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OCTOBER 1971

**REACTOR PRIMARY COOLANT SYSTEM
RUPTURE STUDY
QUARTERLY REPORT No. 25
JULY-SEPTEMBER 1971**

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

ATOMIC POWER EQUIPMENT DEPARTMENT
GENERAL ELECTRIC

SAN JOSE, CALIFORNIA

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ABSTRACT

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

1. INTRODUCTION

The Reactor Primary Coolant System Rupture Study is being conducted for the Division of Reactor Development and Technology, USAEC. This Progress Report No. 25 documents work done in the period, July 1 to September 30, 1971. The overall objective of the program is to improve the reliability of reactor system piping by increasing current knowledge of failure-causing mechanisms and by enhancing capability for design evaluation and analysis.

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

- Task A—Probability Study
- Task D—Low-Cycle Fatigue
- Task K—Effect of BWR Environment

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

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

Quarterly Reports

GEAP-4911	Reactor Primary Coolant System Rupture Study Quarterly Progress Report No. 1, April—June 1965.
GEAP-4964	No. 2, July—August 1965.
GEAP-5082	No. 3, October—December 1965
GEAP-5147	No. 4, January—March 1966.
GEAP-5192	No. 5, April—June 1966.
GEAP-5279	No. 6, July—September 1966.
GEAP-5427	No. 7, October—December 1966.
GEAP-5474	No. 8, January—March 1967.
GEAP-5512	No. 9, April—June 1967.
GEAP-5554	No. 10, July—September 1967.
GEAP-5587	No. 11, October—December 1967.
GEAP-5637	No. 12, January—March 1968.
GEAP-5680	No. 13, April—June 1968.
GEAP-5716	No. 14, July—September 1968.
GEAP-5770	No. 15, October—December 1968.
GEAP-10024	No. 16, January—March 1969.
GEAP-10072	No. 17, April—June 1969.
GEAP-10120	No. 18, July—September 1969.
GEAP-10143	No. 19, October—December 1969.
GEAP-11069	No. 20, January—March 1970.
GEAP-10207	No. 21, April—June 1970.
GEAP-10207-22	No. 22, July—September 1970.
GEAP-10207-23	No. 23, October—December 1970.
GEAP-10207-24	No. 24, January—June 1971

Topical Reports

GEAP-4445	A Survey of Water Reactor Primary System Conditions Pertinent to the Study of Pipe Rupture, January 1964.
GEAP-4446	A Review of Fracture Modes as Related to Reactor Primary Coolant Pipe Rupture, May 1964.
GEAP-4474	Experimental and Analytical Program Recommendations—Reactor Pipe Rupture Study, January 1965.
GEAP-4574	Survey of Piping Failures for the Reactor Primary Coolant Pipe Rupture Study, May 1964.
GEAP-4578	Mechanical Design Considerations in Primary Nuclear Piping, March 1964.
GEAP-4678	Fracture Mechanics and the Stability of Engineering Structures, September 1965.
GEAP-5014	Fracture Toughness of Some Engineering Alloys, March 1966.
GEAP-5410	Low-Cycle Fatigue Strength Reduction in Notched Flat Plates, January 1967.
GEAP-5471	PAPA—Structural Analysis of Plates and Shells Using Trapezoidal and Triangular Plate Elements, March 1967.
GEAP-5553	PAPA—The Digital Computer Program for the Static Analysis of Structures Made up of Plate and Panel Elements, October 1967.
GEAP-5557	Stress Intensity for a Circumferential Through-Wall Crack in a Straight Pipe, January 1968.
GEAP-5607	Fatigue Crack Growth in Nuclear Reactor Piping Steels, March 1968.
T&AM-677	A Three-Dimensional Photoelastic Study of Stress Near Cracks in Shell Structures, University of Illinois, March 1968.
GEAP-5620	Failure Behavior in ASTM A 106-B Pipes Containing Axial Through-Wall Flaws, April 1968.
GEAP-5622	A Failure Diagram for Axially Flawed Pipes, April 1968.
GEAP-5653	Status of Pipe Rupture Study at General Electric—II, July 1968.
GEAP-5714	Notched High-Strain Fatigue Behavior of Three Low-Strength Structural Steels, September 1968.
GEAP-5724	BWR Primary Piping Stresses for System Reliability Analysis, September 1968.
GEAP-5726	Influence of Stress/Strain Concentration and Mean Stress on the Low-Cycle Fatigue Behavior of Three Structural Steels at Room Temperature, September 1968.
GEAP-10007	Restart for the PAPA Program, March 1969.
GEAP-10090	The 550°F Notched High-Strain Fatigue Behavior of Three Low-Strength Structural Steels, August 1969.
GEAP-10135	Low-Cycle Fatigue of Prototype Piping, January 1970.

- GEAP-10140 The Effect of Cyclic Strain Aging on the Embrittlement of a Plain Carbon Steel Plate, July 1970.
- GEAP-10170 The Effect of Stress Concentration on the Low-Cycle Fatigue of Three Low-Strength Structural Steels at Room Temperature and 500°F, March 1970.
- GEAP-10181 Low Cycle, Strain Controlled Fatigue Crack Propagation in Nuclear Piping Steels, May 1970
- GEAP-10205 Status of Pipe Rupture Study at General Electric Company, Part III, June 1970.
- GEAP-10236 Failure Behavior of Flawed Carbon Steel Pipes and Fittings, October 1970.

2. SUMMARY

2.1 TASK A—PROBABILITY STUDY

A compilation from several sources of conventional plant steam piping failure rates indicates values from 1.67×10^{-3} to 44.3×10^{-3} events per plant year, where an event is either leakage or severance. The assumptions used in the leak and severance analysis appearing in the Twenty-Third Quarterly Progress Report, GEAP-10207-23, led to an average estimate of 40×10^{-3} to 90×10^{-3} events per plant year. Thus, while the analysis draws heavily upon judgmental input, the results are of the same order of magnitude as published experience.

2.2 TASK D-3—PROTOTYPE PIPE FATIGUE

Testing was completed on the series of three axially notched piping specimens and started on a series of three 550°F stainless steel girth-welded specimens. The following were tested during the report period:

- a. CCANS-160-1—Room temperature, carbon steel, axially-notched specimen at PWR pressure
- b. HW-10—550°F stainless steel welded specimen.

Testing was started on specimen HW-11, the second of the three girth (butt)-welded, Type-304 stainless steel prototype pipes.

