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**REACTOR PRIMARY COOLANT
SYSTEM PIPE RUPTURE STUDY
PROGRESS REPORT NO. 39
JANUARY—MARCH 1977**

U.S. NUCLEAR REGULATORY COMMISSION
CONTRACT AT(49-24)-0202
PROJECT AGREEMENT 37

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**REACTOR PRIMARY COOLANT SYSTEM PIPE RUPTURE STUDY
PROGRESS REPORT NO. 39
JANUARY — MARCH 1977**

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Division of Reactor Safety Research
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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 Research Branch of Division of Reactor Safety Research, USNRC. This Progress Report No. 39 documents work done in the period January 1, 1977 to March 31, 1977. 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-10207-33	No. 33, January — June 1975.

GEAP-10207-34	No. 34, July — December 1975.
GEAP-10207-35	No. 35, January — March 1976.
GEAP-10207-36	No. 36, April — June 1976.
GEAP-10207-37	No. 37, July — September 1976.
GEAP-10207-38	No. 38, October — December 1976.

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.
GEAP-21382	Detection of Sensitization in Stainless Steel Using Electrochemical Techniques.
GEAP-20244	Low-Cycle Fatigue Evaluation of Primary Piping Materials in a BWR Environment.

2. SUMMARY

2.1 TASK K — EFFECT OF BWR ENVIRONMENT

A topical report* summarizing the work done over the past several years on environmental fatigue crack initiation (Task K_a) has been completed and is presently out for review.

Environmental fatigue crack growth testing continued with both slow and moderate frequency high R ratio** tests underway. Data from eight specimens removed from these two tests are presented.

Preparations are underway for two additional environmental fatigue crack growth tests needed to complete the planned test matrix for the current contract year.

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

Laboratory measurements using an Electrochemical Potentiokinetic Reactivation (EPR) field test cell were made on the outer surface of a weld section from a 4-inch, Schedule 80 Type-304 stainless steel pipe.

A piping component weld specimen was fabricated which incorporates four test welds and a standard 4-inch Schedule 80 butt weld elbow. This specimen will be used to qualify the EPR field test cell.

An analysis of the constant extension rate and EPR data from 21 heats of welded and sensitized Type-304 stainless steel was conducted to determine whether there was any statistical correlation.

*D. A. Hale, *Fatigue Evaluation of Primary Piping Steels in a BWR Environment*, General Electric Co., February 1977 (GEAP-20244).

**R ratio = Minimum Load ÷ Maximum Load

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 A516 carbon steel plus A533 and A508 low alloy vessel steels. Testing is currently being done in a simulated BWR water environment (550°F, 1150 psig, no radiation) and is focused on fatigue crack growth.

3.2 SUMMARY

A topical report* summarizing the work done over the past several years on environmental fatigue crack initiation (Task K_a) has been completed and is presently out for review.

Environmental fatigue crack growth testing continued with both slow and moderate frequency high R ratio** tests underway. Data from eight specimens removed from these two tests are presented.

Preparations are underway for two additional environmental fatigue crack growth tests needed to complete the planned test matrix for the current contract year.

3.3 FATIGUE CRACK INITIATION (Tasks K_a + K_b)

Work was conducted under Tasks K_a and K_b, during previous report periods, 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 work focused on fatigue crack initiation in 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 topical report summarizing this work was completed and is presently out for review. The final report will be issued early in the next report period. This report concludes that the high-temperature, high-purity BWR water environment does affect the low-cycle fatigue behavior of some piping material in some metallurgical conditions. For example, high heat input welds of Type-304 stainless steel can exhibit intergranular crack propagation and show reduced fatigue lives in the BWR environment. On the other hand, normal heat input welds and as-received (i.e., mill-annealed) Type-304 stainless steel material show no effect of the BWR environment. The furnace-sensitized Type-304 and -304L stainless steels exhibit the greatest environmental fatigue strength reduction. In this condition it is shown that these materials develop intergranular stress corrosion cracks and corresponding shortened fatigue life. Use of Type-304 stainless steel in the furnace-sensitized condition has been excluded from use in the BWR since 1969.

