EFFECT OF RELATIVE HUMIDITY ON THE FATIGUE CHARACTERISTICS OF MILD STEEL IN REVERSED TORSION

by

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I. INTRODUCTION

It is well-known that corrosion simultaneous with fatigue stressing has a detrimental effect on the fatigue lives of many metals. Most of the research on this subject, known as corrosion fatigue, has been concerned with the effects of highly corrosive liquid environments such as salt water, fresh water, or various chemical environments. There are, however, several references in the literature which indicate that some of the constituents of the normal atmosphere, which are not corrosive in the absence of stress, have a considerable effect on the fatigue lives of metals. Water vapor is believed to be one of the most important of these atmospheric constituents.

Although there have been quite a few papers concerning the subject of atmospheric corrosion fatigue, much of the available data is inconsistent and many gaps have remained to be filled. For example, much of this previous work has been conducted without adequate humidity or other environmental control. There is a conspicuous absence of data on ferrous materials as most of the previous work has been concerned with aluminum or aluminum alloys. Perhaps the most important aspect, however, is that most of the previous investigators have not used enough test specimens to allow a sound statistical analysis of results.

The objective of this investigation was to determine the effect of relative humidity on the fatigue life of a mild steel in completely reversed torsion. It was undertaken as an extension of three previous investigations by Stallings (1)*, Gray (2), and Harton (3). These three investigators were concerned with the effects of relative humidity on mild steel in various types of bending fatigue. It seemed reasonable, therefore, to extend this work to include torsion fatigue. As far as the author is aware there have been no previous investigations of this type concerning torsion fatigue.

The material used in this work was SAE 1018 steel, chosen because of its widespread use and availability. The tests were made on a Sonntag Universal Fatigue Testing Machine. This machine, equipped with environmental chamber and torsion fixture, subjected the test specimen to completely reversed torsion at the rate of 1800 stress cycles per minute.

Humid air was produced by bubbling laboratory air through a tower of distilled water. This bubble tower

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*Numbers in parentheses refer to literature cited.

apparatus was capable of providing air over a wide range of relative humidities at constant temperature. Thermostatic controls allowed very close control of the humidity.

The fatigue process is considered to take place in two stages: crack initiation and crack propagation. The testing, therefore, was divided into two categories in an effort to determine the effect of humidity on each of these stages. These two categories were called Series A and Series B. The Series A tests involved the stressing of circular specimens with a sharp circumferential notch. These tests were considered to be a study of crack propagation since the fatigue crack would always propagate from the root of the notch. The Series B tests involved the stressing of unnotched, circular specimens, a test of crack initiation plus crack propagation.

II. REVIEW OF LITERATURE

The first investigations on the subject of corrosion fatigue were made in the early 1900's. As early as 1917 Haigh (4,5), in England, conducted experiments to determine the effect of corrosive environments on the fatigue properties of metals. These tests were of the axial tension-compression type and were conducted at the rate of 2000 stress cycles per minute. The results showed that there is a definite reduction in the fatigue lives of metals when stressing takes place under the action of corrosive environments such as fresh water, salt water, dilute ammonia, or dilute acid. Haigh also noted that corrosion simultaneous with fatigue stressing has a much greater effect than corrosion prior to fatigue stressing.

McAdam (6) of the United States, in the year 1926, reported the results of fatigue tests on monel metal and several steels. The fatigue specimens were of the rotating cantilever-beam type and were stressed in completely reversed bending at rates of from two to 1450 stress cycles per minute. Fatigue tests made in a stream of fresh water were compared to tests made in air. The S-N curves for specimens tested in the water stream all fell below the curves for specimens tested in air. Furthermore, this effect increased with the hardness of the steel. Additional testing revealed that very severe corrosion prior to fatigue has much less effect than slight corrosion simultaneous with fatigue.

Gough and Sopwith (7) in 1932 were the first to investigate, to any extent, the influence of ordinary atmospheric constituents on the fatigue properties of metals. They conducted fatigue tests in a partial vacuum (0.0005 to 0.001 mm of mercury) and compared the results with tests made in air. The tests were of the rotating beam and rotating cantilever-beam type and were conducted at the rate of 2200 cycles per minute. The specimens were unnotched. The results were as follows: substitution of a partial vacuum for air produced improvements in fatigue life of 5 percent, 13 percent, and 26 percent for mild steel, annealed copper, and annealed brass, respectively. The absence of water vapor and/or oxygen in the partial vacuum tests was assumed responsible for the increased fatigue life. A few tests were made to determine the effect of a lanoline grease coating on specimens tested in air. The coating was found to have no beneficial effect on fatigue life. In a manner typical of most early fatigue investigators, Gough and Sopwith used only five or six test specimens to determine each S-N curve.

Gough and Sopwith continued their research with the publication of two later papers (8,9). The subject of the first of these papers was the testing of three theories which had been proposed to explain the atmospheric corrosion fatigue effect. The theories were: (1) that oxygen is the primary factor with water vapor necessary as a catalyst, (2) that atmospheric impurities are responsible, or (3) that impurities dissolved in the metal react with the metal during fatigue stressing. To examine theories (1) and (2), axial tension-compression tests, conducted at a rate of 2200 cycles per minute, were made on unnotched brass and copper test pieces. The tests were made in laboratory air, a partial vacuum, dry purified air, and damp purified air of 55 percent relative humidity. To examine theory (3) similar tests, both in air and a partial vacuum, were made on copper containing cuprous oxide, on oxygen-free copper, and on copper deoxidized with phosphorous. As before, only a small number of test specimens was used to determine each S-N curve. On the basis of these tests, Gough and Sopwith concluded that oxygen, with water vapor as a catalyst, is responsible for the atmospheric corrosion fatigue effect. Another series of tests made on copper in an atmosphere of nitrogen with and without water vapor was the subject of the second of these papers. The results confirmed the conclusion drawn previously, i.e., oxygen and water vapor together are responsible for the atmospheric effect on copper.

With the exception of this early work by Gough and Sopwith there was little interest in the subject of atmospheric corrosion fatigue until the 1950's. At this time there was a sudden increase of interest in the field resulting from the need for more reliable fatigue data.

In 1958, Wadsworth (10) reported on fatigue tests made on uniform-strain specimens under various conditions of pressure and gaseous environments. These tests were conducted at the rate of 6000 stress cycles per minute with pure copper, pure aluminum, and an aluminum alloy. Ten to fifteen specimens were used for each S-N curve. For copper, reduction of the atmospheric pressure to 0.00001 mm of mercury produced a fatigue life 20 times the fatigue life in air. In contrast to the findings of Gough and Sopwith, Wadsworth found that oxygen by itself had an effect on the fatigue properties of copper. Water vapor by itself had no effect. In the case of pure aluminum the reduction of pressure to 0.00001 mm of mercury produced a fatigue life 10 times that at atmospheric pressure. Water vapor alone was found to have a detrimental effect on the fatigue lives of aluminum and aluminum alloys. For both copper and aluminum, cracks were found to form very early in the fatigue stressing. Therefore, it was concluded that the environment had an effect on the crack propagation stage and little, if any, on the crack initiation stage of the testing.

Wadsworth also made a few tests on iron specimens of very low carbon content. The results indicated that the substitution of vacuum for air produces a considerable increase in fatige life. There was some evidence that the same is true for iron of higher carbon content.

Broom and Nicholson (11) conducted a series of fatigue tests on age-hardened, aluminum alloys in a variety of gaseous environments. The tests were of the axial tension-compression type and were conducted at the rate of 9600 cycles per minute. Unlike their predecessors, Broom and Nicholson used a large number of test specimens, thus allowing a sound statistical analysis of their data. At least six specimens were used at each combination of stress level and environmental condition. The results indicated that water vapor is the only constituent of the normal atmosphere that affects the fatigue life of age-hardened, aluminum alloys. Fatigue cracks were found to form sooner in an atmosphere of air as opposed to a partial vacuum, indicating that the presence of water vapor influences crack initiation. The crack propagation stage was also found to be affected. A coating of butyl rubber increased the lives of specimens fatigued in damp air.

Mantel, Robinson, and Thomson (12) conducted tests on hardened SAE 52100 steel. Completely reversed and unidirectional bending stresses were applied to test specimens in a variety of moist and dry inert atmospheres. The results indicated that the fatigue life of 52100 steel is extremely sensitive to moisture in the ambient atmosphere (i.e., increasing with decreasing moisture). Unfortunately, the speed of testing and the number of specimens used were not reported.

The most extensive work concerning the effect of the atmosphere in the fatigue of metals was carried out by Bennett and his associates at the National Bureau of Standards (13-18). This work began as an effort to assess the effectiveness of oleophobic film coatings in increasing the fatiuge lives of metals. The investigations were then extended to include the evolution of gas from metals during fatigue and the effect of humidity on fatigue life.

The first of these papers from the National Bureau of Standards (13) was concerned with the effect of oleophobic film coatings on the fatigue lives of metals. These films are organic substances and are called oleophobic because they are not wetted by any but the lowest boiling point hydrocarbons. They were chosen for this work because they are highly hydrophobic and are known to be effective in preventing corrosion. Unnotched specimens of several metals, including SAE 4340 steel, were fatigued in pure bending at the rate of 2000 cycles per minute in a variety of environments. The results indicated that an oleophobic coating can cause a marked increase in the life of some metals, including 4340 steel. Oleophobic compounds with a carbon chain length of 12 were found to be the most effective of the compounds tested. Cracks did not form in these specimens until after 85 to 90 percent of the total fatigue life. Therefore, it was concluded that the improvement obtained with the oleophobic coatings was primarily a measure of their effect on crack initiation. This work was continued in a later investigation (14) with sharply notched specimens. Dodecyl alcohol was used as the coating because it had been found to be highly effective in the previous tests. The results of these tests indicated that the oleophobic film is effective in the crack propagation stage as well as the crack initiation stage.

This work at the National Bureau of Standards was extended by Holshouser and Bennett (15) who reported that a gas is often released from a metal during fatigue stressing. Completely reversed torsion tests were made on several metals including SAE 1020 steel and an aluminum alloy. These tests were made on a constant load amplitude machine at the rate of 1800 stress cycles per minute. Bubbles of gas were found to form under a pressure-sensitive tape which was stuck to the test piece. These bubbles were formed only with the SAE 1020 steel and the aluminum alloys. An analysis of the gas showed that it consisted mainly of hydrogen. Additional testing showed that bubbles were formed only when the applied stress was greater than the endurance limit and the cracks developed soon after the bubbles appeared. These bubbles did not form under static loads, indicating that gas evolution is a result of the fatigue process.

In two papers, Bennett (16,17) reported the results of tests conducted to determine the effect of relative humidity on fatigue life. Test pieces of 6061-T6 aluminum alloy were fatigued in completely-reversed bending at the rate of 1800 cycles per minute. Specimens tested in moist air (95 percent relative humidity) were compared with specimens tested in dry air (5 percent relative humidity). Nine or ten specimens were used to determine each S-N curve. There was a 14 percent reduction in the fatigue life of the specimens tested in moist air as compared with those tested in dry air. Further tests indicated that there was an initial period in the fatigue life of the metal in which moisture had no effect. Shives and Bennett (18) later extended these tests to include several other materials, including AISI 4340 steel. Notched specimens were stressed in rotating bending at the rate of 9000 cycles per minute. As before, nine or ten specimens were used to determine each S-N curve. The results indicated that high relative humidity has a rather small effect on the fatigue life of steel. It was felt that the high speed of testing was partially responsible for the insignificant results, (i.e., the short testing time did not allow humidity to have its full effect).

In addition to this work at the National Bureau of Standards, there have been several recent papers from other investigators concerning the atmospheric corrosion fatigue effect on aluminum and aluminum alloys. Meyn (19) reported that for low stress amplitudes the rate of crack propagation in 2024 aluminum alloy in air is about three times greater than in a vacuum. Eeles and Thurston (20) reported that moist air has an effect on the fatigue life of 57S aluminum alloy. Dunsby and Wiebe (21) reported on bending fatigue tests made on sheet specimens of an aluminum alloy in air of three humidity levels: dry (12 percent relative humidity), medium (19 to 30 percent), and moist (90 percent). They found progressively lower fatigue life with increasing humidity level. Investigations by Leybold, Hardrath, and Moore (22) and by Feeney, McMillan, and Wei (23) also resulted in the conclusion that atmospheric moisture reduces the fatigue life of aluminum and aluminum alloys.

Masumoto, Ebara, and Ueda (24) conducted fatigue tests on mild, high strength, and weather-resistant steels. Unnotched, round notched, and V-notched plate specimens were fatigued in reversed bending in a variety of atmospheres. The results indicated that both oxygen and water vapor in the atmosphere reduce the fatigue life of mild steel. The effect was found to be confined to the crack propagation stage of the test. Unfortunately, only a small number of specimens were used and the humidity level of the damp air used was not reported.

The most recent investigations into the subject of atmospheric corrosion fatigue were those mentioned in the introduction to this report. Stallings (1) made rotating-bending fatigue tests on round, mild steel specimens with profile keyway. The specimens were stressed at the rate of 10,000 cycles per minute. Nine specimens were used for each S-N curve. An increase in the relative humidity from less than five percent to above ninety percent produced a decrease in fatigue life of about five percent.