2.3 TASK D-5—FATIGUE DATA FOR PIPING CODE

A newly installed materials testing system (MTS) has been made available for conducting the fatigue tests of this task. Materials for testing have been received and specimens for determining the monotonic and cyclic stress-strain properties of the materials (needed for the analysis) are being fabricated. The checkout of the computer code and the procedures to be used for the elastic-plastic analysis of the test specimens has been completed. Representative results obtained for the sample problem are presented. The results show that notch strains can be calculated with good accuracy.

2.4 TASK K—EFFECT OF BWR ENVIRONMENT

The Dresden 1 test loop has accumulated 3800 hours of operation at test conditions (510° F, 1040 psig). A total of 84 of the 149 fatigue specimens being cyclically loaded in the loop have failed: 38 out of 71 Type-304 stainless steel, 16 out of 28 Type-304L stainless steel, 3 out of 23 Inconel-600, and all of the 27 carbon steel specimens. The first series of high-temperature tests to establish baseline curves is under way in the air test facility in San Jose. The unit has accumulated a total of 1000 hours of operation at design test conditions. All of the first ten air test specimens have signalled cracking. Design of the third vessel (crack growth fatigue unit) neared completion. The vessel will be installed in the Dresden 1 loop following shakedown testing at San Jose.

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

3.1 OBJECTIVES

The objectives of the probability study task are to develop methods for:

- Estimation of the reliability of a reactor primary piping system in terms of leak rate and time of reactor service.
- Identification of the principal sources of real variability or uncertainty in service life.

3.2 SUMMARY

A compilation from several sources of conventional plant steam piping failure rates indicates values from 1.67×10^{-3} to 44.3×10^{-3} events per plant year, where an event is either leakage or severance. The assumptions used in the leak and severance analysis appearing in the Twenty-Third Quarterly Progress Report, GEAP-10207-23, led to an average estimate of 40×10^{-3} to 90×10^{-3} events per plant year. Thus, while the analysis draws heavily upon judgmental input, the results are of the same order of magnitude as published experience.

3.3 HISTORICAL EXPERIENCE, STEAM PLANT PIPING FAILURE RATE

In Table 3-1 appears a tabulation, drawn from several sources, of failure rates of steam plant piping. It can be seen that the judgmental input used in the leak and severance analysis appearing in the Twenty-Third Quarterly Progress Report, GEAP-10207-23, led to failure rates of the same order of magnitude as those tabulated from related experience.

Table 3-1
HISTORICAL EXPERIENCE:
STEAM PLANT PIPING FAILURE RATE SUMMARY

	Source	No of Events* And Population	Rate: Events Per Plant Year
1.	Records, National Bureau of Casualty Underwriters: 4-1/2 years to 6/61. Steam, feedwater and blowoff piping on watertube boilers of > 10,000 sq. ft. heating surface. Reported in Reference 1.	Not reported	1.67×10^{-3}
2.	Survey by UKAEA AHSB: British and US power and research reactors to 6/67, primary circuit envelope. Reported in Reference 2.	17 events in 1352 reactor years	12.6×10^{-3}
3.	Survey by Pipe Study to 2/29/64: largely steam plant piping, 75% of replies from utilities. Reported in Reference 1.	399 events by 0.3 of utilities, in 30,000 unit years for all utilities, based on Reference 4.	44.3×10^{-3}
4.	"Leak and Severance Analysis" reported in Reference 3.	Not applicable	$40-90 \times 10^{-3}$

* "Event" is either leak or severance

3.4 REFERENCES FOR SECTION 3

1. Gibbons, W. S. and Hackney, B. D., *Survey of Piping Failures for the Reactor Primary Coolant Pipe Rupture Study*, May 1964 (GEAP-4574).
2. Phillips, C. A. G. and Warwick, R. G., *A Survey of Defects in Pressure Vessels Built to High Standards of Construction and its Relevance to Nuclear Primary Circuit Envelopes*, 1968 [AHSB (S) R 162] . Only Sections 43 to 51 are reported herein.
3. *Reactor Primary Coolant System Rupture Study, Quarterly Progress Report No. 23*, October–December 1970 (GEAP-10207-23), Section 3.
4. *Steam-Electric Plant Construction Cost and Annual Production Expenses*, Seventeenth Annual Supplement, 1964, Federal Power Commission. This report gives number of units and first year of operation at a plant site. Total unit-years in the United States was estimated by sampling, and assigning intervening startup years to units in keeping with the growth of the electric power industry.

4. TASK D—LOW CYCLE FATIGUE

4.1 OBJECTIVE

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

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

4.2.1 Summary

Testing was completed on the series of three axially notched piping specimens and started on a series of three 550°F stainless steel girth-welded specimens. The following were tested during the report period:

- a. CCANS-160-1—Room temperature carbon steel axially notched specimen at PWR pressure.
- b. HW-10—550°F stainless steel welded specimen.

Testing was started on specimen HW-11, the second of the three girth (butt)-welded, Type-304, stainless steel prototype pipes. A summary of the test data is given in Table 4-1.

4.2.2 Data Obtained

a. Axially Notched Pipe Specimens

A series of three axially notched specimens was tested to determine whether or not axial notches in straight pipe sections pressurized at BWR or PWR pressures and fatigue tested would leak or break. Failure in all three specimens was a leak rather than a sudden break. After failure analysis, these specimens showed no crack initiation or growth at any point in the machined notch. Figure 4-1 shows sections of the uncracked machined notches of the three specimens. Penetration by cracking (and consequent leakage) occurred either at a weld* or in the pipe wall [see Figure 4-1(c)]. A stress analysis was performed according to the procedure specified in the Nuclear Power Piping Code B 31.7, as if these were room temperature weld specimens. Results of the analysis are shown in Table 4-2 and plotted in Figure 4-2.

b. Girth-Welded Stainless Steel Pipe Specimens

Of the three 550°F stainless steel weld specimens planned one was completed and a second test started. These tests and previous weld tests were analyzed according to the procedures of B 31.7, and the results of the analysis are shown in Table 4-2 and in Figure 4-2.

Through-wall leakage was used as the failure criterion here because crack initiation data could not be obtained in all cases. A factor of safety is given in Table 4-2 which is defined as the ratio of the number of full amplitude stress cycles to cause leakage in the test specimen to the number of cycles allowed by the code (design cycles) for the alternating stress intensity range imposed. The stress intensity range was calculated as follows:

$$S_{alt} = 1/2 [S_p + A (S_p - S_n)] \frac{S_n}{3 S_m}$$

$$\text{or } S_{alt} = 1/2 S_n \cdot K_f \cdot \left(\frac{S_n}{3 S_m} \right)$$

where

S_n = The elastic stress range based on the peak-to-peak specimen deflection,

K_f = $S_p/S_n + A (S_p/S_n - 1) = K_t + A (K_t - 1)$,

A = Material property, given in Appendix D of B31.7, and

S_{alt} = Equivalent elastic stress amplitude.

