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REACTOR PRIMARY COOLANT SYSTEM RUPTURE STUDY

QUARTERLY
PROGRESS REPORT NUMBER 3
OCTOBER - DECEMBER 1965

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PROJECT AGREEMENT 37

ATOMIC POWER EQUIPMENT DEPARTMENT

GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

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REACTOR PRIMARY COOLANT SYSTEM
RUPTURE STUDY

Quarterly Progress Report No. 3
October - December 1965

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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 report covers progress in the period from October 1 to December 31, 1965.

Previous reports on this program are listed below:

Quarterly Progress Reports

GEAP-4964	July - September 1965
GEAP-4911	April - June 1965

Topical Report

GEAP-4678	Fracture Mechanics and the Stability of Engineering Structures, M. B. Reynolds, September 1965
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Phase I Reports

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

SECTION II

SUMMARY

2.1 TASK A - RELIABILITY ENGINEERING

During the current report period, initial development of the basic reliability equations has been completed. Work on the BWR Primary Piping System Reliability model has continued and parametric evaluation of component and system reliabilities is being initiated.

2.2 TASK B - STRESS ANALYSIS

Third quarter computer code development efforts have concentrated on programming flat and curved trapezoidal and triangular plate elements. Both flat and curved trapezoidal elements have been completely programmed. The flat triangular element equations have been derived and the program coded for the GE 625. Checkout of this element is underway.

Development of an analytical model of a 6×10 piping tee is underway using a network of beams which approximate the properties of the tee. A general procedure is being developed for locating the beam ends so the gridwork of the model is small near the shell intersections where the stresses change rapidly.

Initial scoping of the experimental stress analysis program has been completed. Two types of experiment are being considered: a) a full scale photo-elastic model of a thin wall pipe component and b) a full scale metal model of a thin wall pipe component.

2.3 TASK C - FRACTURE MECHANICS

Third quarter efforts in the fracture mechanics area have concentrated on developing a method for obtaining fracture toughness data for piping steels. A series of tests is being conducted to investigate the limitations on fracture toughness measurements with specimens small enough to be cut from the walls of typical pipes. Tests thus far have been limited to impact tests with Charpy-type specimens and tensile tests with the so-called wedge-opening loading (Manjoine) specimen. Initial results indicate that reasonably good agreement can be obtained from Charpy specimens which have been nitrided to suppress shear lip formation.

2.4 TASK D - FATIGUE

2.4.1 Crack Growth Studies (Task D-1)

Both the analytical and experimental work has continued. Experimental efforts consisted of measurement of cyclic crack growth in A-212 Grade B steel at room temperature and at 480 F and in Type-304 stainless steel at room temperature. Crack growth rate for the carbon steel at elevated temperature was found to be significantly higher than at room temperature.

In the analytical effort, some available data on the size of natural defects in welded piping were examined to obtain an estimate of the magnitude of defects in service piping and thus provide some guidance for plate and prototype tests.

2.4.2 Low Cycle Fatigue Crack Initiation Studies (Task D-2)

Strain gage evaluation work and determination of cycles to failure data for smooth bar specimens has been completed. Machining of notched cylinder and plate specimens is complete and testing is being initiated.

2.4.3 Prototype Testing (Task D-3)

Work on this task during the current report period was limited to completing necessary facility procurement activities. Equipment bids were evaluated and vendors selected. Purchase orders are being placed with the suppliers.

SECTION III

TASK A - RELIABILITY ENGINEERING

(J. L. Jaech)

3.1 OBJECTIVES

The Reliability Engineering effort is an attempt to develop procedures which can be used to estimate the reliabilities of primary piping systems for specific reactors.

3.2 RELIABILITY MODEL DEVELOPMENT

The development of a reliability model requires identification of all paths to failure, establishing the mathematical relations for each of these paths and finally, combining all the component parts into an overall estimate. In the first 6 months of the program, efforts were devoted to obtaining an understanding of the problems involved and identifying the sensitive factors. During the period covered by this report, the work has been crystallized into an initial reliability equation. This equation is discussed in the following section.

3.2.1 Reliability Equation Scope (K. B. Stewart)

The reliability of a primary piping system will be developed in terms of the possible paths to failure. Let μ_i denote the occurrence of a failure in the i^{th} possible path to failure. Let $\mu_i + \mu_j$ denote the occurrence of a failure in either the i^{th} or j^{th} path or both, and $\mu_i \mu_j$ the occurrence of failures in both paths. Let $P(\mu)$ denote the probability of the occurrence μ . Then the reliability of the system is given by

$$\begin{aligned}
 R &= 1 - P(\mu_1 + \mu_2 + \dots + \mu_n) \\
 &= 1 - P(\mu_1) - P(\mu_2) - \dots - P(\mu_n) \\
 &\quad + P(\mu_1 \mu_2) + P(\mu_1 \mu_3) + \dots + P(\mu_1 \mu_n) \\
 &\quad + P(\mu_2 \mu_3) + \dots + P(\mu_2 \mu_n) \\
 &\quad \dots + P(\mu_{n-1} \mu_n) \\
 &\quad - \sum_{S_3} P(\mu_i \mu_j \mu_k) + \dots
 \end{aligned}$$

where S_3 is the set of all possible combinations of i , j , and k , taken 3 at a time. The reliability analysis of the system will be correct to the extent that the enumeration of paths to failure is exhaustive of all possible paths to failure and the (un) reliability is accurately predicted for each path.

The determination of the probability of a failure in any path will require the development of a composite function whereby all the variables that affect the failure mechanism(s) are included either directly or implicitly so that the effects of the variables as well as the over-all reliability of the path can be deduced.

There is a natural hierarchy of the variables which needs to be summed over for system reliability. A step-by-step development of a symbolic formula follows.

Variable	Comments
Time	Goal-life for the reactor could be used as a common value for all possible paths to failure if the possibilities of inspection, surveillance, and maintenance were not present. Let $F(t)$ be the probability that no failure will occur in the system before time (t) .
Location within a reactor	<p>Location could be defined in several ways. However, for purposes of providing a convenient index of summation it is convenient to denote the location by the component and its order in the sequence of components from the pressure vessel, confining the components to those of concern in P.A. 37. Let $F(t, \bar{i})$ denote the probability that no catastrophic failure will occur in the first i components before time t. Let $F(t, i)$ denote the probability that no catastrophic failure will occur before time t for the i^{th} component. Let $F(t, .)$ denote the probability that no failures will occur before time t in all the components in the system.</p> $F(t, i) = F(t, \bar{i}) - F[t, (\bar{i}-1)]$ <p>The probability that a failure will occur between time t and t' is given by $F(t, .) - F(t', .)$.</p>
Component type	The different components have some order on the basis of complexity. Let $t_{ee} = 1$, and $e_{ll} = 2$, and so on. Then $F(t, \bar{i}, j)$ is the probability that no catastrophic failures will have occurred in the first t units of time in the first i components downstream from the pressure vessel where the i^{th} component is of type j .
Area within component	<p>A notation for these could be standardized too. The areas could be broken down into types according to whether they are welds, are close to welds, have a small radius of curvature, have a given thickness or by combinations of these or other variables.</p> <p>Denote these by k. Then $F(t, \bar{i}, j, \bar{k})$ can denote the probability that no failure will occur in the first k area types in the first i components before the time t.</p>
Failure mechanisms	Let ℓ = the ℓ^{th} possible failure mechanism. Then $F(t, \bar{i}, j, \bar{k}, \bar{\ell})$ denotes the probability that no catastrophic failure will occur due to failure mechanisms 1 to ℓ , area types 1 to k , components 1 to i before time t .

$F(t, \dots)$ is the probability that no failure will occur in any component before time t .

$F(\dots)$ denotes system reliability.

It seems superfluous to have a j for component type. However, one may wish to elicit reliability information about a given type of component for the total system.

In the over-all development of an estimate of $R = F(\dots)$ it will be necessary to characterize the individual (i, j, k, l) paths further according to material type, chemical and physical properties, geometry and loadings which are a function of location within the system. Methods are attached for several paths to failure.

Example 1*

Path to Failure $(i, j, k, l) = (8, 3, 2, 2)$

8 = 8th component downstream from pressure vessel

3 = ell

2 = area type 2

2 = high cycle fatigue

Prediction relationship $F(t, 8, 3, 2, 2)$ is given by

$$G[x(t)] = \int_{RT} \int_{Rs} h(s, T) \cdot H[x(t)] ds dT,$$

where

$$H[x(t)] = 1 - \exp - \left(\frac{x(t) - \epsilon(s)}{\alpha(s) - \epsilon(s)} \right)^{\beta(T)}$$

s = stress

t = time

T = thickness.

