: VLO = VF
         NUM = 1: CALL STEAMSUB: HLO = HF
         NUM = 3: CALL STEAMSUB: SLO = SF
         NUM = 26: CALL STEAMSUB
        ELSEIF ISTATE = 2 THEN
         PRESS = PO: PSAT = PO
         NUM = 6: CALL STEAMSUB: VLO = VF
         NUM = 2: CALL STEAMSUB: HLO = HF
         NUM = 4: CALL STEAMSUB: SLO = SF
         NUM = 25: CALL STEAMSUB: TTO = TSAT
        ELSEIF ISTATE = 3 THEN
         TEMP = TTO: PRESS = PO
         IF ZHLO > 1! THEN
              ENTH = HLO
              NUM = 34: CALL STEAMSUB: TEMP = T
              TTO = T
```

```
         END IF
         NUM = 5: CALL STEAMSUB: VLO = VF
         NUM = 32: CALL STEAMSUB: HLO = H
         NUM = 4: CALL STEAMSUB: SLP = SF
         NUM = 2: CALL STEAMSUB: HLP = HF
         NUM = 1: CALL STEAMSUB: HLT = HF
         NUM = 25: CALL STEAMSUB: TTP = TSAT + 460!
         NUM = 26: CALL STEAMSUB
         SLO = SLP - 2! * (HLP - HLT) / (TTP + TTO + 460!)
        END IF
        IF ALD <= 12! THEN GOTO 400
        IF PFLAG > 1 THEN LPRINT "2   ", "DRK", DRK, "FF", FF, "TEMP", TEMP, "PO", PO, "VLO", VLO,
"HLO", HLO, "SLO", SLO
        GOTO 10
REM
REM
REM   SCREEN 0
5000 REM SCREEN 9: COLOR 10, 1
        SSL = 304.8: SSP = 6.8947333#
        IF PB < PSAT THEN
       PRESS = PB
       NUM = 25: CALL STEAMSUB: TB = TSAT
       NUM = 2:  CALL STEAMSUB: HLB = HF
       NUM = 10: CALL STEAMSUB: HGB = HG
       XEHB = (HLO - HLB) / (HGB - HLB)
        ELSE
       ENTH = HLO
       NUM = 34: CALL STEAMSUB: TB = T
       XEHB = 0!
        END IF
        IF P2 < PSAT THEN
       PRESS = P2
       NUM = 25: CALL STEAMSUB: T2 = TSAT
        ELSE
       ENTH = HLO
       NUM = 34: CALL STEAMSUB: T2 = T
       XEHC = 0!
        END IF
        SROUGH = ROUGH * SSL
        SWALL = WALL • SSL
        SAL = AL * SSL
        SEGAP = EGAP * SSL
        SIGAP = IGAP * SSL
        SAREA = AREA * SSL * SSL
        SPER = PER * SSL
        SDH = DH * SSL
        EROUGH = ROUGH * 12!
        EWALL = WALL * 12!
        EAL = AL * 12!
        EEGAP = EGAP * 12!
        EIGAP = IGAP * 12!
        EAREA = AREA * 12! * 12!
        EPER = PER * 12!
        EDH = DH * 12!
        PTOT = PO - P2
        SPTOT = PTOT * SSP
        SPSAT = PSAT * SSP
        SPO = PO * SSP
        SP2 = P2 * SSP
        SPB = PB * SSP
        SPE = PE * SSP
        SPA = PA * SSP
        SPF = PF * SSP
        SPAA = PAA * SSP
        SPK = PK * SSP
        STTO = (TTO - 32!) / 1.8
        ST2 = (T2 - 32!) / 1.8
        STB = (TB - 32!) / 1.8
        SHLO = HLO * 2.3260091#
        SSLO = SLO * 4.18681638#
        GA = SQR(G2)
        SGA = GA * 4.8824
        AMA = GA * AREA
        AVA = AMA * 60 * 7.481 / 62.3
        SAVA = AMA * 60 * .45359
```

```
         SAMA = SAVA / 60!
REM
REM  CHECK IF FLOW RATE CALCULATED HAS MET THE INPUT FLOW RATE CRITERIA
REM
REM
REM  IF CRITERIA MET DISPLAY AND PRINT RESULTS  ALSO DELETE INTFACE.NDG SO THE PROCEDURE STOPS
REM
REM  IF CRITERIA NOT MET THAN CHANGE CRACK LENGTH APPROPRIATELY
REM        INCREASE CRACK LENGTH IF CALC FLOW IS LESS THEN CRITERIA
REM        DECREASE CRACK LENGTH IF CALC FLOW IS GREATER THEN CRITERIA
REM        RETURN TO PROCEDURE TO RUN NRCPIPE AGAIN
REM
REM
       KITER = KITER + 1
       CRK(KITER) = ZAL
       CRITER(KITER) = MITER
       IF (NUNITS = 1 OR NUNITS = 2) THEN
             IF (NFUNIT = 1) THEN
             AMAC = AMA
             ELSE
             AMAC = AVA
             END IF
       ELSE
             IF (NFUNIT = 1) THEN
             AMAC = SAMA
             ELSE
             AMAC = SAVA
             END IF
       END IF
       CFLOW(KITER) = AMAC
       CLS
       OPEN "RESULTS.DAT" FOR OUTPUT AS #7
       PRINT #7, "---------------------------------- SCREEN #17 ----------------------------------"
        IF NBEND = 2 THEN
            PRINT #7, "   ITER          LOAD         CRACK,2L      REQD. FLOW     LEAK FLOW"
       IF NUNITS = 1 THEN
            IF (NFUNIT = 1) THEN
             PRINT #7, "   #              KIPS         INCHES         LBS/SEC        LBS/SEC  "
            ELSE
             PRINT #7, "   #              KIPS         INCHES         GPM            GPM      "
         END IF
       END IF
       IF NUNITS = 2 THEN
            IF (NFUNIT = 1) THEN
             PRINT #7, "   #              LBS          INCHES         LBS/SEC        LBS/SEC  "
            ELSE
             PRINT #7, "   #              LBS          INCHES         GPM            GPM  "
            END IF
       END IF
       IF NUNITS = 3 THEN
            IF (NFUNIT = 1) THEN
             PRINT #7, "   #              MN           M              KG/SEC         KG/SEC"
            ELSE
             PRINT #7, "   #              MN           M              L/MIN          L/MIN "
            END IF
       END IF
       IF NUNITS = 4 THEN
            IF (NFUNIT = 1) THEN
             PRINT #7, "   #              N            mm             KG/SEC          KG/SEC"
            ELSE
             PRINT #7, "   #              N            mm             L/MIN           L/MIN "
            END IF
       END IF
        END IF
        IF NBEND = 1 THEN
            PRINT #7, " ITER            MOMENT       CRACK,2L      REQD. FLOW     LEAK FLOW"
       IF NUNITS = 1 THEN
            IF (NFUNIT = 1) THEN
             PRINT #7, " #                IN-KIPS      INCHES         LBS/SEC         LBS/SEC  "
            ELSE
             PRINT #7, " #                IN-KIPS      INCHES         GPM             GPM    "
            END IF
       END IF
       IF NUNITS = 2 THEN
            IF (NFUNIT = 1) THEN
```

```
            PRINT #7, " #                 IN-LBS       INCHES        LBS/SEC        LBS/SEC  "
           ELSE
            PRINT #7, " #                 IN-LBS       INCHES        GPM            GPM     "
           END IF
      END IF
      IF NUNITS = 3 THEN
           IF (NFUNIT = 1) THEN
            PRINT #7, " #                 MN-M         M             KG/SEC         KG/SEC"
           ELSE
            PRINT #7, " #                 MN-M         M             L/MIN          L/MIN  "
           END IF
      END IF
      IF NUNITS = 4 THEN
           IF (NFUNIT = 1) THEN
            PRINT #7, " #                 N-mm         mm            KG/SEC         KG/SEC"
           ELSE
            PRINT #7, " #                 N-mm         mm            L/MIN          L/MIN "
           END IF
      END IF
       END IF
           PRINT #7,
"------------------------------------------------------------------------------"

      FOR J = 1 TO KITER
      CRKP = CRK(J)
      IF NUNITS = 3 THEN
      CRKP = CRKP / 1000!
      END IF
      PRINT #7, J, PFLOW, CRKP, AFLOW, CFLOW(J), CRITER(J)
      NEXT J
      CLOSE #7
REM    INPUT "Enter any character", DUMMY
REM
REM
REM  CHECK CURRENT RUN  IF SINGLE PHASE FLOW
REM
      IF (CRITER(KITER) = 0 AND KITER > 1) THEN
REM
REM   INTERPOLATE
REM
      AFLOW1 = CFLOW(KITER - 1)
      AFLOW2 = CFLOW(KITER)
      CRKP1 = CRK(KITER - 1)
      CRKP2 = CRK(KITER)
      CRKP = CRKP1 + (CRKP2 - CRKP1) * (AFLOW - AFLOW1) / (AFLOW2 - AFLOW1)
       IF NUNITS = 3 THEN
        CRKP = CRKP / 1000!
       END IF
      ELSE
      IF (AMAC = AFLOW) THEN GOTO 5099
      IF (AMAC < (AFLOW + .01 * AFLOW) AND AMAC > (AFLOW - .01 * AFLOW)) THEN GOTO 5099
      IF (AMAC < AFLOW) THEN
      JFLAG1 = KITER
              IF (JFLAG2 = 0) THEN
                 ZAL = 1.1 * ZAL
                 GOSUB MODIFY
              ELSE
                 ZAL = (CRK(JFLAG1) + CRK(JFLAG2)) / 2!
                 GOSUB MODIFY
              END IF
      ELSE
      JFLAG2 = KITER
              IF (JFLAG1 = 0) THEN
                 ZAL = .75 * ZAL
                 GOSUB MODIFY
              ELSE
                 ZAL = (CRK(JFLAG1) + CRK(JFLAG2)) / 2
                 GOSUB MODIFY
REM
REM   INTERPOLATE
REM
REM           AFLOW1 = CFLOW(KITER - 1)
REM           AFLOW2 = CFLOW(KITER)
REM           CRKP1 = CRK(KITER - 1)
REM           CRKP2 = CRK(KITER)
```

```
REM           CRKP = CRKP1 + (CRKP2 - CRKP1) * (AFLOW - AFLOW1) / (AFLOW2 - AFLOW1)
REM           IF NUNITS = 3 THEN
REM             CRKP = CRKP / 1000!
REM           END IF
REM           GOTO 5099
               END IF
            END IF
        SYSTEM
        END IF
5099 :
          OPEN "FINAL.OUT" FOR APPEND AS #7
          PRINT #7, CRKP
          CLOSE #7
          SHELL "DEL " + "INTFACE.NDG"
          GOSUB 5500
5100 : CLS : GOSUB BOUNDARY
         LOCATE 2, 20: PRINT "SCREEN #18:  CRACK GEOMETRY OUTPUT";
         LOCATE 5, 2: PRINT "  1. THE CRACK IS ASSUMED TO BE HAVE A ";
REM       IF TYPE$ = "CORR" THEN
REM          PRINT "STRESS CORROSION";
REM       ELSEIF TYPE$ ="FATI" THEN
REM          PRINT "FATIGUE";
REM       END IF
REM       PRINT " GENERATED CRACK WITH A";
         LOCATE 6, 2
         IF SHAPE$ = "DIAM" THEN
        PRINT "      DIAMOND SHAPE";
         ELSEIF SHAPE$ = "RECT" THEN
        PRINT "      RECTANGULAR SHAPE";
         ELSEIF SHAPE$ = "ELLI" THEN
        PRINT "      ELLIPTICAL SHAPE";
         END IF
         PRINT " AND A SURFACE ROUGHNESS OF          IN. (          MM)";
         LOCATE 7, 2: PRINT "     THE CRACK GEOMETRY IS DESCRIBED BELOW:";
         LOCATE 9, 8: PRINT "2. CRACK DEPTH              =         INCHES   (           MM)";
         LOCATE 10, 8: PRINT "3. LENGTH OF CRACK          =         INCHES   (           MM)";
         LOCATE 11, 8: PRINT "4. EXTERIOR CRACK GAP       =         INCHES   (           MM)";
         LOCATE 12, 8: PRINT "5. INTERIOR CRACK GAP       =         INCHES   (           MM)";
         LOCATE 13, 8: PRINT "6. CRACK OPENING ANGLE      =         DEGREES";
         LOCATE 14, 8: PRINT "7. EXTERIOR AREA OF";
         LOCATE 15, 8: PRINT "    CRACK OPENING           =         IN.^2    (           MM^2)";
         LOCATE 16, 8: PRINT "8. CRACK WETTED PERIMETER =           INCHES   (           MM)";
         LOCATE 17, 8: PRINT "9. CRACK HYDRAULIC DIAM.  =           INCHES   (           MM)";
         LOCATE 18, 7: PRINT "10. RATIOS: CRACK DEPTH TO:";
         LOCATE 19, 8: PRINT "    HYDRAULIC DIAMETER      =           TO ROUGHNESS     =";
         LOCATE 20, 7: PRINT "11. PATH LOSS COEFFICIENT  =          VELOCITY HEADS";
         LOCATE 6, 52: PRINT USING ".###^^^^"; EROUGH;
         LOCATE 6, 66: PRINT USING ".###^^^^"; SROUGH;
         LOCATE 9, 38: PRINT USING "##.###"; EWALL;
         LOCATE 9, 55: PRINT USING "####.#"; SWALL;
         LOCATE 10, 38: PRINT USING "##.###"; EAL;
         LOCATE 10, 56: PRINT USING "###.##"; SAL;
         LOCATE 11, 36: PRINT USING ".###^^^^"; EEGAP;
         LOCATE 11, 55: PRINT USING ".###^^^^"; SEGAP;
         LOCATE 12, 36: PRINT USING ".###^^^^"; EIGAP;
         LOCATE 12, 55: PRINT USING ".###^^^^"; SIGAP;
         LOCATE 13, 39: PRINT USING "##.##"; PHI;
         LOCATE 15, 36: PRINT USING ".###^^^^"; EAREA;
         LOCATE 15, 55: PRINT USING ".###^^^^"; SAREA;
         LOCATE 16, 38: PRINT USING "##.###"; EPER;
         LOCATE 16, 56: PRINT USING "###.##"; SPER;
         LOCATE 17, 38: PRINT USING "##.###"; EDH;
         LOCATE 17, 56: PRINT USING "###.##"; SDH;
         LOCATE 19, 39: PRINT USING "###.#"; ALD;
         LOCATE 19, 67: PRINT USING "###.##"; EDH / EROUGH;
         LOCATE 20, 38: PRINT USING "####.#"; EVLOSS;
         GOSUB WINDOWA
         KEY(11) OFF: KEY(14) ON: KEY(1) ON: KEY(2) ON: KEY(3) ON
5150 ON KEY(14) GOSUB 5200

         ON KEY(1) GOSUB 5400: ON KEY(2) GOSUB 5500
         ON KEY(3) GOSUB WRITE18
         GOSUB IDLEA: GOTO 5150
REM
IDLEA: RETURN
```

```
REM
5200 CLS : GOSUB BOUNDARY
        LOCATE 2, 15: PRINT "SCREEN #19: FLUID THERMODYNAMIC CONDITIONS";
        LOCATE 5, 3: PRINT "1. THE FLUID ENTERING THE CRACK IS ";
        IF STATE$ = "SUBC" THEN
       PRESS = PO: NUM = 25: CALL STEAMSUB: TTOS = TSAT:  TSUB = TTOS - TTO: STSUB = TSUB / 1.8
       PRINT "SUBCOOLED BY       DEG F (       DEG C)";
       LOCATE 5, 51: PRINT USING "###.#"; TSUB;
       LOCATE 5, 64: PRINT USING "###.#"; STSUB;
       PRINT ""
        ELSE
       PRINT "SATURATED AT:"
        END IF
        LOCATE 6, 8: PRINT "2. STAGNATION FLUID PRESSURE    =          PSIA  (          KPA)";
        LOCATE 7, 8: PRINT "3. SATURATION PRESSURE          =          PSIA  (          KPA)";
        LOCATE 8, 8: PRINT "4. STAGNATION FLUID TEMPERATURE =          DEG F (          DEG C)";
        LOCATE 9, 8: PRINT "5. STAGNATION FLUID ENTHALPY    =          BTU/LB (         KJ/KG)";
        LOCATE 10, 8: PRINT "6. STAGNATION FLUID ENTROPY     =          BTU/LB/F(
KJ/KG/C)";
REM      LOCATE 11,11: PRINT "STAGNATION FLUID QUALITY     =          PERCENT";
        LOCATE 13, 3: PRINT "AT THE EXIT PLANE OF THE CRACK, THE FLUID PROPERTIES ARE:";
        LOCATE 14, 8: PRINT "7. EXIT PLANE FLUID PRESSURE    =          PSIA  (          KPA)";
        LOCATE 15, 8: PRINT "8. EXIT PLANE FLUID TEMPERATURE =          DEG F (          DEG C)";
        LOCATE 16, 8: PRINT "9. EXIT PLANE FLUID QUALITY     =          PERCENT";
        LOCATE 17, 3: PRINT "AFTER EXPANSION TO THE OUTSIDE PRESSURE, THE FLUID PROPERTIES ARE:";
        LOCATE 18, 7: PRINT "10. OUTSIDE FLUID PRESSURE      =          PSIA  (          KPA)";
        LOCATE 19, 7: PRINT "11. OUTSIDE FLUID TEMPERATURE   =          DEG F (          DEG
C)";
        LOCATE 20, 7: PRINT "12. OUTSIDE FLUID QUALITY       =          PERCENT";
        LOCATE 6, 43: PRINT USING "####.#"; PO;
        LOCATE 6, 60: PRINT USING "#####.#"; SPO;
        LOCATE 7, 43: PRINT USING "####.#"; PSAT;
        LOCATE 7, 60: PRINT USING "#####.#"; SPSAT;
        LOCATE 8, 44: PRINT USING "###.#"; TTO;
        LOCATE 8, 62: PRINT USING "###.#"; STTO;
        LOCATE 9, 43: PRINT USING "####.#"; HLO;
        LOCATE 9, 61: PRINT USING "####.#"; SHLO;
        LOCATE 10, 43: PRINT USING "#.####"; SLO;
        LOCATE 10, 61: PRINT USING "#.####"; SSLO;
REM      LOCATE 11,43:  PRINT USING "###.##"; XO * 100.;
        LOCATE 14, 43: PRINT USING "####.#"; P2;
        LOCATE 14, 60: PRINT USING "#####.#"; SP2;
        LOCATE 15, 44: PRINT USING "###.#"; T2;
        LOCATE 15, 61: PRINT USING "####.#"; ST2;
        LOCATE 17, 43: PRINT USING "###.##"; XEHC * 100!;
        LOCATE 18, 43: PRINT USING "####.#"; PB;
        LOCATE 18, 59: PRINT USING "#####.#"; SPB;
        LOCATE 19, 44: PRINT USING "###.#"; TB;
        LOCATE 19, 61: PRINT USING "###.#"; STB;
        LOCATE 20, 43: PRINT USING "###.##"; XEHB * 100!;
        GOSUB WINDOWB
        KEY(11) ON: KEY(14) ON: KEY(1) ON: KEY(2) ON: KEY(3) ON
5285 ON KEY(11) GOSUB 5100: ON KEY(14) GOSUB 5300
        ON KEY(1) GOSUB 5400: ON KEY(2) GOSUB 5500
        ON KEY(3) GOSUB WRITE19
        GOSUB IDLEA: GOTO 5285
REM
5300 CLS : GOSUB BOUNDARY
        LOCATE 2, 15: PRINT "SCREEN #20:  LEAK RATE PARAMETERS";
        LOCATE 5, 3: PRINT "1. FOR THE PRESSURE LOSS CALCULATIONS, A FRICTION FACTOR (
)";
        LOCATE 6, 6: PRINT "CORRESPONDING TO FULLY TURBULENT FLUID FLOW THROUGH A TUBE WITH THE";
        LOCATE 7, 6: PRINT "SAME EQUIVALENT HYDRAULIC DIAMETER AS THE CRACK WAS ASSUMED.  2.
THE";
        LOCATE 8, 6: PRINT "TOTAL PRESSURE DROP ACROSS THE CRACK IS        PSIA  (         KPA)";
        LOCATE 9, 6: PRINT "AND IS COMPOSED OF THE FOLLOWING TERMS:";
        LOCATE 10, 8: PRINT "3. ENTRANCE LOSS     =          PSIA   (          KPA)";
        LOCATE 11, 8: PRINT "4. ACCELERATION LOSS =          PSIA   (          KPA)";
        LOCATE 12, 8: PRINT "5. FRICTION LOSS     =          PSIA   (          KPA)";
        LOCATE 13, 8: PRINT "6. AREA CHANGE LOSS  =          PSIA   (          KPA)";
        LOCATE 14, 8: PRINT "7. CRACK PATHWAY LOSS=          PSIA   (          KPA)";
        LOCATE 15, 2: PRINT
"-----------------------------------------------------------------------------";
        LOCATE 16, 6: PRINT "THE FLUID MASS FLUX AT THE EXIT PLANE OF THE CRACK IS:";
```

