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U.S. ENERGY RESEARCH
AND DEVELOPMENT ADMINISTRATION
MARCH 1975

**REACTOR PRIMARY
COOLANT SYSTEM
PIPE RUPTURE STUDY
PROGRESS REPORT NO. 32
JULY—DECEMBER 1974**

U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
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**REACTOR PRIMARY COOLANT SYSTEM PIPE RUPTURE STUDY
PROGRESS REPORT NO. 32
JULY — DECEMBER 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) basic fatigue studies focused on Elastic/Plastic ASME Code Design Rules, (b) at-reactor tests of the effect of primary coolant environment on the fatigue behavior of piping steels, and (c) studies directed at quantifying weld sensitization in T-304 stainless steel.

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. 32 documents work done in the period July 1, 1974 to December 31, 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 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.
GEAP-10207-31	No. 31, January—June 1974.

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-5657	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-5614	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.
GEAP-20662	Effect of Constraint and Loading Mode on Low-Cycle Fatigue, Crack Initiation — Comparison with Code Design Rules, October 1974.
GEAP-20615	Estimating the Relative Probability of Piping Severance by Fault Cause.

2. SUMMARY

2.1 TASK A — PROBABILITY STUDY

A topical report entitled "Estimating the Relative Probability of Piping Severance by Fault Cause" (GEAP-20615) was issued.

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

A topical report entitled "Effect of Constraint and Loading Mode on Low-Cycle Fatigue Crack Initiation-Comparison with Code Design Rules" (GEAP-20662) was issued. Design, fabrication and checkout of fixturing and specimens needed to run the combined bending and axial loading tests was completed.

2.3 TASK K — EFFECT OF BWR ENVIRONMENT

The Dresden I Corrosion Fatigue Loop was operated for a total of 6 days during the report period, prior to being taken out of service due to problems with the plant B secondary recirc loop. This B loop and the Corrosion Fatigue test loop remained out of service for the remainder of the report period.

Testing was begun on a third group of 12 fatigue crack initiation specimens in 500°F air in San Jose.

Fatigue crack growth data for A-516 carbon steel was obtained in a 500°F air environment and compared to similar data obtained earlier in a simulated BWR primary water environment. Metallographic examination of this A-516 carbon steel BWR specimen was completed. The A-516 500°F air and BWR crack growth data are discussed in light of these metallographic results.

Metallography was completed on a statically-loaded 1T-WOL specimen of 17-4 PH stainless steel (H-1100) which had been loaded to an initial stress intensity value of $\sim 50 \text{ ksi} \sqrt{\text{in.}}$ and exposed in the Dresden I test loop for ~ 3500 hours. The original fatigue precrack was found to have extended — the stress intensity corresponding to this extended length was $37 \text{ ksi} \sqrt{\text{in.}}$.

3. TASK D-5 — ASME ELASTIC/PLASTIC CODE RULES FOR FATIGUE EVALUATION

(J. D. Heald, W. Briggs, S. Meza)

3.1 OBJECTIVE

The objective of this task is to confirm or improve nuclear piping fatigue design procedures for nominal stress ranges above $3 S_m$. Work done in fiscal year 1974, was confined to uniaxial loading, and was summarized in a topical report.* Work currently underway, is concerned with extending this work to include the case of combined, axial plus bending, stress situations for one material — Type 304 stainless steel.

3.1.1 Summary

A fixture was designed to allow loading of smooth bar, notched or grooved specimens under combined axial and bending loads. These three specimen geometries (see Figure 3-1) are geometrically similar to the three corresponding specimens used in the axial loading tests run last year. This current work is devoted to one material, T-304 stainless steel.

A fixture was designed and fabricated, capable of applying a cyclic bending load to any of these three specimens in the presence of a constant axial load. This fixture (Figure 3-2) relies upon an air cylinder, mounted on the end of twin lever arms, to maintain a constant axial load on the specimen independent of the cyclically applied bending load. The specimen is cyclically loaded in four-point bending using a 100 KIP, servo-controlled testing machine. This bending loading may be imposed as either a deflection-controlled or a load-controlled cyclic mode.

A shakedown test was performed, using a smooth specimen made from un-characterized T-304 material, to verify that the fixturing and specimen design were satisfactory with respect to the original design objectives. The system was operated satisfactorily and all design objectives were satisfied.

