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**REACTOR PRIMARY COOLANT SYSTEM
RUPTURE STUDY
QUARTERLY PROGRESS REPORT NO. 19
OCTOBER-DECEMBER 1969**

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

ATOMIC POWER EQUIPMENT DEPARTMENT
GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

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**REACTOR PRIMARY COOLANT SYSTEM RUPTURE STUDY
QUARTERLY PROGRESS REPORT NO. 19**

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1. INTRODUCTION

The Reactor Primary Coolant System Rupture Study is being conducted for the Safety Branch, Division of Reactor Development and Technology, USAEC. This nineteenth quarterly report documents progress for the period of October 1 to December 30, 1969. 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 is proceeding on the following tasks:

Task A—Probability Study,
Task B—Stress Analysis,
Task C—Fracture Mechanics,
Task D—Fatigue, and
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 listed 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.

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 Factor 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 A106-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.

2. SUMMARY

2.1 TASK A—PROBABILITY STUDY

The availability of damage prediction equations was reviewed for the damage mechanisms and stages of damage accounted for in the piping probability diagram. In the absence of established relationships, candidate equations were hypothesized. The problem of estimating the probability of severance was characterized in terms of the distribution of time to damage method, and the need for certain essential relationships was identified. One such key relationship was that between type of loading, such as membrane or bending, and the variation in K around the leading edge of a crack.

2.2 TASK B—STRESS ANALYSIS

Preparation of the assessment report, incorporating a review and evaluation of the PAPA code and related finite element codes, was continued.

2.3 TASK C—FRACTURE MECHANICS

Based on a very limited number of tests, ASTM A234 plain carbon steel elbows appear to be somewhat less sensitive to axial (parallel to flow), part-through flaws than are straight segments of ASTM A106-B pipe containing axial flaws of equivalent depth and length. The program of burst testing piping components completed thus far includes: one unflawed tee, one unflawed elbow, three elbows with axial flaws, and one elbow with a circumferential flaw. Fifteen specimens will be tested in the next quarter.

2.4 TASK D—LOW CYCLE FATIGUE

In laboratory studies, crack growth rates were measured in the welds of butt-welded plain carbon and Type-304 stainless steel seamless pipe. The rates were essentially the same as measured on the base pipe materials. A prototype pipe test was completed of a stainless steel elbow specimen loaded out-of-plane at 550°F.

2.5 TASK K—EFFECT OF BWR ENVIRONMENT

The fatigue test machine was successfully shutdown-tested at San Jose, completing 96,000 cycles at operating conditions: 500°F, 1000 psi, and simulated loads. The test included six fatigue test specimens with axial holes for failure detection which signalled through-cracks in the predicted number of cycles.

At the Dresden I test loop, the valve stem (damaged on initial checkouts last August) was replaced, but on checkout testing, a motor failure then occurred on the other isolation valve. A new motor was ordered immediately.

The electrochemical monitoring system was completed at the Dresden I loop except for the new instrumentation—the automatic rate monitor—which will be installed in January. The system will monitor specimens mounted in two flanges: one at the take-off from the primary coolant circuit, and one adjacent to the test vessel containing the fatigue specimens.

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

The availability of damage prediction equations was reviewed for the damage mechanisms and stages of damage accounted for in the piping probability diagram. In the absence of established relationships candidate equations are hypothesized. The problem of estimating the probability of severance is characterized in terms of the distribution of time to damage method, and the need for certain essential relationships is identified. One such key relationship is that between type of loading (membrane, bending, etc.) and the variation in K around the leading edge of a crack.

3.3 CANDIDATE DAMAGE PREDICTION EQUATIONS

Considerations follow on application of the distribution of time to damage method of probability estimation to damage events other than growth through to leakage by low cycle fatigue; that is, what information is at hand to proceed with estimation of reliability?

This method is implemented by first drawing a piping probability diagram showing the successive stages of damage that can be caused by applicable damage mechanisms, and then devising a damage prediction equation or graphical relationship for each stage of damage, and for each mechanism. A piping probability diagram simplified from Figure 3-1, Ninth Quarterly Report, GEAP-5512, is presented here as Figure 3-1. Processes linking each stage of damage by each damage mechanism are numbered from 1 to 15. Following is a list where a candidate damage prediction is hypothesized for each process. *These relationships are highly tentative; scaling, where used, is purely illustrative.* But these relationships are presented at this time to serve the following objectives:

- a. To ensure that a probabilistic approach is available for all damage mechanisms and stages of damage, particularly for critical crack size.
- b. To identify those processes on which there is incomplete information, and which appear to have importance in assessing plant safety with respect to piping.
- c. To form the basis for experimental programs having the objectives of verifying or modifying the model, estimating parameters therein, and identifying other important variables.
- d. To indicate any variables for which quantified measurement scales are needed, so that each variable may appear in an equation and so its uncertainty distribution may be devised.

