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FRACTURE MECHANICS EVALUATION
OF
HIGH ENERGY PIPING LINES
AT THE
R.E. GINNA NUCLEAR POWER PLANT

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1.0 INTRODUCTION/EXECUTIVE SUMMARY

High energy line break (HELB) analyses were completed for the resolution of open items for the NRC Systematic Evaluation Program (SEP) Topic III-5.A for the R.E. Ginna Nuclear Power Plant. This report addresses leak-before-break fracture mechanics evaluations of the Ginna pressurizer surge and accumulator piping lines.

1.1 Background

The SEP was initiated by the NRC to review the designs of older operating nuclear reactor plants to reconfirm and document their safety. The review compared the as-built plant design with current criteria in 137 different areas defined as "topics" (Reference 1). Many of these topics met current criteria or were acceptable on another defined basis for Ginna. The objective of this study is the resolution of SEP Topic III-5.A for Ginna, as defined in Reference 1.

Appendix A of 10CFR Part 50 requires that structures, systems and components important to safety (Engineered Safety Features, ESFs) be appropriately protected against the dynamic effects of postulated pipe breaks. The goal is to protect these ESFs so the plant can be

shut down and maintained in a safe shutdown condition in the event of a postulated rupture of a piping system containing high energy fluid.

Current designs protect ESFs against the consequences of high energy line breaks (HELBs) through the use of pipe whip restraints, jet impingement shields, physical separation and other methods. However, plants designed before the existence of current requirements generally do not have the full complement of such features. Furthermore, in many cases modifications to incorporate these features may be impractical due to physical plant configurations or other considerations. Therefore, the NRC has given guidance on other acceptable methods for the resolution of Systematic Evaluation Program (SEP) Topic III-5.A, for High Energy Line Breaks Inside Containment.

1.2 Objectives and Technical Approaches for Ginna

In Reference 1, the NRC advises that breaks in the accumulator line or pressurizer surge line could adversely affect nearby safety-related equipment. Additionally, guidance for performing fracture mechanics leak-before-break evaluations to resolve this issue was forwarded to Rochester Gas and Electric Corporation

(RGE) by the NRC (Reference 2). This approach was employed for these piping lines. It is based on a combination of inservice inspection (ISI) and leak detection, to detect the presence of cracks, and of fracture mechanics analysis to assure that crack instability will not occur for cracks smaller than those detectable by these methods. These detection methods complement each other, since ISI is especially suited to finding long cracks, and leak monitors detect short, through-thickness cracks. Reference 2 provides the methodology to compute crack opening areas for determining leak rates for comparison with detection limits. The ISI involves volumetric inspection in accordance with ASME Section XI for a Class 1 system, regardless of actual system classification. The goal is to detect and limit any service induced flaws to allowable sizes prescribed by the ASME Code, Section XI (crack depth limited to less than approximately 10% of pipe wall thickness). Fracture mechanics subcritical crack growth analyses are employed to assure that this goal for limiting crack growth is met. These limits on crack size imposed by leak monitors and ISI are compared to the critical crack sizes predicted for instability and pipe rupture, computed in accordance with Reference 2. Adequate margin between crack detection and the crack size for rupture must exist. In this way, crack

detection and corrective actions will precede any chance for HELBs and subsequent postulated effects on ESFs.

In accordance with the latest NRC guidance (Reference 2), the leak-before-break technique was evaluated for the Ginna pressurizer surge and accumulator lines. The elements of this evaluation include the definition of the following:

a) Largest crack size which will remain stable

b) Leak rate resulting from a crack of length 2t (twice the pipe wall thickness)

c) Size of crack which will leak at a rate greater than 1 gpm, if b) results in less than 1 gpm.

d) Analysis of part-through-thickness cracks for subcritical crack growth rates to establish ISI intervals.

Very conservative analyses were performed to predict the largest stable crack sizes, by using worst case stresses (References 3 and 4), as well as ASME Code maximum allowable stresses. In this way, sets of analyses were performed to envelope all locations in each line, as

well as to compensate for potential future load increases. The subcritical crack growth rate analyses were also enveloped in a similar manner, by using a conservative load cycling spectrum based on Ginna design transients and the most severe transient loads in the stress reports (References 3 and 4).

1.3 Conclusions

Conclusions resulting from the preceding analyses are reflected in terms of critical through-wall crack lengths for instability and crack lengths for 1 gpm leak rates in the following table:

GINNA STRESS REPORT "WORST CASE" STRESSES
Crack Length for Instability (in.)

Line	Crack Orien-tation	Net Section Collapse	Tearing Modulus	Crack Length for 1 gpm Leak Rate
Pressurizer	circ.	7.8	>20	2.6
Surge	long.	-	>12	<2
Accumulator	circ.	10	22	3.5
	long.	-	16	2.66

Both Net Section Plastic Collapse and Tearing Modulus approaches are used to predict critical crack lengths for instability, based on worst-case stresses. The worst case (Ginna stress report) stresses used for the

pressurizer surge line analyses are $P_m + P_b = 34,747$ psi. The corresponding stresses for the accumulator line are $P_m + P_b = 30,133$ psi. Only normal operating pressure stresses were used to compute leak rates. Thus, this analysis is considered to be conservative.

RG&E (References 5 and 6) has current bulk leak detection capabilities to detect 1 gpm leak rates for these lines in at least 6.4 hr. Since a margin of at least a factor of 2 exists between the crack lengths for a 1 gpm leak and the "worst actual stress" lengths for instability (consistent with Reference 2 guidance), these current leak detection systems are considered adequate. Furthermore, subcritical crack growth rate analyses show that inservice inspection intervals of 10 years are appropriate to detect part-through-thickness cracks before they approach instability.

2.0 FRACTURE MECHANICS LEAK-BEFORE-BREAK ANALYSIS

Postulated breaks in the accumulator line or pressurizer surge line could adversely affect nearby safety-related equipment. These lines at the Ginna Plant are shown in Figures 2-1 and 2-2, and the piping system parameters are given in Table 2-1. Additionally, guidance for performing fracture mechanics leak-before-break evaluations to resolve this issue was forwarded to Rochester Gas and Electric Corporation (RGE) by the NRC (Reference 2). This approach was employed for these piping lines. It is based on a combination of inservice inspection (ISI) and leak detection, to detect the presence of cracks, and of fracture mechanics analyses to assure that pipe rupture will not occur for cracks smaller than those detectable by these methods. These detection methods complement each other, since ISI is especially suited to finding long cracks, and leak monitors detect short, through-thickness cracks. These types of cracks are represented in Figure 2-3.

In accordance with the latest NRC guidance (Reference 2), the leak-before-break technique was evaluated for the Ginna pressurizer surge and accumulator lines. The elements of this evaluation include the definition of the following:

a) Largest crack size which will remain stable;

b) Leak rate resulting from a crack of length 2t (twice the pipe wall thickness);

c) Size of crack which will leak at a rate greater than 1gpm, if b) results in less than 1 gpm;

d) Analysis of part-through-thickness cracks for sub-critical crack growth rates to establish ISI intervals.

Very conservative analyses were performed to predict the largest stable crack sizes, by using ASME Code maximum allowable stresses, and also, by using the maximum stresses in the piping stress reports (References 3 and 4). In this way, sets of analyses were performed to envelope all locations in each line, as well as to compensate for potential future load increases. The subcritical crack growth rate analyses were also enveloped in a similar manner, by using a conservative load cycling spectrum based on Ginna design transients (Reference 8) and the most severe transient loads in the stress reports (References 3 and 4).

2.1 Critical Crack Sizes for Instability

Three methods of analysis to predict critical crack sizes for the Ginna accumulator line and pressurizer surge line were considered according to the guidance given by the NRC in Reference 2. These methods are:

a) linear elastic fracture mechanics;

b) J-Integral and Tearing Modulus approaches (Reference 9); and

c) the net section plastic collapse criterion (References 10 and 11).

As seen in Table 2-1, these piping materials are Type 316 austenitic stainless steel, which has a very high level of toughness. Reference 7 reports a critical J-Integral value, J_{IC}, for fracture initiation of Type 316 at 600°F, of 5260 $\frac{\text{in-lb}}{\text{in}^2}$ in a one inch thick test specimen. Other results for Type 304 stainless steel (a similar material) are shown in Figure 2-4 and are also at a high toughness level. Figure 2-4 shows crack extension as a function of applied J-Integral loading. In some cases, J_{IC} values can be simply converted to K_{IC} (linear elastic fracture toughness) and used for a

conservative analysis of fracture resistance in a component. However, this conversion is suspect for materials which do not meet the following validity criterion (Reference 12):

$$B > 25 \frac{J_{Ic}}{\sigma_y}$$

where, B = Specimen thickness (in.)

J_{Ic} = Critical J-Integral Value $(\frac{in\text{-}lb}{in^2})$

σ_y = Material yield strength (psi)

By solving the preceding equation for B, using $J_{Ic} = 5{,}260 \frac{in\text{-}lb}{in^2}$ and σ_y = 30,000 psi (the room temperature yield strength), it can be seen that B must be greater than 4.4 inches for a valid conversion to linear elastic fracture mechanics parameters (K_{Ic}) and analysis. At higher temperature, as the yield strength decreases, the thickness requirement becomes even greater. Thus, for this combination of high material toughness and low yield strength, the approach of linear elastic fracture mechanics is not considered valid. Other approaches, based on elastic-plastic fracture mechanics are required. The approaches of J-Integral, Tearing Modulus, and net section plastic collapse criterion are used in this program, as detailed in the following subsections.

2.1.1 J-Integral and Tearing Modulus Analyses

These analyses follow the methodology of Reference 9 for the stainless steel accumulator and pressurizer surge lines at Ginna. In accordance with Reference 2, Level D stresses were used for this analysis. ASME Code allowable stresses for these lines are given in Table 2-2. For the case of these elastic-plastic crack stability analyses, only the primary stresses are considered, because of the relatively large deformations accompanying fracture, which would relieve any secondary stresses. This is consistent with Reference 10, where it is recognized that secondary and peak stresses have no effect on the limit load because they are produced by the action of imposed strains or are locally confined and self-limiting.

2.1.1.1 Stresses

The Code maximum allowable primary stresses (membrane plus bending) from Table 2-2 are equal to S_{hy}. For the accumulator line, this gives $P_m + P_b = 37{,}600$ psi. For the pressurizer surge line, $P_m + P_b = 56{,}400$ psi.

