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**REACTOR PRIMARY COOLANT SYSTEM
PIPE RUPTURE STUDY
PROGRESS REPORT NO. 27
APRIL-JUNE 1972**

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

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REACTOR PRIMARY COOLANT SYSTEM PIPE RUPTURE STUDY

PROGRESS REPORT NO. 27

APRIL-JUNE 1972

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ABSTRACT

The pipe rupture study is designed to extend the understanding of failure-causing mechanisms and to provide improved capability for evaluating reactor piping systems to minimize the probability of failures. Following a detailed review to determine the effort most needed to improve nuclear system piping (Phase I), analytical and experimental efforts (Phase II) were started in 1965. This progress report summarizes the recent accomplishments of a broad program in (a) fatigue studies through both bench-scale and large-component tests, (b) at-reactor tests of the effect of primary coolant environment on the fatigue behavior of piping steels, and (c) failure probability study of actual reactor piping systems.

1. INTRODUCTION

The Reactor Primary Coolant System Pipe Rupture Study is being conducted for the Division of Reactor Development and Technology, USAEC. This Progress Report No. 27 documents work done in the period April 1, 1972 to June 30, 1972. The overall objective of the program is to improve the reliability of reactor system piping by increasing current knowledge of failure-causing mechanisms and by enhancing capability for design evaluation and analysis.

Toward the attainment of this objective, work was continued on the following tasks:

- Task A—Probability Study
- Task D—Low-Cycle Fatigue
- Task K—Effect of BWR Environment

The specific objectives of the tasks and technical progress are covered in the following sections. Previous reports issued as a part of this program are as follows:

Quarterly Reports

GEAP-4911	Reactor Primary Coolant System Rupture Study Quarterly Progress Report No. 1, April—June 1965.
GEAP-4964	No. 2, July—August 1965.
GEAP-5082	No. 3, October—December 1965
GEAP-5147	No. 4, January—March 1966.
GEAP-5192	No. 5, April—June 1966.
GEAP-5279	No. 6, July—September 1966.
GEAP-5427	No. 7, October—December 1966.
GEAP-5474	No. 8, January—March 1967.
GEAP-5512	No. 9, April—June 1967.
GEAP-5554	No. 10, July—September 1967.
GEAP-5587	No. 11, October—December 1967.
GEAP-5637	No. 12, January—March 1968.
GEAP-5680	No. 13, April—June 1968.
GEAP-5716	No. 14, July—September 1968.
GEAP-5770	No. 15, October—December 1968.
GEAP-10024	No. 16, January—March 1969.
GEAP-10072	No. 17, April—June 1969.
GEAP-10120	No. 18, July—September 1969.
GEAP-10143	No. 19, October—December 1969.
GEAP-11069	No. 20, January—March 1970.
GEAP-10207	No. 21, April—June 1970.
GEAP-10207-22	No. 22, July—September 1970.
GEAP-10207-23	No. 23, October—December 1970.
GEAP-10207-24	No. 24, January—June 1971
GEAP-10207-25	No. 25, July—September 1971
GEAP-10207-26	No. 26, October 1971—March 1972

Topical Reports

GEAP-4445	A Survey of Water Reactor Primary System Conditions Pertinent to the Study of Pipe Rupture, January 1964.
GEAP-4446	A Review of Fracture Modes as Related to Reactor Primary Coolant Pipe Rupture, May 1964.
GEAP-4474	Experimental and Analytical Program Recommendations—Reactor Pipe Rupture Study, January 1965.
GEAP-4574	Survey of Piping Failures for the Reactor Primary Coolant Pipe Rupture Study, May 1964.
GEAP-4578	Mechanical Design Considerations in Primary Nuclear Piping, March 1964.
GEAP-4678	Fracture Mechanics and the Stability of Engineering Structures, September 1965.
GEAP-5014	Fracture Toughness of Some Engineering Alloys, March 1966.
GEAP-5410	Low-Cycle Fatigue Strength Reduction in Notched Flat Plates, January 1967.
GEAP-5471	PAPA—Structural Analysis of Plates and Shells Using Trapezoidal and Triangular Plate Elements, March 1967.
GEAP-5553	PAPA—The Digital Computer Program for the Static Analysis of Structures Made up of Plate and Panel Elements, October 1967.
GEAP-5557	Stress Intensity for a Circumferential Through-Wall Crack in a Straight Pipe, January 1968.
GEAP-5607	Fatigue Crack Growth in Nuclear Reactor Piping Steels, March 1968.
T&AM-677	A Three-Dimensional Photoelastic Study of Stress Near Cracks in Shell Structures, University of Illinois, March 1968.
GEAP-5620	Failure Behavior in ASTM A 106-B Pipes Containing Axial Through-Wall Flaws, April 1968.
GEAP-5622	A Failure Diagram for Axially Flawed Pipes, April 1968.
GEAP-5653	Status of Pipe Rupture Study at General Electric—II, July 1968.
GEAP-5714	Notched High-Strain Fatigue Behavior of Three Low-Strength Structural Steels, September 1968.
GEAP-5724	BWR Primary Piping Stresses for System Reliability Analysis, September 1968.
GEAP-5726	Influence of Stress/Strain Concentration and Mean Stress on the Low-Cycle Fatigue Behavior of Three Structural Steels at Room Temperature, September 1968.
GEAP-10007	Restart for the PAPA Program, March 1969.
GEAP-10090	The 550°F Notched High-Strain Fatigue Behavior of Three Low-Strength Structural Steels, August 1969.
GEAP-10135	Low-Cycle Fatigue of Prototype Piping, January 1970.

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- 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 (not yet released).

2. SUMMARY

2.1 TASK A—PROBABILITY STUDY

Work was directed toward the preparation of a memorandum whose purpose was to place clearly in perspective the numerical estimates of leak and severance reliability of the reference piping system, reported in Quarterly Progress Reports Nos. 23 and 25. Specifically, the following questions are discussed:

- a. What is the basis of the leak and severance analysis?
- b. What is the basis for the input values, distributions, assumptions, and simulation structure used in illustrating the method and leading to the reported results?
- c. Exactly what damage events are covered by the reported results?

2.2 TASK D-3—PROTOTYPE PIPE FATIGUE

Testing was completed on the second (and last) combined cyclic pressure and cycling bending of a stainless steel elbow. Test performance has been analyzed according to ASME Section III code rules, and the design safety factor has been evaluated.

2.3 TASK D-5—ASME ELASTIC-PLASTIC CODE RULES FOR FATIGUE EVALUATION

The objective of this task is to confirm or improve the ASME Section III nuclear piping fatigue design procedures for nominal stress ranges above $3 S'_m$. Work toward this objective is proceeding along two parallel paths. Analytically, fatigue specimens have been analyzed using a new elastic-plastic finite element computer program. Experimentally, peak notch strains and cyclic life have been measured and compared with smooth bar data and analytical predictions.

Fourteen load-controlled fatigue tests of smooth, grooved, and shoulder Type-304 stainless steel fatigue specimens have been completed. Although both the grooved and shoulder specimens have $K_t = 2$, at a life (based on crack initiation) of 1000 cycles, the fatigue strength reduction factor of grooved specimens is approximately one, while the factor for shoulder specimens is three. Mechanical properties of solution-annealed Type-304 stainless steel are compared with properties of as-received material.

