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GEAP-10207-35
NRC-5
MAY 1976

REACTOR PRIMARY COOLANT SYSTEM PIPE RUPTURE STUDY PROGRESS REPORT NO. 35 JANUARY — MARCH 1976

U.S. NUCLEAR REGULATORY COMMISSION
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**REACTOR PRIMARY COOLANT SYSTEM PIPE RUPTURE STUDY
PROGRESS REPORT NO. 35
JANUARY—MARCH 1976**

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U.S. Nuclear Regulatory Commission,
Metallurgy and Materials Branch of
Division of Reactor Safety Research
Under Contract E(04-3)-189
Project Agreement No. 37

Printed in U.S.A. Price ^{4.00}~~\$5.00~~

Copies available from National Technical Information Service
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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 crack growth rate studies focused on LWR primary piping materials in a simulated BWR primary coolant environment, and (b) studies directed at quantifying weld sensitization in Type-304 stainless steel.

1. INTRODUCTION

The Reactor Primary Coolant System Pipe Rupture Study is being conducted for the Metallurgy and Materials Branch of Division of Reactor Safety Research, USNRC. This Progress Report No. 35 documents work done in the period January 1, 1976 to March 31, 1976. 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 G — Effect of Sensitization on Type-304 Stainless Steel

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.
GEAP-10207-32	No. 32, July — December 1974.
GEAP-10207-32	No. 32, July — December 1974.
GEAP-10207-33	No. 33, January — June 1975.
GEAP-10207-34	No. 34, July — December 1975.

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-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 K — EFFECT OF BWR ENVIRONMENT

A fatigue crack initiation test with 12 specimens being run in 500°F air was concluded. The data are being factored into a topical report on fatigue crack initiation.

An environmental fatigue crack growth test, begun in the previous report period, was completed. The resultant fatigue crack growth data are compared to ASME Section XI data and comparable data from other investigators.

2.2 TASK G — EFFECT OF SENSITIZATION ON TYPE-304 STAINLESS STEEL

The degree of sensitization of six heats of Type-304 stainless steel was evaluated electrochemically. Samples from butt welds are being fabricated for stress corrosion cracking evaluation.

3. TASK K — EFFECT OF BWR ENVIRONMENT (D. A. Hale, D. Vogelhuber)

3.1 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. Typical light water reactor materials are being investigated — Type-304 and -304L stainless steel, Inconel 600 and A-516 carbon steel plus A533 and A508 low alloy vessel steels. Testing is currently being done in a reference 500°F laboratory air environment and a simulated BWR water environment (550°F, 1150 psig, no radiation).

3.2 SUMMARY

A last 500°F baseline air, fatigue crack initiation test was terminated after 66,913 loading cycles with eleven of the twelve specimens having failed. The results of this test are being factored into the topical report on fatigue crack initiation presently in preparation.

The last phases of the moderate frequency, high R ratio, environmental fatigue crack growth test, begun in the previous report period, were completed. A combination of post-test fractographic measurements and cycles-to-failure test data were used to establish the crack length versus cycle behavior for the six specimens involved. The resultant data were analyzed using linear elastic fracture mechanics techniques to produce fatigue crack growth data. These data are compared to ASME Section XI and similar data from other sources.

3.3 FATIGUE CRACK INITIATION (Tasks Ka and Kb)

Work has been conducted under Tasks Ka and Kb, to obtain fatigue crack initiation data needed to determine whether existing ASME fatigue design rules adequately account for the effect of a BWR primary water service environment. This initiation work focuses on light water reactor (LWR) primary piping materials (Types-304 and -304L stainless steel, Inconel 600, and A516 carbon steel) with testing done in both a BWR primary water environment (a special test loop at Dresden 1*) and a 500°F laboratory air environment.