Gray (2) ran fatigue tests on sharply notched, round specimens of SAE 1018 steel. The specimens were fatigued in rotating-bending at the rate of 4000 cycles per minute. The tests were conducted in an atmosphere of air at three relative humidity levels: low (0-10 percent), medium (45-55 percent), and high (90-100 percent). A large number of specimens (15-20) was used to determine each curve. The results indicated that humidity does have a slight effect on fatigue life of mild steel. However, heating problems inside the test chamber were encountered and the results are somewhat inconclusive.

Harton (3) continued this investigation with sheet specimens of mild steel. Notched specimens were fatigued on both constant-displacement and constant-stress amplitude machines at a rate of approximately 1800 cycles per minute. The tests were made in air of two humidity levels: low (0 to 5 percent relative humidity) and high (85 to 89 percent). Again 15 to 20 specimens were used for each S-N curve. The results indicated that humidity has a slight beneficial effect on fatigue life, which is in contrast to all previous investigations. Harton offered the following explanation for the surprising results: air for the low humidity tests was supplied directly from the laboratory air supply while air was bubbled through hot water for the high humidity tests; therefore, there must have been some corrosive agent present in the air supply which was partially removed during the bubbling process.

In summary, moisture in the atmosphere has been shown to be detrimental to the fatigue life of many metals, especially aluminum and aluminum alloys. There is some evidence that the same is true for ferrous metals, although the existing data is scarce and inconclusive.

III. INVESTIGATION

Test Apparatus

The test apparatus consisted of a fatigue testing machine, humidity equipment, and various supporting equipment and instrumentation. This apparatus is shown in Figures 1 through 6.

The tests were conducted on a Sonntag Universal Fatigue Testing Machine (Model No. SF-01-U). This machine was fitted with an environmental test chamber and a fixture for producing torsion. The machine with torsion fixture and environmental chamber in place is shown in Figure 1. The function of the Sonntag machine is to apply a vertical, vibratory force of constant amplitude to any specimen fastened between a vibrating and a stationary platen. The force is produced by a rotating, unbalanced mass which can be adjusted to create a maximum force amplitude of 200 pounds. The test specimen can also be subjected to a static preload of up to 200 pounds if desired. The machine stresses a specimen at the rate of 1800 stress cycles per minute.

Two automatic cut-off switches stop the machine at failure of a specimen. A reset-type counter registers the number of cycles to failure. Figure 2 is a schematic showing the principle of operation of the

Sonntag machine.

The torsion fixture consists of a lever arm with one end connected to the vibrating platen and the other end connected to a shaft free to rotate between two large bearing blocks. A coupling is used to attach one end of the test specimen to the shaft while the other end of the specimen is attached to a heavy fixed block. The vertical, oscillating motion of the vibrating platen applies a torque to the shaft which in turn transmits this torque to the test piece. The heavy bearing blocks on either side of the connection between the lever arm and the shaft eliminate any possibility of bending in the specimen. The fixture is shown in Figures 1, 3, and 4 with test piece in place.

A controlled atmosphere was maintained around the test specimen by means of a plastic sleeve (Figure 1) placed between the coupling and the fixed block and secured by wide rubber bands. Air of controlled relative humidity entered one side of the chamber and was exhausted on the other.

Air of very low relative humidity (zero to five percent) was obtained directly from the laboratory air supply. This air was passed through a filter and pressure regulator prior to use.

A bubble tower apparatus (Figure 5) was used to provide high humidity air (90-95 percent relative humidity) for Series A and high (90-95 percent) and low (20-25 percent) humidity air for Series B. Filtered laboratory air was forced through a column (bubble tower) of distilled water. The temperature of the distilled water was controlled by circulating a water-antifreeze mixture which was either heated or cooled by means of a heater and chiller in the circuit. A thermostatic switch located on the bubble tower controlled the heating and cooling of this mixture.

After leaving the bubble tower, the air was passed through a coil of plastic tubing where it was brought to room temperature (approximately 74 F). Several moisture traps were placed in the system to remove condensation. The relative humidity of the air obtained from this apparatus could be controlled over a wide range of values (between 15 percent and 95 percent) to within approximately ± two percent.

Prior to entering the environmental chamber the air was passed through a flowmeter, a final condensation trap, and a small chamber used for measuring the relative humidity. Located in this measuring chamber was a humidity sensor connected to an electric hygrometer. A chart recorder was used to record the hygrometer reading during the fatigue tests. The hygrometer, chart recorder,

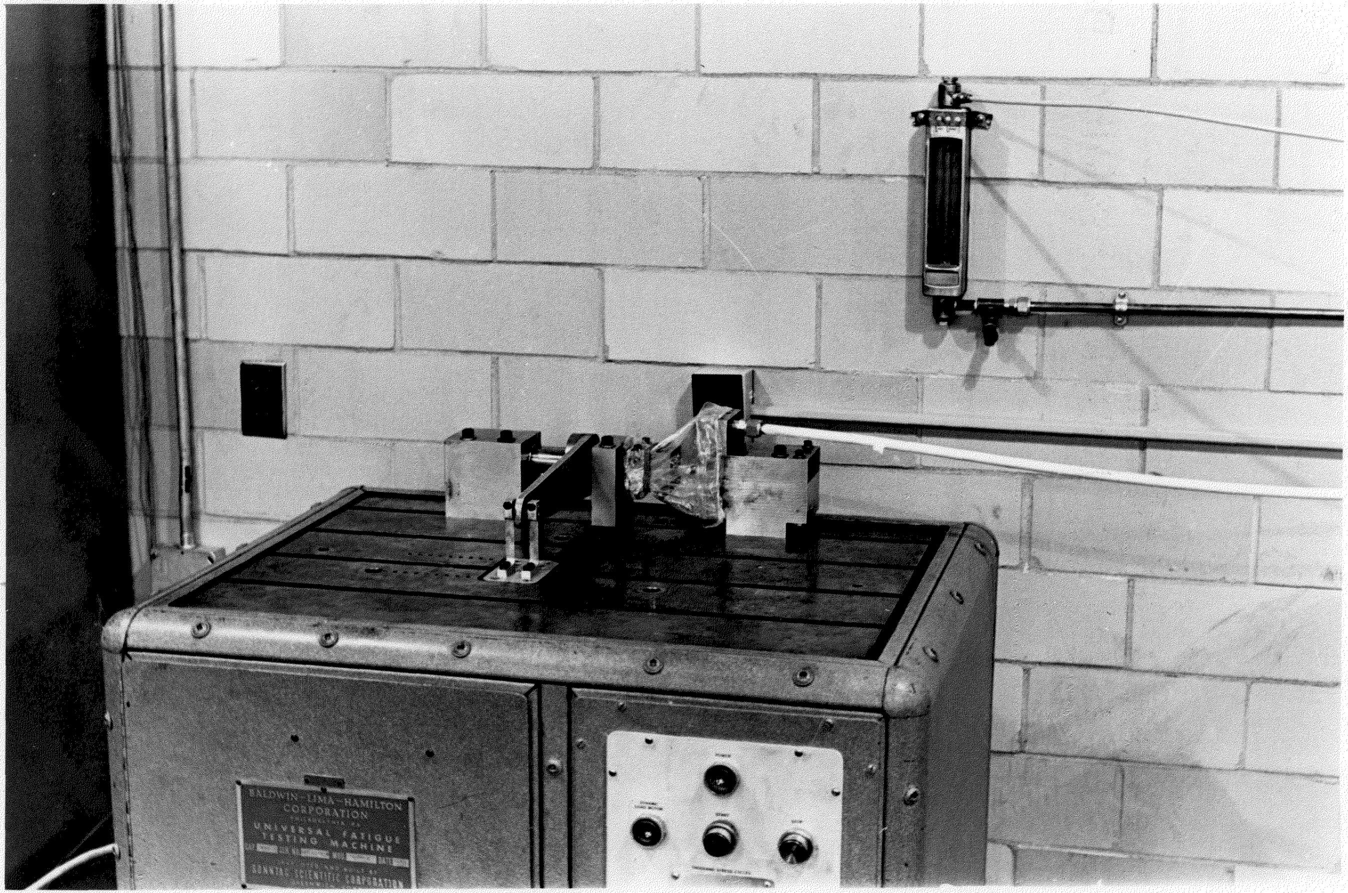
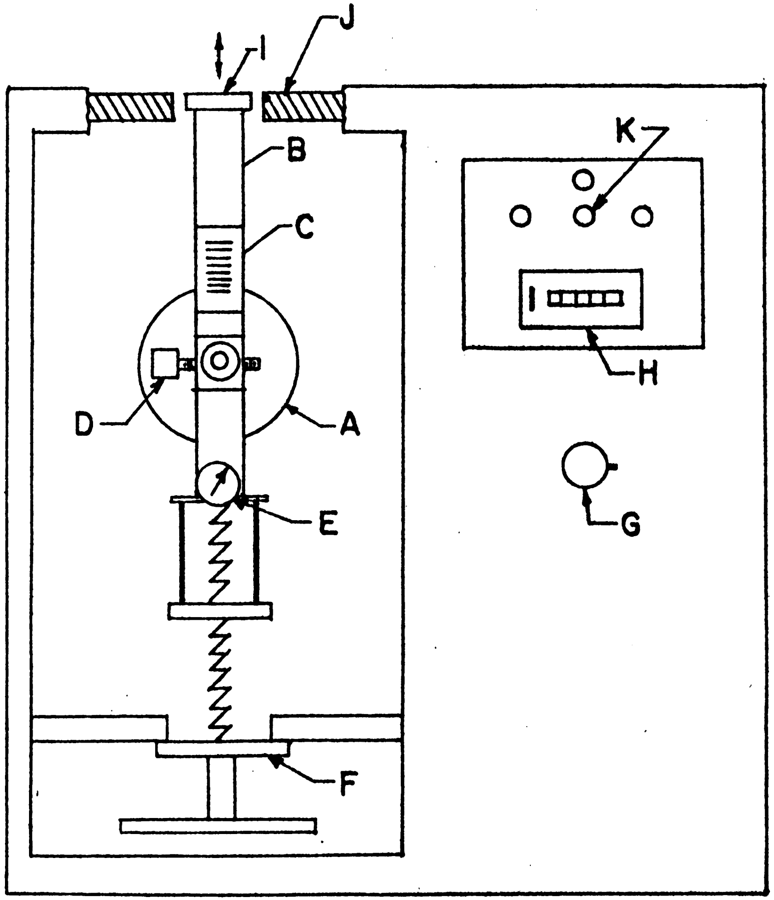


FIGURE I. SONNTAG MACHINE WITH TORSION FIXTURE AND ENVIRONMENTAL CHAMBER IN PLACE



A. MOTOR
B. OSCILLATING CAGE
C. FORCE INDICATOR
D. ROTATING UNBALANCED MASS
E. DIAL INDICATOR FOR STATIC PRELOAD
F. HANDWHEEL FOR APPLYING STATIC PRELOAD
G. VARIABLE TRANSFORMER
H. COUNTER
I. VIBRATING PLATEN
J. STATIONARY PLATEN
K. START SWITCH

