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**REACTOR PRIMARY COOLANT SYSTEM
RUPTURE STUDY
QUARTERLY PROGRESS REPORT NO. 16
JANUARY-MARCH 1969**

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. 16

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 Number 3, October—December 1965.

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

The Reactor Primary Coolant System Rupture Study is being conducted for the Safety Branch, Division of Reactor Development and Technology, USAEC. This sixteenth quarterly report documents progress for the period of January 1 to March 30, 1966. 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 following tasks:

Task A—Reliability Engineering
 Task B—Stress Analyses,
 Task C—Fracture Mechanics,
 Task D—Fatigue and
 Task K—Effect of 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.
 Number 9, April—June 1964.

GEAP-4446—A Review of Fracture Modes as Related to Reactor Primary Coolant Pipe Rupture.
 Made up of Plate and Barrel Elements.

GEAP-4474—Experimental and Analytical Program Recommendations for Reactor Pipe Rupture Study.
 Number 10, July—September 1964.

GEAP-4574—Survey of Piping Failures for the Reactor Primary Coolant Pipe Rupture Study.
 Straight Pipe, January 1965.

GEAP-4578—Mechanical Design Considerations in Primary Nuclear Piping.
 Flows, April 1965.

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

GEAP-4684—Fatigue Crack Growth in Nuclear Reactor Piping Steels, March 1966.

GEAP-4911—Reactor Primary Coolant System Rupture Study Quarterly Progress Report

Number 1, April—June 1965
 GEAP-4987—Reactor Primary Coolant System Rupture Study Quarterly Progress Report
 Number 11, October—December 1965.

GEAP-4964—Reactor Primary Coolant System Rupture Study Quarterly Progress Report

Number 2, July—August 1965
 GEAP-5037—Reactor Primary Coolant System Rupture Study Quarterly Progress Report
 Number 12, January—March 1966.

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-4192—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-5553—PAPA—The Digital Computer Program for the Static Analysis of Structures
Made Up of Plate and Panel Elements.

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

GEAP-5557—Stress Intensity Factor for a Circumferential Through-Wall Crack in a
Straight Pipe, January 1968.

GEAP-5620—Failure Behavior in ASTM A-106B Pipes Containing Axial Through-Wall
Flaws, April 1968.

GEAP-5607—Fatigue Crack Growth in Nuclear Reactor Piping Steels—March 1968.

GEAP-5587—Reactor Primary Coolant System Rupture Study Quarterly Progress Report
Number 11, October—December 1967.

GEAP-5637—Reactor Primary Coolant System Rupture Study Quarterly Progress Report
Number 12, January—March 1968.

GEAP-5622—A Failure Diagram for Axially Flawed Pipes, April 1968.

GEAP-5680—Reactor Primary Coolant System Rupture Study Quarterly Progress Report
Number 13, April—June 1968.

GEAP-5653—Status of Pipe Rupture Study at General Electric—II, July 1968.

GEAP-5716—Reactor Primary Coolant System Rupture Study Quarterly Progress Report
Number 14, July—September 1968.

GEAP-5770—Reactor Primary Coolant System Rupture Study Quarterly Progress Report
Number 15, October—December 1968.

GEAP-5724—BWR Primary Piping Stresses for System Reliability Analysis,
September 1968.

GEAP-5726—Influence of Stress/Strain Concentration and Mean Stress on the Low-Cycle
Fatigue Behavior of Three Structural Steels at Room Temperature,
September 1968.

SECTION II

SUMMARY

2.1 TASK A—RELIABILITY ENGINEERING

By Monte Carlo runs using importance sampling, a preliminary estimate of the probability of leakage in 40 years at one chosen pipe cross section, due to uncertainties on variables appearing in the low-cycle fatigue equation, has been made; it is less than 10^{-3} . This is considered to be an upper limit because of conservative features of the reference conditions used for these runs. Refinements of this estimate are planned.

2.2 TASK B—STRESS ANALYSIS

Computer runs of the 180-degree elbow case have shown some problems with the PAPA Code. Torus elements do not show the desired degree of accuracy as a result of numerical problems encountered in the mathematical formulation of the equations. Also, triangular plate elements reflected difficulties. The solution program (Hyper Simeq) has been checked fully and efforts at further economizing this part of the program have been intensive. A Users' Manual for the PAPA Program has been submitted for publication.

2.3 TASK C—FRACTURE MECHANICS

Two circumferentially flawed, 6-inch pipe specimens of A-106B were loaded to failure by application of very high bending loads but without pressurization. One specimen had a through-wall flaw 4 inches (68 degrees) long, and the other a halfway-through flaw 360 degrees in length. These are compared with earlier tests of similar pipe specimens which featured (1) axial flaws, pressurized only; and (2) circumferential flaws under combined bending and pressure. Existing formulations for K_C are apparently unsatisfactory for long circumferential flaws if much plastic flow occurs in the ligament under the flaw.

2.4 TASK D—FATIGUE

2.4.1 TASK D-1—Crack Growth Studies

Crack growth rates were measured and compared on A-106B pipe as flattened into plate and in the semicylindrical pipe geometry—both heat treated to provide identical metallurgical structures. The semicylindrical geometry showed a higher crack growth rate by a factor of 10.

2.4.2 TASK D-2—Crack Initiation in the Presence of Stress Concentration

As a part of crack initiation studies, ratcheting in smooth bar specimens of the three piping grades, subjected to fully-reversed, load-controlled, low-cycle fatigue, was shown to occur only at the high stress range of 110,000 psi.

2.4.3 TASK D-3—Prototype Pipe Fatigue Tests

Prototype pipe tests were completed on three elbows, one tee, and a straight pipe with a welded section.

2.4.4 TASK D-4—Cyclic Strain Aging

Notched bend fracture tests of carbon steel bars at -105°F showed no significant effect from prior cyclic strain aging (200 cycles at 350°F).

2.5 TASK K—EFFECT OF BWR ENVIRONMENT

The fatigue machine, including specimens, was assembled in preparation for shakedown testing at 550°F in a test loop at San Jose. The large vessel that will contain the fatigue machine in the Dresden experimental loop was received. Seven axial-hole specimens, fatigued to failure, showed reasonably consistent and predictable behavior. Engineering drawings and operating instructions for the complete experimental loop system were distributed for final approvals.

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	in	10	years of	
or		20		service.
complete severance		30		
leaks		40		

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

3.2 SUMMARY

By Monte Carlo runs using importance sampling, a preliminary estimate of the probability of leakage in 40 years at one chosen pipe cross section, due to uncertainties on variables appearing in the low cycle fatigue equation, has been made; it is less than 10^{-3} . This is considered to be an upper limit because of conservative features of the reference conditions used for these runs. Refinements of this estimate are planned.

3.3 INTRODUCTION

One of the milestones of the current effort is discussed in this section—the estimate of a probability by the Distribution of Time to Damage Method. In particular, this is the probability of leakage by low-cycle fatigue—given a starting crack—in 40 years, at a chosen pipe cross section. The present solution can be extended to other time periods and to other cross sections. Appropriately summing probabilities over other cross sections gives probability of such leakage anywhere in the piping system in the chosen time period; this is probability-line E on the Piping Probability Diagram, Figure 3-1, Ninth Quarterly (GEAP-5512). These extensions are planned.

The present result has been reached by having a damage prediction equation proposed, with uncertainty distributions for each of the variables in the equation; selecting only those variables whose variances contribute substantially to the variance of the equation; and, finally, estimating the probability that cycles required to leak, n_t , is less than operating cycles in 40 years, n_c , by importance sampling in the Monte Carlo method.* All work through the theory of importance sampling has been given in previous quarterly reports; the remainder of this section includes:

* The Monte Carlo program was specified and written by G. T. Vernon of GE, San Jose.

Subsection 3.4—Illustrating in a simple case the idea of importance sampling in Monte Carlo,
 Subsection 3.5—Describing the weighting functions used for this problem,
 Subsection 3.6—Reviewing the uncertainty distributions used in this problem, and
 Subsection 3.7—Presenting the probability estimates obtained.

Remarks on the notation appearing in Section III of the current quarterlies are appropriate. While variables are designated by any convenient symbols in the text, more definite meanings are conveyed in the probability statements.

A "random variable" is a variable which may take on different values under apparently identical circumstances, merely by chance. The name of the random variable, such as "expansion stress," is designated by a capital letter, as X . Values which X may take on are designated by lower-case letters, such as x (also $x_1, x_2, \dots, x_n$). The frequency distribution of X —known as the probability density function, PDF—is designated $f_X(x)$, "the PDF of random variable X evaluated at x ;" or simply $f(x)$, "little f of x ." The cumulative frequency distribution of X , known as the cumulative distribution function, CDF, is designated $F_X(x)$, or simply $F(x)$, "capital F of x ." Areas under $f(x)$ are probabilities, so $\Pr[x_1 \leq X \leq x_2]$ is the probability that X may take on values between x_1 and x_2 ; the total area under $f(x)$ is 1; any function for which this is true can be a PDF, and it must be true for a function to be a PDF. Thus, $f(x)$ values may cover any range, depending on the scale of X , but must be positive or 0. But $F(x)$ values themselves are probabilities; $\Pr[X \leq x_1]$; thus, they are "lower tail" probabilities. $F(x)$ values range from 0 to 1. $F(x)$ and $f(x)$ are related by $F(x) = \int_{-\infty}^x f(t)dt$.

3.4 ILLUSTRATING IMPORTANCE SAMPLING IN MONTE CARLO

Attention is restricted to the problem of estimating the fraction of a distribution which lies less than some chosen value, as compared to describing the entire distribution. We illustrate the single variable case. Consider the random variable X . We wish to estimate $\Pr[X \leq x_0]$. In this elementary illustration, the distribution of X is known, so no doubt this probability could be calculated analytically. But let us illustrate the Monte Carlo approach, first by "ordinary Monte Carlo," then by importance sampling. Theory for both appears in Subsection 3.5 of the Fifteenth Quarterly, GEAP-5770, and in Hammersley and Handscomb.* We could sample at random n times from the distribution of X , assign 1 to each trial where $x \leq x_0$, and 0 otherwise. Then an estimate of $\Pr[X \leq x_0]$ is the sum of 1's and 0's, divided by n . But if this probability is small, such as 10^{-4} , then on the average only one result in 10,000 will be assigned 1, and a large number of trials is required to achieve a satisfactory confidence interval on the estimate; indeed, to discover that $\Pr[X \leq x_0]$ is not 0 with 0 variance. We require a procedure for making a more correct estimate with fewer trials; such procedures are called "variance reduction procedures," of which importance sampling is one. Before illustrating importance sampling, let us note how one draws random samples from a distribution.

Random values of X may be chosen by solving $F(x)$ for x , resulting in the inverse cumulative, designated $x = F^{-1}(x)$, selecting random numbers uniformly distributed from 0 to 1 for $F(x)$, and finding the corresponding x values.

* "Monte Carlo Methods," J. M. Hammersley and D. C. Handscomb, John Wiley and Sons, New York, 1964.

This procedure is illustrated in Figure 3-1(a)2 where a right triangular density function, $f_1(x)$, is shown in dotted lines, with cumulative $F_1(x)$ shown in solid lines, for $0 \leq x \leq 10$. If one enters the figure on the $F_1(x)$ scale with uniformly distributed random numbers, $0 \leq U \leq 1$, the x values given by the $F_1(x)$ line are randomly drawn in proportion to their frequency of occurrence in the distribution of X .

Suppose that we wish to estimate a lower-tail probability, say $\Pr[X \leq x_0]$. We may introduce a weighting function on the random $0 \leq U \leq 1$ values. Since for this illustration we know $f(x)$, we may also know that $\Pr[X \leq x_0] = 0.2$. We could make a perfectly correct estimate of this probability with every random draw by introducing a weighting function $f_2[F_1(x)]$, uniformly distributed over $0 \leq F_1(x) \leq 0.2$, as shown by dotted lines in Figure 3-1(e)1, $f_2[F_1(x)] = 5$ at all values of $F_1(x)$ in this range. We show the CDF, $F_2[F_1(x)]$, of this weighting function in solid lines also in Figure 3-1(e)1. Now we choose random values of U , uniformly distributed as before $0 \leq U \leq 1$, assign them to $F_2[F_1(x)]$, choose the corresponding $F_1(x)$ values, and then the corresponding X values. All such values of X will fall less than x_0 ; but instead of assigning 1 to these outcomes, we assign a weight which is $1/f_2[F_1(x)]$. This is $1/5 = 0.2$ for all possible U values. Thus, $\Pr[X \leq x_0]$ is estimated exactly correctly as 0.2 on every trial.

