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AEC RESEARCH AND
DEVELOPMENT REPORT
MARCH 1969

**REACTOR PRIMARY COOLANT SYSTEM
RUPTURE STUDY
QUARTERLY PROGRESS REPORT NO. 15
OCTOBER-DECEMBER 1968**

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

ATOMIC POWER EQUIPMENT DEPARTMENT
GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

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GEAP-5770
AEC Research and
Development Report
March 1969

REACTOR PRIMARY COOLANT SYSTEM RUPTURE STUDY

QUARTERLY PROGRESS REPORT NO. 15

OCTOBER—DECEMBER 1968

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Prepared for the
U. S. Atomic Energy Commission
Contract AT(04-3)-189
Project Agreement 37

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SECTION I

INTRODUCTION

The Reactor Primary Coolant System Rupture Study is being conducted for the Safety Branch, Division of Reactor Development and Technology, USAEC. This fifteenth quarterly report documents progress for the period of October 1 to December 31, 1968. 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.

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

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

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

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

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

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

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

GEAP-5014—Fracture Toughness of Some Engineering Alloys.

- GEAP-5082—Reactor Primary Coolant System Rupture Study Quarterly Progress Report Number 3, October—December 1965.
- GEAP-5147—Reactor Primary Coolant System Rupture Study Quarterly Progress Report Number 4, January—March 1966.
- GEAP-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-5770

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, 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.

GEAP-5714—Notched High-Strain Fatigue Behavior of Three Low-Strength Structural
Steels, September 1968.

SECTION II

SUMMARY

2.1 TASK A—RELIABILITY ENGINEERING

A brief description and status of the "Distribution of Time to Damage Method" of probability estimation, which is underlying the work in Task A, is given. Some additional properties of the low cycle fatigue n_f equation are illustrated; namely, distributions of maximum crack depth for selected crack occurrence rates both with and without ultrasonic testing, and the variance of an n_f solution with ultrasonic testing. An introduction to importance sampling by the Monte Carlo method is presented.

2.2 TASK B—STRESS ANALYSIS

Writing of a Users Manual and Programmers Reference Manual for the RESTART program is in progress. Work on the elastic-plastic computer code development was continued. The schedule for running test cases using the PAPA code has been delayed by code development problems. The final report covering experimental stress analysis studies of photoelastic models of pipe components at the University of Illinois was distributed.

2.3 TASK C—FRACTURE MECHANICS

Analysis was continued on results of burst tests of components with the various flaw configurations (axial, through wall, long and short part-through wall). Experimental work on pipes containing axial part-through flaws of varying lengths and depths was performed.

2.4 TASK D—FATIGUE

2.4.1 Task D-1—Crack Growth Studies

Studies on experimental portions of the work are continuing. Experimental determinations of crack growth rates in flattened and reheat-treated A106 pipe suggest slightly higher growth rates in the axial versus the circumferential direction; however, these differences are within the scatter observed in the correlation between stress intensity factor and crack growth rate.

Analysis of all stress-controlled and strain-controlled tests to date of both 5-inch- and 14-inch-wide plates of 2-1/4 Cr—1 Mo steel reveal no significant effect of specimen width on the correlation between stress intensity factor and crack growth rate.

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

Additional tests on grooved cylinders with uniaxial stress-concentration factors of 1.3 and 2.5 were run at room temperature. Determination of 550°F, smooth bar, low-cycle fatigue life under the completely reversed, strain-controlled condition continued. Analysis of notched bend tests progressed.

2.4.3 Task D-3--Prototype Pipe Fatigue Tests

Testing was completed on the 550°F, 1000 psi pressurized pipe straight, HSNP-80-1. Also completed were two elbows, one "good" circumferential butt weld specimen, and one "defective" circumferential butt weld specimen. Testing has started on the second "defective" circumferential butt weld specimen.

2.4.4 Task D-4--Cyclic Strain Aging

All results to date of the effect of cyclic strain aging on the Charpy impact transition temperature of carbon steel are described. It is observed that the influence of test temperature for a given cyclic strain range and number of cycles parallels the effect of temperature on the properties of statically loaded tensile specimens; maximum embrittlement occurs at about 350°F.

2.5 TASK K--EFFECT OF BWR ENVIRONMENT

Delivery of the dynamic vessel, to contain the fatigue testing machine, was scheduled for March by the vendor, National Forge. Piping drawings were completed for internal reviews. A surplus AEC vessel was acquired and modified to use for shakedown testing of the fatigue machine in an existing test loop at San Jose. Several alternate designs of specimens were selected for evaluation by fatigue testing in air. Not only is it necessary to demonstrate consistent failure behavior, but reliable crack detection means must be assured. This phase will continue into the next quarter.

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

$$\left[\begin{array}{c} \text{through wall leaks} \\ \text{or} \\ \text{complete severance} \\ \text{leaks} \end{array} \right] \quad \text{in} \quad \left[\begin{array}{c} 10 \\ 20 \\ 30 \\ 40 \end{array} \right] \quad \text{years of service.}$$

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

3.2 SUMMARY

A brief description and status of the "Distribution of Time to Damage Method" of probability estimation, which is underlying the work in Task A, is given in subsection 3.3. In subsection 3.4, some additional properties of the low cycle fatigue n_f equation are illustrated; namely, distributions of maximum crack depth for selected crack occurrence rates both with and without ultrasonic testing, and the variance of n_f solution with ultrasonic testing. An introduction to importance sampling by the Monte Carlo method is given in subsection 3.5.

3.3 APPLICATION OF THE DISTRIBUTION OF TIME TO DAMAGE METHOD

The reliability estimation method adopted for this task, and outlined in the sequence of steps given in subsection 3.2 of the Sixth Quarterly (GEAP-5279), is now called "The Distribution of Time to Damage Method." This name is appropriate because the method involves the distribution of an equation which predicts the time to damage by some damage mechanism. The area under this distribution lying less than some time of interest, as 40 years, is the probability of damage prior to 40 years, and is the particular value to be estimated. Work in subsequent quarters has been on understanding the properties of an equation which predicts the number of low-cycle fatigue cycles to grow a crack through a pipe wall from some starting depth. This equation is given in current form for computing as Equation (8) in the Fourteenth Quarterly, GEAP-5716. The variance of this function at a chosen pipe cross section was found in that Quarterly by the propagation of error method to identify the variables whose variability makes the largest contribution to the variability of the function. These were found to be initial crack depth, stress, and the two fracture mechanics parameters, A (or C) and B. Since the distribution shape of n_f is analytically inaccessible, the probability that n_f is less than n_c , the

number of operating cycles in 40 years, will be estimated by the Monte Carlo method, in particular using importance sampling, the introduction to which is given in subsection 3.5 of this Quarterly. The first estimate will be for one cross section. To find reliability with respect to low cycle fatigue for the entire system, it remains to estimate such probabilities at all other cross sections, and then to sum the estimates over the piping system. It is expected that such estimates will be smooth functions of stress and wall thickness (since initial crack depth distribution is in terms of a_o/t) which can be defined by Monte Carlo simulations at a few points, and obtained for others by interpolation.

3.4 ADDITIONAL PROPERTIES OF THE LOW-CYCLE FATIGUE n_t EQUATION

3.4.1 Distributions of $(a_o/t)_{\max}$ With and Without Ultrasonic Testing

Table 3-1 of the Thirteenth Quarterly, GEAP-5680, describes the first piping cross section at which the probability of leakage by low-cycle fatigue in 40 years is being estimated. Within that 1/4-circumference surface of the 1-inch-wide cross section that is subject to the maximum axial stress (due to bending and pressure), it is assumed that the initial defect that will leak first is the deepest one, designated $(a_o/t)_{\max}$. The distribution of this variable is specified by the distribution of a_o/t by depth, and the occurrence rate λ , cracks per square inch. Two judgmental distributions of a_o/t —with and without ultrasonic testing—were given in the Sixth Quarterly, GEAP-5279, but to see the distributions of $(a_o/t)_{\max}$ for chosen values of λ , see Figures 3-1 and 3-2. The distribution being used in the first reliability estimate is without ultrasonic testing (Figure 3-1) for $\lambda = 0.1$ cracks per square inch. It is seen that distribution of the deepest starting crack concentrates increasingly over the large values as higher occurrence rates are considered. The same would be true as larger surfaces are considered, since surface area and occurrence rate appear as a product ($\alpha\lambda$) in the probability density function of $(a_o/t)_{\max}$. It is also seen that the distributions of $(a_o/t)_{\max}$ take on values at 0, and then over the same continuous range as the distributions for a_o/t : from 0.01 to 0.8 for the case without ultrasonic testing and from 0.01 to 0.12 with ultrasonic testing, since for this case it is assumed that defects exceeding approximately 10% of the wall thickness are detected. The probability of 0 initial defect is seen to increase as the crack occurrence rate, λ , decreases, and is given by Equation (5) (shown later) as $F_{\max X}(x=0) = e^{-\alpha\lambda}$. Probability at 0 plus area under curve equals 1.

Specifically, Figures 3-1 and 3-2 display the p.d.f. of $(a_o/t)_{\max}$ which is the derivative with respect to x of Equation (5) (shown later), which is

$$f_{\max X}(x) = \frac{dF_{\max X}(x)}{dx} = \frac{d}{dx} e^{-\alpha\lambda} [1 - F_X(x)] \quad \text{or} \quad \frac{d}{dx} e^{-\alpha\lambda} [1 - F_{\log X}(x)] \quad (1a \text{ and } 1b)$$

$$= \alpha\lambda F_{\max X}(x) \left[\frac{dF_X(x)}{dx} = f_X(x) \right] \quad \text{or} \quad \alpha\lambda F_{\max X}(x) \left[\frac{dF_{\log X}(x)}{dx} = f_X(x) \right] \quad (2a \text{ and } 2b)$$

It is more convenient to write $F_X(x)$ as $F_{\log X}(z)$, where X is the random variable a_o/t , and z is a dummy scale designator for $\log a_o/t$, since the judgmental distributions for a_o/t were given on a $\log a_o/t$ scale. $\log a_o/t$ may be either common or natural log; for convenience, the differential given below is found for the natural log. The required equations are stated as follows:

FIGURE 3-1. PROBABILITY DENSITY FUNCTIONS OF MAXIMUM σ_0 † FOR SELECTED λ 's, WITHOUT ULTRASONIC TESTING

FIGURE 3-2. PROBABILITY DENSITY FUNCTIONS OF MAXIMUM a_0/t FOR SELECTED λ 's, WITH ULTRASONIC TESTING

	$1 - F_{\log X}(z)$	$f_{\max X}(x)$
Without ultrasonic testing	Equation, mid. p. 3-20, Fourteenth Quarterly	Table 3-2, $f_1 X(x)$ for Figure 3-8a, Sixteenth Quarterly. Equation at top, p. 3-20, Fourteenth Quarterly, is dF/dz not dF/dx , i.e., density on log x scale.
With ultrasonic testing	Equation (4)	Table 3-2, $f_1 X(x)$ for Figure 3-8b, Sixteenth Quarterly. Equation (3) herein is dF/dz

Thus, the two density functions for $(a_o/t)_{\max}$ can be compiled, per Equation (2), and plotted in Figures 3-1 and 3-2. Note that $\alpha\lambda$ appears as a product, as in the Poisson distribution by which it is assumed initial cracks are distributed over the pipe surface. Thus, the Poisson parameter is in effect $\alpha\lambda$. The specific α value used for Figures 3-1 and 3-2 is for the chosen pipe cross section, as follows:

$$\alpha = \frac{\ell C}{4} = \frac{\ell \pi d}{8} = \frac{1 \pi 6.624}{8} = 5.2025 \text{ in.}^2$$

λ and a_o/t are as shown on the figures.

3.4.2 Dispersion of n_t Under an Alternative a_o/t Distribution (G. T. Vernon)

A method was described in subsection 3.4 of the Fourteenth Quarterly, GEAP-5716, for measuring the dispersion of n_t by approximating the variance of the natural log of n_t , $\text{var } \ell n n_t$. This method was applied to the pipe cross section which had been chosen for first study (see subsection 3.4 of the Thirteenth Quarterly, GEAP-5680) on the basis of its having highest design stress. The results showed that the variables whose variances contributed most to $\text{var } \ell n n_t$ were a_o/t , B, stress and A. The contribution of each variable depends on the distribution used for each. Because of the predominating contribution of a_o/t (71%) and because a conservative (wide) a_o/t distribution had been used—for the case of no ultrasonic testing having been performed—it was decided to check the contribution of a_o/t using the narrower distribution for the case of ultrasonic testing having been performed. Reference distributions for both of these cases appear on page 3-9 of the Sixth Quarterly, GEAP-5279.

