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EXPERIMENTATION, ANALYSIS AND PREDICTION FOR ENVIRONMENTAL CREEP

C. J. Giemza

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FOREWORD

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This is a final report summarizing the results of work performed from May 1959 to November 1960.

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ABSTRACT

An examination was made of the environmental creep behavior of bare 7075-T6 aluminum alloy sheet with the aim of developing an experimental approach as well as relations for characterizing a material's response to an arbitrary stress-temperature-time environment following a prior history during which a metallurgical change has occurred.

A technique called Random Balance (Ref. 2), partly modified to a multiple balance design, was employed to select from several million possible environment test combinations a representative group. The general employment of associated techniques for analysis, common to the statistical field, was precluded because of the creep scatter which was attributed to inhomogeneity in the aluminum sheet.

It was found that a loss of strength in the order of 5% caused by overaging could result in an increase of total creep strain of several hundred percent in subsequent cycles. However, it was also observed that a recovery mechanism, following overaging, could restore a significant degree of resistance to creep.

In every instance, it was found that a transient stage of creep was manifested in each cycle upon reapplication of load. The magnitude of transient creep strain, as well as duration of the transient stage after the initial cycle, diminished as the number of cycles increased for combinations of high stress and high temperature or low stress and low temperature. At test conditions which could be identified with a service environment, the transient creep stage comprised a relatively large fraction of the total creep strain generated during a given cycle.

A qualitative association of creep behavior of the specimens to their origin in the aluminum sheet revealed a pronounced inhomogeneity which could not be related to static tensile properties. Furthermore, small creep strain differences which specimens exhibited at moderate stresses were magnified during subsequent recycling as the magnitudes of stress and temperature increased; slight overaging further severely aggravated the initial disparities among the specimens.

Excellent reproducibility of an arbitrary test environment was possible when the repeat tests were made with specimens which were obtained from adjoining positions in the sheet. Accordingly, as the distances between specimens in the sheet increased, the differences in creep behavior became greater for identical tests, regardless of nominal identities of static properties.

A method was developed which made it possible to predict the environmental creep behavior for an arbitrary test condition during which overaging at 350° F took place and subsequently, when creep resistance was restored as the result of a recovery mechanism. The technique was based on the strain hardening rule compensated with empirically determined factors to account for creep damage and/or subsequent restoration of creep resistance.

During the examination of compatibility of mathematical forms for the representation of the creep phenomenon, an expression ($\epsilon_c = Kt^N$) provided a good fit in the primary creep region and a reasonably good approximation for part of the secondary stage of creep; an apparently unique correspondence between the values of K and N and the test variables, stress and temperature also was revealed.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

W. J. Trapp

W. J. TRAPP
Chief, Strength and Dynamics Branch
Metals and Ceramics Laboratory
Materials Central

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I. INTRODUCTION

In spite of significant contributions of individual investigators, which have provided a better understanding for creep behavior, a substantial disparity exists between this knowledge and the practical employment of creep for the design of advanced systems structures.

This unresolved situation will continue to exist until:

(1) The variability among materials, which governs creep behavior, is reduced to a level that will permit an explicit characterization of creep behavior for each class of metals.

(2) Experimental techniques are devised that will generate a body of creep data from which the precise creep behavior of a structural element can be reconstructed for an arbitrary stress-temperature profile.

(3) Nonlinear stress analysis is developed which can account for any change in the material's state.

If it becomes possible to employ creep for the design of elevated temperature structures, a considerable reduction of gross takeoff weight can be effected by the more efficient utilization of the structural material. For example: if the prevailing design practices are applied to elevated temperature design, then a limit design stress at a service temperature of 800° F for 17-7PH (F_{tu} = 160,000 psi at 800° F, Ref. 1) would be about 105,000 psi. However, in order to preserve an essentially elastic structural state (thereby avoiding creep) a stress limit of about 60,000 psi would be required (Ref. 1). The design margin for this illustration would have increased from about 0.5 to 1.66--which represents a significant increase of structural weight. This weight increase may be greatly magnified in terms of gross takeoff weight as required by a particular mission.

The purpose of this investigation has been to examine experimental means for characterizing the creep behavior of an aluminum alloy for a simple environment during which metallurgical changes would occur, and means for predicting the creep behavior of a specimen subjected to an arbitrary stress-temperature environment within the boundaries of stress, temperature, and time selected for the experiments.

The environment to which 7075-T6 aluminum alloy specimens were subjected was comprised of stress-temperature-time combinations in four cyclic sequences. The test variables were selected at levels of severity which would produce a small degree of metallurgical change and which may be associated with elevated temperature design.

Because several million possible combinations of the applied variables, stress-temperature-time, were possible, a statistical technique called Random Balance, developed by Satterthwaite (Ref. 2), was employed for the design of the environmental creep tests to effect an economy of tests. By this means, a statistical sample is created which makes it possible to describe the creep behavior of a specimen for any stress-temperature-time combination from the entire population of variables.

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The environmental creep data were examined with regard to factors which would be significant to design such as, transient creep, recovery, overaging and inhomogeneity. The importance of these factors was comparatively assessed with respect to an average virgin creep behavior.

A method for predicting the environmental creep behavior was developed and experimentally verified.

A mathematical relation, $\epsilon_c = Kt^N$, was examined with regard to its representation of transient creep and a portion of the second stage of creep. In addition, its possible use for characterizing environmental creep behavior, in general, by adjusting the parameters of the expression was studied. A unique relation of the values of this expression and stress and temperature was found.

The investigation was aimed toward the development of experimental and analytical approaches that would have significance for elevated temperature design when creep becomes important for complex stress-temperature-time environmental conditions.

II. EXPERIMENTAL PROCEDURE

A. MATERIAL

One 0.125-in. gage 7075-T6 bare aluminum alloy sheet was selected so as to minimize experimental difficulties associated with elevated temperature testing. Furthermore, because of its general popularity and availability, questions regarding various phenomena of interest could be explored readily. The detailed specification of heat-treatment, chemistry, processing and properties for this material are given on a typical basis in the Alcoa handbook; the average static tensile properties for the material used in this work from room temperature to 350° F are contained in this report.

B. TEST SPECIMENS

The aluminum sheet was divided into nine 16-in. x 32-in. sections (Fig. 1) and further subdivided into thirty-two 2-in. x 8-in. units (Fig. 2) for creep and tension test specimen blanks. In order to avoid the influence of anisotropy, as a test variable, the longitudinal direction of the specimens was arbitrarily specified to be coincident with the sheet rolling direction.

The sheet was assumed to possess an indeterminate degree of inhomogeneity developed as a consequence of unknown processing variables. In order to minimize the chance of selecting groups of specimens with extreme values of characteristics, specimen numbers--representing both identification and order of testing--were assigned in accordance with a table of random numbers. Random selection of specimens for testing was used: (1) to avoid the combination of groups of specimens possessing unusual qualities and a unique test situation, i.e., an error in test temperature or stress which may be sustained on the positive side for an extended period of operation, and (2) to provide an equal opportunity for all regions to experience the test environments which are to be examined. By this means, the chance occurrence of a large number of weak (or strong) specimens was minimized, and the detection of significant differences through the aluminum sheet would be possible.

The detailed specifications for both tension and environmental creep tests were identical (Fig. 3). A mill and drill fixture was employed to provide a close control of locations and tolerances (Fig. 4).

C. TEST EQUIPMENT AND PROCEDURE

The test equipment which was employed for this investigation incorporates certain features which were developed in our laboratories. A universal testing machine was employed for the environmental creep tests rather than the conventional creep testing machine since it provided better control of the stress (or strain) rate during initial loading and explicit identification of the zero time at which maximum load occurred.

A Marshall furnace (1)* equipped with a recirculating fan to minimize thermal gradients was employed for the environmental creep and elevated temperature tension tests. Infrared quartz heating elements were employed for the elevated temperature tensile tests for auxiliary heating. A cooling fan was employed during a required decrease of the environmental test temperature.

A PTE 5000-lb. capacity universal testing machine (2) was employed for the tension and environmental tests. For the environmental creep tests, the loads were cycled manually and maintained automatically with an integral load maintainer and load control. The strain rate during loading was maintained at 0.005 min^{-1} in the case of tension tests to failure, and in the case of environmental creep tests to the maximum test stress.

A holding time of 0.5 hours was maintained between sequences of the environmental tests to permit the stabilization of the test temperature. In addition, a positive increment of stress, approximately 400 psi, was maintained during the interval between test sequences.

The elastic, plastic and thermal strain differences between the platinum and aluminum given in Tables 2 and 3 were subtracted from the total strain value to obtain creep strain.

The automatic data recording system was comprised of a Samenco automatic timer (3); a K-100 Kodak 16-mm camera (4) shown in detail in Fig. 5; a Gaertner microscope (5), equipped with an NBS-calibrated scale and vernier; a massive steel pedestal (6) to minimize vibrations; a Leeds and Northrup temperature controller-recorder (7); camera solenoid (8); and a Brown potentiometer (9).

A platinum "Battelle-type" slide rule gage (10) with a 2-inch gage length was employed for strain measurement. An enlarged view of the gage, attached to the specimen, reveals the calibrated reference lines at 0.01-inch intervals. Gage clamps (11) were employed to attach the gages to the specimens. To avoid premature specimen failure because of a stress concentration, 0.005-inch aluminum shims were placed between the specimen and gage at the pressure point of the clamps.

Calibrated iron-constantan thermocouples (12) attached to the extremeties of the specimen gage section were used for temperature measurement. A third thermocouple located at the center of the specimen provided the output for temperature control.

Load forks approximately 18 inches long and ball seat joints (13) were employed to minimize possible bending stresses.

The strain measuring system had an overall sensitivity of 0.00001 inch and an accuracy of 0.0001 inch as determined by comparison to an Mziz Gaertner calibration scale for micrometer microscopes (NBS certified). The accuracy of strain determination after reduction in a Benson-Lehner photoanalyzer is not less than 0.0002 inch. The specified test loads were maintained by the PTE load maintainer within ±2.5 pounds. The temperature variation over the specimen gage length was held to less than 2° F. An enlarged view of one frame of the film showing the slide-rule gage and reference marks for strain measurement is pictured in Fig. 9.

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*Numbers in parentheses identify the items in Figs. 6, 7 and 8.

D. DESIGN OF THE EXPERIMENT

Because of the large number of experimental variables comprised of four levels each of stress, temperature and time, as well as four sequences of various stress-temperature-time combinations, the statistical techniques (multiple and Random Balance) were used. By this means, it made possible the representation of a large number of tests, comprised of all possible combinations of the test variables, with a few randomly selected combinations.

This approach, based on sampling theory and its ability to accurately interpolate within the domain represented by the sample, depends upon the homogeneity of the sample. In the practical assessment of the data, curves would be constructed, as illustrated in the Appendix, which are piece-wise continuous. These curves would relate cause and effect. However, the scatter of data originating from experimental error and material inhomogeneity may exceed the magnitude of an environmental effect.

Based on the probability consideration, $\sigma_{\bar{x}} = \dfrac{\sigma_x,}{\sqrt{N}}$

where $\sigma_{\bar{x}}$ is the standard deviation of the averages of observations

σ_x is the standard deviation of the individual observations

N is the number of observations

30 tests will provide a sample which will give a preliminary but adequate representation of a domain (Refs. 2 through 6). The measure of precision is related to the value of $\sqrt{N}$. For example: increasing the number of observations from 10 to 100 increases the precision, based on $\sqrt{N}$, from 3.16 to 10 or approximately 300%. However, if the number of observations is increased from 100 to 200 (value of $\sqrt{N}$ 10 and 14.1), the improvement is 40%.

Multiple balance was employed for the first sequence of four. A factorial matrix related the stress-temperature-time environment for all possible combinations. From this exact balance matrix, which has 64 possible combinations (4 stresses* x 4 temperatures x 4 times), 32 combinations (indicated by an X in Fig. 10) were selected.

The 32 stress-temperature-time combinations were then assigned to the test specimens in accordance with a table of random numbers. For example: six was the first number which occurred and the stress-temperature-time combination number six was assigned to test No. 1 of Sequence I (Table 1). Twenty-nine occurred next, and specimen No. 29 was assigned to test No. 2.

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*Although 16 different stresses are represented by the four percentages, the choice of stress on the basis of percent of yield strength was done for convenience and to assure compatible combinations of stress-temperature-time.

The 32 test conditions obtained from the half-factorial matrix were similarily assigned a test order for Sequences II, III, and IV. A necessary condition for using random number tables is that the selection of numbers must be continuous, i.e., if the 32 numbers were selected for four sequences from the beginning of the table for each set of 32, an indeterminate repetitious effect may be established which may confound the experiment.

In cases where the repetition of a factor or combinations might produce early failure, i.e., in the first sequence, arbitrary changes were effected to yield an adequate exposure environment and, thereby, to produce meaningful results.

Referring to Table 1, the behavior of the virgin specimens in Sequence I is within limits predictable from experience. However, after Sequence I has been accomplished, the character and response of each specimen are unique. Presuming that a mathematical analog exists which can represent the behavior of the material in a general way at any point in the environmental test, then it may be possible to relate the effect of prior history to a subsequent behavior with a suitable influence function. In contrast to the experimental approach of this program, a complete test, one in which every possible combination of the variables and sequences would appear, would require 64^4 (approximately 16,000,000) environmental tests. The material's environmental creep behavior may be analyzed completely with a lesser number of tests, but even 10% of this figure would still present a formidable quantity.

Some 70 additional environmental tests were conducted which were comprised of the untested combinations of the factorial matrix (Fig. 10), intermittent load tests, repeat tests and experimental verification of predicted creep behavior.

III. RESULTS AND DISCUSSION

A. STATIC PROPERTIES--ROOM AND ELEVATED TEMPERATURES

Static properties are employed as a reference for obtaining design values and, in most experimental studies, to identify the initial character of the material. Generally, the only property which exhibits some degree of quantitative consistency is the modulus of elasticity. However, there is often a considerable difference, even for this property, among the values reported from various sources. With respect to the utilization of static properties in design, it was stated earlier that a factor of safety accounted for the indeterminate design conditions. Similarly, in addition to the factor of safety, materials are supplied on the basis of some minimum value. As a matter of interest, strength values for bare 7075-T6 aluminum alloy sheet, determined previously in our laboratory, were compared to the values obtained in this study and to the ANC-5 values. These data are summarized in Table 4. There is a difference of approximately 12,000 psi between the maximum and minimum values for both yield and ultimate strengths. This large variation in commercially available material is believed to be one of the main reasons that solution of the creep design problem has not progressed beyond the preliminary stages.

A significant variation of strength values, shown in Table 5, existed within the aluminum sheet employed for this program. The difference of strength values for these cases, for both yield and ultimate, was about 3500 psi--which is about 4%. This difference of strength values throughout the sheet diminished as the test temperature increased. It will be shown later that low strength regions (insignificant compared to the average), and possibly other factors, can influence the creep behavior of a material substantially, particularly in the ability to reproduce an event.

Subsequent to the environmental tests, tensile tests from R.T. to 350° F were performed. The static property data for R.T. and for 200 to 350° F are summarized in Tables 6 and 7. The temperatures and time of exposure at each temperature are listed without reference to order of application at temperatures of the environmental tests. A general trend to overaging was observed, i.e., the loss in strength increased with increased test temperature and holding time. However, for an arbitrary specimen, a precise relation between loss of strength--based on an initial strength of a region from which the specimen was taken--and the prior history was not evident for the small amount of overaging which occurred.

Averaged values of the tensile data, obtained before and after the environmental creep tests, are plotted against the test temperature in Fig. 11. Although the histories of the previously tested specimens varied considerably, their average values varied uniformly with test temperature.

The yield and ultimate strength values of the control test specimens, without prior history, declined and converged gradually as the test temperature increased. However, although the specimens sustained a loss of strength at low and high test temperatures, there was no loss and even a slight gain in yield strength at 250° F.

As the test temperature increased, there was a nearly constant positive difference of modulus of elasticity for the specimens with prior history and a corresponding negative difference of the elongation, compared to the values for the virgin material. Although the modulus of elasticity is considered an invariant property, at a given temperature, for a metal, the increase observed is a real change of the straight-line portion of the load-elongation curve and has an engineering significance. The divergence of elongation values at 350°F (Fig. 11) for the two test conditions appears to be related to the relatively large scatter of this property at 350°F.

The data can be related to their source in the aluminum sheet with respect to the location of individual specimens by referring to Table 8 and Figs. 1, 2 and 13.

B. TEST REPRODUCIBILITY AND MATERIAL INHOMOGENEITY

Generally, the scatter of values which was obtained in generating material property data is expected and accepted. As a rule, the data are reduced to averages of the various properties for the general representation of a material; thus, it is always necessary to redetermine the static properties if an explicit inference is to be drawn when comparing experimental results to the static properties.

Material design properties usually represent some average or confidence limit related to a large number of tests. In the case of static properties, a possible disparity between the representative design values and the true character of a structural element, if unconservative, is obscured by a factor of safety. If creep is to be incorporated, in a precise way, for the design of structures, the instantaneous state of the material must be known throughout its life.

In this investigation, reliance was placed on the correlation of creep behavior with yield strength, because no other parameter for assessing creep behavior, prior to the fact, was available. The total variation of 0.2% offset yield strength was approximately 2% as determined by a tensile test. Because the test stresses which were employed were appreciably below the yield strength, it was first suspected that the scatter of the data was the result of experimental error. When the first group of repeat tests was completed, a plot of the resultant pairs of curves revealed an unexpected coincidence (Figs. 12A through 12D). In fact, the plots of the environmental creep data for one pair of identical tests produced a single curve (Fig. 12A). However, during the course of conducting the environmental tests, significant differences were noted for identical stress-temperature test conditions in Sequence I. Therefore, it was deemed necessary to re-examine the experimental technique by conducting additional repeat tests. After a second group of repeat tests was conducted, a plot of the pairs of curves revealed rather large differences in creep behavior. Although the reproducibility of two of the tests (shown in Figs. 12E and 12F) was quite good for one or two cycles, relatively large differences in total creep strain (and strain rate) occurred in subsequent cycles. These differences ranged from 20 to over 100% based on the value of the lower value of total creep strain of the pairs of specimens. In view of the aims of this investigation, these large differences in creep behavior would make the task of relating the effect of small changes in the material (as the result of prior history) to changes in creep behavior very difficult if not impossible.

The reasons were not apparent for the exceptional agreement of repeat tests conducted during the early phases of the program, and the disappointing results of the subsequent repeat tests, particularly after the experimental routine had become well established. It was tentatively accepted that some unknown factor, which was originating either from within the equipment or within the technique, was responsible.

After the accumulation of data had approached the concluding experimental phases, the creep data from Sequence I were reduced to average values by employing the Larsen-Miller parameter (Refs. 7 and 8). Having established the reference average, the strain hardening rule was employed--with regard to its inapplicability to cases where overaging occurred--to determine the differences which existed between the individual creep curves and their average value.

The creep behavior of each specimen was related to its original location in the aluminum sheet. A color coding was originally employed in Progress Report No. 7 for this investigation, to emphasize possible patterns--red for creep behavior higher than average, green for less than average, and black, for average creep behavior. (In this report, dotted marking was employed to signify creep which is higher than average, horizontal hatch marking represents creep which is lower than average, and average creep behavior is identified by a vertical hatch marking.) This matching of creep behavior to an average was done for the tests or initial portions of tests which were not considered to be affected by metallurgical change.

The specimen test identification number and a number corresponding to its original location in the aluminum sheet are given in Table 8. The coded profile representing the qualitative creep behavior of the test specimens relative to their average is shown in Fig. 13. The yield strength determined for each panel section is indicated.

An examination of the qualitative creep behavior of the specimens referred to their origin in the sheet (Fig.13), revealed a concentration of specimens which exhibited higher than average creep in and near panels 2 and 3. Although the nominal yield strength values in panels 5, 6 and 9 were equal to or less than that for panel 2, the specimens in the former exhibited a higher resistance to creep. From this graphic representation of the general creep behavior, it was indicated that scatter of creep data occurred as the result of unique differences among the specimens and was attributable to the inhomogeneity which existed within the sheet. Furthermore, it was indicated that the static tensile properties were not a sensitive index for characterizing creep behavior.

In searching for an explanation for the deviations from expected creep behavior, the coding system provided a graphic representation of a clue to the cause for the data scatter. On re-examination of the repeat tests, it was found that when the specimens for the duplicate test conditions were obtained from adjacent positions in the sheet (such as 20 and R5)*, excellent reproducibility was possible. However, small physical separations in the sheet of duplicate test specimens (such as 1 and R2) produced significant differences in creep behavior. These differences increased for identical test conditions as the distances between specimens increased.

A reappraisal was made of the small differences between the average ** and a given creep curve. The total creep strain in Sequence I rarely exceeded 0.2% and the error, compared to the average, was often less than 0.02%. However, this

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* The R signifies a repeat test.

** The average creep curves were based on the Larsen-Miller method for resolving virgin creep data and the strain hardening rule.

error represented 10% of the total creep strain; since the creep data are obtained by graphic construction, interpretation and mechanical inaccuracies could conceal much of the actual disparity. The consequence of the small initial error, if on the high side, with a small degree of overaging, i.e., a 2 to 3% loss in strength will greatly increase the creep rate at a subsequent application of stress and temperature. In several instances, the creep strain difference between two similarly overaged specimens was in the order of 100% for the same test conditions.

Reproducibility of experiments requires homogeneity among the specimens and, in addition, that experimental system accuracy be reflected in the final reduction of the data. The photographic techniques which were employed in this investigation to record the strain-time values have satisfied the second condition. Several typical datum point sets have been included (Figs. 12G, 14C and 14D) to illustrate their close relation to the curve drawn through them. This degree of agreement was general. Significant relative scatter which did occur was at the very low stresses when the creep rate approached zero or when the slide rule gage slipped. Datum point sets typical of the three illustrations given above were obtained in over 80% of test runs.

As the result of this phase of the examination of the data, it was concluded that the factors which contributed to the scatter of data were primarily of metallurgical origin arising out of fabrication or subsequent processing. It was further reasoned that a partial solution toward minimizing the effect of inhomogeneity may be achieved through the redesign of the specimen, if it is not deemed practical to establish a source for a "standard" homogeneous material. An increase of the specimen size (i.e., to approximately 6 inches in width) would provide an inherent averaging characteristic for obtaining a quasi-homogeneous specimen if the distribution of regions of high creep would be substantially less concentrated than that obtained in this study.

C. INTERMITTENT STRESS EFFECTS ON CREEP BEHAVIOR

Previous investigation (Ref. 9) has shown that the influence of intermittent stress-temperature on creep was negligible providing metallurgical changes had not occurred.

The results of intermittent stress tests which were conducted in this program bear out this contention in a general way but reveal that after the reapplication of load, a primary stage of creep is evidenced (Fig. 14). In some cases, depending on the stress-temperature combination, the constant load creep curve meets the interrupted creep curve near the end of each cycle. The differences which are indicated may prove sufficiently significant to be accounted for in creep stress analysis.

There appears to be an influence, related to recovery and aging, affecting the magnitude of the transient creep behavior which depends on time at rest between cycles. Figures 16A and 16B illustrate a constant load, an interrupted load (with 0.5-hour no-load rest intervals), an interrupted load (with 5-minute no-load rest intervals), and creep curves for the same stress-temperature conditions. The 0.5-hour rest interval appears to have permitted more strain recovery than did the 5-minute rest interval and a consequent increase of the magnitude and duration of transient creep. The effect of resting between cycles of load on transient creep is still noticeable at high stress and high temperature, but the transient creep stage has diminished considerably (Fig. 14C).

When the stress is in the order of 75% of 0.2 offset yield strength for a high temperature condition (300 to 350°F) or in the order of 80 to 85% of the yield strength at low temperatures (200 to 250°F), the magnitude of the primary stage of creep is a large fraction of the total creep (Figs. 14E and 16F). The creep strain difference between the transient creep, occurring after reapplication of load, and the envelope formed by the constant load creep curve is greater initially for higher temperatures with low stress and for lower temperatures at high stress.

A comparison of the cases of intermittent load creep in Figs. 14A through E indicates that the primary creep stage:

(1) Increases with increased rest time between cycles.

(2) Decreases for high temperature-high load or low temperature-low load combinations.

(3) Decreases for succeeding cycles.

D. THE LARSEN-MILLER PARAMETER

The creep data which were obtained from Sequence I of the environmental tests (comprising about 100 tests) and from the results of several selected 5-hour constant load creep tests were reduced to an average representation by means of the Larsen-Miller parameter. The plot of stress against the Larsen-Miller parameter is shown in Fig. 15. The assurance that the Larsen-Miller relation represented an average behavior was established by comparing the values from the stress-Larsen-Miller plot to the original creep data. In this comparison, the creep curves were divided approximately equally--one-third above average, one-third average and one-third below average. The representation of creep data obtained in this program by the Larsen-Miller plot should not be considered to represent bare 7075-T6 aluminum alloy sheet material as a class.

E. STRAIN AND TIME HARDENING RULES FOR PREDICTING ENVIRONMENTAL CREEP BEHAVIOR

The principal limitation of the strain and time hardening rules for predicting creep behavior for cyclic loads is the inability to account for prior history effects during which metallurgical changes occur. Furthermore, the time hardening rule may become unstable under certain conditions. Their mathematical treatment is given in Ref. 10, and application is discussed in Refs. 7, 11 and 12.

Because interest has grown in the use of the creep rules, particularly the more reliable strain hardening rule, their relation with regard to fitting the environmental creep curves was examined.

Typical comparisons ranging from a good fit of the rule to the data are shown in Figs. 16A through D and those comparisons which show increasing disparity in the ability of the rules to match the experimental data are shown in Figs. 16E through I.

The common fault of the rules in all instances is illustrated in Fig. 16D. In Sequence II, transient creep begins at about 0.35% strain and the rules indicate 0.4% strain. This error of approximately 20% would be significant in stress analysis

The difference during the first sequence in creep strain between the rules and the curve in Fig. 16C would be expected to increase because the creep resistance of specimen No. 22 appears to be higher than average.

As the test condition became more severe and was coupled with overaging within the expected permissible strength loss in design (generally, the order of 3 hours at 350°F and possibly about 20 hours at 300°F would be considered moderate to the extent that strength losses would be about 10 percent of ultimate), the deviation between the average creep behavior represented by the creep rules and the experimental creep curve increased rapidly. The relative change in creep behavior for the same stress and temperature, resulting from lowered creep resistance brought about by metallurgical change, is shown by comparing Sequences I, II and IV of Figs. 16C, 16F and 16H, respectively. Even a more dramatic difference in creep behavior in which one specimen has been affected by prior history is shown by comparing Sequences I and IV of Figs 16E and 16I, respectively.

The strain and time hardening rules are unable to account for the transient creep which may occur on recycling and creep behavior following overaging. In the case of 7075-T6, significant overaging may occur in 50 hours at temperatures as low as 250°F. As the exposure temperature increases from 250°F, the time for significant creep behavior effects may decrease to 1 hour.

F. THE POWER LAW

From the designer's point of view, the mathematical expression $\epsilon_c = Kt^N$ which has been employed for the representation of creep (Refs. 1 and 13) is ideal in its simplicity. Furthermore, the log-log relation plots as a straight line; however, this expression is not reliable far beyond the primary stage, the limit for creep design.

Based on the encouraging results in its use in previous studies (Refs. 1 and 13), it was considered worthwhile to briefly examine the possibility of its application to this investigation.

Rather than plot the original data, the creep strain against time (log-log) of the average values obtained from the Larsen-Miller relation was plotted (Figs. 17 through 21). The values for 400°F are completely extrapolated, as are those curves beyond the limits of the test conditions which were employed.

As expected, the slopes of the creep curves (the exponent "N" of the relation $\epsilon_c = Kt^N$) were constant for a given test temperature. Values from selected creep curves, i.e., those which were of sufficient time duration and agreed with the established average value, are plotted to demonstrate that reasonable correspondence of the data to a straight line can be achieved.

In the next step of the examination of the power law, attention was given to the dependence of the "K" and "N" values on stress and temperature. It had been observed that "K" was dependent on temperature and stress while "N" depended on temperature alone (Refs. 1 and 13). A plot of "N" against temperature reveals that "N" increases uniformly at a decreasing rate with increasing temperature

(Fig. 22). In the plot of stress against log K (determined from Log ϵ_c = Log K + N Log t at t = 1 hour), the expected linearity existed; however, in addition, a surprisingly uniform change of log K occurred with a change of temperature or stress. The variation of log K was proportional to stress and temperature (Fig. 23). The displacement of the creep curves (Figs. 17 through 21) for the tested and untested conditions was established from these values obtained from Fig. 23 and, at least, a tentative agreement exists with respect to the selected experimental data.

As a matter of further interest, a plot of "N" for 7075-T6 against log temperature was made (Fig. 24) and compared to some preliminary values of "N" for 2024-T86. The resulting parallelism of the exponents for the two aluminum alloys, if valid, could prove very significant for characterizing the creep behavior of any aluminum base alloy. However, the manner in which the data were converted and the speculative nature of the values of 2024-T86 for "N" preclude the suggestion of conclusions of the general versatility of the power law.

One point should be reiterated--the representation of creep with the mathematical expression $\epsilon_c = Kt^N$ is not valid beyond the inflection point at which the creep rate reached a minimum value. An examination of the data reveals a general tendency for this inflection of the changing creep rate to occur at a constant value of strain for a given temperature. Furthermore, the point of inflection decreases from about 0.5% (creep strain) at 200°F to about 0.35% at 400° F.

Finally, it is suggested that if the reliability of the power expression is established, it would be applicable for the representation of creep for the practical range of strain values useful in structural design analysis.

G. THE PREDICTION OF ENVIRONMENTAL CREEP BEHAVIOR

Prior history effects involving metallurgical changes are not considered by the strain and time hardening creep rules. In particular, the existing creep rules for cyclic conditions do not account for three of the significant phenomena which may be significant for stress analysis. These are:

(1) The repeated occurrence of the primary stage of creep, during which a structural element would possess a greater load carrying capacity.

(2) The effects of aging mechanisms which may increase the load carrying capacity of a structural element.

(3) The marked decrease of creep resistance following moderate overaging.

Although the scatter, which is now related to the material inhomogeneity, obscured the influence of many undetermined factors on environmental creep behavior, it has been possible to show a clear relation between overaging and, subsequently, an undetermined phenomenon interpreted as aging (recuperative change), and the environmental creep behavior. A sufficient number of distributed test conditions and patterns, and specimen selection were examined to assure the presence of this characteristic.

The employment in this program of the strain hardening rule for predicting environmental creep involved the compensation of creep behavior for each sequence of the environment as required. In the graphic application of this compensated rule, the reconstruction of an environmental creep curve is based on a body of averaged creep data obtained from the experiments. Its application in accounting for prior history effects on creep behavior required a comparison of the difference in strain at a given time. This difference in creep strain could be adjusted by a change of temperature or change of stress (or perhaps both). Somewhat arbitrarily, the temperature was chosen as the factor to account for a deviation in creep behavior. For example: If a stress of 50 ksi and a temperature of 300°F generate a creep strain of 0.1% in a unit time for a standard creep test, the value of the Larsen-Miller parameter would be 14.5×10^3. Following a change in creep resistance, the same test conditions may generate a strain of 0.2% with a parameter value of about 15×10^3. If the time is held constant, to satisfy the value of the parameter, the apparent test temperature would increase. In this manner, an apparent temperature for creep, which represented the actual creep behavior for an overaged material at a lower test temperature, was determined to establish a family of "damage" curves. This approach for relating creep damage to prior history is suggested by the scatter plot technique (illustrated in the Appendix) for associating cause and effect.

The formulation which relates material damage to creep behavior is shown in Fig. 25. An apparent creep temperature is related by the actual test temperature to prior exposure at 350°F. These relations were obtained by comparing the experimental data, i.e., the environmental creep curves, to a standard represented by the creep curve established with the strain hardening rule. The standard creep behavior employed by the strain hardening rule was in turn established by averaging the creep data of the material in a virgin condition by employing the Larsen-Miller relation. A pair of damage curves is shown for each test temperature; the solid lines govern the case when the given cycle follows immediately the exposure at 350° F, and the broken lines govern the case when some intermediate cycle has occurred between exposure at 350°F and the given cycle. For example, if a specimen had been exposed to 350°F for 2 hours and is immediately tested at some stress σ_1 and 200°F, the creep curve which would be generated would appear similar to one obtained for a test condition of σ_1 and 267.5°F. On the other hand, if the specimen were exposed 350°F for 2 hours and some intermediate σ_i, T_i is applied, a subsequent application of σ_1 and 200°F would generate a creep curve which would appear similar to one obtained at σ_1 and 250°F.

The phenomenon of overaging and subsequent recovery is illustrated in the comparison of Tests Nos. 16 and 30 in Fig. 26. In both cases, the damage incurred during overaging at 350° F was essentially similar; however, specimen No. 16, following the overaging, was immediately reloaded to the severe test condition (300° F, -49.4 ksi) with the resultant severe creep rate. Conversely, specimen No. 30 was reloaded to a moderate test condition intermediate to the 300° F, -49.4 ksi condition with a less severe effect. Of course, because of inhomogeneity, exceptions have occurred to this general behavior, but the relations for creep damage could be validly established for the overaging effect at 350° F. The recuperative effect, though explicitly established, could not be attributed to a specific factor.

Because the time interval during each cycle was identical for both the standard and experimental creep data, specifically, if overaging had occurred prior to a new sequence, the reference creep curve for the strain hardening rule would be selected for the apparent temperature determined from Fig. 25 to represent the creep behavior at the lower actual test temperature.