In real problems, however, X may be a complicated physical equation, or the sum of production and delay times of a part through a shop, or conditional probabilities in a network of events leading to a system reliability estimate, etc. Its distribution is not known, and cannot be found readily—or at all—because the distributions of the participating variables cannot readily be combined analytically in accordance with the function. This is the case for the n_t equation. Thus, it may be possible to arrive only roughly at a satisfactory shape of weighting function for each variable; only the correct end of the distribution of each variable to be weighted may be known, if the function is monotonic in that variable; or the weighted end may change for one or more variables, depending on values of other variables chosen. While, in principle, multidimensional weighting functions would be appropriate, it may be necessary to weight each variable separately. Weighting functions should be high in the region of favorable outcome, and low over the remaining region. Illustrative results for other one-dimensional weighting functions are illustrated in Figure 3-1, and tabulated in Table 3-1. Figure 3-1(b)1 shows a weak function, Figure 3-1(c)1 a very strong function, and Figure 3-1(d)1 a tapered step function. Note in each illustration how the weighting function governs what value of $F_1(x)$ is selected for the same uniform random value, and thus what value of X is selected. Also note how the variance of estimate of the $\Pr[X \leq x_0]$ is 0 for Figure 3-1(e)1 and increases to Figure 3-1(a)1 where there was no weighting, except for Figure 3-1(c)1 which shows that weighting can be excessive. This pattern was evident with only 30 trials.

3.5 WEIGHTING FUNCTIONS FOR THE LOW-CYCLE FATIGUE EQUATION

In the low-cycle fatigue equation for n_t we have four variables: initial crack depth, expansion stress, and parameters C and B . It has not been possible to devise a four-dimensional function, but separate one-dimensional functions have been applied to the uncertainty distribution for each variable. Now the weight on 1 in the event $n_t \leq n_c$ for, say 40 years, is the product of the weights found for each variable separately.

Weighting functions have been drawn from the beta distribution, which may assume a wide variety of shapes on the scale zero to one. Since $0 \leq F_1(x) \leq 1$, the beta distribution is convenient.

FIGURE 3-1. WEIGHTING FUNCTIONS FOR IMPORTANCE SAMPLING IN A MONTE CARLO ESTIMATE OF $\Pr[X \leq x]$
(SEE TABLE 3-1)

TABLE 3-1

DETAILS FOR WEIGHTING FUNCTIONS ILLUSTRATED IN FIGURE 3-1

Random Variable X: $f_1(x) = 0.02x$ for $0 \leq x \leq 10$
 $F_1(x) = 0.01x^2$ for $0 \leq x \leq 10$
 $x = F_1^{-1}(x) = 10\sqrt{F_1}$ for $0 \leq x \leq 10$

When $\Pr[X \leq x_0] \equiv F_1(x) = 0.2$, $x = 4.476$.

Description of Weighting PDF Figure 3-1	Weighting PDF $f_2[F_1(x)] =$	Weighting CDF $F_2[F_1(x)] =$	Weighting Inverse CDF $F_2^{-1}[F_1(x)] =$	$\Pr[X \leq x_0]$	
				Estimate	Variance of Estimate in 30 Trials Using Identical Random Numbers $U = F_2$
a. No Weighting: Uniform, "Ordinary Monte Carlo"	(1)	(F_1)	(F_2)	0.133	0.00385
b. Weak Weighting: Right Triangular plus Small Uniform	$1.9 - 1.8 F_1$	$1.9 F_1 - 0.9 F_1^2$	$\frac{1.9 - \sqrt{3.61 - 3.6 F_2}}{1.8}$	0.1297	0.001911
c. Strong Weighting: $1/F_1^2$ plus Small Uniform	$\frac{0.01}{(F_1 + 0.01)^2} + 0.009901$	$1 - \frac{0.01}{F_1 + 0.01} + 0.009901 F_1$	$\frac{(F_2 - 1.0009901) + \sqrt{(1.0009901 - F_2)^2 + 0.000396 F_2}}{0.019802}$	0.1999	0.01076
d. Tapered Step Weighting: $\left. \begin{array}{l} 0 \leq F_1 \leq 0.15 \\ 0 \leq F_2 \leq 0.744 \end{array} \right\}$ $\left. \begin{array}{l} 0.15 \leq F_1 \leq 0.25 \\ 0.744 \leq F_2 \leq 0.9925 \end{array} \right\}$ $\left. \begin{array}{l} 0.25 \leq F_1 \leq 1.0 \\ 0.9925 \leq F_2 \leq 1.0 \end{array} \right\}$	4.96 $12.385 - 49.5 F_1$ 0.01	$4.96 F_1$ $-0.556 + 12.385 F_1 - 24.75 F_1^2$ $0.99 + 0.01 F_1$	$F_2/4.96$ $\frac{12.385 - \sqrt{98.344 - 99 F_2}}{49.5}$ $(F_2 - 0.99)/0.01$	0.1954	0.0001042
e. Exact Step Weighting: $\left. \begin{array}{l} 0 \leq F_1 \leq 0.2 \\ 0 \leq F_2 \leq 1 \end{array} \right\}$	5	$5 F_1$	$F_2/5$	0.2	0

The beta CDF, known as the incomplete beta function, is

$$F(x) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \int_0^x t^{\alpha-1} (1-t)^{\beta-1} dt, \quad 0 \leq x \leq 1 \quad (1)$$

If $\beta = 1$, then the CDF becomes simply

$$[F(x) \text{ for } \beta = 1] = x^\alpha; \quad (2)$$

$$\text{so the cumulative inverse, } F^{-1}(x), \text{ for this case is } x = [F(x)]^{1/\alpha}; \quad (3)$$

and the PDF is

$$[f(x) \text{ for } \beta = 1] = \alpha x^{\alpha-1}. \quad (4)$$

Characteristic shapes of the beta distribution CDF and PDF for $\alpha = 2, 3, 5, 10, 20$, and 40 are illustrated in Figures 3-2 through 3-7. The distribution will weight the low rather than high values of $F_1(x)$ by reversing the roles of α and β .

We wish to estimate $\Pr[n_t \leq n_c]$ where n_c is a critical number of cycles chosen to represent 40 years of service at the pipe cross section chosen. Investigation of the behavior of the n_t function indicates that minimum n_t values are always given by maximum values of a_o/t , S_E , and C . Therefore, these distributions should always be sampled near their maximum ends. But B values should be chosen from the minimum end of that distribution only for common values of the other variables. For combinations of high values of the other variables, B can be unweighted, or maximum B values should be chosen, to give $n_t \leq n_c$. An algorithm has been devised for choosing a β value in the beta distribution, with $\alpha = 1$, to tend to give $n_t \leq n_c$, depending on the values of a_o/t , S_E , and C previously chosen. [The behavior of n_t with respect to B is introduced in step 26, subsection 3.5.5 of the Fourteenth Quarterly, GEAP-5716, by noting the fact that the analysis method calls for the crack growth lines to pivot at the mean ΔK of Schenectady testing, taking random positions governed by means and variances of B and C . If the starting ΔK is small (i.e., a_o and S_E are small), then n_t is large for large B and small for flat slope; but as the starting ΔK moves up toward $\tilde{\Delta K}$, a point is reached beyond which the reverse is true, because then most of crack growth time is spent along the portion of the crack growth line which extends upward from its crossing of $\tilde{\Delta K}$.]

3.6 UNCERTAINTY DISTRIBUTIONS FOR THE LOW-CYCLE FATIGUE EQUATION

As indicated above, the n_t equation [Equations (9), (10), and (11), Thirteenth Quarterly, GEAP-5680] has been repeatedly solved, using weighted randomly selected values of four variables. The uncertainty distribution for each of these has been identified previously (see Table 3-1, page 13, of the Thirteenth Quarterly, GEAP-5680), but all are given here in common format for comparison in Figures 3-8 through 3-11 for a_o/t MAX, S_E^* , $\log C$ and B , respectively. Table 3-2 gives the pertinent references. Note that trial graphical weighted random sampling is facilitated by the $F_1(x)$ scales' for the weighting functions—Figures 3-2 through 3-7—being drawn to the same scale as those for the uncertainty distributions—Figures 3-8 to 3-11.

FIGURE 3-2. BETA DISTRIBUTION

FIGURE 3-3. BETA DISTRIBUTION

FIGURE 3-4. BETA DISTRIBUTION

FIGURE 3-5. BETA DISTRIBUTION

FIGURE 3-6. BETA DISTRIBUTION

FIGURE 3-7. BETA DISTRIBUTION

FIGURE 3-8a. PDF AND CDF OF a_0/t MAX WITHOUT U/S TEST (CONDITIONS IN TABLE 3-2).

FIGURE 3-8b. PDF AND CDF OF a_0/t MAX WITH U/S TEST (CONDITIONS IN TABLE 3-2)

FIGURE 3-9. ORIGINAL AND FITTED CDF's OF S_E^* (CONDITIONS IN TABLE 3-2)

FIGURE 3-10. PDF AND CDF OF LOG C (CONDITIONS IN TABLE 3-2)

FIGURE 3-11. PDF AND CDF OF B (CONDITIONS IN TABLE 3-2)

TABLE 3-2

DETAILS FOR UNCERTAINTY DISTRIBUTIONS SHOWN IN FIGURES 3-2 TO 3-7
FOR VARIABLES IN LOW CYCLE FATIGUE CRACK GROWTH EQUATION

Figure	Random Variable	Original Display (See Also Table 3-1 GEAP-5680)	Density Function $f_{1X}(x) =$	Cumulative $F_{1X}(x) =$	Inverse Cumulative $F_{1X}^{-1}(x) =$
3-8a	Maximum Initial Crack Depth Ratio, $X = a_o/t$ MAX ($Z = a_o/t$)	Cause 2.1, GEAP-5279 for Z, "Without U/S Testing," with $\alpha = \pi d/4$ for $d = 6.624$ in., and $\lambda = 0.1$ cracks/in. ²	$\frac{2\alpha\lambda}{x} e^{-\alpha\lambda [1-F_Z(x)]} \frac{(\ln 0.8 - \ln x)}{(\ln 0.8 + \ln 100)^2}$ [This is $dF_1(x)/dx$, the density on the x scale, as in Figure 3-8. For the density on log x scale, find $dF_1(x)/d \log x$.] $1 - F_Z(x) = \left(\frac{\log 0.8 - \log x}{\log 0.8 + \log 100} \right)^2$ per p. 3-20, GEAP-5716	$e^{-\alpha\lambda [1-F_Z(x)]}$ per p. 3-19, GEAP-5716	$0.8 \left[0.0125^{(-\ln F_{1X}(x)/\alpha\lambda)^{1/2}} \right]$
3-8b	Maximum Initial Crack Depth Ratio, $X = a_o/t$ MAX ($Z = a_o/t$)	Cause 2.1, GEAP-5279, for Z, "With U/S Testing," with $\alpha = \pi d/4$ for $d = 6.624$ in., and $\lambda = 0.1$ cracks/in. ²	For $0.01 \leq x \leq 0.0667$: $\frac{2\alpha\lambda k}{x} (\ln 0.8 - \ln x) e^{-\alpha\lambda [1-F_Z(x)]}$ $1 - F_Z(x) = k[(\ln 0.8 - \ln x)^2 - (\ln 0.8 + \ln 15)(\ln 0.8 - \ln 0.12)]$ For $0.0667 \leq x \leq 0.12$: $\frac{2\alpha\lambda k}{x} (\ln 0.12 - \ln x) \left(\frac{\ln 0.8 + \ln 15}{\ln 0.12 + \ln 15} \right) e^{-\alpha\lambda [1-F_Z(x)]}$ $1 - F_Z(x) = k \left(\frac{\ln 0.8 + \ln 15}{\ln 0.12 + \ln 15} \right) (\ln 0.12 - \ln x)^2$ Where $k = 1/[(\ln 0.8 + \ln 100)^2 - (\ln 0.8 + \ln 15)(\ln 0.8 - \ln 0.12)]$ $1 - F_Z(x)$ per Equation (4), GEAP-5770	$e^{-\alpha\lambda [1-F_Z(x)]}$ per Equation (5), GEAP-5770	---
3-9	Uncertainty Coef. on Expansion Stress, S_E	PDF: Curve 4, Figure 3-3, GEAP-5554 CDF: Curve 4, Figure 3-4, GEAP-5554	---	---	(See Supplement to Table 3-2)
3-10	Intercept Parameter, Log C	(Table 3-1, GEAP-5680)	Normal Distribution: $\frac{1}{\sigma\sqrt{2\pi}} \exp \left[-1/2 \left(\frac{x-\mu}{\sigma} \right)^2 \right]$	Normal Distribution: $\int_{-\infty}^x f(x) dx$	Polynomial Approximation to Normal Inverse CDF, Equation 26.2.16, AMS-55
3-11	Slope Parameter, β	(Table 3-1, GEAP-5680)	Same as Log C	Same as Log C	Same as Log C

SUPPLEMENT TO TABLE 3-2

A cumulative inverse for uncertainty coefficient on expansion stress, S_E^* , has been found as a sum of orthogonal polynomials to thirteenth degree by fitting to the computed input points in the "Curve 4" column of Table 3-2, GEAP-5554. The coefficients found, recursion relationship, and scale transformations used, appear below.