$h(s, T)$ is a pdf** so that $h(s, T) \geq 0$,

$$\int_{RT} \int_{Rs} h(s, T) ds dT = 1$$

RT denotes the range of T

Rs denotes the range of s .

What is needed is the distribution of stresses and thicknesses which can occur due to the factors that can influence them.

*This example is pursued further, with numerical values inserted, on page 3-10 of this report.

**Probability density function.

Variable
or
Parameters

Comments

$x(t)$	The number of cycles is obviously a function of time t . Possible candidates for the distribution of cycle lengths are constant, random, (constant + random).
$\epsilon(s)$	ϵ represents a failure threshold for a given set of conditions. The failure threshold is a monotonically decreasing function of stress.
$\alpha(s)$	The scale parameter, α , is a monotonically decreasing function of stress. This implies that for β, ϵ fixed, the mean number of cycles to failure decreases with increasing stress.
$\beta(T)$	The shape parameter β may be a function of thickness at the area of concern, where β would presumably be a monotonically decreasing function of thickness. This in turn would imply that for fixed α, ϵ the mean number of cycles to failure increases with increasing thickness.

$h(s, T)$ needs to be obtained considering all the sources which can introduce uncertainty into these parameters.

Table 3-1 shows the relationships between structural variables and component stages.

TABLE 3-1

STRUCTURAL VARIABLES

	Explicit	Implicit			(1)	(2)
	Cycles x	Time t	Stress s	Thickness T	Material Type	p and c Properties
Reactor service 1	(1, 1)	(1, 2)	(1, 3)	(1, 4)		(1, 6)
Installation 2			(2, 3)		(2, 5)	(2, 6)
Inspection 3					(3, 5)	(3, 6)
Fabrication 4			(4, 3)		(4, 5)	(4, 6)
Manufacture 5						(5, 6)
Procurement 6					(6, 5)	
Design and Requirements 7	(7, 1)	(7, 2)	(7, 3)	(7, 4)	(7, 5)	

- (1) Material type refers to the substitution of an incorrect material or the apparently wrong specified material in design.
- (2) p and c properties refers to ways in which the physical and chemical properties may be varied from nominal specifications.

Comments

- (1, 1) This is the determining relationship where the constants have been fitted from actual data.
- (1, 2) This may be a vital category in the sense that it is necessary to get the distribution of cycle lengths in time in order to estimate how much variation can be expected during goal-life.
- (1, 3) Stresses may change with increased reactor service.
- (1, 4) Fatigue may combine with corrosion or erosion to reduce component thickness.
- (1, 6) Continued cycling may change physical properties although this relationship is implied in prediction formula.
- (2, 3) Installation may place added constraints on the component and thus increase the stress.
- (2, 5) The wrong material may be substituted.
- (2, 6) Welding, burning, striking may affect strength.
- (3, 5) and Inspection may catch substandard quality or gross errors in material.
- (3, 6)
- (4, 3)
- (4, 5) Similar to installation
- (4, 6)
- (5, 6) Poor process control may produce substandard materials.
- (6, 5) Errors in obtaining the wrong material are possible.
- (7, 1)
- (7, 2) Design and requirements obviously affect the component requirements, the conditions of exposure
- (7, 3) and the designer's response to meeting requirements.
- (7, 4)
- (7, 5)

Example 2

Path to Failure (i, j, k, ℓ ,) = (12, 1, 3, 3)

12 = 12th component downstream

1 = tee

3 = area type 3

3 = excessive leaking

Prediction relationship

$F(t, 12, 1, 3, 3)$

is given by $F(., i, j, k, \ell)$

$$L(Z) = \int_{\frac{-\hat{Z}}{\sigma \hat{Z}}}^{\infty} f(\bar{Z}) d\bar{Z},$$

where

$$\bar{Z} = \ell n \widehat{W}(N_D) - \ell n \widehat{W}D$$

$$\sigma \hat{Z} = \sqrt{\sigma^2 \ell n \widehat{W}(N_D) + (\sigma^2 \ell n \widehat{W}D)}$$

$\widehat{W}(N_D)$ = predicted leak rate at the end of N_D design cycles

$\widehat{W}D$ = predicted critical leakage flow value

$$\widehat{W}(N_D) = \frac{a_o^2 \ell_o^2 DRP^{3/2}}{2t^3} \exp\left(\frac{P^3 R^3 K^3 N_D}{8ct^3}\right)$$

$$\sigma^2 \ell n \widehat{W}(N_D) = \sum \left(\frac{\sigma \ell n \widehat{W}(N_D)}{\partial p_i} \right)^2 \left(\frac{\sigma p_i}{p_i} \right),$$

where

$\left(\frac{\sigma p_i}{p_i} \right)$ = the coefficient of variance for the i^{th} parameter, p_j .

TABLE 3-2 STRUCTURAL VARIABLES

	Pressure P	Crack Length ℓ_o	Crack Depth a_o	Leakage Constant D	Stress Analysis Constant K	Crack Growth Constant C	Design Cycles N_D
Reactor service 1	(1, 1)	(1, 2)	(1, 3)				(1, 7)
Installation 2		(2, 2)	(2, 3)		(2, 5)		
Inspection 3		(3, 2)	(3, 3)				
Fabrication 4		(4, 2)	(4, 3)		(4, 5)		
Manufacture 5		(5, 2)	(5, 3)				
Procurement 6							
Design and Requirements 7	(7, 1)				(7, 5)		(7, 7)

Comments on several dependencies

(1, 1) and (1, 7) are subject to variations from nominal specifications, and, (1, 2) and (1, 3) can be undetected or measured inaccurately. The uncertainties in predicted $\ell n \widehat{W}(N_D)$ variances take these into account by the use of the coefficients of variations of these parameters.

The distribution of crack nucleating point densities and crack length densities may be controlled during manufacture (5, 2) and (5, 3).

Example 3

Path to Failure (i, j, k, ℓ) = (6, 4, 4, 5)

6 = 6th component downstream from pressure vessel

4 = straight pipe

4 = area type 4

5 = brittle failure

Prediction relationship

$F(t, 6, 1, 4, 5)$ is given by
$$\int_{R_P} f_1(T_B > T | L_1 = P) f(L_1) d(\ell n L_1)$$

Here R_P means that integration is taken over the range of pressure values that could occur in the pressure-temperature cycle of a reactor. L_1 is the value

$$L_1 = \frac{2t}{RK} \sqrt{\frac{E}{\ell}}$$

where

R = radius of curvature

t = thickness

E = brittle fracture constant

K = stress analysis constant

ℓ = crack length

T_B = brittle temperature of metal

$f_1(T_B > T | L_1 = P)$ is the probability that the brittle temperature is larger than the actual temperature when the pressure is P . $f_2(L_1) d(\ell n L_1)$ is the probability that L_1 will be in the $d(\ell n L_1)$ neighborhood of L_1 .

Comments

The uncertainties in E , K , and ℓ are encoded in the reliability estimate by the formula for the distribution of L_1 ; the uncertainties in T_B by the probability function $f_1(T_B > T | L_1 = P)$.

The crack length ℓ is certainly affected by the parameters which affect the propagation of errors during service life of the reactors. Further manufacture and inspection affect the size and frequency of the cracks.

Since R and t can be influenced by other failure mechanisms such as localized corrosion it would also be necessary in the final analysis to consider the joint effect of these failure mechanisms.

Example 4Path to Failure (i,j,k,ℓ) = (17,1,3,6)17 = the 17th component downstream from the pressure vessel

1 = straight

3 = area type 3

6 = ductile failure

Prediction relationship F(t,17,1,3,6) is given by

$$\int_c^{\infty} f(L_2) d(\ell n L_2), \quad c = \frac{P_{\max} - E(\ell n \hat{L}_2)}{\sigma_{\ell} n \hat{L}_2}$$

$$L_2 = \frac{2t}{RK} \sqrt{\frac{F}{\ell}}$$

where F = ductile fracture constant.

 $f_2(L_2) d(\ell n L_2)$ is the distribution of L_2 due to the uncertainties in F, ℓ, R and k. $P_{\max}$ = the maximum pressure that is sustained in a pressure-temperature cycle.Comments

Most of the comments about crack growth and the factors that affect crack growth in brittle failure are pertinent here too. In addition, $P_{\max}$ may have a distribution of its own from cycle-to-cycle. Then one could be concerned with $(P_{\max})_{\max}$.