A complete set of test specimens is presently being fabricated from characterized T-304 stainless steel plate. Pertinent parameters for this material are listed in Table 3-1 — this is leftover plate from crack growth work¹ previously done under Task D-1 at the M&P Lab. Actual testing will hopefully begin in the next quarter.

* GEAP-20662 Effect of Constraint and Loading Mode on Low-Cycle Fatigue Crack Initiation — Comparison with Code Design Rules, October 1974.

¹ GEAP-5607 "Fatigue Crack Growth in Nuclear Piping Steels"

Table 3-1
TYPICAL PHYSICAL PROPERTIES FOR TYPE 304 STAINLESS STEEL
TASK D-5 MATERIAL

Material: Two plates A-240, hot-rolled, annealed, and pickled Type-304 steel 1-in. plate.

Composition:

	C	Mn	P	S	Si	Ni	Cr	Mo
A-240	0.08	2.00	0.03	0.03	0.75	8-11	18-20	—
Spec. Req.	max.		Max.	max.	max.			
M&P Lab. Test	0.07	1.63	0.016	0.013	0.54	9.50	18.57	0.26

Grain Size: ASTM NO. 3-4

Microstructure—Mixed grain size austenite

Mechanical Properties (Transverse):

Test Temperature (°F)	Ultimate Stress (psi)	0.02% Yield Stress (psi)	0.2% Yield Stress (psi)	Elongation in 1 in. (%)	Reduction in Area (%)
RT	79,700	26,500	34,200	83.5	72.2
550	63,200	13,000	17,000	63.0	70.4
600	63,400	14,100	17,000	64.0	71.8

[illegible]

Technical drawing of a mechanical part showing dimensions and a feature control frame. The drawing includes the following dimensions and features:

- Overall width: $5 \pm \frac{1}{16}$
- Top surface thickness: 1.000
- Bottom surface thickness: $1.000 \pm .002$
- Distance from bottom surface to centerline of first hole: $.500 \text{ BSC.}$
- Distance from centerline of first hole to centerline of second hole: 7.000 BSC.
- Distance from centerline of second hole to centerline of third hole: 3.500 BSC.
- Feature control frame for the second hole:
 - Feature: $\pm \frac{1}{8}$
 - Material: $\frac{3}{4} \text{ R.}$
 - Feature: 2.000
 - Feature: $-A-$
 - Feature: $32 / \pm .001$
 - Feature: $\times .08 \text{ IR.}$
 - Feature: $32 /$

[illegible]

3-3

Figure 3-2. Task D-5 Loading Fixture for Combined Axial and Bending Tests

4. TASK K — EFFECT OF BWR ENVIRONMENT

(D. A. Hale, J. Gallego, W. Briggs, I. M. Coussens)

4.1 OBJECTIVE

The objective of this task is to generate quantitative data on the effects of a high pressure/temperature water environment on crack initiation and growth under steady and cyclic loads. Four typical light water reactor materials are being investigated — T-304 and 304L stainless steel, Inconel 600 and A-516 carbon steel. Testing is being done in a BWR primary water environment, a reference 500°F laboratory air environment and a simulated BWR water environment. The BWR tests are carried out in a special test loop which was installed at the Dresden I plant (Morris, Illinois) in 1970 with the cooperation of Commonwealth Edison Co. Dresden I primary water (500°F, 1040 psig) serves as the BWR test media. Support tests have been run in San Jose in a simulated BWR water environment (500°F, 1040 psig, no radiation) and in a 500°F air environment.

4.2 SUMMARY

The Dresden I test loop was returned to service for a brief period during August. Operation was prematurely suspended due to plant difficulties — the test loop remained out of service for the rest of the report period.

Testing of a second group of 12 fatigue crack initiation specimens in 500°F air was completed and testing begun on a third and final group of 12. Data from these air specimens are compared to comparable D-I BWR data.

Fatigue crack growth data for A-516 carbon steel was obtained in a 500°F, air environment and compared to similar data obtained earlier in a simulated BWR primary water environment. Metallographic examination of this BWR specimen was concluded — the results are summarized in Appendix A.

Metallography was completed on a statically loaded 1T-WOL specimen of 17-4 PH stainless steel (H-1100 condition) which had been loaded to an initial stress intensity value of $53.7 \text{ ksi}/\sqrt{\text{in.}}$ and exposed in the Dresden I test loop for 3500 hours. The original fatigue precrack was found to have extended $\sim 0.44 \text{ in.}$ — the stress intensity corresponding to this final extended crack length is $37 \text{ ksi}/\sqrt{\text{in.}}$. The results are summarized in Appendix B.

