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BIMONTHLY PROGRESS REPORT NO. X

THERMAL-SHOCK INVESTIGATION

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OBJECT

The object of this research is to evaluate optimum design of test specimens and criteria which will permit correlation of thermal-shock data with performance of the material in the form of turbine buckets.

SUMMARY

Thermal-shock tests were run on wrought S-816 alloy that had been solution-treated and aged. Nominal test temperatures were 1600, 1700, and 1800°F. The resistance to cracking of these heat-treated specimens was the same as that of specimens tested in the as-received condition.

Thermal-shock resistance of S-816 alloy decreased monotonically and smoothly with increasing temperature.

On a comparative basis, S-816 alloy is inferior in resistance to cracking by thermal shock to the best N-155 alloy at all temperatures and to practically all Inconel specimens at 1700°F.

The scatter of results was smaller than in most previous tests.

INTRODUCTION

Previous tests on wrought S-816 alloy in the thermal-shock rig had been conducted on the alloy in the as-received condition. Inasmuch

as commercial uses of the alloy frequently dictate a heat-treatment, it was felt that tests should be run on specimens that had been solution-treated and aged. Moreover, it was believed that the test temperature of 1500°F previously employed was too low for tests of reasonable duration.

Tests were conducted on heat-treated specimens at nominal temperatures of 1600, 1700, and 1800°F during the period December 11, 1953, to February 11, 1953.

APPARATUS AND PROCEDURE

The test rig employed in these tests was identical with that described in the latest progress reports. One test unit consisting of air nozzle, specimen holder, and radiation pyrometer was used for all tests in order to eliminate differences in results that might be introduced by variations in test units.

The test specimens were machined from 3/4-inch diameter rod. After machining, the specimens were solution-treated simultaneously for 1 hour at 2150°F, water-quenched, and aged for 16 hours at 1800°F. Four specimens were tested at each of three maximum cycle temperatures, 1600, 1700, and 1800°F. Of the three possible edges available for use as the cooled edge on each specimen, the most nearly perfect edge was selected as the cooled edge.

Specimens were viewed by a telescope, as previously reported, to detect cracks.

The criterion of cracking was the presence of a crack completely across the cooled edge of a specimen.

RESULTS

The results of tests on heat-treated specimens are given in Fig. 1 together with previous results on specimens tested in the as-received condition. The specimens reported in the present report are Nos. 9 through 20; the specimens from previous tests used for comparison are Nos. 3 through 8.

Two specimens which were to have been run at 1600°F were actually run as follows: No. 16 1615°F
No. 20 1660°F

The resistance of these specimens to cracking is in line with the results from other specimens if the higher test temperature is taken into consideration. The tabular results are as follows.

Number of Cycles to First Crack at		
1600°F	1700°	1800°F
5130	2426	1069⁻
4600	1903⁺	956⁻
3620 (1615°F)	1956⁻	1146⁻
3100⁻ (1660°F)	2300⁻	784

The specimen run at 1700°F that shows 1903 cycles to failure was actually found not to be cracked completely through the cooled edge; rather, a crack 0.031 inch long was present in a 0.034-inch edge. The test was stopped because it was felt that oxide had filled the lower 0.003 inch of the crack, but microscopic observation of the cleaned edge showed the incompleteness of the crack. Based on past experience with crack propagation, it is felt that the actual number of cycles to failure would have been closer to 2000 cycles than to 1900 cycles.

The three specimens tested at 1800°F that show 1146, 1049, and 956 cycles to failure all had cracked somewhat beyond the edge thickness. Oxide obscured the cracks to some extent, so that crack detection was difficult. The actual numbers of cycles should thus be less than those shown, probably below 956 cycles.

The two specimens tested at 1700°F showing 2300 and 1956 cycles to first cracking and the specimen tested at 1660°F all had passed the number of cycles to first cracking by the time the test was stopped. Oxide obscured these cracks so that actual determination of crack length was difficult.

It is estimated that scatter of results is about 15% at 1600 and 1800°F, and about 20% at 1700°F. The data are relatively consistent within this range of scatter.

