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EFFECT OF OUTDOOR EXPOSURE AT AMBIENT AND ELEVATED TEMPERATURES ON FATIGUE LIFE OF Ti-6Al-4V TITANIUM ALLOY SHEET IN THE ANNEALED AND THE SOLUTION-TREATED AND AGED CONDITION

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16. Abstract

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The results of the tests indicate that the fatigue lives of solution-treated and aged specimens were significantly reduced by the outdoor exposure at 560 K but not by the exposure at ambient temperature. Fatigue lives of the annealed specimens were essentially unaffected by the outdoor exposure at either temperature. The two test procedures – outdoor fatigue test and indoor fatigue test after outdoor exposure – led to the same conclusions about exposure effects.

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SUMMARY

Specimens of Ti-6Al-4V titanium alloy sheet in the annealed and the solution-treated and aged heat-treatment condition were exposed outdoors at ambient and 560 K (550° F) temperatures to determine the effect of outdoor exposure on fatigue life. Effects of exposure were determined by comparing fatigue lives of exposed specimens to those of unexposed specimens. Two procedures for fatigue testing the exposed specimens were evaluated: (1) fatigue tests conducted outdoors by applying 1200 load cycles per week until failure occurred and (2) conventional fatigue tests (continuous cycling until failure occurred) conducted indoors after outdoor exposure under static load. The exposure period ranged from 9 to 28 months for the outdoor fatigue-test group and was 24 months for the static-load group. All fatigue tests were constant-amplitude bending of specimens containing a drilled hole (stress concentration factor of 1.6).

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INTRODUCTION

Materials used as aircraft exterior skins are continuously exposed to the corrosive action of an outdoor environment. Although it is widely recognized that the outdoor environment could, and probably does, degrade the fatigue properties of these materials over the long years of service, only a few outdoor-exposure fatigue studies have been conducted in the past (refs. 1 to 4). Admittedly, definitive test results which could be included in structural fatigue-life estimates would be almost impossible to obtain because the environment varies with geographical location and with time and because of the long test times needed, 10 to 20 years. Although generation of definitive data may not be feasible, shorter-term tests (1 to 4 years) in an outdoor environment should, at the least, lead to more accurate corrosion-fatigue performance ranking of materials than the artificial environments used in current accelerated tests. Data of this kind would be especially useful for newer materials for which there is no vast backlog of service experience such as is available for aluminum alloys.

The materials studied in the present investigation were Ti-6Al-4V titanium alloy sheet in the annealed and the solution-treated and aged (STA) heat-treatment condition. Titanium alloys, especially Ti-6Al-4V, are being used increasingly in aircraft structures. They are particularly attractive for the structure of supersonic aircraft where elevated temperatures in the range of 450 to 650 K (350° to 700° F) will be experienced. The effects of outdoor exposure at both ambient and 560 K (550° F) temperatures were evaluated in the present study. Two methods of conducting the outdoor-exposure tests were investigated. In one test method, the specimens were fatigue tested outdoors by applying a continuous static load and cyclic loads at regular intervals until failure occurred. In the second method, specimens were exposed under static load but were fatigue tested in the laboratory at the end of the exposure period. In both test methods, the effects of outdoor exposure were determined by comparing the fatigue lives from exposed specimens to those of unexposed specimens. All fatigue tests were constant-amplitude bending of sheet specimens containing a drilled-hole stress-raiser, stress concentration factor of 1.6. Environmental conditions for the outdoor tests were those prevalent at the NASA Langley Research Center, which is located near the Chesapeake Bay on the eastern coast of the United States.

The physical quantities in this paper are given in both the International System of Units (ref. 5) and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units. Appendix A presents factors relating these two systems.

TESTS

Materials and Specimens

Specimens were fabricated from nominally 1.3-mm (0.050-in.) thick sheets of Ti-6Al-4V titanium alloy in two heat-treatment conditions, the annealed and the solution-treated and aged (STA) condition. Two sheets of material in each heat-treatment condition were used. Material chemical analyses and processing histories furnished by the manufacturer are given in table I. The average longitudinal tensile properties were obtained at the Langley fatigue research laboratory and are given in table II.

The configuration of the cantilever bending specimen used in the fatigue tests is shown in figure 1. The dashed lines indicate the shape of a constant-stress cantilever.

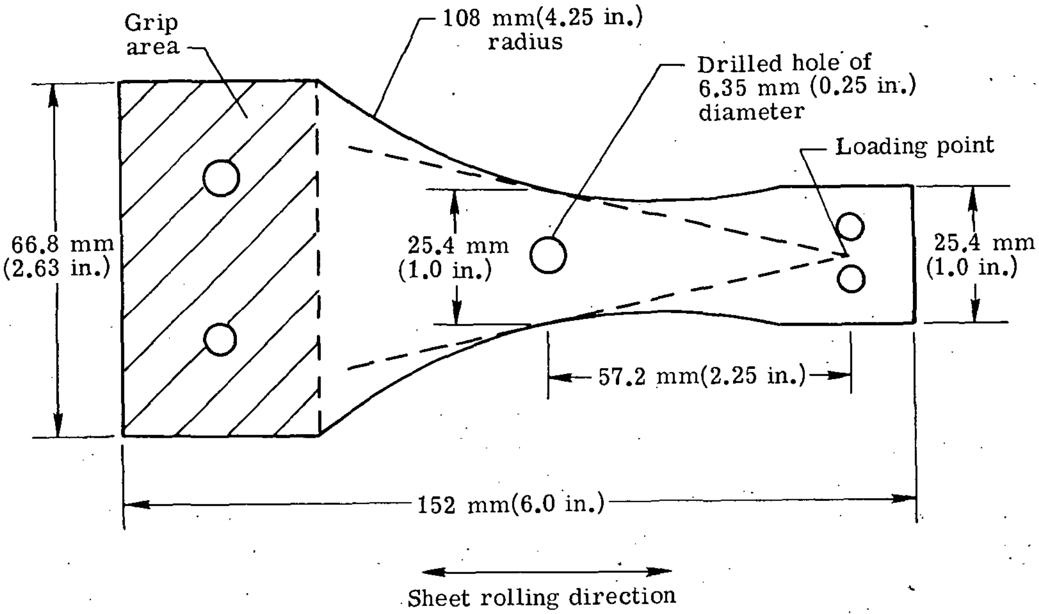

Figure 1.- Fatigue-specimen configuration.

Maximum bending stress occurs in the section at which these lines are tangent to the boundary of the specimen. The specimen contained a drilled hole of 6.35-mm (1/4 in.) diameter in the maximum-stress section. Holes were deburred before testing. The stress concentration factor K_T for this specimen loaded in bending is approximately 1.6 (ref. 6).

After fabrication, all specimens were chemically cleaned according to the procedures given in appendix B. After cleaning, each specimen that was to be exposed at 560 K (550° F) was instrumented with a thermistor and a thermocouple for temperature control and monitoring, respectively (fig. 2). The specimens were exposed outdoors in a horizontal position under downward static loads. To avoid extraneous failure sites and clutter on the top surface, the instrumentation (sensors, sensor shield, and wire tie-down straps) was spotwelded to the bottom surface.

