139
-7-13

457

GEAP-10207-29
AEC RESEARCH AND
DEVELOPMENT REPORT
AUGUST 1973

**REACTOR PRIMARY COOLANT SYSTEM
PIPE RUPTURE STUDY
PROGRESS REPORT NO. 29
JANUARY-JUNE 1973**

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.

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. 29
JANUARY—JUNE 1973**

Approved:

E. Kiss

E. Kiss
Project Engineer

Approved:

D. H. Imhoff

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

GENERAL ELECTRIC

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

24

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
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 Low-Cycle Fatigue Design	2-1
2.4 Task K-Effect of BWR Environments	2-1
3. TASK A—PROBABILITY STUDY	3-1
3.1 Objectives	3-1
3.2 Summary	3-1
3.3 Stress Categories	3-1
3.4 Format for Input Probability Distributions for Stresses	3-4
3.5 Format for Input Probability Distributions for Crack Sizes and Detectability	3-4
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	4-4
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
5.4 500°F Baseline Air Tests	5-11
5.5 Third Test Vessel (D-1 Test Loop)—Crack Growth Investigations	5-12

APPENDIX A

METALLURGICAL EXAMINATION TASK K FATIGUE SPECIMENS

OBJECTIVE	A-1
SUMMARY	A-1
INTRODUCTION	A-2
RESULTS OF METALLURGICAL INVESTIGATION	A-2

LIST OF ILLUSTRATIONS

Figure	Title	Page
3-1	Stress Amplitude versus Elastic Strain Range/ S_m for Secondary Stresses	3-7
3-2	Relationship of Crack Size Blocks to Critical Stress Values for 6 Inch Schedule 80 Pipe	3-8
3-3	Input for Crack Size: Crack Size Blocks for 2 Inch to <6 Inch D Pipe	3-9
3-4	Input for Crack Size: Crack Size Blocks for 6 Inch to <10 Inch D Pipe	3-10
3-5	Input for Crack Size: Crack Size Blocks for 10 Inch to <16 Inch D Pipe	3-11
3-6	Input for Crack Size: Crack Size Blocks for 16 Inch to 28 Inch D Pipe	3-12
4-1	Fatigue Specimens	4-6
4-2	Displacement Amplitude over 4-inch Gage Length (mils), Stress versus Displacement, Carbon Steel Grooved Specimen	4-7
4-3	Displacement Amplitude over 4-inch Gage Length (mils), Stress versus Displacement, Carbon Steel Shouldered Specimen	4-8
4-4	Average Net-Section Stress Amplitude (ksi), vs Local Surface Strains, Carbon Steel Grooved Specimen	4-9
4-5	Average Net-Section Stress Amplitude (ksi), vs Local Surface Strains, Carbon Steel Shouldered Specimen	4-10
5-1	Dynamic Test Specimen	5-5
5-2	Equivalent Stress Amplitude (psi) versus Cycles to Failure for Type-304 Stainless Steel	5-6
5-3	Equivalent Stress Amplitude (psi) versus Cycles to Failure for Type-304L Stainless Steel	5-7
5-4	Equivalent Stress Amplitude (psi) versus Cycles to Failure for Inconel-600	5-8
5-5	Equivalent Stress Amplitude (psi) versus Cycles to Failure for A516 Carbon Steel	5-9
5-6	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.	5-14
5-7	Equivalent Stress Amplitude versus Cycles to Failure for Type-304L Stainless Steel. Comparison of fatigue data from BWR environment with 500°F air baseline case.	5-15
5-8	Equivalent Stress Amplitude (psi) versus Cycle to Failure for Inconel 600. Comparison of fatigue data from BWR environment with 500°F air baseline case.	5-16
5-9	Equivalent Stress Amplitude versus Cycles to Failure for A516 Carbon Steel. Comparison of fatigue data from BWR environment with 500°F air baseline case.	5-17
5-10	Test Vessel III Test Scheme	5-18
5-11	Crack Growth Test Vessel	5-19

LIST OF ILLUSTRATIONS (Continued)

Figure	Title	Page
5-12	2T-WOL Specimen for Crack Growth Rate Study of Task K _c	5-20
5-13	GE In-House Tests, 1T-WOL, Type-304 SS, Room Temperature	5-21
5-14	Measured Crack Opening, Displacement versus Crack Length	5-22
5-15	Crack Growth Test Vessel Control Console	5-23
1a	SEM Fractograph of Flash-Annealed and Pickled 304 SS (100X). Specimen No. 187 (2999)	A-3
1b	Fatigue Striations on Fracture Surface of Specimen Shown in Figure 1a (1000X). Specimen No. 187 (3109)	A-3
2a	Fracture Surface of Plunge Ground Cold-Worked 304L SS (300X). Specimen No. 1135 (2996)	A-4
2b	Fatigue Striations on Fracture Surface of Specimen Shown in Figure 2a (1000X). Specimen No. 1135 (3452)	A-4
3a	Fracture Surface of Air-Tested 304 SS (100X). Specimen No. 204 (3840)	A-5
3b	Fatigue Striations on Fracture Surface of Specimen Shown in Figure 3a (3000X). Specimen No. 204 (3841)	A-5
4a	Cross Section of Flash-Annealed and Pickled 304 SS (22X). Specimen No. 187.	A-6
4b	Higher Magnification View of Specimen Shown in Figure 4a (100X). Specimen No. 187	A-6
5a	Cross Section of Fracture and Machined Surface for Air-Tested 304 SS (100X).	A-8
5b	Secondary Cracking Observed on Specimen Shown in Figure 5a	A-9
6	Cross Section of Fracture and Machined Surface of Plunge Ground Cold-Worked 304L SS (100X). Specimen No. 1135	A-9
7a	Cross Section of Welded 304L SS (22X). Specimen No. 1076	A-10
7b	Same as Specimen Shown in Figure 7a, Except Higher Magnification (100X). Specimen No. 1076	A-10
8a	Surface of Fatigue Specimen of Pickled Furnace-Sensitized Flash-Annealed 304 SS (300X). Specimen No. 147 (3013)	A-11
8b	Same as Figure 8a, Except Higher Magnification (1000X). Specimen No. 147 (3014)	A-11
9a	Cross Section of Furnace-Sensitized 304 SS (22X). Specimen No. 166	A-12
9b	Secondary Crack, Mixed Mode, of Specimen Shown in Figure 9a	A-12

LIST OF ILLUSTRATIONS (Continued)

Figure	Title	Page
9c	Same Specimen as Shown in Figure 9a, Except at Higher Magnification (100X). Specimen No. 166.	A-13
10a	Cross Section of DNPS-1 Pipe Weld 304 SS (22X). Specimen No. 114B	A-15
10b	Secondary Crack on Machined Surface of Specimen Shown in Figure 10a (250X). Specimen No. 1148	A-16
11	Cross Section of As-Welded Inconel 600 (100X). Specimen No. 1042	A-17
12a	Fracture Surface of Air-Tested Inconel 600 (100X). Specimen No. 118 (4042)	A-18
12b	Striation Spacing for Air-Tested Inconel 600 (3000X). Specimen No. 118 (4039)	A-18
13a	Fracture Surface of Air-Tested A-516 Carbon Steel (100X). Specimen No. 1044 (3844)	A-21
13b	Striation Spacing on Fracture Surface of Air-Tested A-516 Carbon Steel (1000X). Specimen 1045 (4078).	A-21
14a	Cross Section of As-Machined and Stress-Relieved A-516 Carbon Steel (22X). Specimen No. 1009	A-22
14b	Micrograph of Polished Cross Section of As-Machined and Stress-Relieved A-516 Carbon Steel Showing Fracture Surface (250X). Specimen No. 1009	A-22
14c	Micrograph of Polished and Etched Cross Section of As-Machined and Stress-Relieved A-516 Carbon Steel Showing Fracture Surface (250X). Specimen No. 1009	A-23
15a	Cross Section of Welded and Stress-Relieved A-516 Carbon Steel (22X). Specimen No. 1060	A-23
15b	Fracture and Secondary Crack in Very Fine Grain Region of Welded and Stress-Relieved A-516 Carbon Steel (250X). Specimen No. 1060	A-24
16	Cross Section of Welded A-516 Carbon Steel (22X). Specimen No. 1053	A-24

LIST OF TABLES

Table	Title	Page
3-1	Application of Stress Categories by Panel Number to Location and Orientation	3-3
3-2	Stress Amplitudes for Primary and Secondary Stresses	3-5
3-3	Stress Cells for Input Probability Distributions	3-6
4-2.1	Summary of Section III Fatigue Analysis Per NB-3653.6 for Welds and Components	4-2
4-2.2	Summary of Section III Fatigue Analysis Per NB-3653.6 for Notched Specimens	4-3
5-1	Dresden Test Loop Operating Summary	5-2
5-2	Task K Fatigue Specimen Layout	5-3
5-3	Fatigue Test Results from Dresden I Loop	5-4
5-4	Fatigue Specimen Test Plan Series IV Baseline "Air" Tests	5-13
A-1	Metallographic Identification of Weld HAZ in A-516 Carbon Steel	A-20

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. 29 documents work done in the period January 1, 1973 to June 30, 1973. 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.
GEAP-10207-28	No. 28, July–December 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
GEAP-10763	Low-Cycle Fatigue of Prototype Pipe Components, January 1973.

2. SUMMARY

2.1 TASK A—PROBABILITY STUDY

With the objective of applying the leak and severance methodology (GEAP-10207-23), modified to identify on a relative basis fault cause contributions to the probability of severance, a stress category structure and a structure for probability distributions for crack sizes and detectability have been devised.

