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NRC Leak-Before-Break (LBB.NRC) Analysis Method for Circumferentially Through-Wall Cracked Pipes Under Axial Plus Bending Loads

Topical Report

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Prepared for
U.S. Nuclear Regulatory Commission

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NRC Leak-Before-Break (LBB.NRC) Analysis Method for Circumferentially Through-Wall Cracked Pipes Under Axial Plus Bending Loads

Topical Report

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CAVIAT

This document records the present status of the LBB.NRC fracture mechanics computer program for analysis of degraded piping. Only circumferential through-wall cracks are considered. Because of the developmental nature of leak-before-break estimation procedures, neither the NRC nor BCL assume responsibility for the accuracy of results. The LBB.NRC methodology is expected to evolve with time as more pipe experiments are performed, particularly with larger diameter and thicker wall pipes as are found in PWR main coolant systems for instance.

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ABSTRACT

The fracture mechanics analysis procedure used by the NRC to evaluate utility leak-before-break submittals is described in this report. This methodology is an estimation technique based on J-tearing theory. This approach is intended to provide a conservative approximation of the applied crack driving parameter, J, for postulated through-wall leakage-size cracks in nuclear power plant pipes. Piping integrity evaluations can then be accomplished for various loading conditions and assumed flaw sizes. Because the method can be used to obtain a rather rapid computer generated approximation of the applied crack driving parameters, NRC evaluation of applicant or licensee submittals can be accomplished in an expeditious manner without resorting to elaborate finite element techniques. The NRC program should not be considered as fixed in time. As piping fracture mechanics technology matures, it may be refined in the future.

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ACKNOWLEDGMENTS

This document was prepared as part of the NRC/BCL Degraded Piping Program. Various personnel at the NRC and at BCL made contributions in its preparation. The authors wish to acknowledge this help. In particular at the NRC, Dr. Sam Lee and John Tsao participated in generating the LBB.NRC computer program and Dr. Lee prepared the supplemental programs and plotting routines via Lotus 123. Earlier versions of LBB.NRC were programmed by Dr. John Schiffgens who is now with the ACRS staff. Others including K. Wichman and E. Sullivan helped in proofreading.

Battelle staff members making valuable contributions to this report include J. Ahmad, B. Blanton, and B. Saffell. Dr. Jwo Pan, currently at the University of Michigan, also assisted in development efforts while he was at Battelle.

1. INTRODUCTION

This report describes the fracture mechanics analysis procedure developed by the NRC staff and used in its review of leak-before-break submittals. The leak-before-break (LBB) approach is the application of fracture mechanics technology to demonstrate that high energy fluid system piping is very unlikely to experience double-ended ruptures or their equivalent as longitudinal or diagonal splits. This means that, in the unlikely event pipe cracks develop during operation, leakage monitoring systems and/or inservice inspections must be capable of detecting these cracks long before they grow to a sufficient size to cause concern for the overall integrity of the pipe(s).

The application of LBB technology requires:

1) Knowledge of the loads to which a pipe or piping system is or could be subjected to during operation;

2) Details of the geometry and materials properties of the pipe(s); and

3) A method for analyzing pipes with flaws; that is, a fracture mechanics procedure.

Each of the three areas listed above is subject to inherent uncertainties. Therefore, any LBB analysis for licensing purposes must include safety margins that adequately envelop these uncertainties. The NRC limitations and acceptance criteria for the application of LBB technology are provided in Volume 3 of NUREG-1061 (Ref. 1). Also, the state-of-the-art status of LBB technology is described in some detail in this reference.

The NRC fracture mechanics analytical procedure described in the following sections of this report was developed primarily for use by the NRC staff in its evaluations of LBB submittals by the nuclear industry. It is based on earlier work by Paris and Tada in NUREG/CR-3464 (Ref. 2) with modifications by the NRC staff to account for the strain-hardening characteristics of typical nuclear facility piping materials. These modifications and the rationale for them are discussed in this document. The reader is assumed to have a basic understanding of stress analysis, materials technology and fracture mechanics.

The systems of a nuclear facility for which LBB is generally applied are made of ductile materials. Ductile fracture mechanics (FM) methods employ analytical techniques ranging from elaborate finite-element models (FEM) to various FM estimation procedures to simple limit-load analyses. FEM analyses are expensive and time consuming to perform and the purpose of the simple models is to facilitate the performance of FM analyses in a timely and relatively inexpensive manner.

Although all FM methods are based to some extent on theory, it is necessary to include certain idealizing assumptions related to crack shapes, consistent geometry and crack behavior if the crack initiates and grows as a result of increased loads. Also under most circumstances, it is necessary to obtain materials property data from other than the component being evaluated.

In reality, however, actual flaws can have complex shapes, the component being evaluated may deform under high loads particularly in the vicinity of the flaw (e.g., a pipe may ovalize and its wall may become thinner near the flaw) and a growing crack may develop shear lips. These reasons plus the inherent variability of material properties from specimen to specimen lead to the conclusion that perfect correspondence between analytical and experimental results should not be expected. On the other hand, to be useful at all, analytical methods should be able to predict results within an acceptable uncertainty band which can then be accounted for by appropriate margins.

The main objective of the NRC FM analytical procedure is to obtain a conservative approximation of the applied crack driving parameter, J, for postulated through-wall leakage-size cracks in nuclear power facility pipes to demonstrate their integrity under specified loading conditions; that is, to demonstrate that they will not experience a large rupture. A secondary objective is to have a relatively simple analytical procedure that can be used in an expeditious manner to cross-check results in submittals by applicants or licensees.

To meet the above objectives, the NRC FM method includes certain simplifying assumptions. Some of these assumptions are the same as in the Paris-Tada report (Ref. 2), while others were introduced by the NRC staff based on engineering judgement. Although not theoretically rigorous, this approach can be justified if the method of analysis results in reasonable predictions of pipe experimental results and/or the results are in reasonable agreement with those of more sophisticated FM analyses.

The staff recognizes the desirability of adhering to deformation theory to the extent practicable; however, in view of the overall analytical uncertainties cited earlier (loads, material properties, pipe ovalization, wall thinning, etc.), engineering judgement must still be used in interpreting results. Thus, the NRC requires that margins of safety be included in any LBB application for licensing purposes. This does not mean that this or any other analytical procedure should not continue to be refined as more experience and knowledge is gained from future piping experiments. As the analytical technology evolves to become more precise, margins may be reduced accordingly.

The needs for FM analyses in the licensing arena are somewhat different from those of an experimenter. Typical piping loads in a nuclear facility piping system are generally low enough so that even with a modest postulated leakage size through-wall crack, the margin to incipient failure of the pipe is reasonably large (or is required to be so). For licensing purposes, a determination of the loads and crack driving parameter, J, at crack initiation (on-set of crack growth) is more important than prediction of J at ultimate failure loads because of the margins used for the latter. At most in its evaluations, the NRC staff considers only short crack growth (1/4 inch or less)* provided that valid material J-resistance (J-R) data exist for this range. By contrast, pipe test experiments may result in significant crack growth when the pipe is tested to failure. Based on experience to date, these larger crack growths can be quite complex. Even sophisticated analyses cannot predict this crack behavior precisely and engineering (and/or metallurgical) judgement is required to interpret the results.

This report describes the NRC J-estimation procedure (LBB.NRC) for assessing the stability of through-wall cracked piping systems subjected to axial loads including the affect of internal pressure plus bending loads. The LBB.NRC method represents an alternative to numerically developed J-estimation schemes, such as the EPRI-technique (Ref. 3). This method should be considered as state-of-the-art, as improvements in the technique should be expected with time. This analytical procedure is based on the NUREG/CR-3464 (Ref. 2) procedure, but modified to account for material strain hardening.

A description of the LBB.NRC method is presented in Section 2. The reader may obtain an applications-oriented, working-knowledge of the procedure by studying Section 2. Detailed information related to the development of the NRC.LBB method is provided in Appendices A through D. Section 3 and the appendices describe some of the assumptions involved with the technique and, consequently, the potential limitations inherent in the LBB.NRC method. Also included is a brief discussion of the theoretical limitations inherent in J-tearing theory. It must always be kept in mind that a J-estimation procedure for characterizing elastic-plastic fracture of piping systems is only as good as the limitations necessarily imposed on J-tearing theory.

The LBB.NRC method is implemented in a computer program called LBB.NRC. Example calculations are provided in the Appendices E, F and G with a copy of the LBB.NRC computer program given in Appendix H. The remaining appendices supplement the descriptive information in Section 2. Note in Appendix C that the NRC staff fits the true stress-true strain data in a certain way to obtain the Ramberg-Osgood parameters. The results of any J-estimation procedure depend on the values selected for these parameters. Thus, to duplicate NRC results, users of the program must fit the stress-strain data in the same manner.

In summary, the NRC staff recognizes the state-of-the-art status of piping FM analyses. Thus, the reader is advised that the procedures

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* This limit is an example only and is subject to modification as more experience is gained.

described in this document may evolve with time as more pipe tests are conducted, especially larger and thicker walled pipe tests. In the interim, the procedure is being used by the staff in its evaluations of licensing submittals in conjunction with adequate margins to account for uncertainties. The staff believes that the LBB.NRC procedure yields acceptable results for the purpose intended. A typical example of the staff analysis actually used in a licensing case is provided in Appendix F. Also shown in this appendix are the results determined by the organization that submitted the LBB application. They used both a finite element procedure and a procedure based on the EPRI approach described in Reference 3. The results of all three analyses are in reasonable agreement at the applied loads. The NRC staff also benchmarked its procedure against a series of pipe tests described in Appendix A of Reference 1. As described in Appendix E, the NRC staff subsequently revised these calculations using its current procedure for determining the Ramberg-Osgood parameters and obtained more conservative results. Finally, in Appendix G, illustrative results of the staff's procedure with large axial as well as bending loads are provided.

2. LEAK-BEFORE-BREAK ANALYSIS

The NRC leak-before-break program for degraded piping is based on and generally follows the procedures of NUREG/CR-3464 (Ref. 2) except for the modifications discussed in this document. In this section linear-elastic fracture mechanics methodology is first discussed. This includes definition of terms and statement of geometric assumptions. Secondly, extension of the linear-elastic methodology to elastic-plastic conditions is described.

2.1 Geometry Assumptions (See Figure 2.1)

- Thin-wall pipe, $4 \leq R/t \leq 16$ (If the R/t is outside this range, LBB.NRC assumes either 4 or 16 as appropriate.)
- Thin-wall crack of half angle, θ_o
- R = mean radius
- t = wall thickness.

Although a pipe with an R/t = 4 is not really a thin-walled pipe, typical applications of this procedure for licensing purposes are for pipes with higher R/t ratios for which the thin-wall assumption is reasonable in view of other uncertainties.

2.2 Applied Stresses

F and M are the applied loads at the ends of a pipe where:

- F = axial load including the effect of pressure
- M = applied moment
- Nominal axial stress = $\sigma_t = \dfrac{F}{2\pi Rt}$
- Nominal bending stress = $\sigma_b = \dfrac{M}{\pi R^2 t}$
- ϕ = kink angle.

2.3 Normalized Parameters

This report utilizes normalized or non-dimensional parameters which are defined in the various sections of the report. This is done for analytical convenience and to be consistent with NUREG/CR-3464 (Ref. 2). For instance, the bending and tensile stresses are normalized by the flow stress.

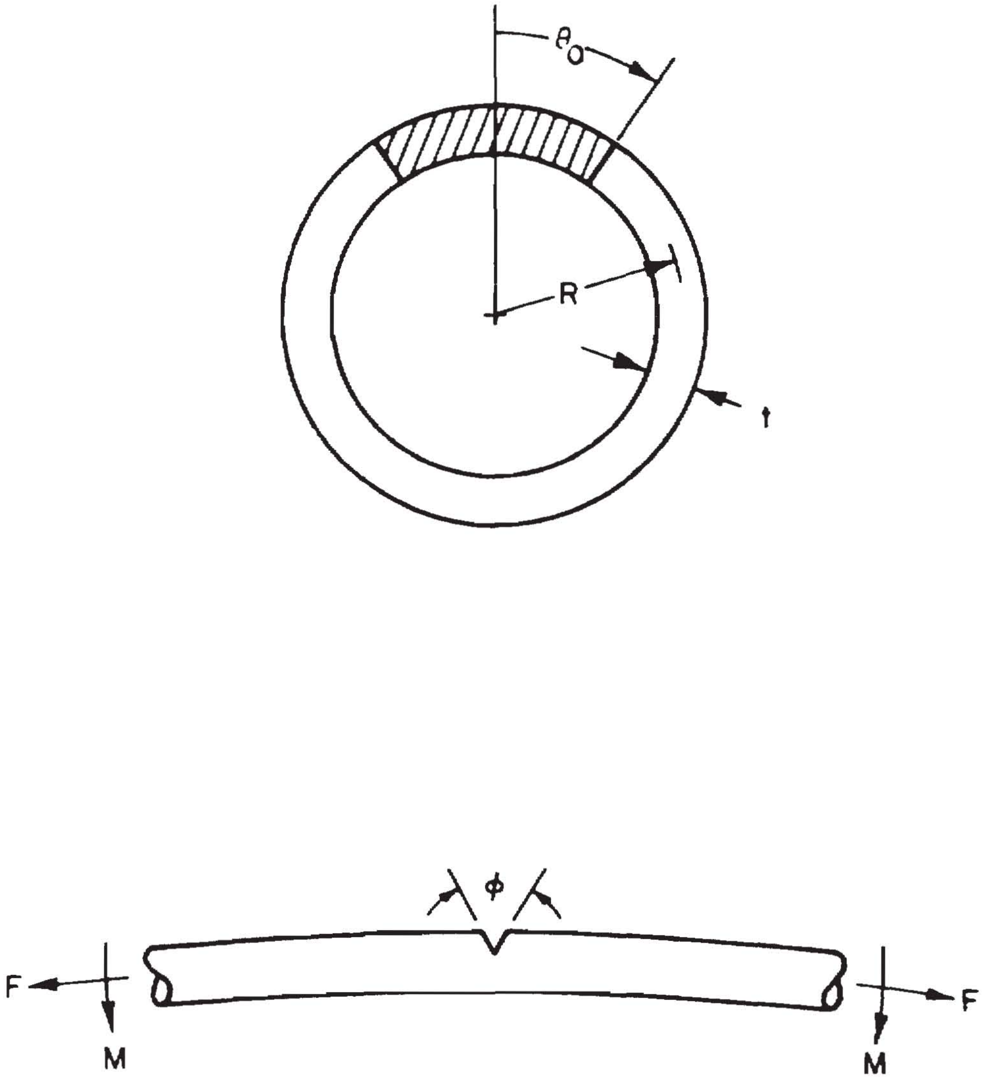

Figure 2.1. Schematic of circumferential through-wall cracked pipe.

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$$\text{Flow stress} = \sigma_f \equiv \frac{\sigma_u + \sigma_y}{2}$$

σ_u = ultimate strength of the material
σ_y = yield strength of the material.

The normalized stresses are thus:

$$S_t = \frac{\sigma_t}{\sigma_f} \quad , \quad S_b = \frac{\sigma_b}{\sigma_f} \quad .$$

2.4 Linear-Elastic Fracture Mechanics

In the low stress range, linear elastic fracture mechanics (LEFM) is applicable. The basic LEFM equation is:

$$K = \sigma \sqrt{\pi a}\, F(a) \qquad (2.1)$$

where:

K is the stress intensity factor
σ = nominal far field stress
a = crack length or depth
F(a) = a geometry factor (F function).

For the assumed through-wall circumferential crack,

$$a = R\theta \quad .$$

where θ is 1/2 the total crack angle. In this report $K \equiv K_I$, that is the mode I stress intensity factor.

Because there are two components of stress,

$$K = K_t + K_b = \sigma_t\sqrt{\pi R\theta}\, F_t(\theta) + \sigma_b\sqrt{\pi R\theta}\, F_b(\theta) \quad . \qquad (2.2)$$

In NUREG/CR-3464 (Ref. 2), simplified formulas for $F_t(\theta)$ and $F_b(\theta)$ are used. The NRC program utilizes F-functions (Ref. 4) based on Sander's analysis of circumferentially cracked pipe under tension and bending.

$$F_t = 1 + A_t\left(\frac{\theta}{\pi}\right)^{1.5} + B_t\left(\frac{\theta}{\pi}\right)^{2.5} + C_t\left(\frac{\theta}{\pi}\right)^{3.5} \quad \text{for tension}$$

$$(2.3)$$

$$F_b = 1 + A_b\left(\frac{\theta}{\pi}\right)^{1.5} + B_b\left(\frac{\theta}{\pi}\right)^{2.5} + C_b\left(\frac{\theta}{\pi}\right)^{3.5} \quad \text{for bending} \quad .$$

The coefficients of the F-functions (A_t, B_t, C_t, A_b, B_b, and C_b) are a function of the R/t ratio of the pipe. A more detailed discussion of them is provided in Appendix A.

2.5 Plastic Zone Size Correction

As the stress level increases, a plastic zone forms ahead of the crack. The depth of this zone is usually designated as "r_y". In the literature, various authors define r_y by different equations. In this report, the Irwin plastic zone correction* is used:

$$r_y = \frac{1}{\beta\pi} \left(\frac{K}{\sigma_f}\right)^2 \quad . \tag{2.4}$$

This equation is consistent with NUREG/CR-3464 except that α is used in the NUREG instead of β and the flow stress, σ_f, is used as the limiting stress. The term β is used so as to avoid confusion with the Ramberg-Osgood parameter "α" to be introduced later.

Generally, β is taken as 2 for plane stress or 6 for plane strain. The NRC program, LBB.NRC, utilizes the rationale of NUREG/CR-3464 and derives a unique value of β which forces the solution to reach the limit load of a cracked pipe for large K values. Discussion of this assumption may be found in Section 3.

2.6 Derivation of β for Bending Plus Axial Loads

$$K = \sigma_b \sqrt{\pi R \theta_e}\, F_b(\theta_e) + \sigma_t \sqrt{\pi R \theta_e}\, F_t(\theta_e) \tag{2.5}$$

where $\theta_e = \theta_o + \Delta\theta$ is the effective half-crack angle corrected for plastic zone size.

$\theta_o = \frac{a}{R}$, is the original crack size, and

$\Delta\theta = \frac{r_y}{R}$, is the plastic zone correction.

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* The plastic zone size is, of course, not circular as suggested here. This is merely an Irwin correction to the plastic zone size (Ref. 5) to estimate the reduced compliance of the pipe due to plastic deformation near the crack tip.

Using the normalized stresses and squaring the above equation:

$$\frac{K^2}{\pi R \sigma_f^{\,2}} \equiv G(\theta_e) = \theta_e [S_b F_b(\theta_e) + S_t F_t(\theta_e)]^2 \ . \qquad (2.6)$$

Note: This $G(\theta)$ differs from that in NUREG/CR-3464 in that it includes the relative stresses.

Also, from

$$r_y = \frac{1}{8\pi} \frac{K^2}{\sigma_f^{\,2}} = R(\theta_e - \theta_o) \qquad (2.7)$$

$$\frac{K^2}{\pi R \sigma_f^{\,2}} = G(\theta_e) = \beta(\theta_e - \theta_o) \quad . \qquad (2.8)$$

These two values of $G(\theta_e)$ must be equal for a given stress level. S_p is defined as the value of S_b at fully plastic limit load conditions:

$$S_b \equiv S_p = \frac{4}{\pi} [\cos(\frac{\theta_o}{2} + \frac{\pi}{2} S_t) - \frac{1}{2} \sin \theta_o] \quad .$$

The rationale presented in NUREG/CR-3464 requires that at the limit load the straight line, labeled (2) in Figure 2.2, be tangent to the curve labeled (1). This occurs at $\theta = \theta_F$. At lower stress levels:

$$g(\theta) = \theta [S_b F_b(\theta) + S_t F_t(\theta)]^2$$

from which θ_e can be determined once β and θ_F are established (see the dashed curve in Figure 2.2). As shown in this figure:

$$\beta = \frac{G(\theta_F)}{(\theta_F - \theta_o)} = G'(\theta_F)$$

or $\theta_o = \theta_F - \frac{G(\theta_F)}{G'(\theta_F)}$ where the prime denotes $\frac{\partial}{\partial\theta}$, the derivative of G with respect to θ.

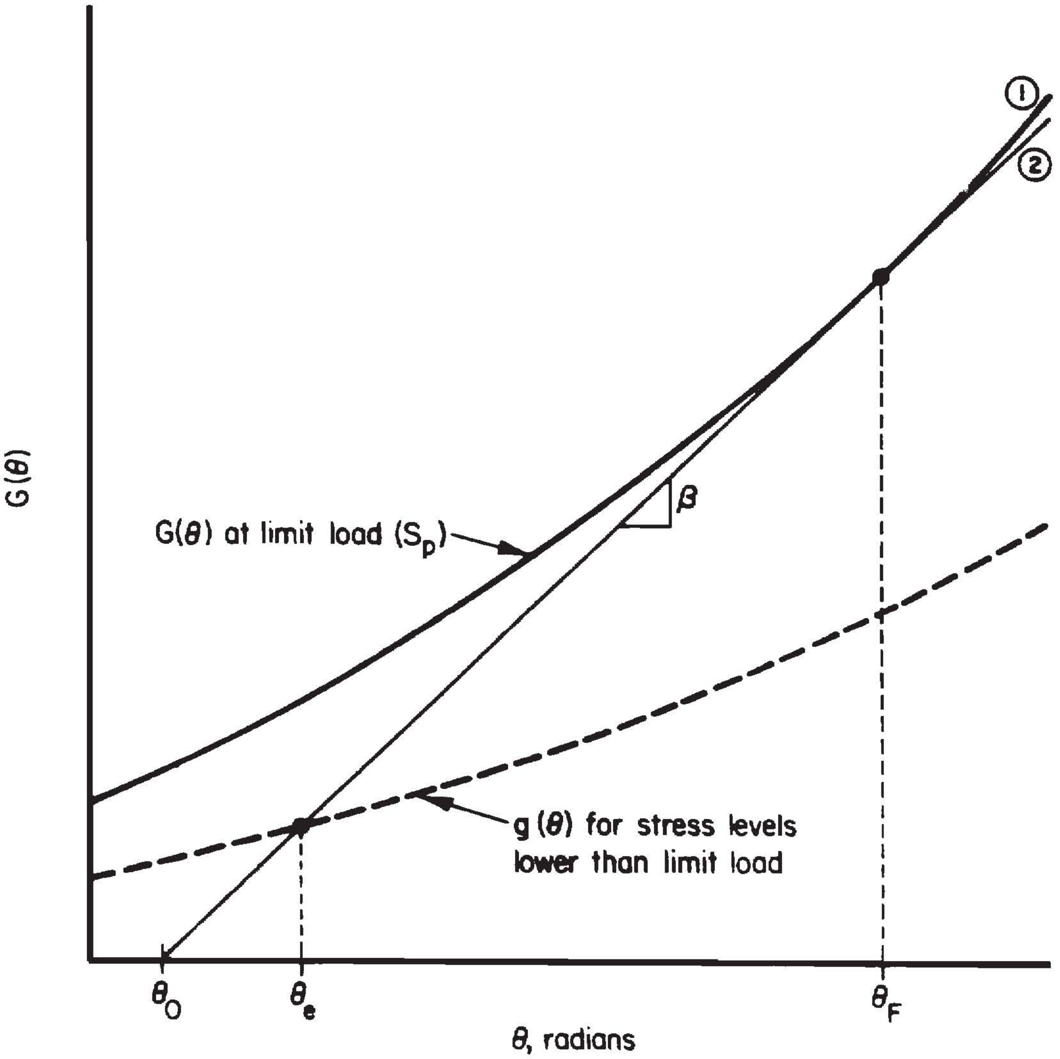

Figure 2.2. Typical plot of $G(\theta)$ versus θ defining θ_F (at $S=S_p$) and θ_e (at arbitrary level S).