Test Conditions

Groups of specimens from each heat treatment were subjected to test conditions selected to determine the effects of outdoor exposure, exposure temperature, and test method. Specimens for each test group were selected from locations within the two sheets

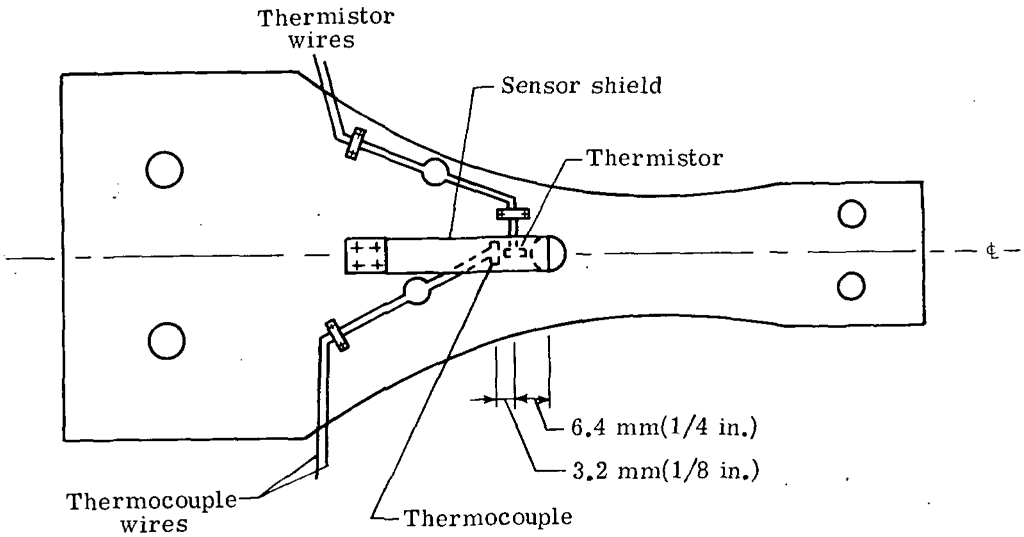

Figure 2.- Location of thermistor, thermocouple, and sensor shield on bottom surface of specimen.

according to a randomization procedure based on a table of random numbers. The test conditions are summarized in the following table:

Outdoor-exposure conditions	Fatigue-test conditions
No exposure	Conventional indoor fatigue test (static and constant-amplitude cyclic loading applied continuously at room temperature until failure occurred)
Ambient temperature	Conventional indoor fatigue test conducted after outdoor exposure
Continuous static load	Fatigue test conducted outdoors by applying 1200 constant-amplitude load cycles each week until failure occurred
Ambient and 560 K (550° F), about half time at each temperature	Conventional indoor fatigue test conducted after outdoor exposure
Continuous static load	Fatigue test conducted outdoors by applying 1200 constant-amplitude load cycles at ambient temperature each week until failure occurred

The no-exposure test group provided the base-line fatigue-life data to which the results of all other test groups were compared in order to determine the effects of the outdoor test conditions. The two temperatures are roughly representative of subsonic and of Mach 3 supersonic aircraft. For the latter condition, the specimens were at ambient temperature for about half the time and at 560 K (550° F) for the remainder. The specimens were at ambient temperature during an 8-hour period each night, when rain or snow was falling, when cyclic loads were applied, and during maintenance work. The two outdoor test procedures were selected to determine if simple, static-load exposure tests would lead to the same conclusions as the more difficult outdoor fatigue tests. From a test cost standpoint, the static-load exposure method is obviously desirable, especially for test programs with long exposure times.

The first day of the outdoor exposure period for all test groups was October 7, 1970. The static-load exposure group remained exposed until median lives were achieved in all the outdoor fatigue test groups. Thus, the exposure period for all static-load groups was 2 years. The exposure period for individual specimens in the outdoor fatigue tests ranged from 9 to 28 months. Meteorological data for the duration of the tests were taken from records of the Langley Flight Service Office and are summarized in table III.

All fatigue tests were of the constant-amplitude loading type. A single-stress-level condition was used for all tests on each material. In terms of outer-fiber net-section stresses, the test stresses were 172 ± 517 MPa (25 ± 75 ksi) for STA material and 172 ± 538 MPa (25 ± 78 ksi) for annealed material. The mean stress level was selected on the basis of published information (ref. 7), which indicated that that level was a realistic 1g design stress for a titanium-alloy lower-wing skin of a transport aircraft. The alternating stresses were chosen to produce failures in approximately 10^5 cycles on the basis of preliminary indoor bending fatigue tests.

Test Apparatus

Outdoor tests.- The outdoor-exposure test apparatus was located in an open area adjacent to the Langley fatigue research laboratory. The test area is about 5 km (3 miles) from salt water in the Chesapeake Bay. The outdoor fatigue-testing machine and the static-load exposure apparatus were within 10 m (30 ft) of each other.

The outdoor fatigue tests were conducted with a machine that accommodates 76 specimens at one time. A photograph of the testing machine is shown as figure 3 and a diagram of the machine is shown as figure 4. Basically, this machine consists of a vibrating table supported on coil springs and restricted to vertical motion by a system of flexure arms (not shown). The table has a natural frequency of vibration in the vertical direction of approximately 7.2 Hz (430 cpm) and was excited to vibrate at this frequency by an adjustable crank and a clutch mechanism. The electric drive motor was started with the clutch disengaged. When the motor reached operating speed, the clutch was engaged until the table vibrated at an amplitude equal to the throw of the crank. A preset counter was used to stop the machine automatically after a predetermined number of load cycles had been applied to the specimens.

