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REACTOR PRIMARY COOLANT SYSTEM PIPE RUPTURE STUDY PROGRESS REPORT NO. 30 JULY - DECEMBER 1973

U.S. ATOMIC ENERGY COMMISSION
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**REACTOR PRIMARY COOLANT SYSTEM PIPE RUPTURE STUDY
PROGRESS REPORT NO. 30
JULY—DECEMBER 1973**

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U. S. Atomic Energy Commission
Under Contract AT(04-3)-189
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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 Pipe Rupture Study is being conducted for the Division of Reactor Development and Technology, USAEC. This Progress Report No. 30 documents work done in the period July 1, 1973 to December 31 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.
GEAP-10207-29	No. 29, January—June 1973

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

Efforts continue to apply the previously developed Leak and Severence Method (GEAP—10207-23) to allow for identification, on a relative basis, of fault cause contributions to the probability of severence.

Current work focused on development of a scheme for checking quantitative information on uncertainty distributions of primary and secondary stresses, by interview with experienced personnel.

2.2 TASK D-3—PROTOTYPE PIPE FATIGUE

This task was completed and a summary (GEAP-10763) topical report issued last report period.

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

Load and deflection controlled fatigue tests of A516 carbon steel specimens have been completed. As was true of the Type-304 stainless steel tests conducted earlier, groove and shoulder specimens with equal K_t behave differently in fatigue. Comparison of both the carbon steel and stainless steel results with ASME Section III, Design Rules demonstrates that the code rules are conservative.

2.4 TASK K—EFFECT OF BWR ENVIRONMENT

The Dresden 1 test loop remained out of service for the entire report period due to a plant maintenance/refueling outage.

Testing of the second group of 12 fatigue specimens cycled at 500°F in the Air Test Facility in San Jose was completed. Data from the 24 hot air specimens tested to date are compared to ASME Section III design criteria and comparable data from the Dresden 1 (D-1) environmental test loop.

Final checkout of the equipment associated with the crack growth (third) test vessel, which is to be added to the Dresden test loop, was completed. Fatigue testing of seven 2T-WOL specimens was completed as part of these hot shakedown tests.

Modification of the D-1 test loop piping to accomodate this new vessel has begun.

Post-test metallographic investigations, including scanning electron microscopy, of selected specimens removed from the Dresden test loop, continues.

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

In furthering the method for calculating relative probability of severance in a piping system by fault cause, a standardized scheme for designating stress uncertainty distributions is needed. Since the ASME Section III stress categories will be used, separate schemes for primary and for secondary stresses have been prepared.

3.3 STANDARDIZED STRESS UNCERTAINTY DISTRIBUTIONS

Distributions of realized stress values relative to calculated values are needed as input in the problem of calculating relative probability of piping severance by fault cause. To facilitate obtaining such judgemental distributions from interviewees, candidate alternative distributions have been prepared which may simply be selected, rather than each such distribution having to be originated in its entirety. Different sets of distributions have been prepared for primary and secondary stress categories.

Figure 3-1 shows five alternative distributions for primary stresses. The stress scale is intended to be appropriate for entering a critical stress diagram in which the critical stress value is presented relative to crack size (length and depth) at which the stress causes failure. For a primary stress due to a load-limited cause such as system pressure or piping system weight, this stress increases in proportion to the load. In Figure 3-1 a probability is assigned to successive stress ranges, forming a discrete uncertainty distribution of six intervals. If, in a particular case, an interviewee believes that none of the standard uncertainty distributions applies, he is at liberty to sketch the most appropriate distribution. Even though a distribution will be chosen as a result of a fault cause, so that nearly all values in the distribution will be higher than the calculated stress, it may prove desirable in practice for the "1- Σ " interval to include lower stress values as well as the interval shown.

Figure 3-2 shows five alternative uncertainty distributions for secondary stresses. Since secondary stresses are deflection-limited, such as due to thermal expansion, stress amplitudes should be approached in terms of their related strain ranges, through the stress-strain curve. It may be convenient for some interviewees also to visualize uncertainty values in terms of coefficients on S_m , shown along the bottom scale as the ratio S_n/S_m . Note that $3 S_m$ is at yield stress. Probabilities are assigned to successive stress ranges forming a discrete uncertainty distributions of seven intervals. Again, it may be desirable for the "1- Σ " interval to include lower values.

Figure 3-1. Candidate Uncertainty Distributions for Primary Stresses

T10-1

Figure 3-2. Candidate Uncertainty Distributions for Secondary Stresses

T10-2

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 D-3 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.

4.3 TASK D-5 ASME ELASTIC – PLASTIC CODE RULES FOR FATIGUE EVALUATION (T. L. Gerber)

4.3.1 Objective

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

4.3.2 Summary

Load and deflection controlled fatigue tests of A516 carbon steel specimens have been completed. As was true of the Type-304 stainless steel tests conducted earlier, groove and shoulder specimens with equal K_t behave differently in fatigue. Comparison of both the carbon steel and stainless steel results with ASME Section III, Design Rules demonstrates that the code rules are conservative.

