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**REACTOR PRIMARY COOLANT SYSTEM
RUPTURE STUDY
QUARTERLY REPORT NO. 20
JANUARY-MARCH 1970**

U. S. ATOMIC ENERGY COMMISSION
CONTRACT AT(04-3)-189
PROJECT AGREEMENT 37

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**REACTOR PRIMARY COOLANT SYSTEM RUPTURE STUDY
QUARTERLY PROGRESS REPORT NO. 20**

January -- March 1970

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1. INTRODUCTION

The Reactor Primary Coolant System Rupture Study is being conducted for the Safety Branch, Division of Reactor Development and Technology, USAEC. This twentieth quarterly report documents progress for the period of January 1 to March 31, 1970. 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 was continued on the following tasks:

Task A—Probability Study,

Task B—Stress Analysis,

Task C—Fracture Mechanics,

Task D—Fatigue, and

Task K—Effect of BWR Environment.

No further work is planned for Tasks B and C. Task B effort terminated with the preparation of an assessment report recommending cessation of additional studies in view of the advanced status of other codes—in particular, the work of Clough at the University of California (Berkeley). Task C studies ended with the completion of scheduled burst tests of flawed elbows and tees.

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 as follows.

Quarterly Reports

GEAP-4911	Reactor Primary Coolant System Rupture Study Quarterly Progress Report No. 1, April–June 1965.
GEAP-4964	No. 2, July–August 1965.
GEAP-5082	No. 3, October–December 1965.
GEAP-5147	No. 4, January–March 1966.
GEAP-5192	No. 5, April–June 1966.
GEAP-5279	No. 6, July–September 1966.
GEAP-5427	No. 7, October–December 1966.
GEAP-5474	No. 8, January–March 1967.
GEAP-5512	No. 9, April–June 1967.
GEAP-5554	No. 10, July–September 1967.
GEAP-5587	No. 11, October–December 1967.
GEAP-5637	No. 12, January–March 1968.
GEAP-5680	No. 13, April–June 1968.
GEAP-5716	No. 14, July–September 1968.
GEAP-5770	No. 15, October–December 1968.
GEAP-10024	No. 16, January–March 1969.
GEAP-10072	No. 17, April–June 1969.
GEAP-10120	No. 18, July–September 1969.
GEAP-10143	No. 19, October–December 1969.

Topical Reports

GEAP-4445—A Survey of Water Reactor Primary System Conditions Pertinent to the Study of Pipe Rupture, January 1964.

GEAP-4446—A Review of Fracture Modes as Related to Reactor Primary Coolant Pipe Rupture, May 1964.

GEAP-4474—Experimental and Analytical Program Recommendations—Reactor Pipe Rupture Study, January 1965.

GEAP-4574—Survey of Piping Failures for the Reactor Primary Coolant Pipe Rupture Study, May 1964.

GEAP-4578—Mechanical Design Considerations in Primary Nuclear Piping, March 1964.

GEAP-4678—Fracture Mechanics and the Stability of Engineering Structures, September 1965.

GEAP-5014—Fracture Toughness of Some Engineering Alloys, March 1966.

GEAP-5410—Low-Cycle Fatigue Strength Reduction in Notched Flat Plates, January 1967.

GEAP-5471—PAPA—Structural Analysis of Plates and Shells Using Trapezoidal and Triangular Plate Elements, March 1967.

GEAP-5553—PAPA—The Digital Computer Program for the Static Analysis of Structures Made Up of Plate and Panel Elements, October 1967.

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

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

T&AM-677—A Three-Dimensional Photoelastic Study of Stress Near Cracks in Shell Structures, University of Illinois, March 1968.

GEAP-5620—Failure Behavior in ASTM A106-B Pipes Containing Axial Through-Wall Flaws, April 1968.

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

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

GEAP-5714—Notched High-Strain Fatigue Behavior of Three Low-Strength Structural Steels, September 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

GEAP-10007—Restart for the PAPA Program, March 1969.

GEAP-10090—The 550°F Notched High-Strain Fatigue Behavior of Three Low-Strength Structural Steels, August 1969.

GEAP-10135—Low-Cycle Fatigue of Prototype Piping, January 1970.

2. SUMMARY

2.1 TASK A—PROBABILITY STUDY

To estimate the probability of leakage due to low-cycle fatigue at a selected section of pipe in 40 years by the distribution of time-to-damage method, it is necessary to introduce the concept of computing mean $\log \Delta K$ for each random crack. The probability of leakage at the selected section (by Monte Carlo using importance sampling by weighting functions chosen by density tip truncation of beta distribution) was estimated to be 0.008. To estimate the probability of leakage in a piping loop, the stress uncertainty values at all selected sections will be related to each other (for purposes of analysis, will be the same), whereas initial crack depth, intercept, and slope values may be chosen independently.

2.2 TASK B—STRESS ANALYSIS

The assessment report, incorporating a review and evaluation of the PAPA code and related finite element codes, was completed. Areas of the PAPA code requiring further work were identified. It was recommended that additional studies on PAPA be suspended in view of the advanced status of other codes.

2.3 TASK C—FRACTURE MECHANICS

A total of 19 flawed A234 elbows and tees (13 this quarter) were hydrostatically pressurized to failure, augmenting the tests of straight pipe conducted in the previous year. The failure diagram—developed for A106-B pipe with short, part-through, axial flaws—accommodated the data for axially flawed elbows, provided the change in hoop-to-axial-stress ratio was considered.

2.4 TASK D—LOW-CYCLE FATIGUE

Testing was completed on the following samples during the report period:

- CSTS-3: A cold stainless steel tee, out-of-plane loading through the branch
- CCTS-2: A cold carbon steel tee, out-of-plane loading through the branch
- CCTS-1: A cold carbon steel tee, in-plane loading through the branch

Review copies of the topical report, GEAP-10135, "Low Cycle Fatigue of Prototype Piping," covering tests through 1969, were submitted for approval.

2.5 TASK K—EFFECT OF BWR ENVIRONMENT

2.5.1 Schedule

Barring unforeseen difficulties, the test loop with specimens will start up in June.

2.5.2 Test Hardware

All the Dresden fatigue test machine parts are complete, awaiting specimen installation. The adjustments made as a result of the hot shakedown tests have been completed.

The low-cycle fatigue machine for conducting the "baseline" tests in air at 500°F is nearing completion.

2.5.3 Test Specimen Manufacture

The manufacture of all the fatigue specimens, static WOL specimens, and static stress bend specimens is close to completion. The major item still underway is the attachment of the capillary tubes to the individual fatigue specimens.

2.5.4 Electrochemical Study

Installation of the electrochemical monitoring system was completed at the test loop at the Dresden I plant. The linear polarization behavior of samples of stainless steel and plain carbon steel is being continuously monitored at the loop inlet flange. The second flange, which is adjacent to the fatigue unit, will be operational when the loop starts up.

