139
5-8-78
uc-18

Dr. 128

GEAP-10207-28
AEC RESEARCH AND
DEVELOPMENT REPORT
FEBRUARY 1973

**REACTOR PRIMARY COOLANT SYSTEM
PIPE RUPTURE STUDY
PROGRESS REPORT NO. 28
JULY - DECEMBER 1972**

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

MASTER

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.

GEAP-10207-28
UC-78
AEC Research and
Development Report
February 1973

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.

**REACTOR PRIMARY COOLANT SYSTEM PIPE RUPTURE STUDY
PROGRESS REPORT NO. 28
JULY-DECEMBER 1972**

Approved:

E. Kiss
E. Kiss
Project Engineer

Approved:

J. L. Murray for
D. H. Imhoff, Manager
Development Engineering

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

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

82p, 215c/Des. Engrg.
MM-3/73

GENERAL ELECTRIC

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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

LIST OF ILLUSTRATIONS	v
LIST OF TABLES	ix/x
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—ASME Elastic-Plastic Code Rules for Fatigue Evaluation	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
3.3 Fault Cause List	3-1
3.4 Interview and Calculation Structure	3-2
4. TASK D—LOW CYCLE FATIGUE	4-1
4.1 Objectives	4-1
4.2 Task D-3—Prototype Pipe Fatigue	4-1
4.3 Task D-5—ASME Elastic-Plastic Code Rules for Fatigue Evaluation	4-3
5. TASK K—EFFECT OF BWR ENVIRONMENT	5-1
5.1 Objective	5-1
5.2 Summary	5-1
5.3 Dresden Test Loop	5-1
5.4 Metallurgical Evaluation	5-5
5.5 500°F Baseline Air Tests	5-11
5.6 Third Test Vessel (D-1 Test Loop)—Crack Growth Investigation	5-22
APPENDICES	
A METALLURGICAL EXAMINATION TASK K FATIGUE SPECIMENS	A-1
B STATISTICAL ANALYSIS COMPARING TASK K LOW CYCLE FATIGUE DATA IN AIR AND IN BWR WATER	B-1

LIST OF ILLUSTRATIONS

Figure	Title	Page
4-1	Task D3 Carbon Steel Girth Buttweld Specimens	4-4
4-2	Elbow Specimen (CSLS-7) After Failure	4-3
4-3	Fatigue Specimens	4-4
4-4	Cycles to Crack-Initiation as a Function of Nominal Stress Range in Load-Controlled Tests	4-5
4-5	Cycles to Specimen Fracture as a Function of Nominal Stress Range in Load-Controlled Tests	4-6
4-6	Cycles to Crack-Initiation as a Function of the Fictitious Elastic Stress Amplitude in Load-Controlled Tests	4-8
4-7	Cycles to Crack-Initiation as a Function of Deflection Range (over 4-inch Gage Length) in Deflection-Controlled Tests	4-9
4-8	Cycles to Crack-Initiation as a Function of Nominal Stress Range in Deflection-Controlled Test	4-10
4-9	Cyclic Stress-Strain Curves for Type-304 Stainless Steel	4-12
4-10	Average Net-Section Stress Amplitude (ksi), Notch Root Strains, Stainless Steel Grooved Specimen.	4-13
4-11	Displacement Amplitude over 4-inch Gage Length (mils), Stress versus Displacement, Stainless Grooved Specimen	4-14
4-12	Average Net-Section Stress Amplitude (ksi), Surface Strains, Stainless Shouldered Specimen	4-15
4-13	Displacement Amplitude over 4-inch Gage Length (mils), Stress versus Displacement, Stainless Shouldered Specimen	4-16
4-14	Cycles to Crack-Initiation as a Function of the Local Predicted Strain Amplitude.	4-17
4-15	Cyclic Stress-Strain Curves for A212 Grade B Carbon Steel	4-18
4-16	Average Net-Section Stress Amplitude (ksi), Surface Strains, Carbon Shouldered Specimen	4-19
4-17	Displacement Amplitude over 4-inch Gage Length (mils), Stress versus Displacement, Carbon Shouldered Specimen	4-20
4-18	Average Net-Section Stress Amplitude (ksi), Notch Root Strains, Carbon Steel Grooved Specimen	4-21
4-19	Displacement Amplitude over 4-inch Gage Length (mils), Stress versus Displacement, Carbon Steel Grooved Specimen	4-22
5-1	Dynamic Test Specimen	5-4
5-2	Equivalent Stress Amplitude (psi) versus Cycles to Failure for Type-304 Stainless Steel	5-7
5-3	Equivalent Stress Amplitude (psi) versus Cycles to Failure for Type 304L Stainless Steel	5-8
5-4	Equivalent Stress Amplitude (psi) versus Cycles to Failure for Inconel-600	5-9

LIST OF ILLUSTRATIONS (Continued)

Figure	Title	Page
5-5	Equivalent Stress Amplitude (psi) versus Cycles to Failure for A516 Carbon Steel	5-10
5-6	Carbon Steel 1%E	5-12
5-7	Inconel 600 1%E	5-13
5-8	As Received 304 1%E	5-14
5-9	Furnace Sensitized 304 1%E	5-15
5-10	Furnace Sensitized 304. 5%E	5-16
5-11	304L Weld Sensitized 1%E	5-17
5-12	Equivalent Stress Amplitude versus Cycles to Failure for Type-304 Stainless Steel. Comparison of fatigue data from BWR environment with 500°F air baseline case.	5-19
5-13	Equivalent Stress Amplitude (psi) versus Cycle to Failure for Inconel 600. Comparison of fatigue data from BWR environment with 500°F air baseline case.	5-20
5-14	Equivalent Stress Amplitude versus Cycles to Failure for A516 Carbon Steel. Comparison of fatigue data from BWR environment with 500°F air baseline case.	5-21
5-15	Test Vessel III Test Scheme	5-23
5-16	2T-WOL Specimen for Crack Growth Rate Study of Task K _c	5-24
5-17	2T-WOL Under Test	5-25
A-1	SEM Micrographic of Machined Surface of as Received 304SS (300X) . Specimen #S-201 (30-80) (30-81)	A-3
A-2	Optical Micrograph of Machined Surface of Air Tested Calibration Specimen of 304SS (160X)	A-4
A-3	Cold Worked Surface of 304L SS (300X). Specimen #1135 (30-21)	A-4
A-4	Optical Micrograph of Thick Oxide on Surface of Cold Worked 304L SS Specimen (500X) Specimen #1135 (2SE-11-7)	A-5
A-5	Fracture Surface of as Received 304SS (100X). Specimen #177 (35-69)	A-5
A-6	Fatigue Striations on Fracture Surface of as Received 304SS (100X). Specimen #S-201 (31-12)	A-6
A-7	Fatigue Striations on Fracture Surface of as Received 304SS (1000X). Specimen #201 (30-78)	A-6
A-8	Fracture Surface of Air Tested 304SS Specimen (100X). (30-11)	A-7
A-9	Fatigue Striations on Air Tested 304SS Specimen (300X). (30-09)	A-8
A-10	Fracture Surface of Furnace Sensitized 304SS (100X). Specimen #180 (34-48)	A-8
A-11	Fracture Surface of Furnace Sensitized 304SS (100X). Specimen #166 (30-63)	A-9

LIST OF ILLUSTRATIONS (Continued)

Figure	Title	Page
A-12	Fracture Surface of Furnace Sensitized 304SS (50X). Specimen #179 (29-83)	A-9
A-13	Fatigue Striations on Furnace Sensitized 304SS Specimen (1000X). Specimen #179 (29-82)	A-10
A-14	Fracture Surface of as Welded 304SS (50X). Specimen #1144 (35-72)	A-10
A-15	Fracture Surface of as Welded 304SS (200X). Specimen #1076 (29-98)	A-11
A-16	Fracture Surface of as Welded Inconel 600 (300X). Specimen #1028 (38-25)	A-12
A-17	Fracture Surface of as Welded Inconel 600 (300X). Specimen #1028 (38-27)	A-12
A-18	Machined Surface of as Welded Inconel 600 (300X). Specimen #1042 (30-23)	A-13
A-19	Fatigue Striations on as Welded Inconel 600 (1000X). Specimen #1028 (38-28)	A-13
A-20	Oxide Crystals on Fracture Surface of A516 Carbon Steel. (1000X). Specimen #48 (34-57)	A-14
A-21	Pits on Machined Surface of A516 Carbon Steel (50X). Specimen #1060 (29-67)	A-14
A-22	Surface Cracks Through Pits on Surface of A516 Carbon Steel (100X). Specimen #1060 (29-66)	A-15

LIST OF TABLES

Table	Title	Page
5-1	Dresden Test Loop Operating Summary	5-2
5-2	Fatigue Test Results from Dresden Loop (Operating Period XIII)	5-5
5-3	Task K Fatigue Specimen Layout	5-6
5-4	Fatigue Specimen Test Plan, Series III-B Baseline "Air" Tests	5-18
5-5	Fatigue Specimen Test Plan Series IV Baseline "Air" Tests	5-22
5-6	2T-WOL Test Parameters	5-26
B-1	Failure Data for Estimating Fatigue Life Reduction Factors.	B-4

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 Pipe Rupture Study is being conducted for the Division of Reactor Development and Technology, USAEC. This Progress Report No. 28 documents work done in the period July 1, 1972 to December 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

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
GEAP-10207-26	No. 26, October 1971–March 1972
GEAP-10207-27	No. 27, April–June 1972

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

A literature search was conducted for the purpose of finding information dealing with identification of fault causes as related to a procurement system when product reliability is the principal aim. This problem is complicated for piping reliability by the fact that many vendors, working in succession, contribute to the final product. It has been concluded that the reactor pipe provisioning system described in GEAP-5192 appears to be the most comprehensive document on the subject, and it is being revised to include pipe procurement practices.