The compensated strain hardening rule was compared to the environmental creep data. The comparison of the synthesized curves and their experimental counterparts is shown in Figs. 27A, 27B and 27C. Tests Nos. R1 and 9 had experienced identical conditions except for the 1 hour 350° F unstressed condition for R1. The specific difference in creep behavior occurred in Sequence III where the weakened condition of R1 resulted in a higher creep rate. In both cases, the compensated creep rule followed the creep path faithfully. Test No. 54 differed from Test No. 9 only in the last sequence, and its trend was followed by the compensated rule. For contrast, the conventional S. H. R. was employed and, as shown, was substantially unconservative.

In order to obtain a more objective verification of the techniques evolved for prediction of environmental creep behavior, several arbitrary test conditions were selected--conditions which would include various degrees of overaging and subsequent aging. The predicted curves were drawn (Figs. 28A through D) and the tests were run. Although the fit of the predicted creep curves to the experimental curves was not precise for the case of Figs. 28C and 28D, the disparity was not great and the slopes of the pairs of curves in both cases were very nearly alike. A general coincidence of predicted and experimental creep behavior illustrated in Fig. 28 was found in this investigation.

The empirical means for predicting the simple environmental creep behavior evolved from this investigation is not in itself important. However, under somewhat more ideal conditions (particularly the requirement of homogeneity without which it is doubtful that any analysis technique could be made practical), it has been indicated that quantitative values to establish the basis for environmental creep behavior can be obtained experimentally.

Assuming that material could be produced which is approximately homogeneous but not necessarily isotropic, it may be possible to incorporate damage factors, such as those discussed above, for adjusting the analytical representation in a more explicit way. It has been shown in Figs. 17 through 21 that $\epsilon_c = Kt^N$ provides a good fit for the creep curve for creep in the practical design range. If the relations "K" and "N" in Figs. 24 through 26 can be shown to be valid, a new family of curves (T versus Log K) could be established by a displacement of the basic family. The data from Fig. 25 indicate a lateral shift to the right would be required for the curves of Fig. 23 to accommodate the effect of prior history.

H. MULTIPLE AND RANDOM BALANCE

Statistical techniques (multiple and random balance) were employed for designing the experiments in this investigation as a means of characterizing a material's behavior for several million environmental conditions with a few randomly selected test combinations. Theoretically, 50 test combinations approach the maximum practical confidence limits (Refs. 2 through 6). This approach provides a "sample" which is a piece-wise continuous representation of the creep behavior for all possible combinations of the test environment. From this sample it is possible to synthesize the environmental creep behavior of a specimen for an arbitrary test condition within the bounds of the experimental data. The employment of the statistical methods for experiments is illustrated in the Appendix.

In this investigation, the data were not sufficiently precise to permit the detection of small influences on creep behavior. However, a degree of success was achieved in the determination of the damage curves of Fig. 25 which were employed for predicting the environmental creep behavior of the tests shown in Fig. 28. In addition, the random choice of test specimens and the random assignment of test conditions revealed the inhomogeneity in the aluminum sheet which may otherwise have been obscured or overlooked.

The precision for predicting environmental creep behavior by the methods examined in this investigation depends on the homogeneity of the virgin specimens from which the basic data are obtained.

It has been shown in the results of this investigation that it is possible to obtain nearly identical responses for duplicate environmental creep tests for specimen pairs which could be considered as metallurgical identities. If, through controlled processes, it becomes possible to obtain homogeneous materials, the general merit of the statistical approach may be realized.

IV. CONCLUSIONS

A number of significant conclusions which result from this investigation are presented.

(1) Static properties as they are determined for the initial condition of the material or subsequent to some metallurgical change do not provide a reliable index for characterization of creep behavior.

(2) The possible large variation of strength properties of material from lot to lot (particularly the 7075-T6 aluminum) and the inhomogeneity which was shown to exist within a sheet would make generation of meaningful creep data for precise design analysis of airframe and missile structures impossible.

(3) Within practical design limits, the degradation of a material is a reasonably gradual process and the perception of degradation appears to be amendable to analytical representation.

(4) An appreciable increase of the secondary modulus of elasticity (engineering) can result as the consequence of overaging for 7075-T6 aluminum.

(5) The generation of creep data for precise stress analysis would require the establishment of rigid standards for materials.

(6) A significant recuperation of resistance to creep following degradation was indicated when the material was permitted to rest during a moderate test condition before reapplying a severe combination of stress and temperature.

(7) The Larsen-Miller parameter is an excellent means for concisely representing creep behavior for a material. However, each construction of the creep data representation with the Larsen-Miller parameter is unique and inherently averages the creep characteristics.

(8) The primary or transient creep stage can occupy a substantial portion of each cycle, and the cumulative creep strain which would occur in a structure may be comprised entirely from the transient creep region.

(9) With the simple device of changing the reference temperature of creep, the strain hardening rule, thus compensated, generally predicted environmental creep within 10% compared to errors of up to several hundred percent when the standard strain hardening rule was employed.

(10) The means of accounting for a change in creep behavior may be possible by adjusting the reference base of the initial creep behavior. If the relations among the values contained in the power expression of creep $\epsilon_c = Kt^N$, are valid, as shown in the text, then it may be possible to describe the creep behavior of a material by substituting one or more empirically determined damage parameters for the values K and N, thereby reducing the characterization of an instantaneous material state to a machine calculation.

(11) The method of random balance for designing experiments may prevent the occurrence of unusual experimental situations, i.e., the choice of specimens from a region possessing unusual properties and the coincidence of increasing equipment error. It may also provide a broad objective representation of the experimental region to be examined with the greatest economy of tests.

(12) The employment of multiple and random balance provided experimental data which are statistically sound. Furthermore, it was possible to draw inferences from the data which were not fortuitous.

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VI. TABLES AND ILLUSTRATIONS

TABLE 1

Experimental Design

Test No.	Section No.	Sequence I Temp (°F)	Sequence I Stress (%)*	Sequence I Time (hr)	Sequence II Temp (°F)	Sequence II Stress (%)*	Sequence II Time (hr)	Sequence III Temp (°F)	Sequence III Stress (%)*	Sequence III Time (hr)	Sequence IV Temp (°F)	Sequence IV Stress (%)*	Sequence IV Time (hr)
1	7	300	80	0.5	250	80	2.0	300	70	1.0	350	75	1.5
2	9	250	80	2.0	200	80	1.5	250	85	1.0	250	75	0.5
3	3	250	85	1.0	350	75	1.5	250	80	0.5	300	75	2.0
4	5	250	75	0.5	250	85	1.0	350	75	1.5	200	70	2.0
5	1	300	75	2.0	200	85	0.5	200	75	1.5	350	80	1.0
6	3	200	85	0.5	300	85	1.0	300	70	1.5	350	85	2.0
7	2	300	85	1.0	200	70	0.5	200	80	1.5	250	75	2.0
8	6	300	80	2.0	250	70	1.5	350	75	1.0	300	80	0.5
9	7	350	70	0.5	350	75	1.0	250	85	1.5	350	70	2.0
10	5	250	70	1.5	300	80	2.0	200	70	0.5	200	80	1.0
11	4	350	75	1.5	350	85	2.0	200	85	0.5	250	85	1.0
12	9	250	85	1.5	250	80	0.5	350	85	2.0	300	70	1.0
13	5	200	75	1.5	250	75	0.5	200	85	2.0	300	85	1.0
14	9	300	70	1.5	250	75	2.0	300	85	1.0	350	85	0.5
15	8	200	75	1.0	200	70	2.0	350	85	0.5	200	75	1.5
16	6	250	75	2.0	350	70	0.5	300	85	1.5	250	70	1.0
17	4	250	80	0.5	350	80	1.0	250	70	1.5	200	85	2.0
18	3	300	70	1.0	300	85	1.5	250	75	0.5	300	80	2.0
19	2	200	70	2.0	200	75	1.0	350	70	0.5	200	80	1.5
20	2	350	80	1.0	200	75	1.5	250	80	2.0	200	70	0.5
21	7	350	75	1.0	350	80	1.5	300	80	2.0	200	85	0.5
22	7	300	85	1.5	200	80	1.0	200	70	2.0	250	80	0.5
23	8	300	75	0.5	250	85	1.5	200	75	1.0	250	80	2.0
24	4	350	70	2.0	300	80	0.5	350	80	1.5	350	75	1.0
25	6	350	80	1.5	250	70	1.0	250	75	2.0	350	70	0.5
26	9	200	80	1.5	200	85	2.0	300	75	0.5	200	75	1.0
27	5	350	85	2.0	300	70	1.5	350	80	1.0	300	75	0.5
28	8	250	70	1.0	300	75	2.0	300	80	0.5	350	80	1.5
29	1	200	70	0.5	300	70	1.0	300	75	2.0	250	70	1.5
30	6	200	85	2.0	350	85	0.5	250	70	1.0	300	85	1.5
31	1	350	85	0.5	350	70	2.0	200	80	1.0	300	70	1.5
32	8	200	80	1.0	300	75	0.5	350	70	2.0	250	85	1.5
Replicates													
1	7	350	70	0.5	350	75	1.0	250	85	1.5	350	70	2.0
2	7	300	80	0.5	250	80	2.0	300	70	1.0	350	75	1.5
3	9	300	70	1.5	250	75	2.0	300	85	1.0	350	85	0.5
4	8	250	70	1.0	300	75	2.0	300	80	0.5	350	80	1.5
5	2	350	80	1.0	200	75	1.5	250	80	2.0	200	70	0.5

*Percent of yield strength at test temperature.

TABLE 2

Magnitudes of Elastic and Inelastic Strains for Various Stresses and Temperatures--Bare 7075-T6 Aluminum Alloy Sheet

Test Temperature (°F)	200° F Strain x 10^5			250° F Strain x 10^5			300° F Strain x 10^5			350° F Strain x 10^5		
% YS at Test Temperature	ϵ	ϵ_P	Total	ϵ	ϵ_P	Total	ϵ	ϵ_P	Total	ϵ	ϵ_P	Total
70	479	1	480	472	3	475	449	7	456	405	15	420
75	515	3	518	508	5	513	482	11	493	434	21	455
80	550	6	556	539	9	548	515	16	531	464	29	493
85	583	10	593	575	14	589	549	23	572	494	40	534

TABLE 3

Thermal Strain Differences Between Bare 7075-T6 Aluminum Alloy Sheet and Platinum--from R. T. to 350° F

From Temperature (°F)	Temperature (°F) 75	200	250	300	350
75	0	-0.00100	-0.00142	-0.00185	-0.00230
200	0.00100	0	-0.0042	-0.00085	-0.00130
250	0.00142	0.00042	0	0.00043	-0.00088
300	0.00185	0.00085	0.00043	0	-0.00045
350	0.00230	0.00130	0.00088	0.00045	0

TABLE 4

Strength Variation of Bare 7075-T6 Aluminum Alloy Sheet at Room Temperature for Various Lots*

Martin File Record No.	Material Gage (in.)	Specimen No.	F_{TU} (ksi)	F_{TY} (ksi)
387	0.090	19314-1	73.6	68.8
		2	75.4	70.1
		3	73.5	68.6
	0.124	19130-1	82.3	75.9
		2	81.3	75.4
		3	80.4	74.6
367	0.126	33-1	86.5	78.1
		2	86.0	78.0
	0.247	34-1	76.3	67.6
		2	76.8	68.0
368	0.110	74-1	83.8	74.7
		2	85.6	76.0
		3	84.8	75.6
	0.110	76-1	84.2	74.3
		2	84.5	74.0
		3	85.3	74.3
**	0.125		80.3	72.2
ANC-5 A	0.040 to 0.249		77.0	67.0
*** B	0.040 to 0.249		79.0	70.0

* Unidentified lots examined during 1956.

** Average strength values from this investigation.

*** A and B values are based on confidence levels statistically determined-- A minimum values and B, the 90% confidence limit.

TABLE 5

Static Tensile Properties from RT to 350° F (without prior history) Bare 7075-T6 Aluminum Alloy Sheet

Test Temperature (°F)	Sheet Section No.	F_{TY} (ksi)	F_{TU} (ksi)	Elongation (%)	Modulus of Elasticity E x 10^{-6} psi
Room	1	74.5	81.5	12.5	10.1
	1	73.1	81.0	13.0	9.62
	2	71.9	79.9	11.0	9.37
	3	69.7	78.4	11.0	9.36
	4	72.8	80.4	12.0	9.65
	5	71.3	79.9	12.0	9.33
	6	71.7	80.1	12.5	9.43
	7	73.1	80.8	12.5	9.46
	8	72.4	80.3	12.0	9.37
	9	71.9	80.3	12.0	9.45
	Average	72.2	80.3	12.1	9.57
200	2	66.4	70.9	15.5	8.6
200	2	65.1	69.2	14.0	8.9
200	4	68.3	72.2	17.0	9.2
200	7	68.9	72.2	17.0	9.1
	Average	67.2	71.1	15.9	9.0
250	1	63.9	66.5	15.5	8.7
250	5	63.1	65.2	13.0*	8.8
250	8	64.6	66.5	17.0	8.5
	Average	63.9	66.1	16.8	8.7
300	3	58.0	59.2	13.0*	8.1
300	6	57.4	58.0	16.0	8.5
300	9	58.9	59.4	19.0	8.4
	Average	58.1	58.9	17.5	8.3
350	1	50.8	51.6	13.0*	8.0
350	4	50.7	51.2	22.5	7.9
350	7	50.0	51.3	22.0	8.1
350	2	50.5	51.7	13.0*	7.9
	Average	50.5	51.5	22.3	8.0

*Broke at clamps. Not included in average.

TABLE 6

Static Tensile Properties at Room Temperature for Bare 7075-T6 Aluminum Alloy Sheet (after prior history)

Test No.	Experimental Test Temperature (°F) and Time of Exp (hr)*				F_{TU} (ksi)	F_{TY} (ksi)	Elongation (%)	Modulus of Elasticity (psi x 10^{-6})
	200	250	300	350				
1	-	2	1.5	1.5	75.27	66.74	-	10.2
R2	-	2	1.5	1.5	76.31	68.15	12.0	10.3
2	1.5	3.5	-	-	79.87	74.21	-	10.2
3	-	1.5	2	1.5	74.53	66.35	11.0	10.1
4	2	1.5	-	1.5	75.66	67.57	12.0	10.1
5	2	-	2	1	75.66	67.34	12.0	9.99
7	2	2	1	-	80.00	72.28	12.5	10.1
8	-	1.5	2.5	1	76.49	68.65	13.0	10.1
9	-	1.5	-	3.5	70.99	61.16	11.0	10.0
R1	-	1.5	-	3.5	67.95	58.11	9.0	10.05
10	1.5	1.5	2	-	79.39	72.16	14.5	9.93
11	-	-	-	3	Fail. in Seq II	-	10.0	Fail in Seq II
12	-	2	2	1	78.20	70.46	12.0	10.2
13	3.5	0.5	1	-	79.81	72.93	13.5	9.97
14	-	2	2.5	0.5	76.07	67.57	12.0	10.0
R3	-	2	2.5	0.5	75.83	67.56	10.0	10.05
R3A	-	2	2.5	0.5	76.70	68.78	10.5	10.0
15	4.5	-	-	0.5	77.52	69.81	13.0	10.1
16	-	3	1.5	0.5	76.10	69.03	13.0	9.94
17	2	2	-	1	77.18	69.47	12.5	9.87
18	-	0.5	4.5	-	77.78	70.11	12.5	9.98
19	4.5	-	-	0.5	75.86	67.50	11.5	9.96
20	2	2	-	1	75.08	67.06	10.5	10.2
R5	2	2	-	1	75.08	67.43	12.0	10.15
21	0.5	-	2	2.5	72.36	65.51	10.5	9.73
22	3	0.5	1.5	-	80.63	74.60	14.0	10.0
23	1	3.5	0.5	-	80.25	74.41	13.0	9.97
24	-	-	0.5	4.25	-	Failure in Seq IV		
25	-	3	2	-	73.24	63.85	10.5	9.95
26	4.5	-	0.5	-	80.57	74.25	13.5	10.2
27	-	-	3	2	66.25	60.91	9.5	9.95
28	-	1	2.5	1.5	74.61	65.62	12.0	10.15
R4	-	1	2.5	1.5	74.45	65.46	10.5	10.0
R4A	-	1	2.5	1.5	73.97	65.08	10.0	9.98
29	0.5	1.5	3	-	79.16	72.24	12.0	10.1
30	2	1	1.5	0.5	77.92	71.07	13.5	10.2
31	1	-	1.5	2.5	72.78	63.96	11.5	10.1
32	1	1.5	0.5	2	75.72	69.59	11.5	10.15

*Without regard to order of application of temperature

TABLE 6 (continued)

Test No.	Experimental Test Temperature (°F) and Time of Exp (hr)*				F_{TU} (ksi)	F_{TY} (ksi)	Elongation (%)	Modulus of Elasticity (psi x 10^{-6})
	200	250	300	350				
49	1	1	1	3	74.98	67.35	12	9.74
50	1	1	1	3	73.68	66.25	12	9.87
51	1	1	3	1	73.88	67.84	11.5	9.93
52	1	1	3	1	73.88	64.94	10.0	10.19
53	1	1	3	1	76.39	69.16	13.0	10.21
54	-	1.5	-	3.5	76.42	68.19	12.0	10.34
55	1	1	3	1	77.71	70.68	12.5	9.90
56	-	1	5	1	76.75	68.92	13.0	10.11
58	-	1	-	6	75.38	68.33	12.0	9.77
61	1	1	1	3	75.72	68.35	12.0	10.12
62	-	1	1	5	71.81	64.71	10.5	9.38
85	-	1	1	5	72.56	64.81	11.5	9.68
86	1	1	-	5	73.05	65.49	11.0	10.13
87	1	-	1	5	71.71	64.44	12.0	10.03
88	1.5	-	-	2	71.50	66.34	9.0	10.86
89	1.5	1.5	-	2	72.90	67.60	8.5	9.18
90	-	-	-	-	74.31	67.12	9.0	9.66
91	1	1	1.5	2	73.99	66.97	9.0	9.46
92	-	-	-	-	73.82	66.38	8.5	10.26
93	-	-	-	-	73.21	66.34	11.0	9.82
94	1	-	1.25	3	72.82	65.34	10.5	9.57
95	1	1	-	5.5	68.50	58.74	12.0	9.35
96	-	-	1.0	5.5	68.12	58.37	8.5	9.64
97	-	-	-	2.5	70.99	61.43	11.0	10.03
98	-	-	-	2.5	69.38	60.19	11.0	10.01
99	-	-	-	4	71.38	61.60	13.0	10.05
100	-	-	-	4	70.39	60.31	13.0	9.79
101	-	-	-	5.5	66.71	56.56	12.5	9.59
102	-	-	-	5.5	61.38	54.65	10.0	9.88
30R	-	-	-	-	75.99	69.07	10.5	9.96
88R	1.5	0.5	-	2	73.04	67.25	9.0	10.25
89R	1.5	2.5	-	2	71.98	66.35	8.5	10.05
90R	1	1	1.5	2	73.88	66.41	10.5	9.62
91R	1	-	1.5	2	69.31	63.70	8.0	9.73
92R	1	1.5	1	2	74.51	66.67	10.5	9.74
93R	1	1.5	1	2	71.90	65.61	9.0	10.11
Grand Average					73.74	66.62	10.13	9.95

*Without regard to order of application of temperature

TABLE 7

Static Tensile Properties from 200° to 350° F for Bare 7075-T6 Aluminum Alloy Sheet (after prior history)

Specimen No.	Exp Test Temp (°F) and Time of Exp (hr)*				Test Temp (°F)	F_{TU} (ksi)	F_{TY} (ksi)	Elongation (%)	Modulus of Elasticity (psi x 10^{-6})
	200	250	300	350					
33	5	-	-	-	200	73.55	69.70	13.5	9.24
34	5	-	-	-		72.79	69.43	16.0	8.97
41	1.25	1.25	1.25	1.25		69.94	66.73	13.0	9.16
45	1.25	1.25	1.25	1.25		67.20	63.90	11.0	9.27
48A	1.25	0.67	0.67	1.25		65.02	63.92	8.5	9.08
67	5.0	-	-	-		72.55	68.74	15.0	8.99
71	-	-	-	5		73.45	69.95	16.0	9.58
77	5	-	-	-		73.31	69.76	16.0	9.32
					Average	70.98	67.77	13.6	9.20
35	-	5	-	-	250	67.49	65.58	18.5	9.02
36	-	5	-	-		67.83	65.57	16.5	9.03
44	1.25	1.25	1.25	1.25		62.75	60.47	12.5	9.01
48	-	-	-	-		60.81	60.81	10.0	8.74
57	0.5	1.0	1.25	1.25		64.34	64.18	12.0	8.84
64	1	1.5	0.5	2		61.36	61.36	12.0	8.73
65	-	5	-	-		67.98	65.64	16.5	9.51
69	-	5	-	-		67.59	65.41	15.0	8.87
75	-	5	-	-		67.83	65.65	17.0	9.27
81	-	5	-	-		67.61	65.80	15.0	9.22
					Average	65.67	65.88	14.5	9.02
37	-	-	5	-	300	59.64	58.63	16.0	8.75
38	-	-	5	-		57.39	56.37	19.5	8.72
43	1.25	1.25	1.25	1.25		58.69	57.20	14.0	8.78
47	1.25	0.67	0.8	1.25		52.81	52.81	8.0	8.22
63	1	-	0.25	2.5		53.18	53.18	8.5	8.41
68	-	-	5	-		59.14	57.65	19.0	8.76
74	-	-	5	-		58.25	56.76	19.0	8.53
79	-	-	5	-		53.75	53.75	19.0	7.84
					Average	56.61	55.79	15.4	8.50
39A	-	-	-	5	350	45.68	45.21	10.0	8.09
39B	-	-	-	5		47.23	46.22	10.0	7.94
40	-	-	-	5		45.55	44.69	8.5	8.17
40A	-	-	-	5		47.83	46.81	10.0	8.32
42	1.25	1.25	1.25	1.25		50.20	49.11	15.5	8.31
46	1.25	1.25	1.25	1.25		49.84	49.21	14.0	8.35
54	-	1.5	1.75	1.5		43.47	43.47	8.0	8.08
60	-	-	0.5	4.5		38.96	38.96	8.5	7.87
66	-	-	-	5		44.51	43.33	14.0	7.99
73	-	-	-	5		44.21	42.79	12.0	8.35
					Average	45.85	44.98	11.5	8.15

*Without regard to order of application of temperature

TABLE 8

Location of Environmental Test Specimens in Aluminum Sheet

Specimen No.	Panel Section No.	Specimen No.	Panel Section No.	Specimen No.	Panel Section No.
1	7	46	4	96	2
2	9	47	4	97	2
3	3	48	7	98	2
4	5	48A	9	99	5
5	1	49	9	100	5
6	3	50	8	101	5
7	2	51	2	102	2
8	6	52	2	R1	7
9	7	53	5	R2	7
10	5	54	7	R3	9
11	4	55	1	R4	8
12	9	56	7	R5	2
13	5	57	5	R9	8
14	9	58	8	R30	2
15	8	59	6	88R	5
16	2	60	9	89R	2
17	4	61	8	90R	5
18	3	62	1	91R	2
20	2	63	8	92R	5
21	7	64	5	93R	2
22	7	65	4	94R	5
23	8	66	2		
24	4	67	1		
25	6	68	3		
26	9	69	1		
27	5	70	1		
28	8	71	4		
29	1	72	3		
30	6	73	2		
31	1	74	3		
32	8	75	4		
33	7	76	1		
34	6	77	9		
35	4	78	3		
36	3	79	6		
37	7	80	4		
39	3	81	6		
39A	5	82	3		
39B	4	83	2		
40	9	84	1		
40A	8	85	6		
41	7	86	7		
42	5	87	8		
43	6	94	5		
44	1	95	2		
45	3				

Identical tests for three sequences

63 = 31
32 = 64
57 = 16
9 = R1 = 54

Identical tests for four sequences

R1 = 9
R2 = 1
R4 = 28
R5 = 20
R30 = 30
39A = 39B
R3 = 14
40 = 40A

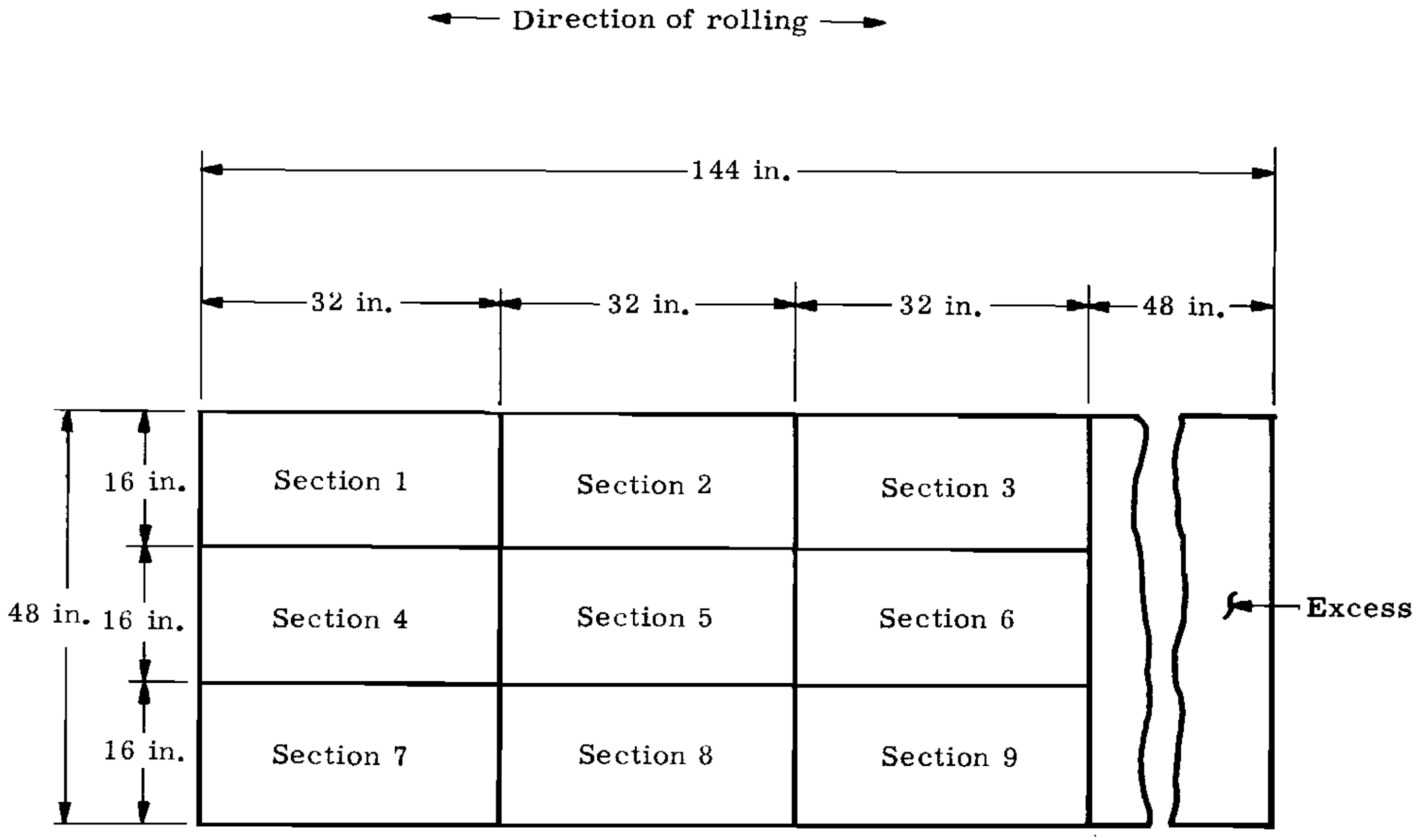
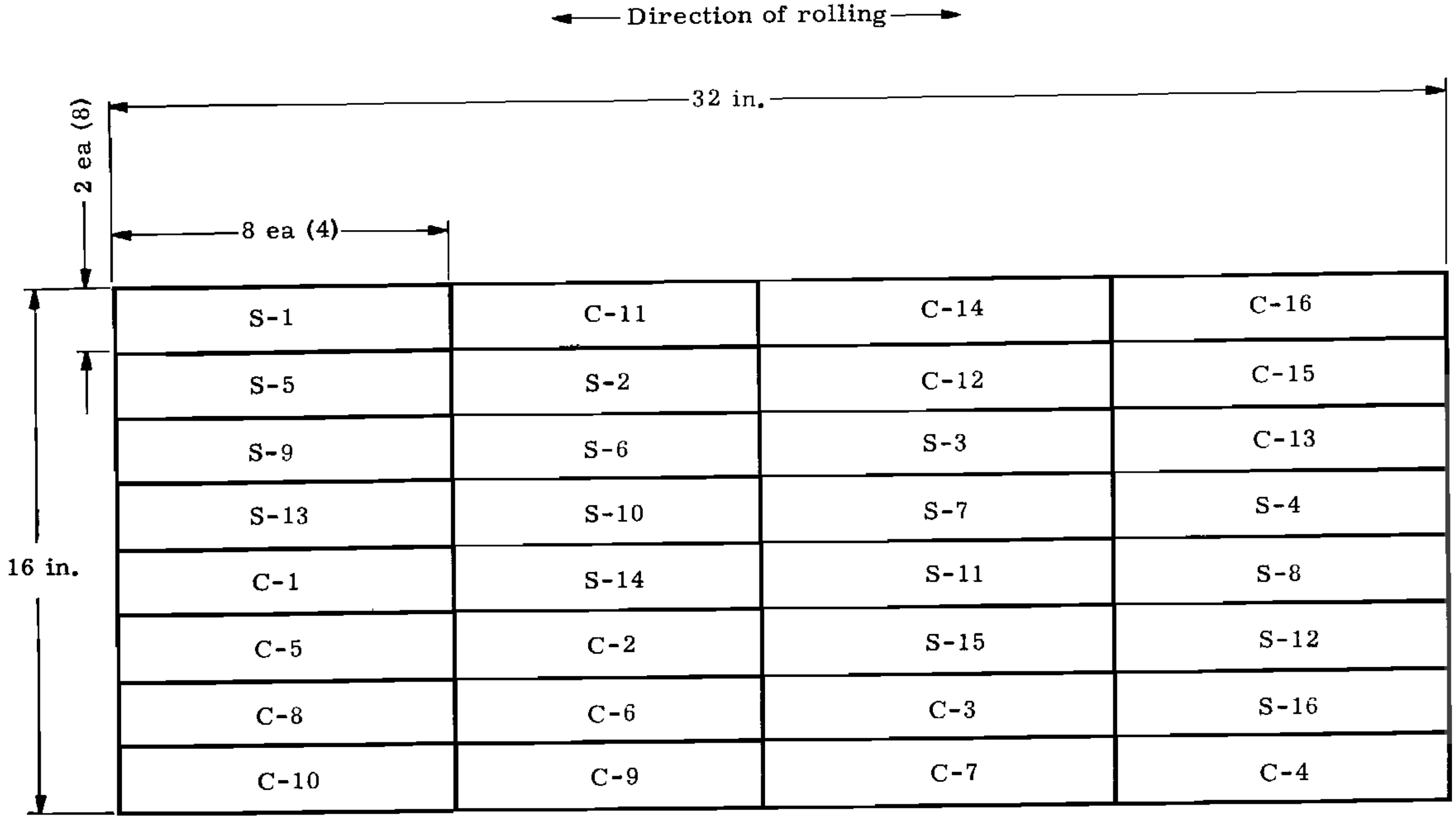


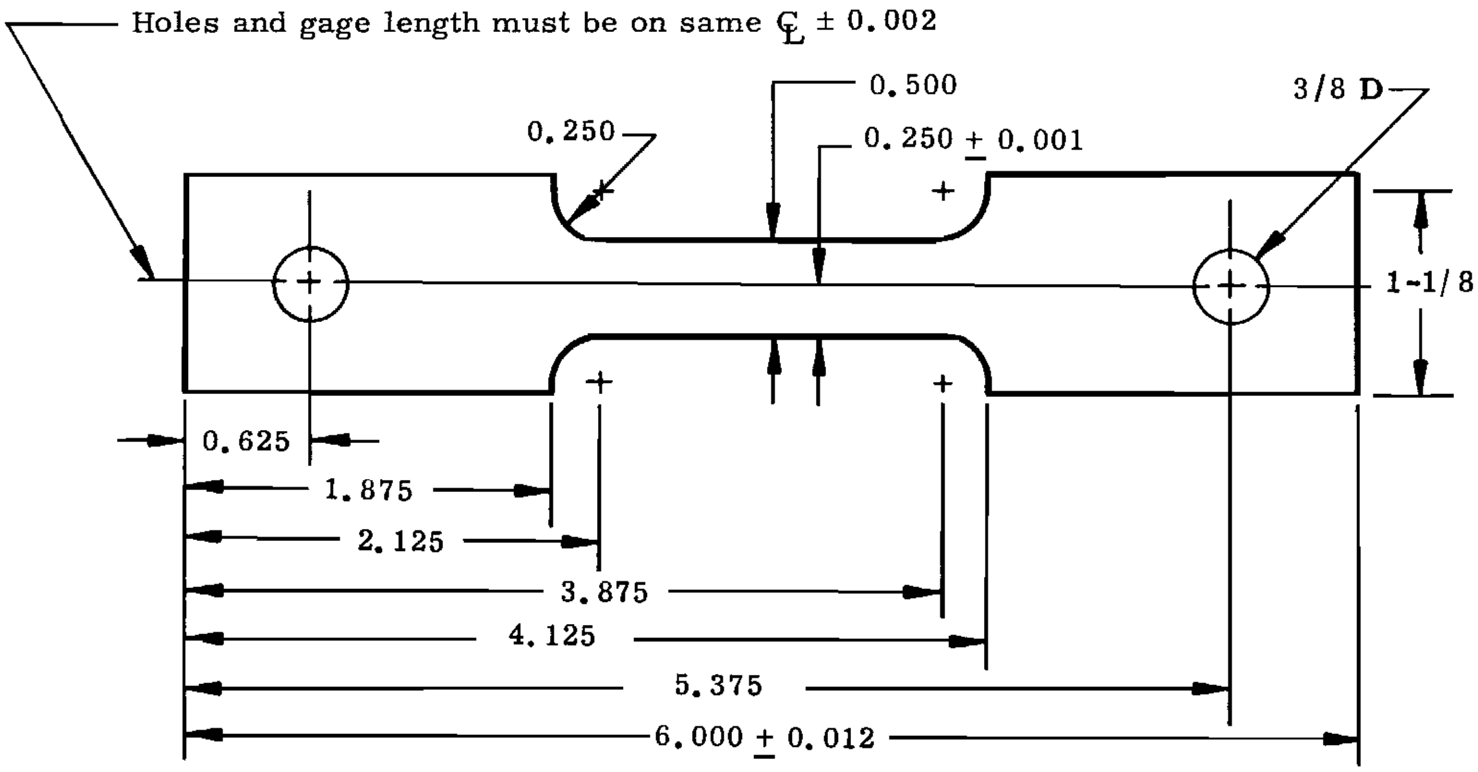
Fig. 1. Distribution of Nine Sections (16 in. x 32 in. of a 48 in. x 144 in. Bare 7075-T6 Aluminum Sheet) for Randomization of Creep Specimen Location



S-1	C-11	C-14	C-16
S-5	S-2	C-12	C-15
S-9	S-6	S-3	C-13
S-13	S-10	S-7	S-4
C-1	S-14	S-11	S-8
C-5	C-2	S-15	S-12
C-8	C-6	C-3	S-16
C-10	C-9	C-7	C-4

S--Static--room elevated temperature--total of 16 pieces
C--Creep--total of 16 pieces--maximum of 8 pieces (Section 6) projected
Specimen size approximately 2 in. x 8 in. as sheared and 1-1/2 in. x 8 in. as machined.