Component Type (j)

The types of components that are to be of concern in the reliability analysis are as follows:

1. tee
2. nozzle
3. ell
4. straight
5. wye
6. flange
7. clip or gusset
8. instrument penetration

Component Areas (k)

1. Welds
2. Flat areas (radius of curvature $\rho = \infty$ for any surface curve).
3. Cylindrical portions (radius of curvature $\rho = \infty$ along cylindrical pencil, radius of curvature $\rho = R$ along circumferential surface curves).
4. Spherical portions (radius of curvature $\rho = \text{constant}$ for any surface curves).
5. Radius of curvatures are finite and reach maximum and minimum values for surface curves $\pi/2$ radians apart.
6. Saddle type areas with finite radii of curvatures.

There are other possibilities and other considerations which must be taken into account such as inner surface, outer surface, convexity, proximity to welds, thickness, etc. , but this type of list represents a start. Further, within a component it may be necessary to evaluate the reliabilities of several similar type areas which have different exposures to severity of loadings.

Failure Mechanisms (l)

A list of all possible structural failure mechanisms is given in GEAP-4578, "Mechanical Design Considerations in Primary Nuclear Piping", S. W. Tagart, Jr. , March 1964. These are:

1. Gross primary type overload resulting in
 - 1.1 plastic instability
 - 1.2 ductile rupture
 - 1.3 creep rupture
 - 1.4 excessive gross distortion
 - 1.5 elastic, plastic or creep instability
 - 1.6 plastic collapse.

2. Brittle fracture
3. Crack formation or growth which can lead to 1 or 2 and results from
 - 3.1 steady or cyclic loading of a defect
 - 3.2 fatigue crack
 - 3.3 creep fatigue
 - 3.4 environmental fatigue.
4. Excessive local distortion
5. Progressive distortions such as ratchet mechanism which can lead to or accelerate 1., 2., 3., and 4.

It is apparent that in developing a list of all possible paths to failure, many of the failure mechanism cannot be considered independently. Here a matrix of dependencies between failure mechanisms needs to be developed.

An Example -- Possible Failure due to Fatigue

The type of approach for the failure mechanisms in Examples 2., 3., and 4. have been handled elsewhere. The following gives an example of high-cycle fatigue.

Suppose that the failure law is

$$H(x) = 1 - \exp - \left\{ \frac{x(t) - \epsilon(S)}{\alpha(S) - \epsilon(S)} \right\}^{\beta(T)}$$

where

- x = the number of cycles which is a function of time,
- ϵ = the failure threshold which is a function of stress,
- α = the scaling parameter which is a function of stress,
- β = the Weibull modulus which is a function of material thickness.

The actual functional dependencies may be much more involved than this of course.

Suppose that due to natural reactor variation and lack of precise knowledge about reactor conditions in certain area, the variation in stress is given by

$$f(s) = \frac{1}{30\sqrt{2\pi}} \exp - 1/2 \left(\frac{s - 1000}{30} \right)^2$$

This says that near nominal stress conditions ($s = 1000$ psi), a standard deviation of 30 psi can be expected. Suppose that it has been determined that

$$\epsilon(s) = 10^7/s$$

so that under nominal stress conditions failures would not happen before 10^4 cycles. The distribution of ϵ would be approximately as follows:

$$f_1(\epsilon) = \frac{1}{300 \sqrt{2\pi}} \exp - 1/2 \left(\frac{\epsilon - 10^4}{300} \right)^2$$

Suppose that $\alpha(s) = 2 \times 10^5 - 106s$. Then, at $s = 1000$ psi, $\alpha(s) = 10^5$ cycles. The probability density function for α , then becomes,

$$f_2(\alpha) = \frac{1}{3000 \sqrt{2\pi}} \exp - 1/2 \left(\frac{\alpha - 10^5}{3000} \right)^2$$

Then

$$\begin{aligned} E(\alpha) &= 10^5 \text{ cycles} \\ \sigma \alpha &= 3 \times 10^3 \text{ cycles,} \\ &\text{due to stress uncertainties.} \end{aligned}$$

Suppose $\beta = 1.5/T$

where

$$\begin{aligned} \beta &= \text{the Weibull Modulus} \\ T &= \text{thickness in inches.} \end{aligned}$$

If the pdf for thickness when the nominal is 0.50 inches is

$$f_3(T) = \frac{1}{0.05 \sqrt{2\pi}} \exp - 1/2 \left(\frac{T - 0.50}{0.05} \right)^2$$

then the pdf for the Weibull modulus is

$$f_4(\beta) = \frac{1}{0.3 \sqrt{2\pi}} \exp - 1/2 \left(\frac{\beta - 3}{0.3} \right)^2$$

Suppose that the cycling rate over time is Poisson so that for a given time t , the pdf is

$$f_5(x) = \exp(-\lambda t) (\lambda t)^x / x!$$

where

$$\lambda = 1000 \text{ cycles/year.}$$

Then at the end of

1 year	$E(x) = 1000$ cycles	$\sigma x = 32$ cycles
10 years	$E(x) = 10000$ cycles	$\sigma x = 100$ cycles
20 years	$E(x) = 20000$ cycles	$\sigma x = 144$ cycles
40 years	$E(x) = 40000$ cycles	$\sigma x = 200$ cycles

In determining the point estimate of reliability, the nominal values are inserted into the $H(x)$ formula. In order to determine the range of possible reliability estimates (the interval estimates), the distributions of the parameter values must be taken into account. The point estimate of $H(x)$ is

$$H(x) = 1 - \exp \left(\frac{x - 10,000}{(100,000 - 10,000)} \right)^3 \quad \text{for } x \geq 10,000 \text{ cycles}$$

$$H(x) = 0 \quad \text{for } x < 10,000 \text{ cycles.}$$

This implies that

$$\begin{aligned} E(x(t)) &= (10^{15})^{1/3} \Gamma(1.33) + 10^4 \\ &= 9.9 \times 10^4 \text{ cycles} \\ \sigma x &= (10)^5 \left[\Gamma(2/3 + 1) - \Gamma^2(1/3 + 1) \right] \\ &= 3.2 \times 10^4 \text{ cycles.} \end{aligned}$$

This results in the following table:

<u>x</u>	<u>H(x)</u>	<u>Time</u>
$< 10^4$ cycles	0	-
10^4 cycles	0	10 years
2×10^4	0.00137	20 years
3×10^4	0.0109	30 years
4×10^4	0.0366	40 years

Thus, the probability of a failure due to fatigue for this component with its material, geometrical and loading characteristics is 0.0366. In practice it would be hoped that no event with this high degree of credibility would be observed.

An Example of System Reliability

This simple system is assumed to consist of five components designated by:

- 1.) the serial ordering of the component from the pressure vessel,
- 2.) the component type,
- 3.) the areas of concern within the component and the type of areas to which they belong,
- 4.) the failure mechanism which could cause a failure within these areas.

Table 3-3 gives the details of the reliability computation. For the other failure mechanisms a failure law was assumed. Paths to failure are assumed to be mutually independent.

TABLE 3-3

PROBABILITIES OF FAILURE AFTER N YEARS OF SERVICE

A Value: $C_i = 1$, $e_i = -4$ For Example Means 1×10^{-4}

Paths to Failure

Location	Component Type	Area Type	Failure Mechanism	1 Year		5 Years		10 Years		20 Years		30 Years		40 Years	
				C_i	e_i	C_i	e_i	C_i	e_i	C_i	e_i	C_i	e_i	C_i	e_i
1	3	1	1	0		0		0		1	-3	8.2	-3	2.74	-2
			2	1	-4	5	-4	1	-3	2	-3	3	-3	4	-3
2	2	1	1	0		0		0		1	-3	8.2	-3	2.74	-2
			2	1	-4	5	-4	1	-3	2	-3	3	-3	4	-3
		2	2	1	-4	5	-4	1	-3	2	-3	3	-3	4	-3
		3	1	0		0		0		1	-3	8.2	-3	2.74	-2
			2	1	-4	5	-4	1	-3	2	-3	3	-3	4	-3
			3	1	-5	1	-4	2	-4	4	-4	6	-4	8	-3
			4	1	-5	1.5	-5	3	-4	6	-4	9	-4	1.2	-3
3	3	1	1	0		0		0		1	-3	8.2	-3	2.74	-2
			2	1	-4	5	-4	1	-3	2	-3	3	-3	4	-3
4	1	1	1	0		0		0		1	-3	8.2	-3	2.74	-2
			2	1	-4	5	-4	1	-3	2	-3	3	-3	4	-3
		2	2	1	-4	5	-4	1	-3	2	-3	3	-3	4	-3
5	3	1	1	0		0		0		1	-3	8.2	-3	2.74	-2
			2	1	-4	5	-4	1	-3	2	-3	3	-3	4	-3
System Unreliability				8.2×10^{-4}		4.11×10^{-3}		8.47×10^{-3}		2.29×10^{-2}		7.21×10^{-2}		1.87×10^{-1}	
System Reliability				0.99918		0.99589		0.99153		0.9771		0.9279		0.8122	

Some Conclusions From Table 3-3

- 1.) The reliability of the system after 40 years is estimated to be $R = F(.,.,.,.,.,.) = 0.8122$.
Write $F(.,.,.,.,.,.) = 0.8122$.
- 2.) The probability of a type 1 failure mechanism in a type 1 area within a type 1 component in location 1 is 0 because a type 3 component is used in location 1. Write $F(.,1,1,1,1) = 1.0$, or $1 - F(.,1,1,1,1) = 0$.