4.3.3 Fatigue Tests

In this task the fatigue behavior of three specimen geometries, fabricated from two materials, and tested under two loading modes are being studied. Results from tests of Type-304 stainless steel specimens were reported earlier.¹ During this report period load and deflection controlled fatigue tests were conducted with specimens fabricated from as-received A516 carbon steel plate.

The geometries of these carbon steel specimens and the previously tested Type-304 stainless steel specimens, were identical. Smooth specimens and specimens with groove and shoulder geometric discontinuities were tested (see Figure 4-7). The grooved and the shouldered specimens had a theoretical elastic stress concentration factor, K_t , equal to 2.0.

The cycles required to initiate a fatigue crack in the load controlled tests are shown in Figure 4-1. The cyclic load was completely reversed axial loading and tests were conducted in room temperature air. Crack initiation was determined by periodically inspecting the specimen surface with a hand glass and microscope. In addition, the specimen compliance was monitored.

The cycles required for specimen fracture are shown in Figure 4-2.

The load controlled carbon steel test results are similar to the stainless steel results reported earlier. Note that even though groove and shoulder specimens have the same K_t , groove specimens survive longer than shoulder.

The cycles required for crack initiation in the deflection controlled tests of carbon steel specimens are shown in Figure 4-3. In these tests a completely reversed axial cyclic deflection was imposed over a gage length of 4 inches. Crack initiation was determined as in the load controlled tests. Note that in the deflection controlled tests, shoulder specimens survive longer than groove.

Figure 4-1. Crack Initiation of Load Controlled Carbon Steel Specimens

Figure 4-2. Failure of Load Controlled Carbon Steel Specimens

Figure 4-3. Crack Initiation of Deflection Controlled Carbon Steel Specimens

4.3.4 Comparison with Code Rules

As stated earlier, the objective of this task is to confirm or improve nuclear piping fatigue design procedures for nominal stress ranges above $3 S_m$. In the next few paragraphs the load and deflection controlled fatigue test results from both the Type-304 stainless steel and the A516 carbon steel specimens are compared with the ASME Boiler and Pressure Vessel Code, Section III,² Fatigue Rules.

The specific rules to be checked are the rules for Simplified Elastic-Plastic Analysis (NB-3228.3). These rules state that when the primary plus secondary stress range, S_n , exceed $3 S_m$, the value of alternating stress, $S_n/2$, used for entering the fatigue design curve should be multiplied by a factor, K_e , where

$$K_e = 1.0 \text{ for } S_n \leq 3 S_m \quad (1)$$

$$= 1.0 + \frac{(1-n)}{n(m-1)} \left(\frac{S_n}{3 S_m} - 1 \right) \text{ for } 3 S_m < S_n < 3m S_m \quad (2)$$

$$= 1/n \text{ for } S_n \geq 3m S_m \quad (3)$$

n and m are material properties and are given for various classes of code materials. For stainless steel, $m = 1.7$, $n = 0.3$, and for carbon steel, $m = 3.0$, $n = 0.2$.

Section NB-3222.4 of the code states that when stress concentrations are present, the nominal alternating stress also should be multiplied by the theoretical elastic stress concentration factor, K_t . Therefore the stress term for entering the code design curve is $(S_n/2)K_t K_e$. $K_t K_e$ can be thought of as a fatigue strength reduction factor.

The Task D-5 fatigue tests yield an experimentally determined fatigue strength reduction factor, K_f . This factor is defined as

$$K_f = S_a / (S_n / 2) \quad (4)$$

where S_a is the fatigue strength of a smooth specimen at the same life as that of the specimen for which K_f is being determined. S_a can be taken from the smooth specimen data generated in this Task or from the ASME Code Criteria curves.³ The smooth specimen Code Criteria curve is used in the following calculations.

The code (NB-32116) states that the nominal alternating stress calculation should be based on elastic analysis. Therefore, the alternating stress term, $S_n/2$, to use in determining K_f from the Task D-5 tests should also be based on elastic analysis. That is, for both the load and deflection controlled tests in which the nominal alternating stresses were above yield, the fictitious elastic stress, which would produce the same nominal strain, needs to be estimated. The results of the finite element analysis of the Task D-5 specimens completed and reported earlier enable one to make this estimate.

Figure 4-4 shows a generalized nominal stress amplitude versus the nominal strain amplitude for a specimen with a stress concentration. The stress amplitude to use in estimating K_f for the deflection controlled tests is simply the elastic stress amplitude corresponding to the imposed strain amplitude. For load controlled tests, one must first determine the corresponding strain amplitude and then the elastic stress that corresponds to that strain. This is shown schematically in Figure 4-4.