A special specimen was developed for this application. This specimen (Figure 3-1) is a modified, constant-stress cantilever beam with a reduced thickness test section located near the clamped end of the specimen. A small diameter capillary hole is located on the neutral axis of this specimen running from the clamped specimen end to the center of the reduced thickness test section. Capillary tubing welded into the end of this axial capillary hole connects to an external pressure switch. Specimen failure is automatically signalled as soon as a fatigue crack develops deep enough to intersect this axial capillary hole. In the BWR specimens, this axial capillary hole is initially at atmospheric pressure and the external pressure switch detects the 1000 psig pressure from the BWR environment. In the 500°F air specimens this axial capillary hole is pressurized to 50 psig with an inert gas — the external pressure switch detects the drop in pressure due to development of the fatigue crack.

3.3.1 BWR Results — Dresden 1 Test Loop

Testing had previously been done in a BWR primary water environment in a special test loop at Dresden 1 in which specimens were exposed to 500°F, 1040 psig Dresden 1 primary water. A detailed description of the testing done in this loop is contained in a previous progress report (GEAP-10207-33, Subsection 4.3). This loop was deactivated in June 1975; therefore, activity related to this task during the current report period was confined to a post-test visual inspection of fatigue crack initiation specimens removed from the loop in June 1975.

This inspection was done to verify that the failure data (i.e., the remote failure pressure indication) previously received from these specimens during the ~8700 hours of operation of the Dresden 1 test loop, were valid.

* Commonwealth Edison Co., Morris, Illinois.

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

Figure 3-1. Fatigue Test Specimen

This inspection was completed; the results are being factored into the statistical data analysis portion of the topical report on fatigue crack initiation (GEAP-20224) currently being prepared.

3.3.2 500°F Air Results

Fatigue crack initiation tests have been conducted in a 500°F laboratory air environment to provide the baseline data needed to interpret the Dresden 1 BWR data.

Two groups of 12 specimens were previously run in these baseline tests. The results were discussed in GEAP-10207-30, Table 5-7, and GEAP-10207-28, Table 5-4. This current test represents the last test series; pertinent test parameters are summarized in Table 3-1.

The decision was made late in the report period to terminate testing. A total of 66,913 cycles had been accumulated by the one unfailed specimen (No. SS-1023). This specimen was removed and visually checked for cracks — none were found. This specimen is undergoing dye penetrant inspection and will be examined metallographically for microcracking. The results will be factored into the topical report on fatigue crack initiation presently being prepared.

Table 3-1
SPECIMEN LAYOUT, AIR TEST V

Material	Test Condition	Specification Number	Tip Deflection (in.)	Cycles to Failure
304L	As-Received	SL-1005	+0.124 ^a -0.000	18,913
304L	As-Received	SL-44	+0.124 ^a -0.000	19,517
304L	As-Received	SL-1064	+0.156 ^b -0.000	11,483
304	As-Received	SS-1023	±0.062 ^a	>66,913 ^c
304	AR + FS ^d	SS-132	±0.062 ^a	12,776
304	AR + FS ^d	SS-129	±0.078 ^b	10,193
304	AR + FS ^d	SS-135	±0.094 ^e	9,995
304L	As-Received	SL-43	±0.062 ^a	17,930
304L	As-Received	SL-30	±0.062 ^a	17,508
304L	As-Received	SL-33	±0.062 ^a	21,508
304L	As-Received	SL-13	±0.078 ^b	8,485
304L	As-Received	SL-4	±0.094 ^e	6,814

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

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

^c Testing suspended after 66,913 cycles with no failure indication received.

^d FS furnace sensitized (40 hours at 1150°F)

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

3.4 FATIGUE CRACK GROWTH TESTING IN SIMULATED BWR WATER ENVIRONMENT (Task Kd)

Work continues, under Task Kd, to provide fatigue crack growth data in a simulated BWR primary water environment.*

Two test vessels, accommodating up to 10 1T-WOL test specimens (Figure 3-16), are committed to this program. A schematic of these vessels and the test loop which provides the controlled high pressure/temperature water environment for testing is shown in Figure 3-2. This loop is a flowing loop capable of supplying up to 10 gpm of 550°F, 1150 psig water to this vessel while constantly monitoring and controlling the conductivity and oxygen content of the water.

