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**LOW-CYCLE, STRAIN-CONTROLLED
FATIGUE CRACK PROPAGATION
IN NUCLEAR PIPING STEELS**

MASTER

A.J. BROTHERS

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IN NUCLEAR PIPING STEELS**

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ABSTRACT

Crack growth rates under reversed tension-compression strain-controlled loading were measured for both the axial and bending mode for A-212B carbon steel, 2-1/4 Cr-1 Mo and Type 304 stainless steel at room temperature. Both through-cracked, center-slotted plates and surface-cracked specimens were employed for axial loading, and a surface-cracked specimen for bending tension-compression; these latter specimens were also tested at 550°F. All results are correlated with the nominal total strain range and, where applicable, with the stress intensity factor, K . A method is proposed for correlating geometry effects for low-cycle, strain-controlled fatigue.

1. INTRODUCTION

Previous studies (GEAP-5607) of fatigue crack growth in nuclear piping steels determined growth rates for cycling conditions over stress or load-controlled limits; stress levels up to and near the yield stress were evaluated.¹ For these conditions, it was observed that crack growth rates correlated well with the stress intensity factor calculated from linear elastic fracture mechanics. It was also possible to correlate growth rates for several different geometries in both axial and bending stress fields.

The purpose of this study was to determine similar properties for carbon, 2-1/4 Cr-1 Mo and Type 304 steel under cycling conditions for which the specimen is loaded over controlled strain or extension ranges at nominal stresses exceeding yield strength. These are conditions which might result from a limited number of cycles resulting from strains induced by cyclic thermal stresses and/or gross relative displacement of system components. Growth rates were measured using through-crack plate specimens in tension loading, and part-through surface cracks of various geometry in both axial and bending loading. Although most tests were conducted at room temperature, some were performed at 550°F to evaluate these properties in the service operating range.

2. GENERAL TESTING PLAN

The general aspects of fatigue crack growth considered in this study are described in the following paragraphs.

2.1 SERIES A—CRACK GROWTH RATES IN THROUGH-CRACKED SPECIMEN IN AXIAL TENSION-COMPRESSION AT ROOM TEMPERATURE

To establish a reference condition for comparison of the effects of various variables, the primary tests of all materials were performed at room temperatures using a 5-inch wide plate specimen with a centrally located, 0.5-inch long, through-slotted plate. These were cycled under axial tension-compression conditions; the variable of initial slot length was explored.

2.2 SERIES B—CRACK GROWTH RATES OF PART-THROUGH CRACKED SPECIMENS IN AXIAL TENSION-COMPRESSION

These tests evaluated the influence on crack growth rate of various part-through, semielliptically shaped surface defects. The purpose of these tests was to determine whether simple analytical procedures based on fracture mechanics principles could correlate results for part-through cracked specimens with those containing through-thickness cracks.

2.3 SERIES C—CRACK GROWTH OF PART-THROUGH SURFACE CRACKS IN REVERSE BEND LOADING

To determine the growth rate of part-through surface cracks in bending tension-compression, cantilever beams containing shallow surface slots were loaded in reversed bending tension-compression under conditions of controlled deflection. The specimen used was previously developed,² and is one for which extensive results are available.³ However, these test procedures differ somewhat from those of Crooker and Lange,³ who controlled tests to a constant strain range rather than constant deflection. As described in Reference 3, constant-deflection tests produce somewhat higher growth rates; however, the differences are believed to be slight. These results are compared with others on similar material tested under constant strain range.

3. EXPERIMENTAL PROCEDURES

Materials and Test Specimens

The source, composition and mechanical properties of the plate materials used are listed in Table 1. Typical microstructural features are shown in Figure 1.* Rolling direction for the 2-1/4 Cr-1 Mo and Type 304 alloys is vertical in the photograph; the orientation of the micrograph for the carbon steel is uncertain. All steels were tested in the as-received conditions without additional heat treatment.

The configurations of the test specimens used are shown in Figure 2. In all cases, the plate specimens were tested with the axial length of the specimen perpendicular to the rolling direction (i.e., a transverse specimen). The notch in all specimens was prepared by electro-discharge machining; the nominal notch radius specified for through-slot specimens was 0.005 inch.

Cycling was performed in universal testing machines at rates of about 3 to 6 cpm. Strain ranges were measured and controlled in the axial specimens (Series A and B) using dual SR4-type extensometers mounted within 1 inch of the edges of the specimen; strain and load range were monitored periodically. For the cantilever bend tests (Series C), strain gages were glued to the surface of the specimen on both sides of the center slot within 1/4 inch of the edges. Cycling in these tests was deflection-controlled to maintain a deflection identical to that established during initial cycles with operative strain gages. Since these strains for a given deflection may change with cycles as a result of strain hardening or softening, or changing compliance of the specimens, it is doubtful that local strain ranges remain constant throughout the test. Thus, the strains reported are initial strain values only. Loads were monitored periodically to determine the applied tensile and compressive moment required to obtain constant deflection.

Heating for elevated temperature tests was performed using circulating air cabinets. Surface crack lengths in all specimens were measured optically at magnifications to 16X using a scale graduated in hundredths of an inch attached to the specimen near the fracture path. Crack depth through the thickness in some of the axial tests containing semielliptical, part-through surface cracks was determined by postmortem examination of fracture surfaces. An understressing technique consisting of about 2000 cycles at low alternating stress was used to mark the crack depth with "optically visible beach marks" at about 0.06-inch intervals. From these results, it was possible to determine the crack shape at various intervals during crack growth.

Each of the crack growth curves was analyzed to determine the slope (i.e., crack growth rate as a function of increasing surface crack length, $2a$, or crack depth, c). Increments of crack length or depth, and corresponding cyclic intervals, were taken such that the crack growth curve was ostensibly linear with each increment.

4. EXPERIMENTAL RESULTS

The following paragraphs describe the results of the above series of tests. The crack growth data from these tests are tabulated in the Appendix. A summary of crack growth rates is listed in Table 2.

4.1 SERIES A—CRACK GROWTH IN THROUGH-CRACKED PLATES IN AXIAL LOADING

The crack growth curves for the through-cracked plates loaded in reversed axial loading are shown in Figures 3 through 5. Generally, the slope or crack growth rate is constant over short increments of the crack growth curve. The discontinuous changes in slope of some of the curves, as well as the occasional lack of an effect of higher strain range to produce higher growth rates, are believed to reflect either scatter or aberrations in strain control, with an inherently high dependence of crack growth rate on total strain range.

Because of the above anomalies, as well as uncertain transcription of raw data, the author was uncertain regarding the nominal strain range level in initial through-crack plate tests. It was uncertain whether the nominal strain range was equal to

* See Section 6 for all illustrations referenced in text.

Table 1
SOURCE, COMPOSITION AND MECHANICAL PROPERTIES OF
EXPERIMENTAL STEELS

Material: Three 1-inch-thick plates of mill-annealed A-212B steel plate.

Composition:

	C	Mn	P	Si	S	N ₂
A-212B Spec Reg	0.30	0.29–1.06	0.048	0.10	0.058	—
M & P Lab. Test	0.24	0.74	0.015	0.24	0.031	0.007

Grain Size: ASTM No. 6.5

Microstructure—Fine pearlite-ferrite mixture (Figure 1)

Mechanical Properties (Transverse):

	Test Temp (°F)	Ultimate Str (psi)	0.02% Yield Str (psi)	0.20% Yield Str (psi)	Elong in 1 in. (%)	Red in Area (%)
Plate No. 1	RT	74,825	49,250	45,000	41.5	47.3
Plate No. 2	RT	76,425	48,875	45,000	42.0	46.0
Plate No. 3	RT	76,400	48,500	44,000	41.0	45.1
Plate No. 1	125	72,500	44,800	44,700	—	—
Plate No. 1	200	75,250	—	—	—	—
Plate No. 1	300	80,250	40,500	41,500	—	—
Plate No. 1	400	83,400	38,700	39,700	20.0	28.5
Plate No. 1	500	85,000	30,300	36,700	31.0	31.2

Charpy Impact Properties (Transverse):

Test Temp (°F)	Impact Energy (ft-lbs)	% Fibrous Fracture	
-75	5.0	8	
-50	7.0	19	
-25	15.5	48	
0	18.0	60	50% FATT
+25	24.0	98	-10°F
+75	24.5	100	
+125	25.0	100	

Table 1.—(Continued)

Material: Two plates A-387D, mill-annealed and 2-1/4 Cr—1 Mo alloy 1-inch-thick plate.

Heat Treatment: Annealed 1650-1700°F — 1-1/2 hrs — FC to 800°F — AC - SR 1175°F — 1 hr FC

Composition:

	C	Mn	P	S	Si	Cr	Mo
A-387D	0.15	0.30—0.60	0.035	0.035	0.50	2.00—2.50	0.90—1.10
Spec Reg	max		max	max	max		
Mill Check	0.14	0.46	0.011	0.025	0.38	2.30	0.91
M & P Lab Test	0.17	0.48	0.008	0.019	0.38	2.18	0.92

Grain Size: ASTM No. 5.7

Microstructure: Pearlite-ferrite mixture (Figure 1).

Mechanical Properties (Transverse):

Test Temp (°F)	Ultimate Str (psi)	0.02% Yield Str (psi)	0.02% Yield Str (psi)	Elong in 1 in. (%)	Red in Area (%)
RT	77,900	32,500	37,000	44.0	56.8
RT	78,250	26,000	32,750	43.0	56.8
450	66,500	22,250	23,900	38.0	52.2
550	68,100	23,250	28,550	33.0	49.5
600	70,250	22,300	28,600	31.0	47.5
650	71,000	19,700	28,300	32.0	46.9

Charpy Impact Properties (Transverse):

Test Temp (°F)	Impact Energy (ft-lbs)	% Fibrous Fracture
0	2.5	5
75	9.5	19
125	26.5	42
150	44.0	61
175	52.5	89
225	63.0	100

50% FATT = +135°F

Table 1.—(Continued)

Material: Two plates A-240, hot-rolled, annealed and pickled Type-304 steel 1-inch-thick plate.

Composition:

	C	Mn	P	S	Si	Ni	Cr	Mo
A-240	0.08	2.00	0.03	0.03	0.75	8–11	18–20	—
Spec Reg	max		max	max	max			
M & P Lab Test	0.07	1.63	0.016	0.013	0.54	9.50	18.57	0.26

Grain Size: ASTM No. 3-4

Microstructure - Mixed grain size austenite (Figure 1).

