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**REACTOR PRIMARY COOLANT SYSTEM
RUPTURE STUDY
QUARTERLY PROGRESS REPORT NO. 11
OCTOBER-DECEMBER 1967**

U.S. ATOMIC ENERGY COMMISSION
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PROJECT AGREEMENT 37

ATOMIC POWER EQUIPMENT DEPARTMENT

GENERAL ELECTRIC

SAN JOSE, CALIFORNIA

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REACTOR PRIMARY COOLANT SYSTEM RUPTURE STUDY
QUARTERLY PROGRESS REPORT NO. 11
OCTOBER—DECEMBER 1967

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SECTION I

INTRODUCTION

The Reactor Primary Coolant System Rupture Study is being conducted for the Safety Branch, Division of Reactor Development and Technology, USAEC. This eleventh quarterly report documents progress for the period of October 1 to December 31, 1967. The overall objective of the program is to improve the reliability of reactor system piping by increasing current knowledge of failure-causing mechanisms and by enhancing capability for design evaluation and analysis.

Toward the attainment of this objective, work is proceeding on the tasks:

- Task A Reliability Engineering
- Task B Stress Analyses
- Task C Fracture Mechanics
- Task D Fatigue
- Task K BWR Environment

The specific objectives of the tasks and technical progress are covered in the following sections. Previous reports issued as a part of this program are listed below:

GEAP-4445—A Survey of Water Reactor Primary System Conditions Pertinent to the Study of Pipe Rupture.

GEAP-4446—A Review of Fracture Modes as Related to Reactor Primary Coolant Pipe Rupture.

GEAP-4474—Experimental and Analytical Program Recommendations - Reactor Pipe Rupture Study.

GEAP-4574—Survey of Piping Failures for the Reactor Primary Coolant Pipe Rupture Study.

GEAP-4578—Mechanical Design Considerations in Primary Nuclear Piping.

GEAP-4678—Fracture Mechanics and the Stability of Engineering Structures.

GEAP-4911—Reactor Primary Coolant System Rupture Study Quarterly Progress Report Number 1, April—June 1965.

GEAP-4964—Reactor Primary Coolant System Rupture Study Quarterly Progress Report Number 2, July—August 1965.

GEAP-5014—Fracture Toughness of Some Engineering Alloys.

GEAP-5082—Reactor Primary Coolant System Rupture Study Quarterly Progress Report Number 3, October—December 1965.

GEAP-5147—Reactor Primary Coolant System Rupture Study Quarterly Progress Report Number 4, January—March 1966.

GEAP-5192—Reactor Primary Coolant System Rupture Study Quarterly Progress Report Number 5, April—June 1966.

GEAP-5279—Reactor Primary Coolant System Rupture Study Quarterly Progress Report Number 6, July—September 1966.

GEAP-5410—Low-Cycle Fatigue Strength Reduction in Notched Flat Plates.

GEAP-5427—Reactor Primary Coolant System Rupture Study Quarterly Progress Report Number 7, October—December 1966.

GEAP-5471—PAPA - Structural Analysis of
Plates and Shells Using Trapezoidal
and Triangular Plate Elements.

GEAP-5474—Reactor Primary Coolant System
Rupture Study Quarterly Progress
Report Number 8, January—March
1967.

GEAP-5512—Reactor Primary Coolant System
Rupture Study Quarterly Progress
Report Number 9, April—June
1967.

GEAP-5554—Reactor Primary Coolant
System Rupture Study Quarterly
Number 10, July—September 1967.

SECTION II

SUMMARY

2.1 TASK A—RELIABILITY ENGINEERING

Given that more combinations and sequences of damage mechanisms are at work in piping than can be analyzed in detail, priorities were assigned those considered most important. The kinds of information needed for the selected cases include, besides an analytical model (or equation): design values, parameter estimates, their distributions, and a measure of uncertainty for the equation form itself. The top priority models are:

A low-cycle fatigue relationship for circumferential, inside, and outside crack initiation in sound material and in the presence of stress concentrations.

A low-cycle fatigue relationship for growth of a circumferential leaking crack around the pipe to the critical size for severance.

Definition of the critical size for severance for leaking circumferential cracks; and for long, shallow nonleaking circumferential cracks.

A low-cycle fatigue relation for initiation and growth through to leakage of a circumferential crack in Type-304 stainless steel as affected by the BWR environment.

2.2 TASK B—STRESS ANALYSIS

2.2.1 Task B-1—Computer Program Development

The elastic plastic code (EPS) development was suspended during the quarter to concentrate on reduction to practice demonstration of PAPA, the basic code for calculation of stresses in complex piping geometries in the elastic range. PAPA was applied to a TEE problem and yielded results which compare reasonably with experimental measurements. The correct trends are noted although some deviations are present which are being investigated.

2.2.2 Task B-2—Problem Solutions

Analytical expressions were derived for: (1) through-wall crack growth where stresses in the plastic region are applied (an extension of a relation developed earlier on this study), and (2) the sequential step in piping (unless removed from service) which is circumferential growth of a through-wall crack. Using a simplified approach, an estimate was made of the probability of a pipe break as a result of progressive crack growth to a critical size. The importance of in-service leak detection capability is the key conclusion.

2.2.3 Task B-3—Experimental Stress Analysis

At the University of Illinois, evaluation of the three-dimensional photoelastic data obtained from the many slices and subslices of the various plastic models has continued. Data analysis has taken longer than originally estimated primarily because of the asymmetry of the stress distributions. At San Jose the two-dimensional stress studies (testing of metal models which have plastic sheet molded to the high stress regions of interest) are experimentally complete; analysis and the preparation of a topical report are in progress.

2.3 TASK C—FRACTURE MECHANICS

Augmenting the data from burst tests of flawed 6-inch pipe performed earlier, eight additional specimens with axial through-wall flaws were hydraulically pressurized to failure. These included 4- and 8-inch sizes. Plotting burst pressure versus the ratio of flaw half-length to pipe radius yields a reasonably smooth curve, showing reduced pressure required to burst pipe as the ratio increases. A somewhat better fit of the data is obtained thereby, rather than simply plotting burst pressure against flaw size.

The conclusion drawn is that pipe size must be quantitatively taken into account before predictions of critical flaw size can be valid. Calculations using two relationships for the critical stress intensity factor, K_c , supported the same conclusion.

2.4 TASK D—FATIGUE

2.4.1 Task D-1—Fatigue Crack Growth Studies

Crack growth rates measured at room temperature in split sections of $2\frac{1}{4}$ Cr-1 Mo steel prototype pipe material were higher than the rates measured in plate of the same

material. This result was in the same pattern as previously noted for plain carbon steel and for Type-304 stainless steel. However, a summary comparison of the results indicates the same relative ranking of materials observed in plate tests, i.e., the highest rate is shown by the carbon steel, then $2\frac{1}{4}$ Cr-1 Mo steel, and finally Type-304 stainless steel.

2.4.2 Task D-2—Fatigue Crack Initiation Studies

Testing was completed for grooved cylinder specimens of the three grades of steel under completely reversed, load-controlled conditions at 550°F. The temperature was determined for maximum strain aging of carbon steel as evidenced by the tensile ductility minimum.

2.4.3 Task D-3—Prototype Pipe Fatigue Tests

Tests of three room temperature and the first elevated temperature (550°F) straight pipe specimens were completed. Cyclic bending loads were applied to the specimens with 1000 psi pressure at room temperature but no pressure on the 550°F specimen. Measurements were made of cycles for crack initiation, for crack growth through the pipe wall, and finally for growth circumferentially. In no case to date has severance failure occurred (the most crack growth was about 70% of the circumference).

2.4.4 Task D-4—Effect of Cyclic Strain Aging on Brittle Fracture Properties

High precision tensile testing was conducted using an Instron machine to determine the maximum strain aging temperature of both carbon steel plate and pipe. Both sets of results indicated a minimum ductility and maximum strength in the range of 350°–400°F. The initial cyclic strain aging tests of plates which will later be

machined into Charpy bars are underway at 350°F. The fracture appearance transition temperature (FATT), a measure of brittle behavior, will be measured on the broken Charpy bars.

2.5 TASK K—EFFECT OF BWR ENVIRONMENT

Approval to fabricate the necessary experimental equipment was received at

about the middle of the period. Activities concentrated on the preparation of drawings and specifications suitable for ordering the low-cycle fatigue unit and containing pressure vessel. Procurement procedures (requests for bids) were initiated.

SECTION III

TASK A—RELIABILITY ENGINEERING

(S. A. Wilson)

3.1 OBJECTIVES

The objectives of the reliability engineering task are to develop methods for:

- a. Estimation of the reliability of a reactor primary piping system in terms of leak rate and time of reactor service. In particular, to find 1 minus the probability that such a piping system will develop one or more

through-wall leaks or complete severance leaks	in	10 20 30 40	years of service
---	----	----------------------	------------------------

- b. Identification of the principal sources of real variability or uncertainty in service life.

The present effort is on Subtask A-2:
"Make preliminary estimate of system reliability."

3.2 SUMMARY

Priorities for models of continuous damage mechanisms were assigned for piping cross-sections of interest. The kinds of information needed for each model are stated, including design values, parameter estimates, judgmental uncertainty distributions for design values, distributions for the parameters, and a measure of uncertainty for equation form.

A modified low-cycle fatigue crack growth equation is introduced, and sensitivity results presented. Possible variation in initial crack depth leads to greatest uncertainty in cycles to completion.

Methods for estimating crack growth material parameters A and B are surveyed, which involve varying degrees of smoothing of original data. No smoothing will be adopted in order to carry experimental variability ahead correctly to variances of A and B. A hyperbola of form $1/a = C_1 + C_2 n$ fitted to load-controlled experimental a versus n data leads to a straight line of slope 4.0 on $\log da/dn$ versus $\log \Delta K$.

3.3 PRIORITIES FOR EQUATIONS OF CONTINUOUS DAMAGE MECHANISMS

Figure 3-1, the "Probability Diagram for Continuous Damage Mechanisms for One Pipe Cross Section,"* shows that a large number of probabilities associated with continuous damage mechanisms are required to evaluate completely piping system reliability.

*Initially presented as Figure 3-1 in the Ninth Quarterly Report, GEAP-5512.

LETTERS ARE PROBABILITIES OF EVENTS CAUSED BY TIME-CONSUMING (OR CONTINUOUS) DAMAGE MECHANISMS, SUCH AS LOW-CYCLE FATIGUE.

NUMBERS ≤ 70 ARE PROBABILITIES OF EVENTS NOT ARISING FROM THE DISTRIBUTION OF A TIME-CONSUMING DAMAGE MECHANISM, SUCH AS THE PROBABILITY THAT A LEAK WILL BE DETECTED.

NUMBERS OVER 70 ARE PROBABILITIES OF ACHIEVING THE CONDITION SHOWN: "80" IS THE PROBABILITY THAT A SHORT CRACK IS INITIATED, BY ALL POSSIBLE PATHS.

○ EQUATIONS FOR THESE PROBABILITIES ARE ASSIGNED FIRST PRIORITY

FIGURE 3-1. PROBABILITY DIAGRAM FOR CONTINUOUS DAMAGE MECHANISMS FOR ONE PIPE CROSS SECTION

Some of these probabilities are believed to be larger than others, based on both conventional and nuclear steam plant operating

experience. Accordingly, those that have been given first priority are listed in the following tabulation and are identified on Figure 3-1.

Probability Designation on Figure 3-1	Related Pipe Study Task	Case	Code	Continuous Damage Mechanism, Stage of Damage, and Material
		1		Crack initiation
		11		In sound material
		111		Outside and circumferential (air environment)
o'	B	1111		By low-cycle fatigue (CS, LAS, SS*)
		112		Inside and circumferential (water or steam environment)
i'	K	1121		By fatigue assisted stress corrosion (SS)
k'	K	1122		By stress corrosion without fatigue (SS)
		12		In material containing a "short groove" (stress concentrator with stress field such that crack grows through to leakage prior to reaching critical size for severance)
		121		Outside and circumferential (air environment)
e	B	1211		By low-cycle fatigue (CS, LAS, SS)
		122		Inside and circumferential (water or steam environment)
g	B	1221		By low-cycle fatigue (CS, LAS, SS)
i	K	1222		By fatigue assisted stress corrosion (SS)
k	K	1223		By stress corrosion without fatigue (SS)
		13		In material containing a "long groove" (stress concentrator with stress field such that crack grows around to critical size for severance prior to leakage)
		131		Inside and axial (water or steam environment the only axial case of initiation given first priority)
r	K	1311		By stress corrosion without fatigue (SS)
		132		Inside and circumferential (water or steam environment)
s	K	1321		By stress corrosion without fatigue (SS)
		2		Crack growth through to leakage from a "short crack" which has been initiated or was present initially
		21		Outside and circumferential (air environment)
E	B	211		By low-cycle fatigue (CS, LAS, SS)
		22		Inside and circumferential (water or steam environment)
G	B	221		By low-cycle fatigue (CS, LAS, SS)
I	K	222		By fatigue assisted stress corrosion (SS)
K	K	223		By stress corrosion without fatigue (SS)
		3		Crack growth through and around (or along) to critical size for severance without leakage from a "long crack" which has been initiated or was present initially
		31		Inside and axial (water or steam environment, the only axial case of growth given first priority)
R	K	311		Stress corrosion without fatigue (SS)
		32		Inside and circumferential (water or steam environment)

* CS—Carbon steel, LAS—Low alloy steel, SS—stainless steel.

S	K	321	Stress corrosion without fatigue (SS)
			(First priority for this type of damage was assigned to only the stress corrosion without fatigue failure mechanism, because any fatigue loading was judged to lead to leakage before severance.)
		4	Growth of a leaking crack around to critical size for severance
		41	Circumferential crack
B	B	411	Low-cycle fatigue (CS, LAS, SS)
		5	Length-depth-stress conditions defining critical size for severance
		51	Leaking
11, 14	C	511	Circumferential slot (CS, LAS, SS)
		52	Not leaking
17	C	521	Axial crack (SS)
17	C	522	Circumferential crack (SS)

Of the models associated with the foregoing probabilities, low-cycle fatigue crack growth through a pipe wall (211) has served as a prototype, and is reproduced in revised form in subsection 3.4. The same mechanism, but with crack growth around the pipe (411) appears in Section IV [Equation (8)] of this quarterly for the first time.

The above probabilities require the following information for their evaluation:

- An equation which predicts the time or cycles for the damage to be completed (i. e., for a crack to be initiated, for a stress corrosion crack to grow through the wall thickness, etc.).
- Design values for the variables in the equation for each pipe cross section of interest in the system.
- Estimates of any parameters in the equation.
- A judgmental uncertainty distribution for each cause of uncertainty in each variable in the equation.
- A distribution—experimental or judgmental—for each parameter in the equation.
- Some measure of the uncertainty of the correct form of the equation.

3.4 MODIFIED EQUATION FOR PROBABILITY "E": CIRCUMFERENTIAL CRACK GROWTH THROUGH WALL BY LOW-CYCLE FATIGUE

As a result of investigating the behavior of this equation, it has been modified* to the following form (new portions are underlined):

$$n_t^* = \frac{1}{A^*A} \int_{\left(\frac{a_0}{t^*t}\right)}^{t^*t} \left\{ \left[C^{*2} \frac{\sigma_{PB}^* \sigma_{PB}}{\dots} \right. \right. \\ \left. \left. + 3 (C^*)^2 (E^*)^{3/2} \frac{\sigma_{PM}^* + C^* \sigma_{SB}^* \sigma_{SB}}{\text{bending portion}} \right. \right. \\ \left. \left. + 3 C^* (E^*)^{3/2} \frac{\sigma_{SM}^* \sigma_{SM}}{\dots} \right] \sqrt{0.52 (t^*t - a) \tanh(5.5 E^*)} \right. \\ \left. + \left[\sigma_{PM}^* + (1/C^*) \frac{\sigma_{SM}^* \sigma_{SM}}{\dots} \right] \sqrt{2 t^*t \tan\left(\frac{\pi}{2} E^*\right)} \right\} \\ \left. \right\}^{-B^*B} \left[1 + 0.0325 (1 + \cos \pi E^*)^2 \right] da \quad (1)$$

*By joint effort with J. D. Gilman.

where

n_t^* = Distribution of number of cycles to completion of through-wall crack,

$\left(\frac{a_0}{t^*t}\right)^* t^*t$ = Uncertainty distribution of a_0 , initial crack depth, inches,

t = Wall thickness, inches,

t^* = Coefficient uncertainty distribution of t ,

σ_{PB} = Primary bending stress, psi,

σ_{SB} = Secondary bending stress, psi,

σ_{SM} = Secondary membrane stress, psi,

σ_{PB}^* = Coefficient uncertainty distribution of σ_{PB} ,

σ_{SB}^* = Coefficient uncertainty distribution of σ_{SB} ,

σ_{SM}^* = Coefficient uncertainty distribution of σ_{SM} ,

$$\sigma_{PM}^* = \frac{P^* (P - \Delta P^*) d^* d}{4 t^* t}$$

P = Pressure, psi,

ΔP^* = Difference uncertainty distribution of P , psi,

d = Diameter, inches.

