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AEC RESEARCH AND
DEVELOPMENT REPORT
SEPTEMBER 1974

MASTER

**REACTOR PRIMARY
COOLANT SYSTEM
PIPE RUPTURE STUDY
PROGRESS REPORT NO. 31
JANUARY - JUNE 1974**

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

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REACTOR PRIMARY COOLANT SYSTEM PIPE RUPTURE STUDY. 3#
PROGRESS REPORT NO. 31,
JANUARY ¹⁰ JUNE 1974

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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 bench-scale 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.

ACKNOWLEDGMENTS

The author wishes to acknowledge the cooperation received from Commonwealth Edison Company, especially the Operations Staff at the Dresden Nuclear Power Station (Morris, Illinois).

1. INTRODUCTION

The Reactor Primary Coolant System Pipe Rupture Study is being conducted for the Division of Reactor Safety Research, USAEC. This progress Report No. 31 documents work done in the period January 1, 1974 to June 30, 1974. 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.
GEAP-10207-30	No. 30, July—December 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

A topical report summarizing the Leak and Severance Method is being prepared.

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

A topical report summarizing the work done on this task is being prepared.

2.3 TASK K — EFFECT OF BWR ENVIRONMENT

The crack growth (third) test vessel was installed in the Dresden 1 test loop and checked out.

The Dresden 1 test loop was out of service for the entire report period due to a plant maintenance/refueling outage. The Dresden 1 plant resumed full power operation during the final weeks of the report period. Preparations are underway to resume test loop operation.

Preparations were completed to begin testing of a third group of 12 fatigue specimens in 500°F air in the Air Test Facility in San Jose.

Post-test metallographic investigations continued. The fracture surfaces of the 2T-WOL specimens, tested in simulated BWR water during the third test vessel hot shakedown test, were examined.

3. TASK K — EFFECT OF BWR ENVIRONMENT

(D. A. Hale, W. A. Briggs)

3.1 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 three test vessels.

3.2 SUMMARY

The third test vessel was transferred to the Dresden 1 site and tied into the existing corrosion fatigue test loop piping early in the report period. The Dresden 1 BWR remained out of service until late in the report period due to a refueling/maintenance outage. Therefore, the test loop was out of service for the entire report period, and no additional information concerning loop operating time and/or fatigue failure beyond that presented in Progress Report 29 (GEAP-10207-29) is available.

Setup of the third and final group of 500°F baseline air specimens is under way.

The self-loaded 1T-WOL specimens removed from the Dresden 1 corrosion fatigue test loop during the previous report period were unloaded and preparations were begun for metallographic examination.

Metallurgical examination of the 2T-WOL specimens tested during the hot shakedown tests of the third test vessel during the previous report period was completed.

An interim topical report summarizing the work done to date on Task K was prepared (GEAP-20244).

3.3 DRESDEN CORROSION FATIGUE TEST LOOP

3.3.1 Fatigue Test Results

One hundred forty-nine fatigue specimens (Figure 3-1), 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 3-1) 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 Dresden 1 plant, which has been shut down since late 1973 for maintenance and refueling, was returned to service late in the report period. Engineering personnel from GE-San Jose are presently on site to return the corrosion fatigue test loop to service. Therefore, no fatigue data beyond those discussed in Progress Report No. 29 (GEAP-10207-29) are available.

3.3.2 Specimen Inspection

The five 1T-WOL test specimens removed from the D-1 static test vessel during the previous report period were unloaded; the load present in these specimens was measured (at room temperature). The values of final stress intensities corresponding to these loads and final crack lengths are shown in Table 3-2, along with other pertinent information for these five specimens.

3.3.3 Metallurgical Evaluation

Metallurgical efforts for this report period were confined to examining the 2T-WOL specimens from the third test vessel hot shakedown tests. The results are discussed in the Appendix.