```
        LOCATE 17, 8: PRINT "8. EXIT PLANE MASS FLUX    =            LBM/FT^2/S  (
KG/M^2/S)";
        LOCATE 18, 6: PRINT "THE LEAKAGE FLOW RATE THROUGH THE CRACK IS:";
        LOCATE 19, 8: PRINT "9. FLUID MASS FLOW RATE    =            LB/SEC (               KG/SEC)";
        LOCATE 20, 7: PRINT "10. FLUID VOLUME FLOW RATE =             GPM    (               L/MIN)";
        LOCATE 5, 62: PRINT USING ".###^^^^"; FF;
        LOCATE 8, 46: PRINT USING "####.#"; PTOT;
        LOCATE 8, 60: PRINT USING "#####.#"; SPTOT;
        LOCATE 10, 33: PRINT USING "###.#"; PE;
        LOCATE 10, 49: PRINT USING "####.#"; SPE;
        LOCATE 11, 33: PRINT USING "###.#"; PA;
        LOCATE 11, 49: PRINT USING "####.#"; SPA;
        LOCATE 12, 33: PRINT USING "###.#"; PF;
        LOCATE 12, 49: PRINT USING "####.#"; SPF;
        LOCATE 13, 33: PRINT USING "###.#"; PAA;
        LOCATE 13, 49: PRINT USING "####.#"; SPAA;
        LOCATE 14, 32: PRINT USING "####.#"; PK;
        LOCATE 14, 48: PRINT USING "#####.#"; SPK;
        LOCATE 17, 36: PRINT USING "#.###^^^^"; GA;
        LOCATE 17, 60: PRINT USING "#.###^^^^"; SGA;
        LOCATE 19, 36: PRINT USING "#.###^^^^"; AMA;
        LOCATE 19, 56: PRINT USING "#.###^^^^"; SAMA;
        LOCATE 20, 36: PRINT USING "#.###^^^^"; AVA;
        LOCATE 20, 56: PRINT USING "#.###^^^^"; SAVA;
        GOSUB WINDOWC
        KEY(11) ON: KEY(1) ON: KEY(2) ON: KEY(3) ON
5385 ON KEY(11) GOSUB 5200: ON KEY(1) GOSUB 5400: ON KEY(2) GOSUB 5500
       ON KEY(3) GOSUB WRITE20
        GOSUB IDLEA: GOTO 5385
REM
5400 GOTO 5
5500 CLS : SYSTEM
REM
BOUNDARY:
        LOCATE 1, 1: FOR I = 1 TO 21: PRINT "|
                     |": NEXT I
        LOCATE 1, 2: PRINT
"-----------------------------------------------------------------------------";
        LOCATE 3, 2: PRINT
"-----------------------------------------------------------------------------";
        LOCATE 21, 2: PRINT
"-----------------------------------------------------------------------------";
        RETURN
REM
WINDOWA:
        LOCATE 22, 5: PRINT "PRESS FUNCTION KEY (F3) TO WRITE THIS OUTPUT TO FILE "; WORK$
        LOCATE 23, 5: PRINT "PRESS NUMERIC KEYPAD DOWN KEY TO VIEW SECOND OUTPUT SCREEN";
        LOCATE 24, 5: PRINT "PRESS PRINT SCREEN (PRTSC) KEY TO OBTAIN A PRINTED COPY OF THIS
SCREEN ";
        LOCATE 25, 5: PRINT "PRESS FUNCTION KEY (F1) TO BEGIN NEW ANALYSIS OR (F2) TO EXIT";
        RETURN
REM
WINDOWB:
        LOCATE 22, 5: PRINT "PRESS FUNCTION KEY (F3) TO WRITE THIS OUTPUT TO FILE "; WORK$
        LOCATE 23, 5: PRINT "PRESS NUMERIC KEYPAD DOWN (UP) KEY TO VIEW NEXT (PREVIOUS) OUTPUT
SCREEN";
        LOCATE 24, 5: PRINT "PRESS PRINT SCREEN (PRTSC) KEY TO OBTAIN A PRINTED COPY OF THIS
SCREEN";
        LOCATE 25, 5: PRINT "PRESS FUNCTION KEY (F1) TO BEGIN NEW ANALYSIS OR (F2) TO EXIT";
        RETURN
REM
WINDOWC:
        LOCATE 22, 5: PRINT "PRESS FUNCTION KEY (F3) TO WRITE THIS OUTPUT TO FILE "; WORK$
        LOCATE 23, 5: PRINT "PRESS NUMERIC KEYPAD UP KEY TO VIEW PREVIOUS OUTPUT SCREEN";
        LOCATE 24, 5: PRINT "PRESS PRINT SCREEN (PRTSC) KEY TO OBTAIN A PRINTED COPY OF THIS
SCREEN ";
        LOCATE 25, 5: PRINT "PRESS FUNCTION KEY (F1) TO BEGIN NEW ANALYSIS OR (F2) TO EXIT";
        RETURN
WRITE18:
REM
REM   APPEND TO OUTPUT FILE WORK$  OR UNIT 8
REM
        PRINT #8, " "
        PRINT #8, TAB(10); "-----------------------------------------------"
        PRINT #8, TAB(10); "THERMAL HYDRAULIC OUTPUT:  CRACK GEOMETRY      "
```

```
        PRINT #8, TAB(10); "-----------------------------------------------"
        PRINT #8, " "
        PRINT #8, " "
        PRINT #8, TAB(2); "  1. THE CRACK IS ASSUMED TO BE HAVE A "
REM      IF TYPE$ = "CORR" THEN
REM         PRINT "STRESS CORROSION";
REM      ELSEIF TYPE$ ="FATI" THEN
REM         PRINT "FATIGUE";
REM      END IF
REM      PRINT " GENERATED CRACK WITH A";
        IF SHAPE$ = "DIAM" THEN
       PRINT #8, TAB(2); "     DIAMOND SHAPE";
        ELSEIF SHAPE$ = "RECT" THEN
       PRINT #8, TAB(2); "     RECTANGULAR SHAPE";
        ELSEIF SHAPE$ = "ELLI" THEN
       PRINT #8, TAB(2); "     ELLIPTICAL SHAPE";
        END IF
        PRINT #8, " AND A SURFACE ROUGHNESS OF ";
        PRINT #8, USING ".###^^^^"; EROUGH;
        PRINT #8, " IN. ( ";
        PRINT #8, USING ".###^^^^"; SROUGH;
        PRINT #8, " MM)"
        PRINT #8, TAB(2); "     THE CRACK GEOMETRY IS DESCRIBED BELOW:"
        PRINT #8, " "
        PRINT #8, TAB(8); "2. CRACK DEPTH             = ";
        PRINT #8, USING "##.###"; EWALL;
        PRINT #8, " INCHES  ( ";
        PRINT #8, USING "####.#"; SWALL;
        PRINT #8, " MM)"
        PRINT #8, TAB(8); "3. LENGTH OF CRACK         = ";
        PRINT #8, USING "##.###"; EAL;
        PRINT #8, " INCHES  ( ";
        PRINT #8, USING "###.##"; SAL;
        PRINT #8, " MM)"
        PRINT #8, TAB(8); "4. EXTERIOR CRACK GAP      = ";
        PRINT #8, USING ".###^^^^"; EEGAP;
        PRINT #8, " INCHES  ( ";
        PRINT #8, USING ".###^^^^"; SEGAP;
        PRINT #8, " MM)"
        PRINT #8, TAB(8); "5. INTERIOR CRACK GAP      = ";
        PRINT #8, USING ".###^^^^"; EIGAP;
        PRINT #8, " INCHES  ( ";
        PRINT #8, USING ".###^^^^"; SIGAP;
        PRINT #8, " MM)"
        PRINT #8, TAB(8); "6. CRACK OPENING ANGLE     = ";
        PRINT #8, USING "##.##"; PHI;
        PRINT #8, " DEGREES "
        PRINT #8, TAB(8); , "7. EXTERIOR AREA OF";
        PRINT #8, TAB(8); "     CRACK OPENING         = ";
        PRINT #8, USING ".###^^^^"; EAREA;
        PRINT #8, " IN.^2   ( ";
        PRINT #8, USING ".###^^^^"; SAREA;
        PRINT #8, " MM^2)"
        PRINT #8, TAB(8); "8. CRACK WETTED PERIMETER = ";
        PRINT #8, USING "##.###"; EPER;
        PRINT #8, " INCHES  ( ";
        PRINT #8, USING "###.##"; SPER;
        PRINT #8, " MM)"
        PRINT #8, TAB(8); "9. CRACK HYDRAULIC DIAM.  = ";
        PRINT #8, USING "##.###"; EDH;
        PRINT #8, " INCHES  ( ";
        PRINT #8, USING "###.##"; SDH;
        PRINT #8, " MM)"
        PRINT #8, TAB(7); "10. RATIOS: CRACK DEPTH TO:"
        PRINT #8, TAB(8); "   HYDRAULIC DIAMETER     = ";
        PRINT #8, USING "###.#"; ALD;
        PRINT #8, " TO ROUGHNESS       = ";
        PRINT #8, USING "###.##"; EDH / EROUGH
        PRINT #8, TAB(7); "11. PATH LOSS COEFFICIENT  = ";
        PRINT #8, USING "####.#"; EVLOSS;
        PRINT #8, " VELOCITY HEADS"
        PRINT #8, " "
        RETURN
WRITE19:
        PRINT #8, " "
```

```
        PRINT #8, TAB(10); "----------------------------------------------------------"
        PRINT #8, TAB(10); "THERMAL HYDRAULIC OUTPUT:  FLUID THERMODYNAMIC CONDITIONS"
        PRINT #8, TAB(10); "----------------------------------------------------------"
        PRINT #8, " "
        PRINT #8, " "
        PRINT #8, TAB(2); "1. THE FLUID ENTERING THE CRACK IS ";
        IF STATE$ = "SUBC" THEN
       PRESS = PO: NUM = 25: CALL STEAMSUB: TTOS = TSAT:  TSUB = TTOS - TTO: STSUB = TSUB / 1.8
       PRINT #8, "SUBCOOLED BY ";
       PRINT #8, USING "###.#"; TSUB;
       PRINT #8, " DEG F ( ";
       PRINT #8, USING "###.#"; STSUB;
       PRINT #8, " DEG C)"
       PRINT #8, " "
        ELSE
       PRINT #8, "SATURATED AT:"
        END IF
        PRINT #8, TAB(8); "2. STAGNATION FLUID PRESSURE    = ";
        PRINT #8, USING "####.#"; PO;
        PRINT #8, " PSIA  ( ";
        PRINT #8, USING "#####.#"; SPO;
        PRINT #8, " KPA)"
        PRINT #8, TAB(8); "3. SATURATION PRESSURE          = ";
        PRINT #8, USING "####.#"; PSAT;
        PRINT #8, " PSIA  ( ";
        PRINT #8, USING "#####.#"; SPSAT;
        PRINT #8, " KPA)"
        PRINT #8, TAB(8); "4. STAGNATION FLUID TEMPERATURE = ";
        PRINT #8, USING "###.#"; TTO;
        PRINT #8, " DEG F ( ";
        PRINT #8, USING "###.#"; STTO;
        PRINT #8, " DEG C)"
        PRINT #8, TAB(8); "5. STAGNATION FLUID ENTHALPY    = ";
        PRINT #8, USING "####.#"; HLO;
        PRINT #8, " BTU/LB ( ";
        PRINT #8, USING "####.#"; SHLO;
        PRINT #8, " KJ/KG)"
        PRINT #8, TAB(8); "6. STAGNATION FLUID ENTROPY     = ";
        PRINT #8, USING "#.####"; SLO;
        PRINT #8, " BTU/LB/F( ";
        PRINT #8, USING "#.####"; SSLO;
        PRINT #8, " KJ/KG/C)"
        PRINT #8, " "
        PRINT #8, TAB(3); "AT THE EXIT PLANE OF THE CRACK, THE FLUID PROPERTIES ARE:"
        PRINT #8, TAB(8); "7. EXIT PLANE FLUID PRESSURE    = ";
        PRINT #8, USING "####.#"; P2;
        PRINT #8, " PSIA  ( ";
        PRINT #8, USING "#####.#"; SP2;
        PRINT #8, " KPA)"
        PRINT #8, TAB(8); "8. EXIT PLANE FLUID TEMPERATURE = ";
        PRINT #8, USING "###.#"; T2;
        PRINT #8, " DEG F ( ";
        PRINT #8, USING "####.#"; ST2;
        PRINT #8, " DEG C)"
        PRINT #8, TAB(8); "9. EXIT PLANE FLUID QUALITY     = ";
        PRINT #8, USING "###.##"; XEHC * 100!;
        PRINT #8, " PERCENT "
        PRINT #8, " "
        PRINT #8, TAB(3); "AFTER EXPANSION TO THE OUTSIDE PRESSURE, THE FLUID PROPERTIES ARE:"
        PRINT #8, TAB(7); "10. OUTSIDE FLUID PRESSURE       = ";
        PRINT #8, USING "####.#"; PB;
        PRINT #8, " PSIA  ( ";
        PRINT #8, USING "#####.#"; SPB;
        PRINT #8, " KPA)"
        PRINT #8, TAB(7); "11. OUTSIDE FLUID TEMPERATURE    = ";
        PRINT #8, USING "###.#"; TB;
        PRINT #8, " DEG F ( ";
        PRINT #8, USING "###.#"; STB;
        PRINT #8, " DEG C)"
        PRINT #8, TAB(7); "12. OUTSIDE FLUID QUALITY        = ";
        PRINT #8, USING "###.##"; XEHB * 100!;
        PRINT #8, " PERCENT "
        PRINT #8, " "
        RETURN
WRITE20:
```

```
        PRINT #8, " "
        PRINT #8, TAB(10); "-----------------------------------------------"
        PRINT #8, TAB(10); "THERMAL HYDRAULIC OUTPUT:  LEAK RATE PARAMETERS"
        PRINT #8, TAB(10); "-----------------------------------------------"
        PRINT #8, " "
        PRINT #8, " "
        PRINT #8, TAB(3); "1. FOR THE PRESSURE LOSS CALCULATIONS, A FRICTION FACTOR ( ";
        PRINT #8, USING ".###^^^^"; FF;
        PRINT #8, " )"
        PRINT #8, TAB(6); "CORRESPONDING TO FULLY TURBULENT FLUID FLOW THROUGH A TUBE WITH THE"
        PRINT #8, TAB(6); "SAME EQUIVALENT HYDRAULIC DIAMETER AS THE CRACK WAS ASSUMED.  2. THE"
        PRINT #8, TAB(6); "TOTAL PRESSURE DROP ACROSS THE CRACK IS "
        PRINT #8, USING "####.#"; PTOT;
        PRINT #8, " PSIA  ( ";
        PRINT #8, USING "#####.#"; SPTOT;
        PRINT #8, " KPA)"
        PRINT #8, TAB(6); "AND IS COMPOSED OF THE FOLLOWING TERMS:"
        PRINT #8, TAB(8); "3. ENTRANCE LOSS     = ";
        PRINT #8, USING "###.#"; PE;
        PRINT #8, " PSIA  ( ";
        PRINT #8, USING "####.#"; SPE;
        PRINT #8, " KPA)"
        PRINT #8, TAB(8); "4. ACCELERATION LOSS = ";
        PRINT #8, USING "###.#"; PA;
        PRINT #8, " PSIA  ( ";
        PRINT #8, USING "####.#"; SPA;
        PRINT #8, " KPA)"
        PRINT #8, TAB(8); "5. FRICTION LOSS     = ";
        PRINT #8, USING "###.#"; PF;
        PRINT #8, " PSIA  ( ";
        PRINT #8, USING "####.#"; SPF;
        PRINT #8, " KPA)"
        PRINT #8, TAB(8); "6. AREA CHANGE LOSS  = ";
        PRINT #8, USING "###.#"; PAA;
        PRINT #8, " PSIA  ( ";
        PRINT #8, USING "####.#"; SPAA;
        PRINT #8, " KPA)"
        PRINT #8, TAB(8); "7. CRACK PATHWAY LOSS= ";
        PRINT #8, USING "####.#"; PK;
        PRINT #8, " PSIA  ( ";
        PRINT #8, USING "#####.#"; SPK;
        PRINT #8, " KPA)"
        PRINT #8, TAB(2);
"-----------------------------------------------------------------------------"
        PRINT #8, TAB(6); "THE FLUID MASS FLUX AT THE EXIT PLANE OF THE CRACK IS:"
        PRINT #8, TAB(8); "8. EXIT PLANE MASS FLUX    = ";
        PRINT #8, USING "#.###^^^^"; GA;
        PRINT #8, " LBM/FT^2/S  ( ";
        PRINT #8, USING "#.###^^^^"; SGA;
        PRINT #8, " KG/M^2/S)"
        PRINT #8, TAB(6); "THE LEAKAGE FLOW RATE THROUGH THE CRACK IS:"
        PRINT #8, TAB(8); "9. FLUID MASS FLOW RATE    = ";
        PRINT #8, USING "#.###^^^^"; AMA;
        PRINT #8, " LB/SEC ( ";
        PRINT #8, USING "#.###^^^^"; SAMA;
        PRINT #8, " KG/SEC)"
        PRINT #8, TAB(7); "10. FLUID VOLUME FLOW RATE = ";
        PRINT #8, USING "#.###^^^^"; AVA;
        PRINT #8, " GPM    ( ";
        PRINT #8, USING "#.###^^^^"; SAVA;
        PRINT #8, " L/MIN)"
        RETURN
REM
REM   MODIFY NRCPIPE INPUT TO REFLECT CHANGE IN CRACK LENGTH
REM
MODIFY:
       OPEN "INTFACE.NDG" FOR OUTPUT AS #3
       WRITE #3, KITER, JFLAG1, JFLAG2
       FOR I = 1 TO 20
       WRITE #3, CRK(I), CFLOW(I), CRITER(I)
       NEXT I
       CLOSE #3
       OPEN "INTFACE.DAT" FOR OUTPUT AS #3
       WRITE #3, WORK$, GWORK$
       WRITE #3, NUNIT
```

```
        WRITE #3, NLODE
        WRITE #3, NTASK
        WRITE #3, NSIZE
        WRITE #3, NBEND
        IF (NUNIT = 3) THEN
        ZAL = ZAL / 1000
        END IF
        TWOA = ZAL
        AC = TWOA / 2
        CA = TWOA / 2
        WRITE #3, DIA, THICK, ARMLENGTH, TWOL, TWOS, TWOA, RADIUS, AC, CA
        WRITE #3, NFUNIT, PFLOW, AFLOW, SIGTEN
        WRITE #3, GROUGH, LROUGH, GLFACT, LLFACT, N90TURN
        WRITE #3, APRESS, ATEMP, EXTPRESS, DCOEFF
        WRITE #3, YIELD, UTS, SCOLL, SOX, EO, ALPHA, ANNN, E
        WRITE #3, JR$, GFIL$
        CLOSE #3
        RETURN
DEFALT:
         RETURN
```

LISTING OF STEAM.BAS

```
DECLARE SUB STEAMSUB ()
COMMON SHARED NUM
COMMON SHARED US$
COMMON SHARED PRESS, TEMP, VF, VG, SF, SG, HF, HG, H, TSAT, PSAT, T
COMMON SHARED ENTH, ENTR, UF, UG, S, V, U
COMMON SHARED PO, TTO, ALD, FF, AR, ISTATE, CD, DH, THETA
COMMON SHARED PTOT, SPTOT, PE, SPE, PA, SPA, PF, SPF, PAA, SPAA, PK, SPK, GA, SGA, AMA, SAMA,
AVA, SAVA
60240 DATA
10,650,696.4,660,714.9,690,784.5,696,804.4,698,812.6,700,822.4,702,835.0,704,854.2,705,873.0,705.
47,906
60330 DATA
11,2400,719.0,2500,731.7,2700,757.3,2900,785.1,3000,801.8,3100,824.0,3150,840.5,3180,856.0,3190,8
63.9,3200,875.5,3208.2,906.0
60440 DATA
12,548,1191.9,560,1187.7,600,1167.7,640,1133.7,680,1068.5,684,1058.4,692,1033.6,700,995.2,702,979
.7,704,956.2,705,934.4,705.47,906.0
60570 DATA
14,800,1199.4,850,1198.0,1100,1189.1,1500,1170.1,1800,1152.3,2300,1113.2,2600,1082.0,2800,1055.8,
3000,1020.3,3100,993.3,3160,967.5,3180,954.1,3200,931.6,3208.2,906
61320 DATA
11,580,1326.2,600,1543.2,630,1919.5,660,2365.7,680,2708.6,690,2895.7,696,3013.4,700,3094.3,702,31
35.5,704,3177.2,705.47,3208.2
61490 DATA
12,2600,.9247,2700,.9356,2800,.9468,2900,.9588,3000,.9728,3100,.9914,3130,.9990,3150,1.0053,3180,
1.0185,3190,1.0251,3200,1.0351,3208.2,1.0612
61600 DATA
13,400,1.5274,450,1.4797,500,1.4333,550,1.3856,600,1.3330,650,1.2667,676,1.2179,690,1.1810,695,1.
1632,700,1.1359,702,1.1252,704,1.1046,705.47,1.0612
61620 DATA
14,32,2.1873,33,2.1837,35,2.1767,40,2.1594,50,2.1262,70,2.0645,90,2.0086,110,1.9577,150,1.8686,20
0,1.7764,250,1.7000,300,1.6351,350,1.5784,400,1.5274
61680 DATA
14,.08865,2.1872,.2,2.1160,.3,2.0809,.5,2.0370,1.0,1.9781,3.0,1.8864,5,1.8443,10,1.7879,15,1.7552
,25,1.7141,50,1.6586,100,1.6027,200,1.5454,400,1.4847
61700 DATA
13,1380,1.3494,1500,1.3373,1800,1.3079,2200,1.2676,2500,1.2345,2800,1.1958,2900,1.1803,3000,1.161
9,3100,1.1373,3160,1.1145,3190,1.0947,3200,1.0832,3208.2,1.0612
62080 DATA
7,2400,662.11,2600,673.91,2800,684.96,3000,695.33,3100,700.28,3160,703.18,3208.2,705.47
62420 DATA 6,32,.016022,35,.016020,40,.016019,50,.016023,75,.016060,100,.016130
62440 DATA
13,600,.02364,630,.02526,660,.02768,680,.03037,686,.03157,690,.03256,695,.03415,697,.03498,700,.0
3697,702,.03824,704,.04108,705,.04427,705.47,.05078
62520 DATA
14,1600,.02387,1700,.02428,2000,.02565,2300,.02727,2600,.02938,2780,.03112,2900,.03262,3000,.0342
8,3100,.03681,3140,.03847,3160,.03965,3180,.04137,3200,.04472,3208.2,.05078
63230 DATA
16,460,.99424,500,.67492,540,.46513,580,.32216,620,.22081,640,.18021,660,.14431,672,.12424,680,.1
1117,688,.09799,696,.08371,700,.07519,702,.06997,704,.06300,705,.05730,705.47,.05078
63250 DATA
16,70,868.4,80,633.3,90,468.1,100,350.4,120,203.26,140,123.00,160,77.29,180,50.22,200,33.639,240,
16.321,280,8.6446,320,4.9138,360,2.9573,400,1.8630,440,1.21687,460,.99424
63270 DATA
14,1300,.32991,1500,.27719,1750,.22713,2000,.18831,2500,.13068,2700,.11194,2800,.10305,2900,.0942
0,3000,.08500,3100,.07452,3150,.06785,3180,.06240,3200,.05663,3208.2,.05078
63290 DATA
19,.08865,3302.4,.1,2945.5,.15,2004.7,.2,1526.3,.25,1235.5,.3,1039.7,.35,898.6,.4,792.1,.5,641.5,
.6,540.1,.7,466.94,.8,411.69,.9,368.43,1.0,333.60,1.2,280.96,1.4,243.02,1.6,214.33,1.8,191.85,2.0
,173.76
63310 DATA
15,2.0,173.76,2.2,158.87,3.2,111.75,4.2,86.59,5.5,67.249,10,38.420,14.696,26.799,15,26.290,20,20.
087,30,13.7436,40,10.4965,50,8.514,60,7.1736,80,5.4711,100,4.4310
63330 DATA
13,100,4.4310,125,3.5857,150,3.0139,200,2.2873,250,1.84317,300,1.54274,400,1.16095,500,.92762,600
,.76975,700,.65556,900,.50091,1100,.40058,1300,.32991