Carbon steel also exhibits a reduction in fatigue life in the BWR environment. However, this reduction is adequately accounted for by the fatigue design rules and criteria in the ASME Section III design code. Likewise, all other material conditions and their corresponding environmental effects are shown to be adequately accounted for by the ASME Code.

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

Work continues, under Task K_d, to provide fatigue crack growth data in a simulated BWR primary water environment.‡ These data are needed to evaluate the growth of flaws in piping or pressure vessels and to critique ASME flaw evaluation rules.

*D. A. Hale, *LOC CIT.*

**R ratio = Minimum Load ÷ Maximum Load

†Commonwealth Edison Company, Morris, Illinois.

‡550°F, 1130 psig demineralized water, 300 ppb O₂, conductivity > 0 μmho, no radiation.

Table 3-1
TASK K_d
ENVIRONMENTAL FATIGUE CRACK GROWTH TEST PARAMETERS

Test Environment: 1150 psig, 550°F demineralized water, 300 ppb dissolved O₂, conductivity <1 μ mho

Common Loading Parameters: Maximum Load, 7700 pounds; Minimum Load, 4620 pounds

Test Specimen: 0.9T or 1T WOL

I. Slow Frequency Test, Test A

Loading Parameters: R Ratio = 0.6, $f = 0.3$ cpm, skewed sawtooth waveshape*

Specimen Layout:	Specimen Identification	Specimen Type
1. T-304 SS, As-Received	1. S-9 ^b	0.9T-WOL
2. T-304 SS, Furnace Sensitized	2. S-8 ^b	0.9T-WOL
3. T-304 SS, Cast	3. S-24 ^f	0.9T-WOL
4. T-304L SS, As-Received	4. SL-1 ^b	0.9T-WOL
5. Inconel 600	5. IN-1 ^f	0.9T-WOL
6. A516 Gr. 70, CS, As-Received	6. C-2, ^a C-6 ^{c,f}	0.9T-WOL
7. A508-2 CS, As-Received	7. C-10, ^a C-12, ^a C-11 ^{c,f}	1T-WOL
8. A508-2 CS, Sub Arc Weld HAZ	8. C-15 ^{c,f}	1T-WOL

II. Moderate Frequency Test, Test B

Loading Parameters: R Ratio = 0.6, $f = 1.25$ cpm skewed sawtooth waveshape*

Specimen Layout:	Specimen Identification	Specimen Type
1. T-304 SS, As-Received	1. S-10 ^d	0.9T-WOL
2. A516 CS, As Received	2. C-7 ^e	0.9T-WOL
3. A508-2 CS, As-Received	3. C-9 ^{f,g}	1T-WOL

*Special waveform details

^a Removed at N = 5454 cycles

^b Removed at N = 10,120 cycles

^c Replacement specimen installed at N = 5454 cycles

^d Removed at N = 23,394

^e Removed at N = 25,133

^f Presently under test

^g Special loads used for this specimen only,

$P_{max} = 8800$ pounds, $P_{min} = 5280$ pounds

1. 0.007 in. MAX. RADIUS (EDM)
2. LAY MARKS TO FALL PARALLEL TO AXES OF RADIUS SURFACE
FINISH TO BE 32.

Figure 3-1. WOL Specimen for Crack Growth Rate Study

Figure 3-2. Simulated BWR Water Test Loop Schematic

Two test vessels, accommodating up to 11 1T-WOL test specimens (Figure 3-1), are committed to this program. A schematic of these vessels and the GE environmental 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.

Testing continued using both test vessels during the report period — pertinent parameters for both tests are summarized in Table 3-1. These two tests are both being conducted using a loading waveshape which incorporates a high mean stress ($R^* = 0.6$). The purpose of Test A is evaluate the effect of slow frequency, high R ratio loadings. The Test B parameters were chosen to provide high R ratio data at an intermediate loading frequency midway between the previous 5 cpm data and the 0.3 cpm Test A data.