FIGURE 2. SCHEMATIC OF SONNTAG MACHINE

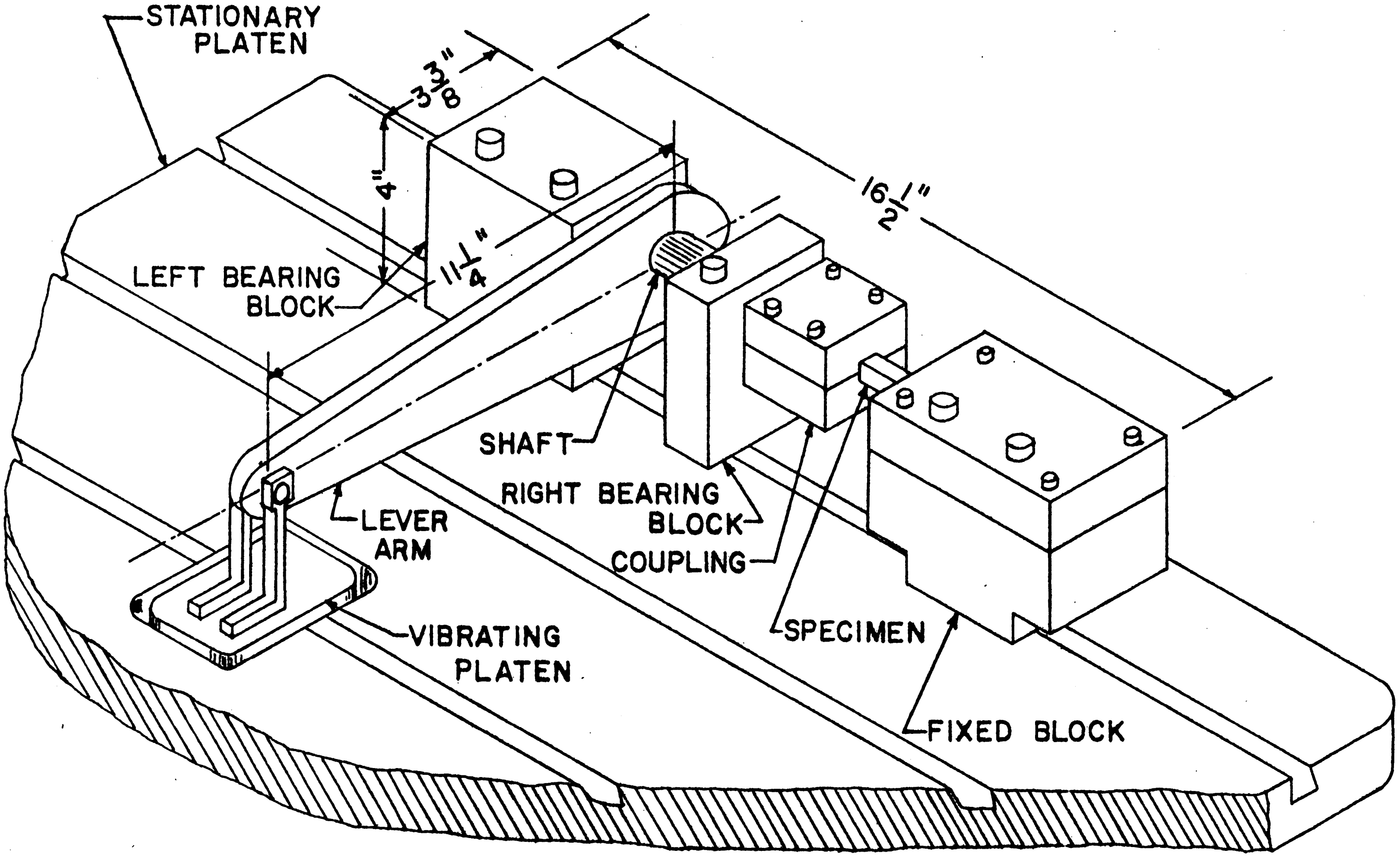


FIGURE 3. TORSION FIXTURE – COMPONENTS AND DIMENSIONS

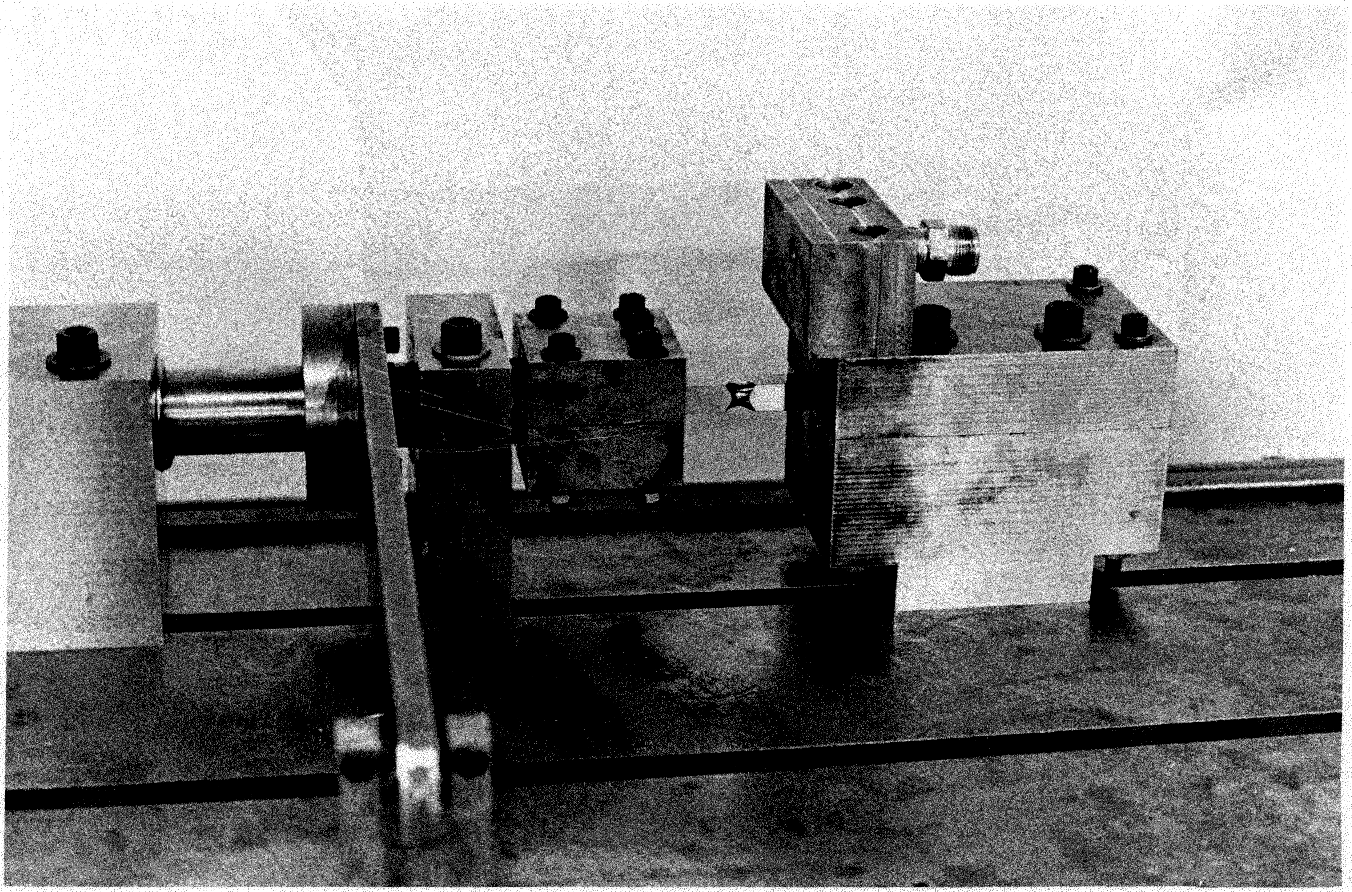


FIGURE 4. TORSION FIXTURE

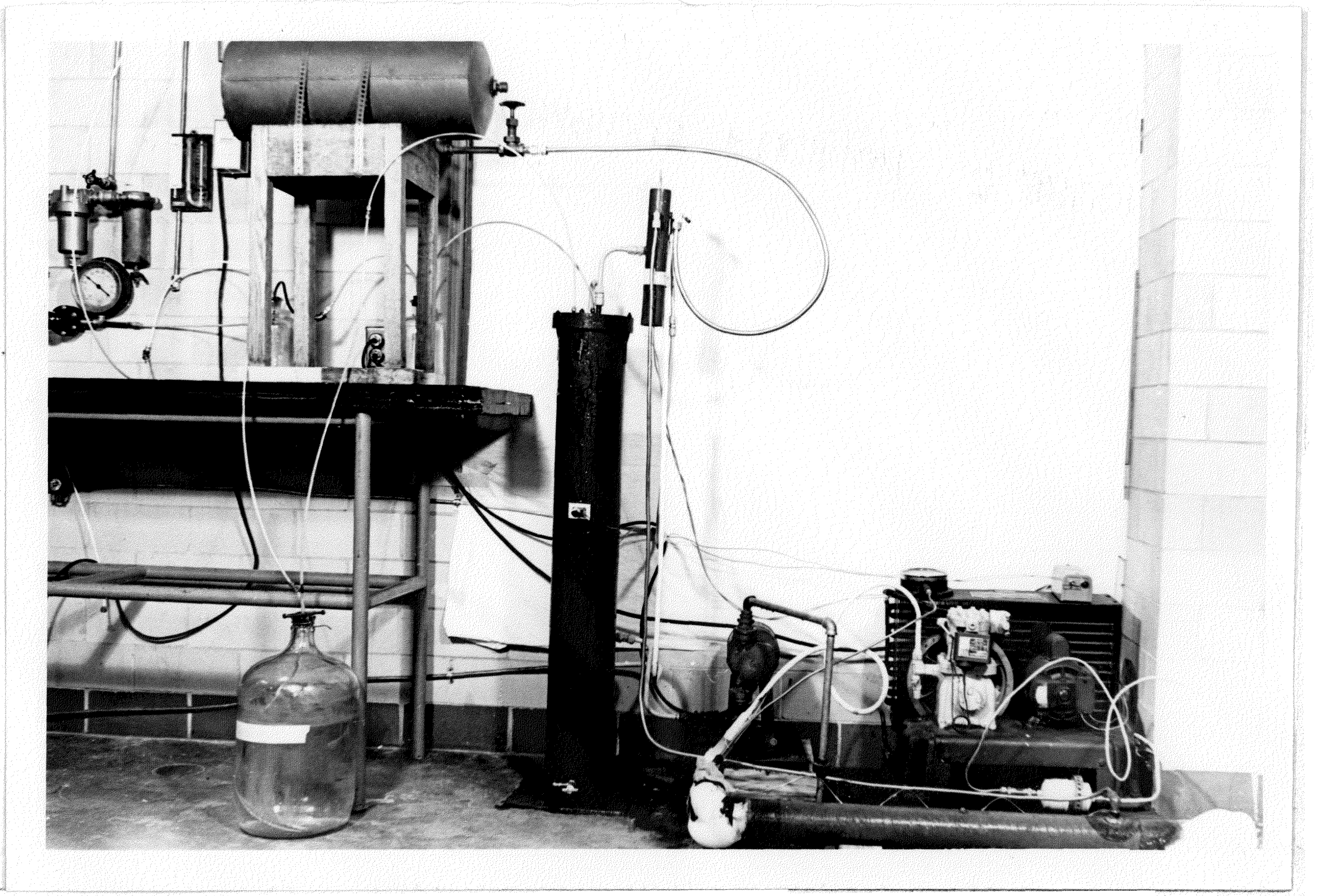


FIGURE 5. HUMIDITY EQUIPMENT

FIGURE 6. HUMIDITY MONITORING EQUIPMENT

and measuring chamber are shown in Figure 6. The flowmeter can be seen in Figure 1.

As an added precaution the temperature of the laboratory was controlled at 74 F (with approximately a two degree variation in either direction) by means of a heating and cooling thermostat.

Test Specimens

The test specimens for Series A were machined from SAE 1018 cold-rolled steel, supplied in 20 foot lengths of one-half inch round section. All specimens for this series were cut from one bar. The properties of this material determined from test are given in Table 1. Specimen dimensions are given in Figure 7 and pictures of the specimens before and after testing are shown in Figure 8. The method of manufacture is given in the following paragraph.

All specimens for Series A were fully machined except for the V-shaped notch, and then all specimens for that series were notched. Very close tolerances were held on the specimen ends to ensure that they would be held tightly by the torsion fixture. The condition (i.e., surface finish and tolerances) of the major diameter was not considered critical since cracks would always occur at the root of the notch. The notches were

Table 1. Material Properties of SAE 1018 Cold-Rolled Steel

Mechanical Properties From Test*:

	Series A	Series B
Ultimate Strength (psi)	76,900	90,000
Yield Strength (psi)	64,100	83,000
Elongation In 2 Inches (Percent)	18.0	16.5
Reduction In Area (Percent)	57.0	52.8
Hardness (Rockwell B)	82	91

Composition Limits From The 1971 SAE Handbook (25):

Carbon	0.15-0.20%
Manganese.	0.60-0.90%
Phosphorus	0.04% Max
Sulfur	0.05% Max

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*Tensile tests conducted on Instron Tensile Testing Machine.

