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**LOW CYCLE FATIGUE
OF PROTOTYPE
PIPE COMPONENTS**

J. D. HEALD
E. KISS

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

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LOW CYCLE FATIGUE OF PROTOTYPE PIPE COMPONENTS

J. D. Heald
E. Kiss

Approved:

D. H. Imhoff
D. H. Imhoff, Manager
Development Engineering

*Prepared for the
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ATOMIC POWER EQUIPMENT DEPARTMENT • GENERAL ELECTRIC COMPANY
SAN JOSE, CALIFORNIA 95114

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ABSTRACT

This report describes the results of low cycle fatigue testing and ASME Boiler and Pressure Vessel Code, Section III analysis of 28 prototype piping components. In addition, updated Section III analysis is included for the 32 notched prototype pipe specimens previously reported in reference 1. The pipe components and weld specimens were fabricated from Type-304 stainless steel and A106B carbon steel and are identical to those used for the primary piping of lightwater nuclear reactors. Specimens included 6-in., schedule 40 and 80 elbows, tees and girth butt-welded straight sections.

Fatigue testing consisted primarily of subjecting the specimens to deflection-controlled, cyclic bending with cyclic load monitored. Thus, these tests simulate thermal expansion type loading. Tests were conducted at room temperature and 550°F. At room temperature the specimens were subjected to 1050 psi constant internal pressure. In two tests at room temperature, however, stainless steel elbows were subjected to combined simultaneous cyclic internal pressure and cyclic bending.

Predictions of the fatigue life of each of the specimens tested have been made according to the procedures specified in Section III,³ "Nuclear Power Plant Components," in order to assess the code design safety factor. For the purpose of the assessment, fatigue life has been defined as the number of significant fatigue cycles to produce complete through-wall crack growth (leakage). For some tests, however, ultrasonic inspection was performed periodically to determine when cracking had occurred. In the cases where ultrasonic data are available, a comparison of cycles to "initiation" and "leakage" is made.

1. INTRODUCTION

The ASME Boiler and Pressure Vessel Code, Section III, *Nuclear Power Plant Components** provides detailed stress analysis procedures, materials data and a rational design philosophy for prevention of low cycle fatigue failure. Specifically for Class I nuclear piping components, the code provides that fatigue analysis be performed in accordance with ASME Section III, Paragraph NB3200 (*Design by Analysis*) or, alternatively, in accordance with Paragraph NB3650 (*Simplified Analysis of Piping Components*). Considering the various loading histories and geometric complexity of many piping components, the advantages of the latter become obvious from a practical point of view.

The purpose of this work is to evaluate the actual design safety factor inherent in the NB3650 ASME Code rules for low cycle fatigue for various prototype components. The results reported herein complement the work previously performed for low cycle fatigue of notched prototype piping.

The ASME Section III design fatigue curves relate cyclic strain range to cycles to failure of small uniaxial tensile specimens. A safety factor of 2 on stress or 20 on cycles (whichever is more conservative) is then applied to a best fit of the data to obtain the design curve. Thus, it follows that, prior to use of the ASME Code rules and design fatigue curve to evaluate actual prototype fatigue performance, one must be aware of and consider several important factors. First, failure of the uniaxial test specimen used to generate the code fatigue data can be considered "crack initiation data" when applied to a prototype structure. This is due to the fact that fatigue damage is essentially uniform in the smooth specimen, so that the number of cycles required to initiate a crack is the major part of the total cycles to failure. This is usually not the case for the piping component, where stress concentration and local bending produce through-wall stress gradients, which allow a significant period of stable crack growth,² prior to leakage or fracture, even after crack initiation has occurred. Thus, for a real structure, exceeding the number of allowable design cycles does not imply sudden failure, but rather is an indication that fatigue damage is progressing with increasing probability of subsequent failure. Secondly, it is important to remember that, in essence, the code rules for low cycle fatigue evaluation provide procedures to evaluate local plastic strain by using numerical factors (>1) as multipliers for elastically evaluated nominal strains. Hence, comparison of prototype data with code design procedures can be done either by comparing actual test cycles with code-predicted cycles, or calculated stress range with code-predicted stress range for actual test cycles.

