8042

GEAP-10207-26
AEC RESEARCH AND
DEVELOPMENT REPORT
APRIL 1972

MASTER

**REACTOR PRIMARY COOLANT SYSTEM
RUPTURE STUDY
PROGRESS REPORT NO.26
OCTOBER 1971 – MARCH 1972**

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

GENERAL ELECTRIC

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

REACTOR PRIMARY COOLANT SYSTEM RUPTURE STUDY
PROGRESS REPORT NO. 26
OCTOBER 1971 - MARCH 1972

Approved:

S. R. Vandenberg
S. R. Vandenberg
Project Engineer

Approved:

D. H. Imhoff
D. H. Imhoff
Development Engineering

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

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ATOMIC POWER EQUIPMENT DEPARTMENT • GENERAL ELECTRIC COMPANY
SAN JOSE, CALIFORNIA 95114

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

TABLE OF CONTENTS

	Page
ABSTRACT	1-1
1. INTRODUCTION	1-1
2. SUMMARY	2-1
2.1 Task A—Probability Study	2-1
2.2 Task D-3—Prototype Pipe Fatigue	2-1
2.3 Task D-5—Fatigue Data for Piping Code	2-1
2.4 Task K—Effect of BWR Environment	2-1
3. TASK A—PROBABILITY STUDY	3-1
3.1 Objectives	3-1
3.2 Summary	3-1
4. TASK D—LOW CYCLE FATIGUE	4-1
4.1 Objective	4-1
4.2 Task D-3—Prototype Pipe Fatigue	4-1
4.2.1 Summary	4-1
4.2.2 Data Obtained	4-2
4.3 Task D-5—Fatigue Data for Piping Code	4-7
4.3.1 Summary	4-7
4.3.2 Material Properties	4-7
4.3.3 Computer Analysis of Specimens	4-8
4.3.4 Notch Strain Measurements	4-14
5. TASK K—EFFECT OF BWR ENVIRONMENT	5-1
5.1 Objective	5-1
5.2 Summary	5-1
5.3 Dresden 1 Test Loop	5-1
5.3.1 Specimen Inspection	5-1
5.3.2 Fatigue Test Results	5-3
5.3.3 Metallurgical Effects	5-17
5.4 500°F Baseline Air Tests	5-17
5.4.1 Test Results	5-18
5.4.2 Hot Strain Data (Dresden Test Loop)	5-18
5.5 Third Test Vessel	5-21
5.5.1 Specimen Manufacture	5-24

APPENDIX. ACOUSTIC EMISSION MEASUREMENTS ON PIPE RUPTURE TEST PERFORMED NOVEMBER 1971

A.1 Summary	A-1
A.2 The Test Setup	A-1
A.3 The Test Procedure	A-1
A.4 Operation of the Acoustic Emission Instruments	A-1

DISTRIBUTION	1
------------------------	---

LIST OF ILLUSTRATIONS

Figure	Title	Page
4-1	Task D-3 Code Analysis Summary	4-3
4-2	Task D-3 Elbow Specimen Shown in Test Bed	4-6
4-3	Tensile Specimens Used for Stress-Strain Curves	4-8
4-4	Stable Hysteresis Loops Developed in Strain-Controlled Cyclic Testing of Type-304 Stainless Steel	4-9
4-5	Monotonic and Cyclic Stress-Strain Curves for Type-304 Stainless Steel	4-10
4-6	Monotonic and Cyclic Stress-Strain Curves for A212 Grade B Carbon Steel	4-11
4-7	Finite Element Grid-Grooved Specimen	4-12
4-8	Shakedown Stress-Strain Diagram, ASTM-A276 Type-304 Stainless Steel (As-Received)	4-13
4-9	Elastic Stresses on Minimum Section, Groove Specimen	4-15
4-10	Notch Root Strains, Stainless Steel Grooved Specimen	4-16
4-11	Stress versus Displacement, Stainless Grooved Specimen	4-17
4-12	Progression of Elastic-Plastic Boundaries, Stainless Grooved Specimen	4-18
4-13	Finite Element Grid, Shouldered Specimen	4-19
4-14	Surface Strains, Stainless Shouldered Specimen	4-20
4-15	Stress versus Displacement, Stainless Shouldered Specimen	4-21
4-16	Progression of Elastic-Plastic Boundaries, Stainless Shouldered Specimen	4-22
4-17	Fatigue Specimens	4-23
4-18	Notch Fatigue Specimen Showing Displacement Gage and Strain Gages	4-24
4-19	Comparison of Extensometer and Strain Gage Strain Readings	4-25
4-20	Adjusted Shakedown Stress-Strain Diagram, ASTM-A276 Type-304 Stainless Steel (As Received)	4-26
5-1	Optical Crack Length Measurement Fixture	5-4

LIST OF ILLUSTRATIONS (Continued)

5-2	Dynamic Test Specimen	5-5
5-3	Equivalent Stress Amplitude (psi) versus Cycles to Failure for Type-304 Stainless Steel	5-8
5-4	Equivalent Stress Amplitude (psi) versus Cycles to Failure for Type-304 Stainless Steel	5-9
5-5	Equivalent Stress Amplitude (psi) versus Cycles to Failure for Inconel-600	5-15
5-6	Equivalent Stress Amplitude (psi) versus Cycles to Failure for A516 Carbon Steel	5-16
5-7	Equivalent Stress Amplitude versus Cycles to Failure for Type-304 Stainless Steel. Comparison of fatigue data from BWR environment with "non-environment" baseline case.	5-19
5-8	Equivalent Stress Amplitude versus Cycles to Failure for A516 Carbon Steel. Comparison of fatigue data from BWR environment with "non-environment" baseline case.	5-20
5-9	Proposed Testing Scheme	5-22
5-10	2T-WOL Specimen for Crack Growth Rate Study of Task KC	5-25
5-11	Typical Microstructures Observed in 2T-WOL Plate Stock	5-26
5-12	2T-WOL Specimen Blank Orientation	5-27
A-1	Arrangement of Acoustic Emission Transducers on Prototype Pipe Fatigue Test	A-2
A-2	Two Views of the Acoustic Emission Equipment (on the left), and the Pipe Being Fatigue Tested (on the right)	A-3
A-3	Block Diagram of Acoustic Emission Indicating and Recording Equipment	A-5
A-4	Recorder Pen Traces of Acoustic Emission During Fatigue Test	A-6
A-5	Recorder Pen Traces of Acoustic Emission Near End of Test	A-7

LIST OF TABLES

Table	Title	Page
4-1	Task D-3 Test Data Summary	4-1
4-2	Task D-3 Butt-Weld Speciment Code Analysis Summary	4-4
4-3	Task D-3 In-Plane Elbow Specimens Section III Analysis Summary	4-5
5-1	Dresden Test Loop Operating Summary	5-2
5-2	Borescope Inspection Results, Specimens Previously Signalling Failure, TIPS Not Separated	5-6
5-3	Task K Fatigue Specimen Layout	5-7
5-4A	Fatigue Test Results From Dresden Loop (Operating Period I)	5-10
5-4B	Fatigue Test Results From Dresden Loop (Operating Period II)	5-11
5-4C	Fatigue Test Results From Dresden Loop (Operating Period III)	5-12
5-4D	Fatigue Test Results From Dresden Loop (Operating Periods IV, V, VI and VII)	5-13
5-4E	Fatigue Test Results From Dresden Loop (Operating Period VIII)	5-14
5-4F	Fatigue Test Results From Dresden Loop (Operating Period IX)	5-14
5-5	Fatigue Specimen Test Plan, Series III-B Baseline "Air" Tests	5-18
5-6	Preliminary Results, 500°F Shakedown Strain Range Data, Series III-B Tests	5-21
5-7	2T-WOL Specimen Plate Material, Chemical Analyses	5-23

ABSTRACT

The pipe rupture study is designed to extend the understanding of failure-causing mechanisms and to provide improved capability for evaluating reactor piping systems to minimize the probability of failures. Following a detailed review to determine the effort most needed to improve nuclear system piping (Phase I), analytical and experimental efforts (Phase II) were started in 1965. This progress report summarizes the recent accomplishments of a broad program in (a) fatigue studies through both bench-scale and large-component tests, (b) at-reactor tests of the effect of primary coolant environment on the fatigue behavior of piping steels, and (c) failure probability study of actual reactor piping systems.

1. INTRODUCTION

The Reactor Primary Coolant System Rupture Study is being conducted for the Division of Reactor Development and Technology, USAEC. This Progress Report No. 26 documents work done in the period October 1, 1971 to March 31, 1972. 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

Work on Task A was limited to the preparation of a topical report, GEAP-10452, "Estimating Pipe Reliability by the Distribution of Time-to-Damage Method," by S. A. Wilson.

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 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-10207-22	No. 22, July—September 1970.
GEAP-10207-23	No. 23, October—December 1970.
GEAP-10207-24	No. 24, January—June 1971
GEAP-10207-25	No. 25, July—September 1971

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.
- GEAP-10236 Failure Behavior of Flawed Carbon Steel Pipes and Fittings, October 1970.
- GEAP-10452 Estimating Pipe Reliability by the Distribution of Time-to-Damage Method, March 1972

2. SUMMARY

2.1 TASK A—PROBABILITY STUDY

Work was limited to the preparation of a topical report, GEAP-10452, "Estimating Pipe Reliability by the Distribution of Time-to-Damage Method," by S. A. Wilson. Review copies have been distributed.

2.2 TASK D-3—PROTOTYPE PIPE FATIGUE

Testing was completed on a series of three 550°F, stainless-steel, butt-weld specimens. Testing was also completed on the first cyclic pressure plus cyclic bending, stainless steel elbow specimen. The following specimens were tested during the report period:

- a. HW-11 — 550°F stainless steel butt-weld specimen
- b. HW-12 — 550°F stainless steel butt-weld specimen
- c. CSLS-5 — Room-temperature stainless steel, long-radius elbow specimen

2.3 TASK D-5—FATIGUE DATA FOR PIPING CODE

The objective of this task is to confirm or improve nuclear piping fatigue design procedures for nominal stress ranges above $3 S_m$. Work toward this objective is proceeding along two parallel paths. Analytically, fatigue specimen notch root strains have been calculated with an elastic-plastic finite element computer program. Experimentally, peak strains during cyclic loading have been measured with miniature strain gages. Fatigue testing in progress will provide data for correlations between peak strain amplitude and fatigue performance.