P^* = Coefficient uncertainty distribution of P .

d^* = Coefficient uncertainty distribution of d ,

A = Material parameter: $\log A$ is intercept of $\log (da/dn)$ versus $\log (\Delta K)$,

A^* = Coefficient uncertainty distribution of A ,

B = Material parameter; slope of $\log (da/dn)$ versus $\log (\Delta K)$,

B^* = Coefficient uncertainty distribution of B ,

$$C^* = \frac{t^*t}{t^*t - a}$$

$$E^* = \frac{a}{t^*t}$$

The development of Equation (1) can be summarized in the following tabulation.

- a. Radius r of notch in material of thickness r synthetically added to outside surface of pipe as an analytical equivalent to stress concentration factor has been removed. Stress concentration factor will appear

Quarterly No.	Document No.	Equation No.	Page No.	Remarks
6	GEAP-5279	1 A-1	3-2 A-1	Original form.
7	GEAP-5427	1	3-2	Added r .
8	GEAP-5474	1	3-3	Added uncertainty coefficients.
11	GEAP-5587	1	5	Deleted r . Added membrane stresses in bending portion. Added plastic stress correction. Distributed σ^* to each stress category separately. Introduced $(E^*)^{3/2}$ and $\cos$ coefficient.

only in the crack initiation equations for probabilities e, g, and i. The reason for this change is that once a crack is initiated, its growth by low-cycle fatigue does not depend on a stress concentration factor, only on total crack depth and stress field.

- b. Membrane stresses, σ_{PM} and σ_{SM} , now appear in the "bending portion" of the equation as well as in the "membrane portion." This change recognizes that as a crack deepens, the loading of a membrane stress becomes eccentric, giving it an additional effect like that of a bending stress.
- c. A new provision for a "plastic stress correction," which does not appear directly in the equation, has the objective

of properly accounting for the stress-strain relationship of the material whenever the sum of the products of the four stresses and their uncertainty coefficients exceeds $3S_m$ (per ASME Code Section III), which is twice yield stress. This correction is described in subsection 4.7.4 and its effect is shown in Figure 3-3.

- d. Uncertainty coefficients have been assigned to each stress category, in place of having one such coefficient for all stress categories.

The "cycles to completion," predicted by Equation (1), differ from those given by the form appearing in the Seventh Quarterly as follows:

Figure No. Seventh Quarterly Report	Figure No. this Report	Comparison
3-2	3-2	Cycles versus crack depth. Characteristic shape, "A" of Seventh Quarterly, Figure 3-2, is maintained for a wide range of conditions, which shows that over 50% of cycles is required to increase crack depth to 10% of wall thickness. Shape "B," for the special case of only σ_{SM} operating, no longer goes to infinity, but has a shape like "A".
3-3	3-3	Cycles to completion versus stress level. For sum of stresses less than that requiring "plastic stress correction," cycles to completion are now less because of greater effect of membrane stresses. For sum of stresses large enough to require "plastic stress correction," cycles to completion become greater than formerly.
3-3	3-4	Cycles to completion versus stress level. Each stress category is considered separately, with the other stresses at 0, to observe the relative effect of each stress category. For the same value of stress the effect among the four stress categories is not greatly different.
3-4		Cycles to completion versus radius r. Now omitted.
3-5 and 3-6	3-5	Cycles to completion versus initial crack depth to wall thickness ratio, a_o/t . Curve shape is the same as for a_o but cycles are slightly fewer for the same stresses. Curves added for different wall thicknesses reflect that cycles to completion decrease greatly for the same a_o/t fraction in heavier wall thicknesses, verifying the Eighth Quarterly observation that cycles to completion depend much more on the value of a_o than on wall thickness.

FIGURE 3-2. CHARACTERISTIC CURVE SHAPES OF CYCLES VERSUS CRACK DEPTH IN LOW-CYCLE FATIGUE FOR CIRCUMFERENTIAL CRACK GROWTH FROM INITIAL DEPTH, a_0 , THROUGH WALL THICKNESS, t .

FIGURE 3-3. CYCLES TO COMPLETION VERSUS UNCERTAINTY COEFFICIENTS ON EACH OF THE FOUR STRESS CATEGORIES, SHOWING EFFECT OF PLASTIC STRESS CORRECTION

EQUATION (1) VALUES:

σ_{SB} , σ_{PB} , σ_{PM} , σ_{SM} : THE STRESS FOR THE CURVE DESIGNATED IS ON THE ABSCISSA, WITH OTHER STRESS CATEGORIES AT 0. EXAMPLE: FOR CURVE " σ_{SB} ", σ_{SB} INCREASES FROM 6000 TO 48,000 psi WITH $\sigma_{PB} = \sigma_{PM} = \sigma_{SM} = 0$.

$$a_0 = 0.010 \text{ inch, } t = 0.4 \text{ inch, } A = 1.66 \times 10^{-19}, B = 3.0$$

○ POINTS ARE PER FIGURE 3-3, SEVENTH QUARTERLY REPORT

FIGURE 3-4. CYCLES TO COMPLETION VERSUS VALUE OF ONE STRESS CATEGORY

FIGURE 3-5. CYCLES TO COMPLETION VERSUS RATIO OF INITIAL CRACK DEPTH TO WALL THICKNESS

All of the foregoing results for cycles to completion of a through-wall crack have been obtained using Simpson's Rule to approximate the integral. To ensure that the degree of approximation is adequate, the number of steps was repeatedly doubled until the relative change became less than 10^{-4} . Additionally, for the Eighth Quarterly form it was possible to integrate directly the special case of only σ_{PM} operating, $\sigma_{SM} = \sigma_{PB} = \sigma_{SB} = 0$; agreement to the numerical solution was exact within 10^{-5} relative. Only the numerical solution is available for the present form, however.

3.5 SENSITIVITY TESTING OF EQUATION (1)

Figure 3-6 shows graphically the variation that can be expected in cycles to completion as the (a) design variables and (b) uncertainty coefficients vary over their expected ranges.

Runs 1 is the reference run, using values given on Figure 3-6.

Runs 2—12 consider changes in the design variables.

Runs 2—5 show effects from material parameters A and B as they take on values in pairs over the ranges of values illustrated in Figure 3-7 for different materials and temperatures, as indicated by the Task D-1 and D-2 testing. Cycles to completion increase with increasing slope, B, when the line pivots at approximately the mean ΔK of the data range, because proportionately more cycles are consumed in the early, low ΔK , slow crack growth rate region, than in the high ΔK rapid crack growth rate region. Cycles to completion decrease with higher intercept $\log A$, because higher crack growth rates apply for all ΔK values.

Runs 6—8 show effects from selected combinations of t and d , where the constant values of a_0/tt^* and P used imply changes

also in a_0 and σ_{PM} as shown in parentheses. Changes in cycles to completion are due mainly to the resulting changes in a_0 and σ_{PM} , rather than t or d directly. Runs 6A—8A show the small effects from the same combinations of t and d for a_0 and σ_{PM} held constant.

Runs 10—12 show that as each stress is decreased, cycles to completion increase.

Runs 13—35 consider changes in the uncertainty coefficients.

Runs 13—20 reflect the estimated uncertainty ranges of A^* (with any variability in B^* assigned to A^*), t^* (with a_0 but not σ_{PM} held constant), ΔP^* , and P^*d^* . Any resulting changes in other variables are shown in parentheses. Changes in cycles to completion are nominal and as expected. Runs 15A and 16A show the small changes due to t^* with a_0 and σ_{PM} held constant.

Runs 22—23 show the effect on cycles to completion of changes in a_0/tt^* , reflecting the pattern of Figure 3-5, which shows that large values of a_0 will have great influence on cycles to completion, mainly independent of t . Runs 30—35 and 30A—35A show that the effect of constant remaining ligaments of 0.1 and 0.3 inch is largest when the wall thickness is large, so that a_0 is large.

Runs 24—29 show the effect of uncertainties on stress. Large unfavorable uncertainty in the secondary stresses materially reduce cycles to completion, even with the plastic stress correction.

This sensitivity analysis shows that for Equation (1), reductions in cycles to completion exceeding a factor of 10 or to below 10,000 cycles can come from unusually deep initial defects, or from high stresses, but not from design values or the uncertainty which can be foreseen in other variables.

FIGURE 3-6. SENSITIVITY TESTS—LOW-CYCLE FATIGUE CRACK GROWTH EQUATION

FIGURE 3-7. A AND B RELATIONSHIPS

FIGURE 3-8. EXPERIMENTAL DATA: CRACK HALF LENGTH, a , VERSUS CYCLES, m . TASK D-1, RUN 30.

3.6 ESTIMATION OF MATERIAL PROPERTIES PARAMETERS "A" AND "B" FROM EXPERIMENTAL DATA

Parameters A and B of Equation (1) are to be estimated from experimental data, particularly from the crack growth rate studies of Task D-1 at Schenectady. These estimates, along with uncertainty in them arising from the variability of the experimental results, are needed to characterize crack growth rate properties of each material at room and elevated temperatures, and to obtain solutions of Equation (1) in order to form the distribution of n_t^* from Equation (1). The purpose of this immediate investigation is to compare several alternate methods for converting the experimental a versus n (crack half-length versus cycles) data to log da/dn versus log ΔK data, and proceeding to estimate A and B. The method should be chosen which is unbiased and which results in the least uncertainty in A and B, but properly reflects experimental variability. The principal methods considered involve (1) no data smoothing, and (2) complete data smoothing. Methods which involve intermediate degrees of data smoothing are discussed subsequently. It is concluded that no data smoothing should be performed. The experiments are load-controlled so $\Delta\sigma_g$ in ΔK remains constant for all methods. Run 30, the first test of specimens from the carbon steel (A-106B) prototype pipe used in Task D-3, was chosen for illustration. For this specimen, $\Delta K = \Delta\sigma_g \sqrt{W \tan \frac{\pi a}{W}}$, where ΔK is the stress intensity factor, $\Delta\sigma_g$ is gross stress range, W is plate width, and a is crack half-length. Experimental data are displayed on Figure 3-8.

Method 1, no data smoothing: Graphical differentiation. The da/dn is estimated by $\Delta a/\Delta n$ between each successive pair of experimental points, and matched with ΔK for the middle a value. This method leads to the greatest possible scatter of log da/dn versus log ΔK points, but preserves experimental variability for point and confidence interval estimates of A and B by linear least square fitting, after showing that the points imply a curve not significantly different from a straight line. The results are plotted on Figure 3-9.

Method 2, complete data smoothing: Curve fitting. One or more functions are found which adequately fit all or portions of the experimental a versus n data. These are differentiated at selected values of a—such as at the experimental values—and matched to corresponding ΔK values. Satisfactory fits to only portions of the data are required. Log da/dn versus log ΔK values will form smooth, but not necessarily straight lines. Results of this method show that different models, which fit portions of the data with essentially equal exactness, have characteristically different log da/dn versus log ΔK curves. Thus, the resulting plot is highly sensitive to the model chosen. This method should be used only after this sensitivity has been judged acceptable for the purpose. Models fit to experimental data are illustrated on Figures 3-10a to 3-10c, and results on log da/dn versus log ΔK scales for Run 30 are shown on Figure 3-11. The models may be described as follows:

FIGURE 3-9. LOG da/dn VERSUS LOG ΔK BY GRAPHICAL DIFFERENTIATION BETWEEN SUCCESSIVE PAIRS OF EXPERIMENTAL POINTS. NO DATA SMOOTHING. TASK D-1, RUN 30.

- ① STRAIGHT LINE: $a = 0.475 + 0.0526 m$
- ② STRAIGHT LINE: $a = 0.183 + 0.0940 m$
- ③ STRAIGHT LINE: $a = 0.837 + 0.198 m$
- ④ STRAIGHT LINE: $a = 4.23 + 0.476 m$

FIGURE 3-10. EXPERIMENTAL DATA FIT BY STRAIGHT LINES, TASK D-1, RUN 30

⑤ PARABOLA, FOCUS LEFT
 $m = -14.8 + 36.6a - 13.1a^2$

⑥ PARABOLA, FOCUS UP
 $a = 3.41 - 0.614m + 0.0385m^2$

FIGURE 3-10b. EXPERIMENTAL DATA FIT BY PARABOLAS, TASK D-1, RUN 30

⑦ HYPERBOLA: $1/a = 1.95 - 0.110 m$

⑧ 6th DEGREE POLYNOMIAL: $a = 0.525 - 0.047m + 0.066m^2 - 0.020m^3 + 0.00280m^4 - 0.000193m^5 + 0.00000516m^6$

FIGURE 3-10c. EXPERIMENTAL DATA FIT BY HYPERBOLA AND HIGH DEGREE POLYNOMIAL, TASK D-1, RUN 30

FIGURE 3-11. LOG da/dn VERSUS LOG ΔK BY DIFFERENTIATION OF MODELS FITTED TO EXPERIMENTAL DATA. COMPLETE DATA SMOOTHING. TASK D-1, RUN 30.

Model	Figure 3-10 Curve Nos.	Figure 3-11 Appearance on Log da/dn versus Log ΔK
Straight line $a = C_1 + C_2 n$	1-4	Horizontal line.
Horizontal parabola, focus left $n = C_3 + C_4 n + C_5 n^2$	5	J shape.
Vertical parabola, focus upwards $a = C_6 + C_7 n + C_8 n^2$	6	Inverted and reversed J shape.
Hyperbola $1/a = C_9 + C_{10} n$	7	Straight line with slope 4.0. This important relationship arises from the derivation in subsection 3.7, which is for the $\Delta K = \Delta \sigma_g \sqrt{\pi a}$ formulation for infinite plate with center through-slot. This formulation is a good approximation for the finite plate up to $a/W = 0.25$, i.e., crack half-length extending 1/4 of plate width. Slight bend of line at upper right reflects tan finite plate correction to ΔK.
Polynomial, degree 3 and higher	8	Oscillating shape.

Methods providing intermediate degrees of data smoothing include the following:

1. Fit points with French curve, graphically measure selected Δa and Δn increments on curve. Log da/dn versus log ΔK points appearing in Tasks D-1 and D-2 of the quarterly reports were obtained this way.
2. Find slopes of lines between adjacent pairs of experimental points; assign to the ΔK value for each point the average slope of the two lines passing through the point.
3. Find midpoints of lines joining, for example, points 1 and 2, and 2 and 3. Assign the slope of a line joining the midpoints to point 2.

Each of these methods reduces the scatter of log da/dn versus log ΔK points without introducing bias. But for most runs there are adequate data points for making point estimates of A and B by method 1, and no other method

accurately makes experimental variability available for confidence interval estimates of the parameters. Thus method 1 is being followed.

3.7 DERIVATION OF LOG da/dn versus LOG ΔK LINE OF SLOPE 4 FOR HYPERBOLA FIT TO LOAD-CONTROLLED CRACK GROWTH DATA FROM INFINITE PLATE WITH CENTER SLOT

This derivation is referred to under the hyperbola model of subsection 3.6.

Hyperbola model chosen:

$$\frac{1}{a} = C_9 + C_{10} n;$$

Differentiating,

$$\frac{da}{dn} = \frac{-C_{10}}{(C_9 + C_{10} n)^2} = -C_{10} a^2.$$

(C₁₀ will be negative.)

For plate of infinite width and center slot,

$$\Delta K = \Delta \sigma_g \sqrt{\pi a} \quad \text{so}$$

$$a^2 = \frac{\Delta K^4}{\Delta \sigma_g^4 \pi}$$

Substituting, $\frac{da}{dn} = \frac{-C_{10} \Delta K^4}{\Delta \sigma_g^4 \pi}$

Taking logs,

$$\log \frac{da}{dn} = \log (-C_{10}) + 4 \log \Delta K - 4 \log \Delta \sigma_g - \log \pi.$$

Thus, on scales $y = \log da/dn$ and

$$x = \log \Delta K, \text{ for which}$$

straight line is $y = C_{11} + C_{12}x$,

$$C_{11} = \log (-C_{10}) - 4 \log \Delta \sigma_g - \log \pi$$

$$C_{12} = 4.$$

Thus, (1) the $\log da/dn$ versus $\log \Delta K$ line will always have slope 4 for the conditions stated, and (2) the intercept will shift depending on C_{10} in the hyperbolic model, and on $\Delta \sigma_g$.