Mechanical Properties (Transverse):

Test Temp (°F)	Ultimate Str (psi)	0.02% Yield Str (psi)	0.02% Yield Str (psi)	Elong in 1 in. (%)	Red in Area (%)
RT	79,700	26,500	34,200	83.5	72.2
550	63,200	13,000	17,000	63.0	70.4
600	63,400	14,100	17,000	64.0	71.8

that reported or was, in fact, half that value. Consequently, replicate tests of the 2-1/4 Cr—1 Mo steel were made under carefully controlled conditions, and the results compared with those obtained previously. On the basis of this comparison, it is believed that the strain levels shown for the axial tension-compression tests are valid. However, in view of these anomalies, use of these data is recommended only with the factor of uncertainty noted above. This qualification applies only to the axial tension-compression tests.

Additional crack growth curves for axial tension-compression tests with short initial crack lengths and part-through surface cracks are shown in Figure 6. This figure shows that, prior to penetration, the crack growth rate is quite low and an apparent function of geometry (i.e., crack length). However, after penetration, the crack growth rates are generally similar to those for the through-crack specimens.

Typical illustrations of the load required to obtain a given strain for the center-slotted, axially loaded plates are shown in Figure 7. Generally, the load required to achieve a given strain decreases with increasing crack length (i.e., decreasing net section area). For the higher strain ranges, there is little difference in the load required to achieve a given strain range, and, in some cases higher strain ranges are associated with lower loads. These effects reflect scatter from specimen to specimen, a relatively low effective plastic modulus, as well as the experimental anomalies noted earlier. Although an attempt was made to estimate the expected load level of these curves from stress-strain properties, the uncertainties of cyclic strain hardening effects and yield point phenomena during crack growth made this approach unreasonable. Generally, the observed loads were much higher than those calculated from uniaxial tensile properties.

Typical fracture appearances of the three alloys are shown in Figure 8. These features are similar to those for the stress-controlled tests, with the exception of the extent of crack growth and reduction in thickness with increasing net section stress. These features, best typified by the Type 304 steel, show crack growth across the full width of the plate with nil reduction in thickness. This is different from the stress-controlled tests, in which the cyclic crack length rarely exceeded the specimen half-width with considerable reduction in thickness. This feature results from the decreasing load characteristics of the strain-controlled test.

Table 2.
SUMMARY OF CRACK GROWTH RATES IN AXIALLY LOADED
THROUGH-CRACKED, CENTER-SLOTTED PLATE SPECIMENS

A-212B Carbon Steel

Spec No.	Estimated Strain Amplitude (%)	Crack Growth Rate da/dN, inches/cycle
A	±0.25	0.00437 — 0.00226
B	±0.375	0.0191
C	±0.15	0.00095 — 0.00064
D ₁	±0.125	0.000116
D ₂	±0.175	0.000375
F	±0.5	0.0182

2-1/4 Cr — 1 Mo Steel

A	±0.4	0.0152
B	±0.4	0.0152
C	±0.4	0.0374
D	±0.4	0.0222
E	±0.3	0.00125 — 0.00191
F	±0.2	0.0010 — 0.00081
G ₁	±0.125	0.000122
G ₂	±0.15	0.000175
G ₃	±0.20	0.00029
H	±0.325	0.014
I	±0.125	0.000107
J ₁	±0.15	0.00015
J ₂	±0.20	0.000323

Type-304 Stainless Steel

A	±0.09	0.000139
B	±0.125	0.0000627
C	±0.20	0.000221
D	±0.30	0.00111
E	±0.375	0.00262
F	±0.50	0.00153

4.2 SERIES B—GROWTH RATES UNDER TENSION-COMPRESSION LOADING WITH PART-THROUGH SURFACE CRACKS

To determine crack growth rates for defect configurations more similar to those anticipated under service conditions, tests were conducted with a 2-1/4 Cr—1 Mo steel employing part-through surface cracks of various length-to-depth ratios ranging from 2.5 to 5.0; two thicknesses (0.25 inch and 0.8 inch) were tested. These results are shown in Figure 9 as a plot of surface crack length versus number of cycles. Note that, for specimen FS, the crack length plotted is that for growth through the thickness. The crack lengths shown for this specimen are twice the nominally measured value to provide valid comparison for the other specimens in which the crack length represents a total value measured at two growing fronts.

These results indicate that, prior to thickness penetration, surface growth rates are substantially lower than those for through-thickness crack growth and are a function of crack geometry. However, shortly before and after thickness penetration, the crack growth rates are constant and similar to that for a through-thickness slotted plate. The dependence of crack growth rate on crack depth and/or geometry prior to penetration indicates that crack growth rate is not a simple and constant function of gross strain range, and that design based on through-cracked plates could be overly conservative. Conversely, design based on crack growth rates for PTC specimens prior to penetration could (for applications involving through-crack tensile loading) be extremely optimistic.

Typical curves of load as a function of cycles for PTC tests are shown in Figure 10. Generally, the loads required to obtain a given strain range are identical for both tension and compression, suggesting that the isolated location of the strain gages does, in fact, reflect actual specimen strain rather than increased compliance of a cracked specimen. Also, equal loads for tension and compression implies that the crack surfaces are not closing completely during compression (i.e., remain fairly open) and hence are not affecting the load required to obtain a given strain. For example, if the crack were closing fully, one would expect the compressive load to remain constant as a function of increasing crack length. The decrease in load with crack length or number of cycles is a simple function of geometry, reflecting lower loads for decreasing net section area. Also, Figure 10 suggests that the load required to obtain a given strain remains fairly constant for crack geometries reasonably small compared to the thickness. For example, the decrease in load with increasing number of cycles is extremely low for PTC 1.0 inch X 0.2 inch for up to 1000 cycles. This suggests that, for nominally small defects, analyses may be based on the assumption of a constant gross stress level, as well as constant strain ranges.

The relation of crack length-to-depth in these tests is shown in Figure 11 and shown qualitatively in the fracture surfaces of Figures 12 and 13. The data of Figure 11 were derived from either beach marks induced by understressing techniques or by dye penetrant marking. Comparison of the surface and depth growth curves of Figure 11 indicates similar growth rates for both surface and depth. Also, inspection of Figure 13 for two specimens with flaw sizes less than the thickness suggests that incipient flaws or cracks tend to assume an equilibrium length-to-depth ratio of about 2.0 to 3.0. This is generally consistent with previous observations of growth of PTC flaws under cyclic loading (GEAP-5607) and is of significance to analysis of flawed components.¹

The correlation of crack growth rates for through-slotted plates, and for part-through cracked plates after specimen penetration, are summarized in Figures 14 through 16. Within scatter, these and all previous results suggest a simple exponential relationship between total cyclic strain range and crack growth rate. Although there appears to be little significant difference between 2-1/4 Cr-1 Mo and carbon steel (Figures 14 and 15), the slope of the Type 304 alloy (Figure 16) indicates a significantly lower slope and lower crack growth rates at higher strain levels.

The nominally constant growth rates (i.e., the linear relationship of crack length to number of cycles for strain-controlled tests of through-cracked plates) differ markedly from those observed for load-controlled tests. In these latter tests, increasing rates are generally observed with increasing crack lengths (GEAP-5607). Since loads were measured in these current strain-controlled tests, and since the through-crack geometry is amenable to analysis by fracture mechanics concepts, these test results were compared with those obtained previously using stress-controlled tests on 14-inch-wide plates (GEAP-5607).¹ This comparison (shown in Figure 17 for the 2-1/4 Cr-1 Mo alloy, for which the most extensive data are available) illustrates within scatter essentially good agreement between these current strain-cycling tests and prior load-controlled tests. For equal stress intensity factor ranges, crack growth rates are similar. This correlation indicates the relevance of fracture mechanics concepts to rationally correlate crack growth rates under both stress-and-strain-controlled loading. It also provides a basis for predicting the influence of geometry on crack growth rate under strain-controlled loading. This is described further below.

On the basis of the correlation of Figure 17, a rational explanation of the constant growth rate in these strain-controlled tests can be obtained. For example, Figure 18 shows the variation in load, crack length and stress intensity factor with cycles for a through-slot plate test of Type 304 steel. Over the range of crack lengths examined, the stress intensity factor stays nominally constant; thus, (from Figure 17) for near-constant K levels, one would expect a near-constant crack growth rate.

Since Figure 17 shows that crack growth rates under strain-controlled loading correlated well with stress-controlled tests on the basis of stress intensity factor, and since this latter quantity includes factors related to geometry, an attempt was made to correlate the incipient crack growth rates in the PTC tests with those measured on through-crack specimens. This correlation, if successful, provides a means of rationally estimating flaw growth of PTC cracks under strain-controlled loading conditions.

From consideration of the general expressions for stress intensity factor, one notes factors of stress, geometry, and crack length; i.e.,

$$K = f(\sigma_g): (f) a, c, t \text{ or } W$$

where

$$\begin{aligned} c &= \text{crack depth,} \\ a &= \text{surface half-crack length,} \\ t &= \text{thickness,} \\ W &= \text{plate width, and} \\ \sigma_g &= \text{gross section stress.} \end{aligned}$$

Specifically, for a center-slotted plate,

$$K = \sigma_g \cdot (\pi a)^{1/2} \left[\frac{2W}{\pi a} \tan \frac{\pi a}{2W} \right]^{1/2} \quad (\text{References 4 and 5})$$

or modification thereof (see Reference 2).

For a part-through surface cracked plate

$$K = \frac{\sigma_g \cdot (\pi c)^{1/2}}{\phi_0} \cdot [1 + 0.12(1 - c/a)] \left[\frac{2t}{\pi c} \tan \frac{\pi c}{2t} \right]^{1/2} \quad (\text{Reference 4})$$

For a constant stress or corresponding strain level, it is possible to determine the relative, or effective, K or strain level for a given surface crack length in a PTC specimen in terms of that for a center-slotted plate of equal through crack length. In the extreme, for the case of a part-through crack which penetrates the specimen thickness, the K level for the PTC plate will equal that of the through-crack plate. Since correlations of crack growth rate versus K or strain range are available for through-cracked plates, the growth rate corresponding to the stress intensity factor or effective strain range in the PTC specimen can be determined; i.e.,

$$\frac{K_{PTC}}{K_T} = \frac{\epsilon_{PTC}}{\epsilon_T} \quad \text{or} \quad \epsilon_{PTC} = \frac{K_{PTC}}{K_T} \times \epsilon_T$$

The results of such an analysis for specimens PTC 1 inch X 0.2 inch and PTC 0.5 inch X 0.2 inch are shown in Table 3 and summarized in Figure 19, which plots both the measured and predicted surface crack growth rate as a function of crack depth. The predicted rates were obtained from the lines shown in Figure 14, using the effective strain range for the PTC specimens.

The correlation shown in Figure 19 is reasonable for crack depths less than about 60 to 75% of the thickness and suggests that this may be a reasonable analytical procedure for compensating for geometry effects of shallow part-through cracks. However, for crack depths greater than the above depth (see Figures 9 and 11), the growth rate becomes constant and equal to that for the through-thickness crack condition. This effect (i.e., constant crack growth at crack depths less than full thickness) may reflect the current inadequacy of the stress intensity analysis for part-through cracks of high relative depth. It

Table 3
SUMMARY OF ANALYSIS OF STRAIN-CONTROLLED
CRACK GROWTH SPECIMENS

PTC 0.5 in. X 0.2 in.