Conservative analyses were also done for the most severe stresses at the worst location in each line, according to the stress reports (References 3 and 4). These stresses also include thermal stresses and assume all events occurring simultaneously for conservatism. For the accumulator line, the worst case $P_m + P_b$ = 30,133 psi at node 8,400 (Reference 4), consisting of the sum of dead weight, RHR malfunction, loss of load, and seismic (SSE) stresses, along with the primary membrane pressure stress, P_m = 5,160 psi. For the pressurizer surge line, the worst case $P_m + P_b$ = 34,747 psi at node 690 (Reference 3), consisting of the sum of dead weight, control rod ejection and seismic (SSE) stresses, along with the primary membrane stress of 5,919 psi.

2.1.1.2 Accumulator Line

Both circumferential and longitudinal through-wall cracks, as shown in Figure 2-3 a) were evaluated.

From Reference 9, the J-integral (J) and Tearing Modulus (T) are calculated from:

$$J = \frac{\sigma_o^2 a}{E} \left\{ \begin{matrix} \text{Stress} \\ \text{Factor} \end{matrix} \right\} [Y^2]$$

$$\text{and, } T = \left\{ \begin{matrix} \text{Stress} \\ \text{Factor} \end{matrix} \right\} [Y^2 + 2\lambda Y.Y']$$

where, σ_o = Flow stress

a = Crack half-length

E = Elastic modulus

{} = Stress factor (Reference 9)

[] = Geometry factor, defined by geometry parameters λ, Y, and Y' (Reference 9)

From the ASME Code Section III Appendices, σ_o is computed as the average of S_y and S_u (minimum expected yield and tensile strengths) to be 52.5 ksi at 100°F and 48.8 ksi at 300°F. A value of 50 ksi is, thus, used for this analysis. Similarly, E = 28.3 X 10^6 psi, at 100°F and 27 X 10^6 psi, at 300°F. Thus, a value of 27.5 X 10^6 psi was selected for this analysis.

The parameter λ is used in Reference 9 to determine the geometry factors. It is defined as:

$$\lambda = \frac{a}{(Rt)^{1/2}}$$

where, R = Pipe radius, 5 inches

t = Pipe wall thickness, 1 inch

Values of J and T for a stress of 30,133 psi and varying crack lengths were computed, as shown in Table 2-3, for circumferential and longitudinal cracks. Another case was computed for a flaw 7 inches long with varying stresses, in Table 2-4. The 7 inch flaw size was selected to be a factor of two greater than the largest flaw which will give a predicted leak rate of 1 gpm (Section 2.2 of this report). The factor of two is consistent with that given in the Reference 2 guidance for the margin between a leaking and an unstable crack.

This was done to define the maximum stresses at which the cracks are predicted to remain stable.

The results of the analyses in Tables 2-3 and 2-4 are plotted in Figure 2-5 for comparison with a representative material J/T curve (Reference 7). Applied J and T values to the left of the material curve are considered to result in stable crack behavior (Reference 9). A ceiling of applied J = 24,000 in-lb/in.^{2} was also placed on this analysis, since this is the highest value represented by the material resistance curve in Figure 2-5. It should be noted that the analyses for longitudinal cracks are especially conservative, since stresses other than pressure stresses are not as likely to affect this orientation of flaw; yet they are included in this evaluation.

Conclusions from Tables 2-3 and 2-4 and Figure 2-5 are that large values of stresses and crack sizes are tolerated by these pipes before instability is predicted. In some cases, the validity of this analysis is exceeded before crack instability is predicted. The largest through-wall crack sizes, evaluated for the worst case stress of 30,133 psi., which remain stable are a 22 inch long circumferential crack and a 16 inch long longitudinal crack. Stresses of at least 55,000 psi, and 50,000 psi, are tolerated for 7 inch long through-wall circumferential and longitudinal cracks, respectively. These stresses are just below the maximum ASME Code allowable primary stress of 56,400 psi, but are well above the worst case stress of 30,133 psi.

2.1.1.3 Pressurizer Surge Line

Analyses similar to those done for the accumulator line were also performed for the Ginna pressurizer surge line. Applied J and T values were computed for a stress of 37,600 psi, the maximum ASME Code allowable primary stress which is greater than the worst case stress of 34,747 psi (Reference 3), for varying crack sizes (Table 2-5). Since higher primary stresses are not permitted by the ASME Code, the calculations for higher stresses

were not performed in this case. Values of σ_O = 45 ksi and E = 25 X 10^6 psi are used. The results of these analyses are plotted on the stability diagram in Figure 2-6, as was done for the accumulator line.

Conclusions from Figure 2-6 are that through-wall cracks longer than 20 inches and 12 inches for circumferential and longitudinal orientations, respectively, are stable for the applied stress of 37,600 psi.

2.1.2 Net Section Plastic Collapse Criterion

The net section collapse criterion (NSCC) follows Reference 10, with several minor changes in the equations used. Specifically, this criterion assumes that failure is defined by plastic instability which occurs when the stress in the net section at the crack reaches the material flow stress. This approach is conservative for austenitic stainless steel, since the flow stress is taken as the average between the minimum expected yield and tensile strengths. In reality, strain hardening of this material would continue beyond this flow stress and would give increased resistance to collapse, which is not taken into account in this analysis.

When a conservative compound crack (a combination of through-wall and part-through wall cracks, as seen in Figures 2-7 and 2-8) is assumed, the analysis becomes slightly more complex because of shifting the pipe neutral axis by the angle β(Figures 2-7 and 2-8). This effect is included in the following equations to compute critical compound crack sizes for instability:

$$\beta = \frac{(\pi - \nu)\,(1-\frac{d}{t}) - (\frac{\pi P_m}{\sigma_o})}{2\,(1-\frac{d}{t})}$$

$$P_b = \frac{2\,\sigma_o}{\pi}\,(1-\frac{d}{t})\,[2\sin\beta - \sin\nu]$$

where:

β = Shift of the neutral axis

ν = Half-crack angle for through-wall crack

d = Depth of part-through wall crack

t = Pipe wall thickness

σ_o = Flow stress

P_m = Primary membrane stress

P_b = Primary bending stress

These parameters are defined further in Figures 2-7 and 2-8

Using the same P_m and P_b stresses discussed in subsection 2.1.1.1 of this report, the preceding equations were solved simultaneously to produce the failure diagrams in Figures 2-7 and 2-8. Numerical values of the critical crack sizes thus computed are also given in Tables 2-6 and 2-7 for the accumulator and pressurizer surge lines at Ginna.

Conclusions for the accumulator line are that circumferential through-wall cracks of 0.318 and 0.116 fractions of the circumference are stable for the worst case stress of 30,133 psi and the maximum ASME Code allowable primary stress of 56,400 psi, respectively. These are cracks 10 and 3.6 inches long, which are more conservative than the Tearing Modulus results of subsection 2.1.1. Such conservatism has also been shown in Reference 7, where net section collapse was analyzed by the J/T approach. Thus, the net section collaspe criterion is truly a conservative estimate of austenitic stainless steel flaw tolerance.

Part-through wall cracks equal to 59.61% and 21.83% of the wall thickness were defined for the onset of instability for the accumulator line with stresses of 30,133 psi and 56,400 psi, respectively.

Conclusions based on the net section collaspe criterion for the Ginna pressurizer surge line are that circumferential through-wall flaws equal to 0.248 and 0.223 fractions of the circumference are stable for the worst case stress of 34,747 psi and the maximum ASME Code allowable primary stress of 37,600 psi. These are cracks greater than 7 inches long.

Part-through wall cracks equal to 47.5% and 43.5% of the wall thickness were defined for the onset of instability for the pressurizer surge line with stresses of 34,747 psi and 37,600 psi, respectively.

2.2 Leak Rates

In accordance with the guidance of Reference 2, crack opening areas and leak rates were computed for through-wall cracks 2 inches (2 t) long. Crack sizes required to give leak rates of 1 gpm were also calculated for the Ginna accumulator and pressurizer surge lines. The leak rates are quite conservative since only pressure stresses are considered. In reality, other stresses will also tend to open the cracks for leakage, especially for circumferential flaws.

2.2.1 Accumulator Line

Crack opening areas were computed for circumferential through wall cracks from the following equations (Reference 2):

$$A_p = \frac{\sigma_p}{E} (2\pi Rt)\, G_p(\lambda)$$

$$\lambda = \frac{a}{(Rt)^{1/2}}$$

$$G_p(\lambda) = \lambda^2 + 0.16\lambda^4, \quad (0 \leq \lambda \leq 1)$$

$$G_p(\lambda) = 0.02 + 0.81\lambda^2 + 0.3\lambda^3 + 0.03\lambda^4, \quad (1 \leq \lambda \leq 5)$$

where, A_p = crack opening area

σ_p = pressure stress, in axial direction

= $1/2 \frac{pR}{t}$, for internal pressure, p

The minimum normal operating pressure of 750 psi (Table 2-1) was employed in this calculation. Crack opening area results are given in Table 2-8.

For a longitudinal through-wall crack the following equations are used to compute A_p (Reference 2):

$$A_p = \frac{\sigma_p}{E} (2\pi Rt)\ G_p(\lambda)$$

$$G_p(\lambda) = \lambda^2 + 0.625\lambda^4 \ , \ (0 \leq \lambda \leq 1)$$

$$G_p(\lambda) = 0.14 + 0.36\ \lambda^2 + 0.72\lambda^3 + 0.405\lambda^4 \ (1 \leq \lambda \leq 5)$$

where, σ_p is the hoop pressure stress and the other terms are as defined for the circumferential through-wall crack. The leak flow rates for the accumulator line are computed for the non-saturated liquid at 120°F, using the Bernoulli equation (Reference 13):

$$G = \rho\left[\frac{2g_c\ \Delta p}{\rho}\right]^{1/2}$$

where, G = Flow rate, (lbm/(sec. - in.^{2}))

ρ = Density at 120°F = 61.71 lbm./1728 in.^{3}

g_c = (32.2) (12) in./sec.^{2}

Δp = Pressure difference, (750 - 14.7) psi.

The results, in gpm, are shown in Table 2-8. For the AL, leak rates of 0.236 gpm and 0.516 gpm result from pressure stresses for 2t long circumferential and longitudinal through-wall cracks. Circumferential and

longitudinal through-wall crack half-lengths of 1.752 and 1.328 inches are required for leak rates of 1 gpm. All these results in Table 2-8 include a leak friction coefficient factor of 0.6 (Reference 14).