SECTION IV

TASK B—STRESS ANALYSIS

4.1 OBJECTIVE

The purpose of the stress analysis task is to develop a method for the stress and strain analysis of those piping components which have been intractable problems. The designer must be able to determine the detailed stress and strain distributions in complex piping geometry under complex loadings for avoidance of leaks and severance in piping and to take into account low-cycle fatigue, corrosion, and critically sized flaws.

4.2 TASK B-1—COMPUTER PROGRAM DEVELOPMENT (E. L. North*)

The primary objective of the computer code development, Task B-1, is to develop the analytical tools required to define the state of stress and strain which will exist in complex piping geometries in service. At present, through use of the PAPA computer code, a

designer can analyze complex piping geometries, i. e., tees, wyes, and laterals for stresses in the elastic range of material behavior. When all portions of the computer code have been developed and checked out, a designer will be able to investigate monotonic or cyclic load behavior for an elastic-linear plastic, or elastic-perfectly plastic material.

4.3 COMPUTER CODE DEVELOPMENT—PAPA

During the eleventh quarter, the computer program, PAPA, has been used to analyze a cylinder-to-cylinder intersection having a diameter of branch to diameter of main pipe equal to 1. This was one of the primary objectives, or final checks for the PAPA computer code. Other analyses using this computer code will now be undertaken to reaffirm the results or to do a parametric study of cylinder-to-cylinder intersections to arrive at a series of design curves.

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4.4 STRESS ANALYSIS OF CYLINDER-TO-CYLINDER INTERSECTION ($D_1/d_1 = 1$)

Analysis of a structural configuration of the magnitude and complexity of a cylinder-to-cylinder intersection, where the D_1/d_1 ratio equals 1, by necessity should be compared to

experimental findings of Taylor and Lind.⁽¹⁾ Such a comparison of analytical-experimental data has been made of a photoelastic model shown in Reference (1). The physical geometry of the structure is shown in Figure 4-1. Appropriate dimensions are as noted.

FIGURE 4-1. PHYSICAL GEOMETRY OF PHOTOELASTIC MODEL

The one restrictive characteristic of using the photoelastic model is the cylinders have a r/t ratio equal to 6 for the branch and lateral portions of the tee. This r/t ratio would imply that the bending stress would not be linear through the thickness of the shells. The analysis was undertaken recognizing that there might be complexities arising from this source.

4.5 DISCUSSION OF RESULTS

The results of the photoelastic and analytic studies are shown in Figures 4-2, 4-3, 4-4, and 4-5. Peak stresses as calculated using the PAPA computer code show good agreement with the photoelastic model. Stress trends away from the point of stress amplifications also show the desired comparisons. Points

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FIGURE 4-2. NORMAL STRESSES ALONG LATERAL-BRANCH CUT AS SHOWN IN FIGURE 4-1

FIGURE 4-3. TANGENTIAL (t) STRESS ALONG LATERAL—BRANCH CUT AS SHOWN IN FIGURE 4-1

FIGURE 4-4. NORMAL STRESSES ALONG LATERAL—BRANCH CUT SHOWN IN FIGURE 4-1

FIGURE 4-5. TANGENTIAL (t) STRESSES ALONG LATERAL—BRANCH BOUNDARY AS SHOWN IN FIGURE 4-1

of deviation are not explainable at this time and investigation of the analytical model is now in progress.

The greatest deviation of stresses occurs in the σ_t directions (note Figures 4-3 and 4-5). No reasonable explanation exists for such a large compressive stress at the inside intersection of the branch and lateral. Figure 4-3 shows a compressive stress calculated analytically of -1.2 at the inside of the intersection. The experimental findings show this stress to equal 0.

Although the σ_t stresses show the differences noted, the desired trends overall are present, and minor differences are attributed to the effects of the r/t ratio.

The point marked with an "*" in Figure 4-2 is the calculated point. The discrepancy here was attributed to the using of a triangular element having an aspect ratio greater than 3 to 1. This is a known problem in using the plate elements and can be alleviated through proper modeling.

On the analytical-experimental comparisons a basic problem exists in drawing the two curves on the same plot. No reference points to align the stress distribution were given in the experimental work. This was approximated from the figures shown in Reference (1). Some shift in the spread of the curves could be made to probably show better agreement; however, it was felt that this shift was not necessary.

4.6 CONCLUSIONS

From the results obtained in the analytical work, it can be concluded that use of the PAPA program will show stress amplifications as desired at intersections of cylinders. Further work on evaluating the results will be made to aid in future refinements of the modeling techniques needed in complex analysis.

Of significance is the operational merging of the PAPA program with the input generated by the TEE preprocessor (developed at San Jose) by running a test case on the computer.

4.7 TASK B-2—PROBLEM SOLUTIONS (J. D. Gilman)

4.7.1 Objectives

This subtask has as its primary objective the application of the PAPA computer code to representative piping components with various loading conditions, as a means of demonstrating the accuracy of computer solutions for complex shell structures. This task also provides input data and establishes stress analysis methods for the piping system reliability study.

4.7.2 Stress Analysis of Piping Components

The effort necessary to achieve a reliable computer tool for the stress analysis of complex piping components may be summarized in four phases as follows:

- a. The basic development of the plate and panel elements and equation solving techniques for the PAPA code. This phase has been completed under subtask B-1.
- b. The development of preprocessor codes which prepare input data for the PAPA code, for specific piping components. This work was reported in detail in the Tenth Quarterly Report, GEAP-5554.
- c. A debug and improvement phase, in which a large test case is generated by the preprocessor, run using PAPA, and the results compared to experimental stress analysis data. The initial problem on this scale conducted at Evendale, using input data provided by San Jose is reported above in subsection 4.2. Errors in both the preprocessor code and the stress analysis code were discovered and corrected.

- d. When the results have been analyzed on the initial large test case and it appears that the PAPA code is working properly, a series of test cases will be run under subtask B-2 to determine the accuracy of the method in various applications to piping components. Any discrepancies encountered in this phase will be examined to determine whether they are:

1. Programming errors which can be corrected,
2. Inaccuracies which can be reduced by improved modeling techniques, or
3. A result of limitations inherent in the finite element method or the thin-shell theory on which it is based.

Errors attributed to (3) above represent a valid criterion of the merit of the stress analysis tool.

4.7.3 Stress Analyses for Reliability Study

Support to the reliability task from subtask B-2 includes the detailed stress analysis of a complete reactor primary piping system, and the development of general methods by which crack initiation and crack propagation in piping components can be predicted using results from the stress analysis. Progress to date includes:

- a. Analysis of the complete piping system to obtain nominal loads and stresses in each component, for several conditions or sources of loading.
- b. Development of a general method for the analysis of the growth of a surface crack through the wall of a piping component.
- c. Calculation of an approximate expression by which the circumferential growth rate of a through-wall crack can be predicted.

The following section pertains to the application of the crack growth analysis noted in (b) above.

4.7.4 Application of Crack Growth Equation in the Plastic Region

In the Sixth Quarterly Report (GEAP-5279, subsection 4.3.1) a mathematical model for crack growth was proposed, based on the crack growth law,

$$\frac{da}{dN} = A(\Delta K)^B, \quad (2)$$

where

da/dN = crack growth rate, per cycle,
 ΔK = cyclic variation of stress intensity,

A and B are experimentally determined material constants.

The variation of stress intensity factor ΔK was subsequently defined in terms of four categories of cyclic stress range:

- σ_{pb} (primary bending)
- σ_{sb} (secondary bending)
- σ_{pm} (primary membrane)
- σ_{sm} (secondary membrane)

The crack growth law, Equation (2), is generally applicable, to some degree of approximation, beyond the range of elastic material behavior, but some relationship must be established between the four stress categories to account for the strain-controlled nature of secondary stresses. This is necessary when a consideration of uncertainties in stress magnitudes results in an otherwise

arbitrary assignment of values to the above four categories. A suitable relationship is proposed here.

4.7.5 Cyclic Stress-Strain Relation

For cyclic crack growth studies, it is appropriate to relate cyclic stress range ($\Delta\sigma$) and cyclic strain range ($\Delta\epsilon$) using data presented in the Third Quarterly Report, GEAP-5082 (Tables 6-1, 6-2, and 6-3). A suitable functional form is

$$\Delta\epsilon = \frac{\Delta\sigma}{E} + D (\Delta\sigma - 3S_m)^d \quad (3)$$

where

E = elastic modulus,

D and d are determined to fit the data,

S_m = allowable design stress by ASME Section III.

To be consistent with design practice, the "shakedown" elastic stress range is taken as $3S_m$. This is reasonably consistent with the test data.

The cyclic stress-strain hysteresis loop appears schematically as in Figure 4-6. The relationship, Equation (3), between $\Delta\sigma$ and $\Delta\epsilon$ is a curve such as Figure 4-7. Numerical values of the material constants are as follows:

Material	D	d	S_m (70°F)	S_m (550°F)
Carbon Steel A-108B	0.945×10^{-10}	1.78	20,000	18,100
Type-304 Stainless Steel	0.348×10^{-6}	1.00	20,000	16,000
Alloy 2 $\frac{1}{4}$ Cr.-1 Mo	0.119×10^{-12}	2.36	20,000	16,850

4.7.6 Stress Modifications for the Plastic Region

The four stress categories σ_{pm} , σ_{pb} , σ_{sm} , and σ_{sb} are nominal stress ranges at a particular location. Each has an associated uncertainty factor σ_{pm}^* , σ_{pb}^* , etc. The sum of nominal stresses will normally be $3S_m$ or less (for a "shakedown" design criterion) but combinations of assigned uncertainties may lead to calculated stresses in excess of $3S_m$. This stress should be reduced to account for yielding. The effect of yielding is to reduce the upper bound of uncertainty on secondary stresses. The primary stresses are not reduced because they are load controlled rather than strain controlled. The sum of primary stresses is normally less than S_m , and can never be much greater than $1.5 S_m$ in a stable structure.

Assume that the stresses and stress uncertainties have values such that

$$\sigma_{pm} \sigma_{pm}^* + \sigma_{pb} \sigma_{pb}^* + \sigma_{sm} \sigma_{sm}^* + \sigma_{sb} \sigma_{sb}^* = c (3S_m)$$

where $c > 1$.

A factor k can be found such that

$$\sigma_{pm} \sigma_{pm}^* + \sigma_{pb} \sigma_{pb}^* + k (\sigma_{sm} \sigma_{sm}^* + \sigma_{sb} \sigma_{sb}^*) = c' (3S_m)$$

The product $c(3S_m)$ is the elastic calculated stress range, and $c'(3S_m)$ is the actual stress range as shown on Figure 4-7.

FIGURE 4-6. CYCLIC STRESS-STRAIN HYSTERESIS LOOP

FIGURE 4-7. CYCLIC STRESS-STRAIN RELATION

FIGURE 4-7a. MEASUREMENT POINT LOCATIONS FOR "UNCRAKED" TEE (SIII-2)

The factor c' is given implicitly by the equation

$$c' = c - DE (3S_m)^{d-1} (C' - 1)^d \quad (4)$$

The factor k is readily obtained by Equation (4). The assumptions that one k applies to both σ_{sm}^* and σ_{sb}^* , and that k is not a function of crack length, are simplifications of the actual situation which is too complex to analyze readily in the general case.

4.7.7 Circumferential Growth of a Through-Wall Crack

The stress analysis of the circumferential crack is currently in preparation for publication as a topical report (GEAP-5557). A satisfactory approximation to the stress intensity factor for the circumferential crack is

$$K = \sigma \sqrt{\pi a} \left(1 + 0.14 \frac{a^2}{Rt} \right) \quad (5)$$

where R is the mean pipe radius, t is the wall thickness, a is half of the crack length, and σ is the nominal axial stress in the pipe. In terms of internal pressure, P , and bending moment, M ,

$$\sigma = \frac{PR}{2t} + \frac{M}{\pi R^2 t} \quad (6)$$

One of the models needed in the reliability study is the number of load cycles required to grow a crack a given distance around the circumference. From the crack growth law [Equation (2)].

$$dN = \frac{da}{A(\Delta K)^B} \quad (7)$$

Integration of this equation with K as in Equation (4) above, gives the number of cycles

(N) required to grow a crack from initial length $2a$ to a final length $2a_F$.

$$N = \frac{1}{A (\sigma \sqrt{\pi})^B} \int_{a_0}^{a_F} \frac{da}{\left[\sqrt{a} \left(1 + 0.14 \frac{a^2}{Rt} \right) \right]^B} \quad (8)$$

The accuracy and the limits of application of this crack propagation equation will be uncertain until some experience is acquired in its use. Data is available from the prototype pipe fatigue tests which will provide a check on Equation (8).

4.8 RELIABILITY TASK

4.8.1 Estimate of the Probability of a Pipe Break

An analysis was undertaken to estimate, on the basis of information presently available from the Pipe Study and other sources, the probability of a line break occurring in a reactor piping system as a result of progressive crack growth. In contrast to the detailed analysis of a reactor piping system, which is in progress under the Reliability Task, this was a simplified approach in which many of the important factors could not be properly incorporated. Reasonable assumptions were made to arrive at numerical results, following this general approach (see Appendix A for a detailed discussion).

- a. The rate of occurrence of leaking cracks in piping was estimated from reactor operating experience, in terms of leaks per component year.
- b. A normal probability density function representing expected values of fracture toughness in the piping system was developed from fracture test data.
- c. The relationship between leak rate from a through-wall crack and the crack-tip

stress intensity factor was calculated using approximate methods.

- d. Results of the two preceding steps were combined to obtain the probability of a line break (crack instability) for a crack having a given leak rate.
- e. For a particular reactor piping system, the leak detection capability is approximately known, and so the largest leak which might escape detection can be estimated. The probability of a line break in the system is then

<u>Leaks</u>	
Component-Year	<ul style="list-style-type: none"> × No. of components × Design life × Probability of break for given leak rate.

Results of this study (see Appendix A, Figure A-3) demonstrates the importance of adequate leak detection capability in maintaining a high piping system reliability. A relatively higher risk of a steam line break, as compared to a water line break, is also indicated, as a result of the lower leak rate and hence more difficult detection of a steam line crack of a given length.

In addition to the limitations imposed by the simplifying assumptions noted in the analysis, there are two possible fracture mechanisms which are not considered by the leak-before-break criteria. These are

- a. A crack which grows to critical size without leaking. Such a very long defect which grows uniformly through the pipe wall is very unlikely compared to the through-wall crack.
- b. A line break as a result of gross overloading in a single event, for example,

as a result of a very severe earthquake, water slug, or secondary effect of another accident.

In spite of the limitations and omissions of this brief study, it does offer an alternative to subjective opinions of piping system reliability, and gives some insight into the relative importance of some of the parameters in the detailed analysis.

4.9 SUBTASK B-3—EXPERIMENTAL STRESS ANALYSIS (E. Kiss and D. N. Patterson)

4.9.1 Three-Dimensional Photoelastic Analysis

Evaluation of the photoelastic data obtained from the many slices and subslices of the various plastic models has continued at the University of Illinois. Analysis of the data is taking longer than was originally estimated, primarily because of the unsymmetrical nature of the stress distributions. In addition to the extra model subslicing, numerical integration of the data is required to achieve the objective of the task which is to provide extremely accurate experimental stress measurements for comparison with the theoretical stress analysis obtained with the PAPA computer program.

4.9.2 Two-Dimensional Photoelastic Analysis

Testing of metal models, SIII-2, SIII-3, SII-1 and SIV-1 has been completed. A description of these models and type loading is shown in Table 3-1, page 30 of the Quarterly Progress Report No. 10 (GEAP-5554). All test work under this task is now complete. A topical report, summarizing the results of this subtask, is in preparation.

Specimen SIII-2, an "uncracked tee" has been loaded both mechanically by in-plane bending and with internal pressure. A photograph of the test setup is shown in Figure 4-5 of GEAP-5554. Table 4-1 shows typical measurements obtained for the principal stress difference indices at several points along the cylindrical intersection in the crotch region of the tee. In addition to the photoelastic measurements, strains have been measured at these several points using 60-degree strain gage rosettes. Figure 4-7a shows the points at which measurements have been made for the uncracked tee. Table 4-1 shows a comparison of the photoelastic and strain gage results for the individual loadings of internal pressure and bending and the combination of both.

Figure 4-8 is a schematic of a "cracked tee" mechanically loaded by in-plane bending. Load 1 indicates bending through the run, while load 3 shows bending applied through the branch. Specimens SIII-1 and -3 have been tested, respectively, as per the schematic. Figure 4-9 is a photograph of the test setup for SIII-1, and Figure 4-10 shows the resulting birefringence for the maximum applied load. The location of stress points and typical measured stress values have been previously reported in GEAP-5554, Figure 4-8 (pages 33 and 34).

Table 4-2 presents the resulting principal stress difference indices obtained in the vicinity of the crack for SIII-3. The stress point loca-

tions are identical to those for SIII-1. Table 4-3 shows a comparison between the optical and strain gage rosette measurements at point 4-B. Note the generally higher resulting stress index from loading the tee through the branch as compared to loading through the run.