2.4 TASK K—EFFECT OF BWR ENVIRONMENT

The Dresden 1 test loop has accumulated over 4600 hours of operation at test conditions (510°F, 1040 psig). A total of 86 of the 149 fatigue specimens being cyclically loaded in the loop have signalled failed: 39 of 71 Type-304 stainless steel specimens, 16 of 28 Type-304L stainless steel specimens, 4 of 23 Inconel-600 specimens, and all of the 27 carbon steel specimens. Detailed inspections of both static and dynamic specimens were conducted at Dresden 1 during the refueling outage. The first group of specimens, being tested under revised test conditions in the Air Test Facility in San Jose, is now under test with over 27,000 cycles accumulated to date. Ten of the twelve specimens in this group have signalled failure at this time. Design of the third vessel (fatigue crack growth rate unit) is complete; however, the vendor has not yet been released for fabrication pending final GE approval of x-ray and anneal procedures. This is consistent with GE Development Engineering Quality Assurance practice.

3. TASK A—PROBABILITY STUDY (S. A. Wilson)

3.1 OBJECTIVES

The objectives of the probability study task are to develop methods for:

- a. Estimation of the reliability of a reactor primary piping system in terms of leak rate and time of reactor service.
- b. Identification of the principal sources of real variability or uncertainty in service life.

3.2 SUMMARY

Work was limited to the preparation of a memorandum for the purpose of placing clearly in perspective the numerical estimates of leak and severance reliability of the reference piping system, reported in Quarterly Progress Reports Nos. 23 and 25. Specifically, the memorandum addresses itself to the following questions:

- a. What is the basis of the leak and severance analysis?
- b. What is the basis of the input values, distributions, assumptions and simulation structure used in illustrating use of the leak and severance analysis leading to the reported results?
- c. Exactly what damage events are covered by the reported results?

While these questions have been discussed in the quarterly reports, the following discussion is offered to aid in more detailed interpretation.

3.3 DISCUSSION

Regarding the first question on the basis of the leak and severance analysis, recall that the objective of Task A is to develop methods for estimating primary piping reliability with respect to the damage events of leak and severance, in a plant lifetime. Such analytical method development is often carried out largely independent of numerical input, as was the case here. Prior to the leak and severance analysis, the distribution of time-to-damage method* was developed and was illustrated for the case of leak by the low cycle fatigue damage mechanism at one piping location. The underlying idea of this method, obtaining a damage-event probability estimate in terms of the extent of overlap of two probability distributions (stress and strength, or more generally, requirement and capability), appeared to be promising for the case of severance. Its use for the severance case was developed based on a certain kind of fracture diagram, showing mean critical stress at severance with respect to crack size at length and depth. The diagram was prepared from the results of burst tests on pipe specimens with machined flaws which had been carried out under Task C of the Pipe Rupture Study.** Thus, in summary, the basis of the leak and severance analysis was use of the distribution of time to damage idea together with a fracture diagram obtained through interpretation of experimental results for burst strength of flawed piping components.

Regarding the second question on the basis of the input values, distributions, assumptions, and simulation structure used for illustrating the leak and severance analysis, these were devised as a reference set to portray their general form, mostly in the absence of the requisite detailed technology, by the engineer responsible for Task A. Included was a reference piping system defined by materials and numbers of components, which is referred to herein as the "plant". Using the fracture diagram in a probabilistic way requires input probability distributions reflecting the difference between design values and actual, as-built or as-operated values for such variables as crack size, stress, and conditions affecting crack growth. These distributions must come mainly from individual experience and judgment, since they are not systematically available from record keeping or test programs.

* GEAP-10542, "Estimating Pipe Reliability by the Distribution of Time-to-Damage Method" (not yet released).

** Reynolds, M. B., "Failure Behavior in ASTM A-106B Pipes Containing Axial Through-Wall Flaws," GEAP-5620.

To achieve suitable accuracy in an application to a particular primary system, a number of such inputs must be obtained because individual judgment varies, particularly on matters of such broad scope. *No attempt to obtain several inputs has been attempted as part of the method development at this time*, and accordingly, no claim can or should be made about the accuracy with which the results obtained for illustrating the method apply to a real power plant. However, that plausible input to the method leads to reasonable output is illustrated by showing that the results obtained are within one to two orders of magnitude of some historical damage-occurrence rates, as shown in Table 3-1 of Quarterly Report No. 25. For many reasons, relating both to the analysis and to the marshalling of the historical rates, such a comparison will not be exact. In summary, a reference set of input values, distributions, assumptions, and simulation structure was devised by the engineer responsible for the task purpose of illustrating their general form, and the use of this method.

Regarding the third question on what damage events are covered by the reported results, these events will be described in terms of the results, which appear in two places: Table 3-5 of Quarterly Report No. 23, and Table 3-1 of Quarterly Report No. 25. The nature of the leak and severance analysis is to give results in terms of the "expected number" (average or mean number) of damage events per plant, in a stated time period. The exact scope of these events is discussed in the second following paragraph. The relationship among the expected number and the probability of one or more such events, and reliability, is discussed in Subsection 3.3.1.

To facilitate discussion of the results, Table 3-1 reproduces a portion of Table 3-5 of Quarterly Report No. 23, and contains added (dotted block) information.

Table 3-1
SUMMARY: EXPECTED NUMBER OF LEAKS AND SEVERANCES

	Per Plant Per 40 Year			Per Plant Average Per Year	
	Ultrasonic With	Testing Without		Ultrasonic With	Testing Without
Expected Number of Leaks	1.53	3.53	X 1/40 =	0.0383	0.0883
Expected Number of Severances	0.019	0.053	X 1/40 =	0.0005	0.0013
Expected Number of Leaks and Severances	1.549	3.583	X 1/40 =	0.0388 ($\approx 40 \times 10^{-3}$)	0.0896 ($\approx 90 \times 10^{-3}$)

THE RESULTS IN THIS TABLE ARE FROM A METHOD UNDER DEVELOPMENT.
DO NOT USE WITHOUT APPROPRIATELY TAKING INTO ACCOUNT THE INPUT USED.

The entries in Table 3-1 are for the entire piping system of a reference plant, per 40-year service life (first two columns), and average per year (last two columns). The "With" and "Without" Ultrasonic Testing columns distinguish between results using different input assumptions on that testing. The "Per Plant, Per 40 Years" entries in Table 3-1 rely on an elementary assumption in the leak and severance analysis that damage events occur independently among each other, and among components, plants, and years. This assumption is a specific condition of statements made in the following three paragraphs, and will be called assumption 1. A discussion of alternative assumptions is beyond the scope of this memorandum. The "Per Plant, Average Per Year" entries in Table 3-1 are calculated assuming that the rate of occurrence of damage events is constant throughout the life of a plant. This condition is specifically assumed in the second following paragraph, and will be called assumption 2. These average per-year values are obtained to facilitate comparison, although the leak and severance analysis method makes separate estimates for three time periods.