On Objective a., all circled process numbers in Figure 3-1 require validation of the damage prediction relationship and the other necessary inputs. For non-circled numbers, such information is available at present. Process "A" is being currently worked with.

On Objective b., it appears that the processes which have great importance in assessing plant safety and about which we have little information are those which lead to severance without prior leakage—Processes 12 through 14, growth into the wall of long shallow cracks. In Subsection 3.4 this problem is discussed in detail.

On Objective c., analytical and experimental work—particularly on processes 12 through 14—appears to be called for.

On Objective d., an example of a variable not now quantitative is the "degree of sensitization." It appears in the equation for Process 2 and requires a quantified scale.

All process numbers (1 through 15 and A) appear here except for A, No. 1, and No. 7. On No. 1, damage prediction equations are available from S-N diagrams and crack initiation studies under Task D-1. The existence of Process No. 7 is doubtful, except for the process of crack extension by flow cutting under constant load (which applies equally to Nos. 6 and 8), and also for which no damage prediction relationship is shown here.

Figure 3-1. Simplified Piping Probability Diagram

PROCESS 2. TIME TO CRACK INITIATION BY STRESS CORROSION ALONE (CONSTANT LOAD)

$$\text{Log } t = \sum_i a_i x_i$$

t = Time to initiation

i = 1 Material

2 Degree of sensitization

3 Environment chemistry

4 Environment temperature

5 Environment flow rate

6 Stress

7 Load and crack growth directions
versus plane of rolling

8 Surface finish and direction

9 Surface cold work

10 Pickling

11 Ferrite content

12 Initial flaw depth

PROCESS 3. TIME OR CYCLES TO CRACK INITIATION BY FATIGUE AND STRESS CORROSION COMBINED

Note: This Diagram is Intended Only To Illustrate Relationships

**PROCESS 4. CRACK GROWTH RATE BY STRESS
CORROSION ALONE (CONSTANT LOAD)**

$$da/dt = A K^B$$

where

da/dt = crack growth rate

K = stress intensity factor

A and B = parameters

B = constant, or as for A below

A = function of most of same variables
as in Process 2.

PROCESS 5. CRACK GROWTH RATE BY FATIGUE
AND STRESS CORROSION COMBINED

Note: These Diagrams are Intended Only To Illustrate Relationships.

**PROCESS 8. CRACK GROWTH RATE AROUND
BY FATIGUE**

**PROCESS 8. CRACK GROWTH RATE AROUND BY FATIGUE
AND STRESS CORROSION COMBINED**

$$da/dn = A (\Delta K)^B$$

where

da/dn = crack growth rate

ΔK = stress intensity factor range

(Same as model for "A," crack growth through by fatigue)

Assume stress corrosion plays no part in growth around,
leaking. See also note on these processes at end of Subsection 3.3.

PROCESS 9. FLOW RATE VERSUS THROUGH CRACK LENGTH
 PROCESS 10. PROBABILITY OF LEAK DETECTION VERSUS FLOW RATE

Note: This Diagram is Intended Only To Illustrate Relationships.

PROCESS 12. LOW-CYCLE FATIGUE
 PROCESS 13. STRESS CORROSION
 PROCESS 14. FATIGUE AND STRESS CORROSION COMBINED

Crack Growth Through—Characteristic Axial Length/Depth Ratio, Depending on Type of Loading

A DIAGRAM OF SIMILAR FORM IS REQUIRED FOR SECONDARY STRESSES, AND FOR CIRCUMFERENTIALLY ORIENTED CRACKS.

Note: This Diagram is Intended Only To Illustrate Relationships.

3.4 A STRATEGY FOR CALCULATING THE PROBABILITY OF SEVERANCE

Consideration is given in this subsection to the case of severance to assess whether the information necessary to making this probability estimate is on hand or must yet be obtained. Herein, "severance" is thought of as full cross-section sudden separation, or axial opening to an area equal to the cross section. In Figure 3-1, Block 11 calls for defining the conditions for severance of a through wall (leaking) crack, and Block 15 corresponds to the part-through (non-leaking) crack. It appears that the probability of severance of a leaking crack will be less than that of a non-leaking crack because of the high probability for the detection of a leak. Thus development of the strategy necessary for making the probability estimate for the non-leaking case will be emphasized.

It is required that critical size for severance of a non-leaking crack be defined for Block 15. Broadly, this is the combination of stress, crack length, and depth at which the crack will extend rapidly. For the same stress, critical size will be longer and/or deeper for tougher materials. To make the desired probability estimate, we need to understand for both axial and circumferential orientations (1) the

fabrication conditions that can create material which is particularly susceptible to crack initiation by any applicable mechanism, as by fatigue and/or stress corrosion; (2) the loading conditions that promote long, shallow crack growth with and without long initiation sites available; and (3) what the probability is that these loading conditions are found in reactor piping systems.