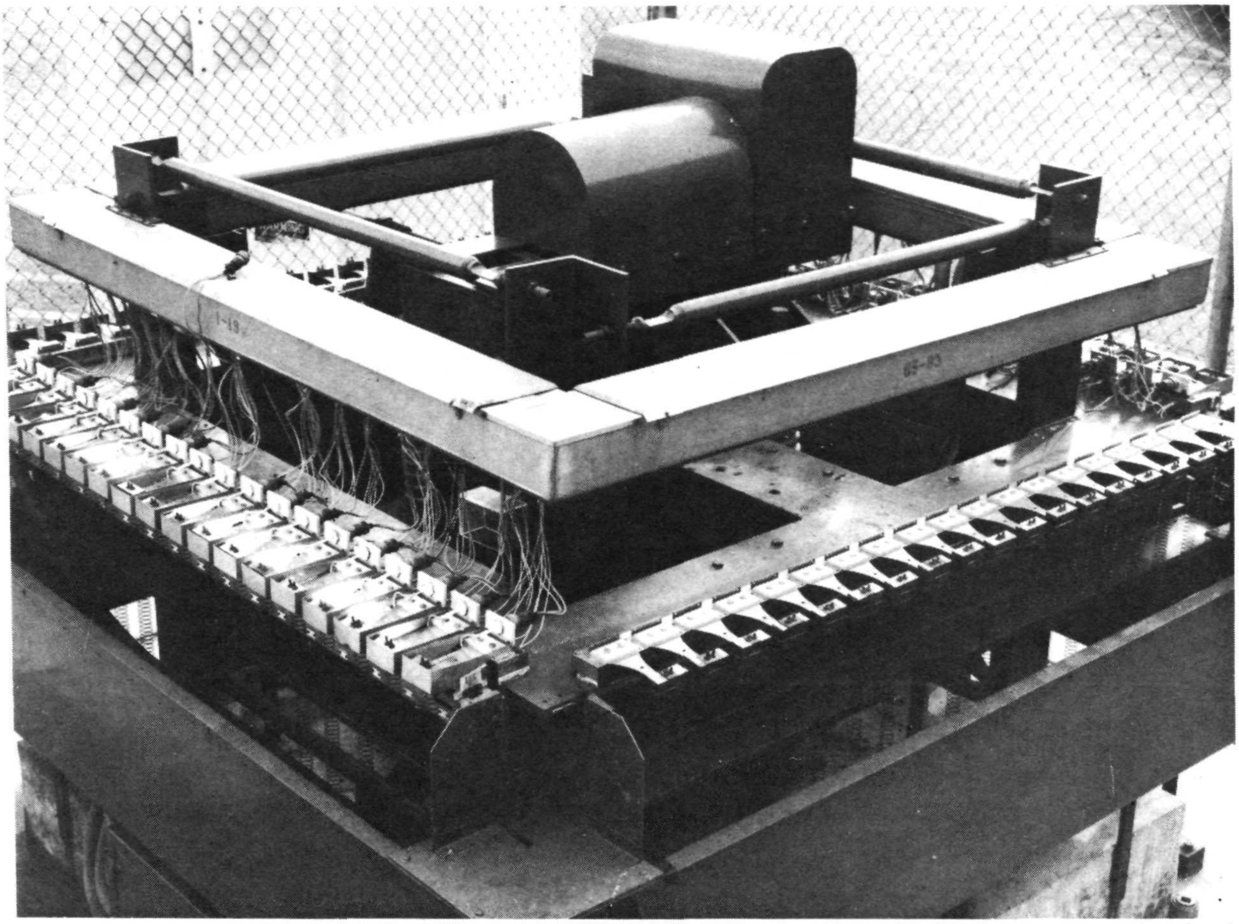

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Figure 3.- Outdoor fatigue-testing machine.

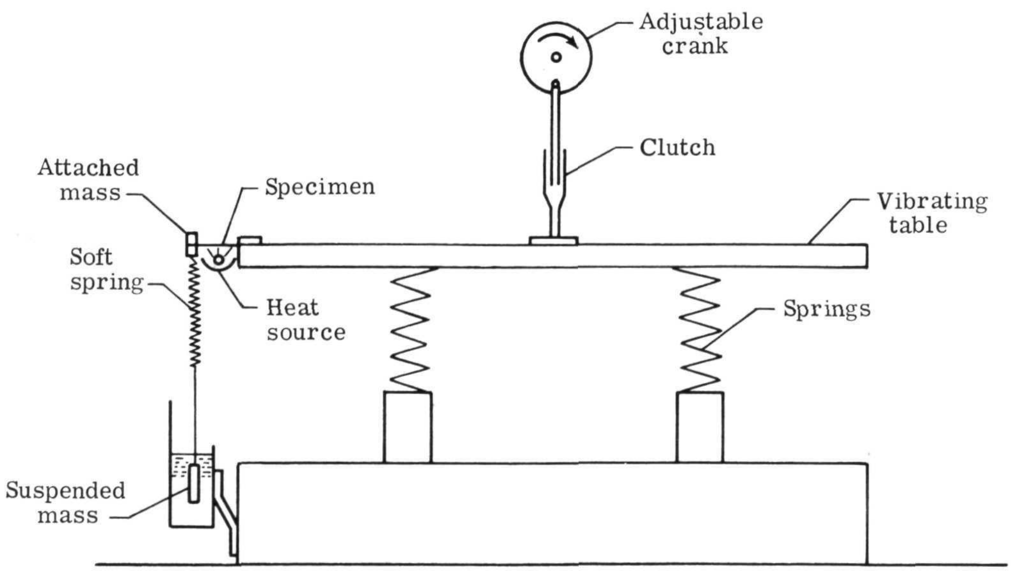

Figure 4.- Diagram of outdoor fatigue-testing machine.

The magnitude of the stresses induced in the specimens by the vibrating table was predetermined by sizing two masses which were attached to the specimen. One mass was rigidly attached to the free end of the specimen. Adjustment of the magnitude of this mass was the primary method of controlling alternating stresses in the specimen. Another mass was suspended from the first by a soft coil spring. The suspended mass was adjusted so that the sum of the two masses produced the desired mean stress in the specimen. The suspended mass was submerged in oil to damp out transient vibrations during starting and stopping. A correction was made for the buoyant force of the oil.

The static-load exposure specimens were mounted and statically loaded in essentially the same way as were the outdoor fatigue test specimens. The only difference was the use of a stiff rod, instead of a spring, to suspend the mass.

Each specimen exposed outdoors at 560 K (550° F) had a separate and complete heating and temperature-control system. The system was composed of two 200-watt quartz-tube radiant heating lamps and a reflector, a thermistor temperature sensor on the specimen, and a solid-state temperature controller. Each specimen also had a thermocouple attached to it for temperature monitoring purposes. The temperature of each specimen was recorded at regular intervals by a central temperature monitoring system. In addition to the radiant heating from the lamps, the specimens were heated in the gripped area by conduction from cartridge heaters which were inserted into drilled holes in the mounting plates. Heating the gripped portion of the specimen reduced the load on the lamps and thus helped to achieve long lamp life and closer temperature control, especially on windy days.

A precipitation sensor was used to automatically turn off the heaters when rain or snow was falling and turn it back on when the precipitation ended. The heaters were programed to deenergize at 8 p.m. and energize at 4 a.m. each day.

Indoor tests.- Both the no-exposure and static-load exposure groups were tested indoors on a small nonresonant vibration table which accommodated only one specimen at a time. The stresses induced in the specimen were controlled by the same mass-adjustment procedure that was used in the outdoor tests. Tests were conducted at a frequency of 10 Hz (600 cpm).

Procedure

The loads to produce the desired stresses in the test section of each specimen were computed with the flexure formula and cross-section measurements taken to the nearest 3 μm (0.0001 in.). These loads were applied statically to the specimens by deadweight loading and the specimen deflections were measured. The deflections were then reproduced in the tests by adjusting the masses attached to the specimen. Deflections were measured with a stroboscope, a scale graduated in 0.3-mm (0.01-in.) increments, and a low-power microscope. The large deflections of 30 to 36 mm (1.2 to 1.4 in.) associated with the maximum-stress levels facilitated adjustment to within ±2 percent of the desired level.

In setting up the tests to achieve the desired cyclic stress levels in the outdoor fatigue tests, all specimens were first mounted on the testing machine and connected to a specimen restraint fixture which prevented the specimens from being loaded when the vibrating table was in motion. Then, one at a time the specimens were disconnected from the restraint system and the masses attached to the specimen were adjusted to produce the correct deflections. Approximately 2000 cycles were applied to each specimen during the mass-adjustment process. When this process had been completed, all specimens were disconnected from the restraint fixture and the test machine was operated for about 6000 cycles while deflection checks were made for several specimens around the periphery of the machine.

Specimen positions on the outdoor-exposure test apparatus were filled by alternating between specimens of the two heat treatments. Specimens were segregated according to exposure-temperature condition.

For those specimens that were to be heated, a temperature of 560 K (550° F) was desired on the top (tensile mean stress) surface. Since the temperature sensors were located on the bottom surface, a correlation had to be established between thermocouple readings on the two surfaces. To do this, specimens having the usual instrumentation on the bottom surface and an array of thermocouples on the top surface were mounted on the machine. The temperature indication of the bottom thermocouple corresponding to a 560 K (550° F) indication on the top surface was recorded and used as the control point in the ensuing test. Temperature was controlled to within ±20 K (±30° F) of the desired 560 K temperature on calm days. Temperature fluctuations due to wind were generally no more than an additional 20 K (30° F).

RESULTS AND DISCUSSION

Test Results

The results of all of the fatigue tests are presented in tables IV and V for the STA and annealed materials, respectively. For each specimen, the number of load cycles required to produce failure (separation into two pieces), the days of exposure, and the number of hours exposed at 560 K (550° F) are listed when appropriate.

The fatigue lives obtained in all tests are plotted in figures 5 and 6 for the STA and annealed materials, respectively.