* The pipe-to-flange weld is about 6 inches from the tip of the axial notch.

Table 4-1
SUMMARY OF TEST DATA

Sample Description	Test Temperature (PF)	Internal Pressure (psi)	Nominal Stress Range (psi)	Cantilever End Deflection (in.)	Cycles to Crack Initiation (N_I)	Cycles to Fully Penetrate Wall Nw	Test Termination (N_ϕ)
CCANS-160-1 ASTM A-106 GrB Carbon Steel Schedule 160 Axial Notch	R.T.	2,200	84,500	± 9.00	< 7824	7824	7824
HW-10 ASTM A312 Type 304 Stainless Steel Schedule 80 Weld Specimen	550° F	None	69,000	± 8.00	< 9200	9200	9200
HW-11 ASTM A312 Type 304 Stainless Steel Schedule 80 Weld Specimen	550° F	None	56,700	± 6.25	Test in Progress	Test in Progress	Test in Progress

Table 4-2
RESULTS OF STRESS ANALYSIS

Specimen	Nominal ^(a) Stress Range (ksi)	S _m (ksi)	S _n (ksi)	S _p (ksi)	$\frac{S_n}{3 S_m}$	K _f	S _{alt} (ksi)	N Design	N Leak ^(c)	Safety Factor
										$\frac{N \text{ Leak}}{N \text{ Design}}$
CARBON STEEL HW-1	56.6(58.2)	18	56.6	101.9	1.05	2.36	70.1	1650	36240 (35740)	21.6
HWD-1	62.4(59.2)	18	62.4	112.3	1.15	2.36 ^(b)	84.7	980	15100 (13600)	13.9
STAINLESS STEEL HW-3	63.9(58.7)	16	63.9	115.0	1.33	2.36	100.3	1300	11300 (11300)	8.7
HW-3A	75.3(61.1)	16	75.3	135.5	1.57	2.36	139.5	460	7950 (6950)	15.1
HWD-3	73.4(59.9)	16	73.4	132.1	1.53	2.36 ^(b)	132.5	550	3600 (2600)	4.7
HW-10	81.6(69.0)	16	81.6	146.9	1.70	2.36	163.7	290	9200 (9200)	31.8
HW-11	63.8(56.7)	16	63.8	114.8	1.33	2.36	100.1	1300	Test in Progress	
ROOM TEMP AXIAL NOTCHED SPECIMENS										
CCANS-80-1 Carbon Steel	62.4(60.0)	20	62.4	112.3	1.04	2.36	76.6	1300	26934 (26934)	20.7
CSANS-160-1 Stainless Steel	97.6(83.0)	20	97.6	175.7	1.63	2.36	187.7	200	7456 (7456)	37.3
CCANS-160-1 Carbon Steel	93.5(84.5)	20	93.5	168.3	1.59	2.68	199.2	110	7824 (7824)	71.0

(a) Elastically calculated Stress Range based on peak to peak deflection. The number in parentheses is the stress range based on peak to peak load at shakedown.

(b) Intentionally defective weld specimens. Leakage in HWD-1 did not occur in the weld defect.

(c) Total cycles when crack penetrated through the wall. Number in parentheses is full amplitude cycles at through wall penetration.

(a) RADIAL VIEW OF NOTCHED REGIONS

(b) SECTIONS IN (a) TURNED 90 DEGREES

NUMBER OF CYCLES SHOWN ARE AT TEST TERMINATION

(c) SKETCH OF TYPICAL TASK D-3 AXIALLY NOTCHED TEST SPECIMEN TO SHOW CRACK LOCATIONS WHICH OCCURRED AWAY FROM NOTCHES.

- ① LEAKING CRACK OCCURRED AT THIS WELD ON SPECIMENS CCANS-160-1 AND CSANS-160-1.
- ② LEAKING CRACK OCCURRED IN THE PIPE WALL AT LOCATION SHOWN 3 INCHES FROM NOTCH TIP IN SPECIMEN CCANS-80-1.

Figure 4-1. No Cracking is Evident in Sections Cut from Axially Notched Pipe Specimens. Number of cycles shown are at test termination.

Figure 4-2. Results of Stress Analysis

4.2.3 Tests Remaining

There are four tests remaining to be completed: the last two 550°F stainless steel welded specimens (one now in progress), and two combined cyclic pressurization and bending tests of stainless steel elbows. Several nonexpendable equipment items, required for the 550°F welded stainless steel pipe tests and the cyclic pressure plus bending tests, have been obtained by transfer from another AEC project. The necessary modifications for conducting the cyclic pressure plus bending tests are now under way and should be completed by November. These tests will be started after the current welded stainless steel tests are completed and the system modifications have been made.

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

4.3.1 Objective

The objective of this task is to perform analyses and provide data to confirm or improve nuclear piping fatigue design procedures for nominal stress ranges above 3 Sm. Specifically, the effects of stress concentration, constraint, mode of loading (load versus deflection control), and type of loading (axial versus bending) on the cycles required to produce crack initiation and/or ratchet failure are being investigated.¹ Work toward this objective is proceeding along two parallel paths. Experimentally, the effect of these variables on fatigue resistance will be evaluated on test specimens of Type-304 stainless and A212 carbon steel. Analytically, notch root stresses and strains (directly relatable to crack initiation and ratcheting) will be calculated for various specimen configurations and loads. The analytic tool is an elastic-plastic finite element computer program.

4.3.2 Summary

A newly installed MTS materials testing system has been made available for conducting the fatigue tests of this task. Specimens for determining the monotonic and cyclic stress-strain properties of the materials (needed for the analysis) are being fabricated. Specimen materials have been received.

The checkout of the computer code and the procedures to be used for the elastic-plastic analysis of the test specimens has been completed. Representative results obtained for the sample problem are presented. The results show that notch root strains can be calculated with good accuracy.

4.3.3 Experimental Study

Fatigue testing will be done with the MTS electro-hydraulic universal testing machine shown in Figure 4-3. The system consists of three major components: load frame, electronic control console, and hydraulic power supply (not shown). Special features of the system include maximum static capacity of $\pm 100,000$ pounds, stroke range of 5 inches, and hydraulic grip assemblies to accommodate flat, round, and threaded specimens. Tests can be conducted with load, stroke, or strain as the controlled test variable. Readout devices include a digital load indicator and an X-Y plotter. Programmers include a cyclic wave generator and an arbitrarily programmed data track.