A number of environmental tests are planned for these two vessels using various combinations of waveshape, frequency, and load levels. The objective of this program is to provide fatigue crack growth data and a rationale to allow a piping designer to adequately account for real LWR operating conditions. The emphasis is on piping steels, primarily Type-304 stainless steel and A-516 carbon steel, with a limited amount of data expected for Inconel 600 and Type-304L stainless steel and A533B and A508 Cl2 RPV steels.

Figure 3-2. Simulated BWR Water Test Loop Schematic

* 550°F, 1130 psig demineralized water, 300 ppb O₂, conductivity <1 μmho.

3.4.1 Test Vessel IV, Test III

The high R ratio, 5 cpm test begun in the last report period was completed. Pertinent parameters for this test are summarized in Table 3-2. These are the same conditions which were used for the seven specimens reported in the previous progress report (GEAP-10207-34, Table 4-2). One of the specimens (04-3Q) from this Phase I test was re-installed for additional cycling. In addition, four new specimens (all with capillary holes*) were added.

Table 3-2
TEST VESSEL IV, TEST III, PHASE II, III AND IV

Environment:

550°F, 1150 psig Demineralized water, 200 to 400 ppb dissolved O₂ content

Loading Parameters:

f = 5cpm (sawtooth), maximum load = 7700 lb, minimum load = 6000 lb

Specimen	Material	Capillary Tubes	Remarks
Phase II (Cycles 0-51,850)			
S-4 ^a	T-304 SS, Furnace Sensitized	Yes	
S-7 ^a	T-304 SS, As Received	Yes	
C-4 ^a	A-516 CS, As Received	Yes	Failed at 51,850
04-3Q ^{b,c}	A-533-B CS, As Received	Yes	
Phase III (Cycles 51,851-68,910)			
S-4 ^a	T-304 SS, Furnace Sensitized	Yes	
S-7 ^a	T-304 SS, As Received	Yes	Failed at 68,910
C-8 ^a	A-516 CS, As Received	No	Installed at 51,850
C-3 ^a	A-516 CS, As Received	Yes	Installed at 51,850
04-3Q ^{b,c}	A-533-B, As Received	Yes	
Phase IV (Cycles 68,911-107-159)			
S-4 ^a	T-304 SS, Furnace Sensitized	Yes	
C-8 ^a	A516 CS, As Received	No	
C-3	A-516 CS, As Received	Yes	
04-3Q ^{b,c}	A-533B, As Received	Yes	Failed at 107,159

^a 0.9T-WOL

^b 1.0T-WOL

^c Accumulated 87,284 cycles during Phase I

*Refer to Figure 4-9 and the discussion, Section 4.4.1.1, in GEAP-10207-34.

Dynamic cycling was resumed using the same loading parameters. Testing was stopped at 51,850 cycles to remove a failed specimen (C-4).

Two new carbon steel specimens (C-3 and C-8) were installed and dynamic cycling resumed. Testing was interrupted again at 68,910 cycles to remove failed specimen S-7. Dynamic cycling was once again resumed and continued until 107,159 cycles when specimen 04-3Q failed signalling the end of the test.

3.4.2 Post-Test Specimen Examination

All specimens were removed and pulled apart. The fracture surfaces for these six specimens are shown in Figures 3-3 through 3-8. A traversing microscope was used to locate the capillary holes and any artifacts which might be present. The resulting crack length measurements were combined with the appropriate values of test cycles* to produce a relationship between crack length and test cycles.

Figure 3-3. Fracture Surface, Specimen S-4

3.5 RESULTS

3.5.1 Type-304 Stainless Steel

Examination of the fracture surfaces of specimens S-4 and S-7 (Figures 3-3 and 3-4, respectively) revealed a number of artifacts which show that the fatigue crack propagated as a relatively straight line. A little crack front curvature was noted at the longer crack lengths relatively late in the life of the specimen.

* Obtained from capillary hole pressure signals, or changes in loading parameters which occurred at some known value of test cycles.