<u>Coefficients</u>			
<u>k</u>	<u>A_k</u>	<u>B_k</u>	<u>C_k</u>
0			3.139856E-01
1	-9.519171E-01,	0.000000E-01,	6.619097E-01
2	5.330312E-01,	7.793274E+00,	1.191141E-01
3	-1.413345E-01,	2.366735E+00,	2.938398E-02
4	1.357726E-01,	4.356831E+00,	-2.581321E-03
5	1.744501E-01,	2.585561E+00,	-3.299919E-03
6	2.288274E-01,	3.186401E+00,	1.944492E-04
7	8.128554E-02,	2.576320E+00,	1.225228E-04
8	-1.087911E-02,	3.574198E+00,	1.294889E-04
9	2.047063E-01,	2.806425E+00,	-1.409403E-04
10	2.309174E-01,	2.977324E+00,	-6.392979E-06
11	3.067348E-01,	2.567445E+00,	6.680158E-05
12	-8.619568E-02,	3.163661E+00,	3.160807E-05
13	2.248075E-01,	3.121400E+00,	8.866768E-06

"E-01" is in computer notation; reads " $\times 10^{-1}$."

$$S_E^* = \exp(E_0)$$

$$E_0 = (C_0 P_0 + C_1 P_1) + (C_2 P_2 + \dots + C_{13} P_{13}),$$

$$\text{where } P_0 = 1,$$

$$P_1 = V - A_1, \text{ and}$$

$$P_k = (V - A_k) P_{k-1} - B_k P_{k-2} \text{ for } 2 \leq k \leq 13.$$

$$V = Y_9 \sqrt{-\ln(1 - |Y_6|)} \quad (\text{scale transformation}),$$

$$\text{where } Y_9 = +1 \text{ if } Y_6 \text{ is } +, \\ = -1 \text{ if } Y_6 \text{ is } -.$$

$$Y_6 = 2Y_3 - 1 \quad (\text{scale transformation}),$$

$$Y_3 = U_3^{1/K_3},$$

where U_3 for Monte Carlo is a random number uniformly distributed $0 \leq U_3 \leq 1$, as $F_2[F_1(x)]$ in Figures 3-2 to 3-7, and K_3 is parameter β in the beta distribution; with $\alpha = 1$; see Equation (3).

3.7 ESTIMATES OF $\Pr[n_t \leq n_c]$ FOR $n_c = 90, 360, \text{ AND } 1000$ CYCLES

Four runs of 100 iterations have been made to date to make subject estimates. The 360-cycle result is taken as characterizing 40 years, per Table 3-1, page 13, Thirteenth Quarterly. Results and properties of each of these runs are given in Table 3-3. Because of the small number of iterations in each run it is not feasible to assign cause for the variation seen among the results.

The estimates result in an estimated upper limit, at this time, of 10^{-2} for the chosen cross section. An upper limit is stated because of the conservative reference conditions used, particularly that conditioning probabilities for the uncertainty distributions are for the case of "no checking and inspection throughout the pipe provisioning system" (i. e., at any time during design or fabrication); and that $n_c = 360$ cycles for 40 years which is an upper limit estimate on operating cycles in that time. Refinements in the probability estimate are contemplated, based on further exploration of the effect of various weighting functions with small runs, and making larger runs. The objective is to make each iteration estimate as close to the final mean estimate as possible; in particular, to choose weighting functions so that it is not necessary to depend on a very few large estimates to give a mean near the true value. This objective is, of course, similar to avoiding having to depend on the rare "1" outcome, with all others zero, in ordinary Monte Carlo. Work toward this objective with density-truncated beta weighting functions is under way.

TABLE 3-3
ESTIMATES OF $\Pr[n_t \leq n_c]$ BY MONTE CARLO USING IMPORTANCE SAMPLING

Run	Number Of Variable Iterations	Weighting Function: Beta Distribution With		Estimates Of $\Pr[n_t \leq (n_c = \text{Cycles Shown})]$			Variance Of Estimate For $n_c = 1000$, Each $\times 10^{-4}$
		$\alpha =$	$\beta =$	1000	360 (40 years)	90	
1	100 a_o/t MAX	40	1	0.00708	0.00664	0.00240	12.23
	Log C	5	1				
	S_E^* , 13 [†]	10	1				
	B	1	1				
2	100 a_o/t MAX	30	1	0.00140	0.000858	0.000610	0.1313
	Log C	10	1				
	S_E^* , 3	20	1				
	B	1	† †				
3	100 a_o/t MAX	30	1	0.0116	0.00962	0.00547	12.89
	Log C	10	1				
	S_E^* , 13	20	1				
	B	1	† †				
4	100 a_o/t MAX	20	1	0.0108	0.00867	0.00474	3.890
	Log C	5	1				
	S_E^* , 13	10	1				
	B	1	† †				

† Cumulative inverse based on sum of orthogonal polynomials through degree shown.

† † Variable, $1 \leq \beta \leq 20$. See subsection 3.5.

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 analyses 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. North)

The 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 exists in complex piping when 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 stress in the elastic range of material behavior. When all portions of the computer code have been developed and checked, a designer will be able to investigate monotonic or cyclic load behavior of an elastic linear plastic, or elastic—perfectly plastic material.

4.2.1 Summary—PAPA Computer Program

The following is the status of the PAPA computer program as of April 1, 1969.

- a. All necessary plate elements have been developed for use in analyzing complex piping geometries. This includes the following plate-panel elements:
 - 1. Flat rectangular or square plate element,
 - 2. Curved or cylindrical plate element,
 - 3. Flat trapezoidal plate element,
 - 4. Conical plate element,
 - 5. Torus element having all positive radii,
 - 6. Torus element having negative and positive radii (saddle element), and
 - 7. Triangular element.
- b. All elements have been developed and are included in the PAPA computer program. Analysis of current difficulties indicates these can be overcome.
 - 1. The torus elements do not show the necessary degree of accuracy. This condition has been traced to numerical problems in the mathematical formulation. Means of alleviating and rectifying this situation have been worked out.
 - 2. Triangular plate elements, which initially were to be used for transitions in element geometries, have shown "weaknesses" when used exclusively as the

modeling element. In recent work, this limitation has been fully investigated and changes in the mathematical formulation were initiated. From preliminary results, accuracy appears to be greatly enhanced. (An example is included in subsection 4.2.3.) The triangular elements have been used to analyze a piping tee having a d/D ratio of 1, with reasonable answers resulting.

- c. The solution program (Hyper Simeq) has been checked fully. Efforts at further economizing this part of the program have been intensive and work in this area is completed.
- d. The addition of the RESTART capability to the PAPA program has further enhanced the economic structure of the program. This is an important consideration in large analyses having many nodes.
- e. Input-output modes have been used extensively. The PAPA program, coupled with the piping preprocessors, further enhances the input portions of the program.
- f. Users manuals and documentation of the theory involved in the PAPA program have been completed.

In reduction to practice, the PAPA computer program has shown growing pains. In the area of numerical difficulties, problems still exist. It is felt that all questions can be answered and a technically sound and accurate computer program can be made available.

4.2.2 Summary—PAPA-EPS Computer Program

The following is the status of the elastic—linear plastic computer program as of April 1, 1969:

- a. The PAPA-EPS computer program has been written and run on the GE-635 computer. This reflects the implementing of the input portions of the program, the solution in an elastic-stepwise-linear plastic manner, and output portions of the program. Still to be run and checked is the unloading portion of the computer program. The ultimate aim is to develop a hysteresis loop for the material as the structure is loaded, yields, and is unloaded.
- b. Investigations of time-dependent loadings are awaiting the results of the hysteresis loop calculations.

The PAPA-EPS program has been used to analyze a flat rectangular plate under uniform pressure. Yielding of the plate is reflected in the nonlinear response of the plate. Details of this analysis are given in subsection 4.2.4 of this report.

4.2.3 PAPA Analysis

Recent analysis of flat triangular plates shows the desired degree of accuracy in bending. The model shown in Sketch A was used to calculate bending stresses and deflections in a cantilever beam.

Sketch A. Model for Calculation of Bending Stresses and Deflections in a Cantilever Beam for Comparison Between PAPA and Theoretical Analysis

Deflections and stresses agreed with theoretical calculation for a cantilever beam. Symmetry was retained at all pertinent points in the structure. Table 4-1 shows theoretical versus PAPA for deflections and stresses versus length.

TABLE 4-1
THEORETICAL VERSUS PAPA FOR DEFLECTIONS AND STRESSES
VERSUS LENGTH

Length (in.)	Deflection (in.)		Stress (ksi)	
	PAPA	Theoretical	PAPA	Theoretical
0	0	0	-1,501	-1,500
1/2	-0.0061	-0.0061	-1,427	-1,425
1	-0.0242	-0.0242	-1,352	-1,350
1-1/2	-0.0535	-0.0534	-1,277	-1,275
4	-0.3472	-0.3466	-901	-900
7	-0.9404	-0.9392	-450	-450
10	-1.6688	-1.6666	0	0

Of particular note are the small changes in stresses and deflections across the transition. With the present formulation, it is anticipated that the triangular element can be eventually a major modeling tool.

4.2.4 PAPA-EPS (Elastic-Plastic Analysis)

A simple test case was run to check the operation and calculation within the PAPA-EPS program. The model is shown in Sketch B. All outer boundaries were simply supported. The two axis of symmetry was used for economy purposes. A pressure of 27 psi was used to load the plate.

Sketch B. Simple Test Plate Model To Check PAPA-EPS

The material constants were inputted as a σ - ϵ curve and a Poisson ratio versus ϵ curve, (Figure 4-1). For generality, the PAPA-EPS program will permit 20 different curves for material constants. This is to allow the user versatility in the input mode for temperature-dependent material curves.

FIGURE 4-1. MATERIALS PROPERTIES USED IN TEST CASES OF PAPA-EPS

Each curve is numbered and is noted on the plate input sheet. This avoids duplication of stress-strain curves in the input portion of the PAPA-EPS computer program.

A typical input sheet is shown in Table 4-2 for the PAPA-EPS analysis. Notes have been added for purposes of explanation.

TABLE 4-2
PLATE AND PANEL ANALYSIS
(ELASTIC-PLASTIC STRUCTURES)

PAPA-EPS

Stress - Strain Curves

Col 2

\$

\$W 1 PROGM = 1031\$

Curve Number (use positive integer less than 1000 for curve number)

\$W 1 DA-22

3

	<u>Tension</u>			<u>Compression</u>		
	Stress	Strain	Poisson Ratio	Stress	Strain	Poisson Ratio
Yield Stress 1 DA(3) =	<u>4.2E4,</u>	<u>0.004,</u>	<u>0.25,</u>	____,	____,	____,
2 DA(9) =	<u>4.8E4,</u>	<u>0.006,</u>	<u>0.40,</u>	____,	____,	____,
3 DA(15) =	<u>5.0E4,</u>	<u>0.008,</u>	<u>0.42,</u>	____,	____,	____,
4 DA(21) =	<u>5.1E4,</u>	<u>0.010,</u>	<u>0.46,</u>	____,	____,	____,
5 DA(27) =	<u>5.2E4,</u>	<u>0.015,</u>	<u>0.48,</u>	____,	____,	____,
6 DA(33) =	<u>5.3E4,</u>	<u>0.025,</u>	<u>0.50,</u>	____,	____,	____,
7 DA(39) =	____,	____,	____,	____,	____,	____,
8 DA(45) =	____,	____,	____,	____,	____,	____,
9 DA(51) =	____,	____,	____,	____,	____,	____,
10 DA(57) =	____,	____,	____,	____,	____,	____,

Results

This problem was chosen for its simplicity in checking. Therefore, the results are quite simple to decipher. Upon loading, the plate developed bending stresses in plate 9 (Sketch B) above yielding in the inner and outer layers. The stiffness of plate 9 was modified and a new solution was calculated. Plate 10 then yielded in the outer and inner layer. The stiffness was recalculated and loading continued. Plate 9 then yielded again in the outer layer. After stiffnesses were recalculated, the plate structure then accounted for all the load (27 psi).

This was a check case, primarily to verify the flow of information through the computer. Tension and compressive stress-strain curves were assumed to be equal. No attempt was made to account for any Bauschinger effect in the flow laws.

Results obtained show that the stepwise incremental loading procedure functions properly. The nonlinear response of the structure is reflected in Figure 4-2.

FIGURE 4-2. NONLINEAR RESPONSE OF STRUCTURE

The upper part of the curve shows the nonlinear response of a portion of the pressurized, simply supported plate shown in Sketch B.

SECTION V

TASK C—FRACTURE MECHANICS

(M. B. Reynolds)

5.1 OBJECTIVE

The objective of this task is the determination of the relationship between flaw configuration and pressure load limit in piping components used in nuclear reactor coolant circuits. Experiments to date have been limited almost entirely to ASTM-A106B pipe of 12-inch or less nominal diameter.

5.2 SUMMARY

Two circumferentially flawed, 6-inch pipe specimens of A-106B were loaded to failure by application of very high bending loads but without pressurization. One specimen had a through-wall flaw 4 inches (68 degrees) long, and the other a halfway-through flaw 360 degrees in length. These are compared with earlier tests of similar pipe specimens which featured: (1) axial flaws, pressurized only; and (2) circumferential flaws under combined bending and pressure. Existing formulations for K_{IC} are apparently unsatisfactory for long circumferential flaws if much plastic flow occurs in the ligament under the flaw.