3. TASK A—PROBABILITY STUDY (S. A. Wilson)

3.1 OBJECTIVES

The objectives of the probability study task are to develop methods for:

- Estimation of the reliability of a reactor primary piping system in terms of leak rate and time of reactor service.
- Identification of the principal sources of real variability or uncertainty in service life.

3.2 SUMMARY

In the problem of estimating the probability of leakage due to low cycle fatigue at a chosen study section of pipe, in 40 years service life, by the distribution of time to damage method, it is shown that it is necessary to introduce the idea of computing mean $\log \Delta K$ for each random crack to permit $\log C$ and B to be selected independently; probability of leakage at the study section by Monte Carlo, using importance sampling by weighting functions chosen by density tip truncation of beta distributions, is estimated as 0.008 using 3000 iterations; area of study section can be chosen arbitrarily; and probability of leakage anywhere in the piping loop must consider that the stress uncertainty values at all study sections will be related to each other (for purposes of analysis, will be the same), whereas initial crack depth, intercept, and slope values may be chosen independently.

3.3 USE OF MEAN $\log \Delta K$ TO MAKE SLOPE AND INTERCEPT INDEPENDENT IN THE n_f EQUATION

When the fundamental low-cycle fatigue crack growth rate equation,

$$da/dn = A (\Delta K)^B, \quad (1)$$

is linearized as

$$\log da/dn = \log A + B (\log \Delta K), \quad (2)$$

corresponding to the standard linear model,

$$y = a + bx, \quad (3)$$

intercept $\log A$ ($\log da/dn$ evaluated at $\log \Delta K = 0$) is not independent of slope B ($\log \equiv \log_{10}$, $\ln \equiv \log_e$, although in descriptions "log" can often be either). Random cracks, described by values of $\log A$ and B drawn independently at random from their respective distributions, along with the nominal crack, are illustrated by Figure 3-1. Obviously, lines 1 and 2 miss entirely the region of observed cracks. We wish to sample independently from the distributions of $\log A$ and B to estimate the probability of leakage in a reactor lifetime using a Monte Carlo method. A device which permits $\log A$ and B to be drawn independently is to write the linear model in mean-adjusted form,

$$y = c + b(x - \bar{x}) \quad (4)$$

$$\log da/dn = \log C + B (\log \Delta K - \text{mean } \log \Delta K) \quad (5)$$

wherein $\log C$ and B are independent. The question is, what should be used for mean $\log \Delta K$? This should be the mean of the $\log \Delta K$'s corresponding to each cycle of growth. Random cracks adjusted for mean $\log \Delta K$ appear in Figure 3-2. Cracks for different values of slope only, adjusted for mean $\log \Delta K$, are illustrated in Figure 3-3. It has been found that mean $\log \Delta K$ varies with starting and stopping $\log \Delta K$ values—and thus with initial crack depth, and stress—and with slope. Conditions were for fixed wall thickness. Mean $\log \Delta K$ does not vary with intercept. Mean $\log \Delta K$ versus initial crack depth, stress, and slope are illustrated in Figures 3-4 through 3-6. Finally, the variations of $\log$ cycles to leak, $\log n_f$, with functions of initial crack depth, stress, slope, and intercept are given in Figures 3-7 through 3-10. The most important observation is that there is now little dependence of n_f on B , and the dependence on stress and intercept is not increased; thus initial crack depth, a_0 , remains as the key variable determining n_f . This compares to the important second-place role played by B , as described in the last column of Table 3-2 of the Fourteenth Quarterly, GEAP-5716. It can be seen by comparison of Figures 3-1 and 3-2 that a

Figure 3-1. Nominal and Two Random Cracks, Showing Improper Pivoting at Log $\Delta K = 0$

Figure 3-2. Nominal and Two Random Cracks, Showing Proper Pivoting at Log $\Delta K = \text{Mean Log } \Delta K$

Figure 3-3. Crack Growth Lines of Cracks Having Fixed Intercept and Random Slope Values, Showing that Line Pivoting Follows Mean $\text{LOG } \Delta K$

Figure 3-4. Initial Crack Depth (as $\sqrt{a_0/t}$) versus Mean Log ΔK

Figure 3-5. Stress (as $\text{Log } \sigma_{PM}$) versus Mean $\text{Log } \Delta K$

Figure 3-6. Slope, B , versus Mean Log ΔK

Figure 3-7. Cycles to Grow Through, n_t , versus Initial Crack Growth (as $\sqrt{a_0/t}$)

Figure 3-8. Cycles to Grow Through, n_t versus Stress (as Log σ_{PM})

Figure 3-9. Cycles to Grow Through, n_t versus Random Component of Intercept, $\Delta \text{Log } C$

Figure 3-10. Cycles to Grow Through, n_t versus Slope, B

reduction in variance n_t results from using mean $\log \Delta K$, for the same variability in B. This was anticipated, as it appeared that any choice of value on the x scale at which to pivot the random line, other than the appropriate $\bar{x}$, would artificially inflate the variability of n_t . It is not shown, but it is likely now that while the variance of n_t (as described in Table 3-2 of the Fourteenth Quarterly, GEAP-5716, and Table 3-1 of the Fifteenth Quarterly, GEAP-5770) is reduced in value, the reduction is due entirely to the way in which the variance of B participates (a compensating term for mean $\log \Delta K$ being foreseen), and thus the major contributing variance will be that of initial crack depth, a_o .

Since all lines in Figures 3-7 through 3-10 are parallel, the variables are independent; and since they are straight lines, with the exception of n_t versus B, n_t may be written as a linear function as shown below, for B fixed at 4.45. Having such a linear expression will speed the Monte Carlo solutions. B will not participate as a variable at this time; probability values so obtained will be slightly low.

A linear expression for n_t , for B = 4.45, is

$$\log n_t = 27.3064 \cdot 1.0084 (\Delta \log C) - 4.5069 (\log \sigma_{PM}) - 6.2615 \sqrt{a_o/t} \quad (6)$$

where n_t = Cycles to leak at the selected piping study section.[†]

$\Delta \log C$ = Random deviation from the nominal intercept $\log C$, at any $\log \Delta K$.

$\log \sigma_{PM}$ = Primary membrane stress per Table 3-1 of the Thirteenth Quarterly GEAP-5680.

$$\sigma_{PM} = S_{exp} \times S_{exp}^* + S_{hoop}/2.$$

$$S_{hoop} = Pd/2t = 1000 \times 6.624/(2 \times 0.432) = 7667 \text{ psi.}$$

a_o/t = Initial crack depth ratio to wall thickness.