The probability density function for a_o/t with ultrasonic testing is read from the graph on the above-mentioned page, to be:

$$\frac{dF_{\log X}(z)}{dz} = \begin{cases} 0 & z < -\log 100 \\ y \cdot 01 \frac{\log 0.8 - z}{\log 0.8 + \log 100} & -\log 100 \leq z \leq -\log 15 \\ y \cdot 01 \frac{\log 0.8 + \log 15}{\log 0.8 + \log 100} \cdot \frac{\log 0.12 - z}{\log 0.12 + \log 15} & -\log 15 \leq z \leq \log 0.12 \\ 0 & z \geq \log 0.12 \end{cases} \quad (3)$$

where

X is a_0/t ,

z is a value on the $\log a_0/t$ scale, and

$y_{.01}$ is the value of this p.d.f. at $z = \log 0.01 = -\log 100$, and may be evaluated as

$$y_{.01} = \frac{2 (\log 0.8 + \log 100)}{(\log 0.8 + \log 100)^2 - (\log 0.8 + \log 15) \cdot (\log 0.8 - \log 0.12)}$$

Let us make the definition:

$$k = 1 / [(\log 0.8 + \log 100)^2 - (\log 0.8 + \log 15) \cdot (\log 0.8 - \log 0.12)] ;$$

then we may integrate the p.d.f. from the right to obtain:

$$1 - F_{\log X}(y) = \begin{cases} 0 & y \geq \log 0.12 \\ k \cdot \frac{\log 0.8 + \log 15}{\log 0.12 + \log 15} \cdot (\log 0.12 - y)^2 & \log 0.12 \geq y \geq -\log 15 \\ k \cdot [(\log 0.8 - y)^2 - (\log 0.8 + \log 15) \cdot (\log 0.8 - \log 0.12)] - \log 15 & -\log 15 \geq y \geq -\log 100 \\ 1 & y \leq -\log 100 \end{cases} \quad (4)$$

and—as in subsection 3.4.5.2 of the Fourteenth Quarterly—we obtain:

$$F_{\max X}(x) = e^{-\alpha \lambda} [1 - F_{\log X}(\log x)] \text{ for } x \geq 0 \quad (5)$$

where

α is the surface area of pipe under consideration, and

λ is the average number of cracks per unit area. (See subsection 3.4.5.2 of the Fourteenth Quarterly for details.)

Equation (5) is the cumulative distribution of the fractional depth of the largest crack in the pipe cross section, given that the cross section has survived the ultrasonic test.

We may use Equations (33) and (34) of the Fourteenth Quarterly to compute the expected value and variance, $E X_{\max}$ and $\text{var } X_{\max}$, of the variable $X_{\max}$, distributed according to Equation (2), from the p.d.f. of X given by Equation (3) (with ultrasonic testing) and find

$$\begin{aligned} E X_{\max} &= 1 - \left\{ \int_0^{0.01} e^{-\alpha \lambda} dx + \int_{0.01}^{1/15} e^{-\alpha \lambda} \cdot k \cdot [(\log 0.8 - \log x)^2 \right. \\ &\quad \left. - (\log 0.8 + \log 15) \cdot (\log 0.8 - \log 0.12)] dx \right. \\ &\quad \left. + \int_{1/15}^{0.12} e^{-\alpha \lambda} \cdot k \cdot \frac{\log 0.8 + \log 15}{\log 0.12 + \log 15} \cdot (\log 0.12 - \log x)^2 dx + \int_{0.12}^{1.0} dx \right\} \\ &= 0.0146,^* \end{aligned} \quad (6)$$

and by a similar method obtain

$$\text{var } X_{\max} = 0.531 \times 10^{-3}.*$$

These compare with 0.0364 and 7.0×10^{-3} , respectively, computed in subsection 3.4.5.2 of the Fourteenth Quarterly, under the assumption of no ultrasonic testing of the weld.

The contributions to the variance of $\ln n_t$, approximated for the cross section detailed in subsection 3.4 of the Thirteenth Quarterly, GEAP-5680, are displayed in Table 3-1. It is to be noted that the change from the assumption of no ultrasonic testing of that quarterly to that of ultrasonic testing of this quarterly causes a change in the partial derivative coefficient with respect to B as well as that with respect to a_o/t because of the change in $E X_{\max}$. The major contributor is now B, the slope parameter in the linear form of the crack growth equation,

$$\log \frac{da}{dN} = C + B \log \left(\frac{\Delta K}{\Delta K} \right) \quad (\text{see subsection 3.3 of the Fourteenth Quarterly}).$$

This one of the two parameters whose distributions derive from analysis of the Schenectady low-cycle fatigue experiments for each of three pipe materials (see Appendix A of the Fourteenth Quarterly, (GEAP-5716)). As to be expected, the contribution of a_o/t has dropped away from its previous dominant position. The expected value of n_t —under the assumptions of the Fourteenth Quarterly except for this (with ultrasonic testing) crack depth distribution—is higher at 4.1 Mc. As in subsection 3.4.7 of the same quarterly, GEAP-5716, 65 to 70% of tests under similar physical conditions would have fatigue lives lying between 0.13 and 129 Mc, that is, within a factor of $\exp(\sqrt{11.9005}) = 31.5$ of 4.1 Mc.

3.5 METHODS FOR CALCULATING PROBABILITY OF SHORT TIME TO DAMAGE (G. T. Vernon)

3.5.1 Introduction

We have mentioned in several Quarterlies that Monte Carlo simulation methods would be needed to make estimates of the lower tails of time to damage distributions (by lower tail, we mean those times to damage which are unusually low and would occur infrequently). In this Quarterly we will show how we hope to generate certain tail probabilities by these methods. The initial application will be on estimating the probability of leakage by low-cycle fatigue at the 1-inch welded cross section in the core spray line detailed in subsection 3.4 of the Thirteenth Quarterly, GEAP-5680. Before describing the Monte Carlo method we are planning to adopt, however, some general orientation might be of help. After an introduction of ordinary (or crude) Monte Carlo technique, we will show how a transformation of the original problem can be more efficient.

* Evaluated with $\alpha = 5.2025 \text{ in.}^2$, $\lambda = 0.1 \text{ crack/in.}^2$ (Thirteenth Quarterly, GEAP-5680, Table 3-1).

3.5.1.1 Ordinary Monte Carlo

The ordinary Monte Carlo method is to simulate the physical situation. Each physical variable in the model is simulated by one or more random numbers. The random numbers interact according to the equations of the model, yielding random numbers which simulate one possible outcome of the physical "test" (or experiment). By statistical techniques we may reduce the outcomes of several such iterations to a characterization of the distribution of possible outcome values. The procedure is analogous to laboratory experimentation, where some interesting aspect of the physical world is simulated under closely controlled laboratory conditions to test certain physical equations of a model. In Monte Carlo simulation, on the one hand, the model must simulate all physical processes by mathematical equations, and introduces distributions of the variables to account for the many perturbations to be found in nature: while in the laboratory, on the other hand, these perturbations are eliminated or failing that, compensations are made. In the laboratory, the complexity of the physical world is reduced to a situation where mathematical equations apply; in Monte Carlo simulation, the mathematical equations are augmented by distributions on the physical variables to approximate the complexity of the world more closely.

In a single Monte Carlo iteration (loop), a certain number of random numbers (which themselves might be random or depend on the random numbers) are generated to be substituted for random variables in the model equations. Let us call the random variables in a Monte Carlo simulation $X_1, X_2, \dots, X_I$ which take on random number values $x_1, x_2, \dots, x_I$ according to a model distribution $F(x_1, x_2, \dots, x_I)$.*

After various manipulations of these random values, we generate the outcome values. It may be clear that the set of instructions by which the outcome is attained is a procedure or—in mathematical terminology—a function of $x_1, x_2, \dots, x_I$, $\phi(x_1, x_2, \dots, x_I)$. This function may not have a large range of possible values; in fact, the values may just be the logical values TRUE (represented by 1 sometimes) to show that some condition occurs, and FALSE that it does not (0 in the above representation)—in which case the question "how often?" is being asked in the simulation. After several iterations, a set of outcome values is built up from which inductive inferences may be drawn by the usual statistical techniques.

In the Fourteenth Quarterly, GEAP-5716, subsection 3.4.2, we introduced many of the necessary concepts and definitions for this subsection. The "expected (or average) value" and "variance" of a function of random variables were defined and were noted to be analogous to the center of mass and second moment about the center of mass. It was not, however, justified how the terminology "average" would also be appropriate. By the "Law of Large Numbers"** under mild assumptions, which hold throughout these Quarterlies, the arithmetic average of a sequence of iterations of $\phi(X_1, X_2, \dots, X_I)$ lies within a given closeness of the expected value, $E \phi(X_1, X_2, \dots, X_I)$, with higher probability as the number of iterations increases

* Defined to be $\Pr\{X_1 \leq x_1, X_2 \leq x_2, \dots, X_I \leq x_I\}$.

** See E. Parzen, "Modern Probability and Its Applications," Wiley, 1960, pp. 371 ff.

TABLE 3-1
 CONTRIBUTIONS TO DISPERSION OF n_t AT CHOSEN CROSS SECTIONS
 (a_o/t with Ultrasonic Testing)

	Symbol	Cause Code No.	Design	Δ Design	Plan	$E \ln U_i \times 10^{-3}$	Expected Value	$\text{var } \ln U_i \times 10^{-3}$	$\text{var } U \times 10^{-3}$	Variance	$\frac{\partial \ln n_t}{\partial x_i}$	$\left(\frac{\partial \ln n_t}{\partial x_i}\right)^2$	$(\text{plan})^2 \cdot \left(\frac{\partial \ln n_t}{\partial x_i}\right)^2$	Contribution to $\text{var } \ln n_t$	Contribution to $\text{var } \ln n_t$ as percentage
Equation parameter	B	--	--	--	--	--	4.45	--	--	1.016	2.242*	5.02*		5.1051*	42.90*
Equation parameter	$\log C$	--	--	--	--	--	-3.96	--	--	0.138	-2.303	5.30		0.7318	6.15*
Thickness, in.	$\begin{matrix} U_1 \\ U_2 \\ U \\ t \end{matrix}$	$\begin{Bmatrix} 1.9 \\ 1.11 \\ 9.1 \end{Bmatrix}$	$\begin{Bmatrix} \\ \\ \\ 0.432 \end{Bmatrix}$	$\begin{Bmatrix} \\ \\ \\ -- \end{Bmatrix}$	$\begin{Bmatrix} \\ \\ \\ 0.432 \end{Bmatrix}$	$\begin{matrix} -0.158 \\ 0 \\ -0.158 \\ -- \end{matrix}$	$\begin{matrix} \\ \\ \\ 0.432 \end{matrix}$	$\begin{matrix} 0.443 \\ 2.012 \\ 2.455 \\ -- \end{matrix}$	$\begin{matrix} \\ \\ \\ 2.454 \\ -- \end{matrix}$	$\begin{matrix} \\ \\ \\ 0.46E-3 \end{matrix}$	$\begin{matrix} \\ \\ \\ 8.324 \end{matrix}$	$\begin{matrix} \\ \\ \\ 69.29 \end{matrix}$	$\begin{matrix} \\ \\ \\ 12.9 \end{matrix}$	$\begin{matrix} \\ \\ \\ 0.0317 \end{matrix}$	$\begin{matrix} \\ \\ \\ 0.27* \end{matrix}$
Initial crack depth	$\frac{a_o}{t}$	2.2	--	--	--	--	0.0146*	--	--	0.531E-3*	-93.934*	8823.59*		4.6826*	39.35*
Diameter, in.	$\begin{matrix} U_1 \\ U_2 \\ U_3 \\ U \\ d \end{matrix}$	$\begin{Bmatrix} 1.12 \\ 10.1 \end{Bmatrix}$	$\begin{Bmatrix} -- \\ -- \\ -- \\ 6.624 \end{Bmatrix}$	$\begin{Bmatrix} -- \\ -- \\ -- \end{Bmatrix}$	$\begin{Bmatrix} 1 \\ 1 \\ 1 \\ 6.624 \end{Bmatrix}$	$\begin{matrix} -0.0003 \\ -0.0033 \\ 0 \\ -0.004 \end{matrix}$	$\begin{matrix} \\ \\ \\ 6.624 \end{matrix}$	$\begin{matrix} 0.000 \\ 0.003 \\ 0.025 \\ 0.029 \end{matrix}$	$\begin{matrix} 0.000 \\ 0.003 \\ 0.025 \\ 0.029 \end{matrix}$	$\begin{matrix} \\ \\ \\ 1.5E-3 \end{matrix}$	$\begin{matrix} -4.821 \\ 3.640 \\ 7.870 \end{matrix}$	$\begin{matrix} 23.24 \\ 13.25 \\ 61.93 \end{matrix}$	$\begin{matrix} 23.2 \\ 13.2 \\ 61.9 \end{matrix}$	$\begin{matrix} 0.0000 \\ 0.0000 \\ 0.0015 \\ 0.0016 \end{matrix}$	$\begin{matrix} 0.00 \\ 0.00 \\ 0.01 \\ 0.01 \end{matrix}$
Pressure, lb/in. ⁻²	$\begin{matrix} U_1 \\ U_2 \\ U \\ p \end{matrix}$	$\begin{matrix} 5.1 \\ 5.2 \\ -- \end{matrix}$	$\begin{matrix} \\ \\ 1200 \end{matrix}$	$\begin{matrix} \\ \\ -200 \end{matrix}$	$\begin{matrix} \\ \\ 1000 \end{matrix}$	$\begin{matrix} -0.134 \\ 0.033 \\ -0.101 \\ -- \end{matrix}$	$\begin{matrix} \\ \\ 1000 \end{matrix}$	$\begin{matrix} 0.267 \\ 0.002 \\ 0.269 \\ -- \end{matrix}$	$\begin{matrix} \\ \\ 0.268 \\ -- \end{matrix}$	$\begin{matrix} \\ \\ 268 \end{matrix}$	$\begin{matrix} \\ \\ -0.0006 \end{matrix}$	$\begin{matrix} \\ \\ 35E-8 \end{matrix}$	$\begin{matrix} \\ \\ 0.35 \end{matrix}$	$\begin{matrix} \\ \\ 0.0001 \end{matrix}$	$\begin{matrix} \\ \\ 0.00 \end{matrix}$
Expansion stress (other than from p, d, and t), lb/in. ⁻²	$\begin{matrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \\ U \\ S \end{matrix}$	$\begin{matrix} 1.1 \\ 1.2 \\ 1.3 \\ 1.4 \\ 1.5 \\ -- \end{matrix}$	$\begin{matrix} \\ \\ \\ \\ \\ 27450 \end{matrix}$	$\begin{matrix} \\ \\ \\ \\ \\ -- \end{matrix}$	$\begin{matrix} \\ \\ \\ \\ \\ 27450 \end{matrix}$	$\begin{matrix} 5.4 \\ -199.3 \\ 44.1 \\ 8.9 \\ 0.5 \\ -140.5 \\ -- \end{matrix}$	$\begin{matrix} \\ \\ \\ \\ \\ 25042 \end{matrix}$	$\begin{matrix} 6.95 \\ 30.85 \\ 50.45 \\ 10.77 \\ 0.70 \\ 99.7 \\ -- \end{matrix}$	$\begin{matrix} \\ \\ \\ 75.3 \\ -- \end{matrix}$	$\begin{matrix} \\ \\ \\ 57E 6 \end{matrix}$	$\begin{matrix} \\ \\ \\ 1.5E-4 \end{matrix}$	$\begin{matrix} \\ \\ \\ 2.4E-8 \end{matrix}$	$\begin{matrix} \\ \\ \\ 17.9 \end{matrix}$	$\begin{matrix} \\ \\ \\ 1.3476 \end{matrix}$	$\begin{matrix} \\ \\ \\ 11.32* \end{matrix}$
Total Variance	$\ln n_t$													11.9005*	100.00