2.2 TASK D-3—PROTOTYPE PIPE FATIGUE

Low cycle fatigue testing of two carbon steel, girth-butt-welded specimens at 550°F was completed. This concludes the testing program for Task D-3. A summary topical report is being prepared.

2.3 TASK D-5—ASME ELASTIC-PLASTIC CODE RULES FOR FATIGUE EVALUATION

The objective of this task is to confirm or improve the ASME Section III 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 specimens have been analyzed using a new elastic-plastic finite element computer program. Experimentally, peak notch strains and cyclic life have been measured and compared with smooth bar data and analytical predictions.

Load-controlled and deflection-controlled axial fatigue tests of smooth, grooved, and shoulder cylindrical fatigue specimens of Type-304 stainless steel were completed. Although the grooved and shoulder specimens have equal theoretical stress concentration factors, fatigue life differs significantly at a given cyclic load or deflection. Fatigue specimen local strains were calculated with the CREEP-PLAST elastic-plastic finite element computer code. Correlation of predicted local strain amplitudes with fatigue life shows only moderate agreement with the supposition that local strain amplitude controls crack initiation.

2.4 TASK K—EFFECT OF BWR ENVIRONMENT

The Dresden 1 test loop has accumulated over 5200 hours of operation at test conditions (510°F, 1040 psig). A total of 90 of the 149 fatigue specimens being cyclically loaded signalled failure. These include 41 of 71 Type-304 stainless steel specimens, 17 of 28 Type-304L stainless steel specimens, 5 of 23 Inconel-600 specimens, and all of the 27 A-516 carbon steel specimens.

Testing of the first material group of fatigue specimens being cycled in air, at 500°F, in the Air Test Facility in San Jose has been completed. These data have been compared with ASME Section III data and comparable data from the Dresden 1 test loop. Preparations have begun for the next group of materials to be fatigued in air in order to establish the baseline air performance.

Preliminary metallography and SEM examination of selected fatigue specimens removed from the Dresden 1 test loop is complete.

Procurement of the hardware for the third test vessel to be added to the Dresden 1 test loop is complete. Calibration and fatigue testing in air of the 2T-WOL specimens has begun.

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

3.1 OBJECTIVES

The objectives of the probability study task are to prepare a comprehensive list of fault causes and to estimate the relative contribution to probability of piping severance which is made by each fault cause.

3.2 SUMMARY

The reactor pipe provisioning system reported in the Fifth Quarterly Progress Report, GEAP-5192, April—June, 1966, is being adopted as the basis for a comprehensive list of fault causes. Stages from specification of operating requirements through plant operation are covered. The immediate need is to prepare a systematic interview and calculation structure which fulfills the objectives and yet can be responded to readily by a number of experienced individuals.

3.3 FAULT CAUSE LIST

The general approach to the preparation of a comprehensive list of fault causes is to make use of the reactor pipe provisioning system set forth in the Fifth Quarterly Progress Report. This choice was made after an extensive literature search for a reference pattern of operation for a procurement system especially oriented toward achieving product reliability for a heavy structural product when many firms are involved in its specification, purchase, manufacture, installation, and use. The fault cause list should systematically identify all those practices which, if omitted or inadequately performed, can adversely affect piping reliability. As the basis for such a list, the reactor pipe provisioning system comprises a list of 1 to 20 characteristics under headings successively subdivided as follows:

Stages (in time):

1. Design Specification Stage
2. Design and Analysis Stage
3. Material Selection Stage
4. Component Manufacture Stage
5. Shop Subassembly Stage
6. Field Subassembly and Installation Stage
7. Startup Testing Stage
8. Nuclear Operation Stage
9. In-Service Inspection Stage

Phases:

1. Performance Phase
2. Check Phase

Level of Generalization:

1. Criteria Level of Generalization
2. Application Level of Generalization

Thus, there are 36 combinations, each having from 1 to 20 characteristics, which, with suitable formatting, will make a satisfactory list of fault causes. Efforts are continuing to identify those fault causes covered by presently applicable design codes and standards.

3.4 INTERVIEW AND CALCULATION STRUCTURE

The judgment of experienced individuals will be sought on the importance each attaches to each fault cause as a potential contributor to piping severance. This was the approach taken in the leak and severance analysis reported in the Twenty-Third Progress Report, GEAP-10207-23, October–December, 1971. Suitable format sheets are in preparation. The interview sheets must be sufficiently detailed to permit adequate discrimination among fault causes, but not so detailed as to be a burden to complete. The alternative of calling for input on the probability that a fault cause leads to a certain stress or crack size category, or simply to severance, is being studied.

4. TASK D—LOW CYCLE FATIGUE

4.1 OBJECTIVES

The objectives of Fatigue Task are: (a) to extend the understanding of low-cycle fatigue cracking in high pressure piping components which may have mechanical or defect flaws, and (b) to apply this knowledge in developing rational design bases for prevention or control of fatigue crack initiation and growth in reactor piping systems.

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

4.2.1 Summary

Fatigue testing of two carbon steel girth-butt-weld specimens at 550°F is complete. This concludes the test program for Task D-3. A summary topical report is in preparation.

The test data for the last two butt-weld fatigue specimens are shown below.

Specimen Number	HW-14	HW-15
Specimen Type	550°F Butt-Weld	550°F Butt-Weld
Material	Carbon Steel	Carbon Steel
Size and Schedule	6-inch Sch 80	6-inch Sch 80
Deflection Range	±8.50 inches	±10.65 inches
Cycles to Leakage, N_L	7278*	3209*
ASME Section III, S_{alt}	175 ksi	356 ksi
ASME Section III, N_D	150	27
Safety Factor, N_L/N_D	48.5	119

* Leakage occurred in the transition piece approximately two inches from the test weld.

4.2.2 Data Evaluation—Butt-Weld Specimens

The butt-weld specimens were cycled to leakage under fully reversed, deflection-controlled bending. Specimens were monitored visually for crack initiation every 200 cycles. Specimen HW-14 was also checked ultrasonically. Leakage in both specimens occurred in the transition piece between the test weld and flange, approximately two inches from the weld. The transition piece is used to provide for change in wall thickness from schedule 80 at the test weld to schedule 160 at the flange. At leakage, there were no indications of cracks in the test welds. Testing was terminated at this point since cycling of the welds had far exceeded the ASME code fatigue design criteria. Section III fatigue analysis has been completed and is shown in Figure 4-1 along with all carbon steel, butt-weld data obtained to date.

4.2.3 Elbow Specimens

The elbow specimens tested during the previous report period (CSLS-5, CSLS-7) were sectioned (pulled apart — Figure 4-2) in order to determine the initiation site and final length. Visual examination revealed that the fatigue cracks initiated on the inside wall surface and propagated through wall. These observations are consistent with the strain predictions made earlier; i.e., the highest predicted strain was on the inside surface very near where initiation occurred.

4.2.4 Topical Report

A final topical report covering all of the Task D-3 work not covered in an earlier topical** is in progress. It is expected that the report will be issued during the first quarter of 1973.

***"Low Cycle Fatigue of Prototype Piping," Kiss, E., Heald, J. D., Hale, D. A., GEAP-10135, January 1970.

Figure 4-1. Task D3 Carbon Steel Girth Butt Weld Specimens

a.

b.

Figure 4-2. Elbow Specimen (CSLS-7) After Failure

4.3 TASK D-5—ASME ELASTIC-PLASTIC CODE RULES FOR FATIGUE EVALUATION

(T. L. Gerber, I. R. Coussens)

4.3.1 Objective

The objective of this task is to confirm or improve nuclear piping fatigue design procedures for nominal stress ranges above $3 S_m$. Currently, the effect of constraint at a geometric discontinuity (or stress concentration) and the effect of loading mode are being investigated both analytically and experimentally.