The stress categories are defined in terms of ASME Section III type categories. These categories are related to real potential stress-causing situations in order to provide for consistent and realistic input on frequency of occurrence and the probability distribution of each, as a result of fault causes. The structure for probability distributions for crack sizes and detectability is defined as an array of discrete two-dimensional blocks based on the fracture diagram described in GEAP-10207-23.

2.2 TASK D—3—PROTOTYPE PIPE FATIGUE

A summary topical report, GEAP-10763, "Low Cycle Fatigue of Prototype Pipe Components," has been written and distributed. Presented in this report is the evaluation of the actual design margins inherent in the ASME Section III Code for Low Cycle Fatigue. Results are presented which show that these code rules are adequately conservative, particularly at the highest stresses.

2.3 TASK D—5—ASME ELASTIC—PLASTIC CODE RULES FOR LOW-CYCLE FATIGUE DESIGN

Grooved and shoulder specimens of carbon steel have been multiple-step tested to determine local cyclic strain and deflection over a specified gage length as a function of applied stress. Agreement between measured strains, deflection and finite element creep-plast predictions is found to be quite good.

2.4 TASK K—EFFECT OF BWR ENVIRONMENTS

The Dresden I test loop has accumulated over 7500 hours and 31,000 cycles at test conditions (500°F, 1040 psig). A total of 96 of the 149 fatigue specimens being cyclically loaded in the loop have signalled failure. These include 43 of 71 Type-304 stainless steel specimens, 19 of 28 Type-304 L stainless steel specimens, 7 of 23 Inconel 600 specimens, and all of the 27 A-516 carbon steel specimens. Test loop operating history is summarized in Table 2-1.

Testing of the second group of 12 fatigue specimens cycled at 500°F in the Air Test Facility in San Jose is continuing. Data from the 6 specimens in this group which have signalled failure to date and the 12 specimens from the first series of hot air tests have been compared to ASME Section III design criteria and comparable data from the Dresden I environmental test loop.

Final checkout of the equipment associated with the crack growth (third) test vessel to be added to the Dresden test loop is underway. Fatigue testing of a 2T-WOL specimen in air at room temperature has been completed. Calibration of the in situ crack growth LVDT sensors has begun. Scheduling for a two-stage modification of the Dresden Test Loop and installation of the crack growth test vessel and electrochemical measurement station has been finalized.

Post-test metallurgical investigations, including scanning electron microscopy, of selected fatigue specimens removed from the Dresden test loop, have been accelerated.

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

With the objective of applying the leak and severance methodology (GEAP-10207-23), modified to identify on a relative basis fault cause contributions to the probability of severance, a stress category structure and a structure for probability distributions for crack sizes and detectability have been devised.

The stress categories are defined in terms of ASME Section III type categories. These categories are related to real potential stress-causing situations in order to provide for consistent and realistic input on frequency of occurrence and the probability distribution of each, as a result of fault causes. The structure for probability distributions for crack sizes and detectability is defined as an array of discrete two-dimensional blocks based on the fracture diagram described in GEAP-10207-23.

3.3 STRESS CATEGORIES

Stress categories were chosen so that they can be consistently interpreted by as wide a spectrum of contributors to and users of the study as possible. This means, specifically, that the categories must be distinguished so that there is common understanding of what physical situation might give rise to the category so that the probability of its taking on values differing markedly from the design value can be accurately assigned by an experienced individual and consistently understood and confirmed by others.

The ASME Section III stress categories were chosen as best fulfilling these criteria. These categories will be described following discussions on location categories and orientation assignment.

In order to make the assignment of frequency distributions to stress categories more specific, the following locations in a typical piping system are distinguished. Note that a "location" may be either a "component" or a "joint."

Component:

- Straight
- Reducer
- Ell: 45°, 90° or 180°; short and long radius, and bend
- Tee, including sweepolets and any branching configurations except when run to branch diameter exceeds 2:1.

Joint; weld metal and heat affected zone (HAZ):

- Between two straights
- Between a straight and fitting (reducer, ell or tee), or between two fittings
- High restraint joint between a pipe and non-pipe component such as nozzle, valve or pump, or a branch connection having run to branch diameter exceeding 2:1, or at a flange or penetration
- Non-standard joint, such as in a built-up tee, in a mitre, or others, tending to concentrate applied stresses, or made to accommodate unusual field conditions. Such joints are not uncommon and are approved; they are in contrast to blended-radius, stress-distributing configurations.

Because cracks may occur with different probabilities for different orientations in the various locations, and because it is assumed that only stresses acting normal to the crack cause failure, it is necessary to determine for each stress category the orientation in which it would be expected to ordinarily act with its maximum value. This has been done by considering equations 9, 10 and 11 in NB-3650 of ASME Section III; the table of stress indices, NB-3683.2-1; and knowledge of the orientation of stresses resulting from each of the terms. Also, a fraction of the maximum value - 1/3 or 1/2 - has been assumed to act normal to the orientation chosen above. No reduction in probability of application

will be proposed to be made for the possibility that some stress categories may not act with their maximum value around the full circumference, or along the full length of a component, so that the probability of simultaneous occurrence of stress and crack at the same place will probably be less than assumed.

In the following list, the stress categories are described and their orientation in each location stated. This information is summarized in 16 stress panels in Table 3-1. For reference and as an aid to visualizing the manner in which each stress category is assumed to act in each location, the following list also states whether the stress acts in the wall of the pipe as a tensile stress, having uniform magnitude through the wall, or as a bending stress, having a range of values from compression to tension through the wall, although it is not proposed to differentiate between tensile and bending stresses as to their critical value for severance, due to lack of suitable data.

3.3.1 P_m , General Primary-Membrane Stress

This stress is the average value of tensile stress across a pipe section, needed to satisfy equilibrium due only to mechanical loads, excluding discontinuities (changes in section, as diameter, wall thickness, or both) and the effect of stress concentrations. The stress arises mainly due to internal pressure (hoop stress), but also due to unsupported weight. It is load-limited. It can be excessive due to overpressure, water slugs, thin wall or lack of support. It is assumed to develop its maximum value circumferentially in all locations, as a tensile stress. A scale factor of 1/2 is assigned axially.

3.3.2 P_L , Local Primary-Membrane Stress, and P_b , Primary-Bending Stress

P_L is the average value of tensile stress across a pipe section, due to mechanical loads only, at discontinuities but excluding the effect of stress concentrations. The stress is additional to P_m . It is load-limited. P_L can be excessive due to improper discontinuity design.

The P_b stress arises due to mechanical loads, such as weight, tending to bend the piping system, excluding discontinuities and the effect of stress concentrations, and is either the average value across the pipe wall on the tensile side of the pipe (tensile stress), of the surface-fiber stress in the wall of a fitting, such as an ell, forced out of round. It is load-limited. P_b can be excessive due to lack of support.

Both stress categories are treated together, and are assumed to most often develop their maximum values axially as a bending stress in straights and joints between straights, and circumferentially as a bending stress in fittings. A scale factor of 1/3 is assigned to the orientations at 90°, and axially to joints other than between straights.

3.3.3 P_e , Secondary Expansion Stress

P_e is the stress resulting from restraint of system thermal expansion or movement of anchor points, including discontinuities but not considering the effect of stress concentrations. It is strain-(displacement)-limited, and can have a high value due to excessive restraint on the piping system. It is assumed to most often develop its maximum value axially in all locations, as a tensile stress, but also circumferentially in fittings, as a bending stress. A scale factor of 1/3 is assigned circumferentially in straights, and axially in fittings and in joints other than between two straights.

3.3.4 Q , Secondary Membrane Plus Bending Stress

Q stresses are self-equilibrating, and arise due to local thermal stress, as when hot and cold streams mix or follow each other, including discontinuities but not considering the effect of stress concentrations. The stress is strain-limited. It is assumed to develop its maximum value both axially and circumferentially at all locations in all components, in effect as a bending stress.

3.3.5 F , Peak Stress

The effect of local stress concentration is included to evaluate the peak local stress. Since it is highly localized it relates mainly to the problem of fatigue rather than severance and is not considered explicitly.

Thus, four stress categories are considered: P_m , P_L and P_b taken together, P_e and Q .

Table 3-1
APPLICATION OF STRESS CATEGORIES BY PANEL NUMBER TO LOCATION AND ORIENTATION

	STRESS PANEL	ASME SEC III CATEGORY STRESS SCALE FACTOR	LOCATION						
			COMPONENT				JOINT		
			STRAIGHT	REDUCER	ELL	TEE	2 STRAIGHTS	STR - FTG OR FTG - FTG	HIGH RESTRAINT NON - STD
PRIMARY STRESSES	1	P_m 1	C						
	2	P_m 1/2	Ax				Ax		
	3	P_m 1		C	C	C			
	4	P_m 1/2		Ax	Ax	Ax		Ax	Ax
	5	P_b^+ P_L 1	Ax				Ax		
	6	P_b^+ P_L 1/3	C						
	7	P_b^+ P_L 1		C	C	C			
	8	P_b^+ P_L 1/3		Ax	Ax	Ax		Ax	Ax
SECONDARY STRESSES	9	P_e 1	Ax	(Ax	Ax	Ax)	Ax	(Ax	Ax
	10	P_e 1/3	C						
	11	Q 1	C						
	12	Q 1	Ax				Ax		
	13	P_e 1		C	C	C			
	14	P_e 1/3		Ax	Ax	Ax		Ax	Ax
	15	Q 1		C	C	C			
	16	Q 1		Ax	Ax	Ax		Ax	Ax

3.4 FORMAT FOR INPUT PROBABILITY DISTRIBUTIONS FOR STRESSES

For each of the stress categories the viewpoint will be taken that the stress occurs in any location as represented by a narrow distribution of design values, or by a wide distribution of values which result when some error is made, only the latter making more than a negligible contribution to probability of severance. First, a probability will be called for that some error (a fault cause) is made so that the value for each stress category is to be drawn from the wide distribution. Second, the shape of this distribution, applicable to all or to selected groups of locations, is to be drawn. This will be done by assigning probability values to discrete stress cells, which are successive ranges of values as in a histogram.