Figure 3-4. Fracture Surface, Specimen S-7

Figure 3-5. Fracture Surface, Specimen C-3

Figure 3-6. Fracture Surface, Specimen C-4

Figure 3-7. Fracture Surface, Specimen C-8

Figure 3-8. Fracture Surface, Specimen 04-3Q

The surface of S-4, the furnace sensitized specimen, is typically much rougher with a more "granular" texture than S-7, the as-received specimen.

The measured crack length values obtained from both artifacts and capillary holes for these two specimens are shown in Figure 3-9. In order to be consistent, artifact measurements were made at a midplane location corresponding to the plane through the axes of the capillary holes. The two abrupt changes noted in both curves at $N \sim 15,000$ and $N \sim 37,000$ are due to stress change marking intervals during which the amplitude and frequency of loading were increased while maintaining the same maximum load. The bands produced by these two intervals are readily visible on these two specimens.

The data shown in Figure 3-9 were used to calculate incremental crack growth rates $(\Delta A / \Delta N)^*$ and average stress intensity ranges $(\Delta K_{ave})^{**}$ based on a mid-increment crack length. The resultant crack growth data is plotted in Figure 3-10. Also shown are data from two General Electric in-house tests on Type-304 stainless steel in the as-received condition and data from specimen S-5 which was part of the first phase of the present TV-IV test. These GE data were obtained using this same WOL specimen geometry, the same test frequency and, in one case, the same environment. The main difference is that these GE data were obtained under $R=0$ loading conditions.

All these data are replotted in Figure 3-11 in terms of an effective stress intensity*** which has been used by other investigators^{1,2} to normalize crack growth data obtained at various R ratios.

$$^* \Delta A / \Delta N = (A_{i+1} - A_i) / (N_{i+1} - N_i)$$

$$^{**} \Delta K_{av} = \frac{\Delta P C_3 (\bar{A} / w)}{\sqrt{B B_N} \sqrt{\bar{A}}}, \text{ where } \bar{A} = (A_{i+1} + A_i) / 2 \text{ and}$$

$$C_3 (A / w) = 30.96 (\bar{A} / w) - 195.8 (\bar{A} / w)^2 + 730.6 (\bar{A} / w)^3 - 1186.3 (\bar{A} / w)^4 + 754.6 (\bar{A} / w)^5$$

$$^{***} K_{eff} = K_{max} (1 - R)^m = \Delta K (1 - R)^{m-1}$$

Figure 3-9. Crack Length versus Cycles, Specimens S-4 and S-7

Figure 3-10. Type-304 Stainless Steel Crack Growth Data.
 All Tests in 550°F Simulated BWR Water Environment at 5 cpm.

Figure 3-11. Type-304 Stainless Steel Crack Growth Data.
 All Tests in 550°F Simulated BWR Water Environment at 5 cpm.

These results indicate that this approach works very well in reducing these particular data. More important, these results suggest that the effect of this simulated BWR water environment is negligible as far as fatigue crack growth is concerned compared to a 550°F laboratory air environment — *at least at this particular frequency (5 cpm)*. Note also that the growth rates obtained in the furnace sensitized material are the same as those seen in the as-received material.

3.5.2 Carbon Steel

The fracture surfaces of the carbon steel specimens were also examined using the traversing microscope. A great many artifacts were noted as can be seen in Figures 3-5 through 3-8. These artifacts and the capillary hole measurements were used to establish the crack length versus cycle data shown in Figures 3-14 and 3-15. The shapes of these artifacts indicate that for the three specimens with capillary holes, the crack front is growing faster near the sides of the specimens than at the midplane of the specimen. This crack front curvature is very pronounced in specimens C-3 and 04-3Q. In C-3, this curvature continues to become more pronounced as the crack grows. In 04-3Q, however, the crack seems to have assumed an equilibrium shape after passing the third capillary hole and maintains this same approximate shape for the remainder of the test. Therefore, for C-3 the crack growth rates which were calculated (and shown in Figures 3-12 and 3-13) based on midplane artifact and capillary hole measurements would underestimate the true crack growth rates especially at longer crack lengths (i.e., at the higher values of ΔK). For specimen 04-3Q, however, the calculated crack growth rates would appear to be valid especially at the longer crack lengths.