4.3.2 Summary

Load-controlled and deflection-controlled axial fatigue tests of smooth, grooved, and shoulder cylindrical fatigue specimens of Type-304 stainless steel have been completed. Although the grooved and shoulder specimens have equal theoretical stress concentration factors, fatigue life differs significantly at a given cyclic load or deflection. Fatigue specimen local strains were calculated with the CREEP-PLAST elastic-plastic finite element computer code. Correlation of predicted local strain amplitudes with fatigue life shows only moderate agreement with the supposition that local strain amplitude controls crack initiation.

4.3.3 Fatigue Tests

The load-controlled fatigue testing procedure and partial test results were described in Progress Report No. 27.¹ In these load-controlled tests the three fatigue specimen geometries shown in Figure 4-3 were tested. These specimens have a minimum cross-section diameter of one inch. Grooved and shoulder specimens have a theoretical elastic stress concentration factor $K_t = 2$. All specimens were machined from as-received Type-304 stainless steel bar stock. Specimens were cycled in a completely reversed, load-controlled mode. Cycles required for crack initiation and specimen failure were determined.

During the most recent report period, four additional load-controlled tests were conducted. These four tests bring the test total to 18 and complete this type of test with this material. The results of all the load-controlled tests with Type-304 stainless steel specimens are present in Figures 4-4, 4-5, and 4-6. Figure 4-4 shows cycles-to-crack-initiation as a function of the applied nominal stress range, and Figure 4-5 shows cycles-to-specimen-fracture as a function of the same stress parameter. Figure 4-6 presents the initiation data in a different manner. In this figure cycles-to-initiate-a-crack is shown as a function of the fictitious elastic stress amplitude. This stress is generated by multiplying the strain amplitude corresponding to the applied nominal stress amplitude (found from the cyclic stress-strain curve) by the elastic modulus.

The addition of four test points does not change the earlier-reached conclusions, namely, for long lives or low applied cyclic loads, the fatigue strength reduction factor (K_f) for both grooved and shoulder specimens is approximately equal to the theoretical elastic stress concentration factor (K_t); at shorter lives or higher loads, these specimens behave differently; and the K_f of the grooved specimens are lower than K_t , while the K_f of the shoulder specimens are higher than K_t .

Figure 4-3. Fatigue Specimens

Figure 4-4. Cycles to Crack-Initiation as a Function of Nominal Stress Range in Load-Controlled Tests

Figure 4-5. Cycles to Specimen Fracture as a Function of Nominal Stress Range in Load-Controlled Tests

Examination of Figure 4-6 shows that the fictitious elastic stress amplitude for all the load controlled tests exceeded the $3 S_m$ stress *range* limit (60 ksi for stainless steel at room temperature). Code rules² dictate that if reactor components are loaded this high, it is not with an active or primary load but with an imposed deflection, strain, or secondary load. Therefore, to investigate the significance of the loading mode, deflection-controlled tests were run with specimens of the same geometry and material as used in the load-controlled tests. In this case, specimens were cycled between completely reversed fixed *deflection* limits rather than between completely reversed fixed *load* limits.

Deflection was measured (and controlled) over a four-inch gage length. The gage was positioned so that the specimen peak strain would occur at the mid-span of the gage. The three types of specimens were tested at three deflection amplitudes. Duplicates were not run.

As was done in the load-controlled tests, crack initiation was detected by visually examining the specimen surface with a low-power microscope on a periodic basis. In addition, a change in specimen compliance was shown to correspond to crack initiation.¹ Therefore, the load in the deflection-controlled tests was monitored. Use of these two techniques made it possible to detect cracks of surface length from 0.1 to 0.2 inches.

The cycles-to-initiate-a-crack as a function of the imposed deflection range is presented in Figure 4-7. As one might expect, there is considerable difference in fatigue lives among smooth, grooved, and shoulder specimens. For a given deflection range, grooved specimens now have shorter lives than both shoulder or smooth specimens even though grooved and shoulder specimens have equal K_t . In the load-controlled tests the shoulder specimens had the shorter lives.

Another way to present the deflection-controlled test results is to plot the cycles-to-initiate-a-crack as a function of the mid-life nominal stress range (determined from the monitored load range). This plot is shown in Figure 4-8. With this interpretation, shoulder specimens have shorter lives than grooved specimens for a given nominal stress range. This figure is similar, though certainly not identical, to Figure 4-5.

Cycles-to-specimen-failure data were not obtained in the deflection-controlled fatigue tests. Following crack initiation the tensile load falls off rapidly and may drop to zero without the specimen separating. Cycling between fixed deflection limits may then continue for millions of cycles with only a small ligament of material connecting the halves.

4.3.4 Finite Element Analyses of Specimens

Detailed analyses of the grooved and shoulder specimen geometries have been performed using the finite element computer program CREEP-PLAST.* The purpose of these analyses was to compute local strain amplitudes as a function of either an applied cyclic load or deflection. Details of the analysis technique were presented in the 25th and 26th Progress Reports.^{3, 4}

The grid patterns and the results of a preliminary analysis of the Type-304 stainless steel specimens were presented in the 26th Progress Report.⁴ Local strain as a function of applied stress amplitude, load-deflection curves, and the progression of the yield zone from the groove or shoulder area, were described. In addition, the predicted local strains were compared with strains measured with miniature strain gages. In this comparison, agreement was considered poor. Since a discrepancy between prediction and measurement existed even while strains were elastic, the analysis was repeated with a refined elastic modulus (31×10^6 as opposed to 25×10^6 psi). The rerun shoulder analysis showed better agreement for elastic strains but continued poor agreement at higher levels.¹ Further study showed that there was an internal problem with the CREEP-PLAST computer code. This problem was related to the manner in which the code calculated the tangent modulus based on the input stress-strain curve, and it was sensitive to the shape of the input stress-strain curve. This sensitivity explains why the problem was not detected in the analysis of the 2 1/4 Cr 1 Mo specimen reported earlier.³

* CREEP-PLAST is an elastic-plastic finite element code employing the von Mises yield criterion and kinematic hardening. To predict cyclic parameters with an otherwise monotonic analysis, the cyclic stress-strain curve is used to describe material behavior.

Figure 4-6. Cycles to Crack-Initiation as a Function of the Fictitious Elastic Stress Amplitude in Load-Controlled Tests

Figure 4-7. Cycles to Crack-Initiation as a Function of Deflection Range (over 4-inch Gage Length) in Deflection-Controlled Tests

Figure 4.8. Cycles to Crack-Initiation as a Function of Nominal Stress Range in Deflection-Controlled Test

Following correction of the code, analysis of the Type-304 stainless steel fatigue specimens was again repeated. Figure 4-9 shows the input stress-strain curve. The calculated local strains and load-deflection curves for the grooved and shoulder specimens are shown in Figures 4-10 through 4-13. Also shown in these figures are the experimentally measured local strains and deflections for specimens which were multiple-step tested (procedure used for generating the cyclic stress-strain curve), and the mid-life strains, measured during fatigue tests, for the few cases where strain gages survived to mid-life.

Correction of the CREEP-PLAST Code has improved agreement between predicted and measured local strains. Even though predicted strains are averaged over a distance equal to the gage length of the strain gage, predicted strains are slightly higher than measured. This is particularly true for the shoulder specimen. For this specimen, part of the discrepancy may be due to difficulty in bonding the strain gage directly at the location of predicted peak strain (on the shoulder radius, 17° from tangent point with minimum section).

In Figure 4-14 are plotted the cycles-to-initiate-a-crack as a function of the predicted local axial-strain amplitude times the elastic modulus for both the load-controlled and deflection-controlled tests. All test results are shown except those of the highest load and highest deflection tests of the shoulder specimens. The computer solution was not carried far enough to predict local strains for these tests. If local alternating strains were controlling crack initiation, one would expect all data to fall on a single line which would be near the ASME code criteria curve. This is not the case. The discrepancy is possibly due to poor predictions of local strains, data scatter, or, more fundamentally, the inadequacy of the assumption of local strain-amplitude, controlled-crack initiation. Following completion of the carbon steel fatigue tests with specimens of the same geometry, other correlations will be attempted.

Figures 4-15 through 4-19 show the inputs stress-strain curve, plus predicted local strains and load deflections for carbon steel specimens. Neither multiple-step tests nor fatigue tests with the carbon steel specimens have been run to date.