Specimens previously reported were tested in the as-received condition at 1500, 1600, and 1700°F. Results from these tests fall along the line of results from the present tests. It appears that the heat-treatment used did not appreciably alter the thermal-shock resistance of the wrought S-816 alloy, but the treatment may have increased the reproducibility of results.

The wrought S-816 alloy specimens were poorer in resistance to thermal cracking than the N-155 alloy, lot I, previously reported, and about the same as the N-155 alloy, lot II, previously reported. Inconel specimens were tested extensively only at 1700°F; practically all of the Inconel specimens were superior to the S-816 alloy at that temperature.

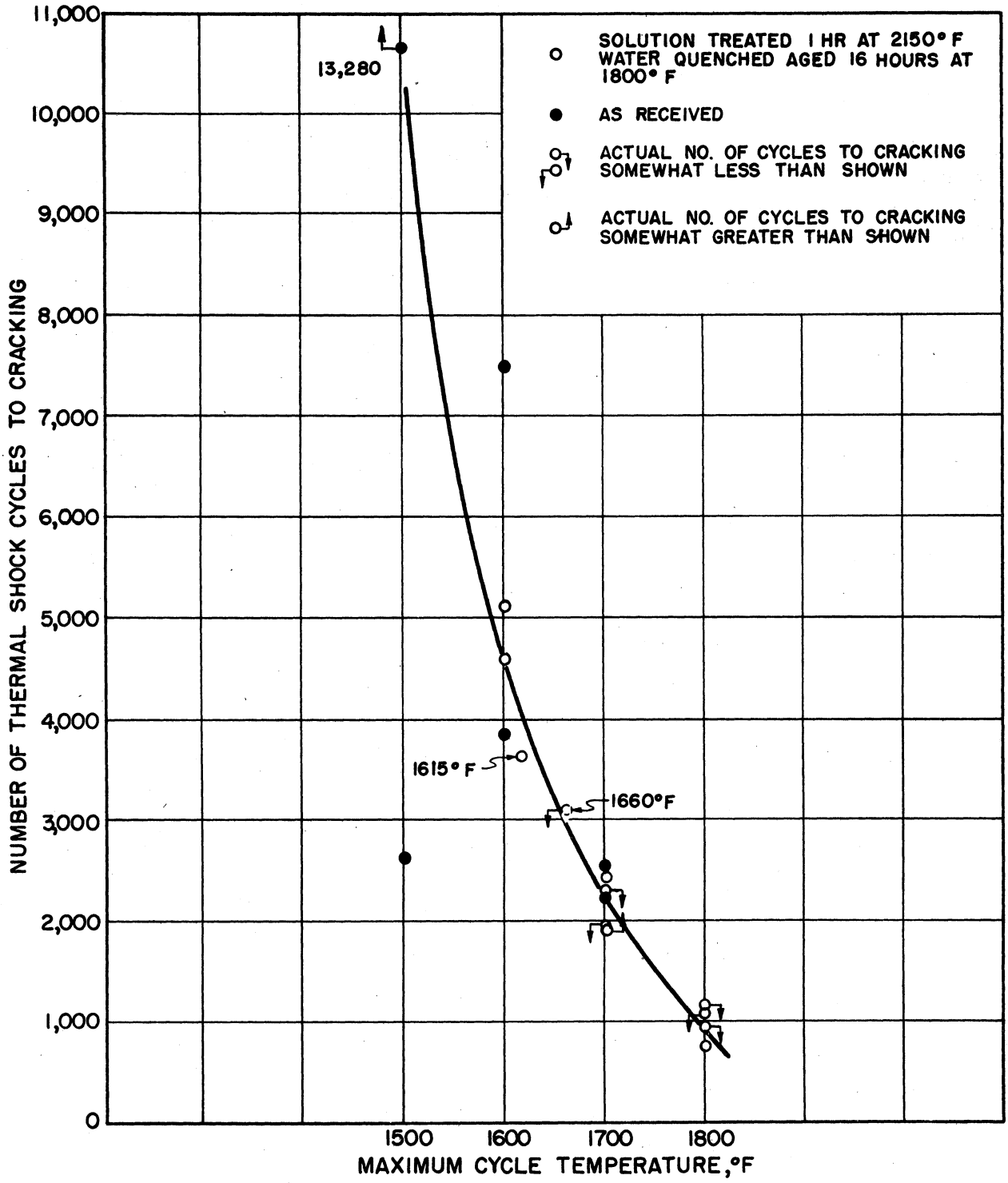
CONCLUSION

1. The heat-treated wrought S-816 alloy specimens manifested thermal-shock resistance that decreased smoothly with increase in test temperature from 1600 to 1800°F.

2. The results from wrought S-816 alloy in the heat-treated and as-received conditions are about the same at 1600 and 1700°F, the only two test temperatures available for comparison. Scatter of results from the heat-treated specimens was smaller than from the as-received specimens.

3. Heat-treated wrought S-816 alloy is inferior to N-155 alloy, lot I, but is about the same as N-155 alloy, lot II, in resistance to thermal cracking at temperatures from 1600 to 1800°F. At 1700°F, Inconel in most cases outperforms S-816 alloy in resistance to thermal cracking.

FIG. I
S-816 ALLOY



KEY TO LOG

Column (1)

(1) Relative position on bar stock
1 Specimen number

Column (2)

Arrow indicates direction and location of cooling jet; cooling medium is air unless otherwise stated

W	Cooling medium is water
.045	Width of cooled edge, inches
P.F.	Previously subjected to rotating beam fatigue as shown in column (6)