The last figures shown in Table 3-1 (40×10^{-3} and 90×10^{-3}) appear in Table 3-1 of Quarterly Report No. 25 under "Rate: Events Per Plant Year", with "Event" defined therein as either leak or severance. In that table and throughout this memorandum, a damage event is *either* a leak event *or* a severance event (their union); certainly for a damage event to occur does not require the occurrence of *both* a leak event *and* a severance event (their intersection). Thus, under assumption 1 the expected number of damage events is the *sum* of the expected numbers of leaks and severances. Therefore, the leak and severance analysis entry ($40-90 \times 10^{-3}$) in Table 3-1 of Quarterly Report No. 25 is the average annual "expected number of both leaks and severances," to use the wording in Table 3-1. This puts the entry on a common basis with the entries from the historical sources in Table 3-1 of Quarterly Report No. 25, which are also for leaks and severances taken together. It can be seen from Table 3-1 of this report that the occurrence rate of *leaks* makes the heavily predominating contribution to the damage event occurrence rate appearing in Table 3-1 of Quarterly Report No. 25 for the leak and severance analysis. Specifically, from Table 3-1 for the "with ultrasonic testing" case, the percentage contribution by leaks is seen to be $1.53/1.549 = 98.8\%$. Leaks no doubt predominate in the historical entries as well.

Under assumption 2, entries in the "Average Per Year" columns of Table 3-1 may also be interpreted as probability of severance, per reference pipe system per year, as will be explained in Subsection 3.3.1.

In summary, the damage events covered by the reported results are either leak events or severance events, so that the expected number of damage events is the *sum* of the expected numbers of leak and severance events.

3.3.1 The Relationship Among the Expected Number of Events, the Probability of One or More Events, and Reliability

If one is to form a relationship between expected numbers of events and the probability of one or more events, an assumption on the frequency distribution of number of events is required. It is reasonable to assume in this case that such events are Poisson distributed, so that the probability that the random variable, X (number of damage events, say, per year), takes on values, x ($x=0, 1, 2, \dots$) is

$$\Pr(X = x) = e^{-m} m^x / x!$$

where m = expected (mean) number of events (per year).

Taking the annual expected number of events as $m = 0.0383$, Table 3-2 gives the probabilities of the first few numbers of events.

Table 3-2
POISSON PROBABILITIES FOR
PARAMETER $m = 0.0383$

x Events	Probability
0	0.9625
1	0.0368
2	0.0006
> 3	0.0001
	1.0000

} 0.0375

Thus, under the Poisson, when the expected number is small, say $m < 0.1$, the expected number of events (0.0383 above) is only very slightly greater than the probability of one or more events (0.0375), which in turn is only slightly greater than the probability of one event (0.0368). These statements will be true whenever the probability of two or more events is negligible, as can be seen by comparing the equations for expected number of events, and probability of one or more events, as follows:

$$\text{Expected number of events} = P(0) \times 0 + P(1) \times 1 + P(2) \times 2 + P(3) \times 3 + \dots$$

$$\text{Probability of one or more events} = P(1) + P(2) + P(3) + \dots$$

where $P(1)$ is the probability of one event, etc. Thus, the equations are identical if $P(2)$, $P(3)$, ... are negligible.

The term "reliability" is often used in relation to the foregoing. Reliability in the statistical sense is the probability that no "failure" (damage event) occurs during a stated time period (usually the service lifetime). Thus, the reliability can be found from the foregoing discussion on probability. For the example given there, for one year, the reliability (i.e., the probability of 0 damage events) is seen in Table 3-2 to be 0.9625.

In summary, it is again emphasized that the numerical results obtained to date using the leak and severance analysis are solely illustrative of a method under development and cannot be used to accurately assess the reliability of modern-day nuclear power plants.

4. TASK D—LOW CYCLE FATIGUE

4.1 OBJECTIVE

The objectives of the Fatigue Task are: (a) to extend the understanding of low-cycle fatigue cracking in high pressure piping components which may or may not have mechanical or defect flaws, and (b) to apply this knowledge in developing rational design bases for prevention or control of fatigue crack initiation and growth in reactor piping systems.

4.2 TASK D-3—PROTOTYPE PIPE FATIGUE (J. D. Heald)

4.2.1 Summary

Testing was completed on the second and last (CSLS-7) combined cyclic pressure plus cyclic bending stainless steel elbow specimen. A summary of the test conditions and results is given as follows:

Specimen Number	CSLS-7
Specimen Type	Long radius elbow
Material	Type 304 stainless steel
Size	6-inch Schedule 40
Bending	In-plane of elbow
Deflection Range	± 6.50 or 13 inches
Pressure Range	100 to 2900 psi
Cycles to Leakage N_L	.2531 cycles
ASME Section III, S_{alt}	.425,000 psi
Equivalent Strain Range	2.8%*
ASME Section III, N_D	.25 cycles

4.2.2 Data Evaluation

In-plane combined cyclic bending and cyclic pressure testing were completed on the second stainless steel elbow specimen. This test specimen (CSLS-7) was loaded such that the total alternating stress intensity (S_{alt}) would be essentially equal to the previous elbow specimen (CSLS-5). For this case, however, the ratio of pressure stress to bending stress was increased. A comparison of the two elbow tests is shown as follows:

	CSLS-5	CSLS-7
S_{alt} total	425 ksi	420 ksi
S_n total	255 ksi	252 ksi
S_n due to pressure	21 ksi	42 ksi
S_n due to bending	234 ksi	210 ksi
Ratio S_{nb}/S_{np}	11.1	50.0

*This is the elastic equivalent of $S_{alt} = 425,000$ psi.

The alternating stress intensity S_{alt} was evaluated as follows:

$$S_{alt} = 1/2 S_n K_t K_e ,$$

where

$$K_t = 1.0,$$

$$K_e = \text{shown below,}$$

$$S_n = C_1 \frac{\Delta P r_0}{t} + C_2 \frac{\Delta M r_0}{I}$$

$$C_1 = \frac{2R-r}{2(R-r)} = 1.28 \text{ for 6-inch, Schedule-40 long-radius elbow,}$$

$$C_2 = \frac{1.95}{b_2^{2/3}} = 4.91 \text{ for 6-inch, Schedule-40 long-radius elbow,}$$

$$\Delta P = \text{cyclic pressure range,}$$

$$\Delta M = \Delta P \ell = K \ell \delta \text{ p-p,}$$

$$K_e = 1.0 \text{ for } S_n < 3 S_m,$$

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

$$K_e = \frac{1}{n} \text{ for } S_n > 3m S_m ,$$

$$m, n = \text{material properties from NB-3228.3,}$$

$$\left. \begin{array}{l} m = 1.7 \\ n = 0.3 \end{array} \right\} \text{ for austenitic stainless steel}$$

$$\left. \begin{array}{l} m = 3.0 \\ n = 0.2 \end{array} \right\} \text{ for carbon steel.}$$

According to code procedures, the allowable number of design cycles is determined from the design fatigue curve based on S_{alt} . Thus, both specimens would have essentially the same predicted cyclic life. Examination of the test results (cycles to leak) in Table 4-1 reveals several important factors. First, it is seen that for both specimens the actual cycles to leak greatly exceed (>100 times) the Code predicted life. Second, it is seen that the elbow specimen with the higher cyclic pressure component had 57% of the cyclic life to leakage, as compared with the other. In this regard, it must be emphasized that this result should be considered inconclusive, since difference in cyclic life (cycles to leak) would be expected just from data scatter. What is most important is that using the Code procedures, design predictions are more than adequately conservative. This is seen to be true in Table 4-1, for all Task D-3 elbow specimens tested in in-plane bending.

Figure 4-1 shows an elbow specimen in the test frame, while Figure 4-2 shows the failed elbow section welded with tabs to provide for pulling apart. Final evaluation of crack length at failure will involve post-mortem evaluation.

4.2.3 Local Strain Measurement

To experimentally determine the magnitude of local strain due to pressure and bending, several strain gages were attached to the elbow in the vicinity where through-wall cracking is known to occur as a result of in-plane loading. For the test condition given in the Summary, a 0.29% total strain range was measured on the outside surface of the elbow.