Table 3-1
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) OT = Zero to tension loading
CT = Compression to tension loading

○ Denotes unfailed specimen

• Denotes specimen failure

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NOTES:

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

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

Table 3-2
1T-WOL SPECIMEN INFORMATION 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	Final Measured Load (kip)	Calculated Final Stress Intensity
17-4-2	17-4PH stainless steel	H-1100 Heat treat	53.7	3500	≈0.050 in.	Industry coop specimen	6.9	(2)
304-2	Type 304 stainless steel	Furnace sensitized	45.9 ⁽¹⁾	3500	None	Industry coop specimen	4.03–4.96 ⁽¹⁾	(2)
SS-304 HH-2	Type 304 stainless steel	Welded, Hi heat process	27.6	7500	None	Original Task K specimen	4.60–6.02	(2)
SS-304L-2	Type 304L stainless steel	Welded, normal heat process	24.8	7500	None	Original Task K specimen	4.71–5.37	(2)
SS-304 NH-2	Type 304 stainless steel	Welded, normal heat process	28.4	7500	None	Original Task K specimen	4.31–6.10	(2)

NOTES:

- (1) Suspect mixup in specimen loading data, this specimen probably loaded to lower stress intensity range (25.0 ksi $\sqrt{\text{in.}}$)
 (2) Calculation of final stress intensity value deferred until accurate value for final crack length is obtained from metallography.

Figure 3-1. Fatigue Test Specimen

3.4 500°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.

3.4.1 Air Data

Two groups of 12 specimens have been tested to date (see Table 5-7 in GEAP-10207-30 and Table 5-4 of GEAP-10207-25). A third and final group of specimens is being prepared for testing (Table 3-3).

Table 3-3
FINAL SPECIMEN LAYOUT, AIR TEST V

Material	Test Condition	Specification Number	Tip Deflection (in.)
304L SS	As-Received	SL-1005	+0.124 ^a
			-0.000
304L SS	As-Received	SL-44	+0.124 ^a
			-0.000
304L SS	As-Received	SL-1064	+0.156 ^b
			-0.000
304 SS	As-Received	SS-1023	±0.062 ^a
304 SS	AR + FS	SS-132	±0.062 ^a
304 SS	AR + FS	SS-129	±0.078 ^b
304 SS	AR + FS	SS-135	±0.094 ^c
304L SS	As-Received	SL-43	±0.062 ^a
304L SS	As-Received	SL-30	±0.062 ^a
304L SS	As-Received	SL-33	±0.062 ^a
304L SS	As-Received	SL-13	±0.078 ^b
304L SS	As-Received	SL-4	±0.094 ^c

^aCorresponds to 0.5% strain range based on previous room temperature strain deflection calibrations.

^bCorresponds to 0.75% strain range based on previous room temperature strain deflection calibrations.

^cCorresponds to 1.0% strain range based on previous room temperature strain deflection calibrations.

The decision was made to run this additional air test group in order to provide data at the lowest strain range (where no previous air data are available) and additional data for the zero-tension loading mode. This test has been delayed by equipment difficulties, but should begin early in the next report period.

3.5 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 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 3-2.

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.

Figure 3-2. Test Vessel III Test Scheme

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

3.5.1 Dresden Site Activity

The third test vessel, along with associated instrumentation and hydraulic equipment, was transferred to the Dresden 1 site early in the report period. The vessel was tied into the existing test loop piping, and all instrumentation was installed and checked out. The Dresden 1 plant remained out of service until the last week of the report period due to a maintenance/refueling outage. Personnel are presently enroute to the site to begin loop testing.

3.6 TASK K-1 — ELECTROCHEMICAL STUDY (M. E. Indig, J. Weber)

A bypass manifold with three insertion ports for making electrochemical potential measurements was added to the Dresden 1 test loop during the current outage. This manifold allows new electrodes to be installed and placed in service relatively quickly without affecting the operation of the three test loop vessels.

The working electrodes and the Ag-AgCl reference electrode that will be used for these measurements are shown in Figure 3-3. All these electrodes have been fabricated and are available for use as soon as the Dresden 1 test loop can be returned to service.

UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING —				TITLE	
APPLIED PRACTICES	SURFACES	TOLERANCES UNLESS OTHERWISE SPECIFIED		ELECTRICAL CONDUCTIVITY GLAND	
209A4270	250	FRACTION	DECIMAL	FIRST MADE FOR DRESDEN	
		$\pm \frac{1}{32}$			

Q2	Q1	Q2	Q1	NAME	DESCRIPTION
1	1	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. # 68-125-A-7
1	10			TEFLON SEAL	SEE DETAIL
1	11			TEFLON SEAL	" "
1	12			ELECTRODE	" " (SAMPLE)
1	13			SPACER	" "
1	14			THRUST WASHER	PACKING FOR CONAX CAT. # 68-125-A-7

NOTES:

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

Figure 3-3. Electrochemical Flange Electrode Details

APPENDIX
METALLURGICAL EXAMINATION OF TASK K FATIGUE SPECIMENS
(J. C. Danko, A. J. Giannuzzi)

A.1 OBJECTIVE

The objective of this subtask is to perform a post-test metallurgical evaluation of the Task K fatigue specimens. This includes the identification and characterization of the mode of failure and provides a rationale on the effect of metallurgical condition and environment on the fatigue behavior of the specimens.