Crack Depth c, inches	c/t	Crack Half Length, a, inches	c/a	ϕ_o	$\{K/\sigma_g\}$ PTC $\sqrt{\text{in.}}$	Measured da/dN $\mu\text{-in./cycle}$	Estimated da/dN, $\mu\text{-in./cycle}$ (max) (min)	
0.395	0.49	0.413	0.957	1.54	0.823	479	630	225
0.495	0.62	0.588	0.842	1.45	1.075	735	850	305
0.565	0.706	0.695	0.812	1.42	1.30	1125	1300	450
0.645	0.806	0.820	0.786	1.41	1.66	1390	3400	820
0.740	0.93	0.990	0.747	1.38	2.92	1400	—	—

PTC 1.0 in. X 0.2 in.

0.338	0.422	0.563	0.601	1.28	0.916	358	475	165
0.395	0.494	0.700	0.565	1.25	1.065	680	530	195
0.483	0.604	0.810	0.594	1.28	1.20	938	610	225
0.662	0.827	0.950	0.697	1.34	1.89	1000	3100	720

Determination of Effective Strain in PTC Spec

	Crack Half Length a, inches	a/W	$\{K/\sigma_g\}$ PTC $\sqrt{\text{in.}}$	$\{K/\sigma_g\}$ PTC/ $\{K/\sigma_g\} a$	Effective Strain Range in PTC Spec $\epsilon_T, \%$
PTC — 0.5 in. X 0.2 in.	0.413	0.083	1.155	0.711	0.284
	0.583	0.118	1.410	0.763	0.305
	0.695	0.139	1.55	0.839	0.335
	0.820	0.410	1.72	0.965	0.386
PTC — 1.0 in. X 0.2 in.	0.563	0.112	1.375	0.666	0.266
	0.700	0.140	1.560	0.683	0.273
	0.810	0.163	1.705	0.704	0.282
	0.950	0.190	2.020	0.936	0.374

Effective strain in PTC spec = $\left[\{K/\sigma_g\} \text{ PTC} / \{K/\sigma_g\} a \right] \times \epsilon_T$; $\epsilon_T = 0.4\%$.

is possible that additional analytical consideration beyond the scope of this report, and similar to that described by Kobayashi,⁶ might influence and effectively improve the correlation.

4.3 SERIES C—CRACK GROWTH IN BENDING TENSION-COMPRESSION LOADING OF PART-THROUGH SURFACE CRACKS

To determine the influence of bending versus tension loading on the crack growth rates of shallow part-through surface defects, tests of cantilever bend specimens (Figure 2), carbon, and 2-1/4 Cr—1 Mo steels were conducted at room temperature and 550°F. These results are shown in Figures 20 through 23. The crack growth curves at room temperature for the carbon steel (Figure 20) and, to a greater extent, the 2-1/4 Cr—1 Mo steel (Figure 21) exhibit increasing crack growth rates with increasing crack length. Although the data points are not shown here, the drawn lines closely reflect the data trends in which extremely low scatter was observed. (Complete crack growth curves are included in the Appendix.)

The crack growth curves for both materials at 550°F are shown in Figures 22 and 23. Also shown on each plot are crack growth curves for $\pm 0.5\%$ strain range measured at room temperature. Examination of the results at 550°F and comparison with rates measured at room temperature indicate lower crack growth rates at the higher temperature for both materials. The observation of lower growth rates in these steels at 550°F is different from the effect observed in previous tests of the same material in through-cracked, axially loaded wide plates at similar temperatures (GEAP-5607).¹ This difference suggests either experimental deficiencies (a specimen geometry effect) or simply the influence of a lower modulus of elasticity at 550°F. In either case, additional verifying results should be obtained prior to generalization of trends derived from these few tests.

A detailed comparison of test procedures indicates no apparent material discrepancies which account for these differences. This comparison revealed the 550°F and room temperature specimens to be of identical orientation with no apparent differences in microstructure from those tested at room temperature. The hardnesses of the two sets of carbon steel specimens were essentially identical ($159 \pm \text{BHN}$); the variation in hardness of the 2-1/4 Cr—1 Mo steel ($164 \pm 8 \text{ BHN}$) was greater but still possibly within scatter. The details of testing at room temperature and 550°F shown in Figures 24 and 25 indicate effects consistent in all respects with observation, but they also indicate a possible discrepancy for the 2-1/4 Cr—1 Mo steel. Generally, total bending moments for the 550°F tests are either equal to or greater than the room temperature values; this indicates no obvious error in strain range magnitude, (e.g., if the imposed strain range had been less than the nominal $\pm 0.5\%$, one would expect a lower rather than a higher applied moment). A possible discrepancy associated with the 2-1/4 Cr—1 Mo results is that of a higher strain range for a short period at the beginning of the test. It is possible that this effect could, because of permanent bending of the bar or strain hardening effects, result in spurious effects. However, even in the initial portions of the test, the nominal crack growth rates are lower than those at room temperature.

Another possible and more reasonable explanation of the reduced growth rates at 550°F is the effect of a reduced elastic modulus at that temperature. Since the modulus of elasticity for steel is 20 to 25% lower at 550°F than at room temperature, the resultant plastic strain at 550°F for equal total strain ranges will be somewhat lower. If the plastic strain range is the primary variable in effecting crack growth, this would presumably reduce the growth rate.

Typical fracture surfaces of the specimens at room temperature and 550°F are shown in Figures 26 and 27, respectively. These features indicate that the surface crack length-to-depth ratios vary for the two alloys. However, there is no apparent influence of temperature on this feature. The primary difference between the two steels is that of lower total crack growth through the thickness in the carbon steel. This appears to result from a crack-retarding influence of transverse fissuring associated with inclusion stringers in the carbon steel plate. The specific values of crack aspect ratio for these tests are listed in Table 4; in both materials the final aspect ratio appears to be independent of strain level.

Comparison of crack growth rate as a function of total strain range for both the bending and tension-compression tests of the carbon steel is shown in Figure 28. Since the strain range in the bend tests is an initial value only and may not remain constant throughout the test, it is somewhat questionable whether these results should be compared with the through-cracked plates for which strain range was controlled. The comparisons of Figures 28 and 29 indicate that the slope of the curve for the bend specimens is slightly less than that for the axial tests. However, the level of crack growth rate for the bending mode is much less than that for the center-slotted tension-compression plates. Since the rates for the 2-1/4 Cr—1 Mo alloy were not constant but increased slightly with increasing crack length, the results for this steel are shown as a range of values (Figure 29). Figure 29 shows that their general magnitude is much less than those measured in tension-compression.

Table 4
CRACK ASPECT RATIO IN BEND SPECIMENS
AT ROOM TEMPERATURE

A-212B

Strain Level (%)	Final Crack Depth (in.)	Final Surface Crack Length (in.)	Final Crack Length-to-Depth Ratio, 2c/a
±0.3	0.17	1.99	11.1
±0.5	0.19	1.90	10.0
±1.0	0.21	2.18	10.9
2-1/4 Cr-1 Mo			
±0.3	0.27	2.11	7.5
±0.5	0.28	2.03	7.6
±1.0	0.33	2.00	6.4

Crack Length-to-Depth Ratio for 2-1/4 Cr-1 Mo
Alloy at ±0.3% Strain Level

Surface Crack Length 2c (in.)	Crack Depth, a (in.)	Crack Length-to-Depth Ratio, 2c/a	a/2c
0.25	0.06	4.1	0.244
0.80	0.14	5.65	0.177
1.63	0.24	6.8	0.147
2.11	0.28	7.5	0.133

Comparison of the results of the bend tests of the 2-1/4 Cr-1 Mo and carbon steel with those for a carbon steel of comparable yield strength³ is shown in Figure 30. There is negligible difference between the 2-1/4 Cr-1 Mo and the carbon steel of this study, or between this carbon steel and another of similar yield strength obtained under controlled constant strain rather than deflection. The good correspondence of the two groups of data suggests that the variable of constant deflection versus constant strain may not be a major one in controlling the general levels of crack growth rates in these specimens and steels.

In view of the significantly lower levels of crack growth rate for the reverse loaded bend tests at room temperature, an attempt was made to compare these results with those for the axially loaded plates using the stress intensity factor approach. For this purpose, the analysis of Smith⁷ for a semielliptical surface cracked beam was employed; i.e.,

$$K_I = M_B \sigma \sqrt{\pi} \sqrt{c/Q} \quad (\text{Reference 7})$$

where

M_B = proportionality constant,

σ = outer fiber bending stress, psi; equal to bending moment ÷ section modulus,

c = crack depth (inches),

$2a$ = surface crack length (inches),

Q = shape factor,

$$Q = \phi^2 - 0.212 (\sigma/\sigma_{YS})^2, \quad (\text{Reference 7})$$

$$\phi = \int_0^{\pi/2} \left[1 - \left(\frac{a^2 - c^2}{a^2} \right) \sin^2 \phi \right]^{1/2} d\phi. \quad (\text{Reference 8})$$

The characteristics of the above relationship are shown in Figure 31, which shows M_B as a function of relative crack depth for various levels of $c/2a$. Details and results of the analysis are shown in Table 5. Although some interpolation of the curves in Figure 31 was required, the major uncertainty is in the value of Q employed. Since the formulation for Q (the shape factor) was originally derived for low stress fracture, and for σ/σ_{YS} ratios of unity or less, there is some question regarding its applicability to the σ/σ_{YS} levels observed in these tests; i.e., 1.3 to 2.0. Consequently, Q values were calculated only for a σ/σ_{YS} of 1.0.

The comparison of the bend test results with those for axial loading (Figure 16) are shown in Figure 32. This figure, which is identical to that of Figure 17 (with the deletion of some points for clarity), indicates within scatter, fairly consistent agreement between axially and bend-loaded, strain-controlled cyclic crack growth rates for the analysis scheme used.

5. SUMMARY AND CONCLUSIONS

Crack growth rates under reversed tension-compression, strain-controlled loading were measured for both the axial and bending case for A-212B carbon steel, 2-1/4 Cr-1 Mo, and Type 304 steels. Both through-cracked and part-through-cracked specimen configurations were employed for axial loading, and the part-through cracked case for bending tension-compression. From the results of these tests, the following conclusions were drawn:

1. Crack growth rates in through-cracked plate specimens tested in strain-controlled, reversed tension-compression are independent of crack length and are an exponential function of strain range with no apparent effect of thickness in the range of 0.25 to 0.8 inch.
2. Crack growth rates in part-through, surface-cracked plates loaded in tension-compression are, prior to penetration, less than those for through-cracked plates at the same nominal strain range and are an apparent function of geometry. This report suggests a procedure for correlating these geometry effects.
3. Crack growth rates at room temperature in part-through, surface-cracked plates loaded in bending tension-compression are considerably less than those in a through-cracked axially loaded plate specimen. For a given strain range, crack growth rates in the bend specimens appear to be less at 550°F than those at room temperature. However, these results are meager and require verification.
4. Comparison of results of both axial and bending strain-controlled tests with those obtained previously under stress-controlled conditions indicates good correlation on the basis of stress intensity factor range, ΔK , derived from currently available fracture mechanics concepts.