Figure 4-4. Observed Elastic-Plastic and Predicted Elastic Behavior of a Specimen with a Stress Concentration

Fatigue strength reduction factors plus the code valued of $K_t K_e$ for the stainless steel and carbon steel specimens are shown in Figures 4-5 and 4-6, respectively. There are a number of observations to be made with respect to these figures.

First, the code rules for estimating K_f (i.e., $K_t K_e$) are conservative. Experimentally determined fatigue strength reduction factors are below $K_t K_e$. This is most true for the A516 carbon steel material.

Second, even though both load and deflection controlled test results were plotted based on calculated elastic stresses, a distinction between the modes of loading remains. Load controlled testing causes higher values of K_f . Because the code limits primary stresses, nuclear components experience a loading more closely related to deflection controlled testing.

Third, even though groove and shoulder specimens have equal theoretical elastic stress concentration factors, they behave differently in fatigue. The shoulder type stress concentration is not as severe with respect to fatigue strength reduction as is a groove type stress concentration. The higher K_f displayed by groove specimens is related to the high elastic constraint in the vicinity of the groove.

Figures 4-5 and 4-6 show that load controlled testing of groove specimens is the most severe type test. Consequently, a few tests at higher loads are planned with specimens with groove geometries already tested and with sharper groove radii (higher K_t).

Figure 4-5. Comparison of Stainless Steel Fatigue Results with ASME, Section III, Design Rules

Figure 4-6. Comparison of Carbon Steel Fatigue Results with ASME, Section III, Design Rules

Figure 4-7. Fatigue Specimens

4.3.5 References

1. Progress Report No. 28, GEAP-10207-29 (July – December 1972).
2. ASME Boiler and Pressure Vessel Code, Section III. Nuclear Power Plant Components, American Society of Mechanical Engineers. New York (1971).
3. Criteria of Section III of the ASME Boiler and Pressure Vessel Code for Nuclear Vessels. American Society of Mechanical Engineers, New York (1964).
4. Progress Report No. 29, GEAP-10207-29 (January June 1973).

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 D-1 test loop remained out of service for the entire report period due to a refueling/maintenance outage of the Dresden 1 plant. Therefore, no additional information concerning loop operating time and/or fatigue failure data beyond that presented in the preceeding Progress Report (GEAP-10207-29) is available. Test loop operating history is summarized in Table 5-1.

All specimens in the Dresden Static Test Vessel were inspected—a selected number were removed and transferred to Vallecitos Nuclear Center for more detailed examination. In addition, a total of 14 fatigue specimen tips were removed from the Dresden Dynamic Test Vessel; these were also transferred to Vallecitos.

Testing has been concluded on the second group of 12 fatigue specimens being tested in a 500°F air environment in San Jose. These data and data from the previous group of 500° air specimens are compared to ASME Section III design criteria and comparable data previously obtained from the Dresden 1 test loop.

Hot shakedown testing (i.e., in "simulated" BWR water) of the third test vessel and associated hardware has been completed. Over 144,000 cycles were accumulated by the group of 7 2T-WOL specimens tested in the third test vessel during these tests.

Modification of the Dresden Test Loop to accomodate this new test vessel is underway.

Post-test metallurgical examination of a number of additional fatigue specimens removed from the Dresden Test Loop has been completed.

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.

The test loop remained out of service for the entire report period due to a plant maintenance/refueling outage. Therefore, no fatigue data, beyond that discussed in the previous Progress Report (GEAP-10207-29) is available.

The Fatigue Test Jig was inspected during this current outage and a total of 14 fatigue specimens tips removed. Ten of these 14 had previously signalled failure, four had not. This brings the total number of fatigue specimens which have failed to date to 102 out of the 149 specimens under test (see Table 5-2).

5.3.2 Specimen Inspection

The D-1 test loop originally began operation in September 1970 with a total of 30 Stressed Bend (Figure 5-2 and Figure 5-1, GEAP-10207-22) and 26 1T-WOL (Figure 5-3) test specimens in place in the Static Test Vessel. Pertinent parameters for these specimens are summarized in Tables 5-3 and 5-4, respectively. These two specimen groups represent the four basic Task K piping materials which were also used for the fatigue crack initiation specimens.

In March 1972, 35 additional 1T-WOL specimens were added to the Static Test Vessel specimen compliment. Primarily, these specimens represent RPV (reactor pressure vessel) materials and were supplied under the aegis of an Industry Cooperative Program. Pertinent parameters for these specimens are summarized in Table 5-5. All of the 1T-WOL specimens in this group of 35 and the original group of 26 had been fatigue precracked.

To date, the original 33 Stressed Bend and 26 1T-WOL test specimens have been exposed to the D-1 primary coolant environment for ≈ 7000 hours while the 35 RPV 1T-WOL's have seen ≈ 3500 hours exposure. All these specimens were inspected during the current outage.