Fig. 2. Randomized Distribution of Tensile and Creep Specimens in the 16 in. x 32 in. Aluminum Sheet Sections



NOTE: (1) All decimal dimensions ± 0.002 unless otherwise specified.
(2) Specimens that do not have above dimensions and accuracy will not be acceptable.

Fig. 3. Dimensional Details of Tension and Environmental Creep Specimens

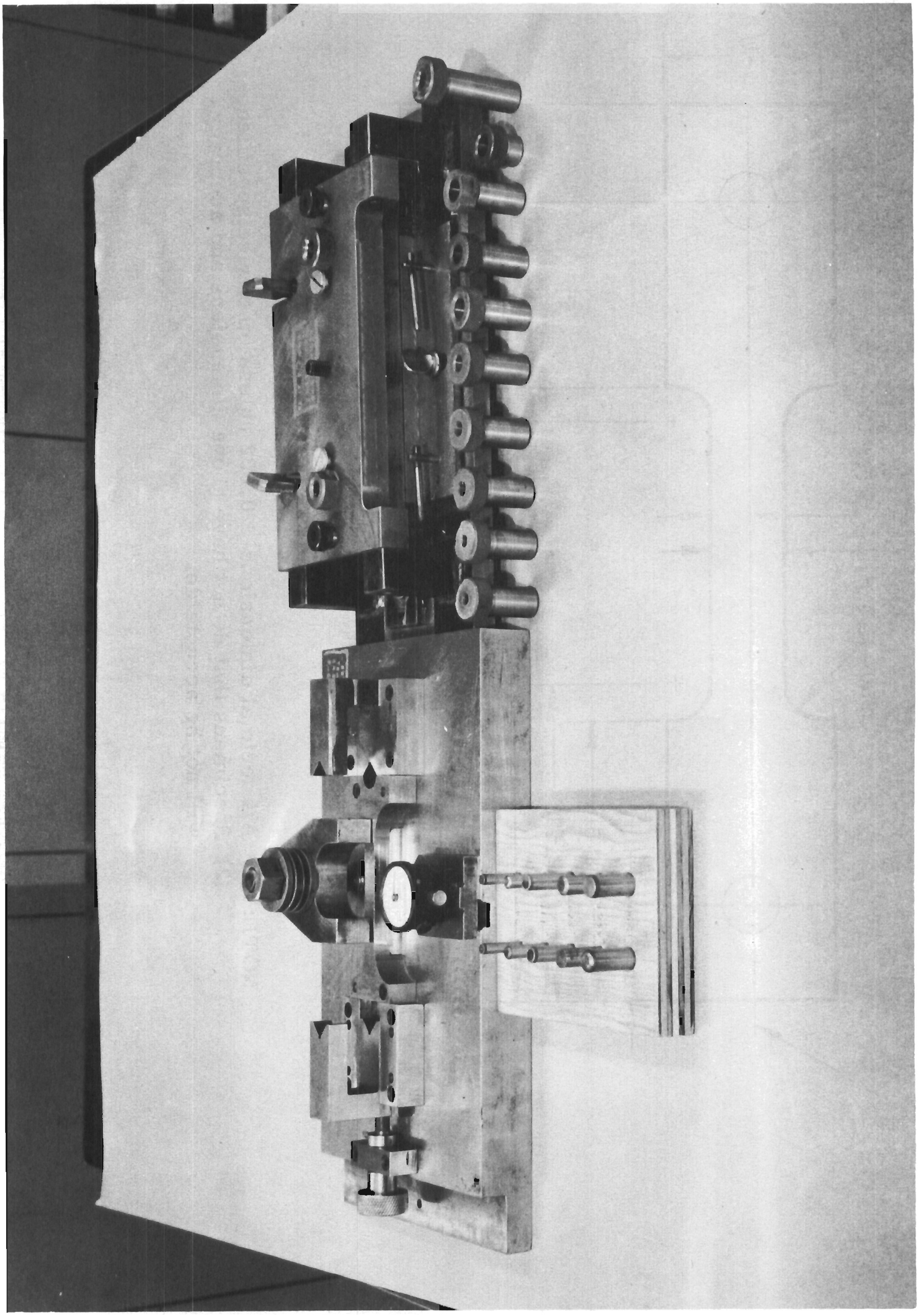


Fig. 4. Mill and Drill Fixture Employed for the Fabrication of Test Specimens

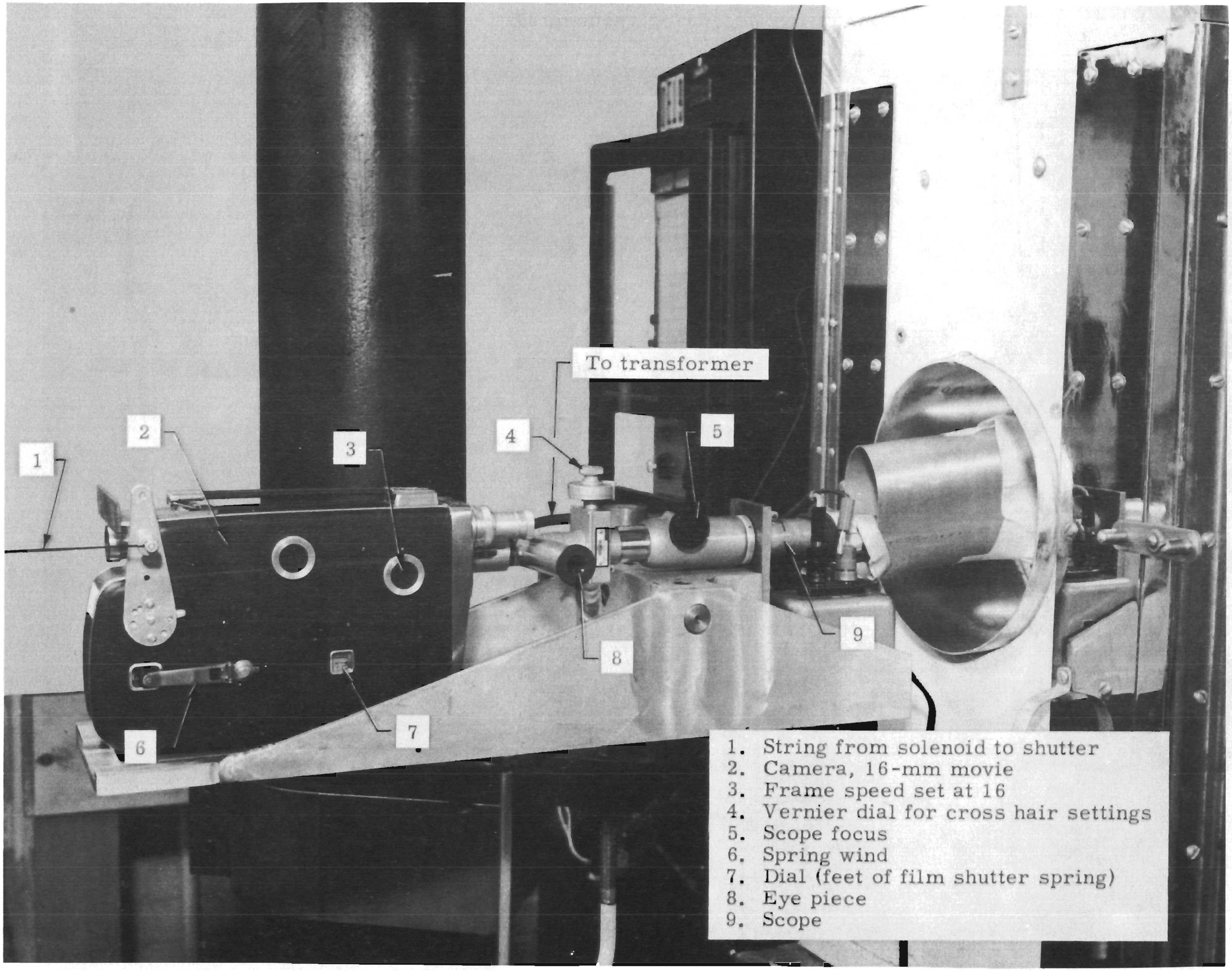


Fig. 5. Details of K-100 Kodak Camera--Automatic Data Recording System

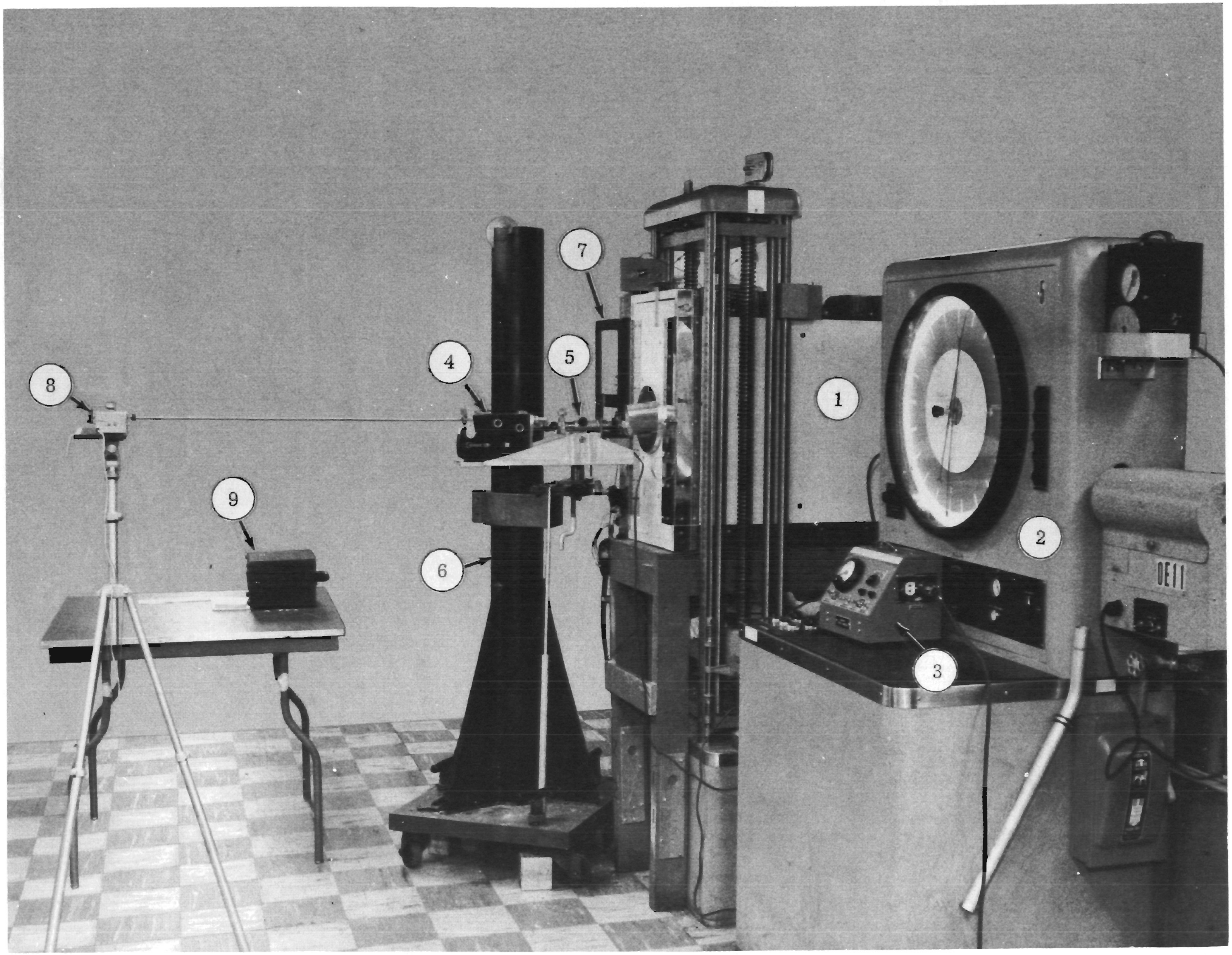


Fig. 6. Experimental Setup for the Environmental Tests

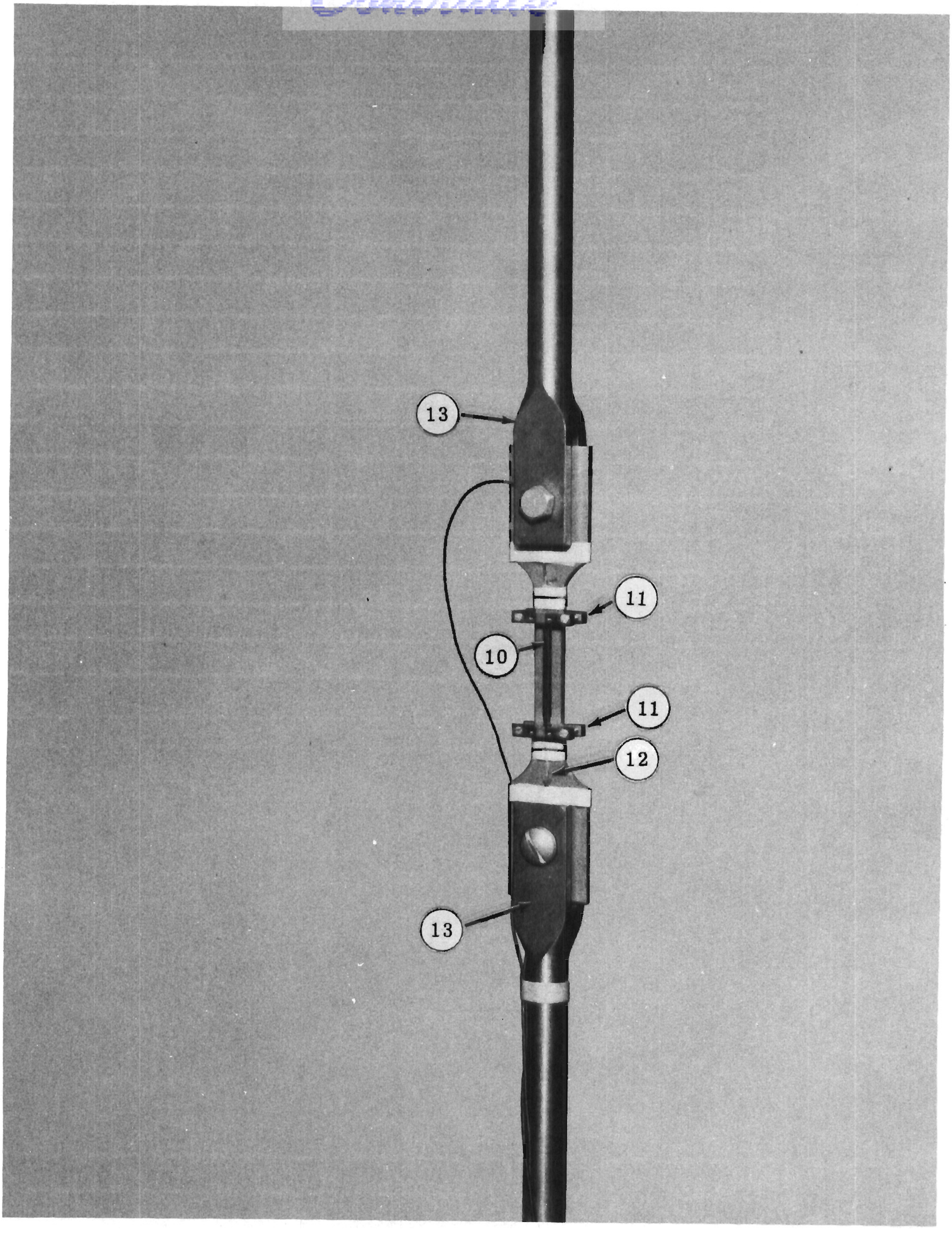


Fig. 7. Details of Test Specimen Assembly

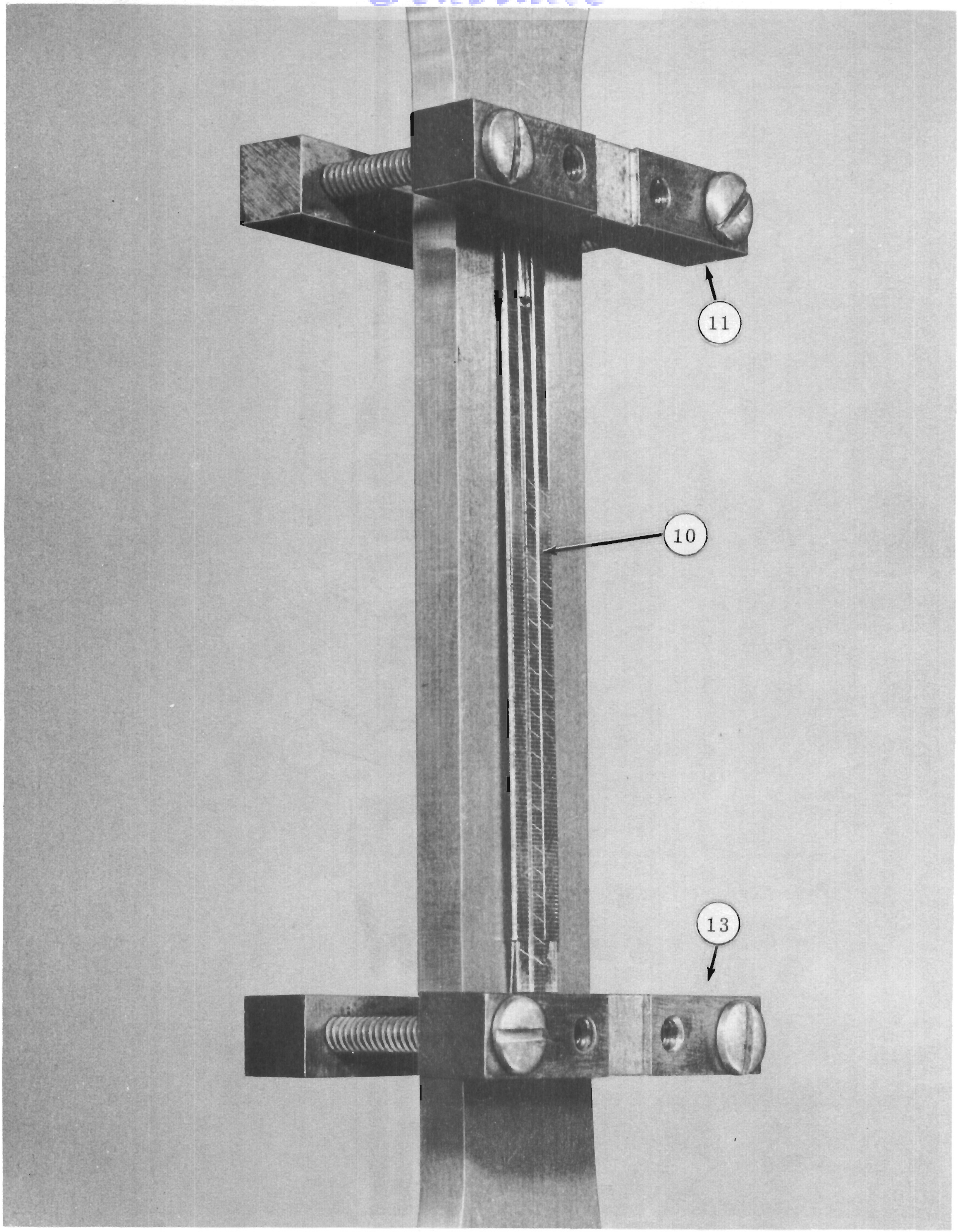
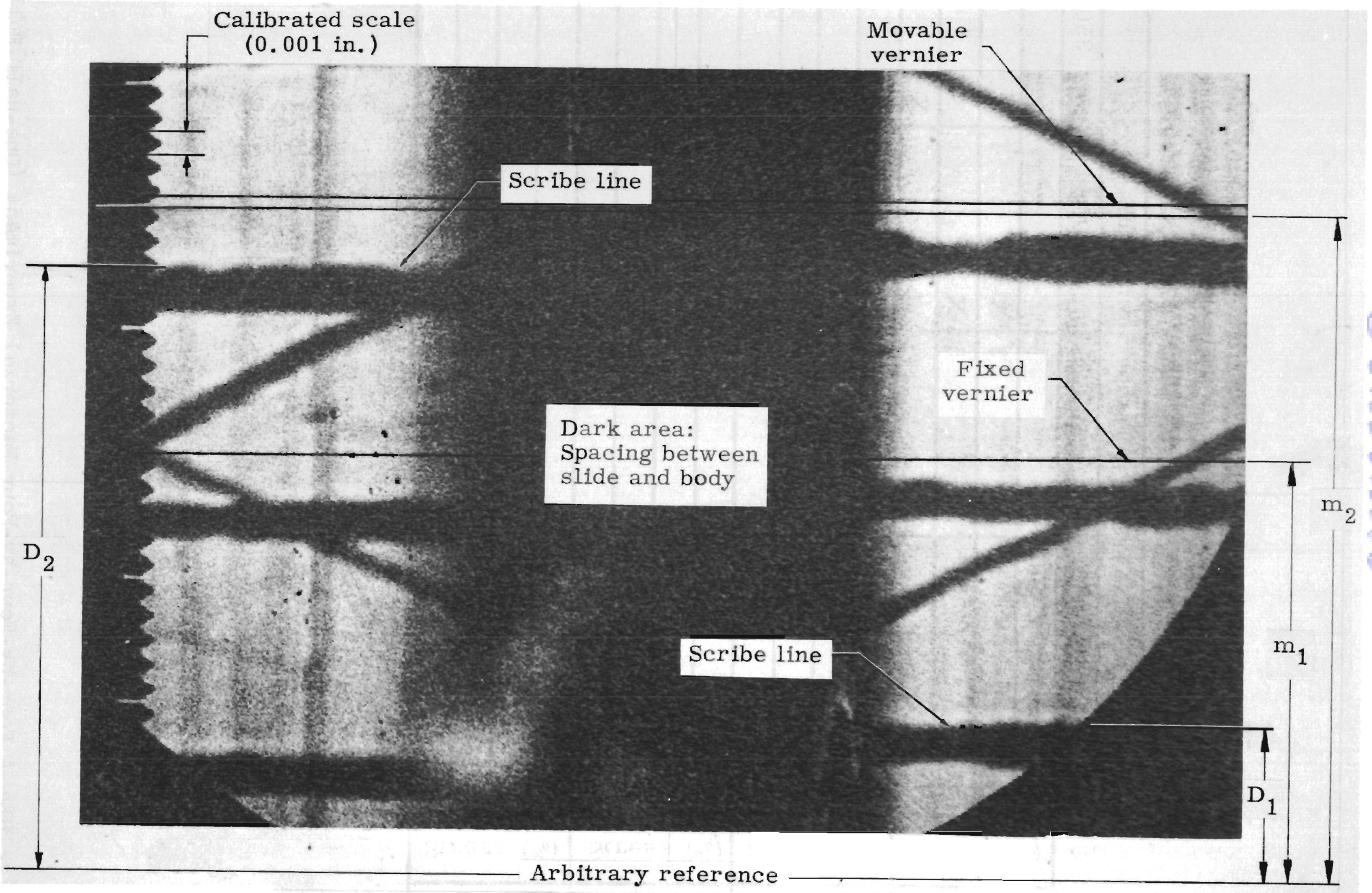


Fig. 8. Enlargement of Instrumentation Detail



$\epsilon = \frac{0.010}{L} \times \frac{D_2 - D_1}{m_2 - m_1}$ in. /in. where L is the gage length

Fig. 9. Photo-Optical Strain Measurement Utilizing Platinum Slide Rule Gage

				Temperature (° F)			
				200	250	300	350
Time (hr)	0.5	Stress (%)	70	X 1			X 2
			75		X 3	X 4	
			80		X 5	X 6	
			85	X 7			X 8
	1.0	Stress (%)	70		X 9	X 10	
			75	X 11			X 12
			80	X 13			X 14
			85		X 15	X 16	
	1.5	Stress (%)	70		X 17	X 18	
			75	X 19			X 20
			80	X 21			X 22
			85		X 23	X 24	
	2.0	Stress (%)	70	X 25			X 26
			75		X 27	X 28	
			80		X 29	X 30	
			85	X 31			X 32

Fig. 10. A Four-by-Four-by-Four Factorial Experiment (One-Half Full)

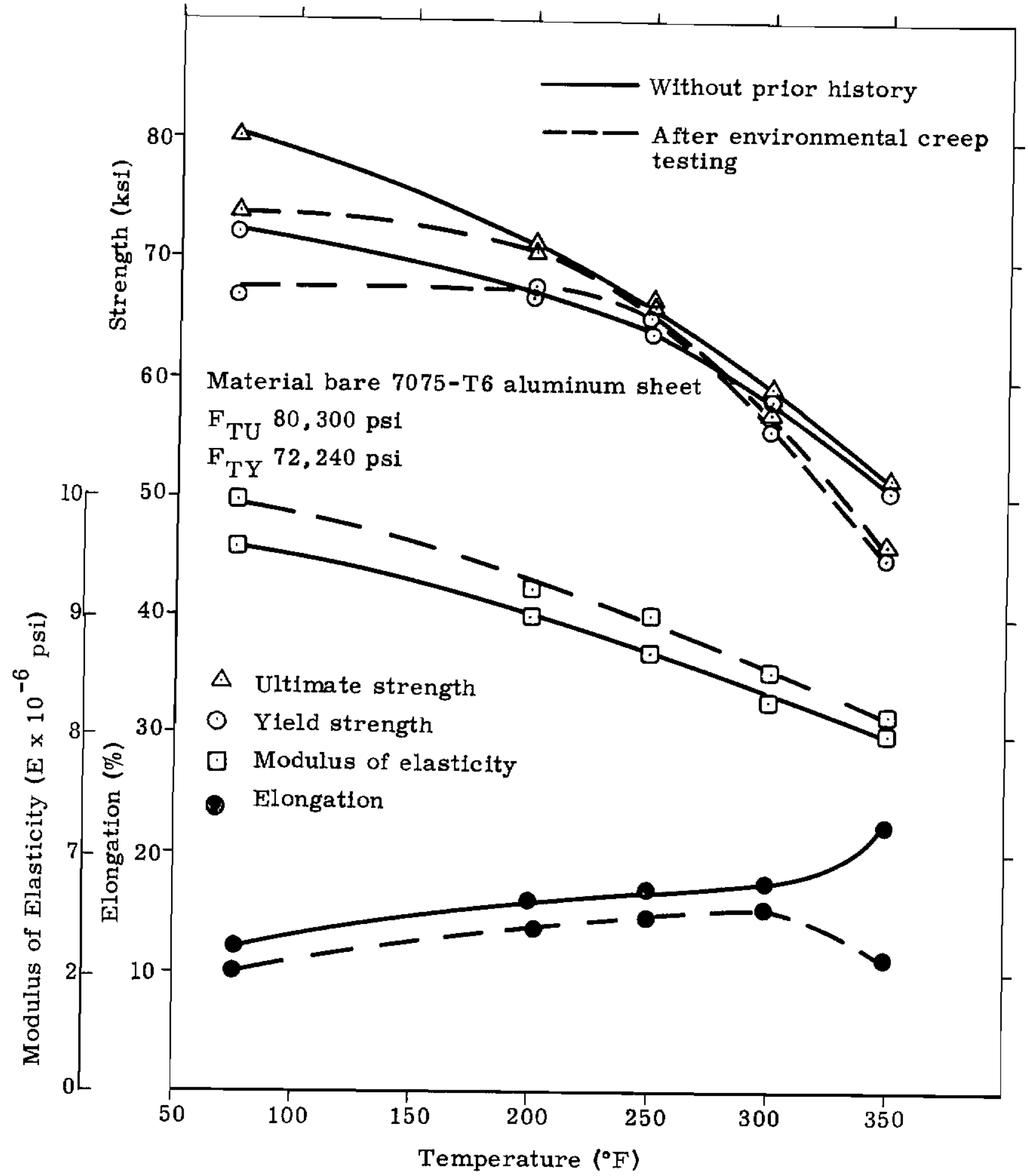


Fig. 11. Comparison of Static Tensile Properties Before and After Environmental Creep Tests--From Room Temperature to 350° F (7075-T6 Bare Aluminum Alloy Sheet)

Test	Seq	Temp (°F)	Stress (ksi)	Percent Yield *
20 R5	I	350	40.4	80
	II	200	50.4	75
	III	250	51.1	80
	IV	200	47	70

* Yield Strength at Test Temperature

— - — Strain Hardening Rule

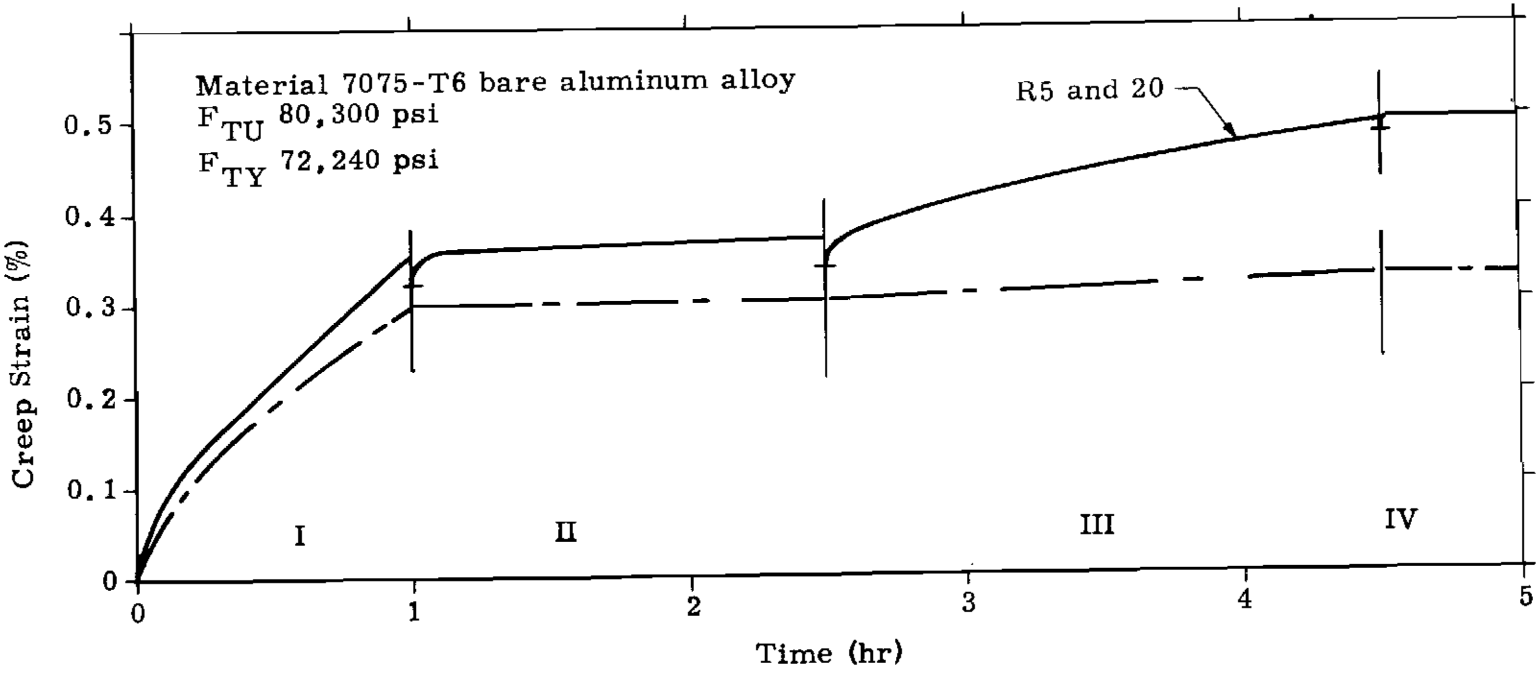


Fig. 12A. Reproducibility of Environmental Tests and Comparison to the Strain Hardening Rule (7075-T6 Bare Aluminum Alloy Sheet)

