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CRACK PROPAGATION, DELAYED FAILURE, AND RESIDUAL STATIC STRENGTH OF TITANIUM, ALUMINUM, AND STAINLESS STEEL ALLOYS IN AQUEOUS ENVIRONMENTS

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SUMMARY

An investigation of crack propagation, delayed failure, and residual static strength was conducted on titanium, aluminum, and stainless steel alloys in air, in a $3\frac{1}{2}$ percent salt solution, and in sea water.

Fatigue cracks grew approximately 2 to 3 times faster in the aqueous environment than in air in Ti-8Al-1Mo-1V (duplex annealed) titanium alloy and 7075-T6 aluminum alloy. In the 2024-T3 aluminum alloy, the aqueous environment had a deleterious effect on the crack growth rate at the lower stress levels and a beneficial effect at the high stress levels.

In general, the delayed failure strengths of the aluminum and stainless steel alloys were essentially the same as their residual static strengths in air. The delayed failure strengths of the titanium alloys were lower than their residual static strengths by various degrees depending on the material and thickness. The residual static strength of the aluminum alloys was not affected by the aqueous environment.

INTRODUCTION

Recent work (ref. 1) has shown that cracked specimens of certain alloys fail in relatively short times under the combined effects of aqueous environment and prolonged static stress. (This type of failure will be referred to herein as delayed failure.) Several of these alloys are being considered for use in the primary structure of supersonic aircraft. Therefore, it is important to determine how environmental factors encountered in service might affect the load-carrying ability of some of these alloys.

Toward this end, crack propagation, delayed failure, and residual static strength tests were conducted on various titanium, aluminum, and stainless steel alloys in air, in a $3\frac{1}{2}$ percent salt solution, and in sea water. The results of these studies are presented in this report.

SYMBOLS

The units used for the physical quantities defined in this report are given both in U.S. Customary Units and in the International System of Units, SI (ref. 2). Appendix A presents factors relating these two systems of units.

a	half-length of internal crack, inches (cm)
E	Young's modulus, ksi (GN/m^2)
e	total elongation in 2-inch (5.1-cm) gage length, percent
N	number of cycles
P_{max}	maximum load in a cycle, lbf (newtons)
R	ratio of minimum cyclic stress to maximum cyclic stress
S_a	alternating stress amplitude, ksi (MN/m^2)
S_m	mean stress, ksi (MN/m^2)
S_{max}	load divided by the net section area remaining after the crack propagation test, ksi (MN/m^2)
S_{net}	tensile strength of cracked specimen at failure (based on net section before loading starts), ksi (MN/m^2)
S_o	load divided by the initial net section area, $P_{max}/(w - x)t$, ksi (MN/m^2)
t	thickness of specimen, inches (cm)
w	width of specimen, inches (cm)
x	length of the starter notch, inches (cm)
σ_u	ultimate tensile strength, ksi (MN/m^2)
σ_y	yield strength (0.2-percent offset), ksi (MN/m^2)

MATERIALS AND SPECIMENS

The specimen configurations used in the crack propagation and delayed failure tests are shown in figure 1. Materials, types of tests, and specimen dimensions are presented in the following table:

Material	Type of test	Thickness		Length		Width	
		in.	cm	in.	cm	in.	cm
Ti-6Al-4V annealed	Delayed failure	0.040	0.10	12.0	30.5	4.0	10.2
Ti-8Al-1Mo-1V mill annealed	Delayed failure	.040	.10	12.0	30.5	4.0	10.2
Ti-8Al-1Mo-1V duplex annealed	Delayed failure	.026	.07	12.0	30.5	4.0	10.2
Ti-8Al-1Mo-1V duplex annealed	Delayed failure	.050	.13	12.0	30.5	4.0	10.2
Ti-8Al-1Mo-1V duplex annealed	Crack propagation	.050	.13	24.0	61.0	8.0	20.4
Ti-8Al-1Mo-1V duplex annealed	Delayed failure	.250	.64	24.0	61.0	8.0	20.4
Ti-13V-11Cr-3Al solution annealed	Delayed failure	.034	.09	12.0	30.5	4.0	10.2
2024-T3	Delayed failure	.090	.23	12.0	30.5	4.0	10.2
7075-T6	Delayed failure	.090	.23	12.0	30.5	4.0	10.2
2024-T3	Crack propagation and residual static strength	.090	.23	35.0	88.9	12.0	30.5
7075-T6	Crack propagation and residual static strength	.090	.23	35.0	88.9	12.0	30.5
AM 350 (CRT)	Delayed failure	.024	.06	12.0	30.5	4.0	10.2

Each alloy of a given thickness was from the same mill heat. The material was tested in the as-received condition with the exception of the Ti-13V-11Cr-3Al (solution annealed) alloy which received subsequent heat treating at the Langley Research Center. Details of the heat treatments and chemical composition are presented in tables I(a) and (b). All phases of heat treating, machining, and handling followed rigid quality control specifications established at the Langley Research Center. The tensile properties of the materials tested were obtained from standard ASTM tensile specimens and are given in table I(c).

The grain direction in all specimens was parallel to the direction of loading. A crack starter in the form of a slit 0.10 inch (0.25 cm) long and 0.01 inch (0.25 mm) wide was cut by a spark-discharge technique in the center of each specimen perpendicular to the direction of loading.

TEST PROCEDURE

A brief outline of the test procedures used in each portion of the study is presented in the following sections. A detailed discussion of the test procedures is presented in appendix B.

Fatigue Crack Propagation

Fatigue crack propagation tests were conducted on Ti-8Al-1Mo-1V (duplex annealed) specimens alternately subjected to cyclic loading in sea water (applied by a wad of cotton saturated with sea water) at room temperature and to static stress at 550° F (561° K). The mean stress on the gross area was maintained constant at 25 ksi (173 MN/m^2) throughout the test. The range of alternating stresses applied was from ±2 ksi to ±25 ksi (±14 to ±173 MN/m^2). A companion test was conducted in which the specimen was continuously cycled while immersed in sea water without the heat soak.

The 2024-T3 and 7075-T6 aluminum alloy specimens were cyclically loaded in sea water (again with saturated cotton) at room temperature throughout the crack propagation test. These tests were conducted at $R = 0$ with maximum stresses ranging from 16 to 50 ksi (110 to 344 MN/m^2). After the crack propagation tests were completed, the 12-inch (30.5-cm) wide aluminum alloy specimens were cycled in air at a net section stress range of 0 to 15 ksi (0 to 103 MN/m^2) until the crack reached a predetermined length.

Delayed Failure Tests

All materials in this investigation were subjected to delayed failure tests at room temperature in a $3\frac{1}{2}$ percent salt solution and in air with the exception of the 0.25-inch (0.64-cm) thick Ti-8Al-1Mo-1V (duplex annealed) material which was not tested in air. In all delayed failure tests in aqueous environments, the test section was completely immersed in the aqueous environment.

Residual Static Strength Tests

Residual static strength tests were conducted on 2024-T3 and 7075-T6 aluminum alloys in both air and sea water at room temperature. In addition, the 2024-T3 alloy was tested in a $3\frac{1}{2}$ percent salt solution.

RESULTS AND DISCUSSION

Fatigue Crack Propagation Tests

The results of the fatigue crack growth tests on the Ti-8Al-1Mo-1V (duplex annealed) specimens subjected to alternate aqueous and thermal soaking are presented in table II. This table gives the average number of cycles required for the crack to grow from a half-length a of 0.15 inch (0.38 cm) to the specified half-lengths.

The fatigue crack growth curves for the Ti-8Al-1Mo-1V (duplex annealed) specimens subjected to alternate aqueous and thermal soaking are shown as solid curves in figure 2. In the tests conducted at $S_o = 30$ and 27 ksi (206 and 184 MN/m^2), step increases in crack length occurred without an increase in the number of cycles. These increases occurred when both the mean load and sea water were left on the specimens overnight (approximately 16 hours). (In other instances in the same tests, the crack did not advance when both mean stress and sea water were left on the specimens for 16 hour periods.) The dashed curves on figure 2 are for 8-inch (20.4-cm) wide, 0.050-inch (0.13-cm) thick Ti-8Al-1Mo-1V (duplex annealed) specimens tested at room temperature in air (ref. 3). The alloy cited in reference 3 was from the same mill heat as the material tested in this investigation. Generally, the fatigue cracks propagated faster (by factors of 2 or 3) under the combined aqueous and thermal soak conditions than in air. There were two indications that this accelerated crack growth was due primarily to the presence of the sea water. First, in no instance was the crack observed to advance during the one-hour, 550° F (561° K) heat soak at mean load. Second, the fatigue crack growth curve for the specimen tested without heat soaking was nearly the same as the curve for the specimen tested with heat soaking (40 ksi (276 MN/m^2) test).

The results of the fatigue crack propagation tests on the 2024-T3 and 7075-T6 specimens tested in sea water are presented in table III. This table gives the average number of cycles required to propagate the crack from a half-length of 0.10 inch (0.25 cm) to the specified half-lengths. The fatigue crack propagation curves for the 2024-T3 and the 7075-T6 are shown in figures 3 and 4, respectively. The dashed curves are "in-air" data from reference 4. (Note: The data from ref. 4 were adjusted to a half-crack length of 0.10 in. (0.25 cm) in order to compare them with the data from this investigation.)

Fatigue cracks in the 2024-T3 aluminum alloy propagated faster in sea water than in air (by a factor of about 1.5) at the lowest stress level. However, at higher stress levels, the sea water was beneficial. At the highest stress level fatigue cracks propagated approximately twice as fast in air as in sea water.

The fatigue cracks in the 7075-T6 alloy (fig. 4) consistently propagated faster in sea water than in air (by a factor of approximately 2).

Fatigue crack growth was sometimes delayed following the transition from the stress level used for the crack growth tests to the stress level (15 ksi (103 MN/m^2), R = 0) used to obtain the crack lengths desired for the residual static strength tests. Occasionally, secondary fatigue cracks initiated during this delay near the tip of the starter notch or at a sharp change in the original crack path (fig. 5). These secondary cracks usually propagated parallel to the direction of loading. In another instance a secondary fatigue crack normal to the direction of loading was initiated a distance away from the initial crack (fig. 6). These cracks had no apparent effect on the residual strength of the materials.

Delayed Failure Tests

The results of the delayed failure tests are presented in table IV. Plots of initial net section stress against time to failure for the individual materials are presented in figures 7(a) to 7(g). (The strengths of the 2024-T3 and 7075-T6 aluminum alloys were not affected by immersion in the $3\frac{1}{2}$ percent salt solution at 90 percent of the in-air failing strength, and thus these data are not presented in figure form.) Curves have been faired through the data. A summary plot of these curves, the time to failure plotted against the ratio of the failing stress in the aqueous environment to the short-time failing stress in air (residual static strength) is presented in figure 8. The delayed failure strengths of the Ti-6Al-4V (annealed) and the AM 350 (CRT) were approximately 90 percent of their residual static strengths. (In this report delayed failure strength is defined as the stress level below which delayed failure does not occur in 168 hours.) The delayed failure strengths of the 0.026-inch (0.7-mm), 0.050-inch (1.3-mm), and 0.250-inch (6.4-mm) thick Ti-8Al-1Mo-1V (duplex annealed) were approximately 90, 65, and 30 percent, respectively, of their residual static strengths. The reasons for this thickness effect are not understood at this time. The delayed failure strength of the Ti-8Al-1Mo-1V (mill annealed) was approximately 15 percent of its residual static strength. This 15 percent is considerably below the 65 percent of the residual static strength exhibited by the duplex annealed Ti-8Al-1Mo-1V of approximately the same thickness; this difference indicates that heat treatment can significantly affect delayed failure characteristics. The delayed failure strength of the Ti-13V-11Cr-3Al (solution annealed) was approximately 70 percent of its residual static strength.

With the exception of the Ti-8Al-1Mo-1V (mill annealed) material, delayed failure tests conducted in air at 90 percent of the residual static strength did not cause failure in 168 hours. The Ti-8Al-1Mo-1V (mill annealed) failed in 0.4 minute.

Plastic coatings applied to some specimens had little effect on delayed failure in Ti-8Al-1Mo-1V (mill annealed). The addition of liquid soap to the $3\frac{1}{2}$ percent salt solution caused a further reduction in delayed failure strength of Ti-8Al-1Mo-1V (mill annealed). Since a very limited number of tests were conducted under these conditions, no general conclusions can be drawn.

Specimens in which the cracks were grown in air prior to static loading and aqueous wetting demonstrated a somewhat higher delayed failure strength than those in which cracks were grown in the salt solution. In one case (the 0.25-inch (0.64-cm) thick Ti-8Al-1Mo-1V (duplex annealed)) where the specimen was fatigue cracked in air and then the aqueous solution applied, a 105-minute delay occurred before the crack began to grow. This specimen subsequently failed 24 minutes after crack growth began. In a companion test, a crack was grown in the salt solution and then the same static net stress was applied. No delay occurred in crack growth and the specimen failed in 27 minutes. This 27 minutes is essentially equal to the 24 minutes of growth observed in the prior test. Some protective mechanism, possibly an oxide film formation, apparently afforded the air-grown crack surfaces temporary protection from the salt solution.

Unsymmetrical crack growth always occurred in the 0.25-inch (0.64-cm) thick Ti-8Al-1Mo-1V (duplex annealed) specimens which (because of the testing machine configuration) were mounted with the cracks vertical. The lower ends of the cracks grew approximately twice as much as the upper ends. Possibly an air pocket formed at the upper end of the crack as the water level rose, thus preventing the aqueous media from reaching the upper crack tip.

Residual Static Strength Tests

Results of residual static strength tests on 12-inch (30.5-cm) wide 2024-T3 and 7075-T6 specimens tested in air, in a $3\frac{1}{2}$ percent salt solution, and in sea water are presented in table V and in figures 9 and 10, respectively. The residual static strength properties of these two materials were not affected by the aqueous environments.

CONCLUSIONS

Axial-load fatigue crack propagation, delayed failure, and residual static strength tests were conducted in air and in aqueous media on sheet specimens of Ti-8Al-1Mo-1V (mill and duplex annealed), Ti-6Al-4V (annealed), Ti-13V-11Cr-3Al (solution annealed) titanium alloys, 2024-T3 and 7075-T6 aluminum alloys, and AM 350 (CRT) stainless steel. Based on the results, the following conclusions were drawn:

1. Fatigue cracks grew faster (by factors of 2 to 3) in Ti-8Al-1Mo-1V (duplex annealed) specimens subjected to alternate thermal and sea water soaking than in specimens tested in air at a given stress.

2. Fatigue cracks in 7075-T6 grew approximately twice as fast in sea water as in air at a given stress.

3. Fatigue crack growth in 2024-T3 aluminum alloy was approximately one and one-half times as fast in sea water as in air at the lowest stress level. However, at the higher stress levels, the sea water was less deleterious. At the highest stress level, fatigue cracks propagated approximately twice as fast in air as in sea water.

4. The delayed failure strengths of the Ti-6Al-4V (annealed) and the AM 350 (CRT) were approximately 90 percent of their residual static strengths. Delayed failure strength is defined herein as the stress level below which delayed failure will not occur in 168 hours.

5. The delayed failure strength of the Ti-13V-11Cr-3Al (solution annealed) was approximately 70 percent of its residual static strength.

6. The delayed failure strengths of the Ti-8Al-1Mo-1V (duplex annealed) specimens having thicknesses of 0.026 inch, 0.050 inch, and 0.250 inch (0.7 mm, 1.3 mm, and 6.4 mm) were approximately 90, 65, and 30 percent, respectively, of their residual static strengths.