3.4.1 Test A

As noted in Table 3-1, a total of eight 1T or 0.9T-WOL specimens were included in the original Test A specimen complement when environmental fatigue testing began during the previous report period.

A total of six of these were removed on two separate occasions during the previous report period and three replacement specimens added. At the present time, this vessel is on line with five specimens under test.

The crack growth data from these six removed specimens are discussed in Subsection 3.4.3.

3.4.2 Test B

Two of the three original specimens in this test vessel complement grew cracks to failure during the previous report period (Table 3-1). On the other hand, the third specimen (C-9)** did not seem to experience any extension of the original fatigue precrack during the ~25,000 loading cycles which it was subjected to prior to the suspension of testing.

This specimen was installed in a fatigue precracking machine to attempt to verify the existence of the original fatigue precrack. Visual surface measurements made on both specimen sides with the specimen under cyclic load confirmed the presence of a crack approximately 0.065 inch longer than the original fatigue precrack. Therefore, the crack did apparently extend, but at a very slow rate.

The fatigue crack in this specimen was extended an additional 15 mils and the specimen reinstalled in the autoclave for testing. Cyclic loading of this specimen resumed earlier in the report period.

The crack growth data from the two failed specimens in this test is discussed in Subsection 3.4.3.

3.4.3 Results

The six failed specimens from Test A and two specimens from Test B were pulled apart at room temperature to allow examination of the fracture surfaces. The resultant surfaces are shown in Figures 3-3 through 3-11. Also shown is the fracture surface from an earlier high R ratio test (Figure 3-11).

These fracture surfaces were examined using a 50X microscope with X and Y axis micrometer positioning and measurement capability. Artifacts noted on the surface were catalogued and measured (i.e., distance from load pin centerline). In addition, measurements of distance from the load pin centerline to the forward edge of each capillary hole were also made.

*R ratio = Minimum Load ÷ Maximum Load

**A508 pressure vessel steel

Figure 3-3. Final Fracture Surface, Specimen C-7 (Test B, Total Cycles 25,133)

Figure 3-4. Final Fracture Surface, Specimen C-10 (Test A, Total Cycles 5,454)

Figure 3-5. Final Fracture Surface, Specimen C-2 (Test A, Total Cycles 5,454)

Figure 3-6. Final Fracture Surface, Specimen C-12 (Test A, Total Cycles 5,454)

Figure 3-7. Final Fracture Surface, Specimen S-8 (Test A, Total Cycles 10,120)

Figure 3-8. Final Fracture Surface, Specimen S-9 (Test A, Total Cycles 10,120)

Figure 3-9. Final Fracture Surface. Specimen SL-1 (Test A. Total Cycles 10,120)

Figure 3-10. Final Fracture Surface. Specimen S-10 (Test B. Total Cycles 25,133)

Figure 3-11. Final Fracture Surface, Specimen C-1 (Test III, Total Cycles 87,284)

3.4.3.1 Carbon/Alloy Steel

The carbon steel specimens display one common fracture surface characteristic — in all cases, the crack front propagates at a nonuniform rate with the crack growing more rapidly near the sides of the specimen. Furthermore, this resultant curvature becomes progressively more pronounced at longer crack lengths. This is especially visible in Figures 3-3 and 3-4 where several intermediate artifacts are seen. This curvature was noted in other carbon steel specimens tested in a previous high R ratio test at a frequency of 5 cpm (Figure 4-10 and 4-11 in Reference 1, and Figures 3-5, 3-6, 3-7, and 3-8 in Reference 2). This curvature was not seen during a previous test where a 2T WOL specimen (Figure 5-9 in Reference 3) from this same heat of material was tested in this same environment. The primary difference in this earlier test, other than use of a larger specimen, was the fact that the loading was carried out at a zero R ratio. It is not clear whether this crack front curvature is due to specimen thickness effects or to the high mean stress. The low R ratio tests, which will be run following conclusion of these high R ratio tests, will produce data which will help resolve this question. These tests will be performed using a 0.9 T-WOL specimen geometry.