Table 4-1
TASK D-3 INPLANE ELBOW SPECIMENS, SECTION III ANALYSIS SUMMARY

Specimen	Material	Pressure Range (psi)	Peak-to-Peak Deflection Range (inches)	$3 S_m$ (ksi)	S_n (ksi)	$3 m S_m$ (ksi)	$\frac{S_n}{3 S_m}$	K_e	Salt (ksi)	N_D (cycles)	N_L (cycles)	N_L/N_D
CSLS-1 Short radius	SS	0	21.6	60	455	102	7.6	3.33	758	< 10	907	> 90
CSLS-3 Long radius	SS	0	14.5	60	234	102	3.9	3.33	390	30	4469	149
CCLS-1 Short radius	CS	0	14.1	60	297	180	4.9	5.0	1485	< 10	1176	> 117
CSLS-5 Long radius	SS	1375	14.5	60	255	102	4.2	3.33	425	25	4440	178
CSLS-7 Long radius	SS	2800	13.0	60	252	102	4.2	3.33	420	25	2531	101

Figure 4.1. Task D-3 Elbow Specimen Shown in Test Bed

Figure 4-2. Fatigued Elbow Section Being Pulled Apart

By using the experimental data for strain resulting from the separate application of internal pressure and bending, the maximum strain range on the inside surface was estimated at 0.6%. A comparison of the Code calculated strain with that estimated from the measurements would indicate that the Code overestimates the local strain by a factor of approximately five (2.82/0.68). The fact that the ratio of actual cycles to leak versus Code design values is greater than 100 is accounted for by virtue of the local strain information.

4.2.4 Acoustic Emission Investigation

Both elbow specimens were monitored during test by acoustic emission and ultrasonic inspection. Results of the acoustic emission work is presented in Appendix A.

4.3 TASK D-5—ASME ELASTIC-PLASTIC CODE RULES FOR FATIGUE EVALUATION (T. L. Gerber, P. N. LeFort)

4.3.1 Summary

Fourteen load-controlled fatigue tests of smooth, grooved, and shoulder Type-304 stainless steel fatigue specimens have been completed. Although both the grooved and shoulder specimens have $K_t = 2$, at a life (based on crack initiation) of 1000 cycles, the fatigue strength reduction factor of grooved specimens is approximately one, while the factor for shoulder specimens is three. Mechanical properties of solution-annealed Type-304 stainless steel are compared with properties of as-received material.

4.3.2 Objective

The objective of this task is to confirm or improve nuclear piping fatigue design procedures for nominal stress ranges above $3 S_m$. Currently, the effect of constraint at a geometric discontinuity (or stress concentration) is being investigated. This investigation is proceeding along two parallel paths. Analytically, fatigue specimen local strains have been calculated with the CREEP-PLAST elastic-plastic finite element computer program. Preliminary analytical results were compared with measured strains in an earlier report.¹ Refinement of this analysis is in progress.

Experimentally, fatigue tests of three geometries of fatigue specimens are being conducted. The load-controlled fatigue tests of Type-304 stainless steel specimens are reported here. In addition, results of an investigation of the effect of a solution anneal on the as-received material mechanical properties are reported.

4.3.3 Fatigue Tests

Three fatigue specimen geometries are being tested. These are the smooth, grooved, and shoulder geometries shown in Figure 4-3. The minimum cross-section diameter of each type of specimen is 1 inch, and the grooved and shoulder specimens have equal theoretical stress concentration factors, $K_t = 2$. All specimens were machined from as-received Type-304 stainless steel bar stock. (Material properties are discussed in Subsection 4.3.4.)

All fatigue tests conducted to date were completely reversed, load-controlled tests; that is, each specimen was cycled between fixed negative and positive load limits of equal magnitude. Cyclic frequency was from 3 to 10 cycles per minute, depending on the specimen geometry and the load level. Specimens were tested at one of three load levels: $\pm 30,000$, $\pm 35,000$, or $\pm 38,000$ lb. Testing was done on a 100,000-lb capacity MTS electro-hydraulic universal testing machine.

Various aspects of specimen behavior during cyclic loading are of interest. Most important of these is the number of cycles required for crack initiation. Initiation in these tests is defined as occurrence of a crack whose surface length is from 0.1 to 0.2 inch.

Different methods of detecting fatigue cracks were evaluated. A replica technique² in which one periodically makes plastic replicas of the specimen surface topography was tried. While this technique is applicable to smooth specimens, it was not suitable for grooved and shoulder specimens. A second method is to periodically visually examine

the specimen surface with a low-power microscope. This method is reliable though time consuming. Also, the sensitivity of this method is no greater than the cycle interval between inspections. A third method for detecting crack initiation involves monitoring of specimen compliance (reciprocal of stiffness) during a test. A theoretical relationship between crack size and the compliance of a round specimen subjected to an axial load was derived (see Appendix B). Using this relationship (and a sufficiently short gage length), one can detect crack initiation by monitoring deflection (in a load-controlled test) or lead (in a deflection-controlled test).

During all load-controlled fatigue tests, specimen deflection over a 4-inch gage length was monitored. For compliance considerations, the effective gage length is more on the order of the length of the minimum specimen cross section. For grooved specimens, this length is about the width of the groove. The deflection versus cyclic curve for the load-controlled test of a grooved specimen is shown in Figure 4-4. The increase in deflection was confirmed to correspond to crack initiation. Because of the longer effective gage length of smooth and shoulder specimens, the change in compliance due to crack initiation is not as sensitive. Therefore, during the majority of the fatigue tests, both periodic visual inspection and continuous compliance measurements were made.

The results of 14 fatigue tests are given in Figures 4-5 and 4-6. Figure 4-5 shows the cycles required for crack initiation as a function of the nominal net section stress range. Figure 4-6 shows cycles required for specimen fracture as a function of this stress range.

Another way to present these results is to convert the nominal net section stress range to a fictitious elastic stress amplitude. This is accomplished by finding the strain range corresponding to the stress range on a cyclic stress-strain curve and multiplying this strain by half the elastic modulus. This is the manner in which the ASME Section III³ design curves are presented.

Figure 4-3. Fatigue Specimens

Figure 4-4 Increase in Displacement with Crack Initiation:

Figure 4-5. Cycles to Crack Initiation as a Function of Nominal Stress Range

Figure 4-6. Cycles to Specimen Fracture as a Function of Nominal Stress Range

The cyclic stress-strain curve for this material is shown in Figure 4-7. The procedure for generating this curve was described earlier.¹ The crack initiation results are presented as a function of the fictitious elastic stress amplitude in Figure 4-8. The ASME Code criteria curve⁴ is also shown in this figure. Note that the smooth bar load-controlled results are very close to the Code criteria curve.

Based on the presentation of results in Figure 4-6, one can define a fatigue strength reduction factor for the grooved or shoulder specimen as

$$K_f (\text{grooved or shoulder}) = \frac{S_A (\text{smooth})}{S_A (\text{grooved or shoulder})}$$

where the stress amplitudes, S_A , are at the same lives. Using this definition at lives of 1,000 and 10,000 cycles, one obtains the following:

Cycles	1,000	10,000
K_f (grooved)	1	2
K_f (shoulder)	3	2

It appears that for long lives or low cyclic loads the fatigue strength reduction factor for both grooved and shoulder specimens is approximately equal to the theoretical stress concentration factor. At shorter lives or higher loads, these specimens behave differently. The K_f of the grooved specimen is lower than K_t , while the K_f of the shoulder specimen is higher than K_t .