- 3.) The probability of failure due to a type 1 mechanism in a type 1 area, within a type 3 component in location 1 is 0.0274. Write $1 - F(. , 1, 3, 1, 1) = 2.74 \times 10^{-2} = 0.0274$.
- 4.) $F(20, 2, 3, 6, 2) = 1.0$ (similar to 2).
- 5.) The probability that a type 2 failure mechanism will cause a failure before 20 years in the second component is 0.006. Write $1 - F(20, 2, 2, . , 2) \cong 2 \times 10^{-3} + 2 \times 10^{-3} + 2 \times 10^{-3} \cong 0.006$.
- 6.) The probability that a type 3 component will fail anywhere in the system is 0.0909. Therefore, the reliability of type 3 components is 0.9091. Write $1 - F(. , . , 3, . , .) \cong 1 - 0.0274 - 0.0040 - 0.0274 - 0.0040 - 0.0274 - 0.0040 + 3(0.0274)^2 + 3(0.0040)^2 + 9(0.0274)(0.0040) \cong 0.9091$. Alternately, $F(. , . , 3, . , .) = (0.9726)^3 (0.9960)^3 = 0.9090$.

The final reliability model will involve hundreds of components each with many areas subject to many kinds of failure mechanisms. A data processing program will no doubt be developed to handle all the computation which is conceptually easy but tedious of execution if done on a hand calculator. A data processing program will allow a variation in input parameters in order to determine which parameters have most effect on the system. Different dependent variables may be called for as output such as the reliabilities due to time, locations, component type, area or failure mechanisms and combinations thereof.

3.3 BWR PRIMARY PIPING SYSTEM RELIABILITY MODEL (J. Torbeck)

The MASS⁽¹⁾ model of the primary piping of a single cycle BWR is nearly complete. Profile views of the piping system included in the existing model are shown in Figures 3-1 through 3-6. These views are line diagrams of the pipe lines obtained with the "quick draw" option of the MASS computer code. These drawings and a plan view of each system were obtained to determine how the systems fit together. This was necessary since the steam, recirculation, feedwater, and emergency condenser systems shown are combinations of existing designs of two reactors. The remaining primary piping systems are being located with reference to these diagrams of the existing model and available reactor designs.

This MASS model shown in the Figure 3-1 through 3-6 is the basis for the reliability model and will be used for the first phase of the parametric investigation of piping stresses discussed in the first and second Quarterly Reports^(2,3). In observing these piping diagrams, three considerations should be made. First, the "quick draw" option pictures an elbow as a straight line connecting the ends of the elbow. Therefore, the actual model does not have as many abrupt corners and straight sections as the diagrams indicate. Secondly, it appears that the lines to the pressure vessel do not actually meet the vessel. This results from the modeling of the lines up to the pressure vessel nozzles. These nozzles fill in the gap between the piping and the pressure vessel. Also, recirculation loops four and five are shown only in Figure 3-4 for clarity.

Figure 3-1. MASS Model of Primary Steam Piping

Figure 3-2. MASS Model of Primary Feedwater Piping

Figure 3-3. MASS Model of Recirculation Loops 1, 2 and 3

Figure 3-4. MASS Model of Recirculation Loops 4 and 5

Figure 3-5. MASS Model of Emergency Condenser Steam Piping

Figure 3-6. MASS Model of Emergency Condenser Condensate Piping

SECTION IV

TASK B - STRESS ANALYSIS

4.1 OBJECTIVES

The stress analysis task is attempting to develop a method for the rational stress and strain analysis of piping components which are presently intractable problems. Major efforts at this time are being applied to the development of a digital computer code for analysis of unsymmetric piping geometries.

4.2 COMPUTER PROGRAM DEVELOPMENT (E. North)*

During the third quarter, the two sections of the computer development work have progressed according to schedule. The work on the elemental plate sections has progressed to the point of having the flat and curved trapezoidal elements programmed and the individual elemental stiffnesses calculated.

Work on the flat triangular element was initiated in the third quarter. To date, the equations for the flat triangular element have been derived and the program coded for use on the GE625. Checkout of the flat triangular element will be starting immediately. As checkout of the flat triangular element is taking place, the equations for the curved triangular element will be derived and programmed.

As presently indicated by the work that has been evolved on the plate elements, the combination of triangular and trapezoidal elements will be used as the transition from one grid size to another. This scheme will more than suffice for any structural analysis involving plates.

The work on modification of the program has been curtailed during the third quarter. This cut-down in effort was expected and was noted in the second quarterly report. Conversion from the IBM to the GE625 computer is a necessary item at the moment at FPD. The conversion work has been progressing satisfactorily and is now nearing completion.

At the present time, the programming of the multi-substructure solution for the program is in progress. This is to allow the 2000 joint capacity which is needed for our analysis.

The programming of the link to incorporate the triangular and trapezoidal elements into the present PAPA⁽⁴⁾ program is 90 percent completed. As soon as this link is checked out, test cases incorporating the triangular and trapezoidal plate elements will be run.

At the present level of effort, no problem exists in meeting the contractual obligations in the time period specified. As presently envisioned, the triangular and trapezoidal elements will be finished in the fourth quarter. Also, all modifications to the PAPA programs will have been completed and checked out.

* FPD, Cincinnati, Ohio

4.3 PAPA PRE-PROCESSOR FOR PIPING TEE

A general procedure for locating the end coordinates of beams which approximate the properties of a piping tee is being developed for use as a pre-processor for the PAPA code. To obtain an accurate solution the grid spacing of the model should be small near shell centersections where stresses change rapidly. This has been considered in developing the system for locating the beam end coordinates for the tee. It appears at this time that using a grid spacing which grows in a geometric progression as distances from discontinuities increase would be the best solution to the general problem. An attempt was made to use orthogonal functions to obtain a beam gridwork resembling a flow net. This procedure was discarded, because of the mathematical problems involved in obtaining the equations of the gridwork which will fit the boundaries of the piping tee geometry. Although this problem could be solved, the difference in the results obtained with the flow net type of spacing and those obtained with the geometric progression gridwork would not warrant the time involved. Also, the geometric progression method will yield a shorter program for the pre-processor of the PAPA code, thereby reducing the amount of computer time used in locating beam end coordinates.

4.4 EXPERIMENTAL STRESS ANALYSIS (W. English)

A series of experiments are being planned for use in verifying the accuracy of the results obtained from the stress analysis computer code which is currently under development. It is intended that these experiments be undertaken in a manner which will provide maximum accuracy commensurate with the high degree of flexibility required to completely verify all options of the computer code, including the type and orientation of loading and the variations in boundary conditions (i.e., method of fixation).

4.4.1 Types of Experiments

Two types of experiments are being considered for this application. The first type of experiment involves the use of a full scale photoelastic model of a thin wall pipe component (e.g., tee, elbow, straight, flange, etc.). The model will be loaded by means of internal pressure, tension, compression, bending and torsion both individually and in combination. With the use of a photoelastic model, the locations of areas of maximum strain can be readily pin-pointed and the variation in magnitude of strain can be observed with changes in loading. The photoelastic method has the advantage of large surface coverage, zero gage length, and continuous visual indication of strain. In addition, the photoelastic material can be readily machined or cast to the desired shape. Strain sensitivity can easily be obtained to 30 micro in/in. with photoelastic materials and optical equipment that are currently available. The photoelastic model provides a maximum amount of flexibility, and is an ideal tool for providing the experimental information necessary to check the code.