2.4 TASK K—EFFECT OF BWR ENVIRONMENT

The Dresden 1 test loop has accumulated over 3900 hours of operation at test conditions (510°F, 1040 psig). A total of 81 of the 149 fatigue specimens being cyclically loaded in the loop have failed: 36 of 71 Type-304 stainless steel specimens, 15 of 28 Type-304L stainless steel specimens, 3 of 23 Inconel-600 specimens, and all of the 27 carbon steel specimens. Detailed inspections of both static and dynamic specimens were conducted at Dresden 1 during the refueling outage. The first group of specimens, being tested under revised test conditions in the Air Test Facility in San Jose, is now under test with over 14,000 cycles accumulated to date. Four of the twelve specimens in this group have signalled failure in the first 14,000 cycles of operation. Design of the third vessel (fatigue crack growth rate unit) is complete; equipment procurement and specimen manufacturing is under way.

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

Work was limited to the preparation of a topical report, GEAP-10452, "Estimating Pipe Reliability by the Distribution of Time-to-Damage Method." Review copies have been distributed.

4. TASK D—LOW CYCLE FATIGUE

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 (J. D. Heald)

4.2.1 Summary

Testing was completed on a series of three 550°F, stainless steel, butt-weld specimens. Testing was also completed on the first cyclic pressure plus cyclic bending, stainless steel elbow specimen. A summary of the test data is given in Table 4-1. The following specimens were tested during the report period:

- a. HW-11 — 550°F, stainless steel, butt-weld specimen
- b. HW-12 — 550°F, stainless steel, butt-weld specimen
- c. CSLS-5 — Room-temperature stainless steel, long-radius elbow specimen

Table 4-1
TASK D-3 TEST DATA SUMMARY

Specimen Description	Test Temperature	Internal Pressure	Peak-to-Peak End Deflection (in.)	Calculated Elastic Stress Range (S_n)	Full Amplitude Cycles to Fully Penetrate the Wall
HW-10* ASTM A312 Type-304 Stainless Steel Schedule 80 Weld Specimen	550°F	None	±8.0	81.6 ksi	9,200
HW-11 ASTM A312 Type-304 Stainless Steel Schedule 80 Weld Specimen	550°F	None	±6.25	63.8 ksi	14,852
HW-12 ASTM A312 Type-304 Stainless Steel Schedule 80 Weld Specimen	550°F	None	±9.50	97.0 ksi	2,894
CSLS-5 ASTM A-182F Type-304 SS Schedule 40 Elbow In-plane Bending	Room Temperature	100 psi to 1475 psi	±7.25**	254.8 ksi**	4,440**

*Tested last quarter.

**Cyclic deflection range was changed from ±2.5 inches to ±7.25 inches after 9950 cycles. See Subsection 4.2.2 of this report.

4.2.2 Data Obtained

a. Butt-Weld Specimens

Testing was completed on a series of three 550°F, stainless steel, butt-weld specimens during the report period. These tests and previous weld tests were analyzed according to the procedures of the Nuclear Power Piping Code USAS B31.7, and ASME Code Section III. The results of both analyses are given in Table 4-2 and in Figure 4-1.

The factor of safety given in Table 4-2 is defined as the ratio of the number of full-amplitude stress cycles to cause leakage in the test specimen to the number of cycles allowed by the respective code.* The alternating stress intensity (S_{alt}) was calculated as follows:

b. USAS B31.7

$$S_{alt} = 1/2 S_n K_f \frac{S_n}{3 S_m}$$

where

$$K_f = K_2 + A (K_2 - 1),$$

$$K_2 = 1.8 \text{ for as-welded pipe,}$$

$$A = \text{material property, Appendix D, B31.7,}$$

$$S_n = \text{elastically calculated stress range based on the peak specimen deflection, and}$$

$$S_n = \frac{3 \sigma E \delta_{p-p}}{l^2}$$

c. ASME Code, Section III

$$S_{alt} = 1/2 S_n K_2 K_e,$$

$$S_n, K_2 = (\text{same as above}),$$

$$K_e = 1.0 \text{ for } S_n \leq 3 S_m,$$

$$K_e = 1.0 + \frac{1-n}{n(m-1)} \left(\frac{S_n}{3 S_m} - 1 \right) \text{ for } 3 S_m < S_n < 3m S_m,$$

$$K_e = \frac{1}{n} \text{ for } S_n > 3m S_m,$$

m, n = material properties from NB-3228.3,

$$\left. \begin{array}{l} m = 1.7 \\ n = 0.3 \end{array} \right\} \text{ for austenitic stainless steel}$$

$$\left. \begin{array}{l} m = 3.0 \\ n = 0.2 \end{array} \right\} \text{ for carbon steel.}$$

When the results from both code analyses are compared (see Figure 4-1), it is seen that the procedures for ASME Code Section III are more conservative for stainless steel butt-welds. However, based on only one carbon steel specimen (HW-1), Section III appears to be less conservative than B31.7.

*Code design cycles for the alternating stress intensity applied to the test specimen.

Figure 4-1. Task D-3 Code Analysis Summary

Table 4-2
TASK D-3 BUTT-WELD SPECIMEN CODE ANALYSIS SUMMARY

B31.7 Analysis

Specimen	Material	Peak-to-Peak Deflection Range (in.)	S_m (ksi)	S_n (ksi)	$\frac{S_n}{3 S_m}$	K_f	S_{alt} (ksi)	$N_{(Design)}^{(a)}$ (cycles)	$N_{(Leak)}^{(b)}$ (cycles)	$\frac{N_{Leak}}{N_{Design}}$
HW-1	CS	10.9	18	56.6	1.05	2.36	70.1	1,650	35,740	21.6
HW-3A	SS	14.8	16	75.3	1.57	2.36	139.5	460	6,950	15.1
HW-10	SS	16.0	16	81.6	1.70	2.36	163.7	290	9,200	31.8
HW-11	SS	12.5	16	63.8	1.33	2.36	100.1	1,300	14,858	11.4
HW-12	SS	19.0	16	97.0	2.02	2.36	231.0	110	2,894	26.3

Section III Analysis

	$3 S_m$	S_n	$3mS_m$	$\frac{S_n}{3 S_m}$	K_e	S_{alt}	$N_{(Design)}$	$N_{(Leak)}$	$\frac{N_{Leak}}{N_{Design}}$
HW-1	54	56.6	162	1.05	1.10	56.0	3,000	35,740	11.9
HW-3A	48	75.3	81.6	1.57	2.90	197	170	6,950	40.8
HW-10	48	81.6	81.6	1.70	3.33	245	100	9,200	92.0
HW-11	48	63.8	81.6	1.33	2.11	121	380	14,858	39.1
HW-12	48	97.0	81.6	2.02	3.33	291	60	2,894	48.2

(a) $N_{(Design)}$ is code allowable number of stress cycles corresponding to the applied S_{alt} .

(b) Total full amplitude cycles at full wall penetration.

d. Elbow Specimens

Testing was completed on the first elbow specimen where both cyclic pressure and cyclic bending were applied. This specimen, as well as previous in-plane bending elbow specimens, was analyzed per Section III. The alternating stress intensity S_{alt} was evaluated as follows:

$$S_{alt} = 1/2 S_n K_t K_e$$

where

$$K_t = 1.0$$

$$K_e = \text{same as above,}$$

$$S_n = C_1 \frac{\Delta P r_0}{t} + C_2 \frac{\Delta M r_0}{I}$$

$$C_1 = \frac{2R-r}{2(R-r)} = 1.28 \text{ for 6-inch, Schedule-40 long-radius elbow,}$$

$$C_2 = \frac{1.95}{b_2^{2/3}} = 4.91 \text{ for 6-inch, Schedule-40 long-radius elbow,}$$

ΔP = pressure range,

$\Delta M = \Delta P L = K l \delta \text{ p-p,}$

where K was determined from the elastic portion of a static load deflection curve of the elbow specimen.

The elbow test was set up initially so that S_n would be equal to $5 S_m$, $1 S_m$ due to internal pressure and $4 S_m$ due to bending. Accordingly, then, S_{alt} is 168 ksi (equivalent strain range of $\frac{S_{alt}}{E} \cong 0.6\%$) with a resulting expected life of ~ 5000 cycles. However, after 9950 test cycles at this applied stress range with no apparent internal or external cracks in the elbow (as determined by visual examination as well as ultrasonic techniques), strain gages were attached to the outside surface of the elbow at the point of maximum strain*. The results of the strain measurements showed the actual strain range on the outside surface to be only 0.08%. Calculations based on the outside strain readings indicated a strain range of approximately 0.10% on the inside surface.

The specimen deflection range was then increased to ± 7.25 inches, which corresponds exactly to a previous long-radius elbow test (CSLS-3). The strain range was again measured and found to be approximately 0.5%. Testing was re-started and continued until through-wall leakage occurred after 4440 cycles at the increased deflection range.

Results of the Section III analysis for the elbow specimens are shown in Table 4-3 and Figure 4-1. The test setup of the elbow specimen is shown in Figure 4-2.

The next elbow specimen to be tested will have a pressure stress range $S_n = 2 S_m$, and an alternating stress intensity equal to this last specimen.

Table 4-3
TASK D-3 IN-PLANE ELBOW SPECIMENS SECTION III ANALYSIS SUMMARY

Specimen	Material	Pressure Range	Peak-to-Peak Deflection Range	3 S _m	S _n	3m S _m	S _n		K _e	S _{alt}	N _{Design}	N _{Leak}	N _{Leak}
							3 S _m						N _{Design}
		(psi)	(in.)	(ksi)	(ksi)	(ksi)				(ksi)	(cycles)	(cycles)	
CSLS-1 Short Radius	SS	0	21.6	60	455	102	7.6	3.33		758	<10	907	>90
CSLS-3 Long Radius	SS	0	14.5	60	234	102	3.9	3.33		390	30	4469	149
CCLS-1 Short Radius	CS	0	14.1	60	297	180	4.9	5.0		1485	<10	1176	>117
CSLS-5 Long Radius	SS	1375	14.5	60	254.8	102	4.2	3.33		425	25	4440	178

4.2.3 Acoustic Emission Measurements

Acoustic emission measurements have been made on the last two specimens tested. Westinghouse has supplied the personnel and equipment to make the measurements.

The first measurements were made on the 550°F butt-weld specimen HW-12. There were problems due to noise coming from metal-to-metal contact where relative motion was involved. Attempts were made to reduce the noise by inserting rubber sheet between mating parts. This helped, but the signal-to-noise ratio was still low.

*The point of maximum strain was determined from previous in-plane elbow tests.

Figure 4-2. Task D-3 Elbow Specimen Shown in Test Bed

The second measurements were made on the elbow specimen CSLS-5, and considerable effort was made to reduce the noise level. Rubber, Teflon, and Durabla* shims were used between mating metal parts. This generally reduced the noise level to acceptable limits. However, with continued cycling, the bolts in the flange had to be tightened at frequent intervals due to plastic flow of the shim materials. The rubber and Teflon shims essentially disintegrated and had to be replaced with Durabla, which seemed to be the most satisfactory material for the purpose.