* Changes from Table 3-2, Fourteenth Quarterly, GEAP-5716.

(when, of course, the variables, $X_1, X_2, \dots, X_I$, take on values drawn from the same distribution at each iteration). This means that the arithmetic average of $\phi(X_1, X_2, \dots, X_I)$ over several iterations is an estimate of $E \phi(X_1, X_2, \dots, X_I)$ which improves as the number of iterations grows larger. The variance, $\text{var } \phi(X_1, X_2, \dots, X_I)$, turns out to be useful for showing how good this improvement will be, as we shall show later in this subsection.

3.5.1.2 Application: Probability of Leakage from Low-Cycle Fatigue Crack

We now demonstrate the application of the ordinary Monte Carlo simulation method to generating the probability that the number of fatigue cycles, n_t , will be less than some critical level, say n_c , the number of thermal cycles expected in the operation of a boiling water reactor in say 10 (or 40) years.

First, we build the model. This consists of the n_t equation, a numerical solution of which was included in subsection 3.3 of the Thirteenth Quarterly, GEAP-5680, together with the distribution function of the physical variables, a_o/t , B , S_E , $\log C$, t , d , and p , each of which may have several uncertainty coefficients. The total number, I , of random numbers to be drawn would be the total number of uncertainty coefficients, or variables, whose distributions are thought to contribute significantly to the distribution of n_t . The distributions for the model we have been using were proposed in the Sixth (GEAP-5279) and subsequent Quarterlies, or were derived from data supplied by Tasks D-1 and D-2 (see subsection 3.5 of the Fourteenth Quarterly, GEAP-5716). In subsection 3.4 of the same Quarterly we showed a way of choosing the significant contributors. Further, the distributions are thought to arise from independent causes, so that the model distribution is separable:

$$F(x_1, x_2, \dots, x_I) = F_{X_1}(x_1) \cdot F_{X_2}(x_2) \cdot \dots \cdot F_{X_I}(x_I) \quad (7)$$

Second, we find a way of generating random numbers according to the distributions of the model. Such methods will be discussed in another context in subsection 3.5.3.1.

Third, we make numerous iterations of the Monte Carlo simulation to generate from the random numbers by the numerical solution of the n_t equation a collection of random numbers of cycles. If the fraction of these which lie below n_c is calculated, then we would feel that such a fraction would be typical of the frequency of leaks to be expected in 10 (or 40) years, provided that the model was realistic.

As we hinted earlier, another equivalent way of describing the above simulation is to let the function $\phi(x_1, x_2, \dots, x_I)$ take on the value TRUE if n_t , calculated from the random numbers $x_1, x_2, \dots, x_I$ (each of which corresponds with one uncertainty coefficient or variable), is less than n_c , and FALSE if not. Representing TRUE as 1 and FALSE as 0, the probability of n_t being less than n_c is then just the expected value, $E \phi(X_1, X_2, \dots, X_I)$, and the estimate of this is the average value of $\phi(X_1, X_2, \dots, X_I)$ over the numerous iterations of the simulation. The latter assertion can be verified readily, while the former must hold true by the Law of Large Numbers if the latter is to be a good estimate and can be verified by methods of the Calculus of Probability. (It is analogous to finding the mass of part of a body of varying specific gravity; see subsection 3.4.2 of the Fourteenth Quarterly.) For ease of conceptualization, we designate this function:

$$I_{\{n_t < n_c\}}(x_1, x_2, \dots, x_I) = \begin{cases} 1 & \text{if } n_t \text{ evaluated at } x_1, x_2, \dots, x_I \text{ is less than } n_c \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

Putting the strands together—when N is the number of iterations—the Monte Carlo simulation generates an estimate:

$$\frac{1}{N} \sum_{\text{over all } N \text{ iterations}} I_{\{n_t < n_c\}}(X_1, X_2, \dots, X_I) \quad (9)$$

$$\text{of } \Pr \{n_t < n_c\} = E I_{\{n_t < n_c\}}(X_1, X_2, \dots, X_I) \\ = \iint \dots \int I_{\{n_t < n_c\}}(x_1, x_2, \dots, x_I) dF_{X_1}(x_1) \cdot dF_{X_2}(x_2) \cdot \dots \cdot dF_{X_I}(x_I) \quad (10)$$

The main drawback of the ordinary Monte Carlo method, when a very small probability such as $\Pr \{n_t < n_c\}$ must be estimated, is the enormous number of calculations that must be made to be reasonably sure of getting even a single iteration where n_t is less than n_c . Similar difficulties arise in the use of Monte Carlo simulations to assist in solving radiation shielding problems. A transformation of the original problem will now be displayed, which can be simulated with many fewer iterations and still will give answers more exact as the number of iterations increases.

3.5.1.3. Importance Sampling Monte Carlo Methods

Importance sampling is a Monte Carlo simulation method that allows one to guide the random numbers to be generated into a region of importance and yet still obtain results similar to those of the ordinary Monte Carlo method. For example, in the analysis of radiation shielding efficiency, mentioned previously, certain random variables may represent the physical coordinates of one or more types of particle on the hot side of a shield, and the region of importance might comprise any combination of the physical coordinates which would be likely to impel the particle (or particles) through the shielding; the other particles may be in the vast majority, but hardly worth simulating, especially in proportion to their numbers.

It is possible, with the random variables $X'_1, X'_2, \dots, X'_I$ taking on random number values $x'_1, x'_2, \dots, x'_I$ under the importance weighted distribution function $F'(x'_1, x'_2, \dots, x'_I)$, to use the estimate:

$$\frac{1}{N} \sum_{\text{over all } N \text{ iterations}} \frac{I_{\{n_t < n_c\}}(X'_1, X'_2, \dots, X'_I)}{\partial I_{F'}(x_1, x_2, \dots, x_I) / \partial x_1 \partial x_2 \dots \partial x_I} \cdot \frac{\partial I_F(x_1, x_2, \dots, x_I)}{\partial x_1 \partial x_2 \dots \partial x_I} \quad (11)$$

of $\Pr \{n_t < n_c\}$ in place of the estimate [Equation (9)] for our application, when the partial derivatives exist for all argument values (the partial derivatives being evaluated at the random numbers taken on by $X'_1, X'_2, \dots, X'_I$). What is written above is incomplete, however, until we display a distribution function, $F'(x'_1, x'_2, \dots, x'_I)$ which is, in some way, better for estimating $\Pr \{n_t < n_c\}$ than ordinary Monte Carlo simulation would be, and we will deal with this aspect next.

3.5.2 Efficient Calculating Procedures

3.5.2.1 Procedure for the Ordinary Monte Carlo Application

Before we spell out in detail the methods available for finding an importance weighted distribution function $F'(x'_1, x'_2, \dots, x'_I)$, we will return to the ordinary Monte Carlo method estimate [Equation (9)] of $\Pr \{n_t < n_c\}$, given in Equation (10). We stated that we were to find a way of generating random numbers according to the distribution function of the model. As a matter of fact, just about all methods of generating random numbers according to a distribution function on an electronic computer start from a selection of one or more random numbers from the interval (0, 1), each number being drawn independent of the others and with a density that is uniform in the interval. Let us investigate how these numbers are transformed into our desired distribution.

Fortunately, it will be sufficient to consider only distributions with the following properties: separability as given by Equation (7), and one-one individual distribution functions $F_{X_1}(x_1), F_{X_2}(x_2), \dots, F_{X_I}(x_I)$. These properties allow us to make the convenient transformation:

$$\begin{array}{lll} y_1 = F_{X_1}(x_1) & dy_1 = dF_{X_1}(x_1) & x_1 = F_{X_1}^{-1}(y_1) \\ y_2 = F_{X_2}(x_2) & dy_2 = dF_{X_2}(x_2) & x_2 = F_{X_2}^{-1}(y_2) \\ \vdots & \vdots & \vdots \\ y_I = F_{X_I}(x_I) & dy_I = dF_{X_I}(x_I) & x_I = F_{X_I}^{-1}(y_I) \end{array}$$

of Equation (10) to yield

$$\Pr \{n_t < n_c\} = \int_0^1 \int_0^1 \dots \int_0^1 \mathbf{1}_{\{n_t < n_c\}} \left[F_{X_1}^{-1}(y_1), F_{X_2}^{-1}(y_2), \dots, F_{X_I}^{-1}(y_I) \right] dy_1 dy_2 \dots dy_I. \quad (12)$$

If we call S the set of all coordinate values $(y_1, y_2, \dots, y_I)$ such that n_t , when evaluated at

$$x_1 = F_{X_1}^{-1}(y_1), x_2 = F_{X_2}^{-1}(y_2), \dots, x_I = F_{X_I}^{-1}(y_I),$$

yields a number of cycles below n_c , then the integrand above becomes merely $1_S(y_1, y_2, \dots, y_I)$, (the function which takes on the value 1 on S and 0 outside S); so that Equation (10) is now written

$$\Pr \{n_t < n_c\} = \int_0^1 \int_0^1 \dots \int_0^1 1_S(y_1, y_2, \dots, y_I) dy_1 dy_2 \dots dy_I. \quad (13)$$

Suppose the random variables $Y_1, Y_2, \dots, Y_I$ take on random number values, drawn from the uniform distribution function on $(0, 1)$: $F_Y(y) = y$, $dF_Y(y) = dy$, then analogously to Equations (9) and (10) we find that

$$\frac{1}{N} \sum_{\text{over all } N \text{ iterations}} 1_S(Y_1, Y_2, \dots, Y_I) \quad (14)$$

generates, as the number of iterations N increases, an improving estimate of

$$\begin{aligned} & \int_0^1 \int_0^1 \dots \int_0^1 1_S(y_1, y_2, \dots, y_I) dF_Y(y_1) \cdot dF_Y(y_2) \cdot \dots \cdot dF_Y(y_I) \\ &= \int_0^1 \int_0^1 \dots \int_0^1 1_S(y_1, y_2, \dots, y_I) dy_1 dy_2 \dots dy_I = \Pr \{n_t < n_c\}. \end{aligned} \quad (15)$$

The following procedure for evaluating the estimate [Equation (14)] on an electronic computer suggests itself:

Put SUM = 0

* Draw I random numbers, using the random number generator.