$\log \equiv \log_{10}$

3.4 MONTE CARLO ESTIMATION OF PROBABILITY OF LEAKAGE

As indicated in subsection 3.5 of the Fifteenth Quarterly, GEAP-5770, the probability of leakage in 40 years service life due to low-cycle fatigue at one piping study section,[†] using the n_t equations appearing as Equations (9), (10), and (11) of the Thirteenth Quarterly, GEAP-5680, and an uncertainty distribution for each variable, can be estimated using importance sampling and the Monte Carlo method. The problem is to select weighting functions so that the variance of estimate is less than would be gotten by using crude Monte Carlo, even with substantially fewer iterations.

[†] A "piping study section" is a length of pipe having a unique nominal value for each of the variables; typically, it is the length to which is assigned the design stress found at one cross stress analysis node or "joint", although a change in nominal value of some other variable might define its extent, such as of mean crack occurrence rate λ due to considering weld or base material. For locations of stress analysis nodes, see "BWR Primary Piping Stresses for System Reliability Analysis," GEAP-5724. A "piping loop" is made up of all its study sections, and a "piping system" comprises all the loops. A "study surface" having area α is the portion of the outside surface of a study section within which the distribution of maximum initial crack depth is formed for the purpose of estimating the probability of leakage in the study section. By subsection 4.3.5 of the Twelfth Quarterly, GEAP-5637, the expansion stress, S_E , computed at a stress analysis node is taken as axial (due to system bending); $\sigma_{PM} = S_E \times S_E^* + S_h/2$ corresponds; and by subsection 3.2.3 of the Ninth Quarterly, GEAP-5512, this stress applies to 1/4 of the circumference. Thus, for circumferential cracks the study surface area will be circumference/4 by the length of the study section. These ideas of study section and study surface are intended to clarify and supersede the idea of "piping cross section" introduced in subsection 3.2.3 of the Ninth Quarterly, GEAP-5512. It is shown in subsection 3.5 herein that α may be chosen arbitrarily.

Weighting functions are probability density functions which, in general, should be high and constant over most of the region of the variable which gives results in the region of the function for which the probability is desired, low and constant in most of the remaining region, and tapered between the two. The approach tried here was to follow these steps:

- Find the value of each variable such that the CDF value $F_1(x)$ for each variable is the same, and $n_t = 360$ cycles, reference number of cycles for 40 years service.
- Find the value of each variable in turn which, when changed separately, give $n_t = 2000$, the other two variables remaining at the values found in Step a.
- Find the α value in the beta distribution [in Equations (1) through (4) of the Sixteenth Quarterly, GEAP-10024] such that the CDF $F_2[F_1(x)]$ of the beta weighting function equals 0.05 at the value of the variable giving $n_t = 2000$ found in Step b.
- Remove the tip, on the density scale, of the PDF $f_2[F_1(x)]$ of the beta weighting function so found and standardize the area back to 1.

This process resulted in the three weighting functions shown in Figures 3-11 through 3-13 (parameters shown in Table 3-1). They are drawn to scales identical to Figures 3-2 through 3-7 of the Sixteenth Quarterly, GEAP-10024. The pattern of estimates by groups of 25 iterations indicates that further variation reduction should be possible by refinement of weighting function selection.

Three runs of 1000 iterations each gave the results shown in Table 3-2. The uncertainty distributions and inverse cumulatives used were as shown in Table 3-3. The inverse cumulative for SE^* is adequate, and faster to evaluate than that used in Table 3-2 in GEAP-10024.

Table 3-1. WEIGHTING FUNCTION PARAMETERS

Figure Number	Random Variable	Common $F_1(x)$ for $n_t = 360$	Corresponding x Value	Beta Distribution α Value for $F_2[F_1(x)] = 0.05$ and $n_t = 2000$ (Each Variable Separately)	Corresponding x Value (Prior to Truncation)	Area of Beta Density after Truncation, before Readjustment to 1
3-11	a_o/t max	0.94647	0.1924	27.70	0.1085	0.5591
3-12	$\Delta \log C$	0.94647	+0.5989	2.88	- 0.1356	0.9925
3-13	SE^*	0.94647	2.0020	34.09	1.3207	0.4488

NOTE: See Figures 3-11 through 3-13

Table 3-2. ESTIMATES OF PROBABILITY OF LEAKAGE
(At One Piping Study Surface Having Area 5.2025 Square Inches)

Run No.	Iterations	n_c = Cycles Shown	Estimate of Probability of Leakage: $P_r [n_t \leq n_c]$	Variance of Estimate, All $\times 10^{-6}$	2 σ Confidence Limits on Estimate		Variance of Same Estimate by Crude Monte Carlo (Binomial), All $\times 10^{-6}$	Reduction in Variance: $\frac{V \text{ (Importance Sampling)}}{V \text{ (Crude Monte Carlo)}}$
					Lower	Upper		
1†	1000	90	0.00535	0.5481	0.00386	0.00683	5.320	0.103
2	1000	90	0.00425	0.4075	0.00297	0.00553	4.232	0.0963
3	1000	90	0.00398	0.1469	0.00321	0.00475	3.960	0.0371
1-3	3000	90	0.00453	0.123	0.00383	0.00523	1.503	0.0818
1	1000	360	0.00867	2.109	0.00576	0.01157	8.594	0.246
2	1000	360	0.00714	0.970	0.00517	0.00911	7.087	0.137
3	1000	360	0.00727	1.072	0.00520	0.00934	7.220	0.148
1-3	3000	360	0.00769	0.461	0.00633	0.00905	2.543	0.181
1	1000	1000	0.01099	2.180	0.00804	0.01394	10.870	0.201
2	1000	1000	0.00917	1.032	0.00714	0.01121	9.086	0.114
3	1000	1000	0.00930	1.153	0.00715	0.01144	9.214	0.125
1-3	3000	1000	0.00982	0.485	0.00843	0.01121	3.241	0.150

NOTE: See Subsection 3.4 for discussion.

† Run 1 was performed simultaneously for $n_c = 90, 360$, and 1000, using the same random numbers and n_t solutions. Runs 2 and 3 were performed in the same way, using entirely different random numbers.

Figure 3-11. Weighting Function for $a_0/t \max$

Figure 3-12. Weighting Function for $\Delta \log C$

Figure 3-13. Weighting Function for S_E^*

Table 3-3. UNCERTAINTY DISTRIBUTIONS

Random Variable	Uncertainty Distribution	Inverse Cumulative, $F_1^{-1}(x) =$
a_0/t max,	Figure 3-8a, Ref. 1 [†]	Table 3-2, Ref. 1 [†]
Maximum initial crack depth ratio	Without ultrasonic testing case Area of study surface: $\alpha = \pi d l / 4 = \pi \times 6.624 \times 1/4$ $= 5.2025 \text{ in}^2$ Mean crack occurrence rate: $\lambda = 0.1 \text{ crack/in}^2$ $t = 0.432 \text{ in.}$	$(F^{-1} = a_0/t \text{ max})$
S_E^* , Uncertainty coefficient on expansion stress	Figure 3-14 herein Nominal expansion stress: $S_E = 27450 \text{ psi}$	See "Supplement to Table 3-3"
$\Delta \log C$, Random deviation of intercept	Figure 3-10, Ref. 1 Normal distribution: Mean = 0 Variance = 0.13802	Table 3-2, Ref. 1 $(F^{-1} = \Delta \log C)$
B, slope	Treated as a constant: $B = 4.45$	None

[†] Reference 1: Sixteenth Quarterly, GEAP-10024.