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Using:

$$G(\theta_F) = \theta_F[S_pF_b(\theta_F) + S_tF_t(\theta_F)]^2$$

$$G'(\theta_F) = 2\theta_F[S_pF_b'(\theta_F) + S_tF_t'(\theta_F)][S_pF_b(\theta_F) + S_tF_t(\theta_F)]$$

$$+ [S_pF_b(\theta_F) + S_tF_t(\theta_F)]^2$$

This results in:

$$\theta_o = \theta_F \frac{2\theta_F[S_pF_b'(\theta_F) + S_tF_t'(\theta_F)]}{[S_pF_b(\theta_F) + S_tF_t(\theta_F)] + 2\theta_F[S_pF_b'(\theta_F) + S_tF_t'(\theta_F)]} \quad . \qquad (2.9)$$

Because θ_o is known and θ_F is not known, this equation is solved by iteration in the LBB.NRC computer program by assuming values of θ_F until a value of θ_o is obtained to the desired accuracy.

Once θ_F is determined, then β is found by:

$$\beta = \frac{[S_pF_b(\theta_F) + S_tF_t(\theta_F)]^2}{(1 - \frac{\theta_o}{\theta_F})} \qquad (2.10)$$

Then:

$$S_b(\theta_e) = \frac{\sqrt{\beta(1 - \frac{\theta_o}{\theta_e})} - S_tF_t(\theta_e)}{F_b(\theta_e)} \qquad (2.11)$$

where θ_e is incremented in steps, $\theta_o \leq \theta_e \leq \theta_F$. This relates $S_b(\theta_e)$ to each θ_e. Typical plots of $G(\theta)$ versus θ and S_b versus $(\theta_e - \theta_o)$ are shown in Figures 2.3 and 2.4.

2.7 J Analyses

As the stress level increases in ductile piping, LEFM methods have to evolve into elastic-plastic fracture mechanics (EPFM) methods. The crack driving parameter in the following discussion is assumed to be J instead of K. In the LEFM range:

$$J_e = \frac{K^2}{E} \qquad (2.12)$$

$$G(\theta) = \theta\left[S_bF_b(\theta) + S_tF_t(\theta)\right]^2, \; S_t = 0.1550$$

Curve	S_b	M, in kips	θ_e	$G(S_b,\theta_e)$
1	0	0	0.2403	0.00708
2	0.3370	34,048	0.2578	0.07459
3	0.6932	70,046	0.3101	0.27714
4	0.8111	81,959	0.3450	0.41217
5	S_p=1.0400	105,085	θ_F=0.6142	1.45333

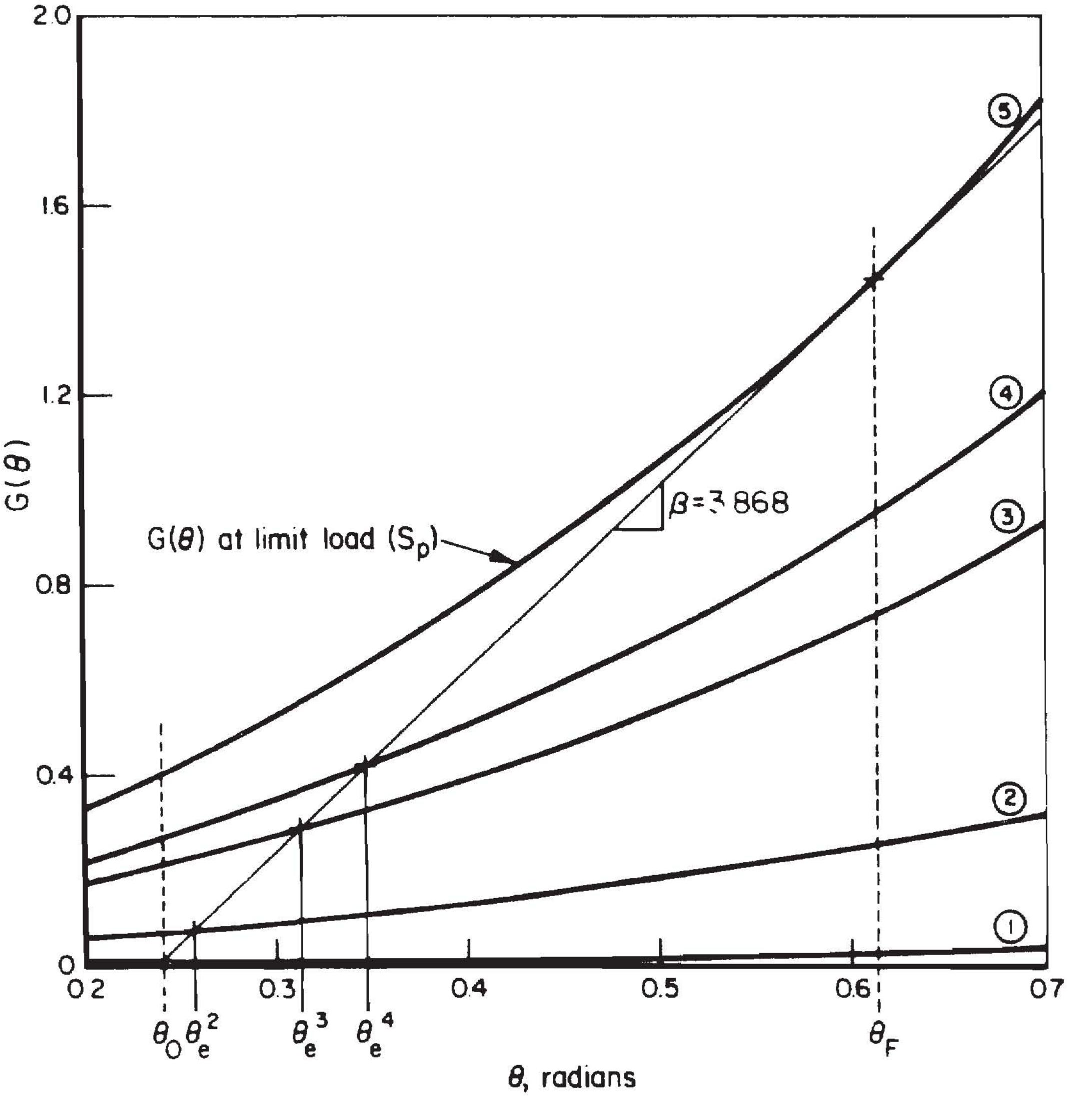

Figure 2.3. Example problems showing values of effective crack size θ_e for S_t = 0.1550 and S_b ranging from zero to S_p.

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$$S_b = \frac{\sqrt{\beta(1-\frac{\theta_o}{\theta})} - S_t F_t(\theta)}{F_b(\theta)} \quad ,$$

β = slope = 3.868
θ_o = 0.2385
θ_F = 0.6142
$\theta_F - \theta_o$ = 0.3757

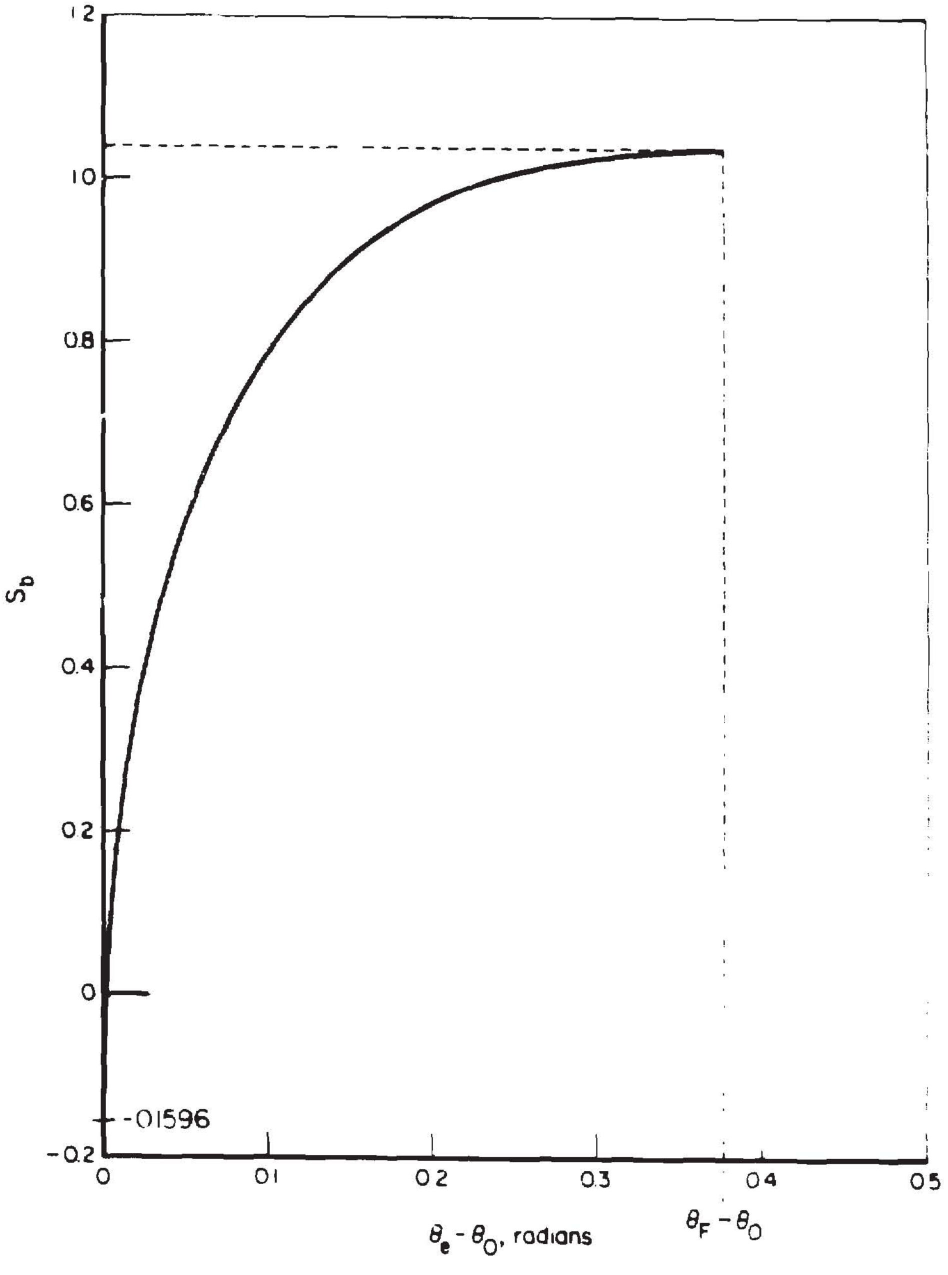

Figure 2.4. S_b versus $(\theta_e - \theta_o)$ curve for S_t = 0.1550 (See Figure 2.3).

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where J_e is the elastic component of the crack driving parameter, J. As in NUREG/CR-3464, J_e is normalized as follows:

$$\bar{J}_e = \frac{EJ_e}{\sigma_f^2 R} = \frac{K^2}{\sigma_f^2 R} = \pi\theta_e[S_b F_b(\theta_e) + S_t F_t(\theta_e)]^2 \quad . \qquad (2.13)$$

The NRC originally considered two versions of LBB.NRC, one in which $\bar{J}_e$ is based on θ_o (MOD 7) and a more conservative version in which J_e is based on θ_e (MOD 8). (The modification numbers are arbitrary and reflect the evolution of the program versus time.) In this report, only MOD 8, which is used for licensing evaluations, is described. However, the user still has the option of using MOD 7 (see line 731 of LBB.NRC in Appendix H).

The total J has to include a plastic component, J_p:

$$J = J_e + J_p \quad \text{or} \quad \bar{J} = \bar{J}_e + \bar{J}_p \quad . \qquad (2.14)$$

J_p is determined by using a moment-rotation relationship for a cracked pipe, which is discussed next. Before developing a procedure to determine J_p, it is necessary to find a relationship between the applied stresses and the kink angle, ϕ. NUREG/CR-3464 defines ϕ as (using Castiglianos' theorem)

$$\phi = \frac{\partial}{\partial M} \int_0^A \frac{K^2}{E}\, dA \qquad (2.15)$$

where:

$A = 2Rt\theta$ is the crack area
$M = \pi R^2 t\sigma_b$
$K^2 = (K_b + K_t)^2 = K_b^2 + 2K_bK_t + K_t^2$.

Therefore:

$$\int_0^A \frac{\kappa^2}{E}\, dA = \frac{2\pi R^2 t}{E} \{\sigma_b^2 \int_0^\theta \theta F_b^2(\theta) d\theta$$

$$+ 2\sigma_b\sigma_t \int_0^\theta \theta F_b(\theta) F_t(\theta) d\theta$$

$$+ \sigma_t^2 \int_0^\theta \theta F_t^2(\theta) d\theta\}$$

and:

$$\Phi = \frac{1}{\pi R^2 t} \frac{\partial}{\partial\sigma_b} \int_0^A \frac{\kappa^2}{E}\, dA$$

$$= 4\,\frac{\sigma_b}{E} \int_0^\theta \theta F_b^2(\theta) d\theta + 4\,\frac{\sigma_t}{E} \int_0^\theta \theta F_b(\theta) F_t(\theta) d\theta$$

$$= \frac{\sigma_b}{E} I_b(\theta) + \frac{\sigma_t}{E} I_t(\theta) \qquad (2.16)$$

where I_b and I_t are compliance functions. The derivation of I_b and I_t are given in Appendix B using the F functions in Appendix A.

The kink angle equation is normalized by:

$$\bar{\Phi} = \frac{E\Phi}{\sigma_f}\ , \quad S = \frac{\sigma}{\sigma_f}\ , \quad \bar{\varepsilon} = \frac{E\varepsilon}{\sigma_f}$$

where $\varepsilon = \frac{\sigma}{E}$.

Then:

$$\bar{\Phi} = \bar{\varepsilon}_b I_b(\theta) + \bar{\varepsilon}_t I_t(\theta)$$

or

$$\bar{\Phi} = [S_b I_b(\theta) + S_t I_t(\theta)] \qquad (2.17)$$

2.8 Estimate of Plastic Rotation Due to Crack

At this point, the NRC procedure begins to depart from the NUREG/CR-3464 method. Note that ϕ as just derived is essentially based on LEFM methods whereas the piping materials to be analyzed can undergo plastic deformation under high loads. The following is an engineering attempt to estimate the plastic rotation of the cracked pipe based on the behavior of a smooth bar tensile specimen. A typical normalized tensile stress-strain diagram is shown in Figure 2.5.

Assuming that the material stress-strain behavior can be adequately described by the Ramberg-Osgood equation

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha\left(\frac{\sigma}{\sigma_o}\right)^n \qquad (2.18)$$

where

$\sigma = \sigma_b + \sigma_t$

σ_o = a reference stress which affects the α obtained

$\varepsilon_o = \frac{\sigma_o}{E}$

α and n are material parameters.

As Eq. 2.18 does not fit a stress-strain curve over its entire range, engineering judgement has to be used to specify α and n. The procedure used by the NRC is described in Appendix C. Users of the LBB.NRC procedure should determine α and n in the same way to reproduce NRC results. Other fits of the stress-strain data may be more appropriate for other J-estimation analyses. This is one area subject to future refinement.

The Ramberg-Osgood equation can be rewritten as follows:

$$\varepsilon = \frac{\sigma}{E} + \alpha\left(\frac{\sigma_f}{E}\right)\left(\frac{\sigma_f}{\sigma_o}\right)^{n-1}\left(\frac{\sigma}{\sigma_f}\right)^n = \frac{\sigma}{E} + \alpha'\left(\frac{\sigma_f}{E}\right)\left(\frac{\sigma}{\sigma_f}\right)^n \qquad (2.19)$$

where:

$$\alpha' = \alpha\left(\frac{\sigma_f}{\sigma_o}\right)^{n-1}$$

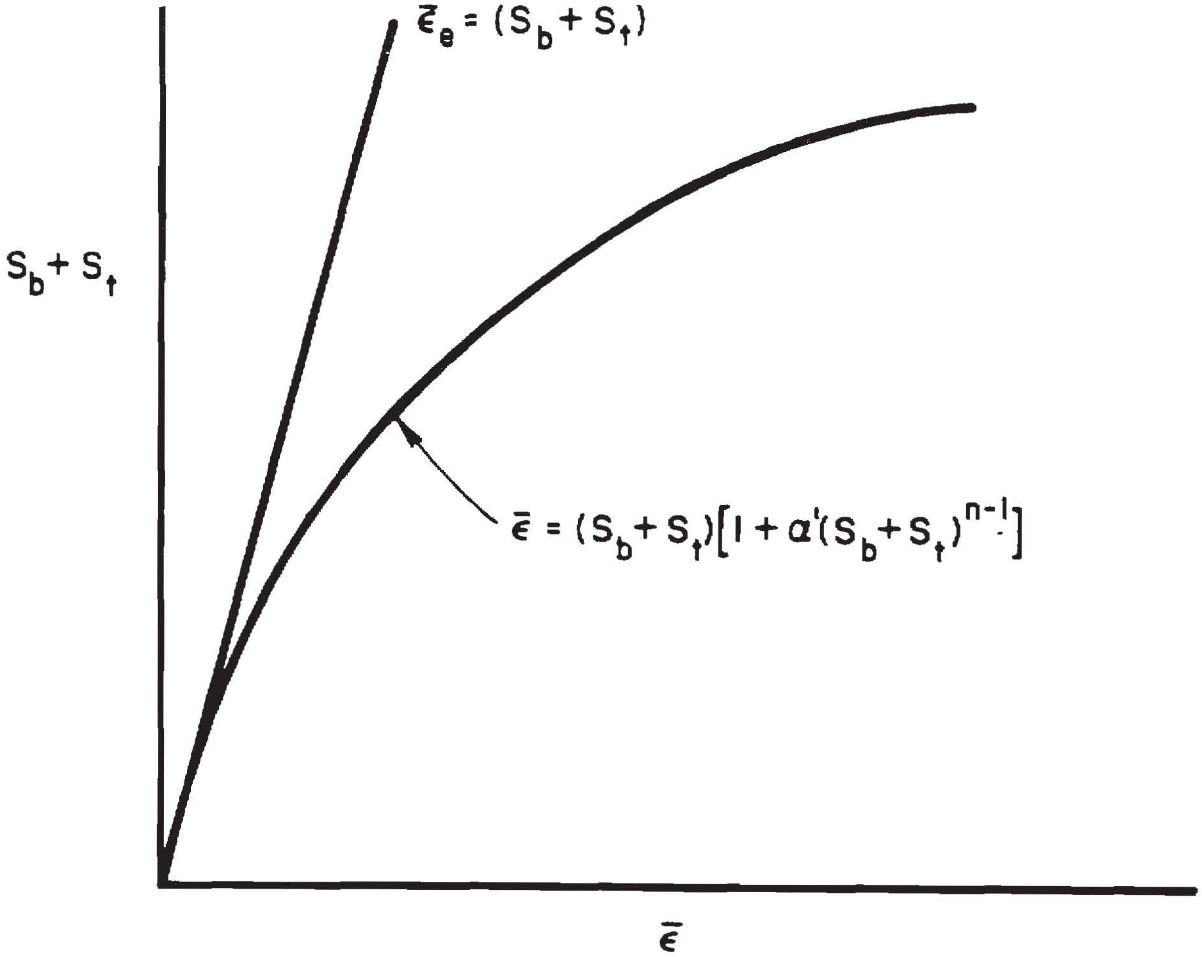

Figure 2.5. Typical normalized stress-strain diagram for a hardening material.

T-4572-F2.5

This last equation merely adjusts the reference stress from σ_o to σ_f. It does not affect the end results.

In normalized form:

$$\bar{\epsilon} = (S_b+S_t)[1 + \alpha'(S_b+S_t)^{n-1}] \quad . \qquad (2.20)$$

Note that $\bar{\epsilon}_e = S_b + S_t$ is the elastic component (see Figure 2.5) and the term

$$[1 + \alpha'(S_b+S_t)^{n-1}]$$

is a correction factor to account for strain hardening. By analogy to the stress-strain diagram in the elastic range:

$$\bar{\phi}_e = [S_b I_b(\theta_e) + S_t I_t(\theta_e)] \quad . \qquad (2.21)$$

Note that this latter $\bar{\phi}_e$ is the total $\bar{\phi}$ in NUREG/CR-3464. By comparison with experimental results of circumferentially cracked pipes under load, it was seen to underestimate the observed kink angle. Assuming that $\phi_p/\phi_e = \epsilon_p/\epsilon_e$ and therefore using the same correction factor, $[1 + \alpha'(S_b+S_t)^{n-1}]$, to go from linear elastic to elastic-plastic conditions, the NRC procedure uses:

$$\bar{\phi} = \bar{\phi}_e[1 + \alpha'(S_b+S_t)^{n-1}] \qquad (2.22)$$

where

$\bar{\phi}_e$ is the elastic component

$\bar{\phi}_p = \bar{\phi}_e\alpha'(S_b+S_t)^{n-1}$ is the plastic component

$\bar{\phi}$ = total relative kink angle.

Eq. 2.22, although applicable for the behavior of a smooth bar tensile specimen, is used here to provide an engineering estimate of the plastic rotation of a cracked pipe.

2.9 J Determination

$$\bar{J}_e = \pi\theta_e[S_bF_b(\theta_e) + S_tF_t(\theta_e)]^2 \qquad (2.23)$$

was previously developed.

The NRC determination of $\bar{J}_p$ differs from NUREG/CR-3464 in that the total stresses rather than just the bending stress are used in the integration formula:

$$\bar{J}_p = \frac{F_J}{(S_p+S_q)} \int_0^{\bar{\phi}_p} [S_b+(F_t/F_b)S_t]d\bar{\phi}_p \quad . \qquad (2.24)$$

This equation was developed based upon engineering judgement. The rationale used is presented and discussed in Appendix D.

In Eq. 2.24 S_q is the applied S_t and

$$F_J = \sin\left(\frac{\theta_o}{2} + \frac{\pi}{2} S_t\right) + \cos \theta_o \quad .$$

F_J is derived in NUREG/CR-3464 (Ref. 2). The LBB.NRC computer program (Appendix H) first integrates S_t from zero to S_q and then with S_q constant, it integrates S_b from zero to S_p (see Figures in Appendix D). In NUREG/CR-3464, S_t is absent in the J_p integration formula.

The reason for including S_t in the $\bar{J}_p$ integration is to account for the plastic contribution of axial stresses, especially if they are comparatively large. Note that for axial loads only, the NUREG/CR-3464 procedure would be inadequate.