This MTS testing system has recently been delivered and installed at General Electric's San Jose Development Engineering Laboratory facility. Preliminary shakedown and acceptance tests have been completed.

The pipe materials to be studied are Type-304 stainless steel and carbon steel. Both materials have been received, and each is out of a single heat. The carbon steel was obtained in the form of a 2-1/2-inch-thick plate. Type-304 stainless steel is in 2-inch-diameter bar stock. The chemical (mill) analyses for these materials are given in Table 4-3.

Figure 4-3. MTS Materials Testing System

Test specimens for generating monotonic and cyclic stress-strain properties are currently being fabricated. Two sizes of specimens will be tested. Specimen details are shown in Figure 4-4. Standard tensile properties will be measured under a monotonically increasing strain controlled ramp loading. Cyclic properties will be determined with completely reversed strain control testing. In the cyclic test, specimens will be cycled until a stable hysteresis loop is established. The imposed strain will then be increased and cycling repeated. The cyclic stress-strain curves (curve formed by connecting the peaks of the stable hysteresis loops) will be used in the analytical calculation of notch root strains. Fatigue test specimens will be fabricated and testing will be started following completion of the mechanical properties tests and preliminary elastic-plastic analysis of the proposed fatigue test specimens.

**Table 4-3
CHEMICAL ANALYSIS (MILL TEST)**

Material and Condition	Vendor and Heat Number	C	Mn	P	S	Si	Ni	Cr	Cu	Co	Mo
ASTM-A276 Type 304 Stainless Steel — Annealed	Republic Steel Number 8044641	0.052	1.90	0.034	0.011	0.46	8.80	18.18	0.38	0.17	0.49
ASTM-A212 Grade B Carbon Steel Norm. 1650°F	U.S. Steel Number 477L3041	0.27	0.65	0.011	0.019	0.20

Figure 4-4. Tensile Specimens

The first group of fatigue specimens to be analyzed and tested is shown in Figure 4-5. The stress concentration factor (K_t) for both specimens (b) and (c) is 2.0.^d Parameters to be studied are notch root strains, cycles required for crack initiation, and cycles required for failure in both load-controlled and deflection-controlled cyclic tests.

4.3.4 Computer Analysis of Specimens

As noted in the foregoing text, detailed analyses will be performed on the fatigue test specimens. A comparison of measured and calculated notch root strains will be the criterion used to establish the ability of the analytical method to define the full field stress-strain state of the specimens.

The analyses will be carried out using the finite element program CREEP-PLAST which has been developed by Y. R. Rashid of GE for ORNL. This program utilizes a constant-strain triangular element and is applicable to plane stress or plane strain (including axisymmetric) conditions. Elastic-plastic analyses are performed using the von Mises yield criterion and kinematic hardening.

To demonstrate the applicability of CREEP-PLAST, an analysis of a notched round bar under completely reversed tension-compression load control is presented, and the notch root strains are compared with experimentally determined strains.

4.3.4.1 Analytical Model

The finite element solution obtained is for one of Krempl's notched round bar specimens³ ($K_t = 1.9$) shown in Figure 4-6. The specimen is an axisymmetric body, and because of the double symmetry present it was necessary to consider only one quadrant of the critical section, as depicted in Figure 4-6. The finite element mesh used is shown in Figure 4-7 and 4-8. To facilitate the preparation of input data, a "pre-processor" was used to conformally map a simple rectangular grid (input) on to the specimen and provide both a plot of the transformed grid and punched cards for node and element input to the finite element program.

Figure 4-5. Fatigue Specimens

Figure 4-6. Grooved Cylinder Fatigue Specimen ($K_t = 1.9$)

Figure 4-7. Finite Element Grid—Remote from Notch

Figure 4-8. Finite Element Grid-Notch Area

The shakedown stress-strain results obtained for 2-1/4 Cr-1 Mo under Task D-2⁴ are shown in Figure 4-9. The values for the yield point and modulus shown in the figure were used to describe the material behavior. The use of a "cyclic" stress-strain curve for a monotonic loading analysis of a fatigued specimen has been found to be helpful by many investigators, the latest of which are Mowbray and McConnelllee.⁵ The shakedown state for this material was achieved in ~ 10 cycles in the smooth-bar tests, so that the results should be representative of the stress-strain properties for the major portion of the notched fatigue life.

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

4.3.4.2 Results

The initial load was chosen just below the cutoff point for completely elastic action. The elastic stress distributions across the minimum section are shown in Figure 4-10 in dimensionless form. The value of $K_t = 1.97$ is about 5% greater than that found in Peterson's work,⁶ based on the analytical solution of Neuber which has been shown to underestimate the stress concentration in similar cases.² The present result agrees with the factor cited by Mowbray and McConnelllee.⁵

The load was then increased in 19 more discrete steps. The progression of the yield zone is shown in Figure 4-11 by contour lines describing regions within which the effective stress has exceeded the proportional limit stress on the shakedown stress-strain curve. While the yield zone initially tends to follow the notch contour, as the net-section stress level is further increased the plastic zone changes direction and rapidly extends completely across the specimens at an angle of 30 to 45 degrees to the minimum section where a large region of elastic material remains. This is in qualitative agreement with results presented in Reference 5 for a similar specimen with $K_t = 3.5$.

The calculated strains were extrapolated to the surface along the notch root, and the average value over the gage area was determined. Calculated and experimentally^{3,5} determined strains are compared in Figure 4-12. The round symbols indicate strains measured on the first loading to the test load range. As described in Reference 3, the procedure

Figure 4-9. 2-1/4 Cr-1 Mo Shakedown Stress-Strain Diagram

Figure 4-10. Elastic Stresses on Minimum Section

Figure 4-11. Progression of Elastic-Plastic Boundaries

Figure 4-12. Comparison of Calculated and Measured Strains

used to reach the test load involved cycling a specimen at several discrete load steps along the way. Thus, while these strains do not correspond to the condition described by the shakedown stress-strain curve, they do represent a strain condition affected by cyclic loading. The triangular symbols indicate strains after 10 cycles of full load, which is the shakedown condition for this material. The calculated strains show good agreement with the measured values. Some error has been introduced into the analysis by the fairly large load increments that were used, which caused deviations from the programmed stress-strain curve. Figure 4-13 shows how the results for the notch root element compare with the shakedown stress-strain curve. In future analyses, smaller load steps will be employed.