It was apparently difficult to determine on the spot whether or not the majority of the signals observed and recorded were noise or real acoustic emissions. The Westinghouse report covering the acoustic emission measurements is included in the Appendix.

4.3 TASK D-5—FATIGUE DATA FOR PIPING CODE (T. L. Gerber and P. N. LeFort)

4.3.1 Summary

The objective of this task is to confirm or improve nuclear piping fatigue design procedures for nominal stress ranges above $3 S_m$. Work toward this objective is proceeding along two parallel paths. Analytically, fatigue specimen notch root strains have been calculated with an elastic-plastic finite element computer program. Experimentally, peak strains during cyclic loading have been measured with miniature strain gages. Fatigue testing in progress will provide data for correlations between peak strain amplitude and fatigue performance.

4.3.2 Material Properties

Two materials are being studied: Type-304 stainless steel and A212 Grade B carbon steel. Chemical analyses and product form were reported previously.**

Monotonic and cyclic stress-strain curves were developed with the specimens shown in Figure 4-3. Monotonic curves were generated with the 1/2-inch-diameter specimens, following standard procedures. Cyclic curves were generated with both the 1/2- and 1-inch-diameter specimens. For the generation of cyclic curves, both sizes of specimens were tested in strain-controlled cyclic loading, and additionally, the 1-inch-diameter specimens were tested in load-controlled cyclic loading.

In the strain-controlled cyclic tests, a constant strain amplitude (zero mean strain) was imposed on the specimen. Cycling was continued until a stable stress amplitude was established. For the Type-304 stainless steel, this required approximately 100 cycles. The A212 carbon steel stress amplitude stabilized in approximately 20 cycles. Following shakedown (stabilized stress amplitude), the imposed strain amplitude was increased and the cycling was repeated.

The procedure for developing load-controlled, cyclic, stress-strain curves was analogous. In this case, a constant load or stress amplitude (zero mean stress) was imposed on the specimen and the specimen was cycled until a stable strain amplitude was established.

Figure 4-4 shows an example of the stable or shakedown hysteresis loops. By definition, the cyclic stress-strain curve is formed by connecting the peaks of the stable hysteresis loops.

Shown in Figures 4-5 and 4-6 are the monotonic and cyclic stress-strain curves for the Type-304 stainless and A212 carbon steel specimens, respectively. Note that there is very little difference between the cyclic data from 1/2- and 1-inch-diameter specimens and between strain- and stress-controlled tests. In comparing monotonic and cyclic stress-strain curves, the Type-304 stainless steel cyclic stress-strain curve is very close to the monotonic curve, showing only a slight softening. On the other hand, the cyclic stress-strain data for the A212 carbon steel show an apparent softening near the monotonic yield strain, with cyclic hardening at higher strain amplitudes.

*A composite plastic asbestos gasket material

**Progress Report No. 25, GEAP-10207-25.

In Subsection 4.3.3, a curve is fitted to the Type-304 stainless steel cyclic stress-strain data. This curve is then incorporated into a finite element computer program, and the program used to predict fatigue specimen strain and load-deflection behavior.

Figure 4-3. Tensile Specimens Used for Stress-Strain Curves

4.3.3 Computer Analysis of Specimens

Detailed analyses of two specimen geometries (grooved and shouldered) have been performed, using the finite element program CREEP-PLAST. This program utilizes a constant-strain triangular element and is applicable to plane stress or plane strain (including axisymmetric) conditions. Elastic-plastic analyses are performed using the von Mises yield criterion and kinematic hardening. The shakedown stress-strain curve is used to describe material behavior. This subsection describes the techniques used and results obtained with this program for both specimen geometries with a stainless steel shakedown stress-strain curve that was fit to the results of smooth bar testing reported in Subsection 4.3.2.

4.3.3.1 Grooved Specimen

The grooved specimen is an axisymmetric body. With the presence of symmetry about the plane through the root of the groove and normal to the specimen axis, consideration of only one quadrant of the critical section was required. The finite element mesh used is shown in Figure 4-7. To facilitate the preparation of input data, a "pre-processor" was used to conformally map a simple rectangular grid (input) on the specimen and provide both a plot of the transformed grid and punched cards for node and element input to the finite element program.

The cyclic stress-strain data for the stainless steel material are shown in Figure 4-5, with a description of test methods given in Subsection 4.3.2. The shakedown stress-strain curve used in the analysis was obtained from a fit of this data and is given in Figure 4-8. The values for the yield point and moduli shown in the figure were used to describe the material behavior.

Figure 4-4. Stable Hysteresis Loops Developed in Strain-Controlled Cyclic Testing of Type-304 Stainless Steel

Figure 4-5. Monotonic and Cyclic Stress-Strain Curves for Type-304 Stainless Steel

Figure 4-6. Monotonic and Cyclic Stress-Strain Curves for A212 Grade B Carbon Steel

Figure 4-7. Finite Element Grid-Grooved Specimen

Figure 4-8. Shakedown Stress-Strain Diagram, ASTM-A276 Type-304 Stainless Steel (As-Received)

The finite element model was subjected to a monotonically increasing load. The load was applied by discrete steps of increasing normal boundary pressure along line CD in Figure 4-7, while restraining nodal movement in the Z direction along line AB and in the r direction along line AC.

The initial load was chosen just below the cutoff point for completely elastic action. The elastic stress distributions across the minimum (net) section are shown in Figure 4-9, where the elastic stress concentration in the root of the notch is found to be 2.15. The load was then increased in 19 more discrete steps. At each of the load increments, the calculated strains were extrapolated to the surface along the notch root, and the average value over the strain gage length (0.031-inch) was determined. Calculated and measured strains are compared in Figure 4-10.

Since the cyclic stress-strain data generated on smooth-bar specimens indicate no appreciable difference from load or strain controlled tests, it is reasonable to expect that results similar to those presented here would be obtained with the grooved specimen under deflection controlled testing. The analytical results may be related to a deflection controlled test through the curve of Figure 4-11 which relates displacement and average net-section stress.

Finally, the progression of the yield zone is shown in Figure 4-12 by contour lines describing regions within which the effective stress has exceeded the proportional limit stress on the shakedown stress-strain curve. While the yield zone initially tends to follow the notch contour, as the net-section stress level is further increased the plastic zone changes direction and extends completely across the specimen at an angle of 30 to 45 degrees to the minimum section, where a large region of elastic material remains to depress the peak surface strains.

4.3.3.2 Shouldered Specimen

While the shouldered specimen is an axisymmetric body, it does not possess the double symmetry of the grooved specimen; therefore, it was necessary to model one-half of the 4-inch test section. The finite element mesh used in the shoulder region is shown in Figure 4-13. Input data were prepared in the same manner as was done for the grooved specimen and the same shakedown stress-strain curve (Figure 4-8) was used.

The model was subjected to a monotonically increasing load applied by discrete steps of increasing normal boundary pressure along the radial line at the larger-diameter end of the model, while restraining nodal movement in the Z direction along the radial line at the smaller-diameter end of the model and restraining nodal movement in the r direction along the $r=0.001$ line.

The initial load was chosen just below the cutoff point for completely elastic action and then increased in 18 more discrete steps. The peak elastic stress concentration was found to be 2.05 and was located at $\phi \sim 17^\circ$, where ϕ is defined in Figure 4-13.

At each load increment, the calculated strains were extrapolated to the surface along the fillet, and the average value over the strain gage length (0.031 inch) was determined, considering the gage centerline to be at $\phi=17^\circ$. Calculated and measured strains are compared in Figure 4-14. The analytical results may be related to a deflection controlled test through the curve of Figure 4-15, which relates displacement average net-section stress.

Finally, the progression of the yield zone is shown in Figure 4-16 by contour lines describing regions within which the effective stress has exceeded the proportional limit stress on the shakedown stress-strain curve. At the higher stress levels (approximately 43 ksi) it is noted that the entire cross section at $\phi=17^\circ$ is plastic and consequently the peak surface strains begin to exceed those found in the grooved specimen where the pocket of elastic material tended to depress the peak surface strains.

4.3.4 Notch Strain Measurements

The analytical portion of this task was undertaken to predict local strain amplitudes as a function of cyclic load or displacement for specimens (or ultimately, engineered structures) with stress concentrations. In Subsection 4.3.3, the notched and shoulder fatigue specimens shown in Figures 4-17(b) and 4-17(c) were analyzed. Prior to fatigue testing of the notch and shoulder specimens, cyclic "shakedown" tests were conducted to check the analytical predictions.

Figure 4-9. Elastic Stresses on Minimum Section, Groove Specimen

Figure 4-10. Notch Root Strains, Stainless Steel Grooved Specimen

Figure 4-11. Stress versus Displacement, Stainless Grooved Specimen

Figure 4-12. Progression of Elastic-Plastic Boundaries, Stainless Grooved Specimen

Figure 4-13. Finite Element Grid, Shouldered Specimen

Figure 4-14. Surface Strains, Stainless Shouldered Specimen

Figure 4-15. Stress versus Displacement; Stainless Shouldered Specimen

Figure 4-16. Progression of Elastic-Plastic Boundaries, Stainless Shouldered Specimen

Figure 4-17. Fatigue Specimens

Displacement of the fatigue specimens during the shakedown tests was monitored with the specially designed displacement gage shown in Figure 4-18. The gage consists of a linear variable displacement transducer (LVDT) and mounting fixture. Set-up blocks (not shown) provide for an accurate gage length of 4.0 inches.

Local strain measurements were made with four axial and two tangential miniature strain gages bonded at the point of highest anticipated strain. The gages used were Micro-Measurements EP-08-031DE-120 and EC-120. Gage length is 0.031 inch. To check accuracy, four gages were placed on a smooth specimen, used to generate a cyclic stress-strain curve. The gage readings showed excellent agreement when compared with clip-on extensometer measurements as shown in Figure 4-19.

The test procedure used in the shakedown tests of the fatigue specimens was similar to that used to generate the load-controlled cyclic stress-strain curves. A constant load amplitude (zero mean load) was imposed and specimens were cycled for 100 cycles. During the last cycle, deflection and strain amplitude were recorded. The load amplitude was then increased and the procedure repeated.

Test results, along with calculated surface strains, are presented in Figures 4-10 and 4-14.