4.3.5 References for Section 4.3

1. Progress Report No. 27, GEAP-10207-27 (April-June 1972)
2. ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components, American Society of Mechanical Engineers, New York 1971
3. Progress Report No. 25, GEAP-10207-25 (July-September 1971)
4. Progress Report No. 26, GEAP-10207-26 (October 1971-March 1972)
5. Criteria of Section III of the ASME Boiler and Pressure Vessel Code for Nuclear Vessels, American Society of Mechanical Engineers, New York, 1964

Figure 4-9. Cyclic Stress-Strain Curves for Type-304 Stainless Steel

Figure 4-10. Average Net-Section Stress Amplitude (ksi), Notch Root Strains, Stainless Steel Grooved Specimen

Figure 4-11. Displacement Amplitude over 4-inch Gage Length (mils), Stress versus Displacement, Stainless Grooved Specimen

Figure 4-12. Average Net-Section Stress Amplitude (ksi), Surface Strains, Stainless Shouldered Specimen

Figure 4-13. Displacement Amplitude over 4-inch Gage Length (mils), Stress versus Displacement, Stainless Shouldered Specimen

Figure 4-14. Cycles to Crack Initiation as a Function of the Local Predicted Strain Amplitude

Figure 4-15. Cyclic Stress-Strain Curves for A212 Grade B Carbon Steel

Figure 4-16. Average Net-Section Stress Amplitude (ksi), Surface Strains, Carbon Shouldered Specimen

Figure 4-17. Displacement Amplitude over 4-inch Gage Length (mils), Stress versus Displacement, Carbon Shouldered Specimen

Figure 4-18. Average Net-Section Stress Amplitude (ksi), Notch Root Strains, Carbon Steel Grooved Specimen

Figure 4-19. Displacement Amplitude over 4-inch Gage Length (mils), Stress versus Displacement, Carbon Steel Grooved Specimen

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

5.1 OBJECTIVE

The objective of Task K is to quantitatively determine the effect of the BWR primary coolant on the low-cycle fatigue performance of piping steels. Measurements of cycles to failure have been obtained by employing a specially designed fatigue testing unit in an experimental piping loop at the Dresden 1 boiling water reactor.

5.2 SUMMARY

The Dresden 1 test loop has accumulated over 5200 hours of operation at test conditions (510°F, 1040 psig). A total of 90 of the 149 fatigue specimens being cyclically loaded in the loop have signalled failure. These include 41 of 71 Type-304 stainless steel specimens, 17 of 28 Type-304L stainless steel specimens, 5 of 23 Inconel-600 specimens, and all of the 27 A-516 carbon steel specimens. Pertinent loop operating parameters are summarized in Table 5-1.

Testing of the first material group of fatigue specimens cycled at 500°F, in the Air Test Facility in San Jose has been completed. These data have been compared with ASME Section III design criteria and comparable data from the Dresden 1 test loop. Preparations have begun for the next group of materials to be fatigued in air in order for them to establish the baseline air data.

Preliminary metallographic and SEM examination of selected fatigue specimens removed from the Dresden 1 test loop is complete. Results are given in Appendix A.

Procurement and delivery of the hardware for the third test vessel to be added to the Dresden 1 test loop has been completed. Fatigue testing in air of the 2T-WOL specimens, which will be evaluated in the third test vessel, has begun.

5.3 DRESDEN TEST LOOP

5.3.1 Instrument Fitting Steam Leakage

In mid-July at the request of Commonwealth Edison Company (CECO), the test loop was shut down because of high airborne activity signalled by the test cubicle monitor. This high airborne activity was found to be a result of steam leakage past the threaded instrument fittings on the fatigue test vessel head. After careful evaluation of several alternate approaches for the permanent elimination of this problem, it was decided to seal weld the fittings to the test vessel head. To minimize exposure of personnel during the seal welding, the head and fatigue jig were removed from the test vessel and supported in a special stand which was then shielded with lead bricks.

To demonstrate the suitability of the proposed seal weld and associated cleaning and inspection procedures, a mockup was fabricated using identical instrument fittings, and test vessel materials. Two mockup welds, made by the same welders who later made the actual seal welds, were sectioned and examined metallographically to determine depth of penetration and overall weld quality. Although these mockup welds proved to be successful, additional weld passes were made around the instrument fittings to ensure elimination of this leakage problem.

In early December, the seal weld repairs were completed and the loop was returned to operation where it has been operating normally.

5.3.2 Fatigue Specimen Examination

Prior to reassembly of the test vessel, the fatigue test jig was examined to determine if any of the fatigue specimens which had signalled failure prior to the leakage shutdown, were cracked sufficiently to allow removal. Seven specimen tips were found, removed, and shipped to GE's Vallecitos Nuclear Center for decontamination and

**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			
1970	I	Sept. 16	Oct. 2	17 days	0	1900	23	Loop shutdown in antici- pation of scheduled plant maintenance outage
	II	Oct. 22	Nov. 5	32 days	1901	3250	18	Loop shutdown in antici- pation of scheduled plant maintenance outage
	III	Nov. 25	Dec. 31	69 days	3251	6494	18	Loop shutdown to repair leaking fitting
1971	IV	Jan. 7	Jan. 14	76 days	6495	7174	2	Loop secured after reactor scram
	V	Jan. 27	Feb. 3	84 days	7175	7891	5	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
1972	IX	March 24	April 14	171 days	14156	16258	3	Loop secured after reactor scram
	X	May 10	May 12	173 days	16259	16516	0	Loop secured for plant shutdown
	XI	May 25	May 26	173 days	16517	16564	0	Loop shutdown to repair leaking fitting
	XII	June 16	July 10	198 days	16565	18833	4	Loop shutdown to sealweld leaking fittings
	XIII	Dec. 8	—	> 218 days	18834		4	Loop still operating on Dec. 27

preparation for future metallographic examination. This brings the total number of failed specimens removed to 77 (out of 89 having signalled failure).

5.3.3 Fatigue Test Results

One hundred forty-nine fatigue specimens (Figure 5-1), representing four material groups, thirty-one metallurgical test conditions, and two specimen loading schemes, are included in the Task K fatigue test program. The test plan (Table 5-3) was designed to allocate the fatigue specimen positions among the selected test conditions to maximize chances of detecting significant differences in cyclic fatigue life which would relate to the specific material conditions and influence of the environment.

Four additional fatigue specimen failure indications have been received since the resumption of normal loop operation in December, bringing the total number received to date to 90. Pertinent test parameters for the 4 specimens are summarized in Table 5-2. Data from the other 86 specimens were previously published in GEAP-10207-26 & -27.

The cycles-to-failure data for the 90 failure indications received to date are compared with ASME Section III fatigue design data in Figures 5-2 through 5-5. The upper line in Figures 5-2, 5-3, and 5-5 represents a best fit of the ASME failure data; the upper line in Figure 5-4 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 5-2 through 5-5 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., $N_{\text{design}} = 1/20 N_{\text{data}}$).

5.3.4 Metallurgical Effects

5.3.4.1 Type-304 Stainless Steel

A total of 71 Type-304 stainless steel specimens are under test in the Dresden dynamic test vessel. To date, failure indications have been received from 41 of them. Detailed statistical analyses of these data will be deferred until data from the surviving 30 Type-304 specimens become available. The preliminary trends noted in Quarterly No. 25 remain valid and are reproduced here for convenience.

- 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.

5.3.4.2 Type-304L Stainless Steel

To date, 17 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 eight failures were divided among three material test conditions:

- Three as-received specimens: two tested at the 1.0% strain range and one at the 0.5% strain range
- Two welded**** specimens tested at the 1.0% strain range
- Three cold-worked specimens: two tested at the 1.0% strain range and one at the 0.75% strain range

* Snow, Langer, and Gibbons, WAPD-T-2083, September 1967.

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

*** See Table 5-3.

**** Welded specimens refer to HAZ condition to evaluate weld sensitization.

Figure 5-1. Dynamic Test Specimen

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

Specimen Number	Cycles to Failure	Material	Shakedown Surface Strain Range ^(a) (%)	Loading Mode ^(b)	Test Condition Code ^(c)	Description
1133	19187	Type-304 L SS	0.75%	C-T	16	As Received + Heavy Cold Work
1106	19309	Type-304 SS	1.0%	C-T	4	Welded, Machined
195	20623	Type-304 SS	0.75%	C-T	1	As Received
100	20665	Inconel	1.0%	C-T	23	As Received, Furnace Sensitized

Total Failure indications received to date: 90 (41 304SS, 17 304L SS, 5 Inconel, 27 Carbon Steel)

(a) Based on room temperature strain-deflection calibration curves.

(b) C-T = Compression-Tension; O-T = Zero-to-Tension Loading.

(c) Reference: Table 5-3.

5.3.4.3 Inconel-600

One additional Inconel failure indication was received during the report period, bringing the total number of failure signals received to date to 5 out of 23 specimens under test. These five specimens represent three test conditions:

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

5.3.4.4 Carbon Steel

All 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. The results have been reproduced in Figure 5-5 for convenience.

5.4 METALLURGICAL EVALUATION

Metallurgical examination of a number of fatigue specimens removed from the Dresden 1 test vessel has been completed. This included metallography and scanning electron microscopy (SEM). The specimens were in metallurgical conditions reported in Subsection 5.3.4 and included:

- a. Type-304 stainless steel — Annealed and furnace-sensitized, and welded.
- b. Type-304L stainless steel — Same as a., plus surface cold-worked.
- c. Inconel-600 — Welded.
- d. Carbon steel — As-machined, welded, with and without stress relief anneal heat treatment.