5.3 FAILURE OF CIRCUMFERENTIALLY FLAWED PIPES UNDER BENDING STRESSES

The axial membrane stress in a thin-walled cylindrical vessel due to internal fluid pressure is equal to one-half the circumferential stress. As a consequence, the pressure burst strength of a pipe or cylindrical vessel is rather insensitive to circumferential flaws. Pressure burst tests on circumferentially flawed ASTM A-106B pipes* showed that unless the circumferential flaw was rather severe, failure was caused by axial splitting rather than by circumferential extension of the flaw. Figure 5-1 shows an example of this behavior: a pipe which contained a 36-degree through-wall axial flaw, yet failed by axial cracking. Earlier tests on pipes with 360-degree part-through circumferential flaws of constant depth showed that the burst pressure of a pipe was not reduced unless the flaw depth exceeded one-half the pipe wall thickness. The circumferential to axial stress ratio in a pressurized pipe thus weighs rather strongly against the failure of a pipe with a circumferential flaw, unless the flaw is very severe or sources of axial stress other than pressure are present. To study the failure of circumferentially flawed pipes under bending stresses, four pipes have been tested under bending loads.

5.4 EXPERIMENTAL RESULTS

The test frame for applying simultaneous bending and pressure loads to 4-foot lengths of 6-inch pipe was illustrated in a previous report,* along with test data on two pipe specimens ruptured under combined pressure and bending loads. During the present reporting period, two additional specimens of circumferentially flawed A-106B pipe in 6-inch Schedule 80 size have been tested under bending loads alone. The test conditions at failure for these two pipes, along

* GEAP-5716, Fourteenth Quarterly Report, P.A. 37

FIGURE 5-1. PIPE WITH THROUGH-WALL FLAW, PRESSURE ONLY

with previously reported data from earlier tests are given in Table 5-1. The condition of the specimens, 6-63-8B and 6-64-8B, after test is shown in Figures 5-2 and 5-3. Both specimens failed by sudden propagating fracture once the load limit was reached. After a bending moment of approximately 6.6×10^5 pound-inches was applied to specimen 6-63-8B, the load was removed to inspect the ends of the 4-inch through-wall flaw. A plastic displacement (COD) of approximately 0.10 inch had occurred. Upon reloading, failure occurred suddenly around the full circumference at an applied moment of 6.50×10^5 pound-inches. The fracture surface was found to be perpendicular to the maximum principal stress, with minimal shear lips. In each case, the applied load at the moment of brittle fracture was grossly in excess of what would be permitted by design codes.

For comparison with data from axially flawed pipes, approximate critical stress intensity factors were calculated for the pipes tested under bending loads. These values are also included in Table 5-1. A relation developed by Harris* was used to calculate the stress intensity factors for the three specimens with 360-degree part-through flaws. The critical stress intensity factors calculated for the three pipes having part-through 360-degree circumferential flaws (one pipe was tested under pressure only) are considerably lower than the $96 \text{ ksi} \sqrt{\text{in.}}$ found for axially flawed pipes. The low K values may be explained by the considerable necking in the ligament at the base of the flaw prior to failure, especially in specimen 6-22-8. This indicates that the Harris formula is not applicable in the cases in which the plastic zone ahead of the flaw extends to the surface opposite the flaw.

TABLE 5-1

BEHAVIOR OF CIRCUMFERENTIALLY FLAWED PIPES
UNDER BENDING AND PRESSURE STRESSES

Specimen Number	6-22-8	6-27-8B	6-28-8B	6-63-8B	6-64-8B
Test Temperature, °F	60	74	89	75	70
Flaw Length	360°	42.7°	360°	68.6°	360°
x/T (a)	0.18	0.0	0.70	0.0	0.475
Burst Pressure, ksi	4.81	6.00	6.52	0	0
Burst Moment, 10^5 lb-in.	0	5.49	6.60	6.50	6.62
K_p , $\text{ksi} \sqrt{\text{in.}}$ (b)	37.9	40.6	17.7	0	0
K_B , $\text{ksi} \sqrt{\text{in.}}$ (b)	0	92.2	40.7	147	64.6
K_c , $\text{ksi} \sqrt{\text{in.}}$ (b)	37.9(c)	133	58.4	147	64.6(c)
Flaw Type	0.020-in. slit	0.045- in. slit	0.020-in. slit	0.045- in. slit	45° vee

(a) x = Ligament thickness
T = Wall thickness

(b) $K_p + K_B = K_c$.

These subscripts refer to pressure, bending, and critical, respectively.

(c) Low values because of inappropriate formulation for K (see text) for 360-degree flaws.

* Harris, D.O., "Stress Intensity Factors for Hollow Circumferentially Notched Round Bars," UCRL-14859, Lawrence Radiation Laboratory, University of California, Livermore, Calif., April 1966.

FIGURE 5-2. PIPE WITH THROUGH-WALL FLAW, BENDING ONLY, SPECIMEN 6-63-8B

FIGURE 5-3. PIPE WITH PART-THROUGH FLAW, BENDING ONLY, SPECIMEN 6-64-8B

For the short through-wall flaws, the critical stress intensity factor K_c is given by an expression* of the form

$$K_c = \sqrt{\pi c} \left[\frac{PR_o}{2t} f_1(c) + \frac{M}{\pi R^2 t} f_2(c) \right],$$

in which c = Crack half-length,
 P = Pressure at failure,
 M = Bending moment at failure,
 t = Pipe wall thickness,
 R = Pipe mean radius,
 R_o = Pipe inside radius, and
 f_1, f_2 = Correction factors for bulging.

There is some uncertainty as to the values of f_1 and f_2 to be used in the calculation, but appropriate values for the crack lengths in question can be estimated from the Folias** relation with an error of probably less than 10%. The values of K_c so calculated are included in Table 5-1, in which the components of stress intensity factor due to pressure stresses (K_p) and bending stress (K_B) are shown separately. The values for K_c appear to be greater than the value for axial flaws, as would be expected from the Charpy data. No plastic zone size correction has been made; such a correction, if it could be estimated correctly, would raise the calculated K_c values somewhat.

* Gilman, J. D., "Stress Intensity Factor for a Circumferential Through-Wall Crack in a Straight Pipe," GEAP-5557, January 1968.

** Folias, E. S., "On the Prediction of Failure in Pressurized Vessels," College of Engineering, University of Utah, Salt Lake City, Utah, Report UTEC-CE-006, January 1969.

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

Comparison of crack growth rates in plate specimens of flattened and reheat treated A-106 pipe with those obtained on identically treated cylindrical pipe specimens indicates significantly higher crack growth rates in the pipe specimen configuration. This confirms an effect of geometry in these and previous pipe tests.

6.2.2 Comparison of Semicylindrical and Flat-Plate Specimens

Previous tests of prototype pipe materials were made, using semicylindrical pipe specimens. The results indicated growth rates higher than those observed in flat-plate tests of similar materials. To determine whether the discrepancy reflects specimen geometry or material differences, tests have been performed on both flattened 6-inch-diameter A-106 pipe and semicylindrical pipe specimens identical to those used previously. The results of the plate (flattened pipe) specimens are reported in Quarterly Report No. 15.

The crack growth rates for the pipe specimens are shown in Figure 6-1; comparison of these results on the basis of stress intensity factor is shown in Figure 6-2. These results show conclusively a significantly higher crack growth rate on pipe specimens, and clearly indicate an influence of specimen geometry. Quantitatively, the crack growth rates in the plate specimens are about 9 to 11 times greater than those in the plates with nearly identical slopes. In previous correlations of plate and pipe specimens, (Figure 6-3), the growth rates in pipe specimens were observed to be 3 to 20 times greater than those of the plate specimens. This wider range results primarily from differences in slopes for the crack growth correlations for the plate and pipe specimens of these various materials.

In view of the differences observed in the tests of both pipe and plate geometry for a single material, it is apparent that previous correlations of crack growth rate and stress intensity factor should, for the purpose of comparison with prior plate results, be reduced by a factor of 10 on crack growth rate. As shown in Figures 6-3, 6-4, and 6-5, comparisons of previous results of pipe and plate specimens on this basis suggest a reasonably close correlation.

FIGURE 6-1. CRACK GROWTH CURVES FOR A106 PIPE SPECIMENS AT ROOM TEMPERATURE

FIGURE 6-2. CRACK GROWTH CORRELATION FOR PIPE AND PLATE SPECIMENS OF A106 CARBON STEEL PIPE AT ROOM TEMPERATURE (PLATE SPECIMENS PREPARED FROM PIPING)

FIGURE 6-3. CRACK GROWTH CORRELATION FOR PIPE AND PLATE SPECIMENS OF A106 CARBON STEEL AT ROOM TEMPERATURE

FIGURE 6-4. CRACK GROWTH CORRELATION FOR PIPE AND PLATE SPECIMENS OF TYPE-304 STAINLESS STEEL AT ROOM TEMPERATURE

FIGURE 6-5. CRACK GROWTH CORRELATION FOR PIPE AND PLATE SPECIMENS OF 2-1/4 CR-1Mo ALLOY STEEL AT ROOM TEMPERATURE

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

6.3.1 Summary

The propensity of three low-strength structural steels to cyclic ratcheting was investigated. Smooth-bar specimens were subjected to completely reversed, load-controlled, low-cycle fatigue tests at a frequency of 6 cpm. Ratcheting was found only at the highest stress range of this investigation, which was 110,000 psi. At stress ranges below that value, no ratcheting was observed. A topical report entitled, "The 550° F Notched High Strain Fatigue Behavior of Three Low-Strength Structural Steels" was drafted for publication.

6.3.2 Low-Cycle Fatigue Behavior Under Completely Reversed, Load-Controlled Tests At Room Temperature

The phenomenon of ratcheting of structural materials under cyclic loading is an important factor in low-cycle fatigue design procedures. Ratcheting usually denotes a continuous growth of a specimen or structure under cyclic loads. This ratcheting is caused by an accumulation of irrecoverable plastic strain, and may lead to instabilities, and finally to fracture of the component under consideration. The purpose of this investigation was to observe possible ratcheting under the condition of uniaxial stress. Load control was used in these tests to allow for the ratcheting effect to occur. Displacement control does not permit a ratcheting effect since the displacement range, and therefore the maximum and minimum displacement, is set by the test conditions.

In this series of tests, the displacements were measured during completely reversed, load-controlled loading of smooth bar specimens. The variation of the displacement then gives an indication of the propensity of the material to undergo ratcheting. The uniaxial state of stress was chosen for its absence of any flow-restraining geometry. In this sense, the uniaxial condition represents the worst condition for ratcheting.

6.3.2.1 Test Material and Procedure

The test materials were the three low-strength steels; carbon steel, 2-1/4 Cr—1 Mo alloy steel, and Type-304 stainless steel. The tensile properties and chemical compositions were reported in GEAP-4911,* and the properties under completely reversed, strain-controlled conditions, the cyclic hardening characteristics, and the cyclic stress-strain diagrams were presented in GEAP-5474.**

To determine the cyclic properties of these materials under load control at room temperature, the following test techniques were employed:

The specimen, shown in Figure 6-6, was placed in a 200,000-pound Tinius Olson servo-controlled testing machine; then the extensometer was clamped onto the specimen, as shown in Figure 6-7. The extensometer was attached to the shoulders; with this procedure only the

* Quarterly Progress Report No. 1.

** Quarterly Progress Report No. 8.

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FIGURE 6-6. SPECIMEN FOR RATCHETING STUDY

FIGURE 6-7. EXTENSOMETER ATTACHED TO SHOULDER SPECIMEN

overall displacement, and therefore the average strain between these points, could be obtained. The strain values reported later were obtained by dividing the displacement range by the average gage length.

The load amplitude was kept constant throughout each test within the capabilities of the testing machine. The variation of the strain range and the mean strain was then recorded throughout the test. Load-displacement hysteresis loops were measured at selected intervals. In addition, the variation of the displacement was continuously monitored on a displacement—time recorder.

Cycling was done at a frequency of 6 cpm. The specimen was inspected for incipient cracks, using a 20× microscope. Complete separation of the bar terminated the test at cycles-to-failure.

6.3.2.2 Test Results

The results of the fatigue tests under completely reversed, load-controlled conditions are listed in Table 6-1. In addition to the usual information on cycles to crack and to failure, the diameter of the specimens before and after testing is given.

Figure 6-8 shows the cyclic lives under load-controlled testing of the three steels. It is noteworthy to observe that the fatigue lives of the three materials are quite different from each other under this mode of cycling. This is in contrast to the behavior in the strain-controlled condition where these same materials had essentially identical lives at high strain ranges in previous tests conducted under this task.

Photographs of the fractured specimens are reproduced in Figures 6-9, 6-10, and 6-11. On each of these figures, two specimens are shown; the specimens at the left were tested at 550° F under completely reversed, strain-controlled conditions and those shown at the right pertain to the conditions of this study (load-controlled).