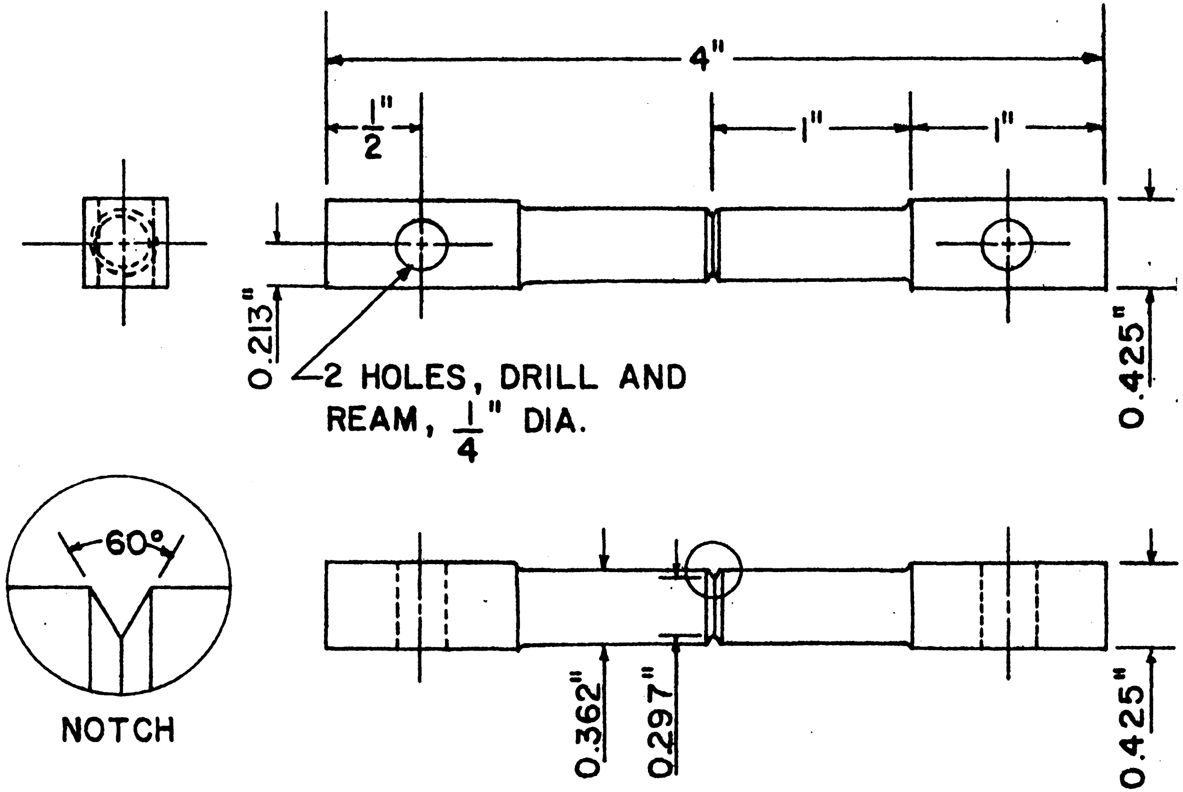

FIGURE 7. SPECIMEN DIMENSIONS - SERIES A

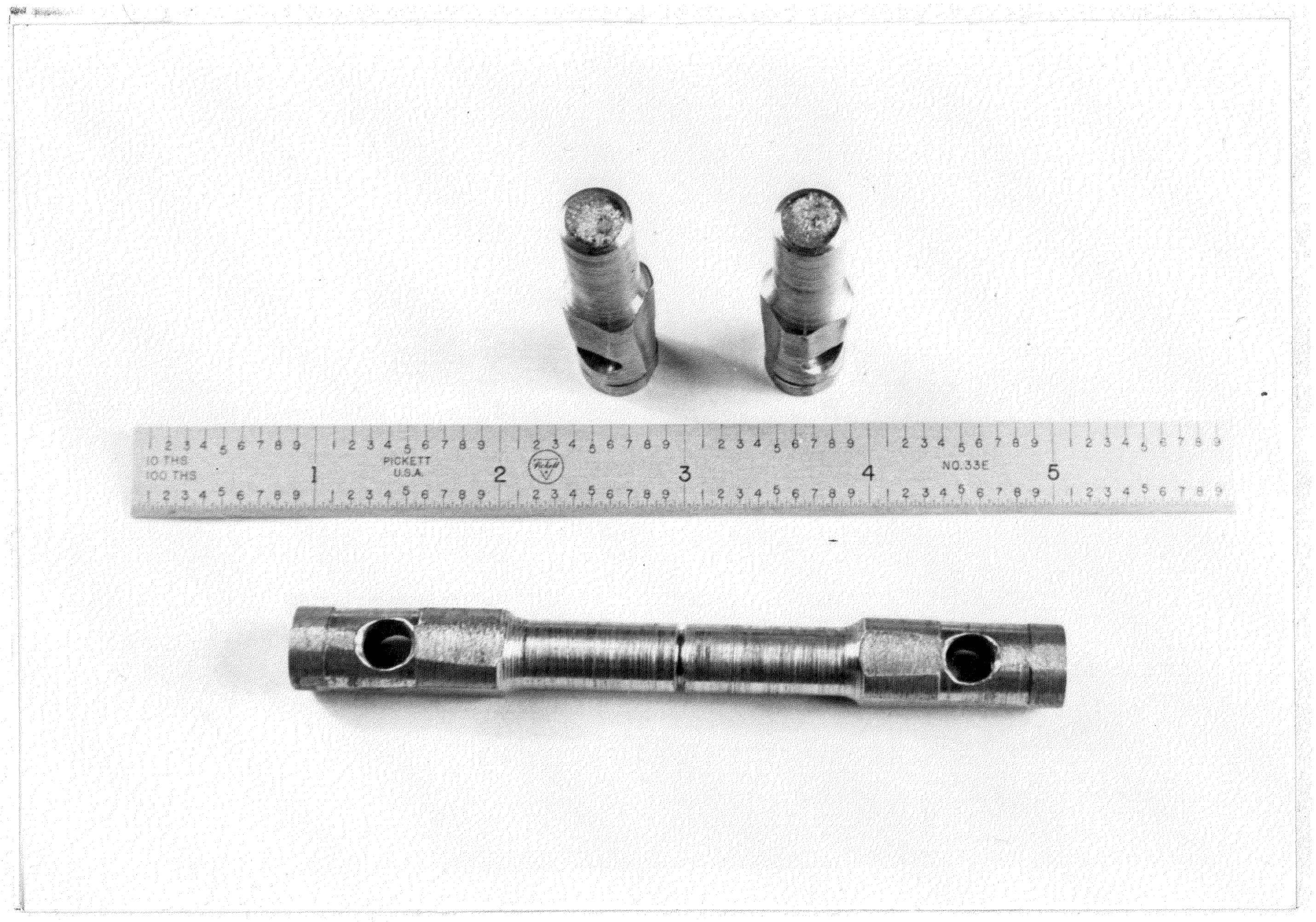

FIGURE 8. SPECIMEN BEFORE AND AFTER TESTING - SERIES A

cut with a carbide-tip tool sharpened to form a 60 degree notch. The notches were first rough cut to a diameter of 0.300 inches and the tool was then resharpened for the finish cut to a diameter of 0.297 inches. The tool tip was inspected on an optical comparator before and after the finish cut and no appreciable tool wear was found. The radius of the notch root was approximately 0.005 inches. The specimens were stored in a clean bath of benezene immediately after machining in order to prevent rusting.

It was assumed that the presence of the sharp notch would cause fatigue cracks to form very early in the fatigue lives of the specimens. Therefore the Series A test was assumed to be primarily an investigation of crack propagation.

Specimens for Series B were machined from SAE 1018 cold-drawn steel, furnished in 20 foot lengths of seven-sixteenths inch square section. All specimens for this series were cut from two bars of stock. The properties of this material determined from test are given in Table 1. Specimen dimensions are given in Figure 9 and pictures of the specimens before and after testing are shown in Figure 10. The method of manufacture is given in the following paragraph.

The bar stock was first cut to the proper lengths.

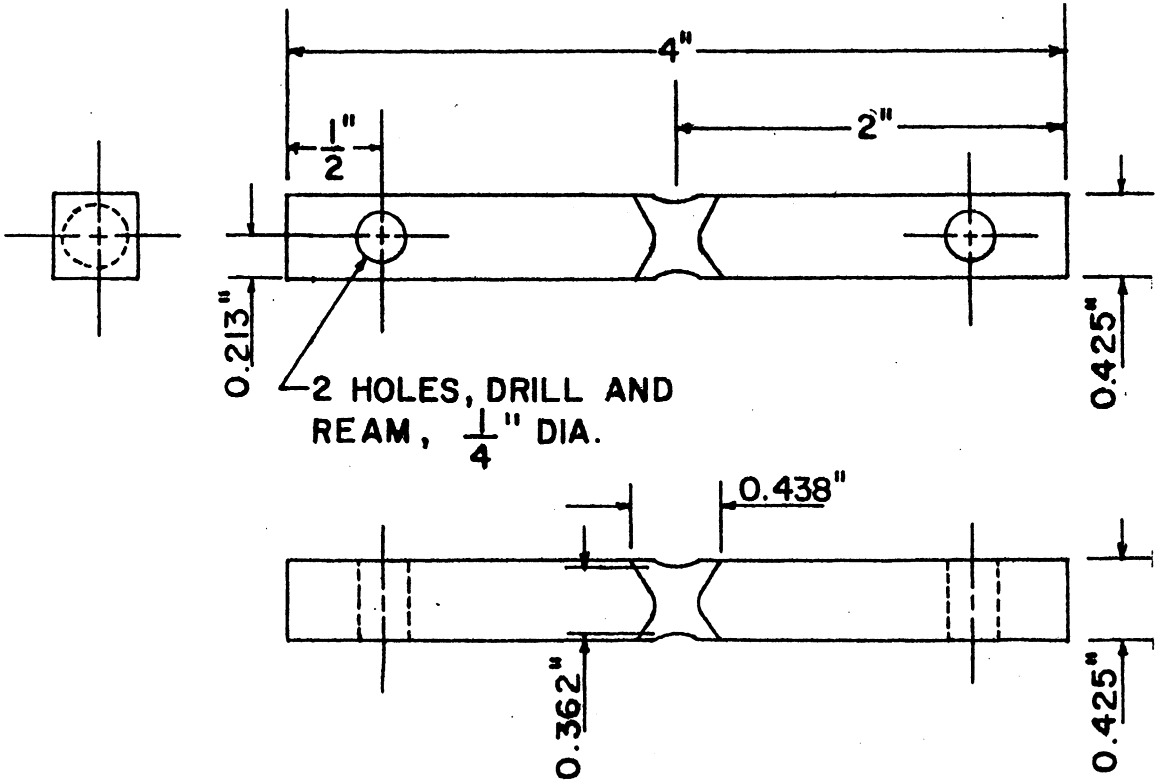

FIGURE 9. SPECIMEN DIMENSIONS – SERIES B

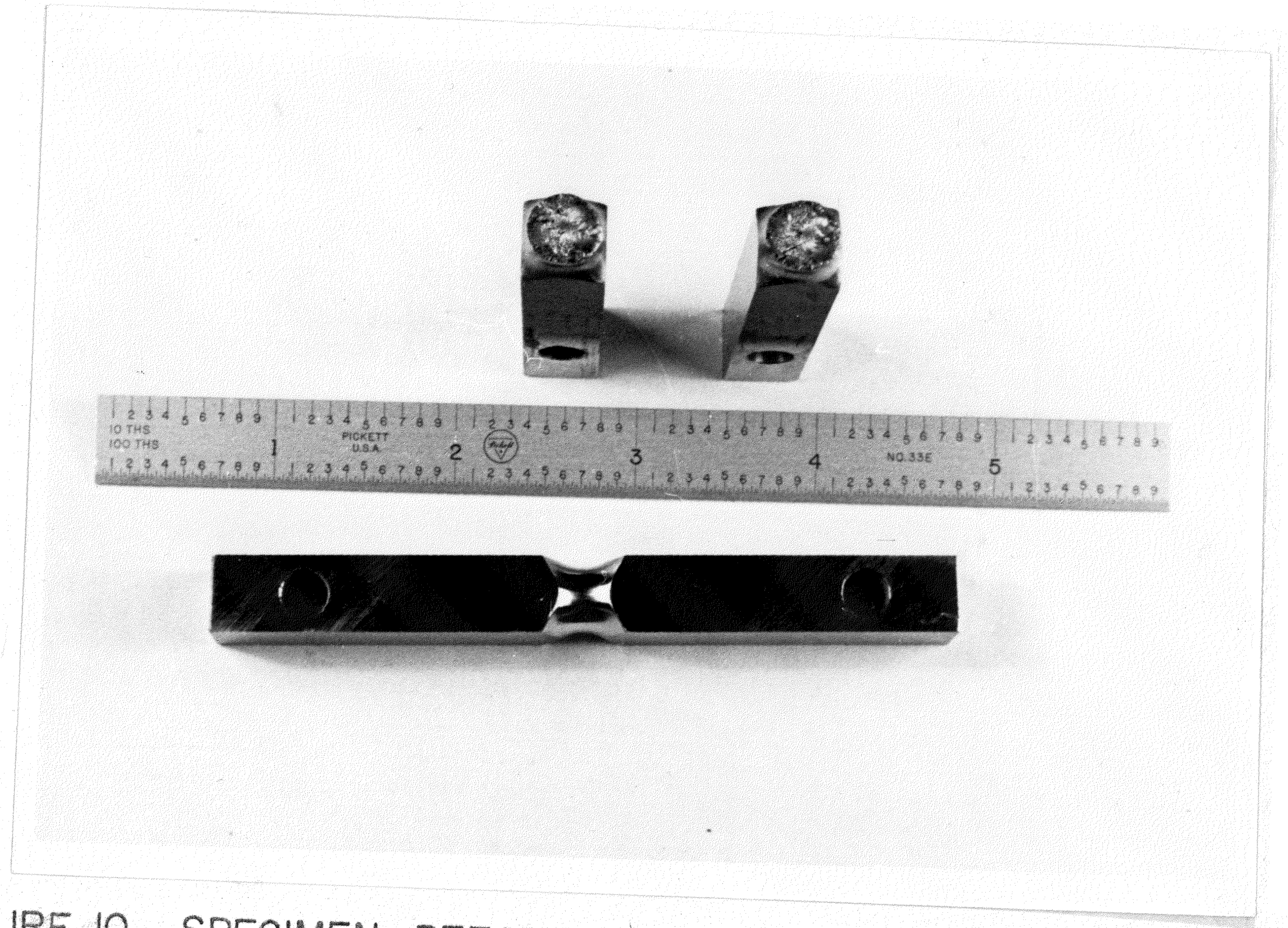

FIGURE 10. SPECIMEN BEFORE AND AFTER TESTING - SERIES B

The critical section (reduced section) of each specimen was then cut to a diameter of 0.364 inches using a nine-sixteenths inch-wide cutting tool. Polishing brought this diameter to 0.362 inches. The machining was done at a low rate of speed and a small depth of cut was taken in order to avoid excessive stressing of the specimen. The tool was inspected both before and after this process and no appreciable wear was found. Each specimen was numbered in the order of manufacture of the reduced section to allow randomization of testing for statistical purposes. The ends of the specimens were then ground and drilled to fit properly in the torsion fixture. Very close tolerances were maintained on the ends in order that the specimens might be held tightly in the fixture.