The second type of experiment involves the use of a full scale metal model of a thin wall pipe component. The metal model will be coated with a photoelastic coating material and instrumented with strain gages in selected locations. The photoelastic coating, in giving full field coverage of the strain pattern on the component, permits the determination of the axes of principal strain and the location of areas of high strain concentration. Strain gages will be applied at selected areas of high strain that have been identified using Photostress techniques. The model instrumented with strain gages in this fashion will give a more accurate measurement of strain at the selected locations and in addition will provide a check on the results obtained from the photoelastic model. Strain sensitivity can be obtained to 5 micro in/in. with bonded strain gages.

4.4.2 Models to be Tested

As part of the experimental program, a number of physical models have been devised with the idea of accurately testing all options of the computer code. The following models and associated loading have been tentatively selected for this use:

1.) Photoelastic Models

- a. Tee - Thin walled, 3-inch plastic tee loaded with internal pressure, bending, and torsion, individually and in combination.
- b. Tee - Thin walled, 3-inch plastic tee having a through wall crack in one branch and loaded the same as 1. a.
- c. Tee - Thin walled, 3-inch plastic tee having a partial crack (not through-wall) in one branch, and loaded the same as 1. a.
- d. Flange - 900 pound flange joint loaded with internal pressure and bending.
- e. Straight - Thin walled, 3-inch plastic, straight section of pipe containing through-wall cracks of axial, circumferential and skew (45°) orientation and loaded the same as 1. a.
- f. Tee - 3-inch plastic tee containing specified amounts of ovality and variations in wall thickness and loaded the same as 1. a.

2.) Metal Models

- a. Tee - Thin walled, 3-inch metal tee, coated with plastic, instrumented with strain gages and loaded the same as 1. a.
- b. Tee - Thin walled, 3-inch metal tee, coated with plastic, instrumented with strain gages having a through-wall crack in one branch and loaded the same as 1. a.
- c. Straight - Thin walled, 3-inch metal straight section of pipe containing through-wall cracks of axial, circumferential and skew (45°) orientation and loaded the same as 1. a.

SECTION V

TASK C - FRACTURE MECHANICS

(M. B. Reynolds)

5.1 OBJECTIVES

Task C is an attempt to extend the present fracture mechanics and plastic instability theories to the more ductile materials of interest in piping systems. A part of the current effort is an attempt to determine the fracture toughness of piping steels.

5.2 FRACTURE TOUGHNESS DETERMINATION BY THE IMPACT TEST

The techniques for measurement of critical stress-intensity factor, K_c , or critical energy release rate, G_c , were reviewed in earlier reports^(2,5). Critical stress-intensity factor for a given material is determined by loading to instability a specimen containing a flaw for which the relation between stress and stress-intensity factor is known. The value of the critical energy release rate, i. e. energy per unit area of fracture surface can be obtained either by calculation from the value of K_c or by direct measurement of the energy required to create a known area of fracture surface. The relation between critical stress-intensity factor and critical energy release rate depends on the elastic constants of the material:

$$EG_c = K_c^2 \quad (1)$$

for the plane stress condition and

$$EG_{Ic} = K_{Ic}^2 (1 - \nu^2) \quad (2)$$

for the plane strain condition. Thus either measurement should provide the toughness data needed to calculate the strength of a structure containing a flaw of known geometry. Equations (1) and (2) are, of course, limited to elastic conditions, i. e., negligible plastic deformation prior to fracture. This limitation is not serious since the sharp instability required for good K_{Ic} determinations is characteristic of essentially brittle fracture. Apart from strain rate effects, direct fracture energy measurements and tensile or bend tests on notched or cracked specimens should yield equivalent results.

It is not possible to completely eliminate plastic deformation and its attendant energy absorption in the fracture of a polycrystalline metal⁽⁶⁾. This plastic energy absorption is a minimum under plane strain or perfectly triaxial stress conditions and the variation in measured values of G_{Ic} or K_{Ic} with experimental conditions such as notch sharpness or specimen size is an indication of the difficulty of suppressing plastic deformation in the fracture process. The minimum or "worst case" value of G_{Ic} is that which prevails under the condition of maximum stress triaxiality; for example, an internal crack in a thick section of material. G_{Ic} is dimensionally equivalent to surface energy; if the stress system is such that the energy absorption due to pre-fracture plastic deformation is constant across the fracture

surface, it should in the limit be independent of specimen size as is surface energy. * Measurements on specimens of varying sizes and materials by many investigators have shown that G_c is dependent on specimen size. ** However, as specimen size and notch sharpness increase, G_c for the most high strength materials does asymptotically approach a constant value G_{Ic} characteristic of the material.

The mode of fracture in ductile materials is quite size dependent, and examination of a broken specimen will usually show regions of fracture surface both normal to and at an angle of 45 degrees to, the maximum principal stress. In material in thin sections only, the 45-degree mode is observed. As section thickness increases, regions of normal fracture appear although plastic deformation still occurs on a microscopic scale before fracture. The volume of material plastically deformed per unit area of fracture surface decreases as the fracture mode changes from shear (45°) to normal. If a ductile material can be said to have a true G_{Ic} it is that value of G_c corresponding to minimum plastic deformation and which is obtained under conditions of highest stress triaxiality.

The values of G_c or K_{Ic} obtained in measurements on ductile materials depend on the fracture mode prevailing in the test. In order to obtain G_{Ic} or K_{Ic} it is necessary either to eliminate or correct for shear mode fracture. The most obvious route to this objective, increasing specimen size, is often limited by available testing machine capacity. There are numerous ways of compensating for shear fracture in fracture toughness. That test technique which, after machine errors and observational errors have been eliminated, gives the lowest toughness values for a given material is probably most nearly correct.

5.2.1 Experimental Results

A series of tests is being carried out to investigate the limitations on fracture toughness measurements with specimens small enough to be cut from the walls of typical pipes. Tests have thus far been limited to impact tests with Charpy-type specimens and tensile tests with the so-called wedge-opening loading (Manjoine) specimen. Cold-rolled steel bar stock has been used as the test material because it is readily available, metallurgically homogeneous, and has a brittle-ductile transition in the same temperature range to be expected in low carbon steel pipe materials.

Impact tests have been carried out over a range of temperatures using a low capacity impact test machine (Man Labs Model CIM-24). Both specimen size and specimen preparation were varied. Both full-size and half-size ($1/2 \times 1 \times 5.5$ cm) Charpy specimens have been tested. In each case the notch was of the standard 0.2 cm depth with 0.025 cm root radius. In a portion of these specimens, the notch was pre-cracked by fatigue† to a depth of 0.05 to 0.1 cm. Another portion of the specimens was surface nitrided in 40 percent dissociated ammonia for 23 hours at 935°F, giving a nitride case of approximately 0.003 cm thickness. Results of these tests, converted to G_c values in inch-pounds per square inch of fracture surface are given in Table 5-1.

*The term G_{Ic} shall be used to denote this limiting value.

**Tetelman⁽⁶⁾ gives the following relation between G_c and specimen size:

$$G_c(\text{ave}) = \frac{t - t_0}{t} G_{Ic} + \frac{t_0}{t} G_c(45^\circ)$$

where $G_c(\text{ave})$ is the critical energy release rate under the existing stress conditions, $G_c(45^\circ)$ is the value for pure ductile fracture, t is the specimen thickness and t_0 is the thickness of the shear lip at the fracture edge.

†Pre-cracking done by Man Labs, Inc., Cambridge, Mass.