4.3 DRESDEN TEST LOOP

Three test vessels are incorporated in the Dresden I Corrosion Fatigue Test Loop (Figure 4-1). The Dynamic Test Vessel (DTV) contains cyclically loaded, fatigue crack initiation specimens (Figure 4-2). The Static Test Vessel (STV) contains both statically loaded crack initiation (Figure 4-3) and crack propagation (Figure 4-4) specimens. The other test vessel (TV-III) contains cyclically-loaded crack propagation specimens (Figure 4-5).

4.3.1 Test Loop Operation

The Dresden I Corrosion Fatigue Test Loop was returned to service on August 6 after conclusion of an extended plant maintenance outage. The DTV remained isolated due to leaking seals. The loop was isolated on August 13 in preparation for a planned isolation of the B primary recirculation loop because of HX tube leaks. The B loop and, therefore, the C. F. test loop remained out of service for the remainder of calendar year 1974 (Table 4-1).

4.3.2 Fatigue Test Results

One hundred forty-nine fatigue specimens (Figure 4-1) 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 4-2) was designed to allocate the available fatigue specimen positions among the selected test conditions to maximize chances of detecting significant differences in cyclic fatigue life related to the specific material conditions and influence of the environment.

**Table 4-1
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		
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
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
XVI	Aug. 7	Aug. 13	333 days	31,040	31,040	0	Dynamic Test Vessel remained out of service, run interrupted by isolation of B recirc loop for repairs, B recirc loop and test loop remained out of service for remainder of year

Table 4-2
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				

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

Figure 4-1. Task K — Dresden 1 Corrosion Fatigue Test Loop

Since the DTV remained out of service for the entire report period — no additional fatigue data beyond that discussed in detail in Progress Report No. 29 (GEAP-10207-29) are available.

4.3.3. BWR Fatigue Crack Growth Results

A total of seven 2T-WOL specimens were installed in the third test vessel (TV-III) for testing - pertinent parameters are listed in Table 4-3. Cyclic loading of these seven specimens began on August 6. The dynamic load range was adjusted to produce the desired loads based on the internal load cell signal. The test frequency was 5 cpm. After 24,200 cycles, a half-amplitude marking front was run (4000 cycles at 1/2 load range). Full amplitude loading was then resumed. A short time later (N=24,814), loading was suspended in preparation for taking the B recirc loop and the C. F. test loop out of service. No additional testing was completed during the report period.

It is hoped that testing can be resumed early in the next report period.

4.3.3.1 Data

Two of these seven specimens were instrumented with LVDT's* for monitoring specimen compliance. Compliance readings obtained from these two units were essentially unchanged over the ~24,000 loading cycles accumulated during this test, indicating little, if any, change in crack length. The premature suspension of testing, then, precluded acquisition of any meaningful crack growth data from these specimens during the current report period.

* Linear Variable Differential Transformers

GEAP-10207-32

Figure 4-3. Stressed-Bend Specimen

Figure 4-4. 1T-Wol Specimen

PART NO.	SPEC. NO.	B	W	C	E	F	G	H	L	M	N	Φ	P	R	S
2	2T-B	2.000 ^{+0.010}	5.110	6.200	0.16B	1.540	1.500	2.480	4.960	0.100	0.094	0.350 ^{+0.010}	1.000 ^{+0.005} -0.010	NO	YES

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

Figure 4-5. 2T-WOL Specimen for Crack Growth Rate Study of Task K_c

Table 4-3
TV-III, DRESDEN I PHASE I SPECIMEN LOADING PARAMETERS

Loading Information:

Frequency: 5 cpm, symmetric triangle

Maximum Cyclic Load: 14,500 lb

Minimum Cyclic Load: 500 lb

R Ratio: 0.03

Specimen Number	Material	Metallurgical Test Condition	Average Fatigue Precrack Length (in.)
SS-02	T-304 SS	As Received	0.040
SS-05	T-304 SS	Furnace Sensitized	0
SL-02	T-304L SS	As Received	0.091
SL-05	T-304L SS	Furnace Sensitized	0
IN-03	Inconel 600	As Received	0.181
IN-04	Inconel 600	Furnace Sensitized	0.790
CS-04	A-516 Carbon Steel	As Received	0.082