Specimens were selected at random and subjected to a three stage polishing process on the reduced section. Preliminary polishing was accomplished with two grades of fine emery cloth. The specimen was turned on the lathe at a high speed and subjected to three minutes of polishing from each cloth. The reduced section was then measured and inspected for major flaws. The specimen was then final polished for four minutes with crocus cloth by again turning on the lathe. Preliminary tests had shown that cracks were formed either longitudinally or at a 45 degree angle to the centerline of the specimen. Therefore the final polishing scratches were put on circumferentially to have a minimum effect on fatigue crack formation. For greater uniformity, new polishing cloth was used for each specimen. Specimens were stored in clean benezene at all times while not being machined or polished. Furthermore, care was taken to prevent scratches on the critical section during storage.

Unnotched fatigue specimens are usually of a different style than those produced for Series B, i.e., they are usually tapered gradually from end to end over a large length of test section. However, because of the large number of specimens required, time and cost considerations prevented the use of this type of specimen. It is believed, however, that the type of specimen produced had a stress concentration factor low enough to consider Series B a test of crack initiation plus crack propagation.

Method of Testing

Series A

In a fatigue experiment it is important that the collection of data be made in as random a manner as possible. For example, tool wear during the manufacture of test specimens may cause those specimens made last to be slightly different in cross-section than those made first. Randomization of specimen testing according to the order of manufacture would account for this unavoidable circumstance. Similarly, randomization would account for other unavoidable errors such as wear of fatigue testing equipment, change in atmospheric conditions, or inhomogeneity of material. Unfortunately, it was not possible to number the specimens of Series A in the order of manufacture. However, they were later grouped together, selected at random, and numbered from one to 32 consecutively. This order of numbering was then randomized for testing purposes by the use of a table of random numbers.

The experiment plan for Series A was set up using two levels of relative humidity and three levels of stress (above the endurance limit). Five or six specimens were designated to be broken at each combination of humidity level and stress level. This experiment plan is explained in Appendix C in connection with the statistical analysis of results. Air of low relative humidity (zero to five percent) was taken directly from the laboratory air supply. Air of high relative humidity (90-95 percent) was obtained from the bubble tower apparatus by bringing the temperature of the water in the tower above room temperature. For reasons which will become evident later, air obtained directly from the air line will be referred to as "unwashed" and air obtained from the bubble tower will be referred to as "washed" as it had been bubbled through the column of distilled water. The stress induced in the specimen was determined by the well-known formula

$$s = \frac{Tc}{J}$$

where: s = nominal shear stress (disregarding stress concentration) at the root of the notch

T = torque delivered to specimen (length of lever arm times force produced by rotating unbalanced mass)

c = radius of specimen at notched section

J = polar moment of inertia of specimen at notched section

Stress levels and humidity levels were also randomized with a table of random numbers.

Immediately before the start of each test the specimen was alternately ultrasonically cleaned in solvents (benezene, acetone, and Freon 11) and dried for periods of three minutes. The specimen was then installed in the torsion fixture and the environmental chamber slipped into place. The required force was set by adjustment of the rotating unbalanced mass. Air of controlled humidity was blown into the environmental chamber at the approximate rate of 67 chamber volumes per minute. The beginning of the test was delayed 30 minutes in order to allow the humidity level inside the chamber to stabilize. Finally the machine was started at a very low rate of speed. A variable transformer was used to bring the testing speed gradually to 1800 stress cycles per minute, thus preventing sudden application of load and overstressing of the specimen. Room temperature was maintained at 74 ± 2 F and the humidity level of the air in the environmental chamber was monitored constantly during each test. When the specimen was broken, the number of cycles to failure was recorded and the above testing procedure was repeated for the next test piece.

Series B

The Series B experiment was conducted in two parts. The first part was set up using two levels of humidity and three levels of stress (above the endurance limit). Seven or eight specimens were designated to be broken at each combination of humidity level and stress level. As noted previously, the investigations of Gray (2) and Harton (3) had indicated that corrosive gases might be present in the air supply. Consequently, an attempt was made to account for this possibility by providing a more uniform source of air for the high and low humidity tests. Air for the high humidity tests (90-95 percent relative humidity) was provided from the bubble tower apparatus as in Series A. Chilling the water in the bubble tower to below room temperature provided air of 20-25 percent relative humidity for the low humidity tests. In this manner any washing effect (removal of impurities) accomplished by the bubbling of air through water was imparted to the tests at each level of humidity. However, it should be noted that air for the high humidity tests was bubbled through hot water while the air for the low humidity tests was bubbled through cold water.

The second part of the experiment was set up with one level of humidity and two levels of stress. Seven specimens were designated to be broken at each stress level. Air (zero to five percent relative humidity) was taken directly from the air line as in the Series A low humidity tests. The two stress levels were the same as the two higher stress levels used in the washed air tests, i.e., the first part of the Series B tests.

Unfortunately, it was not possible to randomize humidity levels in the Series B tests because of the difficulty in changing the temperature of the water in the bubble tower. All tests in low humidity (20-25 percent) washed air were made first followed by the tests in high humidity (90-95 percent) washed air. Finally, the tests in unwashed air (zero to five percent relative humidity) were made. Stress levels and the order of specimen testing were, however, randomized within the humidity levels. The experiment plan for Series B is explained in Appendix C in connection with the statistical analysis of results. The cleaning and testing procedures were the same as for Series A.

pH Readings

In addition to providing a more uniform source of air for the Series B tests, it was desired to obtain information regarding the possible effects of corrosive agents on the fatigue tests. Consequently, an attempt was made to determine the pH values of the various air sources used. It was anticipated that comparison of these values would yield information pertaining to possible differences in the corrosive nature of the various air sources. Eighteen pH readings (nine during the high humidity washed air tests and nine during the low humidity washed air tests) were taken over a period of one month. The procedure used in taking these readings is given as follows:

1. Three small beakers were half-filled with double distilled water.

2. Air directly from the air line was bubbled through one of these beakers while air from the bubble tower was bubbled through another. The third beaker was kept as a reference solution.
3. After 30 minutes of bubbling the pH values of the three solutions were taken with a high precision pH meter and recorded.

No attempt was made to correlate a pH reading with a particular specimen test as the purpose of the procedure was to determine only if the pH value of the air for one humidity level test differed appreciably from the pH value for the other humidity level test.

Results

Series A

The number of cycles to failure of each specimen in Series A is given in Appendix A. The data points for each humidity level are plotted in Figures 11 and 12. A straight line (S-N curve) has been fitted to the data for each humidity level by the method of least squares. A correlation coefficient (Appendix C) is given for each curve. Figure 13 shows the S-N curve for each humidity level together for comparison.

An analysis of variance, conducted at a 95 percent confidence level, showed that humidity had no significant effect on fatigue life. A complete explanation, along with the results, of the statistical analysis is given in Appendix C.

Series B

The fatigue data for Series B is given in Appendix B. The data points for each humidity level are plotted in Figures 14, 15, and 16. An S-N curve has been fitted to each set of data and a correlation coefficient given for each curve as before. The curves are presented for comparison in Figure 17.

An analysis of variance conducted with the data from the washed air tests (90-95 percent and 20-25 percent relative humidity) showed no effect of humidity. However, a similar analysis conducted using data from the unwashed air test (zero to five percent relative humidity) and data from the washed air test (20-25 percent relative humidity) showed humidity to be significant at the 90 percent confidence level. A 90 percent confidence level is considered to be " slightly significant" (26). The results of the statistical analysis are given in Appendix C.

pH Readings

The pH readings taken during the Series B tests are given in Table 2. These values have been adjusted so as not to reflect the pH value of the distilled water through which the air was bubbled (i.e., the pH value of the distilled water was set neutral, 7.0, and the other readings adjusted accordingly). It must be remembered that the pH values given in Table 2 are not the actual pH values of the air itself and can only be used to draw qualitative conclusions as to the acidity or alkalinity of the test air.

From Table 2 it can be seen that all of the sample solutions were acidic. This would seem to indicate that the air supply itself is acidic. The samples taken with air from the bubble tower, in almost all cases, were slightly more acidic than the corresponding samples taken with air directly from the air line. An analysis of variance (Appendix C) showed no significant difference between the pH values of the air used in the two washed air tests, i.e., the 20-25 percent and 90-95 percent relative humidity tests. A similar analysis showed a significant difference, at the 90 percent confidence level, between the pH values of the air used in the 20-25 percent relative humidity test and the air taken directly from the air line.