7. The delayed failure strength of the Ti-8Al-1Mo-1V (mill annealed) was approximately 15 percent of its residual static strength. This 15 percent is considerably below the 65 percent of the residual static strength exhibited by the Ti-8Al-1Mo-1V (duplex annealed) of approximately the same thickness; this difference indicates that heat treatment can significantly affect delayed failure characteristics.

8. Specimens in which the cracks were grown in air prior to static testing in a $3\frac{1}{2}$ percent salt solution demonstrated higher delayed failure strengths than those with cracks grown in the $3\frac{1}{2}$ percent salt solution.

9. With the exception of the Ti-8Al-1Mo-1V (mill annealed) material, delayed failure tests conducted in air at 90 percent of the residual static strength did not produce failure in 168 hours. The Ti-8Al-1Mo-1V (mill annealed) failed in 0.4 minute.

10. Specimens of the 2024-T3 and 7075-T6 aluminum alloys did not fail within 168 hours of immersion in $3\frac{1}{2}$ percent salt solution while loaded to 90 percent of their in-air residual static strengths.

11. The residual static strength of the 2024-T3 and 7075-T6 aluminum alloys tested was not affected by the aqueous environments.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 17, 1966,
126-14-03-01-23.

APPENDIX A

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference of Weights and Measures, Paris, October 1960, in Resolution No. 12 (ref. 2). Conversion factors for the units used herein are given in the following table:

To convert from U.S. Customary Units	Multiply by –	To obtain SI Units
lbf	4.448222	newton (N)
in.	2.54×10^{-2}	meter (m)
ksi	6.894757×10^{6}	newtons/meter^2 (N/m^2)
^{o}F	5/9 (^{o}F + 459.67)	degrees Kelvin (^{o}K)
cpm	1.67×10^{-2}	hertz (Hz)

Prefixes and symbols to indicate multiples of units are as follows:

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

APPENDIX B

EQUIPMENT AND TEST PROCEDURE

Equipment

Either a 120 000 lbf (534 kN) capacity hydraulic jack or a 1 200 000 lbf (5340 kN) capacity testing machine was used to obtain the cracked strength in air. The hydraulic jack was also used to obtain the residual static strength in sea water on the 12-inch (30.5-cm) wide aluminum specimens. A load rate of 30 000 lbf per minute (2.2 kN/s) was used in these tests. The maximum load was read from load-indicating systems which are integral parts of these testing machines.

A 20 000 lbf (89 kN) capacity subresonant fatigue-testing machine (ref. 5) was used to conduct the delayed failure tests on the 4.0-inch (10.2-cm) wide specimens. Static loads were applied with a mechanical mean-load system which is an integral part of the machine. Loads were monitored with a strain-gage dynamometer in series with the specimen. The maximum error anticipated for this monitoring system was ±1 percent.

The fatigue crack propagation and delayed failure tests on the 8.0-inch (20.4-cm) wide specimens were conducted in a combination hydraulic and subresonant fatigue-testing machine described in reference 6. Loads were measured with the same type of monitoring system employed on the 20 000 lbf (89 kN) capacity subresonant machine.

Aqueous Media

Three aqueous media were used: distilled water, a $3\frac{1}{2}$ percent (by weight) NaCl in distilled water, and sea water. The pH of the $3\frac{1}{2}$ percent NaCl solution was 8.05 at 27.0° C (300° K). The solids content of the sea water was 37 grams/liter (37 kg/m^3), and the pH of the sea water was 7.70 at 26.5° C (299.5° K).

Fatigue Crack Propagation Tests

Specimens of Ti-8Al-1Mo-1V (duplex annealed), 8 inches (20 cm) wide and 0.05 inch (0.13 cm) thick, were alternately subjected to fatigue cycling in sea water at room temperature and to static stress at 550° F (561° K). Fatigue cracks were grown in air to a total length $2a$ of 0.15 inch (0.38 cm). A wad of sterilized cotton was saturated with sea water and placed against one side of the specimen. The cotton covered the fatigue crack and adjacent area. A strip of clear plastic was then taped over the cotton to retard evaporation of the sea water. In each test water was observed to flow freely through the fatigue crack onto the opposite surface of the specimen. A companion crack growth test was conducted in sea water without heat soaking to study the effect of the cyclic heating.

The test section of the specimen was immersed in sea water since it was not necessary to periodically remove the sea water to install the furnace. The difference in the method used to wet the crack in the companion test was not expected to affect the fatigue crack growth since with both methods the cracks were continuously exposed to the sea water.

Axial-load fatigue tests were conducted at a positive mean stress of 25 ksi (173 MN/m^2). Alternating stresses ranged from ±2 to ±25 ksi (14 to 173 MN/m^2). (These stress levels were selected to make the data directly comparable with the data from ref. 3.) All stresses mentioned herein refer to the original net area of the specimen. Mean and alternating loads were kept constant throughout the cyclic portion of the test. The mean load was maintained constant throughout the entire test. The specimen was cyclically loaded at the test stress level until the fatigue crack grew a distance of 0.1 inch (0.25 cm). The plastic and cotton were then removed, and a furnace similar to the one described in reference 7 was mounted on both sides of the specimen. The specimen was heated to 550° F (561° K) and held at that temperature for 1 hour. The furnace was then removed and the specimen allowed to cool to room temperature. (During heating and cooling the mean load was continuously monitored and kept constant.) The saturated cotton was again placed against the fatigue crack, and the whole process repeated until the crack reached its terminal length. During each overnight period (approximately 16 hours), the specimens were left at room temperature with the mean stress applied. In some instances, the wet cotton was in place against the crack, depending upon the testing stage at the close of the working day. The significance of leaving the sea water and mean load on overnight is discussed in the results section.

The 2024-T3 and 7075-T6 aluminum alloy specimens were cyclically loaded in sea water throughout the crack propagation test. A cotton wad saturated with sea water was again used to keep the crack surfaces wet. Axial-load tests were conducted at $R = 0$. The maximum stresses ranged from 16 to 50 ksi (110 to 344 MN/m^2). These stress levels made the data directly comparable with the data in reference 4.

The loading frequencies used in these tests were also the same as those used in reference 4 (i.e., approximately 40 cpm (0.7 Hz) in the 50-, 40-, and 30-ksi (344-, 276-, and 207-MN/m^2) tests, and approximately 1200 cpm (20 Hz) in the 20- and 16-ksi (138- and 110-MN/m^2) tests) with two exceptions: the 25-ksi (173-MN/m^2) tests on the 7075-T6 and the 2024-T3 specimens. The 25-ksi (173-MN/m^2) tests in reference 4 were conducted at 1200 cpm (20 Hz), whereas the 25-ksi (173-MN/m^2) tests of this investigation were conducted at 40 cpm (0.7Hz).

In all tests fatigue crack growth was monitored on the surface of the specimen opposite the wet cotton. A grid was photographically printed on each specimen to facilitate measurement of the crack growth. The grid spacing was 0.05 inch (1.27 mm). Previous metallographic and tensile tests revealed that the grid emulsion had no detrimental effects on the material. Additional details of the grid can be found in reference 7. Crack growth was observed through a 10 power monocular telescope while the specimen was illuminated with stroboscopic light. The number of cycles at which the crack tip reached each grid line was recorded; from these data the crack growth curves were plotted.

Delayed Failure Tests

Delayed failure tests were conducted in air, in a $3\frac{1}{2}$ percent salt solution, and in distilled water. For the tests conducted in aqueous environment, clear plastic was taped on the sides of the delayed failure specimens in the vicinity of the crack, thus a container for the liquids was formed. (See fig. 11.) Guide plates were used to restrain local buckling in the test section on all but the 0.25-inch (0.64-cm) thick Ti-8Al-1Mo-1V (duplex annealed) specimens. These guides were prevented from coming in direct contact with the liquids or with the specimen in the test section by the plastic, thus any spurious electro-chemical reactions were prevented.

Fatigue cracks, nominally 1.2 inches (3.05 cm) and 2 inches (5.08 cm) long, were grown in the 4-inch (10.2-cm) and 8-inch (20.4-cm) wide delayed failure specimens, respectively, in either air or aqueous environments. The 4-inch (10.2-cm) wide specimens were mounted with the crack horizontal. The 8-inch (20.4-cm) wide specimens were mounted with the crack vertical. Details of the cyclic stress levels used to grow the cracks are given in table IV. Upon reaching the predetermined crack length, the dynamic cycling was stopped and the static load adjusted to a predetermined value. In some instances the crack grew a short distance and then stopped during application of the static load. In these cases, the net section stresses reported in table IV were based on the remaining net section area after this crack extension. When no extension was observed, the net section stresses were based on the remaining area just prior to static loading. The liquid was then poured into the plastic containers for the cases where the cracks were grown in air. Time to failure was measured from the time at which: (a) the static load was reached for the cracks grown in the liquid, (b) the level of the liquid covered the crack for those cracks grown in air, or (c) when the static load was reached for the specimens tested entirely in air. Automatic timers were used to record time to failure. No records of crack growth as a function of time were kept because the tests were not continuously monitored.

In order to determine if the specimen surface area in contact with the aqueous environment had an effect on the delayed failure characteristics, several specimens were coated with a plastic spray such that the aqueous environment came in contact with only the crack surface. The cracks were grown after the coating was applied and in all cases caused the plastic coating to crack in the vicinity of the crack. In one instance a liquid soap was added to the $3\frac{1}{2}$ percent salt solution to study the effect of surface tension on delayed failure.

Residual Static Strength Tests

After the crack propagation tests were completed, the 12-inch (30.5-cm) wide aluminum alloy specimens were cycled in air at a net section stress range of 0 to 15 ksi (0 to 103 MN/m^2) until the crack reached a predetermined length. This procedure was followed to produce a consistent influence of prior stress on the material immediately ahead of the crack tip.

These specimens were loaded in either air or aqueous environment at a rate of 30 000 lbf per minute (2.2 kN/s) until failure occurred. As in the delayed failure tests, a plastic container was placed over both sides of the crack and filled with sea water. Guide plates with a 1/2-inch (1.27-cm) wide slit were used to accommodate the plastic container and to allow visual observation. These specimens were mounted such that the cracks were horizontal.

REFERENCES

1. Brown, B. F.; Forgeson, B. W.; Lennox, T. J., Jr.; Lupton, T. C.; Newbegin, R. L.; Peterson, M. H.; Smith, J. A.; and Waldron, L. J.: Marine Corrosion Studies – Third Interim Report of Progress. NRL Mem. Rept. 1634, U.S. Naval Res. Lab., July 1965.
2. Mechtly, E. A.: The International System of Units – Physical Constants and Conversion Factors. NASA SP-7012, 1964.
3. Hudson, C. Michael: Studies of Fatigue Crack Growth in Alloys Suitable for Elevated-Temperature Applications. NASA TN D-2743, 1965.
4. Hudson, C. Michael; and Hardrath, Herbert F.: Effects of Changing Stress Amplitude on the Rate of Fatigue-Crack Propagation in Two Aluminum Alloys. NASA TN D-960, 1961.
5. Grover, H. J.; Hyler, W. S.; Kuhn, Paul; Landers, Charles B.; and Howell, F. M.: Axial-Load Fatigue Properties of 24S-T and 75S-T Aluminum Alloy as Determined in Several Laboratories. NACA Rept. 1190, 1954. (Supersedes NACA TN 2928.)
6. Hudson, C. Michael; and Hardrath, Herbert F.: Investigation of the Effects of Variable-Amplitude Loadings on Fatigue Crack Propagation Patterns. NASA TN D-1803, 1963.
7. Hudson, C. Michael: Fatigue-Crack Propagation in Several Titanium and Stainless-Steel Alloys and One Superalloy. NASA TN D-2331, 1964.
8. Weiss, V.; and Sessler, J. G., eds.: Aerospace Structural Metals Handbook. Volume II – Non-Ferrous Alloys. ASD-TDR-63-741, Vol. II, U.S. Air Force, May 1963. (Revised Mar. 1964.)
9. Figge, I. E.: Residual Static Strength of Several Titanium and Stainless-Steel Alloys and One Superalloy at -109° F, 70° F, and 550° F. NASA TN D-2045, 1963.
10. Figge, I. E.: Residual Strength of Alloys Potentially Useful in Supersonic Aircraft. NASA TN D-2613, 1965.
11. Heimerl, George J; Baucom, Robert M.; Manning, Charles R., Jr.; and Braski, David N.: Stability of Four Titanium-Alloy and Four Stainless-Steel Sheet Materials After Exposures up to 22 000 Hours at 550° F (561° K). NASA TN D-2607, 1965.

TABLE I.- MATERIALS

(a) Heat treatments

Material	Condition	Heat treatment
Ti-8Al-1Mo-1V	Mill annealed	1450° F (1061° K) for 8 hours, furnace cooled.
Ti-8Al-1Mo-1V	Duplex annealed	1450° F (1061° K) for 8 hours, furnace cooled; 1450° F (1061° K) for 15 minutes, air cooled.
Ti-13V-11Cr-3Al	Solution annealed (SA)	Solution annealed by producer; aged 24 hours at 900° F (756° K), air cooled.
AM 350	Cold rolled and tempered (CRT)	20 percent cold rolled and tempered 3 to 5 minutes at 930° F (773° K), air cooled.
Ti-6Al-4V	Annealed	1475° F (1075° K) for 1 hour, furnace cooled to 1300° F (977° K), air cooled.
2024	T3	See reference 8
7075	T6	See reference 8

TABLE I.- MATERIALS – Concluded

(b) Typical chemical composition (percents given on weight basis)

Element	Ti-8Al-1Mo-1V (mill or duplex annealed)		Ti-13V-11Cr-3Al (solution annealed)	AM 350 (cold rolled and tempered)		Ti-6Al-4V (annealed)		2024-T3		7075-T6	
	Minimum	Maximum	Nominal	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
C		0.08	0.020	0.08	0.12		0.10				
Mn				.50	1.25			0.30	0.90		0.30
P					.04						
S					.03						
Si					.50				.50		.50
Ni				4.00	5.00						
Cr			11.3	16.00	17.00				.10	0.18	.40
Mo	0.75	1.25		2.50	3.25						
N		.05	.020	.07	.13		.05				
Ti	Balance		Balance			Balance					.20
Fe		.30	.20	Balance			.30		.50		.70
H		.015	.017				.015				
V	.75	1.25	13.4			3.50	4.50				
Al	7.50	8.50	2.8			5.50	6.75	Balance		Balance	
O							.20				
Cu								3.8	4.9	1.2	2.0
Mg								1.2	1.8	2.1	2.9
Zn									.25	5.1	6.1

(c) Average tensile properties (grain direction, longitudinal)

Material	σ_u,		σ_y,		E,		e, percent 2-inch (5.1-cm) gage length	Number of tests
	ksi	MN/m^2	ksi	MN/m^2	ksi	GN/m^2		
Ti-8Al-1Mo-1V (mill annealed) t = 0.040 inch (0.10 cm)[a]	152.6	1050	145.7	1002	18.0×10^3	124	18.5	5
Ti-8Al-1Mo-1V (duplex annealed) t = 0.026 inch (0.07 cm)	136.0	937	125.6	865	15.6×10^3	107	10.6	3
Ti-8Al-1Mo-1V (duplex annealed) t = 0.050 inch (0.13 cm)[b]	152.0	1048	133.6	920	18.3×10^3	126	12.5	3
Ti-8Al-1Mo-1V (duplex annealed) t = 0.250 inch (0.64 cm)[b]	137.4	946	120.0	826	14.8×10^3	102	17.3	3
Ti-13V-11Cr-3Al (solution annealed) t = 0.034 inch (0.09 cm)[c]	152.5	1049					1.5	2
AM 350 (CRT) t = 0.024 inch (0.06 cm)[a]	204.5	1405	182.3	1255	28.6×10^3	197	18.8	5
Ti-6Al-4V (annealed) t = 0.040 inch (0.10 cm)[a]	144.4	992	137.3	946	16.4×10^3	113	12.5	5
2024-T3[d]	72.1	497	52.1	359	10.5×10^3	72	21.6	147
7075-T6[d]	82.9	571	75.5	520	10.2×10^3	70	12.3	152

[a]Data from reference 9.
[b]Data from reference 10.
[c]Data from reference 11.
[d]Data from reference 5.