SUB STEAMSUB
60000 REM Software Systems Corporation Steam Properties Subroutine
60010 REM Copyright (C) 1984 Software Systems Corporation.  All rights reserved.Reproduction or
translation of any part of this work beyond that permitted by Section 117 of the 1976 UNITED
STATES COPYRIGHT ACT without permission of Software
60020 REM Systems Corporation is unlawful.  Request for permission or further   information
should be addressed to Software Systems Corporation.
```

```
60025 REM Publication of STEAMSUB is by permission of John Wiley & Sons,        Publishers,
exclusive licensee for publication of the STEAMCALC program.
60030 Z89 = Z89 + 1
60040 IF Z89 = 1 THEN 60050 ELSE 60055
60050 DIM Z84(20), Z92(20), Z27(20), Z6(20), Z10(20), Z58(20), Z40(20)
60055 IF US$ = "SI" OR US$ = "si" THEN GOSUB 65100
60060 ON NUM GOSUB 60200, 60290, 61390, 61450, 62370, 62480, 64150, 64220, 60400, 60530, 61550,
61630, 63020, 63130, 64280, 64350, 64470, 64530, 64590, 64650, 64710, 64770, 64830, 64890, 62030,
61280, 60610, 61850, 62590, 64410, 62130, 60080, 64950 _
, 62820, 60790
60065 IF US$ = "SI" OR US$ = "si" THEN GOSUB 65160
60070 EXIT SUB
60080 REM ENTHALPY OF A SUBCOOLED LIQUID AS A FUNCTION OF TEMPERATURE AND PRESS
60090 Z67 = TEMP: Z51 = PRESS
60100 Z66 = Z67
60110 IF Z93 = 1 THEN Z66 = Z67 - 459.69
60120 Z69 = Z66 ^ 3
60130 Z70 = Z66 * Z69
60140 Z8 = .75623 + (-.01446 + 9.850371E-05 * Z66) * Z66 + (-2.8685E-07 + 2.87767E-10 * Z66) *
Z69
60150 Z2 = 3.14899E-03 + (-4.867E-06 - 2.1607E-09 * Z66) * Z66 + (4.07626E-11 - 9.304119E-14 *
Z66) * Z69
60160 Z3 = -3.1788E-08 + (2.80539E-11 + 1.75513E-12 * Z66) * Z66 + (-7.4798E-15 + 9.90718E-18 *
Z66) * Z69
60170 HF = -32.46 + (1.02493 + (-4.1498E-04 + 3.07768E-06 * Z66) * Z66) * Z66 + (-1.2602E-08 +
(3.06581E-11 - 3.834E-14 * Z66) * Z66) * Z70 + 1.9907E-17 * Z69 * Z70
60180 H = Z8 + (Z2 + Z3 * Z51) * Z51 + HF
60190 RETURN
60200 REM ENTHALPY OF SATURATED WATER AS A FUNCTION OF TEMPERATURE
60210 Z67 = TEMP
60220 IF Z67 > 650 THEN RESTORE 60240: Z61 = Z67: GOSUB 63370: HF = Z53: RETURN
60230 REM***DATA FOR ENTHALPY OF SATURATED WATER (T)  FOR 650<T<705***
60250 Z66 = Z67
60260 Z70 = Z66 ^ 4
60270 HF = -32.46 + (1.02493 + (-4.1498E-04 + 3.07768E-06 * Z66) * Z66) * Z66 + (-1.2602E-08 +
(3.06581E-11 - 3.834E-14 * Z66) * Z66) * Z70 + 1.9907E-17 * Z66 * Z66 * Z66 * Z70
60280 RETURN
60290 REM ENTHALPY OF SATURATED WATER AS A FUNCTION OF PRESSURE
60300 Z51 = PRESS
60310 IF Z51 > 2390 THEN RESTORE 60330: Z61 = Z51: GOSUB 63370: HF = Z53: RETURN
60320 REM***DATA FOR ENTHALPY OF SAT LIQUID (P)  FOR 2400<P<3208***
60340 Z86 = .4342944 * LOG(Z51)
60350 Z87 = Z86 ^ 4
60360 Z66 = 101.74419# + (77.052576# + (11.951549# + 2.0556205# * Z86) * Z86) * Z86 + (.42075 +
(-6.841091E-02 + .0625368 * Z86) * Z86) * Z87 - 6.59481E-03 * Z86 * Z86 * Z86 * Z87
60370 Z70 = Z66 ^ 4
60380 HF = -32.4599 + (1.02493 + (-4.1498E-04 + 3.0777E-06 * Z66) * Z66) * Z66 + (-1.26029E-08 +
(3.06581E-11 - 3.834E-14 * Z66) * Z66) * Z70 + 1.9907E-17 * Z66 * Z66 * Z66 * Z70
60390 RETURN
60400 REM ENTHALPY OF SAT. STEAM AS A FUNCTION OF TEMPERATURE
60410 Z67 = TEMP
60420 IF Z67 > 550 THEN RESTORE 60440: Z61 = Z67: GOSUB 63370: HG = Z53: RETURN
60430 REM***DATA FOR ENTHALPY OF SAT VAPOR (T) FOR 550<T<705***
60450 Z66 = Z67
60460 Z79 = (Z66 - 32) / 1.8 + 273.16
60470 Z86 = 647.27 - Z79
60480 Z90 = Z86 * (3.2438 + (.0058683 + 1.17024E-08 * Z86 * Z86) * Z86) / (Z79 * (1 + 2.18785E-03
* Z86))
60490 Z51 = 14.696 * 218.167 / (10 ^ Z90)
60500 Z86 = LOG(Z51) / LOG(10)
60510 HG = 1105.9387# + (32.7568 + (4.619847 + (.2067299 + (-.5411693 + (.4924136 - .1788488 *
Z86) * Z86) * Z86) * Z86) * Z86) * Z86
60520 RETURN
60530 REM ENTHALPY OF SATURATED STEAM AS A FUNCTION OF PRESSURE
60540 Z51 = PRESS
60550 IF Z51 > 750 THEN RESTORE 60570: Z61 = Z51: GOSUB 63370: HG = Z53: RETURN
60560 REM***DATA FOR ENTHALPY OF SAT VAPOR (P) FOR 750<P<3208***
60580 Z86 = LOG(Z51) / LOG(10)
60590 HG = 1105.9387# + (32.7568 + (4.619847 + (.2067299 + (-.5411693 + (.4924136 - .1788488 *
Z86) * Z86) * Z86) * Z86) * Z86) * Z86
60600 RETURN
60610 REM ENTHALPY OF SUPERHEATED STEAM AS A FUNCTION OF TEMERATURE AND PRESSURE
60620 Z67 = TEMP: Z52 = PRESS
60630 Z66 = 255.38 + Z67 / 1.8
60640 IF Z88 = 1 THEN Z66 = 255.38 + (Z67 - 459.69) / 1.8
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60650 IF Z66 <= 0 THEN Z66 = 9.999999E-06
60660 Z51 = Z52 / 14.6959
60670 Z12 = (2641.62 * 10 ^ (80870! / (Z66 * Z66))) / Z66
60680 Z11 = 1.89 - Z12: Z13 = 82.54601
60690 Z14 = 162460! / Z66: Z15 = .21828 * Z66
60700 Z16 = 126970! / Z66
60710 Z39 = 1.89 - Z12 * (372420! / (Z66 * Z66) + 2)
60720 Z17 = Z11 * Z14 - 2 * Z39 * (Z13 - Z14)
60730 Z18 = 2 * Z39 * (Z15 - Z16) - Z11 * Z16
60740 Z19 = .4342944 * LOG(Z66)
60750 Z38 = 775.596 + (.63296 + .0001624 * Z66) * Z66 + 47.3635 * Z19
60760 Z20 = Z11 * Z51 * Z51 / (2 * Z66 * Z66)
60770 H = Z38 + .043577 * (Z39 * Z51 + Z20 * (Z11 * (Z13 - Z14 + 2 * Z18 * Z20) - Z17))
60780 RETURN
60790 REM ENTHALPY OF WET OR SUPERHEATED STEAM AS A FUNCTION OF PRESSURE AND ENTROPY
60800 Z51 = PRESS: Z63 = ENTR
60810 Z28 = 0: Z85 = 0: Z36 = 0: Z60 = Z51
60820 IF Z51 > 3000 AND Z63 < 1.23 AND Z63 > .94 THEN Z36 = 1: GOSUB 63720: RETURN
60830 IF Z51 > 3000 AND Z63 < .94 THEN 60880
60840 IF Z51 > 3000 AND Z63 > 1.23 THEN 60910
60850 GOSUB 61450: REM ENTROPY OF SAT LIQUID (P)
60860 GOSUB 61630: REM ENTROPY OF SAT VAPOR (P)
60870 IF Z63 < SF THEN 60880 ELSE 60900
60880 Z28 = 1: REM SUBCOOLED LIQUID
60890 GOTO 60910
60900 IF Z63 < SG THEN Z85 = 1: GOTO 61160: REM UNDER DOME  FIND QUALITY
60910 Z32 = 200: Z29 = 1
60915 Z51 = Z60: GOSUB 62030
60920 Z37 = (Z63 + .06855 * LOG(Z60 / .08865)) / 2.5
60930 Z76 = (491.688 * EXP(Z37)) - 459.67
60940 Z81 = Z76 - Z32
60950 Z82 = Z76 + Z32
60951 IF Z28 = 1 THEN 60960
60952 IF Z60 > 55 AND Z60 < 130 THEN IF Z81 < TSAT THEN Z81 = TSAT
60954 IF Z60 > 55 AND Z60 < 130 THEN IF Z76 < TSAT THEN Z76 = TSAT + .5
60960 IF Z81 < 32 THEN Z81 = 32.018
60970 IF Z28 = 1 THEN 60980 ELSE 61020
60980 TEMP = Z76: GOSUB 61390: SG = SF
60990 TEMP = Z81: GOSUB 61390: Z64 = SF
61000 TEMP = Z82: GOSUB 61390: Z65 = SF
61010 GOTO 61050
61020 TEMP = Z76: Z52 = Z60: GOSUB 61850: SG = S
61030 TEMP = Z81: Z52 = Z60: GOSUB 61850: Z64 = S
61040 TEMP = Z82: Z52 = Z60: GOSUB 61850: Z65 = S
61050 IF ABS(Z63 - SG) < 3.000001E-04 THEN 61200
61060 IF ABS(Z65 - Z64) < 9.999999E-10 THEN 61200
61070 Z66 = ((Z63 - Z64) * (Z82 - Z81)) / (Z65 - Z64) + Z81
61080 IF Z66 < 32 THEN Z66 = 32.018
61090 Z29 = Z29 + 1
61100 IF Z29 > 15 THEN 61110 ELSE 61130
61110 LOCATE 13, 1: PRINT "RESULTS:"
61120 LOCATE 15, 1: PRINT "This function did not converge.  Check inputs of PRESS and ENTR.":
STOP: RETURN
61130 Z32 = ABS(Z66 - Z76)
61140 Z76 = Z66
61150 GOTO 60940
61160 Z54 = (Z63 - SF) / (SG - SF)
61170 GOSUB 60290: REM ENTHALPY SAT LIQUID (P)
61180 GOSUB 60530: REM ENTHALPY SAT VAPOR (P)
61190 H = HF + Z54 * (HG - HF): RETURN
61200 IF Z28 = 1 THEN 61210 ELSE 61260
61210 TEMP = Z76: GOSUB 60200: REM ENTHALPY SAT LIQUID (T)
61220 GOSUB 62370: REM SPEC VOL SAT LIQUID (T)
61230 GOSUB 61280: REM SATURATION PRESSURE (T)
61240 H = HF + VF * (Z60 - PSAT) * 144 / 778.17
61250 RETURN
61260 TEMP = Z76: PRESS = Z60: GOSUB 60610: REM ENTHALPY SUPERHEATED STEAM (T,P)
61270 RETURN
61280 REM SATURATION PRESSURE AS A FUNCTION OF TEMPERATURE
61290 Z67 = TEMP
61300 IF Z67 > 580 THEN RESTORE 61320: Z61 = Z67: GOSUB 63370: PSAT = Z53: RETURN
61310 REM***DATA FOR SAT PRESSURE (T) FOR 580<T<705***
61330 Z66 = Z67
61340 Z79 = (Z66 - 32) / 1.8 + 273.16
61350 Z86 = 647.27 - Z79
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61360 Z90 = Z86 * (3.2438 + (.0058683 + 1.17024E-08 * Z86 * Z86) * Z86) / (Z79 * (1 + 2.18785E-03
* Z86))
61370 PSAT = 14.696 * 218.167 / (10 ^ Z90)
61380 RETURN
61390 REM ENTROPY OF SATURATED WATER AS A FUNCTION OF TEMPERATURE
61400 Z67 = TEMP
61410 Z66 = Z67
61420 Z74 = (Z66 - 360) / 3100
61425 DUM1 = (12035.9 + 123466! * Z74)
61430 SF = .5157751 + (3.96796 - (4.59799 - (34.2517 - (60.7233 + (367.036 - DUM1 * Z74) * Z74) *
Z74) * Z74) * Z74) * Z74
61440 RETURN
61450 REM ENTROPY OF SATURATED WATER AS A FUNCTION OF PRESSURE
61460 Z51 = PRESS
61470 IF Z51 > 2600 THEN RESTORE 61490: Z61 = Z51: GOSUB 63370: SF = Z53: RETURN
61480 REM***DATA FOR ENTROPY OF SAT LIQUID (P)  FOR 2600<P<3208***
61500 Z91 = 1
61510 GOSUB 62060
61520 Z74 = (TSAT - 360) / 3100
61525 DUM1 = (12035.9 + 123466! * Z74)
61530 SF = .5157751 + (3.96796 - (4.59799 - (34.2517 - (60.7233 + (367.036 - DUM1 * Z74) * Z74) *
Z74) * Z74) * Z74) * Z74
61540 RETURN
61550 REM ENTROPY OF SATURATED STEAM AS A FUNCTION OF TEMPERATURE
61560 Z67 = TEMP
61570 IF Z67 > 400 THEN RESTORE 61600: Z61 = Z67: GOSUB 63370: SG = Z53: RETURN
61580 RESTORE 61620: Z61 = Z67: GOSUB 63370: SG = Z53: RETURN
61590 REM***DATA FOR ENTROPY OF SAT VAPOR (T) FOR 400<T<705***
61610 REM***DATA FOR ENTROPY OF SAT VAPOR (T) FOR 32<T<400***
61630 REM ENTROPY OF SATURATED STEAM AS A FUNCTION OF PRESSURE
61640 Z51 = PRESS
61650 IF Z51 > 1390 THEN RESTORE 61700: Z61 = Z51: GOSUB 63370: SG = Z53: RETURN
61660 IF Z51 < 400 THEN RESTORE 61680: Z61 = Z51: GOSUB 63370: SG = Z53: RETURN
61670 REM***DATA FOR ENTROPY OF SAT VAPOR (P)  FOR 0<P<400***
61690 REM***DATA FOR ENTROPY OF SAT VAPOR (P)  FOR 1400<P<3208***
61710 IF Z51 - 100 <= 0 GOTO 61790
61720 IF Z51 - 275 <= 0 GOTO 61830
61730 IF Z51 - 1300 <= 0 GOTO 61770
61740 IF Z51 - 1600 <= 0 GOTO 61830
61750 IF Z51 - 2200 <= 0 GOTO 61810
61760 SG = 5.66316 / (Z51 ^ .19494): GOTO 61840
61770 SG = 1.624697 - 5.093142E-04 * Z51 + 5.123686E-07 * Z51 ^ 2 - 3.113782E-10 * Z51 ^ 3 +
7.470601E-14 * Z51 ^ 4
61780 GOTO 61840
61790 SG = 1.98473 / (Z51 ^ .04589)
61800 GOTO 61840
61810 SG = 1.464191 - 7.538431E-05 * Z51 - 6.347988E-09 * Z51 ^ 2
61820 GOTO 61840
61830 SG = 2.2411 / (Z51 ^ .07007)
61840 RETURN
61850 REM ENTROPY OF SUPERHEATED STEAM-T,P
61860 Z67 = TEMP: Z52 = PRESS
61870 Z66 = 255.38 + Z67 / 1.8
61880 Z51 = Z52 / 14.696
61890 Z12 = (2641.62 * 10 ^ (80870! / (Z66 * Z66))) / Z66
61900 Z11 = 1.89 - Z12
61910 Z13 = 82.54601
61920 Z14 = 162460! / Z66
61930 Z15 = .21828 * Z66
61940 Z16 = 126970! / Z66
61950 Z39 = 1.89 - Z12 * (372420! / (Z66 * Z66) + 2)
61960 Z17 = Z11 * Z14 - 2 * Z39 * (Z13 - Z14)
61970 Z18 = 2 * Z39 * (Z15 - Z16) - Z11 * Z16
61980 Z19 = .4342944 * LOG(Z66)
61990 Z20 = Z11 * Z51 * Z51 / (2 * Z66 * Z66)
62000 Z21 = ((Z11 - Z39) * Z51 + Z20 * (Z17 + Z20 * Z11 * (Z11 * (Z15 - Z16) - 2 * Z18))) / Z66
62010 S = .809691 * Z19 - .253801 * .4342944 * LOG(Z51) + .0001805 * Z66 - 11.4267 / Z66 -
.355579 - .0241983 * Z21
62020 RETURN
62030 REM SATURATION TEMPERATURE AS A FUNCTION OF PRESSURE
62040 Z51 = PRESS
62050 Z91 = 0
62060 IF Z51 > 2400 THEN RESTORE 62080: Z61 = Z51: GOSUB 63370: TSAT = Z53: RETURN
62070 REM***DATA FOR SATURATION TEMPERATURE (P) FOR 2400<P<3208***
62090 Z86 = .4342944 * LOG(Z51)
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62100 Z87 = Z86 ^ 4
62110 TSAT = 101.74419# + (77.052576# + (11.951549# + 2.0556205# * Z86) * Z86) * Z86 + (.42075 +
(-6.841091E-02 + .0625368 * Z86) * Z86) * Z87 - 6.59481E-03 * Z86 * Z86 * Z86 * Z87
62120 RETURN
62130 REM TEMPERATURE OF SUPERHEATED STEAM-H,P
62140 Z52 = PRESS: Z43 = ENTH
62150 Z50 = 0: Z36 = 0
62160 Z35 = .01
62170 Z32 = 2
62180 Z86 = 1.68 * Z43 - 1110
62190 Z67 = Z86
62200 Z88 = 1
62210 GOSUB 60630
62220 Z41 = H
62230 FOR Z44 = 1 TO 10
62240 Z75 = Z86 + Z32
62250 Z67 = Z75
62260 GOSUB 60630
62270 Z86 = Z86 + Z32 * (Z43 - Z41) / (H - Z41)
62280 Z67 = Z86
62290 GOSUB 60630
62300 Z41 = H
62310 IF ABS(Z43 - Z41) - Z35 <= 0 GOTO 62350
62320 NEXT Z44
62330 LOCATE 13, 1: PRINT "RESULTS:"
62340 LOCATE 15, 5: PRINT "This function did not converge.  Check inputs of PRESS and ENTH": Z50
= 1: STOP: GOTO 62355
62350 T = Z86 - 459.69
62355 Z88 = 0
62360 RETURN
62370 REM SPEC. VOL. OF SAT. WATER AS A FUNCTION OF TEMPERATURE
62380 Z67 = TEMP
62390 IF Z67 < 100 THEN RESTORE 62420: Z61 = Z67: GOSUB 63370: VF = Z53: RETURN
62400 IF Z67 > 600 THEN RESTORE 62440: Z61 = Z67: GOSUB 63370: VF = Z53: RETURN
62410 REM ***DATA FOR SPECIFIC VOLUME SAT LIQUID (T) FOR 32<T<100***
62430 REM***DATA FOR SPECIFIC VOLUME SAT LIQUID (T) FOR 600<T<705
62450 Z66 = Z67 / 1000
62460 VF = (1.585285 + (.2603053 + (-.7268563 + (10.972689# + (-25.34296 + 23.07125 * Z66) * Z66)
* Z66) * Z66) * Z66) / 100
62470 RETURN
62480 REM SPECIFIC VOL. OF SATURATED WATER AS A FUNCTION OF PRESSURE
62490 Z51 = PRESS
62500 IF Z51 > 1550 THEN RESTORE 62520: Z61 = Z51: GOSUB 63370: VF = Z53: RETURN
62510 REM***DATA FOR SPEC VOL OF SAT LIQUID (P) FOR 1600<P<3208***
62530 Z86 = .4342944 * LOG(Z51)
62540 Z87 = Z86 ^ 4
62550 Z66 = 101.74419# + (77.052576# + (11.951549# + 2.0556205# * Z86) * Z86) * Z86 + (.42075 +
(-6.841091E-02 + .0625368 * Z86) * Z86) * Z87 - 6.59481E-03 * Z86 * Z86 * Z86 * Z87
62560 Z67 = Z66 / 1000
62570 VF = (1.585285 + (.2603053 + (-.7268563 + (10.972689# + (-25.34296 + 23.07125 * Z67) * Z67)
* Z67) * Z67) * Z67) / 100
62580 RETURN
62590 REM SPECIFIC VOL. OF SUPERHEATED STEAM-T,P
62600 Z67 = TEMP: Z52 = PRESS
62610 Z66 = (Z67 - 32#) * 5# / 9# + 273.16#
62620 Z51 = Z52 * 6894.75729#
62630 Z21 = Z51 / 22120000#: Z78 = Z66 / 647.3#
62640 Z37 = .7633333333# * (1 - Z78)
62650 Z86 = 2.7182818# ^ Z37
62660 Z59 = 461.51#: Z83 = .00317#
62670 Z2 = (Z59 * Z66) / (Z51 * Z83)
62680 Z12 = .06670375918# * Z86 ^ 13 + 1.388983801# * Z86 ^ 3
62690 Z13 = (2 * Z21 * (.08390104328# * Z86 ^ 18 + .02614670893# * Z86 ^ 2 - .03373439453# *
Z86))
62700 Z14 = (3 * Z21 ^ 2 * (.4520918904# * Z86 ^ 18 + .1069036614# * Z86 ^ 10))
62710 Z15 = (4 * Z21 ^ 3 * (-.5975336707# * Z86 ^ 25 - 8.847535803999999D-02 * Z86 ^ 14))
62720 Z16 = (5 * Z21 ^ 4 * (.5958051609# * Z86 ^ 32 - .5159303373# * Z86 ^ 28 + .2075021122# *
Z86 ^ 24))
62730 Z9 = Z12 + Z13 + Z14 + Z15 + Z16
62740 Z24 = (4 * Z21 ^ (-5) * (.1190610271# * Z86 ^ 12 - 9.867174132000001D-02 * Z86 ^ 11)) /
((Z21 ^ (-4) + .4006073948# * Z86 ^ 14) ^ 2)
62750 Z25 = (5 * Z21 ^ (-6) * (.1683998803# * Z86 ^ 24 - .05809438001# * Z86 ^ 18)) / ((Z21 ^
(-5) + .08636081627# * Z86 ^ 19) ^ 2)
62760 Z26 = (6 * Z21 ^ (-7) * (.006552390126# * Z86 ^ 24 + .0005710218649# * Z86 ^ 14)) / ((Z21 ^
(-6) - .8532322921# * Z86 ^ 54 + .3460208861# * Z86 ^ 27) ^ 2)
```

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62770 Z23 = Z24 + Z25 + Z26
62780 Z22 = 15.74373327# - 34.17061978# * Z78 + 19.31380707# * Z78 ^ 2
62790 Z30 = 11 * (Z21 / Z22) ^ 10 * (193.6587558# - 1388.522425# * Z86 + 4126.607219# * Z86 ^ 2 -
6508.211677# * Z86 ^ 3 + 5745.984054# * Z86 ^ 4 - 2693.088365# * Z86 ^ 5 + 523.5718623# * Z86 ^
6)
62800 V = Z83 * (Z2 - Z9 - Z23 + Z30) * 16.0184634#
62810 RETURN
62820 REM TEMPERATURE OF COMPRESSED LIQUID-P,H
62830 Z51 = PRESS: Z43 = ENTH
62840 Z93 = 1: Z50 = 0: Z36 = 0
62850 GOSUB 62060
62860 Z77 = TSAT + 459.69
62870 Z80 = 480
62880 FOR Z44 = 1 TO 100
62890 Z67 = (Z77 + Z80) / 2
62900 GOSUB 60100
62910 Z42 = H
62920 IF ABS(Z43 - Z42) < .01 GOTO 62990
62930 IF Z43 - Z42 < 0 GOTO 62950
62940 Z80 = Z67: GOTO 62960
62950 Z77 = Z67
62960 NEXT Z44
62970 LOCATE 13, 1: PRINT "RESULTS:"
62980 LOCATE 15, 5: PRINT "This function did not converge.  Check inputs of PRESS and ENTH.":
STOP: GOTO 63005
62990 Z66 = Z67
63000 T = Z66 - 459.69
63005 Z93 = 0
63010 RETURN
63020 REM SPECIFIC VOL OF SAT VAPOR AS A FUNCTION OF TEMPERATURE
63030 Z67 = TEMP
63040 IF Z67 < 70 THEN 63080
63050 RESTORE 63230
63060 IF Z67 < 460 THEN RESTORE 63250
63070 GOTO 63100
63080 Z68 = Z67 ^ 2: Z69 = Z67 ^ 3: Z70 = Z67 ^ 4: Z71 = Z67 ^ 5: Z72 = Z67 ^ 6
63090 VG = 10005.09 - 303.0688 * Z67 + 3.15513 * Z68 - 1.001127E-02 * Z69 + 2.398323E-04 * Z70 -
5.884716E-06 * Z71 + 3.556344E-08 * Z72: RETURN
63100 Z61 = Z67
63110 GOSUB 63370: VG = Z53
63120 RETURN
63130 REM SPECIFIC VOL OF SAT VAPOR AS A FUNCTION OF PRESSURE
63140 Z51 = PRESS
63150 RESTORE 63270
63160 IF Z51 < 1300 THEN RESTORE 63330
63170 IF Z51 < 100 THEN RESTORE 63310
63180 IF Z51 < 2! THEN RESTORE 63290
63190 Z61 = Z51
63200 GOSUB 63370: VG = Z53
63210 RETURN
63220 REM***DATA FOR SPECIFIC VOL SAT VAPOR (T)  FOR 705<T<460***
63240 REM***DATA FOR SPECIFIC VOL SAT VAPOR (T)  FOR 460<T<70***
63260 REM***DATA FOR SPECIFIC VOL SAT VAPOR (P)  FOR 1300<P<3208***
63280 REM***DATA FOR SPECIFIC VOL SAT VAPOR (P)  FOR .08865<P<2.0***
63300 REM***DATA FOR SPECIFIC VOL SAT VAPOR (P)  FOR 2.0<P<100***
63320 REM***DATA FOR SPECIFIC VOL SAT VAPOR (P)  FOR 100<P<1300***
63340 REM*******SPECIAL INTERPOLATION SUBROUTINE********
63350 REM**INPUT VARIABLES :  Z61, Z84(Z45), Z92(Z45)********
63360 REM ******* OUTPUT VARIABLE   Z53 **********
63370 READ Z49
63380 FOR Z45 = 1 TO Z49
63390 READ Z84(Z45), Z92(Z45)
63400 NEXT Z45
63410 Z47 = Z49 - 2
63420 Z46 = Z49 - 1
63430 Z27(1) = Z84(2) - Z84(1)
63440 FOR Z55 = 2 TO Z46
63450 Z27(Z55) = Z84(Z55 + 1) - Z84(Z55)
63460 Z6(Z55) = Z27(Z55 - 1)
63470 Z10(Z55) = 2 * (Z6(Z55) + Z27(Z55))
63480 Z58(Z55) = 6 * ((Z92(Z55 + 1) - Z92(Z55)) / Z27(Z55) - (Z92(Z55) - Z92(Z55 - 1)) / Z27(Z55
- 1))
63490 NEXT Z55
63500 Z10(2) = Z10(2) + Z27(1)
63510 Z10(Z46) = Z10(Z46) + Z27(Z46)
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63520 FOR Z45 = 3 TO Z46
63530 Z73 = Z6(Z45) / Z10(Z45 - 1)
63540 Z10(Z45) = Z10(Z45) - Z73 * Z27(Z45 - 1)
63550 Z58(Z45) = Z58(Z45) - Z73 * Z58(Z45 - 1)
63560 NEXT Z45
63570 Z40(Z46) = Z58(Z46) / Z10(Z46)
63580 FOR Z56 = 2 TO Z47
63590 Z48 = Z49 - Z56
63600 Z40(Z48) = (Z58(Z48) - Z27(Z48) * Z40(Z48 + 1)) / Z10(Z48)
63610 NEXT Z56
63620 Z40(1) = Z40(2)
63630 Z40(Z49) = Z40(Z46)
63640 FOR Z45 = 1 TO Z46
63650 IF Z61 <= Z84(Z45 + 1) THEN 63670
63660 NEXT Z45
63670 Z33 = Z61 - Z84(Z45)
63680 Z34 = Z84(Z45 + 1) - Z61
63690 Z31 = Z84(Z45 + 1) - Z84(Z45)
63700 Z53 = Z40(Z45) * Z34 * (Z34 * Z34 / Z31 - Z31) / 6 + Z40(Z45 + 1) * Z33 * (Z33 * Z33 / Z31
- Z31) / 6 + Z92(Z45) * Z34 / Z31 + Z92(Z45 + 1) * Z33 / Z31
63710 RETURN
63720 REM SUBROUTINE FOR ENTHALPY OF WET OR SUPERHEATED STEAM AS A FUNCTION OF PRESSURE AND
ENTROPY
63730 IF Z51 - 100 < 0 THEN 63760
63740 IF Z51 - 2000 < 0 THEN 63770
63750 SG = 5.663159 / (Z51 ^ .1949355): GOTO 63780
63760 SG = 1.984725 / (Z51 ^ .0458907): GOTO 63780
63770 SG = 2.241098 / (Z51 ^ .070069)
63780 IF SG - ENTR < 0 THEN 63800
63790 GOTO 64090
63800 Z86 = .4342944 * LOG(Z51)
63810 Z87 = Z86 ^ 4
63820 IF Z51 - 10 < 0 THEN 63850
63830 IF Z51 - 450 < 0 THEN 63920
63840 GOTO 64000
63850 Z62 = 2.150098 + (-.2543843 + (2.17448E-04 - 9.3986E-04 * Z86) * Z86) * Z86
63860 Z1 = 1223.293 + (-.577813 + (.2303143 - 1.043426 * Z86) * Z86) * Z86
63870 Z2 = 820.0961 + (-1.963417 + (2.606946 - .7684705 * Z86) * Z86) * Z86
63880 Z3 = 895.1208 + (-10.46821 + (7.085838 - 10.321 * Z86) * Z86) * Z86
63890 Z4 = 547.7033 + (195.1106 + (-313.4883 + 166.9476 * Z86) * Z86) * Z86
63900 Z5 = 0
63910 GOTO 64060
63920 Z62 = 2.333556 + (-.3201163 + (.0869149 - .0566468 * Z86) * Z86) * Z86
63930 Z62 = Z62 + (.0183387 - .0024477 * Z86) * Z87
63940 Z1 = 1357.227 + (73.79107 + (-75.92468 + 34.27566 * Z86) * Z86) * Z86 - 6.027015 * Z87
63950 Z2 = 1144.617 + (33.29732 + (-26.45175 + 8.957968 * Z86) * Z86) * Z86 - 1.096801 * Z87
63960 Z3 = 993.7838 + (521.1335 + (-506.5801 + 220.4168 * Z86) * Z86) * Z86 - 37.98249 * Z87
63970 Z4 = 1424.087 + (-1663.604 + (1345.659 - 489.1834 * Z86) * Z86) * Z86 + 73.07568 * Z87
63980 Z5 = 3431.785 + (-7341.258 + (5997.106 - 2208.42 * Z86) * Z86) * Z86 + 297.7455 * Z87
63990 GOTO 64060
64000 Z62 = 1.706677 + (.5440088 + (-.3778053 + .0770932 * Z86) * Z86) * Z86 - 5.54871E-03 * Z87
64010 Z1 = 1400
64020 Z2 = 742.2428 + (661.0354 + (-321.2792 + 53.45692 * Z86) * Z86) * Z86
64030 Z3 = -3491.438 + (4615.432 + (-1470.653 + 145.9465 * Z86) * Z86) * Z86
64040 Z4 = 34807.74 + (-35596.56 + (12288.43 - 1388.081 * Z86) * Z86) * Z86
64050 Z5 = 0
64060 Z6 = ENTR - Z62
64070 H = Z1 + (Z2 + (Z3 + (Z4 + Z5 * Z6) * Z6) * Z6) * Z6
64080 RETURN
64090 Z86 = .4342944 * LOG(Z51)
64100 Z87 = Z86 ^ 4
64110 Z1 = -4.716914 + (-10.04914 + (-7.053283 - 1.947382 * Z86) * Z86) * Z86 + (.1175487 -
.2547345 * Z86) * Z87
64120 Z2 = 561.4616 + (76.93328 + (12.11767 + 2.129136 * Z86) * Z86) * Z86 + (.1285007 + .1443777
* Z86) * Z87
64130 H = Z1 + Z2 * ENTR
64140 RETURN
64150 REM INTERNAL ENERGY SAT LIQUID AS A FUNCTION OF TEMPERATURE
64160 Z67 = TEMP
64170 GOSUB 60200: REM ENTHALPY SAT LIQUID (T)
64180 GOSUB 62370: REM SPEC VOL SAT LIQUID (T)
64190 GOSUB 61280: REM SATURATION PRESSURE (T)
64200 UF = HF - (PSAT * VF * 144 / 778.17)
64210 RETURN
64220 REM INTERNAL ENERGY SAT LIQUID AS A FUNCTION OF PRESSURE
```

```
64230 Z51 = PRESS
64240 GOSUB 60290: REM ENTHALPY SAT LIQUID (P)
64250 GOSUB 62480: REM SPEC VOL SAT LIQUID (P)
64260 UF = HF - (PRESS * VF * 144 / 778.17)
64270 RETURN
64280 REM INTERNAL ENERGY SAT VAPOR AS A FUNCTION OF TEMPERATURE
64290 Z67 = TEMP
64300 GOSUB 60400: REM ENTHALPY SAT VAPOR (T)
64310 GOSUB 63020: REM SPEC VOL SAT VAPOR (T)
64320 GOSUB 61280: REM SATURATION PRESSURE (T)
64330 UG = HG - (PSAT * VG * 144 / 778.17)
64340 RETURN
64350 REM INTERNAL ENERGY SAT VAPOR AS A FUNCTION OF PRESSURE
64360 Z51 = PRESS
64370 GOSUB 60530: REM ENTHALPY SAT VAPOR (P)
64380 GOSUB 63130: REM SPEC VOL SAT VAPOR (P)
64390 UG = HG - (PRESS * VG * 144 / 778.17)
64400 RETURN
64410 REM INTERNAL ENERGY SUPERHEATED VAPOR AS A FUNCTION OF TEMP AND PRESS
64420 Z52 = PRESS: Z67 = TEMP
64430 GOSUB 60610: REM ENTHALPY SUPERHEATED VAPOR (T,P)
64440 GOSUB 62590: REM SPEC VOL SUPERHEATED VAPOR (T,P)
64450 U = H - (PRESS * V * 144 / 778.17)
64460 RETURN
64470 REM ENTHALPY WET STEAM AS A FUNCTION OF TEMPERATURE AND QUALITY
64480 Z67 = TEMP
64490 GOSUB 60200: REM ENTHALPY SAT LIQUID (T)
64500 GOSUB 60400: REM ENTHALPY SAT VAPOR (T)
64510 H = HF + QUAL * (HG - HF)
64520 RETURN
64530 REM ENTHALPY WET STEAM AS A FUNCTION OF PRESSURE AND QUALITY
64540 Z51 = PRESS
64550 GOSUB 60290: REM ENTHALPY SAT LIQUID (P)
64560 GOSUB 60530: REM ENTHALPY SAT VAPOR (P)
64570 H = HF + QUAL * (HG - HF)
64580 RETURN
64590 REM ENTROPY WET STEAM AS A FUNCTION OF TEMPERATURE AND QUALITY
64600 Z67 = TEMP
64610 GOSUB 61390: REM ENTROPY SAT LIQUID (T)
64620 GOSUB 61550: REM ENTROPY SAT VAPOR (T)
64630 S = SF + QUAL * (SG - SF)
64640 RETURN
64650 REM ENTROPY WET STEAM AS A FUNCTION OF PRESSURE AND QUALITY
64660 Z51 = PRESS
64670 GOSUB 61450: REM ENTROPY SAT LIQUID (P)
64680 GOSUB 61630: REM ENTROPY SAT VAPOR (P)
64690 S = SF + QUAL * (SG - SF)
64700 RETURN
64710 REM SPEC VOL WET STEAM AS A FUNCTION OF TEMPERATURE AND QUALITY
64720 Z67 = TEMP
64730 GOSUB 62370: REM SPEC VOL SAT LIQUID (T)
64740 GOSUB 63020: REM SPEC VOL SAT VAPOR (T)
64750 V = VF + QUAL * (VG - VF)
64760 RETURN
64770 REM SPEC VOL WET STEAM AS A FUNCTION OF PRESSURE AND QUALITY
64780 Z51 = PRESS
64790 GOSUB 62480: REM SPEC VOL SAT LIQUID (P)
64800 GOSUB 63130: REM SPEC VOL SAT VAPOR (P)
64810 V = VF + QUAL * (VG - VF)
64820 RETURN
64830 REM INTERNAL ENERGY AS A FUNCTION OF TEMPERATURE AND QUALITY
64840 Z67 = TEMP
64850 GOSUB 64150: REM INTERNAL ENERGY SAT LIQUID (T)
64860 GOSUB 64280: REM INTERNAL ENERGY SAT VAPOR (T)
64870 U = UF + QUAL * (UG - UF)
64880 RETURN
64890 REM INTERNAL ENERGY WET STEAM AS A FUNCTION OF PRESSURE AND QUALITY
64900 Z51 = PRESS
64910 GOSUB 64220: REM INTERNAL ENERGY SAT LIQUID (P)
64920 GOSUB 64350: REM INTERNAL ENERGY SAT VAPOR (p)
64930 U = UF + QUAL * (UG - UF)
64940 RETURN
64950 REM INTERNAL ENERGY SUBCOOLED LIQUID AS A FUNCTION OF TEMPERATURE AND PRESS
64960 Z67 = TEMP: Z52 = PRESS
64970 GOSUB 60080: REM ENTHALPY SUBCOOLED LIQUID (T,P)
```

```
64980 GOSUB 62370: REM SPEC VOL SAT LIQUID (T)
64990 U = H - (PRESS * VF * 144 / 778.17)
65000 RETURN
65100 REM SUBROUTINE TO CONVERT INPUTS FROM SI TO ENGLISH
65110 TEMP = (9 / 5 * TEMP) + 32
65120 PRESS = PRESS / 6.894757
65130 ENTH = ENTH / 2.326
65140 ENTR = ENTR / 4.1868
65150 RETURN
65160 REM SUBROUTINE TO CONVERT OUTPUT FROM ENGLISH TO SI
65170 TEMP = (TEMP - 32) • 5 / 9
65180 PRESS = PRESS * 6.894757
65190 ENTH = ENTH * 2.326
65200 ENTR = ENTR * 4.1868
65210 ON NUM GOSUB 65230, 65230, 65240, 65240, 65250, 65250, 65260, 65260, 65270, 65270, 65280,
65280, 65290, 65290, 65300, 65300, 65310, 65310, 65320, 65320, 65330, 65330, 65340, 65340, 65350,
65360, 65310, 65320, 65330, 65340, 65370, 65310, 65340 _
, 65370, 65310
65220 RETURN
65230 HF = HF * 2.326: RETURN
65240 SF = SF * 4.1868: RETURN
65250 VF = VF * .062428: RETURN
65260 UF = UF * 2.326: RETURN
65270 HG = HG * 2.326: RETURN
65280 SG = SG * 4.1868: RETURN
65290 VG = VG * .062428: RETURN
65300 UG = UG * 2.326: RETURN
65310 H = H * 2.326: RETURN
65320 S = S * 4.1868: RETURN
65330 V = V * .062428: RETURN
65340 U = U * 2.326: RETURN
65350 TSAT = (TSAT - 32) * 5 / 9: RETURN
65360 PSAT = PSAT * 6.894757: RETURN
65370 T = (T - 32) * 5 / 9: RETURN

END SUB
```

