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MASTER

LOW-CYCLE FATIGUE OF PROTOTYPE PIPING

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PREFACE

The forty-six tests discussed herein were performed over a period of several years. Previously reported in Quarterly Progress Reports (listed in Reference 1), they represent the major portion of the planned program of prototype pipe testing. Remaining studies include several more tees and elbows, straights with axial cracks, and finally, pressures of 2200 psi.

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ABSTRACT

Presented in this report are the details of testing, data, and analysis of prototype piping and components subjected to low-cycle fatigue. The specimens were fabricated from materials used for the primary piping of pressurized water and boiling water nuclear reactor systems. Data have been obtained for cycles to crack initiation, through-wall and circumferential crack growth at room temperature and 550°F. Comparisons are made of fatigue data obtained from the prototype piping and laboratory tests of flat plates and round bars of similar materials. In addition, predictions of fatigue life are made according to the procedures of the ASME Nuclear Power Piping Code (B31.7) and compared with prototype test results. Finally, data are presented which show that piping components at BWR operating pressure, subjected to continued low-cycle fatigue loading, are almost certain to leak rather than fracture suddenly.

1. INTRODUCTION

One of the failure mechanisms considered to be of prime importance in the design of water-cooled nuclear primary piping is low-cycle fatigue. Since the number of significant stress cycles for commercial nuclear power plants seldom exceeds several thousand, fatigue failure of piping components will involve cyclic plastic straining that could occur at notches, sharp fillets, and structural discontinuities. Since fatigue damage in the plastic region is a function of cyclic plastic strain, the ASME Nuclear Power Piping Code B31.7 has adopted design rules based on strain-controlled tests of small specimens in the laboratory, and application of appropriate safety factors to produce safe design criteria.

Although the code fatigue design curves relate cyclic stress range and number of cycles to failure, it must be emphasized that failure relates only to the size and geometry of the laboratory specimens used to establish the basic fatigue data. In the majority of cases, these are small polished specimens where cycles to crack initiation and fracture are essentially equal. The validity of subsequent use of such data for design and evaluation of primary system piping components, with the utilization of stress reduction factors, depends on its proven conservatism with respect to fatigue tests on full-size structures. In this regard, it is important to consider the following factors.

For low-cycle fatigue failure of piping components, several stages or mechanisms must be considered: first, the crack initiation stage (N_I); second, the crack growth stage (N_P); and finally, the failure mechanism, i.e., will the component leak or will it suddenly fracture without prior gross plastic yielding (low-energy brittle type fracture)? Thus, the total limiting operational lifetime (N_T) of primary systems

piping will be the sum of $N_I + N_P = N_T$. Predictions indicating that the fatigue life limit of piping components will be exceeded based on laboratory tests of small specimens *do not imply incipient failure*. Rather, a more realistic interpretation would be **CAUTION—INCREASED RISK OF SUBSEQUENT FAILURE**, since the cycles to initiation phase in the fatigue process have been exceeded. These facts are extremely important inasmuch as there is increasing evidence that even with the most modern and sensitive techniques of nondestructive testing, it is impossible to guarantee the absence of flaws in real structures. Consequently, in the assessment of the limiting operational lifetime of piping components the following questions must be answered:

- After crack initiation, in what manner, shape, or form does the crack grow?
- At what rate does the crack grow as a function of applied cyclic stress?

And most important,

- Will the crack penetrate the wall and cause leakage, or will sudden fracture occur at or prior to leakage?

The primary objectives of the prototype pipe fatigue task of the Pipe Rupture Study are to answer these questions; specifically, to determine for actual piping and components

- Cycles to crack initiation as a function of applied stress range, and
- Rate of crack growth as a function of applied cyclic stress;

And then to perform the following:

- Compare the foregoing data with more conventional laboratory tests of flat plates and round bars subjected to low cycle fatigue,

- Determine whether low-cycle fatigue loading causes leakage or sudden fracture, or in other words, whether the low-cycle fatigue loadings prevalent in piping systems produce short through-wall leakers or

long, shallow, part-through growing cracks which, in the presence of system pressure, reach a "critical" size.

2. TEST PROGRAM

2.1 PIPING COMPONENTS

Piping components investigated include

- Straight sections, 6-inch, Schedule-40, 80, -160,
- Elbows, 6-inch, Schedule-40
- Tees, 6-inch, Schedule-40

2.2 MATERIALS

Components are fabricated from

- Carbon Steel - ASTM A106 Grade B
- Low Alloy Steel - ASTM A335-P22 (2-1/4 CR-1 Mo)
- Type-304 Stainless Steel - ASTM A312

Chemical analyses of the three piping materials are given in Table 1. Mechanical properties are given in Table 2. Shown in Figures 1* through 6 are Charpy results for the carbon and low-alloy grades. Additional toughness data have been reported on the A106-B material in Quarterly No. 6. It is evident that the 2-1/2-CR-1 Mo grade was well above its transition temperature in room temperature (70 to 90°F) fatigue tests. Much of the plain carbon steel pipe, however, was fatigue tested right in the transition temperature region.

2.3 TEST SPECIMENS

The design drawings used for specimen manufacture are shown in Figures 7(a) and 7(b). Schematically, these are shown in Fig. 8, and are classified as:

- Straight, notched, or butt welded section
- Elbow (unnotched)
- Tee (unnotched)

All notched, straight-pipe specimens were fabricated with a machined notch having a theoretical elastic stress concentration factor² of 3.6. Butt-welded specimens were fabricated in two ways: as good quality, or as defective welds. Defective welds were produced by purposely causing a lack of fusion "crack" during an incomplete root filler pass. Elbows and tees were unflawed, with stress intensification resulting from the component natural geometry and manner of loading.

2.4 TESTING TEMPERATURE

Specimens were tested at room temperature and 550°F. Pipe and component heating was accomplished by specially designed internal pipe heaters. Uniform temperature was maintained in the test sections by appropriate thermocouple sensors and heater controllers.

2.5 TEST LOADING

All room-temperature specimens were hydraulically pressurized to 1050 psi. Cyclic bending stresses were superimposed to produce low-cycle fatigue. At 550°F, only cyclic bending was imposed.*

Elbow specimens were loaded in-plane and out-of-plane. Tee specimens were loaded in-plane, through the branch or through the run.

2.6 TESTING PROCEDURE

All specimens were cyclically loaded in a fully reversed mode to produce an initiating crack (cycles to initiation). The hydraulic loading ram was deflection controlled, with force continuously measured. Consequently, the imposed "strain controlled" loadings were similar to piping reaction forces imposed as a result of mutual piping restraint during normal plant startup, shutdown, or emergency reactor operating conditions.

Following crack initiation, fully reversed cycling was continued, to produce through-wall crack growth. After the crack penetrated the wall, loading was continued in a zero-to-tension mode, to produce "circumferential" crack growth. For the straight specimens tested at room temperature, an internal rubber boot was developed to prevent leakage even though the crack had grown through the metal pipe wall. Consequently, the condition of leakage without loss of system pressure, and of continued circumferential fatigue growth, has been successfully simulated in the laboratory.

* See Section 7, Illustrations, for all figures.

* Except in one case, HSNP-80-1, a stainless steel, straight, internally notched specimen was pressurized at 550°F. This test demonstrated leak before break at BWR operating conditions.

TABLE 1

CHEMICAL COMPOSITION (MILL ANALYSIS) OF MATERIALS TESTED

	Material	Schedule	C	MN	P	S	Si	Ni	Cr	Mo
φ	Carbon Steel	40	0.17	0.47	0.008	0.222	0.017			
	Carbon Steel	80	0.19	0.66	0.009	0.028	0.015			
	Carbon Steel	160	0.25	0.74	0.010	0.022	0.17			
	304 Stainless Steel	40	0.06	1.54	0.025	0.005	0.59	9.45	18.9	
	304 Stainless Steel	80	0.057	1.56	0.027	0.014	0.62	10.43	18.52	
	304 Stainless Steel	160	0.057	1.63	0.021	0.013	0.59	10.57	18.71	
	2-1/4Cr-1Mo Steel	40	0.10	0.44	0.013	0.016	0.29		2.23	1.01
	2-1/4Cr-1Mo Steel	80	0.10	0.46	0.012	0.018	0.22		2.29	1.0
	2-1/4Cr-1Mo Steel	160	0.09	0.44	0.012	0.012	0.31		2.25	1.01

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Table 2

TENSILE PROPERTIES OF TEST SPECIMEN MATERIALS*General Electric Check Tests***Room Temperature Tests**