2.2.2 Pressurizer Surge Line

A similar analysis to that for the accumulator line for A_p values was done for the pressurizer surge line. Results are given in Table 2-8. For the saturated liquid the flow rate, G, is obtained from Figure 2-9 (Reference 15), for the pressure of 2235 psi and the temperature of 612.2°F (Table 2-1). Again, a flow friction coefficient of 0.6 is employed (Reference 14).

The results, in gpm, are shown in Table 2-8. For the pressurizer surge line, leak rates of 0.567 gpm and 1.245 gpm result from pressure stresses for 2t long circumferential and longitudinal through-wall cracks. A circumferential through-wall half-crack length of 1.314 in. is required for a leak rate of 1 gpm.

2.2.3 Ginna Leak Detection Capabilities

For primary coolant leak detection (the pressurizer surge line), RG&E has provided the NRC documentation (Reference 5) supporting a 1 gpm leak detection in 1 hour. Discussion with RG&E (Reference 6) gave further details regarding these leak detection capabilities. The methods consist of 1) an airborne particulate radioactivity monitor, which can ideally detect 0.013 gpm within 20 minutes, 2) a monitor of condensate flow rate from the air cooler, which can detect 1 gpm within 1 hour and, 3) a chemical volume control system (CVCS) monitor, which can detect 0.25 gpm within 1 hour.

RG&E has two systems of leak detection for the accumulator line (Reference 6). Level detectors consist of high and low level alarms set for 1108 ft^3 and 1134 ft^3. The difference is 26 ft^3 or 194 gal. This results in a time interval of 3.23 hr to detect a leak of 1 gpm for the worst-case, where the initial level is just below the high level alarm. There also is a sump pump ("A" pump) which is activated from a level alarm 30.5 in. from the floor of the 4.5 ft x 4.5 ft sump area. This gives a required volume of fluid of about 51 ft^3 or 385 gal. This results in a time interval of 6.4 hr. to detect a leak of 1 gpm.

From the preceding leak detection systems, it is apparent that RG&E currently has the capability to detect a 1 gpm leak at Ginna for the pressurizer surge and accumulator lines. As seen in Table 2-8, those crack lengths corresponding to a 1 gpm leak rate give significant margins against crack instability, when actual worst-case stresses are used to predict instability. The smallest margin is a factor of 2.86 on crack length for a circumferential crack in the accumulator line. This margin is above the factor of 2 given by the NRC guidance (Reference 2). Thus, the existing RG&E leak detection capabilities appear adequate to support this leak-before-break approach.

2.3 Subcritical Crack Growth Rates

The preceding fracture mechanics analyses and leak rate analyses provide information for protecting against HELB by the leak-before-break approach. However, such information must also be generated to protect against pipe rupture resulting from the growth of long part-through wall, non-leaking cracks. This is accomplished by detecting and preventing such cracks with augmented inservice inspection (ISI). Adequate ISI intervals to prevent postulated part-through wall cracks from becom-

ing critical (unstable) are established by predicting subcritical crack growth rates. Such analyses are presented in the following subsections, for the Ginna pressurizer surge and accumulator lines.

2.3.1 Stress Profiles

Loading conditions for subcritical fatigue crack growth analyses were defined by considering the bounding case in the stress reports (References 3 and 4). The bounding case (most severe stresses) is at node 690 for the pressurizer surge line (Reference 3). These stress profiles were used to envelope both the pressurizer surge line and accumulator line for Ginna.

The stress profiles through the pipe wall thickness are shown in Figure 2-10 for both circumferential and longitudinal cracks. In fatigue analysis, the cycling between minimum and maximum loads is considered. The minimum load condition is for plant shutdown, where loading consists of piping dead-weight and weld residual stresses for circumferential flaws, and is assumed as zero for long longitudinal flaws. The maximum load condition, for all cycles is conservatively assumed to be the case for pressurizer surge line stresses with control rod ejection (Reference 3). For circumferential

cracks, the maximum load condition consists of deadweight, weld residual stresses, pressure (3015 psi stresses, and thermal stresses. For longitudinal cracks, the maximum load condition is comprised of pressure loading. Again, the stress profiles associated with these loadings are shown in Figure 2-10. Welding residual stresses are included in the NUTECH crack growth computer model, NUTCRAK (Reference 16).

2.3.2 Cycling Rate

The transients considered to develop the frequency of cycling (between the preceding maximum/minimum loads) are shown in Table 2-9 (Reference 8). These transients were only used to estimate the number of cycles expected during the plant life, since the assumed loadings are more severe than those associated with these transients. Only transients with significant loads or which were associated with the subject piping lines were considered, as shown in Table 2-9. This resulted in a total of approximately 1200 significant cycles in a 40 year plant design life, or 30 cycles per year. Thus, the load cycling spectrum assumed for the subcritical crack growth analyses are shown in Figure 2-11.

2.3.3 Crack Growth Rate Analysis

The preceding information was input to the following crack growth law (Reference 17):

$$\frac{da}{dN} = (\Delta K)^n$$

where, $\frac{da}{dN}$ = Crack growth rate (in./cycle)

C = Material constant = 2.74×10^{-10}

n = Material constant = 3.97

ΔK = Range in applied stress intensity factor for each cycle.

The equation was solved by the NUTCRAK program (Reference 16) for crack depth as a function of number of cycles. Stress intensity factors for circumferential and longitudinal cracks are a part of the calculation output, and include the effects of maximum-to-minimum loading ratios.

The results of this analysis are shown in Figure 2-12. Two initial crack sizes (depths) were assumed for part-through wall cracks of infinite length: a_i = 0.02 inch

and a_i = 0.10 inch. If it is assumed that a crack of depth 0.02 inch can be detected by ISI, and this is used as the initial flaw size, then insignificant flaw growth occurs over 40 years (1200 cycles).

As an extreme case, it is assumed that a flaw 0.10 inch deep (10% of the wall) is the limit of ISI detectability, and is assumed as the initial crack size. Even for this large crack size, longitudinal crack growth is insignificant. However, circumferential crack extension does occur, growing from 10% of the pipe wall thickness to 20% in about 10 years. This is still well below the crack size of almost 50% of wall thickness (d/t in Tables 2-7 and 2-8 for $\nu/\pi = 0$) predicted for instability on the bases of worst case stresses and the net section plastic collapse criterion. Thus, it is recommended that even for this extreme case, an ISI interval of 10 years should be adequate to detect part-through wall cracks prior to approaching pipe rupture.

3.0 CONCLUSIONS AND RECOMMENDATIONS

The leak-before-break approach for resolution of HELB for the Ginna pressurizer surge and accumulator lines is shown to be feasible and practical.

Critical crack sizes for rupture of the pipes were predicted conservatively by Tearing Modulus and net section plastic collapse criterion approaches. The applied loads were based on the worst case stresses, using the stress reports. Through-wall circumferential cracks 24.7% of the pipe circumference (7.75 inches) are shown to be stable for these loads, based on the net section plastic collapse criterion. Longitudinal through-wall cracks 12 inches long are shown to be stable for these loads, using the Tearing Modulus approach. Circumferential part-through wall cracks equal to almost 50% of the pipe wall thickness are shown to be stable by the net section collapse criterion. Thus, an ample margin of fracture resistance exists in these pipes. The analyses based on maximum ASME Code allowable stresses still predict significant resistance to fracture, but with less margin for leak detection and ISI.

Leak rates, based on internal operating pressure stresses only, were computed for through wall flaws of length 2t (2 inches). Leak rates range from 0.236 gpm to 1.245 gpm for circumferential and longitudinal through-wall cracks in both lines. The worst case crack length to give a minimum leak rate of 1 gpm, is 3.5 inches for a circumferential crack in the accumulator line. This still provides margin against reaching the crack length required for instability (10 inches, Table 2-6) for the accumulator line with worst case stress report stresses. RG&E currently has bulk leak detection systems at Ginna capable of detecting 1 gpm leaks for these lines in less than 6.4 hours, and are considered adequate.

ISI intervals of 10 years are found to be adequate to prevent part-through wall longitudinal and circumferential cracks from reaching instability. A substantial margin against rupture exists even when large initial flaws (10% of wall thickness) are assumed.

TABLE 2-1

PARAMETERS FOR LEAK-BEFORE-BREAK ANALYSIS OF PRESSURIZER SURGE AND ACCUMULATOR LINES

- PRESSURIZER SURGE LINE (REFERENCE 3)

  Size = Outer Dia. = 10.75 in., Thickness = 1 in.
  Material = A376 TP316
  Normal Mode = 612.2°F, 2235 psi. pressure
  Control Rod Ejection Mode = 697.2°F, 3015 psi. pressure

- ACCUMULATOR LINE (REFERENCE 4)

  Size = Outer Dia. = 10.75 in., Thickness = 1 in.
  Material = A376 TP316
  Normal Mode = 120°F, 2235/750 psi. pressure
  Loss of Load Mode = 120°F, 2628/750 psi. pressure
  RHR Hx Malfunction Mode = 120/300°F, 2235/750 psi. pressure

TABLE 2-2

LEVEL D ASME CODE MAXIMUM ALLOWABLE STRESSES USED FOR ANALYSIS OF CRACK INSTABILITY FOR PRESSURIZER SURGE (PSL) AND ACCUMULATOR LINES (AL)

(ASME CODE SECTION III, NC-3600, 1980 EDITION)

Line	T(°F)	P(psi.)	$\sigma_{allowable}$ (psi.)	$\sigma_{p\ell}$(psi.)	$\sigma_x + \sigma_b$ (psi.)	σ_{ph} (psi.)
PSL	600	3,015	65,350	5,919	59,431	14,853
AL	100	2,628	84,600	5,160	79,440	12,947

where:

$\sigma_{allowable} = S_{hy} + S_A$

S_{hy} = smaller of $(3S_h, 2S_y)$

$S_h = 17$ ksi., $S_y = 18.8$ ksi. at 600°F

$S_h = 18.8$ ksi., $S_y = 30$ ksi. at 100°F

$S_A = f(1.25\ S_c + 0.25\ S_h)$

$S_c = 18.8$ ksi. at 100°F

$f = 1$ for thermal cycles < 700

$\sigma_t + \sigma_b = \sigma_{allowable} - \sigma_{p\ell}$

$\sigma_p = pr_i^2/(r_o^2 - r_i^2)$ (r_i = inside radius, r_o = outside radius)

$\sigma_{ph} = P(r_o^2 + r_i^2)/(r_o^2 - r_i^2)$

TABLE 2-3

APPLIED J-INTEGRAL AND TEARING MODULUS VALUES AS FUNCTIONS OF THROUGH-WALL HALF CRACK LENGTH, a, FOR THE GINNA ACCUMULATOR LINE WITH AN APPLIED STRESS OF 30,133 PSI.