TABLE II.- FATIGUE CRACK GROWTH DATA ON Ti-8Al-1Mo-1V (DUPLEX ANNEALED) TITANIUM ALLOY SUBJECTED TO ALTERNATE SEA WATER AND THERMAL SOAKING. S_m = 25 ksi (173 MN/m^2)

S_a, ksi (MN/m^2)	Number of cycles required to propagate a crack from a half-length a of 0.15 inch (0.38 cm) to a half-length a of –									
	0.20 inch (0.51 cm)	0.30 inch (0.76 cm)	0.40 inch (1.02 cm)	0.50 inch (1.27 cm)	0.60 inch (1.52 cm)	0.70 inch (1.78 cm)	0.80 inch (2.03 cm)	0.90 inch (2.29 cm)	1.00 inch (2.54 cm)	1.20 inch (3.05 cm)
25 (173)	1 110	2 500	3 485	4 125						
15 (104)	1 670	4 210	5 450	5 950						
15 (104)	[a]1 040	[a]2 720	[a]4 230							
10 (69)	3 000	6 000	7 600	8 600						
5 (35)	15 000	50 000	[b]69 000	77 000	87 000	96 000	102 000	108 000	112 000	119 000
2 (14)	610 000	1 360 000	1 900 000	2 310 000	2 620 000	[c]2 810 000	[d]2 880 000	2 960 000	2 980 000	3 090 000

[a]Specimen cycled in sea water at room temperature for entire test.

[b]Specimen held 16 hours in sea water at room temperature with mean load applied. Crack grew from a half-length of 0.43 to 0.48 inch (1.09 to 1.22 cm).

[c]Specimen held 16 hours in sea water at room temperature with mean load applied. Crack grew from a half-length of 0.75 to 0.80 inch (1.90 to 2.03 cm).

[d]Specimen held 16 hours in sea water at room temperature with mean load applied. Crack grew from a half-length of 0.89 to 0.99 inch (2.26 to 2.52 cm).

TABLE III.- FATIGUE CRACK GROWTH DATA ON 7075-T6 AND 2024-T3 ALUMINUM ALLOYS TESTED IN SEA WATER. R = 0

S_o, ksi (MN/m^2)	Number of cycles required to propagate a crack from a half-length a of 0.10 inch (0.25 cm) to a half-length a of –									
	0.20 inch (0.51 cm)	0.30 inch (0.76 cm)	0.40 inch (1.02 cm)	0.50 inch (1.27 cm)	0.60 inch (1.52 cm)	0.70 inch (1.78 cm)	0.80 inch (2.03 cm)	0.90 inch (2.29 cm)	1.00 inch (2.54 cm)	1.20 inch (3.05 cm)
					7075-T6					
50 (344)	142	194	208							
40 (276)	332	479	566	618	647	657				
30 (206)	710	1 060	1 280	1 410	1 515	1 590	1 650	1 680	1 690	
25 (173)	1 280	1 850	2 190	2 440	2 630	2 780	2 900	2 980	3 020	
20 (138)	3 200	4 850	5 650	6 120	6 500	6 800	7 000	7 200	7 400	7 700
16 (110)	5 160	7 330								
					2024-T3					
50 (344)	191	224								
40 (276)	660	840	920	965						
30 (206)	2 530	3 600	4 160	4 480	4 700	4 850	4 960	5 030	5 060	
25 (173)	3 200	5 050	6 250	7 030	7 510	7 810	8 030	8 200	8 340	
20 (138)	9 600	15 300	18 900	20 900	22 200					
16 (110)	16 900	26 200	32 600	37 600	41 000	43 200				

TABLE IV.- DELAYED FAILURE TEST RESULTS

(a) Ti-8Al-1Mo-1V (mill annealed): w = 4.0 inches (10.2 cm); t = 0.040 inch (0.10 cm); failing stress in air = 74.8 ksi (515 MN/m^2) (at a load rate of 30 000 lbf/min (2.2 kN/s)); specimen guided

Cyclic stress level, ksi (MN/m^2) Maximum	Mean	Minimum	Cyclic environment	Crack length, inch (cm)	Delayed failure environment	Static net section stress, ksi (MN/m^2)	Time, no growth, minute	Time, growth, minute	Total time to failure, minute	Remarks
35 (238)	25 (173)	15 (104)	Air	1.6 (4.1)	$3\frac{1}{2}$ percent salt solution	65.4 (450)	0	0.2	0.2	Salt solution touched only one side of crack.
35 (238)	25 (173)	15 (104)	Air	1.25 (3.2)	$3\frac{1}{2}$ percent salt solution	32.8 (226)	---	---	Run out[1]	Crack grew in air at 66.6 ksi (460 MN/m^2); stress reduced to 32.8 ksi (226 MN/m^2).
35 (238)	25 (173)	15 (104)	Air	1.25 (3.2)	$3\frac{1}{2}$ percent salt solution	58.9 (406)	0	.9	.9	
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	31.2 (215)	0	.5	.5	
20 (138)	15 (104)	10 (69)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	18.7 (129)	0	3.0	3.0	
15 (104)	10 (69)	5 (35)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	11.4 (79)	0	3.6	3.6	
10 (69)	5 (35)	0 (0)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	6.4 (44)	---	---	Run out	
12.5 (86)	7.5 (52)	2.5 (17)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	9.4 (65)	---	---	Run out	
35 (238)	25 (173)	15 (104)	Air	1.22 (3.1)	$3\frac{1}{2}$ percent salt solution	55.0 (379)	0	.3	.3	
30 (206)	25 (173)	20 (138)	Air	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution plus liquid soap	67.3 (464)	0	.4	.4	Soap added to modify surface tension
20 (138)	15 (104)	10 (69)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	18.8 (130)	0	3.0	3.0	Plastic coating applied
20 (138)	15 (104)	10 (69)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	18.8 (130)	0	2.8	2.8	Plastic coating applied

(b) Ti-8Al-1Mo-1V (duplex annealed): w = 4.0 inches (10.2 cm); t = 0.026 inch (0.07 cm); failing stress in air = 114.6 ksi (790 MN/m^2) (at a load rate of 30 000 lbf/min (2.2 kN/s)); specimen guided

Cyclic stress level, ksi (MN/m^2) Maximum	Mean	Minimum	Cyclic environment	Crack length, inch (cm)	Delayed failure environment	Static net section stress, ksi (MN/m^2)	Time, no growth, minute	Time, growth, minute	Total time to failure, minute	Remarks
35 (238)	25 (173)	15 (104)	Air	1.40 (3.6)	$3\frac{1}{2}$ percent salt solution	103.1 (71)	---	------	Run out[1]	Crack grew in air while applying load[2]
35 (238)	25 (173)	15 (104)	Air	1.30 (3.3)	$3\frac{1}{2}$ percent salt solution	89.0 (614)	---	------	Run out	Crack grew in air while applying load[2]
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.30 (3.3)	$3\frac{1}{2}$ percent salt solution	95.1 (656)	---	------	Run out	Crack grew in salt solution while applying load[2]
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.31 (3.3)	$3\frac{1}{2}$ percent salt solution	108.7 (749)	0	7998.0	7998.0	Crack grew in salt solution while applying load[2]
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.23 (3.1)	$3\frac{1}{2}$ percent salt solution	110.0 (759)	0	.9	.9	Crack grew in salt solution while applying load[2]
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.20 (3.1)	$3\frac{1}{2}$ percent salt solution	110.0 (759)	0	.1	.1	
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.20 (3.1)	$3\frac{1}{2}$ percent salt solution	105.0 (724)	3.3	35.1	38.4	
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.20 (3.1)	$3\frac{1}{2}$ percent salt solution	105.0 (724)	---	1.8	1.8	

[1]Run out – 168 hours without failure.

[2]The crack grew from a nominal length of 1.20 inches (3.1 cm) to crack length indicated (column 3) during application of the static load. The net section stress was based on the indicated crack length.

TABLE IV.- DELAYED FAILURE TEST RESULTS – Continued

(c) Ti-8Al-1Mo-1V (duplex annealed): w = 4.0 inches (10.2 cm); t = 0.050 inch (0.13 cm); failing stress in air = 100 ksi (689 MN/m^2) (at a load rate of 30 000 lbf/min (2.2 kN/s))[3]; specimen guided

Cyclic stress level, ksi (MN/m^2)			Cyclic environment	Crack length, inch (cm)	Delayed failure environment	Static net section stress, ksi (MN/m^2)	Time, no growth, minute	Time, growth, minute	Total time to failure, minute	Remarks
Maximum	Mean	Minimum								
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	60.0 (414)	0	2.75	2.75	
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	80.0 (552)	0	1.1	1.1	
30 (206)	25 (173)	20 (138)	Air	1.2 (3.1)	Air	103.1 (710)	---	----	Run out[1]	
35 (238)	25 (173)	15 (104)	Air	1.2 (3.1)	Air	103.0 (709)	---	----	Run out	

(d) Ti-8Al-1Mo-1V (duplex annealed): w = 8.0 inches (20.4 cm); t = 0.25 inch (0.64 cm); failing stress in air = 85 ksi (586 MN/m^2) (at a load rate of 30 000 lbf/min (2.2 kN/s))[3]; specimen not guided

Cyclic stress level, ksi (MN/m^2)			Cyclic environment	Crack length, inch (cm)	Delayed failure environment	Static net section stress, ksi (MN/m^2)	Time, no growth, minute	Time, growth, minute	Total time to failure, minute	Remarks
Maximum	Mean	Minimum								
30 (206)	25 (173)	20 (138)	Air	2.0 (5.1)	Distilled water	39.8 (274)	230.0	194.0	424.0	
30 (206)	25 (173)	20 (138)	Air	2.0 (5.1)	$3\frac{1}{2}$ percent salt solution	39.7 (273)	0	6.0	6.0	
30 (206)	25 (173)	20 (138)	Air	2.0 (5.1)	$3\frac{1}{2}$ percent salt solution	29.7 (205)	105.0	24.0	129.0	
30 (206)	25 (173)	20 (138)	$3\frac{1}{2}$ percent salt solution	2.0 (5.1)	$3\frac{1}{2}$ percent salt solution	29.7 (205)	0	27.0	27.0	
30 (206)	25 (173)	20 (138)	$3\frac{1}{2}$ percent salt solution	3.0 (7.6)	$3\frac{1}{2}$ percent salt solution	29.0 (200)	0	16.0	16.0	
30 (206)	25 (173)	20 (138)	$3\frac{1}{2}$ percent salt solution	2.0 (5.1)	$3\frac{1}{2}$ percent salt solution	25.0 (173)	0	35.0	35.0	

(e) Ti-6Al-4V (annealed): w = 4.0 inches (10.2 cm); t = 0.040 inch (0.10 cm); failing stress in air = 99.8 ksi (687 MN/m^2) (at a load rate of 30 000 lbf/min (2.2 kN/s)); specimen guided

Cyclic stress level, ksi (MN/m^2)			Cyclic environment	Crack length, inch (cm)	Delayed failure environment	Static net section stress, ksi (MN/m^2)	Time, no growth, minute	Time, growth, minute	Total time to failure, minute	Remarks
Maximum	Mean	Minimum								
35 (238)	25 (173)	15 (104)	Air	1.3 (3.3)	$3\frac{1}{2}$ percent salt solution	91.2 (628)	---	---	Run out[1]	Crack grew in air while applying load[2]
35 (238)	25 (173)	15 (104)	Air	1.27 (3.2)	$3\frac{1}{2}$ percent salt solution	89.8 (618)	---	---	Run out	Crack grew in air while applying load[2]
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.23 (3.1)	$3\frac{1}{2}$ percent salt solution	95.0 (654)	0	0.5	0.5	Crack grew in salt solution while applying load[2]
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.70 (4.3)	$3\frac{1}{2}$ percent salt solution	102.3 (705)	---	---	262.0	Crack grew in salt solution while applying load[2]
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.20 (3.1)	$3\frac{1}{2}$ percent salt solution	100.0 (689)	---	---	-------	Failed while applying load
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.30 (3.3)	$3\frac{1}{2}$ percent salt solution	95.0 (654)	---	---	-------	Failed while applying load
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.26 (3.2)	$3\frac{1}{2}$ percent salt solution	90.0 (620)	---	---	-------	Failed while applying load
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.20 (3.1)	$3\frac{1}{2}$ percent salt solution	80.0 (551)	---	---	Run out	
35 (238)	25 (173)	15 (104)	$3\frac{1}{2}$ percent salt solution	1.26 (3.2)	$3\frac{1}{2}$ percent salt solution	85.0 (585)	---	---	Run out	
35 (238)	25 (173)	15 (104)	Air	1.23 (3.1)	Air	99.8 (687)	---	---	Run out	

[1]Run out – 168 hours without failure.

[2]The crack grew from a nominal length of 1.20 inches (3.1 cm) to crack length indicated (column 3) during application of the static load. The net section stress was based on the indicated crack length.

[3]Stress estimated from results in reference 10.