4.3.4.3 Conclusion

The use of a monotonically increasing load, coupled with the shakedown stress-strain curve in conjunction with the finite element code CREEP-PLAST, has been demonstrated to give satisfactory results in calculating the stress-strain state of notched fatigue specimens. Immediate plans are to prepare the finite element meshes for the notched specimens for this task and to obtain the elastic stress concentration factors.

4.4 REFERENCES FOR SECTION 4

1. *Reactor Primary Coolant System Rupture Study, Quarterly Progress Report No. 22, 1970, (GEAP-10207-22).*
2. Slot, T. and Mowbray, D. F., "A Note on Stress-Concentration Factors for Symmetric U-Shaped Notches in Tension Strips," *Trans. ASME, Series E*, 36, No. 4, p. 882, (December 1969).
3. *Reactor Primary Coolant Rupture Study, Quarterly Progress Report No. 12, 1968, (GEAP-5637).*
4. *Reactor Primary Coolant Rupture Study, Quarterly Progress Report No. 3, 1965, (GEAP-5082).*
5. Mowbray, D. F. and McConnellee, J. E., *Application of Finite Element Elastic-Plastic Stress Analysis to Notched Fatigue Specimen Behavior*, First International Conference on Structural Mechanics in Reactor Technology, Berlin, Germany, September 1971.
6. Peterson, R. E., *Stress Concentration Design Factors*, John Wiley and Sons, Inc., New York, N.Y., 1953.

Figure 4-13. Comparative Stress-Strain Diagram, Input versus Output

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

5.1 OBJECTIVE

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

5.2 SUMMARY

The Dresden 1 test loop has accumulated 3600 hours of operation at test conditions (510°F, 1040 psig). A total of 84 of the 149 fatigue specimens, being cyclically loaded in the loop, have failed: 38 out of 71 Type-304 stainless steel, 16 out of 28 Type-304L stainless steel, 3 out of 23 Inconel-600, and all of the 27 carbon steel specimens. The first series of high-temperature tests to establish baseline curves is under way in the air test facility in San Jose. The unit has accumulated a total of 1000 hours of operation at design test conditions. All of the first ten air test specimens have failed. Design of the third vessel (crack growth fatigue unit) neared completion. The vessel will be installed in the Dresden 1 loop following shakedown testing at San Jose.

5.3 DRESDEN LOOP OPERATION

The test loop was automatically isolated on June 23 in response to a drop in plant primary system pressure that occurred during startup of one of the secondary steam generators. The loop was returned to service on June 28 and operated continuously through August 12, when another automatic isolation took place due to an unscheduled plant shutdown. Although the plant was returned to service on August 16, the "B" secondary steam generator loop, which supplies water to the test loop, remained out of service. The "B" loop, and consequently the Task K loop, did not operate during the remainder of the report period. The plant itself was shut down on September 10 to begin a scheduled 3-month refueling and maintenance outage.

The test loop accumulated 1548 hours (6194 cycles) of operation at design test conditions (510°F, 1040 psig) during the report period, bringing the total exposure to date to 3600 hours and 14,155 cycles; pertinent test parameters are summarized in Table 5-1.

A plan covering maintenance work to be performed on the test loop during the 3-month outage has been submitted to Commonwealth Edison for comments and approval. Also, arrangements are in progress to inspect all the test specimens—both the fatigue specimens and the statically loaded WOL's and Stressbends*—during the outage. A special lead shield that will minimize personnel exposure during the inspections of the fatigue unit has been fabricated and shipped to the Dresden site. The shield, a heavy steel annular structure encasing lead bricks and shot, has rollers on the top surface to facilitate rotation of the fatigue machine. Thus, movement of the unit can be made so that selected specimens are aligned with the viewing penetrations and the borescope.

5.4 FATIGUE SPECIMEN TEST

A total of 149 fatigue specimens (Figure 5-1), representing 4 material groups, 31 different metallurgical test conditions, and 4 specimen loading schemes, are included in the basic Task K test program. For convenience, the test plan, reproduced from GEAP 10207-24, Progress Report No. 24, is shown in Table 5-2. This test plan was designed to allocate the fatigue specimen positions among the selected test conditions to maximize chances of detecting differences in cyclic fatigue life which might be caused by these conditions when the specimens are in the environment.

During the first eight periods of test loop operation, failure was indicated for 84 specimens; pertinent test parameters are summarized in Table 5-3, parts A, B, C, D, and E. Note that because of the geometry of the Task K fatigue specimen (i.e., thin specimen loaded in bending) and the unique method used to define and detect specimen failure, these failure data represent cycles to initiation; very little (~ 5 to 10%) specimen life is devoted to fatigue crack growth. The distribution of these 84 failures among the 4 material groups and 31 test conditions is shown at the bottom of Table 5-2.

* See Tables 7-2 and 7-3 of Quarterly Report No. 18

Table 5-1
DRESDEN TEST LOOP OPERATING SUMMARY

Loop Operating Period	Startup	Shutdown	Cumulative Operating Time	Fatigue Cycles (Cumulative)		Fatigue Test Specimen Failure Indications Received	Remarks
				Start	Finish		
I	Sept. 16 ^(a)	Oct. 2 ^(a)	17 days	0	1900	23	Loop shutdown in anticipation of scheduled plant maintenance outage
II	Oct. 22 ^(a)	Nov. 5 ^(a)	32 days	1901	3250	18	Loop shutdown in anticipation of scheduled plant maintenance outage
III	Nov. 25 ^(a)	Dec. 31 ^(a)	69 days	3251	6494	19	Loop shutdown to repair leaking fitting
IV	Jan. 7	Jan. 14	76 days	6495	7174	2	Loop secured after reactor scram
V	Jan. 27	Feb. 3	84 days	7175	7891	9	Loop shutdown for scheduled plant outage
VI	Feb. 17	Feb. 18	85 days	7892	7960	1	Loop secured to repair steam leaks and install cubicle air monitor
VII	June 3	June 23	105 days	7961	9910	5	Loop automatically isolated due to low pressure trip
VIII	June 29	Aug. 12	150 days	9911	14155	7	Loop secured after reactor scram

(a) 1970

The values of initial surface strain range in Table 5-3 are based on room temperature and strain-deflection calibration curves generated for each material, and represent the shakedown strain ranges corresponding to given specimen deflections. These were measured using miniature strain gages mounted in the reduced thickness test section of each specimen. Although one might expect the strain range in the thin test section to depend only on tip deflection, these strain-deflection relationships could be influenced by temperature and hold times under load by virtue of a possible redistribution of strain between the thin and thick portions of the specimen under the test conditions of temperature and hold time compared with the room temperature, no-hold-time conditions used in calibration. Therefore, preparations are being made to rerun these strain-deflection curves at 500°F, in air, at 4 cycles/h, corresponding to the rate in the Dresden I fatigue test (see discussion in the following subsection).