X	Failed during pre-fatigue

Column (3)

M	Thermal shock cycle manually controlled
1500/5	Automatic cycle control; maximum temperature, °F, and length of cooling period, seconds
P1800	Dead load, 1800 lbs
+10/100	Starting with stated maximum temperature, maximum temperature was increased 10°F after each 100 cycles
40.5K	Reversed-bending (rotating-beam) fatigue tests; maximum stress, 40,500 psi
to 1800	Maximum temperature held constant after 1800°F was reached

Column (4)

A	Air cooling for stated number of cycles
W	Water cooling for stated number of cycles
no symbol	Air cooling for stated number of cycles

Column (5)

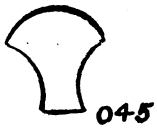
O	No failure visible
F	Fracture
C	Cracks
G	Grooves
FC	Face crack
PC	Possible crack

Column (6)

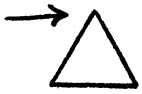
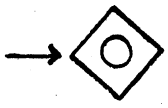
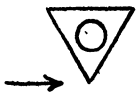
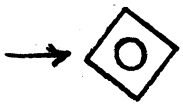
B	Specimen warped due to thermal strains
A 0.14	Area of cross section, square inch
T300/1600	Heat treated before testing 300 hr at 1600°F
G1500	Grooves first appeared at 1500 cycles
OH	Stated maximum temperature was exceeded due to malfunction of control unit
BT	Broke through to thermocouple hole

40.5K/ 82000	Previously subjected to 82000 cycles at 40,500 psi
R	Reproducibility test
N	Specimen formed a neck due to tensile strain.
+100/5108	Maximum temperature was increased 100°F at 5108 cycles.
Check II	Second test to determine the effect of alteration of testing procedure.
P	Study of crack propagation
PT1	Previously subjected to tensile strain of 1% at room temperature
LRSI	Long-time test at reduced severity, Test No. I
T{ }I	Heat treated as shown in braces { }. Lot No. I
C20/1700	Heat treated for 20 hours by heating to 1700°F and allowing to cool for 5 seconds by natural convection.