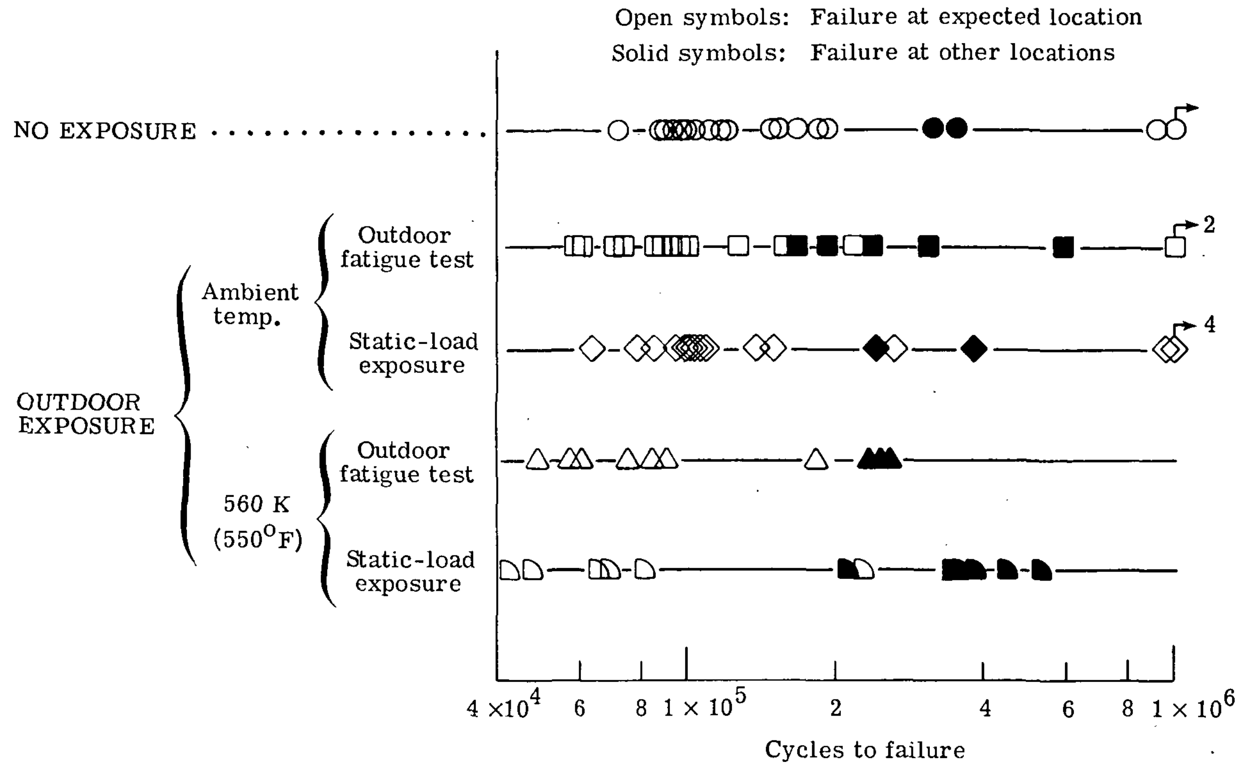

Figure 5.- Results of fatigue tests on Ti-6Al-4V titanium alloy in the STA heat-treatment condition.

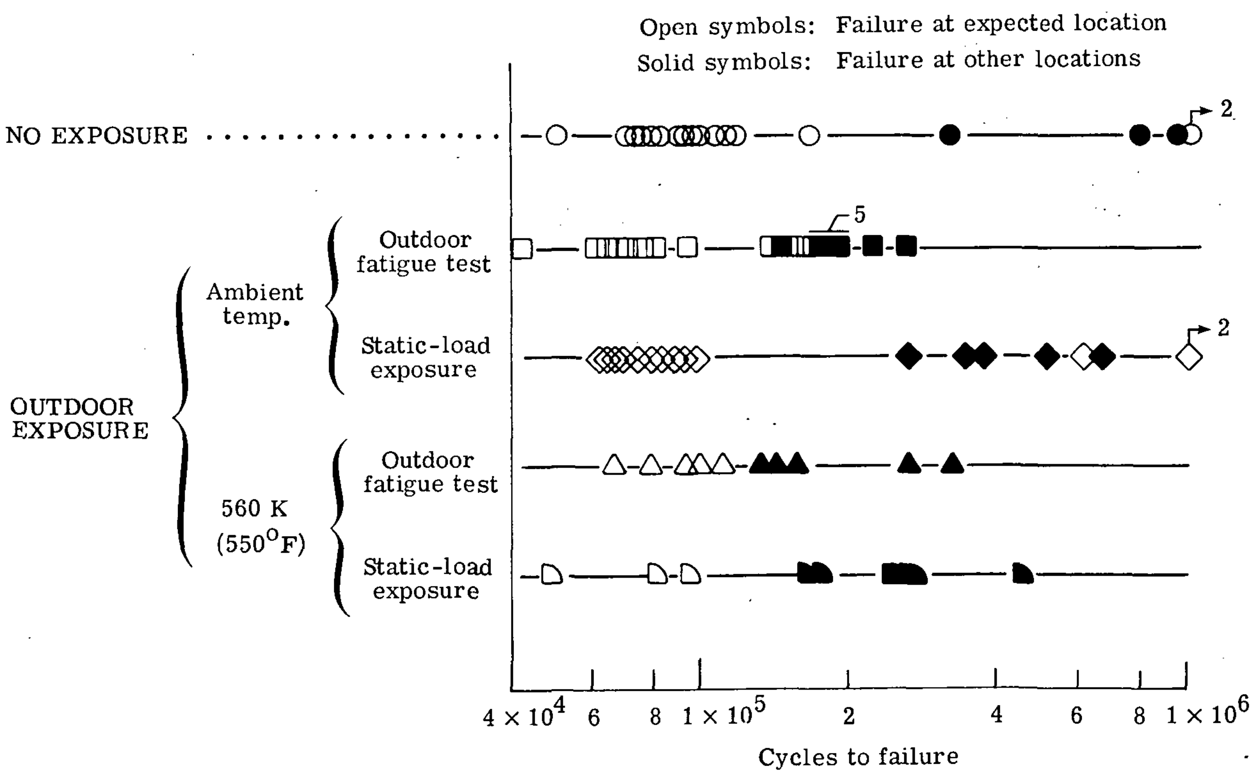

Figure 6.- Results of fatigue tests on Ti-6Al-4V titanium alloy in the annealed heat-treatment condition.

Discussion of Test Results

Examination of figures 5 and 6 indicates that all of the test groups exhibited large scatter in fatigue lives and some groups exhibited a tendency for the data to divide into short- and long-life groups. Specimen failures originated at one of four locations: (1) at the hole on the tensile mean stress surface (the normal failure location), (2) at the hole on the compressive mean stress surface, (3) at spotwelds on the compressive mean stress surface where instrumentation had been attached, and (4) at accidental-damage sites (scratches, dents, etc.) on the edges of the specimens. Two interesting points concerning those specimens that did not fail in the normal location are that: first, they failed at lives which were always longer than the lives of the majority of the normal-failure specimens and, second, they occurred in the no-exposure test group as well as the outdoor-exposure test group. In view of the latter point, failure location cannot be related to test environment, and, therefore, tests in which the specimens failed in a non-normal location can be treated as discontinued tests of the normal failure location in the analysis of test results.