A.2 SUMMARY

During this reporting period, no fatigue initiation specimens were evaluated. Efforts were focused on the metallurgical examination of two Type-304 stainless steel 2T-WOL crack growth rate specimens tested in a hot shakedown run of the third test vessel using a simulated BWR environment (1040 psig, 500°F, 100 to 300 ppb oxygen). One specimen (SS-01) was tested in the as-received condition, the other (SS-04) in the furnace-sensitized condition. The specimens were subjected to over 144,000 loading cycles at a frequency of 5 cpm.

The fracture surfaces of the 2T-WOL Type-304 stainless steel specimens were examined by scanning electron microscopy (SEM) to characterize the mode of failure and to measure instantaneous crack growth rates from fatigue striation spacings. Fatigue marking fronts were also identified and located, and the results were compared with visual and crack opening displacement (COD) measurements:

Optical metallography was performed on the specimens to determine the extent and the morphology of the secondary cracks emanating from the primary fracture. The examinations revealed the following information:

- a. The fracture mode for both the as-received and the furnace-sensitized 2T-WOL Type-304 stainless steel specimens was transcrystalline. No differences in fracture morphology were observed between the specimens.
- b. Instantaneous crack growth rates measured for both specimens were approximately equal at comparable crack lengths.
- c. No significant difference was observed between specimens in the extent or mode of secondary cracking — all secondary cracks were transcrystalline.
- d. Two fatigue marking front locations were identified on the as-received Type-304 stainless steel specimen. These locations were in good agreement with corresponding COD measurements. The corrosion product on the fracture surface obscured the remaining marking fronts on the as-received specimen, and all marking fronts on the furnace-sensitized specimen.

A.3 INTRODUCTION

A metallurgical evaluation was performed on two Type-304 stainless steel 2T-WOL crack propagation specimens tested in a simulated BWR environment. The specimens, one as-received* and the other furnace-sensitized,** were examined by SEM and optical metallography to characterize the failures. The results of the investigation are presented herein.

*Solution-annealed plate as received from mill.

**1150°F for 40 hours, furnace cooled.

A.4 DISCUSSION

The two Type-304 stainless steel 2T-WOL specimens, one as-received (SS-01) and one furnace-sensitized (SS-04), had been subjected to over 144,000 loading cycles during a hot shakedown test in the simulated BWR environment (1040 psig, 500°F, 100 to 300 ppb oxygen, circulating water). Most of the cycles were accumulated at 5 cpm, and a total of four half-amplitude stress reduction marking fronts were imposed on the specimens. The details of the initial stress intensity range, location of the marking fronts, and depth of precrack are given in Section 3. The SEM and optical metallography were used to characterize the failure and microstructure of these specimens.

A SEM fractograph of the as-received Type-304 stainless steel specimen (at a location of 0.900 inch from the root of the machined notch) is shown in Figure A-1. The fracture surface of the furnace-sensitized specimen located 0.800 inch from the root of the notch, is shown in Figure A-2. The fracture surfaces of both specimens exhibited the transgranular quasi-cleavage, riverbed characteristics observed in the fatigue initiation specimens reported earlier (see GEAP-10207-28 and GEAP-10207-29 for details). Some secondary cracking is evident in each fractograph, but no indication of intergranular crack propagation was observed. Optical metallography was performed on a cross section taken parallel to the fracture path to characterize the mode of cracking for the secondary cracks. Figure A-3 illustrates an optical micrograph for the as-received specimen, and Figure A-4 for the furnace-sensitized specimen. The secondary cracks are predominately transgranular for both specimens. Substantial branching can be seen, the origin of which is not presently understood. Based on the SEM and optical metallography, no difference can be seen in the fracture morphology of the two specimens.