TABLE IV.- DELAYED FAILURE TEST RESULTS – Concluded

(f) Ti-13V-11Cr-3Al (solution annealed): w = 4.0 inches (10.2 cm); t = 0.034 inch (0.09 cm); failing stress in air = 60.4 ksi (416 MN/m²) (at a load rate of 30 000 lbf/min (2.2 kN/s)); specimen guided

Cyclic stress level, ksi (MN/m²)			Cyclic environment	Crack length, inch (cm)	Delayed failure environment	Static net section stress, ksi (MN/m²)	Time, no growth, minute	Time, growth, minute	Total time to failure, minute	Remarks
Maximum	Mean	Minimum								
30 (206)	25 (173)	20 (138)	$3\frac{1}{2}$ percent salt solution	1.35 (3.4)	$3\frac{1}{2}$ percent salt solution	55.6 (383)	---	---	--------	Failed while applying load
30 (206)	25 (173)	20 (138)	$3\frac{1}{2}$ percent salt solution	1.30 (3.3)	$3\frac{1}{2}$ percent salt solution	30.9 (213)	---	---	Run out[1]	
30 (206)	25 (173)	20 (138)	$3\frac{1}{2}$ percent salt solution	1.30 (3.3)	$3\frac{1}{2}$ percent salt solution	50.0 (344)	---	0.2	0.2	
30 (206)	25 (173)	20 (138)	$3\frac{1}{2}$ percent salt solution	1.23 (3.1)	$3\frac{1}{2}$ percent salt solution	43.3 (298)	---	---	Run out	
30 (206)	25 (173)	20 (138)	$3\frac{1}{2}$ percent salt solution	1.25 (3.2)	$3\frac{1}{2}$ percent salt solution	45.0 (310)	---	.4	.4	
30 (206)	25 (173)	20 (138)	$3\frac{1}{2}$ percent salt solution	1.20 (3.1)	$3\frac{1}{2}$ percent salt solution	48.0 (331)	---	---	--------	Failed while applying load
30 (206)	25 (173)	20 (138)	Air	1.20 (3.1)	Air	54.4 (375)	---	---	Run out	

(g) AM 350 (CRT): w = 4.0 inches (10.2 cm); t = 0.024 inch (0.06 cm); failing stress in air = 183.4 ksi (1263 MN/m²) (at a load rate of 30 000 lbf/min (2.2 kN/s)); specimen guided

Cyclic stress level, ksi (MN/m²)			Cyclic environment	Crack length, inch (cm)	Delayed failure environment	Static net section stress, ksi (MN/m²)	Time, no growth, minute	Time, growth, minute	Total time to failure, minute	Remarks
Maximum	Mean	Minimum								
50 (344)	40 (276)	30 (206)	Air	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	136.1 (937)	---	---	Run out[1]	
50 (344)	40 (276)	30 (206)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	175.0 (1205)	0	3.0	3.0	
50 (344)	40 (276)	30 (206)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	170.0 (1171)	---	---	55.0	
50 (344)	40 (276)	30 (206)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	160.0 (1102)	---	---	Run out	
50 (344)	40 (276)	30 (206)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	175.0 (1205)	---	.7	.7	
50 (344)	40 (276)	30 (206)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	175.0 (1205)	---	.5	.5	
50 (344)	40 (276)	30 (206)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	170.0 (1171)	6.7	2.0	8.7	
50 (344)	40 (276)	30 (206)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	180.0 (1240)	---	---	--------	Failed while applying load
50 (344)	40 (276)	30 (206)	Air	1.2 (3.1)	Air	183.4 (1264)	---	---	Run out	

(h) 2024-T3. w = 4.0 inches (10.2 cm); t = 0.090 inch (0.23 cm); failing stress in air = 51.1 ksi (352 MN/m²) (at a load rate of 30 000 lbf/min (2.2 kN/s)); specimen guided

Cyclic stress level, ksi (MN/m²)			Cyclic environment	Crack length, inch (cm)	Delayed failure environment	Static net section stress, ksi (MN/m²)	Time, no growth, minute	Time, growth, minute	Total time to failure, minute	Remarks
Maximum	Mean	Minimum								
20 (138)	15 (104)	10 (69)	Air	1.2 (3.1)	Air	46.0 (317)	---	---	Run out[1]	
20 (138)	15 (104)	10 (69)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	46.0 (317)	---	---	Run out	

(i) 7075-T6: w = 4.0 inches (10.2 cm); t = 0.090 inch (0.23 cm); failing stress in air = 50.5 ksi (348 MN/m²) (at a load rate of 30 000 lbf/min (2.2 kN/s)); specimen guided

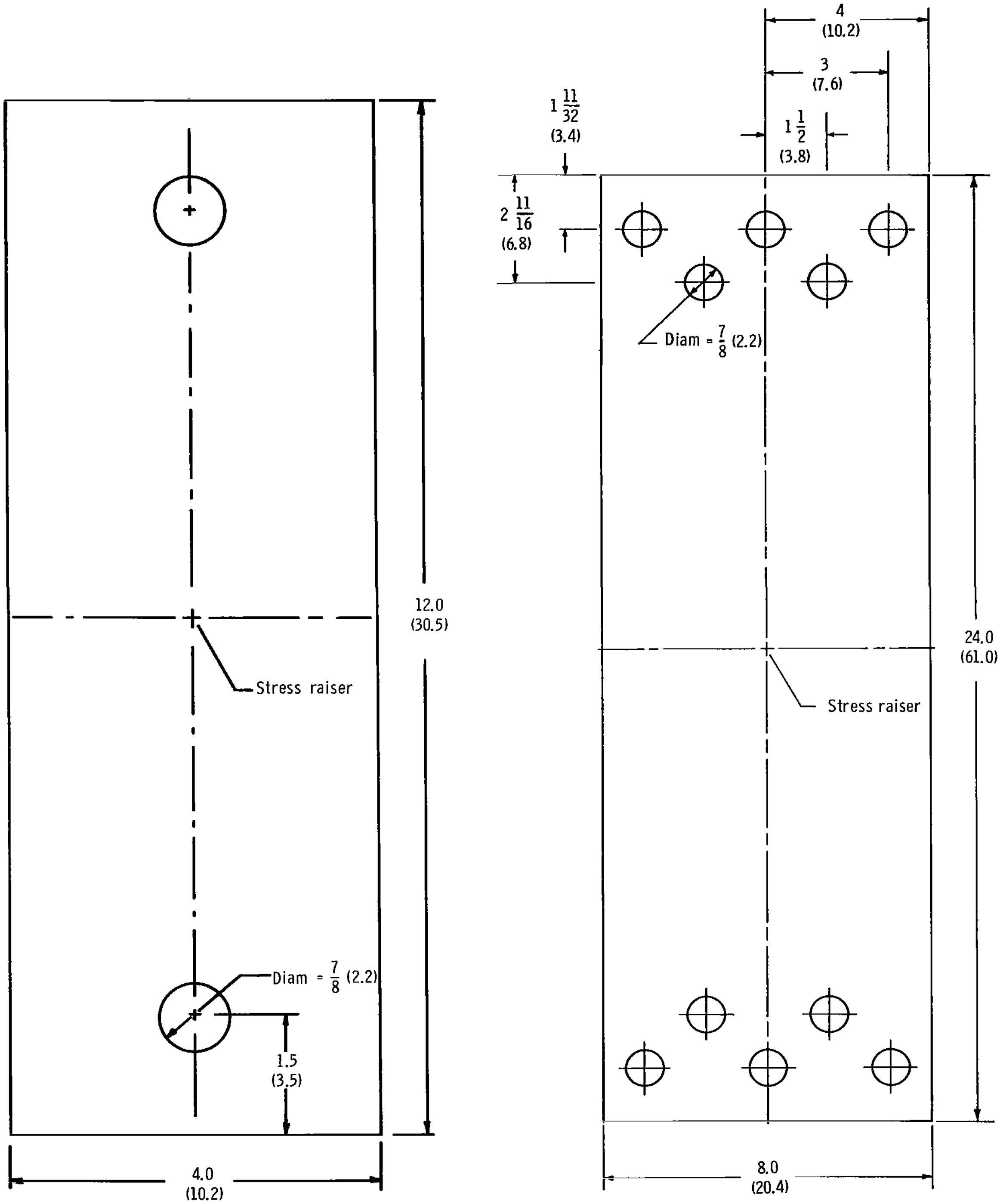
Cyclic stress level, ksi (MN/m²)			Cyclic environment	Crack length, inch (cm)	Delayed failure environment	Static net section stress, ksi (MN/m²)	Time, no growth, minute	Time, growth, minute	Total time to failure, minute	Remarks
Maximum	Mean	Minimum								
20 (138)	15 (104)	10 (69)	$3\frac{1}{2}$ percent salt solution	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	45.5 (314)	---	---	Run out[1]	
20 (138)	15 (104)	10 (69)	Air	1.2 (3.1)	Air	45.5 (314)	---	---	Run out	
20 (138)	15 (104)	10 (69)	Air	1.2 (3.1)	$3\frac{1}{2}$ percent salt solution	45.5 (314)	---	---	Run out	

[1]Run out – 168 hours without failure.

TABLE V.- RESIDUAL STATIC STRENGTH TEST RESULTS[1]

Cyclic environment	Residual strength environment	2a/w	S_{net}, ksi (MN/m^2)
2024-T3: w = 12 inches (30.5 cm); t = 0.090 inch (0.23 cm)			
Sea water	Sea water	0.248	49.1 (338)
Sea water	Sea water	.283	50.2 (346)
Sea water	Sea water	.175	50.4 (347)
Sea water	Sea water	.094	51.4 (354)
Sea water	Air	.211	49.6 (342)
Sea water	Air	.082	52.4 (361)
7075-T6: w = 12 inches (30.5 cm); t = 0.090 inch (0.23 cm)			
Sea water	Sea water	0.252	39.5 (272)
Sea water	Sea water	.250	40.0 (276)
Sea water	Sea water	.183	43.1 (297)
Sea water	Air	.224	42.1 (290)
Sea water	Air	.102	50.3 (346)
$3\frac{1}{2}$ percent salt solution	$3\frac{1}{2}$ percent salt solution	.129	48.8 (336)

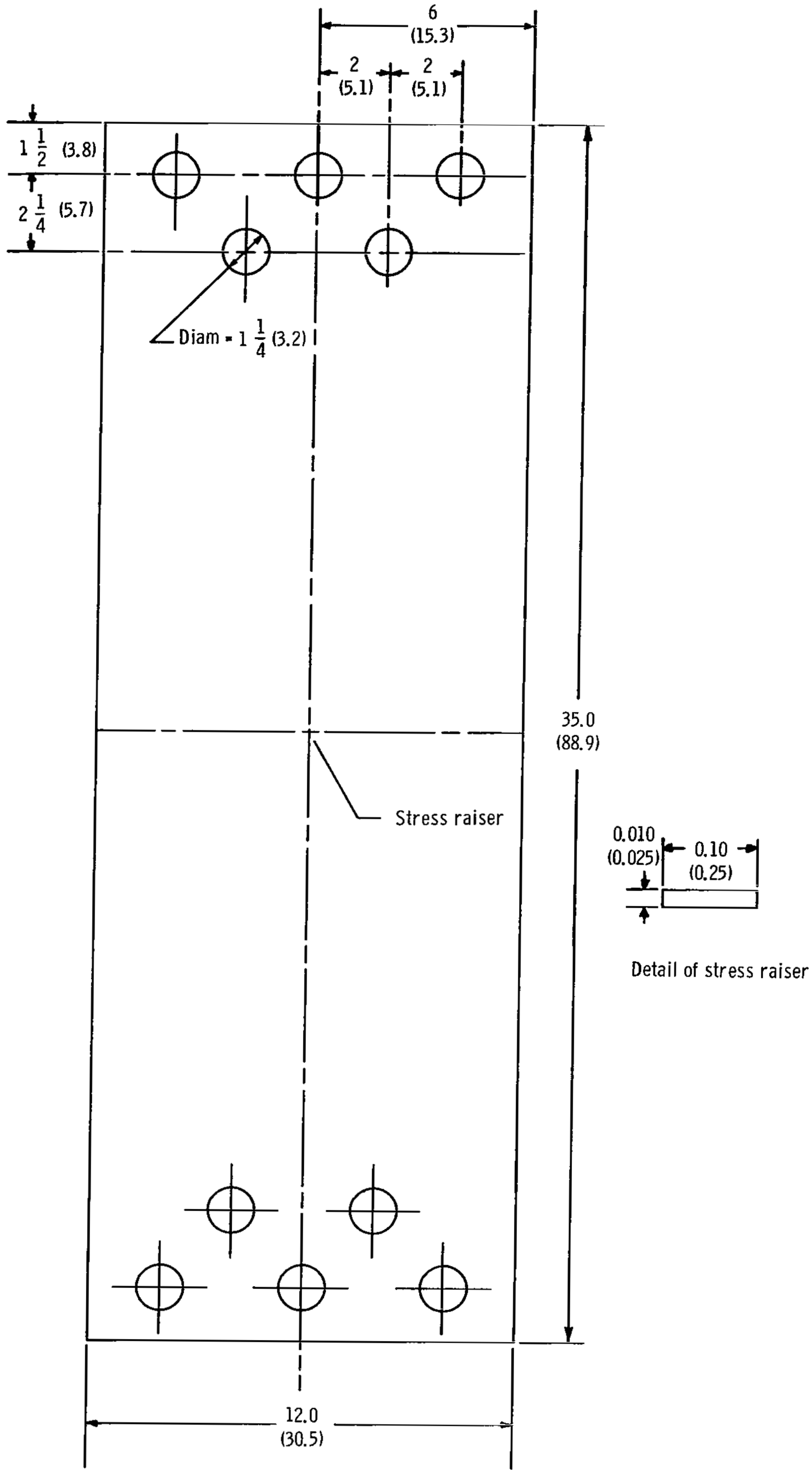
[1]In all tests the final crack length prior to static testing was obtained by fatigue cycling in air at $S_o = 15$ ksi $(104\ MN/m^2)$, $R = 0$.



(a) 4-inch (10.2-cm) wide delayed failure specimen.

(b) 8-inch (20.4-cm) wide crack propagation and delayed failure specimen.

Figure 1.- Specimen configurations. All dimensions in inches (cm).



(c) 12-inch (30.5-cm) wide crack propagation and residual static strength specimen.

Figure 1.- Concluded.

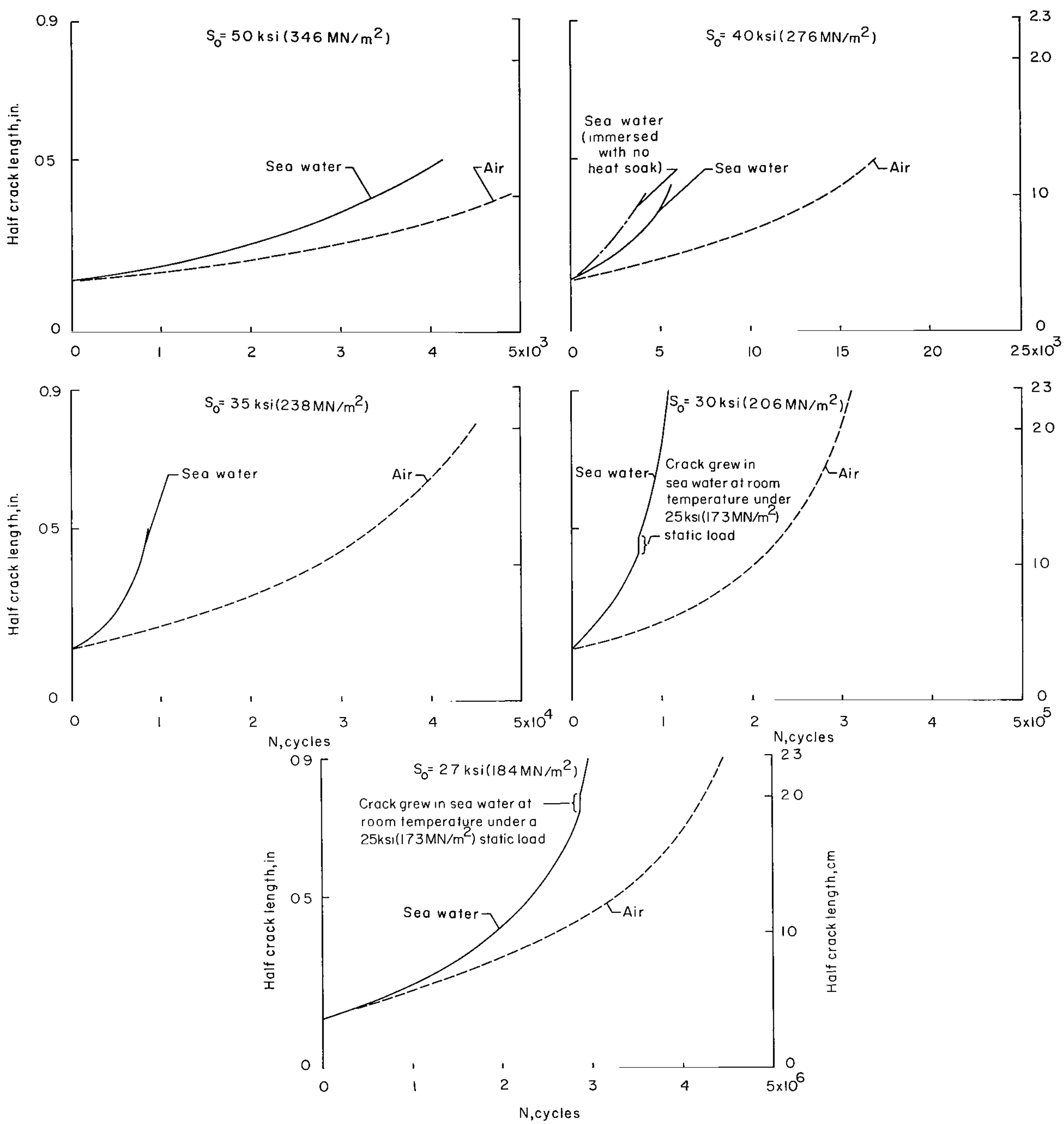


Figure 2.- Fatigue crack growth curves for Ti-8Al-1Mo-1V (duplex annealed) tested in air or under alternate thermal and sea water soaking. All data for tests in air are from reference 3. S_m = 25 ksi (173 MN/m^2).