Material	Pipe Schedule	Specimen Direction	Yield Strength (0.2% psi)	Ultimate Strength (psi)	Elongation (%)	Reduction in Area (%)
Carbon Steel A106, Gr.B	40	Longitudinal	41,200	61,100	37.0	70.5
		Transverse	43,800	62,600	30.4	65.5
	80	Longitudinal	39,600	65,400	34.0	67.6
		Transverse	45,200	66,500	27.4	59.2
Alloy Steel A335-P22	40	Longitudinal	34,260	68,860	24.6	74.7
	160	Longitudinal	39,025	74,250	32.3	75.9
Stainless Steel A312, Type 304	40	Longitudinal	33,100	91,680	43.8	83.6
	160	Longitudinal	37,200	89,800	72.1	80.1

550°F Tests

Carbon Steel A106, Gr.B	40	Longitudinal	31,850	72,900	30.9	60.8
Alloy Steel A335-P22	40	Longitudinal	35,000	61,350	26.8	71.8
Stainless Steel A312, Type 304	40	Longitudinal	27,050	66,800	46.8	77.1

Table 2A

*Vendor Certificate Test Data***Tensile Properties**

Material	Pipe Schedule	Yield Strength (psi)	Tensile Strength (psi)	Elongation (%)
Plain Carbon	40	45,500	62,600	37.5
Steel	80	43,700	66,200	39.0
A106,Gr.B	160	54,600	72,200	40.0
Low Alloy Steel	40	43,340	66,270	35.0
A355-P22	80	41,300	72,000	42.0
	160	40,760	70,930	42.0
Stainless Steel	40	34,990	82,640	69.0
A312, Type 304	80	45,740	84,970	64.0
	160	46,230	81,970	74.0

2.7 EQUIPMENT AND INSTRUMENTATION

2.7.1 Test Frame

Specimens were cyclically loaded in a testing frame designed to support 6-inch, 20-foot-long pipe sections. The test frame design is shown in Figure 9. The flanged ends of the specimens are bolted to the test frame at special flange connections for elbows, tees, or straight pipe sections. A stainless steel elbow being assembled is shown in Figure 10. The free end of the cantilever arm is connected to the hydraulic actuator (Figure 11).

2.7.2 Hydraulic Loading and Control System

The hydraulic loading system, comprising actuator ram, hydraulic pump, power supply, servo controller, and electronic controls, was manufactured by the Rhiele Testing Machine Division of Ametek, Inc. The maximum actuator load and stroke are 5000 pounds and ± 12 inches, respectively. The pump capacity is 16 gpm at 3000 psi hydraulic pressure. The actuator load and stroke are measured by internal load cell and LVDT-type transducers.

The control console includes appropriate signal conditioners, cycle counters, function generator, and actuator servo controller. The control console is shown in Figure 12. Loading can be controlled in either the load, position, or strain controlled mode. The loading control function may be sinusoidal, ramp, or square wave; however, for this study sinusoidal testing at 12 cpm was used.

2.7.3 Data Acquisition System

Transducer signals from the load cell, actuator position indicator, or specimen strain gages are conditioned and

recorded, using a Hewlett Packard DYMEC Data Acquisition System (Figure 13). Analog signals are converted to digital form, printed on paper tape, and stored on magnetic tape. Stored data is later used for input to the GE computer for calculating strain history, applied stress range, and stress intensity factors.

2.7.4 Heater Assembly

Special heater assembly designs were developed for 550°F temperature testing of straight pipe and elbow sections. The heater assembly consists of multiple calrods (banks) supported on rings shaped to fit concentrically within the test pipe. Heater controls are provided to power the top, middle, or lower portion of the calrod bundle individually in order to produce a uniform metal temperature over the test section length (approximately 3 feet). Thermocouples are positioned axially and circumferentially around the test section. Shown in Figure 14 are the heater assembly, controls, and temperature recorder. In some cases, external strap-on pipe heaters are used to balance heat loss to the support flange (Figure 15).

2.7.5 Flexible Boot Seal

To produce experimentally through-wall circumferential crack growth and still maintain internal pressure, a special flexible boot seal was needed; that is, a seal flexible with respect to bending restraint of the pipe section yet still able to prevent leakage. A schematic of the special boot seal design developed for this purpose is shown in Figure 16. The boot seal was installed on all room-temperature and straight pipe sections and, in general, performed very well.

3. TEST RESULTS

3.1 CRACK INITIATION

Experimental data for cycles to crack initiation at the base of the premachined notch were determined visually by using a 40X microscope (Figure 17). Crack initiation is defined as the appearance of a 0.005 to 0.010-inch crack. This microscope is equipped with a micrometer drive that allows for accurate surface crack length measurement while through-wall crack growth occurs.

Summarized in Table 3 are the significant test parameters and data obtained for specimens tested. Data obtained for crack initiation of notched prototype specimens at room temperature and 550°F are shown compared with data from notched round laboratory specimens^{3,4} of carbon steel, low alloy, and stainless steel in Figures 18

through 22. At room temperature—for carbon and alloy steels in the very low cycle range, less than 1000 cycles—data from the notched prototype piping shows higher cycles to initiate than the notched, round bar, laboratory specimens. However, the reverse is true for the Type-304 stainless steel. At 550°F, both the carbon steel and stainless steel piping show higher values for crack initiation than the notched round bars. Since the theoretical elastic stress concentrations of the notched round bars and notched piping were 3.3 and 3.6, respectively, the low-cycle fatigue strength reduction factors are not exactly equal. However, quantitative information can be obtained from the data comparison. Data obtained from butt welded, elbow, and tee specimens cannot be directly compared with the round bar data, and are given only for information.

TABLE 3
TEST PARAMETERS

Sample No.	Schedule	Stress Range	N_I	$N_W^{(a)}$	$N_\phi^{(b)}$
Room Temperature—Carbon Steel					
<u>NOTCHED PIPING</u>					
CSS-3	40	72,800	507	2,109 (578)	2 109
CSS-4	40	66,100	~1,300	8,572 (3,272)	28,096 (19,524)
CSS-5	40	52,800	9,600	13,398 (3,798)	17,186 (3,688)
CSS-6	40	77,000	517	1,759 (936)	2,304 (546)
CSS-7	80	73,200	550	2,289 (752)	2,784 (495)
CSS-8	80	48,800	7,500	14,526 (4,581)	14,526
CSS-9	80	45,000	17,700	34,811 (16,726)	34,811
CSS-10	80	40,200	9,000	16,005 (6,005)	16,005
CSS-11	160	89,000	260	1,660 (693)	1,660
CSS-13	160	64,000	1,050	17,400 (12,550)	36,009 (16,809)
CSS-107	80	74,100	200	4,575 (3,375)	14,205 (9,130)
CSS-109	80	72,300	600	6,000 (3,400)	16,850 (7,611)
<u>ELBOWS</u>					
CCLS-1	40	43,600	<900	1,176	8,000 (6,824)
CCLS-2	40	42,600	<3,249	7,899	13,599 (5,700)

(a) N_W = Total cycles when crack penetrated through wall (includes N_I) Number in parentheses is full amplitude cycles included in N_W N_I

(b) N_ϕ = Total cycles after circumferential crack has grown to length where test terminated (includes N_W and N_I) Number in parentheses is full amplitude cycles in N_ϕ N_W

TABLE 3 (Continued)

Sample No.	Schedule	Stress Range	N_I	N_W (a)	N_ϕ (b)
Room Temperature—Stainless Steel					
<u>NOTCHED PIPING</u>					
CSS-15	40	48,300	4,500	24,630 (15,627)	75,796 (51,166)
CSS-16	40	59,600	1,400	8,596 (7,196)	42,404 (33,908)
CSS-23	160	82,000	165-189	2,350 (1,558)	3,255 (905)
CSS-25	160	70,460	500	16,250 (11,383)	30,629 (14,379)
CSS-119	80	74,600	425	5,156 (4,231)	20,603 (15,047)
<u>ELBOWS</u>					
CSLS-1	40	44,200	<907	907	4,202 (3,295)
CSLS-2	40	42,200	<5,025	6,838	11,096 (4,258)
CSLS-3	40	44,200	<1,500	4,469	13,902 (9,433)
<u>TEE SPECIMENS</u>					
CSTS-1	40	68,700	<4,575	4,575	10,700 (6,125)
CSTS-2	40	67,800	<3,310	3,310	8,000 (4,690)
Room Temperature—Alloy Steel					
<u>NOTCHED PIPING</u>					
CSS-27	40	68,300	330	4,500 (1,170)	20,300 (15,800)
CSS-29	40	52,100	3,100	18,950 (8,850)	48,738 (29,788)
CSS-31	80	75,300	475	6,800 (4,325)	19,000 (9,100)
CSS-35	160	47,500	8,500-9,004	51,400 (31,409)	54,536 (2,636)
CSS-36	160	46,600	5,000-7,000	23,570 (13,070)	26,162 (2,593)
CSS-37	160	91,300	226	5,171 (2,139)	19,661 (4,951)