The variation of the dependent quantities in a load-controlled test (the strains) are listed in Tables 6-2, 6-3, and 6-4. Each of these show the strain range, mean strain, and maximum and minimum strain at various number of cycles.

6.3.2.3 Fatigue Life Under Completely Reversed Load-Controlled Conditions

Figure 6-8 indicates a considerable difference in the fatigue life of the three materials at high stress amplitudes. At 50,000 psi nominal stress amplitude, the life of carbon steel specimens is 850 cycles, compared to 4500 cycles for 2-1/4 Cr—1 Mo steel. The 2-1/4 Cr—1 Mo steel exhibits the highest fatigue resistance of the three materials. The weakest material is carbon steel at nominal stresses above 45,000 psi. Below that value of the stress amplitude, Type-304 stainless steel has the shortest fatigue life.

In completely reversed, strain-controlled conditions, the fatigue life of the three materials was approximately equal for all three materials for a strain range of about 2% with about 800 cycles-to-failure. At a strain range of about 0.7%, the ranking of the fatigue resistance was 2-1/4 Cr—1 Mo steel (about 7,000 cycles), carbon steel (9,000 cycles), and Type-304 stainless

FIGURE 6-8. STRESS AMPLITUDE VERSUS LIFE TO FAILURE FOR LOAD-CONTROLLED TESTING UNDER COMPLETELY REVERSED CONDITIONS FOR THE THREE TEST MATERIALS

FIGURE 6-9. PHOTO OF FRACTURED LOW-CYCLE FATIGUE SPECIMENS. MATERIAL: CARBON STEEL. SPECIMEN C17A, 550°F, COMPLETELY REVERSED, STRAIN CONTROL. SPECIMEN C18A, ROOM TEMPERATURE, COMPLETELY REVERSED, LOAD CONTROL.

FIGURE 6-10. PHOTO OF FRACTURED LOW-CYCLE FATIGUE SPECIMENS. MATERIAL: 2-1/4 CR-1 MO ALLOY STEEL. SPECIMEN A10A, 550°F, COMPLETELY REVERSED, STRAIN CONTROL. SPECIMEN A20A, ROOM TEMPERATURE, COMPLETELY REVERSED, STRAIN CONTROL.

FIGURE 6-11. PHOTO OF FRACTURED LOW-CYCLE FATIGUE SPECIMENS. MATERIAL: TYPE-304 STAINLESS STEEL. SPECIMEN S9A, 550°F, COMPLETELY REVERSED, STRAIN CONTROL SPECIMEN S11A, ROOM TEMPERATURE, COMPLETELY REVERSED, LOAD CONTROL.

TABLE 6-1

COMPLETELY REVERSED, LOAD-CONTROLLED, LOW-CYCLE
FATIGUE TESTS AT ROOM TEMPERATURE

<u>Specimen Number</u>	<u>*Stress Amplitude 10³ psi</u>	<u>N_C Cycles-to-Crack</u>	<u>N_F Cycles-to-Failure</u>	<u>Diameter of Specimen Initially and After Test</u>	
CARBON STEEL					
C20A	40	1, 773	8, 745	0. 505	0. 504
C18A	45	2, 285	3, 266	0. 505	0. 502
C10A	50	117	847	0. 505	** ---
C23A	53	102	303	0. 505	0. 461
2-1/4 Cr—1 Mo ALLOY STEEL					
A12A	42	2, 845	21, 499	0. 505	0. 505
A9A	45	6, 350	9, 920	0. 505	0. 505
A20A	50	980	3, 854	0. 505	0. 497
A23A	55	1, 550	2, 150	0. 505	0. 498
TYPE-304 STAINLESS STEEL					
S19A	40	1, 727	5, 387	0. 505	0. 505
S11A	45	1, 643	2, 406	0. 505	0. 501
S16A	50	516	1, 302	0. 505	0. 502
S15A	55	648	1, 046	0. 505	0. 490

* Stresses are based on the original cross-sectional area.

** Specimen buckled after separation.

TABLE 6-2
STRAIN DATA FOR CARBON STEEL SPECIMENS

Specimen Number	Stress Amplitude 10 ³ psi	Strains (%) at Indicated Cycles				
		Cycle	Tensile	Compressive	Total	Mean
C20A	40	1/4, 3/4, 1	1.47	0.14	1.33	0.78
		1-1/4, 1-3/4, 2	0.78	0.14	0.64	0.46
		13	0.64	0.05	0.59	0.35
		36	0.57	0.03	0.54	0.31
		96	0.56	0	0.56	0.28
		216	0.47	-0.05	0.52	0.21
		456	0.45	-0.12	0.57	0.17
		816	0.39	-0.15	0.54	0.12
		2,016	0.33	-0.20	0.53	0.06
		4,042	0.36	-0.15	0.51	0.10
		6,742	0.34	-0.19	0.53	0.08
		8,272	0.36	-0.19	0.54	0.08
C18A	45	1/4, 3/4, 1	1.36	0.25	1.1	0.8
		1-1/4, 1-3/4, 2	1.03	0.25	0.78	0.64
		10	0.98	0.15	0.83	0.56
		25	1.11	0.20	0.91	0.65
		125	0.71	-0.17	0.88	0.27
		350	0.76	0.01	0.75	0.38
		890	1.00	0.22	0.78	0.61
		1,430	1.01	0.25	0.76	0.63
		2,525	1.10	0.37	0.73	0.73
C10A	50	1-1/4, 1-3/4, 2	0.79	-0.43	1.22	0.18
		20	0.35	-0.86	1.21	-0.25
		32	0.72	-0.30	1.02	0.21
		56	1.03	-0.13	1.16	0.50
		128	1.30	0.15	1.15	0.71
		368	1.36	0.18	1.18	0.77
		728	1.24	-0.01	1.25	0.62
C23A	53	No data, instrumentation failure.				

TABLE 6-3
STRAIN DATA FOR 2-1/4 Cr—1 Mo SPECIMENS

Specimen Number	Stress Amplitude 10 ³ psi	Strains (%) at Indicated Cycles				
		Cycle	Tensile	Compressive	Total	Mean
A12A	42	1/4, 3/4, 1	0.39	-0.14	0.53	0.13
		1-1/4, 1-3/4, 2	0.33	-0.16	0.49	0.09
		15	0.30	-0.10	0.40	0.10
		30	0.31	-0.09	0.40	0.11
		120	0.30	-0.07	0.37	0.11
		480	0.27	-0.09	0.36	0.09
		1,200	0.30	-0.09	0.39	0.10
		2,550	0.30	-0.06	0.36	0.12
		7,150	0.33	-0.04	0.37	0.18
		16,500	0.37	-0.02	0.39	0.19
A9A	45	1/4, 3/4, 1	0.77	-0.11	0.88	0.33
		1-1/4, 1-3/4, 2	0.61	-0.03	0.64	0.29
		17	0.49	-0.08	0.57	0.20
		53	0.44	-0.14	0.58	0.15
		137	0.36	-0.21	0.57	0.08
		281	0.27	-0.27	0.54	0
		580	0.25	-0.25	0.50	0
		1,480	0.30	-0.22	0.52	0.04
		3,222	0.26	-0.25	0.51	0
		7,272	0.36	-0.15	0.51	0.10
		7,500	0.46	-0.13	0.59	0.16
A20A	50	1/4, 3/4, 1	0.93	-0.22	1.15	0.35
		1-1/4, 1-3/4, 2	0.65	-0.19	0.84	0.23
		15	0.76	-0.15	0.90	0.30
		100	0.62	-0.09	0.71	0.27
		340	0.81	+0.06	0.75	0.44
		700	0.90	0.19	0.71	0.54
		1,180	0.98	0.28	0.70	0.63
		2,380	1.25	0.57	0.68	0.91
		2,980	1.37	0.67	0.70	1.02
A23A	55	1/4, 3/4, 1	0.72	-0.08	0.80	0.32
		1-1/4, 1-3/4, 2	0.72	-0.08	0.80	0.32
		18	0.93	-0.20	1.13	0.36
		76	0.81	-0.30	1.11	0.26
		196	0.28	-0.62	0.90	-0.17
		676	0.30	-0.56	0.86	-0.13
		1,276	0.47	-0.41	0.88	+0.03
		1,876	0.67	-0.28	0.95	0.19

TABLE 6-4
STRAIN DATA FOR TYPE-304 STAINLESS STEEL SPECIMENS

Specimen Number	Stress Amplitude 10 ³ psi	Strains (%) at Indicated Cycles				
		Cycle	Tensile	Compressive	Total	Mean
S19A	40	1/4, 3/4, 1	0.31	-0.11	0.42	0.10
		1-1/4, 1-3/4, 2	0.28	-0.09	0.37	0.10
		20	0.27	-0.11	0.38	0.08
		65	0.29	-0.12	0.41	0.08
		155	0.32	-0.13	0.45	0.10
		605	0.27	-0.27	0.54	0
		1,505	0.30	-0.29	0.59	0.04
		3,305	0.31	-0.28	0.59	0
		5,105	0.38	-0.25	0.63	0.06
S11A	45	1/4, 3/4, 1	0.51	-0.16	0.67	0.17
		1-1/4, 1-3/4, 2	0.42	-0.15	0.57	0.14
		10	0.46	-0.15	0.61	0.16
		45	0.49	-0.19	0.68	0.15
		90	0.46	-0.25	0.71	0.11
		270	0.54	-0.29	0.83	0.13
		720	0.58	-0.24	0.82	0.12
		1,170	0.64	-0.21	0.85	0.22
		2,070	0.73	-0.15	0.88	0.29
S16A	50	1/4, 3/4, 1	1.23	+0.17	1.06	0.70
		1-1/4, 1-3/4, 2	1.06	0.17	0.89	0.62
		12	1.30	0.49	0.81	0.89
		72	1.41	0.40	1.01	0.90
		216	1.25	0.26	0.99	0.75
		576	1.21	0.22	0.99	0.71
		936	1.09	0.09	1.00	0.59
		1,236	1.29	0.15	1.14	0.72
S15A	55	1/4, 3/4, 1	1.23	-0.02	1.25	0.60
		1-1/4, 1-3/4, 2	1.07	+0.03	1.04	--
		10	1.16	0.08	1.08	0.62
		22	1.23	0.15	1.08	0.69
		46	1.33	0.12	1.21	0.72
		94	1.56	0.35	1.21	0.95
		214	1.78	0.41	1.37	1.09
		586	2.32	1.05	1.27	1.68
		946	3.39	1.84	1.55	2.6

steel (14,000 cycles). * Therefore, the relative ranking of the fatigue resistance of the three materials is not the same in two different types of fatigue tests.

6.3.2.4 Fatigue Fracture

The fatigue fractures of all the specimens tested in this portion showed the usual characteristics of fatigue fractures. There was always an initial area of fatigue crack initiation and growth, followed by the final overload fracture area. The initial fatigue fracture area was identical for the condition of load and strain control at room temperature. In each case, the fatigue crack grew perpendicular to the specimen axis without any visible distortion. Only the final fracture area differs for load and strain control. In the load-controlled case, a neck-down or distortion of the specimen can be observed around the final fracture area. No such distortion is observed for displacement control (see left half of Figures 6-9, 6-10, and 6-11). This difference in appearance of the final fracture area is caused by the test method.

At loads higher than the ones used in this study, a gradual reduction of the diameter would be observed prior to the formation of the actual fatigue crack. Then, the appearance of the final fracture would be different from those shown. An indication of the reduction in area at higher loads can be observed by comparing the diameter measurements of fractured specimens listed in Table 6-1. The diameter of the fractured specimens reduces with increasing load amplitude.

Comparison of the appearance of the fractured specimens tested at 550° F and at room temperature reveals some differences for carbon steel and 2-1/4 Cr-1 Mo steel. For these two materials, the final fracture at 550° F is not perpendicular to the specimen axis as it is at room temperature. Instead, the 550° F final fracture occurs on an oblique angle, as can be seen in the left portion of Figures 6-9 and 6-10. (The fatigue fracture started always perpendicular to the axis.) This feature was not observed for stainless steel (Figure 6-11).

6.3.2.5 Variation of the Strain During Cycling and Ratcheting

From Table 6-1 it might be suspected that the specimens showing a reduction in diameter would exhibit a ratcheting phenomenon; the results show that this is indeed the case. Figure 6-12 shows mean strain versus cycle behavior for three specimens to illustrate this trend: specimen S15A had a continuous increase in mean strain up to the point of fracture; in specimen A23A, the increase is observed towards the end of the specimen life; and specimen S16A in Figure 6-12 is typical of other specimens showing no such trend. The increase in mean strain, toward the end of the fatigue life, of the specimens tested at stress amplitudes below 55,000 psi is probably caused by the reduction in load-supporting area due to the propagating fatigue crack.

The conclusion is, therefore, that ratcheting occurs only at the highest stress level tested. Below this stress range of 110,000 psi, no significant ratcheting was observed. A reasonable threshold for ratcheting for the materials under investigation can, therefore, be considered to be a stress range of about 110,000 psi.