Crack opening areas calculated by the LBB.NRC program use the equation given on page 77 of NUREG/CR-3464 without the effect of strain-hardening but using the effective crack angle, θ_e:

$$\text{Crack opening area} = \text{COA} = \frac{\pi\sigma_f R^2 I_t(\theta_e)}{E} \left[S_t + \frac{S_b\,(3 + \cos\theta_e)}{4}\right] \quad .$$

The leakage rate constant (gpm/in^2) is user specified in the LBB.NRC program and can be set to be as conservative as desired based on experimental data. The leakage rate is calculated in the LBB.NRC program by multiplying the leakage rate constant and the crack-opening area.

Because of pressure differences between BWRs and PWRs, different values of this constant are appropriate for the respective analyses. Based on available leakage rate data, conservative leakage rate constants of 250 and 125 gpm/in^2 are selected for PWRs and BWRs, respectively. Because the crack opening area is also conservatively estimated without strain-hardening, this introduces further conservatism in the leakage rate calculation. However, leakage through an actual crack is a complex thermal-hydraulic phenomenon. The estimation of leakage rates is subject to improvement with experimental and analytical developments.

3. DISCUSSION

The LBB.NRC method as described in Section 2 and elaborated on and illustrated in the appendices to this document is a modification of the technique presented in Reference 2. The significant modifications made are to include the strain-hardening effect of materials typically used in nuclear power plant piping and to expand the Reference 2 procedure to permit relatively large tensile loads to be combined with bending loads. LBB.NRC is intended to be an engineering approach to solving a cracked pipe problem without having to resort to finite element or finite difference methods when the pipe is subjected to tensile plus bending loads. To meet this objective, certain simplifying assumptions must be made. Some of these are the same as in Reference 2; others are unique to the LBB.NRC procedure. Many of these assumptions are based on engineering judgement and are not consistent with deformation plasticity theory. Their acceptability depends solely on how well the procedure predicts cracked piping behavior and/or how well the results agree with those of more sophisticated analyses. For licensing purposes, the procedure used should be conservative; that is, it should predict crack growth and pipe failure before these events actually occur in a pipe test.

Based on cracked pipe experiments, crack behavior is not always consistent with idealized theory. Cracked pipes generally ovalize under load; wall thinning may occur in the vicinity of the crack; or material property discontinuities may be present such as at weld locations and crack propagation may be somewhat erratic prior to gross pipe failure. In fact, as discussed in Section 1 of this document, even the loads and material properties in a real piping system may include uncertainties. Because these factors cannot be accounted for with precision, a conservative estimation procedure based on experience and judgement will suffice. For licensing purposes, margins must be included in an overall evaluation of a pipe or piping system with postulated cracks to envelop the various uncertainties.

Nevertheless, a discussion of the assumptions used in any analytical procedure is in order so that as more experience is gained, the procedure may be refined and perhaps allow for a decrease in the prescribed margins. With this in mind, three of the assumptions used in the LBB.NRC procedure (labeled i through iii), are discussed in the following paragraphs, noting that some of them are also included in the parent document (Ref. 2).

(i) Utilizing the concept of an effective crack size to estimate the increased pipe compliance due to the presence of crack tip plasticity. Related to this assumption is the necessity of defining β as given by Eq. 2.10.

As discussed in Reference 2, the so-called plastic zone size correction method is often used to account for the effect of local yielding. The method was developed for evaluating the material fracture toughness in small scale yielding conditions where the yielding near the crack tip is well contained within the surrounding elastic field. Both the NUREG/CR-3464 and LBB.NRC procedures are based on the premise that this concept can be extended to large specimens; i.e., pipes with through-wall cracks. Thus, the NRC suggested limit on crack growth for licensing applications of LBB as stated on Page 1-3, should bound the uncertainties associated with the plastic zone assumption to a range acceptable for engineering purposes.

The above approach is based on the acceptance of a limit-load corresponding to a limiting value of stress beyond which fully plastic conditions are assumed. Based on numerous experiments, this limiting stress, referred to as the flow stress, has been found to be approximately the average of the yield and ultimate strengths of a material. Although the use of an elastic solution adjusted for small scale yielding for cracked piping applications does not seem to be theoretically justified, Paris and Tada in NUREG/CR-3464 suggest that the crack size adjustment, r_y, be considered as an index representing the compliance of the cracked body at each level of loading. As the plastic zone spreads across the net ligament ahead of the crack, the compliance increases and, at the limit load or fully plastic state, general yielding of the body may be referred to as the compliance instability. The NUREG/CR-3464 and the LBB.NRC techniques interpolate between the elastic and fully plastic states. The applied loads produce a plastic zone size adjustment which increases the effective crack size until instability is reached at the limit load. This is done via the Eqs. 2.5 through 2.10 in this document and illustrated in Figures 2.2 and 2.3. This is an engineering approach to a complex problem and results in the elastic component of J as given by Eq. 2.23. An alternate approach, proposed by Brust is under consideration (see Appendix E).

(ii) Determination of the plastic component of J by integration of the load-displacement relationship where the displacement in this case is the kink angle, ϕ, due to the presence of the crack.

A problem with this assumption is the determination of the kink angle versus the loads applied to a cracked pipe between the elastic and fully plastic states. Here a great deal of engineering judgement has to be used and the final validity of the assumption has to be determined by the comparison of analytical results with those from cracked piping experiments or with those of more sophisticated analyses such as finite element procedures. Paris and Tada in NUREG/CR-3464 propose a method for estimating the moment versus kink angle between elastic and fully plastic conditions. Additional complexity is incorporated in the LBB.NRC procedure by the introduction of axial plus bending loads and the kink angle adjustment to account for the strain hardening of typical materials used in nuclear power facilities. The NRC staff approach to resolving this problem is described in Section 2 and Appendices C and D of this document. Both the Paris/Tada and the staff approaches assume that the pipe geometry is maintained; i.e., potential ovalization and wall thinning are ignored. Here again, if crack growth is limited for licensing applications, these factors are not believed to be significant and an engineering estimate of J can be obtained for the purpose intended.

(iii) Thin wall pipe - Both the NUREG/CR-3464 and the LBB.NRC procedures assume that thin-wall equations can be used to calculate piping stresses.

For typical applications, this approach is sufficient; that is, a pipe can be characterized by its R/t ratio. However, LBB analyses are being applied to pipes ranging in wall thickness from one-half inches or less to over 4 inches with diameters ranging from about 4 inches to 48 inches. It is quite possible, in fact probable, that cracked pipes with the same R/t ratio but with significant differences in wall thickness will behave differently. Only future experiments will resolve this question.

4. CONCLUSION

The LBB.NRC fracture mechanics (FM) method is an "estimation procedure" used by the NRC for reviewing leak-before-break submittals. It serves as an alternative to more elaborate finite element analyses which are expensive and time consuming to perform and the purpose of simple models is to facilitate the performance of FM analyses in a timely and relatively inexpensive manner. Although all FM methods are based (to some extent) on theory, it is necessary to include in them certain idealizing assumptions related to crack shapes, consistent geometry and crack behavior if the crack initiates and grows as a result of increased loads. Also under most circumstances, it is necessary to obtain materials property data from other than the component being evaluated.

In real life, however, actual flaws can have complex shapes, the component being evaluated may deform under high load particularly in the vicinity of the flaw (e.g., a pipe may ovalize and its wall may become thinner near the flaw) and a growing crack may develop shear lips. These reasons plus the inherent variability of material properties from specimen to specimen lead to the conclusion that perfect correspondence between analytical and experimental results should not be expected. On the other hand, to be useful at all, analytical methods should be able to predict results within an acceptable uncertainty band which can then be accounted for by appropriate margins.

Further, the LBB.NRC methodology is subject to the theoretical limitations discussed in References 6 and 7. For example, it is recognized that for J-integral theory to be rigorously valid, cracked pipe analyses should be consistent with deformation theory plasticity. This requires that Ilyushin's theorem be satisfied. However, as noted, Ilyushin's theorem is not satisfied by this or some other J-integral methods.

The LBB.NRC method is, therefore, an engineering approach for solving complicated cracked pipe problems without having to utilize more elaborate methods. It is expected to evolve with time. In the interim, the reader may judge its applicability and validity for the purpose intended from the examples given in Appendices E, F and G of this document.

5. REFERENCES

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APPENDIX A

ASSESSMENT OF LINEAR ELASTIC F-FUNCTIONS FOR THROUGH-WALL CRACKS IN PIPES

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ASSESSMENT OF LINEAR ELASTIC F-FUNCTIONS FOR THROUGH-WALL CRACKS IN PIPES

The F-function is an analytical relation which correlates the linear-elastic stress-intensity factor (K) of a cracked shell to that for the same size of crack in an infinite flat plate, see Eq. A-1.

$$K = \sigma F\sqrt{\pi a} \qquad \text{(A-1)}$$

where,

K = stress intensity
F = function of crack size
a = half crack length.

Thin shell analyses have been developed by Folias, Erdogan, etc. (Ref. A.1 and A.2), for a circumferentially cracked pipe in pure tension or torsion, but not bending. Here the F-function is usually expressed as a function of the dimensionless shell parameter λ, see Eq. A-2.

$$F = 1 + A\lambda + B\lambda^2 + C\lambda^3 \qquad \text{(A-2)}$$

where

$\lambda = [12(1-\nu^2)]^{\frac{1}{4}} (a/\sqrt{Rt})$

ν = Poisson's ratio

a = half crack length

t = pipe thickness

R = average pipe radius
A,B,C = constants depending on crack orientation and type of loading.

Figure A.1 shows some F-functions analytically and experimentally derived (Ref. A.3).

Sanders (Refs. A.4, A.5) recently developed solutions using an energy integral technique. This was done for circumferentially cracked pipes under pure tension (Ref. A.4) and global bending (Ref. A.5). This analysis was used in NUREG/CR-3464 (Ref. A.6) to develop an F-function for pipes in tension and bending. Sanders' solutions are generally for longer cracks and hence require extrapolation of the F-function to a value of one, as the crack length approaches zero. Figure A.2 shows the Sanders F-function versus circumferential crack size for an (R/t) of five. Note that as the crack angle approaches zero, Sanders' solution for F also approaches zero. In NUREG/CR-3464 the F-function was expressed in the below forms.

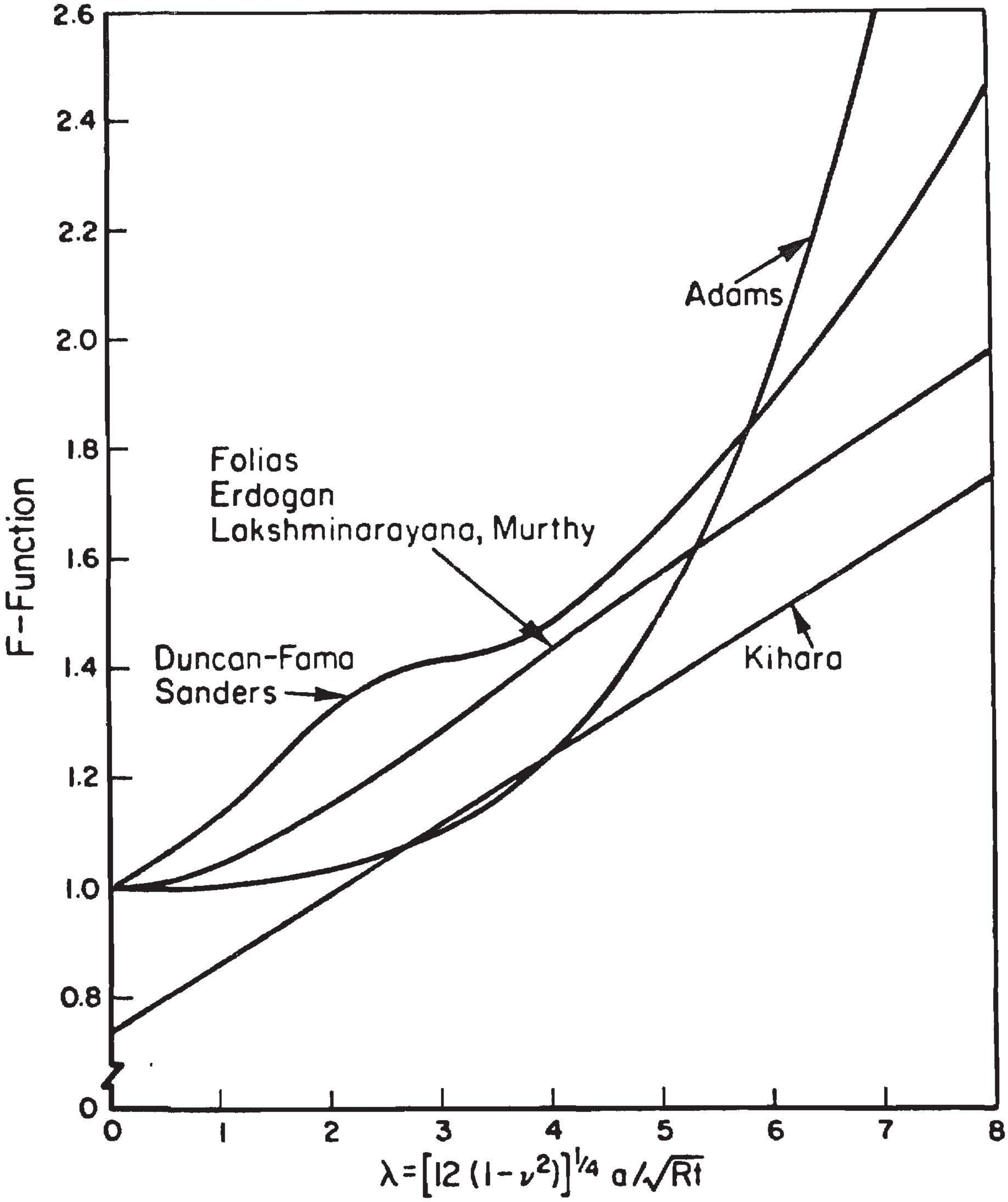

Figure A.1. Comparison of various stress intensity ratio factors, F, for through-wall circumferential flaws in cylinders under uniform axial tension (Ref. A.3).

T-4572-FA.1

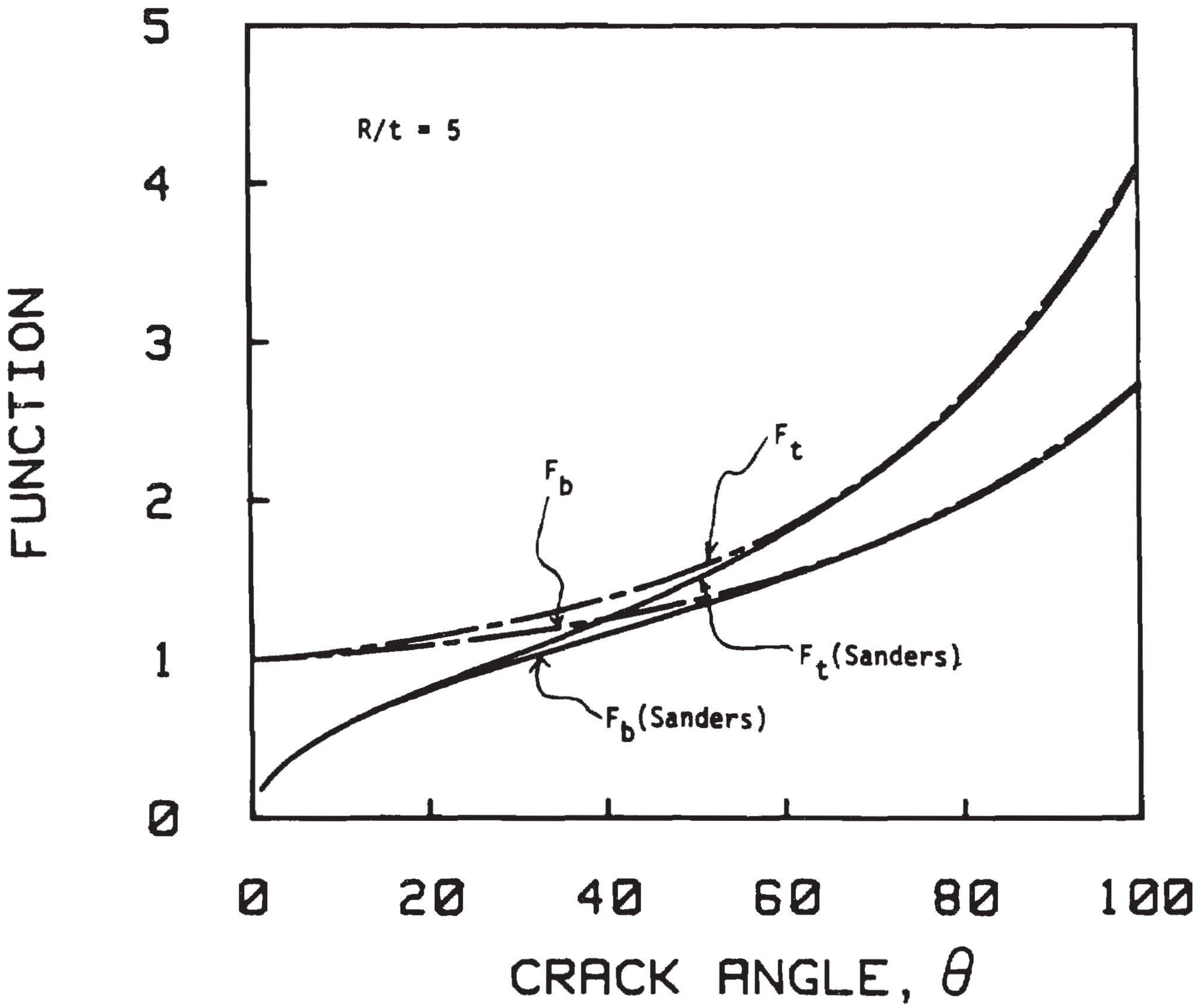

Figure A.2. Comparison of Sanders' F-Functions for R/t = 5 and polynominal fit assuming F = 1 as crack angle approaches zero.

T-4572-FA.2

$$F_t = 1 + A_t(\theta/\pi)^{1.5} + B_t(\theta/\pi)^{2.5} + C_t(\theta/\pi)^{3.5} \qquad \text{(A-3)}$$

for tension and

$$F_b = 1 + A_b(\theta/\pi)^{1.5} + B_b(\theta/\pi)^{2.5} + C_b(\theta/\pi)^{3.5} \qquad \text{(A-4)}$$

for bending.

Here the constants A, B, and C, were curve fitted so that there was good agreement with Sanders' solution for long crack length. Figures A.3 and A.4 show how the F-function changes for R/t values of 10 and 15. Nuclear piping typically has R/t values from 5 to 15. The reliability of Sanders, or other thin-shell analyses at the lower R/t ratios, is a point of concern. This is not addressed in this effort.

The change in the constants for different R/t values is given in Table A.1 as well as graphically displayed in Figure A.5. These constants have been curve fit, and are expressed below. This form (i.e. equations) are quite convenient for computer based on a solution of the circumferential cracked pipe problem.

$$A_t = -2.02917 + 1.67763\ (R/t) - .07987\ (R/t)^2 + .00176\ (R/t)^3$$

$$B_t = 7.09987 - 4.42394\ (R/t) + .21036\ (R/t)^2 - .00463\ (R/t)^3$$

$$C_t = 7.79661 + 5.16676\ (R/t) - .24577\ (R/t)^2 + .00541\ (R/t)^3$$

$$A_b = -3.26543 + 1.52784\ (R/t) - .072698\ (R/t)^2 + .0016011\ (R/t)^3$$

$$B_b = 11.36322 - 3.91412\ (R/t) + .18619\ (R/t)^2 - .004099\ (R/t)^3$$

$$C_b = -3.18609 + 3.84763\ (R/t) - .18304\ (R/t)^2 + .00403\ (R/t)^3$$

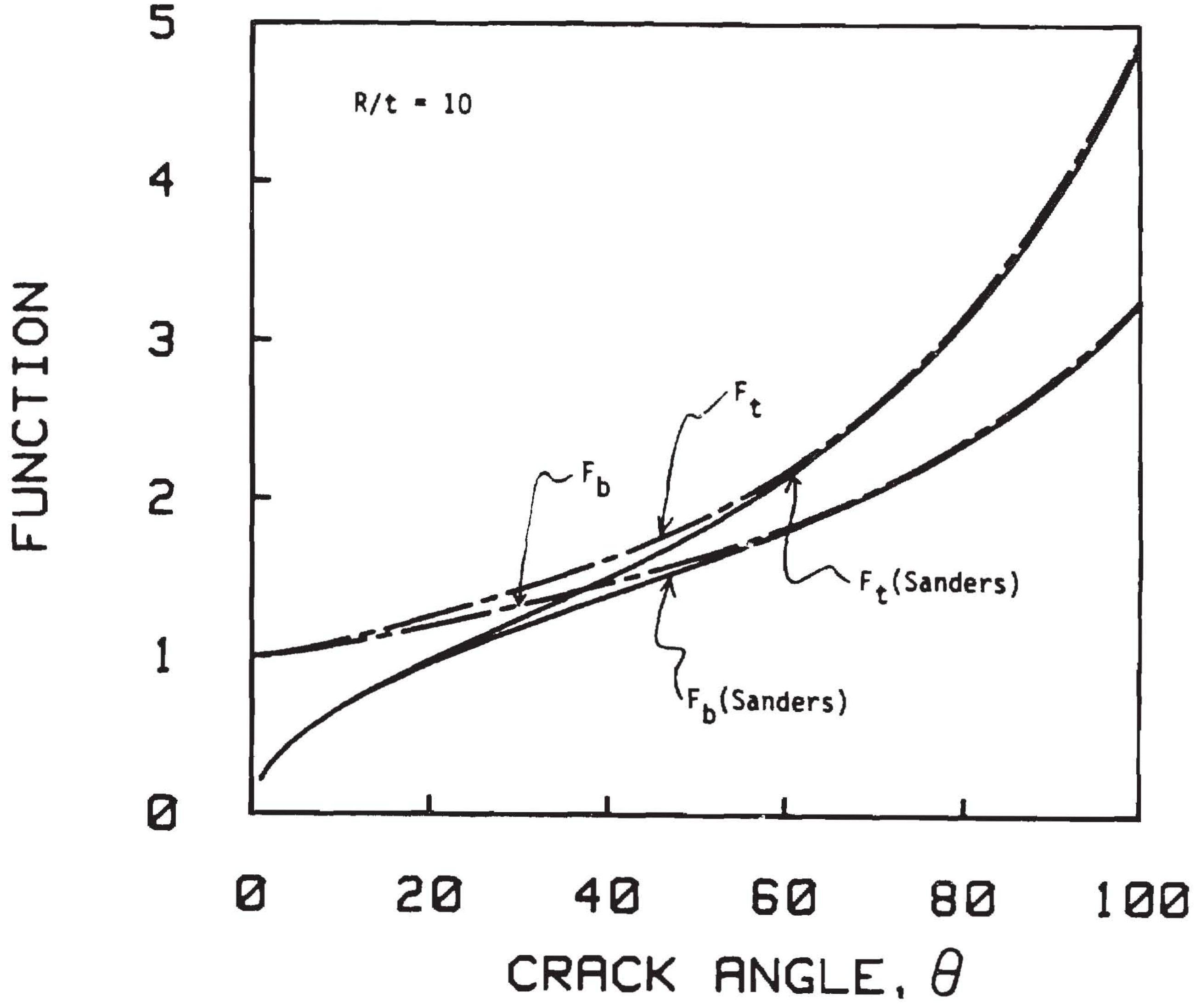

Figure A.3. Comparison of Sanders' F-Function for R/t = 10 and polynominal fit assuming F = 1 as crack angle approaches zero.