Supplement to Table 3-3. Inverse Cumulative for S_E^*

$$0 \leq F_1 \leq 0.89917: \quad (F^{-1} = S_E^*)$$

$$\sim 0.45 \leq F^{-1} \leq 1.0471:$$

$$F^{-1} = \frac{2.2990 + \sqrt{0.0876 + 10.205 F_1}}{5.1024}$$

In Figure 3-14, Curve P

$$0.89917 < F_1 \leq 1 - 9.0 \times 10^{-4}:$$

$$1.0471 < F^{-1} \leq 8.1128:$$

$$F^{-1} = \frac{-\ln(1 - F_1) - 1.6}{0.6631}$$

Curve L1

$$1 - 9.0 \times 10^{-4} < F_1 \leq 1 - 2.2 \times 10^{-5}:$$

$$8.1128 < F_1 \leq 33.755:$$

$$F^{-1} = \frac{-\ln(1 - F_1) - 5.8}{0.1454}$$

Curve L2

$$1 - 2.2 \times 10^{-5} < F_1 \leq 1$$

$$33.755 < F_1 \leq \sim 100$$

$$F^{-1} = \frac{-\ln(1 - F_1) - 7.4}{0.098}$$

Curve L3

3.5 DEMONSTRATION THAT PROBABILITY OF LEAKAGE IN A PIPING LOOP IS INDEPENDENT OF THE AREA OF THE PIPING STUDY SURFACE

The initial crack depth distribution used is that of the *maximum* crack depth which occurs in the study surface when cracks are Poisson distributed over the piping surface at a mean occurrence rate of λ cracks/square inch, and crack depth is given by the uncertainty distribution on page 3-9 of the Sixth Quarterly, GEAP-5279, for the case without ultrasonic testing. The resulting distributions are shown in Figure 3-1 of the Fifteenth Quarterly, GEAP-5770, for values of $\lambda = 0.01, 0.1, 1, 10$, and 100 cracks/square inch. The question is, is the choice of surface area entirely arbitrary from an analytical viewpoint, as it would be for the Poisson distribution alone, or must some adjustment be made depending on the area used? The answer is that the choice is arbitrary, which may be shown as follows:

Case 1: Piping loop consists of, say, 10 identical study sections, each having surface area α . Then, probability of leakage anywhere in the loop is:

$$P[L] = 1 - \prod_{i=1}^{10} (1 - P[C_i])$$

where $P[L]$ = Probability of leakage anywhere in the loop,
 $P[C_i]$ = Probability of leakage at the i^{th} study section.

Figure 3-14. Original and Fitted CDF's of S_E^* , Uncertainty Coefficient on Expansion Stress

Simplify the problem by fixing all variables in the n_t equation, except $a_0/t \text{ max}$. Then $P[C_i]$ is given simply by the probability that $a_0/t \text{ max}$ exceeds some value. This probability is $1 - F(a_0/t \text{ max})$ where $F(a_0/t \text{ max})$ is the CDF of the maximum initial crack depth. For the case of no ultrasonic testing, this expression is found in the "Cumulative" column, Table 3-2 of the Sixteenth Quarterly, GEAP-10024, as

$$F(x) = e^{-\alpha\lambda[1-F_Z(x)]}, \quad (8)$$

where $x = a_0/t \text{ max}$,

α = Surface area at the study section,

λ = Mean crack occurrence rate, and

$F_Z(x)$ = CDF of a_0/t (not $a_0/t \text{ max}$),

so that

$$\begin{aligned} P[L] &= 1 - \prod_{i=1}^{10} \left\{ 1 - [1 - F_i(x)] \right\} \\ &= 1 - \prod_{i=1}^{10} F_i(x), \end{aligned}$$

$$P[L] = 1 - e^{-10\alpha\lambda[1-F_Z(x)]} \text{ for Case 1.}$$

Case 2: Piping loop consists of one study having surface area = 10α . Thus,

$$P[L] = 1 - \Gamma(a_0/t \text{ max}),$$

$$P[L] = 1 - e^{-10\alpha\lambda[1-F_Z(x)]} \text{ for Case 2,} \quad (9)$$

which is the same as for Case 1.

The equivalence may be seen numerically. From Figure 3-1 of the Fifteenth Quarterly, GEAP-5770,

$$\text{For } \lambda = 0.01, F(a_0/t \text{ max} = 0) = 0.94931,$$

$$\text{For } \lambda = 0.1, F(a_0/t \text{ max} = 0) = 0.59437.$$

Using two values of λ as a way of introducing 10 in the exponent:

$$\begin{aligned} \text{Case 1: } P[L] &= 1 - \prod_{i=1}^{10} 0.94931 \\ &= 1 - 0.59437 \\ &= \underline{\underline{0.40563}} \end{aligned}$$

$$\begin{aligned} \text{Case 2: } P[L] &= 1 - 0.59437 \\ &= \underline{\underline{0.40563}} \end{aligned}$$

3.6 INDEPENDENCE OF VALUES OF VARIABLES AT SUCCESSIVE STUDY SECTIONS IN A PIPING LOOP

In computing the probability of leakage at any place in a piping loop in 40 years by the distribution of time to damage method, it is important to consider whether the values of the random variables are independent from study section to study section. It is clear that the values chosen for initial crack depth, intercept and slope are independent among study sections, but that the value of stress is not; that is, if some cause of uncertainty in the piping stress has occurred and the effect is to raise the stress at a chosen study section by a factor of two, then certainly the stress at nearby study sections will also be raised by some factor related to two. Consider the probability of occurrence of E, the event of leakage anywhere in a loop, where A, B and C are the events of leakage at the three study sections making up the loop, and S_E^* is the stress uncertainty coefficient to which event A is subject:

$$P_1[E] = P[A] P[B] P[C], \text{ and} \quad (10)$$

$$P_2[E] = P[A] P[B|S_E^*] P[C|S_E^*]. \quad (11)$$

In equation (10) randomly chosen values of S_E^* apply at each study section, whereas in equation (11) the same value applies.