Table 3-2 shows how stress amplitude values suitable for entering the critical stress diagram are found for primary stresses. Both Table 3-2 and Figure 3-1 show how the same information may be calculated for secondary stresses found using a general elastic stress analysis. Table 3-3 gives the stress cells upon which the frequency distribution is to be formed, by assigning a probability to each cell, given the occurrence of a fault cause. Provision is made in each distribution for the probability of a stress exceeding ultimate strength.

Thus, a structure has been drafted which accounts for locations, stress categories, orientations, and stress frequency distributions.

3.5 FORMAT FOR INPUT PROBABILITY DISTRIBUTIONS FOR CRACK SIZES AND DETECTABILITY

Crack sizes will be defined in an array of "blocks", the two dimensions of the array being crack length and depth. These blocks take advantage of a relationship between crack size and critical stress for fracture determined experimentally from pressure burst testing 59 carbon steel 6-inch schedule 80 pipe specimens.* This relationship, reflected in what is called herein a critical stress diagram, is reproduced for reference as Figure 3-2; it is essentially the same as Figure 3-2 of Progress Report 23, GEAP-10207-23. Since the crack size blocks are discrete, assignment of probabilities of occurrence and of detection is facilitated.

In obtaining critical crack size diagrams for piping in sizes other than 6-inch it was desirable to retain the same relationship between crack size block numbers and critical stresses. To accomplish this the length and depth associated with each block was adjusted. The adjustment is based on additional data from tests of specimens of 12-inch schedule 80, and 4-, 6-, 8- and 10-inch schedule 40 pipe. Figures 3-3 to 3-6 show the increasing ranges of length and depth for the crack size blocks for 2-inch to 28-inch diameter piping, in intervals of 2-inch to 6-inch, 6 inch to 10-inch, 10-inch to 16-inch, and 16-inch to 28-inch diameters.

In securing input frequency distributions for crack size, provision has been made for different probability distributions to be assigned to corresponding crack size blocks in different diameter ranges, although some responders may be satisfied with the same distributions. Furthermore, it is anticipated that Figures 3-3 to 3-6 will be appropriate for differentiating between frequency distributions for axial and circumferential orientations, and for base metal and weld or heat affected zone locations. It is also judged that the same arrays of blocks will be suitable for input on the probability of detection of cracks.

* Task C (Fracture Mechanics)—Pipe Rupture Study, See GEAP-5620 and GEAP-5622.

Table 3-2
STRESS AMPLITUDES FOR PRIMARY AND SECONDARY STRESSES

* STRESS CELLS TABLE 3-3

Table 3-3
STRESS CELLS FOR INPUT PROBABILITY DISTRIBUTIONS

* ALL EVEN NUMBER STRESS PANELS ARE TO HAVE THE SAME PROBABILITY ASSIGNED TO CORRESPONDING STRESS CELLS AS THE PREVIOUS ODD NUMBER PANEL .

Figure 3.1. Stress Amplitude versus Elastic Strain Range/ S_m for Secondary Stresses

Figure 3-2. Relationship of Crack Size Blocks to Critical Stress Values for 6 Inch Schedule 80 Pipe

Figure 3-4. Input for Crack Size: Crack Size Blocks for 6 Inch to < 10 Inch D Pipe

Figure 3-5. Input for Crack Size: Crack Size Blocks for 10 Inch to <16 Inch D Pipe

Figure 3-6. Input for Crack Size: Crack Size Blocks for 16 Inch to 28 Inch D Pipe

4. TASK D—LOW CYCLE FATIGUE

4.1 OBJECTIVES

The objectives of this 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

The test program for task D3 has been completed. A final topical report, "Low Cycle Fatigue of Prototype Pipe Components," J. D. Heald, E. Kiss, GEAP-10763, January 1973; has been distributed.

4.2.2 Topical Report

The objective of the final topical report was to summarize work completed subsequent to publication of GEAP-10135, January 1970. Specifically the new topical described the results of 28 tests and analysis of prototype pipe components, and updated, to present day code rules, analysis of 32 notched pipe components. Predictions of Fatigue Life are compared to measured lives in order to assess the code design margin. Specifically the rules of paragraph NB3653.6, ASME Section III, Simplified Elastic-Plastic Discontinuity Analysis, were employed.

The criteria used to assess the code design margin are based on determining the ratio N_t/N_{cd} , where N_t is the actual number of fatigue cycles to cause through-wall leakage and N_{cd} is the code allowable number of design cycles for the corresponding applied alternating stress amplitude. Although arbitrary, this criterion provides the advantage of employing a relatively consistent and functionally meaningful measurement (cycles to leak), for direct comparison with the design prediction.

A summary of the test data, Section III code analysis, and resulting design margins are given in Table 4.2.1 for 28 piping components and in Table 4.2.2 for 32 notched specimens. Based on the results of these tests and assuming that $N_t/N_{cd} \geq 20$, it can be seen that the code rules (NB3653.6) are adequately conservative, particularly at the highest stress conditions.

4.2.3 Summary Prototype Tests Completed

During the course of this program the following low cycle fatigue prototype tests have been completed.

Type	
Notched	35
Elbows	11
Tees	5
Girth Welds	12
Material	
Stainless Steel	25 (42%)
Carbon Steel	29 (48%)
Alloy Steel	6 (10%)
Temperature	
Room Temperature	40 (67%)
550° F	20 (33%)

Table 4-2.1
SUMMARY OF SECTION III FATIGUE ANALYSIS PER NB-3653.6 FOR WELDS AND COMPONENTS

Specimen Number	Plane	Radius	Material	Schedule	$Y_r^{(1)}$ (in.)	$k^{(2)}$ (lb/in.)	$l^{(3)}$ (in.)	S_m (ksi)	3 S_m (ksi)	3m S_m (ksi)	S_n (ksi)	$\frac{S_n}{3 S_m}$	K_e	S_p (ksi)	Salt (ksi)	$N_{CD}^{(4)}$	$N_L^{(5)}$	$\frac{N_L}{N_{CD}}$
550°F Girth Butt-Weld Specimens																		
HW-1			CS	40	10.9	205	237	18	54	162	62.4	1.155	1.310	112.4	74	1400	35740	25.5
HW-3A			SS	40	14.8	166	237	16	48	81.6	68.7	1.433	2.442	123.8	151	340	6950	20.4
HW-10			SS	80	16.0	255	237	16	48	81.6	79.0	1.650	3.160	142.3	224	120	9200	75.7
HW-11			SS	80	12.5	265	237	16	48	81.6	64.1	1.340	2.130	115.6	123	680	14858	21.9
HW-12			SS	80	19.0	255	237	16	48	81.6	94.0	1.960	3.33	169.5	282	68	2894	42.5
HW-14			CS	80	17.0	265	237	18	54	162	87.2	1.015	2.23	157.1	175	150	7278	48.6
HW-15			CS	80	21.3	285	237	18	54	162	117.8	2.100	3.00	212.0	366	27	3200	119.0
HWD-1			CS	40	12.0	190	237	18	54	162	63.5	1.176	1.35	114.4	77	1300	13600	10.5
HWD-3			SS	40	14.4	180	237	16	48	81.6	72.7	1.505	2.68	130.0	174	240	2600	10.8
Room Temperature Axial Notch Specimens (Analyzed as Welds)																		
CCANS-80-1 Axial			CS	80	22.0	280	237	20	60	180	119.3	1.990	2.98	215	320	35	>1713	>49
CCANS-160-1 Axial			CS	160	18.0	400	237	20	60	180	96.0	1.603	2.21	173	191	120	7724	64
CSANS-160-1 Axial			SS	160	19.1	400	237	20	60	102	101.5	1.693	3.29	183	301	56	7456	133
Room Temperature Elbow Specimens																		
CSLS-1	I.P.	6-in.	SS	40	21.6	114	225	20	60	102	416	6.84	3.33	416	694	<10	907	>91
CSLS-2	O.P.	6-in.	SS	40	13.0	143	225	20	60	102	314	5.23	3.33	314	524	16	6838	427
CSLS-3	I.P.	9-in.	SS	40	14.5	130	225	20	60	102	243	4.05	3.33	243	405	27	4469	166
CSLS-5	I.P.	9-in.	SS	40	14.5	130	225	20	60	102	264	4.40	3.33	264	440	23	3990	173
CSLS-7	I.P.	9-in.	SS	40	13.0	130	225	20	60	102	260	4.33	3.33	260	433	24	2531	105
CCLS-1	I.P.	6-in.	CS	40	14.1	130	225	20	80	180	310	5.17	5.0	310	775	<10	1176	<118
CCLS-2	O.P.	6-in.	CS	40	11.2	168	225	20	60	180	318	5.30	5.0	318	795	<10	7899	<790
550°F Elbow Specimens																		
HSL-1	I.P.	6-in.	SS	40	17.1	93	225	16	48	81.6	269	5.61	3.33	269	448	22	2200	100
HSL-2	O.P.	6-in.	SS	40	20.8	115	225	16	48	81.6	404	8.41	3.33	404	673	<10	1870	>187
HCLS-1	I.P.	6-in.	CS	40	14.5	89	225	18	54	162	218	4.04	5.0	218	545	11	760	69
HCLS-2	O.P.	6-in.	CS	40	14.4	110	225	18	54	162	267	4.95	5.0	267	668	<10	26100	>2610
Room Temperature Tee Specimens																		
CSTS-1	I.P.	Branch	SS	40	14.5	206	222	20	60	102	262	4.37	3.33	262	437	23	4575	199
CSTS-2	I.P.	Run	SS	40	16.6	172	222	20	60	102	260	4.34	3.33	260	434	24	3310	138
CSTS-3	O.P.	Branch	SS	40	17.3	161	222	20	60	102	244	4.07	3.33	244	407	27	3675	136
CCTS-1	I.P.	Branch	CS	40	10.2	256	222	20	60	180	229	3.82	5.0	229	572	10	21079	2110
CCTS-2	O.P.	Branch	CS	40	13.8	196	222	20	60	180	236	3.94	5.0	236	590	<10	9367	>937