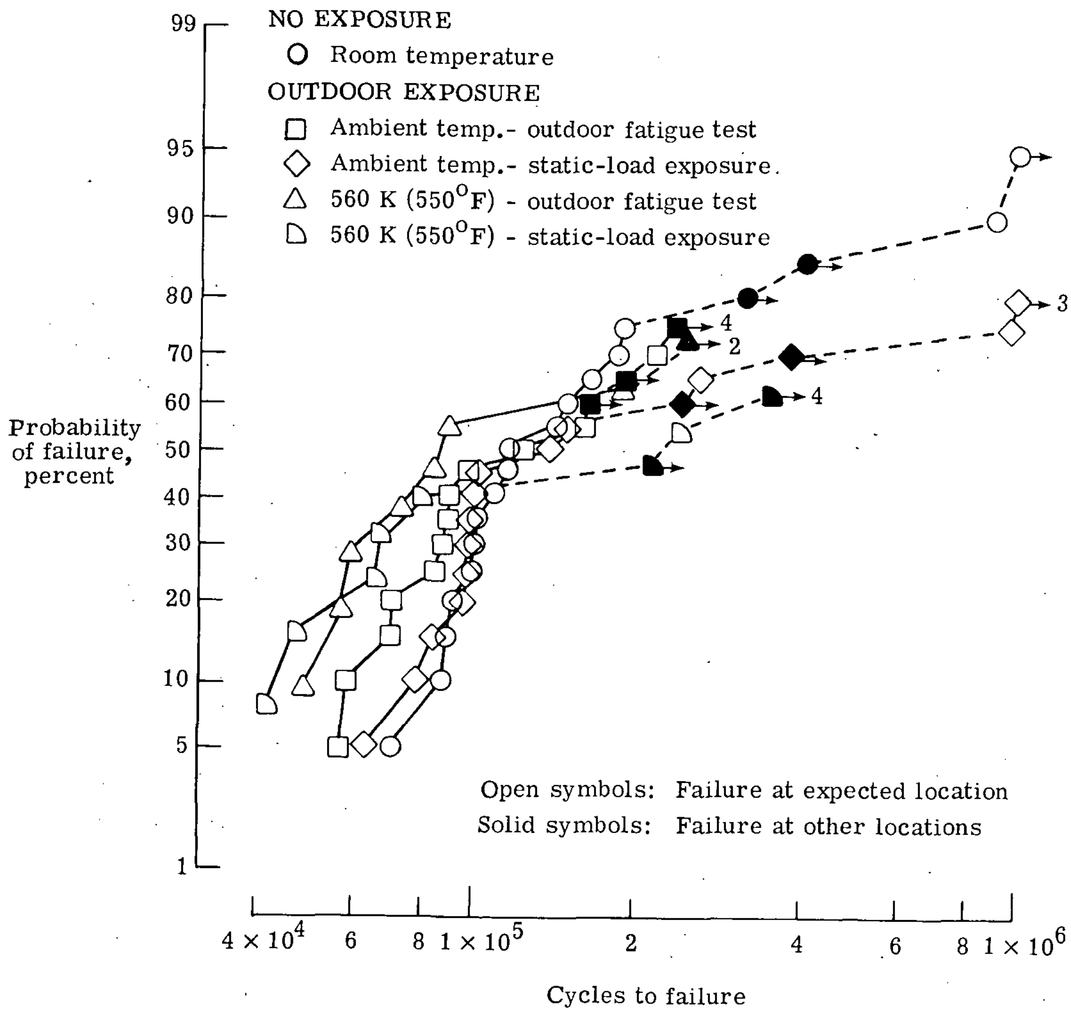

Figure 7.- Fatigue-life data given in figure 5 for STA material replotted on log-normal probability paper.

As has already been mentioned, some of the test groups exhibited a bimodal life distribution behavior in figures 5 and 6. Treating the non-normal failures as discontinued tests and considering that these specimens would have had longer lives if the tests had continued, a bimodal life behavior seems reasonable for all test groups rather than just some of them.

To further examine the life-grouping tendencies of the data, the data in figures 5 and 6 are replotted on log-normal probability paper in figures 7 and 8, respectively. For the sake of clarity, some of the discontinued-test data points are not plotted. The number of discontinued tests with lives beyond the longest life that is plotted is indicated for each test group. Dashed lines have been used in figures 7 and 8 to indicate that the actual paths are unknown because some tests were discontinued. Even with this uncertainty, the plots provide sufficient information to clearly indicate that the life data from most of the test groups cannot be adequately described by a single log-normal life distribution. The abrupt changes in slope apparent in the data plots, for example in the no-exposure test

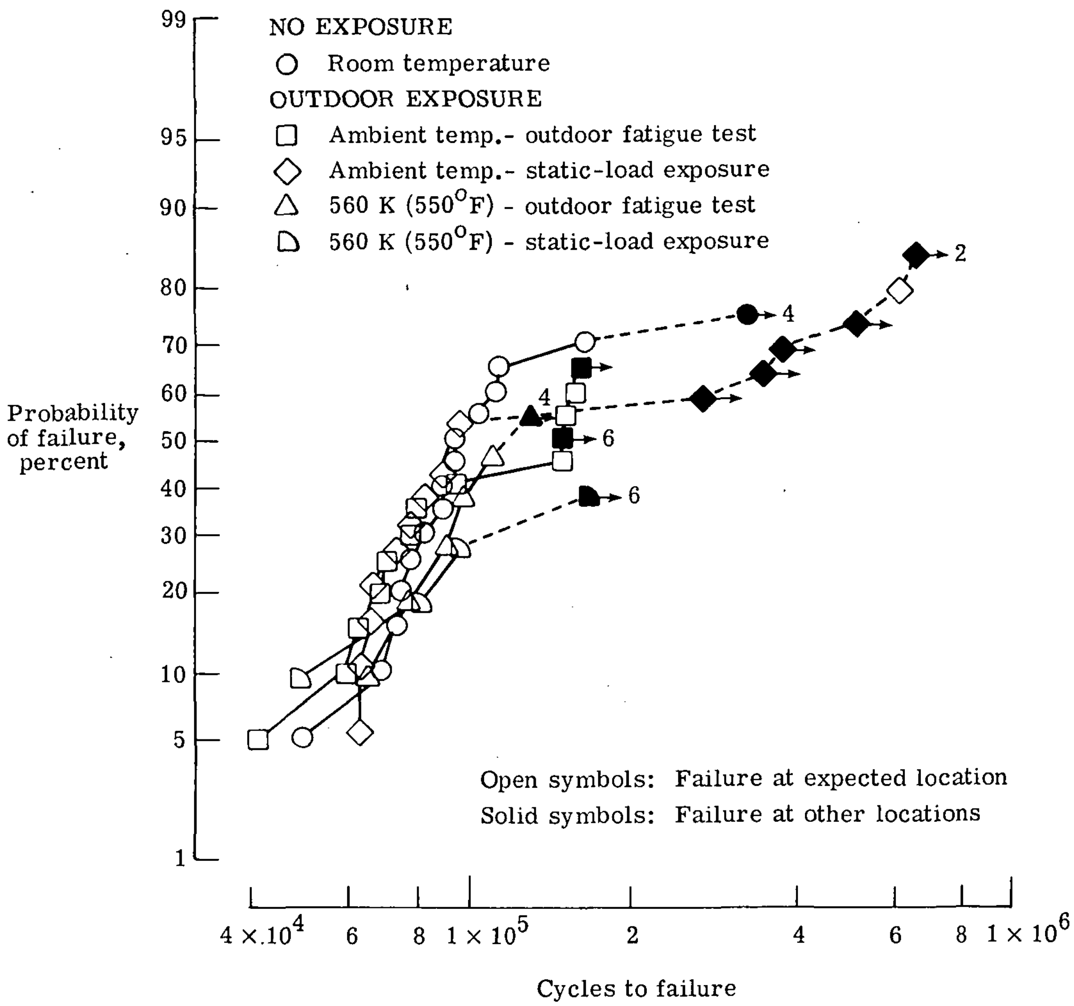

Figure 8.- Fatigue-life data given in figure 6 for annealed material replotted on log-normal probability paper.

group in figure 7, indicate that all of the data do not belong to the same statistical population. Even for those test groups which do not exhibit the abrupt slope change in figures 7 (squares) and 8 (squares and triangles), the bimodal behavior appears reasonable, considering the number and long lives of the discontinued tests. Replotting the data on a Weibull probability scale led to the same conclusions as did the log-normal plots. Interpretation of the data in terms of life groups had an important impact on the analysis of the data, as explained in the following paragraph.