TABLE 3 (Continued)

Sample No.	Schedule	Stress Range	N_I	N_W (a)	N_ϕ (b)
550°F—Carbon Steel					
<u>NOTCHED PIPING</u>					
HCN-40-1	40	52,700	13,250	26,000 (6,748)	137,000 (109,000)
HCN-40-2	40	75,700	925	10,520 (5,595)	21,593 (11,073)
HCN-40-3	40	53,000	6,200	51,337 (39,037)	137,405 (85,068)
HCN-40-4	40	77,100	730	5,800 (3,070)	13,527 (6,727)
<u>PIPE BUTT WELDS</u>					
HW-1	40	58,200	25,000	36,240 (10,740)	38,500 (2,260)
HWD-1	40	59,200	<15,100	15,100 (13,600)	34,905 (19,305)
<u>ELBOWS</u>					
HCLS-1	40	43,500	<700	760	3,449 (2,689)
HCLS-2	40	43,100	<3,299	26,100	31,100 (5,000)
550°F—Stainless Steel					
<u>NOTCHED PIPING</u>					
HSN-40-S	40	57,200	730	8,702 (3,971)	41,304 (31,851)
HSN-40-1	40	58,400	800	5,250 (3,550)	20,500 (14,750)
HSNP-80-1	80	59,500	≈ 800	6,900 (4,100)	7,100 (200)

TABLE 3 (Continued)

Sample No.	Schedule	Stress Range	N_I	N_W (a)	N_ϕ (b)
PIPE BUTT WELDS					
HW-3	40	58,700	3,000-3,500		
HW-3A	40	61,100	5,725	7,950 (1,225)	9,800 (1,350)
HWD-3	40	59,900	2,049	3,600 (551)	9,700 (5,600)
ELBOWS					
HSL-1	40	28,000	<2,200	2,200	3,550 (1,350)
HSL-2	40	42,200	1,799	1,870 (71)	2,089 (219)

Prototype crack initiation data from the notched piping have been used to evaluate experimental results with predictions based on procedures of the Nuclear Power Piping Code¹. Prototype data are compared with the smooth-bar test data used to establish the B31.7 fatigue design curves. Detailed results are discussed in Section 5.

3.2 THROUGH-WALL CRACK GROWTH

Following crack initiation, fully reversed loading was continued as the crack grew through the pipe wall. Two methods were used to determine the rate of through-wall crack growth: macroscopic and microscopic. Both techniques require post-mortem investigation. Macroscopic crack growth was determined using the "stress reduction technique"; that is, the applied stress range was reduced to approximately 1/4 and cycling was continued. The applied stress was then increased, and the procedure was repeated. The result was visual striations, as shown in Figures 23 and 24. The determination of crack growth rate employed electron microfractographic techniques, which provide accurate, measured values of striation spacing. An electron micrograph is shown in Figure A-4 of the Appendix, along with a detailed description of a typical microfractographic investigation and results obtained. The resulting crack growth rate versus wall thickness is illustrated in Figure 25.

3.2.1 Data Correlation

The mechanism of crack growth under low-cycle fatigue leading has been studied^{5 6} in detail over the last

several years. This work has shown that the application of linear elastic fracture mechanics concepts to fatigue crack growth in low- and medium-strength steels can provide accurate and extremely useful data correlations. For example, it has been shown that the relationship of log crack growth rate and log stress intensity is essentially linear in the range of engineering interest; i.e., $10 < \Delta K < 120 \text{ ksi } \sqrt{\text{in}}$. Using the relationship below,

$$\frac{da}{dN} = A \Delta K^B \quad (1)$$

where

Log A = Intercept

B = Slope

a = Crack dimension

N = Cycles

ΔK = Range of stress intensity, $\text{ksi } \sqrt{\text{in}}$.

Shown in Figures 26 and 27 are prototype data obtained for through-wall crack growth correlated with the range of applied stress intensity. The stress intensity factor was calculated assuming the crack shape to be a semi-elliptic type flaw growing under a cyclic tensile stress.* A typical relation of the ratio of stress intensity to nominal tensile stress for Schedule-80 pipe is depicted in Figure 28.

*Nominal pipe bending stress.

In general, prototype data show that crack growth data obtained in the laboratory⁵ using centrally slotted wide plates will overestimate the actual growth. Although prototype calculations for ΔK are approximate, the use of laboratory data on simple specimens such as flat plates will predict the performance of real structures such as piping fabricated from similar material.

Another interesting feature of prototype through-wall crack growth relates to the character of the growth rate. For example, data shown in Figure 25 indicate an approximately linear through-wall crack growth rate until the crack has penetrated about 80 to 90% of the wall thickness. At that point, the growth rate becomes relatively rapid, and through-wall penetration takes place in a relatively few number of cycles. Consequently, for practical purposes it can be assumed that a crack which propagates to 80% of the wall thickness is essentially all the way through.

3.2.2 Cycles to Leakage

An important factor in design or safety analysis relates to prediction of cycles to leakage. Since the appropriate design codes relate only to crack initiation, effort to compute accurately cycles to grow through-wall depends on data determined experimentally such as already described and/or the application of analytical models such as shown in Equation (1). The technique to be used is dependent on knowing the A and B factors to be used for the material of interest, in addition to the proper analytical formulation of the stress intensity range, ΔK . For example, integration of Equation (1) yields

$$N = \int_{a_0}^t \frac{da}{A\Delta KB}$$

where N will be the number of cycles to grow a crack from the depth a_0 through the pipe wall (thickness t).

A computer program has been developed to compute the growth of a semi-elliptic flaw due to cyclic tension or tension plus bending, using the crack aspect ratios determined for the prototype piping and the materials data evaluated by Brothers.⁵ In this program will be the ability to compute circumferential crack growth as a function of cycles.

3.3 CIRCUMFERENTIAL CRACK GROWTH

After through-wall penetration occurred, cycling was continued to produce circumferential crack growth. To

preserve the fractographic record* of through-wall growth, a zero to tension loading mode was used. Since peak load was continuously monitored as a function of cycles, the applied bending movement was known and was used to compute nominal bending stress and/or applied stress intensity. Surface crack length was visually measured and recorded as the crack grew around or along the pipe component. Typical data for circumferential crack length as a function of applied stress cycles are shown in Figures 29 and 30. Since the pipe loading was strain limited (deflection controlled), crack growth typically increased with increased cycling and then "turned off". This was as expected, since the gross pipe compliance (reciprocal stiffness) increased rapidly with large crack lengths and the remaining pipe ligament was essentially strained elastically. Tests were terminated at this point. Shown in Figure 31 is the change in compliance of a cylindrical pipe with a through-wall circumferential crack, as crack arc length increases.

Data for crack length were used to generate an analytical curve using a computer program (Plot 4) written for this purpose. Growth rates were determined by computing the derivative analytically. The computed crack growth rate as a function of cycles is delineated in Figure 32.

As in the case of through-wall crack growth, data for circumferential growth was correlated with the range of applied stress intensity. Formulation of the stress intensity factor for a thin, circumferentially cracked cylindrical pipe shell was developed by Gilman:⁷

$$K_I = \sqrt{\pi a} \left[\frac{P_O a}{2t} f_1(\beta) + \frac{M_O}{\pi a^2 t} f_2(\beta) \right] \quad (2)$$

where

- a = Cylinder radius, inches
- t = Wall thickness, inches
- P_O = Internal pressure, psi
- M_O = Bending moment, in.-lb
- $f_1(\beta)$ = Functional shown in Figure 33
- $f_2(\beta)$ = Functional shown in Figure 33
- β = 1/2 crack arc length, deg

The range of applied stress intensity was calculated for the various prototype pipe specimens during the circumferential growth stage. Results are shown in Figures 34 through 36. Comparison of prototype results with those

* Severe surface scrubbing will result for fully reserved loading, and striation spacing will be lost.

obtained from laboratory tests of centrally slotted, wide, flat plates of similar materials is, in general, very good. The solid line shown is a least-square fit of the wide plate data. However, in most cases predictions using the wide plate data would give higher crack growth than measured for the prototype piping. This observation, which is consistent with that for through-wall growth, indicates that laboratory-type data would be conservative when applied to real piping situations.

3.4 STRESS INDICES

Elastic stress indices for elbow and tee specimens were determined at several locations using strain gage rosettes. Elbow components were loaded in-plane and out-of-plane, while tees were loaded in-plane through the branch and run. The stress index is defined as the ratio σ/S

(σ = local stress, S = nominal bending stress), at a point, resulting from an applied bending moment. See Figures 37 through 39A for several examples of stress indices.

