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**REACTOR PRIMARY COOLANT SYSTEM
RUPTURE STUDY
QUARTERLY REPORT NO. 23
OCTOBER-DECEMBER 1970**

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

GENERAL ELECTRIC

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1. INTRODUCTION

The Reactor Primary Coolant System Rupture Study is being conducted for the Safety Branch, Division of Reactor Development and Technology, USAEC. This twenty-third quarterly report documents progress for the period of October 1 to December 31, 1970. The overall objective of the program is to improve the reliability of reactor system piping by increasing current knowledge of failure-causing mechanisms and by enhancing capability for design evaluation and analysis.

Toward the attainment of this objective, work was continued on the following tasks:

Task A—Probability Study

Task D—Low-Cycle Fatigue

Task K—Effect of BWR Environment

No further work is planned for Task B—Stress Analysis, and Task C—Fracture Mechanics, which terminated at the close of the previous contract year.

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

Quarterly Reports

GEAP-4911	Reactor Primary Coolant System Rupture Study Quarterly Progress Report No. 1, April–June 1965.
GEAP-4964	No. 2, July–August 1965.
GEAP-5082	No. 3, October–December 1965
GEAP-5147	No. 4, January–March 1966.
GEAP-5192	No. 5, April–June 1966.
GEAP-5279	No. 6, July–September 1966.
GEAP-5427	No. 7, October–December 1966.
GEAP-5474	No. 8, January–March 1967.
GEAP-5512	No. 9, April–June 1967.
GEAP-5554	No. 10, July–September 1967.
GEAP-5587	No. 11, October–December 1967.
GEAP-5637	No. 12, January–March 1968.
GEAP-5680	No. 13, April–June 1968.
GEAP-5716	No. 14, July–September 1968.
GEAP-5770	No. 15, October–December 1968.
GEAP-10024	No. 16, January–March 1969.
GEAP-10072	No. 17, April–June 1969.
GEAP-10120	No. 18, July–September 1969.
GEAP-10143	No. 19, October–December 1969.
GEAP-11069	No. 20, January–March 1970.
GEAP-10207	No. 21, April–June 1970.
GEAP-10107-22	No. 22, July–September 1970

Topical Reports

GEAP-4445	A Survey of Water Reactor Primary System Conditions Pertinent to the Study of Pipe Rupture, January 1964.
GEAP-4446	A Review of Fracture Modes as Related to Reactor Primary Coolant Pipe Rupture, May 1964.
GEAP-4474	Experimental and Analytical Program Recommendations—Reactor Pipe Rupture Study, January 1965.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

GEAP-10140 The Effect of Cyclic Strain Aging on the Embrittlement of a Plain Carbon Steel Plate, July 1970.

GEAP-10170 The Effect of Stress Concentration on the Low-Cycle Fatigue of Three Low-Strength Structural Steels at Room Temperature and 500°F, March 1970.

GEAP-10181 Low Cycle, Strain Controlled Fatigue Crack Propagation in Nuclear Piping Steels, May 1970

GEAP-10205 Status of Pipe Rupture Study at General Electric Company, Part III, June 1970.

2. SUMMARY

2.1 TASK A—PROBABILITY STUDY

The method for estimating the probability of severance, described in Quarterly Progress Report No. 21, and for which the first results were given in Quarterly Progress Report No. 22, has been refined and extended for estimating the probability of leakage. Modifications have been made to most of the input distributions; these are reported, together with results for probabilities of both leakage and severance. Because the method is still under development and the selection of inputs judgmental, no use of the results should be made without appropriately taking into account the input used.

2.2 TASK D—LOW-CYCLE FATIGUE

2.2.1 Task D-3—Prototype Piping Fatigue

Testing at room temperature was completed on the stainless steel prototype pipe, CSS-124, the first circumferentially notched specimen to be tested at 2200 psig. The pipe was identical to specimen CSS-25, which was tested at 1000 psig. Generally similar results were obtained for crack initiation and crack growth rate.

2.2.2 Task D-5—Fatigue Data for Piping Code

No work was performed during the report period.

2.3 TASK K—EFFECT OF BWR ENVIRONMENT

The Dresden 1 materials test loop operated at test conditions (510°F, 1040 psig) for a total of 69 days, during the period from initial startup on September 16 to December 31, 1970. A specimen inspection was conducted after the first 17 days of operation to establish the validity of the remote failure detection system. Visual confirmation was made that crack initiation had occurred on the initial fatigue specimens for which cycles to failure had been indicated. After 69 days and 6157 cycles, a total of 60 fatigue specimens (out of 150) have signalled failure (crack initiation). These included: no Inconel-600, twenty-seven Type-304 stainless steel, nine Type-304L stainless steel, and twenty-four carbon steel. Furnace sensitization (24 hours at 1150°F) was particularly effective in reducing the environmental fatigue life of the stainless grades. No changes were noted in the condition of the sustained load stress bend or WOL specimens.

In the electrochemical study, the Ag/AgCl reference electrode was installed at the loop and potentials measured. Steady readings were obtained with respect to bright platinum, Type-304 stainless steel, and carbon steel electrodes.

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

3.1 OBJECTIVES

The objectives of the probability study 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.
- b. Identification of the principal sources of real variability or uncertainty in service life.

3.2 SUMMARY

The method for estimating the probability of severance described in Quarterly Report No. 21 (GEAP-10207), and for which the first results were given in Quarterly Report No. 22 (GEAP-10207-22), has been refined and extended for estimating the probability of leakage. Modifications have been made to most of the input distributions; these are reported, together with results for probabilities of both leakage and severance. Because the method is still under development and the selection of inputs is judgmental, no use of the results should be made without appropriately taking into account the input used.

3.3 PRELIMINARY ESTIMATE OF PROBABILITY OF SEVERANCE

The method for making a preliminary estimate of the probability of severance in a water reactor primary piping system has been refined and extended to include probability of leakage. The essential features of the method are summarized in the following paragraph, using Figure 3-1. Many of the input distributions have been modified; accordingly, these are re-presented in Tables 3-1 through 3-3. Table 3-4 summarizes application of the stresses among the Separate Estimate Categories (SEC's). Figure 3-2, showing crack size versus critical stress for severance, the stress categories, and the crack size blocks, has been modified and is presented for reference. The modified crack growth algorithm* is presented in subsection 3.3.3, and the method of calculating the probability that a random actual stress exceeds the critical stress for a random crack size is in subsection 3.3.4. A summary of new results appears in Table 3-5, with detailed results in Tables 3-7 and 3-8.

The method may be summarized briefly as follows, and by referring to the block diagram in Figure 3-1. References to where details are given are also included.

Input:

1. Fault Causes and SEC's.	Table 3-1a
2. A distribution of initial crack sizes	Table 3-1c and Figure 3-2
3. A distribution of applied elastic-equivalent stresses	Tables 3-1b and 3-4, and
Figure 3-2
4. Distributions of levels of conditions promoting crack growth.	Table 3-1b
5. A measure of the effectiveness of ultrasonic testing versus crack size	Table 3-1c
6. Consideration of the extent to which an applied stress, a crack, and ultrasonic testing might apply to exactly the same piping locations.	Subsection 3.3.1
7. Consideration of the independence of conditions among components and time periods.	Subsection 3.3.2
8. An algorithm for growing cracks	Subsection 3.3.3,
Tables 3-2, 3-3
9. A relationship between crack size and critical stress for severance.	Table 3-1d and
Subsection 3.3.4

*An algorithm is a procedure for solving a mathematical problem.