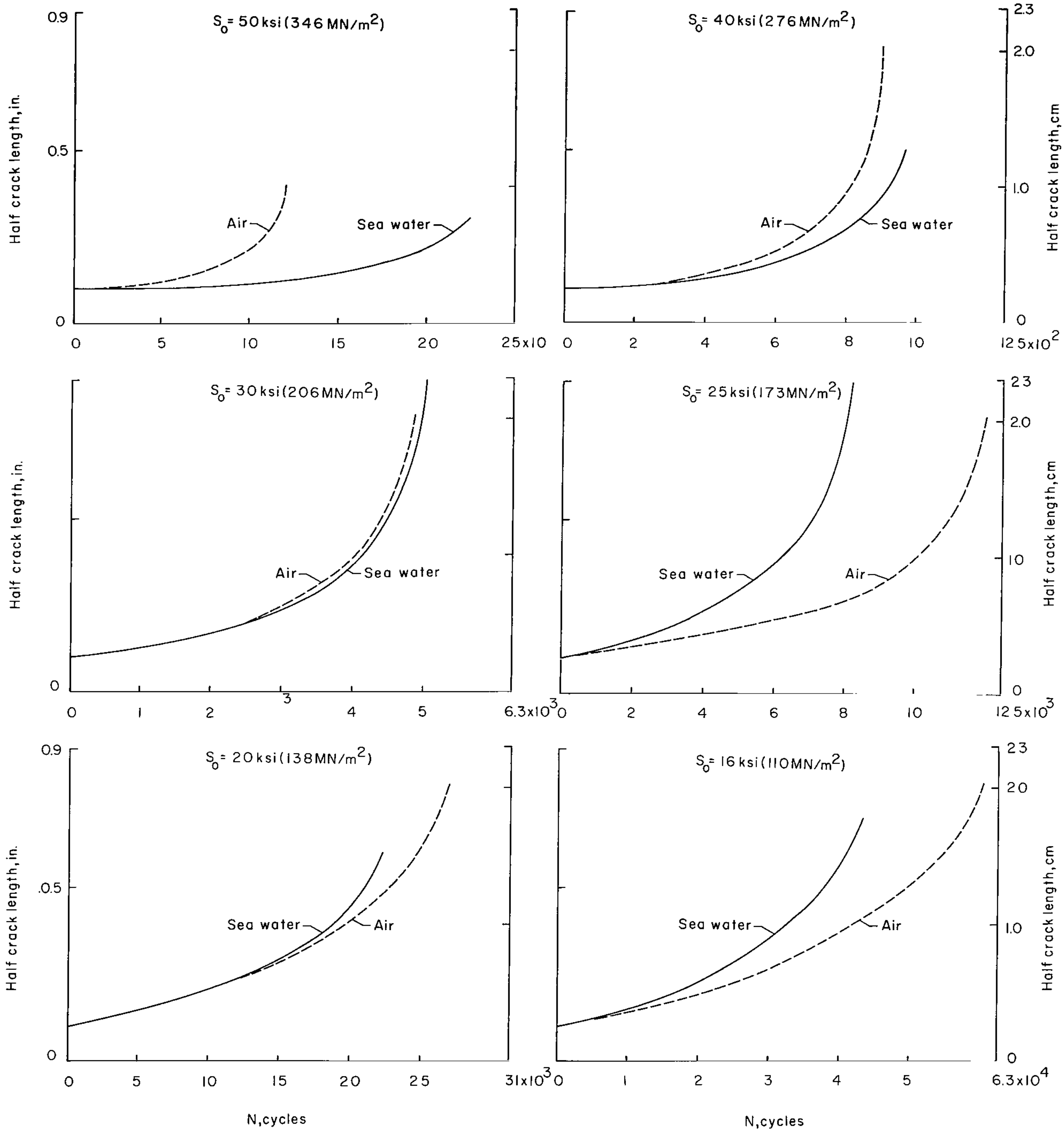


Figure 3.- Fatigue crack growth curves for 2024-T3 tested in air or in sea water. All data for tests in air are from reference 4. R = 0.

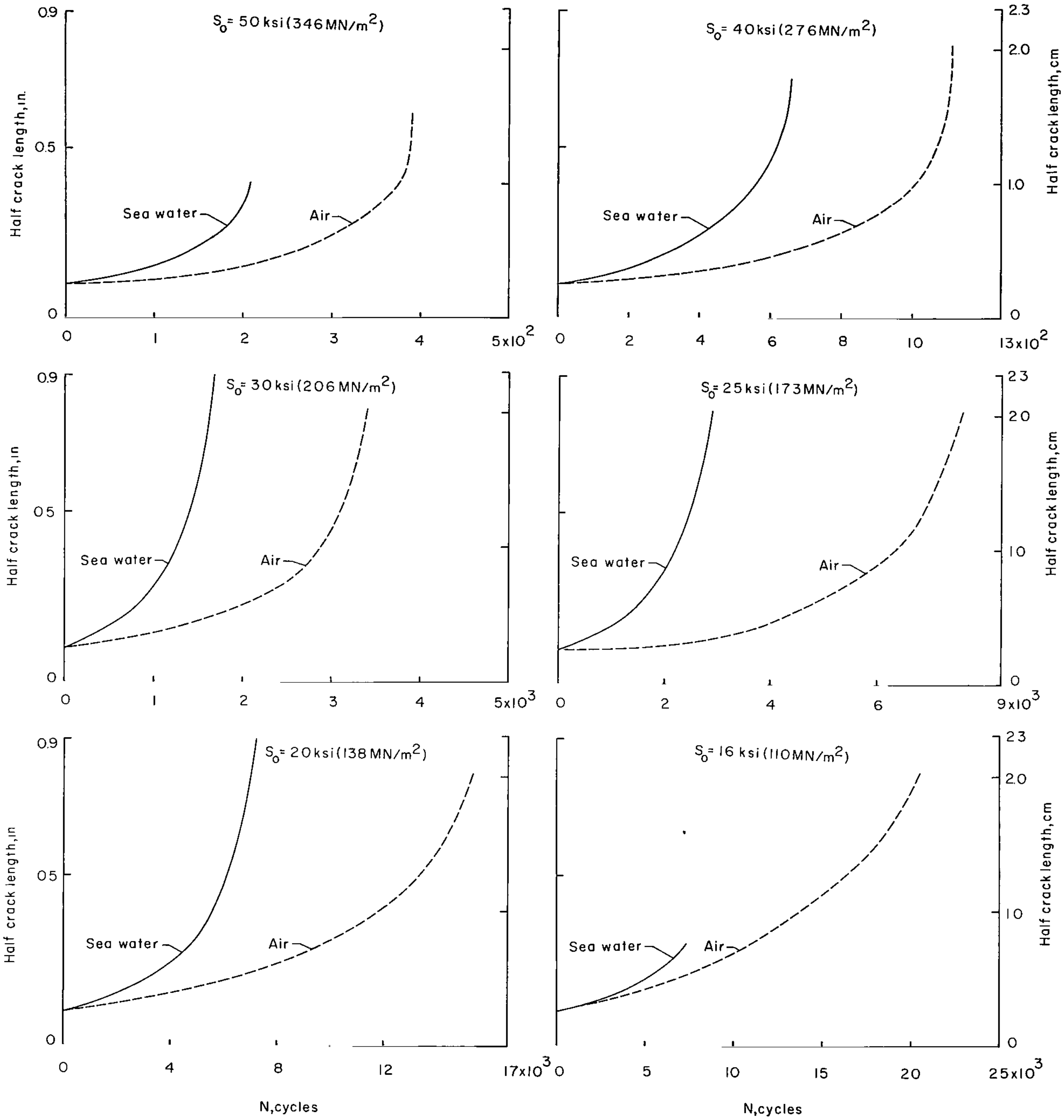
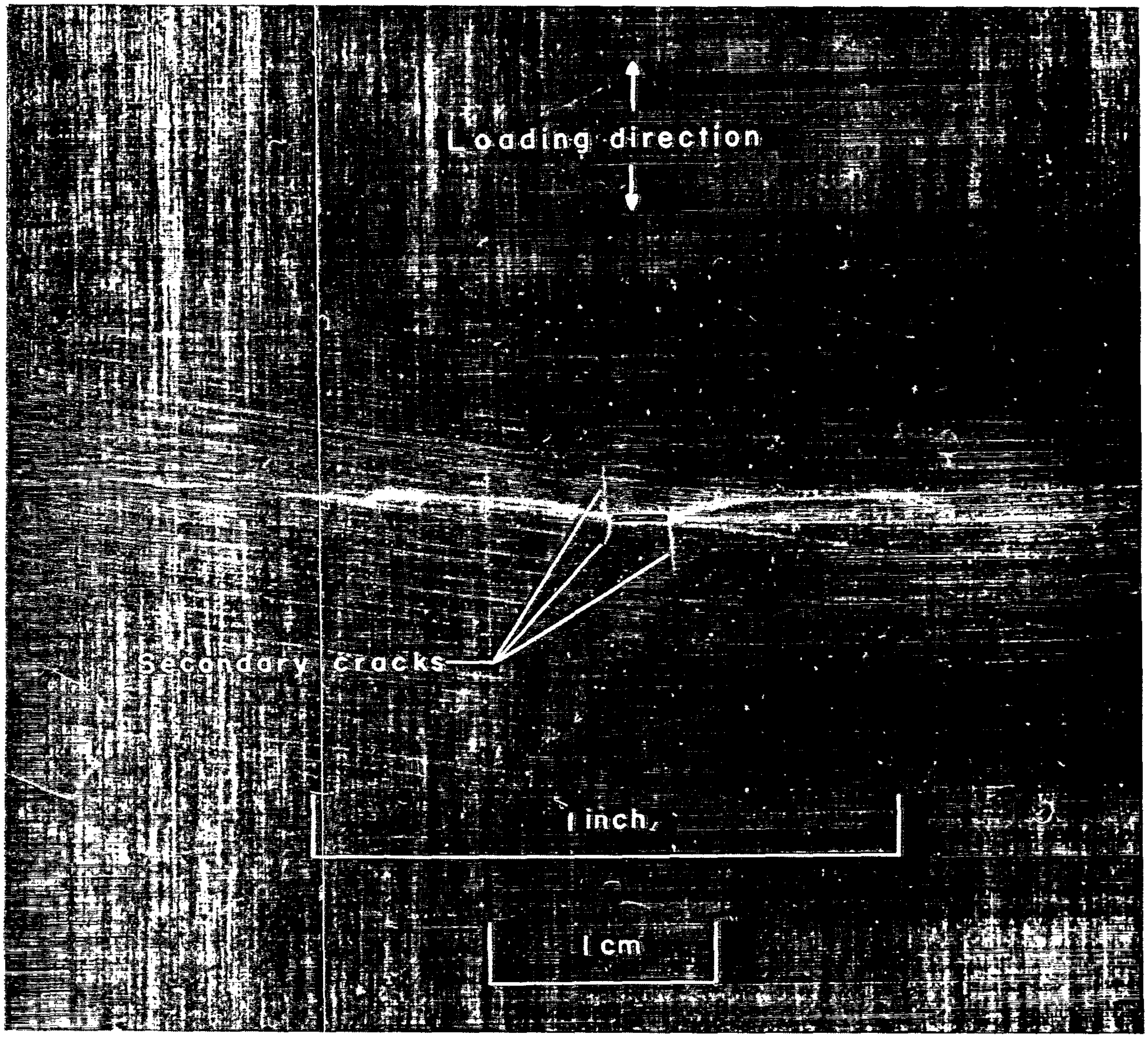
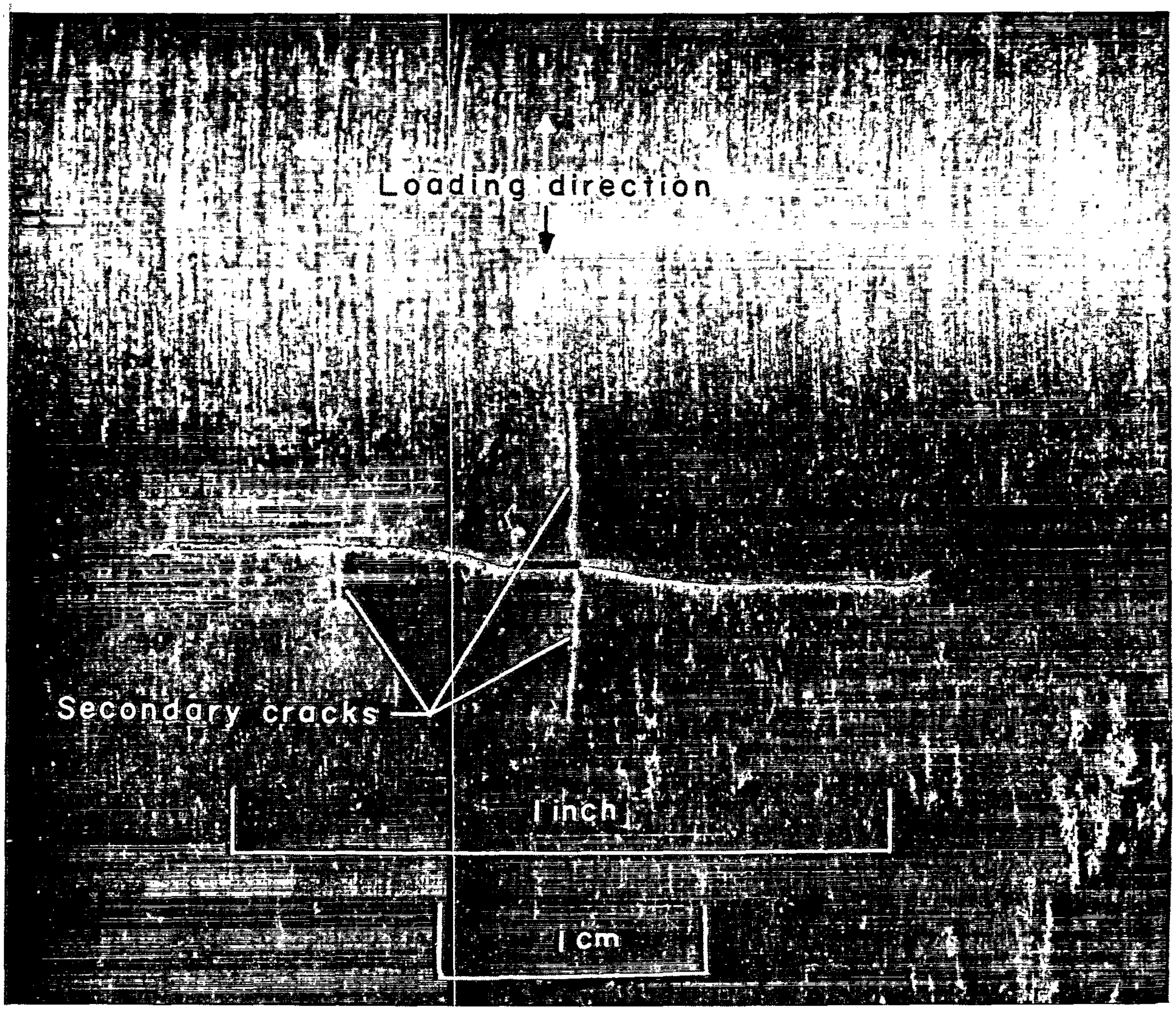


Figure 4.- Fatigue crack growth curves for 7075-T6 tested in air or in sea water. All data for tests in air are from reference 4. R = 0.