Time	Seq	Temp (°F)	Stress (ksi)	Percent Yield*
	I	300	40.7	70
14	II	250	47.9	75
R3	III	300	49.4	85
	IV	350	42.9	85

* Yield Strength at Test Temperature

— - — Strain Hardening Rule

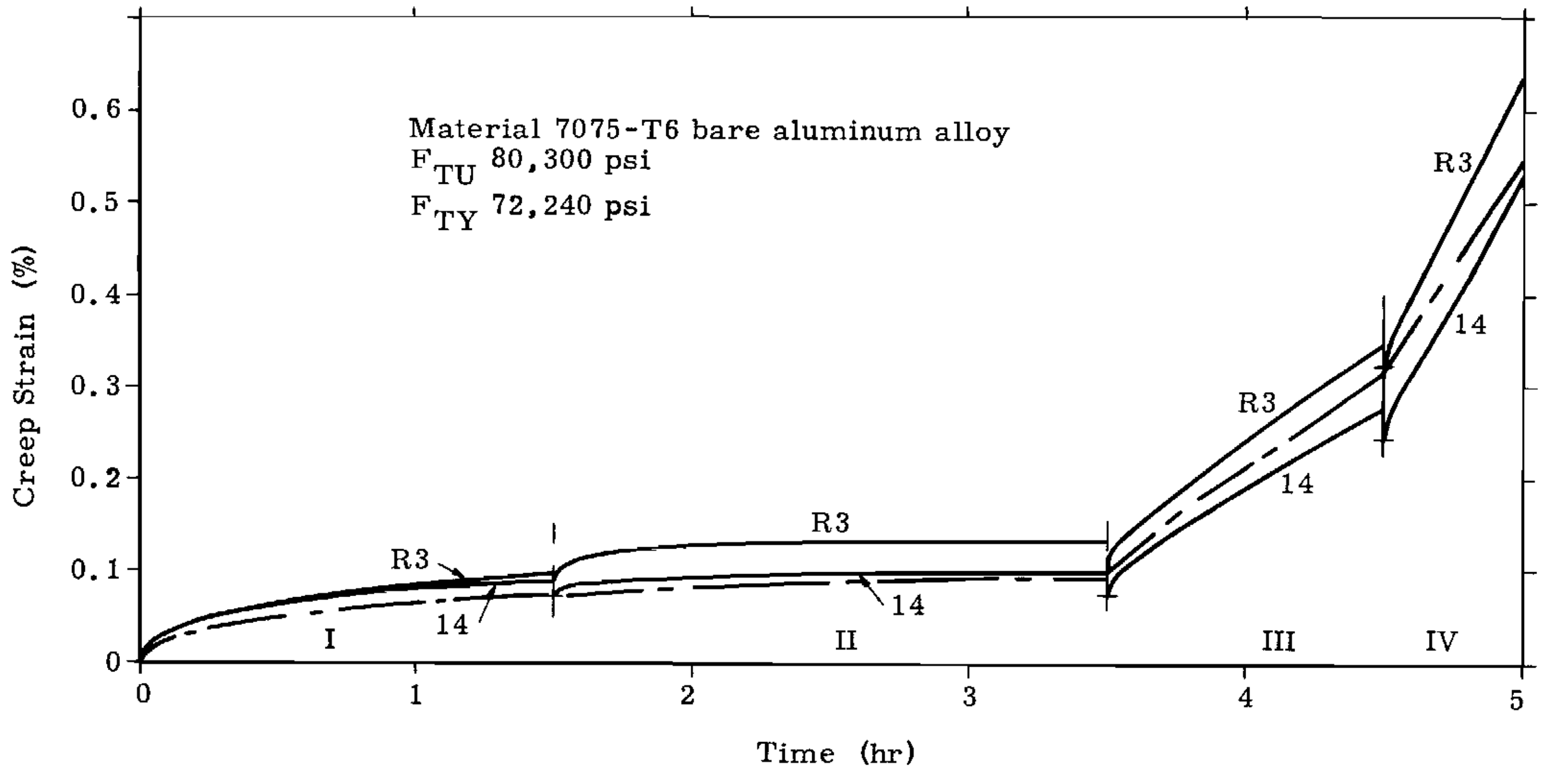


Fig. 12B. Reproducibility of Environmental Tests and Comparison to the Strain Hardening Rule (7075-T6 Bare Aluminum Alloy Sheet)

Test	Seq	Temp (°F)	Stress (ksi)	Percent Yield*
	I	250	44.7	70
28	II	300	43.6	75
R4	III	300	46.5	80
	IV	350	40.4	80

* Yield Strength at Test Temperature

—— - —— Strain Hardening Rule

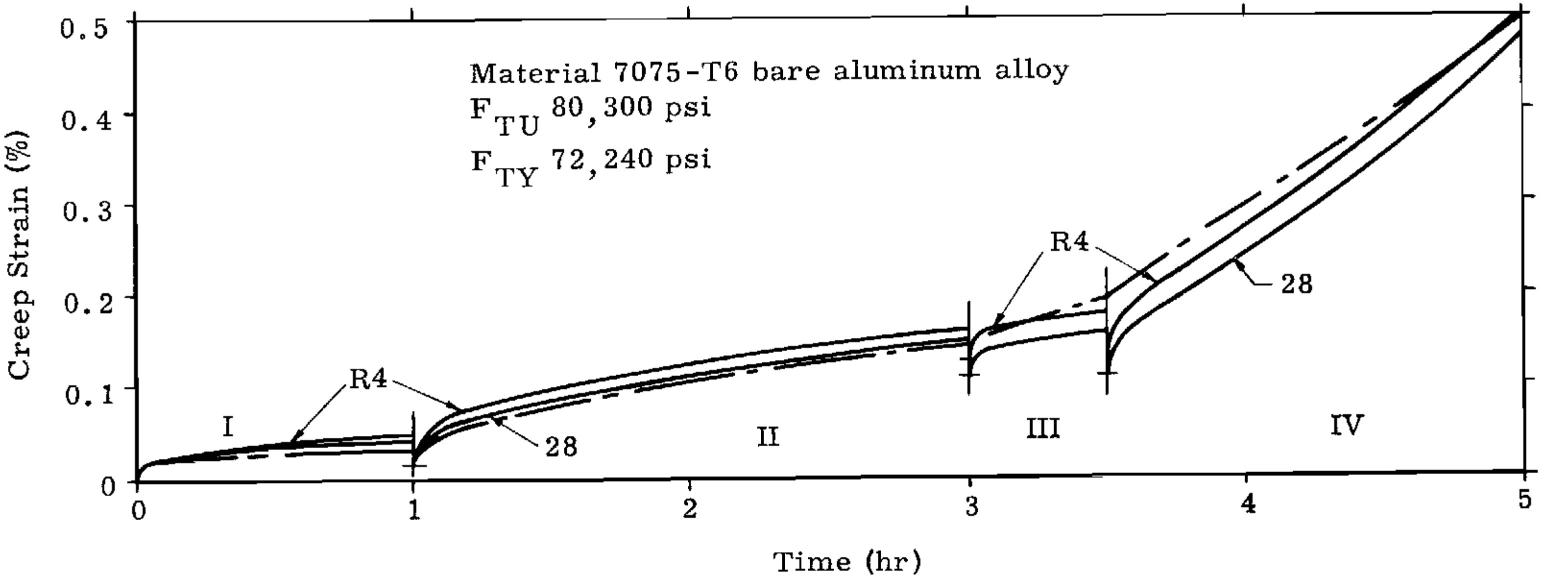
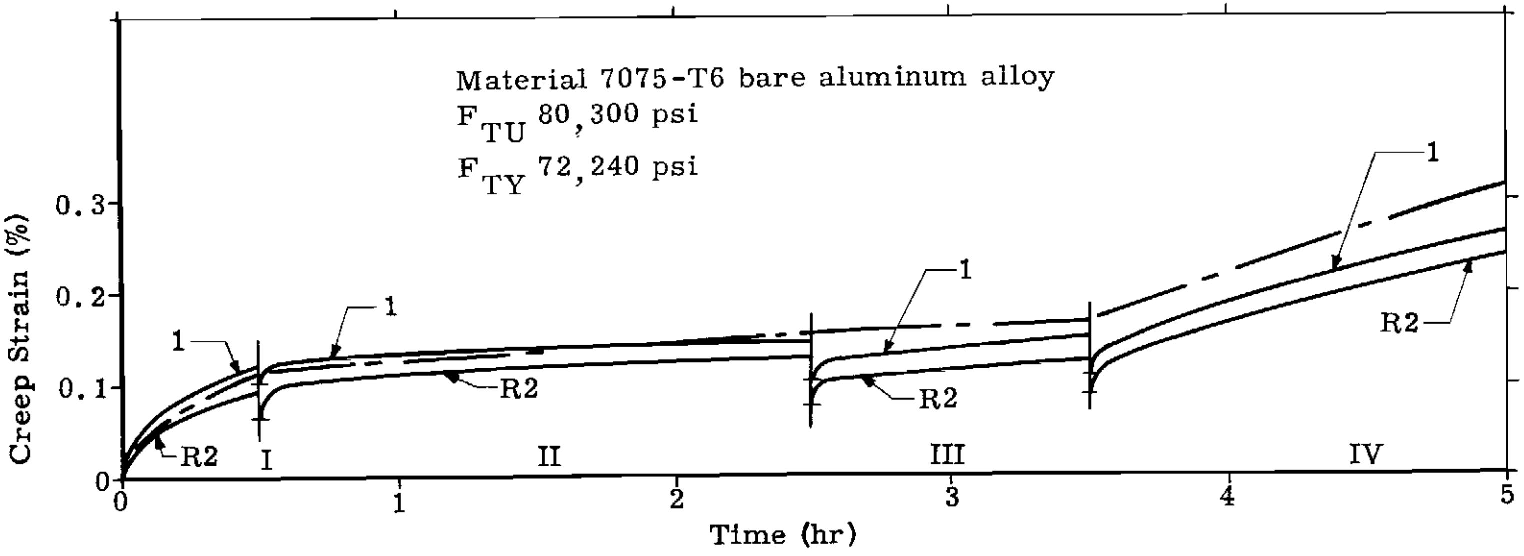


Fig. 12C. Reproducibility of Environmental Tests and Comparison to the Strain Hardening Rule (7075-T6 Bare Aluminum Alloy Sheet)

Test	Seq	Temp (°F)	Stress (ksi)	Percent Yield*
	I	300	46.5	80
1	II	250	51.1	80
R2	III	300	40.7	70
	IV	350	37.9	75

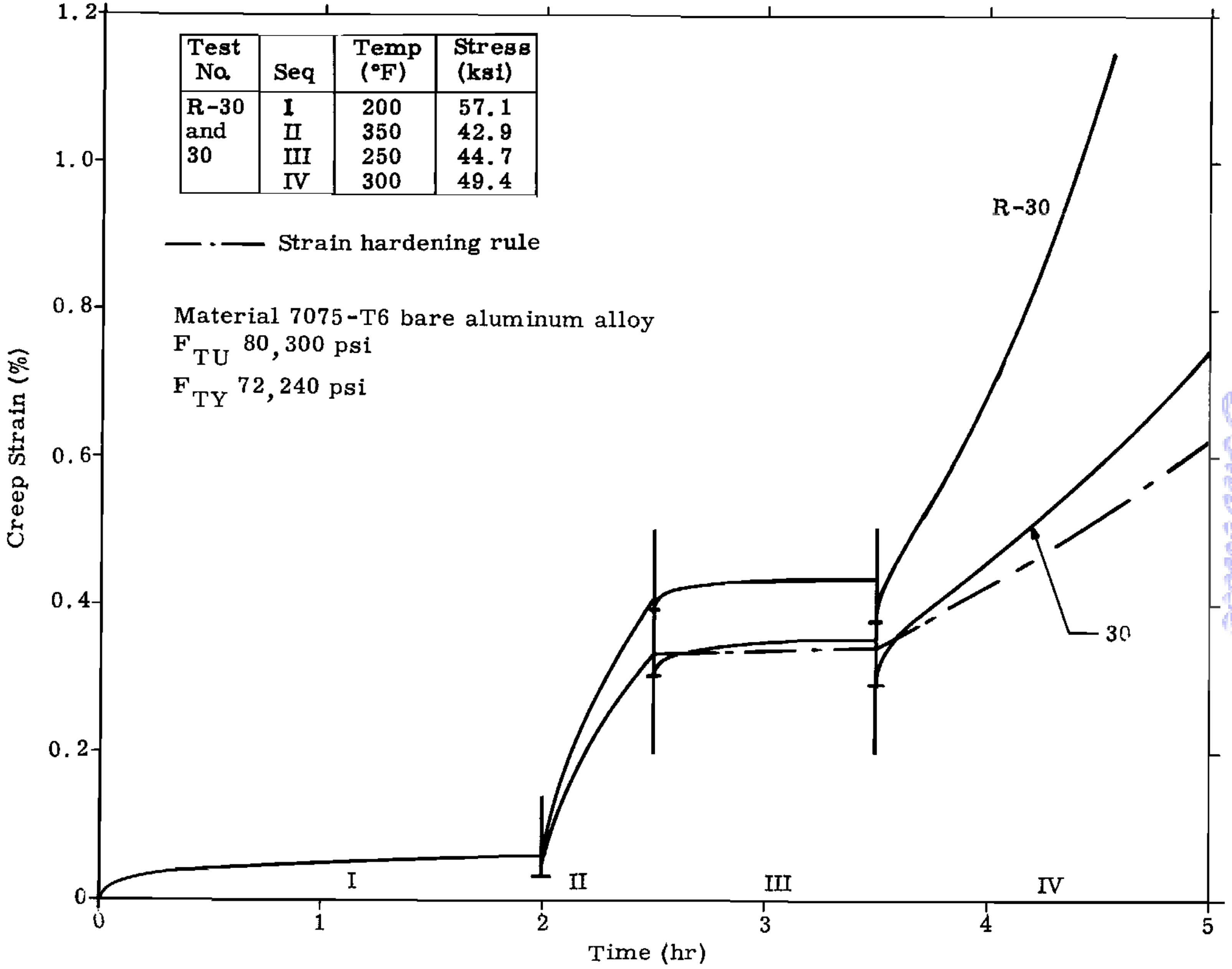
* Yield Strength at Test Temperature

—— - —— Strain Hardening Rule



Material 7075-T6 bare aluminum alloy
F_{TU} 80,300 psi
F_{TY} 72,240 psi

Fig. 12D. Reproducibility of Environmental Tests and Comparison to the Strain Hardening Rule (7075-T6 Bare Aluminum Alloy Sheet)



Test No.	Seq	Temp (°F)	Stress (ksi)
R-30 and 30	I	200	57.1
	II	350	42.9
	III	250	44.7
	IV	300	49.4

Fig. 12E. Reproducibility of Environmental Tests and Comparison to the Strain Hardening Rule (7075-T6 Bare Aluminum Alloy Sheet)

Test	Seq	Stress (ksi)	Percent Yield *
	I	40.4	80
40	II	35.4	70
40A	III	42.9	85
	IV	37.9	75

* Yield Strength at Test Temperature

—·— Strain hardening rule

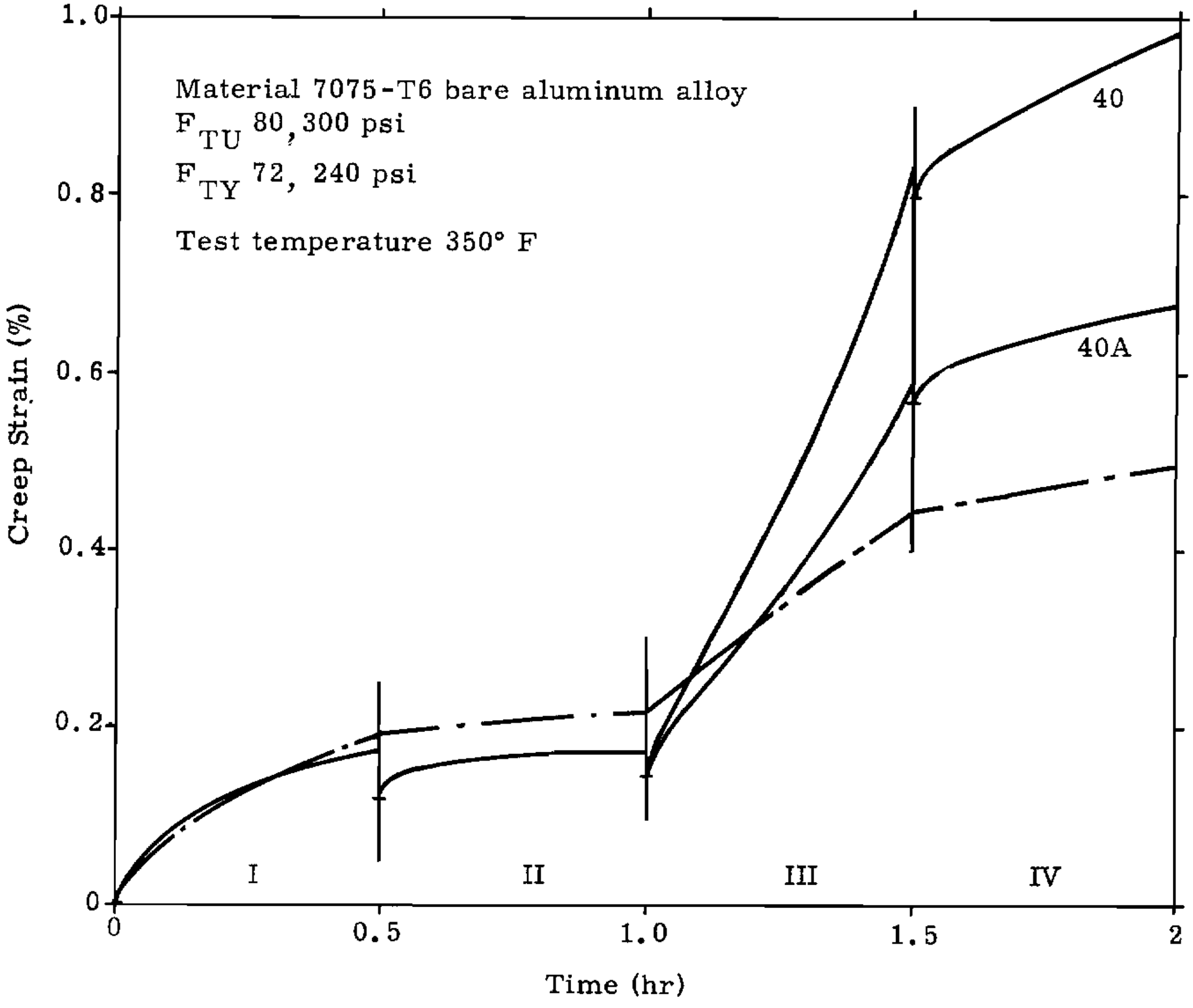


Fig. 12F. Reproducibility of Environmental Tests and Comparison to the Strain Hardening Rule (7075-T6 Bare Aluminum Alloy Sheet)

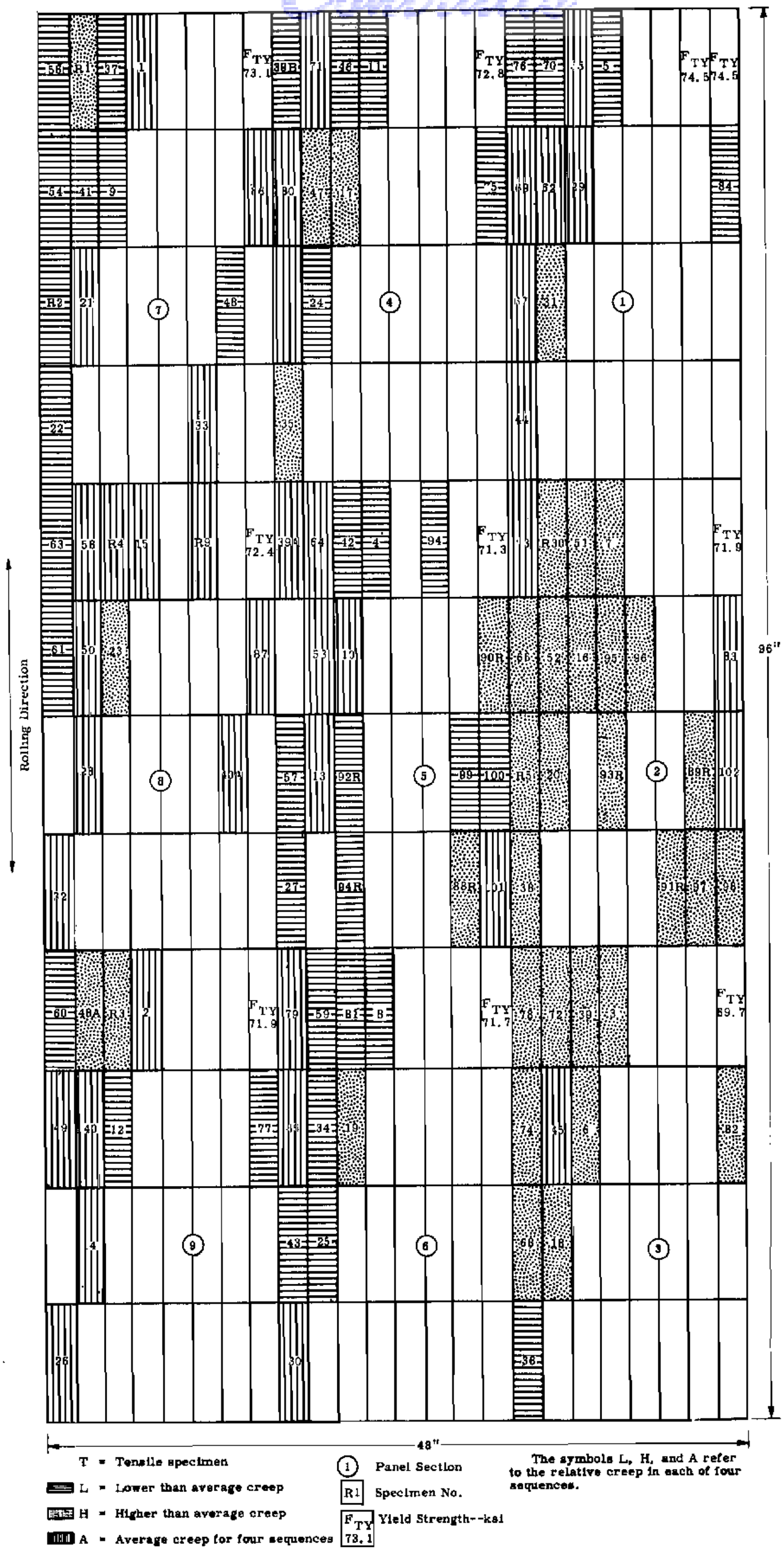


Fig. 13. Relation of Specimen Creep Behavior to Yield Strength and Origin in Aluminum Sheet

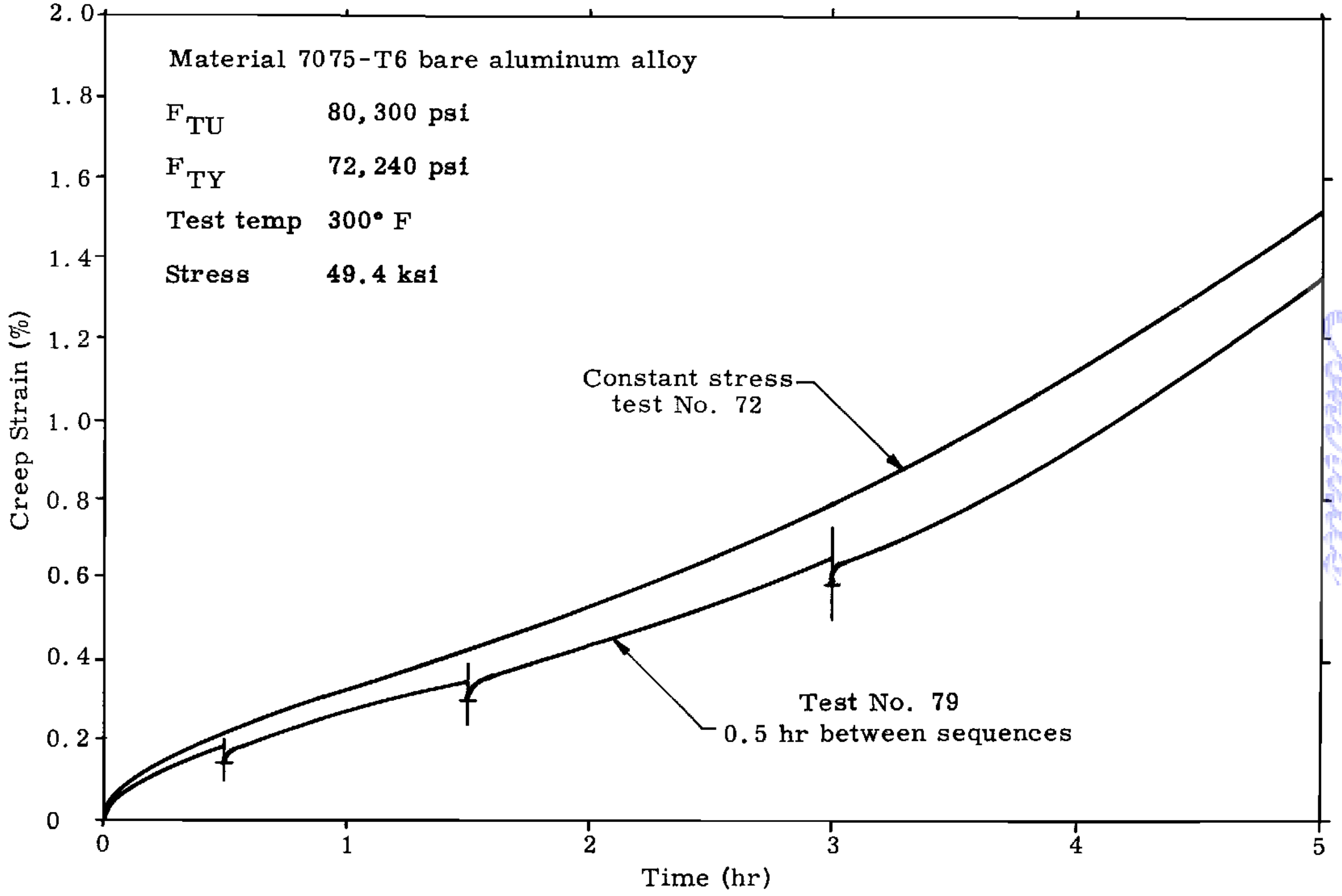


Fig. 14A. Comparison of Creep Curves for Intermittent Stress and Several Temperatures

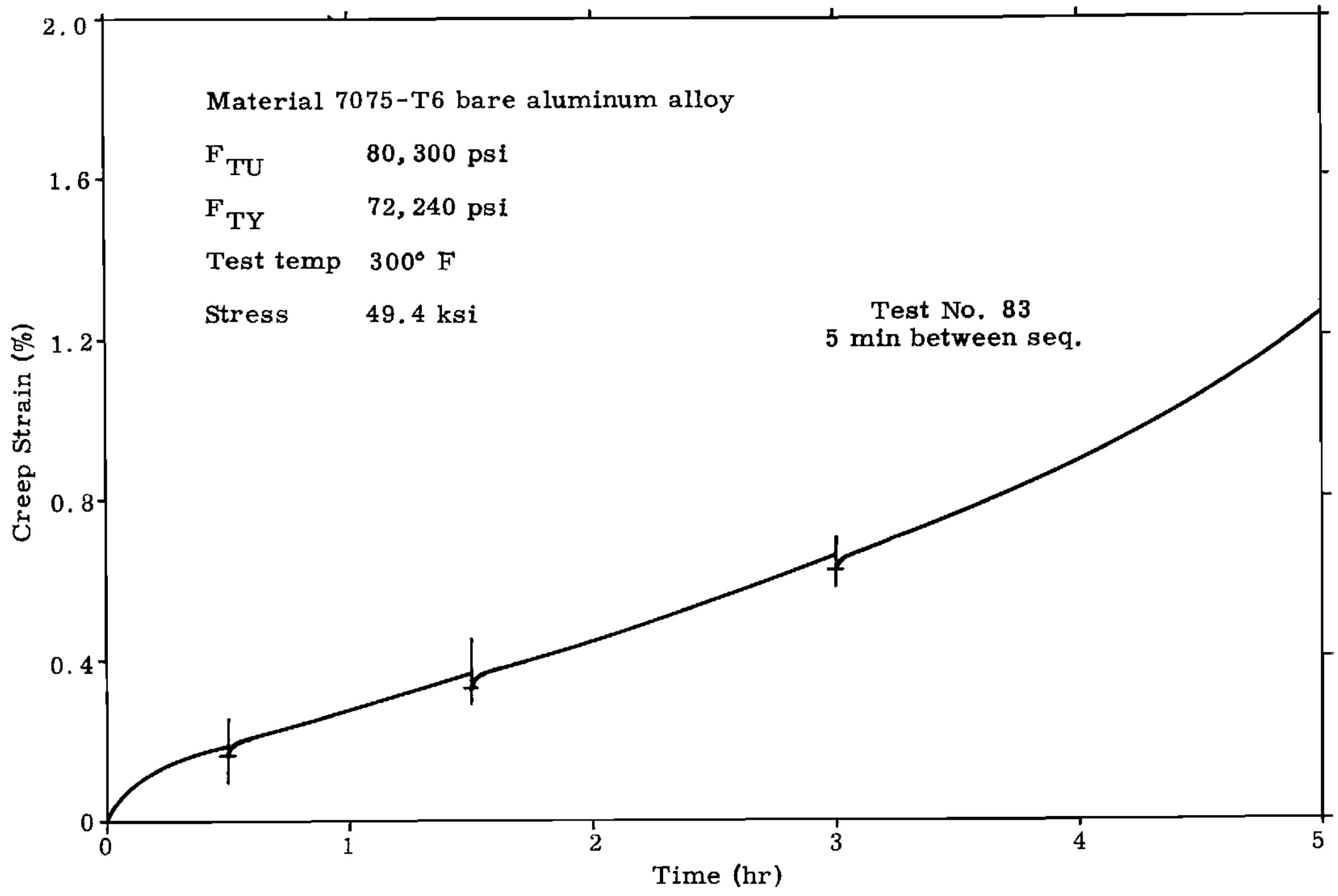


Fig. 14B. Comparison of Creep Curves for Intermittent Stress and Several Temperatures

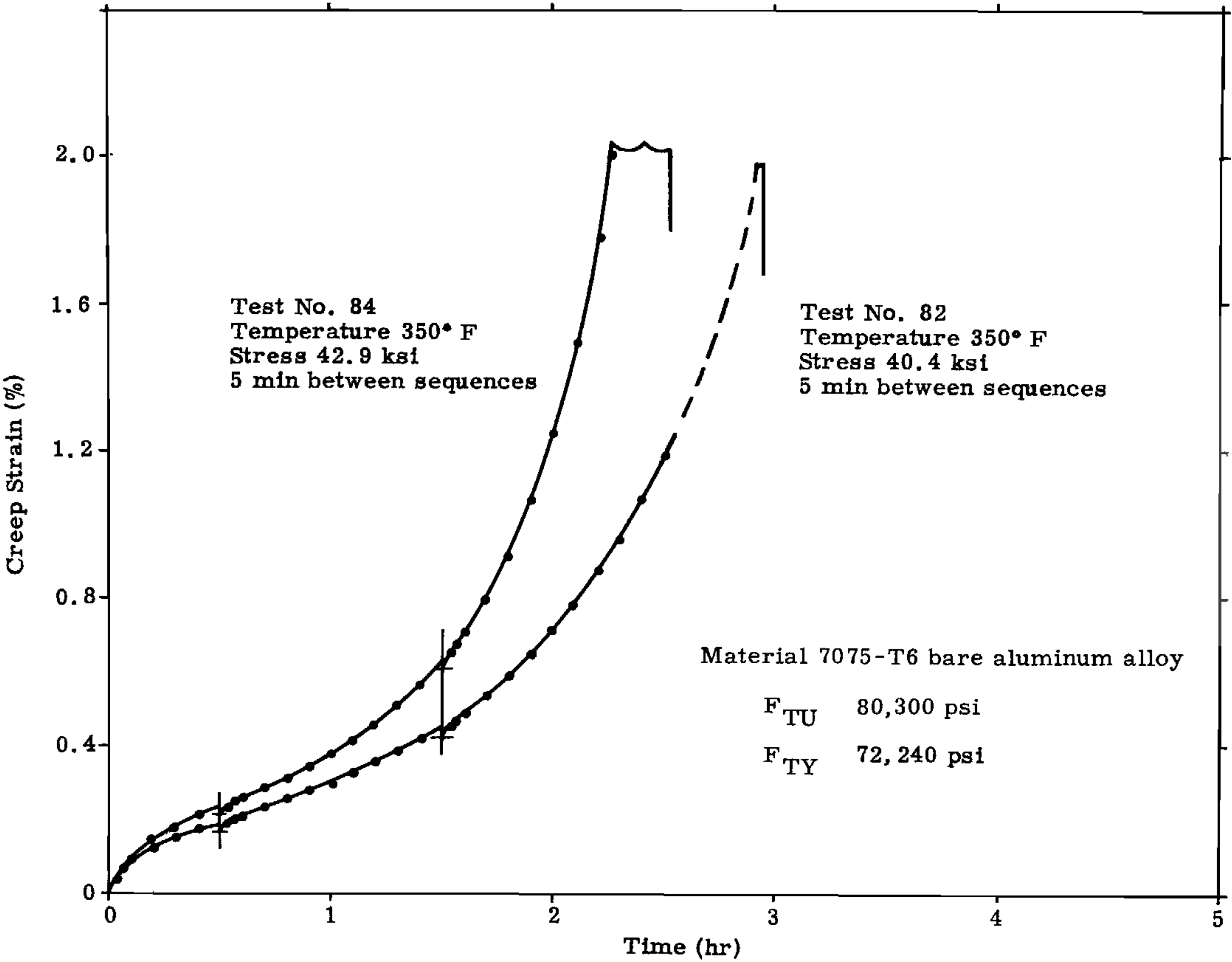


Fig. 14C. Comparison of Creep Curves for Intermittent Stress and Several Temperatures