3.5 STRAIN HISTORY

Cyclic strain history, in the vicinity of the pre-machined notch, was determined for several specimens tested. Indicated in Figures 40 and 41 are the strain gage locations for both the outside and inside notched specimens, respectively. Shown in Figures 42 and 43 is the strain history at these locations as cycling continues. Note that prior to failure, the strain rises sharply under the notch (locations 8 and 12), and yet drops off at locations 9 and 4. This can be explained by the fact that the ligament area is decreasing faster than the load transferred through the ligament.

4. ANALYSIS OF PROTOTYPE PIPING COMPONENTS

Stress analysis of the prototype piping components was made, utilizing the procedures in the ASME Nuclear Power Piping Code B31.7. Specifically, this included evaluation of the primary plus secondary stress, and peak stress intensity range. In most cases, the applied bending stress range used in fatigue testing was such that the 3Sm code limit on secondary stress was exceeded. In that case, the simplified code elastic-plastic⁸ analysis was used to compute the overall fatigue strength reduction factor, and the number of cycles to crack initiation. In most cases, the cycles of applied stress range greater than 3Sm exceeded the 250-cycle code allowable. In all cases, however, the alternating stress intensity was calculated as follows:

$$S_{alt} = 1/2 K_f K_\epsilon S_n$$

S_n = Nominal elastic stress intensity range calculated from measured applied load range* and appropriate stress index (1-705 B31.7)

K_f = Overall fatigue strength reduction factor, $K_f = K_t + A(K_t - 1)$

A = Material property, given in Appendix D, B31.7

K_t = Effective elastic stress concentration factor

K_ϵ = Plastic stress concentration factor, Fg. F-105 (a) B31.7

S_{alt} = Equivalent elastic stress amplitude

Listed in Table 4 is the detailed fatigue evaluation of each prototype component tested. Shown in Figure 44 are the computed stress and measured cycles to initiation as data points for the appropriate material and test temperature. The *solid lines* are the fatigue curves obtained from the *smooth-bar* used to establish the design* curves in ASME B31.7 and ASME Section III.⁹ The *dotted lines* are the ASME fatigue *design* curves. The prototype data are shown compared with the smooth-bar data so that the actual safety factor for crack initiation inherent in the procedures of B31.7 can be assessed. For example, if the prototype data fell on or above the *smooth-bar data* curve, it could be concluded that the full safety factor (20 on cycles) or more was achieved. If the prototype data points fell on or below the *design* curve, then it would be concluded that the code safety factor was insufficient to prevent crack initiation.

* For the prototype tests, the pressure stress range is zero.

* The code design curves are constructed using a safety factor of 20 on cycles in the very low cycle range.

TABLE 4
ANALYSIS OF PIPE FATIGUE DATA

NOTCHED PIPING—ROOM TEMPERATURE

	TEMPERATURE	NOTCH	NOMINAL ^(b) STRESS RANGE (ksi- σ_0)	S_m (ksi)	$3S_m$ (ksi)	$S_n = C_2\sigma_0$ (ksi)	$S_p = K_2S_n$ (ksi)	$\frac{S_n}{3S_m}$	A	K_f	K_c	S_{alt} (ksi)	PROTOTYPE TEST CYCLES N_I
CARBON STEEL													
CSS-3, Schedule 40	RT ^(e)	I ^(a)	72.8	20	60	72.8	262	1.21	0.82	5.7	1.21	250	507
CSS-4, Schedule 40	RT	II	66.1	20	60	66.1	240	1.1	0.70	5.4	1.1	193	$\cong 1,300$
CSS-5, Schedule 40	RT	I	52.8	20	60	52.8	191	—	—	3.6	—	95	9,600
CSS-6, Schedule 40	RT	II	77.0	20	60	77.0	277	1.29	0.83	5.7	1.29	255	$\cong 517$
CSS-7, Schedule 80	RT	I	73.2	20	60	73.2	264	1.21	0.82	5.7	1.21	252	550
CSS-8, Schedule 80	RT	II	48.8	20	60	48.8	173	—	—	3.6	—	88	$\cong 7,500$
CSS-9, Schedule 80	RT	I	45.0	20	60	45.0	156	—	—	3.6	—	81	17,700
CSS-10, Schedule 80	RT	II	40.2	20	60	40.2	143	—	—	3.6	—	72.5	$\cong 9,000$
CSS-11, Schedule 160	RT	I	89.0	20	60	89.0	321	1.5	0.95	6.1	1.5	408	260
CSS-13, Schedule 160	RT	I	64.0	20	60	64.0	230	1.03	0.65	5.3	1.03	175	1,050
CSS-107, Schedule 80	RT	I	74.1	20	60	74.1	270	1.24	0.82	5.7	1.24	262	200
CSS-109, Schedule 80	RT	I	72.3	20	60	72.3	260	1.2	0.182	5.7	1.2	248	600
STAINLESS STEEL													
CSS-23, Schedule 160	RT	I	82	20	60	82	295	1.37	0.7	5.4	1.37	305	175
CSS-15, Schedule 40	RT	I	48.3	20	60	48.3	174	—	—	3.6	—	487	4,500
CSS-16, Schedule 40	RT	II	60.0	20	60	60.0	216	1.0	0.7	5.4	—	162	1,400
CSS-25, Schedule 160	RT	I	70.5	20	60	70.5	254	1.17	0.7	5.4	1.17	223	500
CSS-119, Schedule 80	RT	I	74.6	20	60	74.6	269	1.24	0.7	5.4	1.24	250	425
ALLOY STEEL													
CSS-31, Schedule 80	RT	I	75.3	20	60	75.3	271	1.25	1.7	8.0	1.25	376	475
CSS-27, Schedule 40	RT	I	68.3	20	60	68.3	246	1.14	1.4	7.2	1.14	280	330
CSS-29, Schedule 40	RT	I	52.1	20	60	52.1	188	—	—	3.6	—	94	3,100
CSS-35, Schedule 160	RT	I	47.5	20	60	47.5	171	—	—	3.6	—	85.5	8,550
CSS-36, Schedule 160	RT	II	46.6	20	60	46.6	166	—	—	3.6	—	84.0	$\cong 6,000$
CSS-37, Schedule 160	RT	I	91.3	20	60	91.3	329	1.52	2.4	9.8	1.52	680.0	226

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TABLE 4 (Continued)

NOTCHED PIPING—550°F

	TEMPERATURE	NOTCH	NOMINAL STRESS RANGE								PROTOTYPE		
			(ksi- σ_0)	S _m (ksi)	3S _m (ksi)	S _n = C ₂ σ_0 (ksi)	S _p = K ₂ S _n (ksi)	$\frac{S_n}{3S_m}$	A	K _f	K _E	S _{alt} (ksi)	TEST CYCLES
													N _I
CARBON STEEL													
HCN-1, Schedule 40	550°F	I	52.7	18	54	52.7	190	—	—	3.6	—	95	13,250
HCN-2, Schedule 40	550°F	I	75.7	18	54	75.7	273	1.4	1.0	6.2	1.4	330	925
HCN-3, Schedule 40	550°F	I	53.0	18	54	53.0	191	—	—	3.6	—	96	6,200
HCN-4, Schedule 40	550°F	I	77.1	18	54	77.1	278	1.43	1.0	6.2	1.43	340	730
STAINLESS STEEL													
HSN (sensitized) Schedule 40	550°F	I	57.2	16	48	57.2	206	1.19	0.7	5.4	1.19	184	730
HSN-1, Schedule 40	550°F	I	58.4	16	48	58.4	210	1.21	0.7	5.4	1.21	191	800
HSNP-1 (pressurized),* Schedule 80	550°F	II	59.5	16	48	59.5	214	1.24	0.7	5.4	1.24	200	≅800

* 1000 psi with demineralized water.