Output:

1.	Expected numbers of severances in total, by each level of each SEC, and by each stress level and crack size block.	Tables 3-5, 3-7, and 3-8
2.	Expected number of leaks in total and by each level of each SEC.	Tables 3-5 and 3-6

The probability of severance anywhere in the piping system, prior to or during 40 years of service, is calculated as

$$P = \sum \left[\underset{\text{prob. of stress}}{A(I,T)} \times \underset{\text{prob. of stress}}{X(I)} \times \underset{\text{prob. of crack size}}{H_2(I)} \right] \times \left[\underset{\text{prob. of crack size}}{C(J,T)} \times \underset{\text{prob. of crack size}}{H(J,1)} \right] \times \underset{\text{prob. that actual stress exceeds critical stress for crack size}}{G(J,I)} \times \underset{\text{No. of comp's}}{N}$$

where

- P = total desired probability, as approximated by the expected number of severances.
- $A(I,T)$ = total probability (T) of occurrence of stress level I (Table 3-1a).
- $X(I)$ = area fraction for stress level I (Table 3-2).
- $H_2(I)$ = conditional probability of severance, given occurrence of stress level I and that actual stress exceeds critical stress (Table 3-2).
- $C(J,T)$ = total probability (T) of occurrence of axial crack in block J at end of time period. The term $D(J,T)$ is substituted for circumferential cracks (Table 3-1c).
- $H(J,I)$ = conditional probability of severance, given occurrence of axial crack size J and that actual stress exceeds critical stress. The term $H(J,2)$ is substituted for circumferential cracks (Table 3-1c).
- $G(J,I)$ = conditional probability that actual stress I exceeds critical stress for crack size block J, given both (Table 3-1d).
- N = number of components (not shown subscripted, but applies selectively). See following paragraphs.

Summation is over all appropriate combinations of stress and crack size, and levels of the separate estimate categories; i.e., crack orientation, time period, and numbers of components by size, material, and type.

Figure 3-1. Block Diagram of Method for Making Preliminary Estimate of Probabilities of Leakage and Severance

Figure 3-2. Nominal Critical Stresses, and Axial and Circumferential Crack Size Blocks

Table 3-1a
**FAULT CAUSES AND
 SEPARATE ESTIMATE CATEGORIES**

		FAULT CAUSES																	
Fault Cause Code		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Probability that Fault Cause Occurs to a Component		.2	.2	.03	.03	.03	.2	1	.03	.03	.01	.03	.01	.003	*	.03	.01	.003	.2
Separate Estimate Categories	Separate Estimate Category Code																		
	Size	Large (> 16 in. diameter)	A1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
		Small (≤ 16 in. diameter)	A2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Material	Stainless steel	B1	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.
		Carbon Steel	B2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Orientation	Axial	C1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
		Circumferential	C2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Reactor Service Period	Before startup	D1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
		First 5 years	D2	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X
		Last 35 years	D3	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	X
	Component Type	Straights	E1	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.
		Ells and Bends	E2	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.
		Tees	E3	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.

- NOTES:
- * The fault cause applies to all levels of the separate estimate category.
 - X The fault cause applies to only the levels marked of the separate estimate category.
 - 1—Sum of probabilities of other applicable fault causes, if any.
See subsection 3.3 for discussion.

Table 3-1b
CONDITIONAL PROBABILITIES FOR STRESS AND THE SECONDARY FAULT CONDITIONS

Variable Code for Total Probabilities		Conditional Probability ¹																Total Probability ²	S.E.C. Exceptions ³
	Fault Cause Codes ⁴	14	3	4	5	8	9	11	12	13	15	16	17						
	Fault Cause Probabilities ⁴	1	.03	.03	.03	.03	.03	.03	.01	.003	.03	.03	.003						
	S.E.C. Exceptions ⁴		E2,E3	E1,E3	E1,E2						D1	D1	D1						
	Primary Fault Condition: Stress Categories ⁵																		
A(1,*)	ACCT1	1												1				C2	D2 D3
A(2,*)	ACHT1	1												1				C2	D1
A(3,*)	ACHB2		.03	.03	.1	.03	.03	.03	.3	.03	.03	.1	.01	.00862				A2 C2 D1	E1 E3
A(4,*)	ACHB1		Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	.16738				A2 C2 D1	E1 E3
A(5,*)	AAHT3		0	0	.005	.015	.015	.015	.005	.005	.015	.015	.05	.0023				A2 C1 D1	
A(6,*)	AAHT2		0	0	.15	.05	.15	.15	Δ	Δ	.15	.15	Δ	.0288				A2 C1 D1	
A(7,*)	AAHT1		Δ	Δ	Δ	Δ	Δ	Δ	0	0	Δ	Δ	0	.2049				A2 C1 D1	
A(3,*)	ACHB2													.0172				A1 C2 D1	E1 E3
A(4,*)	ACHB1													.3348				A1 C2 D1	E1 E3
A(5,*)	AAHT3													.0046				A1 C1 D1	
A(6,*)	AAHT2													.0576				A1 C1 D1	
A(7,*)	AAHT1													.4098				A1 C1 D1	
	Fault Cause Codes	1	2	6	14	7	18	16											
	Fault Cause Probabilities	.2	.2	.2	.	1	.2	.03											
	S.E.C. Exceptions					B2	D1	D1											
	Secondary Fault Conditions: ⁶																		
B(2,*)	Transition Temperature													.02				B1	
B(1,*)	T2	.1												.18				B1	
	T1	Δ																	
B(6,*)	Sensitization by welding													.04				A2	B2 C2
B(5,*)	(axial) Y3		.2											.08				A2	B2 C2
B(5,*)	Y2		Δ											.08				A2	B2 C2
B(4,*)	Y1																		
	Sensitization by welding																		
	(circumferential)																		
B(9,*)	Z3			.2										.04				B2	C1
B(8,*)	Z2			.4										.08				B2	C1
B(7,*)	Z1			Δ										.08				B2	C1
	Surface Cold Work																		
B(11,*)	R2				.1									.1				B2	
B(10,*)	R1				Δ									.9				B2	
	Exposure to Elements																		
B(14,*)	W2					1								1				B2	
B(13,*)	W1					Δ								0				B2	
	Reactor Environment																		
B(18,*)	E3				0		1							.2				B2	
B(17,*)	E2				.5		0							.4				B2	
B(16,*)	E1				Δ		Δ							.4				B2	
	Cyclic Frequency																		
B(21,*)	N3				.1			1						.127				D1	
B(20,*)	N2				.04			0						.04				D1	
B(19,*)	N1				Δ			Δ						.833				D1	

NOTES:

- 1 Conditional probability that fault condition occurs, given fault case.
- 2 Total probability that fault condition occurs, for a case involving all fault cause codes. The fault causes being approximated as independent and mutually exclusive events, and the sum of conditional probabilities for one fault cause, over the levels of a primary or secondary fault condition, being 1, the sum of Total Probability entries for these levels should be the sum of the conditioning (fault cause) probabilities. If this sum is less than 1 (for B(1 and 2,*) it is 0.2, for example), the remaining difference to 1 is the probability that none of the levels shown for the fault condition applies to a component. Since the complete absence of a fault condition makes no contribution to the tendency for crack growth or severance, no provision is made for these probabilities. Exceptions are by use of

fault cause 14, assigning to it enough probability to make the sum of fault cause probabilities for a case equal to 1, per footnote marked by asterisk. This technique is also used in Table 3-1c for variables C(J,*) and D(J,*).

- 3 Fault condition applies to all levels of the separate estimate categories except to the level code shown, from Table 3-1a.
- 4 From Table 3-1a.
- 5 From Table 3-2.
- 6 From Table 3-3.

* 1 - sum of probabilities of other applicable fault causes
 Δ Conditional probability is (1 - sum of conditional probabilities on immediately higher lines)
 See subsection 3.3 for discussion