A diagram for illustrating the proposed probabilistic strategy is shown in Figure 3-2. Crack depth is plotted versus log axial crack length; the scales illustrated are for 6-inch Schedule-80 carbon steel pipe at room temperature, having wall thickness of 0.432 inch. For flexible application, diagrams are required for other wall thicknesses, for the circumferential direction, and for other materials and temperatures. The lines at the left represent, for illustration, cracks growing with constant length/depth ratios of 3/1 and 10/1. The lines at the right fit satisfactorily Reynolds' burst data for this pipe, from Task C. Each is a constant hoop stress line representing the mean stress at which a pipe with a defect of a combination of the length and depth shown will fail. It can be seen that if the crack growth line intersects the critical crack line *before* reaching through-wall depth, non-leaking severance will occur. On

NOTE: AXIAL SEVERANCE IS AXIAL OPENING OF PIPE TO AN AREA EQUIVALENT TO THE PIPE CROSS SECTION.
A DIAGRAM OF SIMILAR FORM IS REQUIRED FOR CIRCUMFERENTIALLY-ORIENTED CRACKS.

This Diagram is Intended Only To Illustrate Relationships.

SEE SUBSECTION 3.4 FOR DISCUSSION.

Figure 3-2. Conditions for Axial Severance. Process 11—Part-Through Axial Crack, Process 15—Through-Wall Axial Crack

the other hand, if the crack growth line can reach through-wall depth before reaching a critical size line, only leakage will occur. (Then, in order to achieve severance the crack must grow in length until reaching the critical size line, without detection and shutdown.)

The probabilistic aspect of the crack growth line-critical size line intersection problem can be considered as follows. The distribution of crack length/depth ratio with which a crack will grow through a pipe wall for a certain loading condition, along with the uncertainty of the loading condition at a chosen pipe location, can be represented by a distribution extending on both sides of the appropriate constant length/depth ratio line (or about such a non-constant line, if this ratio changes with crack depth for the loading condition). The need to obtain this information is discussed in the next paragraph. The distribution of stress at which a chosen length/depth of crack is critical will extend on both sides of the nominal stress lines shown. Now, as suggested, if a growing-crack line (or some line within its distribution) intersects the constant-stress line for a pipe location (or a line within the distribution around the nominal line) before the growing-crack line reaches full wall thickness—when the crack will leak—then severance has occurred. Now, the probability of this event can be obtained in terms of the overlapping of the uncertainty distributions surrounding the two nominal lines, taken at the through-wall depth. This difference-between-distributions approach is characteristic

of the distribution of time to damage method of probability estimation.

Some data are on hand to define the nominal critical crack size lines and to give an indication of the distribution around them, but the necessary information for the nominal value and distribution of crack length/depth ratios as the crack proceeds, as dependent upon the type of loading, is not known. Suppose it is assumed that crack growth rate at any point around the leading edge of a crack by either fatigue or stress corrosion varies as K^B for stress intensity factor K at that point. Then, the course of the crack growth line for a chosen type of loading, or combination of types, can be drawn if it can be found that K around a crack's leading edge depends upon the type of loading; i.e., primary membrane, secondary membrane, primary bending, secondary bending, and a limited number of patterns of local thermal and residual stresses. To grow a long shallow crack would require a loading which continues to subject crack tips at the free surface to high K values while permitting K at crack root to drop to a low value; for illustration, it is possible that secondary bending stresses would do this. In any case, in terms of Figure 3-2, for a particular location in the piping system, we need the calculated stress by category and then we need to know how to draw the length versus depth line for this combination of stress categories, as the crack grows through the wall. Moreover, we need to know how to characterize the variability of this line.

4. TASK B—STRESS ANALYSIS

4.1 OBJECTIVE

The purpose of the stress analysis task is to develop a method for the stress and strain analyses of those piping components which have been intractable problems. Designers of nuclear piping systems must be able to determine the detailed stress and strain distributions in complex piping geometry under complex loadings for avoidance of leaks and severance in piping, and to take into account low-cycle fatigue, corrosion, and critically sized flaws.

4.2 TASK B 1—COMPUTER PROGRAM DEVELOPMENT

The objective of the computer code development is to develop the analytical tools required to define the state of stress and strain in complex piping in service.

4.2.1 Summary

As part of the PAPA computer code development work, an evaluation of related computer codes and an engineering review of the PAPA code are in progress. An assessment report is being prepared, stating recommendations for future effort.