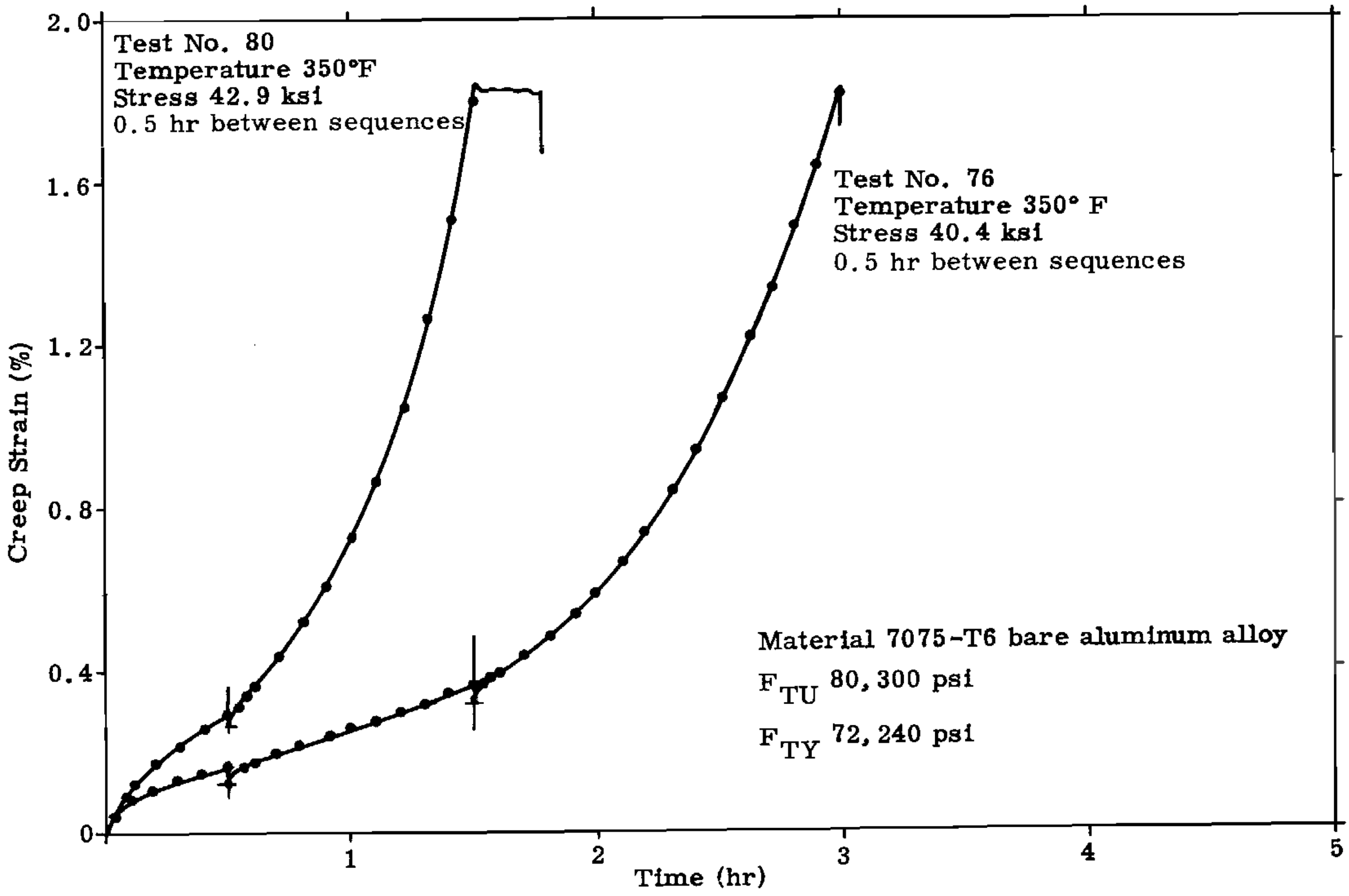


Fig. 14D. Comparison of Creep Curves for Intermittent Stress and Several Temperatures

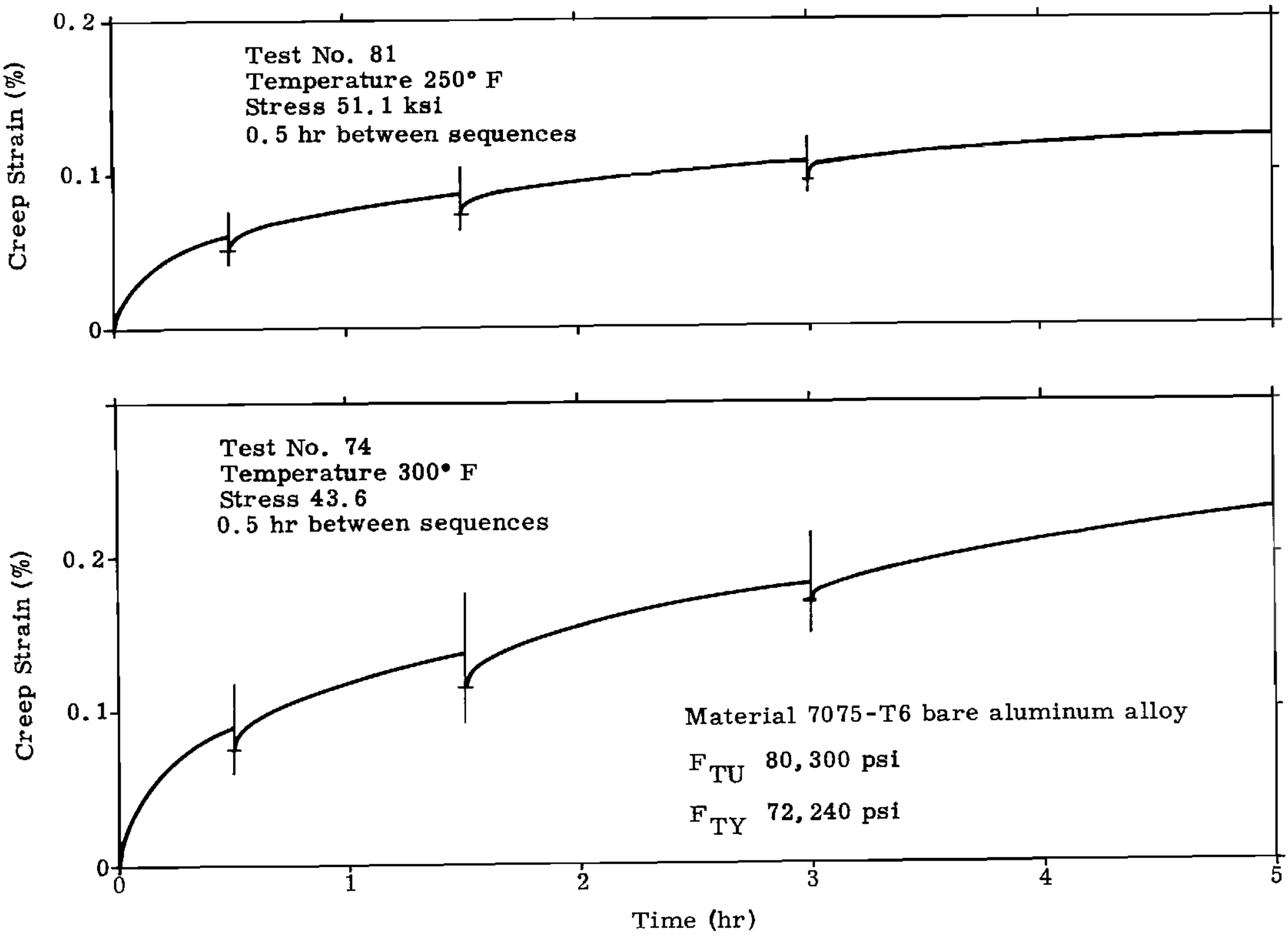


Fig. 14E. Comparison of Creep Curves for Intermittent Stress and Several Temperatures

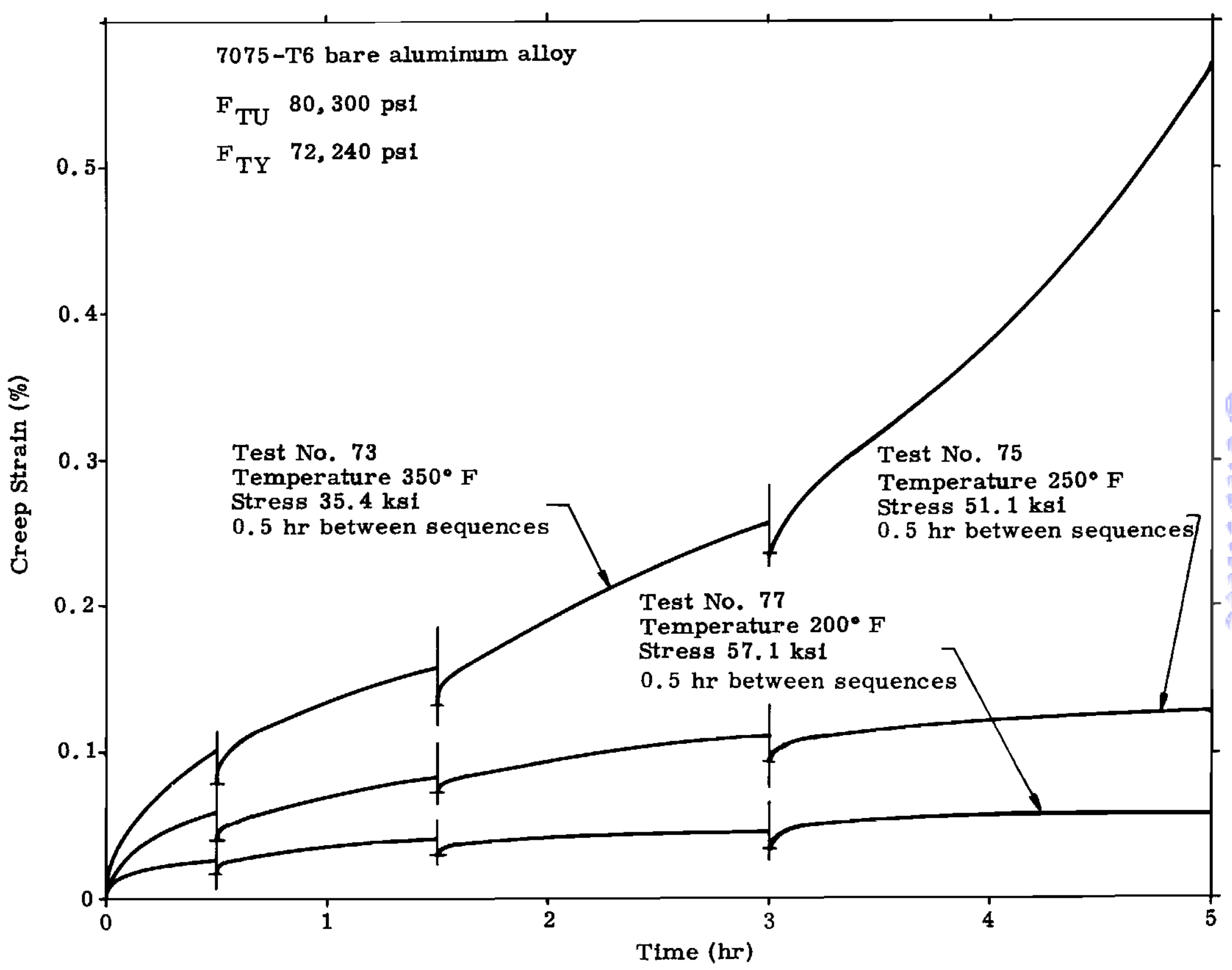
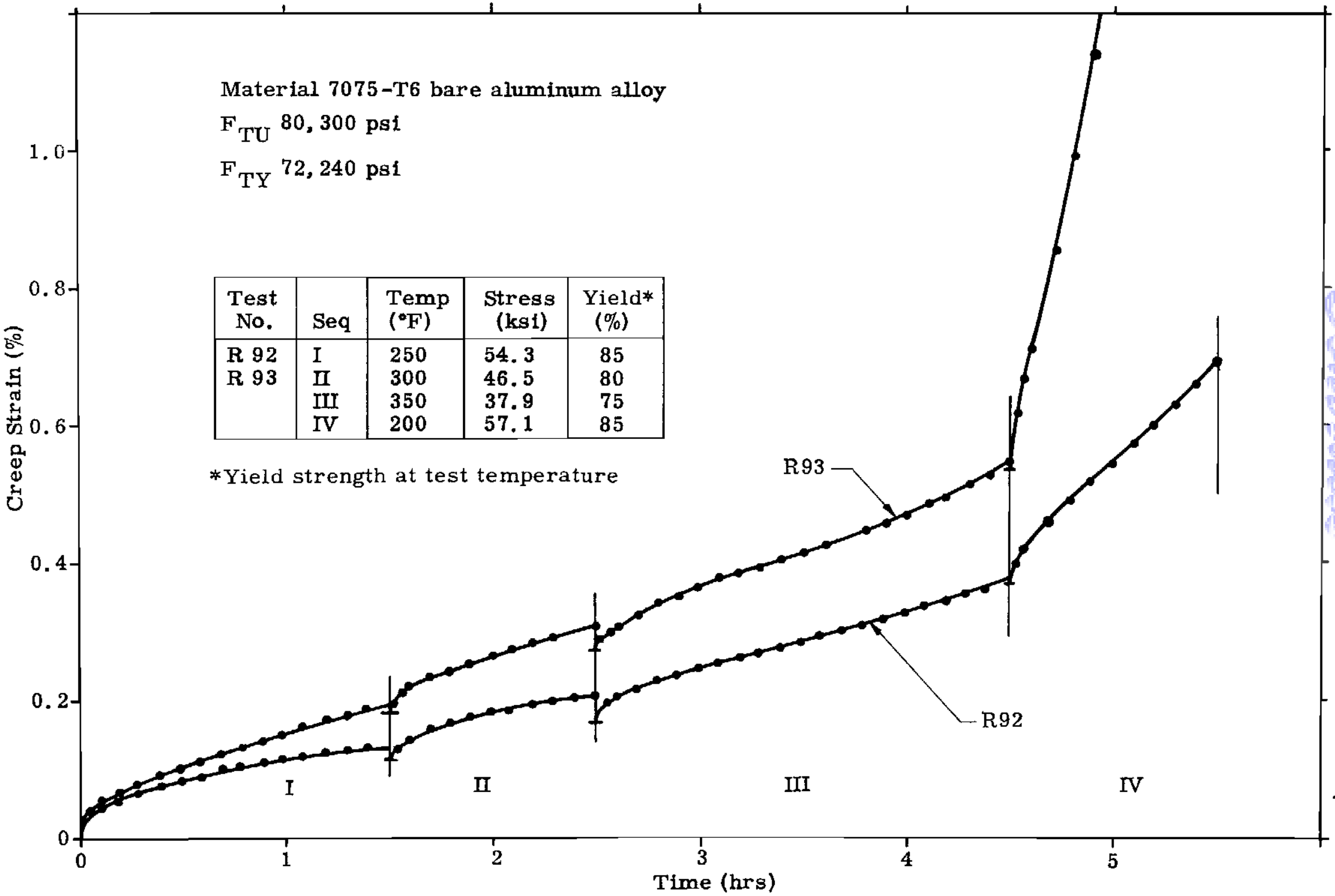


Fig. 14F. Comparison of Creep Curves for Intermittent Stress and Several Temperatures



Test No.	Seq	Temp (°F)	Stress (ksi)	Yield* (%)
R 92	I	250	54.3	85
R 93	II	300	46.5	80
	III	350	37.9	75
	IV	200	57.1	85

*Yield strength at test temperature

Fig. 14G. Comparison of Creep Curves for Intermittent Stress and Several Temperatures

Material 7075-T6 bare aluminum alloy
F_{TU} 80,300 psi
F_{TY} 72,240 psi

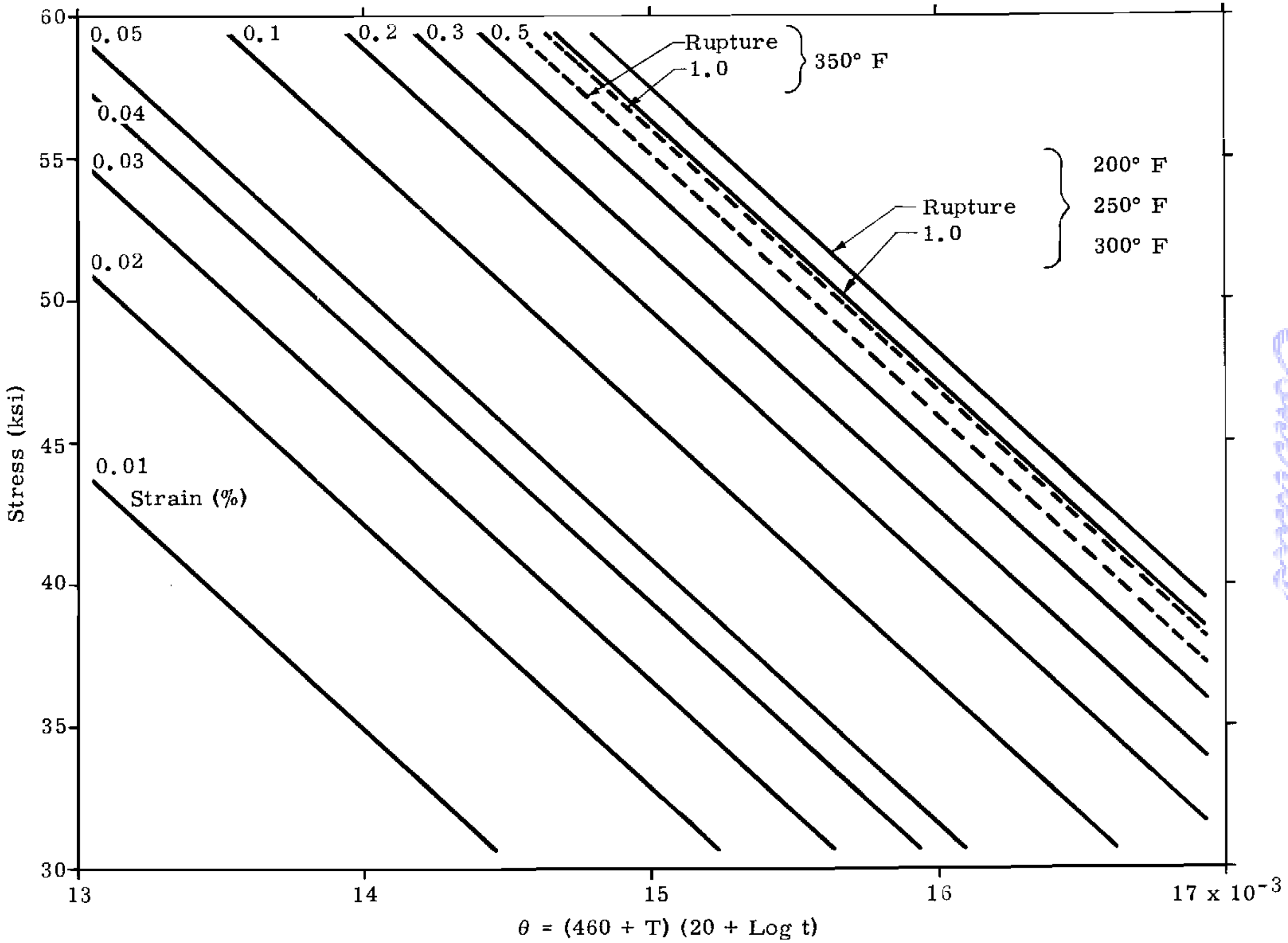
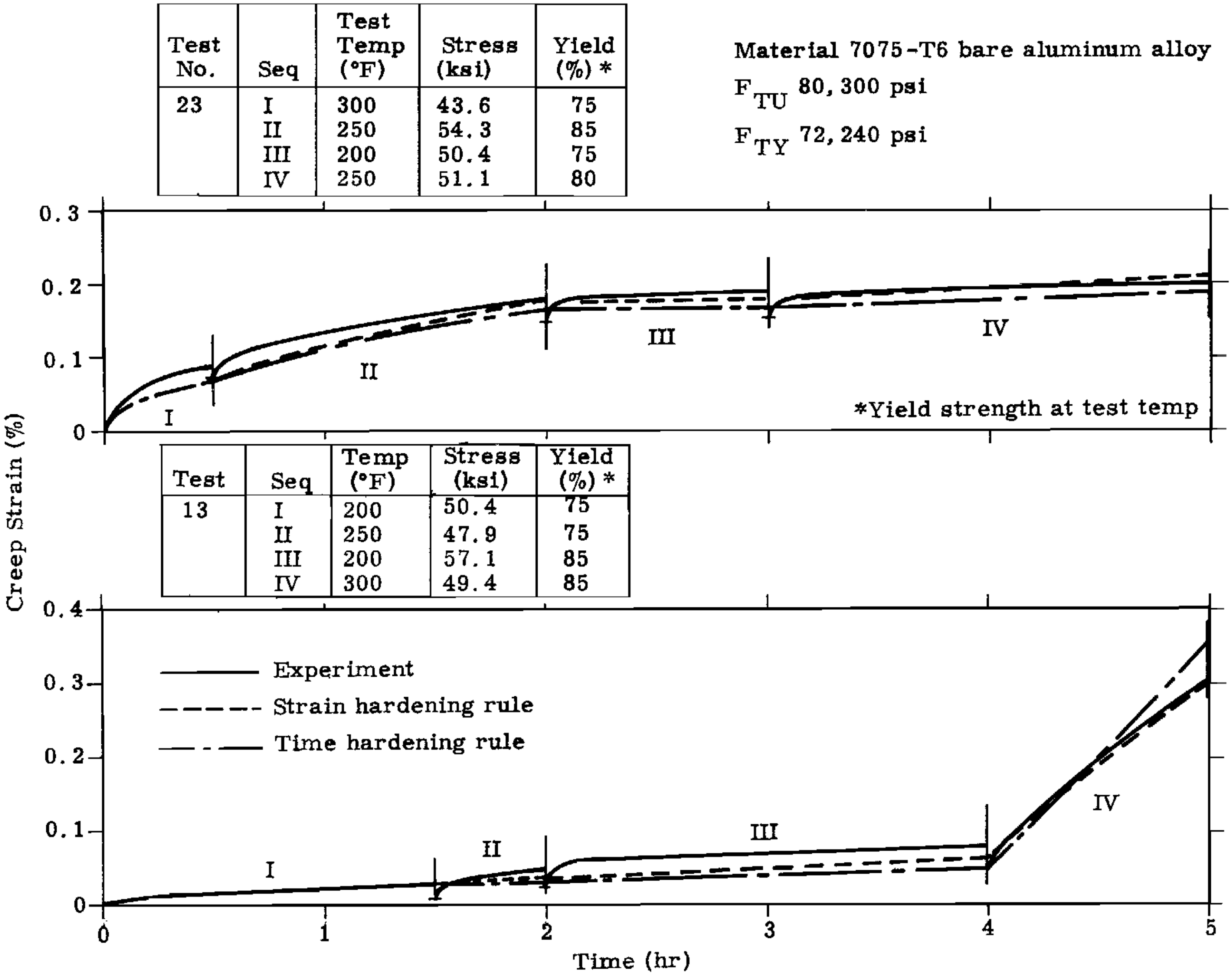


Fig. 15. Larsen-Miller Plot of Creep Data for 7075-T6 Bare Aluminum Alloy Sheet



Test No.	Seq	Test Temp (°F)	Stress (ksi)	Yield (%) *
23	I	300	43.6	75
	II	250	54.3	85
	III	200	50.4	75
	IV	250	51.1	80

Material 7075-T6 bare aluminum alloy

F_{TU} 80,300 psi

F_{TY} 72,240 psi

*Yield strength at test temp

Test	Seq	Temp (°F)	Stress (ksi)	Yield (%) *
13	I	200	50.4	75
	II	250	47.9	75
	III	200	57.1	85
	IV	300	49.4	85

Figs. 16A and B. Environmental Creep Curves (Four Sequences of Stress-Temperature-Time) for 7075-T6 Bare Aluminum Alloy Compared to the Strain Hardening Creep Rule

Test No.	Seq	Temp (°F)	Stress (ksi)	Yield (%)*
22	I	300	49.4	85
	II	200	53.8	80
	III	200	47.0	70
	IV	250	51.1	80

* Yield strength at test temperature

Material 7075-T6 bare aluminum alloy

F_{TU} 80,300 psi

F_{TY} 72,240 psi

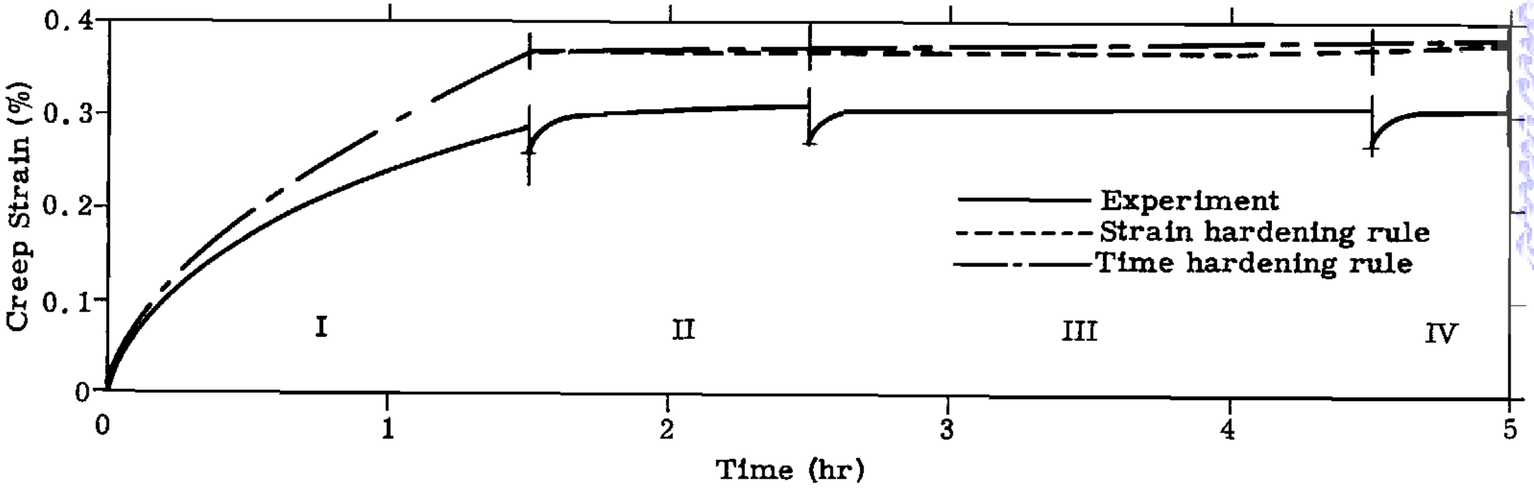


Fig. 16C. Environmental Creep Curves (Four Sequences of Stress-Temperature-Time) for 7075-T6 Bare Aluminum Alloy Compared to the Strain Hardening Creep Rule

Test No.	Seq	Test Temp (°F)	Stress (ksi)	Yield (%)*
25	I	350	40.4	80
	II	250	44.7	70
	III	250	47.9	75
	IV	350	35.4	70

*Yield strength at test temperature

Material 7075-T6 bare aluminum alloy

F_{TU} 80,300 psi

F_{TY} 72,240 psi

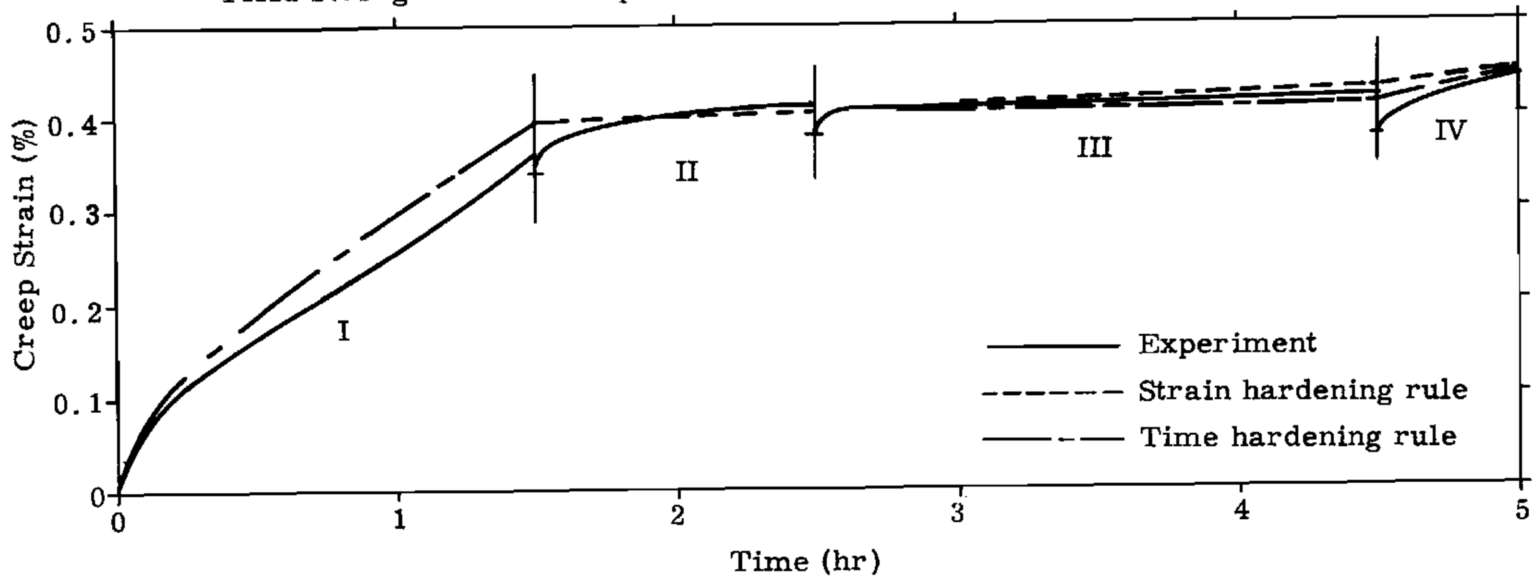


Fig. 16D. Environmental Creep Curves (Four Sequences of Stress-Temperature-Time) for 7075-T6 Bare Aluminum Alloy Compared to the Strain Hardening Creep Rule

Test No.	Seq	Temp (°F)	Stress (ksi)	Yield (%)*
3	I	250	54.3	85
	II	350	37.9	75
	III	250	51.1	80
	IV	300	43.6	75

* Yield strength at test temperature

Material 7075-T6 bare aluminum alloy

F_{TU} 80,300 psi

F_{TY} 72,240 psi

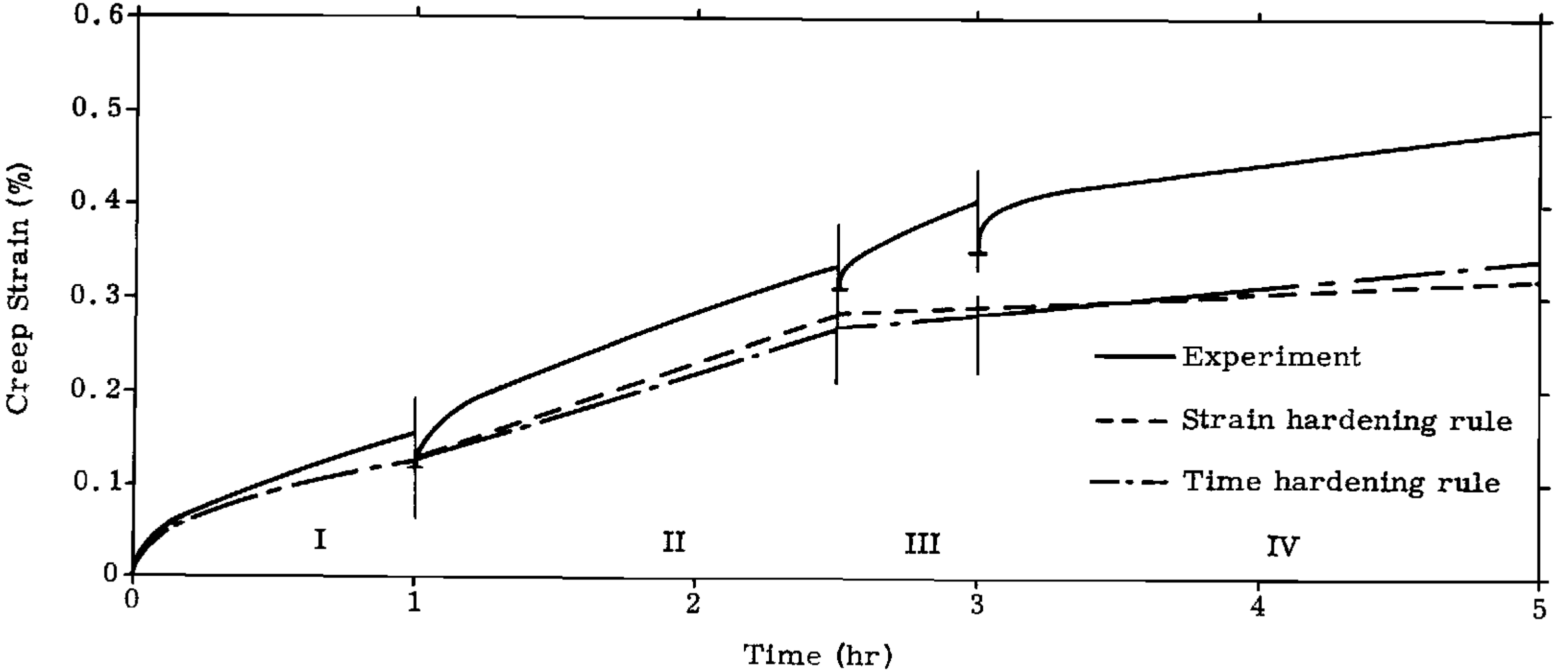


Fig. 16E. Environmental Creep Curves (Four Sequences of Stress-Temperature-Time) for 7075-T6 Bare Aluminum Alloy Compared to the Strain Hardening Creep Rule