In Figure A-5, an optical micrograph shows the cross section of the 2T-WOL specimen tested in air at room temperature and reported in the previous progress report. Only an occasional, small secondary crack was seen in contrast to the substantially larger branched secondary cracking observed in the environmental tests. The small secondary cracks of the room temperature specimen had associated with them significant cold work in contrast to the high-temperature environmental tests where no cold work was observed. It appears that either the water environment, or temperature, or a combination of both contribute to secondary cracking of Type-304 stainless steel in this environment.

Instantaneous crack growth rate (CGR) data were obtained from the measurements of the fatigue striation spacings for the two specimens studied. The crack growth rates varied from approximately $7 \mu\text{ in./cycle}$ at the low stress intensity range, to $80 \mu\text{ in./cycle}$ at the highest stress intensity range for the as-received specimen. The instantaneous crack growth rate for the furnace-sensitized specimen remained approximately constant at 7 to $10 \mu\text{ in./cycle}$. However, when comparing the crack growth rates at equivalent crack depths of both specimens, essentially no difference was observed (see Figure A-7).

Stress reduction marking fronts were identified at two locations for the as-received Type-304 stainless steel specimens. Figure A-6 shows such a marking front at a distance of approximately 1.325 inches from the root of the machined notch. The other marking front was located at approximately 0.820 inch from the root of the notch. These distances agreed to within 0.030 inch of the final two marking fronts identified by the COD. The earlier two marking fronts were obscured by the corrosion product on the fracture surface and could not be conclusively identified. The same problem existed for the furnace-sensitized Type-304 stainless steel specimen where the fourth and last marking front was determined by the COD to be only 0.69 inch from the root of the notch. In this region, the crack growth rate was small ($\sim 10 \mu\text{ in./cycle}$) so that the difference between the full-amplitude striation spacing and the half-amplitude marking front striation spacing was not resolvable, especially in the presence of the fracture surface corrosion product. Consequently, no verification could be made of the accuracy of the COD gage directly from microscopic observations for the furnace-sensitized specimen. However, since the COD measurement accurately identified the final crack length for the furnace-sensitized specimen, and showed good agreement with the SEM observations for the as-received specimen, it appears that the COD accurately measured the CGR for the furnace-sensitized specimen.

150X

Figure A-1. SEM Fractograph of As-Received Type-304 Stainless Steel Specimen (SS-01). Location 0.900 inch from Root of Notch.

150X

Figure A-2. SEM Fractograph of Furnace-Sensitized Type-304 Stainless Steel Specimen (SS-04). Location 0.800 inch from Root of Notch.

Figure A-3. Optical Micrograph of As-Received Type-304 Stainless Steel Specimen, Polished and Etched, Showing Secondary Cracks

Figure A-4. Optical Micrograph of Furnace-Sensitized Type-304 Stainless Steel Specimen, Polished and Etched, Showing Secondary Cracks

100X

Figure A-5. Microstructure of Fracture Area of the 2T-WOL Type-304 Stainless Steel in As-Received Condition, Tested in Air at Room Temperature

300X

Figure A-6. Striations and Marking Front on Fracture Surface of As-Received Type-304 Stainless Steel Specimen. Location 1.325 Inches from Root of Notch

Figure A-7. Instantaneous Crack Growth Rate (da/dn) versus Crack Length (a)

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Der Zweck dieser Rohrbruchstudie ist ein besseres Verständnis des bruchverursachenden Mechanismus zu gewinnen und eine Vervollkommnung der Fähigkeit Reaktorrohrsysteme abzuschätzen, um die Wahrscheinlichkeit von Fehlschlägen zu verringern. Nach einem ausführlichen Überblick der nötigen Schritte zur Verbesserung des Rohrsystems der Kernanlage (Phase I), wurden analytische und experimentelle Studien (Phase II) begonnen. Dieser Forschungsbericht gibt einen Überblick über die Fortschritte eines umfassenden Programmes über

- (a) Materialermüdungsstudien im Laboratoriummassstabe,
- (b) Reaktorversuche über Effekte der Primärkühlerumgebung auf das Ermüdungsverhalten des Rohrstahls, und (c) Studium der Bruchwahrscheinlichkeit des eingesetzten Reaktorrohrsystems.

GENERAL **ELECTRIC**