5. TASK C—FRACTURE MECHANICS

(M. B. Reynolds)

5.1 OBJECTIVE

The objective of this task is an experimental determination of pressure load limits in tees and elbows of plain carbon steel, followed by generation of an empirical relation to estimate load limit in terms of flaw dimensions. A prior phase of this task dealt with the relationship between pressure load limit and flaw size in straight specimens of ASTM A106-B pipe¹ *. The objective of the present effort is a determination of a similar relationship for flawed tees and elbows of the same material.

5.2 SUMMARY

Based on a very limited number of tests, ASTM A234 plain carbon steel elbows appear to be somewhat less sensitive to axial (parallel to flow), part-through flaws than are straight segments of ASTM A106-B pipe containing axial flaws of equivalent depth and length. The program of burst-testing piping components completed thus far includes: one unflawed tee, one unflawed elbow, three elbows with axial flaws, and one elbow with a circumferential flaw. Fifteen specimens will be tested in the next quarter.

5.3 TECHNICAL BACKGROUND

The load limit for any structure is reduced by the presence of a geometrical flaw which results in loss of load-bearing cross section or in local stress concentration, the loss of strength increasing monotonically with increasing flaw size. It was possible to derive load limit-flaw size equations from first principles only for geometrically simple structures (e.g., wide plates or thin cylindrical shells) and then only for homogeneous materials of very limited ductility. It has, however, been possible to extend the applicability of the first-principle equations of linear elastic fracture mechanics to more ductile materials by resorting to empirical modifications to them. Ideally, for small flaws in a large brittle structure, the limiting gross stress is determined by two parameters only: the flaw size, and a single material parameter—the plane strain fracture toughness, K_{Ic} . In dealing with real materials, the load limit-flaw size equation usually contains yield stress as an additional material parameter and, in the case of cylindrical shells, radius and wall thickness. For axially or circumferentially flawed pipes or other cylindrical shells under internal fluid

pressure, reasonably satisfactory empirical equations were developed for predicting pressure load limits in terms of flaw length in case of through-wall flaws, or length plus a depth parameter in case of part-through flaws^{1 2 3}. Information on the failure behavior of ASTM A106-B pipe containing both through-wall and part-through flaws has been obtained in the previous phase of this task^{4 5 6}.

5.4 PRESENT WORK

Present efforts are directed toward determination of pressure load limits for flawed ASTM A-234 tees and elbows. The planned tests are limited to 6-inch Schedule-80 components with part-through flaws, except for reference tests which are unflawed. Flaw configurations being studied are illustrated in Figure 5-1. Since flaw depth is of necessity measured from the outer surface of the fitting in the machining process, the thickness of the remaining ligament at the base of the flaw is influenced by variations in wall thickness. Flaw size is designated in terms of length (arc) and ligament-wall thickness ratio x/T consistent with nomenclature used in earlier reports.⁵ Also, test techniques are as described earlier⁴ with test temperature at 60°F. The elbows and tees were welded to capped A106-B foot long pipe segments.

5.5 RESULTS TO DATE

Data on specimens are given in Table 5-1. The wall thickness of a tee or elbow is greater than that of a pipe segment of the corresponding size and schedule in order to compensate for geometrical stress concentration. Nevertheless, in the burst tests of an unflawed tee and an unflawed elbow, failure initiated in the crotch of the fitting. The break started as a shear fracture, changed to a flat fracture, and propagated to the ends of the attached pipe segments.

Failure strengths of elbows, expressed as a fraction of unflawed strength, are plotted against reciprocal of flaw length in Figure 5-2, the fracture diagram developed for straight pipe. This display of the test results enables comparison with data from straight pipe segments with axial part-through flaws. Although data from only three elbow specimens were available, elbows appear to be somewhat less sensitive to axial (i.e., parallel to flow) flaws than are straight-pipe segments. Additional data are needed to resolve this matter definitely. Since only one circumferentially flawed elbow (Specimen E1-13-8) was tested, no conclusions were drawn.

* See Subsection 5.6 for references.

Table 5-1
FAILURE STRENGTH OF FLAWED ASTM A234 STEEL PIPE COMPONENTS

Specimen	Flaw(f) Type	L(a)	d(b)	x/T(c)	P(d)	P/P ₀ (e)	1/L
T-1-8	None	0	0	1.00	8880	1.00	∞
EL-1-8	None	0	0	1.00	8680	1.00	∞
EL-1A-8	A	3.13	0.30	0.39	6560	0.76	0.32
EL-2A-8	A	6.31	0.164	0.30	4700	0.54	0.159
EL-3A-8	A	6.30	0.322	0.63	6470	0.75	0.159
EI-1B-8	B	7.25	0.316	0.29	5860	0.68	—

- (a) L = Flaw length, inches
 (b) d = Flaw depth, inches
 (c) T = Wall thickness, inches
 x = Ligament thickness, inches
 (d) P = Failure pressure, psi
 (e) P₀ = Failure pressure, unflawed
 (f) See Figure 5-1 (GE Drawing 106D4074)