Figure 4-11 is a photograph of specimen SII-1, a 6-inch Schedule-40 pressure loop containing two 90-degree short radius elbows. Before fabricating the loop, one of the elbows was permanently "ovalized" in a hydraulic press. An ovality equal to one pipe wall thickness was produced, i. e., $\epsilon/2R = 0.280/6.625 = 4.25\%$. The loop was pressurized internally to produce a nominal hoop stress of 13,600 psi.

Figure 4-12 shows the points at which optical strain measurements have been made, and Table 4-4 shows the resulting measurements. Figures 4-13 and 4-14 show the birefringence (isochromatic fringe patterns) on the side of the "good" and "oval" elbows, respectively, at full internal pressure loading. Figure 4-15 is a curve of the distribution of principal stress difference index as a function of distance (s/t) along a 45-degree arc line for the oval elbow. The dotted line shows the distribution for the nonoval elbow in the vicinity of point "2."

Specimen SIV-1, a cantilever specimen with a crack at the junction of the pipe flange weld has been completed. Table 4-5 shows the principal stress difference indices at several points in the vicinity of the crack tip. Point locations are identical to those shown in Figure 4-6 (page 31) of GEAP-5554.

$R_{min} = 0.125$ in.

$R_{int} = 0.250$ in.

$R_{max} = 0.5$ in.

FIGURE 4-8. CRACKED TEE SPECIMEN LOADED 'IN PLANE BENDING'

FIGURE 4-9. SIII-1 TEST SET-UP

FIGURE 4-10. SIII-1 PLASTIC AT 1250 $\mu\text{in./in.}$ STRAIN
BENDING (MAGNITUDE)

FIGURE 4-11. PRESSURE LOOP SPECIMEN (S II-1)

FIGURE 4-12. PRESSURE LOOP SPECIMEN (S II-1)

FIGURE 4-13. BIREFRINGENCE ON THE SIDE OF THE "GOOD" ELBOW

FIGURE 4-14. BIREFRINGENCE ON THE SIDE OF THE "OVAL" ELBOW

FIGURE 4-15. PRINCIPAL STRESS DIFFERENCE INDICES CIRCUMFERENTIAL VARIATION ALONG 45° ARC — FOR OVAL ELBOW

TABLE 4-1

PRINCIPAL STRESS DIFFERENCE INDICES
FOR "UNCRACKED TEE" (SIII-2)

Point	Pressure		Bending		Pressure and Bending	
	Optical	Gage	Optical	Gage	Optical	Gage
6	+0.91	+0.87	+1.85	+1.39	+0.38	+0.39
2	+0.93	+0.92	+1.11	+1.15	+0.081	+0.177
12	-----	0.505	+0.66	+0.47	0.217	+0.21

TABLE 4-2

PRINCIPAL STRESS DIFFERENCE INDICES
FOR "CRACKED TEE" (SIII-3)

Point	$(\sigma_1 - \sigma_2)/\sigma_0$
2-B	4.11
3-B	3.58
4-B	2.32
4-C	2.97
5-B	3.55

TABLE 4-3

COMPARISON STRAIN ROSETTE MEASUREMENTS

Point 4-B	$(\sigma_1 - \sigma_2)/\sigma_0$	σ_1/σ_0	σ_2/σ_0
Photoelastic	2.32	4.90	2.57
Gage	2.03	4.81	2.77

TABLE 4-4

ELBOW LOOP STRESS INDICES

Point	Good Elbow			Oval Elbow		
	$(\sigma_\phi - \sigma_x)/\sigma_0$	σ_ϕ/σ_0	σ_x/σ_0	$(\sigma_\phi - \sigma_x)/\sigma_0$	σ_ϕ/σ_0	σ_x/σ_0
1	0.81	1.03	0.22	0.29	0.94	0.65
2	0.33	0.44	0.11	1.39	1.94	0.55
3	0.49	0.64	0.15	0.05	0.72	0.67

$$\sigma_0 = \frac{\Delta p a}{t}$$

TABLE 4-5

FLANGE SPECIMEN (SIV-1)
PRINCIPAL STRESS DIFFERENCE INDICES

Point	$[(\sigma_1 - \sigma_2)/\sigma_0]$
1	----
2	4.06
3	4.43
4	3.97
5	3.14
6	2.42
7	1.51
8	3.21
9	1.24
10	2.48
11	1.37

SECTION V

TASK C—FRACTURE MECHANICS

(M. B. Reynolds)

5.1 OBJECTIVE

The Task objective is development of a means of predicting the failure load for flawed pipes in terms of the flaw dimensions and material properties. Flaw geometries studied include part-through and through-wall cracks in both the axial and circumferential direction. The applied load has in all cases to date been limited to hydrostatic pressure.

5.2 BEHAVIOR OF PIPES CONTAINING AXIAL THROUGH-WALL FLAWS

In the Tenth Quarterly Report (GEAP-5554) the results of burst tests on a limited number of 6-inch pipes of ASTM A-106B steel containing axial through-wall flaws were presented. Of these specimens, two were of Schedule 40 wall thickness; the balance were Schedule 80. Critical stress intensity factors were computed from these data using both (1) a BMI formula based on an elastic analysis of the effect of curvature, and (2) a modification of the BMI formula. It was found that while K_c values calculated from the BMI relation decreased with decreasing crack length, the modified relation*

$$K_c^2 = \frac{\pi \sigma_h^2 c}{\cos \theta} \left(1 + 0.5 \frac{c^2}{Rt} \right) \quad (9)$$

* σ_h = burst hoop stress
 c = flaw half length
 R = mean radius of pipe
 t = wall thickness
 θ = $\pi/2$ [ratio of strength of flawed to unflawed pipe]

gave K_c values which varied little with crack length. During the period covered by this report, eight additional specimens were tested, including three specimens of 8-inch Schedule 40 pipe and two specimens of 4-inch Schedule 40 pipe. The results of all tests are shown in Figure 5-1 in which burst pressure is plotted against flaw length. If the single point corresponding to the 30°F test is neglected and a curve is drawn through the data points for the 6-inch Schedule 80 pipe, the remaining data points lie consistently above or below the curve depending on whether the pipe diameter is less than or greater than that for the 6-inch Schedule 80 pipe. These differences are considerably greater than the relatively small variations in yield strength among the four pipe sizes. In Figure 5-2 burst pressure is plotted against the ratio of machined crack half length to pipe mean radius. The scatter of the data points is somewhat reduced in this case.

In Figure 5-3 is plotted the critical stress intensity factor calculated both from the unmodified BMI relation and Equation (9). The variation with pipe diameter is seen in each case to remain even at small crack lengths. The fact that the expression in parentheses in Equation (9) introduces little correction for pipe diameter or wall thickness at small crack lengths suggests that a relation of this form will not correctly predict burst strength over a wide enough range of pipe sizes and wall thicknesses to be useful.

To resolve this question and make sure that the data scatter is not due to variation in material properties, toughnesses of

FIGURE 5-1. BURST STRENGTH OF ASTM A-106B PIPES CONTAINING AXIAL THROUGH-WALL FLAWS AS A FUNCTION OF CRACK HALF LENGTH

FIGURE 5-2. BURST STRENGTH VERSUS c/R , ASTM A-106B PIPES WITH AXIAL THROUGH-WALL FLAWS

FIGURE 5-3. CALCULATED K_I FOR ASTM A-106B PIPES WITH AXIAL THROUGH-WALL FLAWS

the different sizes of pipe are being measured using nitrided and as-received impact specimens. To date W/A values for the 6-inch Schedule 80 material have been determined from nitrided impact specimens.

These specimens had a notch root radius of approximately 0.003 inch and were oriented to give crack propagation in the same direction as in the burst specimens. Since no shear lips were observed on the broken specimens, K_c values were estimated using the equation relating G , K , and the elastic constant of the material. The following values were obtained:

Test Temperature, °F	K_c , ksi $\sqrt{\text{in.}}$
60.5	59.7
35	50.9
145	208

These values at 35° and 60.5°F are lower than those calculated from the burst tests. However, flat fractures were obtained in the impact tests while those in the burst tests were typically of the 45-degree type. When more complete data on nitrided and unnitrided impact toughness of the materials from the different sizes of pipe are available,

an estimate of the effect of size-to-size material property variation on burst behavior will be made, after which Equation (9) will be modified to obtain better agreement with experimental data.

5.3 BEHAVIOR OF PIPES CONTAINING LONG PART-THROUGH FLAWS

During the reporting period, one specimen of ASTM A-106B steel pipe in 8-inch Schedule 40 size containing a full length axial flaw one-third through the wall was tested at 60°F. This pipe failed at a hoop stress equal to 96% of the uniaxial yield stress, compared to 91% predicted by the plastic instability hypothesis first reported in the Tenth Quarterly. Briefly, this related the hoop stress to the estimated effective (octahedral shear) stress in the ligament remaining at the base of the flaw. The hypothesis assumes that the load maximum coincides with onset of plastic instability in the ligament; i. e., when the effective stress equals the plastic instability stress for the material. For low carbon steels such as A-106B, this is assumed to be equal to the tensile yield stress.

SECTION VI

TASK D—FATIGUE

6.1 OBJECTIVE

The objectives of the fatigue task are (a) to extend the understanding of low-cycle fatigue cracking in high pressure piping components which have mechanical or defect flaws and (b) to apply this knowledge in developing rational design bases for prevention or control of fatigue crack initiation and growth in reactor piping systems.

6.2 TASK D-1—FATIGUE CRACK GROWTH STUDIES (A. J. Brothers)

6.2.1 Summary

The experimental portions of the work consisting of the measurement of crack growth rates in $2\frac{1}{4}$ Cr - 1 Mo Schedule 160 prototype pipe test material at room temperature have continued (see specimen D, Figure 6-4). The results of these tests are similar to those observed for the A-106B carbon steel and Type 304 steels tested earlier, i. e., the crack growth rates are systematically higher than those for plate material. However, a summary comparison of the results of these tests indicates the same relative ranking of materials observed in plate tests of these alloys.

6.2.2 Crack Growth in $2\frac{1}{4}$ Cr - 1 Mo Pipe at Room Temperature

Crack growth tests of $2\frac{1}{4}$ Cr - 1 Mo Schedule 160 prototype pipe test material under zero-to-tension loading have been performed at room temperature. These crack growth curves are shown in Figure 6-1. The two curves at each stress level represents results from both sides of the parallel

semipipe specimens. In all cases, the da/dN versus ΔK relationship is derived from the crack growth curve exhibiting the higher growth rate.

The correlation between crack growth rate and the range of stress intensity factor for this steel is shown in Figure 6-2. These results indicate excellent correlation and are generally similar to those observed in previous tests of A-106B carbon steel (Quarterly Report No. 9) and Type 304 (Quarterly Report No. 10) in that the crack growth rates for a given ΔK are systematically higher in the pipe specimens than for the centrally-slotted plate. A summary plot of all three materials is shown in Figure 6-3. The relative ranking of the three alloys is qualitatively similar to that observed for the plate specimens tested previously.

Tests of a second heat of A-106 Schedule 40 carbon steel pipe are planned; these specimens are in preparation.

6.3 TASK D-2—CRACK INITIATION STUDIES (E. Krempf)

Testing of grooved cylinders of the three grades of steel under completely reversed, load-controlled conditions at 550°F was completed. The temperature of maximum strain aging for carbon steel as evidenced by the ductility minimum was determined. Progress was made in machining notched bend bars scheduled for testing in the first quarter of 1968.

FIGURE 6-1. CRACK GROWTH CURVES FOR 2-1/4 Cr-1 Mo PIPE SPECIMENS

FIGURE 6-2. CRACK GROWTH CORRELATION FOR 2-1/4 Cr-1 Mo PIPE AT ROOM TEMPERATURE

FIGURE 6-3. SUMMARY PLOT OF CORRELATIONS OF CRACK GROWTH RATE AND STRESS INTENSITY FACTOR FOR PIPE MATERIALS.

LEGEND:

CRACK GROWTH SUBTASKS

D-1A CRACK GROWTH RATE CORRELATION	A, C
D-1B CRACK GROWTH MEASUREMENT ON PROTOTYPE PIPE MATERIALS	D
D-1C CRACK GROWTH RATE UNDER REVERSED PLASTIC STRAINS	B
D-1D CRACK GROWTH IN BEND SPECIMENS	C
D-1E CRACK GROWTH RATE AT ELEVATED TEMPERATURES	B

CRACK INITIATION SUBTASKS

D-2B ROOM TEMPERATURE CYCLIC LOADING TESTS	F, G, H, I
D-2C ELEVATED TEMPERATURE CYCLIC LOADING TESTS	E, F, H, I

FIGURE 6-4. TEST SPECIMENS USED FOR TASKS D-1 AND D-2

6.3.1 550°F Tests of Grooved Cylinders under Completely Reversed, Load-Controlled Condition

Grooved cylinder specimens identical to those shown in Figure 6-4 of Quarterly No. 10 were used. The specimen type is also shown schematically as "F" in Figure 6-4. The theoretical, uniaxial stress concentration factor, K_t , was determined to be 3.3. The tensile properties of the three materials tested (carbon steel, $2\frac{1}{4}$ Cr-1 Mo steel, Type 304 stainless steel) at room temperature and at 550°F are listed in Tables 6-1 and 6-2 of the Ninth Quarterly Report.

Test conditions (frequency 6 cpm) were identical to those described in Quarterly No. 10 except that the temperature was raised to 550°F. To inspect for cracks the furnace was removed at suitable intervals and the specimen cooled to room temperature. Dye penetrant techniques were then used to detect the incipient cracks. The number of cycles at which a 0.005- to 0.015-inch-long crack could be observed, was defined as cycles-to-crack initiation. The crosshead movement of the testing machine was recorded periodically to see whether ratcheting occurred as the crack was growing.

6.3.1.1 Fatigue Characteristics of Grooved-Cylinder Specimens at 550°F

Figures 6-5 through 6-7 plot the nominal stress range versus the number of cycles-to-crack initiation and to failure at a test temperature of 550°F. It was not always possible to stop cycling at the point of initiation, therefore, a range of cycles is given for some specimens. At the first X no crack was visible; at the second X a crack longer than specified was detected. Crack initiation had therefore taken place somewhere between the two.

Figures 6-5 through 6-7 indicate that the increased temperature has the greatest effect on the fatigue life of Type 304 stainless steel. Very little effect of temperature on cycles-to-crack initiation and failure for carbon steel and $2\frac{1}{4}$ Cr-1 Mo alloy steel can be found. The results are therefore consistent with the tests on the flat plates (Quarterly No. 8) and the tensile properties reported in Quarterly No. 9.

The fracture areas of all the specimens tested at 550°F are shown in Figures 6-8 through 6-11. The areas of fatigue crack propagation and the final fracture can be easily distinguished. The ratio

$$R = \frac{\text{Final tensile fracture area}}{\text{Net section area}} \text{ was determined in the same way as described in the Tenth Quarterly. Table 6-1 gives details on the R-ratio and the maximum true stress at fracture. As expected, the true stress at fracture for carbon and } 2\frac{1}{4} \text{ Cr-1 Mo specimens is higher at 550°F than at room temperature.}$$

The true stress at fracture for Type 304 stainless steel is significantly lower at 550°F than at room temperature. This is apparent by comparison of Table 6-1 and Table 6-2 in the Tenth Quarterly.

6.3.2 Strain Aging and Holdtime Effects in Low-Cycle Fatigue

To determine the temperature of maximum strain aging, tensile tests were run with carbon steel. (Room temperature and 550°F tensile properties of the carbon steel are given in the Second and Ninth Quarterlies.) Two crosshead speeds, 0.5 in./min and 0.005 in./min, were used to determine the tensile properties as a function of temperature from room temperature to 530°F. A minimum of the ductility for both crosshead speeds was found at 400°F.

FIGURE 6-5. CYCLES FOR CRACK INITIATION AND FAILURE AT 550°F AND ROOM TEMPERATURE, GROOVED CYLINDER, $K_t \approx 3.3$, CARBON STEEL

FIGURE 6-6. CYCLES FOR CRACK INITIATION AND FAILURE AT 550°F AND ROOM TEMPERATURE, GROOVED CYLINDER, $K_t = 3.3$, 2-1/4 Cr-1 Mo ALLOY STEEL

FIGURE 6-7. CYCLES FOR CRACK INITIATION AND FAILURE AT 550°F AND ROOM TEMPERATURE, GROOVED CYLINDER, $K_t = 3.3$, TYPE 304 STAINLESS STEEL.

FIGURE 6-8. FRACTURE SURFACES OF GROOVED CYLINDER SPECIMENS TESTED AT 550°F. MATERIAL: CARBON STEEL.