T-4572-FA.3

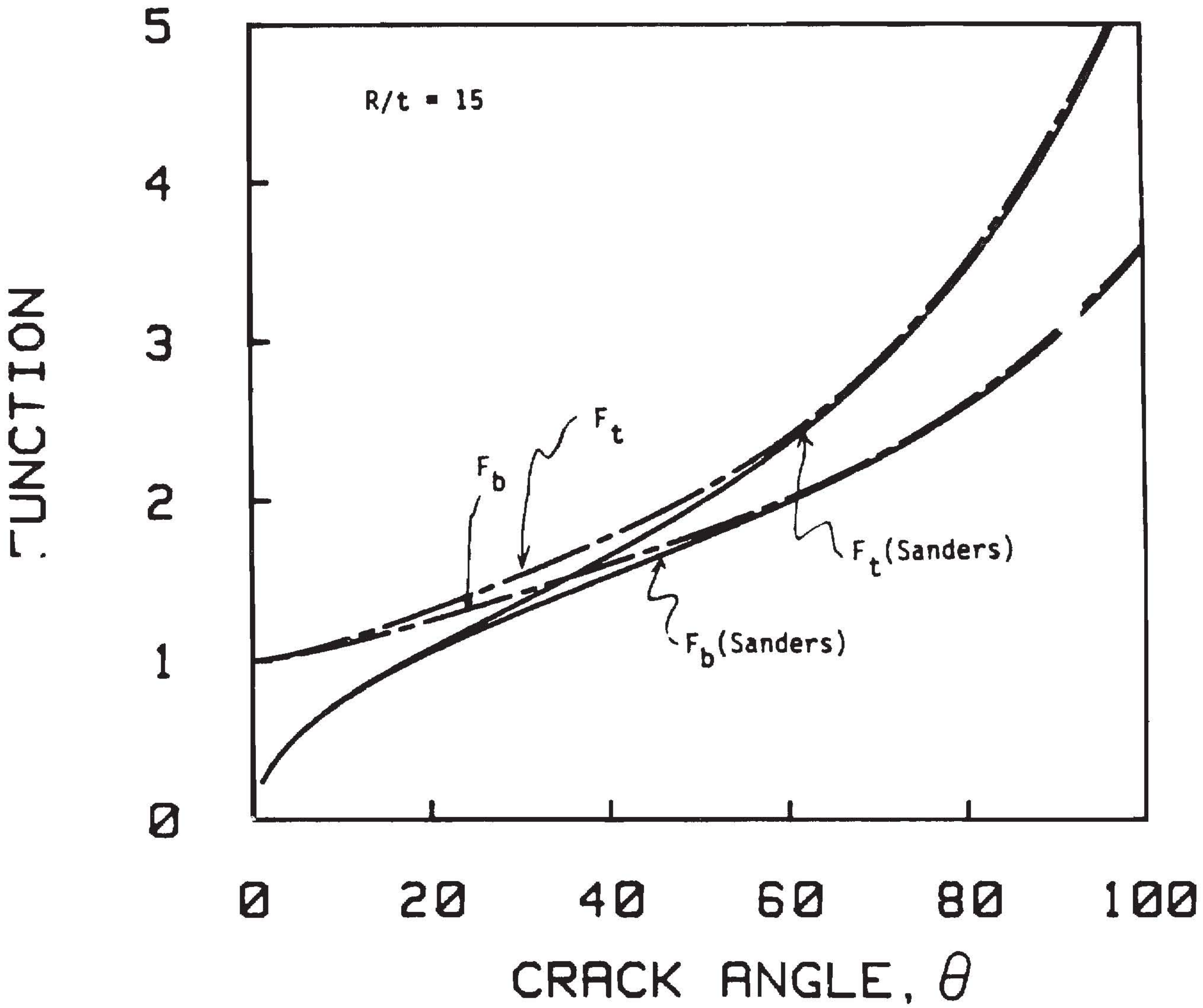

Figure A.4. Comparison of Sanders' F-Functions for R/t = 15 and polynominal fit assuming F = 1 as crack angle approaches zero.

T-4572-FA.4

Table A.1. Coefficients for F-Functions from Sanders' analysis of circumferentially cracked pipe under tension and bending

		Ft	
R/t	a	b	c
4.000	3.488	-7.453	24.792
5.000	4.606	-10.402	28.235
6.000	5.566	-12.936	31.195
7.000	6.413	-15.171	33.804
8.000	7.173	-17.178	36.147
9.000	7.865	-19.005	38.280
10.000	8.501	-20.685	40.242
11.000	9.092	-22.244	42.062
12.000	9.643	-23.700	43.761
13.000	10.161	-25.067	45.358
14.000	10.650	-26.353	46.865
15.000	11.114	-27.581	48.293
16.000	11.554	-28.744	49.651

		Fb	
R/t	a	b	c
4.000	1.760	-1.512	9.470
5.000	2.778	-4.120	12.034
6.000	3.653	-6.362	14.230
7.000	4.424	-8.339	16.181
8.000	5.117	-10.114	17.926
9.000	5.748	-11.730	19.514
10.000	6.328	-13.216	20.975
11.000	6.866	-14.594	22.330
12.000	7.368	-15.882	23.596
13.000	7.848	-17.091	24.785
14.000	8.286	-18.233	25.907
15.000	8.708	-19.314	26.971
16.000	9.110	-20.343	27.982

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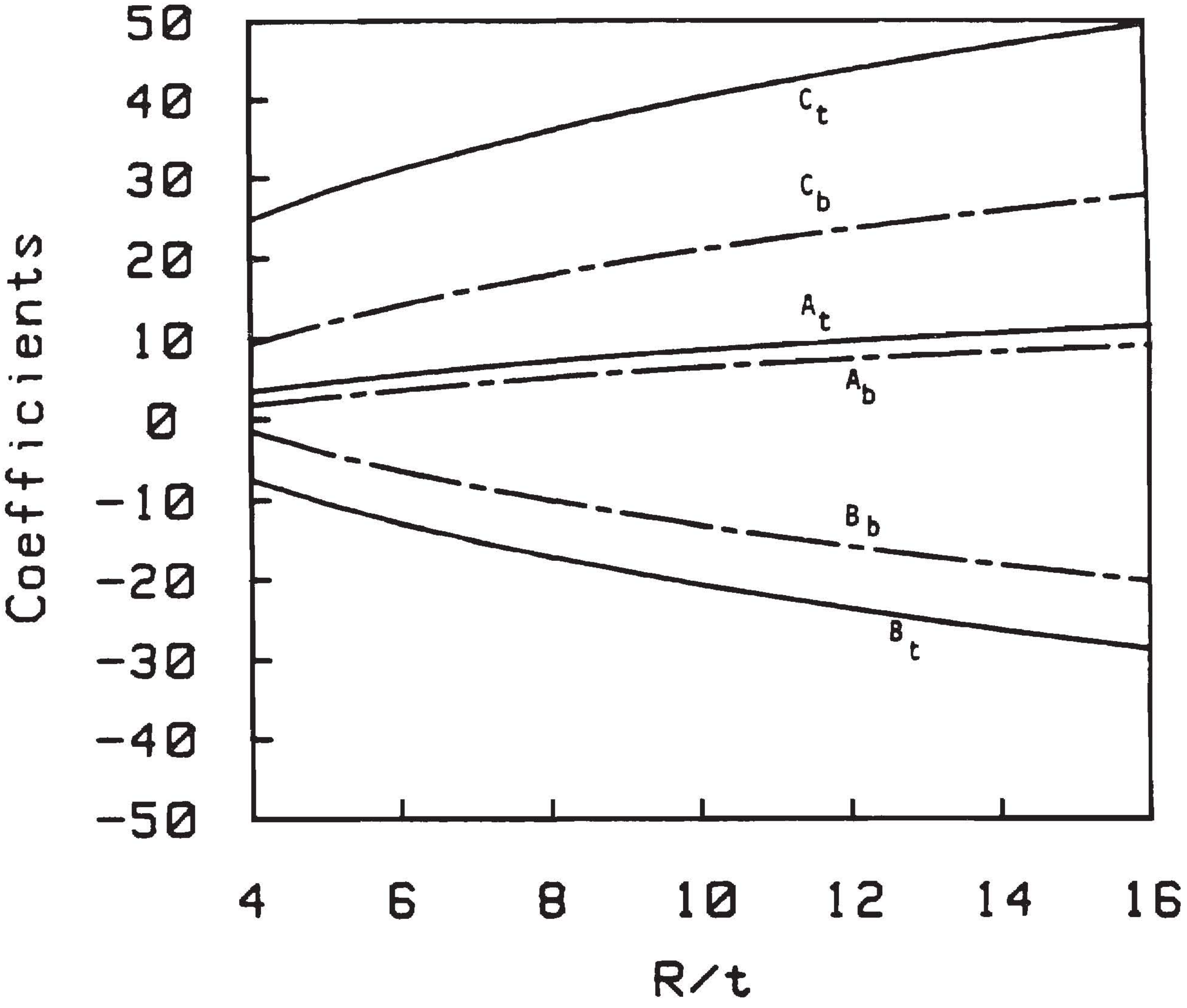

Figure A.5. Variation of coefficients for Sanders' F-Functions - Eqs. A-3 and A-4. A_t, B_t, and C_t for tension; A_b, B_b, and C_b for bending.

T-4572-FA.5

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APPENDIX B

COMPLIANCE FUNCTIONS

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For:

$$F_t(\theta) = 1 + A_t(\frac{\theta}{\pi})^{3/2} + B_t(\frac{\theta}{\pi})^{5/2} + C_t(\frac{\theta}{\pi})^{7/2}$$

$$F_b(\theta) = 1 + A_b(\frac{\theta}{\pi})^{3/2} + B_b(\frac{\theta}{\pi})^{5/2} + C_b(\frac{\theta}{\pi})^{7/2} ,$$

with A_t through C_b given in Appendix A in functional form.

Then:

$$\theta F_t(\theta)F_b(\theta) = \pi \{\frac{\theta}{\pi} + (\frac{\theta}{\pi})^{5/2} [(A_t+A_b)+(B_t+B_b)(\frac{\theta}{\pi})+(C_t+C_b)(\frac{\theta}{\pi})^2]$$

$$+ (\frac{\theta}{\pi})^4 [A_tA_b + (A_tB_b + A_bB_t)(\frac{\theta}{\pi})$$

$$+ (A_tC_b + B_tB_b + A_bC_t) (\frac{\theta}{\pi})^2$$

$$+ (B_tC_b + B_bC_t) (\frac{\theta}{\pi})^3 + C_tC_b (\frac{\theta}{\pi})^4]\}$$

$$I_t(\theta) = 4 \int_0^\theta \theta F_t(\theta)F_b(\theta)d\theta$$

$$= 4\pi^2 \{\frac{1}{2} (\frac{\theta}{\pi})^2 + \frac{2}{7} (A_t+A_b) (\frac{\theta}{\pi})^{7/2} + \frac{2}{9} (B_t+B_b) (\frac{\theta}{\pi})^{9/2} + \frac{2}{11} (C_t+C_b) (\frac{\theta}{\pi})^{11/2}$$

$$+ \frac{1}{5} A_tA_b (\frac{\theta}{\pi})^5 + \frac{1}{6} (A_tB_b + A_bB_t) (\frac{\theta}{\pi})^6$$

$$+ \frac{1}{7} (A_tC_b + B_tB_b + A_bC_t) (\frac{\theta}{\pi})^7$$

$$+ \frac{1}{8} (B_tC_b + B_bC_t) (\frac{\theta}{\pi})^8 + \frac{1}{9} C_tC_b (\frac{\theta}{\pi})^9 \}$$

Let:

$$I_{t_1} = \frac{(A_t+A_b)}{7} + \frac{(B_t+B_b)}{9} (\frac{\theta}{\pi}) + \frac{(C_t+C_b)}{11} (\frac{\theta}{\pi})^2$$

$$I_{t_2} = \frac{(A_t A_b)}{2.5} + \frac{(A_t B_b+A_b B_t)}{3} (\frac{\theta}{\pi}) + \frac{(A_t C_b+B_t B_b+A_b C_t)}{3.5} (\frac{\theta}{\pi})^2$$

$$I_{t_3} = \frac{(B_t C_b+B_b C_t)}{4} (\frac{\theta}{\pi})^3 + \frac{C_t C_b}{4.5} (\frac{\theta}{\pi})^4$$

Then:

$$I_t(\theta) = 2\theta^2 [1 + 4 (\frac{\theta}{\pi})^{3/2} I_{t_1} + (\frac{\theta}{\pi})^3 (I_{t_2} + I_{t_3})]$$

$$I_b(\theta) = 4 \int_0^\theta \theta F_b^2(\theta) d\theta$$

can be obtained by replacing A_t, B_t and C_t with A_b, B_b and C_b in the above equations.

Then:

$$I_{b_1} = \frac{A_b}{7} + \frac{B_b}{9} (\frac{\theta}{\pi}) + \frac{C_b}{11} (\frac{\theta}{\pi})^2$$

$$I_{b_2} = \frac{A_b^2}{2.5} + \frac{A_b B_b}{1.5} (\frac{\theta}{\pi}) + \frac{(2A_b C_b+B_b^2)}{3.5} (\frac{\theta}{\pi})^2$$

$$I_{b_3} = \frac{B_b C_b}{2} (\frac{\theta}{\pi})^3 + \frac{C_b^2}{4.5} (\frac{\theta}{\pi})^4$$

and

$$I_b(\theta) = 2\theta^2 [1 + 8 (\frac{\theta}{\pi})^{3/2} I_{b_1} + (\frac{\theta}{\pi})^3 (I_{b_2} + I_{b_3})]$$

Note: The LBB.NRC program uses $I_t(\theta)$ and $I_b(\theta)$ in the format of the last equations given.

APPENDIX C

RAMBERG-OSGOOD PARAMETERS

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Stress-strain data are often fitted with the Ramberg-Osgood equation

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha \left(\frac{\sigma}{\sigma_o}\right)^n$$

where:

ε = strain

σ = stress

E = elastic modulus

ε_o = σ_o/E

σ_o = a reference stress sometimes assumed to be equal to the yield strength, σ_y, but can be arbitrary. However, the value of α obtained will depend on the value of σ_o used, therefore, mutually consistent parameters must always be used. Note that in the LBB.NRC analytical procedure, α is adjusted to α' by

$$\alpha' = \alpha \left(\frac{\sigma_f}{\sigma_o}\right)^{n-1}$$

where σ_f is the material flow stress.

The Ramberg-Osgood equation can be rearranged as follows:

$$\left(\frac{E\varepsilon - \sigma}{\sigma_o}\right) = \alpha \left(\frac{\sigma}{\sigma_o}\right)^n \quad .$$

This form of the equation is more convenient for fitting stress-strain data on a log-log plot; that is

$$\ln \left(\frac{E\varepsilon - \sigma}{\sigma_o}\right) = \ln \alpha + n \ln \left(\frac{\sigma}{\sigma_o}\right)$$

which is a straight line on log-log paper. α can be determined directly at $\sigma/\sigma_o = 1$ and n can be determined by the slope of the line.

Alternatively, for linear regression analyses, define

$$y = \ln \left(\frac{E\varepsilon - \sigma}{\sigma_0}\right)$$

$$x = \ln (\sigma/\sigma_0)$$

$$a = \ln \alpha$$

Then

$$y = a + nx$$

$$\alpha = e^{a} \text{ (at } x = 0\text{)}$$

$$n = dy/dx$$

The stress-strain data points plotted on a log-log graph usually do not fall in a straight line.

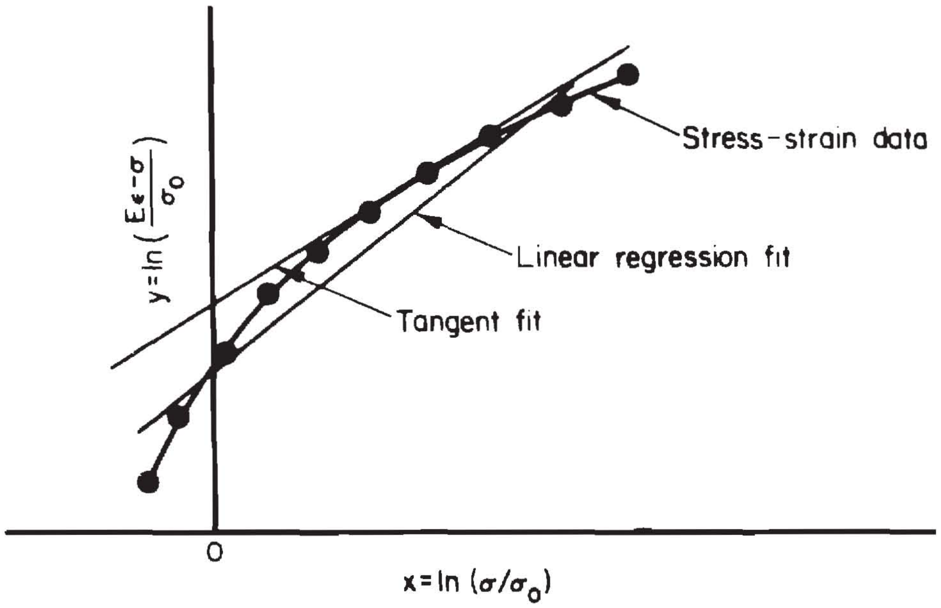

Figure C.1. Schematic of typical stress-strain data.

A typical set of stress-strain data points is shown schematically in Figure C.1. Various values for α and n can be obtained depending on the method used to fit the curved data point plot with a straight line. If linear regression is used, then an appropriate range of data must be used. If a tangent to the data curve is used, then the point of tangency must be assumed.

The stresses used in leak-before-break or other piping integrity analyses of a cracked pipe are remote from the crack vicinity. For linear-elastic analyses, the K, or J_e calculation accounts for the fact that these stresses are not at the crack tip. In elastic-plastic or fully plastic calculations, the J estimation procedure for strain-hardenable materials may not adequately account for complex strain relations in the vicinity of the crack (wall thinning, for instance). Assume a pipe with a through-wall crack of total length, 2θ. For a relatively small θ, say $\leq$ 10 degrees, the remote stresses that lead to crack growth or pipe failure are generally quite high. Conversely, for a large θ, say $\geq$ 90 degrees, crack growth could occur for relatively small or modest remote stresses. Thus, how one fits a Ramberg-Osgood line to the stress-strain data to get α and n could depend on crack length as well as other factors to get best results or those that best predict pipe test results. In that different J estimation procedures are also being used, it is conceivable that one type of fit to the data may be better than another for a particular procedure. This question has not been adequately answered at this time and is one of the reasons (among others) for applying margins for licensing purposes.

For consistency in its analyses to date, the NRC staff has used a tangent fit at $\varepsilon \sim 4$ percent or a linear regression fit in a range close to 4 percent (plus or minus a few percent ε). The staff has found that its LBB.NRC procedure then results in a J at applied loads that closely approximates that reported by applicants/licensees using alternate J estimation procedures or more sophisticated finite element analyses. (See example given in Appendix F.)

Results of NRC analyses of a series of pipe experiments conducted by U.S. David W. Taylor Naval Ship Research and Development Laboratory (NUREG/CR-3740) were reported in the Piping Review Committee report NUREG-1061, Volume 3, Figures A-7, A-8, and A-9. For those analyses, the staff used values of α and n supplied by others so that they would be consistent with the Ramberg-Osgood parameters that were used in the EPRI procedure analyses of these tests. The calculated results were close to agreement with test results. However, they were somewhat nonconservative. The staff has since recalculated these problems using values of α and n determined by the procedure indicated above. (See Appendix E.)

APPENDIX D

NRC STAFF RATIONALE FOR J_p INTEGRATION FORMULA

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NRC STAFF RATIONALE FOR J_p INTEGRATION FORMULA

For a pipe with a circumferential through-wall crack under a bending load, Paris and Tada in NUREG/CR-3464, Section II-2 describe a procedure for estimating J from a load displacement (M-ϕ) diagram. (See discussion in Reference 2 beginning on page 102.) M is the applied moment and ϕ is the angular displacement due to the presence of the crack. After separating J into its elastic and plastic components, J_e and J_p, and using

$$J_p = -\int_0^{\phi_p} \frac{\partial M}{\partial A}\bigg|_{\phi_p} d\phi_p$$

they arrive at

$$\bar{J}_p = \frac{EJ_p}{\sigma_f^2 R} = \frac{F_J(\theta_o)}{S_p(\theta_o)} \int_0^{\bar{\phi}_p} S_b(\phi)d\bar{\phi}_p$$

(Eq. 68 page 107 of Reference 2)

where

$$\bar{\phi}_p = \frac{E\phi_p}{\sigma_f}$$

$$S_b = \frac{M}{\pi R^2 t \sigma_f}$$

$$S_p = \frac{4}{\pi}\left[\cos\frac{\theta_o}{2} - \frac{1}{2}\sin\theta_o\right]$$

$$F_J = -\frac{\pi}{2}\frac{\partial S_p}{\partial \theta_o} = \sin\frac{\theta_o}{2} + \cos\theta_o.$$

Note that the NRC staff uses σ_f as the limiting stress in the above equations.

In Section II-4 of NUREG/CR-3464, Paris and Tada use similar rationale for determining J_p when a pipe is subjected to axial plus bending loads except now:

$$S_p = \frac{4}{\pi}\left[\cos\left(\frac{\theta_o}{2} + \frac{\pi}{2}S_t\right) - \frac{1}{2}\sin\theta_o\right]$$

$$F_J = \sin\left(\frac{\theta_o}{2} + \frac{\pi}{2}S_t\right) + \cos(\theta_o)$$

where

$$S_t = \frac{F}{2\pi R t \sigma_f} \text{ and}$$

F = the total axial force including the effect of pressure.

Their procedure is based on the assumption of a relatively low value of S_t (S_t = 0.1 in the example given). This procedure is adequate for engineering estimates of J_p when S_t is small, however, the NRC staff desired an approach that could be used for larger values of S_t because typical licensing applications of leak-before-break technology involve S_t greater than 0.1.

For $S_t = S_q$ an applied axial relative stress, and plotting

$$S_p = \frac{4}{\pi} [\cos (\frac{\theta_o}{2} + \frac{\pi}{2} S_t) - \frac{\sin\theta_o}{2}]$$

versus S_q one gets a typical limit load curve shown schematically as curve S_o - o in Figure D.1. Note that for positive stresses S_p approaches zero as S_q increases to its limit. Alternatively, for a given value of applied bending stress, $S_b = S_p$, one could calculate the limiting axial stress by

$$S_q = \frac{2}{\pi} [\cos^{-1} (\frac{\pi}{4} S_b + \frac{\sin\theta_o}{2}) - \frac{\theta_o}{2}]$$

to get the limit load point, r, in Figure D.1.

