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DISTRIBUTION OF FAILURE TIMES IN STRESS CORROSION TESTS

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ABSTRACT

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The results of stress corrosion tests on aluminum alloys have been analyzed with respect to the statistical nature of the distribution of failure times. The analyses indicated that the data were represented adequately by a three-parameter Weibull distribution in which the induction period amounted to 85 percent of the time of the first observed failure and 55 percent of the time required for failure of half the specimens.

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DISTRIBUTION OF FAILURE TIMES IN STRESS CORROSION TESTS

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SUMMARY

Results of stress corrosion tests on aluminum alloys have been analyzed with respect to the statistical nature of the distribution of failure times. The analyses indicated that the data were represented adequately by a three-parameter Weibull distribution in which the induction period amounted to 85 percent of the time of the first observed failure and 55 percent of the time required for failure of half the specimens. The results were consistent with a mechanism whereby each specimen in the group was attacked continuously and simultaneously in such a manner that, after the induction period was over, the probability of failure of the remaining specimens increased progressively with time. No evidence for retardation of the process by depletion of reactive sites or accumulation of corrosive products was noted.

INTRODUCTION

The advent of larger and more sophisticated launch vehicles has necessitated the use of materials having high strength-to-weight ratios. This is particularly true with aluminum alloys which comprise approximately 80 percent of the dry weight of the Saturn V vehicles. Unfortunately, those alloys which afford maximum strength-to-weight ratios are generally susceptible to stress corrosion, which severely restricts their application.

Although many investigators have studied the effects of stress level, alloy composition, type of corrosive environment, and other variables on the failure times for such alloys, few systematic investigations have been reported in which large numbers of replicate specimens have been subjected to carefully controlled environments. Consequently, most studies have permitted engineering estimates of the useful life of certain alloys under various environmental conditions but have provided relatively little information regarding the mechanisms of stress corrosion processes.

Accordingly, this division has initiated a comprehensive in-house and contract research program which is intended to elucidate the mechanism of stress corrosion processes, to develop nondestructive test methods for detecting stress corrosion prior to actual failure of a component, and to develop alloys having maximum strength-to-weight ratios which are relatively resistant to stress corrosion.

Previous reports (ref. 1 and 2) have presented the results of screening tests to determine the relative susceptibility of several engineering alloys; this report discusses the statistical distribution of failure times of individual alloys, with particular emphasis on the interpretation of the results with regard to physical mechanisms which may be involved in stress corrosion processes.

DISCUSSION AND CONCLUSIONS

A survey of recent literature yielded little information which could be used to study the distribution of failure times for any given alloy/environment combination. Although many investigations of the effects of environmental factors have been reported, usually only a relatively small number of specimens (from two to five) have been tested in each environment. Also, some form of averaging usually is applied to the data, and the individual results are not reported. Finally, in many instances, it is evident that the samples are inspected only intermittently and that the time intervals between inspections are long enough to influence the results of any analysis of the type of distribution.

For this investigation, data were needed for relatively large groups of specimens subjected to a carefully controlled environment. Moreover, it was essential that a recording technique such as time lapse photography be used to provide substantially continuous inspection or that an alloy/environment combination be selected that would provide short failure times so that continuous visual inspection would be feasible.

Booth and Tucker (ref. 3) recently presented results of electrochemical stress corrosion tests on two large sets of 5056-H14 aluminum alloy specimens that were tested in an environment in which the failure times were relatively short. One set was tested by an intensiostatic method using a current density of 40 mA/in^2; the other set was tested by a potentiostatic method and used a potential of 0.34 volt relative to a saturated calomel electrode. In both methods, the specimens were subjected to a constant stress of 75 percent of the 0.1 percent yield stress. The number of specimens tested was 124 in the potentiostatic test and 77 in the intensiostatic test.

Booth and Tucker's analysis indicated that a log-normal distribution could be used to represent the data; however, it was emphasized that this finding was empirical and that no physical mechanism was associated with the selection of this particular type of distribution.