TABLE 4 (Continued)

ELBOWS AND TEES

	MATERIAL	TEMPERATURE	LOADING TYPE (c)	NOMINAL BEND STRESS RANGE (ksi)	C ₂ INDEX (d)	S _n (ksi)	3S _m (ksi)	Sp = K ₂ S _n (ksi)	S _n 3S _m	A	K _f	K _E	S _{alt} (ksi)	TEST ≈NI (N _w)
ELBOWS														
CCLS-1, Schedule 40	Carbon Steel	RT	IP	43.6	5.35	233	60	233	3.9	1.8	1.0	3.9	455	< 900
CCLS-2, Schedule 40	Carbon Steel	RT	OP	42.6	5.35	228	60	228	3.8	1.75	1.0	3.8	433	< 3,249
CSLS-1, Schedule 40	Stainless Steel	RT	IP	44.2	5.35 ^(d)	236	60	236	3.94	0.7	1.0	3.94	465	< 907
CSLS-2, Schedule 40	Stainless Steel	RT	OP	42.2	5.35 ^(d)	236	60	236	3.94	0.7	1.0	3.94	465	< 5,025
CSLS-3, Schedule 40	Stainless Steel	RT	IP	44.2	4.2	185	60	185	3.08	0.7	1.0	3.08	284	< 4,469 (1,500 wt)
HCLS-1, Schedule 40	Carbon Steel	550°F	IP	43.5	5.35	233	54	233	4.31	2.0	1.0	4.31	502	< 760
HCLS-2, Schedule 40	Carbon Steel	550°F	OP	43.1	5.35 ^(d)	231	54	231	4.28	1.9	1.0	4.28	496	< 3,299
HSLS-1, Schedule 40	Stainless Steel	550°F	IP	28.0	5.35	150	48	150	3.13	0.7	1.0	3.13	235	< 2,200
HSLS-2, Schedule 40	Stainless Steel	550°F	OP	42.2	5.35 ^(d)	226	48	226	4.71	0.7	1.0	4.71	532	< 1,799
TEES														
CSTS-1, Schedule 40	Stainless Steel	RT	IP-Branch	68.7	3.35	230	60	230	3.84	0.7	1.0	3.84	443	< 4,575
CSTS-2, Schedule 40	Stainless Steel	RT	IP-Run	67.8	3.35	226	60	226	3.77	0.7	1.0	3.77	427	< 3,310

- (a) I = Outside Notch
 II = Inside Notch
- (b) MC = Stress, Measured Load
 I
- (c) IP = In Plane
 OP = Out of Plane
- (d) C₂ = for In-Plane used
- (e) RT = Room Temperature

5. DISCUSSION

5.1 COMPARISON OF B31.7 PREDICTIONS AND PROTOTYPE DATA

From Figure 44 it can be seen that in all cases using the computed alternating stress intensity range per B31.7 and the measured cycles to crack initiation, the prototype data points fall on or below the smooth-bar data curve and above the design curve. This implies several things. For example, it might be rationalized that the overall fatigue strength reduction factor computed by code procedures tended to underestimate the true fatigue strength reduction factor. It could also be contended that the measurement of crack initiation of 0.005 to 0.010 inch was too fine in comparison to piping notch dimensions. However, it must be emphasized that the design stress values are based on applying a safety factor of 20 on cycles or 2 on stress, whichever is more conservative, to the best fit data obtained from the smooth-bar tests. These factors are intended to cover the effects of data scatter, size, environment, surface finish, etc. It is not expected that actual prototype structures will operate with the same safety factor used to construct the design curve. What is important, however, is that the design procedures produce conservative results when applied to real structures.

Estimates of the actual design safety factors were determined for the notched prototype structural tests. This safety factor is defined as the ratio of test cycles and predicted B31.7 (1969 Edition) design cycles. Results are shown in Table 5 for notched piping. Since crack initiation could not be accurately measured for the unnotched elbow and tee specimens, through-wall cycle data would yield fictitiously high safety factors and therefore are not reported.

5.2 LEAKAGE OR SUDDEN FRACTURE

Assessment of the true limiting operational lifetime of piping under low-cycle fatigue loading requires the answers to the following questions.

- After crack initiation, at what rate does the crack grow as a function of applied cyclic stress?
- Will the growing crack penetrate the wall and cause leakage, or will sudden fracture occur? This can be rephrased another way: Will the low-cycle fatigue loading, if continued after crack initiation, produce long, part-through-wall growing cracks which, under system pressure, will become critical and result in a sudden, brittle type of fracture?

TABLE 5
ACTUAL DESIGN SAFETY FACTOR—
NOTCHED PROTOTYPE PIPING

Specimen	Material	Test Temperature	Design Safety* Factor
CSS-3	Carbon Steel	Room Temperature	9.1
CSS-4			13.0
CSS-5			15.2
CSS-6			9.9
CSS-7			10.2
CSS-8			9.4
CSS-9			17.7
CSS-10			6.7
CSS-11			13.7
CSS-13			7.8
CSS-107	Stainless Steel	Room Temperature	4.2
CSS-109			10.0
CSS-23			3.8
CSS-15			2.0
CSS-16			5.2
CSS-25	Alloy Steel	Room Temperature	5.0
CSS-119			5.3
CSS-31			20.6
CSS-27			7.5
CSS-29			4.7
CSS-35			11.0
CSS-36			6.7
CSS-37			37.7
HCN-40-1	Carbon Steel	550°F	21.0
HCN-40-2			28.0
HCN-40-3			10.0
HCN-40-4			26.1
HSN-40-S	Stainless Steel	550°F	4.1
HSN-40-1			5.0
HSNP-80-1			5.5

* Cycles experimentally determined for crack initiation divided by "design" cycles per 331.7.

5.2.1 Notched Piping

To determine whether sudden fracture would occur prior to, at, or subsequent to, leakage, all notched piping specimens tested at room temperature were fitted with a flexible boot as described in Subsection 2.6. As a result, leakage was prevented when a crack penetrated the pipe wall, and subsequently, internal pressure was maintained as circumferential crack growth continued. The latter situation simulates pipe leakage in a very large volume, pneumatically loaded system; i.e., pressure maintained while leakage occurs.

All notched piping tested at 1050 psi internal pressure, and subjected to continued low-cycle fatigue after crack initiation, leaked. *No sudden fractures occurred.* Listed in Table 6, for the straight pipe specimens, is the maximum calculated applied stress intensity and the maximum circumferential crack length (percent of pipe circumference) obtained under BWR system operating pressure. The maximum calculated stress intensity is based on a circumferential crack length when the total included crack angle reached 120 degrees (1/3 circumference). This is caused by analytical limitations of the stress intensity formulation. Several test specimens at the completion of testing are shown in Figures 45 through 48. Based on this information, it is possible to state that a critical crack condition was not achieved, even though circumferential cracking was extremely large.

5.2.2 Elbows and Tees

Elbow and tee specimens tested at 1050 psi internal pressure and subjected to low-cycle fatigue, leaked. *No sudden fractures occurred.* Since internal boots were not

installed in elbow and tee specimens, internal pressure was lost when leakage occurred. Displayed in Figures 48 through 53 are several elbow and tee components, initially and at the completion of testing.

It is in order to restate that *all components* tested at 1050 psi and subjected to continued low-cycle fatigue loading after crack initiation, *leaked*.

5.2.3 Data for Sensitized Type-304 Stainless Steel

Data for crack initiation and through-wall crack growth at 550°F in air have been obtained for a fully sensitized* Type-304 stainless steel notched pipe. These data are shown below, compared with similar data obtained on a near-identical, nonsensitized pipe specimen.

Material	Specimen	Cycles to Crack Initiation	Average Through-Wall Growth Rate (μin./cycle)
Sensitized*	HSN 40-S	730	60
Annealed	HSN 40-1	800	66

* 1140°F for 24 hours and air cool.

Based on the limited information shown, it appears that the sensitization has not affected the notched fatigue strength of the component.

6. CONCLUSIONS

As a result of the work described herein, the following important conclusions have been reached.

- Predictions of low-cycle fatigue behavior for crack initiation and crack growth of piping components can be made realistically by using data obtained from round-bar and flat-plate laboratory specimens.
- Design of piping components, based on smooth laboratory specimen fatigue data and fatigue strength reduction factors evaluated by the procedures specified in B31.7, will be conservative with respect to crack initiation.
- For straight piping sections, extremely large (>60% of pipe circumference) circumferential cracks have

been produced in the laboratory at BWR operating pressure and no sudden fracture occurred.

- The results of the prototype fatigue test program show that continued low-cycle fatigue* of piping and components will produce cracks which ultimately tend to leak. Consequently, with reliable leak detection systems, nuclear power plant piping system reliability should be excellent.

The low cycle fatigue loadings considered herein are those due to gross reaction forces and movements imposed on piping components as a result of system restraints during startup, shutdown, and emergency operations.