Cycles accumulated prior to premature shutdown 24,814

4.3.4 A-516 Crack Growth Testing

A baseline crack growth rate test was run using the A-516 plate material which has been utilized for all the Task K crack growth rate studies (Table 5-7) (GEAP-10207-26) — pertinent loading parameters are summarized in Table 4-4. The test was run in a laboratory air environment in a non-circulating test oven capable of maintaining the 2T-WOL test specimen at $500^{\circ}\text{F} \pm 10^{\circ}\text{F}$. An LVDT* was used to continuously monitor the crack opening displacement. Testing was interrupted at appropriate intervals, the oven opened up and optical surface crack length measurements made using a traversing microscope. Specimen compliance measurements were made immediately before and after each crack measurement. The resultant optical crack length versus specimen compliance data points are plotted in Figure 4-6. Also shown on Figure 4-6 is the predicted compliance/crack length relationship calculated using relationships from Reference 1. An "apparent elastic modulus" is derived for use in this calculation by setting the initial measured specimen compliance at a known crack length equal to the predicted value for that same crack length from reference 1. This apparent modulus is used for all subsequent calculations.

The experimentally measured surface crack length/compliance data agree fairly well with the predicted curve up to an a/w value of 0.48. For a/w values above this, the experimental data fall below the predicted curve. Based upon post-test examination of the fracture surface of the simulated BWR test specimen (CS-01), it appears that most of this deviation is due to fatigue crack front curvature near the specimen surface at higher stress intensity values (i.e., estimates of fatigue crack length based upon surface crack measurements will be larger than the true average crack length over the total width of the specimen).

This verified compliance/crack length equation was then used to reduce compliance data obtained for specimen CS-01 previously tested in simulated BWR water (500°F , 1050 psig, 100-300 ppb O_2) as part of the shakedown of the Dresden I fatigue crack growth test vessel. The resultant crack length/cycles relationship for CS-01 agreed reasonably well with crack length information obtained via stress reduction marking fronts applied to CS-01 several times during the test.

Table 4-4
LOADING PARAMETERS — CS-03

Test Environment: 500°F, laboratory air
 Specimen:: 2T-WOL
 Maximum Cyclic Load: 14,500 lb
 Minimum Cyclic Load: 500 lb
 R Ratio: 0.03
 Test Frequency: 20 cycles/min
 Waveshape: Haversine
 Total Full Amplitude Test Cycles: 248,000
 Initial Crack Length: 1.56 in.
 Final Crack Length: 2.65 in.

Range of ΔK over test: $\Delta K_0 \sim 21.8 \text{ ksi}/\sqrt{\text{in.}}$
 $\Delta K_f \sim 46.0 \text{ ksi}/\sqrt{\text{in.}}$

The crack length versus cycles data for both CS-01 and CS-03 were converted to crack growth rate/stress intensity data using a regressive fit computer program.

The da/dN versus ΔK data for both CS-01 and CS-03 are shown in Figure 4-7. Also shown are the results of General Electric in-house tests on SA-508 forging material² run in this same simulated BWR water environment and the results obtained for A-533 Gr B material in a high-temperature, high-pressure water environment.³

4.3.4.1 Results

Comparing the CS-01 BWR data to the CS-03 500°F air data, there seems to be a ~ 4.1 increase in crack growth rates in the BWR environment, at least at the lower values of ΔK . Also, a larger degree of scatter in the CS-01 BWR data compared to the corresponding CS-03 500°F air data and a somewhat weaker dependence on stress intensity range of the CS-01 BWR data are seen. A possible explanation for this might be the higher incidence of secondary cracking observed at higher ΔK values (see Appendix A) for CS-01. The production of these secondary cracks would consume energy normally used for primary crack extension and might manifest itself in non-steady primary crack growth rates.

Present plans call for performing metallography on CS-03 during the next report period to determine whether the same pattern of secondary cracking is present.

Figure 4-6. Compliance/Crack Length, CS03 (500°F, air)

Figure 4-7. Crack Growth Rate Data, A-516 Carbon Steel

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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2. T. L. Gerber, J. D. Heald, E. Kiss, *Fatigue Crack Growth in SA-508-CL2 Steel in a High-Temperature, High-Purity Water Environment*, General Electric Co., Internal Report.
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APPENDIX A

**METALLURGICAL EXAMINATION OF A-516 2T-WOL SPECIMEN
NO. CS-01 FROM DRESDEN TEST VESSEL III
HOT SHAKEDOWN**

(R. B. Davis)