This trend in behavior is predictable from local strain calculations (though not from code design rules). The differences between grooved and shoulder specimen behavior are related to elastic constraint in the vicinity of the stress concentration. More will be said about this phenomenon following completion of the specimen analysis and four more load-controlled fatigue tests. (These four tests are duplicates of test conditions for which there is now only a single test point.)

4.3.4 Material Properties

The fatigue specimens tested to date were fabricated from as-received, 2-inch-diameter, Type-304 stainless steel bar stock. This material was purchased, per ASTM A-276, hot-finished, annealed, and centerless ground. This specification is similar to that required for Type-304 stainless steel piping, ASTM A-312 or A-376. All these specifications require a mill anneal.

Monotonic and cyclic stress-strain curves for the as-received material were reported earlier.¹ Comparison of these curves with those of other investigators—notably with Pipe Study Task D-2 results—shows high yields and relatively few cycles required for shakedown in a cyclic test. This behavior suggests that material used in this study contained some cold work in the as-received condition.

To investigate this possibility, 1/2-inch-diameter specimens of the as-received material were given a solution anneal of 1950°F for 1 hour, followed by an air cool. Monotonic and cyclic stress-strain curves were subsequently generated. Hardness checks were also made on as-received and solution-annealed material. Stress-strain curves are shown in Figures 4-9 and 4-10, and hardness measurements are given in Table 4-2.

These tests show that, indeed, the as-received material contains more cold work than the 1% strain limit used in generating the stress-strain curves. The solution-annealed material has lower monotonic and cyclic yield strengths and lower hardness. Also, the cyclic behavior was not stable after 100 cycles as was the case with the as-received material condition. The cyclic curve generated by connecting the peaks of 1000-cycle hysteresis loops is lower than the 100-cycle curve.

Table 4-2
**AVERAGE ROCKWELL B HARDNESS MEASUREMENTS ON AS-RECEIVED
 AND SOLUTION-ANNEALED TYPE 304 STAINLESS STEEL**

Location on Cross Section of Two-Inch Diameter Bar	As-Received Material	Solution-Annealed Material
Center	83	78
One-Half Radius	85	79
One-Eighth Inch from Edge	94	75

Discussion with the material supplier indicated that cold work in the as-received condition could have resulted from a straightening procedure or from the short-term mill anneal (1900°F, 10 minutes, water quench). Similar procedures are used with piping. Therefore, while mechanical properties of specimens tested in this program can be considered typical of as-received, Type-304 stainless steel piping, they are not typical of fully annealed material.

4.3.5 Analytical and Experimental Comparison of Strains

In the previous quarterly,¹ it was shown that agreement between measured and calculated surface strains for the grooved and shoulder stainless steel specimens was only fair. A possible cause of this discrepancy was suspected to be the low elastic modulus ($E_e = 25.0 \times 10^6$ psi) used to describe the cyclic material behavior. An adjusted cyclic stress-strain curve was suggested (see Figure 4-11).

This curve has been used with the finite element program CREEP-PLAST to re-analyze the fatigue specimens.

The calculated surface strains for the shoulder specimen are shown in Figure 4-12. (The grooved specimen data have not yet been reduced.)

Increasing the elastic modulus has improved agreement between measured and calculated surface strains for low (or elastic) net-section applied stresses. At high stress amplitudes, agreement is worse. Details of the manner in which CREEP-PLAST generates individual element stress-strain behavior from the input stress-strain curve is being investigated. Additional specimen analyses are anticipated.

4.3.5.1 Computer Interpretation of CREEP-PLAST Output

A FORTRAN computer program has been developed for efficiently determining surface strains from interior specimen strains calculated with the CREEP-PLAST finite element program. This program extrapolates the strains from the finite grid to a number of surface points. A polynomial is then fit to these points. The average surface strains are found by integrating over the length of the strain gage used in the experiments. This program has been tested with data already tediously analyzed manually and found to be in good agreement. The results shown in Figure 4-12 and all subsequent CREEP-PLAST analyses will be interpreted with this program.

4.4 REFERENCES FOR SECTION 4

1. Progress Report No. 26, GEAP-10207-26 (October 1971—March 1972).
2. Henry, M. F., *A Technique for Monitoring Time Dependent Surface Damage*, GE-R&DC Report 71-C-338.
3. *ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components*, American Society of Mechanical Engineers, New York, 1971.
4. *Criteria of Section III of the ASME Boiler and Pressure Vessel Code for Nuclear Vessels*, American Society of Mechanical Engineers, New York, 1964.

Figure 4-7. Cyclic Stress-Strain Curves for Type-304 Stainless Steel

Figure 4-8. Cycles to Crack Initiation as a Function of the Fictitious Elastic Stress Amplitude

Figure 4-9. Monotonic Stress-Strain Curves for As-Received and Solution-Annealed Type-304 Stainless Steel

Figure 4-10. Cyclic Stress-Strain Curves for As-Received and Solution-Annealed Type-304 Stainless Steel

Figure 4-11. Adjusted Shakedown Stress-Strain Diagram, ASTM-A276 Type-304 Stainless Steel (As Received)

Figure 4-12. Surface Strains, Stainless Shouldered Specimen

5. TASK K—EFFECT OF BWR ENVIRONMENT (D. A. Hale)

5.1 OBJECTIVE

The objective of Task K is to determine quantitatively the effect of BWR primary coolant on the low-cycle fatigue resistance of piping steels. Measurements of cycles to failure will be obtained, employing a specially designed fatigue testing unit in an experimental piping loop at the Dresden 1 boiling water reactor. The planned test duration is 2-1/2 years, allowing time for corrosion, if any, to affect crack initiation and growth.

5.2 SUMMARY

The Dresden 1 test loop has accumulated over 4400 hours of operation at test conditions (510°F, 1040 psig). A total of 86 of the 149 fatigue specimens being cyclically loaded in the loop have signalled failure: 39 of 71 Type-304 stainless steel specimens, 16 of 28 Type-304L stainless steel specimens, 4 of 23 Inconel-600 specimens, and all of the 27 carbon steel specimens. Detailed inspections of both static and dynamic specimens were conducted at Dresden 1 during the refueling outage.

The first group of specimens, being tested under revised test conditions in the Air Test Facility in San Jose, has accumulated 27,000 cycles to date. Ten of the twelve specimens in this group have signalled failure during the 27,000 cycles of operation. Design of the third vessel (fatigue crack growth rate unit) is complete; procurement of the vessel and associated hardware continues.

5.3 DRESDEN TEST LOOP

The test loop was out of service several times during the report period for a variety of reasons, as noted in Table 5-1. However, the loop was returned to service by the end of the report period and is presently operating normally.

5.3.1 Fatigue Test Results

One hundred forty-nine fatigue specimens (Figure 5-1), representing four material groups, thirty-one metallurgical test conditions, and two specimen loading schemes, are included in the basic Task K test program. For convenience, the test plan has been reproduced from GEAP-10207-24 (Quarterly No. 24) as Table 5-3. This test plan was designed to allocate the fatigue specimen positions among the selected test conditions so as to maximize chances of detecting differences in cyclic fatigue life which might result from these specific material conditions and the influence of the environment.