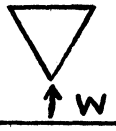
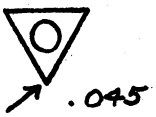
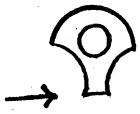
TEST LOG

Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
Type 304 Stainless Steel					
1		M	———	O	B
2		1600/10	4400 A 300 W	C	B
3		1600/4	1783	C	
4a 4b	Fatigue Specimens	40.5K 40.5K	3300 2600	F F	
5		1700/4 1800/4	1100 675	O C	
6		1600/4 1900/4	6240 1240	O C	G6500
7		1500/4 P600	4130	F	A 0.16

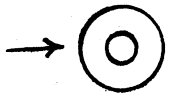
TEST LOG (cont)

Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
8		1600/5 1800/4	3082 517	O C	T300/1600
9		1500/3	5753	O	
10		1600/4 1700/4 1800/4	1000 1000 80	O O C	
11		1500/5 P1800	1000	F	A 0.132
12		1500/5 P600 P900 P1800	 5000 1200 203	 O O F	A 0.133
13		1600/4	1284	C	G 115
14		1500/4	1000	F	OH
15		1600/5	1900	C	T300/1600
16		1600/5	409	C	

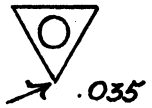
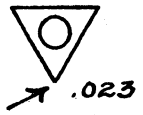
TEST LOG (cont)

Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
17		1500/5 P1800	300	F	A 0.140
18		1800/4	1950	C	G 1500
19		1700/3	530W	C	
20		1500/3	1000	O	BT
Type 347 Stainless Steel					
1		1600/4 +10/100	866	C	
2		1600/4 +10/100	1147	C	
3		1500/4 +10/100	575	C	BT
4a	Fatigue	54K	5200	F	
4b	Specimens	54K	10400	F	40.5K 82000

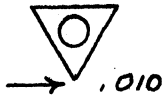
TEST LOG (cont)

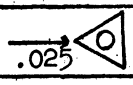
Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
5		1500/4 +10/100	1326	C	
6		1500/4 +10/100	1990	C	
7		1600/3.5 +10/100 to 1800	2700	G	
8	(Defective)				
9		1600/4	2863	C	R
10		1600/4	3787	C	Check II
11		1600/4	2580	C	
12		1600/4	3162	C	G 736
13		1600/4	2204	C	G 2072
14		1600/4	2707	C	G 2604

TEST LOG (cont)

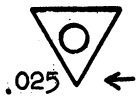
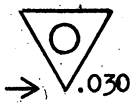
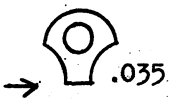
Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
15		1600/4	3003	C	G2820 R
16		1600/4	2518	C	R
17		1600/4	4850	O	Check I
18		Fatigue 64K	7200	F	54K 103300
19		1600/4	1825	C	R
20		Fatigue 64K	4300	F	37K/217100 42K/11000 48K/35600 54K/10000 59K/10400
21		1600/4	4430	C	
22	(Defective)				
23		1600/5	2962	C	
24		Fatigue 59K	52900	F	

TEST LOG (cont)

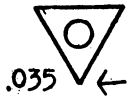
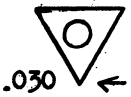
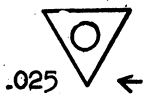
Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
25		1600/5 P.F.	1562	C	54K/50000
26		1600/5	1960	C	53K/52000 59K/12000 64K/1000 70K/1000 75K/500
27		X P.F.	——	F	53K/52000 59K/11300
28		1600/5 P.F.	1594	C	53K/52000 59K/12000 64K/1000 70K/1000 75K/500
29		X P.F.	——	C	53K/52000 59K/12000 64K/1000 70K/1000 75K/300
30		1600/5	1973	C	
31		1600/5	2764	C	
32		1600/5	1500	C	

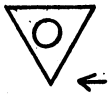
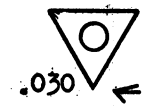
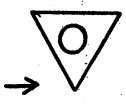
Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
33 (4)		X P.F.	——	F	59K/32600
34 (3)		P.F.	1811	C	60K/39000
35 (2)	(Used for calibration of Heat-Eye)				
36 (1)		1600/5 P.F.	1859	C	58K/30000
37 (5)		1600/5	4635	C	
38		1600/5	2114	C	T2/2000
39 (7)		1600/5	2440	G	G 2440 Rigid Support Nozzle No. 3
40 (8)		1600/5	3143	G	Nozzle No. 4
41		1600/5	2710	C	G 2000 Rigid Support Nozzle No. 3