Suppose, for purposes of this analysis, that the *same* stress uncertainty coefficient applies throughout a loop as applies at the first section studied. Then it can be shown that $P_2[E] > P_1[E]$, and computing only $P_1[E]$ is unconservative. To compute $P_2[E]$ by Monte Carlo using importance sampling, it is appropriate to perform each iteration simultaneously for all study sections, using different randomly chosen values for intercept, slope, and initial crack depth for each study section but the same uncertainty coefficient for stress for all study sections. Since the outcome of any Monte Carlo iteration is a value for $P[C_i]$ of Equation (7), then $P[L]$ of that equation may be found for each simultaneous set of iterations, and a grand mean $P[L]$ is found after n iterations in the same manner as when considering only one study section.

It remains to conduct the foregoing probability estimate demonstration for the piping loop being studied. This would be probability E in Figure 3-1 of the Ninth Quarterly GEAP-5512, for the loop. Then probability E for the reactor system, $P[E_S]$, is

$$P[E_S] = 1 - \prod_{\ell=1}^n [1 - P(E_\ell)],$$

for n loops in the system, assuming all causes of leakage are independent among loops. Even though other loops are larger, the probability of their leakage may be less because of the high design stresses in the loop studied. No other theoretical obstacles are foreseen on the low-cycle fatigue leakage problem. Practical additional work includes:

- Further rationalization of the weighting function selection procedure.
- Reintroducing B as a random variable in Equation (10).
- Finding the variance of n_t for the case of adjustable mean $\log \Delta K$. It is likely that the variance of a_0/t now makes the largest contribution to $\text{var } n_t$, either with or without ultrasonic testing.
- Assigning alternative uncertainty distributions, particularly other values of λ in the a_0/t max equation, to observe their effect on the probability of leakage.

Increased attention will be given to estimating the probability of severance without prior detectable leakage, probability 17 and predecessors on Figure 3-1 of the Ninth Quarterly, GEAP-5512, as begun in subsection 3.4 of the Nineteenth Quarterly, GEAP-10143.

4. 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. Designers of nuclear piping systems 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

The objective of the computer code development is to develop the analytical tools required to define the state of stress and strain in complex piping in service.

4.2.1 Summary

The assessment report,* incorporating a review and evaluation of the PAPA code and related finite element codes, was completed. Areas of the PAPA code requiring further work were identified. It was recommended that additional studies on PAPA be suspended in view of the advanced status of other codes.

* "Engineering Review of PAPA", by E.E. Zwicky, Jr., March 17, 1970.

5. TASK C—FRACTURE MECHANICS

(M. B. Reynolds)

5.1 OBJECTIVE

The objective of this task is an experimental determination of pressure load limits in tees and elbows of plain carbon steel, followed by generation of an empirical relation to estimate load limit in terms of flaw dimensions. A prior phase of this task dealt with the relationship between pressure load limit and flaw size in straight specimens of ASTM A106-B pipe.* The objective of the present effort is a determination of a similar relationship for flawed tees and elbows of the same material.

5.2 SUMMARY

A total of 19 flawed A234 elbows and tees (13 this quarter) were hydrostatically pressurized to failure—augmenting the tests of straight pipe conducted in the previous year. The failure diagram, developed for A106-B pipe with short, part-through, axial flaws, accommodated the data for axially flawed elbows, provided the change in hoop-to-axial stress ratio was considered.

5.3 INTRODUCTION

The maximum load a structure can support without failure by fracture or unstable plastic deformation is decreased by the presence of a flaw, the load limit decreasing monotonically with increasing flaw size. For brittle materials, the relation between load limit and flaw size in geometrically simple structures can be calculated by the techniques of linear elastic fracture mechanics using a single material property parameter—the plane strain fracture toughness K_{IC} . In the structures made of more ductile materials, it is necessary to correct the fracture mechanics equations to account for plastic deformation at the tip of the advancing flaw if the section thickness is great enough to permit use of fracture mechanics at all; otherwise, estimates of load limits must be made from geometrical factors and the stress-strain relation for the material.

In a previous phase of this task, pressure load limits were determined for straight segments of ASTM A106-B steel pipe containing either through-wall or part-through flaws of various lengths and depths. These experimental data were compared with predictions of modified fracture mechanics relations and were also treated empirically.^{2, 3}

In this work, pressure load limits were experimentally determined for a number of flawed ASTM A234-B welding fittings—the fittings commonly welded to ASTM A106-B pipe.

5.4 EXPERIMENTAL

Hydrostatic testing techniques used were identical to those used in testing pipe specimens and have been described in an earlier report. Water was used as the pressurizing fluid, and tests were carried out at 60°F. Tests were limited to tees and "short radius" elbows in 6-inch, Schedule-80 size. Flaw configurations tested were those shown in Figure 5-1. Flaws were of the external, part-through type, machined to as nearly constant depth as permitted by the irregular surface of the fittings. The fittings were closed by welding to them capped 1-foot lengths of 6-inch, Schedule-80 ASTM A106-B pipe. Approximate principal stress ratios at certain flaw locations were determined by pressurizing unflawed fittings equipped with resistance-type strain gages. The Poisson ratio value used in these calculations was based on strain values determined in the midpoint of a straight segment of pipe attached to the fittings.

* See subsection 5.6 for references.

A

B

SEE DETAIL P

C

TYPES OF ELBOW FLAWS

J

TYPES OF TEE FLAWS

K

L

SEE DETAIL P

DETAIL P
(SECT THRU FLAW)

Figure 5-1. Machined Flaws in Elbows and Tees

5.5 RESULTS

Data from the pressure tests are given in Table 5-1. For consistency with previous experiments,³ pressure load limits are reported as the fraction P/P_0 of the value for an unflawed fitting—pipe combination and flaw depths in terms of the ratio X/T of the ligament remaining at the base of the flaw to original wall thickness. Flaw lengths are reported as length at surface of fitting and an estimate of equivalent length of constant depth.

Appearances of the fractures after completion of the tests are shown in Figures 5-2 and 5-3. Only in those cases in which the pressure load limit was greater than 60% of that for an unflawed fitting did the fracture propagate beyond the ends of the original flaw. Review of the load limit data for axial part-through flaws in straight pipe segments³ shows that to produce a given reduction in pressure load limit, a more severe flaw is required in a tee or elbow than in a straight pipe segment. The limited number of fittings experiments done indicates that, as was the case with straight pipe segments, elbows and tees are most sensitive to flaws if the plane of the flaw is perpendicular to the maximum principal stress. In elbows, flaws of Types A and C behave much the same as axial part-through flaws of similar length in pipe segments, if corrections are made for differences in principal stress ratios at the flaw location.

Variations in wall thickness and stress gradients in tees render mathematical treatment of the effect of flaw size on load limit exceedingly difficult on anything more than a very rough basis. Of the three flaw configurations investigated, Types J and K cause the greatest reduction in strength when considered on a basis of flaw size (i.e., depth and length). In the absence of bonding loads, tees are very insensitive to flaws of Type L.