Four additional fatigue specimen failure indications were received during the three most recent operating periods; the total number received to date is 86. Failure data from operating periods IX and XII are summarized in Table 5-2; failure data from earlier operating periods were published in Tables 5-4A, B, C, D, and E of the previous quarterly (GEAP-10207-26).

The cycles-to-failure data for the 86 failure indications received to date are compared with ASME Section III fatigue design data in Figures 5-2 through 5-5. The upper line in Figures 5-2, 5-3, and 5-5 represents a best fit of the ASME failure data; the upper line in Figure 5-4 for Inconel-600 is based on a best fit of failure data contained in the work of Snow, et al.* The lower line in Figures 5-2 through 5-5 represents the ASME Section III recommended fatigue design curve which is derived from ASME data curves by applying a factor of 20** on cycles (i.e., $N_{\text{design}} = 1/20 N_{\text{data}}$).

*Snow, Langer, and Gibbons, WAPD-T-2083, September 1967.

**See ASME Boiler and Pressure Vessel Code, Section III, Criteria.

Table 5-1
DRESDEN TEST LOOP OPERATING SUMMARY

Loop Operating Period	Startup	Shutdown	Cumulative Operating Time	Fatigue Cycles (Cumulative)		Fatigue Test Specimen Failure Indications Received	Remarks	
				Start	Finish			
1970	I	Sept. 16	Oct. 2	17 days	0	1900	23	Loop shutdown in antici- pation of scheduled plant maintenance outage
	II	Oct. 22	Nov. 5	32 days	1901	3250	18	Loop shutdown in antici- pation of scheduled plant maintenance outage
	III	Nov. 25	Dec. 31	69 days	3251	6494	18	Loop shutdown to repair leaking fitting
1971	IV	Jan. 7	Jan. 14	76 days	6495	7174	2	Loop secured after reactor scram
	V	Jan. 27	Feb. 3	84 days	7175	7891	5	Loop shutdown for scheduled plant outage
	VI	Feb. 17	Feb. 18	85 days	7892	7960	1	Loop secured to repair steam leaks and install cubicle air monitor
	VII	June 3	June 23	105 days	7961	9910	5	Loop automatically isolated due to low pressure trip
	VIII	June 29	Aug. 12	150 days	9911	14155	7	Loop secured after reactor scram
1972	IX	March 24	April 14	171 days	14156	16258	3	Loop secured after reactor scram
	X	May 10	May 12	173 days	16259	16516	0	Loop secured for plant shutdown
	XI	May 25	May 26	173 days	16517	16564	0	Loop shutdown to repair leaking fitting
	XII	June 16	—	> 192 days	16565	—	4	Loop still operating on July 5

NOTES:

1. .029 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 5-1. Dynamic Test Specimen

Table 5-2
FATIGUE TEST RESULTS FROM DRESDEN LOOP (OPERATING PERIOD IX, XII)

Specimen Number	Cycles to Failure	Material	Shakedown Surface Strain Range ^(a) (%)	Loading Mode ^(b)	Test Condition Code ^(c)	Description
101	14,232	Inconel	1.0	C-T	23	As received, furnace sensitized
1077	14,798	SS-304L	1.0	C-T	17	Welded, as machined
24	16,021	SS-304L	0.5	C-T	15	As received
150	17,042	SS-304	0.75	C-T	1	As received
92	17,669	Inconel	1.0	C-T	21	As received
1145	17,711	SS-304	0.5	C-T	7	Dresden equalizer line, Weld material, as machined
1125	17,733	SS-304	1.0	C-T	2	As received + Heavy Cold Work

Total failure indications received to date: 86 (39 - 304SS, 16 - 304L SS, 4 Inconel, 27 Carbon Steel)

(a) Based on room temperature strain-deflection calibration curves.

(b) C-T = Compression-Tension; O-T = Zero-to-Tension Loading.

(c) Reference: Table 5-3.

5.3.2 Metallurgical Effects

5.3.2.1 Type-304 Stainless Steel

A total of 71 Type-304 stainless steel specimens are under test in the Dresden dynamic test vessel. To date, failure indications have been received from 39 of them. Detailed analyses of these data will be deferred until data from the surviving 32 Type-304 specimens become available. The preliminary trends noted in Quarterly No. 25 are still valid and are reproduced for convenience as follows.

- There appears to be a significant reduction in LCFL (low cycle fatigue life) associated with the furnace-sensitized condition (Material Condition Code No. 5*) compared with the as-received condition (Material Condition No. 1*) for both the zero-tension and compression-tension loading modes.
- The relatively weak influence of strain range on the furnace-sensitized data suggests that the failure mechanism is stress-corrosion dominated—at least for the strain range examined from 0.5 to 1.0%.
- The zero-tension loading mode is more severe than the compression-tension loading mode for equal strain range, leading to a definite reduction in LCFL in both the as-received and furnace-sensitized materials.

*See GEAP-10120, Quarterly No. 18, p. 3-4.

Table 5-3
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																	
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						
149																																

NOTES:

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

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

Figure 5-2 Equivalent Stress Amplitude (psi) versus Failure for Type-304 Stainless Steel

Figure 5-3. Equivalent Stress Amplitude (psi) versus Cycles to Failure for Type-304L Stainless Steel

Figure 5-4. Equivalent Stress Amplitude (psi) versus Cycles to Failure for Inconel-600

Figure 5-5. Equivalent Stress Amplitude (psi) versus Cycles to Failure for A516 Carbon Steel

5.3.2.2 Type-304L Stainless Steel

To date, 16 failure indications have been received out of a total of 28 specimens under test. All nine of the furnace-sensitized Type-304L specimens under test have failed. The remaining seven failures were divided among three material test conditions:

- Three "as-received" specimens: two tested at the 1.0% strain range and one at the 0.5% strain range
- Two "welded" specimens tested at the 1.0% strain range
- Two "cold-worked" specimens tested at the 1.0% strain range

5.3.2.3 Inconel-600

One additional Inconel failure indication was received during the report period, bringing the total number of failure signals received to date to 4 out of 23 specimens under test. These four specimens represent three test conditions:

- Two "welded" specimens tested at the 1.0% strain range
- One "furnace-sensitized" specimen tested at the 1.0% strain range
- One "as-received" specimen tested at the 1.0% strain range

5.3.2.4 Carbon Steel

All 27 carbon steel fatigue specimens under test had failed prior to the start of this report period; the results are covered in GEAP-10207-24.

5.4 500°F BASELINE AIR TESTS

The baseline 500°F "air" low-cycle fatigue testing, needed for comparison data with the Dresden 1 "BWR" data, continued. A smaller (i.e., only in terms of reduced specimen capacity) sized version of the Dresden fatigue test machine is being used, cycling 12 of the Task K fatigue specimens in precisely the same manner as their Dresden counterparts except that a neutral reference environment is used (500°F air at ambient pressure). The axial cavity within each specimen is pressurized to 50 psig with argon and connected via capillary tubing to an external pressure switch. The loss of argon pressure caused by a fatigue crack sufficiently deep to intersect this internal cavity is used to define and automatically signal specimen failure.

A test of 12 fatigue specimens (4 each of Type-304 stainless steel, Inconel-600, and A516 carbon steel) was still in progress at the close of the report period. The deflections, which duplicate those imposed on their Dresden counterparts, produce the two highest strain ranges, as summarized in Table 5-4.