For this work, the criterion upon which the code safety factor is evaluated is based on $N_t/N_D \geq 20$; where N_t = number of cycles to through-wall leakage. Although arbitrary, this provides the advantage of using a relatively simple measurement (cycles to leak), together with a definition for failure which relates to the functional requirement of the piping.

This paper describes the testing, data obtained and fatigue evaluation of 28 prototype components, including elbows, tees and girth butt-welds. In addition to these pipe components, fatigue testing of two circumferentially notched specimens were performed at 2200 psi internal pressure (PWR conditions). Finally, three specimens containing large (one diameter long, halfway through wall) axial flaws were subjected to low cycle fatigue bending to determine whether the flaw would produce a "leak or fracture." One specimen was tested at 1000 psi internal pressure (BWR) and two at 2200 psi internal pressure (PWR). Data from these axially notched specimens are critiqued in terms of a critical fracture diagram developed from burst testing of flawed straight pipe sections.^{5,6}

*1971 Edition

2. TEST PROGRAM

2.1 PIPING COMPONENTS

Piping components investigated include:

- a. straight butt-welds (6-in., schedule 40, 80);
- b. elbows (6-in., schedule 40); and
- c. tees (6-in., schedule 40).

2.2 MATERIALS

Butt-welded and notched specimens were fabricated from:

- a. carbon steel (ASTM-A106 Gr B), and
- b. stainless steel (ASTM-A312 Type-304).

Mechanical properties and chemical analyses for these materials are given in Tables 2-1 and 2-2.

Components were purchased to the following specifications:

- a. carbon steel (ASTM-A234 WPB), and
- b. stainless steel (ASTM-A 182 F 304).

2.3 TEST SPECIMENS

These design drawings used for the specimen manufacture are shown in Figures 2-1 and 2-2. Schematically, these are shown in Figure 2-3 and are classified as:

- a. notched and butt-welded;
- b. elbows (in- and out-of plane); and
- c. tees (in- and out of plane).

Axially notched and butt-welded specimens were fabricated as shown in Figures 2-4 and 2-5. A transition piece was used for the butt-welded specimens to obtain a gradual transition from the test weld size to a larger size at the flange weld.

Elbows and tees were unflawed with stress intensification resulting from the component's 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 heaters. Uniform temperature was maintained in the test section by appropriate thermocouple sensors and heater controls.

Table 2-1

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 2-1A

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

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

Table 2-2

CHEMICAL COMPOSITION (MILL ANALYSIS) OF MATERIALS TESTED

Material	Schedule	C	MN	P	S	Si	Ni	Cr	Mo
Carbon Steel	40	0.17	0.47	0.008	0.022	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

2-4

UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING:												GENERAL ELECTRIC 719 E 449	
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PROTOTYPE PIPE FATIGUE SPECIMENS NOTCHED AND BUTT WELDED

Figure 2-3. Schematic Test Specimens

Figure 2-4a. Internal Axial Notched Specimen

Figure 2-4b. Test Section Details of Internal Axial Notched Specimen

Figure 2-5. Task D3 Girth Butt-Weld Specimen

2.5 TEST LOADING

All room temperature specimens were hydraulically pressurized to 1050 psi. Cyclic bending stresses were superimposed to produce low cycle fatigue failure. In two tests at room temperature, however, stainless steel elbows were subjected to combined simultaneous cyclic bending and cyclic internal pressure. 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, and out-of-plane, through the branch.

2.6 TESTING PROCEDURE

All specimens were cyclically loaded in a fully reversed mode. The hydraulic loading ram was in the deflection-controlled mode, with force continuously measured. Consequently, loadings were similar to thermally imposed reaction forces resulting from differential thermal expansion caused by normal plant startup, shutdown, or emergency reactor operating conditions.

2.7 EQUIPMENT AND INSTRUMENTATION

2.7.1 Test Frame

Specimens were cyclically loaded in a test frame designed to support 6-in., 20-ft-long pipe specimens. The test frame design is shown in Figure 2-6. 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 2-7. The free end of the cantilever specimen is connected to the hydraulic actuator.

2.7.2 Hydraulic Loading and Control System

The hydraulic loading system (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 lb and ± 12 in., respectively. The actuator load and stroke are measured by load cell and LVDT-type transducer.