NOTES
1. Y_r = Peak-to-peak specimen deflection
2. k = Measured stiffness
3. l = Lever arm length
4. N_{CD} = Allowable number of Code Design cycles
5. N_L = Full amplitude cycles to leakage.

Table 4-2.2
SUMMARY OF SECTION III FATIGUE ANALYSIS PER NB-3653.6 FOR NOTCHED SPECIMENS

Specimen Number	Material	Schedule	Notch ⁽¹⁾ Type	Y _r ⁽²⁾ (in.)	k* ⁽³⁾ (lb/in.)	Sm (ksi)	3 Sm (ksi)	3m Sm (ksi)	Sn (ksi)	$\frac{Sn}{3 Sm}$	Ke	S _p (ksi)	Salt (ksi)	N _{CD} ⁽⁴⁾	Full Amp N _L ⁽⁵⁾	$\frac{N_L}{N_{CD}}$
Notched Piping at Room Temperature																
CSS-3	CS	40	I	15.4	191	20	60	180	80.1	1.338	1.676	288.5	242	66	1085	16.5
CSS-4	CS	40	II	13.0	191	20	60	180	67.6	1.129	1.258	243.5	154	200	4572	22.8
CSS-5	CS	40	I	10.4	191	20	60	180	54.1	0.901	1.0	195.0	98	640	13398	21.0
CSS-6	CS	40	II	14.8	191	20	60	180	77.0	1.285	1.560	277	216	90	1453	16.1
CSS-7	CS	80	I	17.4	275	20	60	180	90.5	1.510	2.020	326	330	34	1202	35.4
CSS-8	CS	80	II	10.3	275	20	60	180	53.5	0.894	1.0	192.5	96	690	12081	17.5
CSS-9	CS	80	I	8.7	275	20	60	180	45.3	0.726	1.0	163	82	1050	34426	32.8
CSS-10	CS	80	II	O-T 8.45*	275	20	60	180	44.0	0.735	1.0	158.5	79	1150	15005	13.0
CSS-11	CS	160	I	22.8	401	20	60	180	118.6	1.980	2.960	427	632	<10	953	>95
CSS-13	CS	160	I	12.9	401	20	60	180	67.1	1.120	1.240	242	150	210	13600	64.8
CSS-107	CS	80	I	15.7	275	20	60	180	81.6	1.363	1.726	294	254	60	3575	59.6
CSS-109	CS	80	I	15.4	401	20	60	180	80.1	1.338	1.676	288.5	242	66	4000	60.7
CSS-111*(6)	CS	160	I	18.8	401	20	60	180	97.9	1.632	2.264	352	398	22	5150	234
CSS-15	SS	40	I	10.0	194	20	60	102	52.7	0.880	1.0	190	95	700	20127	28.8
CSS-16	SS	40	II	11.5	194	20	60	102	60.5	1.010	1.033	218	113	440	8596	19.5
CSS-23	SS	160	I	20.0	406	20	60	102	105.2	1.758	3.33	379	630	10	1747	175
CSS-25	SS	160	I	14.7	406	20	60	102	77.5	1.292	1.973	279	276	70	11883	170
CSS-119	SS	80	I	16.2	279	20	60	102	85.4	1.425	2.415	307	370	34	4656	137
CSS-124*(6)	SS	160	I	14.7	406	20	60	102	77.5	1.292	1.973	279	276	70	15199	217
CSS-27	AS	40	I	14.6	205	20	60	120	81.2	1.355	2.420	292	354	27	1500	55.6
CSS-29	AS	40	I	10.0	205	20	60	120	55.6	0.929	1.0	200	100	600	11950	19.9
CSS-31	AS	80	I	15.9	295	20	60	120	88.5	1.478	2.910	318	463	15	4800	320
CSS-35	AS	160	I	10.0	430	20	60	120	55.6	0.929	1.0	200	100	600	40913	68.3
CSS-36	AS	160	II	O-T 9.7*	430	20	60	120	54.0	0.901	1.0	194	97	660	20070	30.3
CSS-37	AS	160	I	20.4	430	20	60	120	113.5	1.895	4.580	409	463	15	2365	158
Notched Piping at 550°F																
HCN-40-1	CS	40	I	11.5	178	18	54	162	55.6	1.032	1.064	200	108	520	19998	38.4
HCN-40-2	CS	40	I	14.3	178	18	54	162	69.2	1.283	1.566	249	195	110	6520	59.3
HCN-40-3	CS	40	I	9.9	178	18	54	162	48.0	0.890	1.0	173	86	940	45237	48.2
HCN-40-4	CS	40	I	16.2	178	18	54	162	78.5	1.456	1.902	282	268	50	3800	76.0
HSN-40-S	SS	40	I	12.0	177	16	48	81.6	56.6	1.050	1.167	204	119	740	4701	6.3
HSN-40-1	SS	40	I	12.7	177	16	48	81.6	61.0	1.131	1.436	220	158	320	4350	13.6
HSNP-80-1	SS	80	II	14.2	254	16	48	81.6	68.2	1.265	1.820	246	224	120	4900	40.8

NOTES
1. Notch type, I - external, II - internal, K_t for both types is 3.6.
2. Y_r - peak to peak specimen deflection, (Values marked with * are zero-tension tests.)
3. k* - Theoretically calculated stiffness = $3EI/\ell^3$
 ℓ = 231 inches.
4. N_{CD} - Allowable number of Code Design cycles.
5. N_L - Full amplitude cycles to leakage.
6. Specimens tested in the last year at constant PWR pressure of 2200 psi.

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

Groove and shoulder carbon steel fatigue specimens have been multiple-step tested (100 cycles per step) to determine local cyclic strain and cyclic deflection (over a 4-inch gage length) as a function of applied stress amplitude. Agreement between measured and finite element predicted local cyclic strains is good. In addition, good agreement is shown between measured and predicted cyclic deflections.

4.3.3 Background

As stated in the objective, the current focus of this task is the investigation of the effect of constraint and loading mode on the fatigue behavior of piping materials. Two materials and three specimen geometries are being studied.

The three specimen geometries, are shown in Figure 4-1. The smooth, groove and shoulder specimens have a minimum cross-section diameter of one inch. Groove and shoulder specimens have a theoretical elastic stress concentration factor $K_t=2$.

Test specimens were fabricated from Type-304 stainless steel and A516 (former designation A212-B) carbon steel. Material chemical analyses and mechanical properties were reported earlier.^{1,2}

Detailed analyses of the groove and shoulder specimen geometries have been performed using the finite element program CREEP-PLAST. This program is an elastic-plastic program utilizing a constant-strain triangular element. The shakedown stress-strain curve is used to describe material behavior. Details of these analyses and analytical results (predicted local strains and deflections for an imposed cyclic load) were reported earlier.^{2,3}

Local cyclic strains and cyclic deflections have been experimentally determined for the stainless steel specimens. In addition, load and deflection controlled fatigue tests with the stainless specimens are complete.³ During this report period, the cyclic behavior of the carbon steel specimens was experimentally studied.

4.3.4 Cyclic Strain and Deflection Measurements

Groove and shoulder specimens of A516 carbon steel were cyclicly step tested to determine cyclic strains and deflections. This procedure is the same as used in generating the cyclic stress-strain curves with smooth specimens.¹ A constant amplitude cyclic load (zero mean load) was imposed and specimens were cycled for 100 cycles. During the last few cycles, deflections and strain amplitudes were recorded. The load amplitude was then increased and the procedure repeated.

As was done with the stainless steel specimens, local strain measurements were made with 3 axial and 3 tangential miniature strain gages. Gages were bonded at the point of highest anticipated strain. The gages used were micro-measurement EP-08-031 DE-120 and EC-120. Gage length was 0.031 inch.

Displacement of the fatigue specimens during the shakedown tests was monitored with a specially designed displacement gage. Set-up blocks provided for an accurate gage length of 4.0 inches. The gage was located on the specimen such that peak strain occurred at the displacement gage mid-span.

4.3.5 Discussion of Results

Measured and finite element predicted cyclic load-deflection curves for the carbon steel specimens are shown in Figures 4-2 and 4-3. Agreement between prediction and experiment is very good. The load-deflection curve for the shoulder specimen has a very sharp knee, the same general shape as the carbon steel cyclic stress-strain curve. Because of constraint at the minimum section, the groove specimen does not develop a knee in the load deflection curve.