To consider various physical mechanisms which could influence the rate of stress corrosion processes, the data have been replotted on semilogarithmic coordinates in FIG 1. This method of plotting was selected because the slope of the curve at any time is related to the probability of failure of the individual specimens remaining unbroken. To facilitate interpretation of the data shown in FIG 1, several mathematical functions corresponding to well-defined physical mechanisms have been plotted in FIG 2 for comparison. These mechanisms are as follows:

Curve No. 1. - This curve is a straight line and is indicative of expected behavior when the individual specimens of the set are identical in all respects, when there is no lag between the start of the test and the beginning of the process, and when there is no progressive change in the character of the remaining unfailed specimens or test conditions with increasing time. A typical example of this type process would be represented if an individual tossed a group of coins, discarded all coins showing heads as failures, retossed the remaining coins, and so on. Obviously, the individual coins would be identical; the process would start immediately; and the test conditions and coins remaining after any given number of tosses would be unchanged from their original state; i.e, the probability of obtaining a head on any given try would continue to be 50 percent.

Curve No. 2. - For this curve, the numerical value of the slope decreases progressively with time. Such a curve is characteristic of a process in which the individuals in the original set differ in that some have a much greater probability of failure than others. Therefore, the decreasing slope is indicative of a process of natural selection whereby the least resistant specimens tend to fail first. Such a curve also could result from continuous decrease in rate because of changes in test conditions resulting from gradual depletion of reactants or reactive sites, accumulation of reactions products, or other factors.

Curve No. 3. - For this curve, the numerical value of the slope increases progressively with time. Such a curve is characteristic of a process in which the character of the individual specimens or the test conditions change progressively; thus, the probability of failure increases continuously. This is indicative of a process in which some form of deterioration attacks simultaneously and progressively every individual in the set.

Curve No. 4. - This curve is a composite of Curves No. 2 and No. 3. Therefore, it is indicative of a process in which the initial rate of failure is dominated by the progressive increase in the rate of the deterioration process. However, failure rates for extended exposure are dominated either by differences in the resistance of the individual specimens or by a gradual decrease in the rate of the deterioration process because of changing test conditions.

Curve No. 5. - This curve is similar to Curve No. 3 except that it indicates a delay time or induction period before failures occur. Curves indicating delay times similar to Curves 1, 2, and 4 also could be drawn.

A visual comparison of FIG 1 and FIG 2 permits the following inferences concerning the mechanism of the particular stress corrosion processes represented by the data in FIG 1:

1. The rate of the deterioration process resulting in failure is extremely slow at first but increases progressively with time.

2. Each individual in the set of specimens is attacked simultaneously with deterioration continuing gradually until failure occurs.

3. There is a notable lack of evidence for marked differences between individual specimens or for eventual retardation of the deterioration process because of accumulation of corrosion products, depletion of reactive sites, or other factors.

In view of the dominating influence of the continuously increasing probability of failure on the overall behavior pattern, the data in FIG 1 were analyzed further with respect to this variable. As indicated previously, the probability of failure at any given time is related to the slope of the line. Inspection of the plotted data indicates that this slope is equal to zero over the interval, t equal zero to t equal t_o, and increases numerically thereafter. This corresponds to a three-parameter Weibull distribution of the type commonly used to represent failure data.

$$\ln F = \frac{(t - t_o)^b}{a}$$

where:

F	=	fraction of specimens remaining unbroken at time t
t	=	time
t_o	=	a delay time or induction period before which failures do not occur
a, b	=	constants

By a combination iteration and least squares technique, equations of this type were obtained for the two sets of data as follows:

$$\ln F = -3.798 \times 10^{-5}(t - 56)^{2.545} \qquad \text{(equation 1)}$$

$$\ln F = -1.168 \times 10^{-5}(t - 43)^{3.035} \qquad \text{(equation 2)}$$

Figure 1 includes plots of these equations which are in excellent agreement with the data; the scatter of the individual points correspond to a standard error of about 2.5 percent for both sets.

The values for t_o in both equations correspond to approximately 85 percent of the time at which the first failure was actually observed and to approximately 55 percent of the time required for failure of half of the specimens. The values, 3.035 and 2.545, for the exponents in the two equations are of a magnitude frequently determined by previous investigators for processes in which failure resulted from a chemical change in the specimen.

It should be emphasized that the data in FIG 1 were obtained under conditions of constant stress. Efforts to locate equivalent sets of data for failure of specimens subjected to constant strain have not been successful; most data consist of results for rather small numbers of specimens inspected at long intervals of time. Plots of results for several sets of five specimens each (ref. 4) are shown in FIG 3. Although, as expected for such small sets, the data tend to scatter appreciably, the overall behavior pattern is entirely similar to that noted for the constant stress test results which are shown in FIG 1.