Test No.	Seq	Temp (°F)	Stress (ksi)	Yield (%) *
18	I	300	40.7	70
	II	300	49.4	85
	III	250	47.9	75
	IV	300	46.5	80

* Yield strength at test temperature

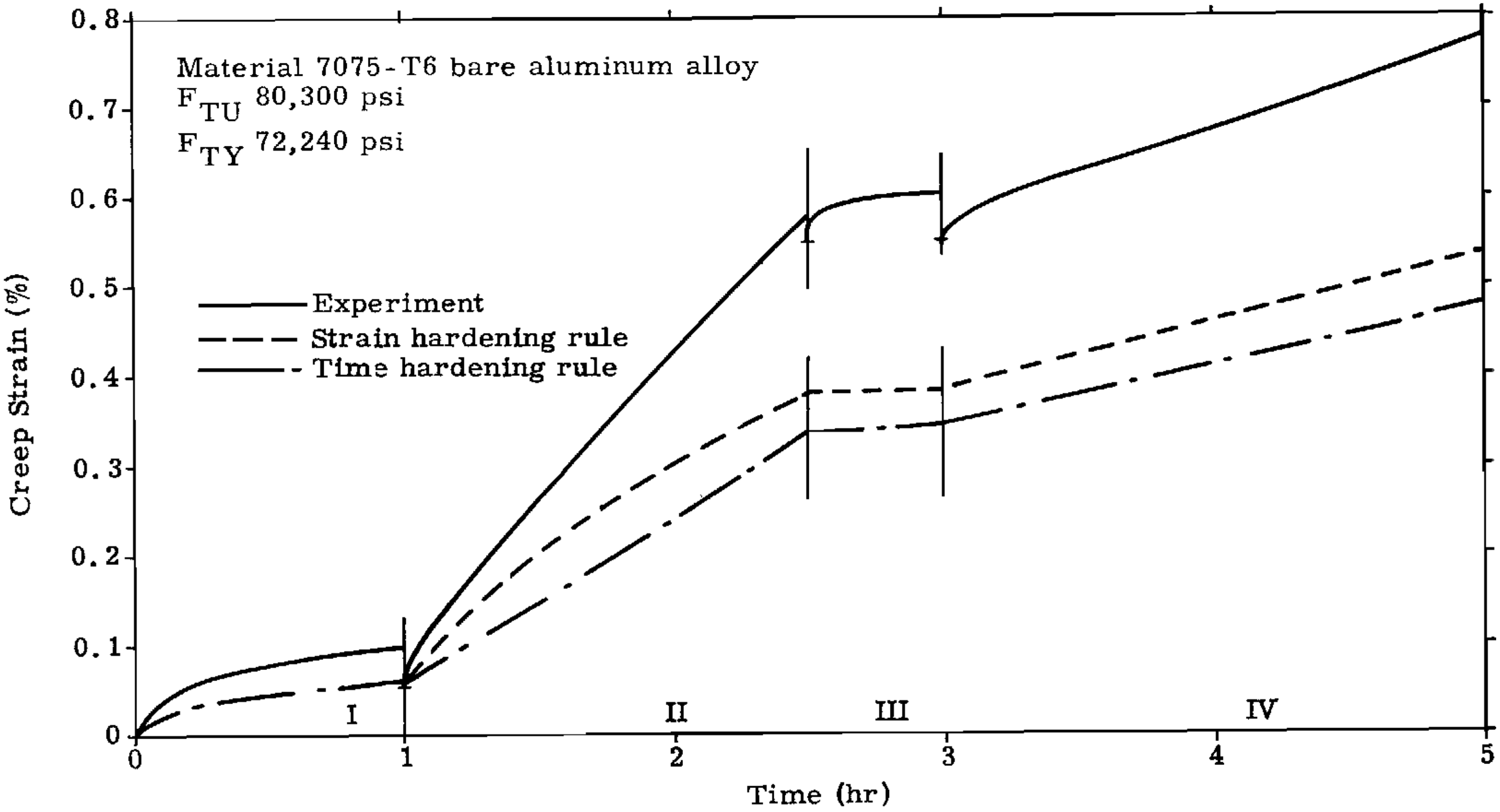


Fig. 16F. Environmental Creep Curves (Four Sequences of Stress-Temperature-Time) for 7075-T6 Bare Aluminum Alloy Compared to the Strain Hardening Creep Rule

Test No.	Seq	Test Temp (°F)	Stress (ksi)	Yield (%)*
9	I	350	35.4	70
	II	350	37.9	75
	III	250	54.3	85
	IV	350	35.4	70

* Yield strength at test temperature

Material 7075-T6 bare aluminum alloy

F_{TU} 80,300 psi

F_{TY} 72,240 psi

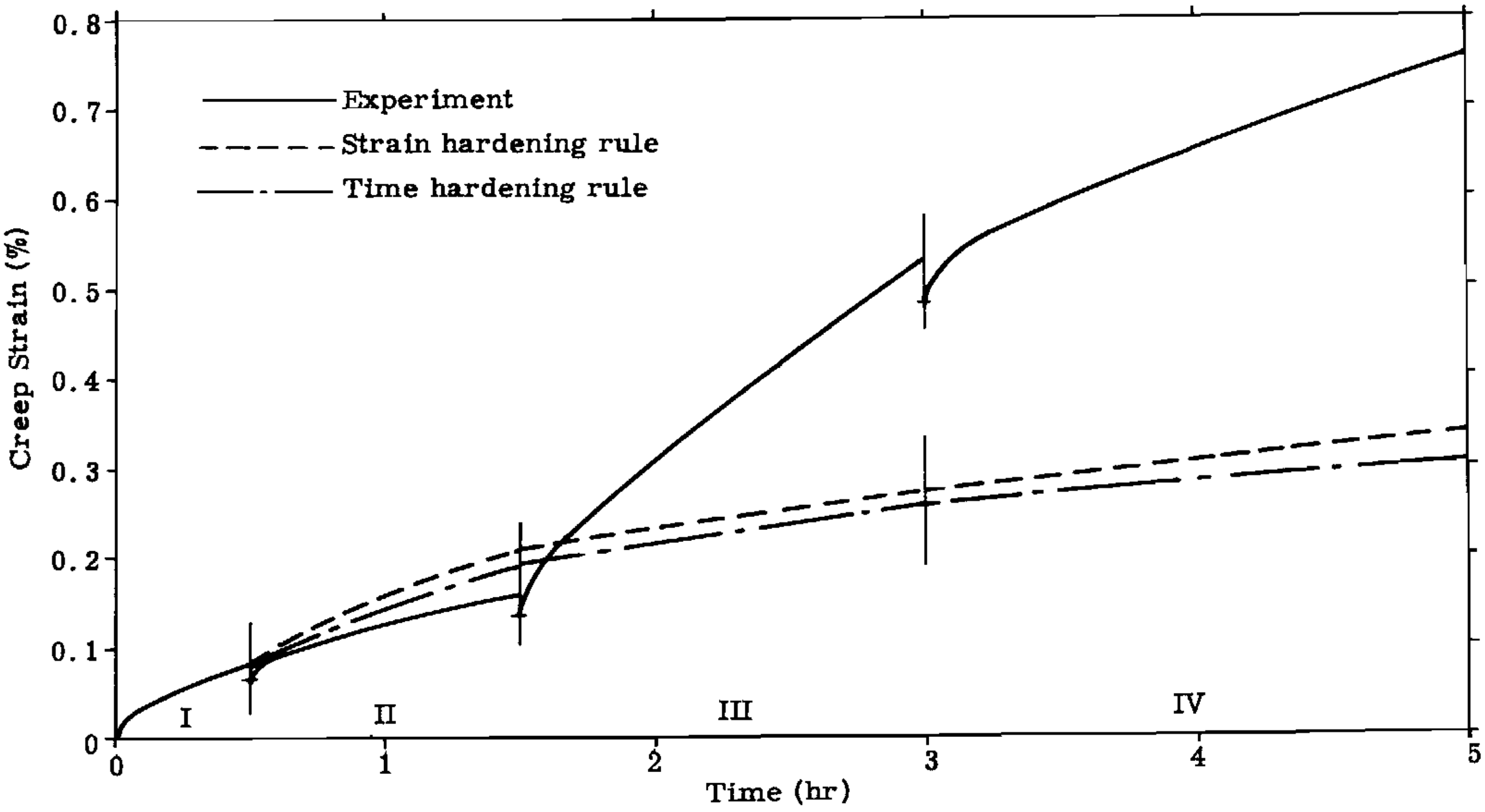
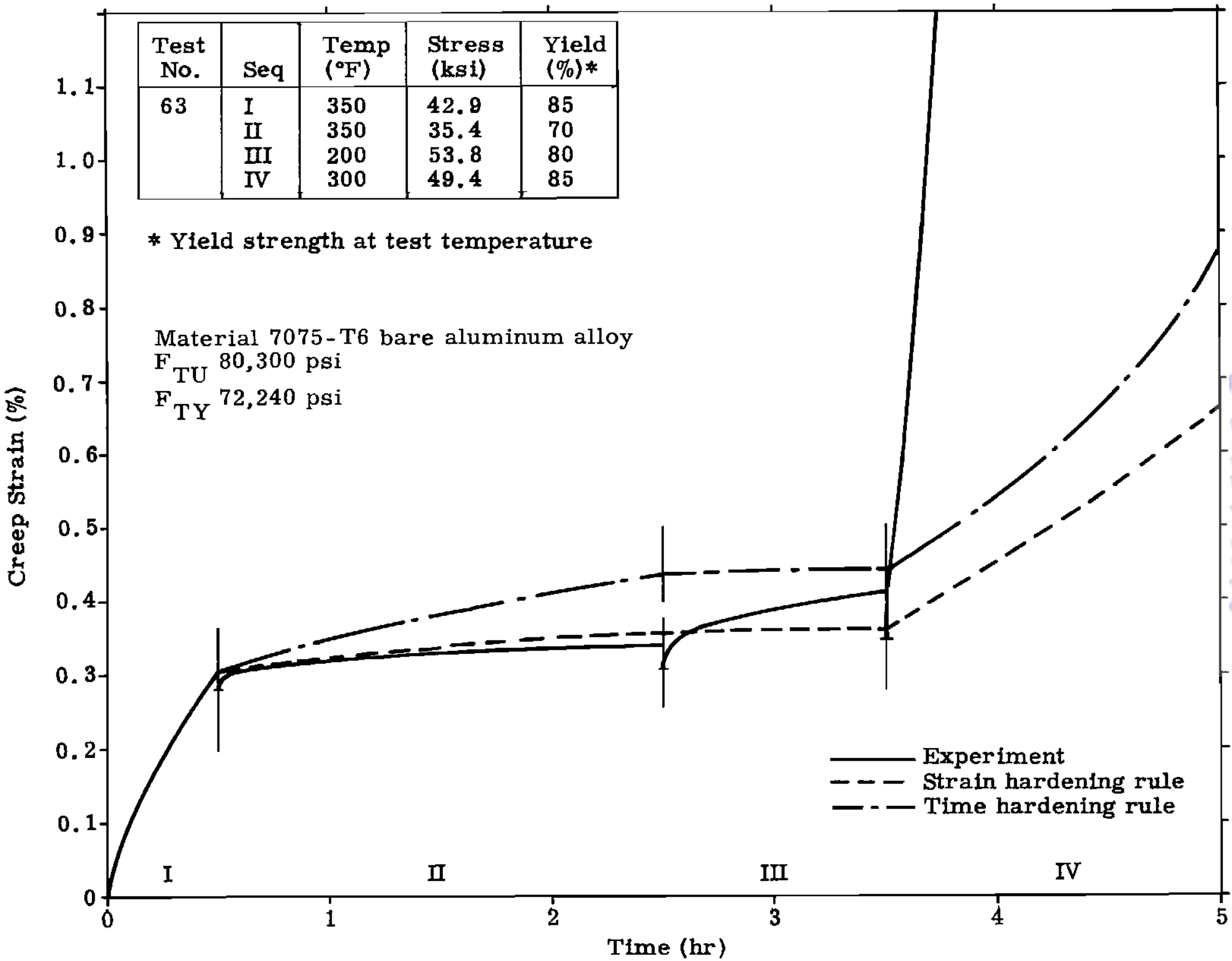
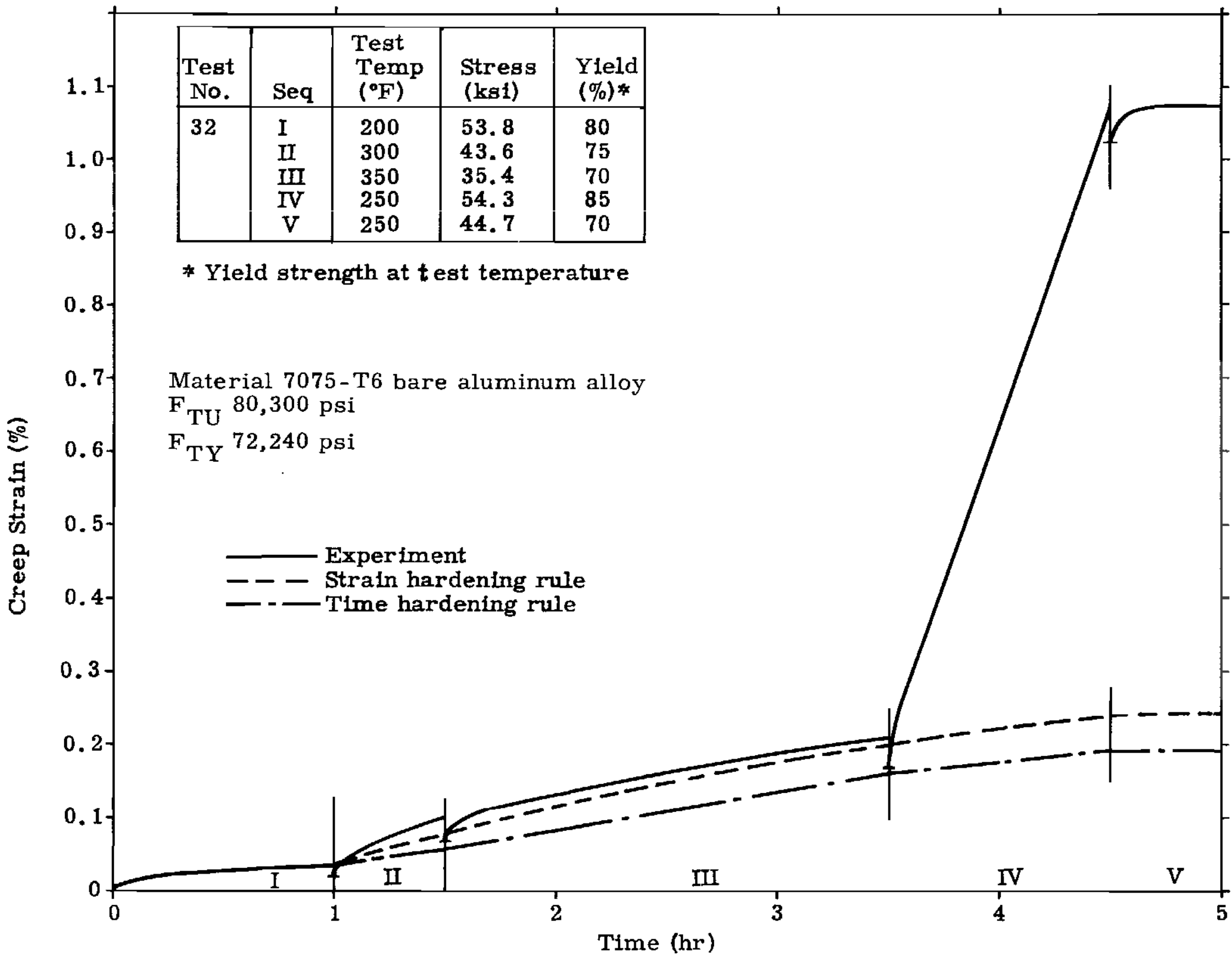


Fig. 16G. Environmental Creep Curves (Four Sequences of Stress-Temperature-Time) for 7075-T6 Bare Aluminum Alloy Compared to the Strain Hardening Creep Rule



Test No.	Seq	Temp (°F)	Stress (ksi)	Yield (%)*
63	I	350	42.9	85
	II	350	35.4	70
	III	200	53.8	80
	IV	300	49.4	85

Fig. 16H. Environmental Creep Curves (Four Sequences of Stress-Temperature-Time) for 7075-T6 Bare Aluminum Alloy Compared to the Strain Hardening Creep Rule



Test No.	Seq	Test Temp (°F)	Stress (ksi)	Yield (%)*
32	I	200	53.8	80
	II	300	43.6	75
	III	350	35.4	70
	IV	250	54.3	85
	V	250	44.7	70

* Yield strength at test temperature

Material 7075-T6 bare aluminum alloy
F_{TU} 80,300 psi
F_{TY} 72,240 psi

Fig. 16I. Environmental Creep Curves (Four Sequences of Stress-Temperature-Time) for 7075-T6 Bare Aluminum Alloy Compared to the Strain Hardening Creep Rule

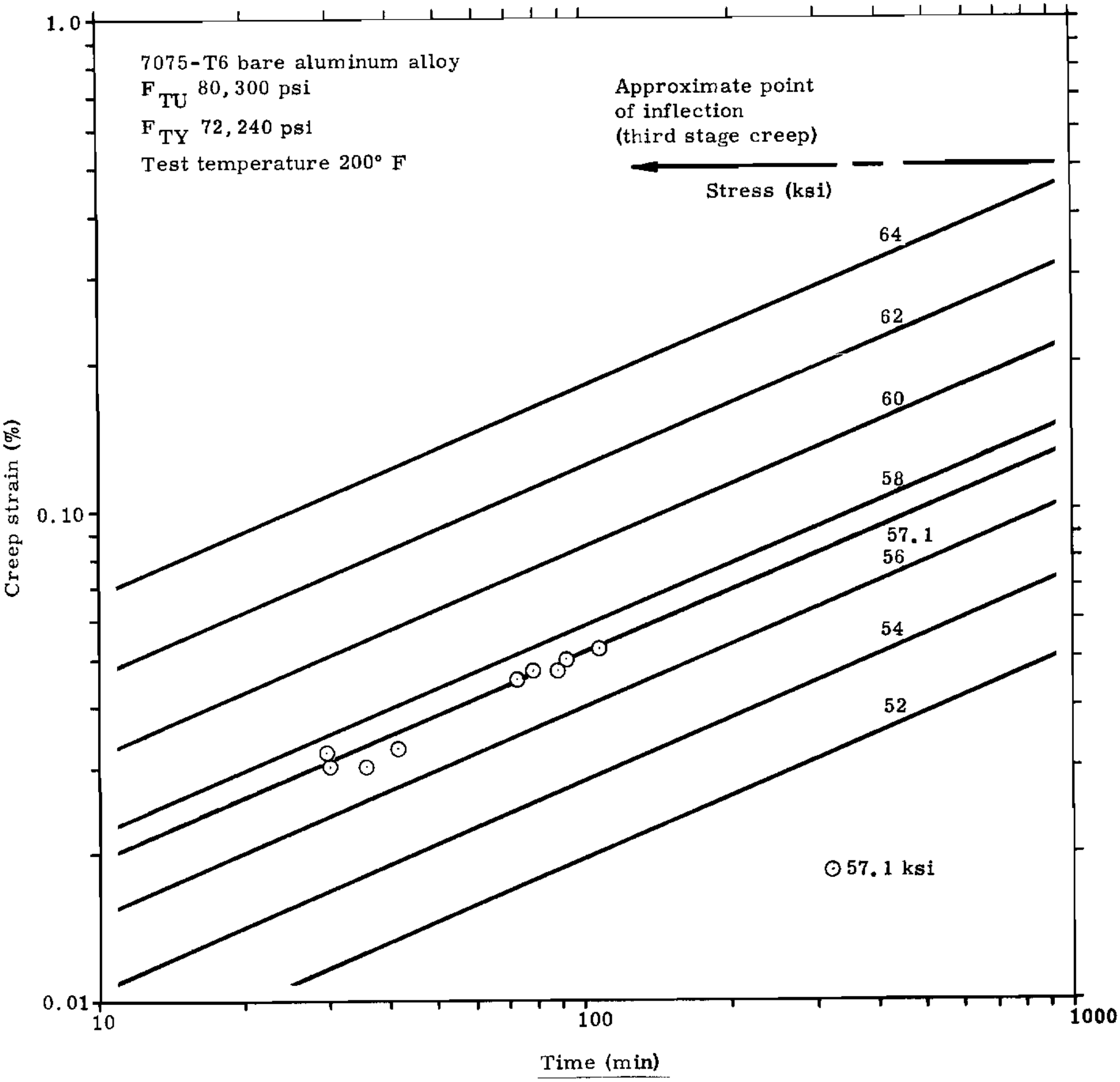


Fig. 17. Log-Log Plot of Creep Versus Time at 200° F for 7075-T6 Bare Aluminum Alloy (Valid for Primary and Secondary Stages of Creep)

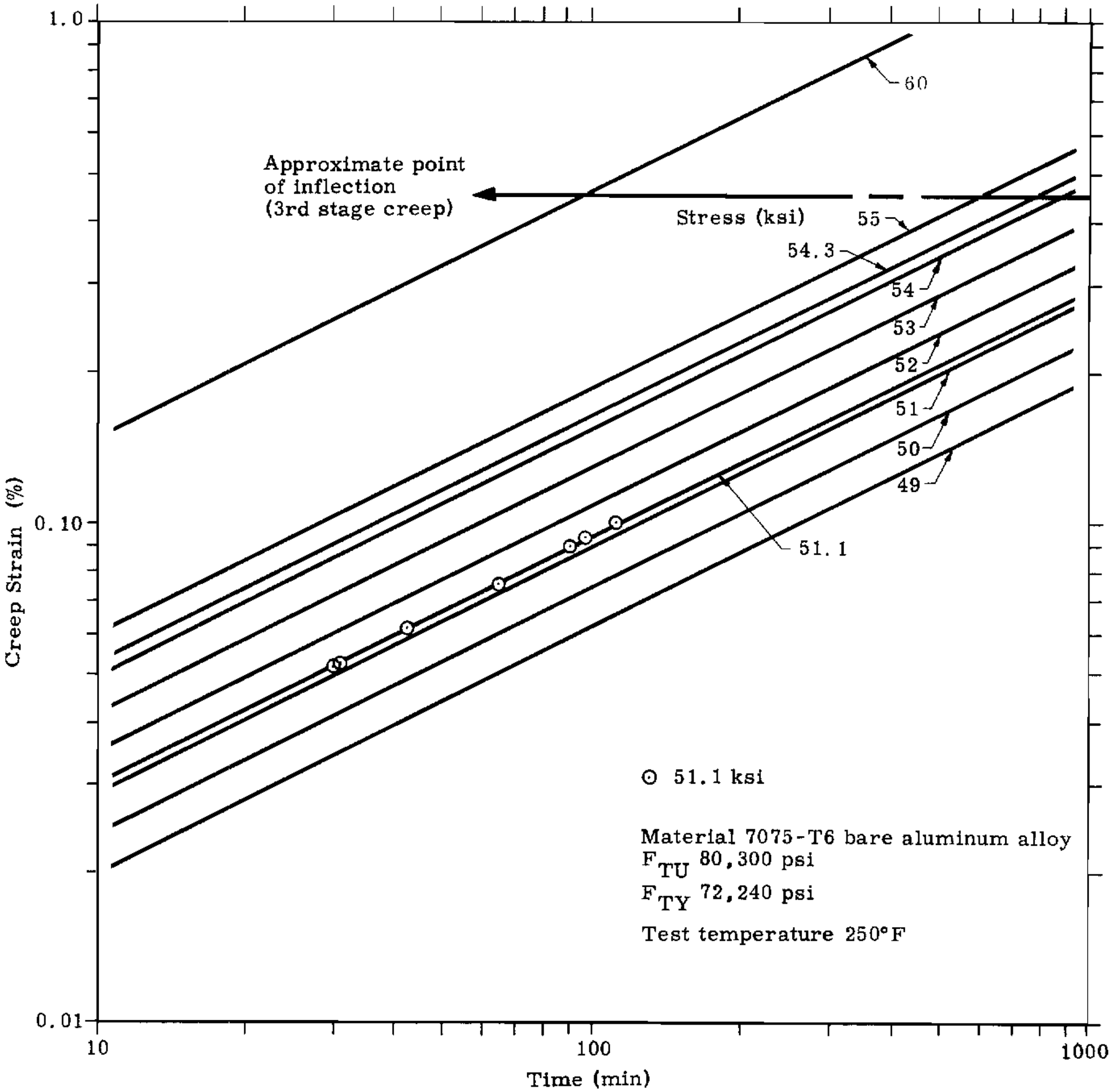


Fig. 18. Log-Log Plot of Creep Versus Time at 250° F for 7075-T6 Bare Aluminum Alloy (Valid for Primary and Secondary Stages of Creep)

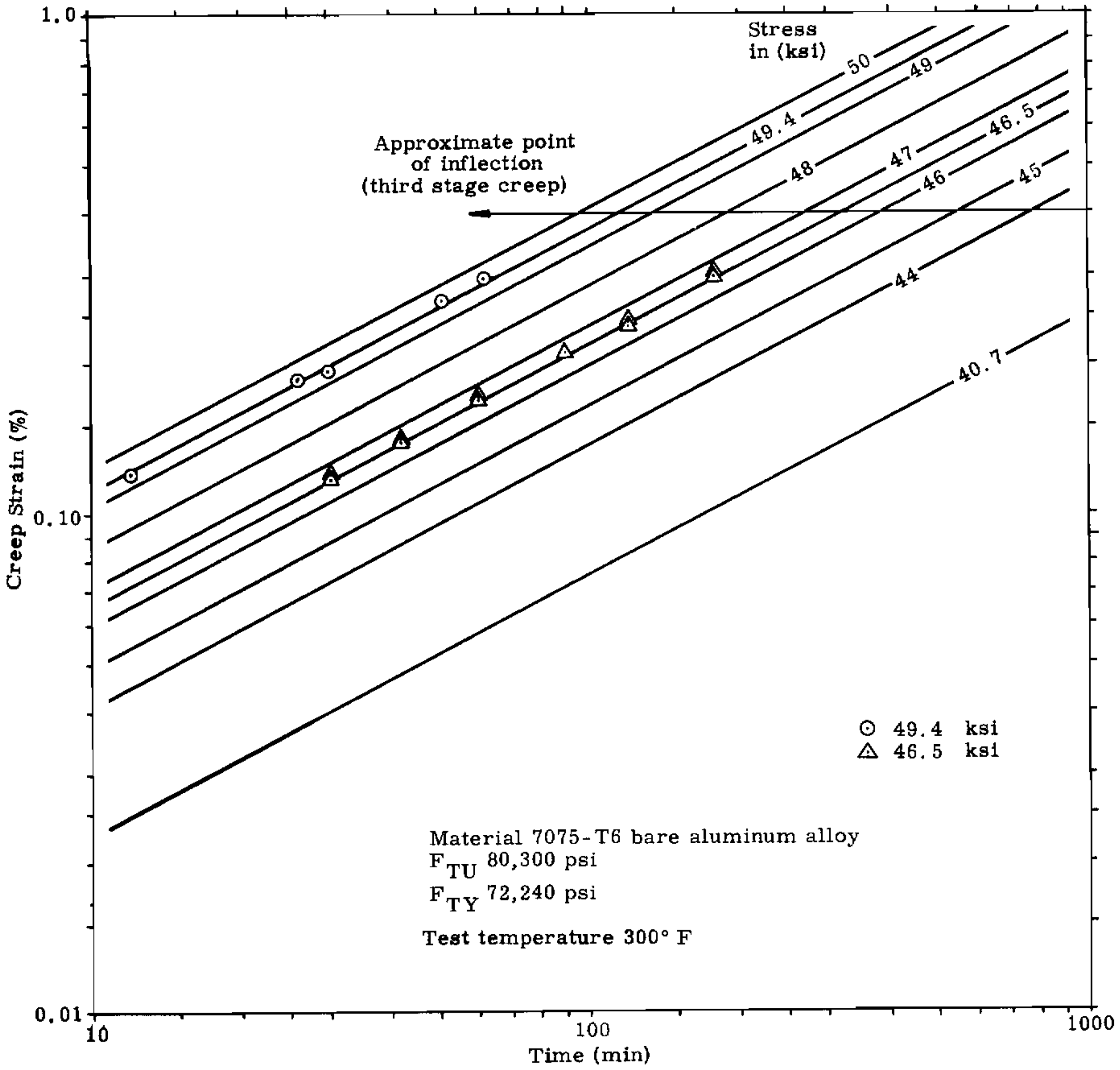


Fig. 19. Log-Log Plot of Creep Versus Time at 300° F for 7075-T6 Bare Aluminum Alloy (Valid for Primary and Secondary Stages of Creep)

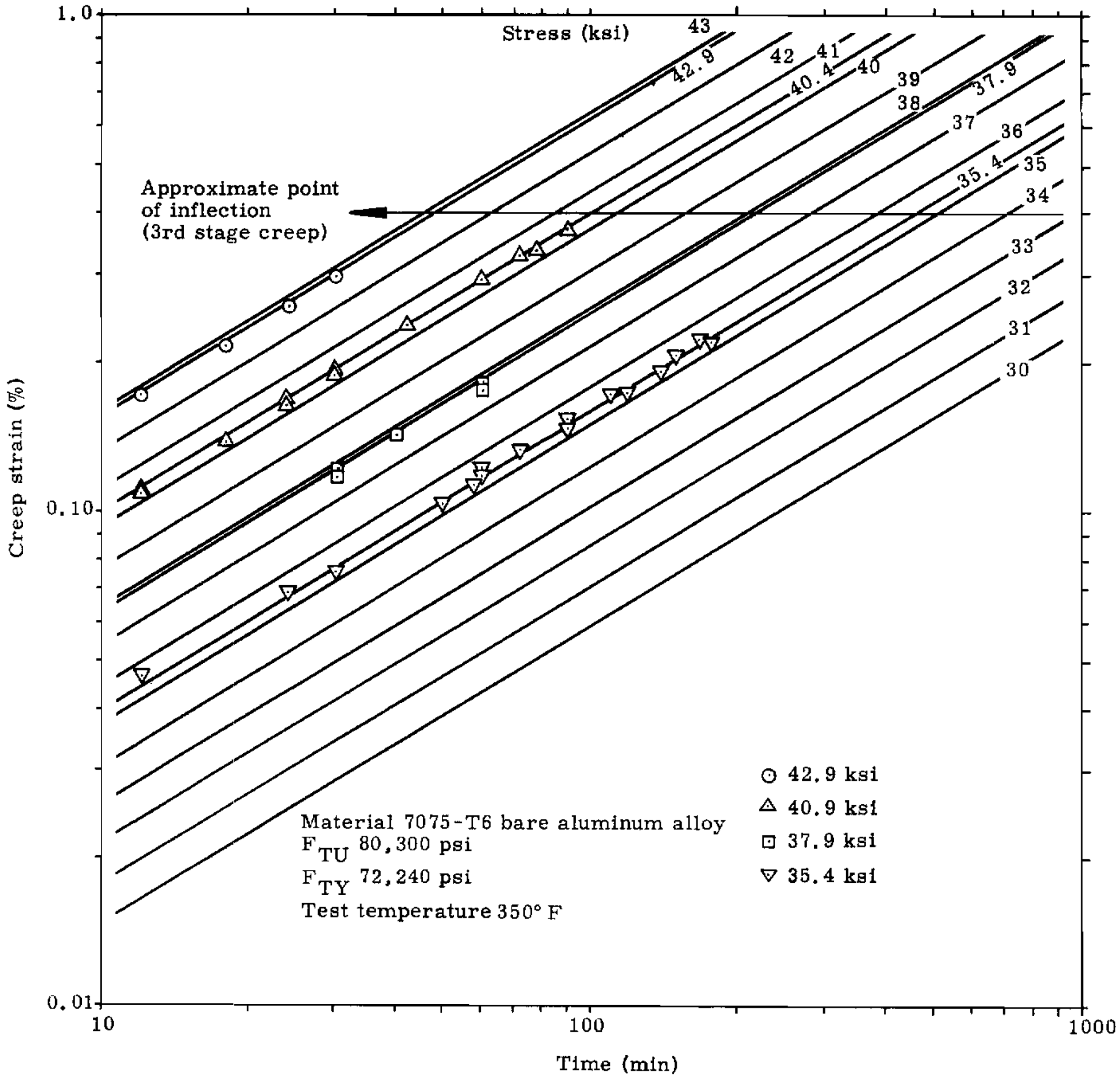


Fig. 20. Log-Log Plot of Creep Versus Time at 350° F for 7075-T6 Bare Aluminum Alloy (Valid for Primary and Secondary Stages of Creep)