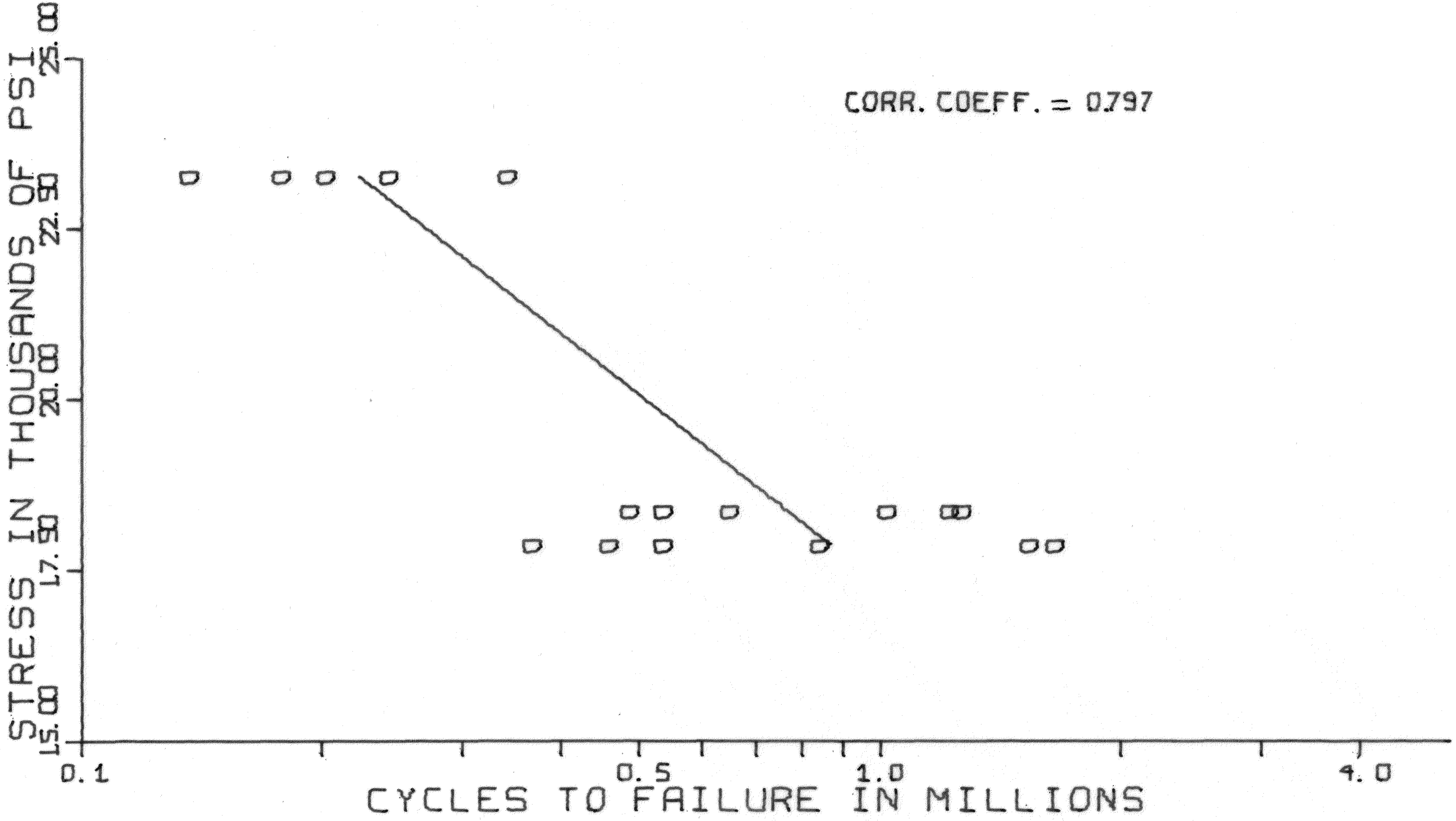

FIGURE 11. 0-5 PERCENT RELATIVE HUMIDITY, SERIES A, NOTCHED SPECIMENS

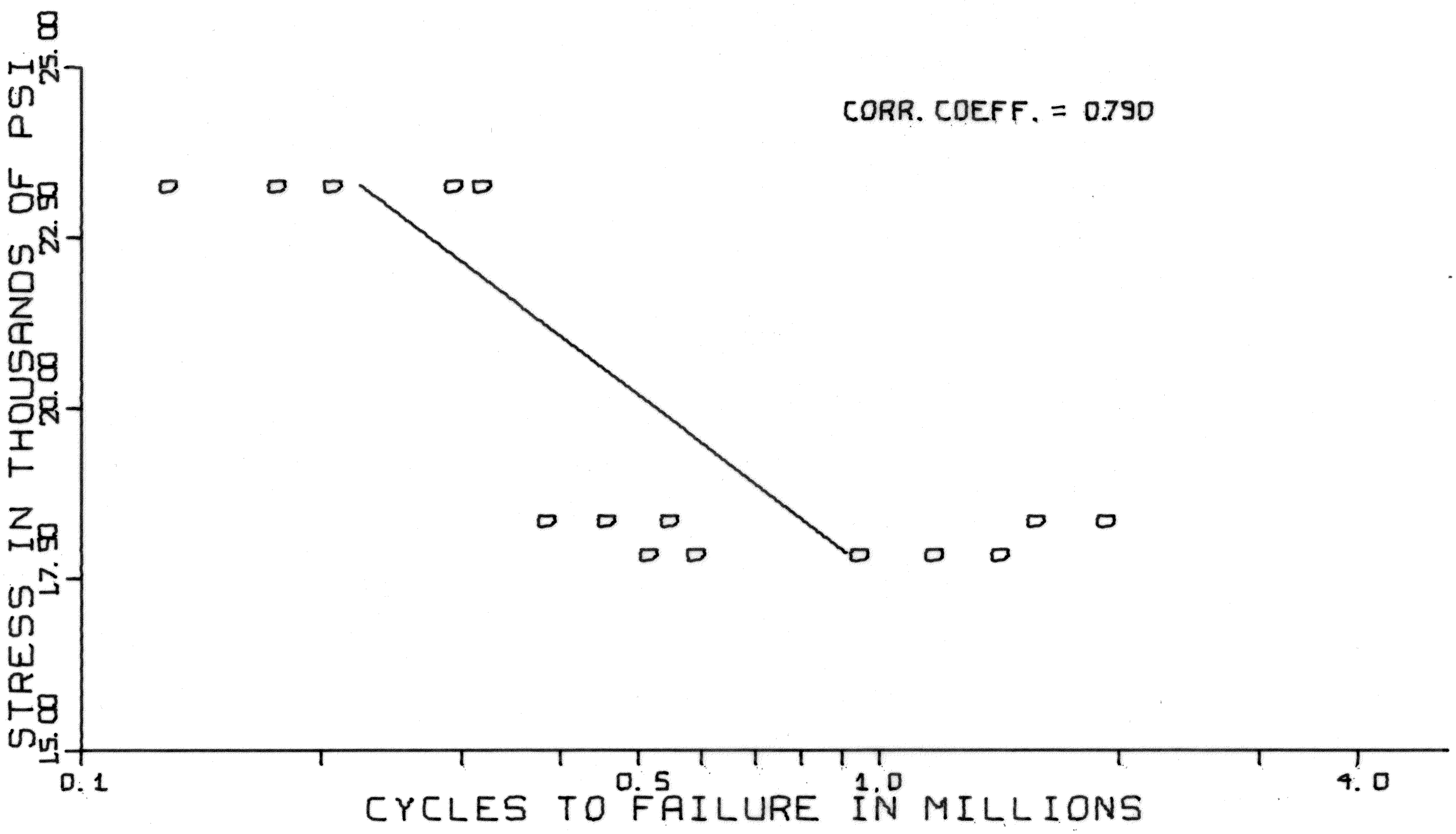

FIGURE 12. 90-95 PERCENT RELATIVE HUMIDITY, SERIES A, NOTCHED SPECIMENS

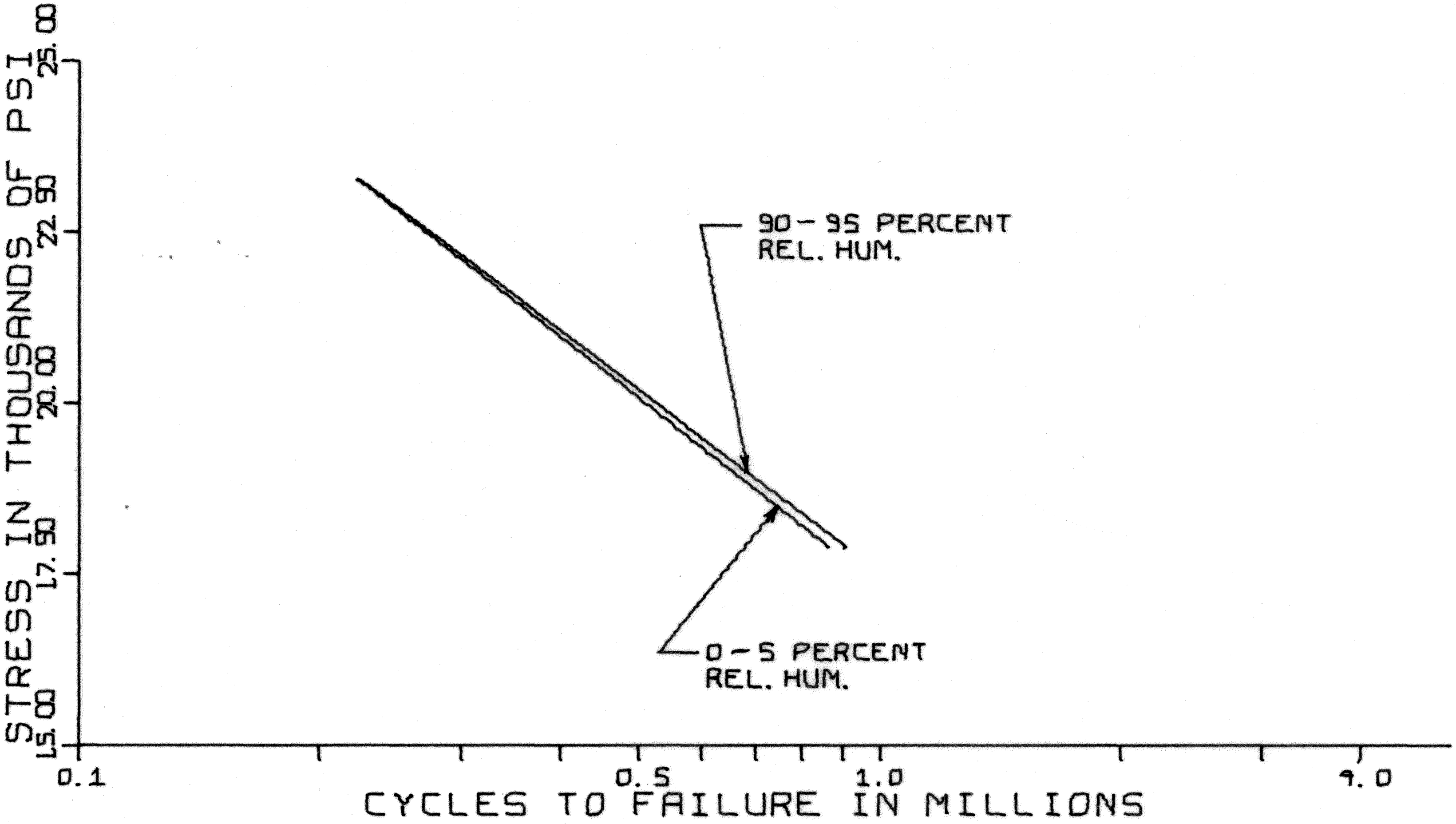

FIGURE 13. SUMMARY OF SERIES A, NOTCHED SPECIMENS

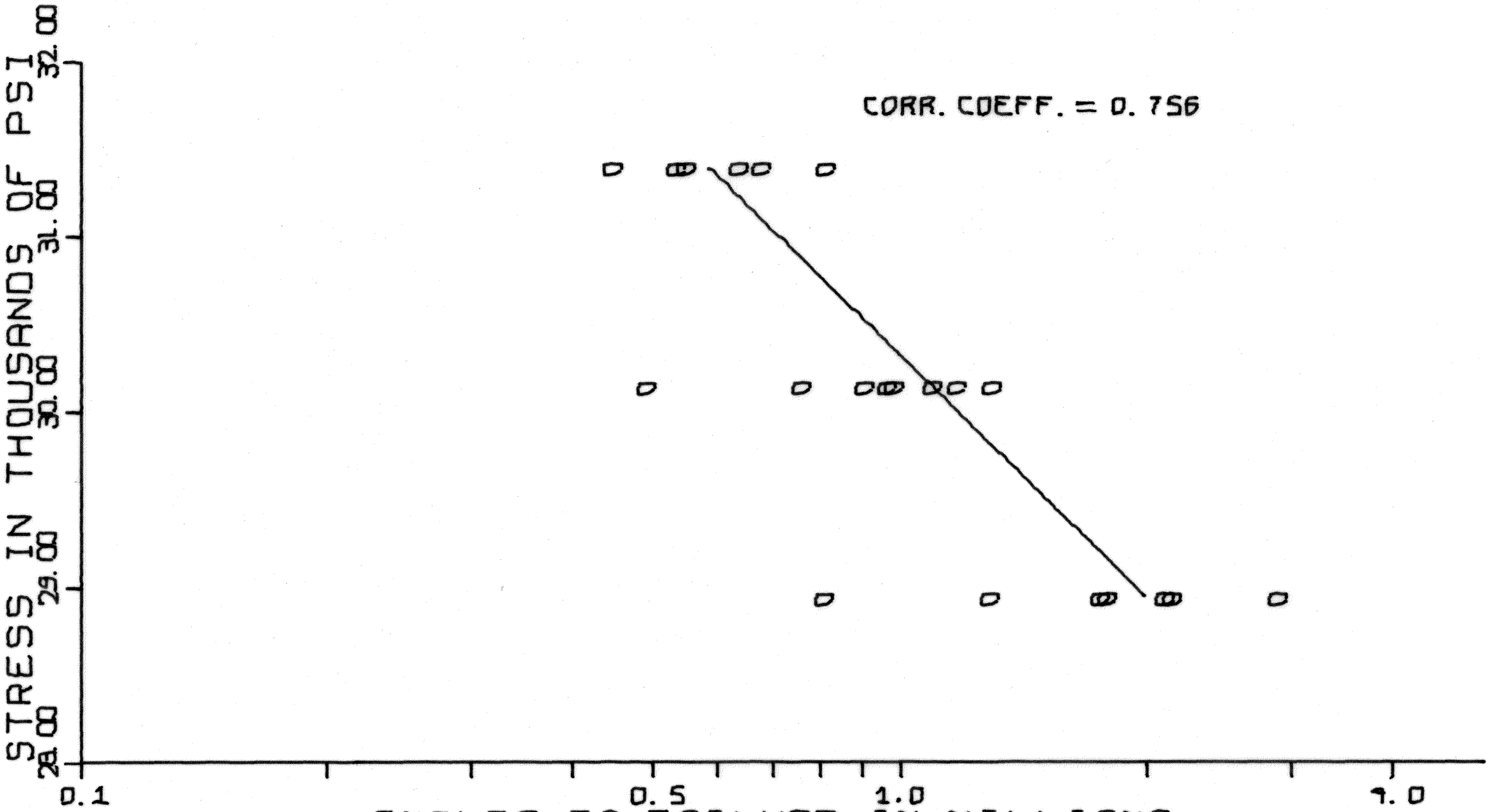

FIGURE 14. 20-25 PERCENT RELATIVE HUMIDITY, SERIES B, UNNOTCHED SPECIMENS

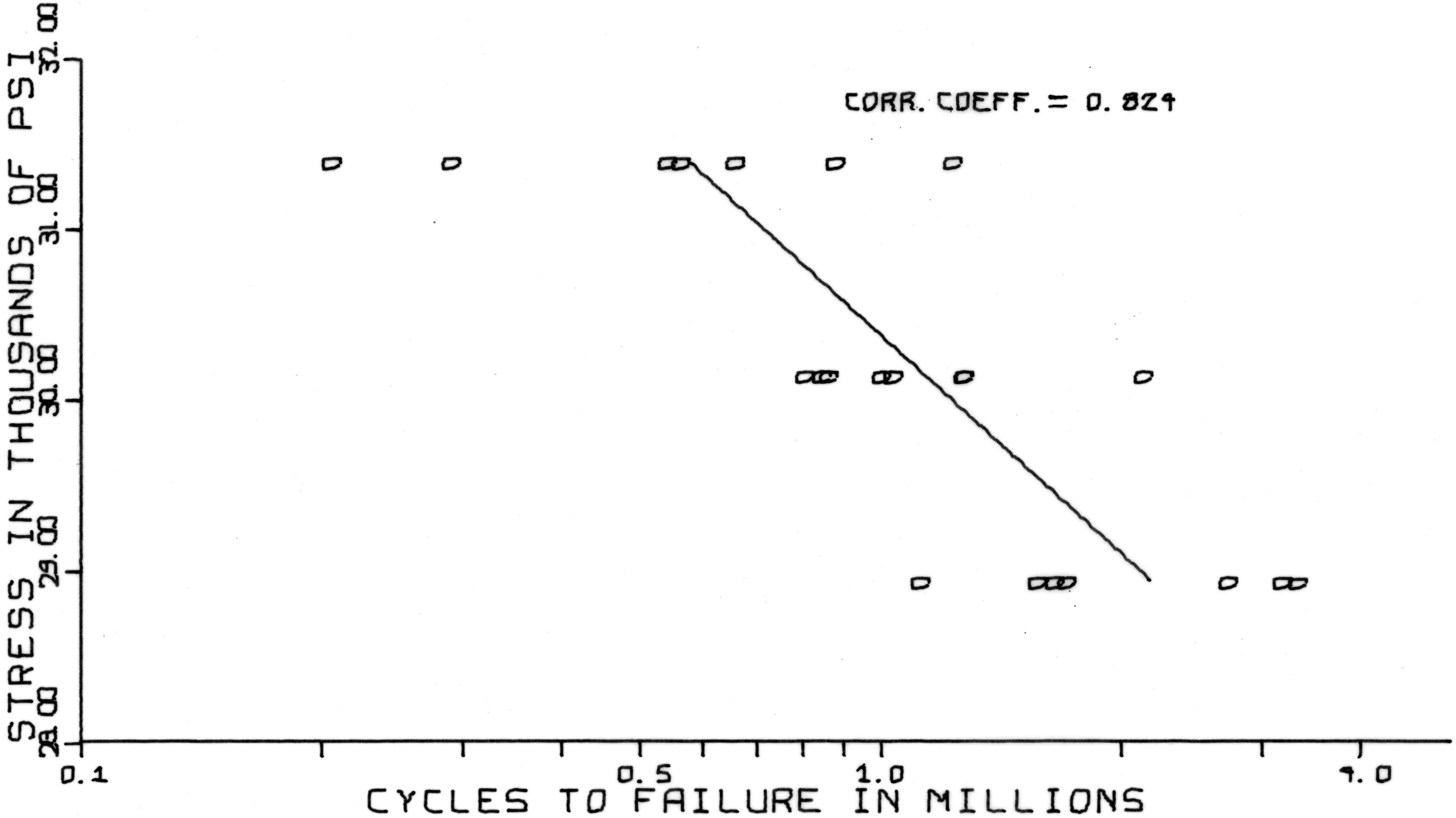

FIGURE 15. 90-95 PERCENT RELATIVE HUMIDITY, SERIES B, UNNOTCHED SPECIMENS

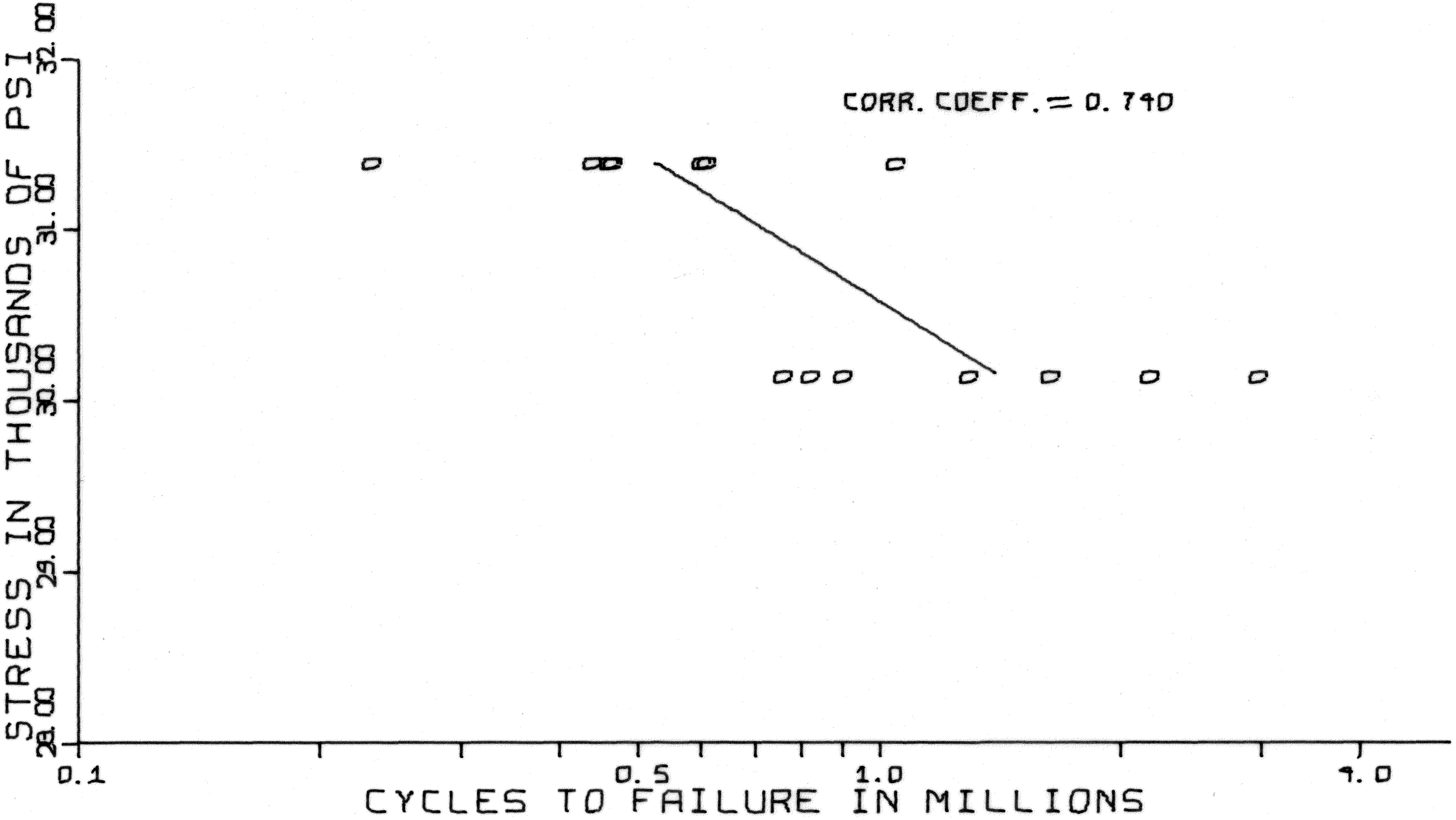

FIGURE 16. 0-5 PERCENT RELATIVE HUMIDITY, SERIES B, UNNOTCHED SPECIMENS

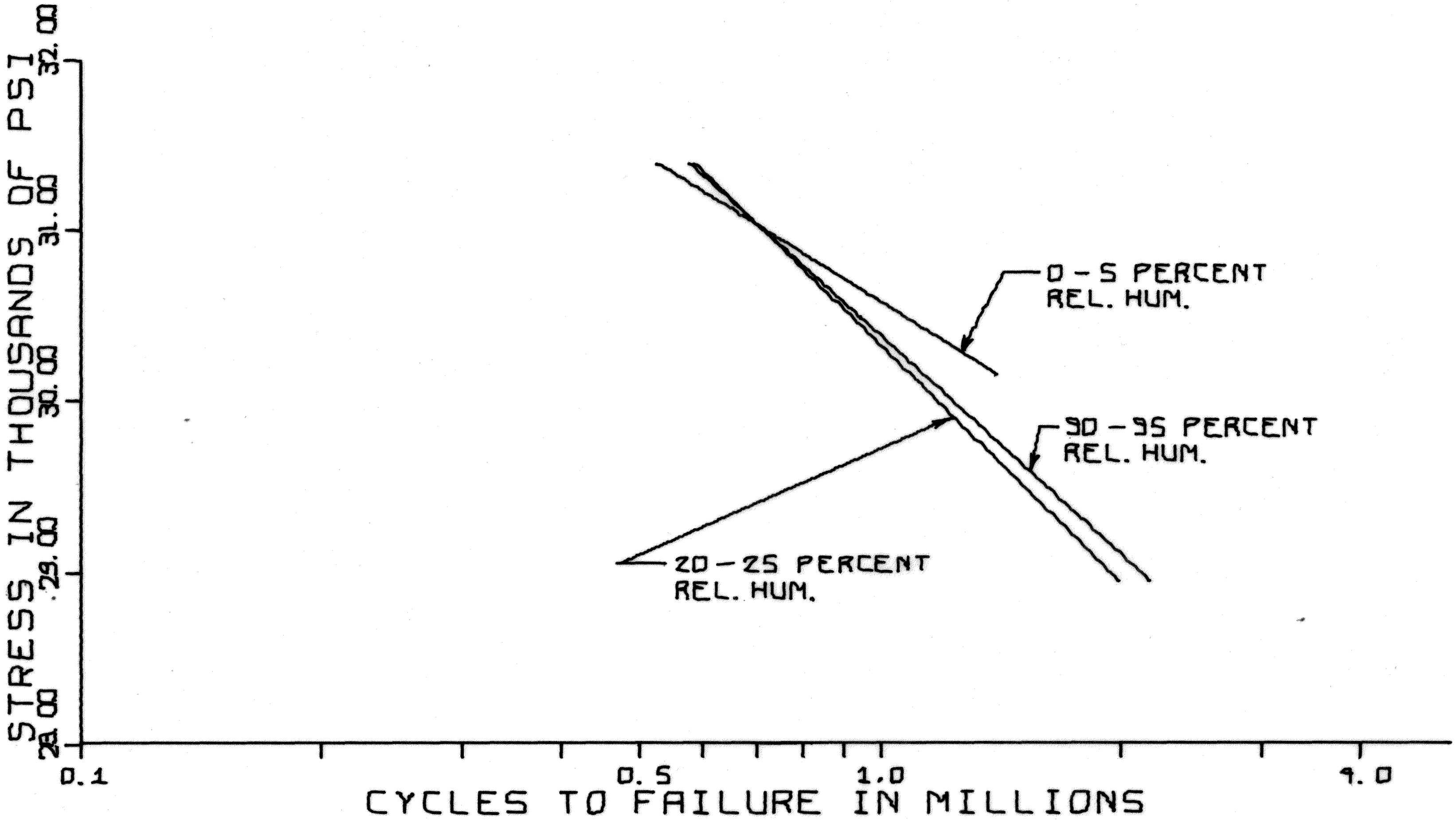

FIGURE 17. SUMMARY OF SERIES B, UNNOTCHED SPECIMENS

Table 2 - pH Readings

High Humidity Washed Air (90-95% Relative Humidity)

Date	Lab Air Solution (Unwashed)	Test Air Solution (Washed)
5/31/72	6.43	6.31
6/1/72	6.41	6.29
6/2/72	6.42	6.37
6/7/72	6.45	6.43
6/8/72	6.34	6.24
6/9/72	6.51	6.38
6/12/72	6.33	6.10
6/13/72	6.42	6.29
6/14/72	6.27	6.14
	Mean Value = 6.40	Mean Value = 6.28

Low Humidity Washed Air (20-25% Relative Humidity)

Date	Lab Air Solution (Unwashed)	Test Air Solution (Washed)
6/15/72	6.28	6.27
6/15/72	6.32	6.19
6/16/72	6.14	6.21
6/17/72	6.32	6.21
6/19/72	6.31	6.25
6/21/72	6.30	6.08
6/22/72	6.39	6.40
6/23/72	6.40	6.50
6/26/72	6.32	6.17
	Mean Value = 6.31	Mean Value = 6.25

IV. Discussion of Results

The results of the Series A tests (Figure 13) and the Series B tests (Figure 17) indicate that humidity has an effect only during the crack initiation stage of the fatigue of mild steels in reversed torsion. Furthermore, it appears that the reduction of fatigue life below that in very dry air (zero - five percent relative humidity) is just as great in air of 20-25 percent