Table 3-1c
CONDITIONAL PROBABILITIES FOR INITIAL CRACK SIZE AND ULTRASONIC DETECTION

Variable Code for Total Probabilities		C(J,*)					D(J,*)					E(J,*)		F(J,*)		
Fault Conditions		Primary										Not Detected by U/S				
		Initial Crack Size														
		Axial					Circumferential					Axial		Circumferential		
	Conditional Probability ¹			Total Probability ²	S.E.C. Exceptions ³	Conditional Probability			Total Probability	S.E.C. Exceptions	Total Probability	S.E.C. Exceptions	Total Probability	S.E.C. Exceptions		
Applicable Fault Cause Codes from Table 3-1a		1	2	14			6	10	15	14						
Probability Fault Cause Occurs, from Table 3-1a		.2	.2	*			.2	.01	.03	*						
S.E.C. Exceptions from Table 3-1a									D1							
Crack Size Block Number from Figure 3-2	J= 1	0	0	0	0	0	0	0	0	0	0	C1	0	0	0	C1
	2 ⁴	Δ	Δ	1	.6	.332	.51	.38	.80	1	.89	C1	1	1	1	C1
	3	0	0	0	0	0	0	0	0	0	0	C1	0	0	0	C1
	4	0	0	0	0	0	0	0	0	0	0	C1	0	0	0	C1
	5	0	0	0	0	0	0	0	0	0	0	C1	0	0	0	C1
	6 ⁴	0	0	1	.6	.332	.51	.38	.80	1	.89	C1	1	1	1	C1
	7	.83	.83	0	.02	.032	.04	.013	.006	.006	.006	C1	1	1	1	C1
	8	.05	.05	0	.004	.004	.016	.02	.0084	.0032	.0032	C1	1	1	1	C1
	9	.01	.01	0	0	0	0	0	0	0	0	C1	1	1	1	C1
	10	0	0	0	0	0	0	0	0	0	0	C1	1	1	1	C1
	11	0	0	0	0	0	0	0	0	0	0	C1	0	0	0	C1
	12	.025	.025	0	.01	.032	.04	.013	.006	.006	.006	C1	.1	.1	.1	C1
	13	.005	.005	0	.0004	.0004	0	0	0	0	0	C1	.05	.05	.05	C1
	14	.001	.001	0	0	0	0	0	0	0	0	C1	.02	.02	.02	C1
	15	0	0	0	0	0	0	0	0	0	0	C1	.02	0	0	C1
	16	0	0	0	0	0	0	0	0	0	0	C1	0	0	0	C1
	17	.01	.01	0	.004	.004	.016	.02	.0084	.0032	.0032	C1	.05	.05	.05	C1
	18	.002	.002	0	.0008	.0008	.0016	.002	.0008	.0003	.0003	C1	.02	.02	.02	C1
	19	.0005	.0005	0	.0002	.0002	0	0	0	0	0	C1	.01	.01	.01	C1
	20	0	0	0	0	0	0	0	0	0	0	C1	.01	0	0	C1
	21	0	0	0	0	0	0	0	0	0	0	C1	0	0	0	C1
	22	0	0	0	0	0	0	0	0	0	0	C1	0	0	0	C1
	23	0	0	0	0	0	0	0	0	0	0	C1	0	0	0	C1
	24	0	0	0	0	0	0	0	0	0	0	C1	0	0	0	C1
	25	0	0	0	0	0	0	0	0	0	0	C1	0	0	0	C1

- NOTES: 1 Conditional probability that fault condition occurs, given fault cause.
 2 Total probability that fault condition occurs, for a case involving all fault cause codes.
 3 Fault condition applies to all levels of the separate estimate categories except to level code shown, from Table 3-1a.
 4 Blocks 2 and 6 considered as one starting block.
 * 1 - sum of probabilities of other applicable fault causes.

See subsection 3.3 for discussion.

Table 3-1d
 CONDITIONAL PROBABILITIES FOR ACTUAL STRESS EXCEEDING CRITICAL, AND FOR SEVERANCE

Variable Code		G(J,I)							H(J,I)
		Conditional Probability that Actual Stress Exceeds Critical Stress, Given Actual Stress and Crack Size							Conditional Probability that Severance Occurs, Given that Actual Stress Exceeds Critical Stress [Condition of Variable G(J,I)] and Initial Crack Size
		ACCT1	ACHT1	ACHB2	ACHB1	AAHT3	AAHT2	AAHT1	
I =		1	2	3	4	5	6	7	
Axial Crack Size Block Number from Figure 3-2	J = 1	0	0	0	0				I = 1
	2	0	0	0	0				0
	3	0	0	0	0				1
	4	0	0	0	0				0
	5	0	0	0	0				0
	6	0	0	0	0				0
	7	0	0	0	0				0
	8	0	0	0	0				1
	9	0	0	0	0				1
	10	0	0	0	0				1
	11	0	0	0	0				0
	12	0	0	0	0				1
	13	0	0	0	0				1
	14	0	0	0	0				1
	15	0	0	0	0				1
	16	0	0	0	0				0
	17	0	0	0	0				1
	18	0	0	0	0				1
	19	.1	.1	.35	.08				1
	20	.4	.4	.97	.28				1
	21	0	0	1	.52				1
	22	0	0	0	0				0
	23	0	0	0	0				0*
	24	0	0	0	0				0*
	25	0	0	0	0				0
Circumferential Crack Size Block Number from Figure 3-2	1					0	0	0	I = 2
	2					0	0	0	0
	3					0	0	0	1
	4					0	0	0	0
	5					0	0	0	0
	6					0	0	0	0
	7					0	0	0	1
	8					0	0	0	1
	9					.05	0	0	1
	10					.064	.015	0	1
	11					1	.5	0	0
	12					0	0	0	0
	13					0	0	0	1
	14					.4	0	0	1
	15					.96	.45	0	1
	16					1	.825	.08	0
	17					0	0	0	0
	18					.5	.15	0	1
	19					.85	.5	.08	1
	20					1	.88	.28	1
	21					0	1	.52	0
	22					0	0	0	0
	23					0	0	0	0*
	24					0	0	0	0*
	25					0	0	0	0

* Cracks entering these blocks leak but do not sever.
 See subsection 3.3. for discussion.

Table 3-2
REFERENCE AND ACTUAL STRESS CATEGORIES

Reference Stress:						X(I)	H2(I)			
Axial Hot:	RAH	(expansion + ½ hoop = 14,000 + 4,000 = 18,000 psi)								
Axial Cold:	RAC	(4,000 psi = ½ hoop)								
Circumferential Hot or Cold:	RC	(8,000 psi = hoop)								
Circumferential Hot (for both sides of elbows):	RCH	(expansion + hoop = 10,000 + 8,000 = 18,000 psi)								
						Rank Weight		Area Fraction of Component To Which Stress Level 1 Applies	Conditional Probability of Severe Given Occurrence of Stress Level 1 and That Actual Stress Exceeds Critical Stress	
					Rank Weight Code	Before Service	First 5 Years			Last 35 Years
	Level Code									
Actual Stress:					S					
Tensile Stress:										
Axial Hot Tension	AAHT3	3 · RAH < AAHT ≤ 4 · RAH					20	20	0.25	1
	AAHT2	2 · RAH < AAHT ≤ 3 · RAH					10	10	0.25	1
	AAHT1	0 ≤ AAHT ≤ 2 · RAH					4	4	0.25	1
Axial Cold Tension	AACT1	AACT ≈ 1 · RAC (negligible)				0				
Cicumferential Hot Tension	ACHT1	ACHT ≈ 1 · RC					2	2	1	0.2
Circumferential Cold Tension	ACCT1	ACCT ≈ 1 · RC				1			1	0.2
Local Bending Stress:										
Axial Hot Bending	AAHB1	AAHB = 0					0	0		
Axial Cold Bending	AACB1	AACB = 0				0				
Circumferential Hot Bending	ACHB3	ACHB = 0 in straights					0	0		
	ACHB2	2RCH < ACHB ≤ 4 · RCH in elbows					16	16	0.3	1
	ACHB1	0 < ACHB ≤ 2 · RCH in elbows					6	6	0.3	1
Circumferential Cold Bending	ACCB1	ACCB = 0				0				

NOTE: See subsections 3.3 and 3.3.3 for discussion.

Table 3-3
SECONDARY FAULT CONDITIONS

Secondary Fault Conditions and Levels	Level Code	Rank Weight Code	Rank Weight		
			Before Service	First 5 Years	Last 35 Years
Transition temperature:		T			
Temperature at 10 ft-lb by Charpy V $\geq 0^{\circ}\text{F}$	T2		10S	10S	10S
Temperature at 10 ft-lb by Charpy V $< 0^{\circ}\text{F}$	T1		0	0	0
Sensitization by welding (axial, circumferential):		Y, Z,			
Highly sensitized	Y3, Z3		5S	5S	5S
Moderately sensitized	Y2, Z2		S	2S	2S
Not sensitized	Y1, Z1		0	0	0
Surface cold work:		R			
Surface cold work $> 40\%$	R2		S	2S	2S
Surface cold work $\leq 40\%$	R1		0	0	0
Exposure to the elements before service (Cl^- , F^-):		W			
Exposed	W2		C*/4	C/2	0
Not exposed	W1		0	0	0
Unfavorable environment chemistry (Cl^- , O_2) in service:		E			
Exposed, non-flow line	E3		0	C	2C
Exposed, normal flow line	E2		0	C/4	C/2
Not exposed	E1		0	0	0
Frequency of cyclic loading:		N			
Frequency $> 10/\text{minute}$, stress amplitude $< 0.1 \cdot (\text{actual random stress})$ (high cycle fatigue)	N3		0	S	2S
Frequency $\approx 1/\text{hour}$, stress amplitude = actual random stress (low cycle fatigue)	N2		0	2S	5S
Normal frequency ($\leq 90/\text{year}$), stress amplitude = actual random stress	N1		0	0	0

See subsections 3.3 and 3.3.3 for discussion.