LISTING OF FDACS.FOR

```
C     ==============================================================
C     THIS PROGRAM CONDUCT STATISTICAL ANALYSES OF LBB DETECTABLE
C     CRACK SIZE FOR PROBABILISTIC PIPE FRACTURE EVALUATIONS
C
C     IN PARTICULAT IT CALCULATES THE FOLLOWING:
C
C     1.  MEAN CRACK SIZE
C     2.  STANDARD DEVIATION OF CRACK SIZE
C     3.  RANGE OF CRACK SIZE
C     4.  NORMALIZED HISTOGRAMS (AREA UNDER HISTOGRAM = 1)
C
C     ORIGINALLY WRITTEN BY S. RAHMAN, 1992.
C     ==============================================================
C
      IMPLICIT REAL*8 (A-H,O-Z)
      CHARACTER*20 DATA,OPTION
      DIMENSION X(10000),DIV(1000), TABLE(1000)
C
C     --------------------------------------------------------------
C     ENTER INPUT-OUTPUT INFOR
C
      PRINT*, 'ENTER DATAFILE NAME'
      PRINT*, '---> '
      READ (5, '(A)') DATA
      OPEN (1,FILE=DATA,STATUS='OLD')
      OPEN (2,FILE='PDF.DAT',STATUS='UNKNOWN')
      OPEN (3,FILE='CDF.DAT',STATUS='UNKNOWN')
      OPEN (4,FILE='RCDF.DAT',STATUS='UNKNOWN')
      OPEN (10,FILE='CDF2.DAT',STATUS='UNKNOWN')
C
      PRINT*, 'ENTER NUMBER OF OBSERVATION - DATA SIZE  [NOBS]'
      PRINT*, '---> '
      READ*, NOBS
C
      READ (1,*) (X(I),I=1,NOBS)
C
      PRINT*, 'OPT FOR MULTIPLYING WITH A CONSTANT (Y/N)  [N] '
      READ(5,'(A)') OPTION
      IF (OPTION .EQ. ' ') OPTION = 'N'
      IF (OPTION .EQ. 'Y' .OR. OPTION .EQ. 'Y') GO TO 212
      GO TO 213
212   PRINT*, 'ENTER THE MULTIPLIER'
      PRINT*, '---> '
      READ*, FACTOR
      DO 214 I = 1,NOBS
214   X(I) = X(I)*FACTOR
C
C     --------------------------------------------------------------
C     COMPUTE LOWER AND UPPER BOUNDS OF SAMPLES
C
213   XMAX = X(1)
      XMIN = X(1)
      DO 20 I = 1,NOBS
      IF (X(I) .GE. XMAX) XMAX = X(I)
      IF (X(I) .LE. XMIN) XMIN = X(I)
20    CONTINUE
C
      PRINT*
      PRINT*, 'XMAX,XMIN:',XMAX,XMIN
C
      PRINT*
      PRINT*, 'OPT FOR SUBTRACTING A VALUE FROM SAMPLES (Y/N)   [N] '
      READ(5,'(A)') OPTION
      IF (OPTION .EQ. ' ') OPTION = 'N'
      IF (OPTION .EQ. 'Y' .OR. OPTION .EQ. 'Y') GO TO 812
      GO TO 813
```

```
812   PRINT*, 'ENTER A VALUE FOR SUBTRACTION'
      PRINT*, '---> '
      READ*, VALUEL
      DO 814 I = 1,NOBS
814   X(I) = X(I) - VALUEL
      XMIN = XMIN -VALUEL
      XMAX = XMAX - VALUEL
C
C     -------------------------------------------------------------
C     COMPUTE MEAN AND STD. DEV
C
813   PRINT*
      PRINT*, 'COMPUTING ESTIMATES OF MEAN AND STD. DEVIATION......'
C
      XMOM1 = 0.
      XMOM2 = 0.
      DO 961 I = 1,NOBS
      XMOM1 = XMOM1 + X(I)
961   XMOM2 = XMOM2 + X(I)**2
      XMOM1 = XMOM1/DFLOAT(NOBS)
      XMOM2 = XMOM2/DFLOAT(NOBS)
C
      PRINT*
      PRINT*, 'MEAN = ', XMOM1
      PRINT*, 'STANDARD DEVIATION = ', DSQRT( XMOM2 - XMOM1**2 )
C
      PRINT*
      PRINT*, 'ENTER NUMBER OF CELLS OF HISTOGRAM [K]'
      PRINT*, '---> '
      READ*, K
C
      DX = (XMAX-XMIN)/DFLOAT(K)
      PRINT*
      PRINT*, 'DX =',DX
      PRINT*
C
C     CALL DOWFRQ (NOBS,X,K,IOPT,XLO,XHI,CLHW,DIV,TABLE)
C
C     -------------------------------------------------------------
C     START FREQENCY CALCULATIONS
C
      DO 100 I = 1,K
100   DIV(I) = XMIN + DFLOAT(I)*DX - 0.5*DX
C
      DO 200 I = 1,K
      TABLE(I) = 0.
      DO 200 J = 1,NOBS
      IF (  X(J) .GE. (DIV(I)-0.5*DX) .AND.
     &        X(J) .LT. (DIV(I)+0.5*DX)   ) TABLE(I) = TABLE(I)+1.
200   CONTINUE
C
C
C     -------------------------------------------------------------
C     WRITE-OUT RESULTS
C
      AREA = 0.
      WRITE (2,111) DIV(1)-0.5*DX, 0.
      DO 10 I = 1,K
      WRITE (2,111) DIV(I)-0.5*DX, TABLE(I)/(DFLOAT(NOBS)*DX)
      WRITE (2,111) DIV(I)+0.5*DX, TABLE(I)/(DFLOAT(NOBS)*DX)
C
      AREA = AREA + TABLE(I)/DFLOAT(NOBS)
C
      WRITE (3,111) DIV(I)-0.5*DX, AREA
      WRITE (3,111) DIV(I)+0.5*DX, AREA
C
```

```
      WRITE (4,111) DIV(I)-0.5*DX, 1.- AREA
      WRITE (4,111) DIV(I)+0.5*DX, 1.- AREA
C
      WRITE (10,111) DIV(I)+0.5*DX, AREA
C
10    CONTINUE
      WRITE (2,111) DIV(K)+0.5*DX, 0.
C
111   FORMAT (5X, 2(5X,E20.8))

C     -------------------------------------------------------------
C     MENTION FILE NAMES OPENED
C
      PRINT*
      PRINT*, 'PDF.DAT  IS OPENED FOR HISTOGRAM'
      PRINT*, 'CDF.DAT  IS OPENED FOR CDF (WITH STAIRCASE)'
      PRINT*, 'RCDF.DAT IS OPENED FOR 1 - CDF'
      PRINT*, 'CDF2.DAT IS OPENED FOR CDF (W/O STAIRCASE)'
      PRINT*
      PRINT*, 'AREA UNDER HISTOGRAM =',AREA
C
C
      STOP
      END
```