TABLE 5-1
FRACTURE TOUGHNESS OF COLD-ROLLED STEEL

Specimen Type	Test Temperature, °F						
	-320	-160	-109	-14	32	72	150
5S	65.4	84.0	117.2	164	362	590	
5F	52.4	58.0	92.6	180	213.5	211	1780
5N	40.0	46.4	51.0	66.5	87.2	174	517
10S	76.5	79.6	106.2	143	149	312	
10F	58.5	87.9	81.0	150	202	342	1010
10N	43.9	52.7	63.9	64.5	116	106.3	445

Key {
 10 = $1 \times 1 \times 5.5$ cm
 5 = $1/2 \times 1 \times 5.5$ cm
 F = Pre-cracked notch
 N = Nitrided
 S = Standard notch

Example: 5N, Nitrided; $1/2 \times 1 \times 5.5$ cm

It will be noted that the G_c values obtained with the nitrided specimens were consistently lower than those from the standard specimens or the pre-cracked specimens. It is interesting to note that at the higher temperatures the G_c values, which take into account the actual area of fracture surface, are higher for the pre-cracked full-size specimens than for the comparable standard specimens. Examination of the broken specimens showed pre-cracking to be ineffective in suppressing the shear lip at the sides of the specimen, while the nitrided specimens exhibited little shear lip even at the higher temperatures. The G_c values from the nitrided specimens were converted to K_{Ic} values using Equation (2) and assuming ν and E to be 0.3 and 29.6×10^6 psi respectively, over the temperature range covered. These data along with the values previously obtained for the same material with the Manjoine specimens, are plotted in Figure 5-1. The impact test values are seen to be higher than the Manjoine test values at the lower temperatures. This is believed to represent energy lost in the kinetic energy of the broken fragments. If the fragments were assumed to fly off with the velocity of the hammer at impact, this energy loss could amount to a maximum of 18 inch-pounds per square inch with specimens of standard Charpy dimensions. The actual magnitude of this error remains to be measured as does the effect of the nitriding treatment on the mechanical properties of the specimen material.

Work in progress includes:

1. Investigation of kinetic energy loss in impact test.
2. Investigation of effect of nitriding on bulk mechanical properties of material.
3. Modification of impact machine to accommodate larger specimens.

4. Microhardness studies on region about crack tips in Type-304 stainless steel sheet under tension.
5. Investigation of impact specimen with side notches.

Figure 5-1. Comparison of Results of Impact and Tensile Tests for Fracture Toughness Determination

SECTION VI

TASK D - FATIGUE

6.1 OBJECTIVES

The fatigue task has as its objectives; a) extending the understanding of fatigue cracking in high pressure asymmetric piping components which may 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 FATIGUE CRACK GROWTH STUDIES (A. J. Brothers)*

Studies on both the analytical and the experimental portions of the work have been continued during the current report period. The experimental work consisted of measurement of cyclic crack growth in A-212 Grade B steel both at room temperature and at 480°F, and in the Type-304 steel at room temperature.

In the analytical effort, some available data on the size of natural defects in welded piping were examined to obtain an estimate of the magnitude of defects in service piping, and thus provide some guidance for plate and prototype tests. The test fixtures for determining crack growth rate under plastic strain cycling were designed.

6.2.1 Experimental Studies

In the past quarter, crack growth rate data for center slotted plate specimens were obtained on the Type-304 stainless steel at room temperature and on the A-212 Grade B steel both at room temperature and at 480°F. The results to date for the stainless steel are shown in Figure 6-1, which shows the correlation with the stress-intensity factor. It was found that even at a gross alternating stress of 45,000 psi, i. e., at about 130 percent of the 0.2 percent yield strength, extensive crack growth requires thousands of cycles. Furthermore, Figure 6-1 shows that these recent data correlate extremely well with the earlier results obtained at a lower stress on the basis of the stress-intensity factor. This indicates that the stress-intensity factor approach derived from elastic stress analysis appears valid under this loading condition, even for nominal stresses well above the yield strength. This suggests the possibility of extending this concept to conditions in the prototype tests in which nominal stresses and strains exceed yield levels.

The initial measurements of crack growth rate in the A-212 steel at elevated temperature are shown in Figure 6-2. For comparison, this figure also shows results at room temperature at stresses identical to those used at 480°F. These data indicate that the crack growth rate is significantly greater at the higher temperature for both levels of stress. This is most evident at the higher stress level at which the number of cycles for fracture at 480°F were about 25 percent of the number required for fracture at room temperature.

*M and PL, Schenectady, N. Y.

Figure 6-1. Correlation of Type 304 Crack Growth Rate With Stress Intensity Factor

Figure 6-2. Comparison of Crack Growth in A-212 Grade B Steel at 480°F and Room Temperature (RT)

Comparison of these results using the stress-intensity factor correlation is shown in Figure 6-3, and as noted in the crack growth curves there appears to be considerable difference in the crack growth rate at the two temperatures. It is of interest to note that the crack length at fracture is the same for both room temperature and 480°F. This indicates that there is no apparent serious loss in toughness at the high temperature.

In an attempt to determine the cause and significance of the higher crack growth rates at 480°F, the nominal tensile properties are being determined at this temperature. It is not possible as yet to determine whether the significantly greater crack growth rates at 480°F merely reflect a depressed yield strength, or whether this effect results from a cyclic-dependent combined strain-temperature effect. This phenomenon will be studied more extensively in future testing.

The composition and mechanical properties of the 2½ Cr - 1 Mo alloy steel has been evaluated to ensure conformance of this material with the applicable specification A-387D; this comparison is shown below. The data were derived from tests of two separate plates.

Composition

	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Cr</u>	<u>Mo</u>
Specification Requirement	0.15 max.	0.30-0.60	0.035 max.	0.035 max.	0.50 max.	2.00-2.50	0.90-1.10
M and P Lab. Check	0.17	0.48	0.008	0.019	0.38	2.18	0.92

Mechanical Properties

	<u>Ultimate Tensile Strength, psi</u>	<u>0.2 Percent Yield Strength, psi</u>	<u>Elongation, Percent</u>	<u>V-Notch Charpy FATT, °F</u>
Specification Requirement	60,000-85,000	30,000	20	--
M and P Lab. Check	78,400	35,560	28.8	135-140

With the exception of the carbon content, all of the specification requirements are satisfied. The small difference between actual and specification requirements of carbon content will not deter from the usefulness of this material for the general purpose of this program.

6.2.2 Analytical Studies

To obtain some data regarding the possible magnitude of weld defects in reactor piping, and thus determine the sizes of artificial defects to be employed in future tests, the results of previous GE-HAPO pipe tests were reviewed. (7) These defects which were identified as a form of hot-weld cracking consisted of separations which penetrated into the weld metal from and roughly perpendicular to the fusion line. In a group of 36 defects, the following dimensions were reported:

<u>Depth of Defect, Inches</u>		<u>Defect Length, Inches</u>		<u>Length to Depth Ratio</u>	
Minimum	0.007	Minimum	0.060	Minimum	0.9
Maximum	0.178	Maximum	1.746	Maximum	37.8
Average	0.070	Average	0.374	Average	9.5

Figure 6-3. Correlation Between Crack Growth Rate and Stress Intensity Factor for A-212 Grade B Steel at 480°F and Room Temperature (RT)

The foregoing data indicate that a defect depth of 0.100-0.200 inch, which is that to be used in the crack shape study, is a reasonable selection both from practical as well as experimental considerations.

6.2.3 Cyclic Strain Crack Propagation Test

In accordance with the scope of the first year's effort, a preliminary test to measure crack propagation under cyclic plastic strains is planned. The tentative design of the specimen is shown in Figure 6-4. In this first test the specimen will be loaded in fully reversed cycling under a plastic strain range amplitude of ± 0.5 percent. Proper specimen alignment will be attempted using tee-shaped face plates which bolt mutually both to the specimen and the testing machine crossheads.

6.3 LOW CYCLE FATIGUE CRACK INITIATION IN THE PRESENCE OF STRESS/STRAIN CONCENTRATION (E. Krempl)*

During the report period Subtask D-2.1 and Subtask D-2.2 have been completed. Machining of specimens for Subtask D-2.3 is also finished. Progress was made in applying strain gages to edge-notched plane-stress specimens and low cycle fatigue testing of these specimens.

6.3.1 Determination of Smooth Bar Data (Subtask D-2.1)

The final cycles-to-failure curves for completely reversed strain-controlled conditions are given in Figures 6-5, 6-6, and 6-7 for Type-304 stainless steel, $2\frac{1}{4}$ Cr - 1 Mo alloy steel and carbon steel, respectively. In these figures a straight line representing Coffin's method⁽⁸⁾ of prediction of fatigue life is also shown. A good agreement between experimental results and predictions of Coffin's method was obtained only in the case of carbon steel. For the other two materials, the observed lives were less than the predicted lives.

Tables 6-1 through 6-3 summarize the results of the low cycle fatigue tests. The designations of the various quantities are illustrated in Figure 6-12. "Shake down" refers to steady value of the stress range and the plastic strain range when plotted against the number of applied cycles. In the case of Type-304 stainless steel "shake down" refers to the condition shortly before fracture. A fracture is termed gradual when the stress range decreases slowly to zero stress levels. It is termed abrupt when the specimen fractured suddenly during the process of crack propagation.

Crack initiation has been determined either by visual inspection or from the stress-range versus cycles curves. An abrupt change in the stress range towards the end of the tests was taken as point of crack initiation. In lieu of a better criterion this somewhat arbitrary definition was used.