In any case, the presence of a curved crack front which changes geometry over the duration of the test, complicates analyses of these tests. No matter what technique is used to monitor the progress of the fatigue crack — compliance, capillary holes, or even surface measurements — this curvature must be somehow accounted for. Therefore, the data from these four carbon steel specimens were analyzed using an approach which relies upon a special crack front curvature correction factor — K_{cf} . This factor is used to correct the capillary hole cycle data, which are measured at the specimen midplane, to account for the observed curved crack front geometry.

The specimen fracture surfaces shown in Figures 3-3 through 3-10 were examined using a special XY traversing microscope. Crack length measurements were made on all artifacts at each side of the specimen and at the 1/4, 1/2, and 3/4 positions across the width of the specimen. These resulting five measurements were averaged

where

$$A_{ave} = \sum_{i=0}^4 A_{i/4}/5$$

A value for K_{CF} was calculated for each value of $A_{1/2}$

where

$K_{CF} \triangleq$ Crack Front Curvature Correction Factor

$$\triangleq \left[\sum_{i=0}^4 A_{i/4}/5 \right] \div A_{1/2}$$

This factor, then, provides a rational basis for increasing the midplane crack length measurements to recognize the more rapid crack growth taking place near the specimen sides. Figure 3-12 shows the manner in which K_{CF} increases as a function of the midthickness measured crack length for these four specimens. Note that in some cases the correction becomes as large as 10%.

The best fit line from Figure 3-12 for each individual specimen was then used to correct the midplane measured crack lengths for that specimen. The resultant corrected crack length* versus cycles data for these four specimens are shown in Figures 3-13 and 3-14. Note that both capillary hole and surface artifact data are used to construct these curves.

These crack length/cycles data were used to calculate incremental crack growth rates ($\Delta A/\Delta N = (A_{i+1} - A_i)/(N_{i+1} - N_i)$). Corresponding stress intensity values based on the applied load range were calculated using the corrected midincrement crack length. The resultant crack growth/stress intensity range data are shown in Figure 3-15. The solid lines in Figure 3-15 represent the recommended design lines for an air and water environment from Section XI of the ASME Boiler and Pressure Vessel Code. The dotted lines represent upper and lower bounds for data previously obtained, as part of a GE in-house program.** In this program A508-2 material was tested in this same environment over a loading frequency range from 0.037 to 5 cycles per minute under zero-tension loading ($R=0$).

These same data, shown in Figure 3-15, are replotted in Figure 3-16 in terms of an "effective" stress intensity factor which incorporates R ratio to attempt to normalize data obtained at various R ratios.

3.4.3.2 Type-304 and -304L Stainless Steel

In all four stainless steel specimens, the fatigue crack front seems to have grown at a relatively uniform rate across the specimen width (Figures 3-9 through 3-12). Only the furnace-sensitized Type-304 specimen (S-8, Figure 3-7), tested at the slower frequency, displays local curvature near the outer edges, indicating a somewhat more rapid growth rate near the edges.

These relatively straight crack fronts simplify the analysis of these data somewhat eliminating the need to resort to the crack front curvature correction factor approach previously used for the carbon/alloy steel specimens.

Fracture surface measurements were obtained for all four of these specimens using the techniques previously described in Subsection 3.4.3.1. The resultant crack growth data are plotted in terms of stress intensity range in Figure 3-17.

*i.e., corrected crack length = K_{CF} x midplane crack length

**Gerber, Heald, and Kiss, "Fatigue Crack Growth in SA508-CL2 Steel in a High-Temperature, High-Purity Water Environment," *Journal of Engineering Materials and Technology*, October 1974, Volume 96, Series H, Number 4.