The length of the existing crack in each of the WOL's was measured using a special traversing microscope previously used to establish the initial crack lengths (see Figure 5-1, Quarterly No. 26). The results of these inspections are noted below:

1. No evidence of cracking was noted on any of the Stressed Bends:
2. No signs of crack extension were noted on any of the 26 original 1T-WOL's; and
3. One of the 35 RPV 1T-WOL's (a 17-4 PH stainless specimen (see Table 5-6) showed evidence of some crack extension.

Three of the Stressed Bend specimens were unloaded using special fixturing which allowed the amount of recovered end deflection to be measured for each specimen. All three of these specimens were stainless steel weld specimens; two Type 304 (one high heat input, one normal heat input) and one Type 304L (normal). All three had originally been loaded to deflections selected to produce a 1.0% maximum surface strain (based on an experimental room temperature strain deflection calibration. See Table 5-1 GEAP-10207-22).

While it is not possible to calculate the true maximum surface stress present in these specimens prior to unloading, it is possible to make an estimate which bounds the true value. This estimate is based on the observation that these beams unload elastically and the assumption that the bending stress distribution is:

- a. elastic, and
- b. perfectly plastic.

**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	~31,040	4	Loop secured for plant shutdown, remained out of service through Jan. 1, 1974

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										x	x	x	x	x		
Solution Annealed	x				x			x	x	x	x	x	x	x			x	x	x	x		x	x	x							
Pickled	x				x			x	x	x	x	x	x	x			x	x	x	x		x	x	x							
Sensitized (c)					x				x		x		x				x		x			x		x							
Stress-Relieved																										x		x	x		
Simulated Crack Preparation																															
Mechanical								x	x									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) UT = Zero to tension loading

CT = Compression to tension loading

○ Denotes unfailed specimen

• Denotes specimen failure

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- * Specimen tips removed 11/71 with no previous failure indication signal received
- Specimen tips removed 11/73 with no previous failure indication signal received

Table 5-3

TASK K STATIC STRESS BEND LOADING SCHEDULE

Material	Material Condition Code	Welded Normal Heat	Welded High Heat	Machined	Solution Annealed + Pickled	Sensitized	Stress Relieved	Initial Surface Strains		
								0.25%A	0.5%A	1.0%A
Type 304 S.S.	1			X	X			X	X	X
Type 304 S.S.	2			X				X		X
Type 304 S.S.	3		X	X				X		R
Type 304 S.S.	4	X		X				X		R
Type 304 S.S.	5			X	X	X		X	X	X
Type 304L S.S.	1			X	X			X	X	X
Type 304L S.S.	2			X				X		X
Type 304L S.S.	4	X		X				X		R
Type 304L S.S.	5			X	X	X		X	X	X
Inconel-600	1			X	X			X	X	X
Inconel-600	2			X				X		
Inconel-600	4	X		X				X		X
Inconel-600	5			X	X	X		X	X	X
Carbon Steel	2			X						
	4	X		X			X	$\frac{X}{13}$	$\frac{X}{6}$	$\frac{X}{11}$

R Specimens unloaded and removed 11/73

Table 5-4
STATICALLY LOADED 1T-WOL SPECIMEN LAYOUT

Material				Material Condition								Load Level		
Type-304 Stainless Steel	Type-304L Stainless Steel	Inconel-600	Carbon Steel	Material (a) Condition Code	Welded, Low Heat (Normal)	Welded, High Heat (Block)	Machined (Ground)	Solution Annealed	Pickled	Furnace Sensitized	Stress Relieved	Initial Applied Load		No. of Specimens
x				2			x					1	1	2
x				3		x ^(b)	x					1	1 ^(a)	2
x				4	x ^(b)		x					1	1 ^(a)	2
x				5			x	x		x		1	1	2
	x			2			x					1	1	2
	x			4	x ^(b)		x					1	1 ^(a)	2
	x			5			x	x		x		1	1	2
		x		1			x					1	1	2
		x		4	x ^(b)		x					1	1	2
		x		5			x	x		x		1	1	2
			x	2			x					1	1	2
			x	7A	x ^(b)		x				x	1	1	2
			x	7	x ^(c)		x				x	1	1	2

(a) Removed 11/73, transferred to Vallecitos Nuclear Center for metallography

(b) Test section in HAZ.

(c) Test section in filler metal.

Table 5-5
INDUSTRY COOPERATIVE PROGRAM, 1T-WOL SPECIMEN LOADING DATA

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

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

(b) Average of visual measurements on specimen sides.