Because both axial plus bending loads contribute to the strain in the material of a cracked pipe, any J estimation procedure must account for them both, especially if the resulting stress magnitudes are comparable, as is the case in some piping systems.

In Appendix A of NUREG-1061, Volume 3 (Subsection A.3.3.2), a method for combined tension and bending loads is discussed. As seen from Figure A-11 of this reference, the axial load is approximated as an increase to the applied moment to get an equivalent moment according to:

$$M_{eq} = M + \frac{R}{2} \frac{F_t}{F_b} F$$

where M and F are applied loads.

(The NUREG formula used P instead of F. F is used here for internal consistency in this document.)

Using the thin-wall pipe assumption and dividing all terms by $\pi R^2 t \sigma_f$, the above equation can be rewritten as:

$$S_{b_{eq}} = S_b + \frac{F_t}{F_b} S_t$$

There are several ways in which tension plus bending stresses can be incorporated into a J estimation procedure. One approach used by an organization submitting a LBB application was to assume that F = o. Then, using the EPRI/GE procedure, they calculated J versus an equivalent moment as suggested in NUREG-1061, Volume 3 (see also Appendix F of this document). They then get J at their applied moment from $J(M_{eq})$ where M_{eq} is defined above and M and F are their applied loads. In effect, the J versus M plot of results is shifted to the left by $\frac{R}{2} \frac{F_t}{F_b}$ F and J is then obtained at the applied moment. The LBB.NRC procedure could also be used in the same manner as is illustrated in the example given in Appendix F.

The LBB.NRC procedure now being used combines the axial and bending stresses in the J_p integration formula as follows:

$$\bar{J}_p = \frac{F_J}{(S_p + S_q)} \int_0^{\bar{\Phi}_p} (S_b + \frac{F_t}{F_b} S_t)\, d\bar{\Phi}_p$$

in which F_J and S_p include the applied $S_t = S_q$. S_q is added in the denominator of the integration constant based on engineering judgment to avoid J_p resulting in unreasonably high values at relatively large values of S_q when S_p approaches zero.

Both of the above procedures are recognized to be engineering approximations that can be used until a more theoretically correct method is formed for combining tensile plus bending loads. Example analyses are given in Appendix G.

Further rationale for including S_t in the $\bar{J}_p$ integration for relatively large values of S_q is illustrated schematically in Figure D.2. The NUREG/CR-3464 equation for J_p would result from the area shown as (1) in the figure. This area approaches zero as S_q approaches its limit. The NRC program uses the area shown as (2) in the figure. Typical results using the NRC approach appear to be quite reasonable for an engineering estimation of J_p at nominal applied loads.

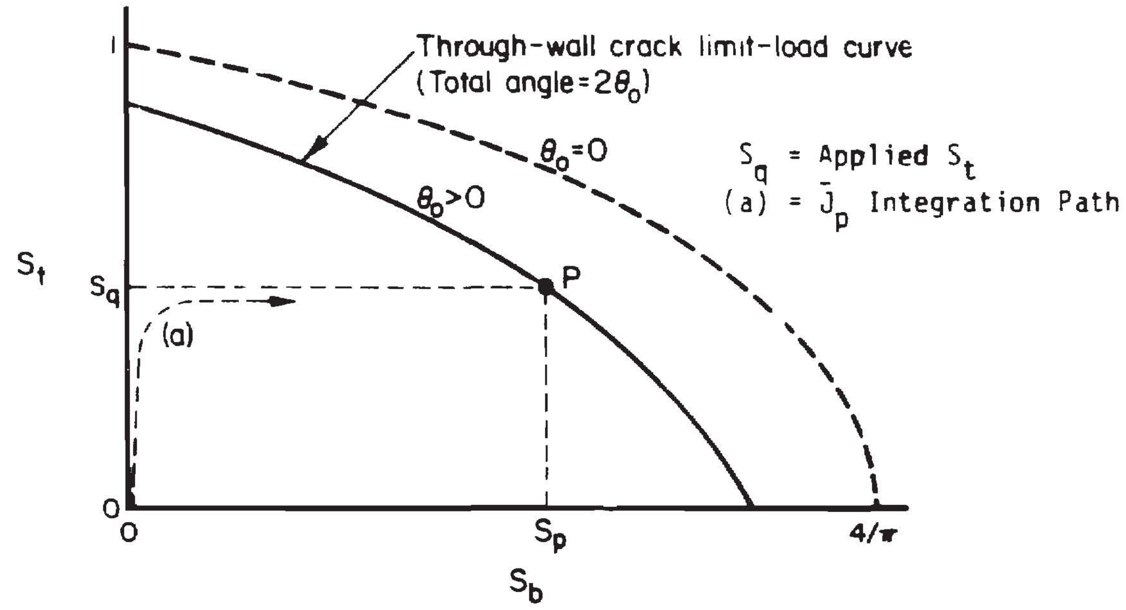

Figure D.1. Typical limit-load curve for through-wall crack.

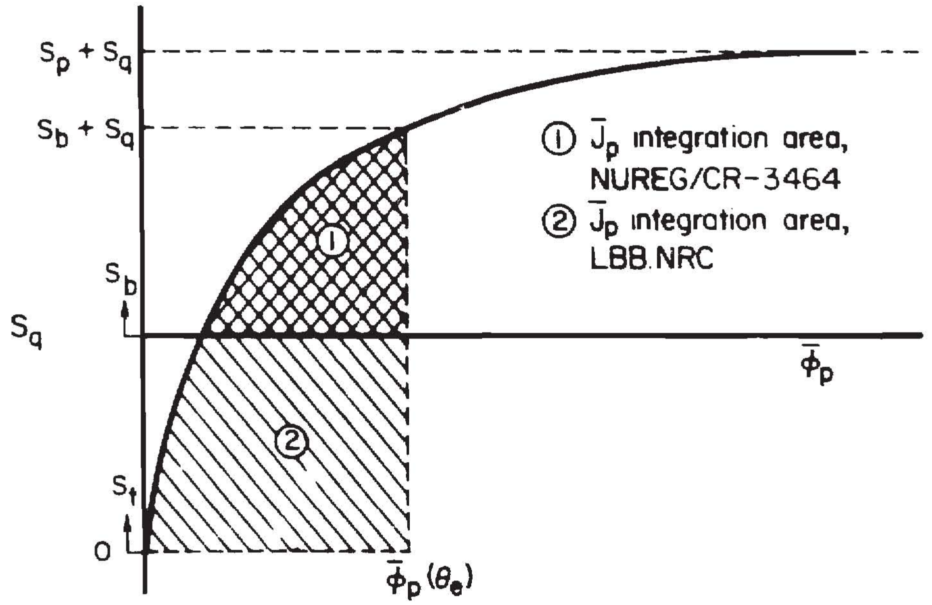

Figure D.2. Typical normalized stress variation as a function of the kink angle.

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APPENDIX E

COMPARISON OF LBB.NRC PROCEDURE WITH PIPE EXPERIMENT RESULTS

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COMPARISON OF LBB.NRC PROCEDURE WITH PIPE EXPERIMENT RESULTS

During the preparation for writing NUREG-1061, Vol. 3, the NRC staff analysed a series of pipe experiments performed by the U.S. David W. Taylor Naval Ship Research and Development Laboratory as reported in NUREG/CR-3740. For those analyses the staff used Ramberg-Osgood parameters provided by others. The staff's results are discussed in Appendix A of NUREG-1061, Vol. 3.

Subsequently, the NRC staff derived revised values of the Ramberg-Osgood parameters using the procedures described in Appendix C of this document. The original and the new parameters are shown in Table E.1 and the new results in Table E.2. The more recent results are more conservative and a comparison of the results of the new and the original analyses illustrates their sensitivity to the selection of the Ramberg-Osgood parameters. Results for one of the pipe experiments are plotted on the following revised Figure A-9 from NUREG-1061, Vol. 3.

A number of full scale pipe experiments have been carried out at BCL for pure bending. Predicted results using the BCL's NRCPIPE computer program which includes the LBB.NRC procedure and allows for crack growth compared favorably with these experimental results for both crack initiation and maximum load. These results are discussed fully in Reference E.1.

Brust recently proposed two modifications to the NRC method. In one version, the plastic kink angle is obtained from the elastic kink angle using a modification which depends on the G.E. h-function. This version, which is referred to as the "G.E. Functions Modification", is the most accurate if the h-functions are correct. The second version obtains the plastic kink angle from the elastic kink angle using an "engineering estimate". The "engineering estimate" is obtained by approximating the stiffness of the cracked section of pipe by using a short length of pipe with an appropriately reduced thickness. This method is referred to as the "engineering estimate modification". A description of both of these modifications will be described in an upcoming Battelle report. An encouraging feature of the results is that the "engineering estimate modification" produces results which are very close to the "G.E. function modification" results. This is important because it means that analyses can be made in R/t ranges not covered by the G.E functions. Moreover, this method may be extended to crack geometries not encompassed by the G.E. functions.

Table E.1 DTNSRDC 8 Inch Ferritic Pipe Tests.

Parameters	Original Calculations for NUREG-1061, Vol. 3	New NRC Calculations with NRC Method for α & n
α	1.35	3.6
n	6.2	4.159
σ_0, ksi	35	35
E, ksi	29,000	29,000
σ_f, ksi	56.4	56.4

T-4572-TE.1

Table E.2 Analysis results from LBB.NRC using the original and new parameters listed in Table E.1.

(See also Table A-3, NUREG-1061, Vol. 3.)

Test #	M_i, (in-k)	$J_i(\frac{\text{in-k}}{\text{in}^2})$	Original NRC J/J_i @ M_i	New NRC J/J_i @ M_i	New NRC M/M_i @ J_i
N3	935.69	3.680	1.035	1.856	0.910
N7	828.90	5.400	0.564	1.022	0.998
N8	801.31	4.420	0.402	0.690	1.075
N11	1061.8	2.340	0.922	1.545	0.929
N12	1090.70	3.110	1.195	1.898	0.901
N14	1228.00	4.300	0.671	0.991	1.000
N15	1189.40	2.850	1.428	2.135	0.870
Average			0.888	1.448	0.955

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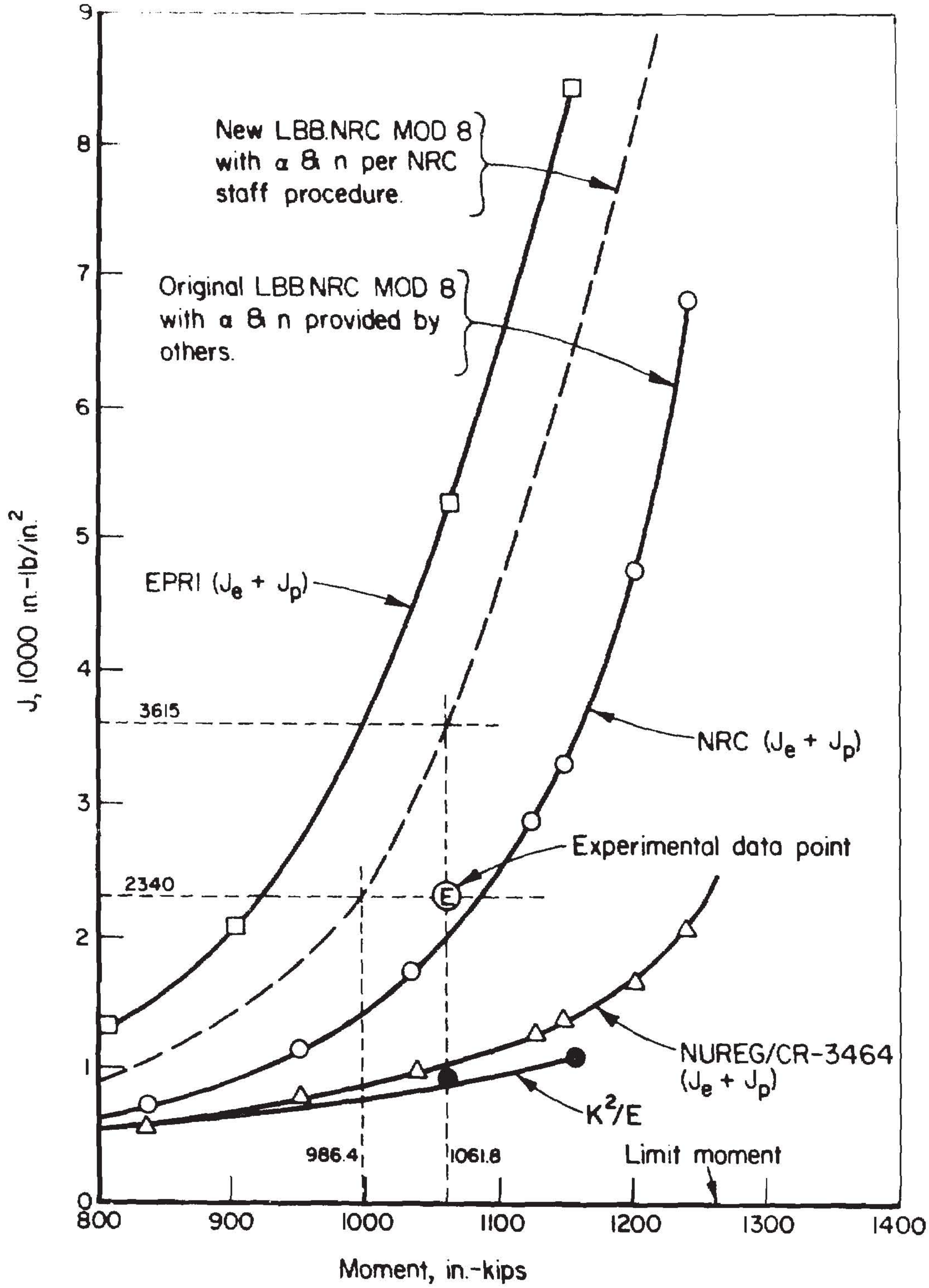

Figure E.1. Comparison of various J-estimation schemes to average values from DTNSRDC ferritic pipe test data at crack initiation.

T-4572-FE.1

[redacted]

REFERENCES (APPENDIX E)

(E.1) Wilkowski, G. M., et al., "Degraded Piping Program - Phase II", Semiannual Report, April 1985-September 1985, NUREG/CR-4082, BMI-2120, Vol. 3, March 1986.

APPENDIX F

APPLICATION OF LBB.NRC IN A LICENSING APPLICATION

APPENDIX F

APPLICATION OF LBB.NRC IN A LICENSING APPLICATION

The Ramberg-Osgood parameters are determined from the stress-strain data submitted in the licensing application. Table F.1 shows the stress-strain data and the determined Ramberg-Osgood parameters. The stress-strain data and the Ramberg-Osgood correlation are plotted in Figures F.1 and F.2.

LBB.NRC is evaluated using the Ramberg-Osgood parameters. Tables F.2 and F.3 show the input parameters. The results for an axial force of 1685.7 kips and an applied bending moment of 37171 in-kips are shown in Figure F.3. The results for an axial force of 2383.9 kips and an applied bending moment of 52568 in-kips are shown in Figure F.4. As a comparison, the finite element (FEM) results provided in the licensing application are also indicated in Figures F.3 and F.4. The reported EPRI/GE results, obtained by combining the axial force and the bending moment into an equivalent bending moment according to Figure A.11 in NUREG-1061, Vol. 3, are also plotted in Figure F.3. (The axial force of 1685.7 kips is equivalent to a bending moment of 13093 in-kips.) The numbers in parentheses are the values of J obtained from the various approaches.

To further demonstrate that the axial force and bending moment can be combined into an equivalent bending moment according to Figure A.11 in NUREG-1061, Vol. 3 to yield an estimate of J, LBB.NRC is evaluated using the input parameters shown in Table F.4 (no axial force). The results are plotted in Figure F.5 after the curve has been shifted to the left by 13093 in-kips to account for the axial force. As a comparison, the LBB.NRC results in Figure F-3 is also plotted in Figure F.5.

The J values for an axial force of 1685.7 kips and a bending moment of 37171 in-kips estimated from the various approaches are summarized in Table F.5.

Table F.1 Determination of Ramberg-Osgood parameters using the NRC computer program*

```
                 1, 23 1987, [illegible]
Determination of Strain Hardening Using Ramberg-Osgood
Equation and Linear Regression Over User Selected
Range of Strain From Data File of Stress and Strain

  Reference Stress, SIGO (ksi)  =   39
      Elastic Modulus, E (ksi)  =   26500
  Linear Regression Fit :
          Starts at Strain of (%)  =   1.45
            Ends at Strain of (%)  =   6.05
Filename of Stress-Strain Data = TYPICAL

     SIGMA(ksi)  EPSILON        X          Y
     ----------  -------      -----      -----

     42.0000     0.005000     1.077      2.321
     48.0000     0.010000     1.231      5.564
     52.0000     0.015000     1.333      8.859
     56.0000     0.020000     1.436     12.154
     63.0000     0.030000     1.615     18.769
     69.0000     0.040000     1.769     25.410
     73.0000     0.050000     1.872     32.103
     77.0000     0.060000     1.974     38.795

X = SIGMA/SIGO ; Y = (E*EPSILON-SIGMA)/SIGO
Data File Contains a Total of  8  Pairs of Points
A Total of  8  Pairs of Points are Plotted
A Total of  6  Pairs of Points are in Linear Regression
Resulting Correlation Coefficient, r  =  0.9[illegible]

Ramberg-Osgood Coefficients:    alpha  =  [illegible].102  ;  n  =  3.[illegible]
```

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* Calculations are performed by BASICA and plotting is done by LOTUS 123.

T-4572-TF.1

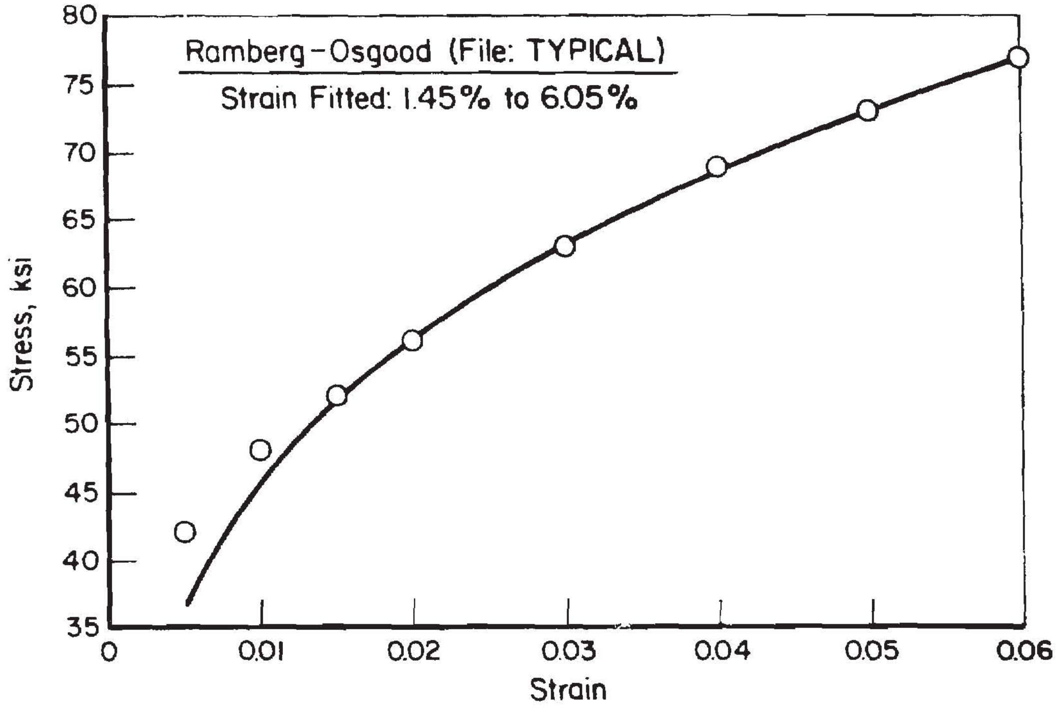

Figure F.1. Stress versus strain plot with associated Ramberg-Osgood correlation.

T-4572-FF.1

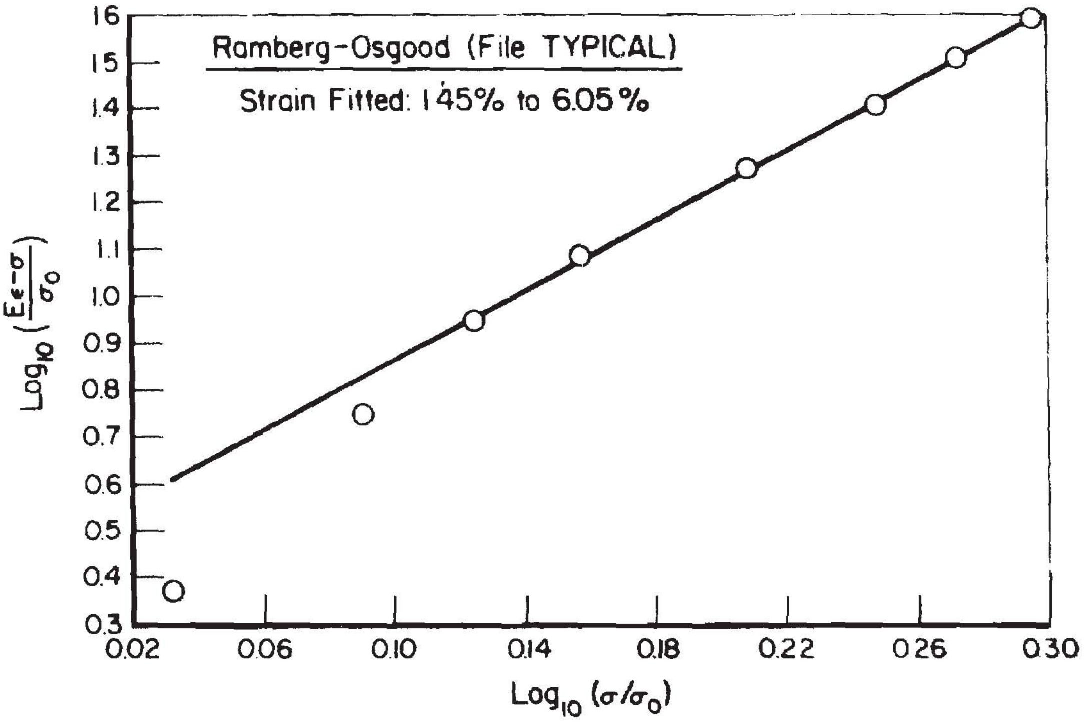

Figure F.2. Log-log plot with associated Ramberg-Osgood correlation indicated as straight line.