Table 5
ANALYSIS OF PTC CANTILEVER BEND TESTS
OF 2-1/4 Cr-1 Mo STEEL

A. Typical Crack Front Contours and Calculations

	↓ 0.11 in. ↑	→ 0.500 in. ←	→ 1.30 in. ←	↓ 0.30 in. ↑	
c	0.11	0.30			
c/2a	0.22	0.231			
c/a	0.44	0.46			$K_I/\sigma = M_B \sqrt{c/Q} \sqrt{\pi}$ (Reference 7)
c/t	0.14	0.375			
a	0.25	0.65			$Q = [\phi^2 - 0.212 (\sigma/\sigma_{ys})^2]$
M_B	0.85	0.85			
ϕ^2	1.42	1.39			$\phi = \int_0^{\pi/2} \left[1 - \left(\frac{a^2 - c^2}{a^2} \right) \sin^2 \phi \right]^{1/2} d\phi$ (Reference 8)
Q_1	1.21	1.18			
$\sqrt{c/Q_1}$	0.301	0.50			
$M_B \sqrt{c/Q_1} \sqrt{\pi}$	0.45	0.75			
K	0.45 σ	0.75 σ			

B. Results for 2-1/4 Cr-1 Mo Steel

Total Strain Range (%)	Crack Length 2a, inches	Total Moment (in.-lb)	Total Range of Stress (psi)	Stress Intensity Factor Range ΔK , psi $\sqrt{\text{in.}}$	da/dN $\mu\text{-in./cycle}$
±0.3	0.50	14,100	135,500	93,000	0.00009
	1.30	12,900	124,000	93,300	0.00015
±0.5	0.50	13,200	127,000	87,000	0.00018
	1.30	11,820	114,000	85,700	0.0003
±0.7	0.50	16,400	157,500	108,000	0.000445
	1.30	14,600	141,000	106,000	0.00071
±1.0	0.50	18,200	175,000	120,000	0.001
	1.30	16,200	156,000	117,500	0.002

SECTION 6

ILLUSTRATIONS

This section contains illustrations 1 through 32.

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Type 304

100X

Carbon Steel 250X

2-1/4 Cr - 1 Mo 250X

Figure 1. Microstructural Features of Plate Steels

(A) Through crack plate spec.

(C) Cantilever bend spec.

(B) Part-through crack spec.

Figure 2. Configuration of Crack Growth Specimens

Figure 3. Crack Growth Curves for A-212B Steel at Room Temperature

Figure 4. Crack Growth Curves for 2-1/4 Cr-1Mo Steel at Room Temperature

Figure 5. Crack Growth Curves for Type-304 Steel at Room Temperature

Figure 6. Crack Growth Curves for 0.25-Inch-Thick 2-1/4 Cr-1Mo at Room Temperature, Strain Range = $\pm 0.4\%$

Figure 7. Tension Load as a Function of Crack Length in Tension-Compression Through-Cracked Plates

A-212B

2 1/4 Cr - 1 Mo

Type 304

Figure 8. Typical Fracture Appearance of Axially-Loaded Plate Specimens. 2X

Figure 9. Surface Crack Growth Curves for PTC Specimens and Through-Crack Plates of 2-1/4 Cr-1 Mo Tested at $\pm 0.2\%$ Total Strain at RT

Figure 10. Load as a Function of Cycles for PTC Specimens of 2-1/4 Cr-1 Mo Steel Tested at $\pm 0.2\%$ Total Strain Range

Figure 11. Comparison of Surface and Depth Crack Growth Curves for Part-Through Crack Specimens of 2-1/4 Cr-1 Mo

(a) PTC - 1" x 0.2"

(b) PTC - 2" x 0.2"

(c) FS - 5" x 0.1"

Figure 12. Macroscopic Features of Fracture Surfaces of 0.8-Inch-Thick 2-1/4 Cr-1 Mo Specimens Cycled $\pm 0.2\%$ at Room Temperature 2X

PTC - 0.5" x 0.2"

PTC - 0.5" x 0.1"

Figure 13. Fracture Appearance of PTC Specimens of 0.8-Inch-Thick 2-1/4 Cr-1 Mo Cycled $\pm 0.2\%$ at Room Temperature

Figure 14. Correlation of Crack Growth Rate and Total Strain Range for 2-1/4 Cr-1 Mo Steel at Room Temperature

Figure 15. Crack Growth at Room Temperature as a Function of Total Strain Range for A-212B Carbon Steel

Figure 16. Crack Growth at Room Temperature as a Function of Total Strain Range for Type-304 Stainless Steel

Figure 17. Crack Growth Correlation for 2-1/4 Cr-1 Mo Alloy with Various Loading Schemes for Both 5.0-Inch- and 14.0-Inch-Wide Specimens

Figure 18. Change in Crack Length, Load, and Stress Intensity Factor for a Through-Crack Plate Specimen as a Function of Number of Cycles for Type-304 Stainless Steel, Strain Range = 0.4%

Figure 19. Correlation Between Measured and Predicted Crack Growth Rates in PTC Specimens of 2-1/4 Cr-1 Mo Steel Tested at Total Strain Range of 0.4% at Room Temperature

Figure 20. Crack Growth Curves for A-212B Carbon Steel at Room Temperature in Reversed Bending-Loaded Beams

Figure 21. Crack Growth Curves for 2-1/4 Cr-1 Mo Steel at Room Temperature in Reversed Bend-Loaded Beams

Figure 22. Crack Growth Curves for Reverse-Loaded Bend Beams of A-212B at 550°F

Figure 23. Crack Growth Curves for Reverse-Loaded Beams of 2-1/4 Cr-1 Mo at 550°F

Figure 24. Crack Length and Applied Moments as a Function of Cycles for A-212B at Room Temperature and 550°F at $\pm 0.5\%$ Total Strain

GEAP-10181

Figure 25. Crack Length and Applied Moment as a Function of Cycles for 2-1/4 Cr-1 Mo at Room Temperature and 550°F at $\pm 0.5\%$ Total Strain

A-212B Carbon Steel

2 1/4Cr-1Mo Alloy

Figure 26. Fracture Surfaces of Bend Specimens at Room Temperature 1X

$\pm 0.35\%$

$\pm 0.5\%$

A-212B Carbon Steel

$\pm 0.35\%$

$\pm 0.5\%$

2 1/4 Cr-1 Mo Steel

Figure 27. Fracture Surfaces of Bend Specimens at 550°F 2X

Figure 28. Comparison of Tension-Compression Versus Bend Loading on Correlation of Crack Growth Rate and Total Strain Range for A-212B Steel at Room Temperature

Figure 29. Comparison of Tension-Compression Versus Bend Loading on Correlation of Crack Growth Rate and Total Strain Range For 2-1/4 Cr-1 Mo Alloy at Room Temperature.

Figure 30. Comparison of 2-1/4 Cr-1 Mo and A-212B with A-201 Steel (Ref. 3) Tested as Surface-Cracked Cantilever Beams

Figure 31. Approximate Stress Intensity Factors at $\alpha = 0^\circ$ and $\alpha = 90^\circ$ for Surface Flaws in Bending (Ref. 7)

Figure 32. Crack Growth Correlation for 2-1/4 Cr-1 Mo Alloy Under Various Loading Schemes

APPENDIX

TABULATION OF CRACK GROWTH CURVES

No.	Material	Temp. (°F)	Total Strain Range, %	Notes
A-1	2-1/4 Cr - 1 Mo	RT	0.8	PTC 0.25 in. x 0.050 in., Axial
B-1	"	"	0.8	" " "
C-1	"	"	0.8	Through-cracked plate, Axial
D-1	"	"	0.8	" " "
E-1	"	"	0.6	" " "
F-1	"	"	0.4	" " "
G-1	"	"	0.25, 0.30, 0.4	" " "
H-1	"	"	1.0	" " "
I-1	"	"	0.25	" " "
J-1	"	"	0.25, 0.30, 0.40	" " "
K-1	"	"	0.6	Part-through crack, bending
L-1	"	"	1.0	" " "
M-1	"	550	0.7	" " "
N-1	"	RT	1.4	" " "
O-1	"	"	2.0	" " "
P-1	"	"	1.0	" " "
Q-1	"	"	0.4	Part-through crack, Axial, 0.8 in.
R-1	"	"	0.4	" " "
S-1	"	"	0.4	" " "
T-1	"	"	0.4	" " "
U-1	"	"	0.4	Face-slotted plate
V-1	"	550	1.0	Part-through crack, Bending
A-2	A-212B	RT	0.25	Through-cracked plate, Axial
B-2	"	"	0.75	" " "
C-2	"	"	0.30	" " "
D-2	"	"	0.25	" " "
E-2	"	"	0.35	" " "
F-2	"	"	1.0	" " "
G-2	"	"	1.0	" " "
H-2	"	"	0.6	Part-through crack, Bending
I-2	"	"	1.0	" " "
J-2	"	"	0.7	" " "
K-2	"	"	1.0	" " "
L-2	"	"	1.4	" " "
M-2	"	550	1.0	" " "
N-2	"	"	0.7	" " "
A-3	Type 304	"	0.18	Through-cracked plate, Axial
B-3	"	"	0.25	" " "
C-3	"	"	0.4	" " "
D-3	"	"	0.6	" " "
E-3	"	"	0.75	" " "
F-3	"	"	1.0	" " "

Spec.: A-1-Axial

2-1/4 Cr - 1 Mo

RT

Total Strain Range: 0.8%

0.25" Plate - PTC 0.25" x 0.050"

GEAP-10181

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length (2a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
1	67,200	67,900	.25
10	67,200	67,900	.25
20	67,200	68,200	.26
30	67,200	68,300	.30
40	67,100	68,300	.32
50	67,100	68,300	.35
60	67,100	68,500	.36
75	67,500	69,000	.38
90	67,100	68,800	.40
100	66,100	68,300	.56
110	56,700	61,900	.93
120	53,700	67,000	1.35
130	43,500	48,000	2.10
140	36,000	41,800	2.45
150	32,200		2.78
160	28,800	34,500	3.12
170	25,200	31,800	3.35
180	22,500	27,100	3.55
190	19,500	24,000	3.92
200	16,500	21,700	4.02
210	14,500	13,800	4.25
220	11,200	10,400	4.38
230	7,900	8,100	4.55
240	5,700	6,800	4.72