Tables 6-1 through 6-3 show that cycles-to-crack initiation are not very much shorter than cycles-to-failure. It was therefore concluded that these two measures of cyclic lives are equal for practical purposes for the smooth bar specimens. Therefore, only the cycles-to-failure curves are shown.

*M and PL, Schenectady, N. Y.

Figure 6-4. Specimen Configuration for Cyclic Strain Crack Propagation Test

Figure 6-5. Total Strain Range and Plastic Strain Range Versus Cycles-To-Failure for Completely Reversed, Strain Controlled Low Cycle Fatigue Tests.
Material: Type-304 Stainless Steel

Figure 6-6. Total Strain Range and Plastic Strain Range Versus Cycles-To-Failure for Completely Reversed, Strain Controlled Low Cycle Fatigue Tests
Material: 2 1/4 Cr - 1 Mo Alloy Steel

Figure 6-7. Total Strain Range and Plastic Strain Range Versus Cycles-To-Failure for Completely Reversed, Strain Controlled Low Cycle Fatigue Tests
Material: Carbon Steel

Figure 6-8.

The Variation of Stress Range, Total Strain Range and Plastic Strain Range During Cycling. Completely Reversed Strain Controlled Condition.
Material: Type-304 Stainless Steel

Figure 6-9. The Variation of Stress Range, Total Strain Range and Plastic Strain Range During Cycling. Completely Reversed Strain Controlled Condition. Material: $2\frac{1}{4}$ Cr - 1 Mo Alloy Steel

Figure 6-10. The Variation of Stress Range, Total Strain Range and Plastic Strain Range During Cycling. Completely Reversed Strain Controlled Condition.
 Material: Carbon Steel

Figure 6-11. Hysteresis Loops at the Beginning of the Test with Specimen S-3.

Figure 6-12. Hysteresis Loop at the 100th Cycle of Specimen A-6 and Stress-Strain Diagram of Tensile Test Pulled Immediately After Cycling was Discontinued

All of the carbon steel and $2\frac{1}{4}$ Cr - 1 Mo alloy steel specimens showed an increase of the stress range with the number of applied cycles. The stress range increased sharply initially, followed by a much slower increase. Figures 6-9 and 6-10 show the variation of the stress range, the plastic and the total strain range with the number of applied cycles for carbon steel and $2\frac{1}{4}$ Cr - 1 Mo alloy steel, respectively. The minor changes in the total strain range are due to slight variations of the crosshead speed of the testing machine and due to material changes which take place during cycling. These changes will alter the amount of overshoot at the points of load reversal.

Stainless steel specimens cycled below a total strain range of 1.20 percent show an increase in the stress range initially which is followed by a continuous decrease to the point of final fatigue fracture. This behavior is illustrated in Figure 6-8, which shows the same quantities as a function of the number of applied cycles as Figures 6-9 and 6-10. When the total strain range was greater than 1.20 percent, the stainless steel showed a continuous increase in stress range up to failure.

In conclusion, it can be said that all three materials strain-harden during cycling, with the exception of Type-304 stainless steel, below a total strain range of about 1.20 percent. Below this value, Type-304 stainless steel exhibits initial strain-hardening followed by a long period of strain-softening. It will be interesting to note whether the peculiar behavior of this material will have any influence on the behavior of notched specimens tested in this range.

The form of the stress-strain diagram will, among other factors, determine the magnitude of the strain in the root of the notch and hence the strain concentration factor. Therefore, attention was directed at the change of the hysteresis loop during cycling. In addition, a tensile test was performed after a predetermined number-of-cycles at a certain total strain range.

The hysteresis loops at the beginning of the test with specimen S-3 are shown in Figure 6-11. The initial loading takes place along O-A. At A the machine reverses, it unloads the specimen and forces the specimen into compression. The well known Bauschinger effect can be observed at point B. The beginning of the second cycle of loading follows path D-E. This loading curve is different from the initial loading curve O-A in that the linear elastic portion has disappeared completely. This general shape of the loop then remains throughout subsequent cycles until fatigue crack initiation alters its shape.

After a number of previous strain cycles, the stress-strain curve of a tensile test will follow the tensile loading portion of the hysteresis curve as demonstrated in Figure 6-12. The last hysteresis loop of the cyclic test (100th cycle) and the stress-strain curve of the immediately following tensile test are shown there. It can be seen that the stress-strain curve follows the curve of the hysteresis loop. This was usually the case, but not with two carbon steel specimens and one $2\frac{1}{4}$ Cr - 1 Mo specimen. With these specimens, some time had elapsed between the end of the cycling test and the start of the tensile test. For these three tests, the stress-strain curve of the tensile test was above the curve for the last cyclic tensile loading. The most pronounced effect was found with a carbon steel specimen. The virgin stress-strain diagram, the hysteresis loop at the 4000th cycle and the stress-strain diagram of the tensile test, performed 36 hours after the cycling was stopped, are shown in Figure 6-13.

The results of the tensile tests of specimens with various kinds of cyclic pretreatment are summarized in Tables 6-4, 6-5, and 6-6. It can be seen that the proportional limit is lower for specimens with pretreatment and tested immediately after cycling than for virgin specimens. If, however, some time elapses between discontinuing the cyclic test and the start of the tensile test the proportional

limit and the yield stress are raised considerably. This effect is considered to be a consequence of strain aging.

The pre-cycled tensile tests reported in Table 6-4, 6-5, and 6-6 are too limited in number to draw quantitative conclusions concerning this strain aging type behavior. It can be stated, however, that the time elapsed between discontinuing the cyclic test and the starting of the tensile test has a pronounced effect on the stress-strain diagram of carbon steel and $2\frac{1}{4}$ Cr - 1 Mo alloy steel.

These changes in the stress-strain behavior will certainly affect the strains present in the root of the notch. Whether these changes will have any effect on the fatigue life and on the fatigue strength reduction factor remains to be determined by the notched specimen fatigue tests.

6.3.2 Quality Assurance of Strain Gages (Subtask D-2. 2)

The results of this study on the behavior of strain gages during plastic strain cycling will be published shortly in a separate topical report now being prepared. For this Quarterly Report, the conclusions derived from the investigation are: a) under cyclic plastic strain conditions, a strain gage is no longer the precision tool which it is under elastic strain conditions; b) the strain gages investigated showed considerable zero shift and peeled off the specimen after a number of applied cycles; c) the strain range indicated by these strain gages, however, was generally constant up to the point of complete failure of the gage. Therefore, it is possible to use these gages in the plastic range if proper precautions are taken. The results of this study will be helpful for the evaluation of the strain measurements to be performed on notched specimens and on prototype pipe tests.

6.3.3 Low Cycle Fatigue Tests of Notched Specimens (Subtask D-2. 3)

Grooved cylinder specimens are ready for testing.

Edge-notched flat-plate specimens were instrumented with strain gages. All specimens will have strain gages in the apex of the notch. A special technique was developed to position the tiny gages (1/32-inch gage length) properly in the root of the notch. The technique developed is very successful and with it gages were positioned accurately as shown in Figure 6-14.

Two carbon steel specimens have been fully equipped with strain gages, one of them is shown in Figure 6-15. These specimens will be used to try to determine the strain distribution in the net section of the specimen during cycling.

There was a delay in testing the edge-notched flat-plate specimens. The first specimen tested caused a fatigue fracture in the grips of the testing machine scheduled to cycle the plates. It was then decided to use another machine for low cycle fatigue testing and adapters for the fixtures had to be made. The adapters are ready and testing will resume in the second week of January.

Figure 6-13. Hysteresis Loop at the 4000th Cycle of Specimen C-15 and Stress-Strain Diagram of Tensile Test Pulled 36 Hours After Cycling was Discontinued. The Stress-Strain Curve of the Virgin Material is also Shown.