The cycles-to-failure data for these 84 specimens are compared with the 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 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 recommended fatigue design curve which is derived from the ASME data curves by applying a safety factor of 20[†] on cycles (i.e., $N_I \text{ Design} = N_I \text{ Data}/20$).

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

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

Table 5-2
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						
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															
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						
Stress-Relieved																										x		x	x	
Simulated Crack Preparation																														
Mechanical								x	x									x	x										x	
Chemical										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

Table 5-3A
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIOD I)

Specimen Number	Cycles to Failure	Material	Shakedown Surface Strain Range*	Loading Mode**	Test Condition Code***	Description
1059	797	Carbon Steel	1.0%	C-T	29	Welded, stress relief
1060	909	Carbon Steel	1.0%	C-T	29	Welded, stress relief
1010	995	Carbon Steel	1.0%	C-T	27	As machined, stress relief
1009	1027	Carbon Steel	1.0%	C-T	27	As machined, stress relief
131	1027	Type-304 SS	0.5%	O-T	12	As received, furnace sensitized
57	1065	Carbon Steel	1.0%	C-T	26	As machined, no stress relief
64	1123	Carbon Steel	1.0%	C-T	26	As machined, no stress relief
48	1176	Carbon Steel	1.0%	C-T	25	As machined, no stress relief
179	1365	Type-304 SS	0.75%	O-T	12	As received, furnace sensitized
1008	1378	Carbon Steel	0.75%	C-T	27	As machined, stress relief
53	1380	Carbon Steel	1.0%	C-T	23	As machined, no stress relief
1053	1423	Carbon Steel	1.0%	C-T	23	Welded, no stress relief
1052	1455	Carbon Steel	1.0%	C-T	23	Welded, no stress relief
188	1493	Type-304 SS	0.5%	C-T	10A	As received, furnace sensitized mechanical notch
170	1506	Type-304 SS	1.0%	C-T	5	As received, furnace sensitized,
1017	1524	Carbon Steel	0.75%	C-T	29	Welded, stress relief
165	1651	Type-304 SS	0.5%	C-T	5	As received, furnace sensitized
1061	1708	Carbon Steel	0.75%	C-T	29	Welded, stress relief
1024	1738	Type-304 SS	0.5%	C-T	9	As received, furnace sensitized, mechanical notch
180	1771	Type-304 SS	1.0%	C-T	5	As received, furnace sensitized
128	1778	Type-304 SS	0.5%	O-T	12	As received, furnace sensitized
166	1838	Type-304 SS	0.75%	C-T	5	As received, furnace sensitized
185	1896	Type-304 SS	0.75%	O-T	12	As received, furnace sensitized

* Based on Room Temperature Strain-Deflection Calibration Curves

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

*** Reference: Table 5-2

Table 5-3B
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIOD II)

Specimen Number	Cycles to Failure	Material	Shakedown Surface Strain Range*	Loading Mode**	Test Condition Code***	Description
157	1917 ⁽¹⁾	Type-304 SS	0.5%	C-T	5	As received, furnace sensitized
189	1919 ⁽¹⁾	Type-304 SS	0.75%	C-T	5	As received, furnace sensitized
1080	1920 ⁽¹⁾	Type-304 SS	0.75%	C-T	5	As received, furnace sensitized
1085	1922 ⁽¹⁾	Type-304 SS	1.0%	C-T	5	As received, furnace sensitized
1079	1922 ⁽¹⁾	Type-304 SS	1.0%	C-T	5	As received, furnace sensitized
1084	1919 ⁽¹⁾	Type-304 SS	1.0%	C-T	5	As received, furnace sensitized
147	2132	Type-304 SS	0.5%	C-T	5	As received, furnace sensitized
38	2242	Type-304L SS	1.0%	C-T	18	As received, furnace sensitized
36	2286	Type-304L SS	1.0%	C-T	18	As received, furnace sensitized
34	2488	Type-304L SS	0.75%	C-T	18	As received, furnace sensitized
197	2706	Type-304 SS	0.5%	C-T	10A	As received, furnace sensitized, mechanical notch
50	2313	Carbon Steel	0.75%	C-T	26	As machined, no stress relief
1018	2321	Carbon Steel	0.5%	C-T	29	Welded, stress relieved
1144	2868	Type-304 SS	1.0%	C-T	7	Dresden equalizer line weld material, as machined
1051	2998	Carbon Steel	0.5%	C-T	30	As machined, stress relieved, mechanical notch
1048	3144	Carbon Steel	0.5%	C-T	30	As machined, stress relieved, mechanical notch
1019	3231	Carbon Steel	0.5%	C-T	29	Welded, stress relieved
1007	3235	Carbon Steel	0.5%	C-T	27	As machined, stress relieved

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

- * Based on Room Temperature Strain-Deflection Calibration Curves
- ** C-T = Compression-Tension; O-T = Zero to Tension Loading
- *** Reference: Table 5-2

Table 5-3C
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIOD III)

Specimen Number	Cycles to Failure	Material	Shakedown Surface Strain Range*	Loading Mode**	Test Condition Code***	Description
1058	3556	Carbon Steel	0.75%	C-T	28	Welded, no stress relief
195	3683	Type-304 SS	0.5%	C-T	9	As received, furnace sensitized mechanical notch
82	3766	Carbon Steel	0.5%	C-T	27	As machined, stress relieved
26	3990	Type-304L SS	0.5%	C-T	18	As received, furnace sensitized
81	4007	Carbon Steel	0.5%	C-T	26	As machined, no stress relief
1055	4015	Carbon Steel	0.5%	C-T	28	Welded, no stress relief
1146	4093	Type-304 SS	0.75%	C-T	7	Dresden equalizer line, weld material, as machined
1092	4418	Type-304 SS	1.0%	C-T	6	Dresden equalizer line base material, as machined
22	4724	Type-304L SS	0.5	C-T	18	As received, furnace sensitized
201	5215	Type-304 SS	0.75%	O-T	11	As received
72	5292	Carbon Steel	0.5%	C-T	26	As machined, no stress relief
29	5359	Type-304L SS	1.0%	C-T	15	As received
40	5435	Type-304L SS	0.5%	C-T	20	As received, furnace sensitized, mechanical notch
5	5617	Type-304L SS	0.5%	C-T	20	As received, furnace sensitized, mechanical notch
42	5859	Type-304L SS	1.0%	C-T	15	As received
190	5920	Type-304 SS	0.75%	O-T	11	As received
187	6110	Type-304 SS	1.0%	C-T	1	As received
1121	6140	Type-304 SS	0.5%	C-T	2	As received, heavy cold work
1148	6157	Type-304 SS	1.0%	C-T	7	Dresden equalizer line weld material, as machined