Spec: B-1-Axial

GEAP-10181

2-1/4 Cr - 1 Mo

RT

Total Strain Range: 0.8%

0.25" Plate - PTC 0.25" x 0.050"

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length (2a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
10	66,600	67,000	.25
20	64,500	65,900	.26
30	64,300	65,200	.28
40	64,800	65,200	.29
50	64,700	65,200	.29
75	63,800	64,700	.31
100	63,800	64,700	.36
125	63,800	64,600	.37
150	63,500	64,600	.41
175	63,500	64,700	.49
200	60,700	63,000	.71
210	55,800	60,800	.88
220	52,900	57,300	1.17
230	50,700	54,000	1.38
240	47,700	51,300	1.60
250	44,800	48,800	1.82
260	41,700	45,800	2.07
270	38,100	41,300	2.25
280	35,700	39,400	2.50
290	34,200	37,600	2.68
300	31,500	34,900	2.79
310	30,000	33,300	2.90
320	27,800	31,700	3.02
330	25,800	29,000	3.16
340	24,300	28,600	3.30
350	22,800	25,500	3.40
360	22,200	24,600	3.47
370	20,700	24,300	3.58
380	18,900	23,700	3.67
390	18,000	22,200	3.71
400	16,600	22,200	3.88
410	15,300	20,300	4.00
420	13,600	18,000	4.10
430	12,300	18,000	4.25
441	9,600	13,800	4.37

Spec: C-1-Axial

2-1/4 Cr - 1 Mo

RT

Total Strain Range: 0.8%

GEAP-10181

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
10	70,800	73,200	.11
20	70,100	72,800	.15
30	48,100	72,200	.23
42	-	-	.40
50	63,100	68,400	.75
60	58,500	63,800	1.04
70	48,800	52,800	1.58
80	46,500	52,800	1.95
90	39,800	45,700	2.32
100	35,200	41,400	2.70
110	30,800	36,100	3.02
120	26,700	32,100	3.32
130	22,600	28,500	3.56
140	18,600	23,700	3.82
150	16,500	22,500	4.02
160	13,500	18,600	4.14
170	9,600	16,500	4.38
180	5,700	11,700	4.67
186	-	-	4.92

Spec: D-1-Axial

2-1/4 Cr - 1 Mo

RT

Total Strain Range: 0.8%

Number of Cycles	Load, Lbs.		Crack Length (2a) Inches
	Tension	Compression	
2	66,300	67,300	.11
10	67,300	67,700	.23
20	63,800	67,300	.41
30	61,400	67,700	.70
40	52,700	58,100	1.28
50	45,400	50,200	1.75
60	40,200	45,800	2.20
70	35,300	40,800	2.60
80	31,700	38,000	2.82
90	27,300	33,400	3.06
100	25,600	31,200	3.22
110	22,800	27,800	3.46
120	20,300	26,000	3.61
130	17,700	23,000	3.83
140	15,400	20,800	3.97
150	13,600	19,600	4.14
160	10,800	17,100	4.30
170	9,000	15,000	4.48
180	3,700	10,800	4.69

Spec: E-1-Axial
 2-1/4 Cr - 1 Mo
 RT
 Total Strain Range, 0.6%

Number of Cycles	Load, Lbs.		Crack Length 2(a) Inches
	Tension	Compression	
3			.51
25	60,700	40,300	.53
50	61,700	40,200	.55
76	62,300	41,500	.66
100	61,700	41,200	.66
125	62,800	41,800	.70
150	63,000	42,000	.75
175	62,500	41,600	.80
200	63,200	42,200	.86
225	61,700	41,100	.92
250	62,400	41,600	.98
275	62,000	41,300	1.07
300	62,400	41,600	1.14
325	62,200	41,500	1.22
350	62,400	41,600	1.30
375	52,500	35,000	1.38
400	52,400	34,900	1.47
425	52,800	35,200	1.58
450	52,300	31,600	1.67
475	48,000	32,000	1.75
500	-	-	1.84
525	-	-	1.96
550	447	29,800	2.07
575	-	-	2.17
600	-	-	2.26
625	-	-	2.36
650	397	26,500	2.44
675	402	26,800	2.56
700	375	24,700	2.68
725	58,100	25,400	2.80
750	35,000	23,300	2.92
775	35,400	23,600	2.98
800	34,500	23,000	3.06
825	35,200	23,400	3.17
850	36,000	24,000	3.21
875	28,600	19,100	3.29
900	30,000	20,000	3.38
925	-	-	3.42
950	29,300	19,500	3.61
975	27,000	18,000	3.74
1,000	26,300	17,500	3.86

Spec: F-1-Axial

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2-1/4 Cr - 1 Mo

RT

Total Strain Range: 0.4%

Number of Cycles	Load, Lbs.		Crack Length 2(a) Inches
	Tension	Compression	
1	84,200	56,000	.52
40	-	-	.56
50	66,200	44,200	.62
75	66,200	44,200	.70
100	65,300	43,500	.77
125	65,300	42,500	.82
150	62,300	41,500	.90
175	-	-	.96
200	60,700	40,500	1.02
225	60,600	40,300	1.07
250	57,800	38,500	1.11
275	55,800	37,200	1.16
300	57,000	38,000	1.21
325	56,300	37,500	1.25
350	56,300	35,000	1.30
375	56,200	37,400	1.36
400	52,800	38,500	1.41
425	53,200	35,500	1.45
450	54,700	36,500	1.49
500	52,800	35,200	1.59
525	53,200	35,500	1.64
550	52,200	34,800	1.69
575	51,700	34,500	1.74
600	51,700	23,500	1.78
650	46,000	30,700	1.87
675	45,700	30,500	1.91
700	45,400	30,300	1.95
725	46,300	30,900	2.00
750	43,000	30,700	2.04
775	43,000	28,700	2.07
800	42,700	28,500	2.11
825	43,200	28,800	2.16
850	43,300	28,900	2.19
875	43,500	29,000	2.23
900	42,700	28,500	2.27
925	42,700	28,000	2.31
950	42,700	28,500	2.36
975	40,600	27,000	2.40
1,000	41,200	27,400	2.44
1,025	40,200	26,800	2.49
1,050	40,200	26,800	2.53
1,100	39,600	26,400	2.62
1,125	37,700	25,100	2.65
1,150	36,800	24,500	2.69

(cont'd.)

Spec: F-1-Axial (cont'd.)

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
1,175	36,600	24,400	2.72
1,200	35,800	23,800	2.77
1,225	35,400	23,600	2.82
1,250	32,300	21,500	2.86
1,275	33,100	22,000	2.90
1,300	33,700	22,400	2.93
1,325	32,300	21,500	2.97
1,350	32,700	21,800	3.00
1,375	32,200	21,400	3.03
1,400	30,800	20,500	3.06
1,425	30,800	20,500	3.09
1,450	30,800	20,500	3.12
1,500	29,100	15,000	3.18
1,550	27,500	18,300	3.22
1,600	26,200	17,500	3.31
1,650	26,200	17,500	3.48
1,675	24,600	16,400	-
1,700	24,400	16,300	3.52
1,725	24,200	16,100	3.58
1,750	22,900	15,300	3.64
1,775	21,700	14,500	3.70
1,800			3.72
1,825			3.72
1,850			3.74

Spec: G-1-Axial

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2-1/4 Cr - 1 Mo

RT

Total Strain Range: 0.25%, 0.30%, 0.4%

Number of Cycles	Load, Lbs.		Crack Length 2(a), Inches
	Tension	Compression	
32	46,600	49,600	.50
225	46,200	48,700	
385			
500	45,800	46,200	.60
733	45,800	48,700	.65
825	46,200	49,500	.69
827			
1,015	43,500	45,800	.73
Increased strain to <u>+0.15%</u>			
1,025	45,800	50,800	.73
1,290	45,200	49,400	.84
1,535	44,800	44,800	.91
1,840	42,800	40,600	1.02
2,080	43,500	44,300	1.06
2,100	46,600	51,800	1.08
Increased strain to <u>+0.20%</u>			
2,150	46,600	51,000	1.10
2,200	46,600	51,800	1.13
2,250	46,600	51,800	1.16
2,300	44,300	51,800	1.19
2,350	46,600	52,700	1.22
2,400	46,600	52,700	1.24
2,450	45,000	51,000	1.26
2,500	44,300	49,600	1.28
2,550	45,000	49,800	1.30
2,600	44,200	49,500	1.33
2,650	45,000	49,500	1.36
2,750	43,500	45,700	1.41
2,800	43,500	45,700	1.43
2,850	42,800	45,500	1.46
2,900	42,800	45,500	1.48
2,950	38,600	45,300	1.51
3,000	42,600	45,000	1.53
3,050	42,700	45,300	1.56
3,100	42,800	45,700	1.58
3,150	42,600	45,500	1.61
3,300	41,200	44,700	1.69
3,350	40,500	41,200	1.72
3,400	40,500	42,000	1.75
3,450	40,200	42,000	1.79
3,500	39,600	39,700	1.82
3,550	39,700	39,700	1.84
3,600	39,600	40,200	1.86
3,650	39,400	39,700	1.88

(cont'd.)

Spec: G-1-Axial (cont'd.)

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
3,700	39,400	40,300	1.90
3,750	39,400	40,000	1.83
3,800	39,000	39,700	1.97
3,850	38,600	40,000	2.00
3,900	38,700	39,900	2.02
3,950	37,800	39,000	2.04
4,000	38,000	39,000	2.06
4,050	37,600	38,800	2.08
4,100	37,700	39,200	2.11
4,150	37,400	39,000	2.15
4,200	37,400	38,800	2.18
4,250	36,000	39,400	2.21
4,300	35,900	39,500	2.23

Spec: H-1-Axial

2-1/4 Cr - 1 Mo

RT

Total Strain Range: 1.0%

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
2	63,740	64,500	.56
10	62,250	61,800	.69
25	58,800	61,500	1.30
50	47,250	51,300	2.15
75	34,500	34,500	2.95
100	26,550	27,300	3.50
125	18,000	20,200	3.95
135	9,750	12,750	4.28

Spec: I-1-Axial
 2-1/4 Cr - 1 Mo
 RT
 Total Strain Range: 0.25%

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
30	541	360	.50
75	543	362	.51
100	543	362	.52
150	548	365	.53
200	546	364	.54
250	543	362	.56
300	527	351	.57
350	522	347	.58
400	524	348	.59
450	524	348	.60
500	518	345	.61
550	523	348	.62
600	520	347	.63
650	502	335	.65
700	518	345	.66
750	525	349	.67
800	525	349	.68
850	523	348	.69
900	520	347	.70
950	520	346	.71
975	520	345	-
1,000	511	340	.73
1,050	537	348	.74
1,100	545	363	.75
1,150	552	368	.75
1,200	534	356	.76
1,250	524	349	.77
1,300	515	343	.78
1,350	512	340	.79
1,400	513	342	.80
1,450	512	340	.81
1,500	495	330	.83
1,550	508	338	.84
1,600	504	336	.85
1,650	460	312	.86
1,700	460	307	.87
1,750	464	309	
1,800	460	307	