For each i evaluate, at the i th random number value, y_i , the inverse distribution function, $F_{X_i}^{-1}(y_i) = x_i$.

Evaluate n_t at $x_1, x_2, \dots, x_I$.

If $n_t < n_c$ go back to * for next iteration.

Otherwise put SUM = SUM + 1 and go back to *.

When N such iterations have been performed, divide SUM by N to obtain the estimate [Equation (14)] of $\Pr \{n_t < n_c\}$ [Equation (15)].

In this estimate [Equation (14)], each iteration is given equal importance and, as we indicated earlier, this will require millions of iterations to attain a reasonable confidence in our estimate of the very small probability, $\Pr \{n_t < n_c\}$. On the other hand, to weight the iterations effectively, we need some criterion to compare one system of weights with another. A statistical tool that is of prime importance for this and other such computations is the Central Limit Theorem,** which we will describe briefly in the following paragraph.

** See E. Parzen, "Modern Probability and Its Applications," Wiley 1960, pp. 371, ff.

3.5.2.2 Efficient Estimating Procedures

Let $\phi(y_1, y_2, \dots, y_I)$ be a function of the random numbers taken on by the random variables $Y_1, Y_2, \dots, Y_I$ from a distribution function $F(y_1, y_2, \dots, y_I)$ [for example, the function $1_S(y_1, y_2, \dots, y_I)$ in the above paragraph]. Define Φ_n to be the random variable taking the value $\phi(Y_1, Y_2, \dots, Y_I)$ at the n th iteration. Suppose also that $E\Phi_n = E\phi(Y_1, Y_2, \dots, Y_I)$ and $\text{var } \Phi_n = \text{var } \phi(Y_1, Y_2, \dots, Y_I)$ are finite real numbers; then, by the Central Limit Theorem, the larger the number of iterations, N , the closer is the distribution function of

$$\frac{1}{N} \sum_{n=1}^N \Phi_n$$

to a normal distribution (i.e., with a bell-shaped density curve) with central location parameter $E\Phi_n$ and dispersion parameter $\text{var } \Phi_n/N$. This is a powerful result, since we can put rough confidence bands around any Monte Carlo simulation estimate of a reasonably large size (N) when we have a rough estimate of $\text{var } \Phi_n$ (from tabled values of the normal distribution). Furthermore, if two estimates $\hat{\theta}_1$ and $\hat{\theta}_2$ have the same expected value θ , then broadly the one with the lowest $\text{var } \Phi_n$ gives the smallest confidence bands at any confidence level. However, one must exercise a degree of caution for bands of high confidence, since one estimate may converge to a normal distribution at a much faster rate than another. This, however, is not generally a problem, when a simulation is expected to contain thousands of iterations, which is usually possible without excessive cost on today's high speed electronic computers. Further, a test for normality may be made on the results for groups of a hundred or so iterations, in case there is doubt about the convergence to the normal distribution of any estimate selected. We are now ready to search for the best importance weighted estimate.

3.5.2.3 Efficient Procedure for the Application

In performing the importance weighting of the estimate (9) to yield the estimate (11) of the probability (10), we used the partial derivative with respect to an unknown distribution function. Here, any strictly positive weighting function, $w(y_1, y_2, \dots, y_I)$, applied to the estimate (14) of the probability (15) may be converted into a distribution function; in fact, we merely make the definition

$$F(y_1, y_2, \dots, y_I) = \int_0^{y_1} \int_0^{y_2} \dots \int_0^{y_I} w'(z_1, z_2, \dots, z_I) dz_1 dz_2 \dots dz_I, \quad (16)$$

where

$w'(z_1, z_2, \dots, z_I)$ is equal to $K \cdot w(z_1, z_2, \dots, z_I)$ for an appropriate constant K , which scales the weighting function, so that the equation $F(1, 1, \dots, 1) = 1$ is satisfied. Therefore, without any loss of generality, we may assume that the weighting function integrates to a distribution function.

Equation (16) may now be written in the form:

$$\Pr \{n_t < n_c\} = \int_0^1 \int_0^1 \dots \int_0^1 \frac{1_S(y_1, y_2, \dots, y_I)}{w(y_1, y_2, \dots, y_I)} w(y_1, y_2, \dots, y_I) dy_1 dy_2 \dots dy_I, \quad (17)$$

which is of the form, $E\phi(Y_1, Y_2, \dots, Y_I)$, when the random numbers taken on by the random variables $Y_1, Y_2, \dots, Y_I$ are drawn from the distribution (16) and when we define:

$$\phi(y_1, y_2, \dots, y_I) = \frac{1_S(y_1, y_2, \dots, y_I)}{w(y_1, y_2, \dots, y_I)}, \quad (18)$$

so that

$$\frac{1}{N} \sum_{\text{over all } N \text{ iterations}} \phi(Y_1, Y_2, \dots, Y_I) \quad (19)$$

is an improving estimate of $\Pr \{n_t < n_c\}$ as the number of iterations increases. And, since this gives us an estimate for each strictly positive weighting function, we will now search for a weighting function which minimizes $\text{var } \phi(Y_1, Y_2, \dots, Y_I)$ —our criterion for efficiency by the Central Limit Theorem.

The solution to this problem is relatively simple. Defining $\theta = \Pr \{n_t < n_c\}$, then, over the strictly positive weighting functions $w(y_1, y_2, \dots, y_I)$, we are to minimize:

$$\int_0^1 \int_0^1 \dots \int_0^1 \left[\frac{1_S(y_1, y_2, \dots, y_I)}{w(y_1, y_2, \dots, y_I)} - \theta \right]^2 w(y_1, y_2, \dots, y_I) dy_1 dy_2 \dots dy_I. \quad (20)$$

But if $w(y_1, y_2, \dots, y_I)$ is put approximately equal to $\frac{1}{\theta}$ on S and a fraction above zero elsewhere, this will imply both $F(1, 1, \dots, 1) = 1$ since $1_S(y_1, y_2, \dots, y_I)$ integrates to θ , and that the variance is near zero. However, things are not quite so simple in practice because it is very difficult to find the shape of the set S , and if we did know it exactly, we would no doubt be able to find its volume by numerical integration to yield the exact value of $\Pr \{n_t < n_c\} = \theta$. So, instead, we must have the following properties for $w(y_1, y_2, \dots, y_I)$:

- It must have a value near $\frac{1}{\theta}$, where we are sure the coordinate values lie in S .
- It must have a value near zero, where we are sure the coordinate values lie outside S .
- It should have intermediate values reflecting our uncertainty elsewhere.
- It must be a density of a distribution function.

Practical aspects of this importance weighted transformed Monte Carlo procedure will be contained in a forthcoming Quarterly, which is expected to give some preliminary numerical results with the use of a crude importance weighting function and approximations to the inverse distribution functions, $F_{X_1}^{-1}(y_1)$, $F_{X_2}^{-1}(y_2)$, $\dots$, $F_{X_I}^{-1}(y_I)$ —in estimate (19). A preliminary estimate of $\theta = \Pr\{n_t \leq n_c\}$ will, of course, be necessary for constructing a better importance weighting function.

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 primary objective of the computer code development, Task B-1, is to develop the analytical tools required to define the state of stress and strain that 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 stresses 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 for an elastic-linear plastic, or elastic-perfectly plastic material.

4.2.1 Summary

Writing of a users manual and programmers reference manual for the RESTART Program is in progress. Work on the elastic-plastic program (EPS) has been continued.

4.2.2 Computer Code Development—PAPA (RESTART)

As discussed in the Fourteenth Quarterly Report, the PAPA program will be able to recover from hardware and software malfunctions at five select points in the program. This is to permit the retention of information, permitting the reinitiation of the PAPA analysis without going back and starting the problem from the beginning. The PAPA program was intentionally aborted after each checkpoint, and then restarted to completion. This was done to simulate hardware or software malfunctions. In every case, the PAPA problems ran to completion after reading the information off the RESTART tapes. A comprehensive programmers manual and PAPA users manual for RESTART is being written.

4.2.3 Problem Solution—PAPA

Analysis of the piping elbow still is pending final checkout of all data from the analysis. At present it seems that possible numerical problems may exist in the saddle-shaped, trapezoidal element. Some loss in accuracy is reflected in the final answers. Identification of the problem existing in this element is being investigated.

4.2.4 Computer Code Development—EPS

Computer coding of the elastic-plastic program (EPS) will be completed during the coming quarter.

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

4.3.1 Summary

A major objective of Task B-2 is to run test cases using the PAPA computer code on complex piping components, thereby demonstrating the usefulness of the code. The schedule for this work has been delayed. No problems were completed during the report period.

4.3.2 Problem Solutions

During the period it was decided to run test cases at Evendale, thus avoiding additional delays which might be encountered in getting the completed code running at San Jose. One test case, a piping tee, has been completed. The satisfactory completion of the second case, a piping elbow, has been delayed due to problems with the code.

Eight test cases (including the two mentioned previously) have been outlined to provide the demonstration of the usefulness of the code as a design tool. A joint effort will be made by Tasks B-1 and B-2 to run the cases. A summary of the cases is as follows:

a. Test Cases for Triangular Elements

These are small cases necessary to resolve inconsistencies noted in the behavior of the triangular plate element.

b. One-to-One Piping Tee

This has been run and results have been reported.

c. Piping Elbow

In progress.

d. Larger, Improved Version of Item b.

Input data has been prepared.

e. Piping Tee with 0.8-to-1 Diameter Ratio

Input data has been prepared.

f. Straight Section of Pipe with Circumferential Crack

g. Thin-Walled Machined Tee

Experimental data, which is being developed by Oak Ridge, will be used if it is available. An alternative is provided by data in Welding Research Council Bulletin No. 108.

h. Piping Tee with Bending Moments Applied

Input data for this case will be prepared from Welding Research Bulletin No. 108.

4.4 SUBTASK B-3—EXPERIMENTAL STRESS ANALYSIS (E. Kiss)

4.4.1 Three-Dimensional Photoelastic Analysis

The final report by the University of Illinois was received and distributed—"A Three Dimensional Photoelastic Study of Stress Near Cracks in Shell Structures," by C. E. Taylor and D. C. Holloway, T.&A.M. Report No. 677, Department of Theoretical and Applied Mechanics, University of Illinois. The work covered five models, fabricated and tested using the "frozen stress" method of three-dimensional photoelasticity. The models, all with "cracks," included a pipe straight, three tees, and a flange. Based on this work, analyses were made at San Jose to determine crack tip stress intensity factors for each of these photoelastic models, using the experimentally determined stress distributions. Initial analysis of the cracked straight pipe, including definitions and terminology, was described in Quarterly No. 13. Results for the other models are presented here.

Figure 4-1 shows the stress intensity ratio (K/S) for the pressurized tee with the part-through symmetrical crack (see Figure 4-6). Figures 4-2 and 4-3 show the K/S at two points for the tee, with a symmetrical through crack loaded by in-plane bending through the branch. This tee is shown in Figures 4-7 and 4-8. It is interesting to note that during cooling, the machined crack ran and stopped (see Slice L-5), and that the resulting measured stress and calculated K/S are based on the actual crack tip distribution. Figure 4-9 shows the unsymmetrically cracked tee loaded out of plane in bending, while Figure 4-10 shows the slice plan for this model. Figures 4-4 and 4-5 show the calculated K/S ratios for points A and B.

Inasmuch as the (K/S) ratio determined from the photoelastic data are not nearly constant for any one crack geometry, it appears that both the point-by-point and averaging method are not satisfactory for determining the crack tip stress intensity. Nevertheless, the basic photoelastic data will provide an experimental check of the analytical stress analysis performed using the PAPA computer program, and as such will establish the usefulness of this analytical tool for a structural evaluation of piping components.