* Based on Room Temperature Strain-Deflection Calibration Curves

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

*** Reference: Table 5-2

Table 5-3D
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIODS IV, V, VI AND VII)

Specimen Number	Cycles to Failure	Material	Shakedown Surface Strain Range*	Loading Mode	Test Condition Code**	Description
1147	6532	Type-304 SS	0.75%	C-T	7	Dresden equalizer line weld material, as machined
1056	6915	Carbon Steel	0.5%	C-T	28	Welded, no stress relief
76	7161	Carbon Steel	0.5%	C-T	26	As machined, no stress relief
177	7756	Type-304 SS	1.0%	C-T	1	As received
1132	7891	Type-304L SS	0.5%	C-T	16	As received + heavy cold work
1042	7891	Inconel	1.0%	C-T	22	Welded, as machined
98	7891	Inconel	0.5%	C-T	23	As received, furnace sensitized
181	7891	Type-304 SS	1.0%	C-T	1	As received
1076	7891	Type-304L SS	1.0%	C-T	17	Welded, as machined
1123	7891	Type-304 SS	0.75%	C-T	2	As received + heavy cold work
1004	7891	Type-304L SS	0.75%	C-T	17	Welded, as machined
142	7930	Type-304 SS	0.5%	O-T	11	As received
184	8040	Type-304 SS	1.0%	C-T	1	As received
1095	8048	Type-304 SS	1.0%	C-T	6	Dresden equalizer line, base material, as machined
75	8869	Carbon Steel	0.5%	C-T	26	As machined, no stress relief
178	9155	Type-304 SS	0.5%	O-T	11	As received
1135	9225	Type-304L SS	1.00%	C-T	16	As received + heavy cold work

* Based on Room Temperature Strain-Deflection Calibration Curves

** Reference: Table 5-2

Table 5-3E
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIOD VIII)

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

Total failure indications received to date = E4 (38 - 304 SS, 16 - 304L, 3 Inconel, 27 Carbon Steel)

- * Based on Room Temperature Strain - Deflection Calibration Curves
 ** Reference: Table 5-2

NOTES:

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

Figure 5-1. Dynamic Test Specimen

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 Type A516 Carbon Steel

5.5 METALLURGICAL EFFECTS

5.5.1 Type-304 Stainless Steel

A total of 71 Type-304 stainless steel specimens are under test in the Dresden test loop. To date, failure indications have been received from 38 of them. Detailed analysis of these data will be deferred until data from the 33 surviving Type-304 specimens become available. However, several preliminary trends are:

- 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 Code 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.

5.5.2 Type-304L Stainless Steel

To date, 16 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 seven failures were divided among three material test conditions:

- a. Two "as-received" specimens tested at the 1.0% strain range
- b. Two "welded" specimens—one each at the 1.0% and 0.75% strain range
- c. Three "cold-worked" specimens—two at the 1.0% and one at the 0.5% strain range

A preliminary trend is that the Type-304L in the furnace-sensitized condition experiences a reduction in LCFL compared with "as-received" material.

5.5.3 Inconel-600

One additional Inconel failure indication was received during the report period, bringing the total number of failure signals received to date to 3 out of 23 specimens under test. These 3 specimens represent 2 test conditions:

- a. Two "welded" specimens tested at the 1.0% strain range
- b. One "furnace-sensitized" specimen tested at the 0.5% strain range

5.5.4 Carbon Steel

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

5.6 HIGH-TEMPERATURE BASELINE TESTS

5.6.1 Operating Summary

A smaller-sized version of the Dresden loop fatigue unit is operating at San Jose. It has the capability to load up to 12 of the Task K fatigue specimens (Figure 6.1) in the same manner as their Dresden counterparts but in a "non-environment." The specimens are tested in a high-pressure (700 psig) neutral atmosphere; this allows specimen failure to be defined in the same manner for Dresden specimens and "non-environment" specimens.

The second test (Series II) was completed with ten specimens cyclically loaded, as summarized in Table 5-4. The tip deflections selected for these ten specimens are the same as those imposed on the Dresden fatigue specimens tested at the highest strain range. Eight of these Series II specimens were instrumented with high-temperature strain gages to attempt to measure the actual shakedown strain ranges corresponding to a particular combination of tip deflection, temperature, and hold time imposed on the Dresden fatigue specimens. Because the strain gages failed during initial heatup due to oxidation, high-purity nitrogen was substituted for the compressed air initially used to pressurize the test facility.

5.6.2 Test Results

Failure indications were signalled by all of the Series II specimens by the end of the report period. The failure data are tabulated in Table 5-4. The data are compared with the ASME best-fit data curve and the Dresden BWR loop data for the same material condition (i.e., Material Condition No. 1) in Figures 5-6 and 5-7.

[#]Refer to Subsection 7.5.1.1, Quarterly Progress Report No. 20, GEAP-11069.

*The "As-Received" condition simulates the metallurgical condition of mill-annealed and pickled piping.

Table 5-4
FATIGUE SPECIMEN TEST PLAN, SERIES II BASELINE TEST

Specimen Number	Material	Tip Deflections* (in.)	Testing Rate	Remarks	Cycles to Failure
SS-130	304 Stainless	± 0.094	8 cph	Specimen accumulated 4602 cycles during Series I Testing ** with no indication of failure received	9980
CS-1015	Carbon Steel	± 0.086	8 cph	Specimen accumulated 4602 cycles during Series I Testing ** with no indication of failure received	8110
SS-134	304 Stainless	± 0.094	8 cph	New specimen ***	6674
SS-136	304 Stainless	± 0.094	8 cph	New specimen ***	8990
SS-144	304 Stainless	± 0.094	8 cph	New specimen *** (Furnace Sensitized)	8110
SS-1023	304 Stainless	± 0.094	8 cph	New specimen *** (Furnace Sensitized)	7078
IN-110	Inconel 600	± 0.100	8 cph	New specimen ***	8473
IN-111	Inconel 600	± 0.100	8 cph	New specimen ***	8492
CS-78	Carbon Steel	± 0.086	8 cph	New specimen ***	5600
CS-1012	Carbon Steel	± 0.086	8 cph	New specimen ***	5126

* Corresponds to deflections imposed on Dresden specimens tested at highest strain range (1.0%)

** In air

*** Switched from air to nitrogen after 2300 cycles

Figure 5-6. Equivalent Stress Amplitude versus Cycles to Failure. Comparison of fatigue data from BWR environment with "non-environment" baseline case.