T-4572-FF.2

Table F.2. Data Sheet for Axial Force of 1685.7 kips
and applied bending moment of 37171 in-kips

```
12-23-1985                LEAK  BEFORE  BREAK
                           LBB.NRC MOD: 8
                        FACILITY: Typical
                        PIPE SYSTEM: 28" ID Carbon Steel Pipe

                            INPUT PARAMETERS
                 1   Strain Hardening          alpha = AL= 3.1
                 2   Strain Hardening                n = N= 3.7
                 3   Reference Stress [ksi]           SIGR= 39
                 4   Flow Stress [ksi]                SIGF= 60
                 5   Initial Half Crack Angle [deg] THO= 17.142
                 6   Axial Force [kips]                  F= 1685.7
                 7   Elastic Modulus [ksi]               E= 26500
                 8   Pipe or Vessel Radius [in]          R= 15.375
                 9   Pipe or Vessel Thickness [in]       T= 2.25
                10   Leak Rate Constant [gpm/si]       LRC= 250
                11   Applied Bending Moment [kk-in] AMB= 37.171

 SIGT=Axial Stress    SIGB=Bending Stress    MB=Bending Moment     PHI=Kink Angle
    J=J Integral    COA=Crack Opening Area    LR=Leak Rate     ST=SIGT/SIGF
                      SB=SIGB/SIGF      CL=Crack Length

***       NORMALIZED          ***   ************       ENGINEERING UNITS        **********
  ST+SB        PHI          J          SIGB        MB        PHI        J         COA         LR
  -----        ---          -          [ksi]   [kk-in]     [deg]    [k/in]      [si]      [gpm]
_______________________________________________________________________________________________

  0.0000      0.000       0.000        0.00      0.00       0.00      0.00      0.000        0.0
  0.1293      0.028       0.021        0.00      0.00       0.00      0.04      0.045       11.4
  0.2316      0.059       0.068        5.14     10.26       0.01      0.14      0.084       20.9
  0.3280      0.108       0.144       11.92     19.93       0.01      0.30      0.122       30.6
  0.4199      0.189       0.259       17.44     29.13       0.02      0.54      0.164       41.1
  0.5070      0.320       0.428       22.66     37.87       0.04      0.89      0.210       52.6
  0.5889      0.519       0.670       27.58     46.08       0.07      1.40      0.262       65.4
  0.6653      0.807       1.012       32.16     53.74       0.10      2.11      0.319       79.6
  0.7358      1.205       1.484       36.39     60.81       0.16      3.10      0.385       96.2
  0.8003      1.736       2.118       40.26     67.28       0.23      4.42      0.459      114.8
  0.8586      2.420       2.951       43.76     73.13       0.31      6.15      0.544      136.1
  0.9109      3.230       4.019       46.90     78.36       0.47      8.39      0.641      160.4
  0.9571      4.334       5.355       49.67     83.00       0.56     11.19      0.752      188.1
  0.9975      5.600       6.993       52.09     87.04       0.73     14.61      0.879      219.8
  1.0322      7.093       8.758       54.17     90.52       0.92     18.31      1.021      255.3
  1.0614      8.823      11.270       55.93     93.45       1.14     23.54      1.187      296.8
  1.0855     10.797      13.942       57.37     95.87       1.40     29.12      [illegible] [illegible]
  1.1046     13.017      16.977       58.52     97.78       1.69     35.46      1.584      395.9
  1.1190     15.479      20.365       59.39     99.23       2.01     42.54      1.821      455.3
  1.1290     18.172      24.086       59.99    100.23       2.36     50.31      2.088      522.[illegible]
  1.1348     21.077      28.108       60.33    100.81       2.74     58.71      2.388      59[illegible]
  1.1365     23.998      32.148       60.44    100.98       3.11     67.15      2.704      [illegible]
-----------------------------RESULTS AT APPLIED LOAD------------------------------
    SIGT=  7.755 ksi, CL= 9.200 in.,   AMB=  37.17 kk-in, J=  0.865 k/in,
    SIGB= 22.245 ksi, PHI= 0.040 deg, COA= 0.207 si,     LR=  51.66 gpm
```

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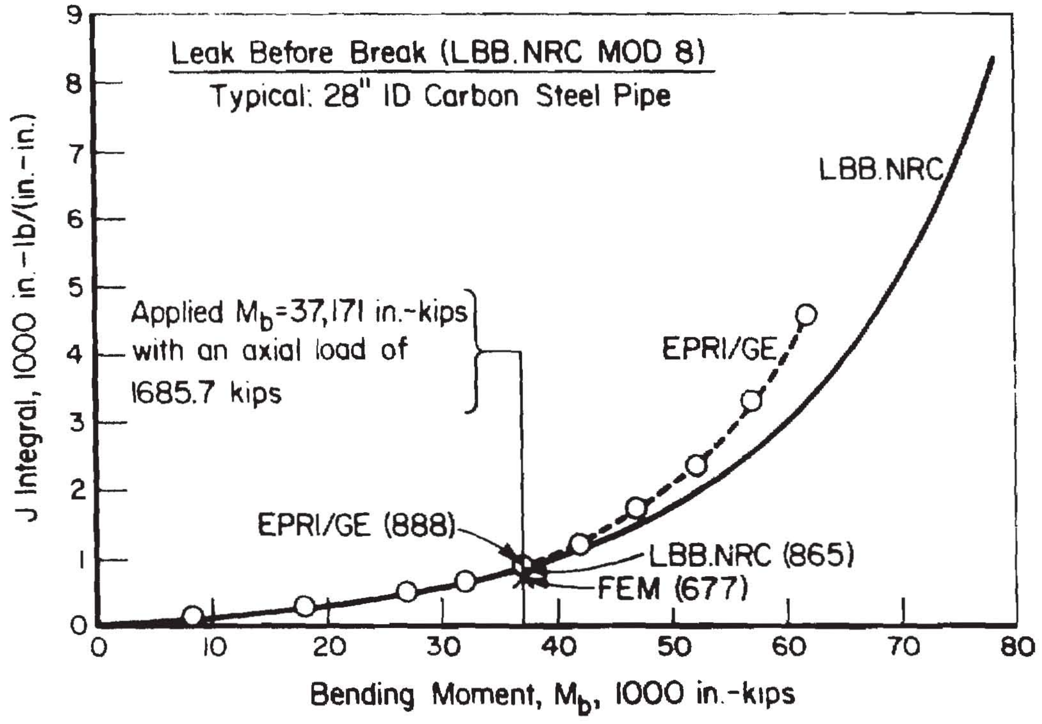


Figure F.3. J versus bending moment for axial force of 1685.7 kips.

T-4572-FF.3

Table F.3. Data sheet for axial force of 2383.9 kips
and applied bending moment of 52568 in-kips

```
12-23-1985              LEAK  BEFORE  BREAK
                         LBB.NRC MOD: 8
                       FACILITY: Typical
                       PIPE SYSTEM: 28" ID Carbon Steel Pipe

                              INPUT PARAMETERS
          1  Strain Hardening              alpha = AL= 3.1
          2  Strain Hardening                  n = N= 3.7
          3  Reference Stress [ksi]            SIGR= 39
          4  Flow Stress [ksi]                 SIGF= 60
          5  Initial Half Crack Angle [deg] THO= 17.142
          6  Axial Force [kips]                  F= 2383.9
          7  Elastic Modulus [ksi]               E= 26500
          8  Pipe or Vessel Radius [in]          R= 15.375
          9  Pipe or Vessel Thickness [in]       T= 2.25
         10  Leak Rate Constant [gpm/si]      LRC= 250
         11  Applied Bending Moment [kk-in] AMB= 52.568

SIGT=Axial Stress   SIGB=Bending Stress   MB=Bending Moment   PHI=Kink Angle
   J=J Integral   COA=Crack Opening Area   LR=Leak Rate   ST=SIGT/SIGF
                  SB=SIGB/SIGF     CL=Crack Length
```

*** NORMALIZED ST+SB -----	FHI ---	J *** -	ENGINEERING UNITS SIGB [ksi]	MB [kk-in]	PHI [deg]	J [k/in]	COA [si]	LR [gpm]
0.0000	0.000	0.000	0.00	0.00	0.00	0.00	0.000	0.0
0.1828	0.043	0.042	0.00	0.00	0.01	0.09	0.065	16.3
0.2682	0.074	0.097	5.00	8.36	0.01	0.19	0.097	24.3
0.3541	0.127	0.174	10.29	17.19	0.02	0.36	0.134	33.5
0.4416	0.215	0.299	15.53	25.95	0.03	0.62	0.175	43.7
0.5262	0.358	0.487	20.60	34.43	0.05	1.01	0.221	55.2
0.6065	0.573	0.750	25.42	42.48	0.07	1.57	0.272	68.1
0.6819	0.881	1.128	29.95	50.04	0.11	2.36	0.331	82.7
0.7518	1.306	1.650	34.14	57.05	0.17	3.45	0.397	99.3
0.8158	1.880	2.357	37.98	63.47	0.24	4.92	0.473	118.2
0.8739	2.645	3.277	41.47	69.29	0.34	6.85	0.559	139.8
0.9259	3.50[illegible]	4.462	44.59	74.50	0.45	9.32	0.658	164.6
0.9720	4.615	5.945	47.35	79.12	0.60	12.42	0.771	192.8
1.0122	5.949	7.762	49.76	83.15	0.77	16.21	0.900	225.0
1.0457	7.519	9.940	51.83	86.51	0.98	20.76	1.047	261.7
1.0758	9.[illegible]	12.501	53.58	89.53	1.21	26.11	1.214	303.4
1.0996	11.401	15.458	55.01	91.92	1.48	32.29	1.4[illegible]	[illegible]
1.1185	13.723	18.812	56.14	93.81	1.78	39.29	1.617	404.2
1.1326	16.292	22.552	56.99	95.23	2.11	47.1[illegible]	1.858	454.5
1.1422	19.096	26.652	57.57	96.19	2.48	55.6[illegible]	2.130	532.4
1.1476	22.115	31.074	57.89	96.73	2.87	64.9[illegible]	2.434	608.5
1.1489	24.707	34.867	57.97	96.86	3.21	72.83	2.508	627.1

```
-------------------------RESULTS AT APPLIED LOAD---------------------------
   SIGT= 10.968 ksi, CL= 9.200 in.,  AMB=  52.57 kk-in, J=  2.749 k/in,
   SIGB= 31.460 ksi, PHI= 0.134 deg, COA= 0.355 si,      LR=  88.68 gpm
```

T-4572-TF.3

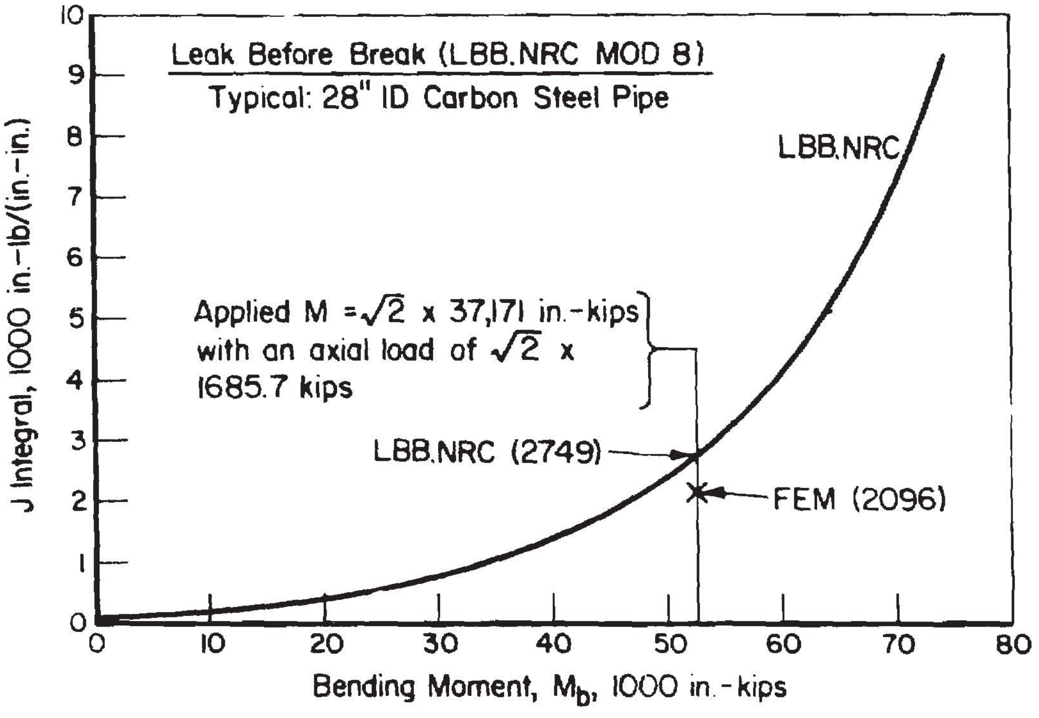


Figure F.4. J versus bending moment for axial force of 2383.9 kips.

T-4572-FF.4

Table F.4. Data sheet for no axial force and equivalent applied bending moment of 50264 in-kips

```
12-26-1985                LEAK   BEFORE   BREAK
                            LBB.NRC MOD: 8
                            FACILITY: Typical
                            PIPE SYSTEM: 28" ID Carbon Steel Pipe

                                INPUT PARAMETERS
                   1   Strain Hardening            alpha = AL= 3.1
                   2   Strain Hardening                n = N= 3.7
                   3   Reference Stress [ksi]           SIGR= 39
                   4   Flow Stress [ksi]                SIGF= 60
                   5   Initial Half Crack Angle [deg] THO= 17.142
                   6   Axial Force [kips]                  F= 0
                   7   Elastic Modulus [ksi]               E= 26500
                   8   Pipe or Vessel Radius [in]          R= 15.375
                   9   Pipe or Vessel Thickness [in]       T= 2.25
                  10   Leak Rate Constant [gpm/si]       LRC= 250
                  11   Applied Bending Moment [kk-in] AMB= 50.264

  SIGT=Axial Stress    SIGB=Bending Stress    MB=Bending Moment     PHI=Kink Angle
      J=J Integral    COA=Crack Opening Area    LR=Leak Rate     ST=SIGT/SIGF
                       SB=SIGB/SIGF      CL=Crack Length

 ***       NORMALIZED        ***    ************     ENGINEERING UNITS     ***********
  ST+SB       PHI         J         SIGB      MB       PHI        J        COA        LR
  -----       ---         -        [ksi]   [kk-in]    [deg]    [k/in]     [si]     [gpm]
 ----------------------------------------------------------------------------------------

  0.0000     0.000      0.000       0.00      0.00     0.00      0.00     0.000       0.0
  0.1829     0.042      0.040      10.97     18.34     0.01      0.08     0.065      16.2
  0.2851     0.083      0.102      17.17     28.68     0.01      0.21     0.105      26.3
  0.3785     0.147      0.195      22.71     37.94     0.02      0.41     0.146      36.5
  0.4639     0.250      0.326      27.84     46.51     0.03      0.68     0.190      47.4
  0.5433     0.406      0.510      32.60     54.47     0.05      1.07     0.238      59.5
  0.6168     0.532      0.763      37.01     61.84     0.08      1.59     0.292      73.0
  0.6844     0.745      1.106      41.07     68.62     0.12      2.31     0.353      88.3
  0.7461     1.362      1.560      44.77     74.80     0.18      3.26     0.423     105.7
  0.8018     1.701      2.149      48.11     80.39     0.25      4.49     0.502     125.5
  0.8517     2.580      2.897      51.10     85.39     0.33      6.05     0.593     148.2
  0.8959     3.414      3.829      53.75     89.82     0.44      8.00     0.696     174.0
  0.9345     4.418      4.965      56.07     93.69     0.57     10.37     0.814     203.6
  0.9677     5.604      6.325      58.06     97.02     0.73     13.21     0.949     237.2
  0.9959     6.932      7.923      59.75     99.85     0.91     16.35     1.102     275.4
  1.0192     8.559      9.769      61.15    102.18     1.11     20.40     1.275     318.8
  1.0379    10.319     11.866      62.27    104.05     1.34     24.78     1.471     367.8
  1.0522    12.319     14.211      63.13    105.49     1.60     29.68     1.693     423.2
  1.0624    14.495     16.793      63.74    106.51     1.88     35.08     1.942     485.5
  1.0687    16.855     19.595      64.12    107.14     2.19     40.93     2.222     555.4
  1.0713    19.384     22.589      64.28    107.40     2.51     47.18     2.535     633.7
  1.0714    19.993     23.308      64.28    107.41     2.59     48.68     2.613     653.1
 ---------------------------RESULTS AT APPLIED LOAD-------------------------------------
     SIGT=  0.000 ksi, CL= 9.200 in.,   AMB=  50.26 kk-in, J=  0.862 k/in,
     SIGB= 30.081 ksi, PHI= 0.042 deg, COA= 0.212 si,       LR=  53.12 gpm
```

T-4572-TF.4

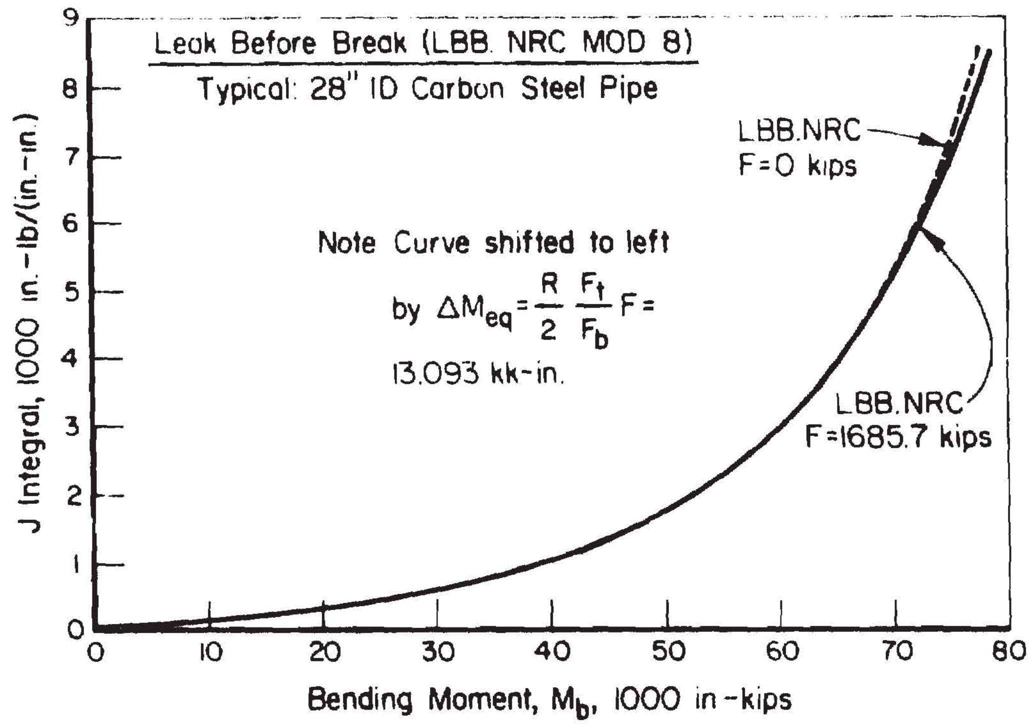


Figure F.5. J versus bending moment for axial force of 1685.7 kips treated as equivalent bending moment.

T-4572-FF.5

Table F.5. J estimates for axial force of 1685.7 kips and bending moment of 37171 in-kips.

	LBB.NRC	LBB.NRC (Equivalent Moment)	Finite Element	EPRI/G.E. (Equivalent Moment)
J (in-lb/in^2)	865	862	677	888

T-4572-TF.5

APPENDIX G

SAMPLE PROBLEMS

APPENDIX G

SAMPLE PROBLEMS

Sample problems to illustrate LBB.NRC with relatively large axial loads together with bending loads (see data sheets for input parameters) are presented in this appendix. Tables G.1 through G.7 give the output from an LBB.NRC analysis. All the analysis parameters are defined in the printout. These outputs can be reproduced by the reader.

The results of these analyses were then plotted in Figures G.1 through G.3. These plots are self-explanatory. The term "data sheet" in Figure G.1 refers to the data listed in Tables G.1 through G.7.

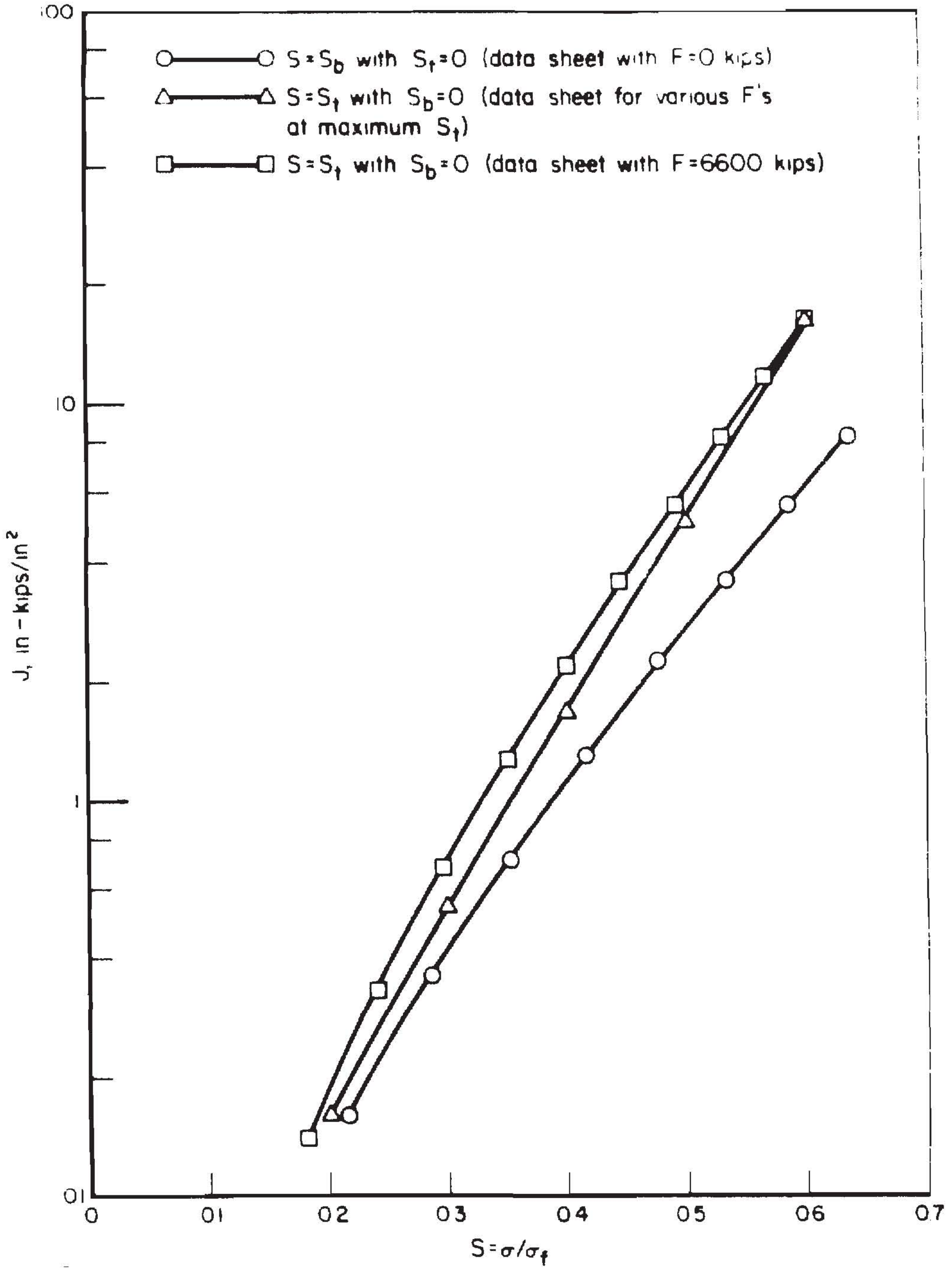


Figure G.1. J versus S for various levels of axial force and bending moment. Data sheet here refers to the appropriate result from Tables G-1 through G-7.