*C = R + Y or R + Z.

Table 3-4
APPLICATION OF THE STRESS CATEGORIES

Orientation of		Direction of Crack Growth	Reactor Service Period			Component Types
Crack	Stress		Before Startup	First 5 Years	Last 35 Years	
Axial	Circum	Depth only	ACCT1	ACHT1	ACHT1	All
Axial	Circum.	Length and depth	—	ACHB1, 2	ACHB1, 2	Ells and bends only
Circum.	Axial	Depth only	—	AAHT1, 2, 3	AAHT1, 2, 3	All
Circum.	Axial	Length and depth	—	—	—	

See subsection 3.3 for discussion.

Table 3-5
SUMMARY: EXPECTED NUMBERS OF LEAKS AND SEVERANCES

	With Ultra- sonic Testing	Without Ultra- sonic Testing
Expected number of leaks	1.53	3.53
Expected number of severances*	0.019	0.053
Expected number of leaks/ Expected number of severances	80.0	66.2

*Practically equal to the probability of one or more severances.

See subsections 3.3 and 3.4 for discussion.

THE RESULTS IN THIS TABLE ARE FROM A METHOD UNDER DEVELOPMENT.
DO NOT USE WITHOUT APPROPRIATELY TAKING INTO ACCOUNT THE INPUT
USED.

Table 3-6
EXPECTED NUMBER OF LEAKS, BY SEPARATE ESTIMATE CATEGORY

Case Code	Level	Number of Comp'ts	Fraction of Comp't's	Average, per Component		Expected Number of Leaks, all X 10 ⁻⁵		Total for System
				With U/S Testing	Without U/S Testing	With U/S Testing	Without U/S Testing	
33344	All levels of all Separate Estimate Categories	300	1	510.	1177.	153,100.	353,100.	
PIPE SIZE								
13344	Large (> 16 in. D)	100	1/3	376.	769.	37,600.	77,000.	
23344	Small (≤ 16 in. D)	200	2/3	578.	1382.	115,500.	276,100.	
MATERIAL								
31344	Stainless Steel	100	1/3	734.	1881.	73,400.	188,500.	
32344	Carbon Steel	200	2/3	398.	824.	79,700.	146,600.	
CRACK ORIENTATION								
33144	Axial	300	1	250.	908.	74,900.	272,400.	
33244	Circumferential	300	1	261.	269.	78,200.	80,700.	
REACTOR SERVICE PERIOD								
33314	Prior to Service	300	1	22.	42.	6600.	12,700.	
33324	First 5 years	300	1	209.	442.	62,800.	132,600.	
33334	Last 35 Years	300	1	279.	693.	83,700.	207,800.	
COMPONENT TYPE								
33341	Straights	150	1/2	358.	956.	53,600.	143,400.	
33342	Ells and Bends	100	1/3	813.	1617.	81,300.	161,500.	
33343	Tees	50	1/6	364.	961.	18,200.	48,200.	

For discussion see subsection 3.4.

THE RESULTS IN THIS TABLE ARE FROM A METHOD UNDER DEVELOPMENT. DO NOT USE WITHOUT APPROPRIATELY TAKING INTO ACCOUNT THE INPUT USED.

Table 3-7
PROBABILITY OF SEVERANCE* BY SEPARATE ESTIMATE CATEGORIES

Case Code	Level	Number of Comp'ts	Fraction of Comp'ts	Average, per Component		Probability of Severance,* all X 10 ⁻⁵	
				With U/S Testing	Without U/S Testing	With U/S Testing	Total for System Without U/S Testing
33344	All levels of all Separate Estimate Categories	300	1	6.38	17.77	1913.	5330.
PIPE SIZE							
13344	Large (> 16 in. D)	100	1/3	1.39	8.00	139.	800.
23344	Small (≤ 16 in. D)	200	2/3	8.88	22.65	1774.	4530.
MATERIAL							
31344	Stainless Steel	100	1/3	6.45	23.42	645.	2342.
32344	Carbon Steel	200	2/3	6.34	14.94	1268.	2988.
CRACK ORIENTATION							
33144	Axial	300	1	3.69	13.13	1106.	3940.
33244	Circumferential	300	1	2.69	4.63	807.	1390.
REACTOR SERVICE PERIOD							
33314	Prior to Service	300	1	0.008	0.68	2.	205.
33324	First 5 Years	300	1	2.55	6.65	764.	1995.
33334	Last 35 Years	300	1	3.82	10.43	1147.	3130.
COMPONENT TYPE							
33341	Straights	150	1/2	3.13	7.54	469.	1130.
33342	Ells and Bends	100	1/3	12.8	38.12	1279.	3812.
33343	Tees	50	1/6	3.31	7.76	165.	388.

*Probability of severance is approximated by the expected number of severances; see subsection 3.3.

THE RESULTS IN THIS TABLE ARE FROM A METHOD UNDER DEVELOPMENT. DO NOT USE WITHOUT APPROPRIATELY TAKING INTO ACCOUNT THE INPUT USED.

Table 3-8
PROBABILITY OF SEVERANCE BY STRESS LEVEL AND CRACK SIZE BLOCK

Stress Category	Probability of Severance, all $\times 10^{-5}$		
	With U/S Testing	Without U/S Testing	
1	2.	205.	ACCT1 Cold circumferential tensile stress, hoop, 8000 psi
2	159.	928.	ACHT1 Hot circumferential tensile stress, hoop, 8000 psi
3	860.	2078.	ACHB2 Hot circumferential local bending stress, 36,000–72,000 psi
4	85.	729.	ACHB1 Hot circumferential local bending stress, 0–36,000 psi
5	511.	298.	AAHT3 Hot axial tensile stress, 54,000–72,000 psi
6	287.	982.	AAHT2 Hot axial tensile stress, 36,000–54,000 psi
7	9.	112.	AAHT1 Hot axial tensile stress, 0–36,000 psi
	<u>1913.</u>	<u>5330.</u>	Total for system

Crack Size Block	Probability of Severance, all $\times 10^{-5}$		
	With U/S Testing	Without U/S Testing	
8	85.	77.	For diagram of crack size blocks see Figure 3-2.
9	1189.	418.	
13	27.	123.	
14	47.	127.	
17	276.	2180.	
18	55.	827.	
19	234.	1578.	
	<u>1913.</u>	<u>5330.</u>	Total for system

See subsection 3.3 for discussion.

THE RESULTS IN THIS TABLE ARE FROM A METHOD UNDER DEVELOPMENT. DO NOT USE WITHOUT APPROPRIATELY TAKING INTO ACCOUNT THE INPUT USED.

For a reference piping system, a total of 300 components was used, made up as follows:

Total number of components		300
Large pipe (> 16 in. diameter)	1/3	100
Small pipe (≤ 16 in. diameter)	2/3	200
Stainless steel	1/3	100
Carbon steel	2/3	200
Straights	1/2	150
Ells and bends	1/3	100
Tees	1/6	50

Categories are proportionate throughout; thus the number of small, carbon steel tees is $300 \times 2/3 \times 2/3 \times 1/6 = 11.1$.

3.3.1 Congruency of Locations

Probability distributions are assigned for stresses and crack sizes on a per-component basis. For a randomly chosen stress to grow a randomly chosen crack, or subject it to severance, the stress and crack must be in effect at exactly the same locations. In the analysis it is assumed that this is the case, the only adjustment being to reduce the probability of such location matching for five of the seven stress levels by an area coefficient between 0 and 1, as shown in Table 3-2.

As for congruency of ultrasonic testing, since the probabilities of crack occurrence are not restricted to any piping locations (such as welds), the probabilities of nondetection ultrasonically given in Table 3-1c assume inspection prior to and in service is done over the same surfaces to which the crack occurrence probability applies.

3.3.2 Independence of Conditions

It is assumed that all conditions occur independently among each other, among components, and among time periods. Thus, if the probability of severance in one component is 10^{-5} , then the probability of severance in 10 components is 10^{-4} . Moreover, if that probability of severance applies in each of two time periods, the probability of severance in those components in either of the two periods is 2×10^{-4} .