FIGURE 4-1. K/S FOR SLICE No. 1 PARTIAL CRACK IN PRESSURIZED SYMMETRIC TEE

FIGURE 4-2. K/S FOR SLICE L5 IN THROUGH-WALL SYMMETRIC TEE SPECIMEN (OUTSIDE SURFACE)

FIGURE 4-3. K/S FOR SLICE R3 IN THROUGH-WALL SYMMETRIC TEE SPECIMEN (OUTSIDE SURFACE)

FIGURE 4-4. K/S FOR POSITION "B" OF NONSYMMETRIC TEE SPECIMEN (OUTSIDE SURFACE)

FIGURE 4-5. K/S FOR POSITION "A" OF NONSYMMETRIC TEE SPECIMEN (OUTSIDE SURFACE)

FIGURE 4-6a. SKETCH AND SLICE PLAN FOR THE PRESSURE VESSEL

FIGURE 4-6b. STRESS PATTERN FOR SLICE 1. $t = 0.125$ in.

FIGURE 4-7. SLICE PLAN FOR THE RIGHT-SIDE CRACK OF THE SYMMETRIC TEE

FIGURE 4-8. SLICE PLAN FOR THE LEFT-SIDE CRACK OF THE SYMMETRIC TEE

FIGURE 4-9. DIMENSIONS AND LOADING CONFIGURATION FOR THE NONSYMMETRIC TEE MODEL

FIGURE 4-10. SLICE PLAN OF TEE, SHOWING ELLIPTIC CROSS SECTION OF INTERSECTION OF THE TWO CYLINDERS AND THE SLICE LOCATIONS

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 EXPERIMENTAL APPROACH

In the experimental program, capped segments of pipe containing flaws of various configurations have been hydrostatically pressurized to failure with water or a water-ethylene glycol mixture supplied by an air-operated piston pump capable of generating pressures up to 300 times the pressure of the driving air. In each test, applied pressure as determined by an electrical strain gage type transducer was recorded as a function of number of pump strokes. The volume of water delivered to the specimen per pump stroke was found to be reasonably insensitive to delivery pressure; hence, the number of pump strokes was taken to be indicative of the volume deformation of the specimen. Nearly all tests were carried out at 60°F.

Flaw configurations investigated have included both longitudinal and circumferential flaws of varying lengths and depths up to through-wall. Most flaws have been simply machined with a slitting saw or vee-cutter; results of early experiments with flaws which had been extended by fatigue were consistent with results with machined flaws.* The recorder and technique for patching through-wall flawed pipes have been described in earlier reports (GEAP-5620 and GEAP-5637).

5.3 RESULTS OF PREVIOUS EXPERIMENTS

5.3.1 Axial Through-Wall Flaws

It was found that the pressure load limit** for pipes containing axial through-wall flaws could be predicted with reasonable accuracy by the expression,

$$K_c^2 = \frac{\pi \sigma_h^2 C}{\cos \theta} \left(1 + 0.4 \frac{C^2}{Rt} \right), \quad (1)$$

in which σ_h is the hoop stress at the load limit, C is the flaw half-length, R is the pipe mean radius, t is the wall thickness, θ is equal to $\pi/2$ times the ratio of σ_h to that for an unflawed pipe, and K_c is a constant having the dimensions of a stress intensity factor.

* This lack of sensitivity to notch tip radius is to be expected from published crack opening displacement (COD) values for carbon steel at the test temperature.

** See GEAP-5620.

5.3.2 Long Part-Through Flaws

It may be shown that the load limit for a pair of series-connected tensile elements of identical material but different cross section coincides with the onset of plastic instability in the element of smaller cross section. From this it might be predicted that the pressure load limit for a pipe containing either a full length axial or complete circumferential part-through flaw of constant depth would coincide with plastic instability in the ligament remaining at the base of the flaw. It was found by experiment that the estimated effective (von Mises) stress in the ligament in such specimens at the load limit was approximately equal to the tensile yield stress of the pipe material. *

5.3.3 Shorter Part-Through Flaws

Since two parameters, length and depth, are required to define a part-through flaw of length less than that of the circumference of a pipe, the load limit—flaw size relation for such flaws is of necessity less simple than for axial through-wall or full-length part-through flaws. It was proposed** that a "failure diagram" for such flaws be drawn by plotting pressure load limit (expressed in terms of that for an unflawed pipe) be plotted against the reciprocal of flaw length. On such a plot, the vertical location of a plotted test data point is determined by the flaw depth. Such a diagram has been developed for ASTM-A106B pipe at 60°F.

5.4 RECENT EXPERIMENTAL WORK

During the present reporting period, efforts have been directed toward an improvement in the relation between pressure load limit and flaw size, both for through-wall and part-through flaws. As was indicated in an earlier report, the scatter in values of K_c calculated from Equation (1) did not correlate with the heat-to-heat variation in circumferential tensile strength of the pipe material. As flaw length decreases and the load maximum approaches that for an unflawed pipe, the value of the plastic zone correction term $1/\cos \theta$ rises sharply and approaches infinity. While it is true that the term $C/\cos \theta$ should converge to the value $K_c^2/\pi \sigma_o^2$ (where σ_o is the burst hoop stress for an unflawed pipe) at C equal to zero, uncertainty in the value of either σ_o or σ_h results in a rather large uncertainty in the value of $1/\cos \theta$ for small flaw size. Consequently, considerable scatter in the values of K_c computed from Equation (1) may be expected at small flaw sizes.

Recently Eiber, et al., at Battelle Memorial have proposed that the load limit for pipes with axial through-wall cracks can be estimated from the relation,

$$\sigma_f^2 = \sigma_h^2 \left(1 + 1.622 \frac{C^2}{Rt} \right), \quad (2)$$

in which σ_f is defined as the flaw stress and is presumably a material constant of value intermediate between the yield and ultimate stress for the material. Values of σ_f calculated from our data using Equation (2) are shown in Figure 5-1. In Figure 5-2 are plotted K_c values

* See GEAP-5554.

** See GEAP-5622.

calculated from Equation (1). From the standpoint of data scatter, Equations (1) and (2) appear to be roughly equivalent. However, if the values of σ_f are normalized by dividing by the average σ_a of yield and ultimate stress for each size of pipe, some improvement results, as shown in Figure 5-3 in which σ_f/σ_a is plotted against C. Normalizing K_c values in a similar manner increases the scatter, as shown in Figure 5-4. A similar effect is observed when σ_h values are divided by σ_a and the logarithm of σ_h/σ_a plotted against the logarithm of C/R. Why this should be is not clear at this time, unless the effect of tensile property variation within a single length of pipe is greater than was anticipated. It is planned to investigate this matter.

Work on pipes containing part-through axial flaws of varying lengths and depths is continuing, with emphasis on the effect of variations in tensile properties.

	DIAMETER	SCHEDULE	R	t	R/t	Rt
▽	4	40	2.10	0.23	9.15	0.48
△	6	40	3.20	0.28	11.4	0.90
●○	6	80	3.12	0.43	7.26	1.34
◇	8	40	4.17	0.32	12.8	1.35
×	10	40	5.22	0.36	14.5	1.88
□	12	80	6.04	0.71	8.51	4.28

FIGURE 5-1. σ_f VERSUS CRACK HALF-LENGTH, ASTM-A106B PIPE

	DIAMETER	SCHEDULE	R	t	R/t	Rt
▽	4	40	2.10	0.23	9.15	0.48
△	6	40	3.20	0.28	11.4	0.90
○	6	80	3.12	0.43	7.26	1.34
◇	8	40	4.17	0.32	12.8	1.35
×	10	40	5.22	0.36	14.5	1.88
□	12	80	6.04	0.71	8.51	4.28

FIGURE 5-2. K_c VERSUS CRACK HALF-LENGTH, ASTM-106B PIPE

	DIAMETER	SCHEDULE	R	t	R/t	Rt
▽	4	40	2.10	0.23	9.15	0.48
△	6	40	3.20	0.28	11.4	0.90
● ○	6	80	3.12	0.43	7.26	1.34
◇	8	40	4.17	0.32	12.8	1.35
×	10	40	5.22	0.36	14.5	1.88
□	12	80	6.04	0.71	8.51	4.28

FIGURE 5-3. σ_t/σ_a VERSUS CRACK HALF-LENGTH, ASTM-A106B PIPE

	<u>DIAMETER</u>	<u>SCHEDULE</u>	<u>R</u>	<u>t</u>	<u>R/t</u>	<u>Rt</u>
▽	4	40	2.10	0.23	9.15	0.48
△	6	40	3.20	0.28	11.4	0.90
● ○	6	80	3.12	0.43	7.26	1.34
◇	8	40	4.17	0.32	12.8	1.35
×	10	40	5.22	0.36	14.5	1.88
□	12	80	6.04	0.71	8.51	4.28

FIGURE 5-4. K_c/σ_a VERSUS CRACK HALF-LENGTH, ASTM-106B PIPE

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

Studies on experimental portions of the work have continued. Experimental determinations of crack growth rates in flattened and reheat-treated A106 pipe suggest slightly higher growth rates in the axial versus the circumferential direction; however, these differences are within the scatter observed in the correlation between stress intensity factor and crack growth rate.

Analysis of all stress-controlled and strain-controlled tests to date, of both 5-inch and 14-inch-wide plates of 2-1/4 Cr—1 Mo steel, reveal no significant effect of specimen width on the correlation between stress intensity factor and crack growth rate.

6.2.2 Comparison of Semicylindrical and Flat Plate Specimens

Previous tests of prototype pipe material were made using semicylindrical pipe specimens. These results indicated higher growth rates than those observed in flat-plate tests of similar materials. To determine if this difference reflects specimen geometry or material differences, tests are under way at room temperature on 6-inch-diameter A106 pipe and plate specimens with both axial and circumferential orientation. These latter specimens were prepared by flattening pipe segments and, where necessary, welding extensions to obtain 5-inch-wide by 0.2-inch-thick specimens containing a 0.5-inch-long center slot. All specimens were reheat-treated at 1650°F for 1 hour, followed by air cooling to remove any possible effects of straightening. Microscopic examination of both pipe and plate specimens revealed identical microstructures with an ASTM grain size of No. 8 and identical hardness in the range Rockwell A 48.0 - 51.5.

The initial results of the comparison between axial and circumferential crack growth are shown in Figures 6-1 and 6-2. The crack growth curves of Figure 6-1 suggest that crack growth rates for a given stress level are somewhat greater for an axial than a circumferential crack. However, a comparison on the basis of stress intensity factor reveals no significant differences within the scatter normally observed in these tests. Pipe tests to determine the correlation between specimens of various geometry are in progress.

FIGURE 6-1. CRACK GROWTH CURVES FOR AXIAL AND CIRCUMFERENTIAL GROWTH IN FLATTENED A106 PIPE

FIGURE 6-2. CRACK GROWTH CORRELATION FOR PLATES OF FLATTENED A-106B PIPE TO DETERMINE EFFECT OF ORIENTATION

6.2.3 Effect of Specimen Width on Crack Growth Correlation

In previous tests of carbon steel plate to evaluate the influence of test temperature, both 5-inch- and 14-inch-wide specimens with center slot lengths of 10% of the width were tested. These tests illustrated a pronounced effect of temperature on crack growth rate; however, there was some question regarding the possible influence of specimen width, and it was believed necessary to consider the possible influence of this variable. To date, no controlled tests have been conducted to test this variable. However, recent tests of 5-inch-wide plates under reversed strain-controlled loading, in addition to few earlier tests under reversed stress loading, provide a set of data for comparison with earlier zero-to-tension tests of identical material tested as 14-inch-wide plates. The results of this comparison for the 2-1/4 Cr—1 Mo alloy steel for which the most complete set of data is available are shown in Figure 6-3. The range of stress intensity factor for the strain-controlled tests was calculated using the instantaneous load ranges and crack lengths measured in these tests. Within scatter, over the range of stress intensity factors evaluated, there is (with the exception of a single test) no apparent influence of specimen width on the correlation between crack growth rate and stress intensity factor.

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

6.3.1 Summary

Additional tests on grooved cylinders with uniaxial stress-concentration factors of 1.3 and 2.5 were run at room temperature. Determination of 550°F, smooth bar, low-cycle fatigue life under the completely reversed, strain-controlled condition continued. Analysis of notched bend tests progressed.

6.3.2 Grooved Cylinder Tests at Room Temperature for $K_t = 1.3$ and 2.5

The objective in conducting these tests was to augment the previously reported results of tests on grooved cylinder specimens having a theoretical elastic stress concentration factor of $K_t = 3.3$ and $K_t = 1.9$.^(1,2) The results of the tests on $K_t = 3.3$ are analyzed and discussed in References (3) and (4). Briefly the test conditions were as follows:

Cycling Mode:	Fully reversed, load controlled, zero mean load.
Frequency:	6 cpm.
Crack-Initiation:	Cycle at which a 0.005- to 0.015-in. long crack appeared in the root of the notch.
Failure:	Complete separation of the bar.
Testing Machine:	Tinius Olsen, 200,000-lb Universal Testing Machine.
Material:	2-1/4 Cr—1 Mo, Type 304 stainless steel, carbon steel. The tensile properties of these materials are listed in Quarterly No. 2.