The variation of the strains during cycling is considerable, as shown in Tables 6-2, 6-3, and 6-4. All the specimens display a tensile mean strain caused by the initial load application in

* GEAP-5082, Quarterly Progress Report No. 3.

FIGURE 6-12. VARIATION OF MEAN STRAIN WITH CYCLES

the tensile direction, as illustrated in Figure 6-13. The stresses applied in this study are far into the plastic range, so that a considerable amount of tensile strain is introduced at the first quarter cycle—OA in Figure 6-13. The maximum compressive stress is attained before the specimen strain has reached the zero strain point again—AB in Figure 6-13. Therefore, a positive mean strain is maintained in many cases throughout the fatigue test.

FIGURE 6-13. SCHEMATIC SHOWING START OF A TEST UNDER LOAD CONTROLLED MODE

Figure 6-13 also indicates the reason for the observed large strain variations. A slight change in the stress at which load reversal takes place causes a considerably greater variation of the strain. This problem is inherent in stress-controlled testing involving the plastic range. It is caused by the shape of the stress-strain diagram.

6.3.2.6 Conclusions

The results of this study of the uniaxial behavior of three low-strength structural steels under completely reversed, load-controlled conditions at room temperature lead to the following conclusions:

- a. Ratcheting, defined as a continuous cyclic elongation of the specimen, was observed at the highest stress range, $\Delta\sigma = 110,000$ psi. The threshold limit for ratcheting is therefore somewhat below that stress range.

- b. Considerable variation of the strain was observed during cycling; both increases and decreases in mean strain were observed.
- c. The fatigue fractures were very similar to those observed on displacement-controlled specimens. Only the final overload fracture area showed the characteristic deformations attributed to the load-controlled mode of testing.
- d. The relative ranking of the fatigue resistance of the materials is different in different types of tests. At fatigue lives of about 10,000 cycles, Type-304 stainless steel shows the shortest fatigue life in load control; however, it ranks first (longest fatigue life) in strain control.

6.4 TASK D-3—PROTOTYPE PIPE FATIGUE TESTING (J.D. Heald)

6.4.1 Summary

Testing was completed on the following prototype pipe specimens:

- a. HWD-3—Hot stainless defective butt weld,
- b. CSTS-1—Cold stainless tee in-plane,
- c. HCLS-1—Hot carbon elbow in-plane,
- d. CSLS-3—Cold stainless elbow in-plane (long radius), and
- e. HSLS-1—Hot stainless elbow in-plane.

Specimen setup was begun on the second cold stainless "tee," CSTS-2. Pertinent test data are summarized in Table 6-5.

6.4.2 Data Obtained

6.4.2.1 Crack Initiation

In general, for pre-notched or butt-welded straight piping specimens, cycles for crack initiation are determined visually, using a 40× microscope. However, crack initiation for the elbow and tee samples usually occurs on the inner surface, and ultrasonics are used to determine crack initiation. In the cases where crack initiation was detected using ultrasonics, the location and crack direction were known from previous samples. In some cases (elbows and tees), crack initiation was not detected before through-wall failure occurred.

Cycles for crack initiation (N_I) reported in Table 6-5 show either ultrasonically indicated values or designate less than the measured cycles to fully penetrate the wall.

Crack initiation versus nominal stress range data for piping components are shown in Figures 6-14 through 18, together with all crack initiation data obtained in Task D-3 to date.

TABLE 6-5
DATA SUMMARY

Sample Description	Test Temperature (° F)	Internal Pressure (psi)	Stress Range (psi)	Cantilever End Deflection (in.)	Cycles to Crack Initiation (N _I)	Cycles to Fully Penetrate Wall (N _w)	Test Terminated (N _φ)
HWD-3, ASTM A-312, Type-304 SS, Schedule 40, "Defective" Weld in Straight Pipe	550	None	59,900	± 7.19 until cycle 4109, + 0/-7.19 after	2049	3600 (551)	9700 (8200)
CSTS-1, ASTM A-182F, Type-304 SS, Schedule 40, Tee	62 ↑ 76	1000, Water and Rust Inhibitor	68,700	± 7.25	< 4575**	4575	10,700 (6125)
HCLS-1, ASTM A-234, WPB Carbon, Schedule 40, Elbow	550	None	43,500	± 7.25	< 760**	760 (760)	3449 (2689)
CSLS-3, ASTM A-182F, Type-304 SS, Schedule 40, Long Radius Elbow	65 ↕ 70	1000, Water and Rust Inhibitor	44,200	± 7.25	≤ 1500*	4469 (2969)	13,902 (7433)
HSLS-1, ASTM A-182F, Type-304 SS, Schedule 40, Elbow	550	None	28,000	± 8.56	< 2200**	2200 (2200)	3550 (1350)

* Determined by ultrasonics.

** Values taken at less than the number of cycles to fully penetrate the wall.

FIGURE 6-14. CARBON 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. NOMINAL STRESS RANGE (psi) VERSUS CYCLES-TO-CRACK INITIATION, ASTM A-106B CARBON STEEL, 550°F

FIGURE 6-17. NOMINAL STRESS RANGE VERSUS CYCLES FOR CRACK INITIATION, TYPE 304 STAINLESS STEEL AT 550°F

FIGURE 6-18. 2-1/4 Cr - 1 Mo ALLOY STEEL, ROOM TEMPERATURE, STRESS RANGE VERSUS INITIATION CYCLES

6.4.2.2 Crack Growth

a. Through-Wall Growth

Examination of the "defective" weld sample (HWD-3) showed that the intended lack-of-fusion defect did not in fact exist. A description of the preparation of this sample is given in Quarterly Report No. 15. Apparently, the heat from the filler weld passes caused fusion to occur in the area intended for the defect. This was suspected during testing because crack initiation occurred on the outside surface instead of at the intended internal defect. The actual location of crack initiation was in the center of the weld on the outside surface.

Through-wall crack growth other than average values cannot be obtained for the elbows and tees due to the extremely rough fracture surface after testing (see Figure 6-19). Summaries of all data for through-wall crack growth rate versus stress intensity factor are shown in Figures 6-20 through 6-23.

b. Circumferential Crack Growth

After through-wall penetration (i.e., leakage) fatigue testing is continued to obtain the following information:

1. Provide crack growth data,
2. Establish whether or not a critical crack size (instability) is obtained under low-cycle fatigue loading conditions, and
3. Provide knowledge of the final fracture characterization for the ell or tee component, i.e., the location, size, shape and extent of the fracture surfaces.

In the case of straight pipe specimens, either notched or butt-welded typical circumferential crack propagation (as shown in Figures 6-26 through 6-30, Quarterly No. 13) occurs subsequent to the through-wall propagation phase.

Circumferential surface crack growth was obtained in the usual manner (reference GEAP-5587, page 71) for the "defective" weld sample HWD-3, and the growth data are shown plotted in Figures 6-24 and 6-25.

In the case of elbows or tees, however, "circumferential cracking" depends on the particular component and on the manner of loading, i.e., in-plane or out-of-plane.

Figures 6-26 and 6-27 show a typical gross fracture of an elbow subjected to in-plane loading. Figures 6-28 and 6-29 show the gross fracture of an elbow subjected to out-of-plane loading. Figures 6-30, 6-31 and 6-32 show the final fracture of a tee specimen subjected to in-plane loading. As can be seen from the above-mentioned figures, crack growth in piping components is complicated, and more testing is required to determine whether the crack growth patterns observed in the first few specimens are typical.

Summaries of all data obtained to date for circumferential crack growth rate versus stress intensity factor for straight pipe samples are shown in Figures 6-33 through 6-37.

FIGURE 6-19. FINAL CRACK SURFACE GEOMETRY, ELBOW SAMPLE. CSLS-1

FIGURE 6-20. THROUGH-WALL CRACK GROWTH RATE VERSUS ΔK , CARBON STEEL, ROOM TEMPERATURE

FIGURE 6-21: THROUGH-WALL CRACK GROWTH RATE VERSUS ΔK , STAINLESS STEEL, ROOM TEMPERATURE

FIGURE 6-22. THROUGH-WALL CRACK GROWTH RATE, da/dN VERSUS ΔK , STAINLESS STEEL, 550°F

FIGURE 6-23. THROUGH-WALL CRACK GROWTH RATE VERSUS STRESS INTENSITY FACTOR FOR 2-1/4 Cr-1 Mo ALLOY STEEL

FIGURE 6-24. CIRCUMFERENTIAL CRACK GROWTH RATE VERSUS CYCLES, ASTM-A312 TYPE-304 STAINLESS STEEL, SPECIMEN HWD-3

FIGURE 6-25. CIRCUMFERENTIAL CRACK GROWTH RATE VERSUS CYCLES, ASTM-A312, TYPE-304 STAINLESS STEEL, SPECIMEN HWD-3

FIGURE 6-26. AXIAL CRACK GROWTH IN LONG RADIUS ELBOW, CSLS-3, LOADED BY IN-PLANE BENDING.

FIGURE 6-27. AXIAL CRACK GROWTH IN LONG RADIUS ELBOW, CSLS-3, OPPOSITE SIDE SHOWN IN FIGURE 6-26.

FIGURE 6-28. BOTTOM VIEW OF CRACK GROWTH IN ELBOW SAMPLE, CSLS-2, LOADED BY OUT-OF-FLANE BENDING

FIGURE 6-29. BOTTOM VIEW OF CRACK GROWTH IN ELBOW SAMPLE. CSLS-2, (BACK SIDE)

FIGURE 6-30. TOP VIEW OF CRACK GROWTH IN ELBOW SAMPLE, CSLS-2

FIGURE 6-31. FINAL CRACK GEOMETRY SAMPLE, CSTS-1 (RIGHT SIDE)

FIGURE 6-32. FINAL CRACK GEOMETRY SAMPLE, CSTS-1 (LEFT SIDE)

FIGURE 6-33. CIRCUMFERENTIAL CRACK GROWTH RATE VERSUS STRESS INTENSITY RANGE FOR A-106B CARBON STEEL AT ROOM TEMPERATURE

FIGURE 6-34. CRACK GROWTH RATE VERSUS STRESS INTENSITY RANGE FOR TYPE-304 STAINLESS STEEL AT ROOM TEMPERATURE

FIGURE 6-35. CIRCUMFERENTIAL CRACK GROWTH RATE VERSUS STRESS INTENSITY RANGE A-106-B CARBON STEEL MATERIAL AT 550°F

FIGURE 6-36. CIRCUMFERENTIAL CRACK GROWTH RATE VERSUS STRESS INTENSITY RANGE FOR TYPE 304 STAINLESS STEEL AT 550°F

FIGURE 6-37. CIRCUMFERENTIAL CRACK GROWTH RATE VERSUS ΔK CORRELATION FOR 2-1/4 Cr-1 Mo MATERIAL

6.4.3 Stress Intensification Factors for Elbows and Tees

Stress intensification factors have been experimentally determined for elbows and tees tested at room temperature using strain gages mounted on the outside surface of the component. The stress intensification factor* is defined as the ratio of the measured stress to the nominal stress at a particular point of interest where

$$(\sigma_{\text{Actual}})_x = \frac{E}{(1-\nu^2)} [\epsilon_x + \nu \epsilon_y] \quad , \text{ and}$$

$$\sigma_{\text{Nominal}} = \frac{Mc}{I} = \text{Calculated nominal pipe bending stress.}$$

Results are shown in Figures 6-38 through 6-40.

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

6.5.1 Summary

Tests of notch bend fracture specimens to determine the influence of a locally embrittled notch region indicate no significant effect of local cyclic strain aging on notch fracture strength at -105° F.

6.5.2 Local Cyclic Strain Aging on Notch Bend Strength

To determine the influence of a locally strain-aged region on the notch fracture strength of carbon steel, bend bars (see Figure 6-41), 2 inches deep by 1 inch thick containing a 20% deep notch with a 0.050-inch radius, were cycled at 350° F for a minimum of 200 cycles at an initial local notch strain of $\pm 0.5\%$. This strain range, measured using a strain gage with a 1/32-inch gage length, has been found to produce a shift of 100° F in previous tests of this alloy. Final loading of the bend bar was performed in compression to avoid inducing residual compressive stresses. Post fracture microhardness tests of the region near the notch indicated that local hardening had occurred, with an average Knoop hardness number of 216 compared with 169 for regions away from the notch. The depth of the locally hardened region has not yet been determined, and this work is in progress.

After cycling, it was observed that some of the bars contained cracks at the notch associated with cyclic strain aging. However, as noted further, the results of tests on specimens both with and without cracks indicated no appreciable effect of cracks on the notch bend strength.

The notch bend fracture properties of this steel over the range of -320° F to room temperature are shown in Figure 6-42 and listed in Table 6-6. These tests were made using a span of about 7.5 inches. Cooling was performed with either an alcohol-dry-ice mixture (-105° F) or liquid nitrogen (-320° F). For intermediate temperatures, the bar was cooled to -320° F and allowed to heat to the test temperature. Specimen temperatures were monitored using a copper-constantan thermocouple embedded 1/4 inch beneath the surface of the specimen near the notch.