3.3.3 Crack Growth Algorithm

The following steps describe the algorithm used for crack growth.

1. Identify Secondary Fault Conditions (SFC's) which promote crack growth, along with the fault causes and any SEC exceptions applicable to each (Table 3-1b).
2. Define levels of the SFC's (Table 3-3).
3. Assign a conditional probability of occurrence to each level of the SFC's given that each applicable fault cause occurs (Table 3-1b).
4. Assign a "Rank Weight" to each level of each stress and SFC, reflecting the ability of that level to promote crack growth. It can be seen in Table 3-3 that the rank weights for all the SFC levels depend on the stress rank weights, and in some cases on the rank weights of the other SFC's (Table 3-3).

For *one combination* of levels of SEC's:

5. Compute the rank weight *sum* for each combination of levels of the SFC's.
6. To calibrate rank weight sums to an expected number of crack blocks grown in a reactor service period, assign such expected numbers to the rank weight sums of 25 selected combinations of levels of the SFC's. A satisfactory calibration expression was found to be

$$\text{Expected number of blocks grown} = \text{Rank weight sum}/15.$$

Any results exceeding 4 are assigned to 4, the maximum possible number of blocks grown. Expected numbers apply to growth in depth and length, depending on the stress category as summarized in Table 3-4; for ACHB1 and 2, the same expected numbers apply to length and depth.

7. Form a normal distribution of actual number of crack blocks grown, having mean equal to the expected number and standard deviation assigned as standard deviation = $\sqrt{\text{expected number}/3}$; and thus obtain probabilities of growth for each number of blocks, dividing at 0.5, 1.5, 2.5, and 3.5 blocks.
 8. Each probability in step 7., times the probability that the SFC levels combination occurred, is a contribution to the probability of growth of each number of crack blocks.
 9. Sum the probabilities in step 8. for the probability of growth each number of crack blocks. Independence of the SFC's is assumed.
-
10. Sum step 9. over all combinations of SEC levels for the probability of growth of each number of crack blocks in the service period.
 11. Assign one-half of the probabilities in step 10. to the first half of the service period, make any ultrasonic detections, recycle leaks and repaired detected cracks, and apply the other half of the growth probabilities to the second half of the service period.
 12. At the end of each service period, note the accumulated probabilities of cracks in each block, and the probability of each actual stress; determine by inspection of Figure 3-2, and use of subsection 3.3.4, the probability that each actual stress level exceeds each crack size block; and sum over all crack size blocks and stresses to obtain the total probability of severance for a component in the service period.*
 13. Sum the probabilities in step 12. over all components to obtain the total probability of severance for the service period.* This assumes initial crack sizes, stresses, and SFC's occur independently among components.
 14. Sum the probabilities in step 13. over the three service periods to obtain the total probability of severance prior to startup and in 40 years of reactor service life.* This assumes cracks, stresses, and SFC's occur independently among service periods.

* This procedure actually calculates the expected number of severances. For values much less than 1, the probability of one or more severances is only very slightly less.

3.3.4 Calculating the Probability that Actual Stress Exceeds Critical Stress

A basis for relating actual stress to critical stress for severance is presented in Figure 3-2. If actual stress is uniformly distributed within each range shown, and crack sizes are uniformly distributed over each block—which implies that nominal critical stresses are trapezoidally distributed over each block due to the constant critical stress lines running diagonally, and these trapezoidal distributions may be approximated by uniform distributions—then the problem reduces to that of finding the probability that one uniformly distributed random variable exceeds a second random variable also uniformly distributed, where the two distributions may overlap entirely or in part. This is a straightforward problem, illustrated as follows. Recall that if two random variables are uniformly distributed over exactly the same range of values, the probability that one exceeds the other is 0.5.

$A1 = \Pr [c \leq A \leq d]$, for example.

$\Pr [A \geq C]$ is required.

$$\begin{aligned} \Pr [A \geq C] &= \sum_{\text{All levels of C}} \sum_{\text{All levels of A}} \left\{ \begin{array}{l} (\text{Probability of each level of A}) \cdot (\text{Probability of each level of C}) \cdot \\ (\text{Probability that the level of A exceeds the level of C, given both}). \end{array} \right. \\ &= A1(C1 + C2) \cdot 1 + A2(C1 \cdot 1 + C2/2) \\ &= A1 + A2 (C1 + C2/2) \end{aligned}$$

For example, if

$$\begin{aligned} A1 &= 0.7, \\ A2 &= 0.3, \\ C1 &= 0.8, \\ C2 &= 0.2, \end{aligned}$$

$$\begin{aligned} \text{Then } \Pr [A \geq C] &= 0.7 + 0.3 (0.8 + 0.2/2) \\ &= 0.97 \end{aligned}$$

It is assumed that severance results if actual stress exceeds the nominal critical stress for a crack size, except for the 8000-psi hoop stresses for which the probability of severance under the above condition is assigned as 0.2, to account in part for the work at BMI-Columbus which identifies 12,000 psi as the lowest stress which will support a running crack. This coefficient appears in Table 3-2. It is also assumed that all stress types (pressure, expansion, and local bending) cause severance at the same stress levels.

3.4 PRELIMINARY ESTIMATE OF EXPECTED NUMBER OF LEAKS

Leakage occurs when a crack grows through the wall; that is, into blocks 22, 23, or 24 in Figure 3-2. Expected numbers of leaks for all components prior to startup and in 40 years of reactor service life are summarized in Table 3-5, with details in Table 3-6.

3.5 NEXT STEPS

The two most sweeping assumptions in the foregoing method are: (1) that initial cracks, stresses, and secondary fault conditions occur independently among components and service periods; and (2) that the same critical stress diagram applies to all piping sizes, to both materials and to operating temperatures as well as room temperature. A simple method for introducing interdependencies is required, along with refining application of the critical stress diagram by introducing critical crack size results which may be available from other programs.

4. TASK D—LOW-CYCLE FATIGUE

(J. D. Heald)

4.1 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.

4.2 TASK D-3—PROTOTYPE PIPE FATIGUE

4.2.1 Summary

Testing at room temperature was completed on pipe specimen CSS-124, the first circumferentially notched specimen to be tested at 2200 psig. The specimen was identical to CSS-25, which was tested at 1000 psig. A comparison of the test results is given as follows:

Sample No.	CSS-124	CSS-25
Material and Schedule	Stainless Steel, Sch. 160	Stainless Steel, Sch. 160
Internal Pressure	2200 psi	1000 psi
Test Temperature	Room Temperature	Room Temperature
Stress Range	70,500 psi	70,460 psi
End Deflection	±7.33 inches	±7.33 inches
Cycles to Initiation	700	500
Cycles to Full Wall Penetration	15,200	16,250
	(12,200)*	(11,383)*
Cycles at Test Termination	29,801	30,629
	(13,601)**	(14,379)**

*Number in parentheses is full amplitude cycles.

**Full amplitude cycles after full wall penetration.

4.2.2 Data Obtained

4.2.2.1 Crack Initiation

A visual inspection of the notch area was made every 50 cycles for crack initiation. At cycle 700, a 0.100-inch-long hairline crack was detected at the root of the machined notch.

Figure 4-1 shows cycles to crack initiation versus nominal stress range for all room temperature stainless steel specimens tested.

4.2.2.2 Through-Wall Growth

During through-wall crack growth, three (1000-cycle) half-amplitude, stress reduction marking fronts were attempted. If successful, this will enable obtaining approximate through-wall crack growth rate data for calculation of stress intensity factors.

Figure 4-1. Type-304 Stainless Steel, Room Temperature, Stress Range versus Crack Initiation Cycles

The specimen was equipped with a boot to prevent water leakage at through-wall penetration. Since leakage was blocked by the boot, through-wall penetration was arbitrarily defined at cycle 15,200 when the outside surface crack length reached 2.44 inches. This length was based on previous experience for Schedule-160 specimens.

When the crack reached 2.44 inches in length, a fourth 1000-cycle marking front was attempted. At the completion of the marking cycles, the fatigue cycling was switched from fully reversed to zero tension cycling.

4.2.2.3 Circumferential Crack Growth

Following through-wall penetration, cycling was continued to obtain circumferential crack growth data.

Water leakage (boot failure) finally occurred at cycle 26699 when the outside surface crack length was 5.94 inches (28.6% of the pipe circumference). The depressurized specimen was then drained. The specimen was tested at zero pressure for the remaining cycles of the test.