Specimen C-4 displays a very moderate amount of crack curvature which increases in a continuous manner as the crack becomes longer. The fracture surface looks very similar as far as the general shape of the artifacts is concerned, to specimen C-1 (see Figure 4-11 in GEAP-10207-34) which was tested in Phase I of this same test and subjected to these same loading conditions.

Specimen C-8 is the only specimen included in these most recent phases of this test which did not have capillary holes. Only one artifact is apparent on the fracture surface and its location is such that it cannot be reasonably attributed to any event during the test. Therefore, only the beginning and end-of-test crack length measurements are shown in Figure 3-14. The geometry of the one artifact and the end-of-test crack is very different from the crack geometries seen in the companion specimens with capillary holes and different from specimen C-5, tested earlier, which also did not have holes. Examination of the fracture surfaces of the specimens with and without capillary holes, shows discontinuities which suggest that the active fatigue crack front is retarded in the region adjacent to these capillary holes. This phenomenon is not observed in every test and the fact that it is not seen in the Type-304 stainless steel specimens tested in this same test would suggest that this effect is not mechanical and is probably tied into the complex interaction of environmental and mechanical fatigue taking place at the fatigue crack tip in this carbon steel material which is known to be susceptible to environmental effects.

The crack growth data from these most recent four specimens are shown in Figures 3-12 and 3-13 as are data from (1) specimens C-1 and C-5 which were tested during Phase I of this test and (2) specimen CS-01 — a 2T-WOL — tested in this same environment and previously reported in Figure 4-7 in GEAP-10207-32.

The value of 0.5 used for the exponent m in Figure 3-12 is a purely empirical choice which seems to do the best job of normalizing the high R-ratio data from these recent specimens to the previous low R-ratio data from CS-01. A more sophisticated search for the most appropriate value for this exponent will be carried out as more data become available.

3.6 WORK IN PROGRESS

The specimens from this first environmental fatigue crack growth test are presently undergoing both scanning electron microscope (SEM) and metallographic examination. Preparations are under way for the next test which will be run at a slow test frequency (0.3 cpm) and a high R ratio (~ 0.6).

Figure 3-12. Carbon Steel Crack Growth Data, Simulated BWR Water Environment

Figure 3-13. Carbon Steel Crack Growth Data, Simulated BWR Water Environment

Figure 3-14. Crack Length versus Cycles, Specimens C-3 and C-8

Figure 3-15. Crack Length versus Cycles, Specimens 04-3Q and C-4

PART No.	SPEC No.	B	W	C	D	E	F	G	H	L	M	N	O	P	R	S
3	1T-B	1.000 ^{+0.010}	2.55	3.200	0.094	0.767	0.650	1.240	2.480	0.050	0.047	0.175 ^{±0.020}	0.500 ^{+0.005} -0.000	-	YES	NO
4	0.9T-B	0.900 ^{±0.010}	2.55	3.200	0.094	0.767	0.650	1.240	2.480	0.050	0.047	0.175 ^{±0.020}	0.500 ^{+0.005} -0.000	-	YES	NO

NOTES:

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

Figure 3-16. WOL Specimen for Crack Growth Rate Study

4. TASK G — EFFECT OF SENSITIZATION — TYPE-304 STAINLESS STEEL (W. L. Clarke, J. C. Danko, V. Romero)

4.1 INTRODUCTION

The purpose of this task is to develop a nondestructive field test for evaluating the degree of sensitization (DOS) of welded Type-304 stainless steel. The electrochemical approach utilizes the polarization behavior of a material to evaluate its DOS. This potentiokinetic reactivation method has been described in GEAP-10207-33.