APPENDIX F THE PROLBB COMPUTER CODE

F.1 The PROLBB Computer Code

PROLBB, which is the acronym for **PRO**babilistic **L**eak-**B**efore-**B**reak, is a computer program to evaluate the failure probability of flawed nuclear piping subjected to combined stresses due to tension and bending. Various failure criteria, depending on the exceedance of (1) Net-Section-Collapse load, (2) crack initiation load, and (3) maximum load from elastic-plastic fracture mechanics, can be used to obtain the corresponding probability of failure.

The deterministic fracture-mechanics model in PROLBB is based on the LBB.ENG2 method that can compute the crack-driving force (J-integral) and load-carrying capacity of a through-wall-cracked pipe (initiation load, maximum load, and Net-Section-Collapse load) under combined bending and tension. The LBB.ENG2 method involves (1) classical deformation theory of plasticity, (2) power-law representations of material constitutive laws and fracture toughness properties, and (3) an equivalence criterion incorporating a reduced thickness analogy for simulating system compliance due to the presence of a crack in a pipe (Refs. F.1 to F.5). The method is general in the sense that it may be applied in the complete range between elastic and fully plastic conditions. The method is computationally efficient and is slightly conservative yet reasonably accurate when compared with experimental pipe fracture data. Recent fracture analyses of circumferentially cracked pipes under bending suggest that the maximum load ratio, defined as the ratio of the experimental maximum load to the predicted maximum load, has a mean and standard deviation of 1.03 and 0.13, respectively, for through-wall-cracked pipes and 1.04 and 0.16, respectively, for complex-cracked pipes.

The probabilistic model in PROLBB is based on four different methods of structural reliability theory. They include the: (1) First-Order Reliability Method (FORM), (2) Second-Order Reliability Method (SORM), (3) Importance Sampling, and (4) Monte Carlo Simulation. FORM has been designed for the approximate computation of the general probability integral over given domains with locally smooth boundaries. SORM has been designed as an improvement over FORM by including a second-order correction term, which can be proved to be asymptotically correct. In order to obtain the design point in FORM/SORM for a given performance function, PROLBB uses modern optimization algorithms for solving the nonlinear programming problem. In addition to FORM and SORM, PROLBB includes Importance Sampling, which can update the second-order results from SORM to an arbitrary degree of precision. It also includes the direct Monte Carlo simulation for performing a generic probability integration. Results of Monte Carlo and Importance Sampling provide a means for evaluating the adequacy of FORM/SORM calculations.

In addition to the calculation of piping reliability, PROLBB can also perform an automatic sensitivity study to determine importance and sensitivity factors to identify important and unimportant random variables and important parameters of a given random variable.

F.2 Validation of PROLBB Code with NRCPIPE Results

In order to verify the results of PROLBB, sample calculations were made to compare its deterministic predictions with the NRCPIPE results. The NRCPIPE (Version 1.4G) code was previously tested (both alpha and beta tests) and was released to the NRC. For numerical comparisons, the following example was considered. It represents a TP304 stainless steel, through-wall-cracked pipe, pressurized first, and then loaded in four-point bending to failure while maintaining a constant pressure, p. Table F.1 shows the pipe and crack geometry and material properties of the pipe. Both NRCPIPE (Version 1.4G) and PROLBB were used to predict the J-integral and maximum-load carrying capacity of the pipe. Figure F.1 shows plots of the J-integral as a function of applied bending moment for several values of internal pressure. Figure F.2 shows the effects of pipe pressure on the maximum loads of the pipe. Comparisons of the results in Figures F.1 and F.2 suggest that the calculated crack-driving force and load-carrying capacity of the TWC pipes by the computer codes PROLBB and NRCPIPE are virtually identical. Also, shown in Figure F.2 is the actual failure load from a pipe experiment (Experiment 4131-1) that was conducted under the Degraded Piping program (Ref. F.6). The pipe had the same geometry, crack size, and material properties as defined in Table F.1. The test temperature was 288 C (550 F) with an internal pressure of 17.238 MPa (2.5 ksi). The maximum moment from this experiment was 19.77 kN-m (175.0 kip-inch). It appears that the results of the LBB.ENG2 method predicted by both the NRCPIPE and PROLBB codes are accurate when compared with the experimental data.

Table F.1 Input details for pipe geometry, crack size, and pipe material properties for validation of PROLBB code

Properties of Pipe	Numerical Values
Outer Diameter, D_o, mm (inch)	166.446 (6.553)
Wall Thickness, t, mm (inch)	13.411 (0.528)
Crack Size, θ/π, percent	37.0
Modulus of Elasticity, E, GPa (ksi)	182.7 (26,500)
Reference Stress, $\sigma_o^{(a)}$, MPa (ksi)	138.59 (20.10)
Ramberg-Osgood Coefficient, $\alpha^{(a)}$	4.87
Ramberg-Osgood Exponent, $n^{(a)}$	3.88
Initiation Toughness, $J_{Ic}^{(b)}$, kJ/m²	1,420.3
J-R Curve Coefficient, $C^{(b)}$, kJ/m²	336.6
J-R Curve Exponent, $m^{(b)}$	0.6176

(a) Stress-strain curve is represented by: $\epsilon/\epsilon_o = \sigma/\sigma_o + \alpha(\sigma/\sigma_o)^n$; $\epsilon_o = \sigma_o/E$
(b) J-R curve is represented by: $J_R = J_{Ic} + C(\Delta a/r)^m$, where r is 1 mm and Δa is in mm.

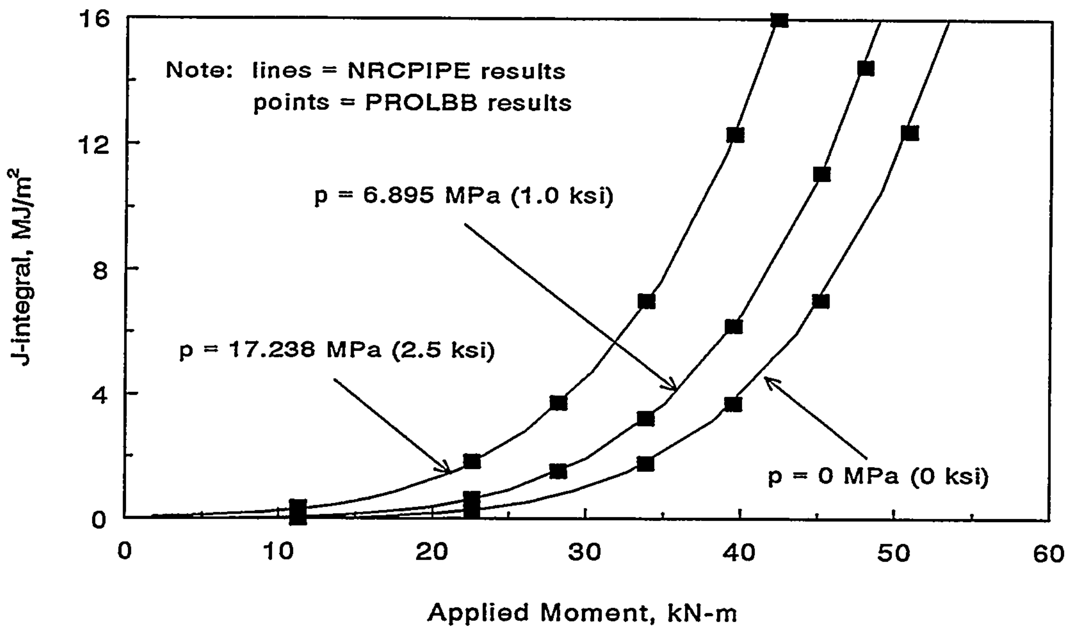

Figure F.1 J-integral predictions for a TWC pipe by NRCPIPE and PROLBB codes

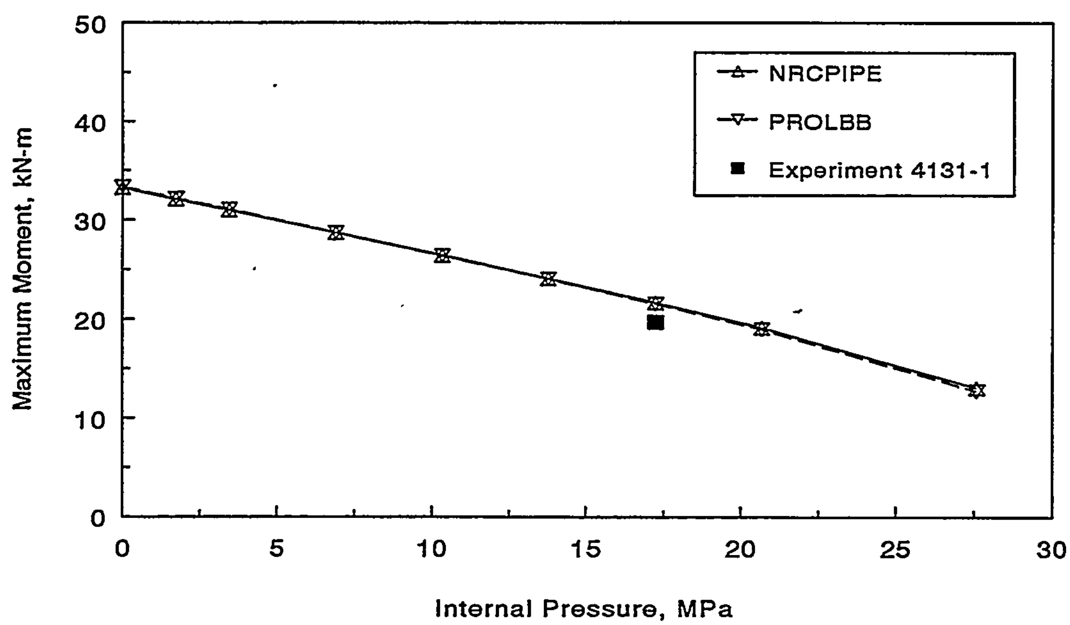

Figure F.2 Predicted maximum loads by NRCPIPE and PROLBB codes as a function of pressure

T-6004-FF.1/F.2

F.3 An Example of PROLBB Analysis

In this section, typical results are presented to illustrate the PROLBB code for conducting probabilistic LBB analysis. As an example, consider the BWR-1 pipe defined in Section 5 of this report. From a previous PSQUIRT analysis (see Appendix E), the mean and standard deviation of leakage-crack length at the mean pipe diameter for a 3.785 l/min (1 gpm) leak rate and normal stress equal to 50-percent of ASME Service Level A are 0.1794 m and 0.0208 m, respectively. In terms of percentage of mean pipe circumference, the mean and standard deviation of the crack length ratio, θ/π, correspond to 0.0844 and 0.0097, respectively. The pipe with a crack in the base metal is subjected to elastically calculated N+SSE stress equal to 194.445 MPa (28,201 psi). Following plasticity correction, this N+SSE stress corresponds to an applied bending moment of 1,723 kN-m (15,251 kip-inch) and an internal pressure of 7.239 MPa (1,050 psi) in the pipe. The material for BWR-1 pipe is TP304 wrought stainless steel. The probabilistic characteristics (e.g., mean, covariance, and probability distribution) of stress-strain and J-R curves of TP304 stainless steel are given in Section 3 and Appendix B of this report. Using the above information, Table F.2 shows the contents of the input file, PROLBB.DAT, required to execute the PROLBB program. Using PROLBB, the conditional failure probability of the BWR-1 pipe for 3.785 l/min (1 gpm) leak rate was calculated using FORM, SORM, and Importance Sampling. The results of the analysis from the output file, PROLBB.OUT, are shown in Table F.3.

Table F.2 Sample input file for probabilistic analysis by PROLBB code

Contents of PROLBB.DAT

```
BWR-1 PIPE WITH CRACK IN BASE METAL
2
0.0844   0.0097     0.
2
0.807271E+01        0.380021E+01
0.                  0.
       0.125377E+02        -0.172740E+01
      -0.172740E+01         0.308061E+00
2
0.124270E+04        0.344189E+03        0.739255E+00
340.                117.                0.3121
       0.340397E+06         0.111216E+05        -0.159383E+02
       0.111216E+05         0.128239E+05        -0.116961E+01
      -0.159383E+02        -0.116961E+01         0.231429E-01
2
0.154782E+03        0.442397E+03
0.                  0.
       0.124502E+03         0.337062E+02
       0.337062E+02         0.588703E+03
1
1.00   0.0     0.
0.3377   0.035814
154.782  182700.
2.498
1.723   1.723   1.723
2      1.000000
3
Y
2   2
6   6
10  10  10
1.0E-2
0
50    1.1
```

Table F.3 Sample output file for probabilistic analysis by PROLBB code

Contents of PROLBB.OUT

BWR-1 PIPE WITH CRACK IN BASE METAL

FORM/SORM/MCIS ANALYSES: SORM MODULE

FOMU1N : FOR IND= 2 IN ITERATION NO.: 9 THERE IS : FU= -0.361E-06 AND VECTOR U:

1.6498	4.5346	-0.3801	-0.9277	-1.1539	-1.5064	0.0000

VECTOR U-* (POINT BETA1) :

1.6498	4.5346	-0.3801	-0.9277	-1.1539	-1.5064	0.0000

OUTPUT OF FORMUN (1ST. ORDER)

ICAGRD= 16 ICALIM= 129 FU= -0.9913E-11 BETA1= 5.2812

NORMALIZED GRADIENT AT THE POINT (U-*) (! ON OUTPUT ON THE VECTOR "U"!):

-0.3106	-0.8593	0.0723	0.1755	0.2184	0.2851	0.0000

UNSCALED AND UNNORMALIZED GRADIENT AFTER FORMUN :

-0.1286	-0.3558	0.0300	0.0727	0.0905	0.1181	0.0000

OUTPUT OF YSORAU (2ND. ORDER)

SCALED MATRIX OF THE 2ND DERIVATIVES AT (U-*)

-0.0019	0.0108	-0.0003	-0.0039	-0.0027	-0.0022	0.0000
0.0108	0.0002	0.0040	-0.0055	-0.0047	-0.0049	0.0000
-0.0003	0.0040	-0.0003	-0.0002	-0.0012	-0.0022	0.0000
-0.0039	-0.0055	-0.0002	0.0348	-0.0050	-0.0218	0.0000
-0.0027	-0.0047	-0.0012	-0.0050	0.0236	0.0130	0.0000
-0.0022	-0.0049	-0.0022	-0.0218	0.0130	0.0543	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

ROTATED MATRIX OF 2ND. DERIVATIVES (ORDER N-1):

0.0075	0.0012	0.0012	-0.0031	-0.0067	0.0000
0.0012	-0.0004	-0.0006	0.0009	0.0021	0.0000
0.0012	-0.0006	-0.0351	0.0064	0.0261	0.0000
-0.0031	0.0009	0.0064	-0.0189	-0.0058	0.0000
-0.0067	0.0021	0.0261	-0.0058	-0.0460	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table F.3 (Continued)

Contents of PROLBB.OUT

```
RADII OF CURVATURE AT (U-*), ORDERED AS THE EIGENVALUES :
RADIUS (NO.  1) OF CURVATURE =        -3.98
RADIUS (NO.  2) OF CURVATURE =       -15.45
RADIUS (NO.  3) OF CURVATURE =       -19.55
RADIUS (NO.  4) OF CURVATURE =      -807.67
RADIUS (NO.  5) OF CURVATURE =      INFINITE
RADIUS (NO.  6) OF CURVATURE =        31.58

IMPORTANCE SAMPLING IMPROVEMENT OVER SORM ESTIMATES

CORRECTION OF BETA2 BY SIMULATION AROUND U-* : YIELDS BETA3
NO. OF SIMULATIONS =  10  EXPECTATION =   0.599  C.O.V. =   13.40 (% )
NO. OF SIMULATIONS =  20  EXPECTATION =   0.770  C.O.V. =   20.06 (% )
NO. OF SIMULATIONS =  30  EXPECTATION =   0.754  C.O.V. =   14.45 (% )
NO. OF SIMULATIONS =  40  EXPECTATION =   0.768  C.O.V. =   11.32 (% )
NO. OF SIMULATIONS =  50  EXPECTATION =   0.785  C.O.V. =    9.64 (% )

RESULTS SUMMARY

AFTER (Y)SORAU : ICALIM  =  382  ERROR FLAG IER =   0

1ST. ORDER THEORY:  BETA1 =    5.281
2ND. ORDER THEORY:   BETA2 =    5.393
SIMULATION IMPROVED: BETA3 =    5.436

EIGENVALUES (ON VECTOR W1) :
   -0.2515   -0.0647   -0.0512   -0.0012    0.0000    0.0317

UNSCALED AND UNNORMALIZED GRADIENT AFTER YGGSR2 (ON VECTOR W3) :
   -0.1286   -0.3558    0.0300    0.0727    0.0904    0.1180    0.0000

VECTOR U-* AT THE END OF SORAU (ON OUTPUT ON W4)
    1.6403    4.5383   -0.3821   -0.9270   -1.1536   -1.5058    0.0000

FAILURE PROBABILITIES BY VARIOUS METHODS:

FORM PROBABILITY =   0.64316384E-07
SORM PROBABILITY =   0.34774904E-07
PROBABILITY BY IMPORTANCE SAMPLING =   0.27312907E-07
```

F.4 Computer Listing of PROLBB Code

The following pages contain the listing for the source code of PROLBB. In subprogram RINDEX, the program calls a major subroutine titled SORAU, which performs the structural reliability calculations by first-order, second-order, and Importance Sampling methods. SORAU is a commercial routine that Battelle purchased from RCP Consulting GMBH, D-800 München, Germany. Due to its proprietary nature, a listing of that routine could not be attached with this report.

F.5 References

F.1 Gilles, P., and Brust, F. W., "Approximate Methods for Fracture Analysis of Tubular Members Subjected to Combined Tensile and Bending Loads," Proceedings of the 8th OMAE Conference, Hague, The Netherlands, 1989.

F.2 Brust, F. W., "Approximate Methods for Fracture Analyses of Through-Wall Cracked Pipe", NUREG/CR-4853, February 1987.

F.3 Rahman, S., Brust, F., Nakagaki, M., and Gilles, P., "An Approximate Method for Estimating Energy Release Rates of Through-Wall Cracked Pipe Weldments," Proceedings of the 1991 ASME Pressure Vessels and Piping Conference, Vol. 215, pp. 87-92, San Diego, California, 1991.

F.4 Gilles, P., and Brust, F., "Approximate Fracture Methods for Pipes - Part I: Theory," Nuclear Engineering and Design, Vol. 127, pp. 1-27, 1992.

F.5 Gilles, P., Chao, K. S., and Brust, F., "Approximate Fracture Methods for Pipes - Part II: Applications," Nuclear Engineering and Design, Vol. 127, pp. 13-31, 1991.

F.6 Wilkowski, G. M. and others, "Degraded Piping Program-Phase II," NUREG/CR-4082, Final and Semiannual Reports, 1985-1989.