Figure 3-12. Crack Front Curvature Correction Factor versus Midthickness Crack Length, Carbon Steel

3.4.4 Discussion

The data shown in Figures 3-15 and 3-17 represent the first, second, and third of a total of five environmental fatigue crack growth tests which will be run during this current contract year.* Therefore, detailed analysis of the data from these first two tests, beyond that represented by Figures 3-15 and 3-17, will be deferred until the data from all five are available. However, several trends are evident which deserve comment:

- a. The carbon and alloy steel data from the slow frequency test (Test A) display about the same degree of scatter and same relatively weak stress intensity range dependence as previously noted in the fast frequency test (Figure 3-13, GEAP-10207-35). On the other hand, the data from the one moderate frequency specimen display a stronger dependence upon stress intensity range.
- b. Preliminary comparison of crack growth rates observed in these slow and moderate frequency carbon steel tests shows they are higher than observed earlier at a relatively fast cyclic frequency of 5 cpm.
- c. The Type-304 and -304L data continue to display the same relatively low degree of scatter and strong dependence upon stress intensity range as previously noted (Figure 3-10, GEAP-10207-35).
- d. The macroscopic growth rates for the as-received and the furnace-sensitized Type-304 stainless steel are not significantly different at this slow loading frequency — a fact previously noted in the fast frequency test.
- e. There appears to be an average 200% to 300% increase in macroscopic growth rates when going from a loading frequency of 1.25 to 0.3 cycles per minute for the stainless steels.

3.5 PRESENT STATUS

Testing continued through the end of the report period, on both Tests A and B, to complete testing of the surviving specimens.

Efforts are underway to prepare the specimens needed for the next two tests (Table 3-2).

*See Table 3-2.

Table 3-2
TASK K_σ TEST MATRIX

Test Number	R Ratio	Loading Frequency (cpm)	Wave Shape	Specimen Layout	Remarks
III	0.78	5	Symmetric Sawtooth	T-304 SS, As-Received T-304 SS, Furnace Sensitized A516 CS, As-Received A533B CS, As-Received	Test complete, data published (GEAP-10207-34, Figure 4-15; and GEAP-10207-35, Figures 3-10 and 3-13)
A	0.6	0.3	Skewed Sawtooth	T-304 SS, As-Received T-304 SS, Furnace Sensitized T-304 SS, Cast CF8 T-304L SS, As-Received Inconel 600, As-Received A516 CS, As-Received A508-2 CS, As-Received A508-2 CS, Weld (HAZ)	Testing continues, summary of data received to date in Figures 3-15 and 3-17.
B	0.6	1.25	Skewed Sawtooth	T-304 SS, As-Received A516 CS, As-Received A508-2 CS, As-Received	Testing continues, summary of data received to date in Figures 3-15 and 3-17.
C	0.05	0.3	Skewed Sawtooth	T-304 SS, As-Received A516 CS, As-Received A508 CS, As-Received	To be completed by September 31, 1977.
D	0.05	5	Skewed Sawtooth	T-304 SS, As-Received T-304 SS, Furnace Sensitized T-304L SS, As-Received Inconel 600, As-Received A516 CS, As-Received A508-2, As-Received	To be completed by September 31, 1977

Figure 3-13. Corrected Crack Length versus Cycles Data, Carbon Steel, Test A

Figure 3-14. Corrected Crack Length versus Cycles Data, Specimen C-7, Test B

Figure 3-15. Carbon Steel Crack Growth Data, Simulated BWR Water Environment

Figure 3-16. Carbon Steel Crack Growth Data, Simulated BWR Water Environment

Figure 3-17. Type-304 Stainless Steel Crack Growth Data.
All Tests in 550°F Simulated BWR Water Environment

4. TASK G

4.1 INTRODUCTION

The objective of this task is to develop and evaluate a nondestructive electrochemical field test unit that is capable of quantitatively measuring the degree of sensitization (DOS) in the heat affected zone (HAZ) of welded Type-304 stainless steel piping.

Efforts this period were directed toward the development of a field test cell and toward performing preliminary in situ measurements in the laboratory on a Type-304 stainless steel welded pipe section. This section consisted of an L-shaped weldment with two vertical and two horizontal welds. Work also continued on the correlation of intergranular stress corrosion cracking (IGSCC) with the electrochemical potentiokinetic reactivation (EPR) charge density value, P_a , on 10 and 11 heats of pipe material in the welded and sensitized condition.