Good agreement is also shown between measured and predicted local strain amplitudes (Figures 4-4 and 4-5). As was the case with the 304 stainless steel specimens tested earlier, measured local strains are less than predicted, particularly for the shoulder specimen. For this specimen, part of the discrepancy may be due to difficulties in bonding strain gages precisely at the location of predicted peak strain (on the shoulder radius, 17° from tangent point with minimum section).

4.3.6 References

1. Progress Report No.-26, GEAP-10207-26 (October 1971—March 1972)
2. Progress Report No.-27, GEAP-10207-27 (April—June 1972)
3. Progress Report No.-28, GEAP-10207-28 (July—December 1972)

Figure 4-1. Fatigue Specimens

Figure 4-2. Displacement Amplitude over 4-inch Gage Length (mils), Stress versus Displacement, Carbon Steel Grooved Specimen

Figure 4-3. Displacement Amplitude over 4-inch Gage Length (mils), Stress versus Displacement, Carbon Steel Shouldered Specimen.

Figure 4-4. Average Net-Section Stress Amplitude (ksi), vs Local Surface Strains, Carbon Steel Grooved Specimen

Figure 4-5. Average Net-Section Stress Amplitude (ksi) vs Local Surface Strains, Carbon Steel Shouldered Specimen

5. TASK K—EFFECT OF BWR ENVIRONMENT

(D. A. Hale)

5.1 OBJECTIVE

The objective of this task is to quantitatively determine the effects of a high-temperature-water environment on crack initiation and growth under steady and cyclic loadings. With the cooperation of the Commonwealth Edison Company, a special test facility was set up within the Dresden 1 sphere and testing begun in late 1970. Materials being investigated include carbon steel, 304 and 304L stainless steel, and Inconel 600 in various metallurgical conditions, simulating as nearly as practicable "as installed" piping. Primary water (500°F 1040 psi) from the Dresden 1 BWR system is piped to the test facility and circulated at 10 gpm through the fatigue test vessel and static autoclave.

5.2 SUMMARY

The Dresden I test loop has accumulated over 7500 hours and 31,000 cycles at test conditions (500°F, 1040 psig). A total of 96 of the 149 fatigue specimens being cyclically loaded in the loop have signalled failure. These include 43 of 71 Type-304 stainless steel specimens, 19 of 28 Type-304L stainless steel specimens, 7 of 23 Inconel 600 specimens, and all of the 27 A-516 carbon steel specimens. Test loop operating history is summarized in Table 5-1.

Testing of the second group of 12 fatigue specimens cycled at 500°F in the Air Test Facility in San Jose is continuing. Data from the 6 specimens in this group which have signalled failure to date and the 12 specimens from the first series of hot air tests have been compared to ASME Section III design criteria and comparable data from the Dresden 1 environmental test loop.

Final checkout of the equipment associated with the crack growth (third) test vessel to be added to the Dresden test loop is underway. Fatigue testing of a 2T-WOL specimen in air at room temperature has been completed. Calibration of the in situ crack growth LVDT sensors has begun. Scheduling for a two stage modification of the Dresden Test Loop and installation of the crack growth test vessel and electrochemical measurement station has been finalized.

Post-test metallurgical investigations, including scanning electron microscopy, of selected fatigue specimens removed from the Dresden test loop, have been accelerated.

5.3 DRESDEN TEST LOOP

5.3.1 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 5-2) 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.

A total of 96 fatigue specimen failure indications have been received to date. Pertinent test parameters for the latest 6 specimens are summarized in Table 5-3. Data from the other 90 specimens were previously published in GEAP-10207-26, -27 and -28.

The cycles-to-initiation data for the 96 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., $N_{\text{design}} = 1/20 N_{\text{data}}$). The symbols to the right of the vertical dotted line in Figures 5-2, 3 & 4 represent surviving "as received" specimens for these three materials.

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

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

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		
1972	IX	March 24	April 14	171 days	14,156	16,258	3	Loop secured after reactor scram
	X	May 10	May 12	173 days	16,259	16,516	0	Loop secured for plant shutdown
	XI	May 25	May 26	173 days	16,517	16,564	0	Loop shut down to repair leaking fitting
	XII	June 16	July 10	198 days	16,565	18,833	4	Loop shut down to sealweld leaking fittings
	XIII	Dec. 8	Feb. 4	256 days	18,834	24,393	4	Loop secured for plant shutdown
1973	XIV	Feb. 8	March 16	292 days	24,394	27,798	2	Loop secured for plant shutdown
	XV	May 9	June 13	327 days	27,799	~31,000	4	Loop secured for plant shutdown

Type-304L
Stainless Steel – 28

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

Table 5-3
FATIGUE TEST RESULTS FROM DRESDEN I LOOP

Specimen Number	Cycles to Failure	Material	Shakedown Strain Range ^a (%)	Loading Mode ^b	Test Condition Code ^c	Description
1006	27,192	Type-304L SS	0.5	C-T	19	As Received + Mech. Notch
39	27,708	Type-304L SS	0.5	C-T	19	As Received + Mech. Notch
1149	28,885	Type-304 SS	0.75	C-T	6	Dresden Equalizer line base material, as machined.
1117	29,013	Type-304 SS	0.75	C-T	3	Welded (Hi Heat), As Machined
97	29,920	Inconel 600	0.75	C-T	23	As Received, Furnace Sensitized
1006	29,997	Inconel 600	0.5	C-T	25	As Received, Furnace Sensitized + Mech. Notch

Total failure indications received to date: 96(43, 304 SS; 19, 304 L SS; 7, Inconel; 27, carbon steel)

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

(b) C-T = Compression-Tension

(c) Ref. Table A-2

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

5.3.2 Metallurgical Effects

Review of the fatigue data together with post-test metallurgical evaluation provide the ability to more completely relate the macroscopic engineering fatigue data to the microscopic material condition.

5.3.2.1 Type-304 Stainless Steel (ASTM A-240, T-304)

A total of 71 Type-304 stainless steel specimens are under test in the Dresden dynamic test vessel in which failure indications have been received from 43 to date.

While detailed statistical analysis of these data has been deferred until a later date, several important trends in the data are evident:

- a) There is a significant reduction in LCFL (low cycle fatigue life) associated with the F.S. (furnace sensitized) condition (material condition code number 5*) compared with the as-received condition (material condition code number 1*) for both the zero-tension and compression-tension loading modes.
- b) The relatively weak influence of strain range on the F.S. data suggests that the failure mechanism is stress-corrosion dominated, at least for the strain range examined (0.5% to 1%). Review of the stainless steel data reveals that in the furnace-sensitized condition there is a significant effect of the environment on crack initiation. Metallographic examination of the sensitized material reveals a mixed mode; i.e., intergranular and transgranular fracture. In the case of the annealed material, most fatigue data fall quite near the corresponding air data (reference Figure 5-6). In turn, the annealed specimens examined to date show strictly transgranular fracture.
- c) For the two strain ranges of 0.75% and 0.5%, the zero-tension loading mode is more severe than the compression-tension loading mode for equal strain ranges, leading to a definite reduction in LCFL in both the as-received and furnace-sensitized materials.
- d) All but 2 of the 17 specimens under test at the 1% strain range have failed. Surprisingly, both the heavily surface cold-worked and the normal weldment HAZ specimens exhibit significantly longer fatigue lives than the as-received base material. Since neither of these two materials received the flash anneal heat treat and pickling operations** given to the as-received material, there is suspicion (see discussion, Appendix A) that the difference in fatigue life is due primarily to the re-anneal and pickling.

5.3.2.2 Type-304L Stainless Steel (ASTM A-240, T-304L)

To date, 19 failure indications have been received out of the total 28 specimens under test. All nine of the furnace-sensitized Type-304L specimens have failed. The remaining ten failures were divided among four material test conditions:

- Three as-received specimens: two tested at the 1% and one at the 0.5% strain range
- Two welded specimens tested at the 1% strain range
- Three cold worked specimens: two tested at the 1% and one at the 0.75% strain range.
- Two as-received and mechanically notched specimens tested at the 0.5% strain range

All eight of the specimens under test at the 1% level have failed. The fatigue lives of the heavily cold-worked and normal welded specimens are significantly longer than the as-received base material. This observation is consistent with that previously noted for the Type-304 stainless.

The most recent failures occurred in pre-cracked (side-notched) as-received specimens (see Figure 7-3, GEAP-11069). The mechanical pre-cracked specimen was tested to evaluate the degree to which a mechanical notch might promote fatigue failure. Note, however, that for both the as-received and furnace sensitized material conditions, failure data for the notched specimens fall among data from their unnotched counterparts.

* See Table 5-2.

** See GEAP-11069, Section 7.5.1 for summary of specimen heat treat procedures.

5.3.2.3 Inconel-600 (ASTM B-168)

Two additional failure indications were received during the report period, bringing the total number of failure signals received to date to seven of 23 specimens under test. The seven failures represent the following four test conditions:

- Two welded specimens tested at the 1% strain range
- Three furnace-sensitized specimens; two tested at the 1% and one at the 0.75% strain range
- One mechanically-notched, furnace-sensitized specimen tested at the 0.5% strain range
- One as-received specimen tested at the 1% strain range

For the Inconel-600 few environmental data have been obtained even through the cycles accumulated have, in most cases, far exceeded the ASME criteria. Nevertheless several trends have been observed and are noted below:

- a) At the 1% and 0.75% strain range there is much less reduction in fatigue life of the furnace-sensitized Inconel compared to the Inconel in the as-received condition, as compared to both the comparable 304 and 304L material.
- b) At these strain ranges, Inconel in the furnace-sensitized condition exhibits a stronger dependence on strain range than either the 304 or 304L stainless.
- c) Weld heat affected material at the 1% strain range exhibits a greater reduction in fatigue life than the furnace-sensitized material condition.