4.3.5 Discussion of Analytical and Experimental Comparisons of Strains and Displacements

The agreement between measured and calculated surface strains and gage length displacements is fair. Considering the large discrepancies under low net-section stresses where elastic action is maintained, and upon reviewing the stress-strain data from the smooth-bar specimens, it is apparent that the major cause of such large discrepancies was the use of too low an elastic modulus ($E_e = 25.0 \times 10^6$ psi) to describe the material behavior. The cyclic stress-strain elastic modulus should be essentially the same as the monotonic modulus; consequently, a better fit to the cyclic stress-strain curve, as shown in Figure 4-20, considerably improves the correlation between experimental and analytical results. An analysis with this adjusted stress-strain curve will serve to point out the sensitivity to the stress-strain curve employed, and to retain confidence in the analytical method.

Figure 4-18. Notch Fatigue Specimen Showing Displacement Gage and Strain Gages

Figure 4-19. Comparison of Extensometer and Strain Gage Strain Readings

Figure 4-20. Adjusted Shakedown Stress-Strain Diagram, ASTM-A276 Type-304 Stainless Steel (As Received)

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 has accumulated over 3900 hours of operation at test conditions (510°F, 1040 psig). A total of 81 of the 149 fatigue specimens being cyclically loaded in the loop have failed: 36 of 71 Type-304 stainless steel specimens, 15 of 28 Type-304L stainless steel specimens, 3 of 23 Inconel-600 specimens, and all of the 27 carbon steel specimens. Detailed inspections of both static and dynamic specimens were conducted at Dresden 1 during the refueling outage.

The first group of specimens, being tested under revised test conditions in the Air Test Facility in San Jose, is now under test, with over 14,000 cycles accumulated to date. Four of the twelve specimens in this group have signalled failure in the first 14,000 cycles of operation. Design of the third vessel (fatigue crack growth rate unit) is complete; equipment procurement and specimen manufacturing is under way.

5.3 DRESDEN 1 TEST LOOP

As a result of the extended plant outage for refueling and maintenance, the test loop was shut down for the major part of the report period. The downtime was used to inspect specimens in both the static and dynamic test vessels, and to complete several needed maintenance items.

Thirty-five 1T-WOL specimens, machined from various primary system materials (Ref. Subsection 5.9, Quarterly Report No. 25), were added to the specimen inventory in the static test vessel during this shutdown.

The loop was returned to service on March 24, beginning loop operating cycle IX. Pertinent operating information is summarized in Table 5-1.

5.3.1 Specimen Inspection

a. Fatigue Specimens

The fatigue test machine was removed from the dynamic test vessel (DTV) and installed on a specially designed inspection shield which, in combination with a miniature borescope, allowed test personnel to examine the fatigue specimens in detail (i.e., at 7X magnification) for evidence of cracking while minimizing radiation exposure.

The entire fatigue unit was examined to locate specimen tips which had broken off from the main specimen body; 28 tips were found and removed. All of the remaining 122 specimens were then checked for cracking by lightly pulling on the specimen tip with a pair of pliers. A total of 48 additional tips was removed. Inventory of the 76 tips removed revealed two from specimens which had not previously signalled failure (Specimens 154 and 156). Counting the one specimen tip taken out in October 1970 (No. 1059, ref. Appendix A, Quarterly No. 23), a total of 77 tips have now been removed. All have been transferred to the Vallecitos Nuclear Center. Detailed inspection of 40 of the remaining 73 specimens was then conducted, using the borescope. The limitation to a total of 40 was influenced by maximum permissible exposure limits.

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		
I	Sept. 16 ^(a)	Oct. 2 ^(a)	17 days	0	1900	23	Loop shutdown in anticipation of scheduled plant maintenance outage
II	Oct. 22 ^(a)	Nov. 5 ^(a)	32 days	1901	3250	18	Loop shutdown in anticipation of scheduled plant maintenance outage
III	Nov. 25 ^(a)	Dec. 31 ^(a)	69 days	3251	6494	19	Loop shutdown to repair leaking fitting
IV	Jan. 7	Jan. 14	76 days	6495	7174	2	Loop secured after reactor scram
V	Jan. 27	Feb. 3	84 days	7175	7891	9	Loop shutdown for scheduled plant outage
VI	Feb. 17	Feb. 18	85 days	7892	7960	1	Loop secured to repair steam leaks and install cubicle air monitor
VII	June 3	June 23	105 days	7961	9910	5	Loop automatically isolated due to low pressure trip
VIII	June 29	Aug. 12	150 days	9911	14155	7	Loop secured after reactor scram
IX	March 24 ^(b)	—	>164 days	14156	—	2	Loop still operating as of 4/14/72

(a) 1970

(b) 1972

Of the total of 150* fatigue specimens originally in the fatigue test fixture, failure was indicated by 84 specimens during the 8 loop operating cycles preceding this inspection. This means that 10** specimens that signalled failure were not cracked to the point that the tip could be removed by the procedure noted previously (light pulling with pliers). As summarized in Table 5-2, five of the ten were examined with the borescope; cracking was noted on two of the five, and no cracks were detected on the other three.***

The results of the inspection of the 35 specimens that had not signalled failure revealed 7 specimens that displayed definite fine surface cracks in the reduced thickness test section.

After completion of these borescope examinations, two pressure checks were performed on the balance of 73 specimens still in the fatigue unit (i.e., all those whose tips had not been removed). The first check was performed by pressuring the axial specimen cavity, plus capillary tube, plus pressure switch system, to 1000 psig with argon. This was done to ensure that the failure detection circuits for each individual specimen were operative. The result was that all 73 circuits functioned properly. A second pressure check was then performed, with the fatigue unit reinstalled on the DTV, the DTV pressurized to 1000 psig with argon, and the fatigue specimens cycled between their maximum deflections. Five specimens signalled failure during this final "dynamic" pressure check; all five were from the previously mentioned group of ten specimens (Table 5-2) which had signalled failure but were still intact (i.e., tips not among the 77 removed).

Therefore, based on the results of the borescope examinations and pressurization checks, the failure detection circuits associated with the other five specimens in the group of ten were reactivated. These specimens have accumulated several hundred additional loading cycles during the current loop operating cycle without incident (i.e., without signalling failure). The data points for these five have also been deleted (see discussion in Subsection 5.3.2).

b. Static Specimens

The entire complement of 32 stressed bend and 26 1T-WOL specimens in the static test vessel were inspected. The stressed bend specimens (Ref. Table 5-1 and Figure 5-1, Quarterly No. 22) were examined for evidence of surface cracking; no cracks were noted in any of the specimens. All 26 1T-WOL specimens were examined, using a specially designed optical crack length measurement device (Figure 5-1) to determine whether any growth of the original fatigue pre-crack had occurred. Details concerning calibration, initial crack length, and loading of these specimens were previously published in Quarterly No. 22 as Appendix A. The small differences noted between the initial visual measurements and the current ones were judged to be within the inherent variability of the technique. No significant crack extension was found.

5.3.2 Fatigue Test Results

One hundred forty-nine fatigue specimens (Figure 5-2), representing 4 material groups, 31 metallurgical test conditions, and 2 specimen loading schemes, are included in the basic Task K test program. For convenience, the test plan has been reproduced from GEAP-10207-24 (Quarterly No. 24) as Table 5-3. This test plan was designed to allocate the fatigue specimen positions among the selected test conditions so as to maximize chances of detecting differences in cyclic fatigue life which might be caused by these conditions when the specimens are in the environment.

*One specimen failed (i.e., signalled failure) during pressure checks performed as part of assembly of the fatigue test fixture in San Jose prior to any mechanical loading of the specimens. Therefore, this specimen does not appear either in the total specimen inventory (Table 5-3) or in the lists of reported failure indications.

**Eighty-four previous specimen failure indications plus two specimens failed without signalling plus one specimen mentioned in previous footnote, equal 87 total failed specimens, minus 77 specimen tips removed, equal 10 specimens.

***It should be noted that previous experience with this specimen in room temperature tests has shown that it is possible to have a tight fatigue crack of sufficient depth to cause a valid failure indication and yet so tight that it is not visible by ordinary inspection techniques.

Figure 5-1. Optical Crack Length Measurement Fixture

NOTES:

1. $\frac{.029}{.027}$ DIA. HOLE CENTERED IN
REDUCED SECTION WITHIN .006 ($\pm .003$)
2. CENTERLINE OF WELD TO BE LOCATED IN MIDDLE
OF REDUCED THICKNESS SECTION FOR WELD
SPECIMENS

Figure 5-2. Dynamic Test Specimen

Table 5-2
BORESCOPE INSPECTION RESULTS,
SPECIMENS PREVIOUSLY SIGNALLING FAILURE,
TIPS NOT SEPARATED

Specimen Number	Borescope Examination	Final Dynamic* Pressure Check	Counter Circuit Reactivated
20	Not Examined	Failed	—
98	No Cracks Visible	Passed	Yes
131	Cracking Noted	—	—
163	Not Examined	Failed	—
1004	Not Examined	Passed	Yes
1101	Not Examined	Failed	—
1121	Not Examined	Passed	Yes
1123	No Cracks Visible	Passed	Yes
1126	Small Cracks Noted	Failed	—
1132	No Cracks Visible	Passed	Yes

*Specimens flexed with DTV at 1000 psig.

Taking into account the 5 specimens which were deleted from previously reported results (see previous discussion), failure indications were received from 79 specimens during the first 8 test loop operating cycles. Two additional failure indications have been received during the current operating cycle (IX), bringing the total number received to date to 81: pertinent test parameters are summarized in Table 5-4, parts A, B, C, D, E, and F. The distribution of these 81 failures among the various test conditions is shown at the bottom of Table 5-3.

Note that because of the geometry of the Task K fatigue specimen (thin specimen loaded in bending) and the unique method used to define and detect specimen failure (based on existence of partial depth fatigue crack), these failure data represent cycles to initiation; very little ($\cong 5$ to 10%) specimen life is devoted to fatigue crack growth.

The values of initial surface strain range in Table 5-3 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 measurements were made using miniature strain gages mounted in the reduced thickness test section of each specimen.

The cycles-to-failure data for the 81 failure indications received to date are compared with ASME Section III fatigue design data in Figures 5-3 through 5-6. The upper line in Figures 5-3, 5-4, and 5-6 represents a best-fit of the ASME failure data; the upper line in Figure 5-5 for Inconel-600 is based on a best-fit of failure data contained in the work of Snow, et al.* The lower line in Figures 5-3 through 5-6 represents the ASME Section III recommended fatigue design curve which is derived from ASME data curves by applying a factor of 20** on cycles (i.e., $N_I \text{ design} = N_I \text{ data}/20$).