Light metallography and SEM fractography were performed on A-516 2T-WOL specimen No. CS-01 which had seen 92,065 cycles in simulated BWR conditions (less radiation) at 5 cpm during the hot shakedown of Dresden Test Vessel III (GEAP-10207-30). For the light metallography, the specimen was longitudinally sectioned perpendicular to the primary fracture surface 0.25 inch from one side and lightly etched. Generally, very small transgranular secondary cracks were observed throughout the specimen with the severity of these cracks increasing with primary crack length. Two of the more dramatic areas with respect to severe secondary crack formation are shown in Figures A-1 and A-2. The primary fracture surface was found to be progressively more jagged with increasing primary crack length. The large primary crack branching observed in T. Mager's A-533 2T-WOL specimens (Westinghouse, HSST Technical Report No. 35, December 1973) was not found on this A-516 specimen.

In an attempt to obtain crack growth rate information from striation spacings, the following electrochemical cleaning technique was used to strip the high temperature oxide from the A-516 fracture surface: The specimen was cathodically cleaned in a solution containing 56 grams of Endox 214 (Enthone Corp., Cleveland, Ohio) per liter of water at 120°F. After rapidly stirring the sample and making it the cathode for 30 seconds at a current density of 0.1 amp/cm² and then the anode for 5 seconds, the specimen was ultrasonically agitated in a 5% solution of NH₄OH in water for 2 minutes. The procedure of cathodic cleaning followed by ultrasonic agitation was repeated until all oxide was removed — usually 2 to 3 cycles. Although the oxide removal was successful (as it has been on A-508 and A-533 specimens) the observed striation spacings were not of sufficient quality or quantity to give da/dN information. (da/dN values varied randomly between 25 and 50 μ in./cycle along the fracture surface length.) As this problem has been experienced previously with plain carbon steel specimens fatigued in air, this result was not totally unexpected. Figures A-3 and A-4 are SEM micrographs showing the clearest striation spacings observed on this specimen.

A516 2T-WOL (CS-01) 250X

Figure A-1. Secondary Cracks 27.7 mm (1.09 inch) from Machined Notch

← DIRECTION OF CRACK GROWTH

A516 2T-WOL (CS-01) 250X

Figure A-2. Secondary Cracks 29.5 mm (1.16 inch) from Machined Notch

Figure A-3. SEM Micrograph of A516 2T-WOL Specimen CS-01 (BWR, 5 cpm), Crack Length, 1.75 inches

Figure A-4. SEM Micrograph of A516 2T-WOL Specimen CS-01 (BWR, 5 cpm), Crack Length 2.59 inches

APPENDIX B

METALLURGICAL EXAMINATION OF 17-4 PH STAINLESS STEEL STATICALLY — LOADED 1T-WOL SPECIMEN

(A. J. Giannuzzi)

SUMMARY

Metallography has just been completed on a self-loaded 1T-WOL specimen of 17-4 PH (1100) which had been exposed in the PA-37 Dresden I Corrosion Fatigue Test Loop. (GEAP-10207-30, Table 5-5, specimen 17-4-2). This specimen had been exposed to the Dresden I primary coolant for 3500 hours at a temperature of approximately 500°F prior to its removal in November 1973. The initial loading deflection was selected to produce a stress intensity of 53.7 ksi/ $\sqrt{\text{in}}$. with the initial fatigue precrack length of 0.090 in.

This specimen was unloaded, and the load corresponding to the final crack length was measured. The specimen was then sectioned longitudinally, polished and etched so that the length of the final crack could be determined. These examinations revealed that the crack had extended approximately 0.445 in. The final crack length was approximately 0.535 in. long. Figure B-1 shows the crack at a magnification of 22 times. The crack is observed to be unbranched, growing roughly normal to the direction of the applied load. In Figure B-2 the tip of the crack is shown. The crack is observed here to be growing intergranularly, following the prior austenitic grain boundaries. Macro hardness measurements were made on this specimen with the Rockwell-C hardness measured as R_c 36.5, (Average of 4). In addition, the final stress intensity calculated from the final crack length and final measured load is 37 ksi $\sqrt{\text{in}}$. This number can be used to provide an upper bound to K_{ISCC} in this environment for this material.

22X (PHOTO REDUCED TO 70% FOR
REPRODUCTION PURPOSES)

Figure B-1. 17-4 PH 1100 Stainless Steel Etched WOL Specimen

500X ETCHED

Figure B-2. Crack Tip of 17-4 PH 1100 Stainless Steel WOL Specimen

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