5.6 REFERENCES FOR SECTION 5

1. Reynolds, M. B., *Failure Behavior in Axially Flawed ASTM A-106H Pipes*, Paper 69-SESA-3, presented at meeting of Society for Experimental Stress Analysis, Houston, Texas, October 1969.
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3. Eiber, R. J., Maxcy, W. A., et al., *Investigation of the Initiation and Extent of Ductile Pipe Rupture*, Report BMI-1866, Battelle Memorial Institute, Columbus, Ohio, July 1969.
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A

B

SEE DETAIL 'D'

C

TYPES OF ELBOW FLAWS

J

TYPES OF TEE FLAWS

K

L

SEE DETAIL 'P'

Figure 5-1. Machined Flaws in Elbows and Tees

Figure 5-2. Fracture Diagram Developed for Straight Pipe, Showing New Data for Elbows for Comparison

6. TASK D—LOW-CYCLE FATIGUE

6.1 OBJECTIVE

The objectives of the Fatigue Task are: (a) to extend the understanding of low-cycle fatigue cracking in high-pressure piping components which 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.

6.2 TASK D-1—FATIGUE CRACK GROWTH STUDIES (A. J. Brothers)

6.2.1 Summary

Crack growth rates have been measured in butt-welded, 6-inch-diameter, Schedule-40 sections of A106-B and Type-304 stainless steel pipe. Comparison of these results with those obtained previously on unwelded pipe sections reveals very similar rates. Features of the crack growth are described.

6.2.2 Crack Growth in the Weld Material of Butt-Welded Pipe

To determine crack growth rates in "prototype"* pipe materials and geometry, the rates were measured earlier in semi-cylindrical pipe specimens of unwelded A106-B, 2-1/4 Cr-1 Mo, and Type-304 steels (Quarterly Reports 8 through 10). These tests indicated crack growth rates considerably greater than those for plate specimens; however, it was later shown (Quarterly Report 16) that this difference reflected an effect of pipe versus plate geometry.

Following is a description of the results of room temperature crack growth tests of butt-welded, 6-inch-diameter, Schedule-40, A106-B and Type-304 stainless steel pipe using the same semi-cylindrical geometry tested earlier (Figure 6-1).

The pipe specimens were welded to established welding procedures for carbon and Type-300-series steels. For the Type-304 stainless pipe, the specification requirement was for a manual inert gas, tungsten arc process with Type-308 stainless steel filler metal. The A106-B pipe was welded by a combination of manual, gas tungsten arc and manual, shielded metal arc, using a filler material of low carbon, high manganese steel. No post-weld heat treatment was used in either case. The hardness of the weld in the A106-B pipe was greater than the base metal: 215 DPH, as compared with 145 DPH. The hardness of the Type-304 steel weld was not determined.

* Made from sections of the pipe used for the prototype pipe fatigue tests at San Jose.

Prior to fatigue testing, the weld metal reinforcement was removed from the outside diameter of the pipe, and the thickness was reduced on the internal diameter to result in a uniform wall thickness of 0.2 inch in the reduced section. Although this process was performed adequately for the Type-304 steel, the reinforcement on the A106-B was not removed flush in all regions, and the weld in some areas was 0.01 inch thicker than the base metal. This difference, though slight, may account for some of the crack path features noted in the following paragraph (Figure 6-6).

Since, in these tests, crack growth was seldom exactly symmetrical and equal in the two halves, crack lengths were measured on both sides of the specimen using an attached hundredths scale, and the results were averaged to determine the crack growth curve of crack length as a function of cycles. To determine the correlation with stress intensity factor, each of the smoothed crack growth curves was analyzed to determine values of crack growth rate as a function of increasing crack length. Increments of crack length and corresponding cyclic intervals were taken so that the crack growth curve was ostensibly linear within each increment. Values of stress intensity factor were calculated for the average crack length corresponding to that over which the growth rate was measured.

The crack growth curves for the A106-B and Type-304 steels tested to date are shown in Figures 6-2 and 6-3, respectively. These characteristics are generally typical of those tested previously, and exhibit increasing slope; i.e., faster crack growth rate as a function of increasing crack length and increasing gross section stress. The seemingly anomalous positions of the curves for the A106-B tests at the two higher stress levels are presumably caused by scatter associated with the very similar stress levels of the two tests.

The correlation of crack growth rate with stress intensity factor is shown in Figures 6-4 and 6-5. These figures also enable comparison of the results with those obtained earlier on unwelded pipe. These comparisons suggest essentially identical results for welded and non-welded Type-304 steel. Similar results for the A106-B piping suggest a slightly lower growth rate for the welded condition.