*Snow, Langer, and Gibbons, WAPD-T-2093, September 1967

**See ASME Boiler and Pressure Vessel Code, Section III, Criteria.

6-7

Figure 5-4. Equivalent Stress Amplitude (psi) versus Cycles to Failure for Type-304 Stainless Steel

Table 5-4A
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIOD I)

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	Welded, stress relief
1060	909	Carbon Steel	1.0%	C-T	29	Welded, stress relief
1010	996	Carbon Steel	1.0%	C-T	27	As machined, stress relief
1009	1027	Carbon Steel	1.0%	C-T	27	As machined, stress relief
131	1027	Type-304 SS	0.5%	O-T	12	As received, furnace sensitized
57	1066	Carbon Steel	1.0%	C-T	25	As machined, no stress relief
64	1123	Carbon Steel	1.0%	C-T	25	As machined, no stress relief
48	1176	Carbon Steel	1.0%	C-T	25	As machined, no stress relief
179	1365	Type-304 SS	0.75%	O-T	12	As received, furnace sensitized
1008	1378	Carbon Steel	0.75%	C-T	27	As machined, stress relief
53	1380	Carbon Steel	1.0%	C-T	25	As machined, no stress relief
1053	1423	Carbon Steel	1.0%	C-T	25	Welded, no stress relief
1052	1455	Carbon Steel	1.0%	C-T	25	Welded, no stress relief
188	1493	Type-304 SS	0.5%	C-T	10A	As received, furnace sensitized, mechanical notch
170	1506	Type-304 SS	1.0%	C-T	5	As received, furnace sensitized
1017	1524	Carbon Steel	0.75%	C-T	29	Welded, stress relief
165	1651	Type-304 SS	0.5%	C-T	5	As received, 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 received, furnace sensitized, mechanical notch
180	1771	Type-304 SS	1.0%	C-T	5	As received, furnace sensitized
128	1778	Type-304 SS	0.5%	O-T	12	As received, furnace sensitized
166	1838	Type-304 SS	0.75%	C-T	5	As received, furnace sensitized
185	1896	Type-304 SS	0.75%	O-T	12	As received, furnace sensitized

* Based on Room Temperature Strain-Deflection Calibration Curves

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

*** Reference: Table 5-2

Table 5-4B
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIOD II)

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 received, furnace sensitized
189	1919 ⁽¹⁾	Type-304 SS	0.75%	C-T	5	As received, furnace sensitized
1080	1920 ⁽¹⁾	Type-304 SS	0.75%	C-T	5	As received, furnace sensitized
1085	1922 ⁽¹⁾	Type-304 SS	1.0%	C-T	5	As received, furnace sensitized
1079	1922 ⁽¹⁾	Type-304 SS	1.0%	C-T	5	As received, furnace sensitized
1084	1919 ⁽¹⁾	Type-304 SS	1.0%	C-T	5	As received, furnace sensitized
147	2132	Type-304 SS	0.5%	C-T	5	As received, furnace sensitized
38	2242	Type-304L SS	1.0%	C-T	18	As received, furnace sensitized
36	2286	Type-304L SS	1.0%	C-T	18	As received, furnace sensitized
34	2488	Type-304L SS	0.75%	C-T	18	As received, furnace sensitized
197	2706	Type-304 SS	0.5%	C-T	10A	As received, furnace sensitized, mechanical notch
50	2813	Carbon Steel	0.75%	C-T	26	As machined, 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 material, as machined
1051	2998	Carbon Steel	0.5%	C-T	30	As machined, stress relieved, mechanical notch
1048	3144	Carbon Steel	0.5%	C-T	30	As machined, stress relieved, mechanical notch
1019	3231	Carbon Steel	0.5%	C-T	29	Welded, stress relieved
1007	3235	Carbon Steel	0.5%	C-T	27	As machined, 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

*** Reference: Table 5-2

Table 5-4C
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIOD III)

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 received, furnace sensitized mechanical notch
82	3766	Carbon Steel	0.5%	C-T	27	As machined, stress relieved
26	3990	Type-304L SS	0.5%	C-T	18	As received, furnace sensitized
81	4007	Carbon Steel	0.5%	C-T	26	As machined, 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 material, as machined
1092	4418	Type-304 SS	1.0%	C-T	16	Dresden equalizer line base material, as machined
22	4724	Type-304L SS	0.5	C-T	18	As received, furnace sensitized
201	5215	Type-304 SS	0.75%	O-T	11	As received
72	5292	Carbon Steel	0.5%	C-T	26	As machined, no stress relief
29	5359	Type-304L SS	1.0%	C-T	15	As received
40	5435	Type-304L SS	0.5%	C-T	20	As received, furnace sensitized, mechanical notch
5	5617	Type-304L SS	0.5%	C-T	20	As received, furnace sensitized, mechanical notch
42	5859	Type-304L SS	1.0%	C-T	15	As received
190	5920	Type-304 SS	0.75%	O-T	11	As received
187	6110	Type-304 SS	1.0%	C-T	1	As received
1148	6157	Type-304 SS	1.0%	C-T	7	Dresden equalizer line weld material, as machined

* Based on Room Temperature Strain-Deflection Calibration Curves.

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

*** Reference: Table 5-2

Table 5-4D

FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIODS IV, V, VI AND VII)

Specimen Number	Cycles to Failure	Material	Shakedown Surface Strain Range*	Loading Mode	Test Condition Code**	Description
1147	6532	Type-304 SS	0.75%	C-T	7	Dresden equalizer line weld material, as machined
1056	6915	Carbon Steel	0.5%	C-T	28	Welded, no stress relief
76	7161	Carbon Steel	0.5%	C-T	26	As machined, no stress relief
177	7756	Type-304 SS	1.0%	C-T	1	As received
1042	7891	Inconel	1.0%	C-T	22	Welded, as machined
181	7891	Type-304 SS	1.0%	C-T	1	As received
1076	7891	Type-304L SS	1.0%	C-T	17	Welded, as machined
142	7930	Type-304 SS	0.5%	O-T	11	As received
184	8040	Type-304 SS	1.0%	C-T	1	As received
1095	8048	Type-304 SS	1.0%	C-T	6	Dresden equalizer line, base material, as machined
75	8869	Carbon Steel	0.5%	C-T	26	As machined, no stress relief
178	9155	Type-304 SS	0.5%	O-T	11	As received
1135	9225	Type-304L SS	1.00%	C-T	16	As received + heavy cold work

* Based on Room Temperature Strain-Deflection Calibration Curves

** Reference: Table 5-2

Table 5-4E
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIOD VIII)

Specimen Number	Cycles to Failure	Material	Shakedown Surface Strain Range*	Loading Mode	Test Condition Code**	Description
25	10,064	SS-304L	0.5%	C-T	18	As Received, Furnace Sensitized
1028	10,577	Inconel	1.0%	C-T	22	Welded
1136	11,654	SS-304L	1.0%	C-T	16	As Received + Heavy Cold Work
1126	12,257	SS-304	1.0%	C-T	2	As Received + Heavy Cold Work
20	12,817	SS-304L	0.5%	C-T	18	As Received, Furnace Sensitized
1101	13,756	SS-304	1.0%	C-T	4	Welded, Machined
163	13,773	SS-304	0.5%	C-T	1	As Received

* Based on Room Temperature Strain - Deflection Calibration Curves

** Reference: Table 5-2

Table 5-4F
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIOD IX)

Specimen No.	Cycles to Failure	Material	Shakedown Surface Strain Range*	Loading Mode**	Test Condition Code	Description
101	14,232	Inconel	1.0%	C-T	23	As Received, Furnace Sensitized
1077	14,798	SS-304L	1.0%	C-T	17	Weldec, As Machined

Total failure indications received to date: 81 - 304SS, 15 - 304L SS, 3 - Inconel, 27 Carbon Steel)

*Based on Room Temperature Strain-Deflection Calibration Curves

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

Figure 5-5. Equivalent Stress Amplitude (psi) versus Cycles to Failure for Inconel-600

Figure 5-6. Equivalent Stress Amplitude (psi) versus Cycles to Failure for A516 Carbon Steel

5.3.3 Metallurgical Effects

5.3.3.1 Type-304 Stainless Steel

A total of 71 Type-304 stainless specimens are under test in the Dresden dynamic test vessel. To date, failure indications have been received from 36 of them. Detailed analyses of these data will be deferred until data from the surviving 35 Type-304 specimens become available. The preliminary trends noted in the previous Quarterly (No. 25) are still valid and are reproduced for convenience as follows.

- a. There appears to be a significant reduction in LCFL (low cycle fatigue life) associated with the furnace-sensitized condition (Material Condition Code No. 5*) compared with the as-received condition (Material Condition No. 1*) for both the zero-tension and compression-tension loading modes.
- b. The relatively weak influence of strain range on the furnace-sensitized data suggests that the failure mechanism is stress-corrosion dominated—at least for the strain range examined from 0.5 to 1.0%.
- c. The zero-tension loading mode is more severe than the compression-tension loading mode for equal strain range, leading to a definite reduction in LCFL in both the as-received and furnace-sensitized materials.

5.3.3.2 Type-304L Stainless Steel

To date, 15 failure indications have been received out of a total of 28 specimens under test. All nine of the furnace-sensitized Type-304L specimens under test have failed. The remaining six failures were divided among three material test conditions:

- Two "as-received" specimens tested at the 1.0% strain range
- Two "welded" specimens tested at the 1.0% strain range
- Two "cold-worked" specimens tested at the 1.0% strain range

5.3.3.3 Inconel-600

One additional Inconel failure indication was received during the report period, bringing the total number of failure signals received to date to 3 out of 23 specimens under test. These three specimens represent two test conditions:

- Two "welded" specimens tested at the 1.0% strain range
- One "furnace-sensitized" specimen tested at the 1.0% strain range

5.3.3.4 Carbon Steel

All of the 27 carbon steel fatigue specimens under test had failed prior to the start of this report period; the results are covered in GEAP-10207-24.

5.4 500°F BASELINE AIR TESTS

The baseline 500°F "air" low-cycle fatigue testing, needed for comparison data with the Dresden 1 "BWR" data, continued. A smaller (i.e., only in terms of reduced specimen capacity) sized version of the Dresden fatigue test machine is being used, cycling 12 of the Task K fatigue specimens in precisely the same manner as their Dresden counterparts except that a neutral reference environment is used (500°F air at ambient pressure). The axial cavity within each specimen is pressurized to 50 psig with argon and connected via capillary tubing to an external pressure switch. The loss of argon pressure caused by a fatigue crack sufficiently deep to intersect this internal cavity is used to define and automatically signal specimen failure.

*See GEAP-10120, Quarterly No. 18, p. 3-4.

A test of 12 fatigue specimens (4 each of Type-304 stainless steel, Inconel-600, and A516 carbon steel) was still in progress at the close of the report period. These were instrumented with high-temperature strain gages prior to installation in the test facility. The deflections, which duplicate those imposed on their Dresden counterparts, produce the two highest strain ranges, as summarized in Table 5-5.