The control console includes appropriate signal conditioners, cycle counters, function generator, and actuator servocontroller. The control console is shown in Figure 2-8. Loading can be controlled in either the load, position, or strain-controlled mode. The 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 and actuator position transducer are conditioned and recorded on a two pen strip chart recorder. Specimen strain gages (when used) are conditioned and recorded using a Hewlett Packard DYMEC data acquisition system (Figure 2-9).

2.7.4 Heater Assembly

Special heater assembly designs were developed for 550°F temperature testing of butt-welded and elbow specimens. 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 (Figure 2-10). Thermocouples are positioned axially and circumferentially around the test section.

Figure 2-6. Test Assembly

Figure 2-7. Assembly Elbow Specimen

Figure 2-8. Hydraulic Control Console

Figure 2-9. Data Acquisition System

Figure 2-10. Heater Assembly and Control

3. ANALYSIS OF PROTOTYPE PIPE COMPONENTS

Fatigue analysis of the prototype piping specimens was performed according to the procedures in Paragraph NB3650 of the ASME, Section III. For most of the specimens tested, the applied stress range (S_n) was such that the $3S_m$ code limit on Primary-Plus-Secondary stress intensity range was exceeded. Therefore, the simplified elastic-plastic discontinuity analysis per NB3653.6 was used. The alternating stress intensity S_{alt} was calculated as follows:

$$S_{alt} = 1/2 K_e S_p \quad (1)$$

When $S_n > 3 S_m$ and $\leq 3mS_m$:

$$K_e = 1.0 + \frac{1-n}{n(m-1)} \left(\frac{S_n}{3S_m} - 1 \right) \quad (2)$$

where m and n are material-dependent parameters as listed below:

Material	m	n	K_e	$(K_e)_{max}$
Carbon Steel	3.0	0.2	$1 + 2 (S_n/3S_m - 1)$	5.0
Stainless Steel	1.7	0.3	$1 + 3.33 (S_n/3 S_m - 1)$	3.33
Alloy Steel	2.0	0.2	$1 + 4 (S_n/3S_m - 1)$	5.0

when $S_n \geq 3m S_m$ then:

$$K_e = 1/n = (K_e)_{max} \text{ from the above table.}$$

The equations for S_n and S_p , excluding the thermal stress terms, are:

$$S_n = C_1 \times \frac{P_o D_o}{2t} + C_2 \times \frac{D_o M_i}{2l} \quad (3)$$

$$S_p = K_1 C_1 \times \frac{P_o D_o}{2t} + K_2 C_2 \times \frac{D_o M_i}{2l} \quad (4)$$

The constants C_1 , C_2 , K_1 and K_2 are obtained from Table NB3682.2-1.

It is possible to use the data obtained from the fatigue tests to calculate S_n and S_p by three alternate methods:

- the measured shakedown load range can be used directly; or
- the elastic load range can be calculated based on the applied specimen deflection and the theoretical elastic stiffness; or
- the elastic load range can be calculated based on the applied specimen deflection and the measured load deflection curve.

The results of using the three methods to determine the load range are shown graphically in Figure 3-1. In reference 1, the shakedown load range was used for the straight-notched specimens and components, while the theoretical elastic load range was used for the reference 2 evaluation. In this report the elastic load range has been determined using the third method, which appears to be the most accurate, particularly for pipe components. By the use of the actual load deflection curve extended linearly to the test deflection, the effect of local flexibilities of the test fixture and uncertainties in the theoretical stiffness is eliminated. Therefore, S_n and S_p have been calculated as follows:

$$M_i = kyL$$

or

$$S_n = C_1 \times \frac{P_o D_o}{2t} + C_2 \times \frac{D_o}{2l} \quad kyL \quad (5)$$

$$S_p = K_1 C_1 \times \frac{P_o D_o}{2T} + K_2 C_2 \times \frac{D_o}{2l} \quad kyL \quad (6)$$

where

- k = measured elastic pipe stiffness;
- y = peak-to-peak specimen deflection;
- L = lever arm length; and
- C, K = stress indices (NB3683.2-1).

ALTERNATE METHODS FOR DETERMINING THE APPLIED SPECIMEN LOAD RANGE

Figure 3-1. Comparison of Alternate Load Range Methods

4. TEST RESULTS

Table 4-1 summarizes the significant test parameters and fatigue data obtained for the 28 piping components tested. Table 4-2 shows the results of the fatigue stress analysis. Figures 4-1a, b, and 4-2a, b compare fatigue data to the ASME design fatigue criteria, using the code-evaluated stress range and the measured cycles to leak.