LISTING OF PROLBB.FOR

```
C     ================================================================
C     THIS PROGRAM IS WRITTEN TO COMPUTE CONDITIONAL PROBABILITY OF
C     FAILURE FOR THROUGH-WALL-CRACKED PIPES UNDER COMBINED BENDING
C     AND TENSION LOADS.
C
C     THE UNDERLYING DETERMINISTIC METHOD FOR PREDICTING J FOR A GIVEN
C     LOADING CONDITION IS BASED ON LBB.ENG2 METHOD (SEE NUREG/CR-6005)
C
C     THE PROBABILISTIC ANALYSIS IS PERFORMED BY FOUR DIFFERENT METHODS:
C
C            1.  FORM
C            2.  SORM
C            3.  IMPORTANCE SAMPLING
C            4.  MONTE CARLO SIMULATION
C
C      SEE NUREG/CR-6005 REPORT FOR FURTHER DETAILS ON THESE METHODS.
C
C      IN ADDITION TO CALCULATING FAILURE PROBABILITIES, THE PROLBB CODE
C      CAN CALCULATE PROBABILISTIC CHARACTERISTICS OF
C
C          1.  J-INTEGRAL
C          2.  INITIATION MOMENT (EPFM)
C          3.  MAXIMUM MOMENT (EPFM)
C          4.  NET-SECTION-COLLAPSE MOMENT
C
C     WRITTEN BY S. RAHMAN, JUNE 1992 (ORIGINAL)
C
C     ----------------------------------------------------------------
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION U(20),A(1000),PVEC(1)
      CHARACTER*20 OPT1,OPTPAR,INPUT,OUTPUT,STYPE
      CHARACTER*80 TITLE
      COMMON /SR52/   OPT1,OPTPAR,INPUT,OUTPUT,STYPE,TITLE
      COMMON /SR53/   NBV,NAUS,IDIM,NPVEC,NPRI,ISTEM,IUDEF
      COMMON /YCONFO/ IND1,IND2,LIMIT1,LIMIT2,LIMIT3,EPSCON,
     1                MAJIT,MINIT,ICAGRD,ICALIM,ISTAT,ICRT,
     2                IGRFL,SCAL,
     3                NSIMUL,SIMSTA
C
C
C
C     ----------------------------------------------------------------
C                                       PRINT PROGRAM NAMES/PURPOSE
      CALL NAME
C
C     ----------------------------------------------------------------
C                                     READ INPUT/OUTPUT INFORMATION
      CALL INFO
C
C     ----------------------------------------------------------------
C                                       COMPUTE RELIABILITY INDICES
      CALL RINDEX
C
C
      STOP
      END
C
C
C
C     ================================================================
      SUBROUTINE INFO
C
C     Defines input-output, open files, etc.
C     ----------------------------------------------------------------
C
      IMPLICIT REAL*8 (A-H, O-Z)
```

```
      REAL*8 N,MAPP
      REAL*8 MTHOPI,MRO(2),MFT(3),MSIG(2),MLRAT
      REAL*8 ATHOPI,ARO(2),AFT(3),ASIG(2),ALRAT
      REAL*8 COVRO(2,2),COVFT(3,3),COVSIG(2,2)
      REAL*8 TEMP1(2,2),TEMP2(3,3),TEMP3(2,2)
      CHARACTER*20 OPT1,OPTPAR,INPUT,OUTPUT,STYPE
      CHARACTER*80 TITLE
      COMMON /SR52/   OPT1,OPTPAR,INPUT,OUTPUT,STYPE,TITLE
      COMMON /SR53/   NBV,NAUS,IDIM,NPVEC,NPRI,ISTEM,IUDEF
      COMMON /YCONFO/ IND1,IND2,LIMIT1,LIMIT2,LIMIT3,EPSCON,
     1                MAJIT,MINIT,ICAGRD,ICALIM,ISTAT,ICRT,
     2                IGRFL,SCAL,
     3                NSIMUL,SIMSTA
      COMMON /RV1/    MTHOPI,STHOPI
      COMMON /RV2/    MRO,COVRO
      COMMON /RV3/    MFT,COVFT
      COMMON /RV4/    MSIG,COVSIG
      COMMON /RV5/    MLRAT,SLRAT
      COMMON /SHFT/   ATHOPI,ARO,AFT,ASIG,ALRAT
      COMMON /PROG1/  SSTART,SEND,DS,S
      COMMON /PROG2/  NUMFC
      COMMON /MATL1/  ALPHA,N,SIG0,E,SIGY,SIGU
      COMMON /GEOM/   R,THETA,THETA0,T
      COMMON /LOAD/   MAPP
      COMMON /TYPE/   ITYPE1,ITYPE2,ITYPE3,ITYPE4,ITYPE5
      COMMON /PRESS/  P
C
C     ----------------------------------------------------------------
C     OPEN-UP INPUT FILE
C
100   PRINT*, 'ENTER NAME OF INPUT FILE                   [PROLBB.DAT]'
      PRINT*,'---> '
      READ (5,'(A)') INPUT
      IF (INPUT .EQ. ' ') INPUT = 'PROLBB.DAT'
      OPEN (1,FILE=INPUT,STATUS='OLD',ERR=102)
      GO TO 782
C
102   PRINT*, 'DATA FILE DOES NOT EXIST.....TRY AGAIN'
      PRINT*
      GO TO 100
C
C     ----------------------------------------------------------------
C     READ PARAMETERS OF THE PROBLEM
C
782   READ(1,'(A)') TITLE
C
C     RANDOM VARIABLES - ITYPEi TELLS YOU DIST PROPERTY, E.G., IF
C                        ITYPE = 1 = > GAUSSIAN VARIABLE/VECTOR
C                        ITYPE = 2 = > LOGNORMAL VARIABLE/VECTOR
C
      READ(1,*) ITYPE1
      READ(1,*) MTHOPI,STHOPI,ATHOPI
      READ(1,*) ITYPE2
      READ(1,*) (MRO(I), I=1,2)
      READ(1,*) (ARO(I), I=1,2)
      DO 20 I = 1,2
20    READ(1,*) (COVRO(I,J), J=1,2)
      READ(1,*) ITYPE3
      READ(1,*) (MFT(I), I=1,3)
      READ(1,*) (AFT(I), I=1,3)
      DO 21 I = 1,3
21    READ(1,*) (COVFT(I,J), J=1,3)
      READ(1,*) ITYPE4
      READ(1,*) (MSIG(I), I=1,2)
      READ(1,*) (ASIG(I), I=1,2)
      DO 22 I = 1,2
```

```
22    READ(1,*) (COVSIG(I,J), J=1,2)
      READ(1,*) ITYPE5
      READ(1,*) MLRAT,SLRAT,ALRAT
C
      IF (  (ITYPE1 .EQ. 1 .OR. ITYPE1 .EQ. 2)  .AND.
     &      (ITYPE2 .EQ. 1 .OR. ITYPE2 .EQ. 2)  .AND.
     &      (ITYPE3 .EQ. 1 .OR. ITYPE3 .EQ. 2)  .AND.
     &      (ITYPE4 .EQ. 1 .OR. ITYPE4 .EQ. 2)  .AND.
     &      (ITYPE5 .EQ. 1 .OR. ITYPE5 .EQ. 2)  ) GO TO 444
      PRINT*, 'DISTRIBITION PROPERTY NOT CORRECT - STOP CALC NOW!'
      STOP
C
444   IF (ITYPE1 .EQ. 1) GO TO 445
      MTHOPI = MTHOPI - ATHOPI
      VTHOPI = STHOPI/MTHOPI
      MTHOPI = DLOG(MTHOPI) - 0.5*DLOG(1. + VTHOPI**2)
      STHOPI = DSQRT(  DLOG(1. + VTHOPI**2)   )
C
445   IF (ITYPE2 .EQ. 1) GO TO 446
      DO 91 I = 1,2
91    MRO(I) = MRO(I) - ARO(I)
      CALL LNSTAT(MRO,COVRO,2,TEMP1)
C
446   IF (ITYPE3 .EQ. 1) GO TO 447
      DO 92 I = 1,3
92    MFT(I) = MFT(I) - AFT(I)
      CALL LNSTAT(MFT,COVFT,3,TEMP2)
C
447   IF (ITYPE4 .EQ. 1) GO TO 448
      DO 93 I = 1,2
93    MSIG(I) = MSIG(I) - ASIG(I)
      CALL LNSTAT(MSIG,COVSIG,2,TEMP3)
C
448   IF (ITYPE5 .EQ. 1) GO TO 449
      MLRAT = MLRAT - ALRAT
      VLRAT = SLRAT/MLRAT
      MLRAT = DLOG(MLRAT) - 0.5*DLOG(1. + VLRAT**2)
      SLRAT = DSQRT(  DLOG(1. + VLRAT**2)   )
C
C     DETERMINISTIC VARIABLES
C
449   READ(1,*) R,T
      READ(1,*) SIG0,E
      READ(1,*) P
C
C     PROGRAMMATIC VARIABLES
C
      READ(1,*) SSTART,SEND,DS
      READ(1,*) NUMFC,MAPP
      READ(1,*) ISTEM
C
C     DEFINE NUMBER OF BASIC VARIABLES
C
      IF (NUMFC .EQ. 0) NBV = 4
      IF (NUMFC .EQ. 1) NBV = 5
      IF (NUMFC .EQ. 2) NBV = 7
      IF (NUMFC .EQ. 3) NBV = 4
C
      READ(1,'(A)') OPTPAR
      IF (OPTPAR .EQ. 'N' .OR. OPTPAR .EQ. 'n') GO TO 900
      READ(1,*) NAUS,NPRI
      READ(1,*) IND1,IND2
      READ(1,*) LIMIT1,LIMIT2,LIMIT3
      READ(1,*) EPSCON
      READ(1,*) IGRFL
      READ(1,*) NSIMUL,SIMSTA
```

```
C
C
C     ----------------------------------------------------------------
C     OPEN-UP OUTPUT FILE
C
900   PRINT*, 'ENTER NAME OF OUTPUT FILE                  [PROLBB.OUT]'
      PRINT*,'---> '
      READ (5,'(A)') OUTPUT
      IF (OUTPUT .EQ. ' ') OUTPUT = 'PROLBB.OUT'
C      OPEN (NAUS,FILE=OUTPUT,STATUS='NEW',ERR=109)
      RETURN
109   PRINT*, 'SUCH A FILE ALREADY EXISTS.....TRY ANOTHER'
      PRINT*
      GO TO 900
C
C
      END
C
C
C     ================================================================
      SUBROUTINE LNSTAT(MEAN,COVAR,NRV,YVAR)
C
C     Computes mean and covariance of associated gaussian vector
C     when the statistics of lognormal vector are given
C     ----------------------------------------------------------------

      IMPLICIT REAL*8 (A-H, O-Z)
      REAL*8 MEAN(NRV),COVAR(NRV,NRV),YVAR(NRV,NRV)
      REAL*8 V(20)
C
C     ----------------------------------------------------------------
      DO 10 I = 1,NRV
      V(I) = DSQRT( COVAR(I,I) )/MEAN(I)
10    MEAN(I) = DLOG( MEAN(I) ) - 0.5*DLOG( 1. + V(I)**2 )
C
      DO 20 I = 1,NRV
      DO 20 J = 1,NRV
      IF (I .EQ. J ) GO TO 111
      RTILDE = COVAR(I,J)/(   DSQRT( COVAR(I,I)*COVAR(J,J) )    )
      YVAR(I,J) = DLOG(     1. + RTILDE*V(I)*V(J)     )
      GO TO 20
111   YVAR(I,J) = DLOG( 1. + V(I)**2 )
20    CONTINUE
C
      DO 30 I = 1,NRV
      DO 30 J = 1,NRV
30    COVAR(I,J) = YVAR(I,J)
C
C
      RETURN
      END
C
C
C     ================================================================
      SUBROUTINE RINDEX
C
C     Calls SORAU routine for computing reliability index and hence,
C     corresponding failure probabilities
C     ----------------------------------------------------------------
C
      IMPLICIT REAL*8 (A-H, O-Z)
      DIMENSION U(20),A(1000),PVEC(1),ALPVEC(1),LPAVEC(1)
      CHARACTER*20 OPT1,OPTPAR,INPUT,OUTPUT,STYPE
      CHARACTER*80 TITLE
      COMMON /SR52/   OPT1,OPTPAR,INPUT,OUTPUT,STYPE,TITLE
      COMMON /SR53/   NBV,NAUS,IDIM,NPVEC,NPRI,ISTEM,IUDEF
```

```
      COMMON /YCONFO/ IND1,IND2,LIMIT1,LIMIT2,LIMIT3,EPSCON,
     1                MAJIT,MINIT,ICAGRD,ICALIM,ISTAT,ICRT,
     2                IGRFL,SCAL,
     3                NSIMUL,SIMSTA
      COMMON /PROG1/  SSTART,SEND,DS,S
      COMMON /PROG2/  NUMFC
      EXTERNAL LSTATE
C
C     ----------------------------------------------------------------
C     DETERMINE METHOD OF ANALYSIS
C
      PRINT*, 'WANT TO DO M/C SIMULATION DIRECTLY ? ENTER OPTION (0/1)'
      PRINT*, '(Note: Enter 1 for MCS, 0 for FORM/SORM/MCIS)'
      PRINT*, '---> '
      READ*, KOPT
      IF (KOPT .NE. 0) GO TO 666
C
C     ----------------------------------------------------------------
C     SET DEFAULT VALUES FOR SORM LIBRARY
C
708   IF (NPRI .EQ. 0) NPRI = 1
      IF (ISTEM .EQ. 0) ISTEM = 3
      IF (IUDEF .EQ. 0) IUDEF = 0
      IF (NAUS .EQ. 0) NAUS=2
      OPEN(NAUS,FILE=OUTPUT,STATUS='UNKNOWN')
      WRITE(NAUS,982) TITLE
982   FORMAT (/5X,A65//)
      IF (NPVEC .EQ. 0) NPVEC=1
      IF (IDIM .EQ. 0) IDIM = 1000
C
C     ----------------------------------------------------------------
C     ALSO SET EXTRA PARAMETERS OF SORMP
C
      KEYPAR = 0
      KLP = 1
      LPAVEC(1) = 1
C
C     ----------------------------------------------------------------
C     CALL SORM LIBRARY TO GET RELIABILITY INDICES - NOTE, THE ROUTINE
C     SORAU IS PROPRIETARY AND BATTELLE HAS ONLY THE OBJECT CODE;
C     HENCE, IT CANNOT BE LISTED IN NUREG REPORT.
C
      NPROB = IDINT(((SEND-SSTART)/DS)+0.5)
      DO 10 IPROB = 1,NPROB+1
C
      S = SSTART + REAL(IPROB-1)*DS
C
      PRINT*
      PRINT*, 'IPROB = ', IPROB, '    LOAD THRESHOLD = ', S
      PRINT*
      CALL SORAU (NBV,LSTATE,U,FU,BETA1,BETA2,BETA3,VARSIM,IER,
     1            ISTEM,IUDEF,NAUS,NPRI,A,IDIM,PVEC,NPVEC,
     2            KEYPAR,ALPVEC,LPAVEC,KLP)
C
C     ----------------------------------------------------------------
C     COMPUTE FAILURE PROBABILITIES
C
      PF1 = YPHIN(-BETA1)
      PF2 = YPHIN(-BETA2)
      PF3 = YPHIN(-BETA3)
C
      PRINT*
      IF (ISTEM .GE. 1) PRINT*, 'BETA1 = ', BETA1, '  PF1 = ', PF1
      IF (ISTEM .GE. 2) PRINT*, 'BETA2 = ', BETA2, '  PF2 = ', PF2
      IF (ISTEM .EQ. 3) PRINT*, 'BETA3 = ', BETA3, '  PF3 = ', PF3
C
```

```
C     ----------------------------------------------------------------
C     WRITE-OUT FAILURE PROBABILITIES
C
      WRITE(NAUS,115)
115   FORMAT(//5X,'FAILURE PROBABILITIES BY VARIOUS METHODS:')
      IF (ISTEM .EQ. 1) WRITE(NAUS,116) PF1
      IF (ISTEM .EQ. 2) WRITE(NAUS,117) PF1,PF2
      IF (ISTEM .EQ. 3) WRITE(NAUS,118) PF1,PF2,PF3
116   FORMAT(/5X,'FORM PROBABILITY = ', E18.8)
117   FORMAT(/5X,'FORM PROBABILITY = ', E18.8,
     &        /5X,'SORM PROBABILITY = ', E18.8)
118   FORMAT(/5X,'FORM PROBABILITY = ', E18.8,
     &        /5X,'SORM PROBABILITY = ', E18.8,
     &        /5X,'PROBABILITY BY IMPORTANCE SAMPLING = ', E18.8)
C
      IF (ISTEM .EQ. 1) WRITE(30,113) S,PF1
      IF (ISTEM .EQ. 2) WRITE(30,113) S,PF1,PF2
      IF (ISTEM .EQ. 3) WRITE(30,113) S,PF1,PF2,PF3
113   FORMAT (5X, 4E18.8)
C
10    CONTINUE
      RETURN
C
C
666   CALL SIMUL
C
      RETURN
      END
C
C
C     ================================================================
      SUBROUTINE LSTATE (NBV,NMAX,U,FU,IER,PVEC,NPVEC)
C
C     Defines limit-state function corresponding to user-defined
C     failure criteria for FORM/SORM/MCIS analyses
C     ----------------------------------------------------------------
C
      IMPLICIT REAL*8 (A-H, O-Z)
      DIMENSION U(NMAX),PVEC(NPVEC)
      REAL*8 N,J1C,M
      REAL*8 MTHOPI,MRO(2),MFT(3),MSIG(2),MLRAT
      REAL*8 ATHOPI,ARO(2),AFT(3),ASIG(2),ALRAT
      REAL*8 COVRO(2,2),COVFT(3,3),COVSIG(2,2)
      REAL*8 X(20),UU(20),XX(20),WK(20)
      REAL*8 BRO(2,2),BFT(3,3),BSIG(2,2)
      CHARACTER*20 OPT1,OPTPAR,INPUT,OUTPUT,STYPE
      CHARACTER*80 TITLE
      COMMON /SR52/   OPT1,OPTPAR,INPUT,OUTPUT,STYPE,TITLE
      COMMON /YCONFO/ IND1,IND2,LIMIT1,LIMIT2,LIMIT3,EPSCON,
     1                MAJIT,MINIT,ICAGRD,ICALIM,ISTAT,ICRT,
     2                IGRFL,SCAL,
     3                NSIMUL,SIMSTA
      COMMON /PROG1/  SSTART,SEND,DS,S
      COMMON /PROG2/  NUMFC
      COMMON /MATL1/  ALPHA,N,SIG0,E,SIGY,SIGU
      COMMON /MATL2/  J1C,C,M
      COMMON /GEOM/   R,THETA,THETA0,T
      COMMON /RV1/    MTHOPI,STHOPI
      COMMON /RV2/    MRO,COVRO
      COMMON /RV3/    MFT,COVFT
      COMMON /RV4/    MSIG,COVSIG
      COMMON /RV5/    MLRAT,SLRAT
      COMMON /SHFT/   ATHOPI,ARO,AFT,ASIG,ALRAT
      COMMON /TYPE/   ITYPE1,ITYPE2,ITYPE3,ITYPE4,ITYPE5
C
C
```

```
C     THIS MODULE IS REQUIRED FOR TRANSFORMATION OF NON-GAUSSIAN
C     R.V.s AND THEN FOR THE DEFINITION OF LIMIT STATE
C
C
      PI = 3.141592654
      IER=0
C
C
C     -----------------------------------------------------------------
C     TRANSFORM BASIC R.V.s INTO STANDARD GAUSSIAN SPACE
C
C     VARIABLES AND THEIR NUMBERS WILL BE FUNCTION OF NUMFC
C
      IF (NUMFC .EQ. 0) GO TO 505
      IF (NUMFC .EQ. 1) GO TO 515
      IF (NUMFC .EQ. 2) GO TO 525
      IF (NUMFC .EQ. 3) GO TO 535
      PRINT*, 'CHECK YOUR NUMFC -  STOP CALCULATIONS'
      STOP
C
C     -----------------------------------------------------------------
C     CALCULATE J-INTEGRAL
C
C     1.  THOPI  --->  GAUSSIAN OR LOGNORMAL
C
505   X(1) = U(1)*STHOPI + MTHOPI
      IF( ITYPE1 .EQ. 2 ) X(1) = DEXP( X(1) )
C
C     2.  {RO}   --->  CORRELATED GAUSSIAN OR LOGNORMAL
C
      CALL CHLSKY (2,COVRO,BRO)
      DO 100 I = 1,2
100   UU(I) = U(I+1)
      DO 110 I = 1,2
      WK(I) = MRO(I)
      DO 110 J = 1,2
      WK(I) = WK(I) + BRO(I,J)*UU(J)
110   CONTINUE
      DO 120 I = 1,2
      XX(I) = WK(I)
120   IF( ITYPE2 .EQ. 2 ) XX(I) = DEXP( WK(I) )
      DO 130 I = 1,2
130   X(I+1) = XX(I)
C
C     3.  RHO   --->  GAUSSIAN OR LOGNORMAL
C
      X(4) = U(4)*SLRAT + MLRAT
      IF( ITYPE5 .EQ. 2 ) X(4) = DEXP( X(4) )
C
C     ADD THE SHIFTS, IF ANY
C
      X(1) = X(1) + ATHOPI
      X(2) = X(2) + ARO(1)
      X(3) = X(3) + ARO(2)
      X(4) = X(4) + ALRAT
C
      THETA = X(1)*PI
      THETA0 = THETA
      ALPHA = X(2)
      N = X(3)
      RHO = X(4)
C
C      PRINT*, 'THOPI,ALPHA,N: ', X(1),X(2),X(3)
C      PRINT*
      GO TO 888
C
```

```
C      -----------------------------------------------------------------
C      CALCULATE INITIATION MOMENT
C
C      1.  THOPI   --->  GAUSSIAN OR LOGNORMAL
C
515    X(1) = U(1)*STHOPI + MTHOPI
       IF( ITYPE1 .EQ. 2 ) X(1) = DEXP( X(1) )
C
C      2.  {RO}    --->  CORRELATED GAUSSIAN OR LOGNORMAL
C
       CALL CHLSKY (2,COVRO,BRO)
       DO 400 I = 1,2
400    UU(I) = U(I+1)
       DO 410 I = 1,2
       WK(I) = MRO(I)
       DO 410 J = 1,2
       WK(I) = WK(I) + BRO(I,J)*UU(J)
410    CONTINUE
       DO 420 I = 1,2
       XX(I) = WK(I)
420    IF( ITYPE2 .EQ. 2 ) XX(I) = DEXP( WK(I) )
       DO 430 I = 1,2
430    X(I+1) = XX(I)
C
C      3.  J1C    --->  GAUSSIAN OR LOGNORMAL
C
       P1 = MFT(1)
       P2 = DSQRT( COVFT(1,1) )
       X(4) = U(4)*P2 + P1
       IF( ITYPE3 .EQ. 2 ) X(4) = DEXP( X(4) )
C
C      4.  RHO    --->  GAUSSIAN OR LOGNORMAL
C
       X(5) = U(5)*SLRAT + MLRAT