4.2 SUMMARY

Laboratory measurements using an EPR field test cell were made on the outer diameter (O.D.) of a section of 4-in. Schedule 80 weld section of Type-304 stainless steel pipe at four azimuths. The results showed an average P_a value of 1.186 C/cm².

A 49-in. long pipe section of an L-configuration containing four welds was fabricated and will be used to qualify the field test cell.

Statistical evaluation of the P_a value as a function of constant extension rate test (I_{bs}) value revealed a 0.70 and 0.89 correlation coefficient for 10 and 11 heats of as-welded and sensitized 304 stainless steel material, respectively.

4.3 RESULTS AND DISCUSSION

4.3.1 EPR Cell Testing on Pipe Outside Diameter

Initial laboratory testing of the EPR field test cell for DOS measurement was performed on the outside diameter of a 4-inch welded Type-304 stainless steel pipe section (8 inches in length) from heat M0063. The 6-inch-long tubular cell (2-inch diameter) was positioned adjacent to the weld in the HAZ and electrical connections made to the Hokuto-Denko Polarization system. A scan rate of 6 volts per hour and a 0.5 M H₂SO₄ + 0.01 M KSCN electrolyte at 25°C was used to carry out the test at four different circumferential azimuths of the pipe. Two readings were made at each position — the calculated P_a values obtained are listed in Table 4-1. The reason for the poor reproducibility of the welds using the O.D. cell is not clearly understood at this time but is probably related to the cell design and operation. With further testing and refinement, consistent polarization curves are expected to be achieved.

Base material readings were performed using conventional practices with a mounted sample that was removed from the pipe a distance of 4 inches away from the weld fusion line. Although these values were generally reproducible, measurements were not completed on the base material using the O.D. cell at the time this report was prepared.

4.3.2 Fabrication of Pipe Test Specimen

During this report period, a 49-inch-long weldment containing four welds with a centered 90-degree elbow was fabricated from a documented and characterized heat of 4-inch Schedule 80 pipe material of Type-304 stainless steel (heat M7772). The test specimen is shown in Figure 4-1. The welds were produced with two different sets of moderated heat inputs as shown in Table 4-2. The chemical composition of the welding material utilized is given in Table 4-3. The welded test specimen is to be used to qualify the EPR field cell in the laboratory on a simulated field pipe component. After *in situ* measurements with the cell are completed, the test specimen will be sectioned and retested for the DOS using conventional laboratory techniques such as weld profiling by EPR and constant extension rate and constant load stress corrosion tests.

Table 4-1
DEGREE OF SENSITIZATION MEASUREMENTS*
OBTAINED FROM WELDED 4-INCH SCHEDULE 80 TYPE-304 STAINLESS STEEL PIPE
UTILIZING THE OUTER DIAMETER EPR CELL
(P_a, C/cm²)

OUTSIDE PIPE MEASUREMENTS

Pipe Azimuth	No. 1	No. 2
0°	2.612	2.133
90°	0.208	0.903
180°	1.211	1.046
270°	0.285	1.097
†Base Material	0.0582	0.062

*Tests performed in 0.5 M H₂SO₄ + 0.01M KSCN electrolyte at 25°C *without* N₂ Sparging.

†Test performed in 0.5 M H₂SO₄ + 0.01M KSCN electrolyte at 30°C *with* N₂ sparging.

Table 4-2
WELDING FABRICATION PARAMETERS
FOR THE
PIPE TEST SPECIMEN*

Weld Positions

	2 G	5 G
Heat Input (Average)	24 kJ/inch	44.88 kJ/inch
Interpass Temperature	350°F Maximum	350°F Maximum
Grinnell Insert	308 SS 4-in. (Ht. No. 20585)	—
GTAW* Bare Wire	308 SS (Ht. No. S-0099)	—
Filler Metal	308 SS (Ht. No. 8680)	—
SMAW* Passes	4 layers	6 layers