Some investigators (ref. 5) have suggested that the driving force resulting in specimen failure is the ratio of applied stress to the effective cross sectional area of the specimen. Under conditions of constant stress, this ratio would be expected to increase with time as a result of deterioration and subsequent decrease in the effective cross sectional area of the specimen. Under conditions of constant strain, this ratio could decrease because of stress relief which would result from formation of minute cracks at the stressed surface.

The similarity of the overall behavior patterns indicated in FIG 1 and FIG 3 suggests that this stress relief during the test period was not an important variable for these data and that the progressive reduction in the effective cross sectional area dominated the failure rate pattern for both types of tests. It should be noted that at the very beginning of the exposure period there may be no difference in the two types of test methods, depending on the particular test configurations used.

Confirmation of these findings by testing large groups of replicate specimens under constant stress and strain conditions for which the test configurations are similar is needed. Also, studies of the influence of stress level and alloy type on the statistical nature of the failure time distribution would be of much interest. To define the most suitable index of stress corrosion susceptibility, a study of the ratios between the values for the delay time, the time of the first observed failure, and the time for half of the specimens to fail for results obtained under accelerated test conditions and under conditions of actual exposure at various geographic locations would be most helpful.

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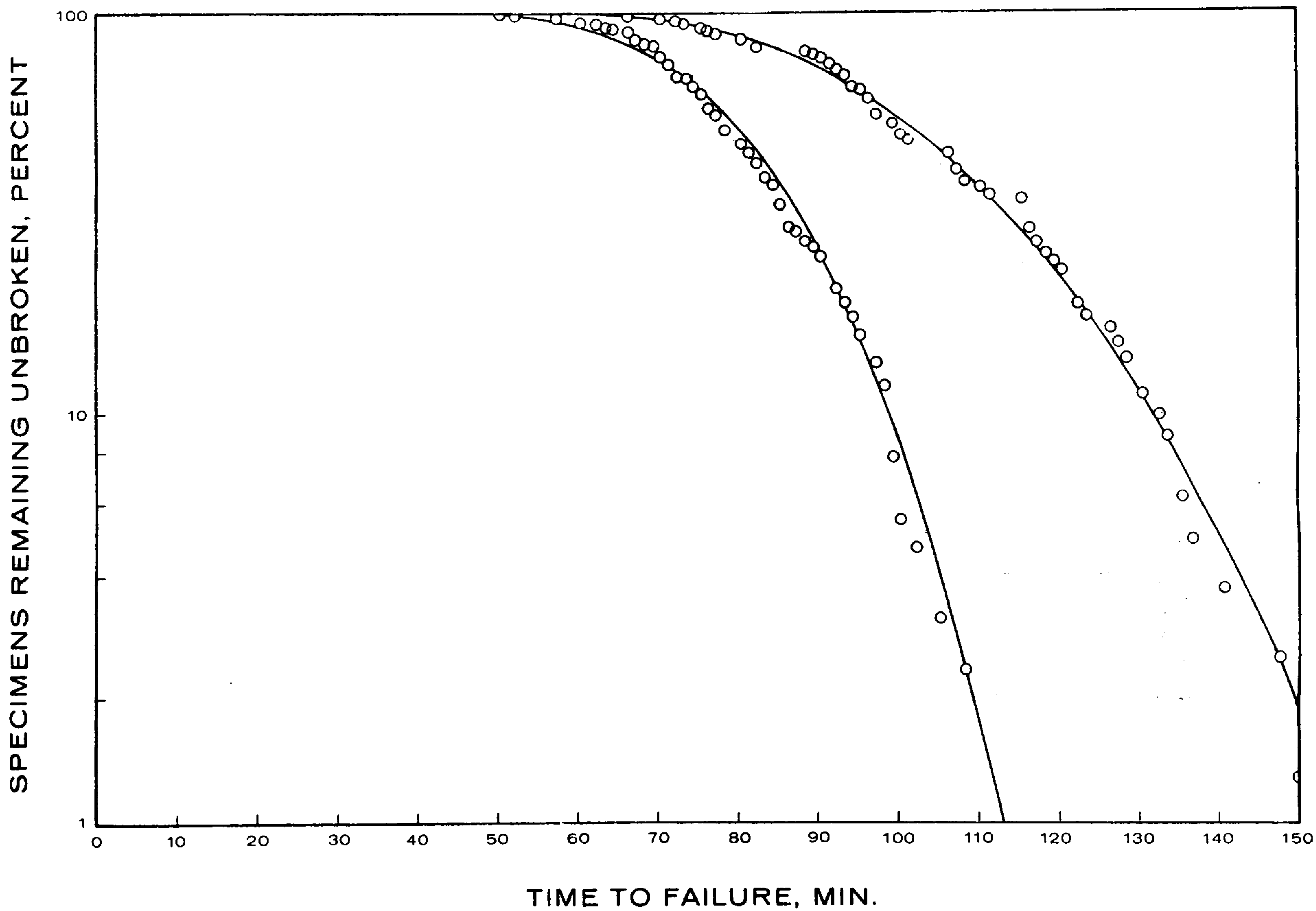