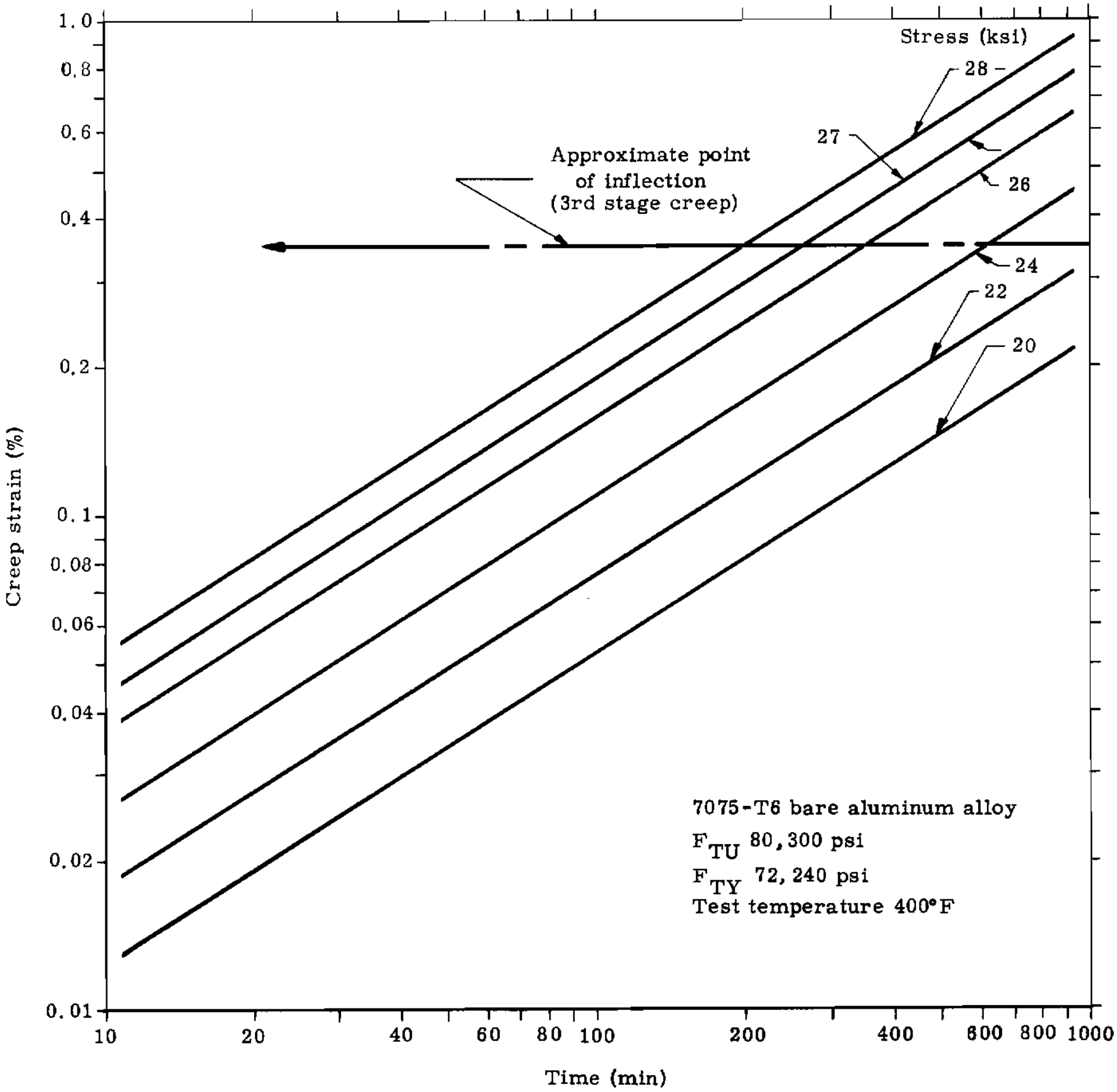


Fig. 21. Log-Log Plot of Creep Versus Time at 400° F for 7075-T6 Bare Aluminum Alloy (Valid for Primary and Secondary Stages of Creep)

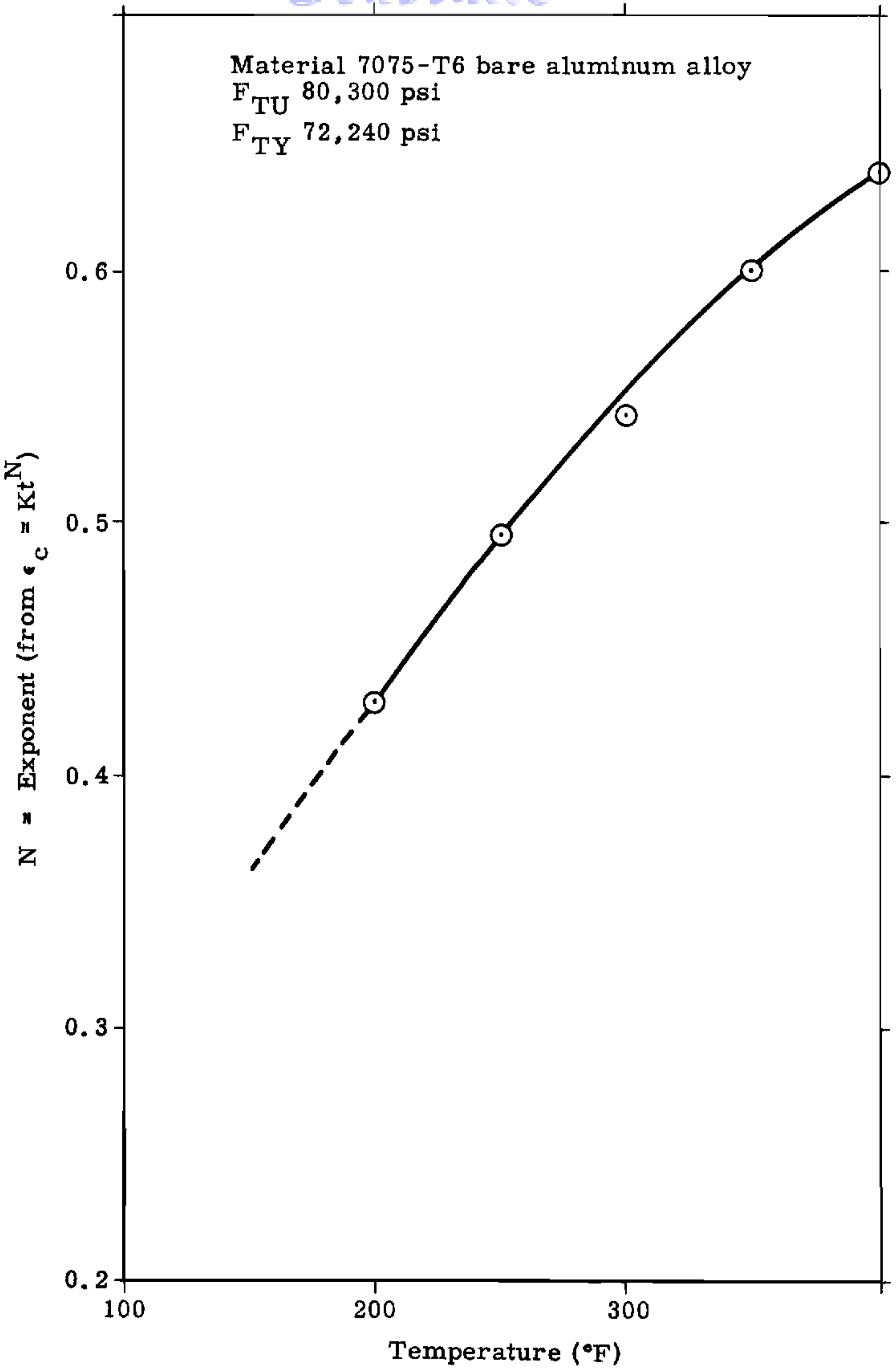


Fig. 22. Plot of Exponent "N" (From $\epsilon_c = Kt^N$) Versus Temperature

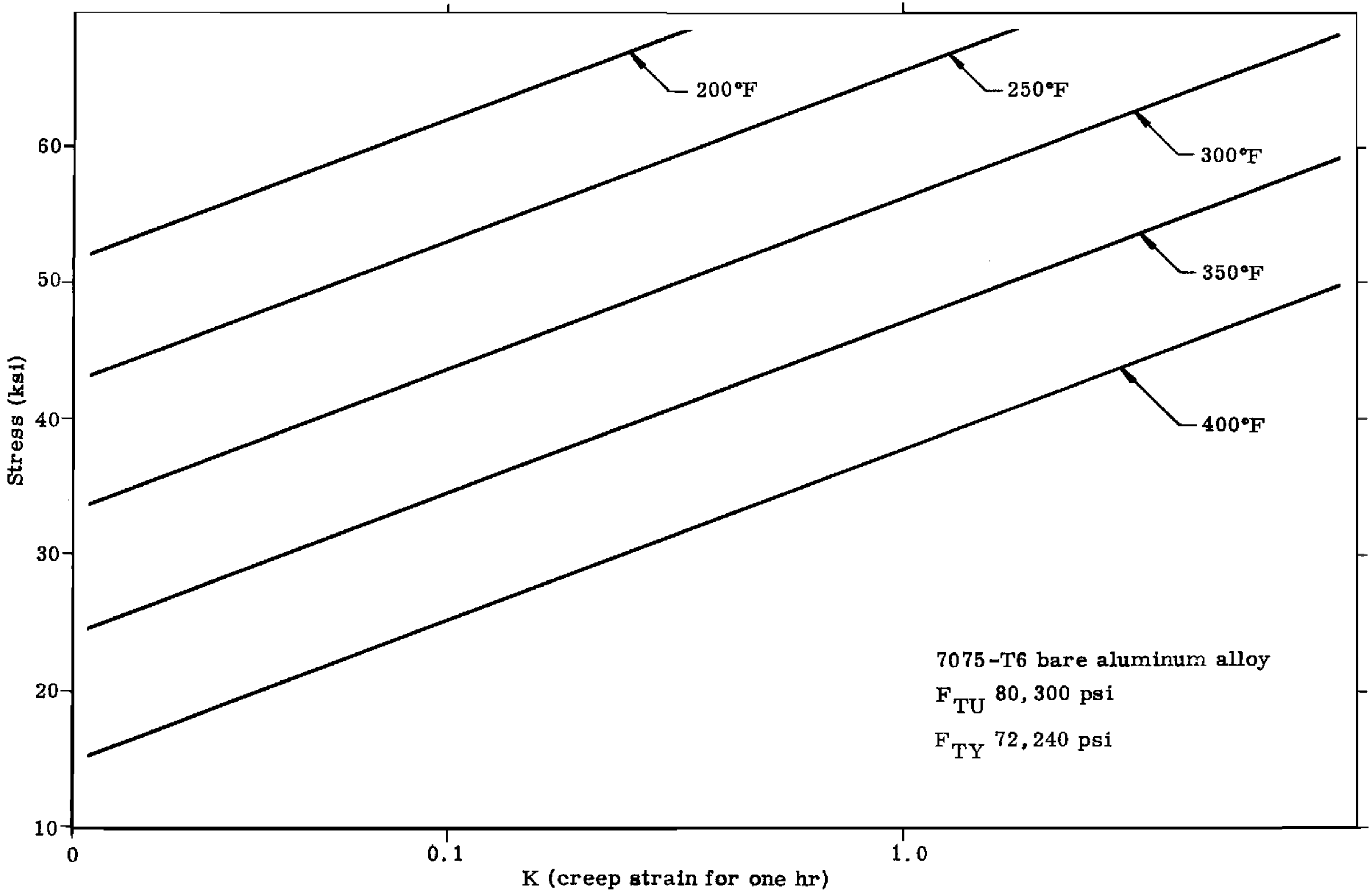


Fig. 23. Plot of Stress Versus Log K ($K = \epsilon_c$ at 1 Hour) for 7075-T6 Bare Aluminum Alloy (for $\epsilon_c = Kt^N$)

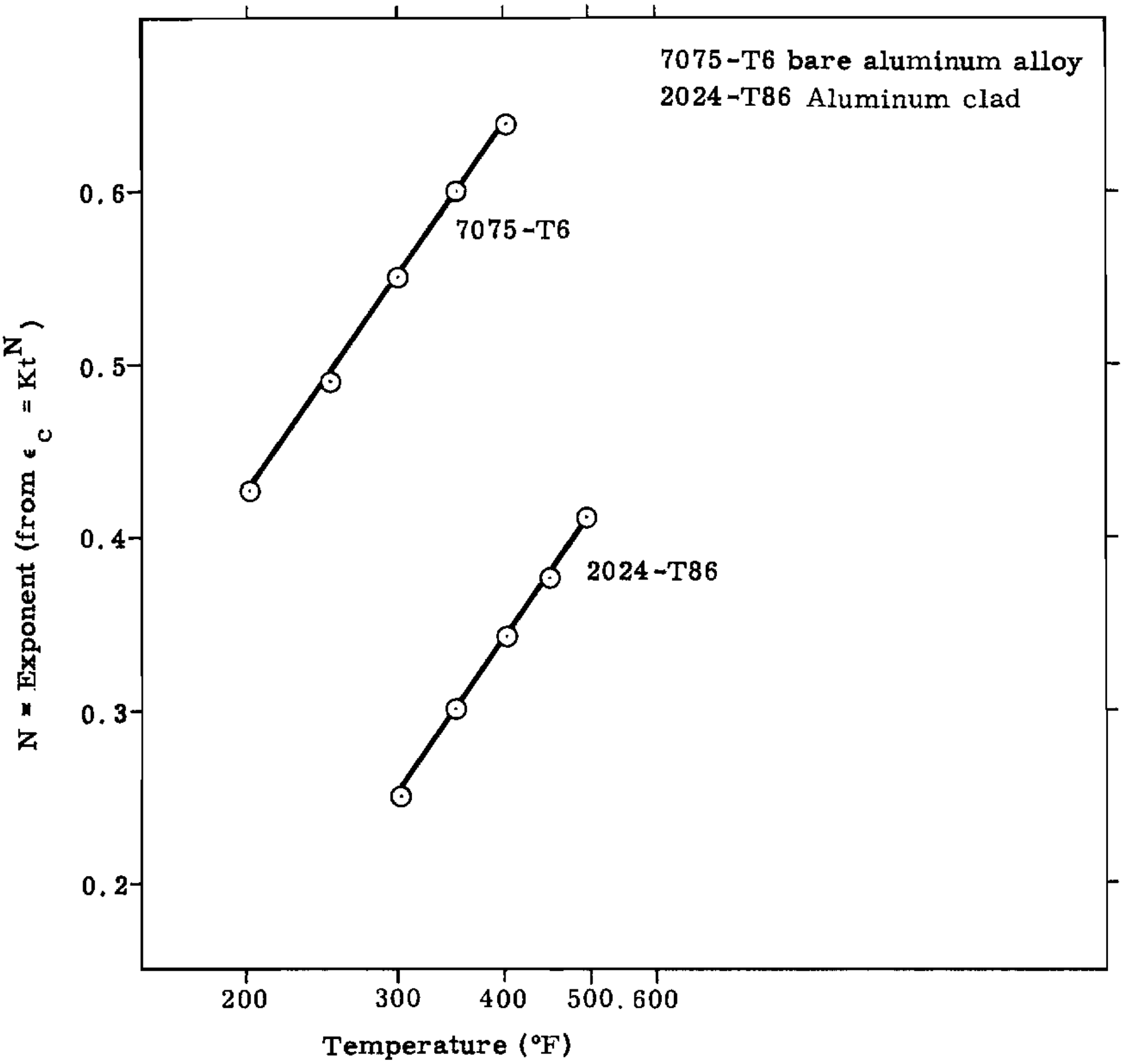
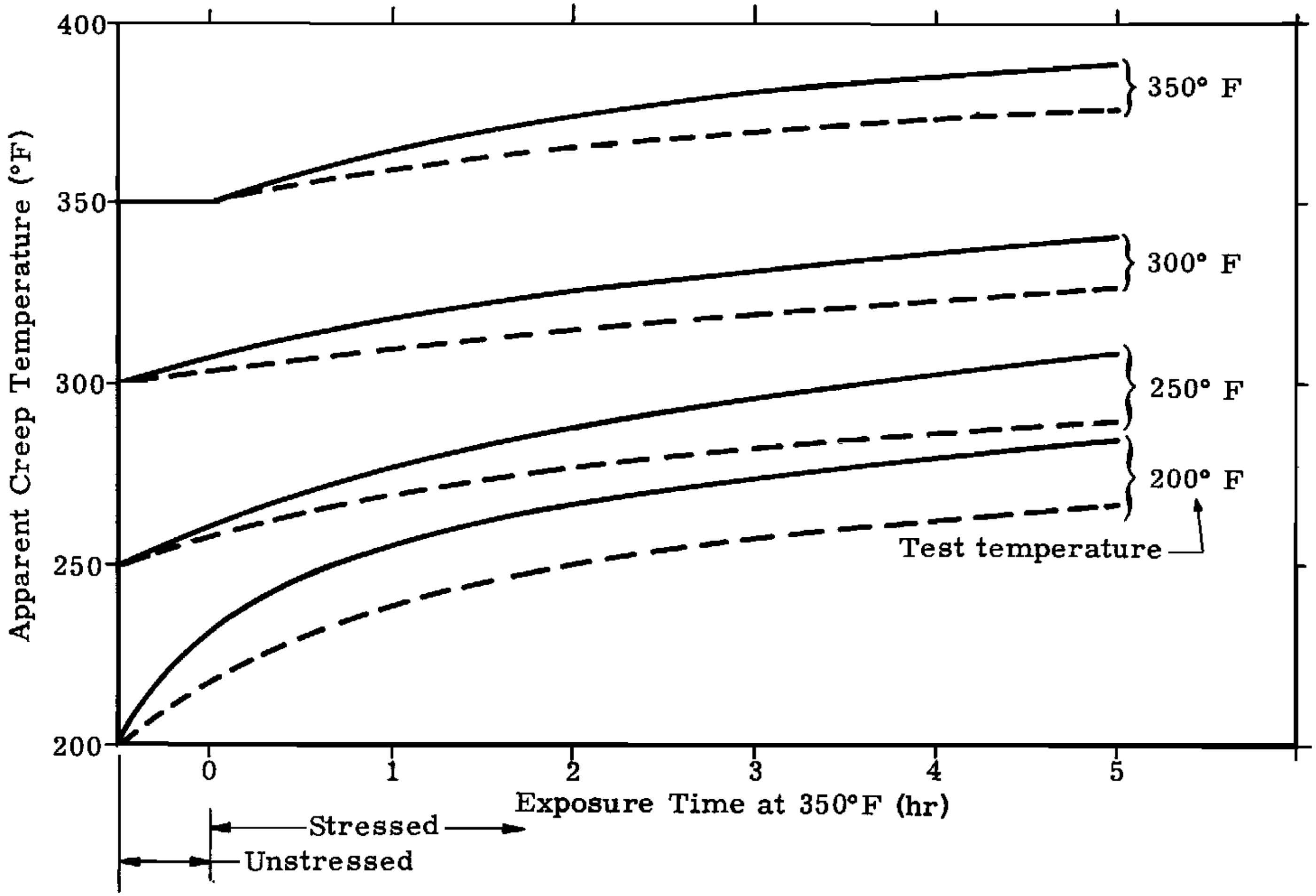


Fig. 24. Plot of "N" Versus Log Temperature ($\epsilon_c = Kt^N$) and Comparison of "N" for Aluminum Alloys 7075-T6 and 2024-T86



—— Degradation curve for indicated test temperature immediately following 350°F exposure

– – – – Degradation curve for indicated test temperature following exposure at 350°F and other intermediate test conditions less than 350°F

7075-T6 bare aluminum alloy

F_{TU} 80,300 psi

F_{TY} 72,240 psi

Fig. 25. Degradation of Creep Resistance Following Exposure at 350° F (Apparent Creep Temperature Versus Exposure Time at 350° F)

Test No.	Temp (°F)	Stress (ksi)	Time (hrs)	Seq No.
30	200	57.1	2	I
	350	42.9	.5	II
	250	44.7	1	III
	300	49.4	1.5	IV
16	250	47.9	2	I
	350	35.4	.5	II
	300	49.4	1.5	III
	250	44.7	1.0	IV

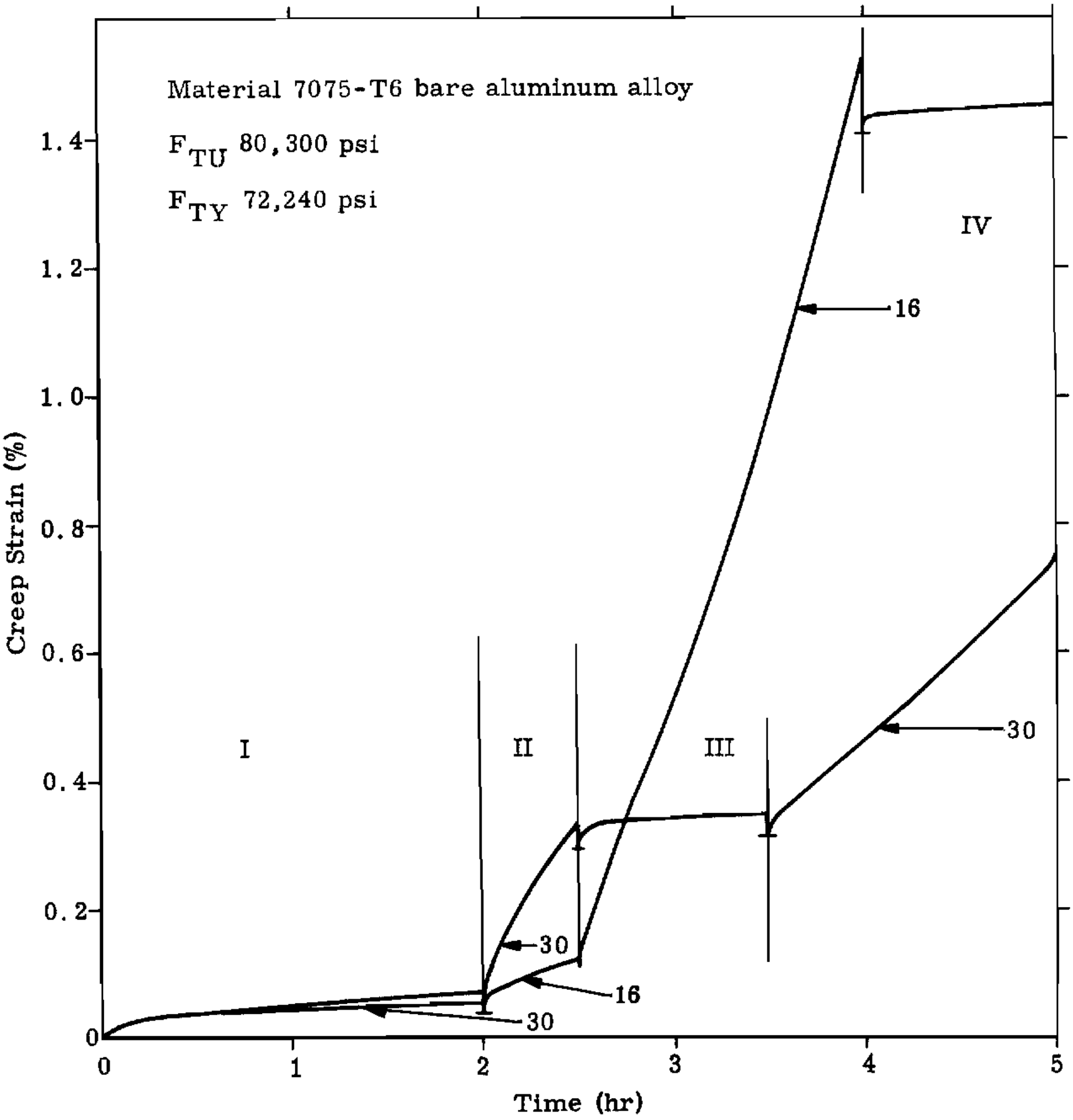


Fig. 26. Illustration of Overaging Effects on Creep and Subsequent Recovery

Test No.	Sequence	Test Temp (°F)	Stress (ksi)
R1	1 hour	350	0
54, 9, R1	I	350	35.4
54, 9, R1	II	350	37.9
54, 9, R1	III	250	54.3
54	IV	350	40.4
R1, 9	IV	350	35.4

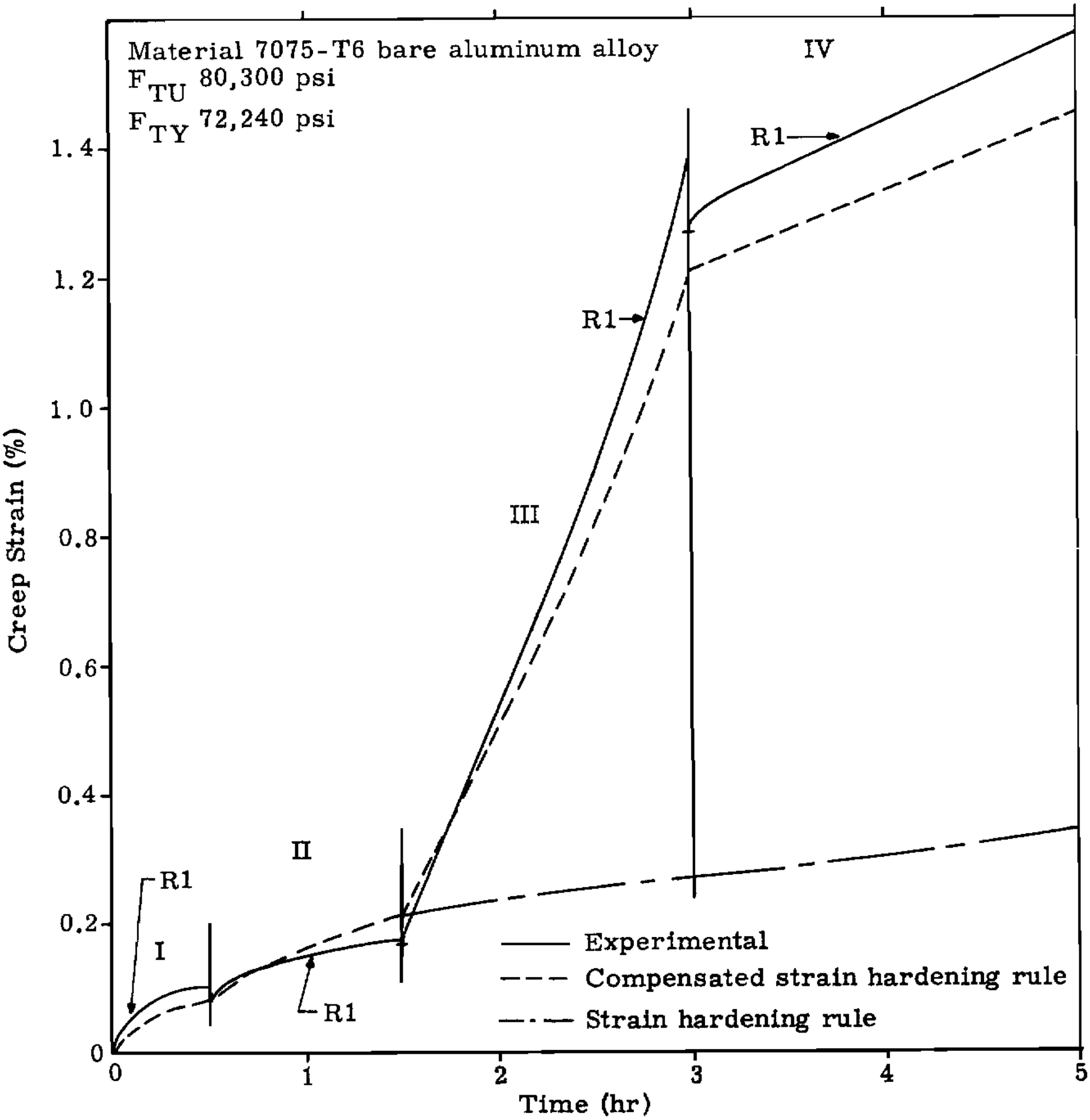


Fig. 27A. Comparison of Compensated Strain Hardening Rule Environmental Creep for 7075-T6 Bare Aluminum Alloy

Test No.	Sequence	Test Temp °F	Stress (ksi)
R1	1-Hour	350	0
54,9,R1	I	350	35.4
54,9,R1	II	350	37.9
54,9,R1	III	250	54.3
54	IV	350	40.4
R1,9	IV	350	35.4

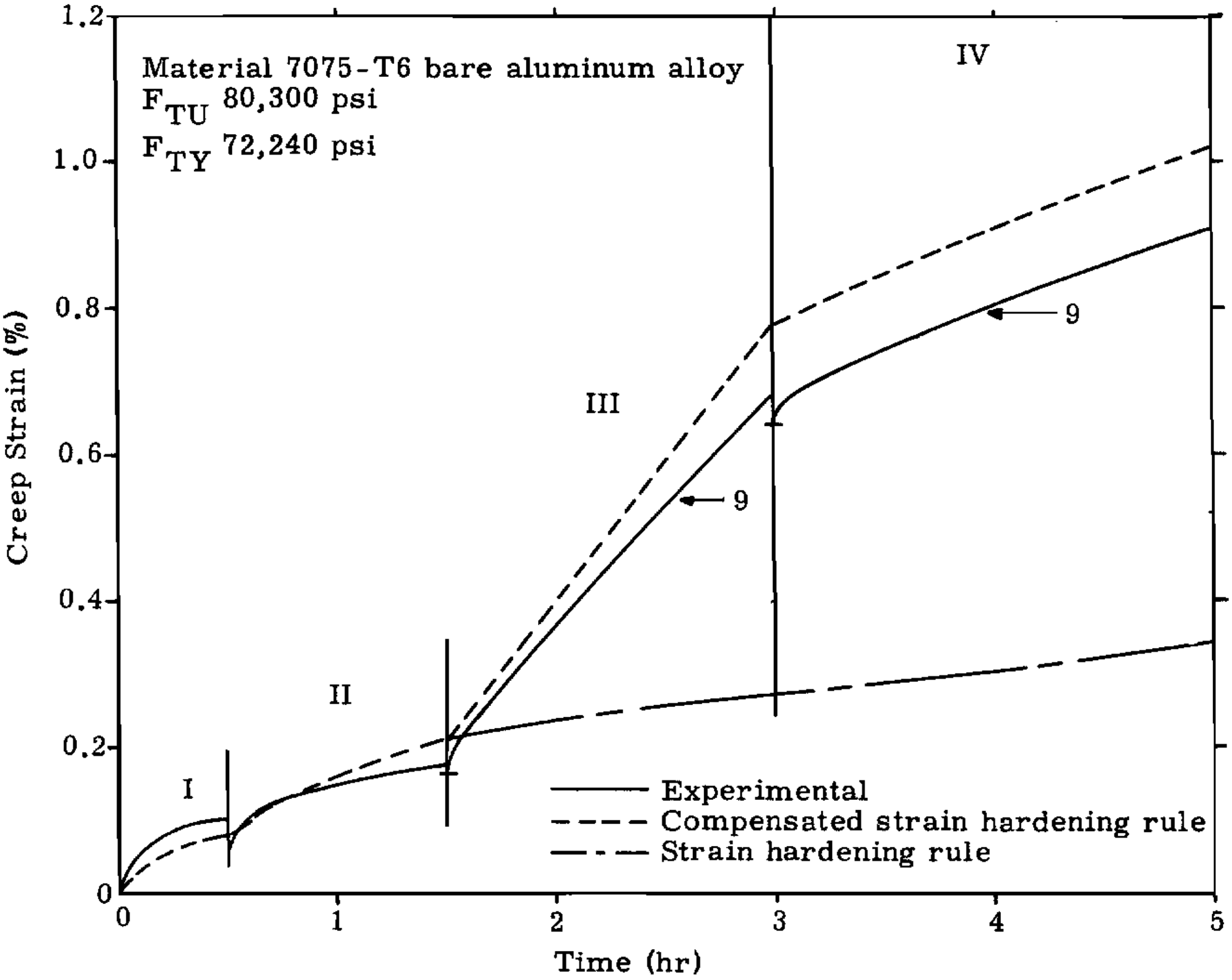


Fig. 27B. Comparison of Compensated Strain Hardening Rule Environmental Creep for 7075-T6 Bare Aluminum Alloy

Test No.	Sequence	Test Temp °F	Stress(ksi)
R1	1-Hour	350	0
54,9,R1	I	350	35.4
54,9,R1	II	350	37.9
54,9,R1	III	250	54.3
54	IV	350	40.4
R1,9	IV	350	35.4