Examination of the crack growth path for the two steels indicates that crack growth in the Type-304 steel occurred exclusively within the weld zone, suggesting that this region has equal or slightly lower crack growth resistance than the base metal. The crack path in the A106-B, though initially through the weld, exhibited at the higher

Figure 6-1. Sketch Showing Two Halves of Butt-Welded Pipe Specimen Arranged for Cyclic Tensile Loading

stresses a tendency with increasing length to diverge toward the base metal; this behavior indicates either a slightly greater resistance to crack growth of the weld metal, or the possible influence of a slightly greater thickness of the weld in this material (see Figure 6-6).

6.3 TASK D-2—CRACK INITIATION (E. Krempf)

The summary report is in the final stages of preparation.

Figure 6-2. Crack Growth Curves for Weld in A106-B Butt-Welded Pipe

Figure 6-3. Crack Growth Curves for Weld in Type-304 Butt-Welded Pipe

Figure 6-4. Crack Growth Correlation for Butt Weld Compared to Base Material in A106-B Plain Carbon Steel Pipe

Figure 6-5. Crack Growth Correlation for Butt Weld Compared with Base Material in Type-304 Stainless Steel Pipe

1/2X

Figure 6-6. Macroscopic Features of Pipe Specimens Showing Variation in Crack Path

6.4 TASK D-3—PROTOTYPE PIPE FATIGUE

(J. D. Heald)

6.4.1 Summary

Testing was completed on a prototype elbow, HSL-2, loaded out-of-plane at 550°F. The data summary for this specimen is as follows.

Sample Number	HSL-2
Material	Type-304 Stainless Steel Schedule-40
Specimen Type	Elbow
Test Temperature	550°F
Loading	Out-of-Plane
Internal Pressure	None
Stress Range, Nominal	42,200 psi
Cantilever End Deflection	±10.30 inches
Cycles to Crack Initiation (N_I)	1799
Cycles to Full Wall Penetration (N_W)	1870
	(81)*
Cycles at Test Termination (N_ϕ)	2089
	(219)**

* Full amplitude cycles during through-wall growth ($N_W - N_I$).

** Full amplitude cycles after penetration ($N_\phi - N_W$).

6.4.2 Data Obtained

6.4.2.1 Crack Initiation

At cycle 893, a 2.20-inch-long crack was discovered visually on the bottom of the pipe adjacent to the lever arm to elbow weld. This crack was repaired by welding and the test was continued. At cycle 1307, a 2.00-inch-long crack was detected visually on the top of the pipe adjacent to the lever arm to elbow weld. This crack was also repaired and the test was continued. Both cracks, though detected visually, were through-wall, as shown by inert gas leakage test. At cycle 1799, three separate cracks were detected visually on the outside surface of the elbow (Figure 6-7). Cracks A and C were on the top of the elbow, oriented in the circumferential direction. Crack B was on the bottom of the elbow.

6.4.2.2 Through-Wall Penetration

At cycle 1870, a leak (full wall penetration) was detected at Crack A. At cycle 1874, a fourth crack (Crack D) was detected on the bottom of the elbow in the heat affected zone of the first weld repair mentioned previously. After penetration, only cracks A and D continued to grow. Final crack geometry is shown in Figures 6-8 and 6-9.

6.4.3 Topical Report

A topical report entitled "Low Cycle Fatigue of Prototype Piping," has been prepared and submitted for publication. The report covers all work on Task D-3 through 1969.

Figure 6-7. Closeup of Top Cracks, Stainless Elbow, Sample HSL-2, After 1799 Cycles

Figure 6-8. Final Fracture Geometry (Top Side), Sample HSL-2, After 2089 Cycles

Figure 6-9. Final Fracture Geometry (Bottom Side), Sample HSL-2, After 2089 Cycles

7. TASK K—EFFECT OF BWR ENVIRONMENT

(D. A. Hale)

7.1 OBJECTIVE

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

7.2 SUMMARY

- a. The fatigue test machine was shakedown tested for $\approx 96,000$ cycles at design conditions of load, temperature, and pressure. All the mechanical components of the test machine functioned satisfactorily. Six fatigue specimens with capillary tube—pressure switch failure detection circuits were also qualified for operation at loop operating conditions.
- b. Dresden I Materials Test Loop. During the plant outage,* a replacement stem was installed in place of the one damaged while testing the root isolation valves last August. The motor on the other isolation valve then failed during the December operational checkout. A new motor was ordered immediately. Drawings were made covering minor piping changes to accommodate a third unit in parallel with the static test vessel.
- c. The manufacture of the dynamic fatigue, static stress bend, and static WOL specimens is well under way.
- d. Design work was completed on air test equipment which will be used to generate the base line "air" fatigue test data at 500°F .