As can be seen from the safety factors reported in Table 4-2 for butt-weld specimens, the highest safety factors at the highest stress ranges are for the Tucker wall pipe (schedule 80). This is consistent with intuition since, for the same alternating stress range and growth rate, it should take longer to propagate the crack through wall for the thicker piping.

Table 4-3 shows the results of fatigue stress analysis of the notched piping specimens previously reported.¹ This is included since reference 1 evaluation had been based on ASME Code B31.7 (*Nuclear Power Piping*). Figures 4-3a, b show these data compared to the ASME* criteria.

*ASME fatigue design curves are the same for Section III and B31.7.

Table 4-1
TEST PARAMETERS AND DATA OBTAINED
(Piping Ells, Tees, Welds and Axial Notches)

Specimen Number	Plane	Radius	Material	Schedule	Deflection Range (in.)	Measured Stiffness (lb/in.)	Applied Pressure (lb/in. ²)	Full Amplitude ⁽⁷⁾ Cycles-to-Crack Initiation (N _i)	Full Amplitude ⁽⁷⁾ Cycles-to-Leakage (N _L)
550°F Girth Butt-Weld Specimens									
HW-1			CS	40	10.9	206	0	25000*	35740
HW-3A			SS	40	14.0	160	0	<5225	6950
HW-10			SS	80	16.0	255	0	—	9200
HW-11			SS	80	12.5	265	0	—	14858
HW-12			SS	80	19.0	255	0	1800*	2894
HW-14			CS	80	17.0	265	0	—	7278
HW-15			CS	80	21.3	285	0	—	3208
HW-1			CS	40	12.0	190	0	—	13600
HW-3			SS	40	14.4	180	0	2049	2600 ⁽⁹⁾
Room Temperature Axial Notch Specimens									
CCANS-80-1			CS	80	22.0	280	1050	—	>1713 ⁽¹⁰⁾
CCANS-160-1			CS	160	18.0	400	2200	—	7724 ⁽¹⁰⁾
CSANS-160-1			SS	160	19.1	400	2200	1099	7456 ⁽¹⁰⁾
Room Temperature Elbow Specimens									
CSLS-1	I.P.	6	SS	40	21.6	114	1050	—	907
CSLS-2	O.P.	6	SS	40	13.0	143	1050	—	6838
CSLS-3	I.P.	9	SS	40	14.5	130	1050	1500*	4469
CSLS-5	I.P.	9	SS	40	14.5	130	100 to 1475	250*	3990
CSLS-7	I.P.	9	SS	40	13.0	130	100 to 2900	<2500*	2531
CCLS-1	I.P.	6	CS	40	14.1	130	1050	900*	1176
CCLS-2	O.P.	6	CS	40	11.2	168	1050	—	7889
550°F Elbow Specimens									
HSL-1	I.P.	6	SS	40	17.1	93	0	—	2200
HSL-2	O.P.	6	SS	40	20.8	115	0	<1799	1870
HCLS-1	I.P.	6	CS	40	14.5	89	0	<700*	760
HCLS-2	O.P.	6	CS	40	14.4	110	0	—	26100
Room Temperature Tee Specimens									
CSTS-1	I.P.	Br	SS	40	14.5	206	1050	—	4575
CSTS-2	I.P.	Run	SS	40	16.6	172	1050	—	3310
CSTS-3	O.P.	Br	SS	40	17.3	161	1050	2699*	3675
CCTS-1	I.P.	Br	CS	40	10.2	256	1050	9800*	21079
CCTS-2	O.P.	Br	CS	40	13.8	196	1050	7700*	9367

NOTES

1. I.P. — In-plane loading.
2. O.P. — Out-of-plane loading.
3. Br — Loaded through branch.
4. Run — Loaded through run.
5. CS — Carbon Steel.
6. SS — Stainless Steel.
7. Does not include half-amplitude marking cycles.
8. * First ultrasonic indication.
9. Did not leak at weld defect.
10. Leaked at weld and no cracking at internal axial notch.