FIGURE 6-9. FRACTURE SURFACES OF GROOVED CYLINDER SPECIMENS TESTED AT 550°F. MATERIAL: 2-¼ Cr-1 Mo ALLOY STEEL.

FIGURE 6-10. FRACTURE SURFACES OF GROOVED CYLINDER SPECIMENS TESTED AT 550°F. MATERIAL: TYPE 304 STAINLESS STEEL.

FIGURE 6-11. FRACTURE SURFACES OF GROOVED CYLINDER SPECIMENS TESTED AT 550°F. MATERIAL: TYPE 304 STAINLESS STEEL.

TABLE 6-1

TEST RESULTS, GROOVED CYLINDER SPECIMENS,
COMPLETELY REVERSED, LOAD CONTROLLED CONDITION
TEMPERATURE 550°F

Specimen No.	Nominal Stress Amplitude, σ_a ***	Cycles-to-Crack	Cycles-to-Failure	R*	σ_t^{**} 10 ³ psi
Material: Carbon Steel					
TCG-6A	35.00	600	15,391	0.43	81
TCG-10A	31.25	1572-1900	20,329	0.36	87
TCG-9A	27.50	1000-2500	30,182	0.32	86
Material: 2 $\frac{1}{4}$ Cr-1 Mo Alloy Steel					
TAG-10A	41.0	200	9,290	0.35	117
TAG-11A	35.0	600	15,391	0.30	116
TAG-9A	27.0	2000	63,520	0.23	117
Material: Type 304 Stainless Steel					
TSG-11A	35.0	100-300	719	0.50	70
TSG-10A	32.0	300-600	1,500	0.45	71
TSG-7A	32.0	-	1,950	0.41	78
TSG-8A	27.0	300-600	3,950	0.41	66
TSG-12A	24.0	200	19,487	0.33	73
TSG-9A	20.0	3500	89,676	0.22	91

$$* R = \frac{\text{Final tensile fracture area}}{\text{Net section area}}$$

$$** \sigma_t = \frac{\sigma_a}{R}, \text{ true stress at fracture}$$

$$*** \sigma_a = \frac{\text{Load amplitude}}{\text{Net section area}}$$

Low-cycle fatigue tests with holdtime will be run at this temperature. A life reducing holdtime effect should be most pronounced at the temperature of maximum strain aging.

6.4 TASK D-3—PROTOTYPE PIPE FATIGUE TESTING (E. Kiss, D. A. Hale)

6.4.1 Summary

Testing of three room temperature and one elevated temperature (550°F) straight pipe specimens was completed during the report period. Samples were cyclically loaded in bending and measurements of crack initiation, through-wall crack growth, and circumferential crack growth rates were obtained. Table

6-2 summarizes the significant test parameters. Parameters for CSS-15 are repeated for convenience of comparison.

6.4.2 Data Obtained

a. Crack Initiation

Cycles for crack initiation at the base of the premachined notch has been determined for all specimens tested. Crack initiation is detected visually using a 40× microscope (see Figure 6-12). The device is equipped with a micrometer drive which allows for accurate measurement of surface crack lengths while the crack extends during through wall crack growth.

TABLE 6-2

DATA SUMMARY

Sample Description	Test Temperature	Internal Pressure	Stress Range	Cantilever End Deflection	Cycles to Crack Initiation (N_I)	Cycles to Fully Penetrate Wall (N_w)	Test Terminated (N_ϕ)
CSS-15, ASTM A-312 TP-304 Schedule 40, Type I (External) Notch	57°F ↓ 85°F	1000 psig, Water and Rust Inhibitor	48,300 psi	±4.98 in. until cycle 24,655 +0/-4.98 in. after	4,500	24,630 (15,535)	75,796 (51,166)
CSS-16, ASTM A-312 TP 304, Schedule 40, Type II (Internal) Notch	55°F ↓ 85°F	1000 psig, Water and Rust Inhibitor	59,600 psi	±5.76 in. until cycle 8596, +0/-5.76 in. after	1,400	8,596 (7,196)	42,404 (33,908)
CSS-25, ASTM A-312 TP 304, Schedule 160, Type I (External) Notch	55°F ↓ 74°F	1000 psig, Water and Rust Inhibitor	70,460 psi	±7.33 in. until cycle 16,533 +0/-7.33 in. after	500	16,250 (11,383)	30,629 (14,379)
HCN-40-1 ASTM A-106 Gr B, Schedule 40, Type I (External) Notch	550°F	None	52,700 psi	±5.75 in. until cycle 28,005, +0/-5.76 in. after	13,250	26,000* (6,748)	137,008 (109,003)
CSS-29, ASTM A-335, P22 Schedule 40, Type I (External) Notch	46°F ↓ 72°F	1000 psig Water and Rust Inhibitor	52,100 psi	±5.00 in. until cycle 18,950, +0/-5.00 in. after	3,100	18,950 (8,850)	48,738 (29,788)

*This number of cycles actually corresponds to only 83% of full wall penetration.

NEGATIVE NO. 48512

FIGURE 6-12. SURFACE CRACK DETECTION AND MEASURING DEVICE, 40X OPTICS

Data for crack initiation for A-106B carbon steel, $2\frac{1}{4}$ Cr-1Mo steel and Type-304 stainless steel is shown in Figures 6-13, 6-14, and 6-15, respectively. The prototype pipe test results for all specimens tested to date are shown with respective test number, while the solid line denotes the most recent laboratory test results obtained at the M and P Laboratory under Task D-2. These results (Krempl) have been obtained for grooved cylinders under fully reversed loading (see GEAP-5554). As can be seen, cycles for crack initiation at the high stress range for the carbon and alloy steels is generally greater than for the laboratory specimens, whereas for the stainless steel piping the reverse is true.

b. Crack Growth

1. Through-Wall Growth

Following crack initiation, the fully reversed loading is continued and the crack grows through the pipe wall. Although electron microfractography is being employed as the principal means of accurately determining through-wall crack growth rates, a stress interruption technique is also used to provide macroscopic through-wall growth history. Figures 6-16 and 6-17 show the macroscopic crack front markings obtained using the stress interruption technique on specimens CSS-25 and CSS-10.

The determination of through-wall crack growth rate by means of electron microfractographic techniques has been successfully employed for three pipe specimens during this quarter. Specifically, through-wall crack measurements have been made for a $2\frac{1}{4}$ Cr-1 Mo alloy steel specimen (CSS-36) and two Type-304 stainless steel specimens (CSS-15 and -16). Figure 6-18

shows schematically typical results⁽²⁾ obtained for the through-wall crack growth rate as a function of the crack depth. It appears that crack growth changes during progress through the wall, revealing three significantly different growth modes, e. g.,

- (a) An initial, almost constant growth followed by,
- (b) A region of relatively slow, but increasing crack growth rate, followed by,
- (c) A sharp transition to an increased crack growth rate (by a factor of 10) at 75 to 85% of the wall.

In addition, U. Wolff,⁽²⁾ has shown that these regions can reasonably be approximated by straight lines, and that the crack growth rates (striation spacing) can be accurately determined.

Using these post-mortem experimental observations as a guide, an analysis was performed of the critical crack size, corresponding to the "point" of increased crack growth. The approach taken is one of applied fracture mechanics, that is, the stress intensity factor for a semielliptical notch as derived by Paris and Sih⁽³⁾ and corrected for localized yielding by an Irwin⁽³⁾ correction factor, has been used to compute the value of effective K_{IC} for the material tested. This equation is estimated to be valid within 10 to 20% for values of

FIGURE 6-13. CARBON STEEL, ROOM TEMPERATURE, STRESS RANGE VERSUS INITIATION CYCLES

FIGURE 6-14. 2.1/4 Cr - 1 Mo ALLOY STEEL, ROOM TEMPERATURE, STRESS RANGE VERSUS INITIATION CYCLES

FIGURE 6-15. TYPE 304 STAINLESS STEEL, ROOM TEMPERATURE, STRESS RANGE VERSUS INITIATION CYCLES

FIGURE 6-16. CSS-25, STRESS DEGRADATION MARKING FRONTS (3)

FIGURE 6-17. CS3-10, STRESS DEGRADATION MARKING FRONT

FIGURE 6-18. CRACK GROWTH RATE (da/dN) VERSUS CRACK DEPTH RATIO (a/t) FOR ALLOY SPECIMEN CSS-36, INTERNAL STARTER NOTCH

crack depth up to 80—85% of the full wall thickness. Figures 6-19(a), (b), and (c) show the Paris and Sih equation plotted as stress intensity ratio K/σ_0 versus (a/t) for the three schedule prototype pipes being tested. Table 6-3 presents the calculations of the effective $\bar{K}_C$ at the critical points (onset of rapid through-wall crack growth) for the fractographic specimens analyzed. It is interesting to note that the $\bar{K}_C$ values for both stainless steel specimens are almost identical. This approach will be checked and modified if necessary as more data becomes available. If it yields consistent results, one will be able to predict the critical crack size, or onset of rapid crack growth, for through-wall flaws in piping if the effective fracture toughness of the material is known.

At this time measurements of K_{IC} for the piping material are not known, since for these relatively low strength, high ductility materials, adequate size fracture toughness specimens cannot be machined from the actual thin walled piping used for fatigue testing.

Figure 6-20 shows a comparison of the crack growth rate versus range of stress intensity factor for through-wall growth for the Type-304 stainless steel prototype piping and the corresponding results obtained in the M and P Laboratory tests of tensile "prototype piping."

2. Circumferential Crack Growth

Circumferential crack growth measurements have been obtained

for all specimens tested. Crack length is visually monitored using equipment for macroscopic examination. The data, i.e., crack length versus fatigue cycles is used to generate an analytical curve by means of a computer program developed for this purpose. Crack growth rates (derivative values) are computed and evaluated at specific points (cycles) of interest using the analytic curve. The computer program (PLOT4) and an illustrative example are described in Appendix B. In addition to the measurement of circumferential crack length and growth rate, the stress intensity factor has been computed at various circumferential crack lengths for each of the specimens tested. Figures 6-21 through 6-28 show the respective data and curve fit for crack length and growth rates, respectively for specimens CSS-15, 16, 25, and HCN 40. Tables 6-4 through 6-7 show the calculated values of the stress intensity range and corresponding crack growth rate. The prototype data for the Type-304 stainless steel is shown in Figure 6-29 for comparison with the data obtained at the M and P Laboratory (Brothers) for prototype piping material.

Figures 6-30 and 6-31 show the appearance of a circumferentially cracked low alloy steel (CSS-36) and stainless steel (CSS-25) piping. To date, both the carbon and low alloy piping display the rough, discontinuous circumferential crack path, while the stainless piping typically

FIGURE 6-19a. STRESS INTENSITY RATIO — SEMIELLIPTICAL SURFACE CRACK

FIGURE 6-19b. STRESS INTENSITY RATIO — SEMIELLIPTICAL SURFACE CRACK

FIGURE 6-19c. STRESS INTENSITY RATIO — SEMIELLIPITICAL SURFACE CRACK

FIGURE 6-20. THROUGH-WALL CRACK GROWTH RATE VERSUS STRESS INTENSITY FACTOR FOR TYPE 304 STAINLESS STEEL

FIGURE 6-21. CIRCUMFERENTIAL CRACK GROWTH VERSUS CYCLES, ROOM TEMPERATURE,
TYPE 304 STAINLESS STEEL, SPECIMEN NO. CSS-15

FIGURE 6-22. CIRCUMFERENTIAL CRACK GROWTH VERSUS CYCLES, ROOM TEMPERATURE, TYPE 304 STAINLESS STEEL, SPECIMEN NO. CSS-15

FIGURE 6-23. CIRCUMFERENTIAL CRACK GROWTH VERSUS CYCLES, ROOM TEMPERATURE, TYPE 304 STAINLESS STEEL, SPECIMEN NO. CSS-16

FIGURE 6-24. CIRCUMFERENTIAL CRACK GROWTH VERSUS CYCLES, ROOM TEMPERATURE, TYPE 304 STAINLESS STEEL, SPECIMEN NO. CSS-16

FIGURE 6-25. CIRCUMFERENTIAL CRACK GROWTH VERSUS CYCLES, ROOM TEMPERATURE, TYPE 304 STAINLESS STEEL, SPECIMEN NO. CSS-25

FIGURE 6-26. CIRCUMFERENTIAL CRACK GROWTH VERSUS CYCLES, ROOM TEMPERATURE, TYPE 304 STAINLESS STEEL, SPECIMEN NO. CSS- 25

FIGURE 6-27. CIRCUMFERENTIAL CRACK GROWTH VERSUS CYCLES, 550°F,
A-106B, SPECIMEN NO. HCN-40-1

FIGURE 6-28. CIRCUMFERENTIAL CRACK GROWTH VERSUS CYCLES, 550°F,
CARBON STEEL, SPECIMEN NO. HCN-40-1

FIGURE 6-29. CRACK GROWTH RATE VERSUS ΔK_{max} FOR TYPE 304 STAINLESS STEEL, ROOM TEMPERATURE

NEG. NO. 48274

FIGURE 6-30. CSS-36, CIRCUMFERENTIAL CRACK GEOMETRY

NEG. NO. 48409

FIGURE 6-31. CSS-25, CIRCUMFERENTIAL CRACK GEOMETRY

TABLE 6-3

CRITICAL CRACK DEPTH FOR ONSET OF
RAPID THROUGH-WALL CRACK GROWTH

Specimen No. and Material	$\Delta\sigma_o$ ksi	$\sigma_y^{(1)}$ ksi	$a_o^{(2)}$ inches	t inches	$\frac{\Delta\sigma_o}{\sigma_y}$	$\left(\frac{a}{t}\right)_{N_{critical}}^{(3)}$	$\frac{K_o^{(4)}}{\sigma_o}$	$\bar{K}_c^{(5)}$ ksi $\sqrt{\text{in.}}$	$\left(\frac{da}{dN}\right)_{critical}$ $\frac{\mu\text{-in.}}{\text{cycle}}$
CSS-36 2 $\frac{1}{4}$ Cr-1 Mo	46.6	39.0	0.112	0.690	1.2	0.814	1.97	92	≈ 85
CSS-15 Type 304 Stainless Steel	48.4	33.1	0.043	0.268	1.46	0.840	1.41	68	≈ 40
CSS-16 Type 304 Stainless Steel	60.0	33.1	0.041	0.296	1.81	0.760	1.16	69.5	≈ 80

(1) Average 0.2% offset yield stress of material.

(2) Initial depth of premachined notch.

(3) Crack depth ratio from fractographic analysis at which rapid crack growth occurred.

(4) From Figure 6-19 (Paris and Sih).

(5) Effective Critical fracture toughness for onset of rapid through-wall crack growth.

TABLE 6-4

STAINLESS DATA

Sample CSS-15

Cycles	Average Half Crack Length (inches)	β ($^\circ$)	$K_{pressure}$ (ksi $\sqrt{\text{in.}}$)	$K_{bending}$ (ksi $\sqrt{\text{in.}}$)	K_{total} (ksi $\sqrt{\text{in.}}$)	da/dN ($\mu\text{in.}/\text{cycle}$)
44,144	1.18	20.4	11.5	42.0	53.5	52.5
51,746	1.65	28.5	13.8	49.5	63.3	79.0
54,546	1.92	33.2	15.9	58.6	74.5	136
57,054	2.35	40.6	21.6	68.2	89.8	234
59,298	3.04	52.5	39.7	81.5	121	378
60,210	3.53	61.0	51.0	87.4	138	463

TABLE 6-5

STAINLESS DATA

Sample CSS-16

Cycles	Average Half Crack Length (inches)	β (°)	K _{pressure} (ksiv/in.)	K _{bending} (ksiv/in.)	K _{total} (ksiv/in.)	da/dN (μ in./cycle)
15,819	1.17	20.2	11.3	48.8	60.1	71
19,779	1.62	28.0	13.8	57.7	71.5	150
23,583	2.23	38.6	0	63.5	63.5	141
26,523	2.62	45.3	0	80.2	80.2	165
28,551	3.12	53.9	0	107	107	345
29,751	3.66	63.2	0	116	116	575

TABLE 6-6

STAINLESS DATA

Sample CSS-25

Cycles	Average Half Crack Length (inches)	β (°)	K _{pressure} (ksiv/in.)	K _{bending} (ksiv/in.)	K _{total} (ksiv/in.)	da/dN (μ in./cycle)
16,000	1.14	19.7	4.32	44.2	48.5	75
18,503						
21,500	1.57	27.2	5.20	55.8	61.0	114
23,500	1.82	31.5	5.80	60.3	66.1	152
26,000	2.34	40.5	8.40	76.0	84.4	278
27,500	2.99	51.7	14.9	101.4	116	707
27,900	3.31	57.2	18.1	113.0	131	979

TABLE 6-7

A-106B PLAIN CARBON STEEL DATA

Sample HCN-40-1

Cycles	Average Half Crack Length (inches)	β (°)	K _{pressure} (ksiv/in.)	K _{bending} (ksiv/in.)	K _{total} (ksiv/in.)	da/dN (μ in./cycle)
133,735	1.375	23.8	0	57.1	57.1	120
134,506	1.510	26.1	0	60.4	60.4	160
135,004	1.610	27.9	0	63.4	63.4	200
136,498	2.120	36.7	0	73.3	73.3	720
136,750	2.330	40.3	0	80.5	80.5	1300
137,002	3.010	52.0	0	117	117	2550

displays a very smooth, "seam-like" crack path. Figures 6-32, 6-33, and 6-34 show the contrasting through-wall fractures of a low alloy and two stainless steel piping specimens.