TABLE 6
SUMMARY OF CIRCUMFERENTIAL CRACK LENGTH
AND MAXIMUM CALCULATED STRESS INTENSITIES FOR NOTCHED PIPING

Specimen	Material	N_w	$N_\phi^{(1)}$	$N_\phi^{(2)}$	Total Crack Length $L^{(1)}$ $L^{(2)}$		Percent Circumference %C ⁽¹⁾ %C ⁽²⁾		ΔK_{120}^* (ksi $\sqrt{\text{in.}}$)
CSS-7	Carbon Steel	2,289	—	2,784	—	10.1	—	47	90
CSS-5	Carbon Steel	13,398	—	17,186	—	16.3	—	78	110
CSS-13	Carbon Steel	17,300	33,775	36,009	13.88	15.47	66.7	74.4	133
CSS-4	Carbon Steel	8,572	23,650	28,096	12.27	15.25	58.9	73.3	134.1
CSS-6	Carbon Steel	1,759	1,759	2,304	—	15.17	—	75.4	213.3
CSS-107	Carbon Steel	4,575	11,020	14,205	10.54	17.30	50.7	83.1	152.6
CSS-109	Carbon Steel	6,000	10,650	16,850	8.74	16.85	42.0	81.0	141.9
CSS-23	304 Stainless Steel	2,350	2,959	3,255	3.4	15.0	16	71	150
CSS-15	304 Stainless Steel	24,630	60,214	75,795	7.06	15.75	34	75.7	138
CSS-16	304 Stainless Steel	8,596	23,161	42,404	4.36	16.34	21	78.6	116
CSS-25	304 Stainless Steel	16,250	29,635	30,629	13.80	14.565	66.4	70	131
CSS-119	304 Stainless Steel	5,156	13,974	20,603	10.76	16.97	51.7	81.85	159.4
CSS-27	Alloy	4,500	17,700	20,304	7.80	15.880	37.5	76.4	170
CSS-29	Alloy	18,950	—	48,738	—	15.840	—	76.2	112
CSS-37	Alloy	5,170	—	10,661	—	10.830	—	52.1	160
CSS-36	Alloy	23,570	25,885	26,162	12.82	13.97	61.7	67.1	—
CSS-31	Alloy	6,800	14,530	19,000	10.33	17.14	49.6	82.4	169.6

* ΔK_{120} = Calculated stress intensity range when the total included crack angle reached 120 degrees (1/3 circumference).

N_w = Total cycles at through-wall completion.

$N_\phi^{(1)}$ = Total cycles at time internal pressure lost because of internal bolt failure

$N_\phi^{(2)}$ = Total cycles at end of test

$L^{(1)}$ = Total circumferential crack length at $N_\phi^{(1)}$.

$L^{(2)}$ = Total circumferential crack length at $N_\phi^{(2)}$.

7. ILLUSTRATIONS

This section contains the following illustrations.

Figure 1. Charpy Results for 2-1/4 Cr–1 Mo Alloy Steel, Schedule 40 Pipe, Longitudinal Specimens

Figure 2. Charpy Results for 2-1/4 Cr–1 Mo Alloy Steel, Schedule 160 Pipe, Longitudinal Specimens

Figure 3. Charpy Results for Plain Steel, Schedule 80 Pipe A106-B, Circumferential Specimens

Figure 4. Charpy Results for Plain Carbon Steel, Schedule 40 Pipe A106-B, Circumferential Specimens

Figure 5. Charpy Results for Plain Carbon Steel, Schedule 80 Pipe A106-B, Circumferential Specimens

Figure 6. Charpy Results for Plain Carbon Steel, Schedule 40, A106B, Longitudinal Specimens

Figure 7(a). Prototype Fatigue Test Specimen (Sheet 1)

Figure 7(b). Prototype Fatigue Test Specimen (Sheet 2)

Figure 8. Schematic Test Specimens

Figure 9. Test Bed Details

Figure 10. Mounting an Elbow Specimen in Test Frame

Figure 11. Test Specimen Connected to Actuator

Figure 12. Hydraulic Control Console

Figure 13. Data Acquisition System

Figure 14. Heater Calrod Assembly and Control Console

Figure 15. Test Setup—550°F

Figure 16. Schematic of Boot Seal

Figure 17. Surface Crack Detection

Figure 18. Cycles for Crack Initiation for Carbon Steel, Room Temperature

Figure 19. Cycles for Crack Initiation for Stainless Steel, Room Temperature

Figure 20. Cycles for Crack Initiation for 2-1/4 Cr–1 Mo Alloy Steel, Room Temperature

Figure 21. Cycles for Crack Initiation for Carbon Steel, 550°F

Figure 22. Cycles for Crack Initiation for Stainless Steel, 550°F

- Figure 23. Through-Wall Fracture Surface, Stainless Steel, Room Temperature (CSS-25)
- Figure 24. Through-Wall Fracture Surface, Carbon Steel, Room Temperature (CSS-13)
- Figure 25. Through-Wall Crack Growth
- Figure 26. Through-Wall Crack Growth Rate versus ΔK , Stainless Steel, Room Temperature
- Figure 27. Through-Wall Crack Growth Rate, da/dN versus ΔK , Stainless Steel, 550° F
- Figure 28. Stress Intensity Ratio—Semi-Elliptical Surface Crack
- Figure 29. Circumferential Crack Growth versus Cycles
- Figure 30. Circumferential Crack Growth versus Cycles
- Figure 31. Compliance Change, Cracked Pipe
- Figure 32. Circumferential Crack Growth Rate versus Cycles
- Figure 33. Stress Intensity Factor (K) for Cracked, Thin, Cylindrical Shell
- Figure 34. Circumferential Crack Growth Rate versus Stress Intensity Range, Carbon Steel, Room Temperature
- Figure 35. Crack Growth Rate versus Stress Intensity Range, Type-304 Stainless Steel, Room Temperature
- Figure 36. Circumferential Crack Growth Rate versus Stress Intensity Range, Carbon Steel, Room Temperature
- Figure 37. Stress Indices, Elbow In-Plane Bending
- Figure 38. Stress Indices, Elbow Out-of-Plane Bending
- Figure 39. Stress Index, Tee In-Plane Bending through Branch
- Figure 39A. Stress Indices for In-Plane Bending, Loaded through the Run, and Pressure for a 6-inch, Schedule-40 Stainless Steel Tee
- Figure 40. Strain Gage Locations with External Defect
- Figure 41. Strain Gage Locations with Internal Defect
- Figure 42. Strain History, External Notch
- Figure 43. Measured Strain Range versus Fatigue Cycles (CSS-16)
- Figure 44. Alternating Stress Intensity versus Cycles to Initiation. Comparison Pipe Fatigue Data and ASME B31.7
- Figure 45. Final Fracture, Carbon Steel, Room Temperature (CSS-13)
- Figure 46. Final Fracture, Stainless Steel, Room Temperature (CSS-25)
- Figure 47. Final Fracture, Stainless Steel, 550° F (HSN-40-1)

Figure 48. Elbow—Initial Setup

Figure 49. Elbow—In-Plane Completion of Test

Figure 50. Elbow—Out-of-Plane Completion of Test

Figure 51. Tee, Loaded In-Plane (Branch), Initial Setup

Figure 52. Tee, Loaded In-Plane (Branch), at Completion of Test

Figure 53. Tee, Loaded In-Plane (Run), at Completion of Test

1

2

3

4

5

6

Figure 1. Charpy Results for 2-1/4 Cr-1 Mo Alloy Steel, Schedule 40 Pipe, Longitudinal Specimens

Figure 2. Charpy Results for 2-1/4 Cr-1 Mo Alloy Steel, Schedule 160 Pipe, Longitudinal Specimens

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Figure 3. Charpy Results for Plain Carbon Steel, Schedule 80 Pipe A106-B, Circumferential Specimens

Figure 4. Charpy Results for Plain Carbon Steel, Schedule 40 Pipe A 106-B, Circumferential Specimens

Figure 5 Charpy Results for Plain Carbon Steel, Schedule 80 Pipe A106-B, Circumferential Specimen

Figure 6. Charpy Results for Plain Carbon Steel, Schedule 40, A106-B, Longitudinal Specimens