CIRCUMFERENTIAL CRACK:

σ(psi)	a (in)	λ	σ/σ_o	{Stress Factor}	$[Y^2]$	$[Y^2+2\lambda Y.Y']$	$J(\frac{in-lb}{in^2})$	T
30,133	2	0.89	0.6	1.38	1.2	1.8	301	2.5
30,133	4	1.79	0.6	1.38	1.8	3.2	904	4.4
30,133	6	2.68	0.6	1.38	2.6	4.8	1,959	6.6
30,133	8	3.57	0.6	1.38	3.3	6.2	3,315	8.6
30,133	10	4.46	0.6	1.38	4.1	8.0	5,149	11.0
30,133	11	4.91	0.6	1.38	4.5	8.4	6,216	11.6

LONGITUDINAL CRACK:

σ(psi)	a (in)	λ	σ/σ_o	{Stress Factor}	$[Y^2]$	$[Y^2+2\lambda Y.Y']$	$J(\frac{in-lb}{in^2})$	T
30,133	2	0.89	0.6	1.38	2.0	4.1	502	5.7
30,133	4	1.79	0.6	1.38	4.89	12.	2,456	16.6
30,133	6	2.68	0.6	1.38	9.07	23.	6,834	31.7
30,133	8	3.57	0.6	1.38	14.53	38.	14,597	52.4
30,133	10	4.46	0.6	1.38	21.22	58.	26,648	80.0

TABLE 2-4

APPLIED J-INTEGRAL AND TEARING MODULUS VALUES AS FUNCTIONS OF APPLIED STRESS FOR THE GINNA ACCUMULATOR LINE WITH A THROUGH-WALL HALF CRACK LENGTH OF 3.5 IN.

CIRCUMFERENTIAL CRACK:

σ/σ_o	σ(ksi.)	a (in.)	λ	{Stress Factor}	[Y^2]	[$Y^2+2\lambda Y.Y'$]	J($\frac{in-lb}{in^2}$)	T
0.7	35	3.5	1.56	2.05	1.65	2.85	1,077	5.8
1.0	50	3.5	1.56	16.1	1.65	2.85	8,461	45.9
1.1	55	3.5	1.56	37.9	1.65	2.85	19,917	108.0
1.2	60	3.5	1.56	89.1	1.65	2.85	46,824	253.9

LONGITUDINAL CRACK:

σ/σ_o	σ(ksi.)	a (in.)	λ	{Stress Factor}	[Y^2]	[$Y^2+2\lambda Y.Y'$]	J($\frac{in-lb}{in^2}$)	T
0.7	35	3.5	1.56	2.05	4.0	11.0	2,612	22.6
1.0	50	3.5	1.56	16.1	4.0	11.0	20,511	177.1
1.1	55	3.5	1.56	37.9	4.0	11.0	48,285	416.9

TABLE 2-5

APPLIED J-INTEGRAL AND TEARING MODULUS VALUES AS FUNCTIONS OF THROUGH-WALL HALF CRACK LENGTH, a, FOR THE GINNA PRESSURIZER SURGE LINE WITH AN APPLIED STRESS OF 37,600 PSI.

σ(psi.)	a(in.)	λ	σ/σ_o	{Stress Factor}	[Y^2]	[$Y^2+2\lambda Y.Y'$]	J($\frac{in-lb}{in^2}$)	T
CIRCUMFERENTIAL CRACK:								
37,600	2	0.89	0.84	4.6	1.2	1.8	894	8.28
37,600	4	1.79	0.84	4.6	1.8	3.2	2,683	14.72
37,600	6	2.68	0.84	4.6	2.6	4.8	5,813	22.08
37,600	8	3.57	0.84	4.6	3.3	6.2	9,837	28.52
37,600	10	4.46	0.84	4.6	4.1	8.0	15,277	36.80
LONGITUDINAL CRACK:								
37,600	2	0.89	0.84	4.6	2.0	4.1	1,490	18.86
37,600	4	1.79	0.84	4.6	4.89	12.	7,288	55.20
37,600	6	2.68	0.84	4.6	9.07	23.	20,277	105.80
37,600	8	3.57	0.84	4.6	14.53	38.	43,311	174.80

TABLE 2-6

FAILURE CRACK SIZES * FOR POSTULATED COMPOUND CRACK IN GINNA ACCUMULATOR LINE, BASED ON NET SECTION PLASTIC COLLAPSE CRITERION

$P_m + P_b$ = 30,133 PSI.		$P_m + P_b$ = 56,400 PSI.	
d/t	ν/π	d/t	ν/π
0	0.318	0	0.116
0.1	0.291	0.05	0.094
0.2	0.257	0.1	0.070
0.3	0.216	0.15	0.043
0.4	0.165	0.2	0.012
0.5	0.096	0.2183	0
0.5961	0		

*TERMS DEFINED IN FIGURE 2-7

TABLE 2-7

FAILURE CRACK SIZES * FOR POSTULATED COMPOUND CRACK IN GINNA PRESSURIZER SURGE LINE, BASED ON NET SECTION PLASTIC COLLAPSE CRITERION

$P_m + P_b$ = 34,747 PSI.		$P_m + P_b$ = 37,600 PSI.	
d/t	ν/π	d/t	ν/π
0	0.248	0	0.223
0.1	0.215	0.1	0.189
0.2	0.176	0.2	0.148
0.3	0.127	0.3	0.096
0.4	0.063	0.4	0.029
0.4749	0	0.4350	0

*TERMS DEFINED IN FIGURE 2-8

TABLE 2-8

LEAK RATE RESULTS FOR CIRCUMFERENTIAL THROUGH-WALL CRACKS (CTWC) AND LONGITUDINAL THROUGH-WALL CRACKS (LTWC) IN THE PRESSURIZER SURGE AND ACCUMULATOR LINES (PSL AND AL) FOR NORMAL OPERATION PRESSURE STRESSES

Line	Crack	Pressure Stress σ_p (psi)	Crack Area A_p (in.^{2}) for Half-Length a = 1 in.	Leak Rate*** (gpm.) for a = 1 in.	Crack Half-length a (in.) for 1 gpm Leak Rate***
PSL*	CTWC	4,889	0.00113	0.567	1.314
	LTWC	9,778	0.00248	1.245	<1
AL**	CTWC	1,640	0.00038	0.236	1.752
	LTWC	3,281	0.00083	0.516	1.328

* Saturated Liquid

** Non-saturated Liquid

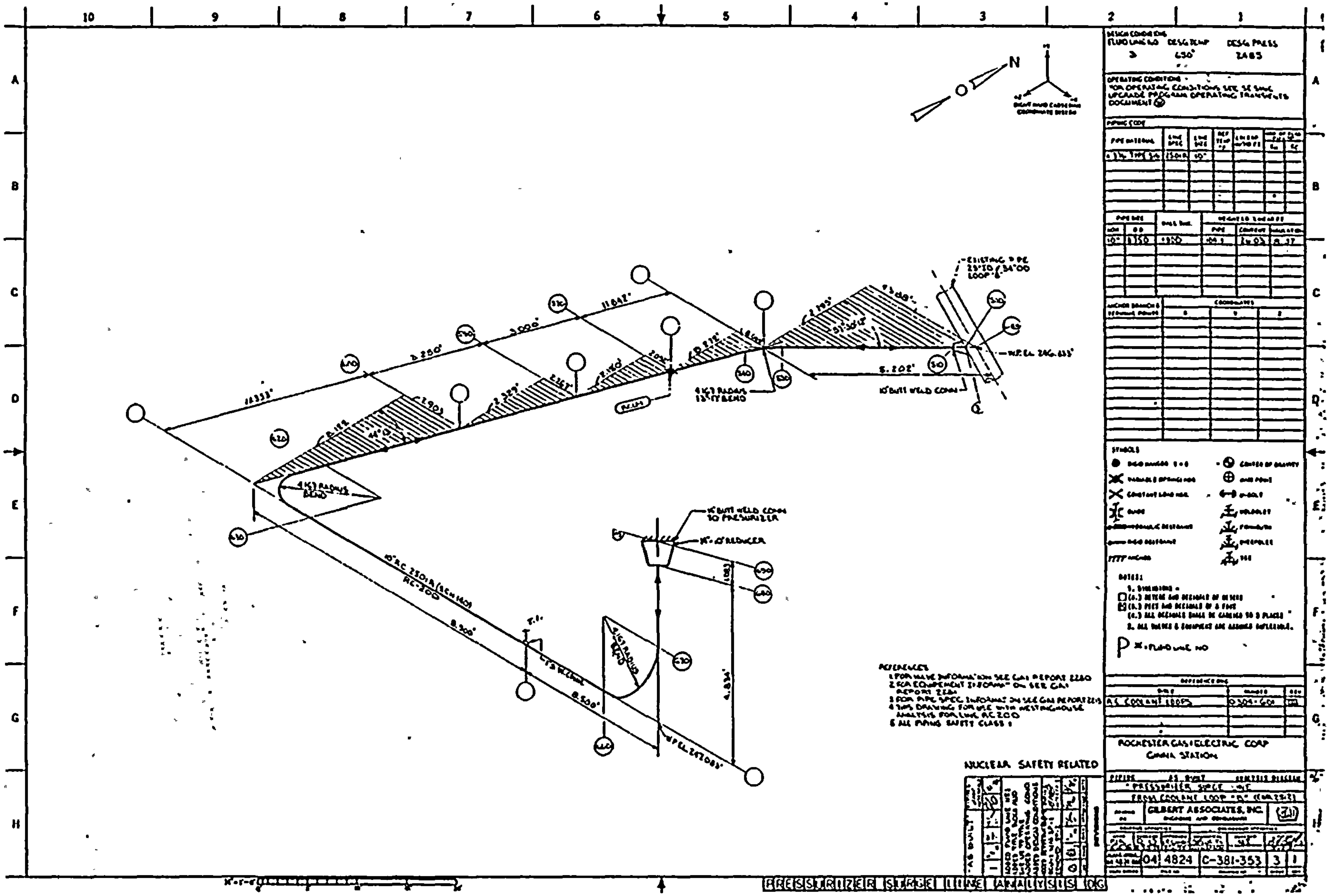
*** Based on Friction Factor C_f = 0.6

TABLE 2-9

TRANSIENTS CONSIDERED IN SUBCRITICAL CRACK GROWTH RATE ANALYSES FOR PRESSURIZER SURGE AND ACCUMULATOR LINES (REFERENCE 8)

	Operating Cycle	Occurrences in 40 yr. Design Life
1.	Startup and Shutdown	200
2.	Large Step Decrease in Load (with steam dump)	200
3.	Loss of Load (without immediate turbine or reactor trip)	80
4.	Loss of Power (blockout with natural circulation in Reactor Coolant System)	40
5.	Loss of Flow (partial loss of flow, one pump only)	80
6.	Reactor Trip from Full Power	400
7.	Hydrostatic Test (before initial startup, and post operation)	55
8.	High Head Safety Injection	50
		1105

Assume 1200 Significant Cycles in 40 yr. Design Life (30 cycles/yr.)