As stated previously, the effects of the different test conditions can be determined by comparing the results from the test groups. The conventional method of comparing results from two test conditions is to perform some type of statistical test to determine if the mean or median lives of the two groups are significantly different. Usually, the results from all specimens tested under a given test condition are included in making the statistical test. However, if the data for the various test conditions consistently divide into two or more groups, an unconventional analysis approach is necessary. A conventional approach will not effectively detect environmental effects which result in life reductions smaller than the life separation between groups. But, detection of relatively small differences between test groups can reveal trends which may be significant when extrapolated to longer exposure periods. The consistent occurrence of the bimodal behavior for the various test conditions indicates that, regardless of the reason for the bimodal behavior, the specimens for each test condition must be considered as having come from two populations. Therefore, for the best analysis approach for data such as in the current study, comparisons should be made between the corresponding short- and long-life groups for each test condition.

The data in this study were divided into short- and long-life groups at the point of gross slope changes in figures 7 and 8. In cases where a discontinued test could conceivably belong to either life group, it was arbitrarily assigned to the long-life group. Since the discontinued-test data prevented a quantitative definition of the long-life group, only the short-life data were evaluated for effects of the outdoor test conditions.

Ti-6Al-4V STA.- Data for the short-life groups are plotted on log-normal probability paper in figure 9. All of the specimens represented in figure 9 exhibited about the same failure characteristics; that is, number of cracks, extent of cracking before failure, and fracture surface appearance at a magnification of 60 times.

The data in figure 9 reveal a consistent trend related to exposure condition: the no-exposure condition produced the longest lives, the outdoor exposure at ambient-temperature conditions produced somewhat shorter lives, and the outdoor exposure at 560 K (550° F) produced the shortest lives. The outdoor exposure at 560 K reduced median life to almost 1/2 of that obtained for the no-exposure group. These differences between test groups were tested for statistical significance using the unpaired rank test (ref. 8) for differences between medians. These comparisons indicated that at the 5-percent significance level both of the 560 K exposure groups were significantly different from the no-exposure group, but that neither of the ambient-temperature exposure groups were significantly different from the no-exposure group. Moreover, the static-load group exposed at 560 K was significantly different from that exposed at ambient temperature.

The results from the two test methods (outdoor fatigue test and fatigue test after exposure) did not indicate a consistent trend. The outdoor fatigue test method resulted in shorter lives than the static-load exposure method for the ambient-temperature exposure but resulted in longer lives than the static-load exposure method for the 560 K exposure. At the 5-percent significance level, the unpaired rank test indicated no significant difference between the results from the two fatigue test methods at either temperature condition.

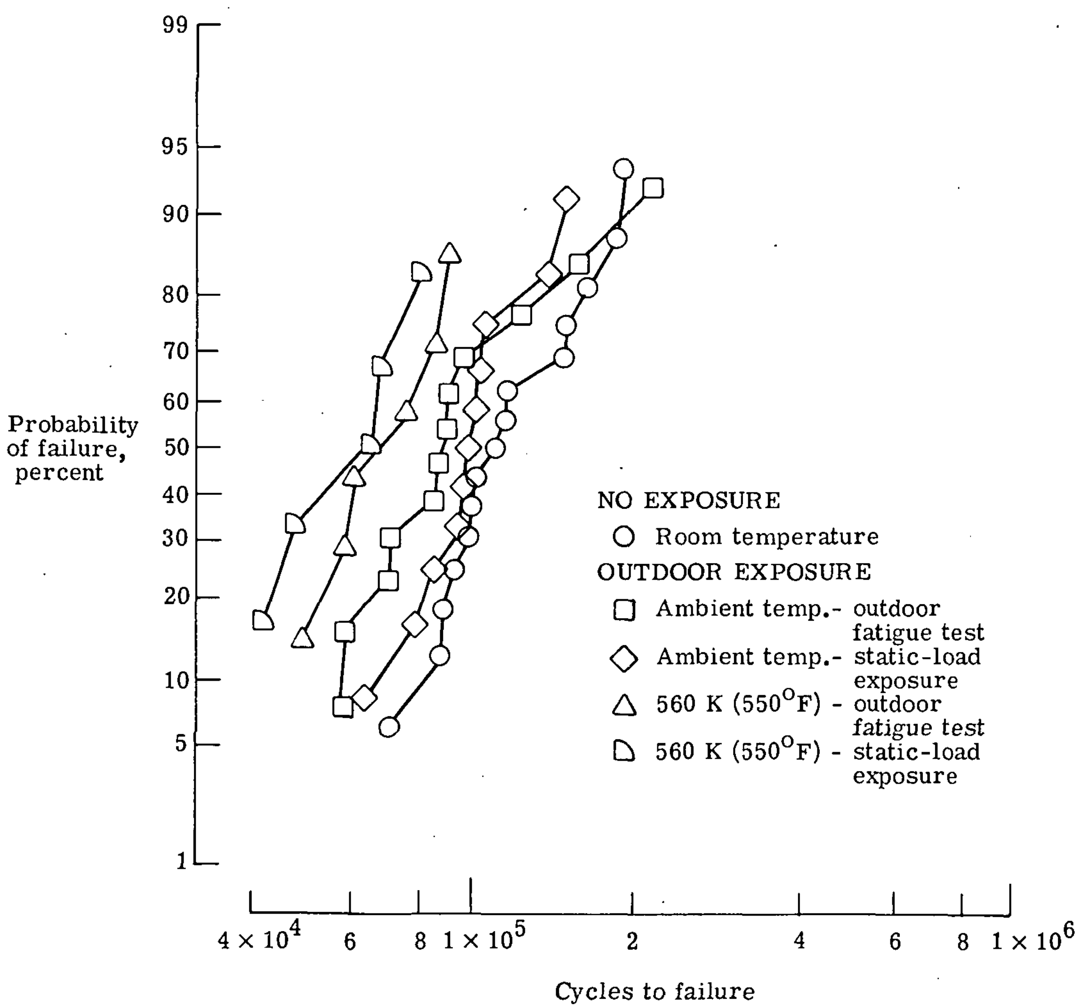

Figure 9.- Short-life data population identified in figure 7 for STA material replotted on log-normal probability paper.