FIGURE 1. - DISTRIBUTION OF FAILURE TIMES FOR SAMPLES SUBJECTED TO CONSTANT STRESS

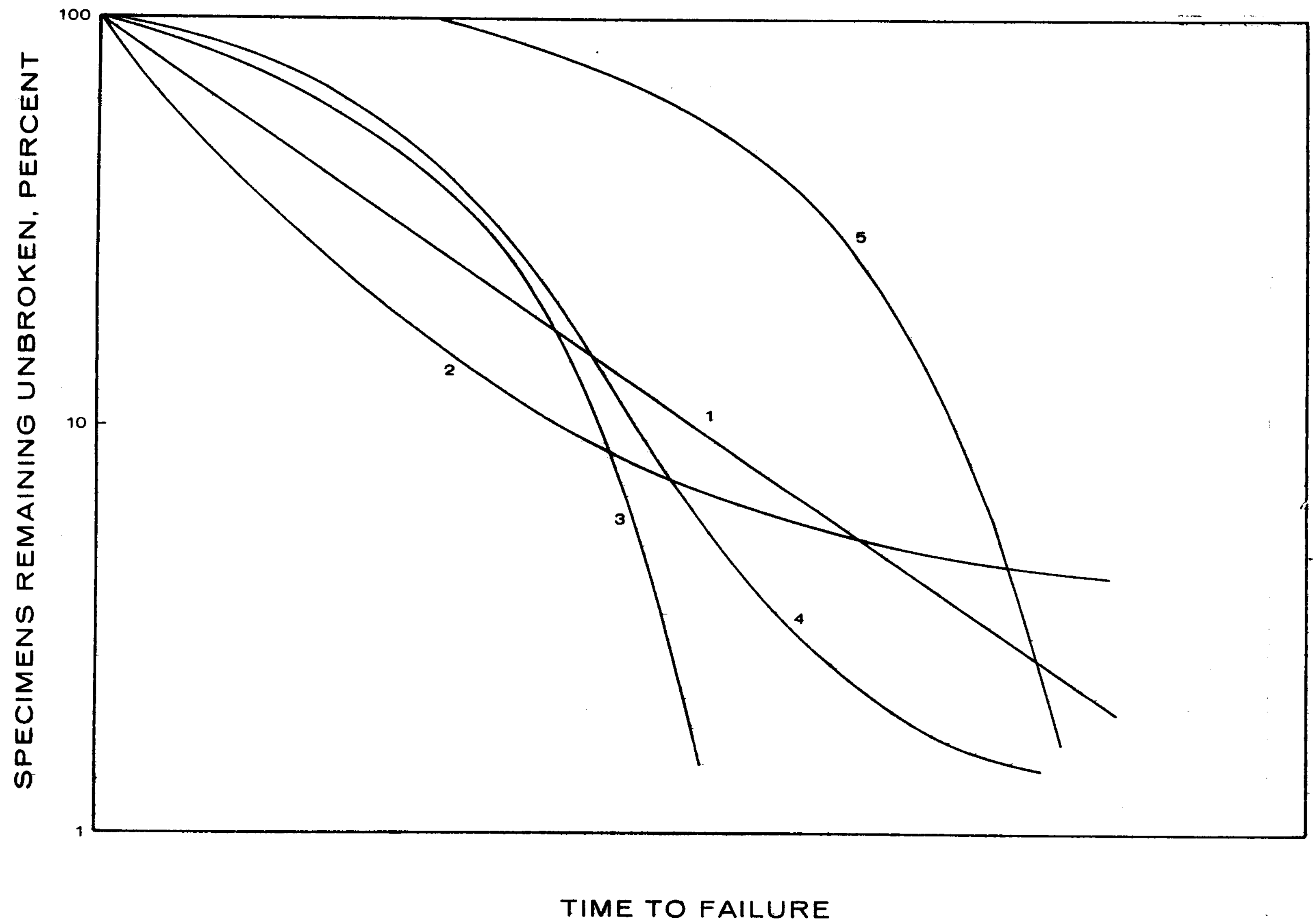

FIGURE 2. - TYPICAL DISTRIBUTION PATTERNS