4.2 SUMMARY

1. The DOS and intergranular stress corrosion cracking (IGSCC) behavior of six heats of Type-304 stainless steel seamless piping were evaluated after sensitizing samples 40 hours at 621°C (1150°F). The results revealed that all six heats were highly susceptible to IGSCC, and all possessed large DOS as measured electrochemically.
2. Butt welds (circumferential) have been produced joining two segments from each of the six piping heats above. Electrochemical DOS measurements were completed on outside and inside locations from two azimuths of the weld HAZ's of each pipe. Samples are being fabricated for IGSCC testing.
3. Two electrochemical parametric studies were performed on welded samples in 0.5M H₂SO₄ + 0.01M KSCN at 30°C. In the first series of tests, it was found that slower reactivation sweep rates (~3 V/h) are more sensitive; the P_a values decrease with increasing sweep rate. Also, the optimum time-at-passivating-potential appears to be between 1 and 15 minutes. Additional testing needs to be conducted to confirm these findings.
4. Weld profiles were completed to characterize the DOS in the HAZ's (i.d.) in 10-in. seamless and 26-in. rolled-and-welded Type-304 stainless steel pipes.

4.3 RESULTS AND DISCUSSION

4.3.1 Furnace Sensitized Condition

Intergranular stress corrosion cracking tests have been completed on six heats of Type-304 stainless steel seamless piping. The tests were performed in 289°C (550°F) water containing 36 ppm dissolved oxygen at an applied stress of 40 ksi after first sensitizing triplicate samples 40 hours at 621°C (1150°F). The results of these tests, presented in Table 4-1, indicate that all six heats are highly susceptible to IGSCC in this oxygenated environment.

Table 4-1
IGSCC TEST RESULTS FOR TYPE-304
SEAMLESS PIPE
(289°C WATER, 36 ppm O₂)

Heat	Applied Stress ^a (ksi)	Failure Time (h)			Avg
		Test 1	Test 2	Test 3	
454659	40	136	674	125	312
2P6396	39.2	81	184	139	135
M7616	41.7	100	165	45	103
TH6656	39.6	84	203	116	134
2P6424	39.6	84	123	18	57
M7772	41.8	78	138	32	83

^a 60% UTS at 289°C

After conducting the IGSCC tests, the tab ends of each sample were removed for electrochemical reactivation measurement (DOS) in 0.5M H₂SO₄ + 0.01M KSCN at 30°C. These measurements are listed in Table 4-2. For comparative purposes, any charge (P_a) value in excess of 0.010 C/cm² is considered sensitized. The test results show that all six piping heats are well sensitized, which in part accounts for the high susceptibility to IGSCC. Because of this high degree of susceptibility after furnace sensitizing, it has become difficult to study and correlate the effects of electrochemical DOS measurements. Consequently, all future measurements will be restricted to as-welded or lightly sensitized conditions; i.e., lightly sensitized conditions based on weld interpass and heat input studies currently in progress for a separate Electric Power Research Institute (EPRI) program.

Table 4-2
DOS FOR FURNACE SENSITIZED TYPE-304
SEAMLESS PIPE MEASURED ELECTROCHEMICALLY IN
0.5M H₂SO₄ + 0.01M KSCN AT 30°C

Heat	Charge, P _a (C/cm ²)	Maximum Peak Height (mA/cm ²)	Flade Potential (mV)
454659	3.864	56.46	172.60
2P6396	3.429	54.48	19.41
M7616	3.555	51.74	51.66
TH6656	2.510	35.10	149.20
2P6424	3.032	43.59	183.20
M7772	3.219	47.11	94.59

4.3.2 Welded Samples

Welding was completed on the six seamless piping heats (five 4 inch and one 10 inch, all Schedule 80) to produce weldments which were sectioned out for electrochemical and stress corrosion sample fabrication. These samples will be tested for DOS using electrochemical potentiokinetic reactivation and IGSCC resistance in 289°C (550°F) water containing 36 ppm dissolved O₂ using constant extension rate (CXR) methods.

Currently, electrochemical reactivation measurements have been completed for samples with an average area of 0.5 cm² taken at locations adjacent to the weld fusion line. The measurements were taken for the pipe o.d. and i.d. at two different arbitrary azimuths (0° and 180°). The results (shown in Table 4-3) reveal moderate sensitization of all pipe heats with no major difference in DOS between the two pipe sizes (4-inch or 10-inch) or angular locations. A difference in DOS was noted between the average inside (0.228 C/cm²) and outside (0.044 C/cm²) locations, possibly attributable to maximum heat input differences during welding.