       IF( ITYPE5 .EQ. 2 ) X(5) = DEXP( X(5) )
C
C      ADD THE SHIFTS, IF ANY
C
       X(1) = X(1) + ATHOPI
       X(2) = X(2) + ARO(1)
       X(3) = X(3) + ARO(2)
       X(4) = X(4) + AFT(1)
       X(5) = X(5) + ALRAT
C
C      NOTE: X(4) WAS INPUT IN KJ/M^2 - NEEDED TO MAKE MJ/M^2
C
       THETA = X(1)*PI
       THETA0 = THETA
       ALPHA = X(2)
       N = X(3)
       J1C = X(4)/1000.
       RHO = X(5)
       GO TO 888
C
C      -----------------------------------------------------------------
C      CALCULATE MAXIMUM MOMENT
C
C      1.  THOPI   --->  GAUSSIAN OR LOGNORMAL
C
525    X(1) = U(1)*STHOPI + MTHOPI
       IF( ITYPE1 .EQ. 2 ) X(1) = DEXP( X(1) )
C
C      2.  {RO}    --->  CORRELATED GAUSSIAN OR LOGNORMAL
C
       CALL CHLSKY (2,COVRO,BRO)
       DO 500 I = 1,2
```

```
500   UU(I) = U(I+1)
      DO 510 I = 1,2
      WK(I) = MRO(I)
      DO 510 J = 1,2
      WK(I) = WK(I) + BRO(I,J)*UU(J)
510   CONTINUE
      DO 520 I = 1,2
      XX(I) = WK(I)
520   IF( ITYPE2 .EQ. 2 ) XX(I) = DEXP( WK(I) )
      DO 530 I = 1,2
530   X(I+1) = XX(I)
C
C     3.   {FT}   --->  CORRELATED GAUSSIAN OR LOGNORMAL
C
      CALL CHLSKY (3,COVFT,BFT)
      DO 600 I = 1,3
600   UU(I) = U(I+3)
      DO 610 I = 1,3
      WK(I) = MFT(I)
      DO 610 J = 1,3
      WK(I) = WK(I) + BFT(I,J)*UU(J)
610   CONTINUE
      DO 620 I = 1,3
      XX(I) = WK(I)
620   IF( ITYPE3 .EQ. 2 ) XX(I) = DEXP( WK(I) )
      DO 630 I = 1,3
630   X(I+3) = XX(I)
C
C     4.  RHO   --->  GAUSSIAN OR LOGNORMAL
C
      X(7) = U(7)*SLRAT + MLRAT
      IF( ITYPE5 .EQ. 2 ) X(7) = DEXP( X(7) )
C
C     ADD THE SHIFTS, IF ANY
C
      X(1) = X(1) + ATHOPI
      X(2) = X(2) + ARO(1)
      X(3) = X(3) + ARO(2)
      X(4) = X(4) + AFT(1)
      X(5) = X(5) + AFT(2)
      X(6) = X(6) + AFT(3)
      X(7) = X(7) + ALRAT
C
C     ----------------------------------------------------------------
C     NOTE: X(4) WAS INPUT IN KJ/M^2 - NEEDED TO MAKE MJ/M^2
C     ALSO, C WAS IN KJ/M^2 - NEEDED TO MODIFY IT SO THAT ALL
C     THE CALCULATIONS TO BE DONE IN UNITS OF M AND MN UNITS NOW
C
      THETA = X(1)*PI
      THETA0 = THETA
      ALPHA = X(2)
      N = X(3)
      J1C = X(4)/1000.
      C = X(5)*1000**( X(6)-1. )
      M = X(6)
      RHO = X(7)
      GO TO 888
C
C     ----------------------------------------------------------------
C     CALCULATE NET-SECTION-COLLAPSE MOMENT
C
C     1.  THOPI  --->  GAUSSIAN OR LOGNORMAL
C
535   X(1) = U(1)*STHOPI + MTHOPI
      IF( ITYPE1 .EQ. 2 ) X(1) = DEXP( X(1) )
C
```

```
C       2.  {SIG}    --->  CORRELATED GAUSSIAN OR LOGNORMAL
C
        CALL CHLSKY (2,COVSIG,BSIG)
        DO 700 I = 1,2
700     UU(I) = U(I+1)
        DO 710 I = 1,2
        WK(I) = MSIG(I)
        DO 710 J = 1,2
        WK(I) = WK(I) + BSIG(I,J)*UU(J)
710     CONTINUE
        DO 720 I = 1,2
        XX(I) = WK(I)
720     IF( ITYPE4 .EQ. 2 ) XX(I) = DEXP( WK(I) )
        DO 730 I = 1,2
730     X(I+1) = XX(I)
C
C       3.  RHO    --->  GAUSSIAN OR LOGNORMAL
C
        X(4) = U(4)*SLRAT + MLRAT
        IF( ITYPE5 .EQ. 2 ) X(4) = DEXP( X(4) )
C
C       ADD THE SHIFTS, IF ANY
C
        X(1) = X(1) + ATHOPI
        X(2) = X(2) + ASIG(1)
        X(3) = X(3) + ASIG(2)
        X(4) = X(4) + ALRAT
C
        THETA = X(1)*PI
        THETA0 = THETA
        SIGY = X(2)
        SIGU = X(3)
        RHO = X(4)
C
C       ----------------------------------------------------------------
C       OTHER COMMON VARIABLES
C
888     IF (THETA .LT. 0.) THETA = 0.
        IF (THETA0 .LT. 0.) THETA0 = 0.
        IF (ALPHA .LT. 0.) ALPHA = 0.
        IF (N .LT. 0.) N = 0.
        IF (J1C .LT. 0.) J1C = 0.
        IF (C .LT. 0.) C = 0.
        IF (M .LT. 0.) M = 0.
        IF (SIGY .LT. 0.) SIGY = 0.
        IF (SIGU .LT. 0.) SIGU = 0.
C
        CALL PIPE (Q)
        Q = Q*RHO
C
        FU = Q - S
        IF (NUMFC .EQ. 0) FU = S - Q
C
C
        RETURN
        END
C
C
C       ================================================================
        SUBROUTINE SIMUL
C
C       Conducts direct Monte Carlo Simulation for a user-defined
C       failure criteria
C       ----------------------------------------------------------------
C
        IMPLICIT REAL*8 (A-H, O-Z)
```

```
      REAL*8 N,J1C,M
      REAL*8 MTHOPI,MRO(2),MFT(3),MSIG(2),MLRAT
      REAL*8 ATHOPI,ARO(2),AFT(3),ASIG(2),ALRAT
      REAL*8 COVRO(2,2),COVFT(3,3),COVSIG(2,2)
      REAL*8 X(20),UU(20),XX(20),WK(20),U(20)
      REAL*8 BRO(2,2),BFT(3,3),BSIG(2,2)
      CHARACTER*20 OPT1,OPTPAR,INPUT,OUTPUT,STYPE
      CHARACTER*80 TITLE
      CHARACTER*20 FMCS
      COMMON /SR52/   OPT1,OPTPAR,INPUT,OUTPUT,STYPE,TITLE
      COMMON /SR53/   NBV,NAUS,IDIM,NPVEC,NPRI,ISTEM,IUDEF
      COMMON /PROG1/  SSTART,SEND,DS,S
      COMMON /PROG2/  NUMFC
      COMMON /MATL1/  ALPHA,N,SIG0,E,SIGY,SIGU
      COMMON /MATL2/  J1C,C,M
      COMMON /GEOM/   R,THETA,THETA0,T
      COMMON /RV1/    MTHOPI,STHOPI
      COMMON /RV2/    MRO,COVRO
      COMMON /RV3/    MFT,COVFT
      COMMON /RV4/    MSIG,COVSIG
      COMMON /RV5/    MLRAT,SLRAT
      COMMON /SHFT/   ATHOPI,ARO,AFT,ASIG,ALRAT
      COMMON /TYPE/   ITYPE1,ITYPE2,ITYPE3,ITYPE4,ITYPE5
C
C
      PI = 3.141592654
C
      PRINT*, 'ENTER NMCS (SAMPLE SIZE FOR MCS)'
      PRINT*, '---> '
      READ*, NMCS
C
      PRINT*,'ENTER OPTION FOR THE FOLLOWING:'
      PRINT*
      PRINT*,'    1  :  GENERATE SAMPLES OF Q  '
      PRINT*,'    2  :  ESTIMATE: PFMCS = Pr[Q < S] '
      PRINT*
      PRINT*, '---> '
      READ*, IOMCS
C
      IF(IOMCS .EQ. 1) GO TO 111
      IF(IOMCS .EQ. 2) GO TO 222
      PRINT*, 'SOMETING WRONG IN MODULE SIMUL ! STOP CALCULATIONS '
C
111   PRINT*, 'ENTER FILENAME TO WRITE-OUT THE SAMPLES OF Q  [MCS.OUT]'
      PRINT*, '---> '
      READ(5,'(A)') FMCS
      IF (FMCS .EQ. ' ') FMCS = 'MCS.OUT'
      OPEN (3,FILE=FMCS,STATUS='UNKNOWN')
      GO TO 707
C
222   PRINT*, 'ENTER THRESHOLD S'
      PRINT*, '[NOTE: DEFINITION OF THRESHOLD PARAMETERS IN INPUT'
      PRINT*, ' IS IGNORED FOR MCS OPTION - REDEFINE A THRESHOLD '
      PRINT*, ' HERE - ONLY ONE VALUE IS PERMITTED AT A TIME]    '
      PRINT*, '---> '
      READ*, S
C
707   IF (NMCS .EQ. 0) NMCS=500
      IF (ISEED .LE. 0) ISEED = 123457
      NSUR = 0
      KK = 1
      KSTEP = NMCS/10
      IF (KSTEP .EQ. 0) KSTEP = 1
C
C     ---------------------------------------------------------------
C     START SIMULATING
```

```
C
      DO 1000 ICS = 1,NMCS
C
      DO 20 I = 1,NBV
      RNUNIF = RANGEN(ISEED)
      U(I) = YNINVP(RNUNIF)
20    CONTINUE
C
C
C     ---------------------------------------------------------------
C     VARIABLES AND THEIR NUMBERS WILL BE FUNCTION OF NUMFC
C
      IF (NUMFC .EQ. 0) GO TO 505
      IF (NUMFC .EQ. 1) GO TO 515
      IF (NUMFC .EQ. 2) GO TO 525
      IF (NUMFC .EQ. 3) GO TO 535
      PRINT*, 'CHECK YOUR NUMFC -  STOP CALCULATIONS'
      STOP
C
C
C     ---------------------------------------------------------------
C     NOTE:  FOR CORRELATED VARIABLE, CHOLESKY DECOMPOSITION NEED TO BE
C            DONE ONLY ONCE - SO CALL CHLSKY ROUTINE ONLY ONCE
C
C     ---------------------------------------------------------------
C     CALCULATE J-INTEGRAL
C
C     1.  THOPI  --->  GAUSSIAN OR LOGNORMAL
C
505   X(1) = U(1)*STHOPI + MTHOPI
      IF( ITYPE1 .EQ. 2 ) X(1) = DEXP( X(1) )
C
C     2.  {RO}   --->  CORRELATED GAUSSIAN OR LOGNORMAL
C
      IF (ICS .EQ. 1) CALL CHLSKY (2,COVRO,BRO)
      DO 100 I = 1,2
100   UU(I) = U(I+1)
      DO 110 I = 1,2
      WK(I) = MRO(I)
      DO 110 J = 1,2
      WK(I) = WK(I) + BRO(I,J)*UU(J)
110   CONTINUE
      DO 120 I = 1,2
      XX(I) = WK(I)
120   IF( ITYPE2 .EQ. 2 ) XX(I) = DEXP( WK(I) )
      DO 130 I = 1,2
130   X(I+1) = XX(I)
C
C     3.  RHO   --->  GAUSSIAN OR LOGNORMAL
C
      X(4) = U(4)*SLRAT + MLRAT
      IF( ITYPE5 .EQ. 2 ) X(4) = DEXP( X(4) )
C
C     ADD THE SHIFTS, IF ANY
C
      X(1) = X(1) + ATHOPI
      X(2) = X(2) + ARO(1)
      X(3) = X(3) + ARO(2)
      X(4) = X(4) + ALRAT
C
      THETA = X(1)*PI
      THETA0 = THETA
      ALPHA = X(2)
      N = X(3)
      RHO = X(4)
      GO TO 888
```

```
C
C     ----------------------------------------------------------------
C     CALCULATE INITIATION MOMENT
C
C     1.  THOPI  --->  GAUSSIAN OR LOGNORMAL
C
515   X(1) = U(1)*STHOPI + MTHOPI
      IF( ITYPE1 .EQ. 2 ) X(1) = DEXP( X(1) )
C
C     2.  {RO}   --->  CORRELATED GAUSSIAN OR LOGNORMAL
C
      IF (ICS .EQ. 1) CALL CHLSKY (2,COVRO,BRO)
      DO 400 I = 1,2
400   UU(I) = U(I+1)
      DO 410 I = 1,2
      WK(I) = MRO(I)
      DO 410 J = 1,2
      WK(I) = WK(I) + BRO(I,J)*UU(J)
410   CONTINUE
      DO 420 I = 1,2
      XX(I) = WK(I)
420   IF( ITYPE2 .EQ. 2 )XX(I) = DEXP( WK(I) )
      DO 430 I = 1,2
430   X(I+1) = XX(I)
C
C     3.  J1C   --->  GAUSSIAN OR LOGNORMAL
C
      P1 = MFT(1)
      P2 = DSQRT( COVFT(1,1) )
      X(4) = U(4)*P2 + P1
      IF( ITYPE3 .EQ. 2 ) X(4) = DEXP( X(4) )
C
C     4.  RHO   --->  GAUSSIAN OR LOGNORMAL
C
      X(5) = U(5)*SLRAT + MLRAT
      IF( ITYPE5 .EQ. 2 ) X(5) = DEXP( X(5) )
C
C     ADD THE SHIFTS, IF ANY
C
      X(1) = X(1) + ATHOPI
      X(2) = X(2) + ARO(1)
      X(3) = X(3) + ARO(2)
      X(4) = X(4) + AFT(1)
      X(5) = X(5) + ALRAT
C
      THETA = X(1)*PI
      THETA0 = THETA
      ALPHA = X(2)
      N = X(3)
      J1C = X(4)/1000
      RHO = X(5)
      GO TO 888
C
C     ----------------------------------------------------------------
C     CALCULATE MAXIMUM MOMENT
C
C     1.  THOPI  --->  GAUSSIAN OR LOGNORMAL
C
525   X(1) = U(1)*STHOPI +.MTHOPI
      IF( ITYPE1 .EQ. 2 ) X(1) = DEXP( X(1) )
C
C     2.  {RO}   --->  CORRELATED GAUSSIAN OR LOGNORMAL
C
      IF (ICS .EQ. 1) CALL CHLSKY (2,COVRO,BRO)
      DO 500 I = 1,2
500   UU(I) = U(I+1)
```

```
      DO 510 I = 1,2
      WK(I) = MRO(I)
      DO 510 J = 1,2
      WK(I) = WK(I) + BRO(I,J)*UU(J)
510   CONTINUE
      DO 520 I = 1,2
      XX(I) = WK(I)
520   IF( ITYPE2 .EQ. 2 )XX(I) = DEXP( WK(I) )
      DO 530 I = 1,2
530   X(I+1) = XX(I)
C
C     3.   {FT}   --->  CORRELATED GAUSSIAN OR LOGNORMAL
C
      IF (ICS .EQ. 1) CALL CHLSKY (3,COVFT,BFT)
      DO 600 I = 1,3
600   UU(I) = U(I+3)
      DO 610 I = 1,3
      WK(I) = MFT(I)
      DO 610 J = 1,3
      WK(I) = WK(I) + BFT(I,J)*UU(J)
610   CONTINUE
      DO 620 I = 1,3
      XX(I) = WK(I)
620   IF( ITYPE3 .EQ. 2 )XX(I) = DEXP( WK(I) )
      DO 630 I = 1,3
630   X(I+3) = XX(I)
C
C     4.  RHO   --->  GAUSSIAN OR LOGNORMAL
C
      X(7) = U(7)*SLRAT + MLRAT
      IF( ITYPE5 .EQ. 2 ) X(7) = DEXP( X(7) )
C
C     ------------------------------------------------------------------
C     ADD THE SHIFTS, IF ANY
C
      X(1) = X(1) + ATHOPI
      X(2) = X(2) + ARO(1)
      X(3) = X(3) + ARO(2)
      X(4) = X(4) + AFT(1)
      X(5) = X(5) + AFT(2)
      X(6) = X(6) + AFT(3)
      X(7) = X(7) + ALRAT
C
      THETA = X(1)*PI
      THETA0 = THETA
      ALPHA = X(2)
      N = X(3)
      J1C = X(4)/1000.
      C = X(5)*1000**( X(6)-1. )
      M = X(6)
      RHO = X(7)
      GO TO 888
C
C     ------------------------------------------------------------------
C     CALCULATE NET-SECTION-COLLAPSE MOMENT
C
C     1.  THOPI  --->  GAUSSIAN OR LOGNORMAL
C
535   X(1) = U(1)*STHOPI + MTHOPI
      IF( ITYPE1 .EQ. 2 ) X(1) = DEXP( X(1) )
C
C     2.  {SIG}   --->  CORRELATED GAUSSIAN OR LOGNORMAL
C
      IF (ICS .EQ. 1) CALL CHLSKY (2,COVSIG,BSIG)
      DO 700 I = 1,2
700   UU(I) = U(I+1)
```

```
      DO 710 I = 1,2
      WK(I) = MSIG(I)
      DO 710 J = 1,2
      WK(I) = WK(I) + BSIG(I,J)*UU(J)
710   CONTINUE
      DO 720 I = 1,2
      XX(I) = WK(I)
720   IF( ITYPE4 .EQ. 2 )XX(I) = DEXP( WK(I) )
      DO 730 I = 1,2
730   X(I+1) = XX(I)
C
C     3.  RHO   --->  GAUSSIAN OR LOGNORMAL
C
      X(4) = U(4)*SLRAT + MLRAT
      IF( ITYPE5 .EQ. 2 ) X(4) = DEXP( X(4) )
C
C     ------------------------------------------------------------------
C     ADD THE SHIFTS, IF ANY
C
      X(1) = X(1) + ATHOPI
      X(2) = X(2) + ASIG(1)
      X(3) = X(3) + ASIG(2)
      X(4) = X(4) + ALRAT
C
      THETA = X(1)*PI
      THETA0 = THETA
      SIGY = X(2)
      SIGU = X(3)
      RHO = X(4)
C
888   IF (THETA .LT. 0.) THETA = 0.
      IF (THETA0 .LT. 0.) THETA0 = 0.
      IF (ALPHA .LT. 0.) ALPHA = 0.
      IF (N .LT. 0.) N = 0.
      IF (J1C .LT. 0.) J1C = 0.
      IF (C .LT. 0.) C = 0.
      IF (M .LT. 0.) M = 0.
      IF (SIGY .LT. 0.) SIGY = 0.
      IF (SIGU .LT. 0.) SIGU = 0.
C
C     ------------------------------------------------------------------
C     THE INPUT ARE FORCED TO HAVE THE FOLLOWING VALUES TO VALIDATE
C     DETERMINISTIC RESULTS WITH NRCPIPE RESULTS;
C     COMMENT THIS WHEN DONE AND RE-COMPILE/LINK CODE
C
C      THETA = 1.1624
C      THETA0 = 1.1624
C      ALPHA = 4.87
C      N = 3.88
C      J1C = 8.11
C      C = 14.17
C      M = 0.6176
C      SIGY = 20.100
C      SIGU = 65.200
C      SIG0 = 20.100
C      RHO = 1.
C
      CALL PIPE (Q)
      Q = Q*RHO
C      ACTIVATE THE LINE BELOW TO GET INPUTS W/O DOING ANY CALC
C      IF (NUMFC .GE. 0) GO TO 889
      GFUN = Q - S
      IF (NUMFC .EQ. 0) GFUN = S - Q
      IF (GFUN .GE. 0.) NSUR = NSUR + 1
C
```

```
      IF (IOMCS .EQ. 1) GO TO 709

      IF (ICS .EQ. KSTEP*KK) GO TO 28
      GO TO 1000
28    KKK = KSTEP*KK
      PSMCS = REAL(NSUR)/REAL(ICS)
      BMCS = YNINVP (PSMCS)
      PFMCS = 1 - PSMCS
      PRINT 39, KKK,BMCS,PFMCS
39    FORMAT(1X,I10,' SAMPLES.....(BETA = ',F9.4,' PF = ',E20.6,')' )

      KK = KK + 1
      GO TO 1000
709   WRITE(3,*) Q
      IF (ICS .EQ. KSTEP*KK) GO TO 904
      GO TO 1000
904   KKK = KSTEP*KK
      PRINT*, KKK, ' SAMPLES.....'
      KK = KK+1
C
C     DE-COMMENT TO WRITE-OUT SAMPLE INPUT/OUTPUT TO CHECK NRCPIPE RES.
C
C      PRINT*
C      PRINT*, 'NUMFC: ', NUMFC
C      PRINT*, 'U(I): ', (U(I), I=1,NBV)
C      PRINT*, 'R,T: ', R,T
C      PRINT*, 'SIG0,E: ', SIG0,E
C      PRINT*, 'THETA0/PI: ', THETA0/3.141592654
C      PRINT*, 'ALPHA,N: ', ALPHA,N
C      PRINT*, 'J1C,C,M: ', J1C,C,M
C      PRINT*, 'SIGY,SIGU: ', SIGY,SIGU
C      PRINT*, 'Q: ', Q
C
C     DE-COMMENT TO WRITE-OUT INPUT TO CHECK ITS PROBABILITY DIST.
C
C889   WRITE (11,*) THETA0/PI
C      IF (NUMFC .NE. 3) WRITE (12,*) ALPHA
C      IF (NUMFC .NE. 3) WRITE (13,*) N
C      IF (NUMFC .EQ. 1 .OR. NUMFC .EQ. 2) WRITE (14,*) J1C*1000
C      IF (NUMFC .EQ. 2) WRITE (15,*) C/1000**(M-1.)
C      IF (NUMFC .EQ. 2) WRITE (16,*) M
C      IF (NUMFC .EQ. 3) WRITE (17,*) SIGY
C      IF (NUMFC .EQ. 3) WRITE (18,*) SIGU
C
C
1000  CONTINUE
C
      IF (IOMCS .EQ. 1) RETURN
      PSMCS = REAL(NSUR)/REAL(NMCS)
      BMCS = YNINVP (PSMCS)
      PFMCS = 1 - PSMCS
      PRINT*
      PRINT 39, KKK,BMCS,PFMCS
      PRINT*
      PRINT*
C
      PRINT*, 'BETA (Monte Carlo Simulation) =', BMCS
      PRINT*, 'ASSOCIATED PROBABILITY OF SURVIVAL =', PSMCS
      PRINT*, 'ASSOCIATED PROBABILITY OF FAILURE =', PFMCS
      PRINT*
C
C
      RETURN
      END
C
C
```

```
C     ================================================================
      SUBROUTINE NAME
C
      IMPLICIT REAL*8 (A-H,O-Z)
C
C     Title page for PROLBB execution
C     -----------------------------------------------------------------
C
      PRINT*, '******************************************************'
      PRINT*
      PRINT*, '                     CODE: PROLBB                      '
      PRINT*, '  (PRO)babilistic (L)eak-(B)efore-(B)reak (A)nalysis   '
      PRINT*
      PRINT*
      PRINT*,'                           by                           '
      PRINT*
      PRINT*,'                      sharif RAHMAN                     '
      PRINT*
      PRINT*
      PRINT*,'     1. Code PROLBB involves calculation of conditional '