FRGE82.01

Figure 2-1

PRESSURIZER SURGE LINE

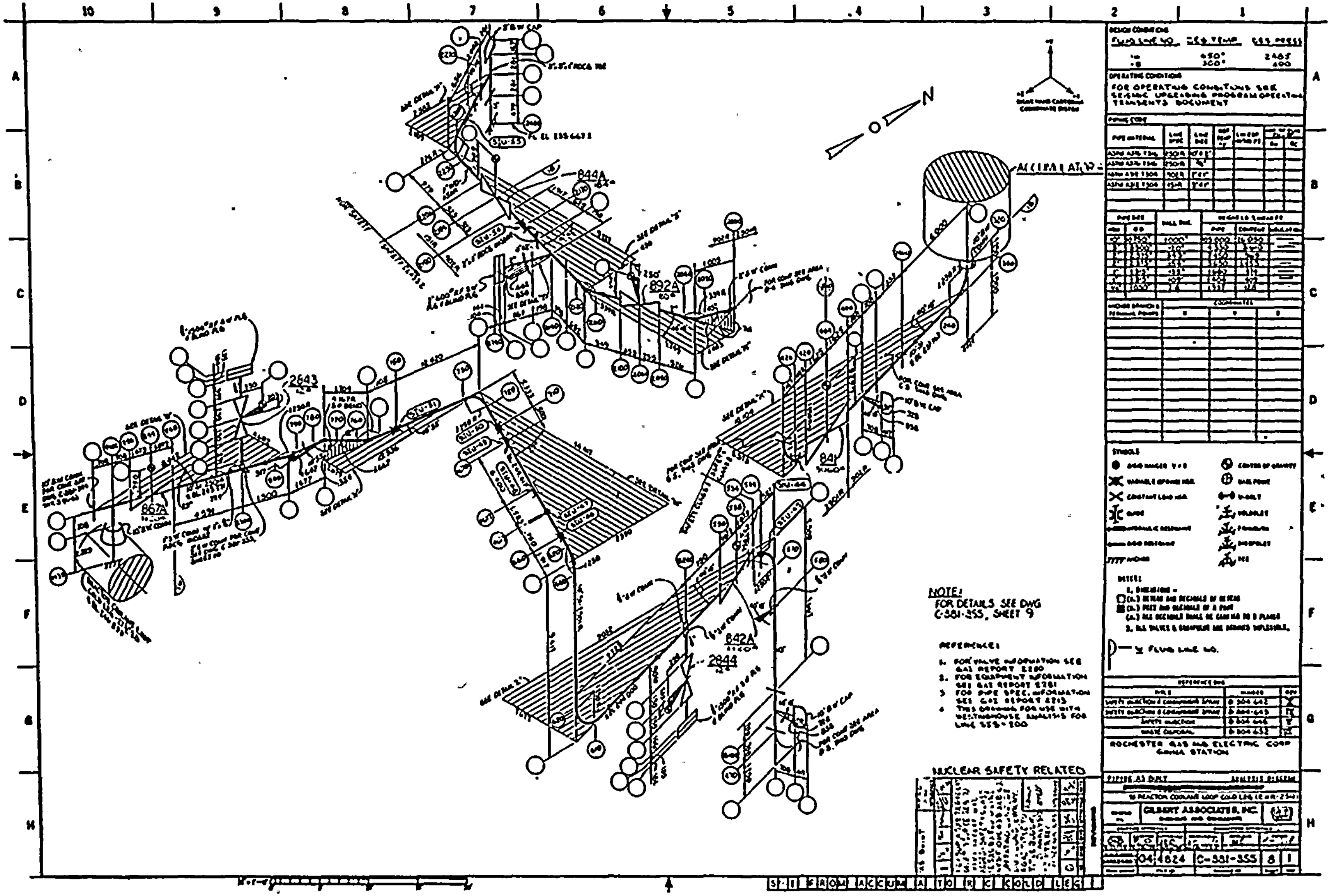


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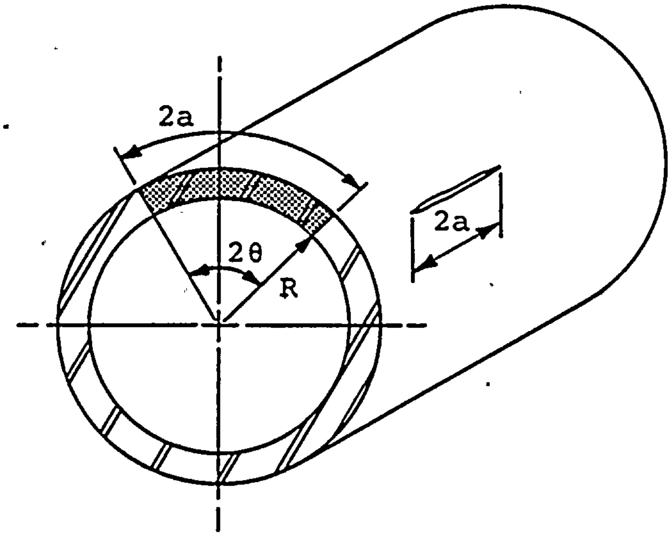
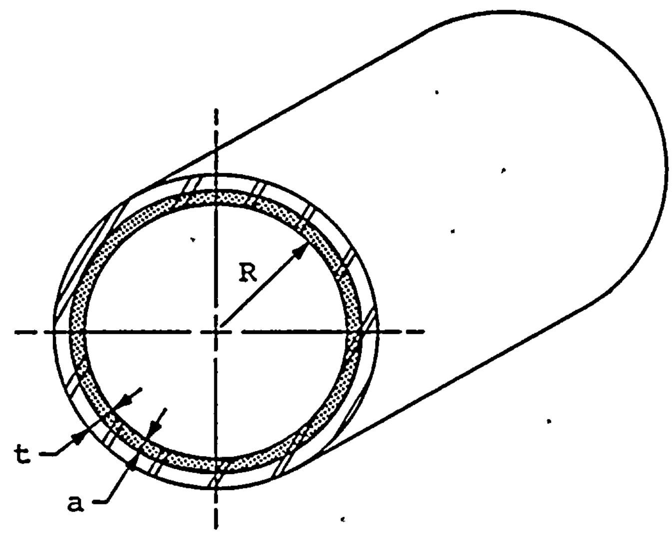
Figure 2-2

SAFETY INJECTION FROM ACCUMULATOR A



a) THROUGH-THICKNESS CIRCUMFERENTIAL AND LONGITUDINAL CRACKS OF LENGTH 2a.



b) PART-THROUGH THICKNESS CIRCUMFERENTIAL CRACK OF DEPTH a.