Table 5-3
TASK K FATIGUE SPECIMEN LAYOUT

Test Condition Number	1	2	3	4	5	6(a)	7(b)	8	9	10	10A	11	12	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Material																														
Type-304 Stainless Steel	x	x	x	x	x	x	x	x	x	x	x	x	x																	
Type-304L Stainless Steel														x	x	x	x	x	x											
Inconel-600																				x	x	x	x	x		x	x	x	x	
Carbon Steel																									x	x	x	x	x	
Material Condition																														
Material Condition Code	1	8	3	4	5	2	2	1	5	1	5	1	5	1	8	4	5	1	5	1	4	5	1	5	2	6	4	7	6	
Welded—Low Heat (Normal)				x												x					x						x	x		
Welded—High Heat (Block)			x																											
Machined	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Surface Cold Work		x													x										x	x	x	x	x	
Solution Annealed	x				x			x	x	x	x	x	x	x			x	x	x	x		x	x	x						
Pickled	x				x			x	x	x	x	x	x	x			x	x	x	x		x	x	x						
Sensitized (c)					x				x		x		x				x	x	x	x			x	x						
Stress-Relieved																										x		x	x	
Simulated Crack Preparation																														
Mechanical								x	x										x	x										
Chemical										x	x												x	x					x	
Number of Specimens Loading																														
OT(d) (Initial Surface Strain Range)																														
0.5%												2	2																	
												•	•																	
												•	•																	
0.75%												2	2																	
												•	•																	
												•	•																	
CT(d) (Initial Surface Strain Range)																														
0.5%	5	2	2	2	5	2	2	2	2	2	2			4	2	2	4	2	2	4	2	4	2	2	4	2	2	2	2	
	•	•	•	•	*	•	•	•	•	•	•			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
	•	•	•	•	*	•	•	•	•	•	•			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
	•				•									•			•			•		•	•	•	•					
	•				•									•			•			•		•	•	•	•					
	•				•									•			•			•		•	•	•	•					
0.75%	3	2	2	2	3	2	2							1	1	1	1			1	1	1			1	1	1	2		
	•	•	•	•	•	•	•							•	•	•	•			•	•	•			•	•	•	•	•	
	•	•	•	•	•	•	•							•	•	•	•			•	•	•			•	•	•	•	•	
	•	•	•	•	•	•	•							•	•	•	•			•	•	•			•	•	•	•	•	
1.0%	4	2	2	2	5	2	2							2	2	2	2			2	2	2			4	2	2	2		
	•	•	•	•	•	•	•							•	•	•	•			•	•	•			•	•	•	•	•	
	•	•	•	•	•	•	•							•	•	•	•			•	•	•			•	•	•	•	•	
	•				•									•			•			•		•	•	•	•					
	•				•									•			•			•		•	•	•	•					
Subtotal	12	6	6	6	13	6	6	2	2	2	2	4	4	7	5	5	7	2	2	7	5	7	2	2	9	5	5	6	2	
Total																														
Type-304 Stainless Steel — 71														Type-304L Stainless Steel — 28					Inconel-600 — 23					Carbon Steel — 27						

NOTES:

(a) Equalizer line base material—8-year service pipe

(b) Equalizer line weld material—8-year service weld

(c) Equivalent to furnace sensitization

(d) OT = Zero to-tension loading
CT = Compression to tension loading

○ Denotes unfailed specimen

● Denotes specimen failure

149

NOTES:

- (a) Equalizer line base material—8-year service pipe
- (b) Equalizer line weld material—8-year service weld
- (c) Equivalent to furnace sensitization
- (d) OT = Zero to-tension loading
CT = Compression to tension loading
- Denotes unfailed specimen
- Denotes specimen failure

*Specimen tips removed 11/71 with no previous failure indication signal received

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

Figure 5-3. Equivalent Stress Amplitude (psi) versus Cycles to Failure for Type-304L Stainless Steel

Figure 5-4. Equivalent Stress Amplitude (psi) versus Cycles to Failure for Inconel-600

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

A description of the various metallurgical conditions for the total program is given in Table 5-3. These were chosen to simulate as near as practical the various metallurgical conditions of as-installed piping. In this regard two comments need be made. First, the term welded does not imply "weldment" but refers to the HAZ metallurgical degree of sensitization. Secondly, cold-work specimen refers to the material conditions produced by "plunge" grinding where an attempt was made to simulate the cold work associated with hand grinding in the field.

It follows then, that postmortem metallurgical evaluation provides the opportunity to relate the macroscopic engineering fatigue data to the microscopic metallurgical condition. Only in this way is it possible to provide understanding of factors which significantly influence the accelerating effects of the environment.

Figures 5-6 through 5-11 are photographs of the fatigue specimen tips and the corresponding fracture surface. A detailed discussion of the metallurgical examination completed to date is given in Appendix A; however, some comments relative to the trends reported in paragraphs 5.3.4.1 through 5.3.4.4 (metallurgical effects) will be made here.

a. **Type-304 Stainless Steel**

In the as-received (annealed) condition, very little influence of environment on fatigue has been observed. This is consistent with the transgranular fracture mode observed for this condition in both 500°F air and the D-1 water environment. In contrast to this, for the furnace-sensitized condition there is a significant effect of the water environment. In this case the fracture was mixed mode, i.e. intergranular and transgranular. An interesting observation can be made by comparing the fracture appearance of the as-received and furnace-sensitized fracture surface. Note the spongy appearance of the sensitized material at both the 1% and 0.5% strain-range levels.

b. **Type-304L Stainless Steel**

Similar comments apply to the Type-304L stainless steel specimens as to the Type-304 stainless steel specimens in the as-received and furnace-sensitized conditions. One additional factor must be emphasized here with respect to the weld data. Examination of one-weld specimen has revealed that the fracture surface was removed from the weld HAZ. Thus, these data are essentially for the base (i.e., as-received) material. It is therefore planned to examine each of the weld specimens in order to establish the fracture material conditions.

c. **Inconel-600**

The fatigue performance of the Inconel-600 specimens has been excellent since data obtained and cycles accumulated to date have exceeded the ASME data criteria.

d. **Carbon Steel**

The carbon steel data obtained at Dresden 1 shows a consistent effect of environment. Statistical evaluation of the data is given in Appendix B. Observation of the failed specimens showed substantial surface pitting, and cracks are seen to have originated within these surface pits. Therefore, it appears that the occurrence of surface pitting was a significant factor in the crack initiation and subsequent failure of the carbon steel specimens.

5.5 500°F BASELINE AIR TESTS

Efforts continue to generate the 500°F baseline air data needed for comparison with the Dresden 1 BWR data. A smaller (in terms of the number of fatigue specimens which can be tested at one time) version of the D-1 fatigue test machine is being used. Twelve of the Task K fatigue specimens are cycled in the same manner as their D-1 counterparts except that the environment used is 500°F air at ambient pressure.

Figure 5-6. Carbon Steel 1%E

Figure 5-7. Inconel 600 1%E

Figure 5-8. As Received 304 1%E

Figure 5-9. Furnace Sensitized 304 1%E

Figure 5-10. Furnace Sensitized 304 .5%E

Figure 5-11. 304L Weld Sensitized 1%E

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 the internal cavity is used to define, and automatically signal, specimen failure.

5.5.1 Test Results

Testing of the first series of 12 specimens in air has been concluded. Pertinent test information is summarized in Table 5-4. These data are shown compared with data from the Dresden 1 BWR specimens in Figures 5-12, 5-13, and 5-14.

5.5.2 500°F Strain-Deflection Data

A second group of 12 fatigue specimens has been instrumented with high temperature, miniature strain gages in preparation for the air testing at 500°F. Attempts will be made to determine at 500°F, the equilibrium shakedown strains developed in these specimens when subjected to the cyclic deflections presently being imposed. At this time strain range predictions for the D-1 specimens are based on cycle strain-deflection characteristics determined at room temperature. Pertinent test and material conditions for the next baseline air test are given in Table 5-5.

Table 5-4
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	±0.094 ^a	8	9,626
202	Type 304 SS, As Received	±0.094 ^a	8	8,679
194	Type 304 SS, As Received	±0.078 ^b	8	15,159
204	Type 304 SS, As Received	±0.078 ^b	8	15,191
118	Inconel, As Received	±0.100 ^a	8	15,757
120	Inconel, As Received	±0.100 ^a	8	20,589
121	Inconel, As Received	±0.089 ^b	8	33,339
123	Inconel, As Received	±0.089 ^b	8	26,428
1044	A516 Carbon Steel, As Machined	±0.086 ^a	8	13,300
1046	A516 Carbon Steel, As Machined	±0.086 ^a	8	10,327
1045	A516 Carbon Steel, As Machined	±0.076 ^b	8	23,789
1047	A516 Carbon Steel, As Machined	±0.076 ^b	8	28,758

^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 5-12. Equivalent Stress Amplitude versus Cycles to Failure for Type-304 Stainless Steel.
Comparison of fatigue data from BWR environment with 500°F air baseline case.