5.3.2.4 Carbon Steel

All 27 carbon steel fatigue specimens under test had failed prior to the start of this report period. Some of the results are covered in GEAP-10207-24. Fatigue data are shown in Figure 5-5 for convenience.

For the carbon steel material, there seems to be a uniform reduction in fatigue life for all material conditions for the strain range investigated. Statistical evaluation of these data shows that the average environmental fatigue-life reduction factor is approximately ten on cycles. Metallographic examination of several specimens has shown them to be very heavily oxidized and that substantial pitting had occurred. The latter effect is believed to contribute to the failures of the carbon steel specimens.

5.3.3 Metallurgical Evaluation

Metallurgical evaluation of selected specimens removed from the Dresden test vessel is continuing. This includes detailed metallography and scanning electron microscopy (SEM). A discussion of the specific work completed to date is given in Appendix A.

5.4 500°F BASELINE AIR TESTS

Efforts continue to generate 500°F baseline air data for comparison with the Dresden 1 BWR data. A smaller version (in terms of the number of fatigue specimens which can be tested at one time) 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 is 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 the internal cavity automatically signals specimen failure.

5.4.1 Air Data

Testing of the second series of 12 specimens is continuing. To date, failure indications have been received from 6 of these specimens. Pertinent data are given in Table 5-4 and are shown compared to the ASME criteria data curve and corresponding D-1 BWR data in Figures 6, 7, 8 and 9.

5.5 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 in the BWR environment for four materials under cyclic loading. Data obtained will complement the crack initiation data generated in the dynamic test vessel. A schematic of the test vessel system is shown in Figure 10, while photographs of the equipment is shown in Figures 11 and Figure 15.

5.5.1 Hardware Procurement

All of the hardware needed for this task is on hand. A control console (Figure 15) has been designed and built to contain the control equipment for the hydraulic loading system, signal conditioning and recorders for the COD transducers. It is now undergoing final calibration and checkout in San Jose. The test vessel was connected to a General Electric test loop and briefly operated with 500°F, 1000 psig demineralized water to verify that the sliding shaft seals functioned properly. Several minor problems have been encountered with the hydraulic load system necessitating replacement of servo-valve seals. Nevertheless, preparations are underway to operate the vessel and control console with a full complement of seven 2T-WOL (Figure 12) test specimens. Crack growth data will be generated in this 3 to 4 week test under simulated BWR conditions.

5.5.2 D-1 Test Loop Modification

The engineering drawings for the piping modifications to the D-1 test vessel and the electrochemical measurement station loop to accommodate the new design are nearly complete. Orders are being placed for the pipe, valves and fittings required for this modification.

5.5.3 Compliance Calibration

A Type-304 stainless steel, 2T-WOL specimen in the as-received condition was tested to failure under cyclic loading at room temperature in air (see Figure 5-17, GEAP-10207-28). Pertinent test parameters are listed in Table 5-5. Measurements of the surface crack lengths on both sides of the specimen were made using a traversing microscope. A computer program was developed to use the resulting raw crack length versus cycles data and the specimen geometry and loading parameters to generate a best fit line for $\log (da/dN)$ versus $\log \Delta K$ (stress intensity range) using multiple regression techniques. The resulting best fit line is shown in Figure 13 compared to other data for 304 stainless steel based on wide plate tests¹ and 1T-WOL² specimens. In addition, the specimen COD (crack opening displacement) which was continuously monitored using the canned LVDT's, destined for use in the 500°F, 1000 psig Dresden 1 primary coolant environment, is compared to the value calculated using equations from Novak and Rolfe³ in Figure 14. The agreement between the predicted and measured COD's is acceptable.

¹ GEAP-5082, TASK D-1 Figure 6-1

² GE in-house data (not published)

³ "Modified WOL Specimen for K_{Isc} Environmental Testing," Novak and Rolfe

Table 5-4
FATIGUE SPECIMEN TEST PLAN
SERIES IV BASELINE "AIR" TESTS

Specimen Number	Material	TIP Deflections (inches)	Testing Rate (cph)	Cycles to Failure
141	Type 304 SS, As Received	$\pm 0.094^{(a)}$	8	8786
145	Type 304 SS, As Received	$\pm 0.094^{(a)}$	8	8933
169	Type 304 SS, As Received	+0.156 $-0.000^{(c)}$	8	----
164	Type 304 SS, As Received	$\pm 0.078^{(b)}$	8	----
1	Type 304L SS, As Received	$\pm 0.094^{(a)}$	8	6837
1068	Type 304L SS, As Received	$\pm 0.078^{(b)}$	8	11,126
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	9023
1016	A-516 Carbon Steel, As Machined	$\pm 0.086^{(a)}$	8	10,119
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.

Table 5-5
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

Figure 5-6. 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 5-7. Equivalent Stress Amplitude versus Cycles to Failure for Type-304L Stainless Steel.
Comparison of fatigue data from BWR environment with 500°F Air baseline case.

Figure 5-8. 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 5-9. Equivalent Stress Amplitude versus Cycles to Failure for A516 Carbon Steel.
Comparison of fatigue data from BWR environment with 500° F air baseline case.

Figure 5-10. Test Vessel III Test Scheme

a. Installation of Specimens Inside Loading Columns

b. Closeup of In-Situ COD Transducer Mounted on 2T-WOL

Figure 5-11 Test Vessel III Hardware

PART NO.	SPEC. NO.	B	W	C	D	E	F	G	H	L	M	N	ϕ	P	R	S
2	2T-B	2.000 ^{+1.00}	5.110	6.200	0.188	1.540	1.500	2.480	4.960	0.100	0.094	0.350 ^{+0.11}	1.600 ^{+0.005}	—	NO	YES

NOTES

1. 0.0017" MAX. RADIUS (EDM).
2. LAY MARKS TO FALL PARALLEL TO AXIS OF RADIUS SURFACE FINISH TO BE 32/.

Figure 5-12. 2T-WOL Specimen for Crack Growth Rate Study of Task K_c

Figure 5-13. Baseline Tests, 2T-WOL, Type-304 SS, Room Temperature

Figure 5-14. Measured Crack Opening, Displacement versus Crack Length

Figure 5-15. Test Vessel III Control Console

APPENDIX A

METALLURGICAL EXAMINATION TASK K FATIGUE SPECIMENS

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

OBJECTIVE

The objective of this subtask is to perform a metallurgical examination of the Task K fatigue specimens. This includes the identification and characterization of the mode of failure for these specimens and providing a rationale on the effect of metallurgical condition and environment on the fatigue lives of the specimens.

SUMMARY

Post-test metallurgical examinations have been performed on fatigue specimens of Types AISI-304 and -304L stainless steel, Inconel-600 and A-516 carbon steel tested under Task K. The 304 and 304L stainless steel specimens were examined in the flash-annealed,* furnace-sensitized, surface cold-worked and as-welded conditions. Two welded Inconel-600 specimens and specimens of A516 carbon steel in the as-machined and as-welded condition, with or without stress relief, have also been examined. All specimens had been tested to failure in the Dresden I Nuclear Power Station (D-I) primary reactor water environment. Scanning electron microscopy (SEM) and optical metallography were used to examine the fracture surfaces and to identify the mode of failure of the specimens. The SEM and metallographic examination has been completed on the initial group of specimens. The examinations revealed the following:

1. The increased fatigue life of the as-received, machined, and non-pickled 304 and 304L stainless steel relative to that of flash-annealed, pickled material may be associated with pickling which may provide a source of micro-crack initiation at the grain boundaries. Pickling may play an important role in the micro-crack initiation of furnace-sensitized 304 and 304L stainless steel as well.
2. The failure mode in flash-annealed, pickled 304 and 304L stainless steel is transgranular with micro-crack initiation appearing to be intergranular.
3. Micro-crack initiation and the failure mode in as-received, machined, non-pickled 304 and 304L stainless steel is transgranular.
4. Micro-crack initiation in flash-annealed, pickled, furnace-sensitized 304 and 304L stainless steel is intergranular. The fracture is mixed mode i.e., inter- and intragranular.
5. Fracture of the D-1 pipe weld specimens is mixed mode suggesting sensitization which may be associated with welding, although the weld HAZ could not be positively identified.
6. The "river bed" appearance of the fracture surface and the failure mode of air-tested 304 stainless steel appears much the same as that of flash-annealed, pickled tested in the high purity water.
7. The mode of failure for welded Inconel-600 is mixed, partly intergranular and partly transgranular. The failure occurred in heat-affected-zone (HAZ).
8. The fatigue failure in the A-516 carbon steel is transgranular. Welding or stress relief heat treatment had no effect on the mode of failure of these specimens.
9. Although welding introduces a variation in microstructure, i.e., grain size, the fatigue life of the A-516 carbon steel specimens is not affected by the welding process in this environment.
10. The stress relief heat treatment affects the fatigue life of A-516 carbon steel in a manner which is not presently understood.

*Heat treatment at 1800°F in air for 5 to 10 minutes, water quench; pickle with an HCL-HF etchant.