TEST LOG (cont)

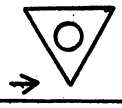
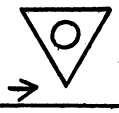
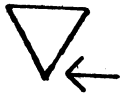
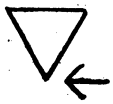
(1) Specimen Number	(2) Cross Section	(3) Cycle	(4) Number of Cycles	(5) Type of Failure	(6) Remarks
42		(Used for calibration)			
43 (11)		1600/5	10708	C	P Rigid Support Nozzle No. 4
44		1600/5	2046	C	T2/2000
45		1600/5	1956	C	T2/2000
H.S. 21 (vitallium) Cast					
1		1500/3.5	1000	C	BT
Inconel					
1		1500/3	1450	C	
2		1500/3 +10/100	2730	C	
3		1500/3 +10/100	428	C	BT
4		1700/5	3167	C	T2/500 T1/3/1400
5		1700/5	1819	C	T2/500 T1/3/1400

TEST LOG (cont)

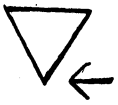
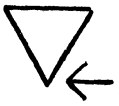
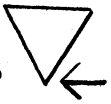
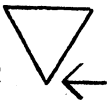
(1) Specimen Number	(2) Cross Section	(3) Cycle	(4) Number of Cycles	(5) Type of Failure	(6) Remarks
6		1600/4	7449	C	
7		1700/5	4706	C	T2/500 T1/3/1400
8		1700/5	2090	C	T1/3/1400 PTI
9		1700/5	6465	C	T2/800
10		1700/5	3680	C	T1/3/1400 PT10
11		1700/5	2860	C	T1/3/1400 PT5
12		1700/5	1884	C	T1/3/1400 C20/1700
13		1700/5	2500	C	T1/3/1400 PT1
14		1700/5	2527	C	T1/3/1400 PT5
15		1700/5	2804	C	T1/3/1400 PT10
16		1700/5	3590	C	T1/3/1400 PT0
17		1700/5	2270	C	T1/3/1400 PTI

(1) Specimen Number	(2) Cross Section	(3) Cycle	(4) Number of Cycles	(5) Type of Failure	(6) Remarks
18		1700/5	2576 3015	PC C	T1/3/1400 PT5
19		1700/5	1830	C	T1/3/1400 PT10
20		1700/5	2898	C	T1/3/1400 PTO
21		1700/5	7498 11265	F.C.(?) C	T1/3/1400 LRSI
22		1700/5	4339 6866	FC? C	T1/3/1400 flex. pipe to nozzle
23		1700/5	2250	C	T1/3/1400
24		1700/5	8145	FC	T1/3/1400 LRSII
25		1700/5	3538 4229	FC C	T1/3/1400
S-816 Alloy (wrought)					
1		1500/4 P700 No load	1788 18391	O C	A 0.08 N +100/5108 +100/10000
2		1500/4 P1100 to P700	2657	F	A 0.08 N
3		1700/4	2256	C	

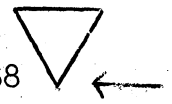
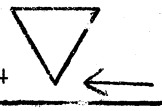
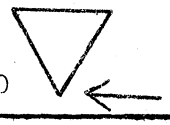
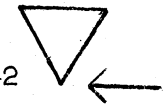
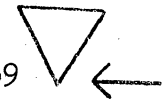
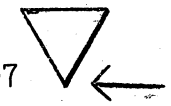
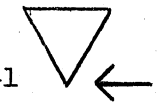
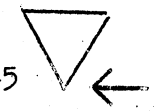
TEST LOG (cont)

(1) Specimen Number	(2) Cross Section	(3) Cycle	(4) Number of Cycles	(5) Type of Failure	(6) Remarks
4		1700/4	2250	C	
5		1600/4	3870	C	
6		1500/4	2630	C	
7		1500/4	13280	C	
8		1600/4	7497	C	
9	.0371 	1800/5	1069⁻	C	T 1/2150 W 16/1800
10	.037 	1700/5	2426	C	T 1/2150 W 16/1800
11	.036 	1600/5	5130	C	T 1/2150 W 16/1800
12	.0388 	1800/5	956⁻	C	T 1/2150 W 16/1800
13	.034 	1700/5	1903⁺	C .003 short	T 1/2150 W 16/1800