Table 5-6

**1T-WOL SPECIMEN INFO, REMOVED FROM
DRESDEN 1 CORROSION FATIGUE TEST LOOP—OCTOBER 1973**

Specimen Number	Material	Material Condition	Initial Stress Intensity	Exposure Time at D-1 (h)	Observed Crack Extension October 1973	Comments
17-4-2	17-4PH Stainless steel	H-1100 Heat treat	53.7	3500	≈0.050 in.	Industry coop specimen
304-2	Type 304 Stainless steel	Furnace sensitized	45.9	3500	None	Industry coop specimen
SS-304 HH-2	Type 304 Stainless steel	Welded, Hi heat process	27.6	7500	None	Original Task K specimen
SS-304L-2	Type 304L stainless steel	Welded, normal heat process	24.8	7500	None	Original Task K specimen
SS-304 NH-2	Type 304 stainless steel	Welded, normal heat process	28.4	7500	None	Original Task K specimen

NOTES:

1. **.029
.027** DIA. HOLE CENTERED IN
REDUCED SECTION WITHIN .006(±.003)
2. CENTERLINE OF WELD TO BE LOCATED IN MIDDLE
OF REDUCED THICKNESS SECTION FOR WELD
SPECIMENS

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Figure 5-1 Fatigue Test Specimen

Figure 5-2. Stressed-Bend Specimen

Figure 5-3. 1T-WOL Specimen

The results of these calculations indicate that the maximum surface stresses present in these specimens prior to unloading were on the order of 50 to 80 ksi. It should be noted that all three of these specimens were weld specimens; i.e., the major portion of the specimen in the region of maximum bending moment was weld filler metal which typically exhibits higher yield strength levels than the base 304 or 304L material.

Five 1T-WOL specimens were also removed during this inspection and transferred to Vallecitos for post-test examination. Four were from the original group of piping steel specimens. These four had been selected for removal prior to this inspection. No evidence of crack extension was noted on any of the four. The fifth specimen was removed after inspection revealed a 0.05 inch crack extension. Pertinent information for these five specimens are listed in Table 5-6.

5.3.3 Metallurgical Evaluation

Metallurgical evaluation of selected fatigue specimens removed from the Dresden Dynamic Test Vessel continues. These efforts include detailed metallography and scanning electron microscopy (SEM). Discussion of these results is covered 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 complete. Pertinent data are given in Table 5-7 and are compared to the ASME, Section III best fit data curve and corresponding Dresden 1 BWR data in Figures 5-4, 5-5, 5-6 and 5-7.

These data indicate that.

1. there is no significant fatigue life reduction due to the BWR environment in the As-Received 304 & 304L stainless steel or the Inconel 600 at the 1.0% and 0.75% strain ranges;
2. the low cycle fatigue performance of the 304 and 304L As-Received materials are not significantly different in the BWR environment at the 1.0% 0.75% and the 0.5% strain ranges;
3. both the 304 & 304L As-Received air data fall below the BWR data at the 0.75% strain range and above the BWR data at the 1.0% strain range. It seems desirable to obtain air data at the 0.5% strain range to better understand this behavior. A final series of 500 air tests will begin during the next report period primarily focused on obtaining data at the 0.5% strain range; and
4. The additional A-516 data fall among previous data, the average 10:1 reduction assigned to the BWR environment remains unchanged.

5.5 THIRD TEST VESSEL (D-1 TEST LOOP)—CRACK GROWTH RATE STUDY

Preparations for adding a third test vessel to the existing D-1 test loop are nearly complete. This vessel will be used to obtain crack growth information in the BWR environment for the four basic Task K piping materials under cyclic loading conditions. Data obtained will complement the crack initiation data presently being generated in the Dynamic Test Vessel. A schematic of the third test vessel system is shown in Figure 5-8.

Table 5-7
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	15,528
164	Type 304 SS, As Received	$\pm 0.078^{(b)}$	8	14,819
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	15,226
127	Inconel 600, As Received	$\pm 0.089^{(b)}$	8	37,842
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	22,857
1014	A-516 Carbon Steel, As Machined	$\pm 0.076^{(b)}$	8	14,695

(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.

Figure 5-4. 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 5-5. 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.

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Figure 5-6. 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 5-7. 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 5-8. Test Vessel III Test Scheme

Two series of tests at Dresden are planned—the first at a loading frequency of 5 cpm, the second at 0.5 cpm, so that the effect of frequency may be examined.

The specimen chain will be subjected to a tensile—tensile, triangular loading wave shape with load being the controlled variable.

5.5.1 Hot Shakedown Testing

The third test vessel system, with a full complement of seven 2T-WOL test specimens, was tested under conditions duplicating (i.e. except for radiation) those expected during the actual Dresden tests.

Simulated BWR water (1040 psig, 500°F, 100-300 ppb oxygen) was circulated through the vessel. The specimens were subjected to over 144,000 loading cycles during these 3 weeks of hot shakedown testing. Most of these cycles were accumulated at the 5 cpm loading rate; however, the system was also operated at 0.5 cpm to verify that the system was capable of functioning at this relatively slow frequency.

Pertinent parameters for these seven hot shakedown specimens are listed in Table 5-8. Testing was suspended twice to remove specimens which were undergoing gross cyclic ratcheting.

A total of four half-amplitude, stress-reduction marking fronts were imposed on these specimens. Five of these seven specimens were also provided with COD transducers (Reference Figure 5-11 b, GEAP-10207-29) to continuously monitor the specimen compliance.