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 I 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.

RESULTS OF METALLURGICAL INVESTIGATION

A. AISI Types-304 and 304L Stainless Steel

SEM fractography and optical metallography have been performed on more than twenty specimens of 304 and 304L stainless steel. The metallurgical condition of these specimens included; (1) flash anneal, (2) flash anneal plus furnace sensitization, (3) plunge ground surface cold worked, (4) as welded and (5) welded D-1 pipe (see GEAP-10207-28 for details of specimen preparation). The fatigue test environments included the D-1 recirculation water at 510°F and test in air at 500°F.

1. SEM and Optical Metallography

a. Flash-Annealed Types-304 and -304L Stainless Steel

A typical fracture surface of a flash-annealed 304 stainless steel specimen is illustrated in Figure 1a. A fine grain, recrystallized region at the bottom of the SEM fractograph is readily identified. The observed river bed, quasi-cleavage appearing fatigue fracture is typical for 304 and 304L stainless steel tested in the BWR environment. An example of fatigue striations, which were observed at high magnification on the fractured surface, is shown in Figure 1b. Measurements of these striations yield a crack growth rate of approximately 1×10^{-4} inches/cycle. The fracture appearance of the surface cold-worked 304L stainless steel specimen investigated in this study is shown in Figure 2a. At low magnification the fracture appearance indicates flat-fracture not unlike the fracture appearance of 304 stainless steel tested in boiling MgCl_2 stress corrosion tests. However at higher magnification, fatigue striations are clearly evident as shown in Figure 2b. Also shown in this Figure are octahedral oxide crystals which partially covered the fracture surface. The crack growth rate, as measured from Figure 2b, is approximately 7×10^{-5} inches/cycle.

Base line fatigue data were determined by air tests on flash-annealed 304 stainless steel. A fractograph of a typical air-tested 304 stainless steel specimen is shown in Figure 3a. For this specimen, the crack initiated at the top of Figure 3a and advanced toward the bottom of the figure. When the specimen signalled failure, the test was stopped and the remaining ligament holding the specimen was pulled apart at room temperature. The ductile fractography seen at the extreme bottom of the figure is the result of specimen removal and not representative of the fatigue test. Recognizing this fact, the fractography shows a flat-fracture with a river bed appearance. Observations at much higher magnification revealed fatigue striations on the fracture surface (Figure 3b). The striation spacing is approximately 1.5×10^{-5} inches. Crack growth rate for this specimen varied from approximately 1.5×10^{-5} inches/cycle to 8×10^{-5} inches/cycle.

Metallographic examinations of cross sections of the flash-annealed 304 and 304L stainless steel revealed the fracture to be transgranular. A macrograph of the specimen in the area of the fracture is shown in Figure 4a, a flash-annealed 304 stainless steel specimen. The fracture is transcrystalline. This is supported by the higher magnification view of Figure 4b. Also evident in this figure are the very fine recrystallized grains which have formed at the surface and the many small secondary cracks penetrating these grains and extending into the large grain material. Observations on another 304 stainless steel specimen in flash-annealed condition revealed identical results.

Figure 1a. SEM Fractograph of Flash-Annealed and Pickled 304 SS (100X). Specimen No. 187 (2999)

Figure 1b. Fatigue Striations on Fracture Surface of Specimen Shown in Figure 1a (1000X). Specimen No. 187 (3109)

Figure 2a. Fracture Surface of Plunge Ground Cold-Worked 304L SS (300X). Specimen No. 1135 (2996)

Figure 2b. Fatigue Striations on Fracture Surface of Specimen shown in Figure 2a (1000X). Specimen No. 1135 (3452)

Figure 3a. Fracture Surface of Air-Tested 304 SS (100X). Specimen No. 204 (3840)

Figure 3b. Fatigue Striations on Fracture Surface of Specimen Shown in Figure 3a (3000X). Specimen No. 204 (3841)

Figure 4a. Cross Section of Flash-Annealed and Pickled 304 SS (22X). Specimen No. 187.

Figure 4b. Higher Magnification View of Specimen Shown in Figure 4a (100X). Specimen No. 187

A cross section of the fracture and machined surface for a specimen of 304 stainless steel tested in air at 500°F is shown in Figure 5a. The fracture surface is at the top of the figure and the fracture is seen to be transcrystalline. The fine recrystallized grains can be observed at the machined surface and much secondary cracking is apparent. A higher magnification micrograph of the secondary cracks emanating from the machined surface is shown in Figure 5b. False cracks appear to have formed at grain boundaries and have proceeded in a transgranular manner into the large grain material.

The fatigue fracture and machined surface for the cold-worked 304L specimen are shown in Figure 6. The fracture is seen to be transgranular and only one small secondary crack can be found. The thick oxide surface which formed on this specimen and was shown in GEAP-10207-28 has been etched black and appears as black background and, therefore, is not evident in this figure.

In the previous progress report (GEAP-10207-28) a specimen of 304L stainless steel which had been welded was examined metallographically to locate the weld and heat-affected-zone (HAZ). The macrograph of Figure 7a shows that the weld and HAZ are clearly well removed from the fracture surface with the weld being approximately 0.125 inch from the fracture. As a result of this observation, this specimen will be treated as an as-received mill-annealed (no flash anneal and pickle) rather than as a welded specimen. Figure 7b shows the fracture surface and an edge of the machined surface, which shows evidence of surface cold working. However, the grain size is uniform; no recrystallized grains can be seen. In addition, the substantial amount of secondary cracking observed in the flash-annealed material is absent in this specimen. It is interesting to note that secondary cracks were also absent in the surface cold-worked 304L stainless steel. In these specimens without the secondary cracking, a longer fatigue life was exhibited under the same test condition. This behavior is believed to be related to two factors. First, the specimens were not pickled. The effect of pickling is to introduce grain boundary attack which may become a mechanical crack nucleator by acting as a local stress concentrator. Second, the machining of these specimens, following the final heat treatment, may introduce residual compressive stresses which are beneficial to enhancing fatigue life. It is noteworthy that the secondary cracking observed for the flash-annealed 304 and 304L stainless steel in the pickled condition appeared to initiate predominantly at grain boundaries, and then the fracture mode shifts and moves transgranularly into the material. If these secondary cracks accurately reflect the micro-initiation behavior of the primary crack, then pickling may play a significant role in reducing the fatigue life of flash-annealed 304 and 304L stainless steel.

b. Furnace-Sensitized 304 Stainless Steel

The fracture appearance of the furnace-sensitized 304 and 304L stainless steel was documented in the previous progress report. However, the effect of pickling on the machined surface was not shown. A statement was made on the fact that the pickling attack observed on the flash-annealed 304 stainless steel was typical of the furnace-sensitized condition as well. Figures 8a and 8b show the grain boundary channelling observed on the surface of a test specimen of 304 stainless steel in the furnace-sensitized condition. The depth of attack and extensive nature of the attack are clearly visible in these micrographs. Pickling is believed to initiate this grain boundary attack which is obviously in an advanced stage because of the cycling loading in the environment.

A cross-section macrograph of a typical furnace-sensitized 304 stainless steel specimen is shown in Figure 9a. Many deep secondary cracks can be seen in this figure. Figure 9b shows the upper-left section of Figure 9a. The primary crack which caused failure is seen to be predominantly transgranular in this region, although the micro-initiation probably began in an intergranular manner. The deep, secondary crack is seen to have initiated and proceeded intergranularly, then switched to a transgranular mode and propagated in that fashion until linking with the primary crack. Figure 9c shows the secondary crack which appears in the left central section of Figure 9a. This crack has initiated and grown in a purely intergranular manner. The crack shown in the upper right section of Figure 9a initiated intergranularly and then switched mode to grow in a predominantly transgranular fashion. For the furnace-sensitized 304 stainless steel investigated in this study the primary crack initiates intergranularly, switches to a transgranular mode and grows as a transgranular crack. The

Figure 5a. Cross Section of Fracture and Machined Surface for Air-Tested 304 SS (100X).

Figure 5b. Secondary Cracking Observed on Specimen Shown in Figure 5a.

Figure 6. Cross Section of Fracture and Machined Surface of Plunge Ground Cold-Worked 304L SS (100X). Specimen No. 1135

Figure 7a. Cross Section of Welded 304L SS (22X). Specimen No. 1076

Figure 7b. Same as Specimen Shown in Figure 7a, Except Higher Magnification (100X). Specimen No. 1076.

Figure 8a. Surface of Fatigue Specimen of Pickled Furnace-Sensitized Flash-Annealed 304 SS (300X). Specimen No. 147 (3013)

Figure 8b. Same as Figure 8a, Except Higher Magnification (1000X). Specimen No. 147 (3014)

Figure 9a. Cross Section of Furnace-Sensitized 304 SS (22X). Specimen No. 166

Figure 9b. Secondary Crack, Mixed Mode, of Specimen Shown in Figure 9a.

Figure 9c. Same Specimen as Shown in Figure 9a, Except at Higher Magnification (100X). Specimen No. 166.

secondary cracks initiate intergranularly and propagate either as intergranular cracks or as transgranular cracks depending on the stress intensity. At high stress intensities the crack propagation mode may change to transgranular whereas at low stress intensities the crack may remain intergranular. It is basically from the transgranular regions on the fracture surface that fatigue striations were observed and measured.