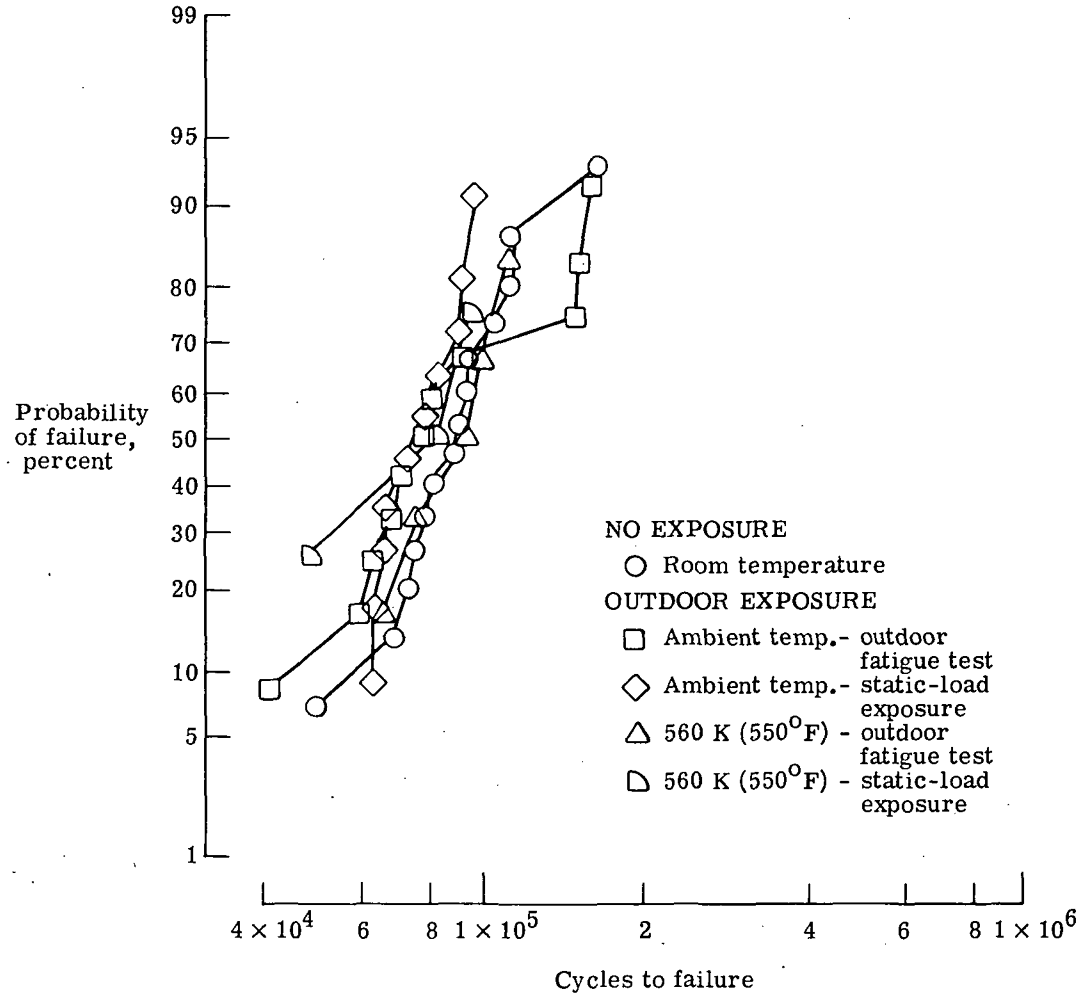

Figure 10.- Short-life data population identified in figure 8 for annealed material replotted on log-normal probability paper.

Ti-6Al-4V annealed.- Data for the short-life groups are plotted in figure 10 in the same way as was done for the STA material data in figure 9. As for the STA material, no differences in failure characteristics were noted among the test groups. The data for all of the test groups are so closely bunched that no consistent trends are evident. Accordingly, the unpaired rank test for difference between medians also indicated no significant differences between test groups at the 5-percent significance level.

CONCLUDING REMARKS

The effects of an outdoor exposure at ambient and 560 K (550° F) temperatures on the fatigue life of Ti-6Al-4V titanium alloy sheet in the STA and the annealed condition have been determined. All fatigue tests were constant-amplitude bending of specimens containing a drilled hole (stress concentration factor of 1.6). Effects of exposure were determined by comparing fatigue lives of exposed specimens to those of unexposed specimens. Two procedures for fatigue testing the exposed specimens were evaluated: (1) fatigue tests were conducted outdoors by applying 1200 load cycles per week at ambient temperature until failure occurred and (2) fatigue tests were conducted indoors at room temperature after outdoor exposure under static load. The exposure period ranged from 9 to 28 months for the outdoor fatigue-test group and was 24 months for the static-load group. Comparisons of the results from the various test groups were limited to the short-life ends of the life distributions because the life data tended to divide into short- and long-life groups and the long-life groups contained discontinued tests. From the data presented, the following were concluded:

1. The outdoor exposure at 560 K reduced the fatigue life of the STA material to about 1/2 of the no-exposure life. The outdoor exposure at ambient temperature also reduced the fatigue life of STA material, but by a smaller amount. Statistical comparisons indicated that, at the 5-percent significance level, the reduction in life caused by the 560 K exposure was statistically significant but that the reduction caused by the ambient-temperature exposure was not significant.

2. The outdoor exposures at both ambient and 560 K temperatures had essentially no effect on the fatigue life of the annealed material. Statistical comparisons at the 5-percent significance level indicated no significant differences between medians of the test groups.

3. The two test procedures – outdoor fatigue test and indoor fatigue test after outdoor exposure – led to the same conclusions about exposure effects.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., February 20, 1974.

APPENDIX A

CONVERSION OF SI UNITS TO U.S. CUSTOMARY UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures held in Paris in 1960 (ref. 5). Conversion factors required for units used herein are given in the following table:

Physical quantity	SI Unit (**)	Conversion factor (*)	U.S. Customary Unit
Force	newtons (N)	0.2248	lbf
Length	meters (m)	39.37	in.
Stress	pascals (Pa)	1.450×10^{-7}	ksi = 10^3 lbf/in^2
Temperature	kelvin (K)	9/5	(^{o}F + 459.67)
Volume	cubic meters (m^3)	264.2	gallon
Frequency	hertz (Hz)	60	cpm

*Multiply value given in SI Unit by conversion factor to obtain equivalent in U.S. Customary Unit.

**Prefixes to indicate multiple of units are as follows:

Prefix	Multiple
giga (G)	10^9
mega (M)	10^6
kilo (k)	10^3
centi (c)	10^{-2}
milli (m)	10^{-3}
micro (μ)	10^{-6}

APPENDIX B

SPECIMEN CLEANING PROCEDURE

1. Remove metal markings such as manufacturer's stamp, crayon, and so forth, with acetone or alcohol and cloth.

2. Perform alkaline cleaning consisting of six steps, using a separate tank for each solution or rinse as follows:

a. Immerse in sodium hydroxide base alkaline cleaner, 45 kg/m^3 (6 ozm/gallon) water, at a temperature of 360 to 370 K (180^o to 200^o F) for 10 minutes.

b. Rinse in hot water for 2 to 3 minutes.

c. Immerse in nitric acid solution, 20 percent nitric acid and 80 percent water by volume, for 30 seconds.

d. Rinse in agitated hot water.

e. Rinse in agitated cold water.

f. Rinse in agitated cold water with continuous supply of fresh water.