humidity as in air of 90-95 percent humidity. Although no strict comparison with previous works is possible, these results are rather surprising in that the data available indicates that humidity is effective in both the crack propagation stage and the initiation stage. Shives and Bennett (18) reported a slight effect of humidity on notched specimens of SAE 4340 steel tested in air. Masumoto, Ebara, and Ueda (24) found humidity to be effective only in the crack propagation stage of the fatigue of mild steel sheet in reversed bending. Their tests, however, were conducted in inert atmospheres rather than air and involved only a small number of test specimens. The only investigation involving reversed torsion was made by Holshouser and Bennett (15) who were mainly concerned with the evolution of gases from metal surfaces during fatigue. They did, however, report that the presence of a pressure-sensitive tape on the specimen retarded the rate of crack development in SAE 1020 steel. Mantel, Robinson, and Thomson (12) reported that humidity has a very significant effect on the fatigue life of unnotched steel specimens in reversed bending. Their work, however, involved much harder steel (SAE 52100) and their tests were conducted in inert atmospheres rather than air. Stallings (1) reported a significant effect of humid air on SAE 1018 steel in reversed bending. Gray (2) and Harton (3) found very little, if any, effect of humidity on the crack propagation stage of the fatigue of SAE 1018 steel tested in air. Except for the work of Shives and Bennett (18) and Stallings (1), all of the above work was conducted at speeds similar in magnitude to that of the present investigation. Shives and Bennett (18) felt that their insignificant results were in part due to the high testing speed.