At the conclusion of testing, all seven specimens were examined and measurements made of the surface crack length on both sides of the specimen. Five of these seven were then pulled apart.* Typical fracture surfaces for the As-Received 304 stainless steel and the As-Machined A-516 carbon steel specimens are shown in Figures 5-9a and 5-9b.

A traversing microscope was used to attempt to locate the stress reduction "beach marks" and to measure the length of the crack present at the end of testing. Based on these measurements it appears that the stress reduction marking technique was only partially successful. On several specimens it was not possible to locate all the "beach marks". More important, the agreement between the actual location of those beach marks which are visible and their predicted location based on COD measurements does not seem to be as close as that previously noted for the room temperature, 304 stainless test (Reference Figure 5-14, GEAP-10207-29)

The fracture surfaces of these five specimens are presently being re-examined to attempt to resolve these discrepancies.

5.6 TASK K-1 ELECTROCHEMICAL STUDY (M. E. Indlg, J. Weber)

A bypass manifold with three insertion ports for making electrochemical potential measurements was added to the D-1 test loop during the current outage. This manifold allows new electrodes to be installed and placed in service with a minimum of time and without effecting the operation of the three test loop vessels.

Design of the working electrodes and the Ag-AgCl reference electrode is complete (see Figure 5-10). Working electrodes were fabricated from each of the four basic Task K piping materials (Type 304 & 304L stainless steel, Inconel 600 and A-516 carbon steel). Fabrication of two Ag-AgCl reference electrodes is underway.

* The two Inconel 600 specimens were not pulled apart because the amount of crack extension measured on the sides of these specimens was so slight that the chances of obtaining any useful data from the fracture surfaces was judged to be minimal.

Table 5-8
T.V. III HOT SHAKEDOWN TESTS, SUMMARY

Specimen No.	LVDT No.	Material	Total Test Cycles	Early Removal	Final Crack Length (in.)	K' for Final Crack (ksi $\sqrt{\text{in.}}$)	Remarks
SS-01	SN006	As received	121,514	Yes unstable growth	3.097	46.7	
SS-04	SN003	Furnace sensitized	143,673	No	2.399	31.2	
SL-01	SN005	As received	143,673	No	3.186	50.0	
IN-04	SN008	Furnace sensitized	143,673	No	1.779	23.8	Specimen was not pulled apart at conclusion of test because amount of crack extension was judged to be insignificant
CS-01	SN009	As machined	92,065	Yes unstable growth	2.926	41.5	
SL04	None	Furnace sensitized	114,224	No, but left out from 92,065 to 121,514	2.356	30.6	
IN-01	None	As received	143,673	No	1.884	24.9	Specimen was not pulled apart at conclusion of test because amount of crack extension during test was judged to be insignificant

Figure 5-9. Typical 2T-WOL Fracture Surfaces, TV-III Hot Shakedown Tests

ELECTRICAL CONDUCTIVITY GLAND

Q2	Q1	NAME	DESCRIPTION
1	1	GLAND	1588897361
1	2	TUBE	SEE DETAIL
1	3	COVER	" "
1	4	WICK	" "
1	5	SHRINK TUBE	" "
5	6	SHRINK TUBE	" "
1	7	TEFLON SEAL	" "
1	8	ELECTRODE TIP	" "
1	9	SEALING GLANDS	PACKING FOR CONAX CAT. " 58-123-A-7
1	10	TEFLON SEAL	SEE DETAIL
1	11	TEFLON SEAL	" "
1	12	ELECTRODE	" " (SAMPLE)
1	13	SPACER	" "
1	14	THRUST	PACKING FOR CONAX CAT. "

* MATERIAL CERTIFICATION PAPERS
ALONG WITH COPIES OF ALL
MATERIAL TEST REPORTS TO
ACCOMPANY EA PART.

6. ACKNOWLEDGEMENTS

The author wishes to acknowledge the cooperation given by the Commonwealth Edison Company, especially the Operation and Engineering staff associated with the Dresden Nuclear Power Station.

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 for the effect of metallurgical condition and environment on the fatigue behavior of the specimens.

SUMMARY

During this reporting period, no new fatigue specimens were received. Efforts were focused on the metallurgical examination of the A-516 carbon steel fatigue specimens and a 2T-WOL Type-304 stainless steel crack growth rate specimen tested in air at room temperature. The fatigue crack propagation test results are reported in GEAP-10207-29, Progress Report No. 29, January - June 1973.

Surfaces of the fatigue specimens in the as-machined condition were examined by Scanning Electron Microscopy (SEM). Surface corrosion pits were observed and a cursory study was initiated to determine if there was any relationship between the presence of the corrosion pits and crack initiation on these specimens.