3. Dry with clean cloth or paper wipers.

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TABLE I.- CHEMICAL ANALYSIS AND HEAT TREATMENT OF MATERIALS

Ti-6Al-4V (STA)

Element	Percent by weight
C	0.02
N	.010
Fe	.17
Al	6.2
V	4.4
O	.123
H	50 PPM

Heat treatment:

(1) 1185 K (1675° F) for 9 minutes, water quenched

(2) 950 K (1250° F) for 4 hours, air cooled

Ti-6Al-4V (annealed)

Element	Percent by weight
C	0.02
N	.010
Fe	.17
Al	6.2
V	4.4
O	.142
H	69 PPM

Heat treatment:

1075 K (1475° F) for 1 hour, furnace cooled to 980 K (1300° F), air cooled

TABLE II.- AVERAGE[a] ROOM-TEMPERATURE LONGITUDINAL TENSILE PROPERTIES OF Ti-6Al-4V IN THE ANNEALED AND THE STA CONDITION

Heat treatment	Ultimate tensile strength		Yield strength (0.2% offset)		Modulus of elasticity		Elongation in 5 cm (2 in.), percent
	MPa	ksi	MPa	ksi	GPa	ksi	
Annealed	1010	147	972	141	121	17.6×10^3	13.9
STA	1040	151	1020	148	121	17.6×10^3	14.7

[a]Based on nine tests.

TABLE III.- METEOROLOGICAL DATA FOR TEST PERIOD

Month and year	Average temperature		Total precipitation		Days of precipitation
	K	^{o}F	mm	in.	
Oct. 1970	290	63	29.0	1.14	9
Nov.	284	52	68.3	2.69	11
Dec.	280	44	98.6	3.88	7
Jan. 1971	276	37	107.2	4.22	14
Feb.	280	44	100.3	3.95	12
Mar.	281	47	79.2	3.12	11
Apr.	286	56	60.5	2.38	6
May	291	65	178.8	7.04	13
June	297	75	58.9	2.32	8
July	299	78	134.9	5.31	13
Aug.	298	77	137.7	5.42	6
Sept.	296	74	156.0	6.14	3
Oct.	293	67	318.8	12.55	16
Nov.	284	52	60.5	2.38	6
Dec.	284	51	63.5	2.50	6
Jan. 1972	280	45	93.5	3.68	11
Feb.	278	41	106.7	4.20	14
Mar.	282	48	82.3	3.24	9
Apr.	286	56	89.9	3.54	12
May	291	64	90.7	3.57	11
June	295	71	154.7	6.09	12
July	298	77	129.3	5.09	10
Aug.	297	75	92.7	3.65	9
Sept.	295	72	291.8	11.49	11
Oct.	289	60	128.3	5.05	8
Nov.	283	50	134.9	5.31	13
Dec.	281	47	131.8	5.19	16
Jan. 1973	278	40	88.4	3.48	11
Feb.	276	38	77.5	3.05	10

TABLE IV.- RESULTS OF FATIGUE TESTS ON CENTRAL-HOLE SPECIMENS $\left(K_T = 1.6\right)$ OF Ti-6Al-4V TITANIUM ALLOY IN THE STA CONDITION AT A STRESS LEVEL OF 172 ± 517 MPa (25 ± 75 ksi)

(a) No exposure	(b) Outdoor fatigue test[a]					(c) Outdoor static-load exposure[a]				
	Ambient temperature		560 K (550° F)			Ambient temperature		560 K (550° F)		
Cycles to failure	Cycles to failure	Days of exposure	Cycles to failure	Days of exposure	Hours exposed at 560 K	Cycles to failure	Days of exposure	Cycles to failure	Days of exposure	Hours exposed at 560 K
71 300	57 800	322	48 800	284	3 000	63 400	732	41 800	558	6400
88 200	58 800	329	57 600	317	3 400	79 100		47 400	703	8500
89 200	70 900	399	60 100	343	4 000	85 700		66 200	688	8400
92 700	71 500	399	75 400	434	5 100	95 700		67 800	705	8500
98 900	86 100	483	85 400	485	5 700	98 400		80 300	732	9000
99 600	87 700	497	90 200	516	6 100	99 800		[c]213 600	677	8000
101 300	90 900	511	[e]181 900	840	10 200	103 300		225 100	704	8300
110 100	91 000	511	[c,e]235 600	827	9 900	103 400		[d]356 700	724	8700
115 700	97 600	552	[c,e]246 500	810	9 200	105 600		[d]365 100	688	8100
116 300	124 700	706	[c,e]253 400	848	10 200	138 300		[d]387 000	705	8700
148 000	[e]159 100	840				149 500		[d]453 600	731	9000
149 300	[c,e]161 800	840				[b]242 700		[d]530 000	716	8700
165 000	[c,e]190 100	846				262 500				
184 900	[e]217 200	846				[b]384 800				
190 200	[c,e]237 800	848				972 900				
[c]315 900	[c,e]309 300	867				[f]$>10^6$				
[c]410 000	[c,e]588 600	867				[f]$>10^6$				
908 600	[f]$>10^6$	867				[f]$>10^6$				
[f]$>10^6$	[f]$>10^6$	867				[f]$>10^6$	732			

[a]Test exposure initiated on Oct. 7, 1970.

[b]Cracking initiated at site of accidental damage to specimen.

[c]Cracking initiated on compression mean stress surface at hole.

[d]Cracking initiated at instrumentation spotweld.

[e]Schedule of applying 1200 cycles per week was abandoned on Jan. 16, 1973; thereafter, large numbers of cycles were applied on days when weather permitted.

[f]No failure.

TABLE V.- RESULTS OF FATIGUE TESTS ON CENTRAL-HOLE SPECIMENS $\left(K_T = 1.6\right)$ OF Ti-6Al-4V TITANIUM ALLOY IN THE ANNEALED CONDITION AT A STRESS LEVEL OF 172 ± 538 MPa (25 ± 78 ksi)

(a) No exposure	(b) Outdoor fatigue test[a]					(c) Outdoor static-load exposure[a]				
Cycles to failure	Ambient temperature		560 K (550° F)			Ambient temperature		560 K (550° F)		
	Cycles to failure	Days of exposure	Cycles to failure	Days of exposure	Hours exposed at 560 K	Cycles to failure	Days of exposure	Cycles to failure	Days of exposure	Hours exposed at 560 K
49 600	40 800	231	65 000	370	4 100	63 000	732	48 200	645	8100
68 800	59 900	336	77 300	416	5 000	63 900		80 000	704	8800
73 100	62 900	357	93 300	531	6 300	66 100		93 200	719	8800
74 800	67 600	377	97 000	577	6 400	66 700		[c]164 800	715	8300
77 300	69 800	392	110 100	621	7 300	72 600		[c]176 200	714	8600
81 600	77 700	441	[c]130 100	762	9 300	78 400		[b]243 700	732	8800
90 500	79 400	448	[d,e]140 000	816	9 800	82 300		[c]248 700	732	8800
90 600	92 100	517	[c,e]156 100	788	9 100	89 400		[c]256 200	716	8700
92 700	146 100	832	[d,e]264 500	833	9 500	90 700		[d]266 100	685	8500
93 200	[c]146 600	832	[d,e]320 900	867	10 000	95 900		[d]451 000	686	7700
103 600	147 900	839				[b]265 000				
110 700	[e]157 000	840				[c]347 000				
111 700	[c,e]162 200	840				[c]373 700				
161 600	[c,e]168 200	840				[c]510 500				
[b]322 400	[c,e]175 900	840				614 300				
[c]799 800	[c,e]181 400	840				[c]660 200				
[b]976 600	[c,e]188 900	846				[f]$>10^6$				
[f]$>10^6$	[c,e]221 800	846				[f]$>10^6$	732			
[f]$>10^6$	[c,e]258 400	848								

[a]Test exposure initiated on Oct. 7, 1970.
[b]Cracking initiated at site of accidental damage to specimen.
[c]Cracking initiated on compression mean stress surface at hole.
[d]Cracking initiated at instrumentation spotweld.
[e]Schedule of applying 1200 cycles per week was abandoned on Jan. 16, 1973; thereafter, large numbers of cycles were applied on days when weather permitted.
[f]No failure.

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