Table 4-2
SUMMARY OF SECTION III FATIGUE ANALYSIS PER NB-3653.6 FOR WELDS AND COMPONENTS

Specimen Number	Plane	Radius	Material	Schedule	Y _r ⁽¹⁾ (in.)	k ⁽²⁾ (lb/in.)	ℓ ⁽³⁾ (in.)	S _m (ksi)	3 S _m (ksi)	3m S _m (ksi)	S _n (ksi)	$\frac{S_n}{3 S_m}$	K _e	Sp (ksi)	Salt (ksi)	N _{CD} ⁽⁴⁾	N _L ⁽⁵⁾	$\frac{N_L}{N_{CD}}$
550°F Girth Butt-Weld Specimens																		
HW-1			CS	40	10.9	205	237	18	54	162	62.4	1.155	1.310	112.4	74	1400	35740	25.5
HW-3A			SS	40	14.8	166	237	16	48	81.6	68.7	1.433	2.442	123.8	151	350	6950	19.9
HW-10			SS	80	16.0	255	237	16	48	81.6	79.0	1.650	3.160	142.3	224	120	9200	75.7
HW-11			SS	80	12.5	265	237	16	48	81.6	64.1	1.340	2.130	115.6	123	680	14858	21.9
HW-12			SS	80	19.0	255	237	16	48	81.6	94.0	1.960	3.33	169.5	282	68	2894	42.5
HW-14			CS	80	17.0	265	237	18	54	162	87.2	1.615	2.23	157.1	175	150	7278	48.5
HW-15			CS	80	21.3	285	237	18	54	162	117.8	2.180	3.36	212.0	356	27	3209	119.0
HWD-1			CS	40	12.0	190	237	18	54	162	63.5	1.176	1.35	114.4	77	1300	13600	10.5
HWD-3			SS	40	14.4	180	237	16	48	81.6	72.7	1.505	2.68	130.0	174	240	2600	10.8
Room Temperature Axial Notch Specimens (Analyzed as Welds)																		
CCANS-80-1 Axial			CS	80	22.0	280	237	20	60	180	119.3	1.990	2.98	215	320	35	>1713	>49
CCANS-160-1 Axial			CS	160	18.0	400	237	20	60	180	96.0	1.603	2.21	173	191	120	7724	64
CSANS-160-1 Axial			SS	160	19.1	400	237	20	60	102	101.5	1.693	3.29	183	301	56	7456	133
Room Temperature Elbow Specimens																		
CSLS-1	I.P.	6-in.	SS	40	21.6	114	225	20	60	102	416	6.84	3.33	416	694	<10	907	>91
CSLS-2	O.P.	6-in.	SS	40	13.0	143	225	20	60	102	314	5.23	3.33	314	524	16	6838	427
CSLS-3	I.P.	9-in.	SS	40	14.5	130	225	20	60	102	243	4.05	3.33	243	405	27	4469	166
CSLS-5	I.P.	9-in.	SS	40	14.5	130	225	20	60	102	264	4.40	3.33	264	440	23	3990	173
CSLS-7	I.P.	9-in.	SS	40	13.0	130	225	20	60	102	260	4.33	3.33	260	433	24	2531	105
CCLS-1	I.P.	6-in.	CS	40	14.1	130	225	20	60	180	310	5.17	5.0	310	775	<10	1176	<118
CCLS-2	O.P.	6-in.	CS	40	11.2	168	225	20	60	180	318	5.30	5.0	318	795	<10	7899	<790
550°F Elbow Specimens																		
HSL-1	I.P.	6-in.	SS	40	17.1	93	225	16	48	81.6	269	5.61	3.33	269	448	22	2200	100
HSL-2	O.P.	6-in.	SS	40	20.8	115	225	16	48	81.6	404	8.41	3.33	404	673	<10	1870	>187
HCL-1	I.P.	6-in.	CS	40	14.5	89	225	18	54	162	218	4.04	5.0	218	545	11	760	69
HCL-2	O.P.	6-in.	CS	40	14.4	110	225	18	54	162	267	4.95	5.0	267	668	<10	26100	>2610
Room Temperature Tee Specimens																		
	Plane	Connection																
CSTS-1	I.P.	Branch	SS	40	14.5	206	222	20	60	102	262	4.37	3.33	262	437	23	4575	199
CSTS-2	I.P.	Run	SS	40	16.6	172	222	20	60	102	260	4.34	3.33	260	434	24	3310	138
CSTS-3	O.P.	Branch	SS	40	17.3	161	222	20	60	102	244	4.07	3.33	244	407	27	3675	136
CCTS-1	I.P.	Branch	CS	40	10.2	256	222	20	60	180	229	3.82	5.0	229	572	10	21079	2110
CCTS-2	O.P.	Branch	CS	40	13.8	196	222	20	60	180	236	3.94	5.0	236	590	<10	9367	>937