6.4.3 Test Measurements and Data Acquisition

a. Data Printout

Magnetic data tapes for several samples were successfully processed during the report period. A typical reduced data group from one of these tapes is shown in Figure 6-35. The raw millivolt signals are converted to proper values of strain (micro-inches/inch), load (pounds), and end deflection (inches), and are referenced to a given sample cycle (T). Peak-to-peak values per cycle for these parameters are also printed out. The pipe weight and measured end load is used to calculate the nominal bending moment at the machined notch location and is used to calculate the quantity $K_2/f_2(\beta)$ as given by Equation (10).

$$K = \frac{K_1}{f_1(\beta)} f_1(\beta) + \frac{K_2}{f_2(\beta)} f_2(\beta) \quad (10)$$

$$K = K_{\text{pressure}} + K_{\text{bending}} \quad (11)$$

where

$$K^{(4)} = \sqrt{\pi \alpha} \left[\frac{P_0 \alpha}{2t} f_1(\beta) + \frac{M_0}{\pi \alpha^2 t} f_2(\beta) \right] \quad (12)$$

K = stress intensity factor, psi $\sqrt{\text{in.}}$

α = cylinder radius, inches

t = wall thickness, inches

P_0 = internal pressure, psi

M_0 = bending moment, in.-lb.

b. Strain Gage Measurements

The peak-to-peak strains for a typical internally notched sample are shown in Figure 6-36. The strain gage locations are also shown.

As the crack front grows through the major portion of the pipe wall, a redistribution of forces takes place in the vicinity of the crack, causing less gross force to be carried across the remaining ligament metal under Gage No. 8. The reduction in ligament load transmission is shown by drop-off of the strain range of Gage No. 9, and to a lesser degree of Gage No. 10. However, the reduction in ligament thickness is occurring faster than the load drop-off and the strain range measured by Gage No. 8 increases rapidly until gage failure. Gage No. 7 sees little change, indicating that the gross section modulus of pipe is relatively unaffected by the advancing through-wall crack. After the crack has fully penetrated the wall the fully reversed loading is terminated, and cyclic bend loading is continued as zero to maximum deflection for the circumferential crack growth portion of the test. This has been found to be necessary in order to preserve the through-wall metallographic fracture history. This is shown by the observed changes in measured strain on Gage No. 7 and Gage No. 11 immediately following full wall penetration.

c. Ultrasonic Measurements

Various attempts have been made to monitor through-wall crack growth using ultrasonic techniques. Although the results to date have been generally unsatisfactory, from the viewpoint of measuring the change in crack length

FIGURE 6-32. CSS-36 (2-1/4 CHROME, 1 Mo) FINAL FRACTURE SURFACE GEOMETRY

FIGURE 6-33. CSS-25 (SS-304) FINAL FRACTURE SURFACE GEOMETRY

FIGURE 6-34. CSS-23 (SS-304) FINAL FRACTURE SURFACE GEOMETRY

COUNT I	GAGE NO	SCAN NO	R1 (VOLTS)	S1	SCAN NO	R2 (VOLTS)	S2	S1-S2
5/ CYCLE	1	0	-0.60500E-02	-0.32670E 04	6	-0.14300E-02	-0.77220E 03	-0.24948E 04
	2	1	-0.22000E-02	-0.11880E 04	7	0.22800E-02	0.12312E 04	-0.24192E 04
	3	2	0.10700E-02	0.57780E 03	8	0.61800E-02	0.33372E 04	-0.27594E 04
	4	3	-0.21700E-02	-0.11718E 04	9	0.24500E-02	0.13230E 04	-0.24948E 04
	5	4	0.74900E-02	0.40446E 04	10	-0.15300E-02	-0.82620E 03	0.48708E 04
REFERENCE:	6	5	-0.19300E-02	-0.10422E 04	11	0.28900E-02	0.15606E 04	-0.26028E 04
FIGURE 6-18 GEAP-5512	7	12	0.28500E-02	0.15390E 04	18	-0.33700E-02	-0.18198E 04	0.33588E 04
	8	13	-0.21400E-02	-0.11556E 04	19	0.24200E-02	0.13068E 04	-0.24624E 04
	9	14	-0.60200E-02	-0.32508E 04	20	-0.90000E-04	-0.48600E 02	-0.32022E 04
	10	15	-0.40900E-02	-0.22086E 04	21	0.13800E-02	0.74520E 03	-0.29538E 04
	11	16	-0.49300E-02	-0.26622E 04	22	-0.90000E-04	-0.48600E 02	-0.26136E 04
	12	17	-0.21300E-02	-0.11502E 04	23	0.24900E-02	0.13446E 04	-0.24948E 04
	13	24	0.10000E-02	0.54000E 03	30	-0.49400E-02	-0.26676E 04	0.32076E 04
END LOAD	L	25	0.34200E-02	0.17100E 04	31	-0.23300E-02	-0.11650E 04	0.28750E 04
END DEFLECTION	P	26	0.64100E-02	0.73715E 01	32	-0.63800E-02	-0.73370E 01	0.14709E 02
	BL	27	0.	0.	33	0.	0.	0.
	BL	28	0.	0.	34	0.	0.	0.
	BL	29	0.	0.	35	0.	0.	0.
K2/P2(BETA) = 0.112865E 06 MDN = 0.337919E 06 MOMENT P/P = 0.657225E 06								
STRESS RANGE = 0.775525E 05								

FIGURE 6-35. DATA PRINTOUT

FIGURE 6-36. CSS-16, MEASURED STRAIN RANGE
VERSUS SAMPLE CYCLES
(σ RANGE = 59,600 psi)
FULLY REVERSED TESTING

per cycle, ultrasonic measurements are useful for nondestructively monitoring the overall progress of the crack. Table 6-8

compares several indicated overall crack depths as determined by ultrasonics, with the actual depth as

TABLE 6-8

ULTRASONIC THROUGH-WALL CRACK GROWTH MEASUREMENTS

<u>Sample</u>	<u>Ultrasonic Indicated Depth, d_u (inches)</u>	<u>Actual Measured Depth, d (inches)</u>
CSS-10	0.21	0.256
CSS-15	0.072	0.035
CSS-15	0.135	0.095
CSS-15	0.192	0.135

was determined by post-mortem examination of the fracture surfaces. Marking of the fracture surface has been accomplished by the stress reduction technique.

d. Elevated Temperature Testing

Testing was completed on the first elevated temperature (550°F) straight notched sample (HCN-40-1). Test parameters are listed in Table 6-5. Heating was accomplished using a six-element Calrod internal heater, banked so that individual heater power could be adjusted to minimize circumferential gradients. An auxiliary surface heater was added to minimize high axial gradients occurring near the flange end of the sample. Sample temperature was monitored with 21 CA thermocouples spot-welded to the sample in the locations specified in Figure 6-37. The maximum axial and circumferential temperature gradients were maintained below 20°F/in. and 4°F/in., respectively.

e. Data Obtained—550°F Testing

1. Through-Wall Crack Growth

Stress reduction techniques were employed to yield quantitative

through-wall crack growth and crack geometry data. Figure 6-38 illustrates the results. Four markings were attempted and four definite fronts were detected on the post-mortem examination of the fracture surface. Fractographic analysis of this specimen will be attempted during the next quarter.

2. Circumferential Crack Growth

Circumferential crack growth was continued until approximately 30% of the cross section was cracked. Figure 6-40 shows the appearance of the circumferential crack at the conclusion of the test. The initial stress range for HCN-40-1 had been chosen to be the same as that for CSS-5. Table 6-9 compares the circumferential surface crack growth rates for a given crack length for these two samples. The circumferential growth rate is noticeably lower for the 550°F specimens.

FIGURE 6-37. HCN-40-1, THERMOCOUPLE LAYOUT

FIGURE 6-38. HCN-40-1, STRESS REDUCTION MARKING FRONTS

FIGURE 6-40. HCN-40-1, CRACK APPEARANCE AT TEST CONCLUSION,
137008 CYCLES, $\Delta_{dn} = -5.75$ INCHES

TABLE 6-9

COMPARISON CIRCUMFERENTIAL CRACK GROWTH
RATE CARBON STEEL (HCN-40-1 versus CSS-5)

Surface Crack Length (ℓ)	Percent Total Circumference	(d ℓ /dn) μ -in. /in.		Percent (d ℓ /dn) Hot (d ℓ /dn) Cold
		CSS-5 Room Temperature	HCN-40-1 550°F	
3.0	14.4	850	160	18.8
3.5	16.8	1750	270	15.4
4.0	19.2	2750	520	18.9
4.5	21.6	3500	1090	31.2
5.0	24	4480	1650	36.8
5.5	26.4	5400	2060	38.2
6.0	28.8	7000	2650	37.9

f. Testing Procedure (Room Temperature)

The detailed test specimen and instrumentation setup and calibration procedures are presented in Appendix C. These procedures are those used for room temperature testing of the cantilevered piping specimens.

tests have been made of A-212B plate after treatment at 1250°F—2.5 hours followed by water quenching. This steel in this condition exhibited a lower magnitude of strain aging, i. e., difference in ductility at room temperature versus 300°F, than that observed in the as-received plate. However, the temperature at which the minimum occurs is identical for both conditions.

6.5 TASK D-4—CYCLIC STRAIN AGING OF CARBON STEEL (A. J. Brothers)

6.5.1 Summary

Tensile tests of A-212B plate have been made over a range of temperatures to determine the temperature range in which maximum dynamic strain aging occurs. Also, tests have been made of commercially-processed A-106 Schedule-40 pipe to determine if these materials exhibit strain aging characteristics similar to the plate material. Both these steels indicate a minimum in ductility and maximum strength in the temperature range 350°—400°F.

To evaluate the possible effects of process-induced thermal treatments, tensile

Initial cyclic strain aging tests are under way at 350°F to determine the influence of cyclic straining on the Charpy 50% FATT.

To determine possible metallurgical effects accompanying, and/or responsible for strain aging effects, relief electron microscopy and thin film transmission microscopy of tensile specimens tested below, at and above the maximum strain aging temperature range, were initiated.

6.5.2 Strain Aging Tests of Carbon Steel

To determine the temperature range of maximum strain aging and to evaluate the

effect of various rates of loading, tensile tests of A-212B plate have been conducted at temperatures in the range of room temperature to 500°F. The test specimen is a 7-inch-long, pin-loaded strip specimen with a 0.20-inch-thick $\times$ 0.5-inch-wide $\times$ 2.25-inch-long gage section. The specimens were machined with their length perpendicular to the rolling direction of the plate, i.e., transverse specimens. After machining to about 0.20-inch thickness, the specimens were stress relieved at 1050°F—1.5 hours and air cooled. Surfaces were prepared by lapping to a fine polish using 14.5 μ alumina powder.

Tests were performed in a 10,000-pound capacity Instron machine at strain rates corresponding to about 0.001 in./in./min, 0.010 in./in./min, and 0.010 in./in./min plus a 30-minute hold at strains corresponding to 1%, 3%, and maximum load levels. Heating was accomplished in a circulating air furnace. In addition to the A-212B plate in the as-received and stress-relieved condition, additional specimens were isothermally annealed at 1250°F—2.5 hours and water quenched. The purpose of this treatment was to evaluate the possible effects of process thermal treatments on propensity to strain age embrittle. Microscopic examination following this treatment revealed no obvious indications of structural change, i.e., this temperature was ostensibly below the temperature of transformation from ferritic to austenitic steel.

The results of these tests are listed in Table 6-10 and illustrated in Figures 6-41 through 6-43. Figure 6-41 shows the load-extension curves for the as-received plate and illustrates the typical features observed for carbon steel in this temperature range. Of specific interest is the appearance of a serrated or saw-tooth stress strain curve at temperatures in the range of 300°—400°F. This phenomenon, associated with discontinuous yielding, is evident at 300°F for strains exceeding those in the yield point region. At 400°F the serrations occur at strains near the yield point but are not

evident at higher strains. This feature suggests a definite, but perhaps minor influence of the level of cyclic strain on the temperature at which maximum embrittlement is likely to occur.

The ductility and strength properties of the steel are shown in Figures 6-42 and 6-43, respectively. These results indicate that the temperature of minimum ductility coincides with that temperature at which serrations are evident in the load-extension curve. The two tests at 0.001 in./in./min indicate a minor effect of lower strain rate and no appreciable effect on the temperature of maximum embrittlement. Figure 6-42 also illustrates similar effects for material given a thermal treatment at 1250°F—2.5 hours, water quenched. This treatment generally decreased the absolute level of strength and increased the ductility; however, the temperature of maximum strain aging was unaffected.

To assess the relative susceptibility to strain aging of commercial A-106 pipe, tests were conducted using 0.252-inch diameter axial specimens of as-received A-106 Schedule-40 pipe. These results were compared with those for the A-212B plate measured previously on cylindrical specimens (Quarterly Report No. 5). These results shown in Figure 6-43 reveal similar strain aging characteristics as measured by the temperature of minimum ductility.

Initial cyclic strain aging tests are under way. These initial specimens, described in Quarterly Report No. 10, have been cycled at nominal total strain ranges of 0.5 and 2.0% for 200 and 9 cycles, respectively, at 350°F. Charpy specimens will be machined from these bars to determine the shift in Charpy FATT compared to specimens that have not had such cyclic strain aging treatment.

FIGURE 6-41. LOAD-EXTENSION CURVES FOR CARBON STEEL (A-212B) SPECIMENS AT 0.010 in./in./min ILLUSTRATING SERRATED OR "SAW-TOOTH" CURVE IN STRAIN-AGING TEMPERATURE RANGE

FIGURE 6-42. EFFECT OF TEST TEMPERATURE ON DUCTILITY AND STRENGTH OF A-212B STEEL TESTED IN TENSION AT VARIOUS STRAIN RATES

FIGURE 6-43. EFFECT OF TEST TEMPERATURE ON DUCTILITY AND STRENGTH OF A-106 PIPE AND A-212B PLATE AT STRAIN RATE ≈ 0.010 in. in./min

TABLE 6-10

TENSILE PROPERTIES OF CARBON STEEL (A-212B PLATE)

Specimen No.	Test Temperature F	Upper Yield Strength ksi	Lower Yield Strength ksi	Ultimate Strength ksi	Elongation in 2 inches %
Condition—As-Received + Stress Relieved 1050°F—0.010 in./in./min					
6	RT*	49.8	46.7	76.1	32.0
14	200	45.6	44.6	74.5	17.0
1	300	44.6	43.1	85.6	14.5
4	400	40.3	42.3	92.1	18.0
15	490	38.8	37.8	89.2	24.0
Condition—As-Received + Stress Relieved 1050°F—0.001 in./in./min					
5	300	47.7	44.2	87.7	12.5
2	400	43.2	42.3	94.4	24.0
Condition—As-Received + Stress Relieved 1050°F—0.010 in./in./min + 30-min hold at 1%, 3%, and strain at maximum load					
7	300	43.5	41.5	85.0	12.5
16	400	43.3	41.1	91.1	15.0
Condition—1250°F—2.5 Hours—Water Quenched—0.010 in./in./min					
17	RT	49.0	46.3	71.6	30.0
13	200	44.9	43.8	71.6	21.5
10	300	43.9	41.4	73.2	19.0
3	400	39.7	36.6	78.0	20.5
11	500	30.6	30.5	74.6	24.0

*Room temperature.

Metallurgical examination of fractured tensile specimens is under way. This examination consists of relief electron microscopy to determine structural changes on a fine scale. Also, thin-film electron transmission microscopy is being employed to determine possible

variations in dislocation-carbon particle relationships as a function of test temperature and degree of strain aging. The test specimens selected for metallurgical analyses are those tested at 0.010 in./in./min at room temperature, 300°F, and 490°F.

SECTION VII

TASK K—EFFECT OF ENVIRONMENT

(B. E. Wilde, F. G. Hodge)

7.1 OBJECTIVE

The purpose of Task K is to determine quantitatively if BWR primary coolant affects the low-cycle fatigue life of Type 304 stainless steel at 550°F. Relevant data will be obtained from operation of a fatigue testing rig in a loop at a Boiling Water Reactor for a test duration of about 2-1/2 years.