Figure 5-13. Equivalent Stress Amplitude (psi) versus Cycle to Failure for Inconel 600.
Comparison of fatigue data from BWR environment with 500°F air baseline case.

Figure 5-14. Equivalent Stress Amplitude versus Cycles to Failure for A516 Carbon Steel.
Comparison of fatigue data from BWR environment with 500°F air baseline case.

Table 5-5
FATIGUE SPECIMEN TEST PLAN
SERIES IV BASELINE "AIR" TESTS

Specimen Number	Material	TIP Deflections (inches)	Testing Rate (cph)
141	Type 304 SS, As Received	$\pm 0.094^{(a)}$	8
145	Type 304 SS, As Received	$\pm 0.094^{(a)}$	8
164	Type 304 SS, As Received	$+0.156^{(a)}$ $-0.000^{(c)}$	8
169	Type 304 SS, As Received	$\pm 0.078^{(b)}$	8
1	Type 304L SS, As Received	$\pm 0.094^{(a)}$	0
1068	Type 304L SS, As Received	$\pm 0.078^{(b)}$	8
125	Inconel 600, As Received	$\pm 0.100^{(a)}$	8
127	Inconel 600, As Received	$\pm 0.089^{(b)}$	8
55	A-516 Carbon Steel, As Machined	$\pm 0.086^{(a)}$	8
1016	A-516 Carbon Steel, As Machined	$\pm 0.086^{(a)}$	8
1043	A-516 Carbon Steel, As Machined	$\pm 0.076^{(b)}$	8
1014	A-516 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 (fully reversed).

(b) Corresponds to 0.75% peak-to-peak strain range based on room temperature strain-deflection curves (fully reversed).

(c) Same as b except zero-tension.

5.6 THIRD TEST VESSEL (D-1 TEST LOOP)—CRACK GROWTH INVESTIGATION

Preparations for adding a third test vessel to the existing D-1 test loop continue. This vessel will be used to obtain crack growth information for materials of interest in the BWR environment under loading conditions. These data will complement the crack initiation data already being generated in the dynamic test vessel. A system schematic for this vessel is shown in Figure 5-15.

5.6.1 Specimen Preparation

Four lots of certified plate stock (Types-304 and 304L stainless steel, Inconel-600, A-516 carbon steel) were previously purchased and characterized in Table 5-7 of Quarterly No. 26. A total of 24 2T-WOL specimens (Figure 5-16) have been machined from this plate.

Figure 5-15. Test Vessel III Test Scheme

NOTES

1. 0.007" MAX. RADIUS (EDM).
2. LAY MARKS TO FALL PARALLEL TO AXIS OF RADIUS SURFACE FINISH TO BE 32/.

Figure 5-16. 2T-WOL Specimen for Crack Growth Rate Study; of Task K_C

5.6.2 Hardware Procurement

The test vessel, internal load fixtures, transducers, and associated signal conditioning and recorders have been received. In addition, the seven channels of special hi-temperature/hi-pressure canned LVDTs*, which will be used to monitor the in-situ CODs** for each individual specimen, have been received.

Preparations are underway to install the third test vessel in a GE-owned test loop in order to circulate simulated BWR water (i.e., demineralized water @ 1000 psig & 500°F) for shakedown testing. Fairly extensive shakedown testing is planned prior to installation in D-1 in order to ensure the long term reliability of the hydraulic loading system and specimen COD monitoring system.

5.6.3 2T-WOL Compliance Calibration

A Type-304 stainless steel, 2T-WOL specimen in the as-received condition is presently undergoing fatigue testing in air (Figure 5-17). The parameters are summarized in Table 5-6. The objectives of this test are two fold. First, it is necessary to generate baseline compliance/crack length information for each type of material at the test load. Secondly, these tests will verify that the mechanical hardware (i.e., fixtures, LVDT-COD transducers, etc.) are functioning properly and provide the basis for proper test procedures. This type of test will necessarily be extended to include 500°F, air baseline evaluation.

Figure 5-17. 2T-WOL Under Test

* Linear Variable Differential Transformer

** Crack Opening Displacement

Table 5-6
2T-WOL TEST PARAMETERS

Test temperature	room temperature
Test environment	ambient air
Test frequency	20 cpm
Max/Min load	+14.35 KIP / +0.35 KIP (tension - tension)
Material	Type 304 stainless steel, "as received" plate

APPENDIX A

METALLURGICAL EXAMINATION TASK K FATIGUE SPECIMENS

(J. C. Danko, A. J. Giannuzzi)

SUMMARY

This section describes the metallurgical evaluation of the fatigue specimens of Types-304 and -304L stainless steel, Inconel-600 and A-516 carbon steel tested under Task K. Specimens examined include Types-304 and -304L stainless steel in the as-annealed, furnace-sensitized, surface-cold-worked and as-welded condition, two welded specimens of Inconel-600, and specimens of A-516 carbon steel in the welded plus stress relief, welded without stress relief, and as-machined with and without stress relief condition. All specimens had been tested to failure exposed to the D-1 primary reactor water environment. The scanning electron microscope and optical metallography were used to examine the fracture surface and identify the mode of failure of the specimens. The results obtained to date are as follows:

1. The as-machined Types-304 and -304L stainless steel failed in a transcrystalline manner.
2. The furnace-sensitized and the as-welded Types-304 and -304L stainless steel failed in a mixed mode; i.e., partially transgranular and partially intergranular.
3. The failure mode for the welded Inconel-600 specimens was mixed, both intergranular and transgranular.
4. The A-516 carbon showed evidence of pitting and was very heavily oxidized. The failure mode for this material was transgranular.
5. In two cases, specifically for the as-machined and furnace-sensitized, Type-304 stainless steel SEM revealed striations on the fracture surface. Preliminary measurements of the striation spacing provide an assessment of the crack growth rates which were of the order of 10^{-4} to 10^{-5} inches/cycles for both material conditions at the 1% strain range.

The SEM investigation for the first batch of specimens is complete and is reported here. The optical metallography is continuing.

INTRODUCTION

Specimens of Types-304 and -304L stainless steel, Inconel-600, and A-516 carbon steel which had been tested under low-cycle fatigue conditions in the Dresden 1 reactor have been metallurgically examined. The scanning electron microscope (SEM) and optical metallography are being utilized to assist in the evaluation of the mode of failure and the fracture appearance of these specimens. SEM fractography and optical micrographs have been obtained on specimens of Types-304 and -304L stainless steel in the as-annealed, furnace-sensitized, cold-worked, and as-welded condition; on two Inconel-600 in the as-welded condition; and on A-516 carbon steel in the as-machined and in the as-welded condition, both with and without stress relief.

SCANNING ELECTRON MICROSCOPE RESULTS

A. Types-304 and -304L Stainless Steel

SEM micrographs have been taken on fifteen specimens of Types-304 and -304L stainless steel. In addition, SEM micrographs were taken on a Type-304 stainless steel specimen air tested at 500°F to provide baseline fractography. The Dresden 1 specimens had been prepared for test by receiving the heat treatment described below.

1. Specimen Preparation

The Types-304 and -304L stainless steel specimens were tested in D-1 in one of the following conditions.

- a. Flash anneal—All Types-304 and -304L stainless steel specimens (except the welded specimens) were subjected to a flash anneal prior to test. The flash anneal consisted of a heat treatment at 1800°F in air for 5 to 10 minutes, water quench, and pickle with an HC1-HF etchant.
- b. Furnace sensitization—The furnace sensitization heat treatment consisted of condition a. (above), then holding at 1150°F for 24 hours in air followed by furnace cool. No additional pickling was permitted following furnace sensitization.
- c. Cold worked—A flash annealed and pickled Type-304L specimen was plunge ground following heat treatment to introduce cold work on the surface.
- d. Welded—No flash anneal or pickle preceded the welding of the Types-304 or -304L stainless steel. All welds were produced by a combination of gas tungsten arc weld (GTAW) and shielded metal arc weld (SMAW) processes.