NOTES
1. Y_r = Peak-to-peak specimen deflection
2. k = Measured stiffness
3. ℓ = Lever arm length
4. N_{CD} = Allowable number of Code Design cycles
5. N_L = Full amplitude cycles to leakage.

Table 4-3
SUMMARY OF SECTION III FATIGUE ANALYSIS PER NB-3653.6 FOR NOTCHED SPECIMENS

Specimen Number	Material	Schedule	Notch ⁽¹⁾ Type	Y _r ⁽²⁾ (in.)	k ^{*(3)} (lb/in.)	S _m (ksi)	3 S _m (ksi)	3m S _m (ksi)	S _n (ksi)	$\frac{S_n}{3 S_m}$	K _e	S _p (ksi)	Salt (ksi)	N _{CD} ⁽⁴⁾	Full Amp N _L ⁽⁵⁾	$\frac{N_L}{N_{CD}}$
Notched Piping at Room Temperature																
CSS-3	CS	40	I	15.4	191	20	60	180	80.1	1.338	1.676	288.5	242	66	1085	16.5
CSS-4	CS	40	II	13.0	191	20	60	180	67.6	1.129	1.258	243.5	154	200	4572	22.8
CSS-5	CS	40	I	10.4	191	20	60	180	54.1	0.901	1.0	195.0	98	640	13398	21.0
CSS-6	CS	40	II	14.8	191	20	60	180	77.0	1.285	1.560	277	216	90	1453	16.1
CSS-7	CS	80	I	17.4	275	20	60	180	90.5	1.510	2.020	326	330	34	1202	35.4
CSS-8	CS	80	II	10.3	275	20	60	180	53.5	0.894	1.0	192.5	96	690	12081	17.5
CSS-9	CS	80	I	8.7	275	20	60	180	45.3	0.726	1.0	163	82	1050	34426	32.8
CSS-10	CS	80	II	O-T 8.45*	275	20	60	180	44.0	0.735	1.0	158.5	79	1150	15005	13.0
CSS-11	CS	160	I	22.8	401	20	60	180	118.6	1.980	2.960	427	632	<10	953	>95
CSS-13	CS	160	I	12.9	401	20	60	180	67.1	1.120	1.240	242	150	210	13600	64.8
CSS-107	CS	80	I	15.7	275	20	60	180	81.6	1.363	1.728	294	254	60	3575	50.6
CSS-109	CS	80	I	15.4	401	20	60	180	80.1	1.338	1.676	288.5	242	66	4000	60.7
CSS-111 ^{*(6)}	CS	160	I	18.8	401	20	60	180	97.9	1.632	2.264	352	398	22	5150	234
CSS-15	SS	40	I	10.0	194	20	60	102	52.7	0.880	1.0	190	95	700	20127	28.8
CSS-16	SS	40	II	11.5	194	20	60	102	60.5	1.010	1.033	218	113	440	8596	19.5
CSS-23	SS	160	I	20.0	406	20	60	102	105.2	1.758	3.33	379	630	10	1747	175
CSS-25	SS	160	I	14.7	406	20	60	102	77.5	1.292	1.973	279	276	70	11883	170
CSS-119	SS	80	I	16.2	279	20	60	102	85.4	1.425	2.415	307	370	34	4656	137
CSS-124 ^{*(6)}	SS	160	I	14.7	406	20	60	102	77.5	1.292	1.973	279	276	70	15199	217
CSS-27	AS	40	I	14.6	205	20	60	120	81.2	1.355	2.420	292	354	27	1500	55.6
CSS-29	AS	40	I	10.0	205	20	60	120	55.6	0.929	1.0	200	100	600	11950	19.9
CSS-31	AS	80	I	15.9	295	20	60	120	88.5	1.478	2.910	318	463	15	4800	320
CSS-35	AS	160	I	10.0	430	20	60	120	55.6	0.929	1.0	200	100	600	40913	68.3
CSS-36	AS	160	II	O-T 9.7*	430	20	60	120	54.0	0.901	1.0	194	97	660	20070	30.3
CSS-37	AS	160	I	20.4	430	20	60	120	113.5	1.895	4.580	409	463	15	2365	158
Notched Piping at 550°F																
HCN-40-1	CS	40	I	11.5	178	18	54	162	55.6	1.032	1.064	200	106	520	19998	38.4
HCN-40-2	CS	40	I	14.3	178	18	54	162	69.2	1.283	1.566	249	195	110	6520	59.3
HCN-40-3	CS	40	I	9.9	178	18	54	162	48.0	0.890	1.0	173	86	940	45237	48.2
HCN-40-4	CS	40	I	16.2	178	18	54	162	78.5	1.456	1.902	282	268	50	3800	76.0
HSN-40-S	SS	40	I	12.0	177	16	48	81.6	56.6	1.050	1.167	204	119	740	4701	6.3
HSN-40-1	SS	40	I	12.7	177	16	48	81.6	61.0	1.131	1.436	220	158	320	4350	13.6
HSNP-80-1	SS	80	II	14.2	254	16	48	81.6	68.2	1.265	1.820	246	224	120	4900	40.8