Micro Measurements EP-Series foil strain gages of 1/32-inch gage length were used to determine the strain in the root of the notch. Both the axial strain and the hoop strain were measured.

FIGURE 6-3. CRACK GROWTH CORRELATION FOR 2-1/4 Cr-1 Mo ALLOY WITH VARIOUS LOADING SCHEMES FOR BOTH 5.0-in. AND 14.0-in.-WIDE SPECIMENS

At the start of each test, the applied load was raised in discrete steps. At each load level the load notch-root strain hysteresis-loop was obtained after which the load was raised to the next step. When the final load had been reached the load-notch strain hysteresis loop was taken at selected cycle intervals until the gage failed.

The test procedure, the instrumentation, the strain gages, and the method of reporting data are the same as those of References (1) and (2). Type-304 stainless steel and 2-1/4 Cr—1 Mo material were used for the specimens having a $K_t = 2.5$. The $K_t = 1.3$ specimens were made of 2-1/4 Cr—1 Mo material. The theoretical uniaxial elastic stress concentration factor was determined from Reference (5). The overall specimen dimensions are given in Figure 6.4 of Reference (1). The notch dimensions of the test specimens are shown in Figure 6-4.

6.3.3 Strain Measurements in the Root of the Notch

The results of the initial step-up tests are given in the form of nominal stress range (based on minimum cross section) versus notch root strain range (axial and transverse) curves. Figures 6-5 and 6-6 show the results for 2-1/4 Cr—1 Mo alloy steel for $K_t = 2.5$ and $K_t = 1.3$, respectively. Figure 6-7 is for $K_t = 2.5$ and Type-304 stainless steel. These curves are similar in shape to those reported in References (1) and (2).

The variation of the axial notch root strain range with cycling was determined up to the point of strain gage failure. In general, the same behavior was found in these tests as in the ones reported earlier. Significant decreases in the axial notch root strain range were observed above about 1.4%. Below that strain range level, very little decrease in strain range occurred for 2-1/4 Cr—1 Mo material. Stainless steel specimens showed a slight increase in notch root strain range at 0.7% total strain. This observation is consistent with the mixed cyclic behavior of smooth bar specimens of the Type-304 stainless steel used in this study. (6)

6.3.4 Crack Initiation and Final Failure

Crack initiation—defined as the appearance of a 0.005- to 0.015-inch-long crack in the root of the notch—and failure of the specimens were determined. The results are listed in Tables 6-1 and 6-2. Photographs of fractured specimens are shown in Figures 6-8 through 6-10. The area ratio $R = \frac{\text{Final tensile fracture area}}{\text{Net section area}}$ was determined by planimetry, and the true fracture stress was calculated as in References (1) and (2). Tables 6-1 and 6-2 give the R and σ_t values for this series of tests.

6.3.5 References for Subsection 6.3

1. GEAP-5554, Quarterly Report No. 10. July through September 1967.
2. GEAP-5637, Quarterly Report No. 12. January through March 1968.
3. GEAP-5714, Krempl, E., "Notched High-Strain Fatigue Behavior of Three Low-Strength Structural Steels."
4. GEAP-5726, Krempl, E., "The Influence of Stress/Strain Concentration and Mean Stress on the Low-Cycle Fatigue Behavior of Three Structural Steels at Room Temperature."
5. Peterson, R. E., "Stress Concentration Design Factors," John Wiley & Sons, New York, London (1953).
6. GEAP-5474, Quarterly Status Report No. 8, January through March 1967.

TOLERANCES AND MAIN BODY OF SPECIMENS PER FIGURE 6-4 OF REF. 1

FIGURE 6-4. DIMENSIONS OF NOTCH OF THE GROOVED CYLINDER SPECIMENS IN THIS REPORT, WITH $K_t = 1.3$ AND 2.5

FIGURE 6-5. NOMINAL STRESS RANGE VERSUS NOTCH-ROOT STRAIN RANGE FOR 2-1/4 Cr-1 Mo SPECIMENS HAVING A $K_t = 2.5$

FIGURE 6-6. NOMINAL STRESS RANGE VERSUS NOTCH-ROOT STRAIN RANGE FOR 2-1/4 Cr-1 Mo SPECIMENS HAVING A $K_t = 1.3$

FIGURE 6-7. NOMINAL STRESS RANGE VERSUS NOTCH-ROOT STRAIN RANGE FOR TYPE-304 STAINLESS STEEL SPECIMENS HAVING A $K_t = 2.5$

FIGURE 6-8. PHOTO OF FRACTURED GROOVED CYLINDER SPECIMENS.
MATERIAL: 2-1/4 Cr-1 Mo, $K_t = 2.5$

FIGURE 6-9. PHOTO OF FRACTURED GROOVED CYLINDER SPECIMENS.
MATERIAL: 2-1/4 Cr-1 Mo, $K_t = 1.3$

FIGURE 6-10. PHOTO OF FRACTURED GROOVED CYLINDER SPECIMENS
MATERIAL: TYPE-304 STAINLESS STEEL, $K_t = 2.5$

TABLE 6-1

FATIGUE CHARACTERISTICS OF GROOVED CYLINDER SPECIMENS OF
2-1/4 CR-1 MO ALLOY STEEL ($K_t = 1.3$ and $K_t = 2.5$)

<u>Specimen No.</u>	<u>σ_a,* Nominal Stress Amplitude 10^3 psi</u>	<u>Cycles to Crack -</u>	<u>Cycles to Failure -</u>	<u>R** -</u>	<u>σ_t*** 10^3 psi</u>
<u>$K_t = 2.5$</u>					
A-2-A	29.8	6,000	23,300	0.43	69.4
A-1-A	37.8	800	5,000	0.58	65.0
A-3-A	45.0	400	1,815	0.53	85.0
<u>$K_t = 1.3$</u>					
A-5-A	38.0	24,300†	34,334	0.58	65.5
A-6-A	43.0	5,763††	12,217	0.64	67.2
A-4-A	47.5	1,600	3,989	0.76	62.5

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

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

$$*** \sigma_t = \frac{\sigma_a}{R}$$

† 0.030-inch-long crack

†† 0.120-inch-long crack

TABLE 6-2

FATIGUE CHARACTERISTICS OF GROOVED CYLINDER SPECIMENS OF
TYPE 304 STAINLESS STEEL ($K_t = 2.5$)

<u>Specimen No.</u>	<u>σ_a,* Nominal Stress Amplitude 10^3 psi</u>	<u>Cycles to Crack -</u>	<u>Cycles to Failure -</u>	<u>R</u>	<u>σ_t 10^3 psi</u>
S-2-S	30	4,785	23,300	0.25	120.0
S-3-S	41	650†	1,694	0.32	128.0

† Cracks at several places in the notch root.

* Symbols are explained in Table 6-1.

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

6.4.1 Summary

Testing was completed on the 550°F, 1000 psi pressurized pipe straight, HSNP-80-1. The specimen simply leaked when wall penetration occurred; no running crack ensued. Also completed were two elbows: one "good" circumferential butt weld specimen, and one "defective" circumferential butt weld specimen. Pertinent test data is summarized in Table 6-3. Testing has started on the second "defective" circumferential butt weld specimen.

6.4.2 Experimental

6.4.2.1 Stainless Steel Pipe Straight Tested at 550°F and 1000 psi

The purpose of this special test was to determine whether or not a pipe break would occur when the combined loading of cyclic cantilever bending plus internal pressure was simultaneously applied under BWR operating temperature and pressure conditions. The test was run to provide a practical demonstration of "leak or break" in BWR piping. To accommodate safety considerations in the laboratory area, extensive additional protective equipment was installed, which is not required for room temperature testing with hydraulic pressurization, or in 550°F tests which are not under pressure. Experience with similar tests at room temperature lent confidence that no spectacular crack propagation would occur at 550°F when a fatigue crack was grown through the wall to the point of leakage: i. e., behavior was entirely as predicted.

Since high-velocity, live steam was expected when through-wall penetration occurred, a shield was provided to protect operating personnel. The specimen, HSNP-80-1, and safety shield are shown installed in the test bed in Figures 6-11 and 6-12. The sample is shown in Figure 6-13, deflected to its lower position (-7.12 inches). Insulation was provided between the pipe and the safety shield, as shown in Figure 6-14.

The sample pressure was controlled between 1000 and 1050 psig, and the inside water temperature was held at $545 \pm 5^\circ\text{F}$ throughout the test. The sample was cycled at a nominal stress range of 59,500 psi for 6,900 cycles, at which time through-wall penetration occurred. The sample cycling continued while the steam blew down, as shown in Figure 6-15. During blowdown, approximately 150 cycles were imposed, which caused continued crack growth.

After the system pressure and temperature reached ambient conditions on the following day, shield and insulation were removed. The through-wall crack appeared as shown in Figure 6-16, with a crack length at the outside diameter of 2.450 inches and at the inside diameter of 3 inches. The maximum crack opening of 0.007 to 0.009 inch occurred at the middle of the crack. The data for through-wall crack growth is presented in a following subsection. No circumferential crack growth data were obtained because the test was terminated following blowdown.

No running crack developed, nor did any damage or injury occur as a result of this test.

FIGURE 6-11. TYPE-304 STAINLESS STEEL PIPE STRAIGHT, HSNP-80-1, INSTALLED IN TEST BED, WAS TESTED AT 550°F AND 1000 psi STEAM PRESSURE

TABLE 6-3

PROTOTYPE PIPE FATIGUE TEST RESULTS

Identification	Component	Specimen Description, Material and Schedule	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) ⁽¹⁾	Total Cycles (N _φ) ⁽²⁾	Remarks
HSNP-80-1	Pipe Straight	ASTM-A312 Type 304 S.S. Schedule 80, Type II, Internal Notch	550	1000 Saturated Water	59,500	±7.12	Not Obtained	6,900 (4,900)	7,100 (200)	Test stopped following leakage
CSLS-2	Elbow	ASTM-A182F Type 304 S.S. Schedule 40, Short Radius Elbow	64-70	1000 Water	42,200	±6.50	Not Obtained	6,838 (6,838)	11,096 (4,258)	Test stopped when crack 14.47 inches. Out-of-plane bending
HW-3A	Pipe Straight	ASTM-A312 Type 304 S.S. Schedule 40, Circumferential Butt Weld Sample	550	None	61,100	±7.38	5725	7,950 (1,225)	9,800 (1,320)	
HWD-1	Pipe Straight	ASTM-A106 Gr. B Carbon S.S. Schedule 40, Defective Circumferential Butt Weld Sample	550	None	59,200	±6.00	Crack Was Built in 0	15,100 (13,600)	34,905 (19,305)	
CCLS-1	Elbow	ASTM-A234 WPB Carbon S.S. Schedule 40, Short Radius Elbow	59-65	1000 Water	43,600	±7.03	<900	1,176 (1,176)	8,000 (6,824)	In-plane bending

(1) N_w = Total cycles when crack penetrated through wall (includes N_I).
Number in parentheses is full amplitude cycles included in N_w - N_I.

(2) N_φ = Total cycles after circumferential crack has grown to length where test terminated (includes N_w).
Number in parentheses is full amplitude cycles included in N_φ - N_w.

FIGURE 6-12. TYPE-304 STAINLESS STEEL PIPE STRAIGHT, HSNP-80-1, INSTALLED IN THE TEST BED

FIGURE 6-13. HOT, PRESSURIZED STAINLESS STEEL PIPE, HSNP-80-1, SHOWN IN FULL DOWN POSITION DURING CYCLIC BENDING

FIGURE 6-14. HOT, PRESSURIZED STAINLESS STEEL PIPE, HSNP-80-1, INNER INSULATION PRIOR TO SECURING SHIELD

FIGURE 6-15. BLOWDOWN OF THE HOT, PRESSURIZED STAINLESS PROTOTYPE PIPE, HSNP-80-1

FIGURE 6-16. HOT, PRESSURIZED STAINLESS PIPE STRAIGHT, HSNP-80-1, THROUGH-WALL CRACK APPEARANCE FOLLOWING BLOWDOWN

6.4.2.2 Out-of-Plane, Short Radius Elbow

The first elbow subjected to "out-of-plane" bending CSLS-2, is shown mounted in the test bed in Figure 6-17. Prior to full-amplitude fatigue testing, a series of small-amplitude, static bend tests were made so that an accurate estimate of surface strains could be obtained. The small amplitude was used to ensure that the elastic limit of the material was not exceeded. The surface strains were measured using three-element, 45-degree rosette strain gages so that the strain directions as well as amplitude could be detected. The strain gages were mounted on the circumference of the elbow at 45-degree intervals, as shown in Figure 6-18.