In addition to the humidity effects, some conclusions may be made as to the possibility of corrosive gases in the air supply. Although there was no direct evidence, Harton (3) concluded that corrosive gases in the air supply were responsible for the ineffectiveness of humidity in the reduction of fatigue life. He reasoned that the air bubbled through water to produce high relative humidity had been partially cleaned of these corrosive gases and therefore specimens tested in this air would have a fatigue life just as long or longer than specimens tested in dry air taken directly from the air line. The series of pH readings (Table 2) taken during the Series B tests indicate that the air was made slightly more acidic by the bubbling process and that the variation of pH values during the 20-25 percent humidity tests was not appreciably different from the variation of values during the 90-95 percent humidity tests. The amount of day-to-day variation in the readings, however, makes it impossible to draw any conclusions other than these. Also if Harton's conclusion was valid, the S-N curve for the specimens tested in unwashed dry air (zero to five percent humidity) would be expected to fall on or below the other two curves. This was definitely not the case as can be seen in Figure 17. Therefore it appears that corrosive gases cannot be held responsible for completely masking the effect of humidity.

V. Conclusions and Recommendations

The results of the completely-reversed torsion fatigue tests on notched and unnotched specimens of SAE 1018 steel appear to justify the following conclusions and recommendations:

(1) An atmosphere of air of 20-95 percent relative humidity in contact with fatigue specimens of mild steel in reversed torsion reduces the fatigue life as compared with tests in dry air of less than five percent relative humidity.

(2) This effect becomes significant only at the lower stress amplitude levels where the testing time is long enough to allow humidity to be effective. It is expected that reduction of the stress levels to values less than those used for this investigation will result in an even more significant humidity effect.

(3) Air of 20-25 percent relative humidity appears to be just as effective in reducing fatigue life as air of 90-95 percent humidity. This would indicate that humidity is not a variable responsible for scatter in fatigue tests, as most normal laboratory atmospheres have a relative humidity somewhere in mid-range, say 40 to 60 percent.

(4) Humidity appears to have an effect on fatigue life only during the crack initiation stage of the process. Further testing at lower stress levels, however, may show that the propagation stage is also affected.

(5) It is recommended that this work be extended in an attempt to clarify the present results. Any further work should include an attempt to procure air of a known purity and the use of different materials, especially harder steels. Confirmation of the result that the humidity effect is the same for a range of relative humidities of 20-95 percent would greatly lessen the importance of this work as most fatigue tests and applications take place in a mid-range of humidity levels.

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VII. APPENDICES

Appendix A. Fatigue Data for Series A

Nominal Stress (psi)	Relative Humidity Level	Cycles to Failure
23,300	0-5%	254,000
23,300	0-5%	212,000
23,300	0-5%	143,000
23,300	0-5%	188,000
23,300	0-5%	358,000
23,300	90-95%	185,000
23,300	90-95%	217,000
23,300	90-95%	334,000
23,300	90-95%	307,500
23,300	90-95%	135,000
18,400	0-5%	510,000
18,400	0-5%	681,000
18,400	0-5%	1,328,000
18,400	0-5%	1,070,000
18,400	0-5%	561,000
18,400	0-5%	1,281,000
18,400	90-95%	511,000
18,400	90-95%	478,000
18,400	90-95%	2,032,000
18,400	90-95%	1,652,000
18,400	90-95%	403,000
17,900	0-5%	883,000
17,900	0-5%	481,000
17,900	0-5%	1,614,000
17,900	0-5%	561,000
17,900	0-5%	1,735,000
17,900	0-5%	385,000
17,900	90-95%	1,490,000
17,900	90-95%	541,000
17,900	90-95%	994,000
17,900	90-95%	619,000
17,900	90-95%	1,233,500

Appendix B. Fatigue Data for Series B

Nominal Stress (psi)	Relative Humidity Level	Cycles to Failure
31,400	0-5%	1,100,000
31,400	0-5%	243,000
31,400	0-5%	640,000
31,400	0-5%	629,000
31,400	0-5%	460,000
31,400	0-5%	482,000
31,400	0-5%	488,000
31,400	20-25%	560,500
31,400	20-25%	852,000
31,400	20-25%	575,000
31,400	20-25%	669,000
31,400	20-25%	141,000*
31,400	20-25%	710,500
31,400	20-25%	468,000
31,400	90-95%	591,000
31,400	90-95%	921,000
31,400	90-95%	305,000
31,400	90-95%	568,000
31,400	90-95%	692,000
31,400	90-95%	216,000
31,400	90-95%	1,293,000
30,150	0-5%	1,716,000
30,150	0-5%	2,287,000
30,150	0-5%	861,000
30,150	0-5%	3,126,000
30,150	0-5%	796,500
30,150	0-5%	944,000
30,150	0-5%	1,360,000
30,150	20-25%	1,233,000
30,150	20-25%	1,150,000
30,150	20-25%	795,500
30,150	20-25%	1,030,000
30,150	20-25%	1,361,000

*Data point discarded for statistical purposes according to Chauvenet's criterion.

Appendix B. continued

Nominal Stress (psi)	Relative Humidity Level	Cycles to Failure
30,150	20-25%	950,000
30,150	20-25%	1,012,000
30,150	20-25%	515,000
30,150	90-95%	887,000
30,150	90-95%	905,000
30,150	90-95%	2,240,000
30,150	90-95%	1,088,000
30,150	90-95%	1,337,000
30,150	90-95%	1,052,000
30,150	90-95%	844,000
30,150	90-95%	1,332,000
28,950	20-25%	1,350,000
28,950	20-25%	849,000
28,950	20-25%	3,038,000
28,950	20-25%	2,254,000
28,950	20-25%	6,436,000
28,950	20-25%	1,842,000
28,950	20-25%	2,210,000
28,950	20-25%	1,878,000
28,950	90-95%	1,176,000
28,950	90-95%	3,496,500
28,950	90-95%	1,733,000
28,950	90-95%	1,650,000
28,950	90-95%	2,860,000
28,950	90-95%	1,795,000
28,950	90-95%	569,000*
28,950	90-95%	3,340,000

*Data point discarded for statistical purposes according to Chauvenet's criterion.

Appendix C. Statistical Analysis of Data

A statistical analysis of the data for Series A and Series B was conducted in a series of steps given as follows:

1. Series A was set up using five or six specimens for each combination of stress level and humidity level. Series B was set up using seven or eight specimens at each combination of humidity level and stress level. This was done in accordance with the recommendations of the American Society for Testing Materials (27), who recommend the use of no less than four specimens at each stress level for determining a portion of the S-N curve.
2. After testing, all fatigue data (i.e., the number of cycles to failure) was converted to logarithmic form. Conversion to logarithmic form presents the data at all stress levels with the same relative accuracy. Also, fatigue data is assumed to follow a normal distribution only in logarithmic form (28).
3. A straight line regression curve was fitted to each set of data by the method of least squares (29). The S-N curve, for most metals, plotted on semi-logarithmic coordinates is practically a straight line for stresses above the endurance limit (30).
4. Chauvenet's criterion (29) for rejection of data

points was applied. A data point may be rejected by this criterion if the possibility of occurence is less than $\frac{1}{2}$ n, where n is the number of data points.

5. A chi-square test (29) was applied to each set of data points. This test may be used to determine the probability that data points are normally distributed.
6. A correlation coefficient (31) was determined for each S-N curve. The correlation coefficient (r) is an indication of how well a curve fits the data points (r=1 for a perfect fit).
7. An analysis of variance (26) was made to determine the effect of humidity. An analysis of variance is used to determine the effect of given variable (humidity level in this case) on experimental data. First a hypothesis is made: there is no variable effect. An F-statistic is created by methods which depend on the type of experimental set-up. This F-statistic is then compared with tabulated values of F-statistics which correspond to certain significance levels. If the F-statistic calculated from experimental data is large compared to the tabulated value, the original hypothesis can be rejected and an alternative accepted, i.e., there is a variable effect.

Series A was a "factorial" type experiment, because two factors (humidity and stress) were varied randomly in different combinations. Series B was a "nested" type experiment, because the stress levels were nested within the humidity levels, i.e., the humidity levels were not randomized.

The results of the statistical analysis are given as follows:

Series A

Relative Humidity Level	Prob. that Data Follows Normal Distribution	Correlation Coefficient
0-5%	0.90-0.95	0.797
90-95%	0.50-0.75	0.790

Analysis of Variance to Determine Effect of Humidity:

F (det. from exp. data)	$F_{0.90}$ (corr. to 90% confidence level)	$F_{0.95}$ (corr. to 95% confidence level)
0.00040	2.91000	4.23000

Hypothesis Accepted: Humidity has no effect.

Appendix C. continued

Series B

Relative Humidity Level	Prob. that Data Follows Normal Distribution	Correlation Coefficient
20-25%	greater than 0.995	0.756
90-95%	greater than 0.995	0.824
0-5%	greater than 0.995	0.740

Analysis of Variance to Determine Effect of Humidity in Comparison of 20-25% Rel. Hum. and 90-95% Rel. Hum. Tests:

F (det. from exp. data)	$F_{0.90}$ (corr. to 90% confidence level)	$F_{0.95}$ (corr. to 95% confidence level)
0.00128	8.53000	18.50000

Hypothesis Accepted: Humidity has no effect.

Analysis of Variance to Determine Effect of Humidity in Comparison of 20-25% Rel. Hum. and 0-5% Rel. Hum. Tests:

F (det. from exp. data)	$F_{0.90}$ (corr. to 90% confidence level)	$F_{0.95}$ (corr. to 95% confidence level)
3.90187	2.93000	4.26000

Hypothesis Accepted: Humidity has significant effect at the 90% confidence level.

Appendix C. continued

pH readings

Analysis of Variance to Determine Difference in pH Value of Air Used in 20-25% Rel. Hum. Test and pH Value of Air Used in 90-95% Rel. Hum. Test:

F (det. from exp. data)	$F_{0.90}$ (corr. to 90% confidence level)	$F_{0.95}$ (corr. to 95% confidence level)
0.69	3.05	4.49

Hypothesis Accepted: There is no significant difference in pH values.

Analysis of Variance to Determine Difference in pH Value of Air Used in 20-25% Rel. Hum. Test and pH Value of Air Used in 0-5% Rel. Hum. Test:

F (det. from exp. data)	$F_{0.90}$ (corr. to 90% confidence level)	$F_{0.95}$ (corr. to 95% confidence level)
4.00	3.05	4.49

Hypothesis Accepted: There is a significant difference in pH values at the 90% confidence level.

Appendix D. List of Equipment

1. Sonntag Universal Fatigue Testing Machine
   Model No. SF-01-U, Serial No. 040-2112-1
   Sonntag Scientific Corp., Greenwich, Conn.

   Use: To provide reversed torsion of test pieces.

2. Van-Air Filter
   Model No. F5
   Van Products Co., Erie, Pa.

   Use: To filter air supply.

3. Lehigh Chiller
   Model No. AM 42F FY 12
   Lehigh Manufacturing Co., Lancaster, Pa.

   Use: To chill circulating water in humidity apparatus.

4. Bell and Gosset Centrifugal Pump
   Model No. P7-4
   Bell and Gosset, Inc., Morton Grove, Ill.

   Use: To circulate water in humidity apparatus.

5. Evaporator Pressure Regulating Valve
   Model No. ORIT-6
   Sporlan Valve Co., St. Louis, Mo.

   Use: Temperature control of chiller evaporator.

6. Expansion Valve
   Model No. 204C
   Controls Co. of America, Milwaukee, Wisc.

   Use: Temperature control of chiller evaporator.

7. Thermostat
   Model No. T42K
   Honeywell, Minneapolis, Minn.

   Use: To control room temperature.

8. Heating Element
   Model No. D-230-U
   Electro-Therm, Inc., Laurel, Md.

   Use: To heat circulating water in humidity apparatus.

9. Ultrasonic Cleaner
   Model No. G-40CIP-12, Serial No. 15900
   Ultrasonic Industries, Inc., Plainview, N. J.

   Use: To clean test pieces.

10. Electric Hygrometer Indicator
    Model No. 4-5170, Serial No. 20877-879
    Hygrodynamics, Inc., Silver Spring, Md.

    Use: To measure relative humidity of test air.

11. Chart Recorder
    Model No. 91, Serial No. 497
    Rustrak Inst. Co., Inc., Manchester, N. H.

    Use: To monitor hygrometer reading.

12. Rotameter
    Model No. FP-1/4-20-G-5/81
    Fisher and Porter Co., Hatboro, Pa.

    Use: To measure flow of test air.

13. Fisher Research pH Meter
    Model No. 320
    Fisher Scientific Co., Pittsburg, Pa.

    Use: To measure pH value of test air solution.

EFFECT OF RELATIVE HUMIDITY ON THE FATIGUE CHARACTERISTICS OF MILD STEEL IN REVERSED TORSION

by

James K. Odle

(ABSTRACT)

Reversed torsion fatigue tests were conducted on both notched and unnotched specimens of SAE 1018 steel. The tests were made on a Sonntag Universal Fatigue Testing Machine at the rate of 1800 stress cycles per minute. The notched specimens were fatigued in air of zero-five percent relative humidity and in air of 90-95 percent relative humidity. The unnotched specimens were tested in air at three relative humidity levels: 0-5 percent, 20-25 percent, and 90-95 percent.

High humidity had a detrimental effect only on the fatigue life of the unnotched specimens indicating that the humidity effect is confined to the crack initiation stage of the fatigue process. The tests conducted in air of 20-25 percent relative humidity indicated that the effect of 20-25 percent humidity is just as great as the effect of 90-95 percent humidity.