T-4572-FG.1

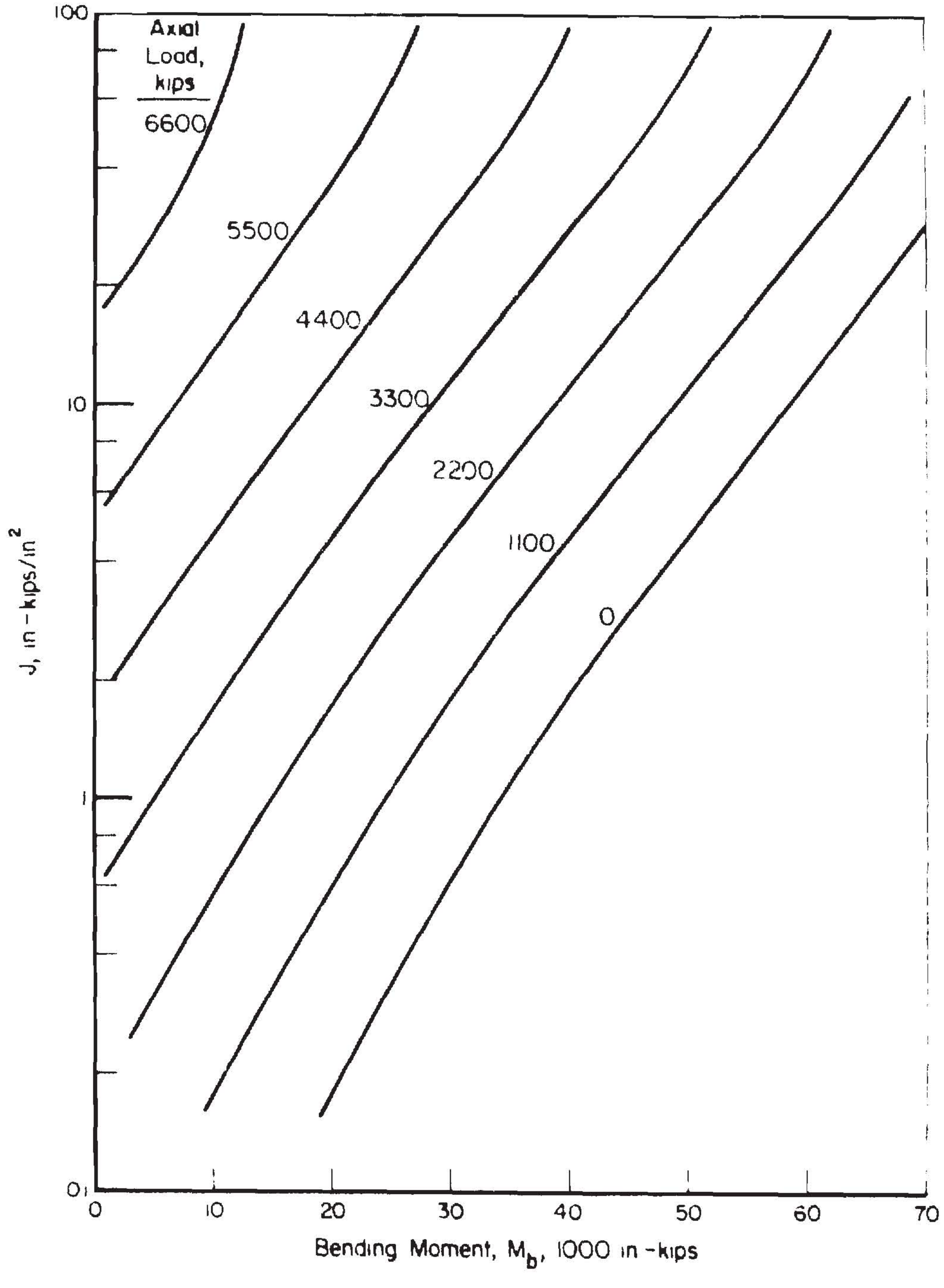


Figure G.2. J versus M for various levels of axial force. From Tables G.1 through G.7.

T-4572-FG.2

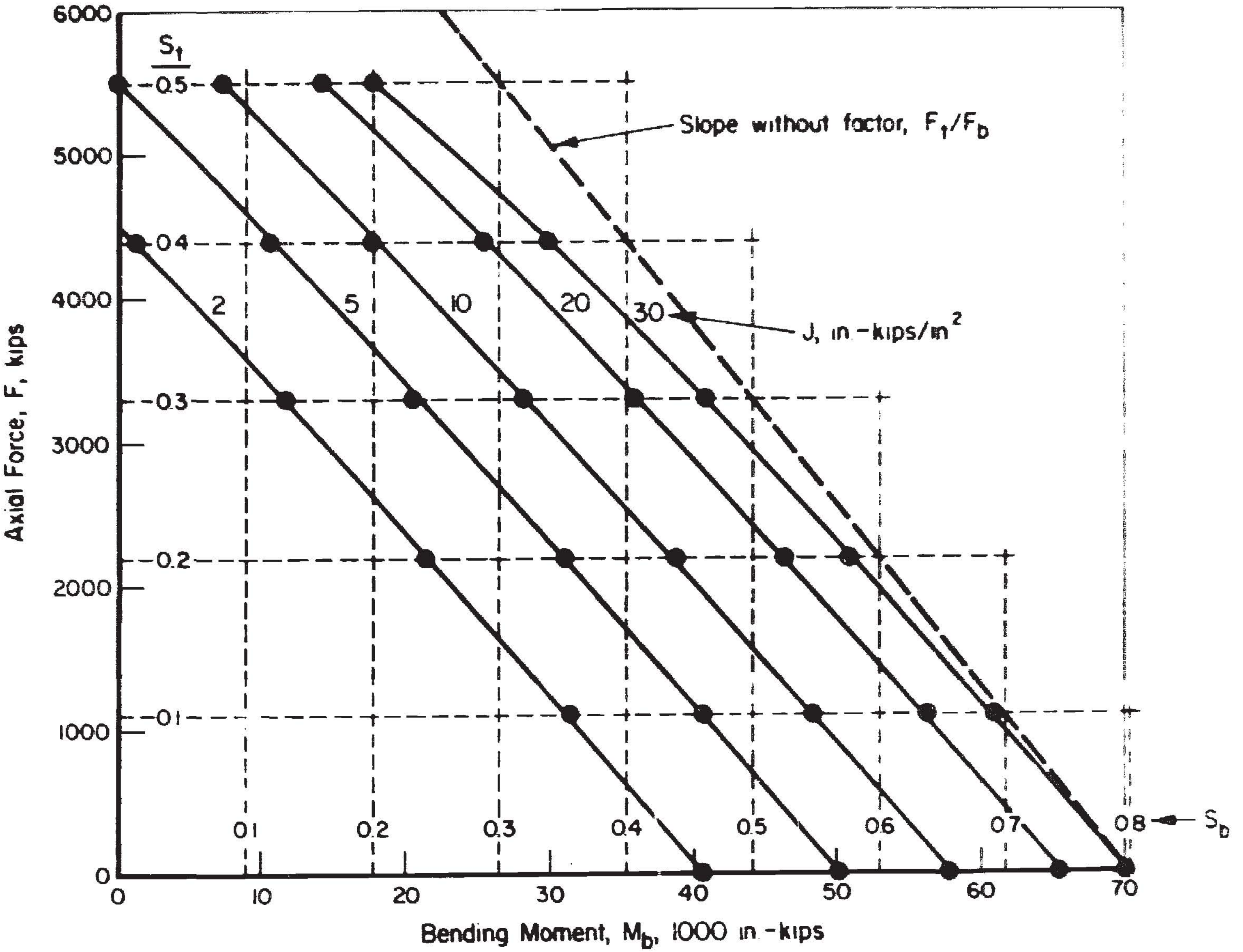


Figure G.3. Equivalence of axial force versus bending moment. From cross-plot of Figure G.2.

T-4572-FG.3

Table G.1. LBB.NRC analysis output

```
                    LEAK   BEFORE   BREAK
                     LBB.NRC MOD: 8
                 FACILITY: Example Calculation
                 PIPE SYSTEM: with various values of F

                     INPUT PARAMETERS
     1  Strain Hardening           alpha = Al = 8
     2  Strain Hardening                n = N= 3.5
     3  Reference Stress [ksi]          SIGR= 20.3
     4  Flow Stress [ksi]               SIGF= 42.084
     5  Initial Half Crack Angle [deg] THO= 30
     6  Axial Force [kips]                 F= 0
     7  Elastic Modulus [ksi]              E= 26000
     8  Pipe or Vessel Radius [in]         R= 16
     9  Pipe or Vessel Thickness [in]      T= 2.6
    10  Leak Rate Constant [gpm/si]      LRC= 250
    11  Applied Bending Moment [kk-in] AMB= 20

SIGT=Axial Stress    SIGB=Bending Stress    MB=Bending Moment     PHI=Kink Angle
     J=J Integral    COA=Crack Opening Area    LR=Leak Rate     ST=SIGT/SIGF
                     SB=SIGB/SIGF      CL=Crack Length

***      NORMALIZED       ***   ***********    ENGINEERING UNITS      ***********
 ST+SB       PHI          J      SIGB     MB       PHI       J        COA        LR
 -----       ---          -     [ksi]   [kk-in]   [deg]    [k/in]     [si]      [gpm]

[illegible]

-------------------------------RESULTS AT APPLIED LOAD-------------------------------
   SIGT=  0.000 ksi, CL=16.755 in.,  AMB=  20.00 kk in, J=  0.192 k/in,
   SIGB=  9.565 ksi, PHI= 0.035 deg, COA= 0.217 si,      LR=  54.27 gpm
```

T-4572-TG.1

Table G.2. LBB.NRC analysis output

```
                        LEAK  BEFORE  BREAK
                          LBB.NRC MOD: 8
                      FACILITY: Example Calculation
                      PIPE SYSTEM: with various values of F

                          INPUT PARAMETERS
         1  Strain Hardening            alpha = AL= 8
         2  Strain Hardening                n = N= 3.5
         3  Reference Stress [ksi]           SIGR= 20.3
         4  Flow Stress [ksi]                SIGF= 42.084
         5  Initial Half Crack Angle [deg] THO= 30
         6  Axial Force [kips]                  F= 1100
         7  Elastic Modulus [ksi]               E= 26000
         8  Pipe or Vessel Radius [in]          R= 16
         9  Pipe or Vessel Thickness [in]       T= 2.6
        10  Leak Rate Constant [gpm/si]       LRC= 250
        11  Applied Bending Moment [kk-in] AMB= 20

SIGT=Axial Stress   SIGB=Bending Stress   MB=Bending Moment    PHI=Kink Angle
    J=J Integral   COA=Crack Opening Area   LR=Leak Rate    ST=SIGT/SIGF
                   SB=SIGB/SIGF      CL=Crack Length

***      NORMALIZED       ***  ***********     ENGINEERING UNITS     **********
  ST+SB       PHI          J       SIGB      MB       PHI       J        COA       LR
  -----       ---          -      [ksi]  [kk-in]   [deg]   [k/in]     [si]     [gpm]

[illegible]

--------------------------RESULTS AT APPLIED LOAD------------------------------
   SIGT=  4.208 ksi, CL=16.755 in.,   AMB=  20.00 kk-in, J=  0.623 k/in,
   SIGB=  9.565 ksi, PHI= 0.097 deg, COA= 0.330 si,      LR=  82.39 gpm
```

T-4572-TG.2

Table G.3. LBB.NRC analysis output

```
                    LEAK   BEFORE   BREAK
                      LBB.NRC MOD: 8
                 FACILITY: Example Calculation
                 PIPE SYSTEM: with various values of F

                       INPUT PARAMETERS
          1   Strain Hardening           alpha = AL= 8
          2   Strain Hardening                n = N= 3.5
          3   Reference Stress [ksi]           SIGR= 20.3
          4   Flow Stress [ksi]                SIGF= 42.084
          5   Initial Half Crack Angle [deg] THO= 30
          6   Axial Force [kips]                  F= 2200
          7   Elastic Modulus [ksi]               E= 26000
          8   Pipe or Vessel Radius [in]          R= 16
          9   Pipe or Vessel Thickness [in]       T= 2.6
         10   Leak Rate Constant [gpm/si]      LRC= 250
         11   Applied Bending Moment [kk-in] AMB= 20

 SIGT=Axial Stress   SIGB=Bending Stress   MB=Bending Moment    PHI=Kink Angle
    J=J Integral   COA=Crack Opening Area   LR=Leak Rate     ST=SIGT/SIGF
                   SB=SIGB/SIGF      CL=Crack Length

***      NORMALIZED       ***  ***********     ENGINEERING UNITS      **********
 ST+SB      PHI        J       SIGB      MB      PHI       J       COA       LR
 -----      ---        -      [ksi]  [kk-in]   [deg]    [k/in]    [si]    [gpm]
-------------------------------------------------------------------------------
[illegible]
 ------------------------RESULTS AT APPLIED LOAD---------------------------
   SIGT=  8.418 ksi, CL=16.755 in.,  AMB=  20.00 kk-in, J=  1.773 k/in,
   SIGB=  9.565 ksi, PHI= 0.228 deg, COA= 0.460 si,      LR= 114.97 gpm
```

T-4572-TG.3

Table G.4. LBB.NRC analysis output

```
-----------------------------------------------------------------------------------------
                         LEAK  BEFORE  BREAK
                         LBB.NRC MOD: 8
                    FACILITY: Example Calculation
                    PIPE SYSTEM: with various values of F

                         INPUT PARAMETERS
    1  Strain Hardening                 alpha = AL= 8
    2  Strain Hardening                     n = N= [illegible].5
    3  Reference Stress [ksi]                SIGR= 29.[illegible]
    4  Flow Stress [ksi]                     SIGF= 42. 84
    5  Initial Half Crack Angle [deg]  THO= 30
    6  Axial Force [kips]                       F= [illegible]
    7  Elastic Modulus [ksi]                    E= 25[illegible]
    8  Pipe or Vessel Radius [in]               R= 15
    9  Pipe or Vessel Thickness [in]            T= 2.6
   10  Leak Rate Constant [gpm/si]            LRC= 250
   11  Applied Bending Moment [kk-in]  AMB= 2[illegible]

SIGT=Axial Stress   SIGB=Bending St ess   MB=Bending Moment   PHI=Kink Angle
  J=J Integral   COA=Crack Opening Area   LR=Leak Rate   ST=SIGT/SIGF
                   SB=SIGB/SIGF     CL=Crack Length

***     NORMALIZED        ***  ***********  ENGINEERING UNITS     ***********
 ST+SB       PHI           J       SIGB      MB       PHI       J        COA       LR
 -----       ---          ---     [ksi]   [kk-in]   [deg]    [k/in]    [si]     [gpm]

---------------------------- --RESULTS AT APPLIED LOAD-------------------------------
   SIGT= 12.626 ksi, CL=16.755 in.,  AMB=  20.00 kk-in, J=  4.795 k/in,
   SIGB=  9.565 ksi, PHI  0.493 deg, COA= 0.626 si,     LR= 156.42 gpm

-----------------------------------------------------------------------------------------
```

T-4572-TG.4

Table G.5. LBB.NRC analysis output

```
                         LEAK  BEFORE  BREAK
                           LBB.NRC MOD: B
                      FACILITY: Example Calculation
                      PIPE SYSTEM: with various values of F

                           INPUT PARAMETERS
               1  Strain Hardening           alpha = AL= 8
               2  Strain Hardening               n = N= 3.5
               3  Reference Stress [ksi]          SIGR= 20.3
               4  Flow Stress [ksi]               SIGF= 42.084
               5  Initial Half Crack Angle [deg] THO= 30
               6  Axial Force [kips]                 F= 4400
               7  Elastic Modulus [ksi]              E= 26000
               8  Pipe or Vessel Radius [in]         R= 16
               9  Pipe or Vessel Thickness [in]      T= 2.6
              10  Leak Rate Constant [gpm/si]     LRC= 250
              11  Applied Bending Moment [kk-in] AMB= 20

SIGT=Axial Stress   SIGB=Bending Stress   MB=Bending Moment    PHI=Kink Angle
    J-J Integral   COA=Crack Opening Area   LR=Leak Rate    ST=SIGT/SIGF
                      SB=SIGB/SIGF     CL=Crack Length

***     NORMALIZED       ***  ***********    ENGINEERING UNITS     **********
 ST+SB       PHI          J       SIGB     MB       PHI       J       COA       LR
 -----       ---          -      [ksi]  [kk-in]   [deg]   [k/in]    [si]     [gpm]
--------------------------------------------------------------------------------

-----------------------------RESULTS AT APPLIED LOAD---------------------------
    SIGT= 16.834 ksi. CL=16.755 in.,   AMB=  20.00 kk-in, J= 12.672 k/in,
    SIGB=  9.565 ksi, PHI= 1.018 deg, COA= 0.872 si,      LR= 217.88 gpm
```

T-4572-TG.5

Table G.6. LBB.NRC analysis output

```
                    LEAK  BEFORE  BREAK
                        LBB.NRC MOD: 8
                  FACILITY: Example Calculation
                  PIPE SYSTEM: with various values of F

                        INPUT PARAMETERS
            1  Strain Hardening            alpha = AL= 8
            2  Strain Hardening                n = N= 3.5
            3  Reference Stress [ksi]           SIGR= 20.3
            4  Flow Stress [ksi]                SIGF= 42.084
            5  Initial Half Crack Angle [deg] THO= 30
            6  Axial Force [kips]                  F= 5500
            7  Elastic Modulus [ksi]               E= 26000
            8  Pipe or Vessel Radius [in]          R= 16
            9  Pipe or Vessel Thickness [in]       T= 2.6
           10  Leak Rate Constant [gpm/si]      LRC= 250
           11  Applied Bending Moment [kk-in] AMB= 20

 SIGT=Axial Stress   SIGB=Bending Stress   MB=Bending Moment    PHI=Kink Angle
    J=J Integral   COA=Crack Opening Area   LR=Leak Rate    ST=SIGT/SIGF
                  SB=SIGB/SIGF     CL=Crack Length

***     NORMALIZED       ***  ***********     ENGINEERING UNITS     **********
 ST+SB     PHI           J       SIGB      MB       PHI      J       COA       LR
 -----     ---           -      [ksi]  [kk-in]   [deg]   [k/in]    [si]     [gpm]

[illegible]

-------------------------RESULTS AT APPLIED LOAD---------------------------
   SIGT= 21.042 ksi, CL=16.755 in.,  AMB=  20.00 kk-in, J= 38.451 k/in,
   SIGB=  9.565 ksi, PHI= 2.332 deg, COA= 1.403 si,     LR= 350.65 gpm
```

T-4572-TG.6

Table G.7. LBB.NRC analysis output

```
                  LEAK  BEFORE  BREAK
                     LBB.NRC M     9
                  FACILITY: Example Calculation
                  PIPE SYSTEM: with various values of F

                      INPUT PARAMETERS
          1   Strain Hardening            alpha = AL= 8
          2   Strain Hardening                n = N= 3.5
          3   Reference Stress [ksi]          SIGR= 20.3
          4   Flow Stress [ksi]               SIGF= 42.084
          5   Initial Half Crack Angle [deg] THO= 30
          6   Axial Force [kips]                 F= 6600
          7   Elastic Modulus  ksi]              E= 26000
          8   Pipe or Vessel Radius [in]         R= 16
          9   Pipe or Vessel Thickness [in]      T= 2.6
         10   Leak Rate Constant [gpm/si]      LRC= 250
         11   Applied Bending Moment [kk-in] AMB= 20

 SIGT=Axial Stress   SIGB=Bending Stress   MB=Bending Moment    PHI=Kink Angle
     J=J Integral   COA=Crack Opening Area   LR=Leak Rate    ST=SIGT/SIGF
                    SB=SIGB/SIGF     CL=Crack Length

***      NORMALIZED       ***  ***********     ENGINEERING UNITS      **********
 ST+SB       PHI          J      SIGB     MB      PHI      J       COA      LR
 -----       ---          -      [ksi]  [kk-in]  [deg]   [k/in]    [si]   [gpm]

-----------------------------RESULTS AT APPLIED LOAD-----------------------------
    SIGT= 25.250 ksi, CL=16.755 in.,  AMB=  20.00 kk-in, J=  0.000 k/in,
    SIGB=  0.000 ksi, PHI= 0.000 deg, COA= 0.000 si,      LR=   0.00 gpm
```

Note: Applied bending moment could not be reached with this axial force.

APPENDIX H

LBB.NRC COMPUTER PROGRAM FOR IBM-PC WITH EPSON FX80 PLOTTER AND "LOTUS" SYSTEM PACKAGE

APPENDIX H

LBB.NRC COMPUTER PROGRAM FOR IBM-PC WITH EPSON FX80 PLOTTER* AND "LOTUS" SYSTEM PACKAGE**

---

* If a printer/plotter other than Epson FX80 is used some lines in the program may have to be changed. For example if an Epson FX85 is used, N=0 should be used instead of N=2 in lines 1900 and 3730.