The results of the small-amplitude bend tests are shown in Figure 6-19, which is a plot of position around the circumference versus "stress intensification factor." Stress intensification factor, as used here, is defined as the ratio of the calculated stress from strain gage data to the nominal bending stress in a straight section of pipe at the same location as the elbow. As can be seen from Figure 6-19, the maximum stress occurs at a location of ~292 degrees counterclockwise from the crotch of the elbow. This is a point at the bottom of the elbow between strain gages nos. 7 and 8. The magnitude of this stress is approximately 3.1 times the nominal stress in a pipe. Figure 6-20 shows the bottom of the cracked elbow after test completion. The transverse crack initiated at the lower right of the small rectangular-shaped piece at the center of the figure, and passed through the area between gages 7 and 8. The remainder of the crack is shown in Figure 6-21. The crack started on the inside and fully penetrated after 6838 test cycles, and then grew to a final length of 14.470 inches at the end of the test. At 9200 cycles, several smaller cracks appeared on the top of the elbow. At the end of the test, these had grown as shown in Figure 6-22.

6.4.2.3 In-Plane, Short Radius Elbow

This second elbow test conducted at 1000 psi and room temperature with "in-plane" bending was on a carbon steel elbow. The component, CCLS-1, was instrumented with a minimum number of strain gages, since complete strain gage data was obtained on the first in-plane bending stainless steel elbow, CSLS-1.* Assisted by the crack location data obtained from sample CSLS-1, the crack prior to through-wall penetration was detected, using ultrasonics. The axial crack was detected after 900 cycles, at which time it appeared to be approximately 50% through the wall. However, ultrasonics showed but a slight change in crack depth at 1176 cycles, at which time through-wall penetration occurred. After depressurizing and draining, the test was continued to obtain crack growth data. Crack growth in this case was not a continuous function. The first crack started on one side of the elbow and grew axially to a length of 7.250 inches, and then a second crack initiated on the other side of the elbow. During the remaining portion of the test, the cracks grew in the same manner as was experienced on sample CSLS-1. The final crack geometry at the termination of the test was almost identical to CSLS-1.

6.4.2.4 Pipe Straights with Test Weld Sections

The pipe straights tested were fabricated with "good" and "defective" circumferential butt welds, HW-3A and HWD-1, respectively.

* Described in Quarterly Report No. 14.

FIGURE 6-17. SHORT RADIUS ELBOW, CSLS-2, INSTALLED IN THE TEST BED FOR CYCLIC OUT-OF-PLANE BENDING

FIGURE 6-18. SHORT RADIUS ELBOW, CSLS-2, STRAIN GAGE LOCATIONS

FIGURE 6-19. STRESS INTENSIFICATION FACTOR CALCULATED FROM STRAIN GAGE DATA FOR OUT-OF-PLANE BENDING ON A 6-in. SCHEDULE 40 STAINLESS STEEL ELBOW, CSLS-2.

FIGURE 6-20. STAINLESS STEEL ELBOW, CSLS-2, BOTTOM INNER RADIUS VIEW AFTER TEST COMPLETION

FIGURE 6-21. STAINLESS STEEL ELBOW, CSLS-2, BOTTOM OUTER RADIUS VIEW AFTER TEST COMPLETION

FIGURE 6-22. STAINLESS STEEL ELBOW, CSLS-1, TOP INNER RADIUS VIEW
AFTER TEST COMPLETION

The good weld sample HW-3A was a repeat of sample HW-3, where stress ranges were changed several times and crack growth rate was not well defined. The circumferential crack growth data is presented in Figures 6-23 and 6-24 for HW-3A.

The defective weld specimen HWD-1, contained a lack-of-penetration flaw in the weld, which was produced by not completing a 1-inch section of the root pass. This left a lack-of-fusion crack at the inside diameter of the test weld. A comparison of test parameters is given below for the good weld sample HW-1* versus the defective weld HWD-1. The circumferential crack growth data is presented in Figures 6-25 and 6-26.

	<u>Good Weld, HW-1</u>	<u>Defective Weld, HWD-1</u>
Material	Carbon Steel	Carbon Steel
Weld Type	Good	Defective
Test Temperature	550°F	550°F
Internal Pressure	None	None
Stress Range	58,200 psi	59,200 psi
$N_I^\dagger$	25,000	Flaw at start of test
$N_w^{\dagger\dagger}$	35,740	13,600

$\dagger N_I$ = Full amplitude cycles for crack initiation.

$\dagger\dagger N_w$ = Full amplitude cycles for wall penetration.

6.4.3 Through-Wall Crack Growth

Stress reduction marking fronts were made on the three pipe straights, HSNP-80-1, HW-3A and HWD-1, and are shown in Figures 6-27, 6-28, and 6-29, respectively.

Electron microfractography analyses of four samples were completed. The results were used in the calculation of stress intensity factor range (ΔK) corresponding to measured through-wall crack growth rates. The values for ΔK and da/dN are given in Table 6-4 and are plotted in Figures 6-30, 6-31, and 6-32.

6.4.4 Circumferential Crack Growth

The crack length and crack growth rate curves for HW-3A and HWD-1 are shown in Figures 6-23 through 6-26. Specimen HW-3A behaved in a normal manner as shown in Figures 6-23 and 6-24.

The stress intensity factor range versus measured circumferential crack growth rate is given in Table 6-5 and plotted in Figures 6-33 and 6-34.

* Described in GEAP-5716, Quarterly Report No. 14.

FIGURE 6-23. CIRCUMFERENTIAL CRACK LENGTH VERSUS CYCLES FOR STAINLESS STEEL PIPE STRAIGHT, HW-3A, CONTAINING "GOOD" WELD.

FIGURE 6-24. CIRCUMFERENTIAL CRACK GROWTH RATE VERSUS CYCLES FOR STAINLESS STEEL PIPE STRAIGHT, HW-3A, WITH "GOOD" WELD

FIGURE 6-25. CIRCUMFERENTIAL CRACK LENGTH VERSUS CYCLES FOR CARBON STEEL PIPE STRAIGHT, HWD-1, WITH DEFECTIVE WELDS

FIGURE 6-26. CIRCUMFERENTIAL CRACK GROWTH RATE FOR CARBON STEEL PIPE STRAIGHT, HWD-1, WITH DEFECTIVE WELD

FIGURE 6-27. HSNP-80-1 STRESS REDUCTION MARKING FRONTS

FIGURE 6-28. HW-3A STRESS REDUCTION MARKING FRONTS

FIGURE 6-29. HWD-1 STRESS REDUCTION MARKING FRONTS

FIGURE 6-30. THROUGH-WALL CRACK GROWTH RATE VERSUS ΔK , R. T. STAINLESS STEEL

FIGURE 6-31. THROUGH-WALL GROWTH RATE da/dN VERSUS ΔK , 550°F STAINLESS STEEL

FIGURE 6-32. THROUGH-WALL CRACK GROWTH RATE VERSUS ΔK , R. T. CARBON STEEL

FIGURE 6-33. CIRCUMFERENTIAL CRACK GROWTH RATE VERSUS STRESS INTENSITY RANGE FOR TYPE 304 STAINLESS STEEL AT 550°F

FIGURE 6-34. CIRCUMFERENTIAL CRACK GROWTH RATE VERSUS STRESS INTENSITY RANGE FOR A-106-B CARBON STEEL MATERIAL AT 550°F

TABLE 6-4

CALCULATED STRESS INTENSITY FACTOR RANGE, ΔK , AND
CORRESPONDING THROUGH-WALL CRACK GROWTH RATE da/dN

<u>a (in.)</u>	<u>a' (in.)</u>	<u>a'/b</u>	<u>a'/t</u>	<u>$\frac{K}{\bar{\sigma}}$</u>	<u>ΔK (ksi$\sqrt{\text{in.}}$)</u>	<u>$\frac{da}{dN}$ (μ in./cycle)</u>
<u>CSS-107*</u>						
0.019	0.080	0.205	0.185	0.525	38.9	33.5
0.039	0.100	0.230	0.230	0.590	43.7	41.3
0.059	0.120	0.255	0.276	0.645	47.8	47.2
0.079	0.140	0.280	0.322	0.695	51.5	55.1
0.098	0.159	0.300	0.366	0.740	54.8	63.0
0.118	0.179	0.325	0.412	0.785	58.1	70.8
<u>CSS-109*</u>						
0.019	0.075	0.205	0.179	0.520	37.6	31.5
0.039	0.095	0.230	0.226	0.575	41.5	39.4
0.079	0.135	0.280	0.321	0.695	50.3	55.1
0.118	0.174	0.330	0.414	0.785	56.7	70.8
0.157	0.213	0.375	0.507	0.885	64.0	84.6
0.197	0.253	0.425	0.602	1.000	72.3	100.0
<u>CSS-119*</u>						
0.039	0.100	0.230	0.239	0.600	44.7	37.4
0.118	0.179	0.330	0.427	0.795	58.3	80.7
0.157	0.218	0.380	0.520	0.900	67.1	102
0.197	0.258	0.430	0.615	1.020	76.0	124
0.236	0.297	0.480	0.710	1.175	87.7	148
0.275	0.336	0.525	0.801	1.405	105.0	295
<u>HSNP-80-1</u>						
0.039	0.114	~0	0.254	0.675	40.1	36.4
0.079	0.154	~0	0.342	0.805	47.9	61.0
0.118	0.193	~0	0.429	0.930	55.3	112
0.157	0.232	~0	0.515	1.070	63.6	163
0.197	0.272	~0	0.605	1.235	73.5	214
0.236	0.311	~0	0.691	1.430	85.0	266

* Described in Quarterly Report No. 14.

TABLE 6-5

CALCULATED STRESS INTENSITY FACTOR RANGE ΔK VERSUS
MEASURED CIRCUMFERENTIAL CRACK GROWTH RATE da/dN
FOR TWO STRAIGHT PIPE SPECIMENS

<u>Cycles</u>	<u>1/2 Crack Length (in.)</u>	<u>β°</u>	<u>ΔK (ksi$\sqrt{\text{in.}}$)</u>	<u>Crack Growth Rate (μ in./cycle)</u>
<u>Specimen</u> <u>HW-3A</u>				
8490	2.475	42.8	100	2,740
8549	2.600	45.0	106	3,570
8625	2.970	51.4	132	3,780
8700	3.282	56.8	150	4,480
8750	3.482	60.2	154	5,540
<u>Specimen</u> <u>HWD-1</u>				
26700	1.302	22.5	56.2	130
28000	1.525	26.4	61.0	185
29200	1.825	31.6	69.0	361
29900	2.355	40.7	88.5	1,440
30200	2.965	51.3	127	3,147
30300	3.370	58.3	152	4,268

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

6.5.1 Summary

All results to date of the effect of cyclic strain aging on the Charpy impact transition temperature of carbon steel are described. It is observed that the influence of test temperature for a given cyclic strain range and number of cycles parallels the effect of temperature on the properties of statically loaded tensile specimens; maximum embrittlement occurs at about 350°F.

6.5.2 Effect of Cyclic Strain Aging on Charpy Impact Properties

All results to date of Charpy impact tests following cyclic strain aging are shown in Figures 6-35 through 6-37. In addition to all previous tests at 350°F, Figure 6-35 shows the shift in transition temperature following cyclic strain at 200 and 550°F. Generally, for a given test temperature, the change in 50% FATT increases directly with both strain range and number of cycles, with evidence of maximum embrittlement at 350°F. The effect of test temperature

FIGURE 6-35. EFFECT OF CYCLIC STRAIN AT VARIOUS NUMBER OF CYCLES AND TEMPERATURE TO SHIFT THE CHARPY 50% FATT

FIGURE 6-36. EFFECT OF TEST TEMPERATURE ON CHARPY IMPACT AND STATIC TENSILE PROPERTIES

FIGURE 6-37. EFFECT OF CYCLIC STRAIN, TEST TEMPERATURE, AND NUMBER OF CYCLES ON CHARPY 50% FATT

is shown more clearly in Figure 6-36 which plots both the tensile properties and the increase in 50% FATT as a function of test temperature for a given cyclic strain range and number of cycles. Although not as sharply defined as the corresponding change in tensile ductility, the similarities in behavior are apparent.