7.3 DRESDEN I TEST LOOP

A new valve stem was installed in MOV-2 to replace the one that failed during the loop pre-startup checks in August. Both motor-operated root isolation valves were operated as a part of checkout procedures; MOV-2 performed satisfactorily and was accepted for operation at loop design conditions. However, the motor on MOV-1 failed during these final performance checks. The motor will be returned to the vendor to determine the cause of the failure. An order was placed immediately for a replacement motor.

* Scheduled plant shutdown for refueling, September—December.

The loop instrumentation panel previously installed in Dresden I loop cubicle was modified to accommodate the expanded Dresden I control room alarms requested by Commonwealth Edison. The alarms now will include status lights for both MOV-1 and -2, and a loop trouble light in parallel with the local loop trouble alarm. The installation of the cable and control room circuitry is scheduled for early in the next quarter.

Design work was completed on the additional piping and valves required to add a third vessel to the test loop in parallel with the existing static test vessel. This third vessel would accommodate a string of WOL specimens cyclically loaded to generate environmental crack growth rate data.

The specimen failure detection counter console (Figure 7-1), which contains the 150 individual specimen counters and all the associated circuitry for the 150 individual failure detection circuits, has been designed and fabrication has started.

7.4 HOT SHAKEDOWN TESTING

Hot shakedown testing was complete. The fatigue test machine accumulated $\approx 96,000$ load cycles while immersed in 1000-psig water which varied in temperature between 475 and 510°F . The six axial hole fatigue test specimens failed, with five of the six pressure switch failure detection circuits functioning. One did not operate as a result of a loose fitting. Pertinent test parameters are listed in Table 7-1.

The test machine was disassembled and all critical parts were checked (Zyglo dye penetrant). Special attention was given to the shaft which forms the "backbone" of the unit. No flaws were detected.

No detectable leakage was noted from the leak-off port in the chevron packing gland seal which seals the shaft penetration through the dynamic test vessel head. However, when the fatigue machine was disassembled, the lower teflon chevron packing rings were found to be partially extruded into the lantern ring which separates the upper and lower stages of the packing gland. It is possible that this extruded seal material could have sealed off the lantern ring cavity, thereby preventing leakage from being detected at the lantern ring leak off port. However, since no leakage was noted at the low-pressure side of the upper stage of the gland, it is reasonable to assume that there were enough packing rings in the upper stage of the gland to accommodate any pressure buildup that may have taken place in the

Figure 7-1. Failure Detection Console

Table 7-1
RESULTS OF HOT SHAKEDOWN TESTS
($\approx 500^{\circ}\text{F}$, 1000 psig water)

Specimen Number	Initial Measured Strain Range ($\mu\text{in./in.}$)	Cycles-to-Failure (Defined by External Pressure Switch Detection Circuit)	Remarks
HD-2	9100	<7,996	Failure detection circuit did not function as a result of loose tubing fitting
HD-3	4900	39,104	—
HD-4	4000	46,082	—
HD-5	6900	12,210–12,648	—
HD-6	8500	10,190–10,266	—
HD-7	6800	12,210–12,648	—

lantern ring leak-off cavity. The gland design will be modified to minimize the possibility of seal ring extrusion.

7.5 TEST SPECIMENS

7.5.1 Fatigue Specimen Strain-Deflection Calibration

The load-strain-deflection characteristics of a Type-304 stainless fatigue specimen were measured at room temperature using the specimen stress fixture (refer to Figure 7-10, GEAP-5770). Based on the results shown in Figure 7-2, a slight reduction in nominal specimen thickness (from 0.126 to 0.120 inch) and a tightening of the tolerances on this dimension (from ± 0.003 to ± 0.001 inch) were incorporated into the final fatigue specimen design. This change decreases the strain deflection sensitivity of the specimen (i.e., reduces the change in strain range due to a decrease in applied tip deflection as might possibly occur due to wear at the contact points over a long period of time).

7.5.2 Specimen Manufacturing Program

7.5.2.1 Dynamic Specimens

Axial holes were EDM'd* in four fatigue specimens (one each of Type-304 stainless steel, Type-304L stainless steel, Inconel, and carbon steel) to qualify the production parameters and electrolyte (demineralized water) to be used for the final group of 150 scheduled for testing in the Dresden I test loop. The completed specimens were sectioned and examined metallographically. The results indicated that only negligible microcracking is introduced in the material immediately adjacent to the axial hole in any of the four test materials. The effects are confined to a layer of material less than 0.001 inch in depth. Based on these results, a production order for 260 EDM'd axial hole specimens has been placed. The total number, 260, allows for spares as well as specimens for the development of air curves.

A total of 82 specimens has been drilled and they are undergoing ultrasonic checks to determine whether the critical tolerance on the centering of the axial hole has been met.