**It is not necessary to use "Lotus" if only printed output is required.

Listing of BASIC - Language LBB.NRC Computer Program

```
10  REM                         LEAK BEFORE BREAK
20  REM                 *Semi-Automated Plotting Using LOTUS*
30  REM                      (LBB.NRC   Version 11-12-85 )
31  REM   The leak-before-break program is coded based on the NRC-NRR
32  REM   (Klecker) method, which is based on the procedure of NUREG/
33  REM   CR-3464 except for the modifications on strain hardening.
34  REM   For reference of the coding, read the IBM Basic manual.
35  REM *---------------------------------------------------------------*
51  REM   Lines 70 and 90 define default input parameters. The parameters
52  REM   can be changed by the user using the EDIT mode.
53  REM
70        AL=8: N1=3.5:SIGR=20.3:SIGF=44.2:THO=22.9:F=1600:TT=2.5
90        E=26000 :RR=16:LRC=250 :AMB=37.8
110 REM *---------------------------------------------------------------*
120 REM   Parameter definition and data format preparation
125 REM *---------------------------------------------------------------*
130 DIM   A(20),A$(20),T(13,2),B(13,2),C$(10),W(50)
150 DIM   A1(5),A2(5),A3(5),X(50),Y(50),Z(50)
170 A$(1) ="  1  Strain Hardening          alpha = AL="
190 A$(2) ="  2  Strain Hardening                n = N="
210 A$(3) ="  3  Reference Stress [ksi]          SIGR="
230 A$(4) ="  4  Flow Stress [ksi]               SIGF="
250 A$(5) ="  5  Initial Half Crack Angle [deg]  THO="
270 A$(6) ="  6  Axial Force [kips]                 F="
290 A$(7) ="  7  Elastic Modulus [ksi]              E="
310 A$(8) ="  8  Pipe or Vessel Radius [in]         R="
330 A$(9) ="  9  Pipe or Vessel Thickness [in]      T="
350 A$(10)=" 10  Leak Rate Constant [gpm/si]     LRC="
370 A$(11)=" 11  Applied Bending Moment [kk-in] AMB="
390 W1$="###.#### "  :W2$="####.### "  :W3$="####.###    "  :W4$="####.## "
410 W5$="######.#"  :W6$="##.### "  :W7$="###.### "
412 A(1)=AL :A(2)=N1 :A(3)=SIGR :A(4)=SIGF :A(5)=THO :A(6)=F :A(7)=E
413 A(8)=RR :A(9)=TT :A(10)=LRC :A(11)=AMB
420 REM *---------------------------------------------------------------*
421 REM   The following are coefficients for F-functions from Sander's
422 REM   analysis of circumferentially cracked pipe under tension and
423 REM   bending.  The radius to thickness ratio (R/t) is limited to
424 REM   between 4 and 16.  The coefficients listed are for unit
425 REM   increments of R/t.
426 REM *---------------------------------------------------------------*
430 DATA   3.488,  -7.453, 24.792,  1.760,  -1.512,  9.470
450 DATA   4.606, -10.402, 28.235,  2.778,  -4.120, 12.034
470 DATA   5.566, -12.936, 31.195,  3.653,  -6.362, 14.238
490 DATA   6.413, -15.171, 33.804,  4.424,  -8.339, 16.181
510 DATA   7.173, -17.178, 36.147,  5.117, -10.114, 17.926
530 DATA   7.865, -19.005, 38.280,  5.748, -11.730, 19.514
550 DATA   8.501, -20.685, 40.242,  6.328, -13.216, 20.975
570 DATA   9.092, -22.244, 42.062,  6.866, -14.594, 22.330
590 DATA   9.643, -23.700, 43.761,  7.368, -15.882, 23.596
610 DATA  10.161, -25.067, 45.358,  7.840, -17.091, 24.785
630 DATA  10.650, -26.358, 46.865,  8.286, -18.233, 25.907
650 DATA  11.114, -27.581, 48.293,  8.708, -19.314, 26.971
670 DATA  11.554, -28.744, 49.651,  9.110, -20.343, 27.982
671 FOR R=0 TO 12  :FOR C=0 TO 5
672 IF C<3 THEN READ T(R,C) ELSE READ B(R,C-3)
673 NEXT C,R
```

```
690 REM  *-------------------------------------------------------------------*
700 REM      Input from the keyboard
711 REM  *-------------------------------------------------------------------*
721 CLS
730 PRINT SPC(32) "LEAK BEFORE BREAK" :PRINT SPC(29) TIME$ SPC(4) DATE$
731 INPUT "          Do you want to use LBB.NRC MOD: 7 or 8 (enter 7 or 8)";ANS
732 INPUT "          Facility Name";C$(2)
733 INPUT "          Pipe System";C$(3)
740 REM *--------------------------------------------------------------------*
741 REM       Open data file LBBOUT.PRN for Lotus plotting input
742 REM       Open files MOD.PRN and PLANT.PRN for titles in plotting
743 REM       Open file LBBOUT.PIC for storage of Lotus generated picture
744 REM *--------------------------------------------------------------------*
761 OPEN "O", #1, "B:MOD.PRN"
762 PRINT #1, "LEAK BEFORE BREAK (LBB.NRC MOD:"ANS")"
763 CLOSE #1
764 OPEN "O", #1, "B:PLANT.PRN"
765 PRINT #1, C$(2)":"C$(3)
766 CLOSE #1
767 OPEN "O", #1, "B:LBBOUT.PIC"
768 CLOSE #1
769 OPEN "O", #1, "B:LBBOUT.PRN"
770 PRINT:PRINT SPC(12) "The current default INPUT PARAMETERS are:":PRINT
800 FOR I=1 TO 11:PRINT SPC(10) A$(I);A(I):NEXT I :PRINT
810 PRINT SPC(12) "Do you want to change any of these parameters"
811 INPUT "               (enter y for yes, or n for no)";Z$ :PRINT
820 IF Z$="y" GOTO 830 ELSE GOTO 930
830 PRINT SPC(5) "To change any parameter, enter its line number, a comma,"
840 PRINT SPC(5) "and then the new parameter value.  For example, enter"
850 PRINT SPC(5) "7,25890 to change the elastic modulus to 25890 ksi.":PRINT
860 INPUT;I,M  :A(I)=M: CLS: GOTO 770
861 REM  *-------------------------------------------------------------------*
862 REM      Select the appropriate Sander's F-function coefficients
863 REM      depending on R/t
864 REM  *-------------------------------------------------------------------*
865 REM      If R/t is less than 4, it is assumed to be 4
866 REM      If R/t is greater than 16, it is assumed to be 16
930 ROT=A(8)/A(9)   :ROTF=FIX(ROT)
940 IF ROT=>4 THEN GOTO 960 ELSE ROT=4
950 ROTF=4
960 IF ROT<=16 THEN GOTO 980 ELSE ROT=16
970 ROTF=16
972 REM        Interpolate Sander's F-function coefficients for R/t
973 REM        between integer values
980 FOR R=0 TO 12
990 RO=R+4
1000 IF RO<> ROTF THEN GOTO 1060
1010 FOR C=0 TO 2
1020 C1=C+12   :C2=C+15
1030 A(C1)=T(R,C)+(ROT-ROTF)*(T(R+1,C)-T(R,C))
1040 A(C2)=B(R,C)+(ROT-ROTF)*(B(R+1,C)-B(R,C))
1050 NEXT C
1060 NEXT R
```

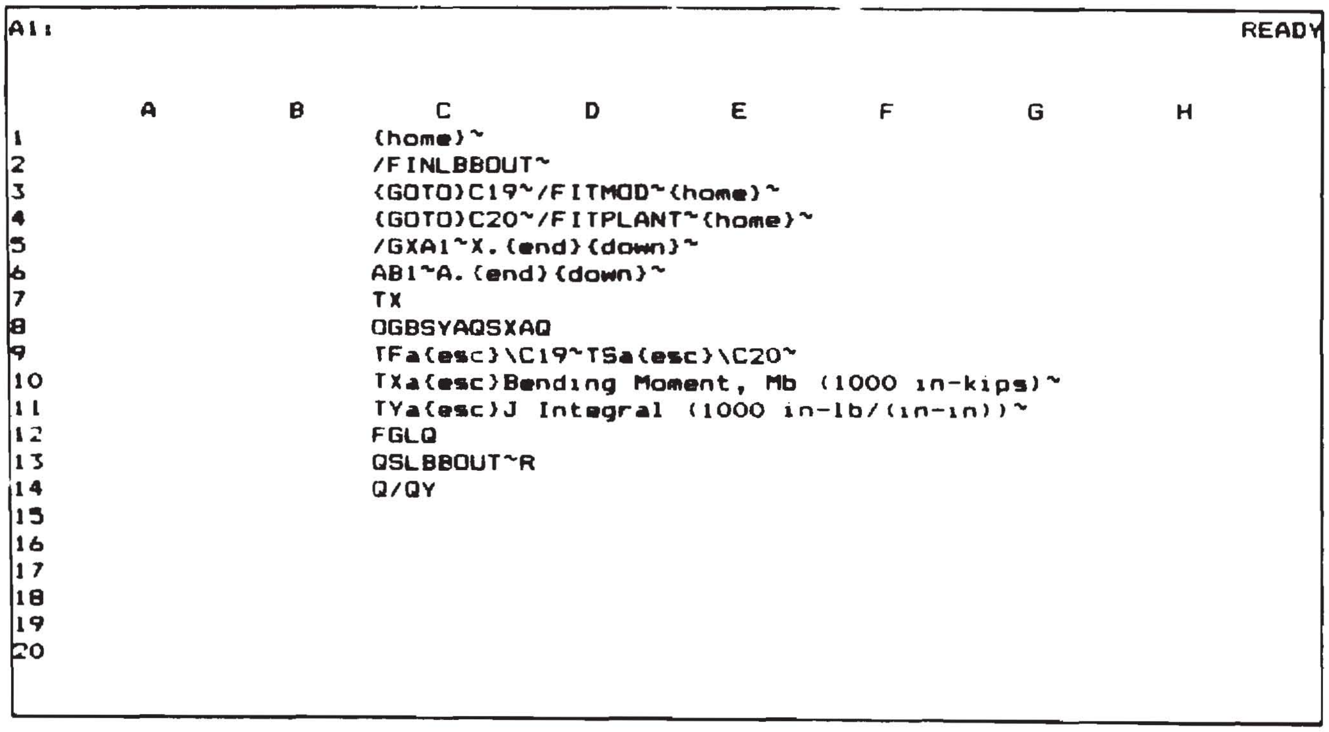
```
1370 REM  *------------------------------------------------------------------*
1390 REM   Print out the top part of the output page
1410 REM  *------------------------------------------------------------------*
1430 N=2: GOSUB 4210 :LPRINT DATE$;
1450 LPRINT TAB(25); :N=56 :GOSUB 4210 : LPRINT "LEAK BEFORE BREAK"
1470 N=24:GOSUB 4210:LPRINT SPC(30) "LBB.NRC MOD:";:LPRINT ANS
1490 N=24:GOSUB 4210:LPRINT SPC(25) "FACILITY: ";:LPRINT C$(2)
1510 N=24:GOSUB 4210:LPRINT SPC(25) "PIPE SYSTEM: ";:LPRINT C$(3):LPRINT
1530 N=24:GOSUB 4210:LPRINT SPC(30) "INPUT PARAMETERS"
1550 N=8: GOSUB 4210
1570 FOR I=1 TO 11
1590 LPRINT SPC(16) LEFT$(A$(I),39) + "=";A(I)
1610 NEXT I:LPRINT
1630 A11$=" SIGT=Axial Stress   SIGB=Bending Stress   MB=Bending Moment  "
1650 A12$="  PHI=Kink Angle"
1670 N=8:GOSUB 4210:LPRINT A11$+A12$
1690 A13$="     J=J Integral   COA=Crack Opening Area   LR=Leak Rate  "
1710 A14$="  ST=SIGT/SIGF"
1720 A15$="     SB=SIGB/SIGF    CL=Crack Length"
1730 LPRINT A13$+A14$: LPRINT SPC(20) A15$
1750 A4$="***      NORMALIZED      ***  "
1770 A5$="***********      ENGINEERING UNITS      **********"
1790 A6$="  ST+SB       PHI        J     "
1810 A7$="  SIGB      MB       PHI       J       COA        LR"
1811 A8$="  -----       ---          -      "
1831 A9$="  [ksi]  [kk-in]  [deg]   [k/in]   [si]      [gpm]"
1851 LPRINT :N=24 :GOSUB 4210 : LPRINT A4$ + A5$
1871 N=8 :GOSUB 4210 :LPRINT A6$ + A7$
1891 LPRINT CHR$(27) "-1" A8$ + A9$;CHR$(27) "-0"
1900 N=2: GOSUB 4210
1910 REM *------------------------------------------------------------------*
1930 REM             Start the calculation
1952 REM *------------------------------------------------------------------*
1970 AL=A(1)   :N1=A(2)   :SIGR=A(3)   :SIGF=A(4)   :THO=A(5)   :F=A(6)   :E=A(7)
1990 RR=A(8)   :TT=A(9)   :LRC=A(10)   :AMB=A(11)   :AT=A(12)   :BT=A(13):CT=A(14)
2010 AB=A(15)  :BB=A(16)  :CB=A(17)
2012 REM      Define constants and normalization constants
2090 ALP=AL*(SIGF/SIGR)^(N1-1)
2110 PI=3.141593 :THO=THO*PI/180 : MM=0 :PHIM=0 :JM=0 : COAM=0 :ST=0
2150 CL=2*RR*THO     :MM=PI*TT*SIGF*RR^2:    PHIM=(180/PI)*SIGF/E
2170 JM=RR*SIGF^2/E
2190 COAM=PI*SIGF*RR^2/E  : ST=F/(2*PI*RR*TT*SIGF)
2230 SP=4/PI*(COS(THO/2+PI*ST/2)-SIN(THO)/2)
2250 FJ=SIN(THO/2+PI/2*ST)+COS(THO):   H=FJ/(SP+ST)
2290 REM *------------------------------------------------------------------*
2292 REM      Determine THF, the final crack angle at the limit load
2294 REM *------------------------------------------------------------------*
2310 THF=THO+.36
2330 TH=THF:GOSUB 3810 : GOSUB 3890
2350 THOI=THF*(FD/(FB*SP+ST*FT+FD)): DELTA=THOI-THO
2370 IF ABS(DELTA)>.000002 THEN THF=THF-DELTA : GOTO 2330
2401 REM      Calculate BETA from THF
2410 BETA=(SP*FB+ST*FT)^2/(1-THO/THF)
2430 TH=THO: GOSUB 3810:  GOSUB 4010
2450 FBO=FB:  FTO=FT:  IBO=IB:  ITO=IT
```

```
2460 REM *-----------------------------------------------------------------------*
2461 REM       Angle TH is increased from THO to the final angle THF in ever
2462 REM       increasing step sizes.  It is assumed that the axial stress is
2463 REM       gradually applied up to the specified value with no bending.
2464 REM       The angle at this point is called THQ.  Then, while holding the
2465 REM       axial stress at the specified value, the bending stress is
2466 REM       gradually applied up to the limit load (or angle THF).  Axial
2467 REM       and bending stresses (ST, SB) are calculated for each step of TH.
2468 REM       Then, LBB.NRC MOD:7 and MOD:8 depart.  For MOD:7, subsequent
2469 REM       output values are based on initial crack angle THO.  For MOD:8,
2470 REM       subsequent output values are based on effective crack angle TH.
2471 REM *-----------------------------------------------------------------------*
2490 NC=0 :SB=0 :THQ=THO+.1  :GOTO 2590
2491 REM       Increment angle TH for specified axial stress and increasing
2492 REM       bending stress
2510 TH=TH+.001714*(NC+1)
2530 IF TH=>THF THEN TH=THF
2550 GOSUB 3810: GOSUB 4010
2570 SB=((BETA*(1-THO/TH))^.5-ST*FT)/FB : GOTO 2690
2580 REM       Determine THQ by iteration
2590 TH=THQ :GOSUB 3310
2610 THOI=TH*(BETA-(ST*FT)^2)/BETA
2630 DELE=THOI-THO
2650 IF ABS(DELE)>.000002 THEN THQ=THQ-DELE  :GOTO 2590
2670 ST=0: TH=THO :FB=FBO:FT=FTO:IB=IBO:IT=ITO
2680 REM       Calculate elastic kink angle
2690 IF ANS=8 THEN PHIE=SB*IB+ST*IT ELSE PHIE=SB*IBO+ST*ITO
2710 ASTSB=ABS(ST+SB)
2720 REM       Introduce strain hardening to the kink angle
2730 PHI=PHIE*(1+ALP*(SB+ST)*ASTSB^(N1-2))
2750 PHIP=PHI-PHIE
2810 IF ANS=8 THEN GOTO 2830 ELSE GOTO 2850
2820 REM       Calculate elastic J integral
2830 JE=PI*TH*(SB*FB+ST*FT)^2 : XF=FT/FB :GOTO 2870
2850 JE=PI*THO*(SB*FBO+ST*FTO)^2 :XF=FTO/FBO
2870 IF FL=1 GOTO 2910 ELSE FL=1
2880 REM       Calculate plastic J integral by numerical integration
2890 JP=.6*H*(SB+XF*ST)*PHIP: GOTO 2930
2910 JP=JP+H*.5*(SB+XF*ST+SBS)*(PHIP-PHIPS)
2920 REM       Total elastic-plastic J integral
2930 J=JE+JP
2940 REM       Calculate crack opening area
2950 COA=IT*(ST+SB*(3+COS(TH))/4)
2960 REM       Rewrite in engineering units
2970 SBS=SB+XF*ST  :PHIPS=PHIP: SBA=SB*SIGF: MBA=SB*MM/1000: PHIA=PHI*PHIM
2980 REM       Calculate leak rate also
2990 JA=J*JM :COAA=COA*COAM: LR=LRC*COAA
3010 IF NMB>0 OR AMB=0 THEN GOTO 3170
3030 A3(0)=SBA  :A3(1)=PHIA  :A3(2)=JA  :A3(3)=COAA  :A3(4)=LR
3050 IF MBA<AMB THEN GOTO 3150 ELSE NMB=1
3060 REM        Interpolate to the applied bending moment
3070 FY=(AMB-PMBA)/(MBA-PMBA)
3090 FOR I=0 TO 4
3110 A1(I)=A2(I)+(A3(I)-A2(I))*FY
3130 NEXT I: GOTO 3170
```

```
3150 A2(0)=SBA :A2(1)=PHIA :A2(2)=JA :A2(3)=COAA :A2(4)=LR :FMBA=MBA
3170 W(NC)=MBA :X(NC)=PHIA :Y(NC)=SBA :Z(NC)=JA :NC=NC+1
3180 REM      Print out on paper calculated values
3190 LPRINT USING W1$;(ST+SB);:LPRINT USING W2$;PHI;:LPRINT USING W3$:J;
3210 LPRINT USING W4$;SBA;MBA:PHIA;JA: :LPRINT USING W2$:COAA;
3230 LPRINT USING W5$;LR
3235 REM      Saving data on disk file up to J of 10 (1000 in-lb/(in-in))
3236 REM      (Only the bending moment and J are saved for plotting)
3240 IF JA>10 GOTO 3250
3245 PRINT #1, MBA, JA
3249 REM      If angle TH < THQ, return (axial stress will increase)
3250 IF THQ>TH GOTO 3330
3260 REM      If angle TH reaches the limit load angle THF, it is all done.
3261 REM      Otherwise, THQ< TH < THF, return (bending stress will increase)
3270 IF TH=THF GOTO 3510 ELSE GOTO 2510
3310 REM      Increment angle TH for zero bending but increasing axial stress
3330 TH=TH+.001714*(NC+1)
3350 IF TH=>THQ GOTO 3410
3370 GOSUB 3810:  GOSUB 4010
3390 ST=(BETA*(1-THO/TH))^.5/FT  :GOTO 2690
3410 TH=THQ :NC=0 : GOTO 3370
3420 CLOSE #1
3430 REM  *------------------------------------------------------------*
3450 REM    Print out the bottom of the output page
3470 REM  *------------------------------------------------------------*
3490 N=8
3510 N=8 :GJSUB 4210  :X$=STRING$(27,45)
3520 REM      Print out results at the applied bending moment
3530 LPRINT X$ "RESULTS AT APPLIED LOAD-" X$ :LPRINT "    SIGT= ";
3550 LPRINT USING W6$;ST*SIGF;:LPRINT "ksi, CL=";:LPRINT USING W6$;CL;
3570 LPRINT "in.,  AMB=";:LPRINT USING W4$;AMB; :LPRINT "kk-in, J=";
3590 LPRINT USING W7$;A1(2);:LPRINT "k/in, ";:LPRINT "    SIGB=";
3610 LPRINT USING W7$;A1(0); :LPRINT "ksi, PHI=";:LPRINT USING W6$;A1(1);
3612 LPRINT "deg, COA=";:LPRINT USING W6$;A1(3);:LPRINT "si,     LR=";
3630 LPRINT USING W4$;A1(4);:LPRINT "gpm"
3730 N=2 :GOSUB 4210 :LPRINT CHR$(12)
3740 PRINT "** Calculation Completed **"
3750 END
3770 REM  *------------------------------------------------------------*
3790 REM     Subroutines
3791 REM  *------------------------------------------------------------*
3800 REM      Calculate functions FT and FB
3810 FT=1+(TH/PI)^1.5*(AT+BT*(TH/PI)+CT*(TH/PI)^2)
3830 FB=1+(TH/PI)^1.5*(AB+BB*(TH/PI)+CB*(TH/PI)^2):RETURN
3850 REM  *------------------------------------------------------------*
3880 REM      Calculate function FD containing derivatives of FT and FB
3890 FD1=3*(AB*SP+ST*AT)
3910 FD2=5*(BB*SP+ST*BT)*(THF/PI)
3930 FD3=7*(CB*SP+ST*CT)*(THF/PI)^2
3950 FD=(THF/PI)^1.5*(FD1+FD2+FD3)  :RETURN
3970 REM  *------------------------------------------------------------*
4000 REM      Calculate compliances IB and IT
4010 IB1=AB/7+BB/9*(TH/PI)+CB/11*(TH/PI)^2
4030 IB2=AB^2/2.5+AB*BB/1.5*(TH/PI)+(2*AB*CB+BB^2)/3.5*(TH/PI)^2
```

```
4050 IB3=BB*CB/2*(TH/PI) 3+CB^2/4.5*(TH/PI)^4
4070 IB=2*TH^2*(1+8*(TH/PI)^1.5*IB1+(TH/PI)^3*(IB2+IB3))
4090 IT1=(AT+AB)/7+(BT+BB)/9*(TH/PI)+(CT+CB)/11*(TH/PI)^2
4110 IT2=AT*AB/2.5+(AT*BB+AB*BT)/3*(TH/PI)+(AT*CB+BT*BB+AB*CT)/3.5*(TH/PI)^2
4130 IT3=(BT*CB+BB*CT)/4*(TH/PI)^3+CT*CB/4.5*(TH/PI)^4
4150 IT=2*TH^2*(1+4*(TH/PI)^1.5*IT1+(TH/PI)^3*(IT2+IT3)):  RETURN
4170 REM *--------------------------------------------------------------*
4190 REM   This subroutine is to emphasize the lettering of the output
4192 REM   characters. For more information, see EPSON printer manual.
4210 LPRINT CHR$(27)"'"CHR$(N);   :RETURN
```

LOTUS macro program for plotting LBB.NRC results.



```
A1:                                                                    READY

          A         B         C         D         E         F         G         H
1                             {home}~
2                             /FINLBBOUT~
3                             {GOTO}C19~/FITMOD~{home}~
4                             {GOTO}C20~/FITPLANT~{home}~
5                             /GXA1~X.{end}{down}~
6                             AB1~A.{end}{down}~
7                             TX
8                             OGBSYAQSXAQ
9                             TFa{esc}\C19~TSa{esc}\C20~
10                            TXa{esc}Bending Moment, Mb (1000 in-kips)~
11                            TYa{esc}J Integral (1000 in-lb/(in-in))~
12                            FGLQ
13                            QSLBBOUT~R
14                            Q/QY
15
16
17
18
19
20
```

NRC FORM 335
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NRCM 1102
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13. ABSTRACT (200 words or less)

The fracture mechanics analysis procedure used by the NRC to evaluate utility leak-before-break submittals is described in this report. This methodology is an estimation technique based on J-tearing theory. This approach is intended to provide a conservative approximation of the applied crack driving parameter, J, for postulated through-wall leakage-size cracks in nuclear power plant pipes. Piping integrity evaluations can then be accomplished for various loading conditions and assumed flaw sizes. Because the method can be used to obtain a rather rapid computer generated approximation of the applied crack driving parameters, NRC evaluation of applicant or licensee submittals can be accomplished in an expeditious manner without resorting to elaborate finite element techniques. The NRC program should not be considered as fixed in time. As piping fracture mechanics technology matures, it may be refined in the future.

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