5.4.1 Test Results

To date, over 14,000 test cycles have been accumulated by these specimens with failure indications from four specimens, as noted in Table 5-5. The failure data from these four specimens are compared with the ASME best-fit data curve and the Dresden BWR data for the same material condition (i.e., Material Test Condition No. 1*) in Figures 5-7 and 5-8.

5.4.2 Hot Strain Data

A limited amount of data was obtained from the high temperature strain gages. These preliminary data indicate that the equilibrium (i.e., shakedown) strain ranges developed in the reduced thickness test section at 500°F for a given imposed constant deflection range may be lower than previously measured in room-temperature, strain-deflection calibration tests. This difference between the room temperature and 500°F data appears to differ from material to material, and also between the two deflection ranges, as noted in Table 5-6. Since the mortality rate on these gages was very high, only one, or at most two, gages in any of the six material-deflection combinations survived long enough to achieve equilibrium shakedown conditions. As a result, efforts to experimentally determine shakedown strain range at 500°F are continuing.

Table 5-5
FATIGUE SPECIMEN TEST PLAN, SERIES III-B BASELINE "AIR" TESTS

Specimen Number	Material	TIP Deflections (in.)	Testing ^c Rate (cph)	Cycles to Failure
200	Type 304 SS, As Received	$\pm 0.094^a$	8	9,020
202	Type 304 SS, As Received	$\pm 0.094^a$	8	8,679
194	Type 304 SS, As Received	$\pm 0.078^b$	8	—
204	Type 304 SS, As Received	$\pm 0.078^b$	8	—
118	Inconel, As Received	$\pm 0.100^a$	8	—
120	Inconel, As Received	$\pm 0.100^a$	8	—
121	Inconel, As Received	$\pm 0.089^b$	8	—
123	Inconel, As Received	$\pm 0.089^b$	8	—
1044	A516 Carbon Steel, As Machined	$\pm 0.086^a$	8	13,300
1046	A516 Carbon Steel, As Machined	$\pm 0.086^a$	8	10,327
1045	A516 Carbon Steel, As Machined	$\pm 0.076^b$	8	—
1047	A516 Carbon Steel, As Machined	$\pm 0.076^b$	8	—

^a Corresponds to 1.0% peak-to-peak strain range based on room temperature strain-deflection curves.

^b Corresponds to 0.75% peak-to-peak strain range based on room temperature strain-deflection curves.

^c Initial 100 cycles accumulated at 4 cph test rate for high temperature strain measurements.

Figure 5-7. Equivalent Stress Amplitude versus Cycles to Failure for Type-304 Stainless Steel.
Comparison of fatigue data from BWR environment with "non-environment" baseline case.

Figure 5-8. Equivalent Stress Amplitude versus Cycles to Failure for A516 Carbon Steel.
Comparison of fatigue data from BWR environment with "non-environment" baseline case.

Table 5-6
PRELIMINARY RESULTS, 500°F SHAKEDOWN STRAIN RANGE DATA, SERIES III-B TESTS

Material	Tip Deflection ($\pm\Delta$) (in.)	ϵ_{PP}^* Shakedown 70°F (%)	ϵ_{PP} Shakedown 500°F (%)	$\frac{\epsilon_{PP} \text{ Shakedown } 500^\circ\text{F}}{\epsilon_{PP} \text{ Shakedown } 70^\circ\text{F}} \times 100\%$ (%)
SS-304	± 0.094	1.0	0.79–0.82	79–82
SS-304	± 0.078	0.75	0.71	94
Inconel-600	± 0.100	1.0	0.69–0.74	69–74
Inconel-600	± 0.089	0.75	No data obtained	—
Carbon Steel (A-516, KC-70)	± 0.086	1.0	0.60	60
Carbon Steel (A-516, KC-70)	± 0.076	0.75	0.60	80

* ϵ_{PP} = Strain peak-to-peak.

5.5 THIRD TEST VESSEL (Dresden Test Loop)

Design was completed and equipment procurement well advanced on the fatigue crack growth unit (third test vessel) for addition to the existing Dresden 1 test loop. Augmenting the crack initiation data now being generated, it will develop crack growth data in the BWR environment (see system schematic, Figure 5-9). Detailed drawings covering the piping changes that must be made in the Dresden test loop to accommodate this additional vessel have been completed.

Major emphasis has shifted from design to equipment procurement. An order has been placed for the vessel; estimated delivery date is early May. Much time and effort have been devoted to quality assurance to minimize delays in obtaining approvals to add this vessel to the Dresden 1 test loop.

The following items are presently on order (Figure 5-9):

- a. One single-channel recorder (Load Recorder)
- b. One six-channel recorder (COD Recorder)
- c. Seven channels Hi Temp—Hi Pressure COD gages and associated Demodulator-Exciters
- d. Weldable, hermetically sealed strain gages (for use on calibrated force link, *in situ* load cell)
- e. One-channel strain gage signal conditioning/dc amplifier (load cell signal conditioning)
- f. Hydraulic loading cylinder

Figure 5-9. Proposed Testing Scheme

Table 5-7
2T-WOL SPECIMEN PLATE MATERIAL, CHEMICAL ANALYSES

Material Specification	Vendor/ Heat Number	Chemical Composition			ASTM Requirements	Vendor Test Results (psi)
		ASTM Requirements* (%)	Vendor Certified Analysis (%)	Check Analysis (%)		
ASTM-A-240 Type 304	Vendor A 2P0600	C — 0.08 max	0.06	0.065	Min Tensile	79,830
		Si — 1.00 max	0.66	0.656	Strength	
		P — 0.045 max	0.024	0.023	75,000 psi	
		Ch — 18.00 - 20.00	18.68	18.25		33,350
		N — 8.00 - 12.00	9.95	10.06	Min Yield	
		S — 0.030 max	0.013	0.022	Strength	
		Mn — 2.00 max	1.43	1.37	30,000 psi	
ASTM A-240 Type 304L	Vendor B 14506	C — 0.03 max	0.029	0.031	Min Tensile	84,600
		Si — 1.00 max	0.35	0.500	Strength	
		P — 0.045 max	0.024	0.021	70,000 psi	
		Ch — 18.00 - 20.00	18.50	18.64		34,140
		N — 8.00 - 12.00	8.70	8.79	Min Yield	
		S — 0.030 max	0.019	0.016	Strength	
		Mn — 2.00 max	1.47	1.62	25,000 psi	
ASTM B-168	Vendor C NX 3286	C — 0.15 max	0.06	0.058	Min Tensile	96,500
		Si — 0.5 max	0.26	0.266	Strength	
		Fe — 6.00 - 10.00	8.33	8.94	80,000 psi	
		Ch — 14.00 - 17.00	15.20	15.34		45,500
		N — 72.00 min	75.75	74.84	Min Yield	
		S — 0.015 max	0.007	0.014	Strength	
		Mn — 1.0 max	0.16	0.11	35,000 psi	
ASTM A-516 KC-70	Vendor D 67A750	Cu — 0.5 max	0.21	0.2		
		C — 0.28 max	0.25	0.245	Min Tensile	
		Si — 0.13 - 0.33	0.22	0.187	Strength	
		P — 0.035 max	0.012	0.038	70,000 psi	49,000
		Ch — —	—	—		
		N — —	—	—	Min Yield	
		S — 0.04 max	0.023	0.022	Strength	
		Mn — 0.8 - 1.25	1.15	1.05	38,000 psi	

*Material Code

C = Carbon	N = Nickel
Si = Silicon	S = Sulfur
P = Phosphorous	Mn = Manganese
Ch = Chromium	Fe = Iron

The only major item still to be procured is the hydraulic pump needed to power the hydraulic loading system for this vessel. Bids covering this pump are presently being evaluated.

5.5.1 Specimen Manufacture

Four lots of certified plate stock were procured for use in the manufacture of the 2T-WOL specimens (Figure 5-10) destined for loading in this third vessel. Mechanical properties and chemical analyses for these plates are summarized in Table 5-7. Metallographic specimens were taken from each of the four plates for the purpose of determining the principal rolling direction, and establishing typical microstructures for these four materials (see Figures 5-11 [a, b, c, and d]). In cases where a definite rolling direction was apparent, the specimen blanks were oriented, as shown in Figure 5-12. The Inconel plate evidently had been subjected to extensive cross-rolling so that it was not possible to establish a definite rolling direction for this material.

The 2T-WOL specimens have been finished-machined and are now undergoing final quality-control dimensional checks.

Figure 5-10. 2T-WOL Specimen for Crack Growth Rate Study of Task KC

10% OXALIC ACID

100X

(a) 304 STAINLESS STEEL

10% OXALIC ACID

100X

(b) 304L STAINLESS STEEL

10% OXALIC ACID

250X

(c) INCONEL-600

3% NITAL

250X

(d) A-516 CARBON STEEL

NOTE: ALL PHOTOS REDUCED TO 56% OF SIZE FOR REPRODUCTION PURPOSES

Figure 5-11. Typical Microstructures Observed in 2T-WOL Plate Stock

Figure 5-12. 2T-WOL Specimen Blank Orientation

APPENDIX

**ACOUSTIC EMISSION MEASUREMENTS ON PIPE RUPTURE TEST
PERFORMED NOVEMBER 1971
(W. K. Luinetti, W. C. Leschek)**

A.1 SUMMARY

Two acoustic emission transducers were installed on the pipe rupture test rig. Data were obtained during the pipe bending tests at temperature and pressure. A large amount of acoustic noise was generated by frictional forces in the test rig. True acoustic emission signals were small; however, definite indications of activity were observed prior to visual crack detection and during a through-leak.

A.2 THE TEST SETUP

The test specimen consisted of a 6-inch-diameter, Schedule-80 pipe section approximately 20 feet long (a carbon steel section about 14 feet long was butt-welded to a 6-foot length of stainless steel) (see Figures A-1 and A-2). The stainless steel section was terminated in a flange that was rigidly bolted to the end of the test frame. The test weld was located about 8 inches from the flange. The other end of the pipe was supported by the hydraulic cylinder mechanisms.

The stainless steel test section was temperature-controlled at 550°F, and the entire pipe length was pressurized at about 15 psig with nitrogen during the leak checks (to enable detection of through-wall cracks with an ultrasonic translator).

Westinghouse NES* instruments, including two acoustic emission transducers and an accelerometer, were mounted on the test section by using hose clamps.

A.3 THE TEST PROCEDURE

The first phase of the test consisted of cycling the test specimen at a frequency of 0.2 Hz and a displacement of ± 10 inches. The pipe was automatically cycled 200 times and was then stopped to allow inspection of the weld, using ultrasonic measuring instruments. After inspection was complete, the pipe was cycled 200 times and inspected again. This procedure was repeated until the pipe had been cycled 2800 times.