Metallography was performed on the welded plates for fatigue specimens to locate precisely the weld, HAZ, and base metal boundaries. Fatigue specimen orientations were chosen to place the specimen reduced thickness test section in the HAZ, as shown in Figure 7-3.

7.5.2.2 Static Specimens

Eleven WOL specimens of base material (material code 2*) have been pre-cracked by fatigue at the M&P Lab in Schenectady. The required heat treatments have been completed on the WOL specimens corresponding to material code 5;* these specimens will be fatigue pre-cracked next.

The welded plates from which the WOL weld specimen blanks (material codes 3, 4, and 7*) will be taken have been examined metallographically to locate the weld metal boundaries (See Figure 7-4). The WOL blanks will be oriented to place the plane of fatigue crack propagation in the HAZ (line XX, Figure 7-4) and in the case of carbon steel, in the weld filler metal (line Y-Y, Figure 7-4).

7.6 AIR TEST FATIGUE UNIT FOR TESTS AT 500°F

The design of a 500°F air fatigue machine which will be used to generate the base line "air" data for comparison with the environmental fatigue data is nearly complete. A heater has been designed to fit inside the test vessel used for the shakedown test noted above. A "mini" fatigue test machine is being assembled, which is mechanically identical to the Dresden I unit except for a reduced specimen capacity of 12. The 1000-psig air in which the air specimens will be tested will allow failure to be defined, using the same external pressure switch concept employed on the Dresden I specimens.

7.7 TASK K-1—ELECTROCHEMICAL STUDY (R. L. Cowan)

7.7.1 Summary

The electrochemical monitoring system was completed at Dresden I, except for the new instrumentation—the automatic rate monitor which will be installed in January. The system will monitor specimens in two flanges, one at the takeoff from the primary coolant circuit, and one adjacent to the test vessel containing the fatigue specimens.

7.7.2 Results

The electrochemical monitoring system was completely installed, except for the automatic monitoring instrumentation. The system includes two 4-inch blind flanges that contain the electrodes. One of these flanges (Flange 1) is located on the take-off cross which is in the B

* Electro Discharge Machining

* Reference GEAP-10120, Table 7-3

secondary steam generator loop, and the other flange (Flange 2) is located immediately downstream of the Task K autoclave. The electrodes on each flange are insulated electrically from the reactor piping by suitable Rulon "A"* seals and alumina insulators (see Figure 7-5). The sample electrodes and the reference electrode are $1/4 \times 1/2$ inch right cylinders. The auxiliary electrode is a piece of stainless steel screen $1/8$ -inch thick and 3 inches in diameter. Flange 1 contains eight electrochemical samples, of which four are annealed Type-304 stainless steel and four are "as received" A106-B steel. Four of these electrodes (two of each material) will be monitored electrochemically for continuous corrosion rate determinations. The other four samples are being used as controls. At the end of the experiment, conventional weight loss corrosion rates will be determined on these samples and compared with the calculated integrated weight loss as determined on the other four samples electro-

* Asbestos impregnated Teflon, made by the Dixon Corporation, Rhode Island.

chemically. All of the samples were weighed precisely before installation of the flange. Flange 2 contains only five samples: three of Type-304 stainless steel, and two of A106-B steel. Four of these will be monitored continuously, and one will serve as a control. Flange 2 contains only five sample electrodes because of space limitations. The electrical wiring to the electrodes is installed and consists of a shielded pair to each electrode (11 pair shielded cable to Flange 1, and 7 pair shielded cable to Flange 2).

The Petrolite ten-station automatic corrosion rate meter will be hooked up early in January. At this time, the anodic and cathodic polarization behavior of both the Type-304 and A106-B will be determined so that the proper constants for the linear polarization equations are available. In addition, the electrolytic resistance between the working electrode and the reference electrode will be determined for each sample electrode so that an appropriate "IR" potential drop correction can be made to the "apparent" overpotential.

Figure 7-2. Fatigue Specimen Strain-Deflection Characteristics

CARBON STEEL, 4.5X

INCONEL-600, 4.5X

HAZ, 250X

HAZ, 250X

HAZ, 250X

HAZ, 250X

Figure 7-3. Typical Fatigue Weld Specimen Orientation

TYPE-304 STAINLESS STEEL, NORMAL WELDMENT, $\approx 2X$

TYPE-304 STAINLESS STEEL, HIGH HEAT WELDMENT, $\approx 2X$

TYPE-304L STAINLESS STEEL, NORMAL WELDMENT, $\approx 2X$

INCONEL-600, NORMAL WELDMENT, $\approx 2X$

CARBON STEEL, NORMAL WELDMENT, $\approx 2X$

X—X ORIENTATION OF CENTERLINE OF SPECIMEN

GEAP-10143

Figure 7-4. WOL Weld Specimen Orientation

Figure 7.5 Electrochemical Flange Assembly

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