Figure 4-2 shows the range of stress intensity factor (zero-tension mode) versus circumferential crack growth rate for this specimen, as well as all other room temperature stainless steel specimens tested.

4.2.3 Further Test Plans

Three more room temperature specimens remain to be tested at 2200 psi. These specimens are listed as follows:

Specimen Material	Pipe Size	Notch Type and Location
1. Carbon Steel	6 in. sch. 160	Circumferential, external
2. Stainless Steel	6 in. sch. 160	Longitudinal, internal
3. Carbon Steel	6 in. sch. 160	Longitudinal, internal

4.2.3.1 Specimen and Equipment Status

The fabrication of the circumferentially notched carbon steel specimen is 80% complete. The test sections for both longitudinal notched specimens have been machined. The remaining parts for these two specimens still require machining and welding.

All equipment is operational and ready for testing.

Figure 4-2. Type-304 Stainless Steel, Room Temperature, Circumferential Crack Growth Rate versus Range of Stress Intensity Factor, ΔK

5. TASK K—EFFECT OF BWR ENVIRONMENT (D. A. Hale)

5.1 OBJECTIVE

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

5.2 SUMMARY

The Dresden 1 test loop continued to operate at test conditions (510°F, 1040 psig, 10 gpm) to the end of the report period. The loop operated a total of 69 days, from initial startup on September 16 to December 31. A specimen inspection was performed at the end of the first loop operating period after 17 days of exposure at test conditions. Visual confirmation was made that crack initiation had occurred on the fatigue specimens for which cycles to failure had been indicated by the instrumentation (failure detection) system. No cracking was noted on any of the static stress bend specimens; no crack extension was noted on any of the pre-cracked static WOL specimens.

A total of 60 fatigue specimen failure indications have been recorded out of a total of 150 specimens. The fatigue failure data were reviewed to determine preliminary trends. The evidence is quite clear that for Types-304 and -304L stainless steels, full furnace sensitization decreases the fatigue life.

5.3 DRESDEN 1 TEST LOOP OPERATION

The test loop operated 69 days at test conditions (510°F, 1040 psig, 10 gpm) during the report period; the operating history is summarized in Table 5-1.

5.4 SPECIMEN INSPECTION

All the static stress bend and WOL specimens were removed from the static test vessel for inspection following the first operating period. The stress bend specimens were checked for surface cracking, using ordinary low-power (5 to 10X), hand-held magnifiers and flashlights; no cracking was noted. No increase in crack size was detected in the WOL specimens.

The fatigue test assembly was removed from the test vessel and placed on the inspection stand. Original plans called for inspecting all 23 fatigue specimens that had signalled failure up to that time. However, the high radiation field (≈ 1.5 R/h $\beta + \gamma$ at 6 in.) caused by crud deposits on the surfaces of the test machine and specimens limited the amount of time available for specimen inspection. A total of 16 specimens were inspected; of these 16, 13 displayed obvious surface fatigue cracks in the specimen test section. One of the 13 was totally separated; the tip was returned to San Jose for metallographic examination.* No cracks could be detected in the other three specimens. In light of the method used for these inspections,** this is not surprising; several of the fatigue specimens tested in air during the fatigue specimen evaluation tests failed with tight fatigue cracks that could not be seen without the use of medium power (20 to 50X) magnifiers.

*See Appendix A

**Hand-held dental mirror (no magnification) and flashlight.

**Table 5-1
DRESDEN TEST LOOP OPERATING SUMMARY**

Loop Operating Period	Startup	Shutdown	Cumulative Operating Time	Fatigue Cycles (Cumulative)		Fatigue Test Specimen Failure Indications Received	Remarks
				Start	Finish		
1	Sept. 16	Oct. 2	17 days	0	1900	23	Loop shutdown in anticipation of scheduled plant maintenance outage
2	Oct. 22	Nov. 5	32 days	1901	3250	18	(Same)
3	Nov. 25	Dec. 31	69 days	3251	6494	9	Loop shutdown to repair leaking fitting

5.5 FATIGUE SPECIMEN TEST DATA

A total of 150 fatigue specimens representing four material groups, thirty-one different metallurgical test conditions, and two specimen loading modes are included in the basic Task K test program. For convenience, the test plan is reproduced from Quarterly Progress Report No. 18 (Table 5-3). This test plan was designed to allocate the fatigue specimen positions among the selected test conditions to maximize chances of detecting differences in cyclic fatigue life which might be caused by these conditions.

During the first three periods of test loop operation, failure was indicated for 60 specimens; pertinent test parameters are summarized in Table 5-2, parts a, b, and c. Note that because of the geometry of the Task K fatigue specimen (i.e., thin specimen loaded in bending) and the unique method used to define and detect specimen failure, these failure data represent cycles to initiation; very little [~5-10%] specimen life is devoted to fatigue crack growth.

The values of initial surface strain range in Table 5-2 are based on room temperature, strain-deflection calibration curves generated for each material and represent the shakedown strain ranges corresponding to given specimen deflections. These were measured using miniature strain gages mounted in the reduced thickness test section of each specimen. Since these strain-deflection relationships could be influenced by temperature and hold times under load, preparations are being made to rerun them at 500°F, using various hold times.

The failure data accumulated to date suggest trends which can be used to rank different test conditions within the material groups. Since many specimens are still under test, the following observations should be viewed as preliminary.

5.5.1 Metallurgical and Surface Condition Effects

a. Type-304 Stainless Steel

The most significant feature of Type-304 stainless steel data is the fatigue life reduction associated with the furnace sensitized condition (material condition No. 5); of the total of 27 failed Type-304 stainless steel specimens, 19 occurred in furnace sensitized material.

The remaining eight failures were divided among four material conditions as noted:

1. Three specimens—Dresden 1 Equalizer Line Weldment material with 8 years service.
2. One specimen—Dresden 1 Equalizer Line Base (i.e., wrought) material with 8 years service.
3. Three specimens—"As-Received" (i.e., mill-annealed and pickled):
 - Two specimens—zero-tension loading
 - One specimen—fully-reversed loading
4. One specimen—Type-304 base material with heavy surface cold work.

Notched specimens (eight total: four with mechanical edge notches [refer to Figure 7-3 in Quarterly No. 20], four chemically etched) were included to attempt to distinguish the portion of total specimen cyclic life consumed in fatigue crack initiation from that consumed in fatigue crack propagation. Both mechanical and chemical notches were provided to promote early fatigue crack initiation. The data indicate (for furnace sensitized Type 304) that the notches were not effective; i.e., the cyclic life of the notched specimens is not appreciably shorter than the un-notched specimens.

Table 5-2a
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIOD ')

Specimen Number	Cycles to Failure	Material	Shakedown Surface Strain Range*	Loading Mode**	Test Condition Code***	Description
1059	797	Carbon Steel	1.0%	C-T	29	Weldec, Stress Relief
1060	909	Carbon Steel	1.0%	C-T	29	Weldec, Stress Relief
1010	996	Carbon Steel	1.0%	C-T	27	As Mach., Stress Relief
1009	1027	Carbon Steel	1.0%	C-T	27	As Mach., Stress Relief
131	1027	Type 304 SS	0.5%	O-T	12	As Mach., Furnace Sensitized
57	1066	Carbon Steel	1.0%	C-T	26	As Mach., No Stress Relief
64	1123	Carbon Steel	1.0%	C-T	26	As Mach., No Stress Relief
48	1176	Carbon Steel	1.0%	C-T	26	As Mach., No Stress Relief
179	1365	Type 304 SS	0.75%	O-T	12	As Mach., Furnace Sensitized
1008	1378	Carbon Steel	0.75%	C-T	27	As Mach., Stress Relief
53	1380	Carbon Steel	1.0%	C-T	26	As Mach., No Stress Relief
1053	1423	Carbon Steel	1.0%	C-T	28	Welded, No Stress Relief
1052	1455	Carbon Steel	1.0%	C-T	28	Welded, No Stress Relief
188	1493	Type 304 SS	0.5%	C-T	10A	As Mach., Furn. Sens., Chem. Notch
170	1506	Type 304 SS	1.0%	C-T	5	As Mach., Furn. Sens.
1017	1524	Carbon Steel	0.75%	C-T	29	Welded, Stress Relief
165	1651	Type 304 SS	0.5%	C-T	5	As Mach., Furnace Sensitized
1061	1708	Carbon Steel	0.75%	C-T	29	Welded, Stress Relief
1024	1738	Type 304 SS	0.5%	C-T	9	As Mach., Furn. Sens., Mech. Notch
180	1771	Type 304 SS	1.0%	C-T	5	As Mach., Furn. Sens.
128	1778	Type 304 SS	0.5%	O-T	12	As Mach., Furn. Sens.
166	1838	Type 304 SS	0.75%	C-T	5	As Mach., Furn. Sens.
185	1896	Type 304 SS	0.75%	O-T	12	As Mach., Furn. Sens.