*Weld Processes — Gas Tungsten Arc (GTAW)
 — Shielded Metal Arc (SMAW)

Table 4-3
CHEMICAL COMPOSITION OF WELD MATERIALS

Heat No.	C	Cr	Ni	Mn	Si	P	S
M7772 (Pipe)	0.050	18.81	10.15	1.80	0.38	0.026	0.015
S-0099 GTAW filler	0.014	20.37	9.62	1.92	0.32	0.005	0.011
8680 SMAW filler	0.050	19.38	9.91	1.14	0.45	0.091	0.013

Figure 4-1. Fabricated Pipe Weld Test Specimen with Two Heat Inputs for In Situ Testing to Qualify the EPR Field Cell

4.3.3 Statistical Analysis of Test Results

This analysis is being performed to determine the relationship between the IGSCC and the EPR measurements. The method of least squares linear regression analysis was applied to 15 sets of accelerated IGSCC data values. These values were I_{DS} , % R.A., and time to failure (T_f). Of the 15 statistical computer runs performed, two sets of correlations were significantly related to the charge density.

The first set analyzed was the I_{DS} values for 11 heats of material which had been exposed to a low-temperature sensitization treatment at 500°C for 24 hours. These results are listed in Table 4-4 and are graphically illustrated in Figure 4-2. For the correlation coefficient of 0.70 a direct proportional relationship exists between P_a and I_{DS} for these heats of material. It is important that heat M7616 which is a IGSCC susceptible heat after welding also becomes highly susceptible to IGSCC following the low temperature sensitization treatment.

A similar correlation was made using the data developed for the 10 heats of welded pipe. Here, a best fit of the data listed in Table 4-5 is shown plotted in Figure 4-2. As shown in Figure 4-3, a more even distribution of the data about the best fit of the curve is obtained for the welded condition, and the correlation coefficient of 0.89 indicates a better relationship between P_a and I_{DS} than the low-temperature sensitized condition. In fact, a correlation coefficient of 0.89 indicates an excellent relationship between degree of sensitization, measured by EPR, and intergranular stress corrosion cracking susceptibility in the constant extension rate test. Again, the most susceptible heat (heat M7616) is revealed by the EPR test in both the low-temperature sensitized and welded condition.

Table 4-4
 P_a AND I_{DS}
FOR 11 HEATS OF TYPE-304
STAINLESS STEEL PIPE SENSITIZED 24 HOURS
AT 500°C

Heat No.	P_a C/cm ²	I_{DS}
159340	2.70	0.55
2P6424	2.60	0.53
2P6396	4.00	0.44
834264	4.60	0.71
454659	7.30	0.77
TH6656	6.50	0.65
M7772	6.70	0.52
8082228	7.40	0.82
78500	12.0	0.65
812292	16.8	0.75
M7616	40.0	0.92

$$I_{DS} = 1 - \frac{\sigma_w (1 + E_w)}{\sigma_A (1 + E_A)}$$

where

- σ_w = Maximum breaking stress in 288°C water
- E_w = Elongation at σ_w
- σ_A = Maximum breaking stress in 288°C argon
- E_A = Elongation at σ_A

Table 4-5
Pa AND I_{DS}
FOR 10 HEATS OF WELDED TYPE-304 STAINLESS STEEL PIPE

Heat No.	Pa (C/cm²)	I_{DS}
00575	1.60	0.000
482038	2.20	0.000
454659	3.60	0.000
482135	4.20	0.000
TH6656	5.00	0.35
2P6396	13.20	0.37
M7772	16.30	0.24
2P6424	16.90	0.61
834264	20.60	0.48
M7616	32.90	0.74

Figure 4-2. Correlation between Degree of Sensitization and IGSCC Resistance for 11 Heats of Type-304 Stainless Steel Sensitized 24 hr at 500°C (Correlation Coefficient $r = 0.70$)

Figure 4-3. Correlation between Degree of Sensitization and IGSCC Resistance for 10 Heats of Type-304 Stainless Steel in As-Welded Condition. (Correlation Coefficient $r = 0.89$)

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