Spec: J1-J2-Axial

2-1/4 Cr - 1 Mo

RT

Total Strain Range: 0.25%, 0.3%, 0.4%

<u>Number of Cycles</u>	<u>Crack Length 2(a) Inches</u>	<u>Number of Cycles</u>	<u>Crack Length 2(a) Inches</u>
25	-	3,300	1.69
100	-	3,500	1.82
200	.53	3,700	1.90
300	.55	3,900	2.02
400	.58	4,100	2.11
500	.60	4,300	2.23
600	.63	4,500	2.35
700	.65	4,700	2.51
800	.68	5,000	2.77
900	.70	5,100	2.87
1,000	.72	5,300	3.06
1,015	.73	5,500	3.19
Changed strain to 0.3%		5,700	3.31
1,100	.76	5,900	3.42
1,200	.80	6,100	3.52
1,300	.84	6,200	3.59
1,400	.87		
1,500	.91		
1,600	.94		
1,700	.98		
1,900	1.03		
2,080	1.06		
Changed strain to 0.4%			
2,100	1.08		
2,200	1.13		
2,400	1.24		
2,600	1.33		
2,700	1.39		
2,900	1.48		

Spec: K-1- Bending

2-1/4 Cr - 1 Mo

RT

Total Strain Range: 0.6%

Number of Cycles	Load, Lbs.		Crack Length 2(a) Inches
	Tension	Compression	
10	870	630	0
40	880	"	0
90	"	"	.26
170	885	"	.28
230	"	"	.29
270	890	"	.29
308	875	660	.29
341	875	"	.30
432	880	"	.32
535	"	650	.33
756	890	620	.35
920	895	640	.37
1,103	900	640	.41
1,180	895	645	.42
1,280	890	"	.43
1,380	"	640	.44
1,560	"	"	.47
1,680	"	635	.49
1,780	895	630	.51
1,880	900	"	.53
1,926	880	645	-
1,980	"	"	.54
2,080	885	640	.56
2,180	890	"	.58
2,250	895	635	.59
2,380	"	630	.61
2,490	"	630	.63
2,700	895	610	.66
2,800	"	630	.69
2,920	890	615	.72
3,200	"	615	.77
3,320	"	610	.79
3,470	"	600	.82
3,620	"	630	.86
3,750	850	610	.88
3,850	880	610	.91
3,930	"	595	.93
4,080	"	595	.96
4,200	890	580	.99
4,290	"	"	1.01
4,400	"	"	1.04
4,500	880	575	1.06
4,640	885	570	1.09
4,730	880	560	1.11
4,880	885	550	1.15
5,000	885	545	1.18

(cont'd.)

Spec: K-1-Bending (cont'd.)

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
5,100	890	540	1.22
5,240	865	555	1.26
5,390	860	540	1.29
5,510	865	530	1.33
5,680	880	510	1.38
5,840	880	500	1.42
5,980	800	490	1.47
6,080	870	490	1.51
6,200	865	485	1.56
6,340	860	460	1.60
6,490	850	445	1.65
6,610	840	430	1.68
6,850	795	420	1.84
6,970	780	390	1.90
7,080	775	370	1.94
7,200	750	340	1.96

Spec: L-1-Bending

2-1/4 Cr - 1 Mo

RT

Total Strain Range: 1.0%

Moment Arm = 9.25"

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<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
5	830	720	-
140	800	680	.27
365	785	690	.31
560	785	685	.38
650	810	710	.40
875	810	710	.42
1,160	890	700	.46
1,420	730	730	.52
1,750	700	705	.57
1,900	690	720	.59
2,340	710	700	.72
2,630	710	700	.75
3,000	705	700	.79
3,300	710	685	.82
3,560	710	690	.85
3,960	710	685	.89
4,320	700	690	.92
4,650	700	690	.95
5,000	690	690	.99
5,410	685	695	1.07
5,700	675	685	1.12
6,067	670	670	-
6,330	670	670	1.24
6,620	650	685	1.32
6,900	660	675	1.38
7,120	660	670	1.46
7,540	625	660	1.60
7,820	615	660	1.77

Spec: M-1-Bending
 2-1/4 Cr - 1 Mo
 550°F
 Total Strain Range: 0.7%

Number of Cycles	Load, Lbs.		Crack Length 2(a) Inches
	Tension	Compression	
9	860	845	0
91	830	840	0
400	850	810	.28
670	850	825	.31
850	850	880	.34
1,100	830	880	.38
1,300	830	830	.42
1,510	830	830	.44
1,650	840	850	.46
1,925	840	850	.50
2,170	880	860	.53
2,550	900	860	.58
3,190	900	840	.64
3,560	840	845	.69
3,711	800	830	.73
4,100	800	830	.77
4,700	800	820	.81
5,510	790	810	.84
5,380	830	840	.88
5,860	830	840	.98
6,530	830	840	1.01
7,020	830	840	1.03
7,600	780	840	1.07
7,950	780	840	1.09
8,630	760	830	1.12
9,000	760	830	1.15
9,370	830	810	1.18
9,640	845	780	1.21
10,350	845	770	1.26
10,930	790	740	1.36
11,120	780	730	0
11,440	800	710	0
11,660	800	720	0
11,980	790	690	0
12,302	800	690	0
12,800	790	700	0
13,125	800	680	0
13,530	820	660	0
13,880	820	660	0
14,110	730	540	0
14,260	730	520	00

Spec: N-1-Bending
 2-1/4 Cr - 1 Mo
 RT
 Total Strain Range: 1.4%
 Moment Arm = 9.81

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<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
6	880	780	0
25	"	780	.26
70	885	"	.28
145	900	"	.32
210	"	"	.35
300	910	785	.40
375	"	765	.45
470	915	755	.51
540	"	750	.54
700	925	750	.68
800	915	730	.79
890	905	710	.90
1,000	890	690	1.00
1,120	880	675	1.16
1,240	870	620	1.36
1,310	870	610	1.45
1,480	860	520	1.75
1,610	820	425	2.03

Spec: 0-1-Bending
 2-1/4 Cr - 1 Mo
 RT
 Total Strain Range: 2.0%
 Moment Arm: 9.13"

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
11	1,110	860	0
20	1,110	865	.26
40	1,115	"	.29
65	1,120	870	.32
130	1,125	"	.40
180	1,125	"	.47
240	"	850	.59
280	"	825	.69
313	1,100	840	-
330	1,110	830	.83
364	1,100	795	.94
400	1,090	760	1.07
420	1,080	740	1.16
460	1,075	700	1.30
500	1,050	680	1.50
540	1,020	560	1.70
590	960	445	2.08

Spec: P-1-Bending
 2-1/4 Cr - 1 Mo
 RT
 Total Strain Range: 1.0%
 Moment Arm - 8.31"

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
350	890	690	.35
500	870	710	.38
700	890	700	.45
900	900	680	.50
1,000	900	675	.54
1,200	900	670	.625
1,300	895	660	.66
1,500	890	640	.73
1,700	885	680	.825
1,900	895	615	.90
2,000	885	620	.95
2,200	885	600	1.03
2,400	890	555	1.125
2,500	890	555	1.175
2,700	890	540	1.30
2,900	885	530	1.40
3,000	870	490	1.45
3,100	865	480	1.50
3,400	810	435	1.63

Spec: Q-1-Axial

2-1/4 Cr - 1 Mo

RT

Total Strain Range: 0.4%

PTC - 0.8" Thick

<u>Number of Cycles</u>	<u>Crack Length 2(a) Inches</u>	<u>Number of Cycles</u>	<u>Crack Length 2(a) Inches</u>
11	0	7,580	1.90
273	.550	7,960	1.90 up to 0.4%
356	0.59 down to 0.2%	8,000	1.96
650	.600	8,040	2.10 down to 0.06%
1,400	.60	8,300	2.12
1,700	.63	8,610	2.13
1,950	.65	9,045	2.15 up to 0.4%
1,989	up to 0.4%	9,066	2.30
2,250	0.750 down to 0.05%	9,100	2.40
2,350	.77	9,166	2.54 down to 0.06%
2,750	.77	9,500	2.54
2,940	.78	9,750	2.55
2,962	-	10,162	2.55 up to 0.4%
3,170	.78	10,200	2.67
3,360	0.78 up to 0.4%	10,236	2.74
3,640	1.06 down to 0.05%	10,275	2.82
3,930	1.06	10,300	2.90
4,180	1.06	10,330	2.95 down to 0.06%
4,646	1.06 up to 0.4%	10,440	2.95
4,710	1.17	10,725	2.96 up to 0.4%
4,770	1.27 down to 0.075%	11,409	2.96
4,890	1.27	11,436	3.04
5,050	1.27	11,480	3.10
5,200	1.28	11,500	3.13
5,281	-		
5,400	1.30 down to 0.06%		
5,420	1.30		
5,500	1.30		
5,620	1.31		
5,770	1.31 up to 0.4%		
5,790	1.40		
5,850	1.51 down to .06%		
6,220	1.51		
6,400	1.51		
6,650	1.52		
6,850	1.52 up to 0.4%		
6,884	1.70		
6,960	1.90 down to 0.06%		
7,220	1.90		
7,420	1.90		

Spec: R-1-Axial

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2-1/4 Cr - 1 Mo

RT

Total Strain Range: 0.4%

PTC - 0.8" Thick

<u>Number of Cycles</u>	<u>Crack Length 2(a) Inches</u>	<u>Number of Cycles</u>	<u>Crack Length 2(a) Inches</u>
7	0	5,200	1.87
50	0	5,273	1.88 down to 0.04%
100	0	5,696	1.90 up to 0.04%
765	0	5,715	2.05
895	.55	5,728	2.12
959	0.60 down to 0.06%	5,740	2.40
1,080	.60	5,755	2.39 down to 0.04%
1,330	.61	6,130	2.40
1,986	0.61 up to 0.04%	6,620	2.40
2,026	.66	6,700	2.40
2,095	.70	6,770	2.46 up to 0.4%
2,178	0.80 down to 0.06%	6,780	2.65
2,260	.80	6,790	2.89
2,470	.80	7,100	2.90
2,640	.80	7,430	2.95
3,050	.80	7,580	2.95
3,195	0.80 up to 0.4%	7,795	2.98 up to 0.04%
3,250	.89	7,802	3.20
3,340	1.05	7,808	3.40
3,420	1.34 down to 0.06%		
3,720	1.36		
3,965	1.40		
4,050	1.40 down to 0.05%		
4,642	1.60		
4,665	1.72		
4,680	1.80 down to 0.05%		
4,900	1.80		
5,095	1.81		