Because of the difference in behavior between the specimens in the as-machined, and as-machined plus stress relieved metallurgical condition, impact tests were performed. The purpose of these tests was to determine if possible embrittlement occurred during the stress relief treatment which might account for this difference in fatigue behavior. Sub-size (1/2 size) Charpy V-notch impact tests were performed and relative effects on the impact values were used to ascertain embrittlement.

The surface of the 2T-WOL Type-304 stainless steel specimen was examined by SEM to characterize the mode of failure and to measure instantaneous crack growth rate from fatigue striation spacings. Fatigue marking fronts were also identified and located and the results compared to the visual measurements.

The examinations performed revealed the following information:

1. A substantial amount of pitting occurred on the surfaces of the A-516 carbon steel fatigue specimens which had been tested in the D-1 BWR environment. This was true for both the as-machined and as-machined plus stress relieved conditions. In a number of these pits, cracks were found which appeared to originate in the centers of the pits. This suggests the possibility that the surface pits may provide nucleation sites for the initiation of fatigue cracks in A 516 carbon steel.
2. The character of the corrosion film on the stress relieved carbon steel specimens was substantially different from that found on the as-machined specimens. The corrosion film appeared to be very brittle with a tendency for film cracking on the stress relieved specimens. This may be related to the surface oxidation that occurred during the stress relieving heat treatment.
3. The impact test results for the A-516 plate showed the stress relieved specimens to have slightly greater notch impact strength than the as-machined specimens. These results do not support the hypothesis of embrittlement occurring during the stress relieving treatment.
4. The fracture mode for the 2T-WOL Type-304 stainless steel specimen tested at room temperature was transcrystalline.
5. The crack growth rates measured macroscopically and microscopically by striation spacing were in excellent agreement up to growth rates of approximately 50μ inches/cycle. Beyond that point, the crack growth rates based upon striation spacing measurements were greater than the values based upon the macroscopic measurements.

6. Fatigue marking front locations measured microscopically and macroscopically agreed to within approximately 0.050 inch in all cases.

INTRODUCTION

Metallurgical examinations were performed on fatigue initiation specimens (Figure 5-1) of A-516 carbon steel piping material in both the as-machined and as-machined plus stress relief condition and on a 2T-WOL Type-304 stainless steel specimen in the as-received (mill annealed) condition tested in air at room temperature. The SEM was utilized to examine the as-machined surface of the carbon steel specimens and the fracture surface of the 2T-WOL Type-304 stainless steel specimen. The results are presented herein.

DISCUSSION

A. A-516 Carbon Steel

The surfaces of a total of nine carbon steel fatigue specimens in the as-machined condition and in the as-machined plus stress relief condition were examined by SEM. Seven had been tested to failure in the D-1 BWR environment, two in 500°F air. The stress relief heat treatment was performed at 1150°F in air for 2 hours followed by an air cool. Figure 1 shows the corroded surface of a typical as-machined carbon steel BWR specimen. In Figure 1a, the fracture surface is at the top of the micrograph. Several secondary cracks can be seen; the crack proceeding through the lower center of the micrograph has grown through some of the corrosion pits present on the surface. In Figure 1b, at higher magnification, two corrosion pits through which a secondary crack has formed, are seen. Although not all pits in Figure 1 have associated with them secondary cracks, enough cracking is seen to be associated with the pits to suggest a strong relationship between pitting and crack nucleation for the as-received carbon steel.

A SEM micrograph of the surface of a stress relieved BWR specimen is shown in Figure 2. Figure 2a shows the fracture surface at the top of the micrograph and several secondary cracks in the surface. Some corrosion pitting is evident along with associated secondary cracks. The general difference in the surface oxide between the stress relieved specimen (Figure 2a) and the as-machined (non-stress relieved) specimen (Figure 1a) is striking. The corrosion product on the surface of the stress relieved specimen appears to have been very brittle; associated with each secondary crack is substantial oxide film cracking and film removal. On the as-machined specimen, no such oxide film cracking is seen. The difference in surface condition between the two specimens can be attributed to the stress relief heat treatment which introduced an oxide layer which was not removed prior to testing. This oxide apparently is more brittle and less tenacious than the corrosion film produced in the reactor water. The characteristics of this film may be important in explaining the difference in fatigue behavior between the as-machined carbon steel specimens and the stress relieved carbon steel specimens. Figure 2b shows another region of the corroded surface of the stress relieved specimen. Here one sees an array of deep pits which appear to be linking together to form a crack. Figure 2c shows a higher magnification view of the largest of these pits. The crack initiation mechanism for the carbon steel BWR fatigue specimens is thought to be related to the corrosion pits and the linking of these pits.

Figure 3 shows the machined surface of a carbon steel specimen tested in air at 500°F. No evidence of pitting is seen on the surface of this specimen. Examination of an additional 500°F air carbon steel specimen confirmed the absence of pits. Consequently, the pitting observed on the as-machined and the stress relieved BWR specimens was clearly the result of the exposure in the D-1 primary reactor water. It appears likely, based on these observations, that both surface pitting and general corrosion of freshly cracked material were major contributors to the fatigue life reduction observed for the carbon steel specimens tested in D-1.