5.4.1 Test Results

To date, over 27,000 test cycles have been accumulated by these specimens, with failure indications from ten specimens. The failure data from these ten specimens are compared with the ASME best-fit data curve and the Dresden BWR data for the same material condition (i.e., Material Test Condition No. 1) in Figures 5-6, 5-7 and 5-8.

5.5 THIRD TEST VESSEL (DRESDEN 1 TEST LOOP)

Preparations continue to add a third test vessel to the existing Dresden 1 test loop. The third test vessel will be used to obtain crack growth rate data in the BWR environment to augment the crack initiation now being generated in the dynamic test vessel.

The original system design has been modified to accommodate a load cell externally mounted to the test vessel head. This load cell will monitor the total load being applied to the chain of 2T-WOL specimens inside the test vessel (see Figure 5-8). The external load cell will serve as the primary test system load control transducer, while the internal force link will provide backup measurement of the applied force.

Table 5-4
FATIGUE SPECIMEN TEST PLAN, SERIES III-B BASELINE "AIR" TESTS

Specimen Number	Material	TIP Deflections (in.)	Testing ^c Rate (cph)	Cycles to Failure
200	Type 304 SS, As Received	±0.094 ^a	8	9,626
202	Type 304 SS, As Received	±0.094 ^a	8	8,679
194	Type 304 SS, As Received	±0.078 ^b	8	15,159
204	Type 304 SS, As Received	±0.078 ^b	8	15,191
118	Inconel, As Received	±0.100 ^a	8	15,757
120	Inconel, As Received	±0.100 ^a	8	20,589
121	Inconel, As Received	±0.089 ^b	8	—
123	Inconel, As Received	±0.089 ^b	8	26,428
1044	A516 Carbon Steel, As Machined	±0.086 ^a	8	13,300
1046	A516 Carbon Steel, As Machined	±0.086 ^a	8	10,327
1045	A516 Carbon Steel, As Machined	±0.076 ^b	8	23,789
1047	A516 Carbon Steel, As Machined	±0.076 ^b	8	—

^aCorresponds to 1.0% peak-to-peak strain range based on room temperature strain-deflection curves.

^bCorresponds to 0.75% peak-to-peak strain range based on room temperature strain-deflection curves.

^cInitial 100 cycles accumulated at 4 cph test rate for high temperature strain measurements.

A comprehensive Quality Assurance program is being developed for procurement of the third test vessel. This procedure will be consistent with DEV-QA-1, Development Engineering Quality Assurance Procedure. At this time the vessel vendor's procedures for x-ray examination and main shell anneal are being reviewed. After final approval by APED, the vessel vendor will be released to begin actual fabrication of the vessel.

All internal fixturing required to support and load the specimens in this vessel has been designed and is out for bid. Seven channels of Hi Temp—Hi Pressure canned LVDTs have been ordered for use as *in situ* COD monitoring devices. The units are presently undergoing final "hot hydro" tests (i.e., pressure checked in 1215 psig, 570°F demineralized water) at the vendor's plant and are expected to be delivered in late July. Design of a control console is under way to contain the components associated with the closed loop servo system, recorders monitoring the output of the LVDT-COD gages and the internal load cell, and miscellaneous signal conditioning.

5.5.1 Specimen Manufacture

A total of 24 2T-WOL specimens (see Figures 5-10 and 5-11) has been machined. This includes six each of Type-304 stainless steel, Type-304L stainless steel, Inconel, and carbon steel. Physical and chemical properties for these four material groups were previously shown as Table 5-7 in Quarterly No. 26.

5.5.2 Compliance Calibration (500°F)

Preparations continue to permit calibration at 500°F of COD versus load for the 2T-WOL specimens for each of the four material groups. The special furnace, procured during the last quarter, is being adapted for use with a GE-owned 100 KIP universal electro-hydraulic test machine. All fixturing needed for the 2T-WOL specimen calibrations is on order.

Figure 5-6. Equivalent Stress Amplitude versus Cycles to Failure for Type-304 Stainless Steel.
Comparison of fatigue data from BWR environment with "non-environment" baseline case.

Figure 5-7. Equivalent Stress Amplitude (psi) versus Cycle to Failure for Inconel 600
Comparison of fatigue data from BWR environment with "non-environment" baseline case.

Figure 5-8. Equivalent Stress Amplitude versus Cycles to Failure for A516 Carbon Steel.
Comparison of fatigue data from BWR environment with "non-environment" baseline case.

Figure 5-9. Test Vessel III Test Scheme

Figure 5-10. 2T-WOL Specimen for Crack Growth Rate Study of Task K_C

Figure 5-11. 2T-WOL Test Specimen

APPENDIX A

ACOUSTIC EMISSION MONITORING DURING PIPE RUPTURE TESTS

(R. K. Steele and W. K. Luinetti)*

SUMMARY

Measurements were performed by Westinghouse PWR Systems Division to detect and record acoustic emission signals indicative of the failure of a pipe elbow subjected to biaxial strains imposed by internal pressure and in-plane bending.

Several electrical and mechanical noise problems were encountered during the tests. Solutions to these problems were found and implemented prior to the tests in May 1972.

During the May test, excellent noise-free data were obtained during fatigue testing with and without fluid pressurization. Figures A-3 through A-6 are time compression plots of the integral of the count rate versus cycles on the specimen and reflect the classical data pattern for the fracture of a stainless specimen.

A.1 TEST SETUP

The test was a duplicate of the test run in February and March 1972. The test specimen was a 6-inch Schedule 40 Type 304 stainless steel elbow, one end of which was welded to a short vertical stainless pipe which was bolted to the test stand. The other end was welded to a short horizontal section which was, in turn, welded to a carbon steel section that was connected to the hydraulic loading mechanism. (Refer to Figure A-1.)

The stainless section was water-tight and was pressure cycled with bending strain. To eliminate metal frictional noise, rubber pads were added between the carbon steel pipe and the hydraulic loading mechanism. Additionally, at the fixed end, Durabla gasket material (a composition of rubber and asbestos) was used to isolate the threads of the flange studs. Teflon strips were taped to the pipe beneath the transducer mounting straps to further eliminate the possibility of generating frictional noise.

A.2 TEST PROCEDURE

The test plan called for cyclic pressure and flexural loading at a frequency of 12 cycles/minute. The deflection, measured at point A on Figure A-1 was $\pm 6\frac{1}{2}$ inches. The pressure was cycled between 100-psi at $-6\frac{1}{2}$ inches to 1500 psi at 0 to 2900 psi at $+6\frac{1}{2}$ inches.

The pressure and flexural loading during the test in March was originally $\pm 2\frac{1}{2}$ inches with the pressure cycled between 0 and 1475 psi. At about 9550 cycles on the specimen the deflection range was increased to $\pm 7\frac{1}{4}$ inches.

The test was stopped at 500 cycle intervals and inspected with an ultrasonic detector. In March, inspection revealed a subsurface fault at 1000 cycles (measured from the start of cycling at higher bending strain). At 2000 cycles subsurface irregularities were detected on both sides, and at 4400 cycles a through wall leak had developed.

During the test in May, inspection was carried out at 500 cycle intervals but there was no definition of a subsurface fault until 2500 cycles were completed at which time a visual inspection revealed a surface dimple. Another ultrasonic inspection was made at that time and subsurface fault about 4 inches long was discovered. Through wall failure occurred at 2531 cycles.

After the initial failure of the elbow in both cases cycling was continued without pressurization for additional acoustic emission data acquisition.