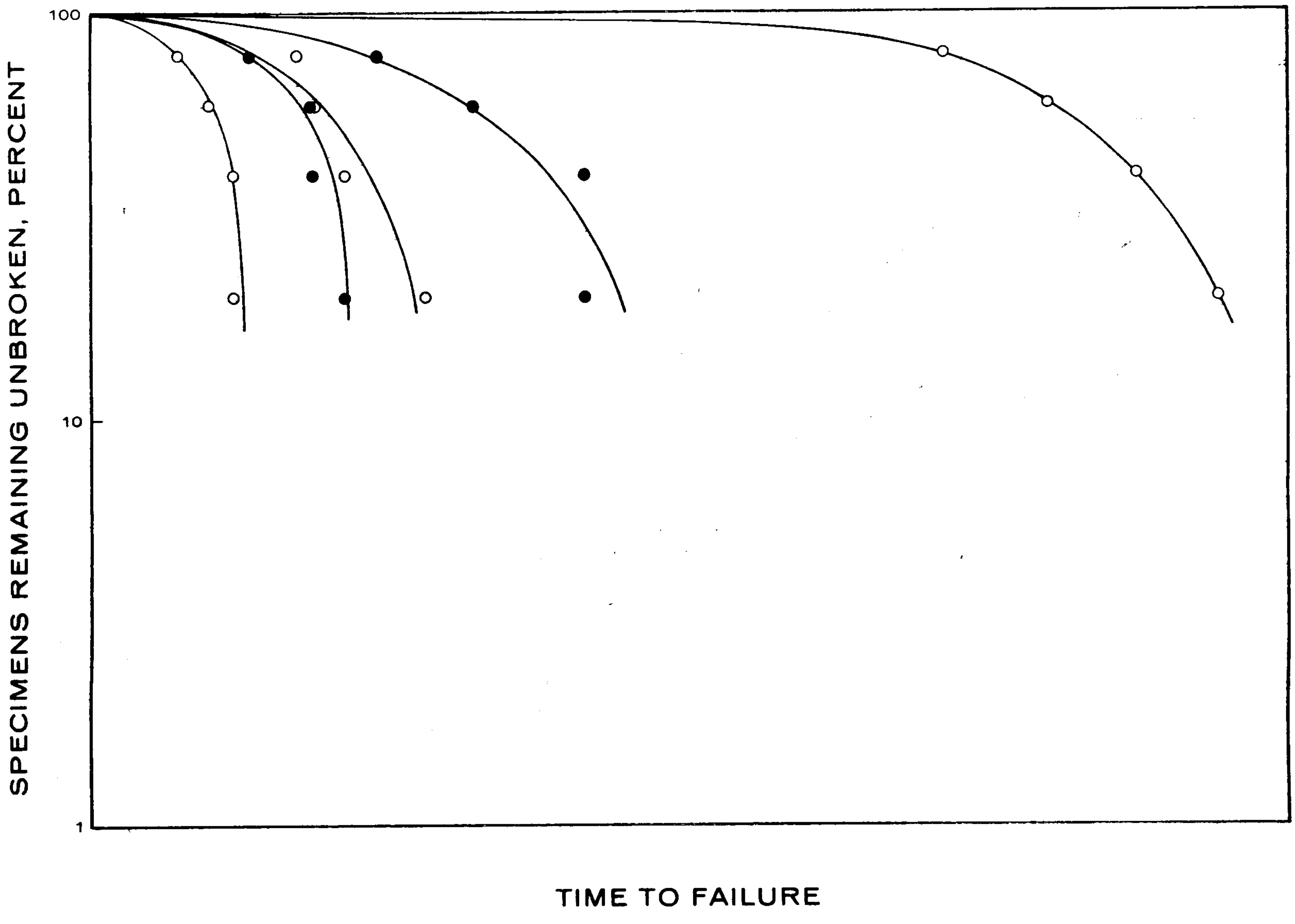

FIGURE 3. - DISTRIBUTION OF FAILURE TIMES FOR SAMPLES SUBJECTED TO CONSTANT STRAIN

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