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

5.7 THIRD TEST VESSEL (DRESDEN TEST LOOP)

Design effort continued on the fatigue crack growth unit (third test vessel) for addition to the Dresden test loop. Augmenting the crack initiation data now being generated, it will develop crack growth rate data in the BWR environment. The design (Figure 5-8) calls for a chain of WOL test specimens loaded in a ramp-hold-ramp waveform to a constant value of maximum load. Individual displacement transducers are mounted on each test specimen to measure the crack opening displacement (COD); a master load cell is provided to measure the true load (i.e., excluding seal friction loads) applied to the specimen chain. Strip chart recorders provide a permanent record of the output signals from the COD and load transducers which are to be analyzed at the conclusion of testing to yield the desired relationship between fatigue crack length and load cycles.

5.8 ELECTROCHEMICAL STUDY (R. L. Cowan)

When the third vessel and associated piping connections are added to the test loop at Dresden 1, a tee will be included for mounting the retractable reference electrode. This will be placed in a vertical position for easy access and use. The retracting system is currently being designed and the reference electrode is undergoing shakedown testing in the laboratory to establish its operating reliability under simulated BWR conditions.

5.9 REACTOR PRIMARY SYSTEM MATERIALS

Thirty-five 1-T WOL specimens and eight stressed-bend specimens fabricated from primary system materials have been prepared for exposure in the D-1 test loop. Preparation included pre-packing of the WOL specimens, plus loading and cleaning of all specimens. The specimens are statically deflected 1-T Wedge-Opening-Loading (WOL) specimens and stressed-bend specimens. Materials, and in some cases specimens, have been contributed by industry (General Electric, Chicago Bridge & Iron, Lukens Steel) and Government (ORNL, NRL).

The thirty-five 1-T WOL specimens (details shown in Figure 5-9) were fabricated from A508, A533, A542, and A543 vessel steels plus weld metal and heat-affected zone material. In addition, there are specimens of both Types 304 and 17-4 PH 1100 stainless steel. Specimen identification and loading data are given in Table 5-5.

Prior to loading, the WOL specimens were fatigue pre-cracked by cyclically loading in room temperature air. Cracks were grown to a nominal depth of 100 mils below the machined slot. The cyclic stress intensity range employed was $20 \text{ ksi} \sqrt{\text{in.}}$. Cycles required to initiate and grow cracks to the depth desired varied from 60,000 to 400,000.

The WOL specimens were loaded to produce a nominal stress intensity of 25 or 50 $\text{ksi} \sqrt{\text{in.}}$. The loading procedure is described in Quarterly Report No. 22 (GEAP-10207-22). Initial stress intensities based on the measured crack opening displacement (COD) and initial crack size were calculated with the calibration curves and equations described in the reference report. The initial stress intensity values are given in Table 5-5.

Eight stressed-bend specimens (details shown in Figure 5-10) were also fabricated. Two specimens were made from each of the four pressure vessel materials.

Stressed-bend specimens were loaded by deflecting in three-point bending (schematically shown in Figure 5-10). The specimen free end was deflected 0.28 inch and held in this position with a set screw. This deflection produces an elastically calculated surface strain at specimen mid-span of 0.9%.

Following loading of both the WOL and stressed-bend specimens, all specimens were cleaned in an ultrasonically agitated acetone bath, dried, and packaged. During the current outage at Dresden, specimens will be unpackaged, inserted in racks, and placed in one of the Task K static vessels.

Figure 5-8. Proposed Testing Scheme

Figure 5-9. I-T WOL Specimen

Figure 5-10. Stressed-Bend Specimen

Table 5-5
1-T WOL SPECIMEN LOADING DATA

Material ^(a)	Specimen Ident. No.	COD (in.)	Initial Crack Length (in.) ^(b)	Initial Stress Intensity (ksi $\sqrt{\text{in.}}$)
A508	508-5	0.0069	0.073	26.0
A508	508-6	0.0136	0.073	50.1
A533	533-1	0.0067	0.085	25.8
A533	533-2	0.0067	0.080	25.7
A533	533-3	0.0137	0.085	51.1
A533	533-4	0.0138	0.065	50.7
A533	533-5	0.0140	0.100	52.7
A533	533-6	0.0070	0.090	26.8
ESW				
A533	533-7	0.0140	0.070	51.4
ESW				
A533	533-8	0.0072	0.080	27.5
SAW				
A533	533-9	0.0147	0.090	53.7
SAW				
A533	533-10	0.0135	0.083	50.5
ES-HAZ				
A533	533-11	0.0138	0.070	50.9
SA-HAZ				
A542	542-7	0.0070	0.055	26.1
A542	542-8	0.0136	0.060	49.6
A542	542-1	0.0069	0.090	26.4
SAW				
A542	542-2	0.0136	0.068	49.9
SAW				
A543	543-1	0.0067	0.098	25.8
A543	543-2	0.0138	0.075	51.1
A543	543-3	0.0071	0.070	26.8
A543	543-4	0.0143	0.075	52.1
A543	543-5	0.0135	0.075	50.2
A543	543-6	0.0140	0.085	52.0
A543	543-7	0.0137	0.080	50.9
ESW				
A543	543-8	0.0072	0.098	28.0
SAW				
A543	543-9	0.0142	0.068	51.8
SAW				
A543	543-10	0.0136	0.065	49.8
SAW				
A543	543-11	0.0140	0.103	52.8
ES-HAZ				
A543	543-12	0.0138	0.088	51.7
SA-HAZ				
17-4	17-4-1	0.0070	0.083	28.5
PH 1100				
17-4	17-4-2	0.0137	0.090	53.7
PH 1100				
304SS	304-1	0.0060	0.118	21.7
Sensitized				

Table 5-5 (Continued)

Material ^(a)	Specimen Ident. No.	COD (in.)	Initial Crack Length (in.) ^(b)	Initial Stress Intensity (ksi $\sqrt{\text{in.}}$)
304SS Sensitized	304-2	0.0130	0.122	45.9
304SS Nitrided	304-3	0.0140	0.000	23.2
304SS Nitrided	304-4	0.0070	0.000	44.2

(a) ESW = electrosag weld, SAW = submerged
arc weld, HAZ = Heat affected zone

(b) Average of visual measurements on specimen sides.

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