Statistical analysis of the macroscopic data (Reference Table 5-4, GEAP-10207-24) had revealed a definite reduction in fatigue life associated with the stress relieved material condition compared to the non-stress relieved material. Impact tests were conducted on the A-516 plate material to determine if possible embrittlements occurred during the stress relief heat treatment cycle which might account for this difference.

Notch impact tests were performed on sub-size (one-half thickness) Charpy V-notch impact specimens of A-516 carbon steel from the same heat as that used for the fatigue initiation specimens. Four specimens were given a stress

relief heat treatment (1150°F/2 hours in air/air cool) following machining but prior to notching and four were tested in the as-machined condition. The specimens were tested at room temperature and at 550°F. The results indicate that the stress relief heat treatment does not embrittle the material but, on the contrary, a slight increase in impact strength from the as-machined condition was noted. Thus, embrittlement of the material cannot be used to rationalize the difference in fatigue behavior of the two metallurgical conditions of the A-516 carbon steel.

Subsized Charpy V-Notch Test Results on A-516 Carbon Steel

Specimen Condition	Test Temperature (°F)	Energy Absorbed (ft/lb)	Lateral Expansion (mils)
As machined.....	75	35.8	66
As machined.....	75	35.0	62
Stress relief.....	75	39.5	64
Stress relief.....	75	44.2	70
As machined.....	550	34.8	54
As machined.....	550	35.0	57
Stress relief.....	550	41.0	57
Stress relief.....	550	41.8	52

b. Type-304 Stainless Steel

A 2T-WOL specimen of Type-304 stainless steel in the as-received condition, tested in air at room temperature, was examined metallurgically. The macroscopic fatigue crack propagation data were previously presented (see Figure 5-13, GEAP-10207-29). The metallurgical investigation was performed to characterize the mode of failure for this specimen, to measure the fatigue striation spacing and, based on these data, to calculate the instantaneous crack growth rate (da/dn).

Figure 4 shows SEM fractographs of a typical region on the fracture surface. In Figure 4a, the failure mode is seen to be transcrystalline. The flat quasi-cleavage river bed fractography has been observed in previous examinations of as-received Type-304 stainless steel subjected to cyclic loading conditions. In Figure 4b, fatigue striations are shown at 5000 X magnification – the crack growth rate is approximately 5μ inches/cycle. Crack growth rate data was collected from the striation spacing measurements and compared to macroscopic crack growth rate information obtained during the test. The results, given in Figure 5, are in excellent agreement up to growth rates of approximately 50μ inches/cycle. For higher da/dn values, the microscopic crack growth rates appeared to be slightly greater than the macroscopic data for a given crack length.

Nine marking fronts were located, identified and compared to the bench mark locations determined visually on the failed specimen. Figure 6 shows one such location. In Figure 6a, the crack is growing from right to left and the marking front is in the center of the fractograph. It can be recognized as a light vertical line in Figure 6a. In Figure 6b, this marking front is illustrated at 3000 X magnification. The crack is seen to have been growing at approximately 8μ inches/cycle up to the marking front. As the load was reduced at the marking front the morphology changed and no striations could be seen. The marking front was formed by 1000 half load cycles. Using that information and the linear extent of the marking front, the crack growth rate was estimated to be 0.3μ inch/cycle in this region – beyond the resolution capability of the SEM. The agreement between the bench mark locations determined microscopically and visually was excellent, agreement was within 0.050 inch in all cases.

50X

Figure 1a. SEM Micrograph of Machined Surface of As-Machined A-516 Carbon Steel (50X) Specimen No. 57 (4374)

200X

Figure 1b. SEM Micrograph of Secondary Crack Through Pits on Machined Surface of As-Machined A-516 Carbon Steel (200X) Specimen No. 57 (4376)

50X

Figure 2a. SEM of Machined Surface of Stress Relieved A-516 Carbon Steel (50X) Specimen No. 1010 (4378)

50X

Figure 2b. SEM of Secondary Crack Composed of Deep Pits on Stress Relieved A-516 Carbon Steel (50X) Specimen No. 1010 (4380)

200X

Figure 2c. Large Pit on Stress Relieved A-516 Carbon Steel Surface (200X) Specimen No. 1010 (4381)

Figure 3. SEM of Machined Surface of Air Tested As-Machined A-516 Carbon Steel (50X) Specimen No. 1045 (4051)

100X

Figure 4a. Typical Fracture Surface of Type-304 Stainless Steel 2T-WOL Specimen (100X) - (5103)

5,000X

Figure 4b. Striations on Fracture Surface of Type-304 Stainless Steel 2T-WOL Specimen (5000X) (5098)

Figure 5. Comparison of Microscopic and Macroscopic Crack Growth Rates for 2T-WOL Type-304 Stainless Steel Specimen, SS-03

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