7.2 SUMMARY

Approval to fabricate the necessary experimental equipment was received at about the middle of the period. Activities concentrated on the preparation of drawings and specifications suitable for ordering the low-cycle fatigue unit and containing pressure vessel. Procurement procedures (requests for bids) were initiated.

Activity on Task K has been concentrated on the finalization of design for the autoclave assembly and the loop piping and the procurement of materials. The design modification increasing the number of specimens from 81 to 150, has been made and the drawings of the autoclave assembly finalized. A schematic drawing of the proposed loop assembly has been prepared and submitted for approval.

Requests for those items listed as nonexpendable equipment have been sent out to vendors for price quotations. Delivery of materials required for the construction of the loop at Dresden I should be in time to complete installation during the plant shutdown scheduled for next spring.

APPENDIX A

ESTIMATE OF PROBABILITY OF PIPE BREAK

(J. D. Gilman)

A.1 PROBABILITY OF LEAKING FAILURES

One of the objectives of the Pipe Rupture Study is to predict, based on our knowledge of stress levels and crack propagation rates in a BWR piping system, the rate of occurrence of through-wall cracks during the life of the plant for each piping system and component. This task, when it is complete, will point out the more critical components and locations within the reactor piping system, so that attention can be directed to those areas. Meanwhile, an estimate of the expected average failure rate for all components can be obtained from our limited reactor operating experience. Leaking failures are tabulated below for four reactor plants:

Plant	Years of Operation	Piping Failures
SENN	5	2
KRB	1	3
Dresden 1	7	4
Consumers	6	1
Totals	19 Years	10 Failures

It is estimated that these failures represent a sample of about 1000 piping components per plant, where a component is defined as an elbow, tee, wye, or a straight section between attachments. The failure rate is

$$\frac{10}{1000 \times 19} = 5.3 \times 10^{-4} \text{ leaking failures per component-year. (A-1)}$$

A.2 CRITICAL CRACK SIZE

The fracture behavior of ductile materials containing cracks or defects is a complex phenomenon for which a satisfactory general theory or description is not yet available.

M. B. Reynolds⁽⁵⁾ summarized the state of the art at the beginning of the Pipe Rupture Study, and since that time has been conducting an experimental investigation of the fracture behavior of piping materials. He has recently conducted a limited number of burst tests on low-carbon steel pipes containing axial through-wall cracks and sawcuts. This data verified the applicability of a previously published⁽⁶⁾ formula for this case,

$$K^2 = \frac{\pi C \sigma_h^2}{\cos \theta} \left(1 + 1.62 \frac{C^2}{Rt} \right) (0.96) \quad (\text{A-2})$$

where

K = stress intensity factor (discussed below)

C = half the crack length

R = pipe radius

t = wall thickness

$$\theta = \frac{\pi}{2} \frac{\sigma_h}{\sigma_c}$$

σ_h = nominal circumferential stress

σ_c = failure stress for unflawed pipe.

The well-established linear elastic fracture theory for perfectly brittle materials states that fracture occurs at some critical value K_c of the stress intensity factor K, where K is a function of crack size and applied stress which can be calculated from elastic theory. For material exhibiting ductility, the brittle theory becomes approximate or inapplicable, depending on the extent of plastic material behavior preceding and accompanying crack extension. The $\cos \theta$ term in the above expression for K^2 is a correction for plastic effects. Even with this correction

factor the correlation is only fair. Reynolds' data for seven tests shows that crack instability occurs for values of K_{IC} between 115 and 185 ksi $\sqrt{\text{in}}$.

Fracture data for a wider range of materials and temperatures may be obtained from the terminal fracture behavior of wide-plate crack growth test specimens, as recorded by Brothers.⁽⁷⁾ Although these tests were not designed as fracture experiments, a record was kept of stress levels and approximate crack lengths at the onset of rapid crack extension, from which the critical stress intensity factor K_{IC} is readily calculated. Brothers' data and Reynolds' data are plotted on Figure A-1, showing stress intensity at fracture and also the ratio of net applied stress to ultimate stress. Those specimens which failed at a net stress less than the ultimate stress showed some degree of strength reduction because of stress concentration at the crack tip, while those specimens which failed near the ultimate stress were apparently insensitive to crack tip stresses.

On this diagram, an ideally ductile material would show a vertical trend of data, while a crack-sensitive material would show a horizontal trend. The horizontal trend is evident from the data indicating that fracture of cracked piping components will depend more heavily on crack-tip stresses than on net section stresses.

The data for elevated temperatures falls in approximately the same range of K_{IC} as the room temperature data. These points represent terminal fracture following several thousand cycles of plastic strain. A much higher value of K_{IC} would be expected for monotonic loading at elevated temperatures. There is some data from BMI⁽⁸⁾ which indicates K_{IC} is about 300×10^3 for A-106B carbon steel at BWR operating conditions, but with monotonic loading. The values of K_{IC} for elevated temperature as shown on Figure A-1 are the lowest that might be expected in an extreme condition of service.

In another task under the pipe study, E. Kiss⁽⁹⁾ has conducted reversed-bending fatigue tests of 6-inch pipe at room temperature, with internal pressure in some cases. Stress intensity factors as high as 111 ksi $\sqrt{\text{in}}$ have been recorded for circumferential through-wall cracks, with no crack instability occurring.

To define a fracture criterion for purposes of this analysis, the somewhat arbitrary but conservative assumption will be made that the average K_{IC} for the data of Figure A-1 represents the average K_{IC} for piping components which may be cracked in service conditions. Furthermore, the deviation of the data from its mean will be taken as representative of that for the reactor piping. From these assumptions, the probability of a very low value of K_{IC} can be determined, based on a normal distribution of K_{IC} . From Figure A-1, the mean value of K_{IC} is 144 ksi $\sqrt{\text{in}}$, and the standard deviation is 22 ksi $\sqrt{\text{in}}$.

A.3 LEAKAGE FLOW FROM CIRCUMFERENTIAL CRACKS

The leak-before-break safety criterion depends on the relationship between leak rate and crack-tip stress intensity factor for a through-wall crack. The stress intensity factor for a circumferential through-wall crack, which is the case of predominant importance in a pipe severance study, is the subject of a forthcoming report.⁽⁴⁾ The leak rate from a crack in a flat plate was calculated in Reference (10). These results were modified for application to a cylindrical pipe. It should be understood that both the leak rate calculations and the stress intensity factor calculation are of necessity rough approximations.

Results of these calculations are shown on Figure A-2. There are three

□ BURST TESTS OF A-106B PIPE WITH AXIAL CRACK (6-INCH SCHEDULE 40 AND SCHEDULE 80)

- ROOM TEMPERATURE
 - ELEVATED TEMPERATURE
- } CENTER-SLOT WIDE PLATE TESTS
(TERMINAL FRACTURE OF FATIGUE TESTS)

POINT	MATERIAL	TEMPERATURE	THICKNESS
1	A-212B	ROOM TEMPERATURE	0.4
2	2-1/4 Cr-1Mo	ROOM TEMPERATURE	0.4 (CLEAVAGE FRACTURE)
3	TYPE 304	ROOM TEMPERATURE	0.4
4	A-212B	485°F	0.4
5	2-1/4 Cr-1Mo	540°F	0.4
6	A-212B	600°F	0.25
7	2-1/4 Cr-1Mo	ROOM TEMPERATURE	0.25

STRESS RATIO = NET SECTION STRESS/ULTIMATE STRESS FOR PLATE TESTS

STRESS RATIO = $\frac{\text{NOMINAL BURST STRESS WITH CRACK}}{\text{NOMINAL BURST STRESS WITHOUT CRACK}}$ FOR PIPE TESTS

FIGURE A-1. SUMMARY OF FRACTURE DATA FOR PIPING MATERIALS

FIGURE A-2. RELATIONSHIP OF LEAK RATE TO STRESS INTENSITY FACTOR

variables which influence the relationship between leak rate and the stress intensity factor K . These are (1) the nominal bending stress in the pipe, (2) the line size, and (3) the fluid, whether steam or water at saturation temperature.

It was found that, for a given value of K , the leak rate is lowest for a bending stress of about 20,000 psi. For lower stresses, the required crack length is greater and the leak rate increases. For higher stresses, local yielding causes an increase in leak rate. The 20,000 psi curve is conservative and will be used as the general relationship for reactor piping.

The line size is significant in the higher range of K . If the leak rate is less than about 40 gpm, the crack is equally dangerous in any line size in the 6-to 24-inch range.

A.4 PROBABILITY OF LINE BREAK

After establishing a probability density function for K_c , and also the relationship between K_c and the leak rate, the next step is to construct Figure A-3, which gives the probability that a crack in a pipe will become

unstable when the leak rate reaches a given value.

A BWR typically has about 250 piping components of size 4 inches or larger which are located between the vessel and the first shutoff valve. Of this total, 100 components are associated with steam and 150 with water. If a detectable leak rate is 5 gpm, then (from Figure A-3) a crack in a steam line has a 3.7×10^{-4} probability leading to line break, and a crack in a water line has 6×10^{-6} probability of line break. The probability of a steam line break in a 40-year plant design life is

$$5.3 \times 10^{-4} \frac{\text{Leaks}}{\text{Component-Year}} \times \quad (\text{A-3})$$

$$\begin{aligned} & \times 100 \text{ components} \\ & \times 40 \text{ years} \\ & \times 3.7 \times 10^{-4} \\ & = 7.8 \times 10^{-4} \end{aligned}$$

This is equivalent to a system reliability of 0.9992.

For water lines, the probability of a break is

$$5.3 \times 10^{-4} \times 150 \times 40 \times 6 \times 10^{-6} = 1.9 \times 10^{-5},$$

or a reliability of 0.99998.

FIGURE A-3. PROBABILITY THAT A LINE BREAK RESULTS FROM A LEAKING CRACK

APPENDIX B

CURVE FITTING—PROTOTYPE PIPE FATIGUE
CIRCUMFERENTIAL CRACK DATA

(D. N. Patterson)

B.1 SUMMARY

To evaluate accurately the crack growth rates obtained from the experimental measurements of circumferential crack growth, an analytical fit of the data is required. To accomplish this, a computer program (PLOT4) has been written. This program mathematically fits an analytical curve to the experimental data and using the results evaluates the crack growth rates at specific points of interest.

Experience with the data presently analyzed indicates that the crack half-length versus fatigue cycles can be characterized by two basic shapes, i.e., the exponential and the polynomial (see Figure B-1). Consequently, the PLOT4 program has been designed to "fit" the data to these shapes once the user has called out the desired transition point as shown in Figure B-1. Once the fits have been made the program will print out the derivatives at values corresponding to the data points.

FIGURE B-1. CRACK HALF LENGTH VERSUS CYCLES OF FATIGUE

B.2 THE PLOT4 PROGRAM

The PLOT4 program is a revised version of POLFIT***. The POLFIT*** program fits the least-square polynomials to bivariate data, using an orthogonal polynomial method. The original POLFIT*** program fit data to the equation,

$$Y = A_0 + A_1X + A_2X^2 + A_3X^3 + \dots A_nX^n \quad (B-1)$$

where

n = any integer 1 through 11.

The altered program PLOT4 uses the same equation as POLFIT*** for fitting the polynomial except the value of n is limited to the integers 3 through 6. The exponential fit is based on the equation,

$$Z = e^Y \quad (B-2)$$

where

Y = Equation (1)

n = any integer 2 through 6.

After the coefficients $A_0, A_1, A_2 \dots A_n$ for the two curve fits have been calculated and the derivatives (crack growth rates) are defined by the equations,

$$Y' = A_1 + 2A_2X + 3A_3X^2 + \dots nA_nX^{(n-1)} \quad (B-3)$$

and

$$Z' = Y' e^Y = Y' Z \quad (B-4)$$

The sequence of data fitting is always done from exponential to polynomial, however, the switch can be made at any desired transition point. It is also possible to make the program fit all the data to either an exponential or polynomial curve.

The capacity of the program (PLOT4) at this time is approximately 6 lines of data or 30 points.

CAUTION

At the beginning of each fit the program prints INDEX of DETERM=.XXXX. This number is an "indication" of the accuracy of the fit. A perfect fit has an INDEX of DETERM equal to 1.000. In some cases the INDEX of DETERM might be 1.000, i.e., the calculated points coincide exactly with the data, however upon plotting the curve and/or examining the calculated derivatives it may be evident that there are inflection points present which did not occur in the plot of the data. In this case this curve fit is not the desired curve and selection of another degree of fit is necessary. This procedure should be followed until the resulting curve yields positive derivative values which "continuously" change, i.e., no oscillations or jumps.

A sample run of specimen CSS-23 is given on the following several pages. The nomenclature used in the program is as follows:

M = number of data point pairs entered in lines 100 through 104.

N = degree of Y in exponential or polynomial fit [see Equations (B-1) and (B-2)].

Term and coefficient = the term A_0 , A_1 , A_2 , A_3 — as in Equations (B-1) and (B-2) and its corresponding value.

$F'(X)$ = the derivative of the appropriate function evaluated at N(cycles).

PLOT4 : 11:27 SF TUE 01/02/68

ENTER M? 28

ENTER VALUE OF X WHERE CURVE FIT CHANGES FROM EXPONENTIAL
TO POLYNOMIAL...? 775

ENTER VALUE OF N FOR EXPONENTIAL FIT? 6

LEAST-SQUARES POLYNOMIALS

NOTE: CODE FOR 'WHAT NEXT?' IS:

- 0 = STOP PROGRAM
- 1 = COEFFICIENTS ONLY
- 2 = ENTIRE SUMMARY
- 3 = FIT NEXT HIGHER DEGREE

POLYFIT OF DEGREE 6 INDEX OF DETERM = .99978 WHAT NEXT? 2

TERM	COEFFICIENT			
0	-3.53242			
1	-3.06167 E-3			
2	1.06048 E-4			
3	-4.71819 E-7			
4	9.76761 E-10			
5	-9.59092 E-13			
6	3.64061 E-16			
X-ACTUAL	Y-ACTUAL	Y-CALC	DIFF	PCT-DIFF
120	.05	4.93769 E-2	6.23078 E-4	1.26188
160	.065	6.75855 E-2	-2.58553 E-3	-3.82557
202	.095	9.21647 E-2	2.83531 E-3	3.07635
240	.12	.118275	1.72458 E-3	1.4581
280	.145	.148917	-3.91663 E-3	-2.63008
320	.185	.182941	2.05872 E-3	1.12535
360	.225	.222033	2.96664 E-3	1.33612
400	.265	.269648	-4.64750 E-3	-1.72354
440	.325	.331086	-6.08557 E-3	-1.83807
480	.415	.413634	1.36646 E-3	.330354
521	.535	.53011	4.88988 E-3	.922428
550	.655	.638843	1.61571 E-2	2.52911
580	.785	.78086	4.14046 E-3	.530244
600	.9	.895705	4.29489 E-3	.479499
620	1.01	1.02966	-1.96631 E-2	-1.90966
640	1.185	1.18597	-9.73441 E-4	-.8.20795 E-2
662	1.365	1.38893	-.023934	-1.7232
680	1.565	1.58476	-1.97586 E-2	-1.24679
704	1.875	1.90043	-2.54319 E-2	-1.33821
720	2.24	2.15714	8.28616 E-2	3.84127
740	2.58	2.55158	2.84155 E-2	1.11364
761	3.085	3.09439	-9.39341 E-3	-.303562
775	3.53	3.56516	-3.51629 E-2	-.986293

ENTER N FOR POLYNOMIAL FIT? 3

POLYFIT OF DEGREE 3 INDEX OF DETERM = .999619 WHAT NEXT? 2

TERM	COEFFICIENT			
0	-436.296			
1	1.30673			
2	-1.25999 E-3			
3	3.94373 E-7			
X-ACTUAL	Y-ACTUAL	Y-CALC	DIFF	PCT-DIFF
795	4.37	4.37221	-2.20860 E-3	-5.05145 E-2
815	5.28	5.26995	1.00515 E-2	.190733
835	5.91	5.93109	-2.10932 E-2	-.355638
850	6.305	6.28307	2.19256 E-2	.348963
860	6.445	6.45365	-8.65144 E-3	-.134055
N(CYCLES)	FXI			
120	3.90931 E-4			
160	5.02291 E-4			
202	6.63030 E-4			
240	7.38144 E-4			
280	7.83675 E-4			
320	9.13495 E-4			
360	1.07989 E-3			
400	1.31405 E-3			
440	1.73262 E-3			
480	2.40975 E-3			
521	3.36310 E-3			
550	4.30411 E-3			
580	5.33793 E-3			
600	6.22599 E-3			
620	7.08816 E-3			
640	8.43331 E-3			
662	9.89921 E-3			
680	1.16014 E-2			
704	1.45394 E-2			
720	1.81503 E-2			
740	2.25265 E-2			
761	2.99191 E-2			
775	3.72986 E-2			
795	5.11174 E-2			
815	3.88144 E-2			
835	2.74579 E-2			
850	1.95616 E-2			
860	1.45932 E-2			

TIME: 18 SECS.