(a) 7075-T6. L-65-8550

Figure 5.- Secondary cracking parallel to the loading direction.



(b) 2024-T3. L-65-8363

Figure 5.- Concluded.

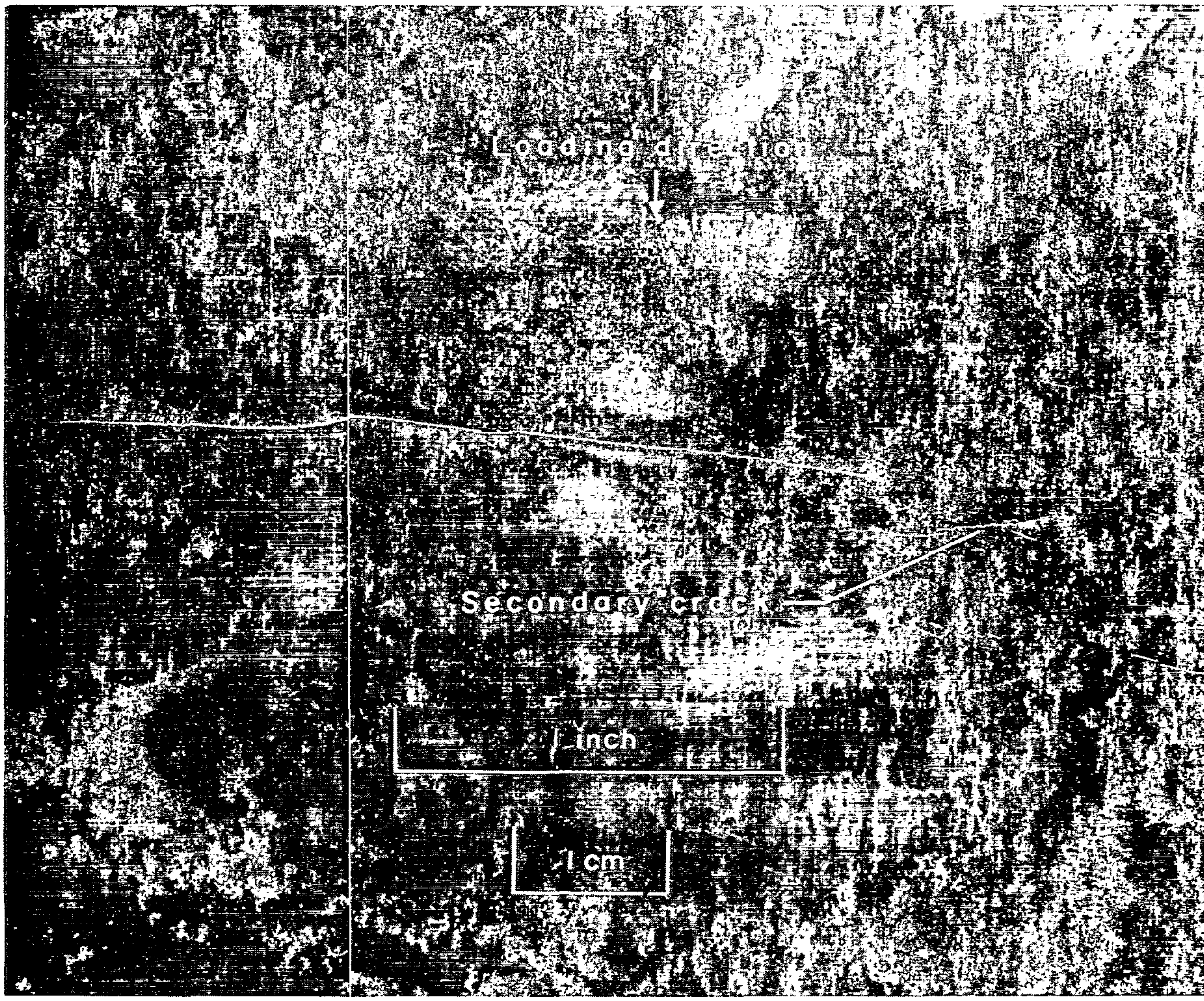
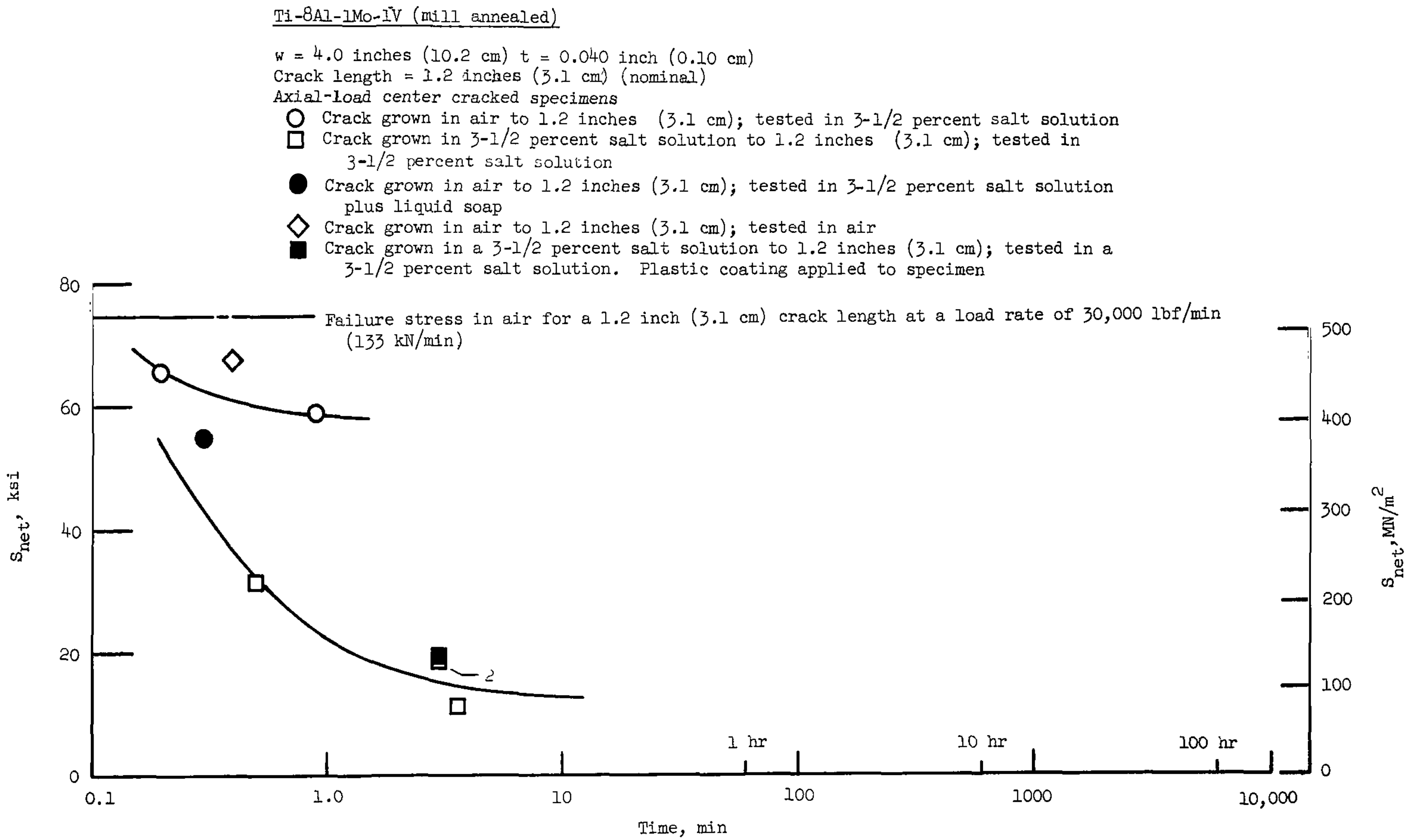
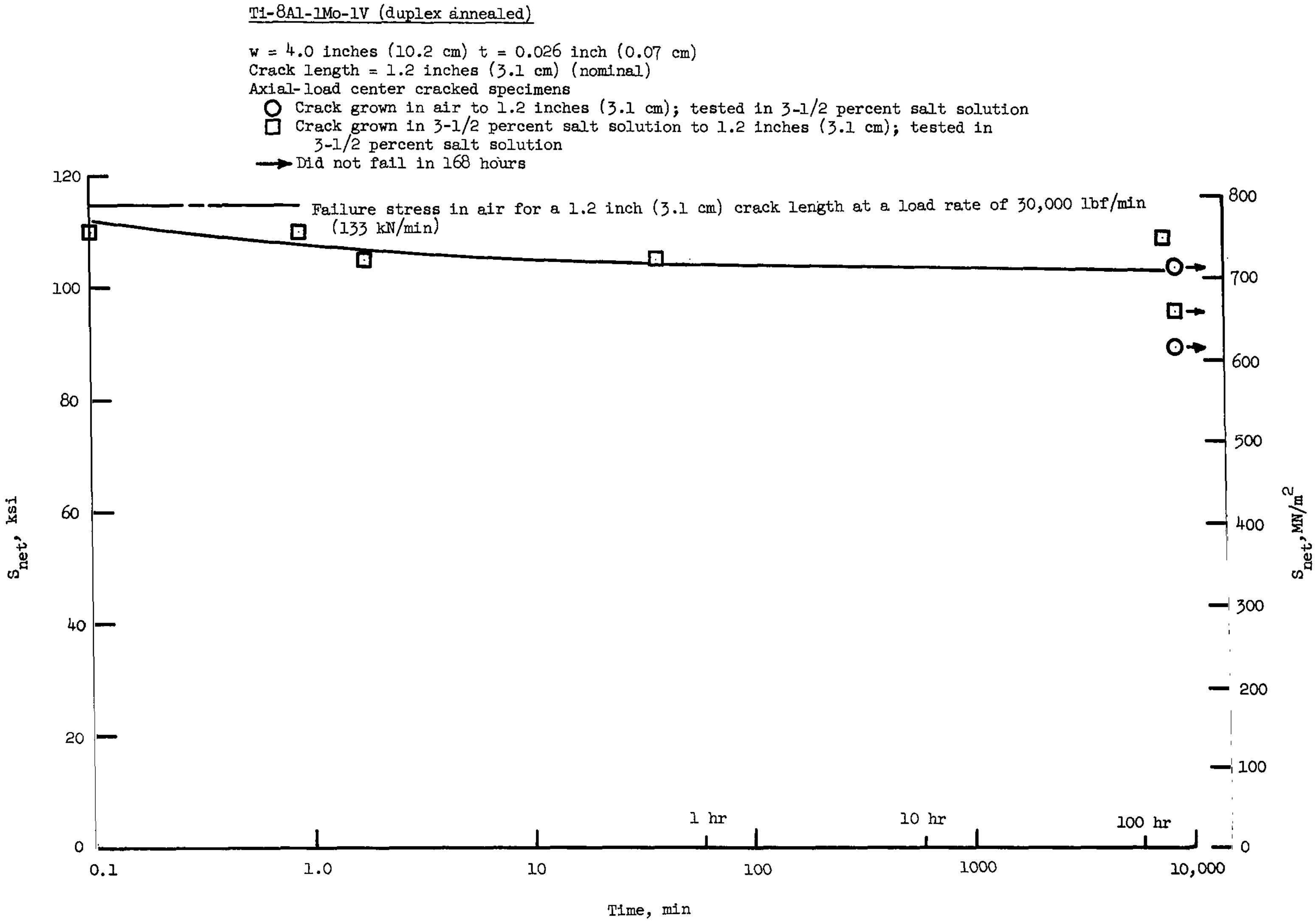


Figure 6.- Secondary cracking normal to the loading direction in 2024-T3. L-65-7725



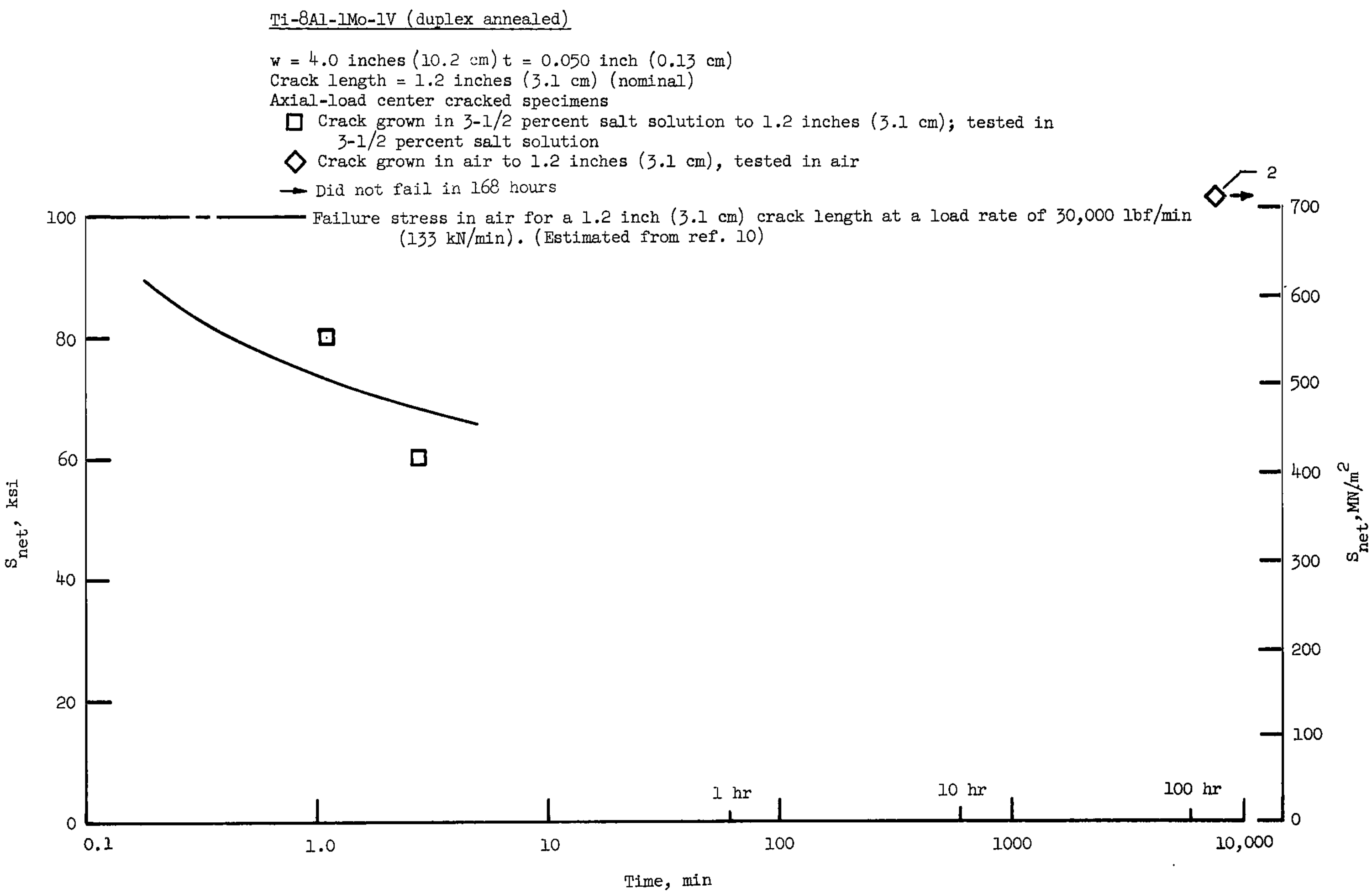
(a) Ti-8Al-1Mo-1V (mill annealed); t = 0.040 inch (0.10 cm).