NOTES
1. Notch type, I - external, II - internal, K_t for both types is 3.6.
2. Y_r - peak to peak specimen deflection. (Values marked with * are zero-tension tests.)
3. k* - Theoretically calculated stiffness = $3EI/\ell^3$
 ℓ = 231 inches.
4. N_{CD} - Allowable number of Code Design cycles.
5. N_L - Full amplitude cycles to leakage.
6. Specimens tested in the last year at constant PWR pressure of 2200 psi.

Figure 4-1a. Stainless Steel Circumferentially Notched Specimen

Figure 4-1b. Carbon and Alloy Steel Circumferentially Notched Specimens

Figure 4-2a. Stainless Steel Girth Butt-Weld Specimens

Figure 4-2b. Carbon Steel Girth Butt-Weld Specimens

Figure 4-3a. Stainless Steel Components

Figure 4-3b. Carbon Steel Components

5. DISCUSSION OF RESULTS

5.1 DEFINITION OF SAFETY FACTOR

The safety factor given in Tables 4-2 and 4-3 is defined as the number of stress cycles to cause specimen leakage N_L divided by the allowable number of stress cycles N_{CD} as per the ASME Section III fatigue analysis procedure. This definition is consistent with reference 4 and provides a relatively simple measurement which relates directly to the functional requirement of the piping.

5.2 TESTS AT PWR PRESSURE

The results obtained for the two circumferentially notched specimens pressurized to constant PWR pressure condition were essentially the same as their duplicate BWR pressure tests. There was no appreciable effect on crack initiation or crack growth due to the higher internal test pressure. An ASME Section III fatigue analysis was also done for these two specimens and the results are given with the notched piping data.

5.3 EFFECT OF AXIAL NOTCHES

Since it is known that axial flaws in straight pipe sections are most likely to become critical with respect to internal pressure, three tests were planned to demonstrate whether low cycle fatigue bending would cause fatigue crack growth and fracture in axially notched pipe sections. In order to establish the initial axial flaw size (length and depth), use was made of the critical flaw size diagram as proposed by S. Wilson.⁶ The initial flaw size is shown in Figure 5-1. Using this critical flaw diagram, it is possible, at least conceptually, to follow the growing flaw path to "leak or break." For example, if the flaw grows only in depth (path A-B), it will intercept the wall thickness prior to attaining the critical stress for rupture. If the growing flaw path is inclined (path A-D), it will fracture, providing it intersects the critical stress line prior to growing through the wall.

In these tests all of the axially flawed specimens leaked at the welds. In one case, specimen CCANS-80-1, the failed weld was repaired three times before leakage occurred in the pipe wall approximately two inches from the axial notch. Figure 5-2 shows etched sections of the axial notches of all three specimens after testing; no crack growth is evident in any of these specimens.