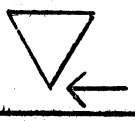
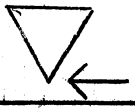
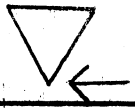
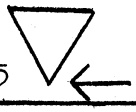
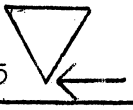
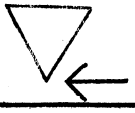
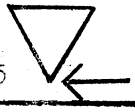
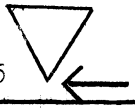
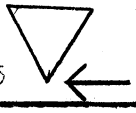
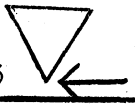
TEST LOG (cont)

(1) Specimen Number	(2) Cross Section	(3) Cycle	(4) Number of Cycles	(5) Type of Failure	(6) Remarks
14	.0350 	1800/5	1146⁻	C	T { 1/2150 W 16/1800
15	.036 	1600/4	4600	C	T { 1/2150 W 16/1800 } I
16	.0335 	1600/4	3620	C	T { 1/2150 W 16/1800 } I Average test temp. was 1615° F.
17	.0362 	1700/5	1956⁻	C	T { 1/2150 W 16/1800 } I
18	.0384 	1800/5	784	C	T { 1/2150 W 16/1800 } I
19	.0345 	1700/5	2300⁻	C	T { 1/2150 W 16/1800 } I
20	.0331 	1600/5	3100⁻	C	T { 1/2150 W 16/1800 } I Average test temp. was 1660° F.

TEST LOG (cont)

(1) Specimen Number	(2) Cross Section	(3) Cycle	(4) Number of Cycles	(5) Type of Failure	(6) Remarks
N-155 Alloy (Wrought)					
1	.038 	1700/5	3764 3878 4949	FC C 2C	T { 1/3/2200 W I 50/1400 }
2	.040 	1700/5	3211	C	T { 1/3/2200 W I 50/1400 }
3	.038 	1700/5	3248	C	T 1/3/2200 W I 50/1400 }
4	.034 	1800/5	1508	C	T 1/3/2200 W I 50/1400 }
5	.036 	1600/5	3886	O	T { 1/3/2200 W I 50/1400 Removed for check; No crack
6	.040 	1700/5	3105	C	T { 1/3/2200 W I 50/1400 }
7	.042 	1800/5	1818	C	T { 1/3/2200 W I 50/1400 }
8	.039 	1700/5	3195	C	T { 1/3/2200 W I 50/1400 }
9	.037 	1700/5	2888	C	T { 1/3/2200 W I 50/1400 }
10	.041 	1600/5	10124	O	T { 1/3/2200 W I 50/1400 }
11	.045 	1800/5	2052	C	T { 1/3/2200 W I 50/1400 }

TEST LOG (cont)

(1) Specimen Number	(2) Cross Section	(3) Cycle	(4) Number of Cycles	(5) Type of Failure	(6) Remarks
12	.038 	1800/5	1228	C	T { 1/3/2200 W 50/1400 } II
13	.048 	1800/5	1095	C	T { 1/3/2200 W 50/1400 } II
14	.035 	1800/5	1042	C	T { 1/3/2200 W 50/1400 } II
15	.0385 	1800/5	990	C	T { 1/3/2200 W 50/1400 } II
16	.0415 	1800/5	1130	C	T { 1/3/2200 W 50/1400 } II
17	.040 	1700/5	2229	C	T { 1/3/2200 W 50/1400 } II
18	.0365 	1700/5	1995	C	T { 1/3/2200 W 50/1400 } II
19	.0395 	1600/5	5153	C	T { 1/3/2200 W 50/1400 } II
20	.0465 	1700/5	2320	C	T { 1/3/2200 W 50/1400 } II
21	.0433 	1600/5	3530	C	T { 1/3/2200 W 50/1400 } II