Figure 7.- Delayed failure of axially loaded center-cracked specimens in aqueous environments. w = 4.0 inches (10.2 cm), 2a = 1.2 inches (3.1 cm), except as noted. Arrows indicate specimens did not fail in 168 hours.



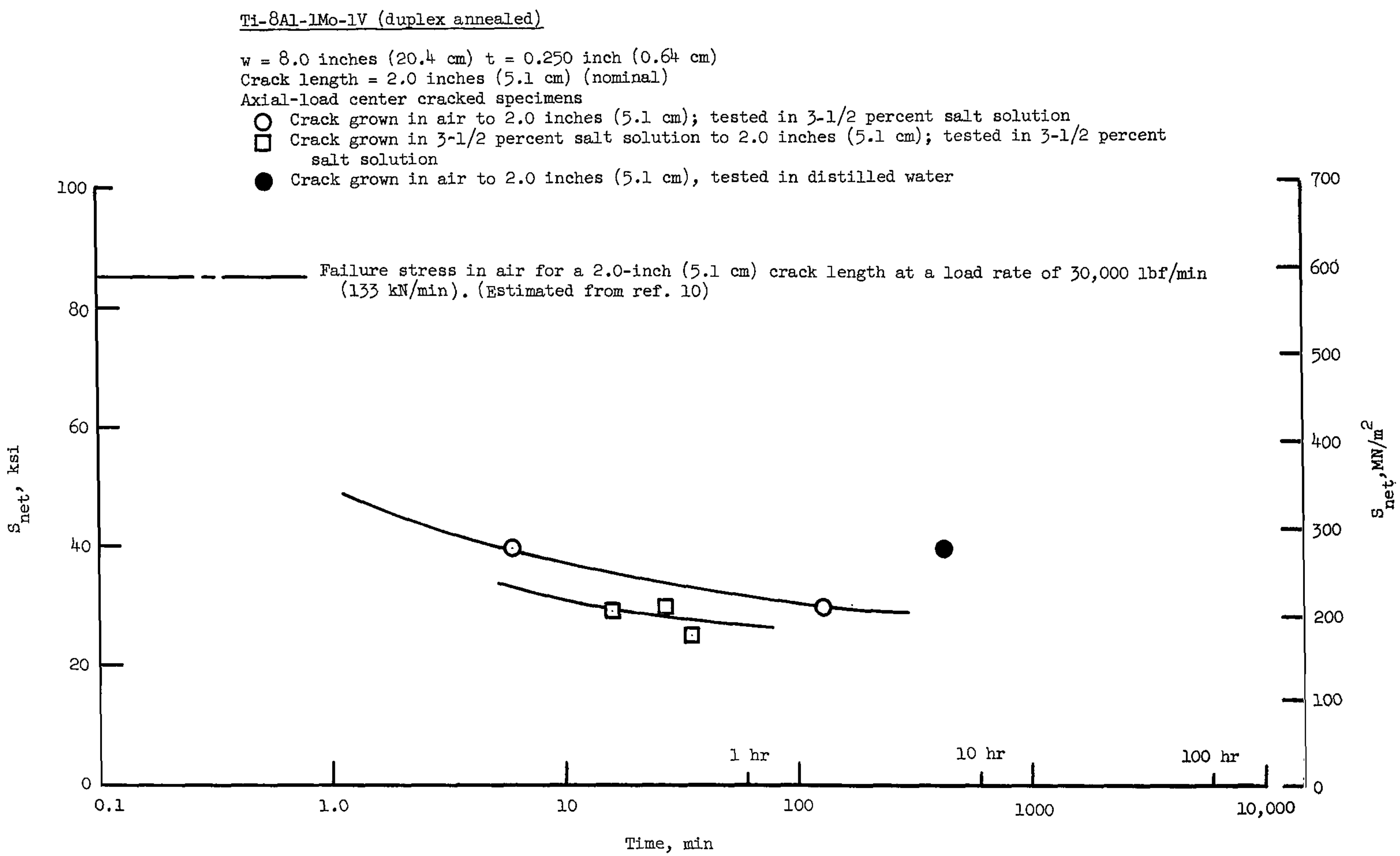
(b) Ti-8Al-1Mo-1V (duplex annealed); t = 0.026 inch (0.07 cm).

Figure 7.- Continued.



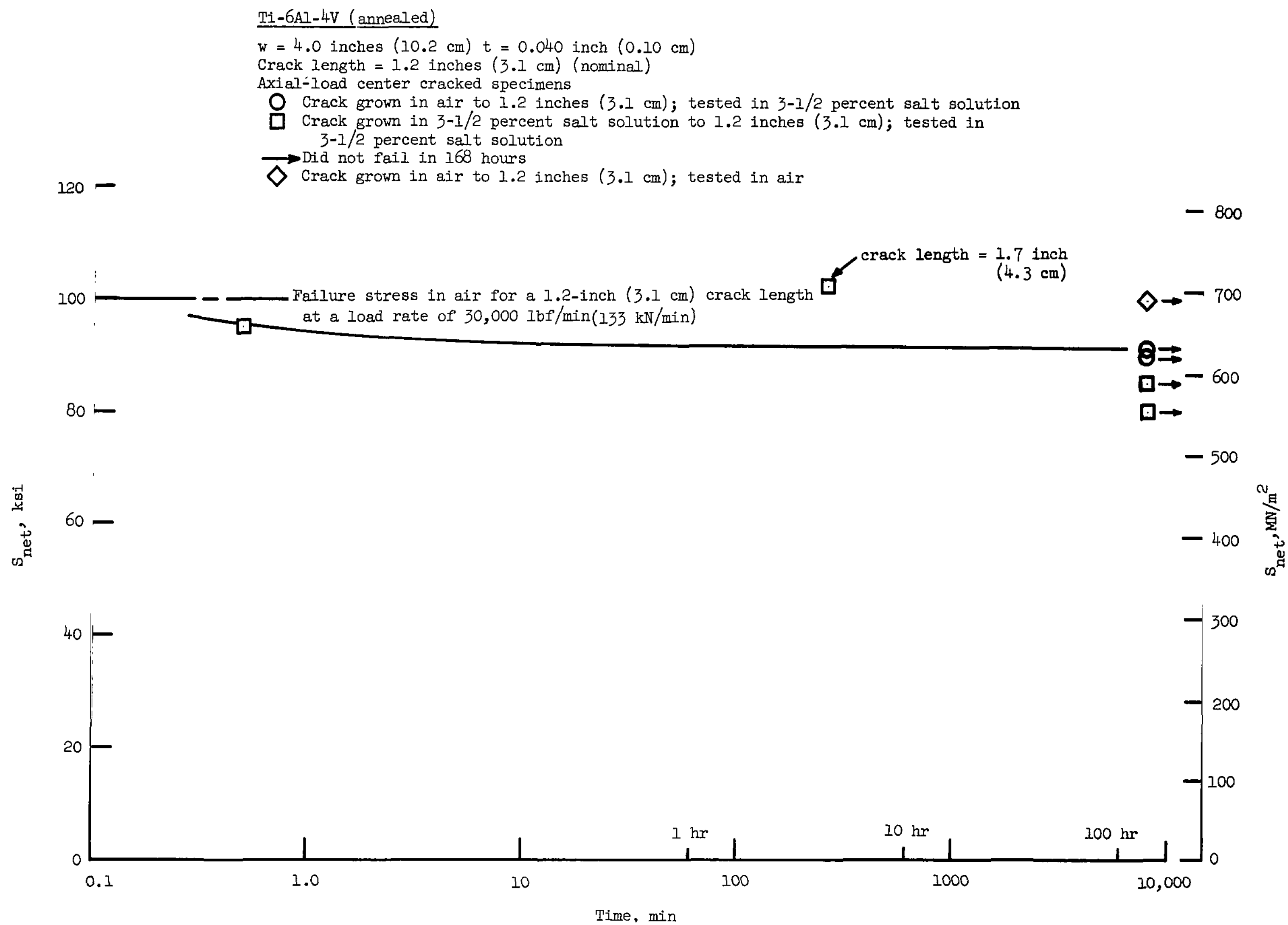
(c) Ti-8Al-1Mo-1V (duplex annealed); t = 0.050 inch (0.13 cm).

Figure 7.- Continued.



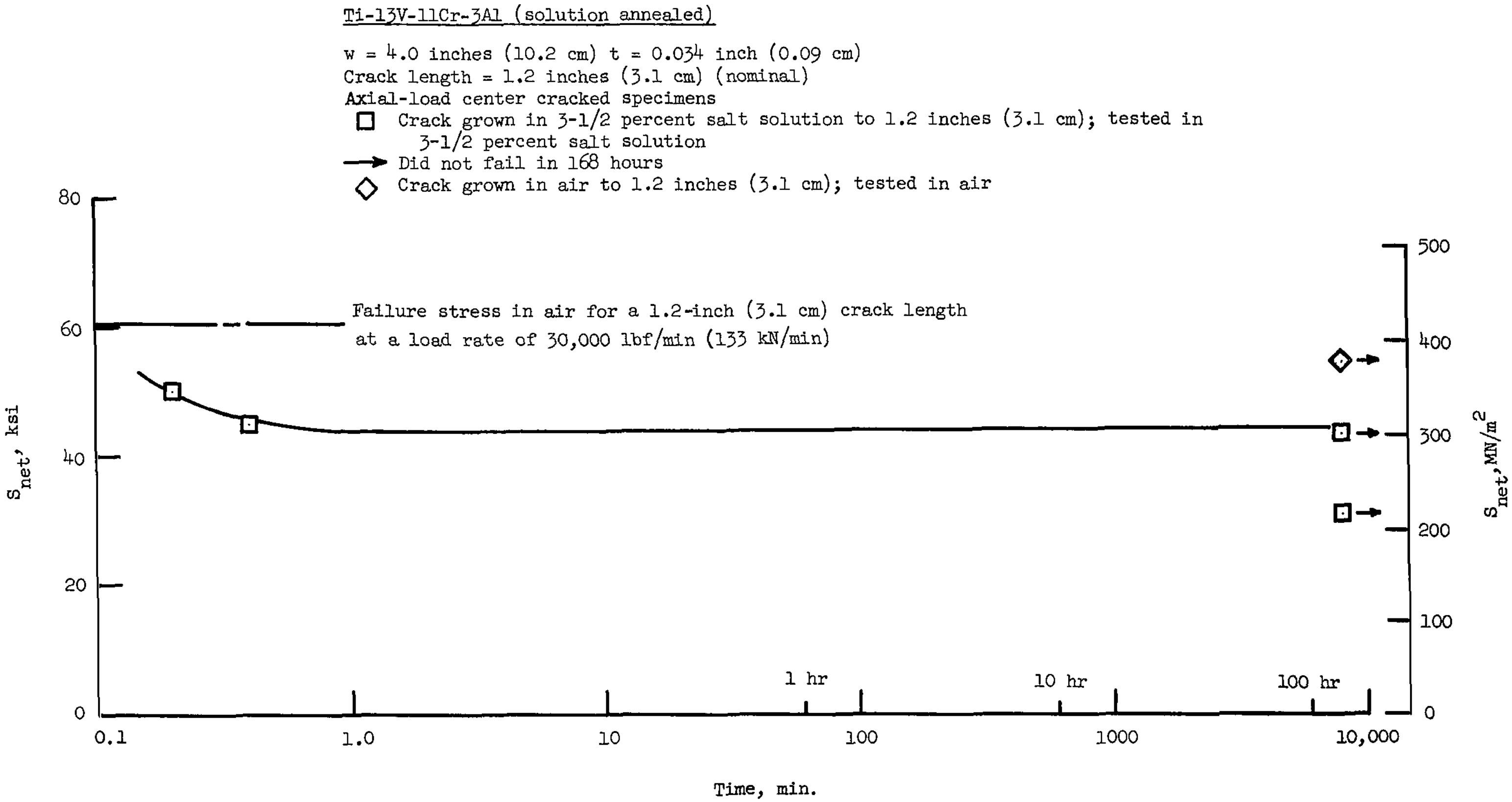
(d) Ti-8Al-1Mo-1V (duplex annealed); t = 0.250 inch (0.64 cm).

Figure 7.- Continued.



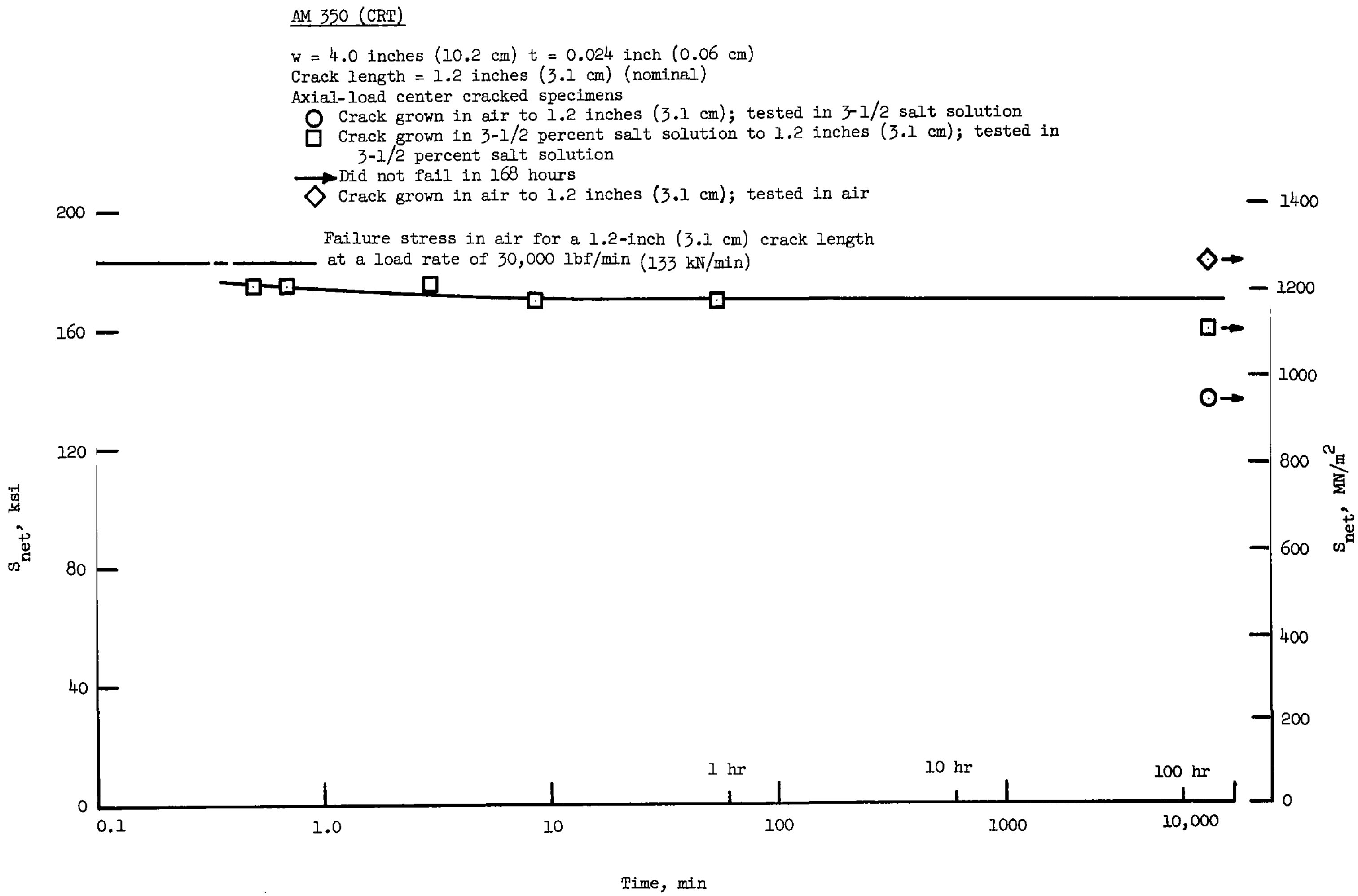
(e) Ti-6Al-4V (annealed); t = 0.040 inch (0.10 cm).