2. SEM Surface Observations

Figure 1 is a SEM view of a typical Type-304 stainless steel surface following test in D-1. Widespread grain boundary attack is in evidence. Based on the results of stress-corrosion cracking in this laboratory, the surface appearance was unusual. Therefore, the origin of this deep grain boundary penetration was investigated. A spare specimen of Type-304 stainless steel which had been used in an air strain gage calibration test was examined metallographically. This specimen (Figure 2) shows a surface condition similar to that seen in Figure 1. Another specimen which had not undergone the flash anneal and pickle was sectioned. One half was subjected to the heat treatment and pickle given the Dresden fatigue specimens while the other half was retained in the as-received condition. The annealed and pickled section showed grain boundary channeling similar to that which is evident in Figures 1 and 2 but the as-received section showed no attack. The origin of the grain boundary channelling, observed in all Types-304 and -304L stainless steel specimens, except the cold-worked Type-304 stainless steel specimen is the result of specimen pickling. Figure 1 also shows general surface corrosion and continued corrosion in the grain boundaries. The surface of the cold worked Type-304 stainless steel specimen is shown in Figure 3. This specimen was plunge ground following pickling. No channeling or grain boundary attack can be seen. The surface is heavily oxidized, and localized removal of the oxide has occurred as shown in Figure 3. The oxide thickness calculated from the optical micrograph shown in Figure 4, is approximately 6×10^{-4} inches.

3. SEM Fractography

a. Flash Annealed Type-304 Stainless Steel

Figure 5 shows the fracture appearance of Type-304 stainless steel in flash annealed condition. The general roughness of the fracture surface is related to a region of very fine grains (ASTM grain size 7-8). This region has recrystallized as a result of cold work prior to heat treatment. The mode of failure for this specimen, typical of all the flash annealed Types-304 and -304L stainless steel, is transcrystalline with typical river pattern associated with transcrystalline fatigue. Figures 6 and 7 show fatigue striations which were in evidence on the fracture surface. As shown in these figures, the crack growth rate in these specimens was far from constant. The approximate crack growth rates, as measured from Figure 6, is 2×10^{-5} inches/cycle and from Figure 7, 1×10^{-4} inches/cycle. The corrosion film partially concealed the fatigue striations on the fracture surface. Figures 6 and 7 show the octahedral oxide crystals on the fracture surface near the striations. The fracture surface of the air tested specimen of Type-304 stainless steel is shown in Figure 8. The failure is transcrystalline and

Figure A-1. SEM Micrographic of Machined Surface of as Received 304SS (300X). Specimen #S-201 (30-80) (30-81)

Figure A-2. Optical Micrograph of Machined Surface of Air Tested Calibration Specimen of 304SS (160X)

Figure A-3. Cold Worked Surface of 304L SS (300X). Specimen #1135 (30-21)

*Figure A-4. Optical Micrograph of Thick Oxide on Surface of Cold Worked 304L SS Specimen (500X)
Specimen #1135 (2SE-11-7)*

Figure A-5. Fracture Surface of as Received 304SS (100X). Specimen #177 (35-69)

Figure A-6. Fatigue Striations on Fracture Surface of as Received 304SS (100X). Specimen #S-201 (31-12)

Figure A-7. Fatigue Striations on Fracture Surface of as Received 304SS (1000X). Specimen #201 (30-78)

Figure A-8. Fracture Surface of Air Tested 304SS Specimen (100X). (30-11)

fatigue striations are evident on the fracture surface even at a magnification of 100 X. As shown in Figure 9, a variation in striation spacing is observed in a localized area. The calculated crack growth rates vary from approximately 3×10^{-5} inches/cycle at the bottom of the micrograph to 1×10^{-4} inches/cycle near the center. The fracture surface of this air tested specimen is free of the corrosion produce which covered the Type-304 stainless steel specimens exposed to the Dresden environment.

b. Furnace Sensitized Type-304 Stainless Steel

The fracture appearance of three furnace-sensitized Type-304 stainless steel specimens is illustrated in Figures 10, 11 and 12. In Figures 10 and 11 the cold-worked, recrystallized surface can be seen. In Figure 10 the failure mode appears to be intergranular because the typical "rock candy" fracture appearance associated with intergranular cracking is evident. In Figure 11, the failure mode appears mixed; near the surface the cracking appears to be intergranular, but in the interior the failure mode appears transcrystalline. In Figure 12, however, a mixed mode of the fracture is observed for the furnace-sensitized Type-304 stainless steel. An intergranular region appears to be bordered by transgranular regions of fracture. Typical fatigue striations for the furnace-sensitized specimens are shown in Figure 13. The striation spacing yields calculated crack-growth rates of 0.5×10^{-4} inches/cycle.

c. Welded Type-304 Stainless Steel

The SEM fracture appearance of the as-welded Types-304 and -304L stainless steel specimens is given in Figures 14 and 15. The fracture surface in Figure 14 is similar to that observed for furnace-sensitized Type-304 stainless steel. The mode of crack propagation near the surface (which in this

Figure A-9. Fatigue Striations on Air Tested 304SS Specimen (300X). (30-09)

Figure A-10. Fracture Surface of Furnace Sensitized 304SS (100X). Specimen #180 (34-48)

Figure A-11. Fracture Surface of Furnace Sensitized 304SS (100X). Specimen #166 (30-63)

Figure A-12. Fracture Surface of Furnace Sensitized 304SS (50X). Specimen #179 (29-83)

Figure A-13. Fatigue Striations on Furnace Sensitized 304SS Specimen (1000X). Specimen #179 (29-82)

Figure A-14. Fracture Surface of as Welded 304SS (50X). Specimen #1144 (35-72)

case does not appear to be recrystallized) is intergranular while the interior appears transgranular. The failure mode for the specimen shown in Figure 15 is transgranular. Subsequent metallography revealed that the weld and heat-affected zones were well removed from the fracture surface. On the basis of this observation, fatigue data from this specimen should be treated as representative of the flash annealed, or as-received, condition.

B. Inconel-600

1. Welded Inconel-600

Two as-welded specimens of Inconel-600 have been examined by SEM. The welds were produced by combining GTAW and SMAW processes. Figures 16 and 17 show typical SEM areas of the fractured surfaces. In Figure 16 the failure mode appears to be intergranular whereas the fracture surface shown in Figure 17 shows a transgranular failure mode. Some surface cracking and corrosion products were present on the surface as shown in Figure 18. Figure 19 shows the fatigue striations observed on the fracture surface; the crack growth rate calculated from these striation measurements is 0.5×10^{-4} inches/cycle. Initial metallography indicates that the fracture surface was located within the weld HAZ.

C. A-516 Carbon Steel

The A-516 carbon steel specimens examined showed a heavy corrosion product on the surface (Figure 20). Figures 21 and 22 show the surface of one of the carbon steel specimens where substantial pitting is evident. In Figure 22 surface cracks are observed which appear to originate in the centers of the pits. The pits, therefore, may provide nucleation sites for fatigue cracks. No analysis of failure mode or striation measurement was possible due to the oxide thickness. However, optical metallography of one of the A-516 carbon steel specimens has indicated that the failure mode is totally transcrystalline.

Figure A-15. Fracture Surface of As Welded 304L SS (200X). Specimen No. 1076 (29-98)

Figure A-16. Fracture Surface of as Welded Inconel 600 (300X). Specimen #1028 (38-25)

Figure A-17. Fracture Surface of as Welded Inconel 600 (300X). Specimen #1028 (38-27)

Figure A-18. Machined Surface of as Welded Inconel 600 (300X). Specimen #1042 (30-23)

Figure A-19. Fatigue Striations on as Welded Inconel 600 (1000X). Specimen #1028 (38-28)

Figure A-20. Oxide Crystals on Fracture Surface of A516 Carbon Steel. (1000X). Specimen #48 (34-57)

Figure A-21. Pits on Machined Surface of A516 Carbon Steel (50X). Specimen #1060 (29-67)

Figure A-22. Surface Cracks Through pits on Surface of A516 Carbon Steel (100X). Specimen #1060 (29-66)

APPENDIX B

**STATISTICAL ANALYSIS COMPARING TASK K LOW CYCLE FATIGUE DATA
IN AIR AND IN BWR WATER
(S. A. Wilson)**

B.1 INTRODUCTION

The principal objective of Task K is to determine the effect on the low cycle fatigue life of materials typically used for nuclear piping due to the environment of an operating BWR. The materials being tested are carbon steel, stainless steel, and Inconel. A unique, leaf-shaped specimen, suitable for reversed loading in bending, was designed for this purpose. So that the change in fatigue life, if any, would represent only the effect of changing the environment from air to BWR water, testing was done on the leaf-shaped specimens, both in BWR water and in air at the same temperature, 500°F. Similar low cyclic rates, four cycles/hour in BWR water and eight cycles/hour in air, and a trapezoidal wave shape, were used.

For this evaluation, data obtained from material in the as-received condition tested in air were compared to data from material in the same condition tested in BWR water. These conditions are briefly described in Table 5-3; they are Material Condition Code 1 for stainless steel and Inconel and Material Condition Code 2 for carbon steel. Data compared were obtained under compression-tension cycling, with the air tests conducted at strain ranges of 1.0% and 0.75% and BWR water tests at 1.0%, 0.75% and 0.5%.

Initial results are on hand. They show a reduction in cyclic life in BWR water for carbon steel and *none* at this time for stainless steel or Inconel. Data are listed in Table B-1, are plotted in Figures 5-6 through 5-8, and are analyzed by material in the following paragraphs.