One of the above pipe welds (Heat TH6656, 10-inch, Schedule 80) was profiled to characterize the weld heat-affected-zone (HAZ). The results are plotted in Figure 4-1 and are compared to data obtained from a 26-in. rolled-and-welded (R&W) pipe (Heat 834264). The data show that the seamless pipe exhibits the greater degree of sensitization (0.125 C/cm² compared to 0.023 C/cm²). The maximum HAZ for the seamless pipe occurs about 100 mils from the weld fusion line (FL), while the R&W pipe maximum occurs over a broader range (100—200 mils from FL).

4.3.3 Parametric Studies

In an effort to determine the optimum test parameters for the potentiokinetic reactivation technique, two parametric studies were conducted on welded Type-304 stainless steel samples. These two studies were concerned exclusively with the effects on the integral P_a of the reverse polarization response due to (1) reactivation sweep rate and (2) the influence of time at a passivating potential of +200 mV.

Table 4-3
DOS AFTER WELDING FOR SIX HEATS OF TYPE-304 STAINLESS STEEL
SEAMLESS PIPING AS MEASURED ELECTROCHEMICALLY IN
0.5M H₂SO₄ + 0.01M KSCN AT 30°C

Heat	Orientation (degrees)	Charge, P _a (C/cm ²)	
		I.D.	O.D.
454659	0	0.033	0.002
454659	180	0.053	0.005
2P6396	0	0.206	0.015
2P6396	180	0.215	0.007
M7616	0	0.370	0.135
M7616	180	0.801	0.097
TH6656	0	0.075	0.011
TH6656	180	0.013	0.172
2P6424	0	0.378	0.035
2P6424	180	0.313	0.012
M7772	0	0.169	0.017
M7772	180	0.116	0.015

The change in P_a as a function of reactivation sweep rate was measured on a sample of welded plate material (Heat X14902) taken within the HAZ. Two samples with different weld heat inputs were tested at four different sweep rates. A trend of decreasing P_a with increase in sweep rate was obtained for both weld samples (Figure 4-2). The optimum sweep rate is that which produces the greatest sensitivity, i.e., largest difference in P_a between various levels of sensitization, but maintains reasonably high positive values. These data suggest that the slower rate (3 V/h) is the most sensitive consistent with the ability to conduct a test in a reasonable time (10 — 30 minutes). Additional testing will be performed using annealed samples, however, to assure that the effects measured are due to sensitization and not to general breakdown of the passive film at the lower reactivation rate.

The influence of time at a passivating potential of +200 mV on P_a was investigated using a welded sample (HAZ region) from the 10-in. seamless pipe (Heat TH6656). The results for these tests are shown in Figure 4-3; a constant reactivation sweep rate of 6 V/h was used for all four tests. For test consistency, it is desirable to select a "hold" time on a portion of the curve where the slope changes only gradually (greater reproducibility). It would appear, therefore, that the optimum time is probably between 1 and 15 minutes (the 2 minutes currently used may not be quite long enough). Additional testing will be performed to fill in the curve between these limits (1 and 15 minutes).

Figure 4-1. Effect of Welding on the Sensitization of Seamless Pipe (Heat TH6656) Compared to Rolled-and-Welded (Heat 834264) as Determined by Potentiokinetic Reactivation in 0.5M H₂SO₄ + 0.01M KSCN at 30°C

Figure 4-2. Effect of Reactivation Scan Rate on Resultant Charge for Type-304 Stainless Steel (Heat X14902) in 0.5M H₂SO₄ + 0.01M KSCN at 30°C (As-Welded HAZ Samples with Two Different Heat Inputs)

Figure 4-3. Effect of Time at the Passivating Potential (+200 mV) on the Resultant Charge for Type-304 Stainless Steel (Heat TH6656) in 0.5M H_2SO_4 + 0.01M KSCN at 30°C (average of three tests)

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