Figure 7.- Continued.



(f) Ti-13V-11Cr-3Al (solution annealed); t = 0.034 inch (0.09 cm).

Figure 7.- Continued.



(g) AM 350 (CRT); t = 0.024 inch (0.06 cm).

Figure 7.- Concluded.

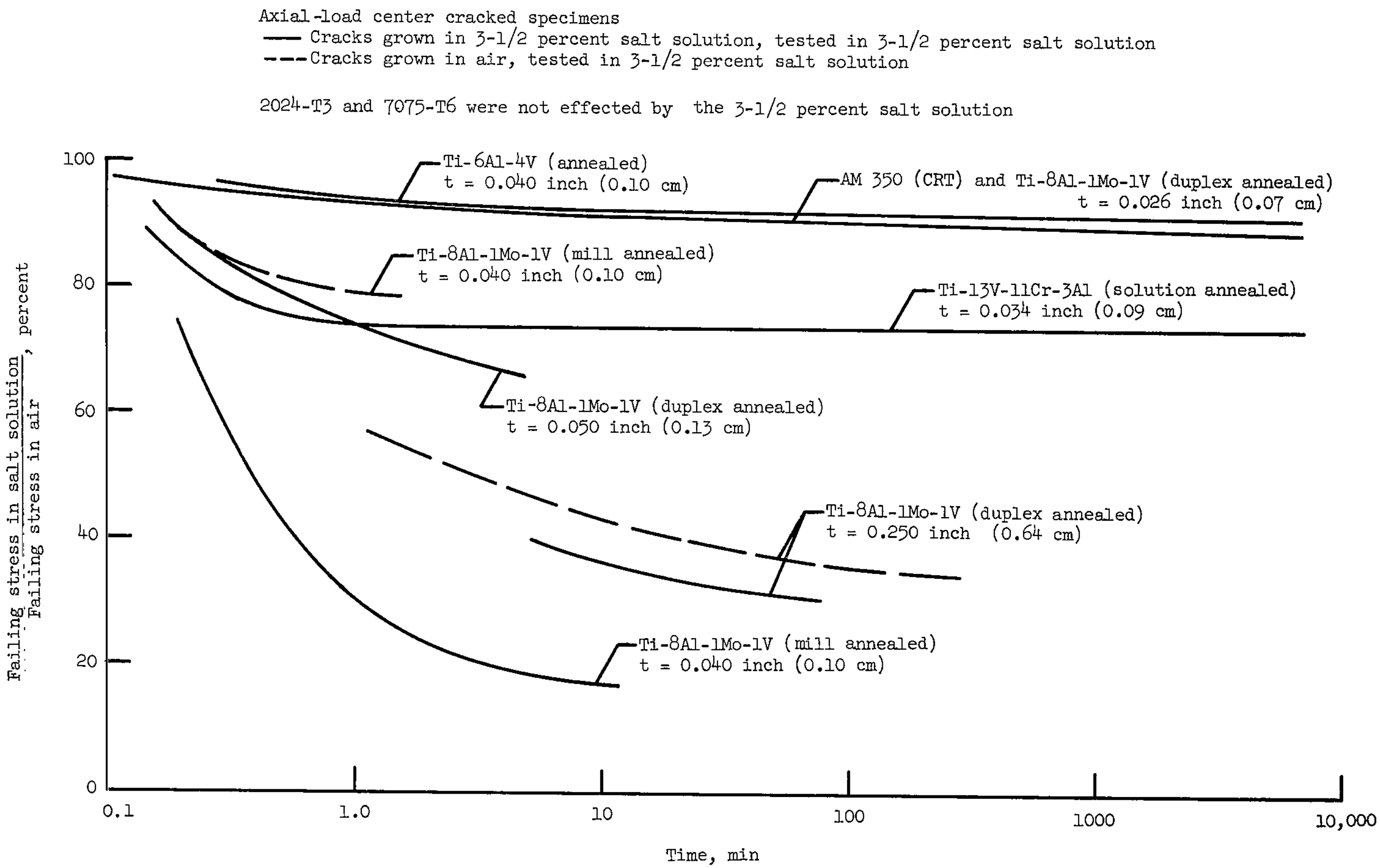


Figure 8.- Summary plot of delayed failure test results.

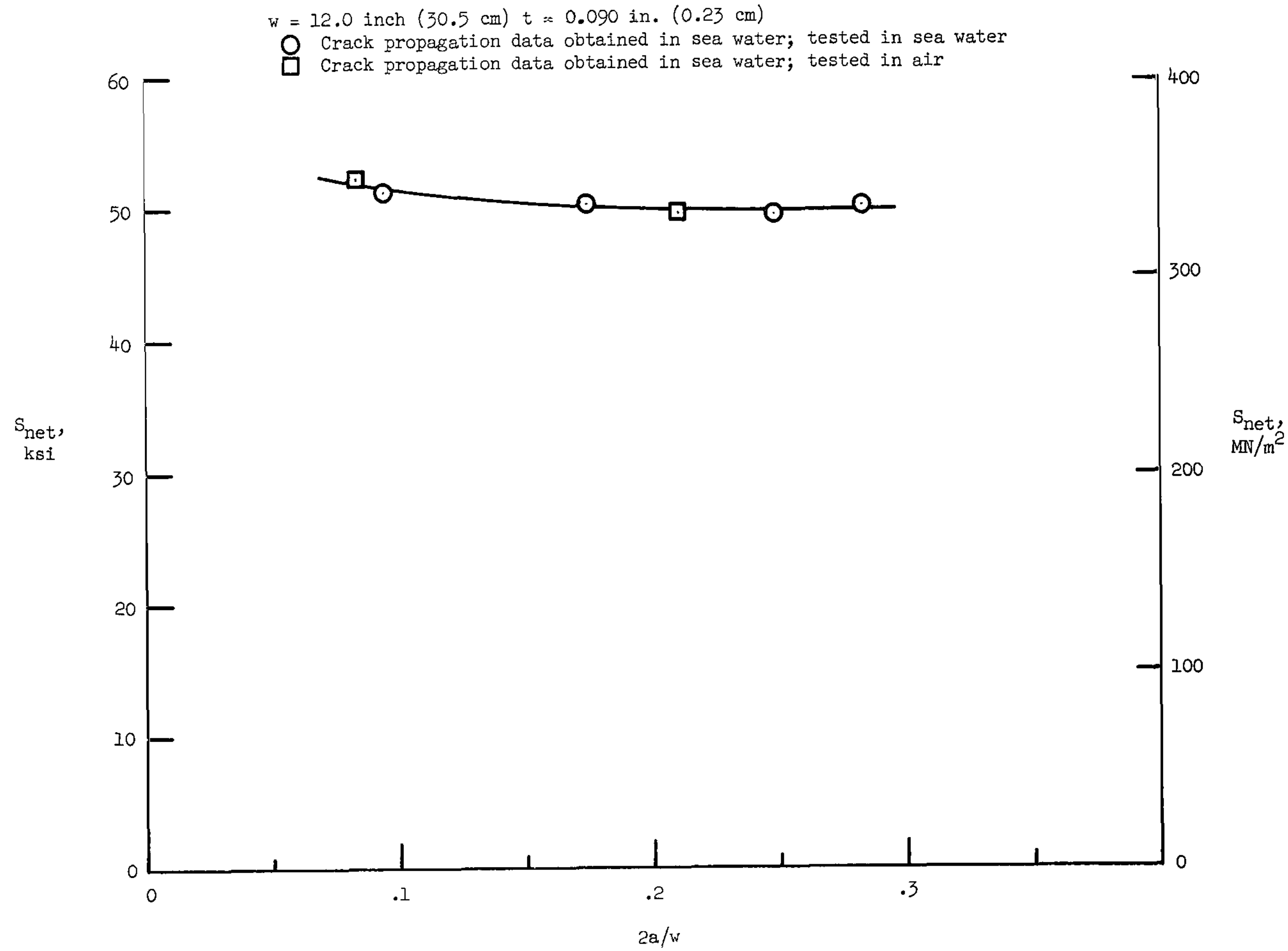


Figure 9.- Residual strength of 2024-T3 in air and sea water. (In all tests the final crack length prior to static testing was obtained by fatigue cycling in air at S_{max} = 15 ksi (104 MN/m^2), R = 0.)

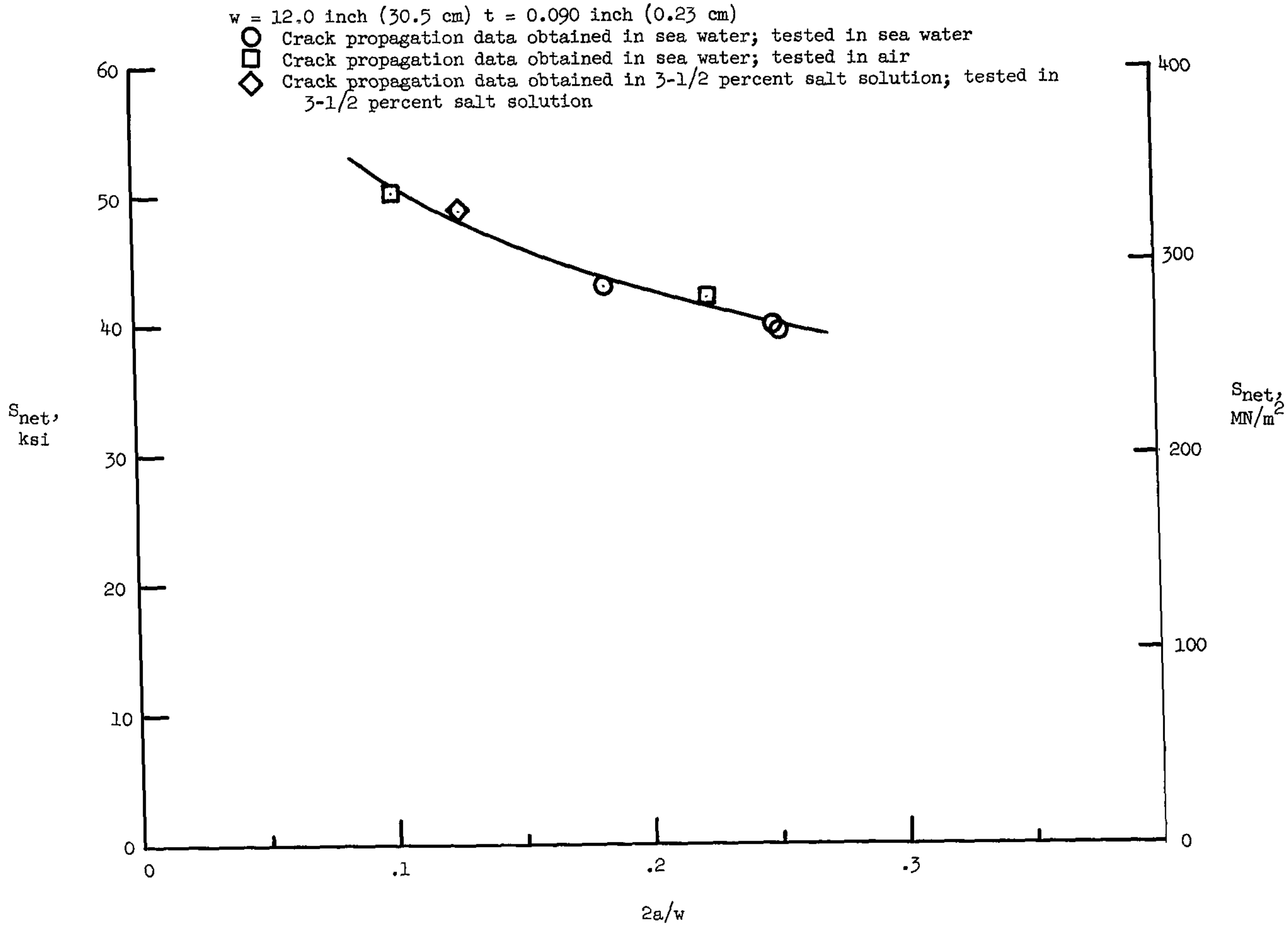


Figure 10.- Residual strength of 7075-T6 in air, sea water, and a $3\frac{1}{2}$ percent salt solution. (In all tests the final crack length prior to static testing was obtained by fatigue cycling in air at S_{max} = 15 ksi (104 MN/m^2), R = 0.)

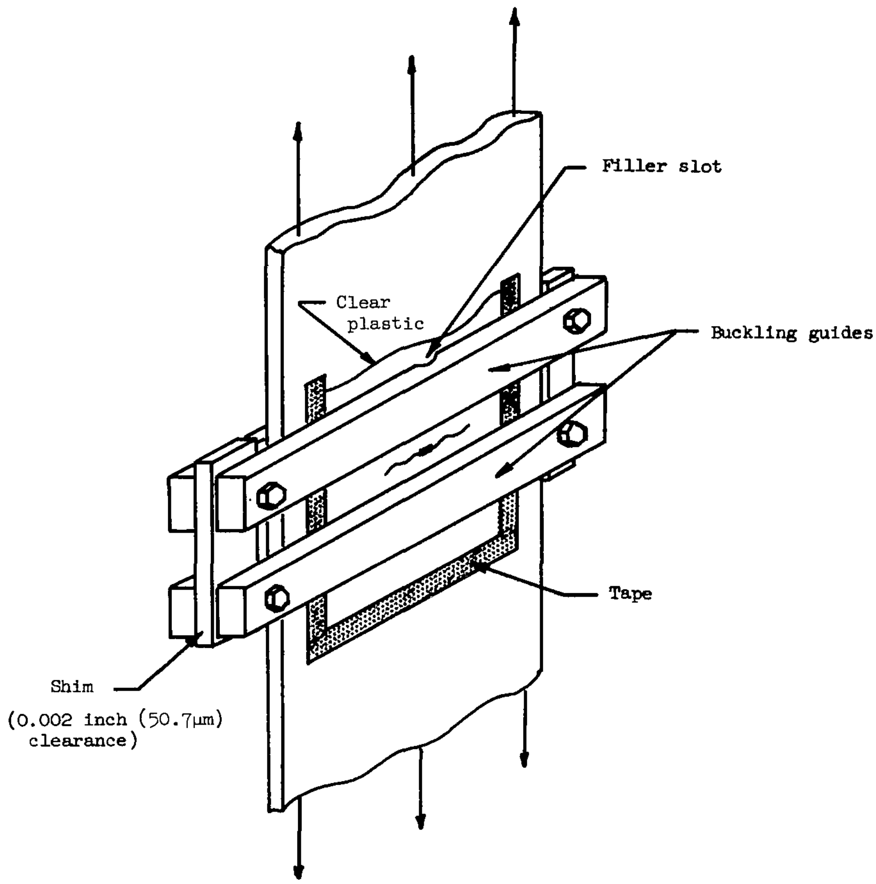


Figure 11.- Delayed failure specimen test setup. (Plastic container on both sides of specimen.)

NASA-Langley, 1967 L-5033

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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