At about 1900 cycles, the first crack was discovered by visual techniques. It appeared circumferentially along the top of the pipe at the edge of the weld.

After inspection of the pipe at the end of 2800 cycles, the pipe was flexed continuously at 0.2 Hz for 1000 cycles at half amplitude (± 5 inches). When this phase was completed and crack length measurements were made, the pipe was cycled again at ± 10 inches.

Within the first 100 cycles at full amplitude, the crack had grown completely through the wall thickness and it was possible to hear the gas escaping from the pipe. The test was continued until the crack had propagated about 80% of the circumference of the weld, at which time the test was stopped.

A.4 OPERATION OF THE ACOUSTIC EMISSION INSTRUMENTS

Prior to the test, the electronics were set up using a pulse generator and an accelerometer to introduce a periodic noise burst. That signal was used to set the logic circuitry so that a pulse arriving from the right (see Figure A-1) would trigger Channel B which would, in turn, inhibit Channel A from seeing the count. In this manner, it was hoped that frictional signals originating at the driving end would be "hidden" from Channel A but signals originating from the test weld would be counted directly.

*Nuclear Energy Systems

Figure A-2. Two Views of the Acoustic Emission Equipment (on the left), and the Pipe Being Fatigue Tested (on the right)

During the test, however, it was apparent that the frictional signals (metal-to-metal contact) and hydraulic system noises were spread out over most of the pipe movement time period. Because of this, inhibiting Channel A from counting signals that originated from the driving end was not possible with the instruments on site. (A rubber pad was added between pipe and holder but it was not possible, with the limited time available, to provide a rubber interface between the U-bolt and the bottom of the pipe; see detail in Figure A-1).

Also during the test it was found by surveillance with an ultrasonic translator that friction between the hose clamp (used to secure the accelerometer in place) and the pipe (while the pipe was under stress) generated undesirable noise. The hose clamp was removed and the threshold levels of the discriminators were reset. The remaining hose clamps holding the acoustic emission transducers in place appeared relatively quiet where surveyed with the translator.

Refer to Figure A-3. The ratemeter outputs of Channels A and B were recorded on a two-pen strip chart recorder. Of particular interest concerning the recorder signals are the following items:

- a. Reference Figure A-4. There were two bursts of activity at about 1430 cycles. The activity occurred during the maximum down position of the pipe (when the upper side of the weld was under maximum strain) before a crack was detected visually. There was no physical activity or noise around the pipe in this time period.
- b. Reference Figure A-5. When the test at full amplitude was resumed, the signal levels were much smaller than they were before the 1000-cycle test. There seemed to be a strong correlation between the volume of escaping gas and the signals recorded.

In addition to the data recorded on the strip chart, the outputs of the amplifiers were amplified and filtered to remove the d-c component and recorded on magnetic tape at 30 in./s for future analysis.

Figure A-3. Block Diagram of Acoustic Emission Indicating and Recording Equipment

Figure A-4. Recorder Pen Traces of Acoustic Emission During Fatigue Test

Figure A-5. Recorder Pen Traces of Acoustic Emission Near End of Test

DISTRIBUTION

Aerojet General Engineering Division Sacramento Plant Sacramento, California 95801 Attn: Dr. F.J. Climent	1	Advisory Committee on Reactor Safeguards Dr. Arlie A. O'Kelly 2421 West Rowland Avenue Littleton, Colorado 80120	1
Advisory Committee on Reactor Safeguards Dr. Spencer H. Bush Consultant to the Director Battelle Memorial Institute Pacific Northwest Laboratory Richland, Washington 99352	1	Advisory Committee on Reactor Safeguards Dr. David Okrent, Senior Physicist Laboratory Director's Office Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois 60439	1
Advisory Committee on Reactor Safeguards Mr. Harold Etherington 84 Lighthouse Drive Jupiter, Florida 33458	1	Advisory Committee on Reactor Safeguards Dean Nunzio J. Palladino College of Engineering The Pennsylvania State University 101 Hammond Building University Park, Pennsylvania 16802	1
Advisory Committee on Reactor Safeguards Dr. William L. Faith 2540 Huntington Drive San Marino, California 91108	1	Advisory Committee on Reactor Safeguards Dr. William R. Stratton Los Alamos Scientific Laboratory P. O. Box 1663 Los Alamos, New Mexico 87544	1
Advisory Committee on Reactor Safeguards Dr. Chester P. Siess Department of Civil Engineering 3129 Civil Engineering Bldg. University of Illinois Urbana, Illinois 61801	1	Advisory Committee on Reactor Safeguards Dr. Carroll W. Zabel Director of Research University of Houston Cullen Boulevard Houston, Texas 77004	1
Advisory Committee on Reactor Safeguards Dr. Stephen H. Hanauer Professor of Nuclear Engineering 606 Dougherty Hall University of Tennessee Knoxville, Tennessee 37916	1	Mr. Raymond F. Fraley Executive Secretary Advisory Committee on Reactor Safeguards U.S. Atomic Energy Commission Room 1034-H Washington, D.C. 20545	3
Advisory Committee on Reactor Safeguards Dr. Joseph M. Hendrie Nuclear Engineering Department Brookhaven National Laboratory Upton, New York 11973	1	Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois Attn: Mr. Paul G. Shewmon	1
Advisory Committee on Reactor Safeguards Dr. Herbert S. Isbin Department of Chemical Engineering University of Minnesota Minneapolis, Minnesota 55455	1	Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois Attn: Dr. P. Lottes	1
Advisory Committee on Reactor Safeguards Mr. Harold G. Mangelsdorf 78 Knollwood Road Short Hills, New Jersey 07078	1	Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois Attn: Dr. C.E. Dickerman	1
Advisory Committee on Reactor Safeguards Dr. Harry O. Monson, Senior Engineer Laboratory Director's Office Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois 60439	1	Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois Attn: Dr. R.O. Ivins	1
		Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois Attn: Dr. S. Fistedis	1

Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois Attn: Dr. R.C. Vogel	1	Atomic Energy Commission Division of Compliance, Region IV 10395 West Colfax Avenue Denver, Colorado 80215 Attn: Mr. John W. Flora	1
Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois Attn: LMFBR Program Office	1	Atomic Energy Commission Division of Compliance Washington, D.C. 20545 Attn: Mr. L. Kornblith, Jr.	1
Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois Attn: Mr. A. Amorosi	2	Atomic Energy Commission Division of Operational Safety Washington, D.C. 20545 Attn: Mr. H. Gilbert	1
Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois Attn: Dr. L. Baker	1	Atomic Energy Commission Division of Reactor Standards Washington, D.C. 20545 Attn: Mr. E.G. Case	10
Atomic Energy Commission Division of Reactor Development and Technology Washington, D.C. 20545 Attn: Col. R.L. Ednie Asst. Director for Army Reactors	1	Atomic Energy Commission Division of Reactor Standards Washington, D.C. 20545 Attn: Mr. M. Bolotsky	1
Atomic Energy Commission Division of Reactor Development and Technology Washington, D.C. 20545 Attn: Mr. M.A. Rosen Asst. Director for Plant Engineering	1	Atomic Energy Commission Division of Reactor Standards Washington, D.C. 20545 Attn: Mr. A.B. Holt	1
Atomic Energy Commission Division of Reactor Development and Technology Washington, D.C. 20545 Attn: Mr. M.J. Whitman Asst. Director for Program Analysis	1	Atomic Energy Commission Division of Reactor Standards Washington, D.C. 20545 Attn: Mr. R. Waterfield	1
Atomic Energy Commission Division of Reactor Development and Technology Washington, D.C. 20545 Attn: Dr. E.E. Sinclair Asst. Director for Reactor Technology	1	Atomic Energy Commission Division of Reactor Standards Washington, D.C. 20545 Attn: Dr. G. Burley	1
Atomic Energy Commission Division of Reactor Development and Technology Washington, D.C. 20545 Attn: Mr. A. Giambusso Asst. Director for Project Management	1	Atomic Energy Commission Water Projects Branch Division of Reactor Development and Technology Washington, D.C. 20545 Attn: Mr. W.H. Layman	1
Atomic Energy Commission Division of Reactor Development and Technology Washington, D.C. 20545 Attn: Mr. E.E. Kintner Asst. Director for Reactor Engineering	1	Atomic Energy Commission Naval Reactors Branch Division of Reactor Development and Technology Washington, D.C. 20545 Attn: Mr. R.S. Brodsky	2
Atomic Energy Commission Division of Reactor Development and Technology Washington, D.C. 20545 Attn: Mr. J. W. Crawford Asst. Director for Engineering Standards	1	Atomic Energy Commission Division of Reactor Development and Technology Washington, D.C. 20545 Attn: A.J. Pressesky	3

Atomic Energy Commission Division of Reactor Development and Technology Washington, D.C. 20545 Attn: Mr. S.A. Szawlewicz	5	Chicago Operations Office Atomic Energy Commission 9800 South Cass Avenue Argonne, Illinois 60439 Attn: Mr. D.M. Gardiner	1
Atomic Energy Commission Division of Production Washington, D.C. 20545 Attn: Mr. George B. Pleat	1	Douglas United Nuclear Richland, Washington Attn: Mr. John Riches	1
Atomic Energy Commission c/o Gulf General Atomic, Inc. P.O. Box 608 San Diego, California 92112 Attn: Mr. Russell H. Ball	1	Harvard Air Cleaning Laboratory Harvard University 665 Huntington Avenue Boston, Massachusetts 02190	1
Atomics International P.O. Box 309 Canoga Park, California Attn: Dr. H. Morewitz	2	IIT Research Institute 10 W. 35th Street Chicago, Illinois 60616 Attn: Dr. T.A. Zaker	1
Babcock & Wilcox Company P.O. Box 1260 Lynchburg, Virginia Attn: Mr. Robert Wascher	1	IIT Research Institute 10 W. 35th Street Chicago, Illinois 60616 Attn: Mr. E.V. Gallagher	1
Battelle Memorial Institute 505 King Avenue Columbus, Ohio 43201 Attn: Dr. D.N. Sunderman	2	Idaho Operations Office Atomic Energy Commission P.O. Box 2108 Idaho Falls, Idaho 83401 Attn: Mr. D. Williams	2
Battelle Memorial Institute 505 King Avenue Columbus, Ohio 43201 Attn: Dr. D.L. Morrison	1	Liquid Metal Engineering Center c/o Atomics International P.O. Box 309 Canoga Park, California 91304 Attn: R.W. Dickinson	1
Battelle Memorial Institute 505 King Avenue Columbus, Ohio 43201 Attn: Mr. S. Paprocki	2	Los Alamos Scientific Laboratory P.O. Box 1663 Los Alamos, New Mexico 87544 Attn: Mr. J.H. Russel, K Division	1
Battelle Memorial Institute 505 King Avenue Columbus, Ohio 43201 Attn: Mr. A.R. Duffy	1	MPR Associates, Inc. 1140 Connecticut Avenue, N.W. Washington, D.C. 20036 Attn: Mr. T. Rockwell III Chairman AIF Safety Task Force	1
Brookhaven National Laboratory Upton, Long Island, New York 11973 Attn: A.W. Castleman	1	National Bureau of Standards Washington, D.C. 20545 Attn: Dr. C. Muehlhause	1
University of California Institute of Engineering Research Berkeley, California 94704 Attn: Prof. V.E. Schrock	1	Naval Ordnance Laboratory White Oak Silver Spring, Maryland Attn: Mr. James Proctor	1
Canoga Park Area Office P.O. Box 591 Canoga Park, California 91305 Attn: Mr. R.L. Morgan RDT Senior Site Rep.	1	North Carolina State University Department of Mechanical Engineering Raleigh, North Carolina 27607 Attn: Prof. M.N. Ozisik	1
Combustion Engineering, Inc. Nuclear Division P.O. Box 500 Windsor, Connecticut 06095 Attn: Mr. M.F. Valerino	1	Nuclear Fuels Services West Valley, New York 14171	1