5.6 REFERENCES FOR SECTION 5

1. Reynolds, M. B., *Failure Behavior in Axially Flawed ASTM A106-B Pipes*, Paper 69-SESA-3, presented at meeting of Society for Experimental Stress Analysis, Houston, Texas, October 1969.
2. GEAP-5620, *Failure Behavior in ASTM A106-B Pipes Containing Axial Through-Wall Flaws*, April 1968.
3. GEAP-5622, *A Failure Diagram for Axially Flawed Pipes*, April 1968.

Table 5-1. FAILURE STRENGTH OF FLAWED AND UNFLAWED ELLS AND TEES

Specimen No.	Type	Flaw* Type	L _{max} Flaw Length Max. (in.)	P Burst Pressure (ksi)	L _{avg} Flow Length Avg. (in.)	P/P ₀ **	X/T***	T _{avg}
EL-1-8	EII	None	0	8.68	0	1.00	1.00	0.453
EL-1A-8	EII	A	3.25	6.56	3.1	0.76	0.39	0.490
EL-2A-8	EII	A	6.41	4.70	6.3	0.54	0.30	0.463
EL-3A-8	EII	A	6.31	6.47	6.2	0.74	0.63	0.444
EL-1B-8	EII	B	8.25	5.86	7.5	0.67	0.29	0.443
EL-2B-8	EII	B	11.59	6.09	10.7	0.70	0.51	0.447
EL-1C-8	EII	C	8.66	5.21	7.9	0.60	0.35	0.471
EL-2C-8	EII	C	7.94	7.05	7.2	0.81	0.63	0.445
EL-3C-8	EII	C	5.69	4.70	4.9	0.54	0.28	0.423
T-1-8	Tee	None	0	8.88	0	1.00	1.00	0.655
T-1J-8	Tee	J	5.69	6.33	5.0	0.71	0.78	0.645
T-2J-8	Tee	J	4.25	6.98	3.0	0.79	0.45	0.622
T-3J-8	Tee	J	6.25	5.84	5.2	0.66	0.45	0.638
T-1K-8	Tee	K	1.95	6.30	1.7	0.71	0.73	0.612
T-2K-8	Tee	K	1.75	6.70	1.0	0.75	0.70	0.641
T-3K-8	Tee	K	2.45	4.88	1.3	0.55	0.43	0.559
T-1L-8	Tee	L	5.5	8.85	4.7	1.00	0.77	0.646
T-2L-8	Tee	L	6.0	9.0	5.0	1.00	0.55	0.645
T-3L-8	Tee	L	4.0	9.18	2.9	1.00	0.43	0.685

* See Figure 5-1.

** P₀ = Failure pressure, unflawed.

*** T = Wall Thickness, inches,
X = Ligament thickness, inches.

EL-1A-8

EL-2A-8

EL-2B-8

EL-1C-8

EL-3A-8

EL-1B-8

EL-2C-8

EL-3C-8

SEE TABLE 5-1

Figure 5-2. Failure Appearances, Flawed Elbows

T-1J-8

T-2J-8

T-3J-8

T-1L-8

T-2L-8

T-3L-8

T-1K-8

T-2K-8

T-3K-8

SEE TABLE 5-1

Figure 5-3. Failure Appearances, Flawed Tees

6. TASK D—LOW-CYCLE 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 TASKS D-1, D-2, AND D-4

Tasks D-1, D-2, and D-4 have been completed. The final reports are in publication.

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

6.3.1 Summary

Testing was completed on the following samples during the report period:

- CSTS-3—Cold stainless steel tee, out-of-plane loading through the branch
- CCTS-2—Cold carbon steel tee, out-of-plane loading through the branch
- CCTS-1—Cold carbon steel tee, in-plane loading through the branch

Review copies of the topical report, GEAP-10135, *Low Cycle Fatigue of Prototype Piping*, covering tests through 1969, were submitted for approval.

6.3.2 Data Obtained

6.3.2.1 Crack Initiation

Ultrasonic inspection test methods have been used to determine cycles to crack initiation for the specimens tested. The results are shown in Table 6-1. The estimated crack depth, when first detected, ranged from 0.008 to 0.014 inch. These data have been added to the previously published data for crack initiation versus nominal stress range and are shown in Figures 6-1 and 6-2.

6.3.2.2 Through-Wall Penetration

Through-wall penetration was detected visually (water leakage) on all specimens tested. A typical example of how through-wall leakage appears when it first occurs is shown in Figure 6-3. After through-wall penetration has been established, the specimens are depressurized and drained. Typical examples of through-wall surface crack appearance are shown in Figures 6-4A and 6-4B. Surface cracks were observed in four places on specimen CSTS-3. Figure 6-5 is an overall view of the specimen, and Figures 6-6A through 6-6D are closeup views of the individual cracks at Cycle 3799. Through-wall penetration occurred in the top-right crotch area (Crack A) at Cycle 3675.

6.3.2.3 Surface Crack Growth

Following through-wall penetration, the cyclic loading is continued and surface crack length is observed and recorded. The tests are terminated when the surface crack growth rate versus test cycles approaches zero. Final surface crack geometry for specimen CCTS-1 and CCTS-2 are shown in Figures 6-7 and 6-8, respectively.

Table 6-1. DATA SUMMARY

Sample Description	Test Temperature (°F)	Internal Pressure (psig)	Stress Range (psi)	Cantilever End Deflection (in.)	Cycles to Crack Initiation (N_I)	Cycles to Fully Penetrate Wall (N_W)	Test Termination (N_ϕ)
CSTS-3							
ASTM A182-F Type-304 SS Schedule 40, Tee Loaded Through the Branch	68–72	1000	68,770	±8.66	2600*	3,675 (1,075)**	5,604 (1,929)***
CCTS-2							
ASTM A234-WPB Carbon Steel Schedule 40, Tee Loaded Through the Branch	69–74	1000	68,300	±6.88	6100*	9,367 (3,267)	10,449 (1,082)
CCTS-1							
ASTM A234-WPB Carbon Steel Schedule 40, Tee Loaded Through the Branch	70–76	1000	68,500	±5.125	9800*	21,079 (11,279)	30,700 (9,621)

* Determined by ultrasonics

** Values in parentheses are full amplitude cycles during through-wall growth ($N_W - N_I$)*** Values in parentheses are full amplitude cycles after full-wall penetration ($N_\phi - N_W$)

Figure 6-1. Stainless Steel, Room Temperature, Stress Range versus Initiation Cycles

Figure 6-2. Carbon Steel, Room Temperature, Stress Initiation Cycles

Figure 6-3. Through-Wall Penetration (Water Leakage), Specimen No. CCTS-2, Cycle 9367

Figure 6-4A. Through-Wall Penetration, Specimen No. CCTS-2. View shows bottom side of specimen (see Figure 6-4B for closeup view of fairline surface crack).