*Based on Room Temperature Strain-Deflection Calibration Curves

**C-T = Compression-Tension; O-T = Zero to Tension Loading.

***Ref. Table 5-3.

Table 5-2b
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIOD 2)

Specimen Number	Cycles to Failure	Material	Shakedown Surface Strain Range*	Loading Mode**	Test Condition Code***	Description
157	1917 ⁽¹⁾	Type 304 SS	0.5%	C-T	5	As Mach., Furnace Sensitized
189	1919 ⁽¹⁾	Type 304 SS	0.75%	C-T	5	As Mach., Furnace Sensitized
1080	1920 ⁽¹⁾	Type 304 SS	0.75%	C-T	5	As Mach., Furnace Sensitized
1085	1922 ⁽¹⁾	Type 304 SS	1.0%	C-T	5	As Mach., Furnace Sensitized
1079	1922 ⁽¹⁾	Type 304 SS	1.0%	C-T	5	As Mach., Furnace Sensitized
1084	1919 ⁽¹⁾	Type 304 SS	1.0%	C-T	5	As Mach., Furnace Sensitized
147	2132	Type 304 SS	0.5%	C-T	5	As Mach., Furnace Sensitized
38	2242	Type 304L SS	1.0%	C-T	18	As Mach., Furnace Sensitized
36	2286	Type 304L SS	1.0%	C-T	18	As Mach., Furnace Sensitized
34	2488	Type 304L SS	0.75%	C-T	18	As Mach., Furnace Sensitized
197	2706	Type 304 SS	0.5%	C-T	10A	As Mach., Furn. Sens., Chem. Notch
50	2813	Carbon Steel	0.75%	C-T	26	As Mach., No Stress Relief
1018	2821	Carbon Steel	0.5%	C-T	29	Welded, Stress Relieved
1144	2868	Type 304 SS	1.0%	C-T	7	Dresden Equalizer Line Weld Matl, As Mach.
1051	2998	Carbon Steel	0.5%	C-T	30	As Mach., Stress Relieved, Mech. Notch
1048	3144	Carbon Steel	0.5%	C-T	30	As Mach., Stress Relieved, Mech. Notch
1019	3231	Carbon Steel	0.5%	C-T	29	Welded, Stress Relieved
1007	3235	Carbon Steel	0.5%	C-T	27	As Mach., Stress Relieved

(1) Failed during cycle No. 2 loop startup on 10/22/70.

*Based on Room Temperature Strain-Deflection Calibration Curves

**C-T = Compression-Tension; 0-T = Zero to Tension Loading.

***Ref. Table 5-3.

Table 5-2c
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIOD 3)

Specimen Number	Cycles to Failure	Material	Shakedown Surface Strain Range*	Loading Mode**	Test Condition Code***	Description
1058	3556	Carbon Steel	0.75%	C-T	28	Welded, No Stress Relief
195	3683	Type 304 SS	0.5%	C-T	9	As Mach., Furn. Sens., Mech. Notch
82	3766	Carbon Steel	0.5%	C-T	27	As Mach., Stress Relieved
26	3990	Type 304L SS	0.5%	C-T	18	As Mach., Furnace Sensitized
81	4007	Carbon Steel	0.5%	C-T	26	As Mach., No Stress Relief
1055	4015	Carbon Steel	0.5%	C-T	28	Welded, No Stress Relief
1146	4093	Type 304 SS	0.75%	C-T	7	Dresden Equalizer Line Weld Matl, As Mach.
1092	4418	Type 304 SS	1.0%	C-T	6	Dresden Equalizer Line Base Matl, As Mach.
22	4724	Type 304L SS	0.5%	C-T	18	As Mach., Furnace Sensitized
201	5215	Type 304 SS	0.75%	O-T	11	As Mach.
72	5292	Carbon Steel	0.5%	C-T	26	As Mach., No Stress Relief
29	5359	Type 304L SS	1.0%	C-T	15	As Mach.
40	5435	Type 304L SS	0.5%	C-T	20	As Mach., Furn. Sens., Mech. Notch
5	5617	Type 304L SS	0.5%	C-T	20	As Mach., Furn. Sens., Mech. Notch
42	5859	Type 304L SS	1.0%	C-T	15	As Mach.
190	5920	Type 304 SS	0.75%	O-T	11	As Mach.
187	6110	Type 304 SS	1.0%	C-T	1	As Mach.
1121	6140	Type 304 SS	0.5%	C-T	2	As Mach., Heavy Cold Work
1148	6157	Type 304 SS	1.0%	C-T	7	Dresden Equalizer Line Weld Matl, As Mach.

Total Failures, 60 → (27 Type 304 SS, 9 Type 304L SS, 0 Inconel, 24 Carbon Steel)

*Based on Room Temperature Strain-Deflection Calibration Curves

**C-T = Compression-Tension; O-T = Zero to Tension Loading.

***Ref. Table 5-3.

Figure 5-1 summarizes the results of these initial 27 Type-304 failures; the upper line represents the best fit line for ASME failure data* in air (i.e., "Mean Cycles to Fail"), while the lower line represents the ASME fatigue design curve.

b. Type-304L Stainless Steel

Seven of the nine Type-304L failures occurred in furnace sensitized material (see Figure 5-2). As previously noted for Type-304 stainless steel, the fatigue lives of the notched 304L specimens are about the same as their un-notched counterparts.

To date, two "As-Received" 304L specimens have failed; these two data points fall within the factor of two on cycles normally assigned to the ASME mean data line to account for data scatter.**

c. Inconel-600

No Inconel specimen has signalled failure to date.

d. Carbon Steel

The carbon steel data (Figure 5-3) suggest little effect due to the various conditions being tested. The stress relief anneal possibly slightly reduces the fatigue life of both wrought and welded material. This minor effect becomes more noticeable at the lower strain ranges.

Similar to the Type-304 stainless steel, the mechanically notched carbon steel specimens do not seem to have appreciably shorter cyclic lives than their un-notched counterparts.

The upper line in Figure 5-3 represents the ASME "Mean Cycles to Failure" air data; the lower line is the ASME fatigue design curve.

5.5.2 Effect of Loading Mode

Due to the limited number of specimen positions available, it was necessary to limit evaluation of the effect of loading mode (i.e., fully reversed loading versus zero-tension loading at the same strain range) to one material (Type-304 stainless steel). The data indicate that, at least for the furnace sensitized Type 304, zero-tension loading is a more severe condition leading to a definite reduction in fatigue life. The four data points for zero-tension loading shown in Figure 5-1 represent raw data points; no correction has been applied to account for effects of mean stress. Application of an equivalent stress correction such as suggested by Snow, Langer, and Gibbons*** (i.e., $S_{eq} = S_{actual} / [1 - (S_{mean} / S_{ult})]$) should not be required if the data (especially with regard to calculated safety factors) are referenced to the ASME fatigue design curve (lower line) which has already been corrected to account for mean stress effects.

Two of the "As-Received," zero-tension specimens have failed to date. None of their fully reversed counterparts (i.e., loaded at the same strain range) have failed, indicating that the same pattern of effect of loading previously noted in the furnace sensitized material may be establishing itself for the "As-Received" material.

*ASME Code, Section III, "Criteria" curves, Figure 11, for stainless steel.

**"Tentative Structural Design Basis for Reactor Vessels. . . etc.," PB-151987, Office of Technical Services, U. S. Department of Commerce, December 1958.