A stress analysis was performed per ASME Section III, considering these as room temperature girth butt-weld specimens. Results of the analysis are included with the weld specimen data.

5.4 ACOUSTIC EMISSION STUDIES

Acoustic emission measurements were made during three fatigue tests by personnel from Instrument Systems Development, Westinghouse Power Systems Division. Results of these measurements are claimed to appear promising. A report covering this work is to be issued separately by Westinghouse.

5.5 EVALUATION OF ASME SECTION III CODE DESIGN CRITERIA

Based on the results obtained from these fatigue tests, the ASME Section III fatigue design procedures (specifically, the procedures in NB3653.6, *Simplified Elastic-Plastic Discontinuity Analysis*) give results which are consistent with the assumptions made when the code rules were adopted. That is, there is a consistent design margin of at least 20 on cyclic fatigue life. In general, the trend of the test data indicates that the code procedures are adequately conservative at low stress levels and even more conservative at the high stress levels. Specifically, components which were tested at very high stress levels indicate factors of safety, based on cyclic life, of greater than 100. It would appear, therefore, that the design rules for components could be adjusted somewhat to give more realistic design margins without sacrificing fatigue integrity.

Figure 5-1. Pipe Fracture Diagram

At first glance, there appears to be considerable data scatter for components; however, a closer review shows that similar components of the same material tested under nearly the same conditions yield comparable results. For example, specimens CSLS-3 and CSLS-5 were tested at nearly the same conditions, as far as code procedures are concerned (i.e., S_{alt} is approximately equal). The resulting safety factors for these specimens show good agreement (i.e., 166 and 173, respectively).

In one case, two elbow specimens were tested to determine the effect of combined cyclic pressure and cyclic bending on fatigue life. Both specimens (CSLS-5 and CSLS-7) were subjected to the same S_{alt} (440 ksi). However, each was loaded so that they had differing amounts of bending and pressure stress. The relative percentages of pressure stress and bending stress to $S_{n_{total}}$ are shown below.

Specimen Number	$\frac{S_n}{T}$ ksi	$\frac{S_{n_{bend}}}{ksi}$	$\frac{S_{n_{press}}}{ksi}$	$\% \left[\frac{S_{n_{bend}}}{S_{n_t}} \right]$	$\% \left[\frac{S_{n_{press}}}{S_{n_t}} \right]$	N_L/N_{CD}
CSLS-5	264	243	21	92	8	173
CSLS-7	260	218	42	84	16	105

Although the pressure stress in one test was twice that of the other, the relative percentage of the pressure stress was small compared to the total stress in both cases. The test conditions were selected so that the primary type cyclic pressure stress would be below $3S_m$ to prevent possible ratcheting, while the cyclic bending stress would be high enough to cause failure in a reasonable testing time; hence the predominant bending stresses. The results indicate a possible effect of the variation of pressure stress on cycles to leakage. However, since this is based on only one test, these results should only be considered qualitative.

(a) RADIAL VIEW OF NOTCHED REGIONS

(b) SECTIONS IN (a) TURNED 90 DEGREES

NUMBER OF CYCLES SHOWN ARE AT TEST TERMINATION

(C) SKETCH OF TYPICAL TASK D-3 AXIALLY NOTCHED TEST SPECIMEN TO SHOW CRACK LOCATIONS WHICH OCCURRED AWAY FROM NOTCHES.

- ① LEAKING CRACK OCCURRED AT THIS WELD ON SPECIMENS CCANS-160-1 AND CSANS-160-1.
- ② LEAKING CRACK OCCURRED IN THE PIPE WALL AT LOCATION SHOWN 3 INCHES FROM NOTCH TIP IN SPECIMEN CCANS-80-1.

Figure 5-2. No Cracking is Evident in Sections Cut from Axially Notched Pipe Specimens. Number of cycles shown are at test termination.

6. CONCLUSIONS

Data obtained from the low cycle fatigue testing of 28 prototype pipe specimens have been evaluated according to the procedures specified in ASME Section III, Paragraph NB3653.6(*Simplified Elastic-Plastic Discontinuity Analysis*), in order to assess the code design safety factor. The criterion used is based on evaluating the ratio of actual cycles to leak and the code predicted value. Results are presented which show that the code rules are adequately conservative, particularly at the highest stress conditions.

7. REFERENCES

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