* Note that stress intensification factor is different from stress intensity factor, a measure of the stress in the region of a crack tip.

FIGURE 6-38. STRESS INTENSIFICATION FACTOR, OUTSIDE SURFACE, CURVED PIPE

FIGURE 6-39. STRESS INTENSIFICATION FACTOR CALCULATED FROM STRAIN GAGE DATA FOR OUT-OF-PLANE BENDING OF A 6-INCH, SCHEDULE-40 STAINLESS STEEL ELBOW PIPE RUPTURE STUDY, TASK D-3

FIGURE 6-40. STRESS INTENSIFICATION FACTOR CALCULATED FROM STRAIN GAGE DATA FOR IN-PLANE BENDING OF A 6-INCH, SCHEDULE-40 STAINLESS STEEL TEE PIPE RUPTURE STUDY, TASK D-3

(a) NOTCH BEND TEST SPECIMEN

(b) TEST SETUP

FIGURE 41. SCHEMATIC FEATURES OF TEST SPECIMEN AND TEST SETUP

FIGURE 6-42. EFFECT OF TEST TEMPERATURE ON NOTCH BEND STRENGTH OF A-212B CARBON STEEL WITH CYCLICALLY STRAIN AGED NOTCH

TABLE 6-6
RESULTS OF NOTCH BEND TESTS OF LOCALLY
CYCLICALLY STRAIN AGED BEND BARS

<u>Test Temperature (° F)</u>	<u>Incipient Cracks at Notch</u>	<u>Notch Fracture Strength on Net Section (psi)</u>	<u>Fracture Appearance [Depth of Fibrous Tear (in.)]</u>
RT	No	105,000	1.6 (100% fibrous)
-105	Yes (0.26 in.)*	138,000	0.32 (0.06)
-105	Yes (0.07 in.)	132,500	0
-150	No	100,000	0
-150	Yes (0.01-0.015)	119,700	0
-200	No	127,600	0
-320	Yes (0.07-0.08)	57,800	0

* Figures in parentheses are crack depths.

The results of these tests shown in Figure 6-42 indicate within scatter that the nominal net section bend strength is essentially constant over the range of room temperature to -220° F, with low fracture strength occurring at -320° F. Comparison of the two tests at -150° F, one of which contained incipient cracks developed during the cyclic straining, revealed no appreciable effect of this variable. Examination of the load-deflection curves revealed no evidence of incipient or partial fracture associated with a shallow brittle region. The appearance of the fracture surface revealed all fibrous fracture at room temperature and a shallow fibrous tear in one test at -150° F.

As soon as reference specimens are tested, it will be possible to determine whether bend bars without a cyclically strain aged region would exhibit essentially identical behavior to that of these current tests. However, the results in Table 6-6 indicate that cyclic strain aging at the conditions evaluated, including incipient cracks, does not result in partial or complete low-stress, brittle fracture over the temperature range of interest.

SECTION VII

TASK K—EFFECT OF ENVIRONMENT

(D. A. Hale)

7.1 OBJECTIVE

The objective of Task K is to determine quantitatively the effect of BWR primary coolant on the low-cycle fatigue life of piping steels. Measurements of cycles-to-failure will be obtained employing a specially-designed fatigue testing unit in an experimental piping loop at a boiling water reactor. The planned test duration is 2-1/2 years, allowing time for corrosion, if any, to affect crack initiation and growth.

7.2 SUMMARY

The fatigue machine, including specimens, was assembled in preparation for shakedown testing at 550° F in a test loop at San Jose. The large vessel, which will contain the fatigue machine in the Dresden experimental loop, was completed and ready for shipment. Seven axial-hole specimens, fatigued to failure, showed reasonably consistent and predictable behavior. Engineering drawings and operating instructions for the complete experimental loop system were distributed for final approvals.

7.3 DYNAMIC TEST VESSEL (DNPS-1)

The vendor (National Forge) has completed fabrication and final hydrotesting of the dynamic test vessel.

7.4 SHAKEDOWN VESSEL AND TEST LOOP

The fatigue test machine was being assembled on the shakedown vessel head at the end of the report period, in preparation for the hot phase of shakedown testing.

An existing contact plate from the fatigue machine has been modified to accept three of the special spring-loaded ball plungers, which will also be evaluated during the hot shakedown testing.

A condenser connected to the leak-off port of the chevron-ring packing gland will enable measurement of packing gland leakage, if any, which occurs during the hot tests. The magnitude of this leakage will determine whether a bellows-type seal will be required.

7.5 STATIC TEST VESSEL

The static test vessel can accommodate the following numbers of static specimens: 63 "1-T" modified WOL specimens (Figure 7-1), and 36 stress bend specimens (Figure 7-2).

Holding fixtures have been designed to support the WOL and stress bend specimens inside the static test vessel. The fixtures are modular in design and couple to form a continuous train

FIGURE 7-1. DETAILED MACHINE DRAWING FOR MODIFIED WOL SPECIMEN

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TITLE
STRESS BEND SPECIMEN
FIRST MADE FOR GENERAL USE

1 MAT'L: PER ENGRG. INST.

UNLESS OTHERWISE SPECIFIED USE	APPLIED PRACTICES	SURFACES	TOLERANCES ON MACHINED DIMENSIONS		
			FRACTIONS	DECIMALS	ANGLES
	145A5481	32✓	$+\frac{1}{32}$ $-\frac{1}{32}$	$+.005$ $-$	$+$ $-$

REVISIONS	PRINTS TO

MADE BY *D. Bechen Oct 10-63*
ISSUED *G.E. Graham NOV. 6 '63*

APPROVALS
A.P.E.D.
SAN JOSE

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FIGURE 7-2. STRESS BEND SPECIMEN

inside the vessel. They can be uncoupled during specimen inspections to facilitate handling of the fixtures in the limited cubicle space.

7.6 FATIGUE SPECIMEN EVALUATION

Room temperature, constant-deflection, dynamic, specimen evaluation testing continued during the report period, with a total of 15 specimen tests completed and an additional 5 specimens under test at the end of the period.

7.6.1 Transverse Hole Specimen Concept

The results of the six transverse hole specimens tested during the report period are summarized in Table 7-1. Initiation and failure data from all the transverse hole specimens tested to date are summarized in Figure 7-3. Smooth bar data from Task D-2 (GEAP-5082, Table 6-1) have been included for reference.

7.6.2 Axial Hole Specimen Concept

Seven axial hole specimens were tested during the report period; pertinent test parameters are summarized in Table 7-2. An additional group of five of these specimens was under test at the end of the period.

Examination of the fracture surfaces of the two specimens that failed in the reduced thickness region (Figure 7-4, MT-D-9; Figure 7-5, MT-D-18) indicated that the crack front that penetrated to the axial cavity initiated on the surface of the reduced thickness section and grew toward the neutral axis of the specimen.

In both these cases, the cycles required to initiate a surface crack represented the major portion of the total lifetime of the specimen (88% for MT-D-9, $\approx 100\%$ for MT-D-18).

7.6.3 Specimen Material Procurement

The specifications for the plate material which will be used for specimen machining are listed as follows:

Type-304 Stainless Steel	ASTM A-240, Type-304
Type-304L Stainless Steel	ASTM A-240, Type-304L
Inconel-600	ASTM B-168
Carbon Steel	ASTM A-516, Grade 70, qualified to A-300 practices and purchased to specified Charpy Impact Test Values (this specification has superseded A-212B).

The stainless Type-304L, carbon steel, and inconel plate materials have been received. Surplus Type-304 plate formerly used for specimens in Task D-1 was being transferred from the M&P Lab in Schenectady at the end of the report period.

Machining of rough specimen blanks from the Dresden-I equalizer line in which in-service cracks were detected was also underway at the end of the report period.

TABLE 7-1

TEST RESULTS—TRANSVERSE SPECIMENS

<u>Specimen</u>	<u>Initial Strain Range</u>	<u>Crack Initiation</u>	<u>Failure</u>	<u>Remarks</u>
MT-D-10	3480 $\mu\epsilon$ ($\pm$ 1740 $\mu\epsilon$)	No crack was detected prior to full section failure	Full section failure near tip <u>away from transverse hole</u> at 25,379 cycles	Since failure did not occur near strain gages, cycles-to-failure cannot be related to a measured strain range
MT-D-11	3350 $\mu\epsilon$ ($\pm$ 1675 $\mu\epsilon$)	Crack ($\approx$ 0.250 in. long) noted near top right edge of specimen <u>over transverse hole</u> at 81,834 cycles	Specimen no longer contacting upper loading screw at 85,002 cycles, full section failure <u>through transverse hole</u> at 85,120 cycles	
MT-D-12	7000 $\mu\epsilon$ ($\pm$ 3500 $\mu\epsilon$)	Specimen cracked across width on top surface at 3998 cycles <u>over transverse hole</u>	Full section failure at 4267 cycles, specimen tip contacted both upper and lower loadings screws until end of test	
MT-D-13	7000 $\mu\epsilon$ ($\pm$ 3500 $\mu\epsilon$)	Specimen cracked across full width on top surface at 5297 cycles <u>over transverse hole</u>	Specimen no longer contacting upper loading screw at 6273 cycles. Full section failure at 9648 cycles	
MT-D-14	4800 $\mu\epsilon$ ($\pm$ 2400 $\mu\epsilon$)	Crack ($\approx$ 0.050 in. long) noted near top left edge of specimen <u>over transverse hole</u> between 18,530 and 18,787 cycles	Specimen no longer contacting upper loading screw between 26,100 and 26,179 cycles, full section failure <u>over transverse hole</u> at 26,454 cycles	
MT-D-15	4950 $\mu\epsilon$ ($\pm$ 2475 $\mu\epsilon$)	Edge crack noted at 3487 cycles near tip <u>away from transverse hole</u>	Full section failure at 3900 cycles near tip <u>away from transverse hole</u>	Since failure did not occur near strain gages, cycles-to-failure cannot be related to a measured strain range

TABLE 7-2

TEST RESULTS—AXIAL SPECIMENS

<u>Specimen</u>	<u>Initial Strain Range</u>	<u>Crack Initiation</u>	<u>Failure</u>	<u>Remarks</u>
MT-D-9	8200 $\mu\epsilon$ ($\pm$ 4100 $\mu\epsilon$)	Fine crack detected visually between 9520 and 9680 cycles on top surface near right edge and approximately 0.350 in. long	Leakage from axial cavity noted at 10,903 cycles, test terminated	Examination of fracture surface indicates that crack did, in fact, initiate on outer surface of specimen and propagate inward
MT-D-16	5000 $\mu\epsilon$ ($\pm$ 2500 $\mu\epsilon$)	No surface cracks detectable under dye penetrant inspection at conclusion of test (131,598 cycles)	-----	Specimen sectioned after conclusion of dynamic testing, <u>no internal cracks</u> found in region of axial cavity
MT-D-17	3200 $\mu\epsilon$ ($\pm$ 1600 $\mu\epsilon$)	No surface cracks detectable under dye penetrant inspection at conclusion of test (131,598 cycles)	-----	Specimen sectioned after conclusion of dynamic testing, <u>no internal cracks</u> found in region of axial cavity
MT-D-18	4600 $\mu\epsilon$ ($\pm$ 2300 $\mu\epsilon$)	No surface cracks noted prior to detection of water leakage from axial cavity	Water leakage detected in <u>reduced thickness section</u> from axial cavity at 105,615 cycles	Examination of fracture surface revealed three distinct and separate "thumbnail"-shaped cracks $\approx$ 0.030 in. deep, one of which penetrated axial cavity.
MT-D-19	3650 $\mu\epsilon$ ($\pm$ 1825 $\mu\epsilon$)	No surface cracks detectable under dye penetrant inspection at conclusion of test (131,598 cycles)	-----	Specimen sectioned after conclusion of dynamic testing, <u>no internal cracks</u> found in region of axial cavity
MT-D-20	6950 $\mu\epsilon$ ($\pm$ 3475 $\mu\epsilon$)	Small edge crack detected at intersection tapered sides and constant width tip (not in reduced thickness section) at 6104 cycles	Full section failure at site of original crack at 6309 cycles	Since failure occurred away from strain gages, cycles to failure cannot be related to a given strain range. Specimen sectioned after conclusion of dynamics testing, <u>no internal cracks</u> found in region of axial cavity
MT-D-21	8000 $\mu\epsilon$ ($\pm$ 4000 $\mu\epsilon$)	Small edge crack detected at intersection tapered sides and constant width tip (not in reduced thickness section) at 1300 cycles	Full section failure at site of original crack at 1677 cycles	Since failure occurred away from strain gages, cycles to failure cannot be related to a given strain range. Specimen sectioned after conclusion of dynamics testing, <u>no internal cracks</u> found in region of axial cavity

FIGURE 7-3. MEASURED STRAIN RANGE ϵ_{pp} , 10^{-2} in./in. VERSUS SPECIMEN CYCLES. MATERIAL: TYPE-304 STAINLESS STEEL, ROOM TEMPERATURE, CONSTANT DEFLECTION TESTS

FIGURE 7-4. SPECIMEN MT-D-9

FIGURE 7-5. SPECIMEN MT-D-18

7.6.4 Specimen Compliance Calibration

The compliance calibration fixture has been completed; final alignment checks were under way at the end of the report period.