FIGURE B-2. CRACK HALF LENGTH VERSUS CYCLES, C5S-23

FIGURE B-3. CRACK GROWTH RATE, CSS-23

LIST

PLOT4 15:03 SF TUE 01/02/68

```

150 LET N=6
152 PRINT"ENTER M";
154 INPUT M
156 PRINT"ENTER VALUE OF X WHERE CURVE FIT CHANGES FROM EXPONENTIAL"
158 PRINT"TO POLYNOMIAL....";
160 INPUT F2
162 FOR I=1 TO M
164 READ X(I),Y(I)
166 IF F2=X(I) THEN 174
168 NEXT I
170 RESTORE
172 GO TO 266
174 LET F2=I
176 LET F3=M
178 LET M=F2
180 LET F8=0
182 RESTORE
184 DIM A(15),B(15),S(15),G(15),U(15)
186 DIM Q(75),P(75),X(75),Y(75),C(75)
188 LET Z=0
190 LET O=1
192 LET K=12
194 IF F8=0 THEN 202
196 PRINT"ENTER N FOR POLYNOMIAL FIT";
198 INPUT N
200 GO TO 208
202 PRINT"ENTER VALUE OF N FOR EXPONENTIAL FIT";
204 INPUT N
206 IF N>12 THEN 596
208 LET N=N+1
210 IF M<N THEN 600
212 IF M>100 THEN 590
214 LET T7=Z
216 LET T8=Z
218 LET W7=Z
220 GO TO 334
222 IF F8=1 THEN 270
224 LET D1=U(2)
226 LET D2=2*U(3)
228 LET D3=0
230 LET D4=0
232 LET D5=0
234 LET D6=0
236 IF (N-1)=2 THEN 264
238 LET D3=3*U(4)
240 LET D4=0
242 LET D5=0

```

```

244 LET D6=0
246 IF (N-1)=3 THEN 264
248 LET D4=4*U(5)
250 LET D5=0
252 LET D6=0
254 IF (N-1)=4 THEN 264
256 LET D5=5*U(6)
258 LET D6=0
260 IF (N-1)=5 THEN 264
262 LET D6=6*U(7)
264 LET M=F3-F2
266 LET F8=1
268 GO TO 188
270 LET M2=U(2)
272 LET M3=2*U(3)
274 LET M4=3*U(4)
276 LET M5=0
278 LET M6=0
280 LET M7=0
282 IF (N-1)=3 THEN 300
284 LET M5=4*U(5)
286 LET M6=0
288 LET M7=0
290 IF (N-1)=4 THEN 300
292 LET M6=5*U(6)
294 LET M7=0
296 IF (N-1)=5 THEN 300
298 LET M7=6*U(7)
300 RESTORE
302 PRINT"N(CYCLES)      F(X) '"
304 FOR I=1 TO F2
306 READ X(I),Y(I)
308 LET D7=D1+D2*X(I)+D3*X(I)+2+D4*X(I)+3+D5*X(I)+4+D6*X(I)+5
310 PRINTX(I),D7*Y(I)
312 NEXT I
314 FOR I=(F2+1) TO F3
316 READ X(I),Y(I)
318 LET D7=M2+M3*X(I)+M4*X(I)+2+M5*X(I)+3+M6*X(I)+4+M7*X(I)+5
320 PRINT X(I),D7
322 NEXT I
324 GO TO 612
326 LET Q8=Y(L)-C(L)
328 PRINT X(L),Y(L),C(L),Q8
330 GO TO 562
332 GO TO 576
334 DATA 0,0
336 FOR I=1 TO M
338 READ X(I),Y(I)
340 IF F8=1 THEN 344
342 LET Y(I)=LOG(Y(I))
344 LET W7=W7+X(I)
346 LET T7=T7+Y(I)
348 LET T8=T8+Y(I)+2
350 NEXT I
352 LET T9=(M*T8-T7+2)/(M+2-M)
354 PRINT
356 IF F8=1 THEN 372

```

```

358 PRINT "L E A S T - S Q U A R E S   P O L Y N O M I A L S"
360 PRINT "  NOTE:  CODE FOR 'WHAT NEXT?' IS:"
362 PRINT
364 PRINT "          0 = STOP PROGRAM"
366 PRINT "          1 = COEFFICIENTS ONLY"
368 PRINT "          2 = ENTIRE SUMMARY"
370 PRINT "          3 = FIT NEXT HIGHER DEGREE"
372 FOR I=1 TO M
374 LET P(I) = Z
376 LET Q(I) = 0
378 NEXT I
380 FOR I = 1 TO 11
382 LET A(I) = Z
384 LET B(I) = Z
386 LET S(I) = Z
388 NEXT I
390 LET E1=Z
392 LET F1=Z
394 LET W1=M
396 LET N4=K
398 LET I=1
400 LET K1=2
402 IF N=0 THEN 406
404 LET K1=N4
406 LET W=Z
408 FOR L=1 TO M
410 LET W=W+Y(L)*Q(L)
412 NEXT L
414 LET S(I)=W/W1
416 IF I-N4>=0 THEN 456
418 IF I-M>=0 THEN 456
420 LET E1=Z
422 FOR L=1 TO M
424 LET E1=E1+X(L)*Q(L)*Q(L)
426 NEXT L
428 LET E1=E1/W1
430 LET A(I+1)=E1
432 LET W=Z
434 FOR L=1 TO M
436 LET V=(X(L)-E1)*Q(L)-F1*P(L)
438 LET P(L)=Q(L)
440 LET Q(L)=V
442 LET W=W+V*V
444 NEXT L
446 LET F1= W/W1
448 LET B(I+2)=F1
450 LET W1=W
452 LET I=I+1
454 GOTO 406
456 FOR L = 0 TO 12
458 LET G(L)=Z
460 NEXT L
462 LET G(1)=0

```

```

464 FOR J=1 TO N
466 LET S1=Z
468 FOR L=1 TO N
470 IF L=1 THEN 474
472 LET G(L)=G(L)-A(L)*G(L-1)-B(L)*G(L-2)
474 LET S1=S1+S(L)*G(L)
476 NEXT L
478 LET U(J)=S1
480 LET L=N
482 FOR I2=2 TO N
484 LET G(L)=G(L-1)
486 LET L=L-1
488 NEXT I2
490 LET G(1)=Z
492 NEXT J
494 LET T=Z
496 FOR L=1 TO M
498 LET C(L)=Z
500 LET J=N
502 FOR I2=1 TO N
504 LET C(L)=C(L)*X(L)+U(J)
506 LET J=J-1
508 NEXT I2
510 LET T3=Y(L)-C(L)
512 LET T=T+T3+2
514 IF F8=1 THEN 518
516 LET C(L)=EXP(C(L))
518 NEXT L
520 IF M<>N THEN 526
522 LET T5=0
524 GOTO 528
526 LET T5=T/(M-N)
528 LET Q7=1-T/(T9*(M-1))
530 PRINT "POLYFIT OF DEGREE";N-1;
532 PRINT "INDEX OF DETERM =" ; Q7;
534 GOSUB 606
536 IF R=0 THEN 612
538 IF R=3 THEN 582
540 PRINT "TERM","COEFFICIENT"
542 FOR J=1 TO N
544 LET I2=J-1
546 PRINT I2,U(J)
548 NEXT J
550 IF R=1 THEN 222
552 PRINT "X-ACTUAL","Y-ACTUAL","Y-CALC","DIFF","PCT-DIFF"
554 FOR L=1 TO M
556 IF F8=1 THEN 326
558 LET Q8=EXP(Y(L))-C(L)
560 PRINT X(L),EXP(Y(L)),C(L),Q8,
562 IF C(L)=0 THEN 568
564 PRINT 100*Q8/C(L)
566 GOTO 570
568 PRINT "INFINITE"
570 NEXT L
572 GO TO 222

```



```
574 PRINT "          STD ERROR OF ESTIMATE FOR Y =" ; SQRT(S)  
576 IF K=N THEN 612  
578 GOSUB 606  
580 GOTO 536  
582 LET N=N+1  
584 IF N> 12 THEN 596  
586 IF M<N THEN 600  
588 GOTO 456  
590 PRINT  
592 PRINT "PROGRAM SIZE LIMIT IS 100 DATA POINTS."  
594 GOTO 612  
596 PRINT "ELEVENTH DEGREE IS THE LIMIT."  
598 GOTO 612  
600 PRINT  
602 PRINT "TOO FEW POINTS FOR FITTING DEGREE";N-1  
604 GO TO 612  
606 PRINT "  WHAT NEXT";  
608 INPUT R  
610 RETURN  
612 END
```

APPENDIX C

PROTOTYPE PIPING FATIGUE TESTING SAMPLE SETUP PROCEDURE
(ROOM TEMPERATURE TESTING)

1. Electrically zero all strain gages with specimen unbolted and fully supported. Print out zeroes and calibrations for all gages. Check gages for drift. Overnight drift shall not exceed $20 \mu\text{ in. / in.}$
2. Bolt specimen in place using all 12 studs. Record scale reading at fully sagged position, i.e., free end of cantilevered pipe unsupported.
3. Print out gage signals at fully sagged position. Check all strain gages for proper response both in sign and magnitude. The magnitude of the signal expected from the gages in the vicinity of the machined notch is listed below for the three pipe schedules; the gages on the top of the pipe should show a positive signal of the proper magnitude while those on the bottom should show a negative signal.

<u>Pipe Schedule</u>	<u>Calculated Sag Strain ($\mu\text{ in. / in.}$)</u>
40	± 161
80	± 168
160	± 183

4. Check DC hold-off level with scope on Ramtec channel which will be used for the test; the DC level should be within 0.1 volt of zero. Check wave output for form; amplitude should be ± 10.0 volts; adjust if necessary
5. Connect actuator to specimen by lowering ram until saddle barely touches specimen; make sure that Tare pot is in mid-range. Monitor load cell feedback sign while lowering actuator; it should barely begin to change in the positive direction as the actuator touches the sample.
6. Check that the Load Cell Range switch is on the 1.0 range.
7. Zero load cell feedback using "Mode 1 Zero Adjust" pot* for the appropriate channel, lock and record pot _____.
8. Using the Mean Level pot, raise the specimen in 1% increments until the strain readings reverse themselves recording strain readings at each increment.
9. Plot Strain versus % Mean Level pot setting using the sag position as the zero.
10. Determine the "Strain Zero" position using the Strain versus % ML plot from the preceding step; this will be defined as the point where the majority of the gages read as close to zero as possible, record Mean Level pot setting _____, record scale reading _____.

*Potentiometer.

11. Zero the sample pointer at strain zero and record scale reading defined as zero _____, record load cell feedback signal $P_0 =$ _____ mV = _____ lb, signal should be POSITIVE.
12. a) Reset "Mean Level" Pot to 50.0%, watch sample end deflection while doing this to prevent accidentally deflecting sample more than 2 inches either side of the strain zero position, compensate with "Mode 2 Zero Adjust" pot as needed.
 b) Monitor position feedback signal, use "Tare" Pot to bring signal as close to zero mV as possible.
 c) Use "Mode 2 Zero Adjust" Pot to bring sample back to strain zero position, position feedback signal should still be reading zero.
13. Raise sample 1.0 inch above strain zero position, check the following:
 - a) Load and Position signal should both be positive
 - b) Position signal calibration should be 1.20"/mV, adjust if necessary.
14. Return sample to strain zero.
15. Fill sample with pressurization medium (using fill pump), do not pressurize.
16. Record load cell feedback signal $P_1 =$ _____ mV = _____ lb.
17. Check gages for stability, filling of the sample may have introduced undesirable temperature transients which will result in excessive drift. It is desirable to schedule filling of the sample so that the full sample can come to thermal equilibrium over night or over the weekend.
18. Electrically zero all strain gages again at the Strain Zero position, print out zeros and cals for all gages.
19. Pressurize sample to 1000 psi, make sure to bleed both outlet valves several times to ensure that no air is trapped within specimen.
20. Set low pressure alarm.
21. Record all strain gages, obtain ultrasonic base data.
 - a) Reduce all Strain Gage data, check to ensure that all gages show the proper positive strain change due to pressurization. Calculated Axial Pressure Strains
 - a) Schedule 40; +75 microinches/in.
 - b) Schedule 80; +47 microinches
 - c) Schedule 160; +27 microinches

22.
 - a) Load Kennedy 1506, Ready lite should be on.
 - b) Scanner Control in "Local", "Single Scan" mode, reset to lower limit (yellow panel front lite should be on).
 - c) Coupler should be in "Auto" mode with "Record" button unlatched.
 - d) Sampling Rate switch on Voltmeter on (full CW).
 - e) Set Record Length selector on top of Coupler panel to "N Scan" position, set "N" thumbwheels to 001, set Clock output interval to 1.
23. Program Dymec to obtain complete data printout for first two cycles.
 - a) Place Enable switch (S-101) located on back of Scanner Control to "Off" position.
 - b) Set "Time Interval" thumbwheel located on Clock operating panel to 3.
24. Check settings on Digital Voltmeter

Range _____ Sample Period _____
Function _____ Sampling Rate On _____
Attenuation Check Off _____

Check settings on Guarded Data Amplifier

Mode Switch _____
Overload Light Off _____
25. Using Mean Level pot, raise specimen until desired stress level based on calculated load of _____ lbs is attained on load cell output _____.
 - a) Record Mean Level pot setting _____
 - b) Record Pointer reading _____
 - c) Check position feedback calibration, should be with 3% of 1.20 in./mV, record calibration factor _____
 - d) Reset Scanner Control to lower limit (yellow panel light should be on, indicating crossbar Scanner is open).
 - e) Turn Sampling Rate Switch Off (full CCW).
26. Press Remote Trigger button and verify that it reads one count into the clock.
27. Place record in "Record" mode by latching "Auto", "Record" buttons on coupler.

28. Press Start button on Scanner Control to initiate scan of all data channels, observe tape to ensure that this data is being committed to tape (digital recorder should be on also).
29. Return Mean Level pot to 50%.
30. Lower sample using Mean Level pot an amount equal to the upward deflection from Step 25.
 - a) Record Mean Level pot _____
 - b) Record pointer setting _____
31. Repeat Step 28.
 - a) Check position feedback calibration.
32. Return Mean Level pot to 50%.
33. Repeat Step 26; clock should now read 2 cycles.
34. Raise sample to deflection level determined in Step 25.
35. Repeat Step 28.
36. Lower sample to deflection level determined in Step 30.
37. Repeat Step 28.
38. Return Mean Level pot to 50%.
39. Place "Enable" switch to the ON position, return Scanner to "Remote", "Single Scan" mode. Dymec is now ready to begin recording the strain gage data in groups of 6 gages starting with Cycle #3.
40. Determine correct Oscillator Amplitude pot setting (1% Mean Level pot change = 2% Oscillator Amplitude pot change). Record Oscillator Amplitude pot setting _____.
41. Check function generator settings.
42. Reset Ramtec counters to zero.
43. Turn Ramtec counter on.
44. Determine peak values of load cell dynamic signal as follows:
 - a) "Record" button on Mag Tape Coupler should be unlatched, "Auto" button latched.

- b) Scanner Control should be in "local," "Single Scan."
- c) Step Scanner until load cell output channel is being monitored, depress "Single Channel" button.
- d) Turn "Sampling Rate" pot full CW (on).
- e) With digital printer on, cycle sample one cycle.
- f) Determine peak values of dynamic load signal from step preceding, record below.

Positive Load Peak _____

Negative Load Peak _____

45. Adjust phasing on trigger meter so that peak readings obtained in Step (f) (preceding step), are obtained under dynamic, automatic scanning conditions.

- a) "Sample Rate" pot full CCW (off).
- b) Scanner Control in "Local", "Single Scan" mode.
- c) Reset Scanner to lower limit (yellow light should be on, under channel ID display).
- d) Scanner in "Remote", "Single Scan" mode.
- e) Mag Tape Coupler in "Auto" "Record" mode.
- f) Start sample cycling dynamically, adjust trigger meter phasing pointers until dynamic load cell printout agrees with readings obtained in Step 44, f).

46. The data sampling frequency and visual inspection intervals will be determined, based on the objectives of each individual test.

The actual dynamic deflection limits of the sample should be marked with tape on the scale, and checked visually at frequent intervals. Any deviation from a symmetrical $\pm$ waveform should be compensated for using the "Mode 2 Zero Adjust" and "Oscillator Amp" pots as necessary.

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