Figure 6-4B. Through-Wall Penetration, Closeup, Specimen No. CCTS-2

Figure 6-5. Out-of-Plane Loading Through the Branch, Specimen CSTS-3, Room Temperature, Stainless Steel (see Figure 6-6 for crack areas)

Figure 6-6A. Surface Cracks in Top Right Crotch Area, Specimen No. CSTS-3

Figure 6-6B. Surface Cracks in Top Left Crotch Area, Specimen No. CSTS-3

Figure 6-6C. Surface Cracks in Bottom Left Crotch Area, Specimen No. CSTS-3

Figure 6-6D. Surface Cracks in Bottom Right Crotch Area, Specimen No. CSTS-3

Figure 6-7A. Final Fracture Geometry, Specimen No. CCTS-1 (see Figure 6-7B for closeup of fracture geometry)

Figure 6-7B. Closeup Showing Final Fracture Geometry for Specimen No. CCTS-1

Figure 6-8. Final Fracture Geometry, Specimen No. CCTS-2. View shows bottom side of tee.

7. TASK K—EFFECT OF BWR 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 the Dresden I 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

Barring unforeseen difficulties, the test loop with specimens will start in June.

The replacement motor for MOV-1 has been received and will be installed during a scheduled plant outage in April. The construction drawings covering additional loop piping to accommodate a third test vessel have been approved by Commonwealth Edison. The third unit will add capability for low-cycle fatigue testing of WOL type specimens.

All the Dresden fatigue test machine parts are complete awaiting specimen installation. The adjustments made as a result of the hot shakedown tests have been completed.

The low-cycle fatigue machine for conducting the "baseline" tests in air at 500°F is nearing completion.

The manufacture of all the fatigue specimens, static WOL specimens, and static stress bend specimens is nearly complete. The major item still underway is the attachment of the capillary tubes to the individual fatigue specimens.

7.3 DRESDEN I TEST LOOP

The replacement motor for the isolation valve, MOV-1, ordered during the last quarter has been received at the Dresden I site and will be installed during the maintenance outage scheduled in April. Present plans, besides replacing the motor, are to complete the pre-startup checks initiated in August of last year.

Commonwealth Edison is reviewing installation details to accommodate test loop control room alarms and will supply cable routing instructions.

The construction drawings covering the piping changes required to add a third test vessel to the test loop were approved by Commonwealth Edison. The hardware not already on site has been transferred to the Dresden Station from San Jose. The installation scheduled in April will be followed by the pre-startup checks.

The specimen failure detection counter console has been completed and checked out, using the same array of 150 pressure switches which will eventually connect to the final group of 150 Dresden fatigue specimens. The setpoints on all the pressure switches were also checked to verify that they had been properly set at the factory.

7.4 TEST HARDWARE

7.4.1 Dresden Fatigue Test Equipment

All modifications to the Dresden fatigue test machine, deemed necessary based on the results of the hot shakedown testing, have been completed. The chevron seal has been upgraded with a carbon-impregnated teflon compound which has been proved to be more satisfactory for this service. The packing gland adapters have been remachined to tighter tolerances to

eliminate excessive clearances formerly present, which contributed to seal extrusion during the shakedown testing. The fixturing to set tip deflections on the 150 Dresden fatigue specimens has also been modified where necessary. The strain-deflection characteristics of the fatigue specimen are such (refer to Figure 7-2, GEAP-10143) that toolmaker's tolerances must be maintained during the adjustment of the specimen deflections to ensure that the specimens are actually loaded to the desired levels of strain.

7.4.2 High-Temperature Air Fatigue Test

The major portion of the electrical and mechanical hardware is on hand for the air fatigue unit which will be used to generate the baseline "air" data for comparison with the Dresden environmental fatigue data. The heater control equipment previously used for the Task D-3 prototype tests will be used to control the test vessel heaters and monitor test temperatures.

This facility is being assembled and will be ready for conducting tests in the next quarter.

7.5 TEST SPECIMENS

7.5.1 Specimen Manufacturing Program

7.5.1.1 Dynamic Specimens

Fatigue specimen "manufacture" was close to completion at the end of March. Approximately 90% of the specimens required for the total Task K test plan (Environment plus Air) have been finish-machined (complete with EDM axial hole per detail A-A, Figure 7-1) and heat-treated. The heat treat procedures used are summarized in the following paragraphs.

a. *Material Condition No. 1*—This process is meant to eliminate any cold work introduced in the specimens during machining and/or grinding and return the material to the "as-received", solution-annealed condition. Therefore, the procedure used does not represent a true solution anneal per se, but a light "re-anneal". Three of the four material groups (Types-304 and -304L stainless and Inconel) receive the following treatment:

- Five to ten minutes in air at 1800°F.
 - Water quench.
 - Pickle with nitric-hydrofluoric acid solution [20 to 25 vol % nitric acid (70%), 3 to 4 vol % hydrofluoric acid (60%), balance water] at 100 to 125°F for 15 minutes, or until clean.
- b. *Material Condition * No. 5*—This process is intended to produce furnace-sensitized material in the stainless steels and in the Inconel. Figure 7-2 represents a typical microstructure of furnace-sensitized, Type-304 stainless steel material produced by this process:
- 1150°F for 24 hours in air; furnace cool.
 - No subsequent pickling.
- c. *Material Condition * Nos. 6 and 7* — Only the carbon steel, both wrought and welded, will be produced in this condition, stress-relief annealed:
- 1150°F for 2 hours in air, furnace cool.
 - No subsequent pickling.

* Table 7-1, GEAP-10120 (Quarterly No. 18).

Fully Sensitized

250X

Figure 7-2. Material Condition No. 5, Type-304 Stainless Steel, 1150°F for 24 hours, Etch per ASTM-A262, Practice A

The centering of the axial hole used to signal specimen failure within the reduced thickness test section is measured, using ultrasonic techniques. The ultrasonic measurements were calibrated by sectioning a number of rejected specimens and measuring the actual eccentricity of the axial hole, using a 50X microscope.

Alternate schemes for attaching the 1/16-in. o.d. capillary tube to the individual fatigue specimens were evaluated. Several trial joints were fabricated by prospective vendors. These joints were sectioned and examined for porosity and/or lack of full fusion. Based on these examinations, a production order was awarded to produce the capillary-tube-to-specimen joints, using an arc-welding technique. To date, 63 joints have been completed; all have passed the final helium leak test (leak rate less than 10^{-9} standard cc/sec).

Machining was also completed on the fatigue specimens corresponding to Material Code No. 8. The reduced-thickness test section on these particular specimens was plunge-ground, using a standard 1-inch-diameter, cylindrical, grinding wheel.* The entire 0.010-inch depth of the transverse groove was ground in one rapid plunge ($\cong 4$ to 5 seconds) to simulate the rapid material removal rates and accompanying surface cold work resulting from typical field grinding operations. The grinding was done without coolant.

* Norton, VBE Bond, No. 23A46J5, at $\cong 14,300$ rpm ($\cong 3,800$ fpm surface velocity).