*Westinghouse PWR Systems Division

A.3 OPERATION OF THE ACOUSTIC EMISSION INSTRUMENTS

A.3.1 Noise Problems

As with the test during March, equipment and the hydraulic test rig were located in close proximity to on-off controllers for ovens, and several arc welding units using HF starters. Placing the instruments on an isolation transformer and grounding all instruments seemed to help. However, the instrument system is highly susceptible to electromagnetic interference. Arrangements were made to have the nearest arc welding unit shut down for the duration of the tests.

A.3.2 Boundary Effect

Much difficulty was encountered during the test in March with fixture noise originating at both ends of the test stand. The rubber used originally at the flanged end deteriorated and was replaced with Durabla at 2700 cycles. Also, there was a periodic knock in the hydraulic system that appeared in the test data. Both of these problems were overcome for the May test.

Additional rubber was used at the hydraulic end and, as mentioned earlier, Durabla was used exclusively at the flanged end along with proper fitting bolts and washers. It was observed, however, that there was still metal to metal contact at the flanged end but because of the semi-rigid character of the gasket material and proper torquing of the bolts it is believed that none of the signals observed originated from metal friction.

A.3.3 Observation of Acoustic Signals

1. A difference in sensitivity of acoustic channels was observed during the test. Although both channels "saw" the same events, the amplitude of the signals from the upper amplifier was ~ 3 times as great as the signals from the lower amplifier. A calibration check of the systems was made using a pulse generator and an accelerometer. A tabulation of the time difference between pulses, the amplitude of the pulses, and the test points along the elbow is attached as Figure A-2. The calibration check did not reveal the sensitivity difference observed during the test. Additional checks such as reinstalling detectors and checking the amplifiers had no effect on the observed difference.
2. As with the test in March, the quiescent noise of the transducer-amplifier system was very low, typically 20 MV on each channel (amplifier-gain 1000 and filter in).
3. The current test data are plotted and attached as Figures A-3 through A-6. The plots were made from the recorded signals of two totalizers. Figures A-3 and A-4 represent data from the upper channel from 0 to 4400 cycles (Figure A-3 from 0 to 2800 cycles, Figure A-4 from 2400 to 4400 cycles). The overlap between 2400 and 2800 cycles provides clarity for the continuity of acoustic signals occurring with and without pressure cycling.

Similar plots were drawn for the lower detector and are attached as Figures A-5 and A-6.

4. The physical appearance of the signals was the burst type emission with a sharp leading edge. They appeared to come in packets. Also, it was observed that with the exception of time where high count rates were observed, most of the activity came as the driven end of the pipe was near the maximum down position (minimum pressure). A possible explanation of why this occurs is revealed in the examination of the deformation of the section during cycling. In the down position without the benefit of internal pressure stability, the section ovulates as shown below along the X-X axis.

In the up position, the section ovulates along the Y-Y axis but not as severely due to internal pressure stabilization. Thus, the fatigue of the section is more severe in the down position. In periods of high activity the packets of energy came in a somewhat random fashion through most of the cycle period.

The authors would like to express their appreciation to the personnel at GE for the effort expended in the preliminary work making the test stand noise free and for the cooperation received during the test to ensure optimum test conditions.

APPENDIX B

FATIGUE SPECIMEN COMPLIANCE AS A FUNCTION OF CIRCUMFERENTIAL CRACK DEPTH (T. L. Gerber)

Consider a round bar of diameter D with a circumferential crack of depth a :

The specimen compliance (reciprocal of stiffness) is given by

$$\lambda = \Delta/P \quad (1)$$

The strain energy release rate, G , can be expressed as a function of the change in compliance with crack extension.

$$G = \frac{P^2}{2} \frac{\partial \lambda}{\partial a} \quad (2)$$

G can also be expressed in terms of the crack tip stress intensity, K_I .

For elastic plane strain conditions, this relationship is

$$G = \frac{(1-\nu^2)}{E} K_I^2 \quad (3)$$

Combining Equations (2) and (3),

$$\begin{aligned} \frac{P^2}{2} \frac{\partial \lambda}{\partial a} &= \frac{(1-\nu^2)}{E} K_I^2, \\ \frac{\partial \lambda}{\partial a} &= \frac{2(1-\nu^2)}{E} \frac{K_I^2}{P^2} \end{aligned} \quad (4)$$

An expression for the stress intensity due to a circumferential cracked round bar subjected to tension* is

$$K_I = \sigma_{\text{net}} (\pi D)^{1/2} F(d/D) ; \quad (5)$$

where

$$\sigma_{\text{net}} = 4P/\pi d^2 \quad (6)$$

and

$$F(d/D) = \left(\frac{d}{D}\right)^2 \left[\frac{1}{\pi} \tan \frac{\pi}{2} \left(1 - \frac{d}{D}\right) \right]^{1/2} h \left(1 - \frac{d}{D}\right) \quad (7)$$

with h tabulated in Table 3 of the reference.*

For small cracks, $F(d/D)$ can be approximated by the expression

$$F(d/D) \approx C \left(1 - \frac{d}{D}\right)^{1/2} \quad (8)$$

with

$$C = 0.67. \quad (9)$$

Substituting Equations (5) and (8) into Equation (4), and using the fact that $d = D - 2a$:

$$\frac{\partial \lambda}{\partial a} = \frac{32C^2(1-\nu^2)}{\pi E} \left[\frac{D}{(D-2a)^4} - \frac{1}{(D-2a)^3} \right] \quad (10)$$

Before integrating, let

$$K = \frac{32C^2(1-\nu^2)}{\pi E} \quad (11)$$

It follows that

$$\frac{\partial \lambda}{\partial a} = K [D(D-2a)^{-4} - (D-2a)^{-3}] ,$$

Integrating this expression

$$\lambda = \frac{2}{3} KD(D-2a)^{-3} - K(D-2a)^{-2} + C_0 ,$$

$$\text{at } a = 0, \quad \lambda = \frac{L}{AE} = \frac{4L}{\pi D^2 E}$$

$$\begin{aligned} \frac{4L}{\pi D^2 E} &= K \left[\frac{2}{3} D^{-2} - D^{-2} \right] + C_0 \\ &= -\frac{K}{3} D^{-2} + C_0 , \end{aligned}$$

*Paris and Sih, "Stress Analysis of Cracks," ASTM STP 381, 1965.

$$\therefore Co = \frac{4L}{\pi D^2 E} + \frac{K}{3D^2},$$

$$\lambda = K \left[-(D-2a)^{-2} + \frac{2}{3} D(D-2a)^{-3} + \frac{1}{3} D^{-2} \right] + \frac{4L}{\pi D^2 E}.$$

$$\lambda = \frac{32C^2(1-\nu^2)}{\pi E} \left[\frac{2}{3} D(D-2a)^{-3} - (D-2a)^{-2} + \frac{1}{3} D^{-2} \right] + \frac{4L}{\pi D^2 E} \quad (12)$$

Equation (12) gives specimen compliance in terms of the circumferential crack depth a .

For the special case where specimen diameter $D = 1$,

$$\lambda = \frac{32C^2(1-\nu^2)}{\pi E} \left[\frac{2}{3} (1-2a)^{-3} - (1-2a)^{-2} + \frac{1}{3} \right] + \frac{4L}{\pi E}.$$

This expression is plotted in Figure B-1.

Figure B-1. Effect of a Circumferential Crack on the Compliance of a 1-inch-Diameter Round Specimen

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