The effect of the number of cycles on the shift in transition temperature is shown in Figure 6-37. Although the available test data define rather clearly the cyclic dependence of transition shift at the higher strain ranges, there is some uncertainty regarding the influence of cycles at lower strains. A currently scheduled test at $\pm 0.5\%$ cyclic strain for 100 cycles is intended to clarify this uncertainty.

SECTION VII

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 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

7.2.1 Dresden Experimental Loop Equipment

Delivery of the dynamic vessel, to contain the fatigue testing machine, was scheduled for March by the vendor, National Forge. Piping drawings were completed for internal reviews. A surplus AEC vessel was acquired and modified to use for shakedown testing of the fatigue machine in an existing test loop at San Jose.

7.2.2 Dynamic Fatigue Testing

Several alternate designs of specimens were selected for evaluation by fatigue testing in air. Not only is it necessary to demonstrate consistent failure behavior, but reliable crack detection means must be assured. This phase will continue into the next quarter.

7.3 DYNAMIC FATIGUE TEST VESSEL (DNPS-1)

The vendor (National Forge) advises that machining of the top head was under way at the end of the report period and that, barring any unforeseen complications, the vessel will be delivered in March 1969.

7.4 SHAKEDOWN VESSEL AND TEST LOOP

Modifications were completed on a surplus AEC test vessel (Figure 7-1) which will allow its use during the shakedown testing of the dynamic fatigue test jig.

Work was also completed on the test loop (Building G, San Jose) in which this shakedown vessel will be installed. This loop will provide a nominal 10 gpm flow of demineralized water at 500°F, 1000 psig; instrumentation has been provided to monitor and record the flow rate, inlet and outlet temperature, and pressure of the demineralized water flowing through the shakedown vessel.

FIGURE 7-1. SHAKEDOWN TEST VESSEL

7.5 FATIGUE SPECIMEN EVALUATION

7.5.1 Static Testing

As a result of the static testing of the various types of triangular-shaped specimens described in the 14th Quarterly (GEAP-5716) and shown in Figure 7-2, the constant thickness (modified taper) and NRL type (reduced thickness) were selected for potential Task K application. A detailed drawing of the constant thickness specimen is shown in Figure 7-3.

7.5.2 Dynamic Testing

Several of each type of specimen were fatigue-tested, using a General Electric Coffin fatigue machine. The purpose of these tests is to demonstrate and evaluate the fatigue behavior of the specimens during the crack initiation and growth process. In particular, these tests will determine:

- a. The location and extent of the growing crack under cyclic loading; and accordingly,
- b. A reliable crack ("failure") detection system.

The initial fatigue test data are shown in Table 7-1. In general, these tests show that the specimens do not fail (break off) after initiation and part-through thickness crack propagation. As was anticipated, the decrease in specimen stiffness resulting from through-wall propagation results in decrease and eventual stopping of the propagating crack. In effect, a small "elastic hinge" results which may keep the specimen "hanging on" almost indefinitely. The consequence of this mechanical behavior is important since the fatigue failure detection system is based on specimen severance.

The initial approach to the problem of failure detection by remote means was to use the full section failure of the specimen to open an electrical circuit and thereby signal failure. Stress corrosion-fatigue crack growth was expected to proceed through the entire specimen. While this may be true in an aggressive environment, tests in air, under deflection controlled loading, do not consistently lead to full section failure. Both designs (constant thickness and NRL type) are susceptible to prolonged cycling with a thin ligament at or near the center (neutral axis) which prevents signaling failure.

Alternate methods of failure detection are being actively pursued. This inherently involves a modification of the failure criterion. Instead of full section failure part-through cracking will be detected—the exact extent of which is being determined in the series of tests noted as follows.

7.5.2.1 Transverse Hole Specimen

Transverse, small diameter (0.020 and 0.033 inch) through holes located on the neutral axis of the specimen are oriented such that they remove the ligament of material making up the hinge which allows the specimen to flex for long periods without separating. A sketch is shown in Figure 7-4.

FIGURE 7-2. CANDIDATE SPECIMEN GEOMETRIES

FIGURE 7-3. TEST SPECIMEN, MODIFIED TAPER

TABLE 7-1

DYNAMIC FATIGUE SPECIMEN EVALUATION TEST

<u>Specimen</u>	<u>Imposed End Deflection, Δ Range (in.)</u>	<u>Measured Strain Range (μ-in.)</u>	<u>Cycles for Crack Initiation</u>	<u>Specimen Failure</u>
<u>Modified Taper Specimens</u>				
MT-D-1	0.216 (± 0.108)	4,850 ($\pm 2,425$)	No crack detectable at 63,125 cycles	-
MT-D-2	0.216 (± 0.108)	4,900 ($\pm 2,500$)	No crack detectable at 63,125 cycles	-
MT-D-3	0.340 (± 0.170)	8,190 ($\pm 4,095$)	Edge crack noted between 22,000 and 23,050 cycles	Tip had not separated as of 63,125 cycles
MT-D-4	0.340 (± 0.170)	8,780 ($\pm 4,390$)	Edge crack noted between 22,000 and 23,050 cycles	Tip separated at 35,091 cycles
<u>NRL Specimens</u>				
NRL-D-1	0.188 (± 0.094)	12,500 ($\pm 6,250$)	<5483	Specimen had virtually no stiffness left at 5,483 cycles, tip was inadvertently broken off during inspection; tip did not separate due to dynamic flexing.
NRL-D-2	0.188 (± 0.094)	Not measured	Cracks noted on both edges of reduced thickness section at 5,483 cycles	Specimen tip inadvertently broken off at 9,914 cycles, virtually zero stiffness remaining in specimen at this time; tip did not separate due to dynamic flexing
NRL-D-3	0.196 (± 0.098)	7,550 ($\pm 3,775$)	Small crack noted in center of reduced thickness section between 11,400 and 12,100 cycles	Specimen tip separated <u>under dynamic cycling</u> between cycles 35,000 and 40,000

FIGURE 7-4. TRANSVERSE HOLE SPECIMEN

Preliminary results (Table 7-2) indicate that a transverse hole diameter-to-thickness ratio of 0.3 is sufficient to cause fatigue crack initiation and growth through the transverse hole section. Unfortunately, the growth is unsymmetrical; growth will occur either through the top or bottom ligament, depending on the localized specimen-hole tolerances and material properties. An example of this is shown in Figures 7-5 and 7-6. A second group of these specimens will be tested in an attempt to establish consistency for specimen crack growth with respect to monitoring specimen failure.

7.5.2.2 Pressurized Cavity Specimen

This specimen is shown in Figure 7-7. Axial cavities are drilled in test specimens by EDM.* A capillary tube is then connected to the cavities by brazing. The use of this kind of specimen is compatible with the Test Autoclave Head design since the capillaries can be routed through to individual external pressure switches. The specimen axial cavities would initially be evacuated and backfilled with an inert gas to ambient pressure. "Specimen failure" would be revealed by the rise in cavity pressure which occurs as the active fatigue crack front breaches the cavity.

* Electrical discharge machining.

TABLE 7-2

PRELIMINARY RESULTS—TRANSVERSE AND AXIAL HOLE SPECIMENS

Specimen	Initial Strain Range	Initial Imposed End Deflection	Crack Initiation ^(a)	Failure
MT-D-5				
0.020 in. ϕ transverse through hole = 20% reduction in net specimen thickness	7600 $\mu\epsilon$ ($\pm$ 3800 $\mu\epsilon$)	0.340 in. ($\pm$ 0.170 in.)	Fine edge crack detected at 43,435 cycles on top surface of specimen away from location of transverse hole.	Full section failure occurred at 45,076 cycles at the site of the original crack initiation.
MT-D-6				
0.020 in. ϕ transverse through hole = 20% reduction in net specimen thickness	4900 $\mu\epsilon$ ($\pm$ 2450 $\mu\epsilon$)	0.220 in. ($\pm$ 0.110 in.)	No detectable cracks were found by 73,420 cycles, two sharp edge notches were cut in specimen at this time and dynamic cycling resumed; a fine (0.010 in.-long) crack was detected at cycle 101,387 using dye penetrant.	Testing was terminated at 101,387 cycles.
MT-D-7				
0.033 in. ϕ transverse through hole = 33% reduction in net specimen thickness	8600 $\mu\epsilon$ ($\pm$ 4300 $\mu\epsilon$)	0.340 in. ($\pm$ 0.170 in.)	Gross, full width cracks were noted on both top and bottom specimen surface between cycles 6,340 and 6,490; they were located directly over the transverse hole.	The loss of specimen stiffness due to fatigue crack propagation was very rapid. By cycle 6,610 the specimen tip sagged enough due to its own weight that it no longer contacted the upper loading screw. by cycle 7,130 the specimen remained in contact with the lower loading screw throughout the entire loading cycle.
MT-D-8-A				
0.020 in. ϕ axial pressurized cavity	7400 $\mu\epsilon$ ($\pm$ 3700 $\mu\epsilon$)	0.340 in. ($\pm$ 0.170 in.)	No detectable crack prior to full section failure.	Full section failure of tip between 36,542 and 36,956 cycles.
MT-D-8-B				
MT-D-8-A continued in test.	2900 $\mu\epsilon$ (+ 2900 $\mu\epsilon$ - 0 $\mu\epsilon$)	Loading point moved to allow specimen to be loaded despite separation of tip, cycling resumed at 43,246 cycles under zero-tension loading.	Fine edge crack detected between 63,108 and 63,924 cycles on top surface of specimen.	Leakage from axial pressurized cavity noted at 65,806 cycles, testing terminated at 65,835 cycles.

(a) Unless otherwise noted, crack initiation is defined as the presence of a crack detectable with no magnification.

FIGURE 7-5. SAMPLE MT-D-7

FIGURE 7-6. SAMPLE MT-D-7, FRACTION SURFACES. THE DARK LINE IN THE BOTTOM LIGAMENT IS THE FINAL HINGE.

FIGURE 7-7. AXIAL PRESSURIZED CAVITY SPECIMEN

7.5.2.3 Change of Compliance Specimen

This concept requires a device capable of sensing and recording a significant change in specimen stiffness. In principle, the change in stiffness can be related to depth of crack during the crack growth progress. A potential difficulty is, of course, transducer sensitivity and compatibility with the BWR environment. Also, the physical geometry of added components must fit the existing hardware. A review of available commercial compliance devices has yielded one potentially suitable. It is essentially a precise, spring-loaded set screw with an insulated ball plunger. A schematic of the compliance sensor and Task K recording system is shown in Figure 7-8. In effect, as the specimen loses stiffness as a result of crack growth, it can no longer exert enough force to compress the spring and results in a no contact signal of failure.

7.6 SPECIMEN COMPLIANCE CALIBRATION

Design was completed of a bench scale test fixture (Figure 7-10) which will be used to calibrate the change in specimen compliance that occurs due to fatigue crack growth. The load cell and linear actuator are on order.

7.7 DYNAMIC FATIGUE TEST MACHINE

The dynamic fatigue test machine (Figure 7-9) was assembled on the shakedown vessel top flange. Initial assembly disclosed several items which required minor rework. Some design adjustments were made to improve the long-term reliability and ease of assembly of the fixture.

FIGURE 7-8. COMPLIANCE SENSOR CONCEPTUAL DESIGN

FIGURE 7-9. CORROSION FATIGUE TEST JIG

7.8 DNPS-1 RELATED ACTIVITY

7.8.1 Loop Piping

Preliminary design of the loop cubicle piping was completed, and check prints were issued for internal review.

Preliminary loop shielding calculations were completed. The results indicate that the use of local lead shielding around each of the test autoclaves would be as effective as a more massive concrete cubicle shield wall. Local shielding is preferable from the standpoint of improving accessibility.

7.8.2 Loop Instrumentation

Fabrication of the loop operating panel is 90% complete. All that remains to be done is to connect and calibrate the six single-pen strip chart recorders which will be delivered in mid-January.

7.8.3 Loop Chemistry

A chemistry sample station will be placed at the fatigue vessel inlet. The chemistry of the loop water will be accurately characterized (see Table 7-3) by monitoring specific conductance and oxygen content on a continuous in-line basis. At approximately 3-month intervals, grab samples will be analyzed for pH, chloride content, and crud* content.

TABLE 7-3

PRECISION ASSIGNED TO LOOP WATER CHEMISTRY

	<u>Measurements</u>
Conductivity	$\pm 0.03 \mu \text{ mho/cm at } 25^\circ\text{C}$
Dissolved Oxygen	$\pm 10 \text{ ppb}$
Crud Level	$\pm 3 \text{ ppb}$
Radiometric Chloride	$\pm 1 \text{ ppb}$

* That portion of the sample collected on a 0.45 micron millipore filter.

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