Spec: S-1-Axial
 2-1/4 Cr - 1 Mo
 RT
 Total Strain Range: 0.4%
 PTC 2" x 0.2"

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
25	140,000	135,000	2.00
35	140,000	135,000	2.005
50	146,000	131,000	2.01
70	146,000	128,000	2.04
100	146,000	121,000	2.05
130	138,000	134,000	2.06
180	133,000	135,000	2.08
250	133,000	124,000	2.16
275	130,000	128,000	2.22
300	130,000	120,000	2.29
325	128,000	122,000	2.29
350	115,000	127,000	2.34
375	120,000	120,000	2.385
400	114,000	92,000	2.42
410	-	-	2.48
425	111,000	132,000	2.50
450	114,000	117,000	2.52
475	110,000	114,000	2.57
500	107,000	109,000	2.58
550	104,000	104,000	2.68
600	98,000	92,000	2.72
650	84,000	90,000	2.81
700	78,000	80,000	3.08
750	73,000	72,000	3.20
800	70,000	69,000	3.30
900	62,000	62,000	3.50
950	48,000	59,000	3.59

Spec: T-1-Axial

2-1/4 Cr - 1 Mo

RT

Total Strain Range: 0.4%

PTC 1.0" x 0.2"

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
20	143,000	146,000	0
70	144,000	148,000	0
100	148,000	147,000	0
300	151,000	146,000	0
415	148,100	148,000	1.07
450	146,000	146,000	1.09
500	148,000	145,000	1.11
550	148,000	147,000	1.13
595	144,000	145,000	1.15
650	145,000	141,000	1.18
750	144,000	141,000	1.26
850	142,000	142,000	1.41
950	138,000	139,000	1.53
1,050	135,000	134,000	1.67
1,150	126,000	126,000	1.88
1,250	109,000	111,000	2.27
1,300	102,000	104,000	2.41
1,350	85,000	80,000	2.81
1,400	79,000	73,000	2.91
1,450	74,000	72,000	2.99
1,550	70,000	68,000	3.14
1,650	62,000	59,000	3.31
1,750	58,000	56,000	3.43
1,850	52,000	55,000	3.58
1,900	50,000	52,000	3.62
1,950	46,000	50,000	3.67
2,025	42,000	43,000	3.76

Spec: U-1-Axial

2-1/4 Cr - 1 Mo

RT

Total Strain Range, 0.4%

Spec FS

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
8	150,000	145,000	0
20	150,400	144,000	.01
40	"	144,000	.02
60	"	143,600	.03
80	"	142,800	.04
100	"	142,400	.05
120	150,000	140,600	.05
140	150,400	140,600	.06
160	"	140,600	.07
180	"	138,800	.07
200	150,600	124,200	.08
210	152,000	126,000	.10
220	"	126,400	.12
225	"	134,000	.15
230	145,000	136,800	.22
235	134,800	132,200	.28
240	118,400	128,000	.30
245	99,000	88,600	.32
250	114,000	130,000	.34
255	108,800	133,600	.38
260	100,400	132,400	.43
265	99,000	134,600	.52

Spec: V-1-Bending
A-212B
550°F
Total Strain Range: 1.0%

<u>Number of Cycles</u>	<u>Crack Length 2(a) Inches</u>
1,250	.475
1,900	.59
2,650	.75
3,150	.80
3,950	.87
5,100	1.0
5,800	1.15
6,350	1.23
6,650	1.31
7,250	1.48
7,850	1.675

Spec: A-2-Axial

A-212B

RT

Total Strain Range: 0.25%

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
22	60,000	80,000	.83
39	54,000	75,000	.99
81	50,250	78,000	1.30
99	46,500	72,000	1.46
135	41,250	67,500	1.90
140	41,000	61,500	1.94
171	32,500	62,000	2.16
219	35,200	61,000	2.43
270	32,300	63,000	2.70
291	30,800	60,800	2.77
321	29,300	60,000	2.90
339	28,100	57,800	2.97
405	24,700	59,200	3.25
444	21,800	60,700	3.43
477	19,500	58,500	3.59
537	16,500	57,700	3.83
573	15,000	57,700	3.93
612	12,700	57,200	3.98

Spec: B-2-Axial
A-212B
RT
Total Strain Range: 0.75%

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
1	56,700	58.5	.50
3	53,200	57.9	.62
10	49,200	52.6	1.20
25	42,750	48.6	1.95
50	28,800	37.5	2.88
60	22,200	29.4	3.36
70	18,300	24.3	3.70
75	15,000	22.6	3.90
85	13,200	20.7	4.15
90	10,200	18.8	4.28
95	9,300	15.0	4.45

Spec: C-2-Axial
 A-212B
 RT
 Total Strain Range: 0.3%

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
200	37,900	25,200	1.71
250	37,300	24,800	1.83
300	37,100	24,700	1.91
350	-	-	1.99
400	35,100	23,400	2.08
450	-	-	2.15
500	32,700	21,800	2.22
550	-	-	2.29
600	31,800	21,200	2.36
650	-	-	2.42
700	-	-	2.49
750	30,000	20,000	2.54
800	29,000	19,300	2.60
850	29,400	-	2.66
900	28,400	-	2.73

Spec: D-2-Axial

GEAP-10181

A-212B

RT

Total Strain Range: 0.25%

Number of Cycles	Load, Lbs.		Crack Length 2(a) Inches
	Tension	Compression	
253	-	-	.52
275	-	-	.53
300	-	-	.54
325	-	-	.55
350	-	-	.56
375	42,800	48,000	.57
400	-	-	.58
575	-	-	.60
625	-	-	.61
675	44,200	44,200	.62
725	-	-	.63
750	-	-	.64
800	45,800	46,500	.65
825	-	-	.66
900	45,800	45,800	.67
925	-	-	.68
975	-	-	.69
1,000	-	-	.70
1,025	-	-	.71
1,050	-	-	.72
1,100	-	-	.73
1,125	-	-	.74
1,175	47,000	48,800	.75
1,200	-	-	.76
1,250	-	-	.77
1,300	-	-	.78
1,350	-	-	.79
1,400	43,200	45,200	.80
1,450	-	-	.81
1,500	-	-	.82

Spec: E-2-Axial

A-212B

RT

Total Strain Range: 0.350%

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
0	51,000	53,200	.83
35	-	-	.85
60	-	-	.87
110	-	-	.89
160	53,400	54,000	.92
210	-	-	.97
260	47,200	51,800	1.00
310	-	-	1.04
360	42,800	51,800	1.09
410	-	-	1.12
460	44,000	51,800	1.16
510	-	-	1.20
560	-	-	1.23
610	-	-	1.27
660	-	-	1.31
710	41,200	53,200	1.35
760	0	-	1.38
810	41,200	53,200	1.41
860	-	-	1.44
910	41,200	51,700	1.49
960	-	-	1.55
1,010	-	-	1.62
1,060	-	-	1.67
1,110	-	-	1.72
1,160	40,500	52,500	1.77

Spec: F-2-Axial
 A-212B
 RT
 Total Strain Range: 1.0%

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
25	53,300	76,500	2.1
34	66,500	73,500	2.3
41	41,300	72,600	2.5
50	36,000	72,000	3.0
59	31,500	72,000	3.25
69	27,000	70,500	3.60
80	21,800	69,600	3.85
90	16,500	70,500	4.30
95	-	-	-

Spec: G-2-Axial

A-212B

R:

Total Strain Range: 1.0%

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
0	70,000	0	0.5
10	0		0.63
20	68,000		0.80
30	65,000		0.90
40	62,000		1.00
50	58,000		1.04
60	56,000		1.12
70	54,000		1.20
80	53,000		1.30
90	52,000		1.40
100	50,000		1.46
110	49,000		1.60
120	47,000		1.70
130	46,000		1.85
140	41,000		1.90
150	0		1.99
160	0		2.09
170	33,000		2.19
180	0		2.28

Spec: H-2-Bending
 A-212B
 RT
 Total Strain Range, 0.6%
 Moment Arm = ND

Number of Cycles	Load, Lbs.		Crack Length 2(a) Inches
	Tension	Compression	
10	870	630	0
40	880	"	0
90	"	"	.26
170	885	"	.28
230	"	"	.29
270	890	"	.29
308	875	660	.29
341	"	"	.30
432	880	"	.32
535	"	650	.33
756	890	620	.35
920	895	640	.37
1,103	900	"	.41
1,180	895	645	.42
1,280	890	"	.43
1,380	"	640	.44
1,560	"	"	.47
1,680	"	635	.49
1,780	895	630	.51
1,880	900	630	.53
1,980	"	645	.54
2,080	885	640	.56
2,180	890	640	.58
2,250	895	635	.59
2,380	"	630	.61
2,490	"	630	.63
2,600	"	625	.64
2,700	895	610	.66
2,800	880	630	.69
2,920	890	615	.72
3,030	"	"	.74
3,200	"	610	.77
3,320	"	605	.79
3,470	"	600	.82
3,620	860	630	.86
3,750	850	610	.88
3,850	880	610	.91
3,930	880	595	.93
4,080	880	595	.96
4,200	890	580	.99
4,290	890	"	1.01
4,400	890	"	1.04
4,500	880	575	1.06
4,640	885	570	1.09
4,730	880	560	1.11
4,880	885	550	1.15

(cont'd.)

Spec: H-2-Bending (cont'd.)

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
5,000	885	545	1.18
5,110	890	540	1.22
5,240	865	555	1.26
5,390	860	540	1.29
5,510	865	530	1.33
5,680	880	510	1.38
5,840	880	500	1.42
5,980	880	490	1.47
6,080	870	"	1.51
6,200	865	485	1.56
6,340	860	460	1.60
6,490	850	445	1.65
6,610	840	430	1.65
6,610	840	430	1.68
6,710	-	-	-

Spec: i-z-Bending

A-212B

RT

Total Strain Range: 1.0%

Moment Arm = 8.44"

Number of Cycles	Load, Lbs.		Crack Length 2(a) Inches
	Tension	Compression	
15	780	670	0
40	785	650	0
90	780	630	.28
200	785	620	.31
244	775	625	0
340	780	615	.36
440	"	610	.40
530	"	600	.44
670	775	595	.48
760	785	590	.52
860	795	"	.55
960	"	580	.60
992	800	"	0
1,070	790	"	.64
1,200	795	570	.69
1,300	"	"	.73
1,440	800	555	.78
1,560	"	550	.83
1,660	805	545	.87
1,750	805	535	.90
1,900	790	545	.96
2,060	795	"	1.04
2,220	795	515	1.10
2,320	795	"	1.15
2,420	795	510	1.20
2,500	795	505	1.24
2,512	770	540	0
2,600	775	525	1.28
2,710	780	510	1.35
2,910	780	490	1.35
3,010	785	480	1.72
3,100	780	475	1.86
3,200	780	460	1.97
3,260	780	455	2.00
3,279	-	-	-

Spec: J-2-Bending

A-212B

RT

Total Strain Range: 0.7%

Moment Arm = not determined.