FGRE82.03

Figure 2-3

REPRESENTATION OF POSTULATED CRACKS IN PIPES FOR FRACTURE MECHANICS LEAK-BEFORE-BREAK ANALYSIS

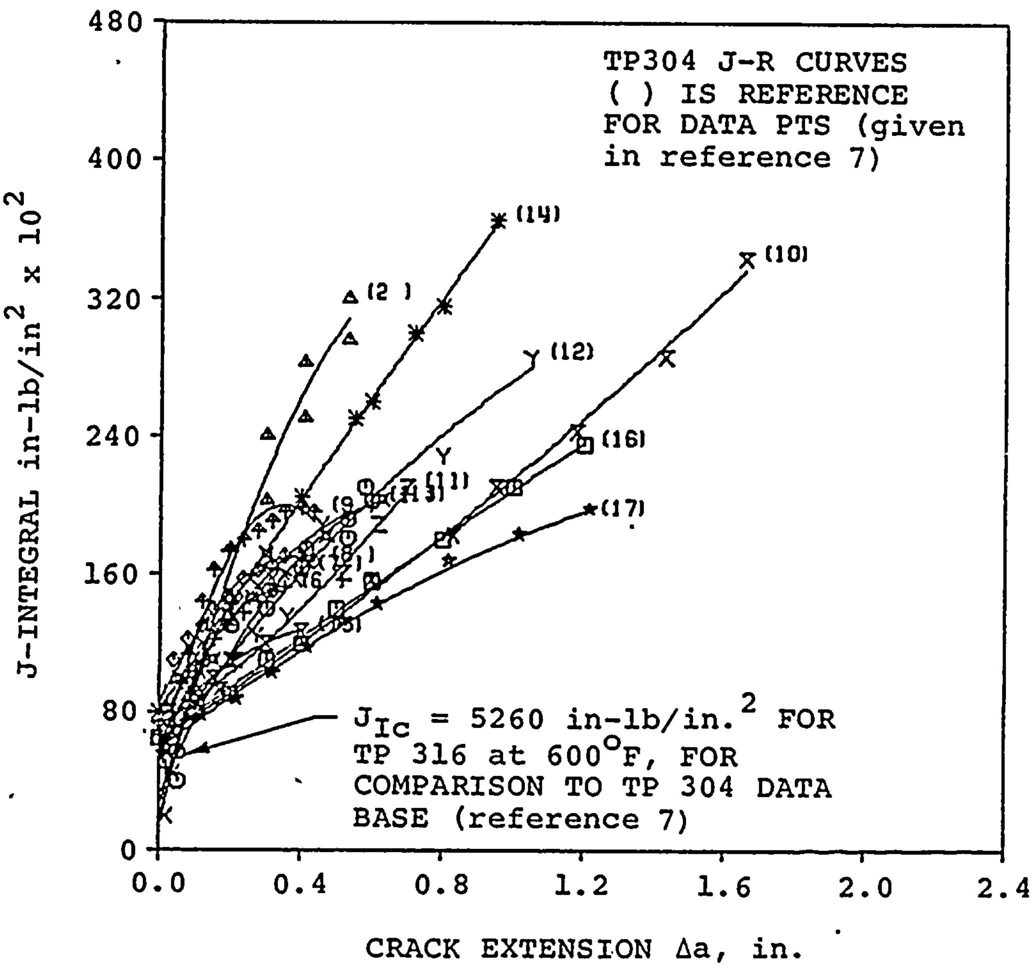


Figure 2-4

<u>J-INTEGRAL RESISTANCE CURVES FOR AUSTENITIC STAINLESS STEEL (reference 7)</u>

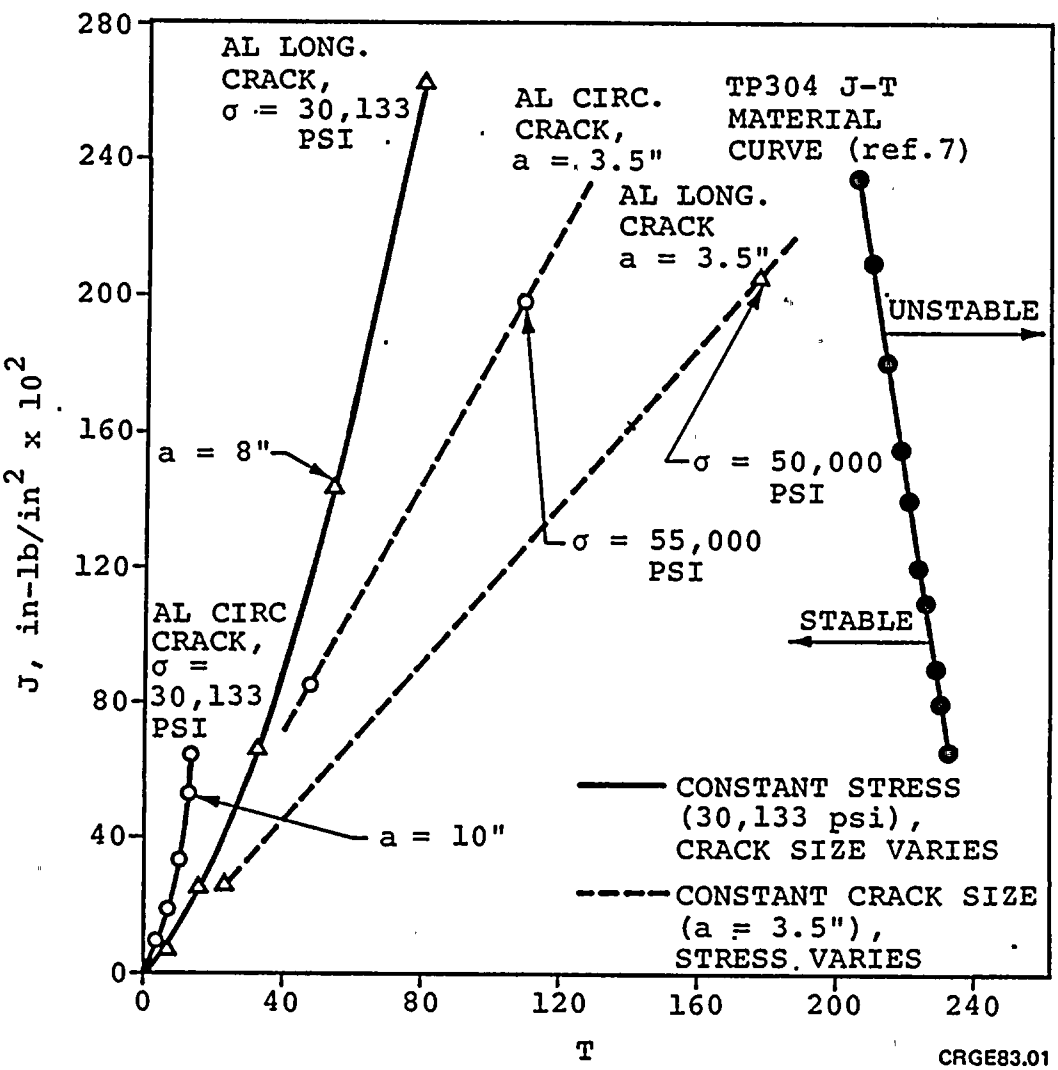
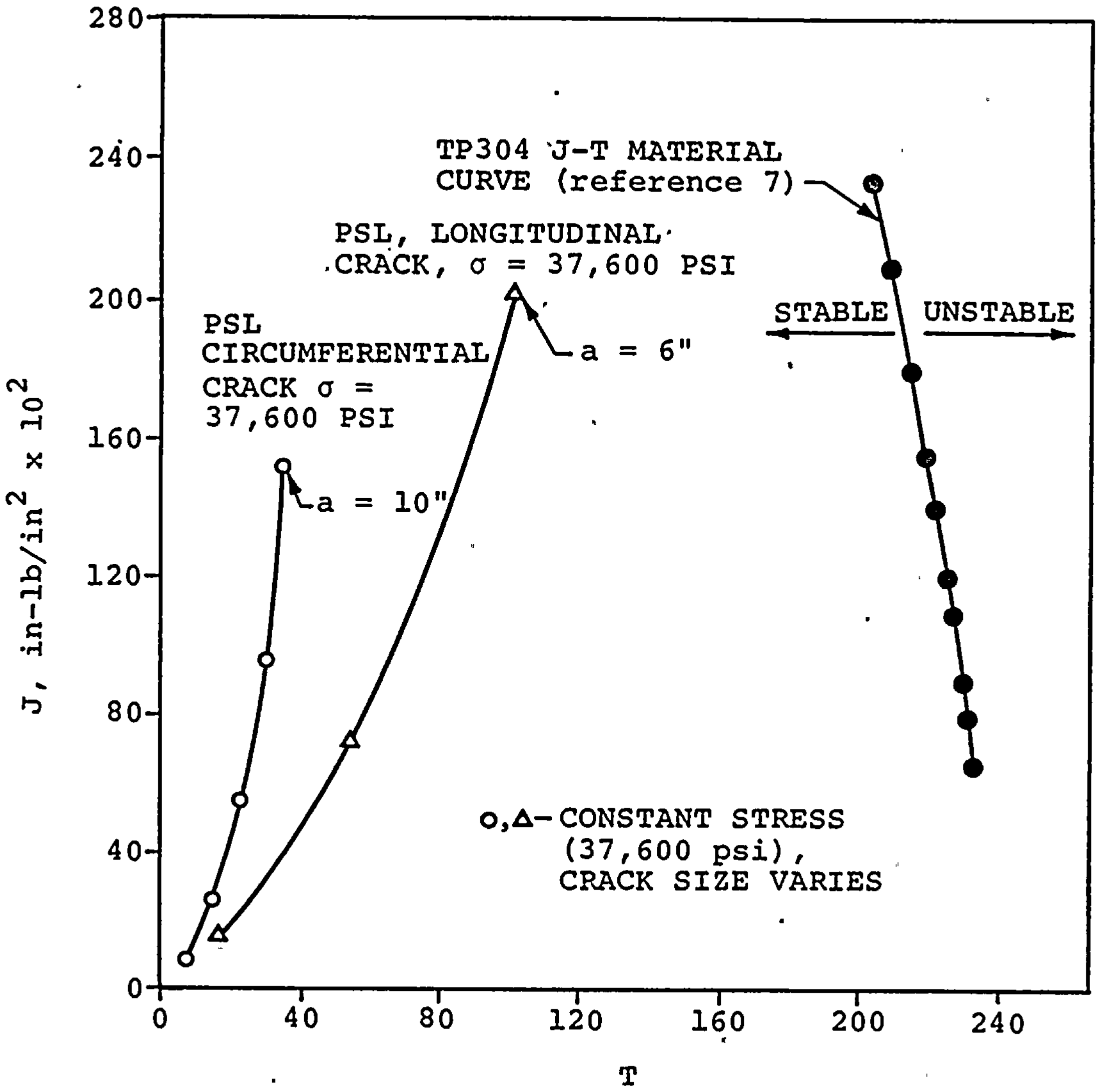