APPLIED PRACTICES 1. E. C. A. S.		UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING SURFACES 500		GENERAL ELECTRIC 719 E 449 PROTOTYPE FATIGUE TEST SPECIMEN					
MAT SPEC		DESCRIPTION		SCH 40		SCH 80		SCH 160	
				QUAN REQ.		QUAN REQ.		QUAN REQ.	
				PTNO	G1 G2 G3 G4	PTNO	G1 G5 G6 G7	PTNO	G1 G8 G9 G10
CARBON STEEL ASTM A 234-WPB	TEE STRAIGHT SMLS 6	1			13			22	
CARBON STEEL ASTM A 234-WPB	ELBOW LONG R 90° SMLS 6	2			14			23	
CARBON STEEL ASTM A 105 GR II	ORF FLG 1500 LB WELD NECK 6	3	1	2	3	2		3	
CARBON STEEL ASTM A 212 GR B	PLATE	4		2	4	2		4	
CARBON STEEL ASTM A 234 WPB	ELBOW SHORT R 90° SMLS 6	5			5			5	
CARBON STEEL ASTM A 234-WPB	CAP SEAMLESS	6	1	1	15	1		24	
CARBON STEEL ASTM A 106 GR B	PIPE 6	7		2	16	2		25	
	PIPE	8	1		17	1		26	
	PIPE	9			18			27	
	PIPE (50 LENGTH)	10			19			28	
	PIPE (50 LENGTH)	11	1	1	20	1		29	
CARBON STEEL ASTM A 106 GR B	PIPE 6	12			21			30	
		PTNO	G11 G12 G13 G14	PTNO	G11 G15 G16 G17	PTNO	G11 G18 G19 G20		
STAINLESS STEEL ASTM A 182 F 304	TEE, STRAIGHT SMLS 6	31			43			52	
STAINLESS STEEL ASTM A 182 F 304	ELBOW LONG R 90° SMLS 6	32			44			53	
CARBON STEEL ASTM A 105 GR II	ORF FLG 1500 LB WELD NECK 6	33	1	2	33	2		33	
CARBON STEEL ASTM A 212 GR B	PLATE	34		2	34	2		34	
STAINLESS STEEL ASTM A 182 F 304	ELBOW SHORT R 90° SMLS 6	35			35			35	
CARBON STEEL ASTM A 234-WPB	CAP SEAMLESS	36	1	1	45	1		54	
STAINLESS STEEL ASTM A 312 TP304	PIPE 6	37		2	46	2		55	
	PIPE	38	1	1	47	1		56	
CARBON STEEL ASTM A 106 GR B	PIPE	39			48			57	
STAINLESS STEEL ASTM A 312 TP304	PIPE (50 LENGTH)	40			49			58	
CARBON STEEL ASTM A 106 GR B	PIPE (150 LENGTH)	41	1	1	50	1			
STAINLESS STEEL ASTM A 312 TP304	PIPE (150 LENGTH)							59	
STAINLESS STEEL ASTM A 312 TP304	PIPE 6	42							
		PTNO	G21 G22 G23 G24	PTNO	G21 G25 G26 G27	PTNO	G21 G28 G29 G30		
ALLOY STEEL ASTM A 182 F 22	TEE STRAIGHT SMLS 6	61			73			82	
ALLOY STEEL ASTM A 182 F 22	ELBOW LONG R 90° SMLS 6	62			74			83	
CARBON STEEL ASTM A 105 GR II	ORF FLG 1500 LB WELD NECK 6	63			63			63	
CARBON STEEL ASTM A 212 GR B	PLATE	64			64			64	
CARBON STEEL ASTM A 234-WPB	CAP SEAMLESS	66			75			84	
ALLOY STEEL ASTM A 335-P22	PIPE 6	67			76			85	
	PIPE	68			77			86	
	PIPE	69			78			87	
	PIPE (50 LENGTH)	70			79			88	
CARBON STEEL ASTM A 106 GR B	PIPE (150 LENGTH)	71			80				
ALLOY STEEL ASTM A 335-P22	PIPE (50 LENGTH)							89	
ALLOY STEEL ASTM A 335-P22	PIPE 6	72			81			90	

REVISIONS

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BY

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SKETCH

-30a-/-30b-

PROTOTYPE PIPE FATIGUE SPECIMENS

NOTCHED AND BUTT WELDED

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GEAP-10135

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4

4

4

4

4

Figure 43. Measured Strain Range
versus Fatigue Cycles
(CSS-16)

1

2

3

4

5

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1

2

3

4

5

APPENDIX

DETERMINATION OF CRACK GROWTH RATES BY
ELECTRON MICROFRACTOGRAPHY

by

U. E. Wolff

A.1 SUMMARY

Detailed electron microfractography has been performed on six pipe fatigue fractures. From the experimental data analytical expressions were derived for each pipe permitting the calculation of any desired crack front location. Comparison of electron microscopic results with the location of macroscopic crack fronts (produced by half-amplitude cycles) showed excellent agreement. A common feature of all curves of crack propagation rate versus crack depth was an abrupt upturn of the rate in the last 10% to 20% of the wall thickness.

A.2 INTRODUCTION

Detailed electron microfractography has been performed on six pipe fatigue fractures. This investigative method has been successful in determining crack propagation rates as a function of crack depth in pipes of different thickness and material, tested with different crack propagation directions and stress ranges. The pertinent data for the six pipes are given in Table A-1.

The purpose of this section is to describe the analytical procedure and to point out the type of results obtainable. Individual results are described at the end of this section. Computations using these results are reported elsewhere.

A.3 EXPERIMENTAL PROCEDURE

After photographing the fracture (Figure A-1) and measuring its dimensions

with a 7× graduated magnifier, a cellulose acetate replica is made of the entire through-wall part of the fracture. The replica is shadowed with chromium in the direction of crack propagation. A thin layer of carbon is then deposited by vacuum evaporation at normal incidence. A strip of about 2 mm width is cut out of the composite replica, including the total width of the fracture at the place of maximum notch depth (i. e., maximum crack propagation rate). This strip is cut into squares, as marked in Figure A-1, with care being taken to preserve the identity and orientation of each square. Depending on the pipe thickness four to nine squares have been required to cover the whole fracture width.

Each square is carefully placed on a special lettered copper grid (Figure A-2a) which serves as the support for the final replica. The cellulose acetate is dissolved in acetone, leaving the Cr-shadowed C replica firmly attached to the grid (Figure A-2b). The outline of each replica on its grid is now accurately marked, by observation in a stereomicroscope, on a 50× image of the grid. This is necessary for subsequent matching of electron micrographs with positions on the fracture.

Each replica is scanned in the electron microscope, and negatives are taken of as many groups of representative striations as is practicable. Magnifications are chosen so that a convenient number of striations is present on each negative. Since each hexagonal grid opening is uniquely identified by a letter which can be recognized in the electron microscope, the position of each pictured area on the grid

30X

FIGURE A-1 FATIGUE FRACTURE OF CSS 25 WITH THREE HALF AMPLITUDE BANDS LOCATION OF THE REPLICAS IS MARKED

FIGURE A-2 SPECIAL LETTERED GRID ~ 40X

TABLE A-1

TEST DATA ON PIPES INVESTIGATED BY
ELECTRON MICROFRACTOGRAPHY*

Specimen No.	Material	Notch	Wall Thickness at Notch (mm)	Maximum Notch Depth (mm)	Remaining Wall Thickness (mm)
CSS-36	2 $\frac{1}{4}$ Cr-1 Mo steel	Internal	18.0	3.0	15.0
CSS-15	Type 304 stainless steel	External			5.7
CSS-16	Type 304 stainless steel	Internal	7.4	0.9	6.5
CSS-10	Carbon steel	Internal	10.8	1.8	9.0
CSS-25	Type 304 stainless steel	External	18.0	3.0	15.0
CSS-35	2 $\frac{1}{4}$ Cr-1 Mo steel	External	17.5	2.8	14.7

*Further details can be found in Table 6-4, GEAP-5554, "Reactor Primary Coolant System Rupture Study," Quarterly Progress Report No. 10, July-September 1967.

can be entered accurately on the 50 $\times$ grid image already containing the replica outline.

$$\frac{da}{dN} = A_i (a - a_0) + B_i \quad (A-1)$$

Average striation spacings are measured on enlarged prints of each negative, and the distance from the notch root of the area shown in each print is measured on the 50 $\times$ magnified grid image marked during electron microscopy. The measured striation spacings divided by the total magnification are plotted against the measured distances from the notch root (Figure A-3).

$$(a_{i-1} - a_0) \quad (a - a_0) \quad (a_i - a_0)$$

$i = 1, 2, \dots, n$

with n being the number of straight-line sections of the plot.

This equation can easily be transformed into one relating the crack propagation rate to the relative crack depth a/t (with t = the pipe wall thickness).

A.4 EVALUATION OF RESULTS

A certain amount of judgment is required to evaluate and reduce the raw data. The individual data points show considerable scatter, and to obtain an analytical expression for the crack propagation rate, straight line sections are fitted to the data by least square calculations.

$$\frac{da}{dN} = A'_i \frac{a}{t} + B'_i \quad (A-2)$$

As an example, experimental results and data reduction for pipe fracture CSS-25 are presented in detail.

Since each striation corresponds to one load cycle the striation spacing y is the crack propagation rate da/dN (with a = the distance of the crack front from the surface of the pipe at cycle number N). This quantity is plotted against $x = a - a_0$ (with a_0 = the depth of the starter notch). The general equation for the stress propagation rate is then:

Pipe CSS-25 was a Schedule 160 pipe of Type 304 stainless steel. The wall thickness measured at the notch was $t = 18.0$ mm. The external notch had a maximum depth of $a_0 = 3.0$ mm = $0.167t$. Three times during the fatigue testing a group of half-amplitude cycles was run; the cyclic sequences were as shown in Table A-2.