Figure 6-14. Strain Gage in the Root of the Notch of the Flat Plate Specimen

Figure 6-15. Photograph of an Edge Notched Plate Specimen with Strain Gages

TABLE 6-1

COMPLETELY REVERSED,
STRAIN CONTROLLED LOW CYCLE FATIGUE TEST RESULTS
TYPE-304 STAINLESS STEEL

Specimen	ϵ_{tot} Percent	ϵ_{pl} Percent		Stress Range 10^3 psi		Cycles to-Crack	Cycles to-Failure	Fracture Location	Fracture Type
		Initial	"Shake- Down"	Initial	"Shake- Down"				
S-7	2.80-2.76	2.42	2.14	115.0	136.5	284	359	C*	Abrupt
S-8	1.88-1.84	1.59	1.39	87.5	111.0	603	693	C	Gradual
S-2	1.17-1.06	0.90	0.71	84.0	82.0	2600	3746	A	Gradual
S-4	1.07-1.02	0.82	0.74	96.0	82.0	2500	3060	A	Gradual
S-3	1.03-0.97	0.72	0.66	92.0	82.0	5345	5530	A	Gradual
S-5	0.60-0.56	0.34	0.39	72.5	67.0	21940	24120	A	Gradual

* A = Gage Length

B = Extensometer Indentation Points

C = Outside Gage Length

TABLE 6-2

COMPLETELY REVERSED,
STRAIN CONTROLLED LOW CYCLE FATIGUE TEST RESULTS
2 $\frac{1}{4}$ Cr - 1 Mo ALLOY STEEL

Specimen	ϵ_{tot} Percent	ϵ_{pl} Percent		Stress Range 10^3 psi		Cycles- to-Crack	Cycles- to-Failure	Fracture Location	Fracture Type	Remarks
		Initial	"Shake- Down"	Initial	"Shake- Down"					
A-4	2.88-2.84	2.36	2.30	103.0	122.0	340	400	A*	Gradual	Several Stops
A-2	1.93-1.97	1.59	1.48	92.0	112.0	694	732	B	Gradual	
A-1	1.03-1.04	0.83	0.70	92.0	99.0	1725	1725	B	Abrupt	
A-5	1.03-1.02	0.75	0.68	81.0	98.0	2400	2530	B	Gradual	
A-10	1.04-0.95	0.76	0.62	81.0	96.0	3280	3360	B	Gradual	
A-16	0.89-0.82	0.44	0.46	89.0	91.0	5650	6000	C	Gradual	
A-8	0.53-0.50	0.32	0.18	77.0	83.4	-	17340	C	Gradual	

* A = Gage Length

B = Extensometer Indentation Points

C = Outside Gage Length

TABLE 6-3

COMPLETELY REVERSED,
STRAIN CONTROLLED LOW CYCLE FATIGUE TEST RESULTS
CARBON STEEL

Specimen	ϵ_{tot} Percent	ϵ_{pl} Percent		Stress Range 10^3 psi		Cycles- to-Crack	Cycles- to-Failure	Fracture Location	Fracture Type	Remarks
		Initial	"Shake- Down"	Initial	"Shake- Down"					
C-8	2.96-2.99	2.60	2.50	82.0	110.0	270	330	C*	Gradual	Specimen Buckled
C-2	2.26-2.54	1.88	2.08	80.0	103.0	-	242	A	-	
C-4	1.94-1.89	1.62	1.50	76.5	107.5	657	675	B	Abrupt	
C-5	1.70-1.61	1.32	1.04	84.0	100.0	1280	1305	B	Abrupt	
C-1	1.14-1.14	0.93	0.80	63.0	86.0	2700	2804	B	Gradual	Changed Crosshead Speed Several Times
C-3	1.03-0.92	0.80	0.75	63.0	90.0	2980	3180	B	Gradual	
C-6	0.83-0.64	0.60	0.35	63.0	81.0	11330	11500	A	Gradual	

* A = Gage Length

B = Extensometer Indentation Points

C = Outside Gage Length

TABLE 6-4

RESULTS OF TENSILE TESTS PERFORMED ON TYPE-304 STAINLESS STEEL SPECIMENS
WITH VARIOUS KINDS OF CYCLIC PRETREATMENT UNDER COMPLETELY REVERSED,
STRAIN CONTROLLED CONDITIONS

Specimen	Treatment		Proportional Limit 10^3 psi	0.2 Percent Yield Stress 10^3 psi	Ultimate Tensile Stress 10^3 psi	True Ultimate Tensile Stress 10^3 psi	True Fracture Stress 10^3 psi	R. A. Percent	Remarks
	Cycles	At Strain Percent							
S-10	4000	$\epsilon_{\text{tot}} = 0.76$ $\epsilon_{\text{pl}} = 0.48$	10.0	29.0	90.5	164.0	331.0	79.5	Tensile test pulled imme- diately after cycling was stopped
S-9	400	$\epsilon_{\text{tot}} = 0.76$ $\epsilon_{\text{pl}} = 0.46$	10.0	33.0	88.5	189.0	310.0	79.3	
S-6	100	$\epsilon_{\text{tot}} = 2.1$ $\epsilon_{\text{pl}} = 1.65$	12.5	35.0	90.0	159.0	297.0	80.5	
S-11		Virgin	25.0	35.0	89.5	150.0	274.0	77.9	

TABLE 6-5

RESULTS OF TENSILE TESTS PERFORMED ON 2½ Cr- 1 Mo ALLOY STEEL
SPECIMENS WITH VARIOUS KINDS OF CYCLIC PRETREATMENT
UNDER COMPLETELY REVERSED, STRAIN CONTROLLED CONDITIONS

Specimen	Treatment		Proportional Limit 10 ³ psi	0.2 Percent Yield Stress 10 ³ psi	Ultimate Tensile Stress 10 ³ psi	True Ultimate Tensile Stress 10 ³ psi	True Fracture Stress 10 ³ psi	R. A. Percent	Remarks
	Cycles	At Strain Percent							
A-7	4000	$\epsilon_{tot} = 0.79$ $\epsilon_{pl} = 0.50$	29.0	43.0*	75.5	93.0	148.0	67.4	Test stopped, tensile test pulled 36 hours later
A-13	400	$\epsilon_{tot} = 0.73$ $\epsilon_{pl} = 0.50$	14.0	37.5	74.5	81.0	155.0	66.8	Tensile test pulled immediately after cycling was stopped
A-6	100	$\epsilon_{tot} = 2.04$ $\epsilon_{pl} = 1.60$	5.0	37.5	75.5	95.0	146.0	67.5	
A-11		Virgin	27.0	37.5	78.0	- -	148.0	68.6	

* 0.2 percent yield stress at the last cycle (determined from point A in Figure 6-12) 38.0×10^3 psi

TABLE 6-6

RESULTS OF TENSILE TESTS PERFORMED ON CARBON STEEL SPECIMENS
WITH VARIOUS KINDS OF CYCLIC PRETREATMENT UNDER
COMPLETELY REVERSED, STRAIN CONTROLLED CONDITIONS

Specimen	Treatment		Proportional Limit 10 ³ psi	0.2 Percent Yield Stress 10 ³ psi	Ultimate Tensile Stress 10 ³ psi	True Ultimate Tensile Stress 10 ³ psi	True Fracture Stress 10 ³ psi	R. A. Percent	Remarks
	Cycles	At Strain Percent							
C-15	4000	$\epsilon_{tot} = 0.73$ $\epsilon_{pl} = 0.49$	45.0	52.5*	66.0	89.0	120.5	59.9	Test stopped, tensile test pulled 36 hours later
C-7	400	$\epsilon_{tot} = 0.77$ $\epsilon_{pl} = 0.49$	21.0	35.0*	63.5	81.5	123.0	60.0	Test stopped, tensile test pulled 14 hours later
C-14	100	$\epsilon_{tot} = 2.00$ $\epsilon_{pl} = 1.60$	14.0	33.5	63.5	83.5	122.0	59.5	Tensile test pulled immediately after cycling was stopped
C-9		Virgin	19.0	25.0	64.7	89.0	120.0	62.6	

*0.2 percent yield stress at the last cycle (determined from point A in Figure 6-12)

C-15 37.0×10^3 psi

C-7 35.0×10^3 psi

6.4 PROTOTYPE TESTING (J. P. Higgins)

Major effort during the quarter has been placed on procurement details of equipment for the prototype test facility. A second specification for the closed loop servo-controlled dynamic testing system for conducting the push-pull low cycle fatigue prototype tests was prepared and submitted for price quotation. This specification utilizes dc-dc transducer excitation circuitry while the original specification called for ac-dc transducer excitation. All bids for this item of equipment were received and evaluated. A decision has been made to place the final purchase order with the Riehle Testing Machine Division of AMTEC, Incorporated.

The A-106B 6-inch pipe (Schedule 40 and 80) ordered for the initial phase of the prototype testing has been received and placed in storage at Vallecitos.

Cost and leadtime estimates for all other major items of equipment for the prototype facility have been obtained. Final procurement of these items is now under way. The building being erected at Vallecitos for housing the prototype facility is near completion.

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