Figure 2-5

J-INTEGRAL/TEARING MODULUS STABILITY DIAGRAM FOR GINNA ACCUMULATOR LINE WITH THROUGH-WALL CRACKS



CRGE83.02

Figure 2-6

J-INTEGRAL/TEARING MODULUS STABILITY DIAGRAM FOR GINNA PRESSURIZER SURGE LINE WITH THROUGH-WALL CRACKS

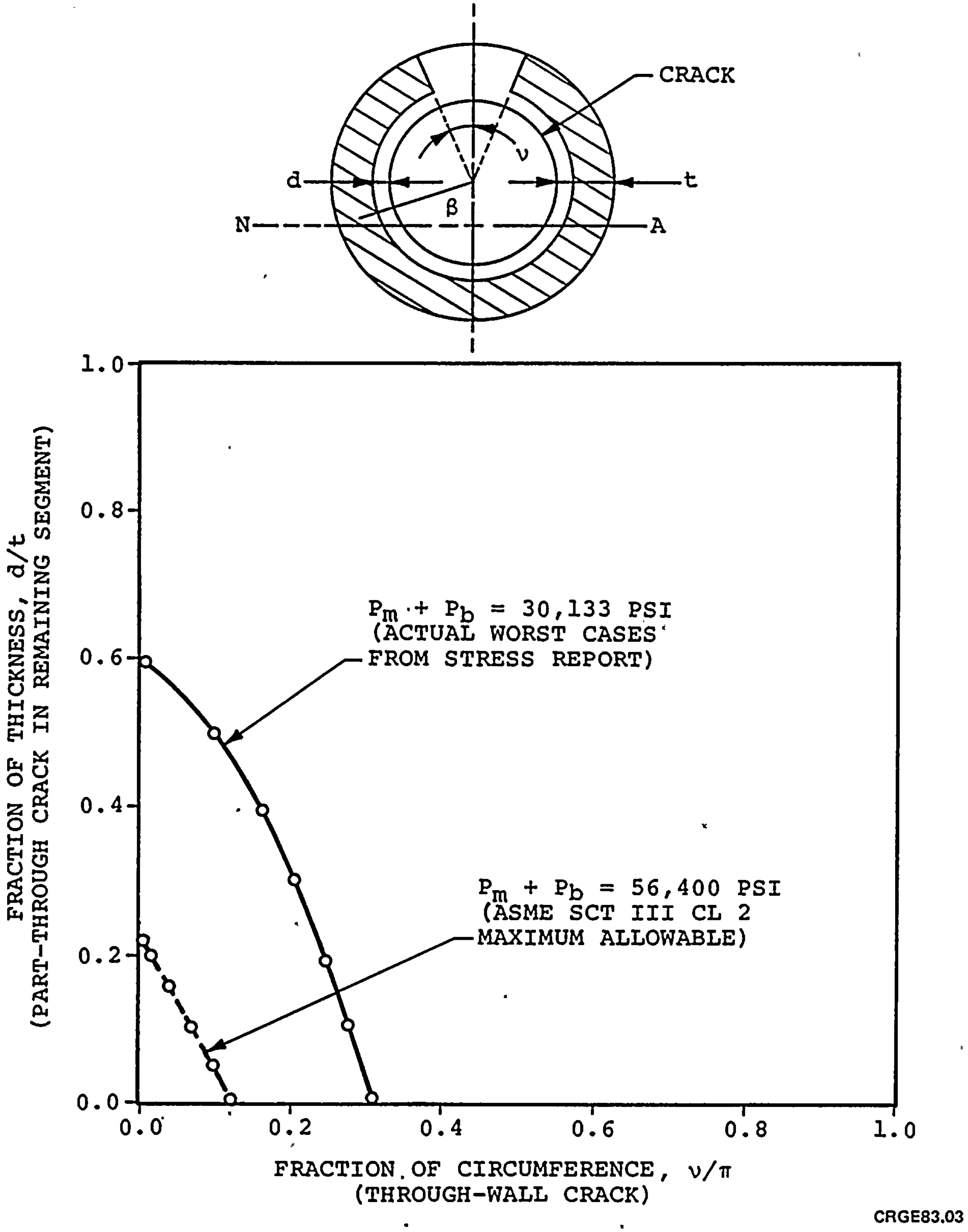


Figure 2-7

FAILURE ANALYSIS DIAGRAM FOR POSTULATED COMPOUND CRACK IN GINNA ACCUMULATOR LINE, BASED ON NET SECTION PLASTIC COLLAPSE CRITERION

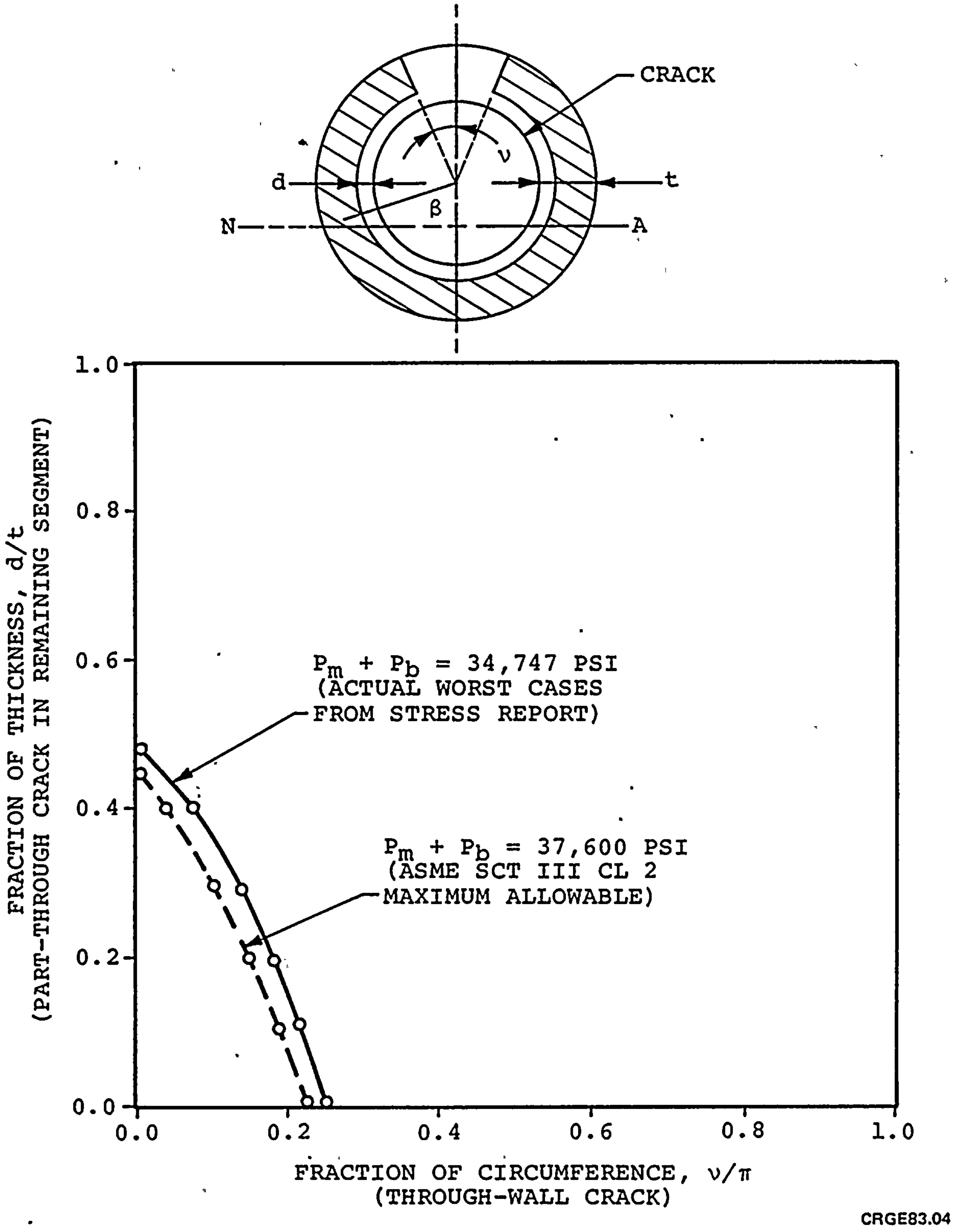
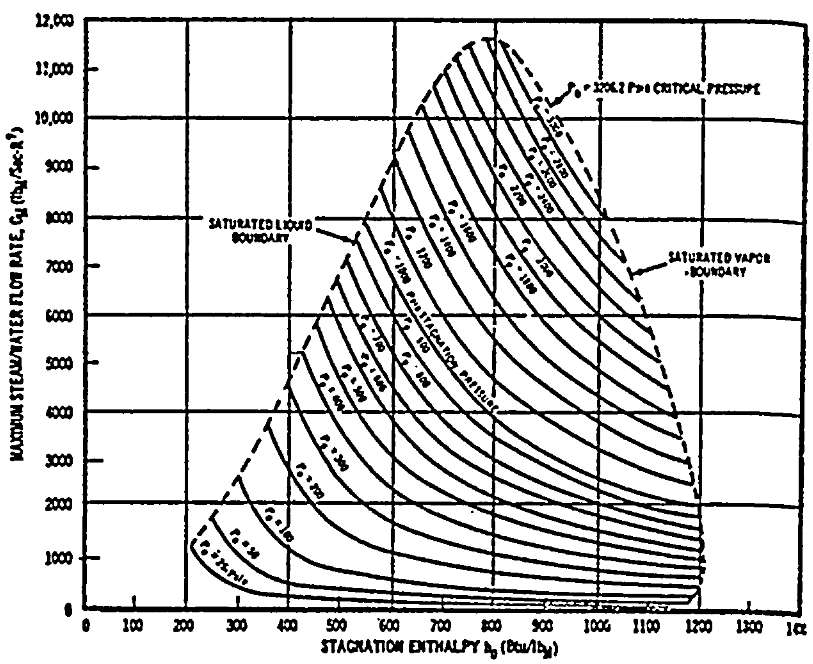


Figure 2-8

FAILURE ANALYSIS DIAGRAM FOR POSTULATED COMPOUND CRACK IN GINNA PRESSURIZER SURGE LINE, BASED ON NET SECTION PLASTIC COLLAPSE CRITERION



FRGE82.05

Figure 2-9

DIAGRAM FOR MAXIMUM STEAM/WATER FLOW RATE TO DETERMINE FLOW RATE FOR SATURATED LIQUID IN THE PRESSURIZER SURGE LINE (MOODY MODEL - REFERENCE 15)