B.2 A-516 CARBON STEEL (AS MACHINED)

Data for this material are plotted in Figure 5-8. Inspection of this figure suggests that the failure data in air and in BWR water should be fitted with straight lines having the same slope, and that the data used should be at the two-strain ranges in air but should include all three strain ranges in BWR water. Note that the slope is nearly the same as the best fit line of the published ASME data, which also appears in Figure 5-8.

There is a constant difference between the two lines on log cycles scale which (by taking the antilog of that difference) gives a fatigue life reduction factor (FLRF) having the same value over at least the range of strain ranges tested.

Fitting the data by the least squares method with lines of the same slope resulted in the following equations:

$$\begin{array}{ll} \text{BWR water:} & y_2 = 5.4836 - 1.4175x \\ \text{Air:} & y_1 = 4.4928 - 1.4175x \end{array}$$

$$\text{Fatigue Life Difference (FLD)} = 0.9908$$

$$\begin{array}{ll} \text{where } y &= \log_{10} \text{ cycles to fail} \\ x &= \text{strain range, percent} \end{array}$$

From these equations, the difference in intercepts, designated fatigue life difference (FLD), is 0.9908. Taking the antilog, a factor of 9.79 is obtained as an estimate of the mean FLRF for this material in the BWR water environment.

Thus, statistical evaluation of the data obtained to date shows that, on the average, a carbon steel specimen is predicted to fail in BWR water in 1/9.79 times as many cycles as in air at the same temperature. As intended by the design of the test specimen, "failure" herein denotes crack initiation.

Because we are making an estimate of FLRF from sample data, there is uncertainty associated with the estimate. It is standard practice to characterize this uncertainty in terms of confidence limits about the estimate, within which the "true" value lies, with the confidence stated. Two-sided, 95% confidence limits on the factor 9.79 may be found as shown below.* These confidence limits will be factors on the mean value. Wider limits which account also for how much an individual future specimen might vary from the 9.79 factor will be found subsequently.

The confidence limits on the estimate will account for uncertainty in the intercepts of the air and BWR water lines. The confidence limits on an individual future specimen will account, in addition, for the distribution of individual values about the BWR water line.

In this evaluation the confidence limits did not consider uncertainty in the slope estimate. The contribution from slope would be small in the region of the data, especially for the individual future specimen limits. Also, including slope uncertainty would make confidence limits a slight function of strain range. For these reasons, plus the excellent agreement of the observed slope with that of the ASME best fit line, it was assumed that slope is known without error.

Two-Sided 95% Confidence Limits on the Estimate of Fatigue Life Reduction Factor

$$\begin{aligned} \text{CLE}_{.95} &= \text{two-sided, 95\% confidence limits on estimate of FLRF in log cycles, i.e. on FLD} \\ &= \text{FLD} \pm t_{df,\alpha} s_{fld} \end{aligned}$$

where:

$$\begin{aligned} \text{FLD} &= \text{fatigue life difference, in log cycles} \\ df &= \text{degrees of freedom} = (n_1 - 1) + (n_2 - 1) \\ n_1 &= \text{number of data points in air} = 4 \\ n_2 &= \text{number of data points in BWR water} = 9 \\ \alpha &= (1 - \text{confidence value}) = 0.05 \\ t_{df,\alpha} &= \text{ordinate from "t" distribution, for df degrees of freedom and } \alpha \text{ sum of probabilities in both tails} \\ t_{11,0.05} &= 2.201 \\ \text{Var}_{\text{res}} &= \text{variance of residuals}^{**} \\ &= 0.009476 \\ s_{fld} &= \text{standard deviation of estimate of FLD in log cycles} \\ &= \left((v_{\text{res}}) (1/n_1 + 1/n_2) \right)^{1/2} \\ &= 0.0585 \\ t_{df,\alpha} &= 2.201 \cdot 0.0585 = 0.1287 \end{aligned}$$

* The meaning of 95% confidence is the standard one in statistics; namely, if the same magnitude of sampling should be done an infinite number of times from the same populations, the claim that the 95% confidence limits found on each trial contain the "true" value will be correct on 95% of the trials.

** Residuals are differences (in log cycles) between observed and fitted values at the same strain range; the variance is combined for the air and BWR water data about v_1 and v_2 respectively.

$$\therefore \text{CLE}_{.95} = 0.9908 \pm 0.1287$$

$$\begin{aligned} \text{antilog } 0.1287 &= \text{factor of } 1.35, \text{ so that } 95\% \text{ confidence limits on the estimate of FLRF} = \\ 9.79 \times 1.35 &\& 9.79/1.35 \\ &= \boxed{13.32, 7.31} \end{aligned}$$

**Two-Sided 95% Confidence Limits
on an Individual Future Specimen**

$$\text{CLE}_{.95} = \text{FLD} \pm t_{df,\alpha} (\text{Var}_{\text{res}} + \text{Var}_{\text{fld}})^{1/2}, \text{ in log cycles}$$

where;

$$\begin{aligned} \text{Var}_{\text{res}} &= \text{Variance of residuals} \\ &= 0.009476 \end{aligned}$$

$$\begin{aligned} \text{Var}_{\text{fld}} &= \text{Variance of estimate of fatigue life difference} \\ &= (s_{\text{fld}})^2 \\ &= 0.003422 \end{aligned}$$

$$\begin{aligned} \therefore t_{df,\alpha} (\text{Var}_{\text{res}} + \text{Var}_{\text{fld}})^{1/2} &= 2.201 \cdot (0.009476 + 0.003422)^{1/2} \\ &= 0.25 \end{aligned}$$

$$\therefore \text{CLE}_{.95} = 0.9908 \pm 0.25$$

$$\begin{aligned} \text{antilog } 0.25 &= \text{factor of } 1.78, \text{ so that } 95\% \text{ confidence limits on the estimate of FLRF for an} \\ \text{individual future specimen} &= 9.79 \times 1.78 \& 9.79/1.78 \\ &= \boxed{17.43, 5.50} \end{aligned}$$

Based on the statistical analysis of the A-516 carbon steel Task K data, the mean low-cycle fatigue reduction factor associated with the BWR water environment is estimated to be 9.79. Furthermore, evaluation of the 95% confidence limits on this estimate lead to these additional conclusions:

1. We are 95% confident that the *average* FLRF in BWR water lies in the range of 7.31 to 13.24.
2. We are 95% confident that the FLRF in BWR water for an individual specimen will lie in the range of 5.50 to 17.43.

It should be emphasized that because analysis is based on data taken in the range of 0.75% to 1.0% strain in air, caution should be used in making inferences outside this range, although the same relationship appears reliable for the 0.5 strain range.

B.3 TYPE-304 STAINLESS STEEL (AS RECEIVED)

Data for this material are listed in Table B-1 and are plotted in Figure 5-6. From this figure it can be seen that the means of log-fatigue life at the two higher strain ranges, in BWR water and air, are nearly identical. Their difference is far from significant statistically. Thus, for Type-304 stainless steel in the as-received condition, there is apparently no reduction in fatigue life due to BWR water, as evidenced by data at the strain ranges of 1.0% and 0.75%.

B.4 INCONEL-600 (AS RECEIVED)

Data for this material are listed in Table B-1 and are plotted in Figure 5-7. Only one failure in BWR water has been observed to date. However, since this data point, and present accumulated cycles on remaining specimens at the 1.0% strain range, closely bracket the four 500°F air data points, it is unlikely that a detrimental effect of the BWR water environment will be found.

TABLE B-1
FAILURE DATA FOR ESTIMATING FATIGUE LIFE REDUCTION FACTORS

Material Material Condition Code (Test Condition Number)	Strain Range (%)	Environment	Number of Specimens			Specimen Number	Cycles to Failure	Further Tests Scheduled ^(a)
			On Test	Failed	Still Running			
Carbon Steel 2 (26)	0.5	Water	4	4	0	81	4007	
						72	5292	
						76	7161	
						75	8869	
	0.75	Water	1	1	0	50	2813	
						57	1066	
	1.0	Water	4	4	0	64	1123	
						48	1176	
						53	1380	
						1045	23789	2
	1.0	Air	2	2	0	1047	28758	
						1046	10327	2
						1044	13300	
Stainless Steel 1 (1)	0.5	Water	5	1	4	163	13773	
						150	17042	
						187	6110	
						177	7756	
	0.75	Water	3	2	1	181	7891	
						184	8040	
						194	15159	
						204	15191	
	1.0	Water	4	4	0	202	8679	2
						200	9626	
Inconel 1 (21)	0.5	Water	1	0	1			
	0.75	Water	2	1	1	92	17669	
						123	26429	1
						121	33339	
	1.0	Air	2	2	0	118	15757	1
						120	20500	

DISTRIBUTION

Copies

U. S. Atomic Energy Commission
Division of Technical Information Extension
P. O. Box 62
Oak Ridge, Tennessee

139