Although, the data are not conclusive it appears that pickling affected the fatigue life of the furnace-sensitized specimens by providing chemical crevices which can act as nucleation sites for intergranular attack as well as mechanical crack nucleation sites.

c. **Welded Type-304 Stainless Steel**

The only welded specimen of 304 or 304L stainless steel that has been examined to date (with the exception of the D-1 pipe weld specimens) was described in an earlier section. This specimen of 304L stainless steel was identified to have the weld and HAZ well removed from the fracture surface and subsequently behaved in the fatigue test like a mill-annealed, machined specimen.

Four specimens from a welded D-1 pipe have been examined by the SEM and metallography. The specimen fractography, as typified by Figure A-15 of GEAP-10207-28, was of mixed mode, i.e., intergranular and transgranular failure. A cross section micrograph of one of the D-1 weld pipe specimens is shown in Figure 10a. As seen in this figure no weld metal is evident in the specimen. It is assumed that the weld was located in the hinge section which is still in the test fixture at Dresden. The fracture appearance is mixed mode although in this figure the appearance is mainly transgranular. There are no recrystallized grains at the surface, however there is evidence of cold work as shown in Figure 10b. only a few secondary cracks were observed. These appeared to initiate intergranularly and switch to a transgranular mode during crack propagation.

Based on the SEM and metallographic evidence, it appears that the D-1 pipe weld specimens have been at least partially sensitized. The fractography and metallography clearly show the failure mode to be mixed. However, it is not certain if this behavior is a result of welding or some other previous thermal mechanical history, since the weld was not located visually. Further investigation including a comparison with the non-welded D-1 pipe material is required to determine the cause of behavior for this material.

B. INCONEL-600

a. **Welded Inconel-600**

The two specimens of welded Inconel-600 examined by the SEM and reported in GEAP-10207-28 have been examined by metallography. A micrograph of one of the specimens is illustrated in Figure 11. As seen in this figure, the fracture is clearly in the weld HAZ. The fracture was also in the weld HAZ of the other Inconel-600 specimen. This material was characterized by a high degree of deformation as evidenced by slip bands near the fracture. The failure mode for these welded specimens was mixed, partly intergranular and partly transgranular. The small secondary cracks seen at the upper left of Figure 11 appear to initiate intergranularly and propagate transgranularly.

b. **Air-Tested Annealed Inconel-600**

A SEM fractograph of Inconel-600 tested in air at 500°F is shown in Figure 12a. The crack front proceeded from right to left and the fatigue test was terminated as the crack front was positioned in the center of the figure. The ductile dimpled rupture shown in the left half of the figure was not part of the fatigue test but part of the post-test removal. At higher magnification, however, as seen in Figure 12b, ductile fatigue striations are in evidence. The crack growth rate, as measured by fatigue striation spacing, was approximately 4×10^{-5} inches/cycle.

Figure 10a. Cross Section of DNPS-1 Pipe Weld 304 SS (22X). Specimen No. 1148

Figure 10b. Secondary Crack on Machined Surface of Specimen Shown in Figure 10a (250X). Specimen No. 1148

Figure 11. Cross Section of As-Welded Inconel 600 (100X). Specimen No. 1042

Figure 12a. Fracture Surface of Air-Tested Inconel 600 (100X). Specimen No. 118 (4042)

Figure 12b. Striation Spacing for Air-Tested Inconel 600 (3000X). Specimen No. 118 (4039)

C. A-516 CARBON STEEL

A total of ten A-516 carbon steel specimens were examined by SEM and optical metallography. The specimens were in the as-machined or as-welded conditions, with or without a stress relief heat treatment. The stress relief was performed at 1150°F in air for two hours followed by an air cool. The fatigue testing was performed either in the D-1 recirculating water environment at 510°F or in the laboratory at 500°F in air.

a. As-Machined A-516 Carbon Steel

All of the specimens of A-516 carbon steel tested at D-1 had a heavy corrosion product on both the machined and fractured surface. This corrosion product precluded SEM characterization of the fracture and measurement of fatigue striation spacing. The air-tested specimens were also oxidized during the air fatigue test. However, the oxidation did not totally obliterate the fracture surface, and some fatigue striation was observed. Figure 13a shows the fracture surface of an air-tested as-machined A-516 carbon steel specimen. The crack front for this specimen proceeded from the bottom of the figure toward the top. A ductile fracture region is evident at the top of the fractograph. This ductile rupture region was formed during the specimen removal and not during the fatigue test. Also evident in the figure are elongated stringers formed from included particles. In Figure 13b, fatigue striations are shown on an as-machined A-516 specimen tested in air. These striations were located in the flat fatigue fracture in the vicinity of the ductile rupture. The crack growth rate, as estimated from striation spacing, was approximately 2×10^{-5} inches/cycle.

The cross section of the fracture surface for a specimen of A-516 carbon steel is shown in Figures 14a through 14c. The specimen is an as-machined carbon steel specimen with a stress relief heat treatment. In Figure 14a the fracture is seen to be rather flat and planar and a few secondary cracks are evident. Figures 14b and 14c are unetched and etched views of a portion of the fracture surface. In Figure 14b the corrosion product which covered and obscured the examination of the fracture surface is clearly evident. The large secondary crack in Figures 14b and 14c is filled with corrosion product and is growing in a transgranular manner into the carbon steel. There was no significant microstructural difference between the stress relieved and the as-machined specimens to account for the difference in fatigue life between the specimen conditions.

b. Welded A-516 Carbon Steel

As in the case of the as-machined carbon steel, the corrosion product that occurred in the high purity water made it impossible to evaluate the fracture of the welded specimens of A-516 carbon steel by SEM. Optical metallography was performed on all of the welded fatigue specimens to identify the mode of failure and to locate the weld relative to the fracture surface. In all cases, the failure mode was transgranular with small secondary cracking observed for some of the specimens. Table A-1 identifies the location of the weld HAZ relative to the minimum test section (MTS) and relative to the fracture for each of the welded specimens of A-516 carbon steel.

Figure 15a shows a macrographic cross section of a welded stress-relieved A-516 carbon steel specimen. In Figure 15b the fracture is shown proceeding through the fine-grained HAZ. A substantial amount of grain refinement is seen for this specimen when compared to an as-machined, stress-relieved specimen of carbon steel (Figure 14c). In the companion specimen, the fracture is out-of-the-weld HAZ and the grain size approximates that of the as-machined, stress-relieved specimen. It is noteworthy that both welded specimens, stress-relieved together and strained at the same strain range, had nearly identical lives even though the fracture passed through the weld HAZ in one case and clearly missed the weld HAZ in the other. This observation supports the fatigue data which indicates that welding process has a negligible effect on the fatigue life of these specimens in this environment.

In the case of one carbon steel specimen welded with no stress relief, the HAZ was at the minimum test section (MTS) and the failure occurred elsewhere. Figure 17a shows a macro cross section of the fracture of the specimen. As is seen in this figure, two small fatigue cracks are seen at the MTS but

they appear to have been arrested in the extremely fine grain structure in the HAZ. The fatigue failure occurred in the coarse grain base material. The fatigue life of this specimen was essentially the same as that of the companion specimen where the crack proceeded through the weld HAZ.

As in the case of the as-machined A-516 carbon steel specimens, no microstructural differences were observed between the stress-relieved welded specimens and the non-stress-relieved welded specimens to account for the differences in the fatigue lives of the specimens. The investigation is continuing to determine the source of the fatigue life reduction due to the stress relief heat treatment.

Table A-1
METALLOGRAPHIC IDENTIFICATION OF WELD HAZ IN A-516 CARBON STEEL

Classification:

- I HAZ at MTS, Failure in HAZ
- II HAZ at MTS, Failure not in HAZ
- III HAZ not at MTS, Failure in HAZ
- IV HAZ not at MTS, Failure not in HAZ

Specimen Number	Strain Range (%)	Heat Treat Condition	Classification
1060	1	Stress Relieved	I
1059	1	Stress Relieved	IV
1053	1	No Stress Relief	II
1052	1	No Stress Relief	I
1058	0.75	No Stress Relief	I
1017	0.75	Stress Relieved	I
1061	0.75	Stress Relieved	I
1018	0.5	Stress Relieved	I
1019	0.5	Stress Relieved	I
1055	0.5	No Stress Relief	II
1056	0.5	No Stress Relief	I

Figure 13a. Fracture Surface of Air-Tested A-516 Carbon Steel (100X). Specimen No. 1044 (3844)

Figure 13b. Striation Spacing on Fracture Surface of Air-Tested A-516 Carbon Steel (1000X). Specimen 1045 (4078)

Figure 14a. Cross Section of As-Machined and Stress-Relieved A-516 Carbon Steel (22X). Specimen No. 1009

Figure 14b. Micrograph of Polished Cross Section of As-Machined and Stress-Relieved A-516 Carbon Steel Showing Fracture Surface (250X). Specimen No. 1009

Figure 14c. Micrograph of Polished and Etched Cross Section of As-Machined and Stress-Relieved A-516 Carbon Steel Showing Fracture Surface (250X). Specimen No. 1009

Figure 15a. Cross Section of Welded and Stress-Relieved A-516 Carbon Steel (22X). Specimen No. 1060

Figure 15b. Fracture and Secondary Crack in Very Fine Grain Region of Welded and Stress-Relieved A-516 Carbon Steel (250X). Specimen No. 1060

Figure 16. Cross Section of Welded A-516 Carbon Steel (22X). Specimen No. 1053

DISTRIBUTION

	Copies
U. S. Atomic Energy Commission	139
Division of Technical Information Extension	
P. O. Box 62	
Oak Ridge, Tennessee	