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
13	640	635	0
80	570	670	0
150	580	670	0
210	580	670	.26
400	580	690	.29
670	585	700	.31
791	580	680	0
900	580	680	.33
1,180	585	675	.34
1,380	580	675	.35
1,640	580	685	.37
1,770	580	685	.39
1,960	580	690	.40
2,300	580	690	.41
2,450	580	680	.42
2,760	580	680	.44
2,960	580	680	.45
3,200	580	690	.45
3,360	580	690	.46
3,550	575	700	.47
3,870	575	700	.47
4,070	575	690	.48
4,550	570	690	.49
	570	690	0
5,420	575	690	.55
6,000	570	690	.57
6,340	570	690	.58
6,930	575	690	.59
7,600	575	690	.60
8,240	575	690	.61
8,526	570	690	.61
9,120	570	680	.62
10,080	565	690	.66
10,680	570	690	.69
11,040	570	690	.70
11,450	570	690	.73
11,900	570	690	.74
13,250	650	715	.79
13,900	640	710	.83
14,300	640	710	.86
14,610	670	777	.90
15,220	670	780	.95
15,790	660	790	1.03
16,526	620	740	1.06
17,900	610	740	1.21
19,340	590	750	1.31
20,780	590	750	1.42
22,660	570	830	1.84

Spec: K-2-Bending
 A-212B
 RT
 Total Strain Range: 1.0%
 Moment Arm - 9.31"

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
15	780	670	-
90	780	630	.28
200	785	620	.31
440	780	610	.40
670	775	595	.48
760	705	590	.52
860	795	590	.55
960	795	580	.60
1,070	790	580	.64
1,200	795	570	.69
1,300	795	570	.73
1,440	800	555	.78
1,560	800	550	.83
1,660	805	545	.87
1,750	805	535	.90
1,900	790	545	.96
2,060	795	545	1.04
2,220	795	515	1.10
2,320	795	515	1.15
2,420	795	510	1.20
2,500	795	505	1.24
2,600	775	525	1.28
2,710	780	510	1.33
2,910	780	490	1.55
3,010	785	480	1.72
3,100	780	475	1.86
3,200	780	460	1.97

Spec: L-2-Bending

A-212B

RT

Total Strain Range: 1.4%

Moment Arm = 8.63"

Number of Cycles	Load, Lbs.		Crack Length 2(a) Inches
	Tension	Compression	
0	900	750	.27
60	860	730	.30
200	840	705	.42
320	830	680	.50
450	"	670	.60
570	825	660	.72
680	820	650	.83
800	"	645	.93
950	810	630	1.09
1,080	805	615	1.21
1,220	800	590	1.35
1,325	795	585	1.49
1,425	790	565	1.66
1,520	785	545	1.70
1,575	780	535	1.76
1,757	750	525	2.09

Spec: M-2-Bending
 A-212B
 550°F
 Total Strain Range: 1.0%

Number of Cycles	Load, Lbs.		Crack Length 2(a) Inches
	Tension	Compression	
70	960	860	.28
175	950	865	.33
233	1,000	880	.36
416	1,000	880	.39
560	1,000	880	.47
650	990	880	.50
800	990	870	.56
900	1,020	870	.57
1,095	990	870	.63
1,200	1,030	870	.66
1,315	1,030	870	.70
1,450	1,020	870	.71
1,610	1,020	870	.77
1,725	1,020	870	.82
1,840	1,020	870	.83
1,990	1,030	870	.84
2,150	1,040	870	.86
2,226	1,050	870	.88
2,415	1,040	870	.92
2,546	1,040	870	.95
2,750	1,030	850	1.00
2,865	1,030	850	1.05
3,065	1,030	850	1.11
3,300	1,040	850	1.16
3,430	1,080	850	1.20
3,510	1,080	850	1.22
3,603	1,080	850	1.27
3,770	1,080	825	1.31
3,975	1,085	825	1.36
4,090	1,080	800	1.38
4,230	1,090	800	1.46
4,341	1,090	800	1.49
4,500	1,010	740	1.57
4,695	1,000	730	1.64
4,805	970	710	1.70
5,050	990	640	1.86
5,210	985	630	1.99
5,300	975	610	2.06
5,450	975	610	2.32
5,475	975	610	2.48

Spec: N-2-Bending

A-212B

550°F

Total Strain Range: 0.7%

Number of Cycles	Load, Lbs.		Crack Length 2(a) Inches
	Tension	Compression	
150	580	670	-
400	580	690	.29
670	585	700	.31
900	580	680	.33
1,640	580	685	.37
1,960	580	690	.40
2,300	580	690	.41
2,760	580	680	.44
3,200	580	690	.45
3,550	575	700	.47
3,870	575	700	.47
4,550	570	690	.49
5,050	575	690	.53
6,000	570	690	.57
6,635	570	690	.59
7,874	575	690	.60
8,820	570	690	.62
9,450	570	690	.63
10,380	565	690	.67
11,270	575	680	.72
11,900	570	690	.74
12,650	530	680	.76
13,250	650	715	.79
14,000	640	710	.84
14,610	670	777	.90
15,790	660	790	1.03
17,350	600	730	1.14
17,900	610	740	1.21
18,620	610	740	1.24
19,340	590	750	1.31
20,060	590	750	1.39
20,780	590	750	1.42
21,960	570	750	1.50
22,660	570	830	1.84

Spec: A-3-Axial

Type 304

RT

Total Strain Range: 0.18%

<u>Number of Cycles</u>	<u>Load (Lbs.)</u>	<u>Crack Length 2(a) Inches</u>
1,000	30,500	.76
2,000	28,500	1.0
3,000	27,000	1.32
4,000	25,000	1.60
5,000	23,200	1.88
6,000	21,000	2.12
7,000	19,200	2.44
8,000	17,000	2.72
9,000	15,000	3.00
10,000	13,000	3.10
11,000	12,000	3.20
12,000	11,000	3.36

Spec: B-3-Axial

GEAP-10181

Type 304

RT

Total Strain Range: 0.25%

<u>Number of Cycles</u>	<u>Load (Lbs.)</u>	<u>Crack Length 2(a) Inches</u>
2,000	23,600	1.48
3,000	22,200	1.60
4,000	21,200	1.75
5,000	20,000	1.87
6,000	19,400	1.98
7,000	19,000	2.10
8,000	18,000	2.22
9,000	17,000	2.32
10,000	16,000	2.44

Spec: C-3-Axial

Type 304

RT

Total Strain Range: 0.4%

<u>Number of Cycles</u>	<u>Load (lbs.)</u>	<u>Crack Length 2(a) Inches</u>
500	44,000	0.8
1,000	40,400	1.20
1,500	38,000	1.55
2,000	35,000	1.75
2,500	32,400	1.98
3,000	30,000	2.20
3,500	28,000	2.43
4,000	25,400	2.65
4,500	23,000	2.75
5,000	20,000	3.10
5,500	18,400	3.30
6,000	16,000	3.50

Spec: D-3-Axial

Type 304

RT

Total Strain Range: 0.6%

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
5	-	-	-
10	-	-	.51
25	-	-	.52
50	43,200	46,200	.55
75	-	-	.58
100	41,400	44,300	.62
125	-	-	.69
150	40,500	44,100	.74
175	-	-	.77
200	39,300	42,600	.81
225	-	-	.83
250	-	-	.88
275	-	-	.95
300	37,900	41,700	1.01
325	-	-	1.06
350	37,400	41,200	1.11
375	-	-	1.18
400	36,000	40,300	1.24
425	-	-	1.28
450	35,700	40,200	1.34
475	-	-	1.39
500	35,100	40,200	1.44
525	-	-	1.50
550	33,600	39,100	1.56
575	-	-	1.62
600	32,700	38,400	1.65
625	-	-	1.71
650	32,200	37,800	1.78
675	-	-	1.84
700	30,600	37,200	1.90
725	-	-	1.98
750	30,000	37,700	2.06
775	-	-	2.15
800	30,000	37,200	2.20
825	-	-	2.26
850	27,000	33,900	2.31
875	-	-	2.37
900	25,200	32,100	2.45
925	-	-	2.49
950	24,200	32,100	2.54
975	-	-	2.59

(cont'd.)

Spec: D-3-Axial (cont'd.)

<u>Number of Cycles</u>	<u>Load, Lbs.</u>		<u>Crack Length 2(a) Inches</u>
	<u>Tension</u>	<u>Compression</u>	
1,000	24,000	31,800	2.66
1,025	-	-	2.74
1,050	23,100	30,000	2.81
1,075	-	-	2.87
1,100	22,200	28,400	2.94
1,125	-	-	2.99
1,150	20,200	27,500	3.06
1,175	-	-	3.12
1,200	19,200	25,800	3.17
1,225	-	-	3.22
1,250	18,800	26,100	3.28
1,275	-	-	3.34
1,300	17,400	26,000	3.40
1,325	-	-	3.48
1,350	14,100	20,800	3.57
1,375	-	-	3.64
1,400	12,900	20,600	3.20

Spec: E-3-Axial

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Type 304

RT

Total Strain Range: 0.75%

Number of Cycles	Load, Lbs.		Crack Length 2(a) Inches
	Tension	Compression	
10	49,000	51,000	-
25	-	-	.56
50	47,000	48,700	.62
75	-	-	.75
100	44,400	47,000	.86
125	-	-	.95
150	39,700	41,000	1.14
175	-	-	1.26
200	38,300	41,000	1.38
225	-	-	1.51
250	35,700	39,200	1.64
275	33,700	38,400	1.86
300	32,800	37,200	1.97
325	30,200	36,200	2.10
350	-	-	2.24
375	-	-	2.36
400	27,600	34,000	2.49
425	-	-	2.60
450	23,600	30,600	2.72
475	-	-	2.85
500	22,200	39,100	2.98
525	-	-	3.09
550	20,600	26,600	3.20
575	-	-	3.29
600	18,700	33,100	3.38
625	-	-	3.48
650	16,900	28,600	3.56
675	-	-	3.64
700	15,300	29,600	3.70
725	-	-	3.75
750	14,700	29,800	3.80
775	-	-	3.86
800	13,200	29,700	3.92
825	-	-	3.98

Spec: F-3-Axial
Type 304

RT

Total Strain Range: 1.0%

<u>Number of Cycles</u>	<u>Load (lbs.)</u>	<u>Crack Length 2(a) Inches</u>
200	39,500	1.05
300	36,000	1.40
400	32,500	1.75
500	29,500	2.06
600	26,000	2.40
700	23,250	2.66
800	21,000	2.90
900	18,250	3.15
1,000	16,250	3.45
1,100	13,500	3.76
1,200	10,500	4.06
1,300	8,250	4.35

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