***Snow, Langer, and Gibbons, "Low Cycle Fatigue of Notched Ni-Cr-Mo Alloy 600 and Low Alloy Steel," WAPD-T-2093.

Figure 5-1. Equivalent Stress Amplitude (psi) versus Cycles to Failure for Type 304 Stainless Steel

Figure 5-2. Equivalent Stress Amplitude (psi) versus Cycles to Failure for Type-304L Stainless Steel

Figure 5-3. Equivalent Stress Amplitude (psi) versus Cycles to Failure for Type A516 Carbon Steel

5.5.3 Factors of Safety per ASME Fatigue Design Curves

Excluding the test results on Types 304 and 304L furnace-sensitized material, it can be seen from Figures 5-1 through 5-3 that all the Type-304 stainless steel data (except for one "cold worked" point) and all the Type 304L, Inconel, and carbon steel data fall on the conservative side of the ASME recommended design curve (i.e., actual "cycles to failure" > predicted "cycles to failure"). Table 5-4 shows the ranges of the safety factors relative to the ASME design curve. The safety factors were calculated at each strain range for which data were available for the four materials; for example, carbon steel specimens 1059 and 1052, tested at 1% strain, are the shortest and longest lived, 797 and 1455 cycles to failure, respectively. Thus, $797/295 = 2.70$, and $1455/295 = 4.94$.

5.5.4 Air Test Facility

The low cycle fatigue equipment and operating procedures were completed for the air environment tests to generate baseline 500°F data. Most of the test specimens have been instrumented (i.e., strain gages attached) preparatory to testing in 500°F air.

5.6 CHEMISTRY OF DRESDEN 1 TEST LOOP WATER (J. H. Holloway)

Results from in-line measurements made on the test loop during the period of November 1 to 5 indicate that the reactor water conductivity was 0.2 $\mu\text{mho/cm}$ at 25°C.

The dissolved oxygen content of the D-1 reactor water was monitored by two techniques:

- a. *Beckman Model 735 Process Oxygen Monitor*: Results from in-line measurements using this instrument indicated an oxygen "normal" content ranging from 260 to 320 ppb. However, short-term duration spikes (to 500 ppb) were observed in the oxygen concentration. These spikes lasted less than 5 minutes and may be associated with trapped air in the loop or sample lines being released past the detector.
- b. *Thallium Column*: Results from oxygen measurements using the thallium column method indicated an oxygen concentration ranging from 195 to 240 ppb. Readings from the thallium were very stable and did not show concentration spikes similar to those observed on the Beckman process oxygen monitor. The response time to instantaneous changes in oxygen concentration is believed to be considerably slower on the thallium column than with the Beckman instrument.

The chloride content of the reactor water was measured by the radiochemical separation of 37.3-minute chlorine-38. The calculated chloride concentration of the D-1 reactor water from the measured amount of chlorine-38 was 0.9 ppb.

Two reactor water crud samples were collected and returned to VNC for analysis. The results were (in ppb):

	Fe	Cu	Ni	Zn
Sampled* on 11-2-70:	56	7	19	19
Sampled** on 11-5-70:	64	27	21	20

*5 liters of water passed through the 0.45 μHA Millipore filter.

**14.7 liters of water passed through the 0.45 μHA Millipore filter.

Table 5-4
RANGES (PRELIMINARY) FOR SAFETY FACTORS
(PER ASME B&PV CODE, SECTION III)

Specimen Numbers	Material	Shakedown Surface Strain Range		N ₁ - "Cycles to Failure" Dresden Test Loop Data		ASME Design Curve	Range
1144,1092	304 SS	1.0%	C-T ^(b)	2868-4418	590		4.87-7.49
1146,201	304 SS	0.75%	C-T, 0-T ^(c)	4093-5215	1400		2.93-3.73
29	304L SS	1.0%	C-T	5359	590		9.08
1059,1052	Carbon Steel	1.0%	C-T	797-1455	295		2.70-4.94
1008,1058	Carbon Steel	0.75%	C-T	1378-3556	630		2.19-5.65
1018,1055	Carbon Steel	0.5%	C-T	2821-4015	1850		1.52-2.17

$$S.F._{ENV}^{(a)} = N_{1BWR} / N_{1ASME}$$

- (a) Safety Factor in Environment
(b) Compression-Tension loading
(c) Zero-Tension loading

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

The electrochemical flange containing the 0.01 N Ag/AgCl electrode was installed in the position downstream of the Task K vessel on October 20, 1970. The flange first saw low-temperature water at 17:00 of the same day. After 18 hours of low flow to slowly heat up the Task K loop, full flow (10 gpm) was initiated past the flange at 10:00 on October 22, 1970.

The potentials (see Table 5-5) were measured with a Keithly 610B electrometer. The 0.01 Ag/AgCl seemed to perform adequately as all potential readings were quite steady. The initial readings in flange No. 2 probably represent unfilmed or partially filmed electrodes. With time, their potentials approached those of the electrodes in flange No. 1 which should represent the steady-state potentials of the materials in reactor water at temperature.

These measurements, converted to the standard hydrogen electrode scale, are shown in Figure 5-4 which is the calculated potential pH stability diagram for water at $\sim 525^{\circ}\text{F}$ (see dissertation* for details of calculating these diagrams at elevated temperature from thermodynamic data). Basically, these diagrams indicate the stability of various species as a function of electrochemical potential and pH. The area between the O_2/OH^- and H^+/H_2 stability lines indicate the range of potential at which water is stable. At 525°F , the calculated neutral pH of water is ~ 5.6 . Also indicated on the diagram are the equilibrium lines for the Ni^{++}/Ni and Fe^{++}/Fe electrode reactions. At potentials more positive than the equilibrium, there will be a driving force for metal dissolution. For both Fe and Ni, the metal oxides are stable at neutral pH at 300°C , and are quite protective for the unstressed specimen. However, the potential measurements do show that if the water were to become acidic, which will be the result in a tight crevice, the Fe^{++} and Ni^{++} species will be stable at the potentials measured in the BWR environment. This result implies that a fatigue crack propagation rate may be accelerated in the BWR, as compared to air. In addition, crack initiation may be influenced by an oxide rupture, dissolution-type mechanism.

Table 5-5
POTENTIAL VERSUS 0.01N Ag/AgCl ELECTRODE (Volts)

	10:00 Flow Initiated	13:00	18:00
Flange No. 2 (Contains Ag/AgCl electrode and new electrodes)			
Bright Platinum	-0.1 to -0.15	+0.10	+0.10
304 Stainless Steel	-0.15 to -0.20	+0.05	+0.10
A106B	-0.2 to -0.25	+0.05	+0.10
Flange No. 1 (Flange installed December, 1969)			
Bright Platinum	---	+0.10	+0.10
304 Stainless Steel	---	+0.20	+0.20
A106B	---	+0.15	+0.15

Temperature = 510°F

Flow Rate = 11 gallons/min

*R. L. Cowan, Ph.D. Dissertation, Ohio State University, Columbus, Ohio, 1969, accepted for publication.

Figure 5-4. E versus pH Stability Diagram for Water at 525°F

APPENDIX A

**METALLOGRAPHY REPORT ON INITIAL TASK K SPECIMEN
(G. R. Lundeen and D. M. Rooney)**

The carbon steel was photographed as received, then cut, and the specimen* was mounted, polished, and etched with 5% Nital. The mounting direction is depicted in Figure A-1. Additional photomicrographs are shown in Figure A-2. The failure appears to have occurred in a mixed mode; i.e., both transgranular and intergranular (see Figure A-3).

Specimen Number	Cycles to Failure	Strain Range	Loading	Test Condition Code
1059	797	1%	Compression- Tension	29

*As identified in Table 5-2A in Section 5.

(a)

MAGNIFICATION

3X

(b)

4X

(c)

6X

Figure A-1. Macrophotographs of the Carbon Steel Tip As Received from the Dresden 1 Materials Test Loop. Additional cracks are apparent in (c)

(a) 5% NITAL ETCH 50X
SECTION A AS INDICATED IN FIGURE A-1(a)

(b) 250X
SECTION B AS SHOWN IN A-2(a)

(c) 500X
SECTION A AS SHOWN IN A-2(a)

Figure A-2. Metallographic Section Taken at the Specimen Fracture

SECTION C SHOWN IN FIGURE A-2(a)

Figure A-2(d). Metallographic Section Taken at the Specimen Fracture (continued)

F

G

(c)

SECTION F AS INDICATED
IN FIGURE A-3(a)

1000X

(d)

SECTION G AS INDICATED
IN FIGURE A-3(b)

1000X

Figure A-3. Higher Magnification of Portions of Microsection of Figure A-2(d) Reveal Intergranular and Transgranular Modes of Cracking

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