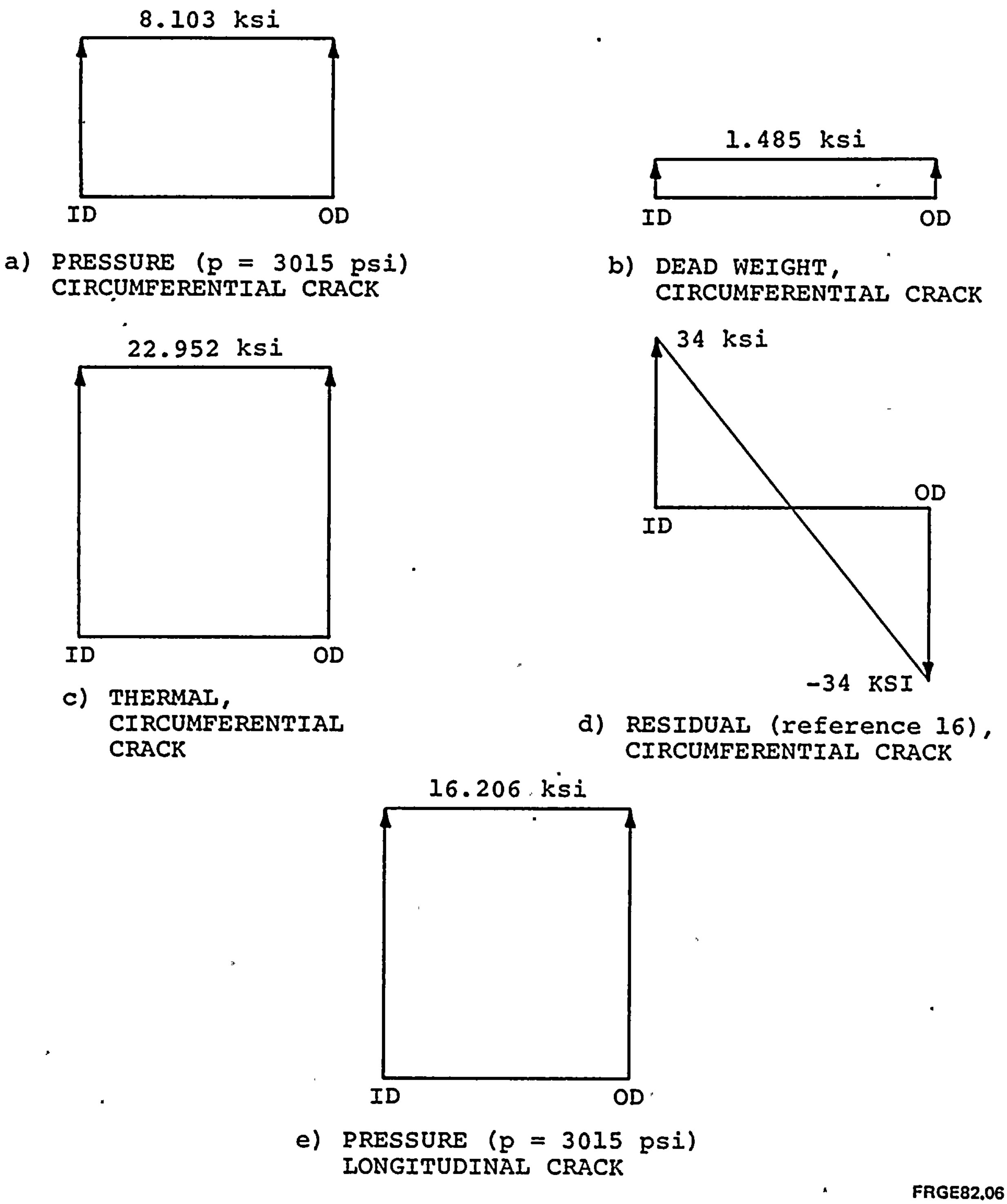
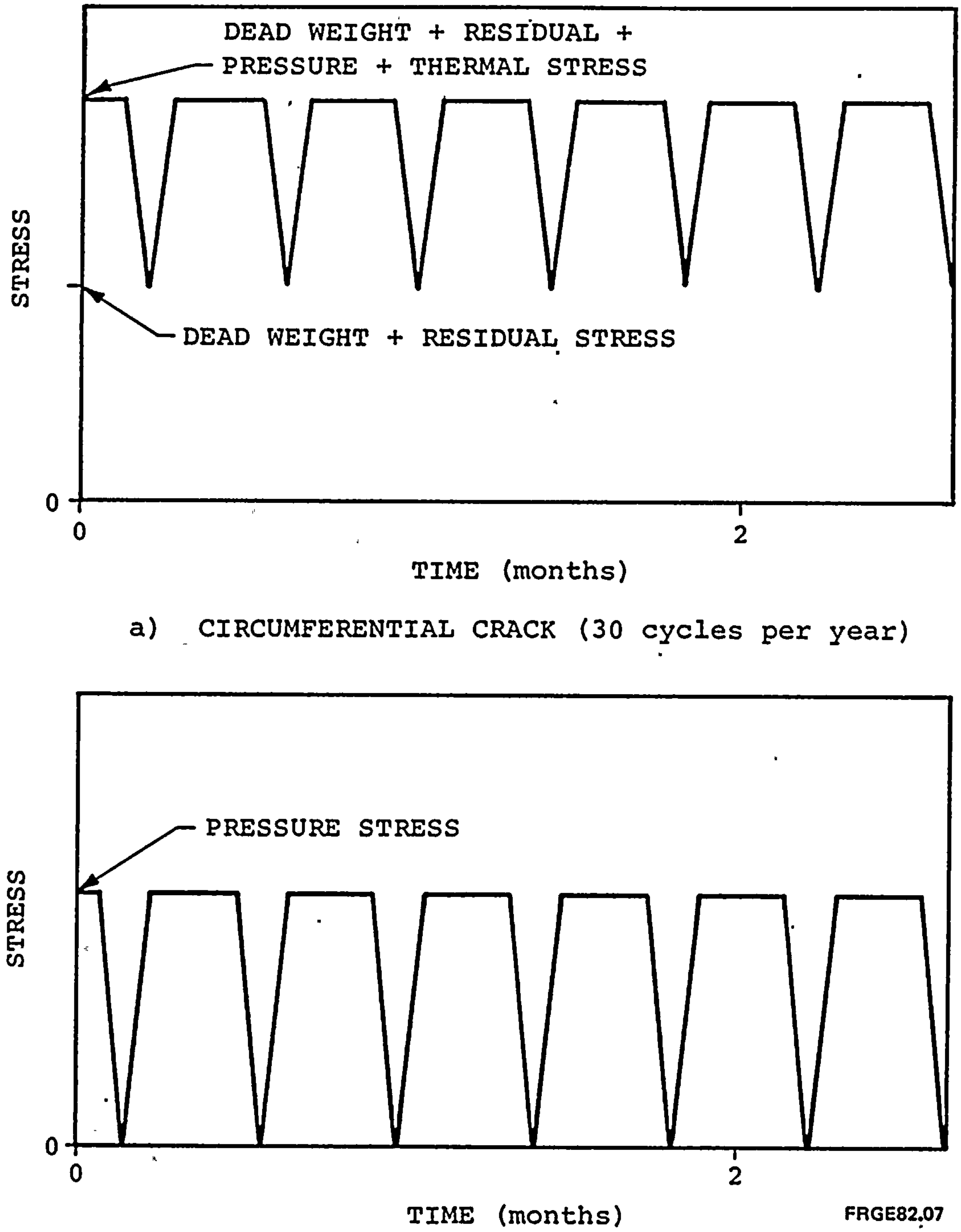


Figure 2-10

STRESS PROFILES FOR BOUNDING CASE (reference 3)
FOR SUBCRITICAL CRACK GROWTH PREDICTIONS



a) CIRCUMFERENTIAL CRACK (30 cycles per year)

b) LONGITUDINAL CRACK (30 cycles per year)

Figure 2-11

CYCLIC LOADING CONDITIONS ASSUMED FOR CONSERVATIVE SUBCRITICAL CRACK GROWTH RATE ANALYSIS OF PRESSURIZER SURGE AND ACCUMULATOR LINES

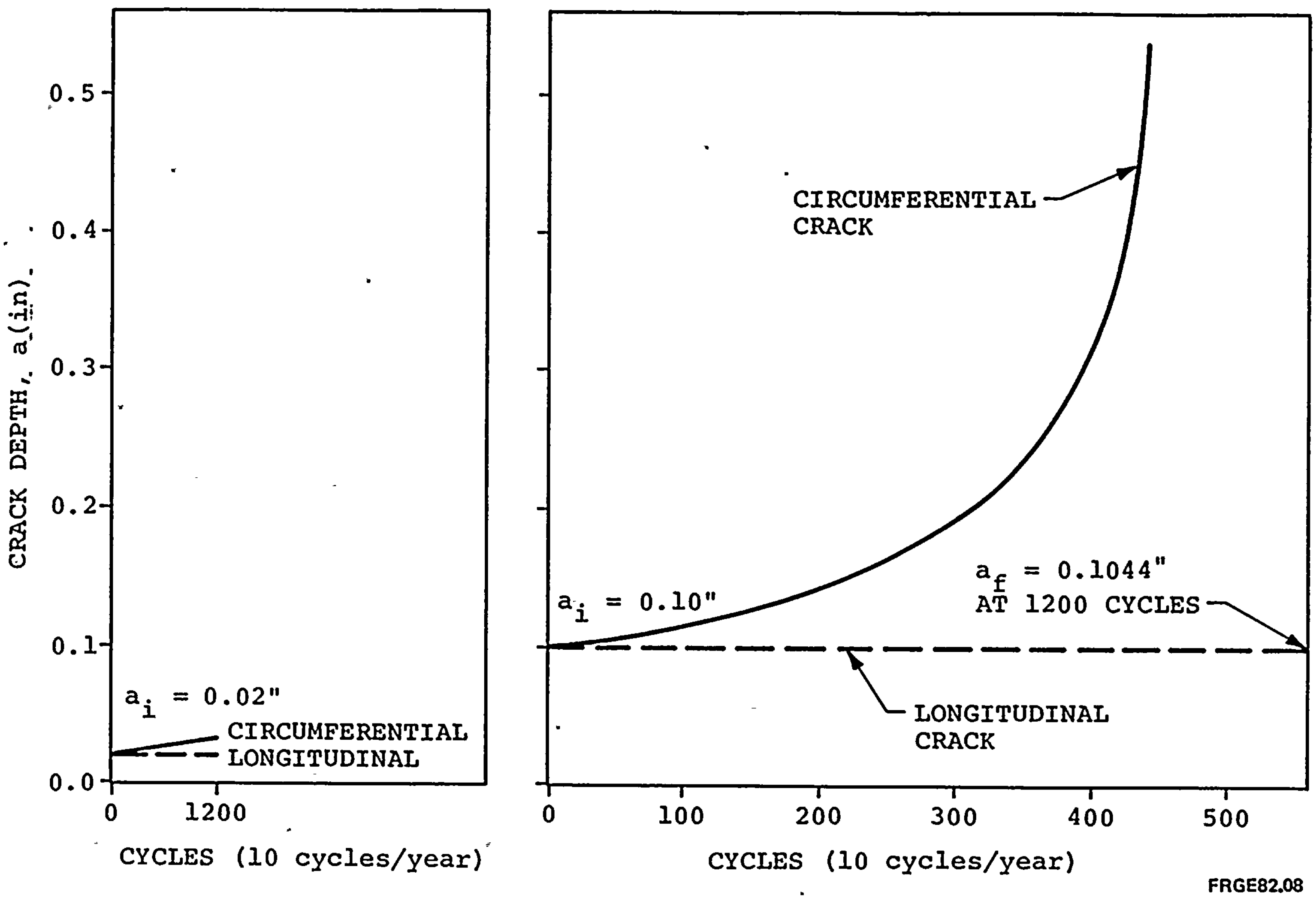


Figure 2-12

PREDICTED SUBCRITICAL CRACK GROWTH RATES FOR CIRCUMFERENTIAL AND LONGITUDINAL CRACKS WITH ASSUMED INITIAL DEPTHS (a_i) OF 0.02 INCHES AND 0.10 INCHES FOR THE PRESSURIZER SURGE AND ACCUMULATOR LINES

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