FIGURE A-3 CRACK PROPAGATION RATE FOR CSS - 25

TABLE A-2
FATIGUE CYCLE HISTORY OF
PIPE CSS-25

Cycle Nos.	Number of Cycles at	
	Full Amplitude	Half Amplitude
1, 404	1404	
2, 405		1001
2, 411	6	
2, 912		501
5, 499	2587	
7, 000		1501
9, 136	2136	
10, 500		1364
16, 250	5750	

On the fracture surface three distinct lines or bands are visible (Figure A-1), marking the crack front at the time of the amplitude reductions. These bands play a major role in correlating macroscopic and microscopic results, as will be shown below.

About 90 electron micrographs were taken covering the whole fracture width. The striation spacing from each micrograph yielded one data point in Figure A-3. All three groups of half-amplitude cycles were detected by their greatly reduced striation spacings (about 1/10 of the full-amplitude spacing). Their locations on the replicas coincided with the macroscopic location of the bands on the fracture (see Figure A-3). A transition area between half- and full-amplitude striations is shown in Figure A-4.

The data points originating from full-amplitude striations were divided into 7 groups; for each of these a straight line equation was computed by least square fit. The equations obtained for sections 2, 3, and 4 were so close to parallel to the abscissa that, considering the scatter of data points, equations of the form $y=C$ were preferred. The seven equations calculated were [with $da/dN=y$ and $(a-a_0)=a'$]:

I	$1000y = 1.37 a' + 0.37$	$0 < a' < 0.5$
II	$1000y = 1.10$	$0.5 < a' < 1.0$
IV	$1000y = 0.85$	$1.14 < a' < 3.24$
VI	$1000y = 0.91$	$3.36 < a' < 5.10$
VIII	$1000y = 0.20 a' - 0.19$	$5.27 < a' < 11.53$
IX	$1000y = 0.65 a' - 5.35$	$11.53 < a' < 14.67$
X	$1000y = 41.5 a' - 604.5$	$14.67 < a' < 15$

The straight lines corresponding to these equations are drawn in Figure A-3. The gaps between II/IV, IV/VI, and VI/VIII are taken up by the half-amplitude striations. The width of these gaps as well as the measured striation spacings within the half-amplitude bands prove the average crack propagation rate within the bands to be about $0.1 \mu\text{m}$, i.e., about 1/10 the propagation rate in the adjacent full-amplitude cycles. This fact justifies the computational expedient of counting half-amplitude cycles at 1/10 of their actual number.

A check of the reasonableness and accuracy of the crack propagation curve now

consists in comparing the singular points of the curve with the known cycle history of the pipe. This is done by stepwise integration of the inverse curve:

$$\frac{dN}{da} = \frac{dN}{da'} \cdot \frac{1}{y} = \frac{1000}{A_i a' + B_i} \quad (\text{A-3})$$

$$N_i = \int_{a'_i}^{a'_{i+1}} \frac{dN}{da'} da' \quad (\text{A-4})$$

Since $N = \sum N_i$ is known for $a' = t - a_0$, we start integrating at the point of wall penetration and work backward to the three half-amplitude

4500X

FIGURE A-4. TRANSITION FROM HALF-AMPLITUDE TO FULL-AMPLITUDE STRIATIONS ON ELECTRON MICROGRAPH

bands, and further on to the crack initiation site at the root of the notch with $a' = 0$

$$N_i = 1000 \int_{a'_i}^{a'_{i+1}} \frac{da'}{A_i a' + B_i} =$$

$$\frac{1000}{A_i} [\log (A_i a'_{i+1} + B_i) - \log (A_i a'_i + B_i)] \quad (A-4a)$$

For $A_i=0$ the equation simplifies to

$$N_i = \frac{1000}{B_i} \int_{a'_i}^{a'_{i+1}} da' = \frac{1000}{B_i} (a'_{i+1} - a'_i) \quad (A-4b)$$

The results of these calculations are listed in Table A-3.

TABLE A-3
CALCULATED AND RECORDED NUMBERS
OF CYCLES ON PIPE FRACTURE CSS-25

Calculated N_i		Recorded N_i (full ampl.)
35	10	
1040	9	5750
4480	8	
1910	6	2136
2470	4	2587
420	2	
800	1	1404
(185)	0	

N_0 is the number of cycles used up for crack initiation. It is the difference between the recorded number prior to the first half-amplitude cycles and the calculated number (based on striation number) for the same portion of the fracture. The number obtained by using the calculated figures (185) is much smaller than that observed (500). However, we expect the actual crack initiation, defined as the first cycle to produce a striation, to be earlier than can be observed visually.

A.5 ERRORS

The difference between calculated and recorded N_i 's is about 3% to 10%. This discrepancy reflects the sum of all experimental errors plus the error made by approximating the curve by straight line portions.

The subdivision of the array of data points into straight line portions is rather arbitrary. It is based on subjective judgment of the array. The only limiting requirement is that the curve should be continuous, i.e., that the straight lines do not form steps at their junctions.

Experimental errors must be considered in both the measurement of location (a) and the measurement of striation spacing (da/dN).

Location measurement is composed of pin-pointing the area of the electron micrograph on the lettered grid image and measuring the distance of this point from the notch root, possibly across several replicas. The plastic replica was found to shrink about 4%, but this was taken into account by measuring the actual fracture width and comparing it with the cumulative widths of the final replicas. The total error in location measurement is estimated to be at most ± 0.1 mm.

Errors in striation spacing measurement are more difficult to assess. Striations are not always uniformly spaced, even within short distances. Striation measurements are therefore more accurate when a large number of striations on a single micrograph can be measured, i.e., when the striation spacing is small. For large striation spacings near the end of the fracture, the magnification in the electron microscope cannot be reduced sufficiently to obtain many striations per negative. (The practical lower limit of magnification is 1500 $\times$). The striation spacing measurement naturally has a low accuracy when only 3 to 5 striations appear on the picture. A constant source of error is the magnification which depends not only on the current

settings and remanent magnetism but also on minute shifts in vertical specimen position in the microscope. The combined error in striation spacing measurement is estimated to be about $\pm 10\%$.

A. 6 RESULTS

With the technique described, crack propagation rates as a function of crack depth were determined for the pipes listed in Table A-1, and are shown in Figures A-3 and A-5 to A-8. Even though the equations characterizing the curves are somewhat fortuitous, all curves have certain features in common. All show a sharp upturn of the rate during the last stages prior to fracture break-through. In four of the six pipes this upturn occurred within the last 15% to 20% of the wall thickness. The other two had it at 10% and 25% respectively. The absolute wall thickness or the type of steel did not seem to be a determining factor. The stress range, however, might have an effect on the location of the discontinuity. There are too few specimens so far for a definite correlation.

The crack propagation rate prior to the discontinuity rose slowly in most specimens. Only in CSS-25 did it remain practically constant until the crack depth was 50% of the wall thickness.

In those specimens where half-amplitude striations were found (Figures A-3, A-5, and A-7) their location correlated very well with the macroscopically observed locations. This fact lends added confidence to the whole procedure. In CSS-16 no half-amplitude cycles

were used. Analysis of the curve nevertheless permits determination of the crack front location at any given cycle. The numbers entered in Figure A-6b mark the crack front for every thousand cycles. The same procedure can, of course, be used for pipes with half-amplitude markings to determine any desired crack front location. The half-amplitude markings are, in fact, not necessary for the complete analysis of the crack propagation rate by electron microscopy. However, the markings have served the very useful purpose of cross checking the results of the so-far untried procedure. In addition, they show visually the shape of the whole crack front, whereas electron microfractography has been carried out (for obvious reasons) only at the location of maximum propagation rate, i.e., along the center line of the advancing crack.

Since the half-amplitude bands are narrow and have very fine spacings, they are often not found in the electron microscope. (The change in load range also might damage the fracture surface in some cases and obliterate the striations.) In CSS-35 none of the 16 half-amplitude bands was found in the electron microscope. Therefore, comparison with macroscopic measurements was not possible.

A. 7 CONCLUSION

From the results obtained by electron microfractographic analysis of six pipe fatigue fractures, the usefulness of the procedure has been demonstrated. Crack propagation rates as a function of crack depth can be determined with good reliability and in greater detail than by macroscopic methods.

FIGURE A-5 CRACK PROPAGATION RATE FOR CSS 36

FIGURE A-6. CRACK PROPAGATION RATE FOR CSS-15, AND CSS-16

FIGURE A-7. CRACK PROPAGATION RATE FOR CSS-10

FIGURE A-8. CRACK PROPAGATION RATE FOR CSS-35

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