7.7 DNPS-1 RELATED ACTIVITY

7.7.1 Loop Piping

The loop cubicle design package was forwarded to Commonwealth Edison during the report period. The package consists of a loop operating manual, a complete set of construction prints, and a summary of the results of the piping stress calculations.

All the brackets, valves, fittings, lead shielding, and miscellaneous adapters required for installation of the cubicle piping have been received or were on order at the end of the report period.

Bids were solicited for A-frame gantry and portable roll-around hydraulic cranes for use in the loop cubicle during specimen inspections. The bids were being evaluated at the end of the report period.

7.7.2 Loop Instrumentation

The loop operating panel has been completed (Figure 7-6); it will be stored at Vallecitos until it is required for loop startup at Dresden.

Final bids have been received for pressure switches suitable for use with the proposed axial cavity specimen concept. A bid review was under way at the end of the report period.

7.7.3 Loop Chemistry Characterization

The panels for the loop chemistry sample station were approximately 50% complete at the end of the report period.

FIGURE 7-6. LOOP OPERATING PANEL

APPENDIX A

FRACTOGRAPHIC CRACK GROWTH RATE ANALYSIS
BY SCANNING ELECTRON MICROSCOPY

(U. E. Wolff)

A.1 SUMMARY

As an alternative to electron microscopy of surface replicas for determination of crack growth rate, scanning electron microscopy was used directly on the surface of a pipe fatigue fracture. Striations across the whole pipe thickness were observed and photographed. The magnification range employed was 100× to 3000×. The lower end of the magnification scale is much lower than in the conventional electron microscope, and such low magnifications, coupled with the large depth of focus of the scanning electron microscope, are very useful for the measurement of wide striation spacings.

From comparatively few striation spacing measurements, the crack propagation rate as a function of crack depth was determined by the same method used for conventional electron microscopy. Crack initiation was calculated to have occurred after about 700 cycles, compared to 2050 cycles observed visually. However, considering the observed crack length of 0.7 in. on the pipe surface at 2050 cycles, the two results do not contradict each other. The second half-amplitude band was found in the scanning electron microscope at the place observed macroscopically, and in general, the calculated values agreed well with the cycle history.

The use of the scanning electron microscope for fatigue striation measurements appears to offer great time savings without sacrifice in accuracy of measurements. The scanning electron microscope has a resolution limit of 200 Å, but for striation spacings larger than $\sim 30\mu\text{m}$, electron microscopy offers the only feasible method of measurement.

A.2 INTRODUCTION

Crack propagation rates in fatigued reactor piping have previously been determined by electron microscopy of replicas of the fracture surfaces.* The specimen preparation for this kind of investigation has been rather laborious, especially since a high degree of accuracy was required in matching the electron micrographs of striations with the place on the fracture containing these striations.

Scanning electron microscopes, which have become commercially available in recent years, require no preparation of metallic surfaces. (Nonconducting surfaces must be coated with a thin film of gold to make them conducting.) An image of such surfaces is produced by scanning the surface with an extremely fine electron beam and collecting the secondary electrons emitted from the surface.** The image is displayed, after amplification by a photo-multiplier tube, on a long persistence fluorescent screen.

* GEAP-5637, Appendix A, June 1968.

** Other modes of image formation are also possible, but will not be discussed here.

Because of the potential time savings in specimen preparation, a scanning electron microscope (JSM of Japan Electron Optics Laboratory Company, Ltd.) was used to examine a pipe fatigue fracture similar to those investigated earlier, and to perform the same type of crack propagation analysis.

A.3 DETAILS OF FATIGUE TEST

The specimen, HWD-3, was a Schedule-40 straight pipe of ASTM-A312, Type-304 stainless steel. It had a circumferential butt weld with an incomplete fusion defect on the internal surface. This defect was expected to provide the nucleation site for the fatigue crack. The pertinent test parameters were as follows: The pipe was tested at 550°F without internal pressure, with a stress range of about 60,000 psi. The cantilever end deflection was ± 7.19 inches. Contrary to expectation, the fatigue crack started from the outside surface and was observed visually after 2049 cycles; at that time the crack was 0.720 inch long. Wall penetration was detected after 3600 cycles. Prior to wall penetration, two bands of 500 half-amplitude cycles were produced—the first from cycle No. 1201 to 1700, and the second from cycle No. 3001 to 3500. The first of these amplitude reductions was applied before the crack was observed on the outside surface. The second amplitude reduction was made 100 cycles prior to crack penetration. This band was visible on the fracture surface as a brown line about 1 mm from the inside surface at its closest approach (see Figure A-1). A third amplitude reduction was made directly after breakthrough, and this also resulted in a dark band visible in Figure A-1.

FIGURE A-1. FATIGUE FRACTURE SURFACE OF PIPE HWD-3. SECOND (ARROW) AND THIRD AMPLITUDE REDUCTIONS ARE SEEN AS DARK BANDS. APPROXIMATE AREA OF FIGURE A-2 IS OUTLINED.

A.4 SCANNING ELECTRON MICROSCOPY

One of the specimen holders of the scanning electron microscope (SEM) can accommodate a maximum specimen size of 1 inch diameter. Therefore, a section containing the whole wall thickness, approximately $3/4$ inch long (in the circumferential direction) and $3/4$ inch high, centered on the crack initiation site was cut out of the fractured pipe. The dark half-amplitude band was marked with a spot of silver paint to facilitate recognition in the SEM.

An attempt at internal calibration was made by mounting an optical stage micrometer side by side with the fracture surface. However, all attempts to find the scale were unsuccessful, probably because of the presence of a protective coating invisible to the eye. The previous calibration of the SEM, therefore, had to be accepted as correct. A different type of internal calibration, however, was also used and is described as follows.

A great advantage of the SEM is that micrographs with magnifications as low as $100\times$ can be taken. Consequently, it was possible to take slightly overlapping SEM pictures at that magnification, covering the whole width of the fracture (the thickness of the pipe) (Figure A-2). After the mounting of this composite, its length—assuming $100\times$ magnification—could be compared with the actual width of the fracture. This comparison gave an indication of the accuracy of the instrument magnification. As seen in Figure A-2, the specimen traverse inadvertently was made at an angle to the tube radius. The approximate location of Figure A-2 is marked in Figure A-1. When this angle is taken into account, the recorded magnification of $100\times$ is approximately 3% greater than the magnification computed from the length of Figure A-2.*

In addition to the $100\times$ pictures, a micrograph at higher magnification containing fatigue striations ($1000\times$ or $3000\times$ as appropriate) was taken from the center or near-center of the area covered by each of those $100\times$ micrographs which did not contain striations wide enough to be measured at $100\times$.

A.5 RESULTS

Figure A-3 shows a portion of Figure A-2 near the inside surface of the tube, i.e., where crack break-through occurred and the widest striation spacings would be expected. As can be seen, the striation spacing is very wide near the inner surface and decreases rapidly with distance from the surface. At 1-mm distance from the inside surface, the brown band was seen on the fracture surface (Figure A-1). In this area in the SEM, a distinct dark band of about 0.15-mm width was seen (arrow in Figure A-3) with no striations resolvable at $100\times$. At $3000\times$, however, very fine striations were observed (Figure A-4) which obviously correspond to the second set of half-amplitude bending cycles applied. On the other side of this band the striation spacing became large again, and then gradually decreased toward the crack initiation site on the outside tube surface (Figures A-5 and A-6). The first half-amplitude band was not found in the SEM.

* A second magnification check would be possible by recording the stage translation on its micrometer. This was not done in the present case, but should be done in future investigations.

OUTSIDE
SURFACE

INSIDE
SURFACE

FIGURE A-2. COMPOSITE OF SCANNING ELECTRON MICROGRAPHS COVERING THE WHOLE FRACTURE WIDTH (ORIGINAL MAGNIFICATION 100x)~ 30x

100x

FIGURE A-3. PORTION OF FIGURE A-2 CONTAINING INSIDE SURFACE AND DARK HALF-AMPLITUDE BAND. AREA OF FIGURE A-4 WITHIN THAT BAND IS MARKED.

2250x

FIGURE A-4. NARROW STRIATIONS IN SECOND HALF-AMPLITUDE BAND (MARKED IN FIGURE A-3)

Evaluation of the striation spacing measurements was done as described previously* for replica electron microscopy.

The relation between striation spacing and crack depth is shown in Figure A-7. The equations for the three straight-line sections are:

$$1000 \frac{da}{dN} = 1.21 a + 0.62 \quad 0 < a < 3.5, \quad (A-1)$$

$$1000 \frac{da}{dN} = 4.14 a - 9.56 \quad 3.5 < a < 5.2, \quad (A-2)$$

$$\begin{aligned} & \text{(Width and location of the half-amplitude band)} \\ & 5.2 < a < 5.35, \quad (A-3) \end{aligned}$$

$$1000 \frac{da}{dN} = 55.44 a - 290 \quad 5.35 < a < 6.3, \quad (A-4)$$

where

a = the crack depth in mm, and

$\frac{da}{dN}$ = the crack propagation rate in mm (with the crack depth " a " at cycle number " N ").

* GEAP-5637, Appendix A, June 1968.

1000x

FIGURE A-5. 2.8 mm FROM OUTSIDE SURFACE

3000x

FIGURE A-6. 0.3 mm FROM OUTSIDE SURFACE

FIGURE A-7. CRACK PROPAGATION RATE FOR HWD-3 DETERMINED FROM SCANNING ELECTRON MICROGRAPHS

The deep dip in the curve corresponds to the half-amplitude band.

The number of cycles within each section is calculated by stepwise integration of the inverse inverse equation as was shown in GEAP-5637, Appendix A:

$$N_i = \int_{a_i}^{a_{i+1}} \frac{dN}{da} da.$$

The thus-calculated numbers of cycles are compared with the recorded cycle history in Table A-1 (going backwards from the inside surface).

TABLE A-1

COMPARISON OF CALCULATED AND RECORDED NUMBERS OF CYCLES

	<u>Calculated</u> <u>Number of Cycles</u>		<u>Cycle History</u> <u>Number of Cycles</u>
Inside Surface (crack breakthrough)	40	Full amplitude	100
Dark Band		Half amplitude	500
	220 } 1080 }	Full amplitude	1300
1640 {		Half amplitude	500
	560	Full amplitude	1200
Outside Surface (crack initiation)			

A few words of explanation are in order:

- a. If one counts, on Figure A-2, all the striations from the dark band to the inside surface, the result is about 40—the same as by integration of the curve. It is therefore concluded that the first breakthrough of the fracture in fact occurred at about cycle No. 3540.
- b. The number of cycles calculated from the straight line extending from 0 to 3.5-mm crack depth is 1690. Since this number ought to contain the first half-amplitude band, 50 cycles were deducted to arrive at the number of full-amplitude cycles (the width of 500 half-amplitude striations usually corresponds to the width of about 50 full-amplitude striations, as explained in more detail in GEAP-5637).
- c. If 1300 cycles between the first and second half-amplitude band are taken as the base for calculating the position of the first half-amplitude band, the result is 0.56 mm below the outside surface of the tube. At about 0.4 mm below the surface, a narrow line was recognized (not visible on Figure A-1) which possibly could represent this half-amplitude band. The striation spacing in this band is expected to be below the resolution limit of the SEM.
- d. If all the calculations are accepted as correct, that leaves only $1200 - 560 = 640$ cycles for crack initiation. If the position of the first half-amplitude band is assumed to be at a crack depth of 0.4 mm, then crack initiation would have occurred after ~730 cycles. Both numbers are far below the macroscopically observed number of 2049 cycles. However, at that time the crack length was measured to be already 0.720 inch long. If the crack is assumed to be elliptical, then from the geometry of the pipe a crack 0.72 inch long should be about 0.022 inch or 0.56 mm deep. At that depth, it would already have passed the first half-amplitude band. These findings agree quite well with the values calculated from the relatively few striation measurements.

A.6 CONCLUSIONS

The advantages of scanning electron microscopy for the measurement of striation spacings and crack propagation rates on fatigue fractures are several-fold:

- a. No specimen preparation is necessary except cutting out a piece with maximum dimensions of 1 inch.
- b. The low magnifications obtainable with the SEM permit quick scanning of the complete fracture and measuring of large striation spacings which exceed the capability of the conventional electron microscope.
- c. Exact location of high-magnification pictures is easy to establish, thus improving the accuracy of crack depth measurements.

- d. The contrast of the striations is at least as good, and probably better in the SEM than on replicas. The depth of focus is comparable with the conventional electron microscope; it far exceeds that in the light microscope, thus making the low- as well as the high-magnification SEM pictures very useful.

Whenever maximum resolution is not required (the resolution limit of the SEM is about 200Å), great time savings can be realized when fatigue fracture analysis is carried out with a scanning electron microscope.

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