      PRINT*,'        failure probability of a through-wall-cracked   '
      PRINT*,'        pipe under combined bending and tension loads   '
      PRINT*,'        for LBB applications                            '
      PRINT*
      PRINT*,'     2. The method of analysis is based on:             '
      PRINT*
      PRINT*,'        (a)    Elastic-Plastic Fracture Mechanics       '
      PRINT*,'        (b)    FORM/SORM/MCIS/MCS                       '
      PRINT*
      PRINT*, '     *************************************************'
      PRINT*
C
C
      RETURN
      END
C
C
C     ================================================================
      SUBROUTINE PIPE (Q)
C
C     Computes load-carrying capacity for applied crack driving force
C     -----------------------------------------------------------------
C
      IMPLICIT REAL*8  (A-H,O-Z)
      REAL*8 N,MAPP,J1C,M
      REAL*8 M1,M2,MACC
      REAL*8 JT,JTDA,JTDM
      REAL*8 JR,JRDA
      COMMON /MATL1/  ALPHA,N,SIG0,E,SIGY,SIGU
      COMMON /MATL2/  J1C,C,M
      COMMON /PROG2/  NUMFC
      COMMON /GEOM/   R,THETA,THETA0,T
      COMMON /SR03/   JT,JTDA,JTDM
      COMMON /SR04/   JR,JRDA
      COMMON /LOAD/   MAPP
      EXTERNAL FUNCD
C
      IF (NUMFC .EQ. 0) GO TO 505
      IF (NUMFC .EQ. 1) GO TO 515
      IF (NUMFC .EQ. 2) GO TO 525
      IF (NUMFC .EQ. 3) GO TO 535
      PRINT*, 'CHECK YOUR NUMFC -  STOP CALCULATIONS'
      STOP
C
C     -----------------------------------------------------------------
C     CALCULATE J-INTEGRAL
```

```
C
505   CALL JINTEG(MAPP)
      Q = JT
      RETURN
C
C     ------------------------------------------------------------------
C     CALCULATE INITIATION MOMENT
C
515   M1 = 0.
      M2 = 1000.
      MACC = 1.0D-4
      Q = RTSAFE(FUNCD,M1,M2,MACC)
      RETURN
C
C     ------------------------------------------------------------------
C     CALCULATE MAXIMUM MOMENT
C
525   M1 = 0.
      M2 = 1000.
      MACC = 1.0D-4
      Q = RTSAFE(FUNCD,M1,M2,MACC)
      IF (JTDA .GT. JRDA) RETURN
C
      A0 = R*THETA0
      M1 = 0.
      M2 = 1000.
C
      AL = R*THETA0
      AR = R*3.141592654 * 0.5
      IF ( (THETA0/3.141592654) .LT. 0.05 ) AR = 0.5*AR
704   ATRY = (AL + AR)/2.
      THETA = ATRY/R
      XXM = RTSAFE(FUNCD,M1,M2,MACC)
      FUNC = JTDA - JRDA
      PI = 3.141592654
C      PRINT*, 'THETA0/PI, THETA/PI:', THETA0/PI, THETA/PI
C      PRINT*, 'JT,JR: ', JT,JR
C      PRINT*, 'JTDA,JRDA,XXM: ', JTDA,JRDA,XXM
C      PRINT*
      IF ( DABS(FUNC) .LE. MACC) GO TO 111
      IF (FUNC .LT. 0.) GO TO 702
      IF (FUNC .GT. 0.) GO TO 703
      PRINT*, 'SOMETHING WRONG IN ROUTINE PIPE'
      STOP
C
702   AL = ATRY
      GO TO 704
C
703   AR = ATRY
      GO TO 704
111   Q = XXM
      RETURN
C
C     ------------------------------------------------------------------
C     CALCULATE NET-SECTION-COLLAPSE MOMENT
C
535   SIGF = 0.5*( SIGY + SIGU )
      Q = 4.0*SIGF*R*R*T* ( COS(THETA/2) - 0.5*SIN(THETA) )
C
C
      RETURN
      END
C
C
C
C     ================================================================
```

```
      SUBROUTINE FUNCD(MM,FUN,DFUN)
C
C     Defines nonlinear function that needs to be solved for load
C     ------------------------------------------------------------------
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 MM
      REAL*8 JT,JTDA,JTDM
      REAL*8 JR,J1C,M,JRDA
      COMMON /SR03/   JT,JTDA,JTDM
      COMMON /SR04/   JR,JRDA
C
      CALL JINTEG(MM)
      FUN = JT - JR
      DFUN = JTDM
C
      RETURN
      END
C
C
C     =================================================================
      SUBROUTINE JINTEG(MOM)
C
C     Computes J for given applied loads (LBB.ENG2 method)
C     ------------------------------------------------------------------
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 N,MOM,M
      REAL*8 JE1,JE2,JE3,JE1DT,JE2DT,JE3DT,JE1DM,JE2DM,JE3DM
      REAL*8 JP1,JP2,JP1DT,JP2DT,JP1DM,JP2DM
      REAL*8 JE,JEDT,JEDA,JEDM
      REAL*8 JP,JPDT,JPDA,JPDM
      REAL*8 JT,JTDA,JTDM
      REAL*8 J1C,JR,JRDA
      REAL*8 IB,IBDT
      REAL*8 LB,LBDT
      REAL*8 IT,ITDT
      REAL*8 LT,LTDT
      REAL*8 IB1,IB2,IB3,IT1,IT2,IT3
      REAL*8 KHAT
      COMMON /SR53/   NBV,NAUS,IDIM,NPVEC,NPRI,ISTEM,IUDEF
      COMMON /MATL1/  ALPHA,N,SIG0,E,SIGY,SIGU
      COMMON /MATL2/  J1C,C,M
      COMMON /GEOM/   R,THETA,THETA0,T
C      COMMON /SR01/   JE,JEDY,JEDA,JEDM
C      COMMON /SR02/   JP,JPDY,JPDA,JPDM
      COMMON /SR03/   JT,JTDA,JTDM
      COMMON /SR04/   JR,JRDA
      COMMON /PROG1/  SSTART,SEND,DS,S
      COMMON /PROG2/  NUMFC
      COMMON /PRESS/  P
C
C      PRINT*, 'R,T: ', R,T
C      PRINT*, 'SIG0,E: ', SIG0,E
C      PRINT*, 'THETA/PI: ', THETA/3.141592654
C      PRINT*, 'ALPHA,N: ', ALPHA,N
C      PRINT*, 'J1C,C,M: ', J1C,C,M
C      PRINT*, 'SIGY,SIGU: ', SIGY,SIGU
C      PRINT*
C
C
C     ------------------------------------------------------------------
C     0.  DEFINE SOME BASIC TERMS
C
      PI = 3.141592654
      X = R/T
```

```
      Y = THETA/PI
      Z1 = 1.0 + 1./(2.*N) - 1.
      Z2 = 1.5 + 1./(2.*N) - 1.
      KHAT = 0.5 * DSQRT(PI) * GAMMA(Z1)/GAMMA(Z2)
      D1 = (ALPHA/(E*SIG0**(N-1)))*(1./(N+1))*(PI*R/2.)*
     &     (1./(2.*PI*R*T))**(N+1)
      D2 = (ALPHA/(E*SIG0**(N-1)))*(1./(N+1))*(PI*R/2.)*
     &     (1./(PI*R**2*T))**(N+1)
C
      AB = -3.26543 + 1.52784*X - 0.072698*X**2 + 0.0016011*X**3
      BB = 11.36322 - 3.91412*X + 0.186190*X**2 - 0.0040990*X**3
      CB = -3.18609 + 3.84763*X - 0.183040*X**2 + 0.0040300*X**3
      AT = -2.02917 + 1.67763*X - 0.07987*X**2 + 0.00176*X**3
      BT =  7.09987 - 4.42394*X + 0.21036*X**2 - 0.00463*X**3
      CT =  7.79661 + 5.16676*X - 0.24577*X**2 + 0.00541*X**3
C
      IB1 = AB/7. + (Y*BB)/9. + (Y**2) * CB/11.
      IB2 = (AB**2)/2.5 + Y*AB*BB/1.5 + Y**2*(2.*AB*CB + BB**2)/3.5
      IB3 = (Y**3)*BB*CB/2. + (Y**4)*CB*CB/4.5
      IT1 = 2.*AT/7. + (2.*Y*BT)/9. + (Y**2) * 2.*CT/11.
      IT2 = (AT**2)/2.5 + Y*2.*AT*BT/3. + Y**2*(2.*AT*CT + BT**2)/3.5
      IT3 = (Y**3)*2.*BT*CT/4. + (Y**4)*CT*CT/4.5
C
C
C     -----------------------------------------------------------------
C     1.  F-, I-, Y-, L-, TBEN-FUNCTIONS AND THEIR DERIVATIVES
C
C     TENSION
C
      FT = CT*(THETA/PI)**3.5+BT*(THETA/PI)**2.5+AT*(THETA/PI)**1.5+1
      IT = 2*THETA**2*(4*IT1*(THETA/PI)**1.5+(IT3+IT2)*THETA**3/PI**3+1)
      YT = -2*ASIN(SIN(THETA)/2.0)/PI-THETA/PI+1
      LT = YT**(1-N)
      TBEN = (P*R*SIN(THETA/2.0)+MOM)**(N+1)
C
C                                     FIRST DERIVATIVES
C
      FTDT = SQRT(THETA/PI)*(7*CT*THETA**2+5*BT*PI*THETA+3*AT*PI**2)/PI*
     1   *3/2.0
      ITDT = 4*THETA*(CT*(THETA/PI)**3.5+BT*(THETA/PI)**2.5+AT*(THETA/PI
     1   )**1.5+1)**2
      YTDT = -(SQRT(4-SIN(THETA)**2)+2*COS(THETA))/(PI*SQRT(4-SIN(THETA)
     1   **2))
      LTDT = -(N-1)*YTDT/YT**N
      TBENDT = (N+1)*P*R*COS(THETA/2.0)*(P*R*SIN(THETA/2.0)+MOM)**N/2.0
      TBENDM = (N+1)*(P*R*SIN(THETA/2.0)+MOM)**N
C
C
C     BENDING
C
      FB = CB*(THETA/PI)**3.5+BB*(THETA/PI)**2.5+AB*(THETA/PI)**1.5+1
      IB = 2*THETA**2*(8*IB1*(THETA/PI)**1.5+(IB3+IB2)*THETA**3/PI**3+1)
      LB = 4**(1-2*N)*PI**(N-1)*(PI/KHAT)**N*(COS(THETA/2.0)-SIN(THETA)/
     1   2.0)**(1-N)
C
C                                     FIRST DERIVATIVES
C
      FBDT = SQRT(THETA/PI)*(7*CB*THETA**2+5*BB*PI*THETA+3*AB*PI**2)/PI*
     1   *3/2.0
      IBDT = 4*THETA*(CB*(THETA/PI)**3.5+BB*(THETA/PI)**2.5+AB*(THETA/PI
     1   )**1.5+1)**2
      LBDT = 2*(N-1)*2**N*PI**(N-1)*(PI/KHAT)**N*(COS(THETA)+SIN(THETA/2
     1   .0))/(4**(2*N)*(2*COS(THETA/2.0)-SIN(THETA))**N)
C
C
C     -----------------------------------------------------------------
```

```
C      2.  H-FUNCTIONS AND THEIR DERIVATIVES
C
C      TENSION
C
       HT1 = 4*FT**2*THETA/IT
       HT2 = LTDT/LT
       HT = HT1 + HT2
C
       HT1DT = -4*FT*(FT*ITDT*THETA-2*FTDT*IT*T
     1   HETA-FT*IT)/IT**2
       HT2DT = (LT*LTDTT-(LTDT)**2)/LT**2
       HTDT = HT1DT + HT2DT
C
C      BENDING
C
       HB1 = 4*FB**2*THETA/IB
       HB2 = (N-1)*(COS(THETA)+SIN(THETA/2.0))/(COS(THETA/2.0)-SIN(THETA)
     1   /2.0)/2.0
       HB = HB1 + HB2
C
       HB1DT = -4*FB*(FB*IBDT*THETA-2*FBDT*IB*T
     1   HETA-FB*IB)/IB**2
       HB2DT = (N-1)*(2*SIN(THETA)**2-5*COS(THETA/2.0)*SIN(THETA)+2*COS(T
     1   HETA)**2+4*SIN(THETA/2.0)*COS(THETA)+2*SIN(THETA/2.0)**2+2*COS(
     2   THETA/2.0)**2)/(SIN(THETA)-2*COS(THETA/2.0))**2/2.0
       HBDT = HB1DT + HB2DT
C
C
C      ----------------------------------------------------------------
C      3.  J-INTEGRAL FOR COMBINED LOADS AND THEIR DERIVATIVES
C
C        NOTE:  JT = JE + JP
C
C      ELASTIC COMPONENT
C
       JE1 = FT**2*P**2*THETA/(E*PI*R*T**2)/4.0
       JE2 = FB**2*THETA*(P*R*SIN(THETA/2.0)+MOM)**2/(E*PI*R**3*T**2)
       JE3 = FB*FT*P*THETA*(P*R*SIN(THETA/2.0)+MOM)/(E*PI*R**2*T**2)
       JE = JE1 + JE2 + JE3
C
C                                     FIRST DERIVATIVES
C
       JE1DT = FT*P**2*(2*FTDT*THETA+FT)/(E*PI*R*T**2)/4.0
       JE2DT = FB*(P*R*SIN(THETA/2.0)+MOM)*(2*FBDT*P*R*THETA*S
     1   IN(THETA/2.0)+FB*P*R*SIN(THETA/2.0)+FB*P*R*THETA*COS(THETA/2.0)
     2   +2*FBDT*MOM*THETA+FB*MOM)/(E*PI*R**3*T**2)
       JE3DT = P*(2*FB*FTDT*P*R*THETA*SIN(THETA/2.0)+2*FBDT
     1   *FT*P*R*THETA*SIN(THETA/2.0)+2*FB*FT*P*R*SIN(THETA/
     2   2.0)+FB*FT*P*R*THETA*COS(THETA/2.0)+2*FB*FTDT*MOM*TH
     3   ETA+2*FBDT*FT*MOM*THETA+2*FB*FT*MOM)/(E*PI*R**2*T**2)/
     4   2.0
       JEDT = JE1DT + JE2DT + JE3DT
       JEDA = JEDT/R
C
       JE1DM = 0.
       JE2DM = 2*FB**2*THETA*(P*R*SIN(THETA/2.0)+MOM)/(E*PI*R**3*T**2)
       JE3DM = FB*FT*P*THETA/(E*PI*R**2*T**2)
       JEDM = JE1DM + JE2DM + JE3DM
C
C
C      PLASTIC COMPONENT
C
       JP1 = D1*HT*IT*LT*P**(N+1)
       JP2 = D2*HB*IB*LB*TBEN
       JP = JP1 + JP2
C
```

```
C                                     FIRST DERIVATIVES
C
      JP1DT = D1*(HT*IT*LTDT+HT*ITDT*LT+HTDT
     1   *IT*LT)*P**(N+1)
      JP2DT = D2*(HB*IB*LB*TBENDT+HB*IB*LBDT*T
     1   BEN+HB*IBDT*LB*TBEN+HBDT*IB*LB*TBEN)
      JPDT = JP1DT + JP2DT
      JPDA = JPDT/R
C
      JP1DM = 0.
      JP2DM = D2*HB*IB*LB*TBENDM
      JPDM = JP1DM + JP2DM
C
C
C     ------------------------------------------------------------------
C     4.  ADD ELASTIC AND PLASTIC COMPONENTS
C
      JT = JE + JP
      JTDA = JPDA + JEDA
      JTDM = JPDM + JEDM
C
C     ------------------------------------------------------------------
C     J-RESISTANCE CURVE
C
      IF (NUMFC .EQ. 0) RETURN
      IF (NUMFC .EQ. 1) GO TO 333
      GO TO 334
333   JR = J1C
      RETURN
334   A = R*THETA
      A0 = R*THETA0
      IF (A .LT. A0) GO TO 111
      IF (A .EQ. A0) A = A0 + 1.0D-10
      JR = J1C + C*(A-A0)**M
      JRDA = C*M*(A-A0)**(M-1)
      RETURN
C
111   PRINT*, 'CRACK GROWTH IS NEGATIVE ! HA ! STOP !'
C
      RETURN
      END
C
C
C     ==================================================================
      FUNCTION GAMMA(Z)
C
C     Defines the gamma function
C     ------------------------------------------------------------------
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 GAMMA
C
C
      GAMMA = 1. - 0.5777191652*Z   + 0.988205891*Z**2
     &           - 0.897056937*Z**3 + 0.918206857*Z**4
     &           - 0.756704078*Z**5 + 0.482199394*Z**6
     &           - 0.193527818*Z**7 + 0.035868343*Z**8
C
C
      RETURN
      END
C
C
C
C     ==================================================================
      FUNCTION RTSAFE(FUNCD,X1,X2,XACC)
```

```
C
C     Solves nonlinear equation by the bi-section method (N. Recipes)
C     ----------------------------------------------------------------
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 RTSAFE
      PARAMETER (MAXIT=1000)
      CALL FUNCD(X1,FL,DF)
      CALL FUNCD(X2,FH,DF)
      IF(FL*FH.GE.0.) PAUSE 'root must be bracketed'
      IF(FL.LT.0.)THEN
        XL=X1
        XH=X2
      ELSE
        XH=X1
        XL=X2
        SWAP=FL
        FL=FH
        FH=SWAP
      ENDIF
      RTSAFE=.5*(X1+X2)
      DXOLD=ABS(X2-X1)
      DX=DXOLD
      CALL FUNCD(RTSAFE,F,DF)
      DO 11 J=1,MAXIT
        IF(((RTSAFE-XH)*DF-F)*((RTSAFE-XL)*DF-F).GE.0.
     *       .OR. ABS(2.*F).GT.ABS(DXOLD*DF) ) THEN
          DXOLD=DX
          DX=0.5*(XH-XL)
          RTSAFE=XL+DX
          IF(XL.EQ.RTSAFE)RETURN
        ELSE
          DXOLD=DX
          DX=F/DF
          TEMP=RTSAFE
          RTSAFE=RTSAFE-DX
          IF(TEMP.EQ.RTSAFE)RETURN
        ENDIF
        IF(ABS(DX).LT.XACC) RETURN
        CALL FUNCD(RTSAFE,F,DF)
        IF(F.LT.0.) THEN
          XL=RTSAFE
          FL=F
        ELSE
          XH=RTSAFE
          FH=F
        ENDIF
11    CONTINUE
      PAUSE 'RTSAFE exceeding maximum iterations'
      RETURN
      END
C
C
C     ================================================================
      FUNCTION RANGEN(IX)
C
C     Random number generator for standard uniform variable
C     ----------------------------------------------------------------
C
      IMPLICIT REAL*8 (A-H,O-Z)
      INTEGER A, P, IX, B15, B16, XHI, XALO, LEFTLO, FHI, K
      DATA A/16807/,B15/32768/,B16/65536/,P/2147483647/
C
      XHI = IX/B16
      XALO = (IX - XHI*B16)*A
      LEFTLO = XALO/B16
```

```
      FHI = XHI*A + LEFTLO
      K = FHI/B15
      IX = (((XALO - LEFTLO*B16) - P) + (FHI - K*B15)*B16) + K
      IF (IX.LT.0) IX = IX + P
      RANGEN = IX*4.656612875E - 10
C
      RETURN
      END
C
C
C     ==============================================================
      SUBROUTINE CHLSKY (NVAR,COV,B)
C
C     Performs Cholesky decomposition
C     --------------------------------------------------------------

      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 COV(NVAR,NVAR), B(NVAR,NVAR)
C
      B(1,1) = DSQRT( COV(1,1) )
      DO 100 K = 2,NVAR
      DO 150 I = 1,K-1
C
      SUM1 = 0.
      IF (I .EQ. 1) GO TO 111
      DO 200 M = 1,I-1
200   SUM1 = SUM1 + B(I,M)*B(K,M)
111   B(K,I) = ( COV(K,I) - SUM1 )/B(I,I)
150   CONTINUE
C
      SUM2 = 0.
      DO 300 M = 1,K-1
300   SUM2 = SUM2 + B(K,M)**2
      B(K,K) = DSQRT( COV(K,K) - SUM2 )
100   CONTINUE
C
      RETURN
      END
```

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11. ABSTRACT (200 words or less)

Regulatory Guide 1.45, "Reactor Coolant Pressure Boundary Leakage Detection Systems," was published by the U.S. Nuclear Regulatory Commission (NRC) in May 1973, and provides guidance on leak detection methods and system requirements for Light Water Reactors. Additionally, leak detection limits are specified in plant Technical Specifications and are different for Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs). These leak detection limits are also used in leak-before-break evaluations performed in accordance with Draft Standard Review Plan, Section 3.6.3, "Leak Before Break Evaluation Procedures" where a margin of 10 on the leak detection limit is used in determining the crack size considered in subsequent fracture analyses. This study was requested by the NRC to: (1) evaluate the conditional failure probability for BWR and PWR piping for pipes that were leaking at the allowable leak detection limit, and (2) evaluate the margin of 10 to determine if it was unnecessarily large. A probabilistic approach was undertaken to conduct fracture evaluations of circumferentially cracked pipes for leak-rate-detection applications. Sixteen nuclear piping systems in BWR and PWR plants were analyzed to evaluate conditional failure probability and effects of crack-morphology variability on the current margins used in leak rate detection for leak-before-break.

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