Oak Ridge Operations Office Atomic Energy Commission Oak Ridge, Tennessee 37830 Attn: Mr. W.L. Smalley	1	Idaho Nuclear Corporation P.O. Box 1845 Idaho Falls, Idaho 83401 Attn: Mr. Curt Haire	1
Oak Ridge National Laboratory Nuclear Safety Information Center P.O. Box Y Oak Ridge, Tennessee 37830 Attn: Mr. Joel Buchanan	1	Idaho Nuclear Corporation P. O. Box 1845 Idaho Falls, Idaho 83401 Attn: Mr. S. O. Johnson	2
Chemical Technology Division Oak Ridge National Laboratory P.O. Box Y Oak Ridge, Tennessee 37830 Attn: Mr. D. Ferguson	1	Idaho Nuclear Corporation P.O. Box 1845 Idaho Falls, Idaho 83401 Attn: Mr. H. L. Coplen	2
Chemical Technology Division Oak Ridge National Laboratory P.O. Box Y Oak Ridge, Tennessee 37830 Attn: Mr. R. Blanco	1	Idaho Nuclear Corporation P. O. Box 1845 Idaho Falls, Idaho 83401 Attn: Mr. O. F. Brockett	1
Oak Ridge National Laboratory P.O. Box Y Oak Ridge, Tennessee Attn: HTGR Safety Program Office	2	Idaho Nuclear Corporation P. O. Box 1845 Idaho Falls, Idaho 83401 Attn: Water Reactor Safety Program Office, Mr. G. O. Bright, Mgr.	3
Oak Ridge National Laboratory P.O. Box Y Oak Ridge, Tennessee Attn: Mr. W. B. Cottrell	4	Richland Operations Office P.O. Box 500 Richland, Washington 99352 Attn: Mr. C. Robinson	1
Oak Ridge National Laboratory P.O. Box Y Oak Ridge, Tennessee Attn: Mr. P. Rittenhouse	1	Richland Operations Office P.O. Box 500 Richland, Washington 99352 Attn: Mr. A.S. Waterhouse	1
Pacific Northwest Laboratories P.O. Box 999 Richland, Washington 99352 Attn: Mr. G. Rogers	1	Richland Operations Office P.O. Box 500 Richland, Washington 99352 Attn: Mr. A. Brunstad	1
Pacific Northwest Laboratories P.O. Box 999 Richland, Washington 99352 Attn: Mr. J.C. Spanner	1	San Francisco Operations Office Atomic Energy Commission 2111 Bancroft Way Berkeley, California 94704 Attn: Mr. C.V. Backlund	1
Pacific Northwest Laboratories P.O. Box 999 Richland, Washington 99352 Attn: Dr. J. Batch	1	Savannah River Laboratories E.I. duPont deNemours and Company Aiken, South Carolina 29802 Attn: Mr. A.H. Peters	1
Pacific Northwest Laboratories P.O. Box 999 Richland, Washington 99352 Attn: Mr. R. Nightingale	2	TRW Inc. TRW Systems Group One Space Park Redondo Beach, California 90278 Attn: Dr. D. B. Langmuir	1
Pacific Northwest Laboratories P.O. Box 999 Richland, Washington 99352 Attn: Mr. L. Schwendiman	1	TRW Inc. TRW Systems Group One Space Park Redondo Beach, California 90278 Attn: Mr. S.M. Zivi	1
Pacific Northwest Laboratories P.O. Box 999 Richland, Washington 99352 Attn: Mr. E.R. Astley, Mgr. FFTF	1		

Westinghouse Electric Corporation Atomic Power Division P.O. Box 355 Pittsburgh, Pennsylvania 15230 Attn: Mr. R.A. Wiesemann	1	Mr. F.M. Moschine Westinghouse Electric Company Atomic Power Department P.O. Box 355 Pittsburgh, Pennsylvania 15230	1
Westinghouse Electric Corporation Atomic Power Division P.O. Box 355 Pittsburgh, Pennsylvania 15230 Attn: Dr. D. Fletcher	1	Dr. P. L. Pfenningwerth Bettis Atomic Power Laboratory P.O. Box 79 West Mifflin, Pennsylvania 15122	1
Westinghouse Electric Corporation Atomic Power Division P.O. Box 355 Pittsburgh, Pennsylvania 15230 Attn: Dr. E. Beckjord	1	Professor C.E. Taylor Department of Theoretical and Applied Mechanics University of Illinois Urbana, Illinois	1
Westinghouse Electric Corporation P.O. Box 19218 Tampa, Florida 33616 Attn: Mr. A. Lohmeier	1	Mr. E. Beauchamp-Nobbs U.S. Marine Engineering Laboratory Annapolis, Maryland	1
Southern Nuclear Engineering, Inc. P.O. Box 10 Dunedin, Florida 33528 Attn: Mr. Gilbert Brown	1	U.S. Atomic Energy Commission Division of Technical Information Extension P.O. Box 62 Oak Ridge, Tennessee	3
Holmes & Narver, Inc. 828 South Figueroa St. Los Angeles, California 90017 Attn: B. Shimizu	1	U.S. Atomic Energy Commission Division of Reactor Licensing Washington, D.C. 20545 Attn: S.S. Pawlicki	1
Mr. Edward T. Wessel Research and Development Center Westinghouse Electric Corporation Beulah Road, Churchill Boro Pittsburgh, Pennsylvania 15235	1	USAEC Site Representative General Electric Company Sunnyvale, California 94086 Attn: Russell H. Ball, RDT Sr. Site Rep.	1
Dr. William E. Cooper Teledyne Materials Research 303 Bear Hill Road Waltham, Massachusetts	1	Mr. B.L. Greenstreet P.O. Box Y Oak Ridge National Laboratory Oak Ridge, Tennessee	1
Roger W. Staehle Metallurgy Department Ohio State University Columbus, Ohio	1	Mr. F.J. Witt P.O. Box Y ORNL - Oak Ridge, Tennessee	1
Mr. Ralph Jones Division of Reactor Development U.S. Atomic Energy Commission Washington 25, D.C.	1	Commonwealth Edison Company Dresden Nuclear Power Station Rural Route 1 Morris, Illinois 60450 Attn: H.K. Hoyt	2
Mr. H.K. Marks Room 2N83 Department of the Navy Washington, D.C.	1	Bechtel Corporation 50 Beale Street San Francisco, California 94105 Attn: R.P. Schmitz	1
H. Thielsch 140 Shaw Avenue Cranston 5, Rhode Island	1	E.B. Branch Sargent and Lundy 140 S. Dearborn Street Chicago, Illinois 60603	1
	1	Babcock and Wilcox Research and Development Division P.O. Box 835 Alliance, Ohio 44601 Attn: W.A. VanDerSluys	1

Robert L. Brooks Market Development Division Lukens Steel Company Coatesville, Pennsylvania 19320	1	Knolls Atomic Power Laboratory P.O. Box 1072 Schenectady, New York 12301 Attn: Dr. Robert A. Barnes	1
Robert M. Bruscatto Metals Research Chicago Bridge and Iron Company 901 W. 22nd Street Oak Brook, Illinois 60521	1	Reactor Materials Branch Metallurgy Division Naval Research Laboratory Washington, D.C. 20545 Attn: Mr. L.E. Steele	1
Jersey Nuclear Corporation 2101 Horn Rapids Road Richland, Washington 99352 Attn: Mr. Dwight Parry	1	Department of Material Science & Engineering Hearst Mining Building University of California Berkeley, California Attn: Mr. William W. Gerberich	1
Commonwealth Edison Company System Mechanical and Structural Engineer 72 West Adams Street Chicago, Illinois 60690 Attn: M.H. Goedjen	3	United Engineers and Constructors, Inc. 1401 Arch Street Philadelphia, Pennsylvania 19105 Attn: Mr. John Crowley	1
United Kingdom Atomic Energy Authority Reactor Materials Laboratory Wigshaw Lane, Culcheth Warrington, Lancs. England Attn: R.W. Nichols	1	Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois Attn: Mr. Craig Cheng	1
Atomic Energy of Canada Limited Chalk River Nuclear Laboratories Chalk River, Ontario, Canada Attn: Dr. George Pon	1	AEG Telefunken AEC Hochhaus Sued 6 Frankfurt/Main 70 West Germany Attn: Mr. Dieter Ewers	1
Mr. Robert D. Wylier Department of Materials Engineering Southwest Research Institute 8599 Culebra Road San Antonio, Texas 78228	1	Division of Reactor Development & Technology U.S. Atomic Energy Commission Washington, D.C. 20545 Attn: J.R. Hunter Chief, Reactor Vessels Branch	1
O.A. Kellerman Institute Fur Reaktorsicherheit Der Technischen Uberwachungs Vereine, e.V. 5 KOLN 1 Glockengasse 2 West Germany	1	Asst. Director, Instruction Division U.S. Atomic Energy Commission Chicago Operations Office 9800 South Cass Avenue Argonne, Illinois 60439 Attn: R.M. Moser	1
C.A.G. Phillips U.K.E.A. Safeguards Division Authority Health & Safety Branch Risley, Warrington, Lancashire England	1	Battelle Memorial Institute 505 King Avenue Columbus, Ohio 43201 Attn: Mr. E. Rodabaugh	1