The mechanically pre-notched specimens (Test Conditions * 8, 9, 19, 20, 24, 25, and 30) are being machined. These specimens (Figure 7-3) have been provided with a very sharp (tip radius — $r < 0.005$ inch), shallow ($\cong 0.010$ inch) notch on both edges of the reduced thickness test section. The "pre-cracking" is meant to eliminate or drastically reduce the cycles required to initiate an active fatigue crack, thereby ensuring that the major portion of the cyclic life will be devoted to fatigue crack growth.

7.5.1.2 Static Specimens

All the WOL specimens required for the Task K test program** have been machined and heat treated. The specimens are now being fatigue pre-cracked at the M&P Lab; approximately 75% have already been completed.

Machining and heat treatment have also been completed on all the stress bend specimens*** destined for exposure in the Dresden test loop.

*Figure 7-3. Mechanically Simulated Crack Preparation
(Test Conditions 8, 9, 19, 20, 24, 25, 30)*

* Table 7-1, GEAP-10120 (Quarterly No. 18).

** Table 7-3, GEAP-10120 (Quarterly No. 18).

*** Table 7-2, GEAP-10120 (Quarterly No. 18).

7.6 TASK K-1—ELECTROCHEMICAL STUDY (R. L. Cowan)

7.6.1 Summary

Installation of the electrochemical monitoring system was completed at the test loop at the Dresden I plant. The linear polarization behavior of samples of stainless steel and plain carbon steel is being continuously monitored at the loop inlet flange. The second flange, which is adjacent to the fatigue unit, will be operational when the loop starts up.

7.6.2 Results

The system was installed to make automatic periodic determinations of corrosion potential (E_{corr}) and corrosion current (i_{corr}) by linear polarization measurements. A schematic diagram of one of the electrochemical flanges is shown in Figure 7-4. The specimens are electrically insulated from the flange by Conax fittings, and the only metallic part of the electrode assembly that "sees" the environment is the sample. All potential measurements are made with respect to the bright platinum reference electrode.

A Petrolite ten-station corrosion rate meter (Model No. M-1010-C1) is currently recording E_{corr} with respect to the platinum electrode and the linear polarization current, i_L , on a semi-continuous basis for Flange No. 2, and will begin to monitor Flange No. 1 when the loop is operative. The corrosion potential is measured through a high impedance circuit so that the sample is not polarized, and this value is recorded on a strip chart and also stored in the memory circuit of the meter. By a series of feedback amplifiers, the potential of the sample is then adjusted to a value of $E_{\text{corr}} - 10 \text{ mV}$ with respect to the platinum electrode by driving current to or from the electrode by means of the auxiliary electrode. This current, i_L , is then recorded after 10 minutes. After a switching operation, the meter performs the same operations on the next specimen, etc. The unit operates for 2 hours out of every 24.

If the predominant oxidation reaction is the anodic dissolution of the metal and both the oxidation and reduction reactions are activation controlled, the value of i_L can be used to calculate the corrosion rate by the use of linear polarization theory. The linear polarization equation is

$$i_{\text{corr}} = \frac{\beta_c \times \beta_a}{2.3 (\beta_a + \beta_c) \frac{\Delta\eta}{\Delta i}} \quad (1)$$

For our purposes, the value of $\Delta\eta$ is equal to $10 \text{ mV} - E_\Omega$, where E_Ω is the value of the resistive component of the overpotential, and can be measured separately. The parameters β_a and β_c are determined by measuring the complete anodic and cathodic polarization curve, and represent the anodic and cathodic Tafel constants, respectively.

Several attempts were made to measure the constants β_a and β_c by galvanostatic methods, but finally it was decided to measure them potentiostatically. A Wenking potentiostat was used for this purpose, and the results are shown in Figures 7-5 and 7-6. In both cases, the potentials are with respect to the bright platinum reference electrode. The potentials in both figures have been corrected for the IR drop in the water between the reference and sample electrode by the formula,

$$E = E_{\text{meas}} - IR_{\text{meas}} \quad (2)$$

The effective electrolyte resistance term was measured by the potential decay technique. The anodic and cathodic curves for each material were run on different electrodes so that the results would not be affected by the previous electrochemical history.

As can be seen in Figure 7-5, both materials exhibit linear behavior in their cathodic polarization. The linear behavior for the A106-B lasts over 400 mV of overvoltage and the Type-304 stainless steel exhibits linear behavior over 550 mV of overpotential. Obviously, the cathodic (reduction) kinetics are not activation controlled. Perhaps the slow step in the

reduction process is in the transport of electrons through the oxide film, as has been suggested by Pryor* for copper. In any event, this type of behavior invalidates the use of Equation (1) which was predicated on the presence of activation controlled anodic and cathodic processes.

The anodic process for both materials appears to be activation controlled. However, it seems that the predominant oxidation reaction may be some process other than the anodic dissolution of the metal. The basis for this hypothesis is that the extrapolation of the straight-line region of the anodic kinetics (activation controlled region) to the corrosion potential gives a corrosion current for each material on the order of $2.5 \mu\text{A}/\text{cm}^2$, which is one to two orders of magnitude higher than expected**, especially for annealed, Type-304 stainless steel. Thus, the electrochemical kinetics appear to be characteristic of some redox reaction such as $\text{H}_2 \leftrightarrow 2\text{H}^+ + 2\text{e}^-$ taking place on the oxide film of the metal. Perhaps the film has rectification properties so that electron transport is the slow step for the cathodic process (electrons going through the film into the metal), but for the anodic reaction the slow step is the activated process (electrons flow easily through film).

A complete theoretical analysis of the electrochemical behavior of this system will have to be made to rationalize the observed experimental behavior. Perhaps an equation of the type shown earlier—Equation 1—can be derived for this case.

The corrosion potentials that are continuously being monitored against the bright platinum electrode seem to be quite steady, which indicates that the platinum electrode is probably a good reference electrode for this service. The changes in potential with time and the differences in potential between Flange No. 1 and Flange No. 2 should serve as an excellent indication of the water redox properties. Interpretation of this type of data should not be limited by the aforementioned kinetic data interpretation.

* Pryor, M., N.A.C.E. Meeting, Philadelphia, Pa., March 1970.

** S. C. Datsko and C. R. Breden, "Corrosion of Metals in High Temperature Water at 500°F and 600°F," U.S.A.F.C. Report ANL-5354, 1954.

Figure 7-4. Electrochemical Flange Assembly

Figure 7-5. Cathodic Polarization Behavior of Type-304 Stainless Steel (Annealed) and A106-B Plain Carbon Steel in Dresden I Loop Electrochemical Flange No. 2

Figure 7-6. Anodic Polarization Behavior of Type-304 Stainless Steel (Annealed) and A106-B Plain Carbon Steel in Dresden I Loop Electrochemical Flange No. 2

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