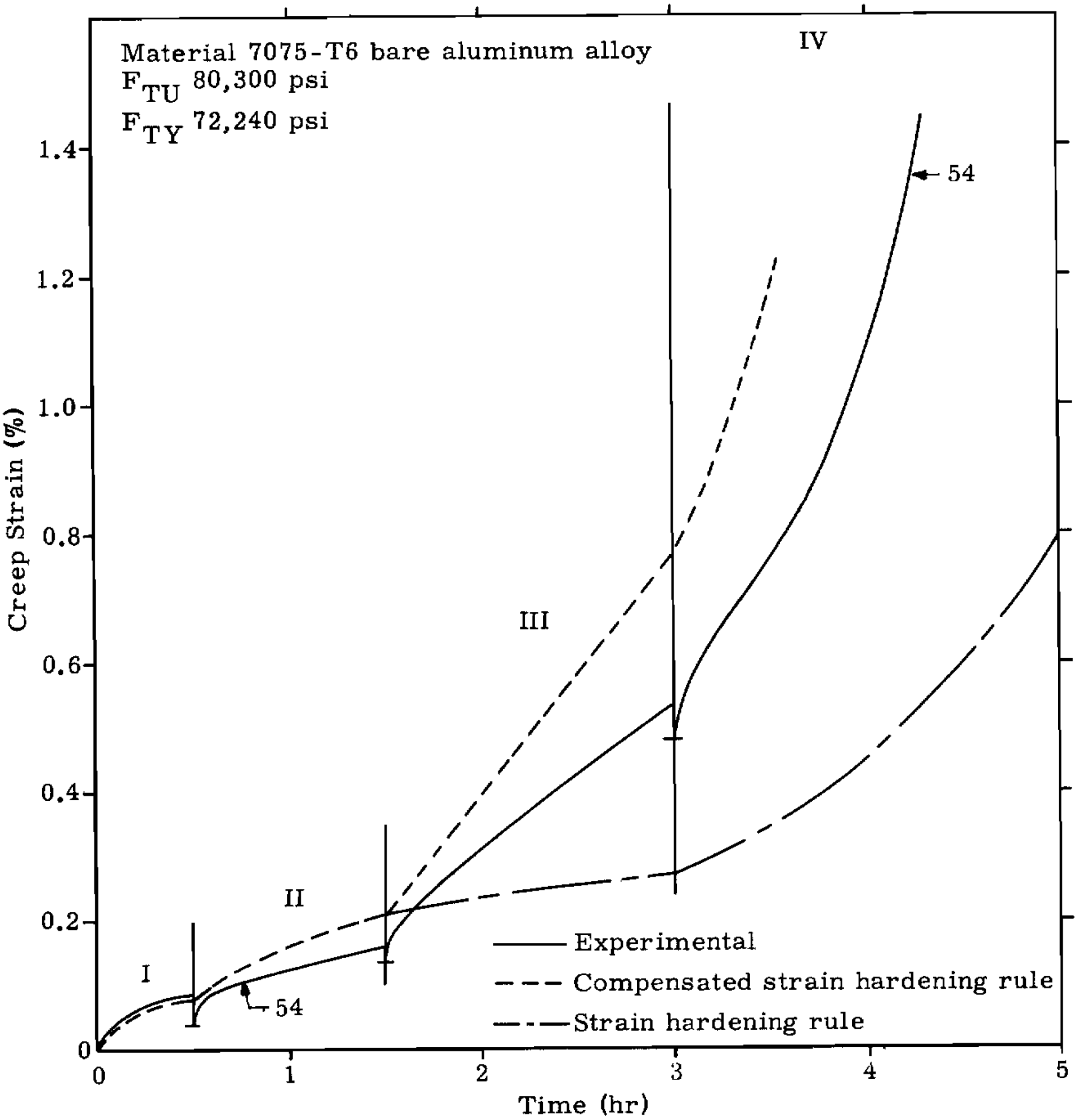


Fig. 27C. Comparison of Compensated Strain Hardening Rule Environmental Creep for 7075-T6 Bare Aluminum Alloy

Test No.	Seq No.	Temp (°F)	Stress (ksi)	Predicted Apparent Test Temp (°F)
103	I	350	20.2	
	II	300	43.6	341
	III	350	37.9	376

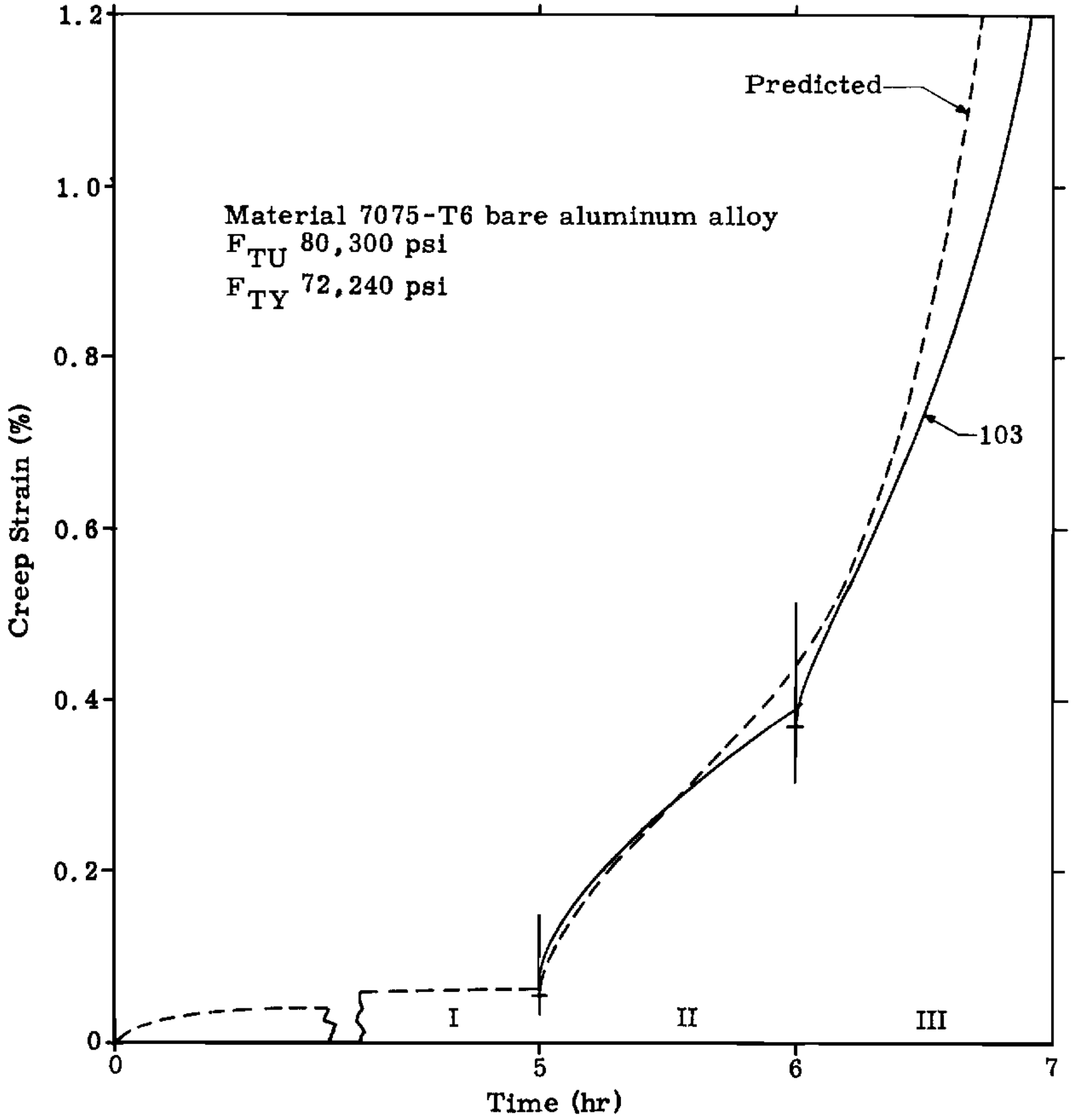
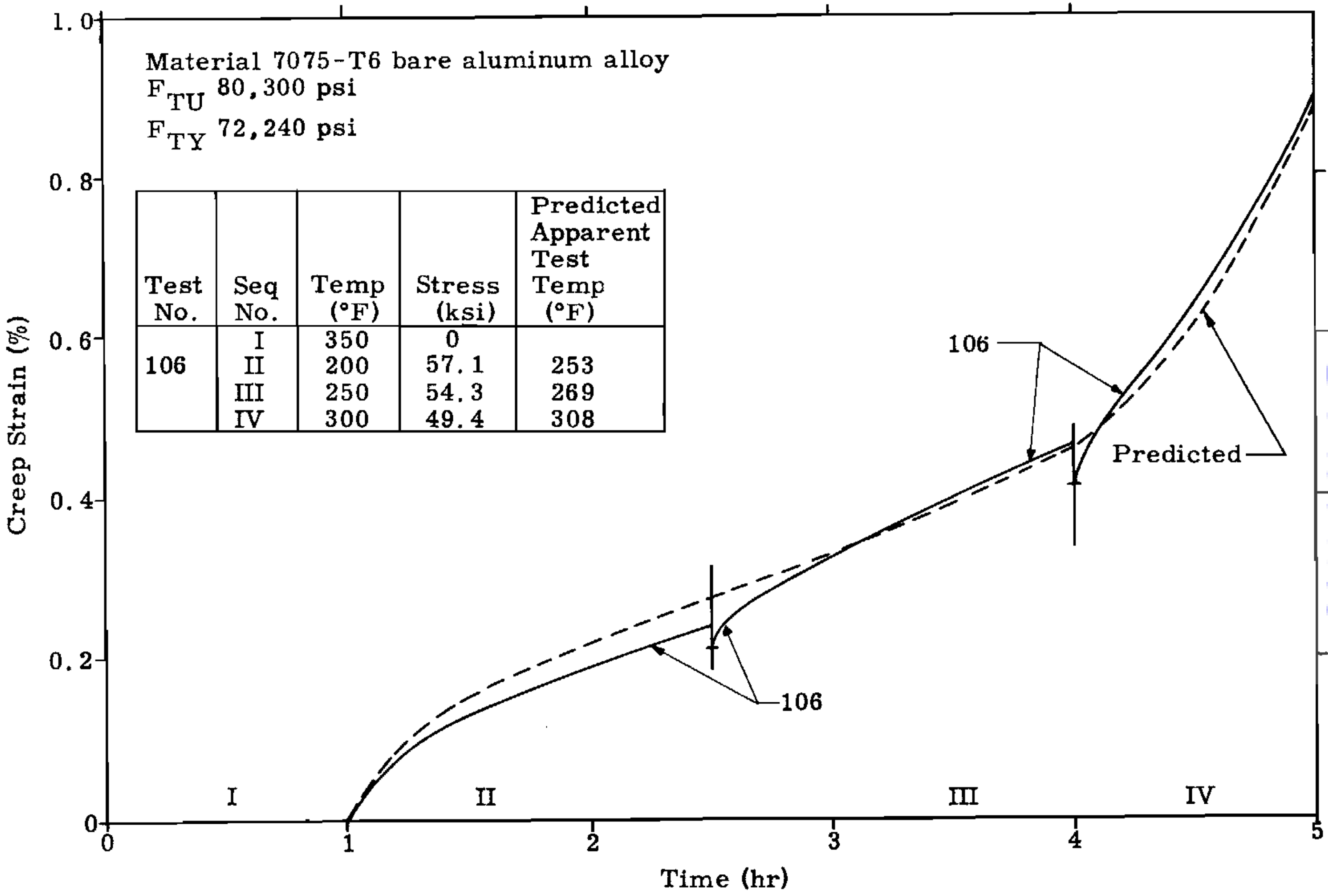


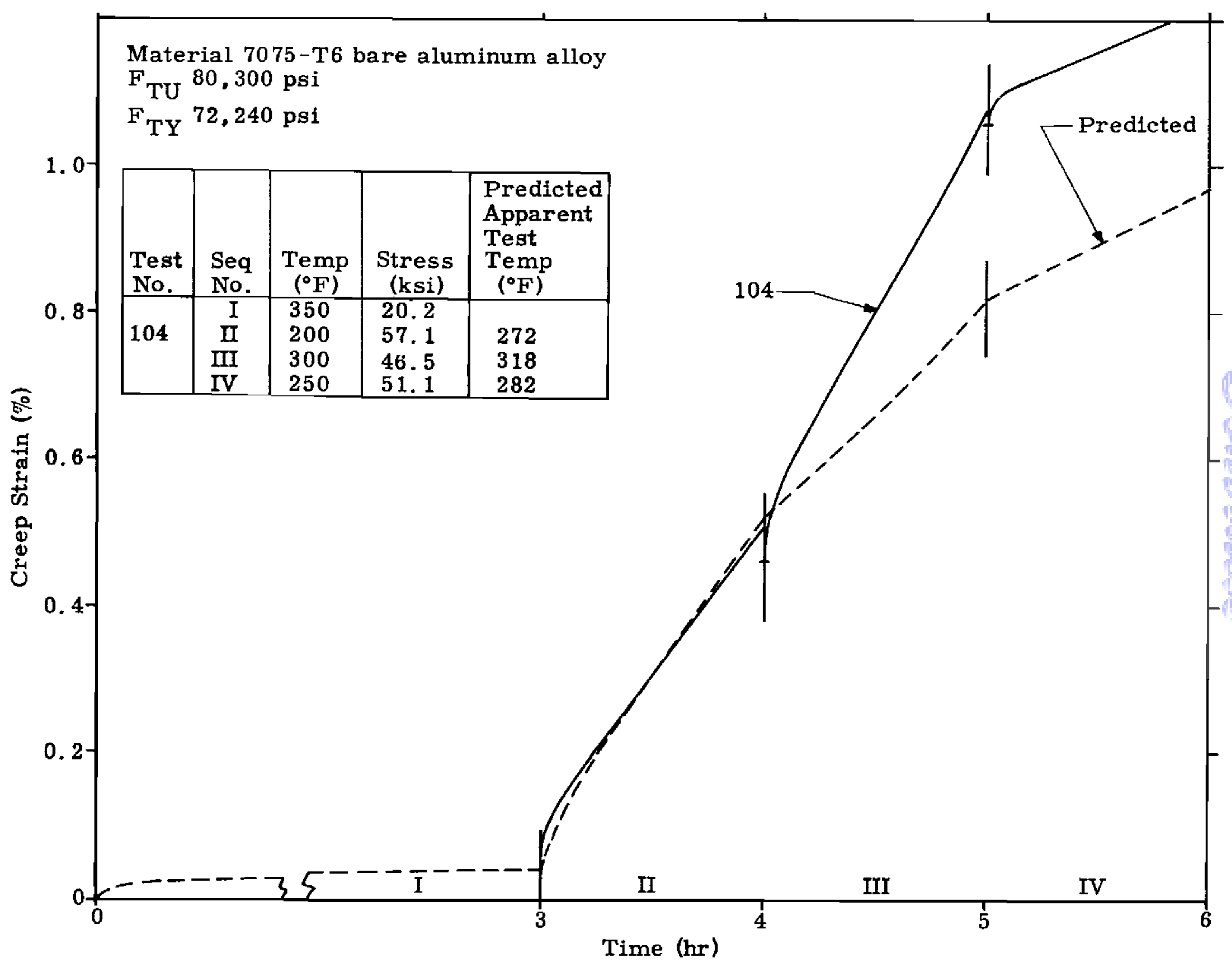
Fig. 28A. Comparison of Predicted Creep Behavior to Subsequent Environmental Tests (7075-T6)



Material 7075-T6 bare aluminum alloy
F_{TU} 80,300 psi
F_{TY} 72,240 psi

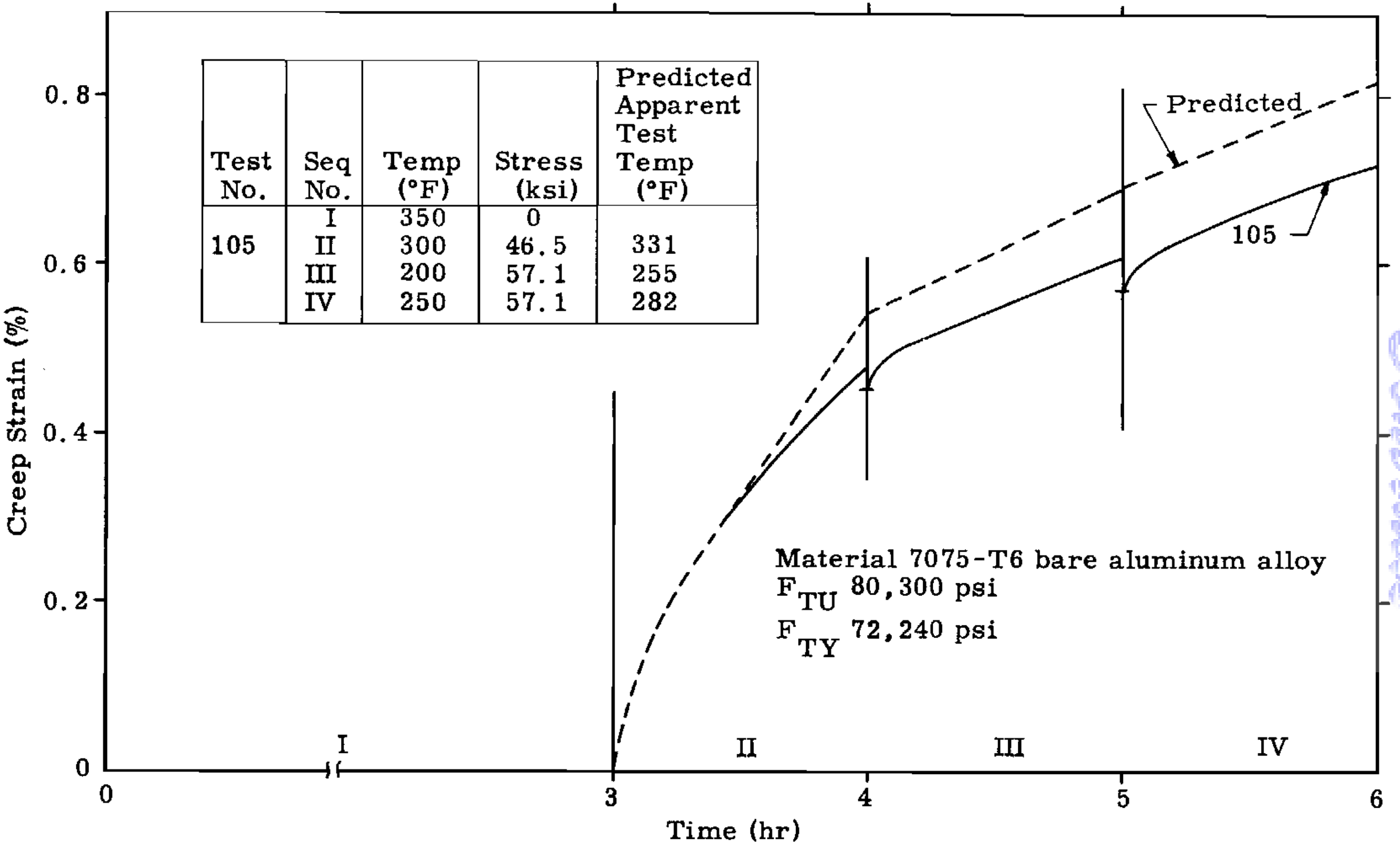
Test No.	Seq No.	Temp (°F)	Stress (ksi)	Predicted Apparent Test Temp (°F)
106	I	350	0	
	II	200	57.1	253
	III	250	54.3	269
	IV	300	49.4	308

Fig. 28B. Comparison of Predicted Creep Behavior to Subsequent Environmental Tests (7075-T6)



Test No.	Seq No.	Temp (°F)	Stress (ksi)	Predicted Apparent Test Temp (°F)
104	I	350	20.2	
	II	200	57.1	272
	III	300	46.5	318
	IV	250	51.1	282

Fig. 28C. Comparison of Predicted Creep Behavior to Subsequent Environmental Tests (7075-T6)



Test No.	Seq No.	Temp (°F)	Stress (ksi)	Predicted Apparent Test Temp (°F)
105	I	350	0	
	II	300	46.5	331
	III	200	57.1	255
	IV	250	57.1	282

Material 7075-T6 bare aluminum alloy
F_{TU} 80,300 psi
F_{TY} 72,240 psi

Fig. 28D. Comparison of Predicted Creep Behavior to Subsequent Environmental Tests (7075-T6)

APPENDIX

THE USE OF STATISTICAL METHODS FOR THE DESIGN AND ANALYSIS OF EXPERIMENTS

P. Snyder*

A. THE DESIGN OF THE EXPERIMENT

If we wished to explore a relatively simple domain of time, temperature and stress and the effects of these factors on a given material, a straightforward "factorial" experiment should suffice. Consider three levels of temperature, three levels of time and three levels of stress:

		T_1	T_2	T_3
σ_1	t_1			
	t_2			
	t_3			
σ_2	t_1			
	t_2			
	t_3			
σ_3	t_1			
	t_2			
	t_3			

The matrix shown above represents all 27 combinations of these inputs. If each combination were tested two times, and proper experimental procedures were followed, we could get a good measure of time, temperature and stress as main effects, as well as information on all possible interactions between various combinations of these factors, and, perhaps of most importance, a measure of our "experimental error"--the lack of repeatability between two tests performed under presumably identical conditions.

An understanding of several fundamental concepts is important at this point.

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* Mr. P. Snyder of Rath and Strong, Inc., Boston, Mass., was a consultant for this investigation.

1. "Balanced" Experiment

The experiment illustrated is "balanced." Each possible combination is represented. Should we wish to study the effect of T alone, totals of results in each T column are equally influenced by all units of T and all units of σ, and the T results, therefore, are not biased by the other factors. Similarly, we could study T and σ effects independently. Exact balance is helpful in the evaluation of the data.

2. Random Selection

Selection of test materials must be randomly performed. Should we wish to draw conclusions about one sheet of material, it is important that all areas of this sheet have an equal opportunity to be represented in the experiment and that each test piece be chosen randomly. Should we wish to extend our inference to several sheets, or indeed more sheets of material than tests in the experiment, we must be sure that all the area of every sheet has, again, an equal opportunity to be represented.

3. Random Testing

The testing must be performed in a random sequence. Conditions which change with time (known or unknown) will undoubtedly cause some variability in test results. This is inevitable, but will not be disastrous unless "confounded" or associated accidentally with a certain level or levels of one or more input factors. Should all T_1 tests be performed first, T_2's second and T_3's last, and our test rig have a progressive (and unknown) drift, this error could be principally associated with T_3 results, and erroneous conclusions thereby drawn. It is desirable to spread this error throughout the entire experiment in a purely random fashion.

The tests, therefore, should be performed in "scrambled" sequence. The probability that effects of unknown variables changing with time will, by chance, associate themselves with any level of our controlled inputs is extremely unlikely.

4. Repeat Testing

Repeat runs give an indication of error and provide the basis for analysis of the data.

Assuming a properly designed, properly executed experiment, the repeat tests take on great significance. Consider two possible situations in which we are studying the effects of two temperatures on creep strain, in percent:

	I		II	
	T_1	T_2	T_1	T_2
ϵ (%)	0.5	1.1	0.1	1.4
	0.4	1.5	1.5	2.3
	0.7	1.5	0.3	0.5
	1.0	1.7	1.4	0.9
	0.9	1.2	0.2	1.9

For T_1 - average ϵ = 0.7

T_2 - average ϵ = 1.4

T_1 - average ϵ = 0.7

T_2 - average ϵ = 1.4

Intuitively, just by "looking" at the data from the two experiments, we would have confidence that the apparent difference in averages was more valid in Case I than in Case II. In other words, we compare the differences in averages to the differences within the group of numbers from which the averages are derived. If the background noise or residual error is small, few tests should suffice to convince us that a real difference exists. If the error is large, many tests may be necessary to convince us that the difference in averages is not pure chance. The analysis of variance--among the most refined statistical techniques--allows us to establish the probabilities that observed differences are real differences (coming from populations with different means) and not chance differences. At times, looking at the data is quite sufficient; at times, the more refined technique is required.

B. MAIN EFFECTS AND INTERACTIONS

In any experiment involving two variables or more, various patterns of results can emerge. Consider the following illustration wherein we are concerned with the combined effects of temperature and stress on a particular material. One measurement, in this instance, is the rate of creep during a specified time period:

		Temperature		
Stress (% of YS)		200° F	250°F	Average Strain Rate
70		0.50	0.90	0.75
		0.45	1.00	
		0.55	1.10	
75	ϵ (%)	45	1.00	0.72
		45	1.00	
		50	0.95	
Average strain rate		0.48	0.99	

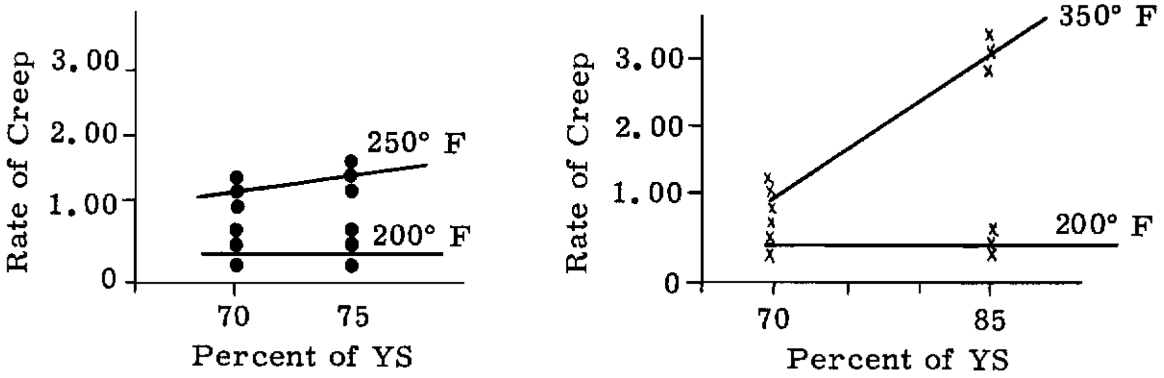
In this illustration, the row and column averages are good indicators of the effects of temperatures and stresses within the limited domain under consideration. Creep rate is relatively unaffected by an increase in stress from 70 to 75%, but is roughly doubled by an increase in temperature from 200° to 250° F. We have one main effect--that of temperature.

Let us consider a second illustration wherein we explore the effects of a higher temperature and stress:

Temperature

Stress (% of YS)		200° F	350° F	Average Strain Rate
70	(%)	0.55 0.45 0.50	1.10 0.90 1.00	0.75
85		0.45 0.50 0.45	3.50 3.80 3.70	1.98
Average strain rate		0.48	2.25	

The row and column averages in this case suggest two main effects for both temperature and stress. Inspection of the data within the matrix, however, indicates no stress effect at 200°, but a very substantial effect at 350° F. The temperature effect at 70% (of yield strength) is moderate, but at 85% it is substantial. We have here an indication of a main effect for temperature and a temperature stress interaction at 350° F and 85% (of yield strength). The row and column averages are virtually meaningless. A graphic presentation of these two sets of data will, perhaps, illustrate more clearly the different patterns.



Nonparallel responses are indications of interaction.

C. THE LIMITATION OF THE FACTORIAL EXPERIMENT

With an understanding of the basic concepts of main effects, interaction, and residual error (our basis for statistical analysis), as well as the importance of randomness in selecting test materials and running tests, let us consider further possibilities for the factorial form of experiment and certain important limitations.

Any number of factors and levels of factors can, in theory, be included in a factorial experiment. Several materials, various temperatures, stresses, times at these stresses and any other inputs may be added that appear interesting to the experimenter. Unfortunately, the number of tests rapidly reaches impossible proportions. Five variables of four levels each would require (4^5) 1024 tests, not including any repeat runs. This, generally speaking, would be prohibitively expensive and time-consuming as the number of factors increase.

Several alternatives are possible:

(1) Fractional factorial experiments.

(2) Random or multiple balanced experiments.

D. THE FRACTIONAL FACTORIAL EXPERIMENT

Fractional factorial experiments are, basically, factorial experiments from which only a selected number of total possibilities are run. We might pick one-half the total possibilities, one-quarter or one-eighth or even one-sixty-fourth. These designs are entirely adequate if only main effects are involved, but they do not allow (because of deliberate confounding) analysis of all interaction effects.

A one-half replicate of three factors of two levels would require that we run either the x's or y's in the following diagram:

		A_1	A_2
B_1	C_1	x	y
	C_2	y	x
B_2	C_1	y	x
	C_2	x	y

A one-third replicate of three factors of three levels (similar to the first illustration involving time, temperature and stress), would require that we run either the x's, y's or z's in the following diagram:

		T_1	T_2	T_3
σ_1	t_1	x	z	y
	t_2	y	x	z
	t_3	z	y	x
σ_2	t_1	z	y	x
	t_2	x	z	y
	t_3	y	x	z
σ_3	t_1	y	x	z
	t_2	z	y	x
	t_3	x	z	y

Another way to represent these three possible groups of nine tests is as follows:

	T_1	T_2	T_3
σ_1	t_1	t_2	t_3
σ_2	t_2	t_3	t_1
σ_3	t_3	t_1	t_2

	T_1	T_2	T_3
σ_1	t_2	t_3	t_1
σ_2	t_3	t_1	t_2
σ_3	t_1	t_2	t_3

	T_1	T_2	T_3
σ_1	t_3	t_1	t_2
σ_2	t_1	t_2	t_3
σ_3	t_2	t_3	t_1

Various other fractional designs are possible and, under certain circumstances, may be useful.

E. RANDOM AND MULTIPLE BALANCE EXPERIMENTS

When we are faced with the task of investigating the effects of a number of variables simultaneously, with several levels of each, particularly when the number of levels vary, a factorial or fractional design may be impractical. Consider a situation in which we have 15 input variables of from two to five levels each.

Variable	Levels
A	5
B	2
C	3
D	2
E	4
F	3
G	3
H	5
I	2
J	2
K	4
L	3
M	2
N	4
O	3

Obviously, it would be thoroughly impractical to run all these combinations (17,241,600) and extremely difficult to devise any kind of a fractional design which would make sense. A possible alternative would be to inspect only a random sample of perhaps 50 of these combinations, to be followed by further tests in areas which look promising. Such a design is called "random balance." The layout and procedure to be followed for such a design is described below. Assuming 50 tests are to be run, we can layout the following table:

	Variable						
Test No.	A	B	C	D	E	F	etc.
1							
2							
3							
4							
5							
6							
. . . . .							
50							

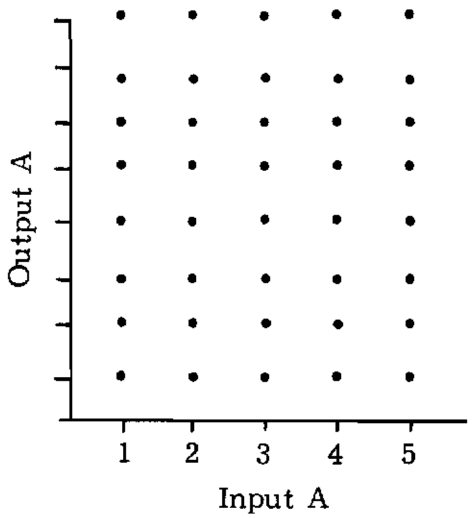
For each test, we assign the level of each variable by a purely random procedure, i.e., rolling dice, random number tables, or some such device. The only restriction that may be desirable to place on the assignment of levels is that each level of each variable be represented an approximately equal number of times. With 50 tests, the 5 levels of A would each appear 10 times; the two levels of B would each appear 25 times and the three levels of C, 17, and 16 times, etc.

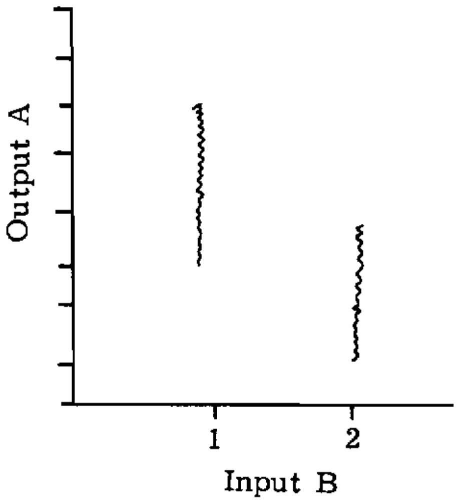
The partial table, filled in, might look as follows:

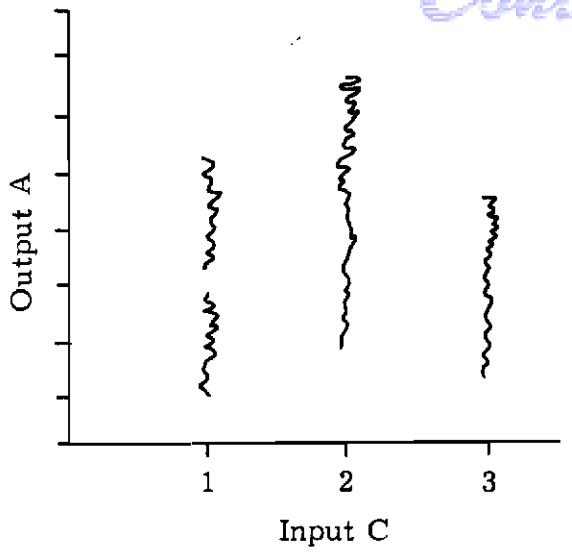
	A	B	C	D	E	F	O	Outputs
1	5	2	1	2	1	1	3	26.2
2	3	2	1	1	3	2	1	29.5
3	4	1	2	2	3	3	2	31.2
4	1	2	3	1	4	1	3	19.6
5	5	1	1	1	2	2	1	14.8
6	2	1	2	2	1	1	2	30.1
50	1	2	3	1	2	3	1	40.6

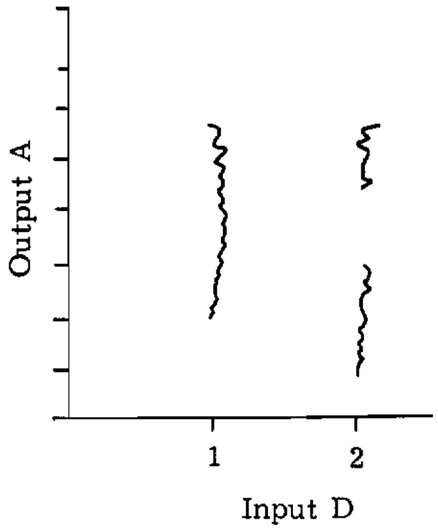
Each test is then run, and the various outputs are recorded.

Rather than laying out the numbers in a matrix, as typically is done with results in factorial experiments, scatter plots for each output might first be constructed to show evidence of main effects and lower order interactions.









From inspection of these plots, areas of interest for further experimentation can be easily located. Input A, for example, shows no effect, input B an apparently significant effect, Input C a moderate effect, and Input D shows evidence of interaction. By such a procedure, a large domain of many factors and levels may be surveyed and follow-up experiments can be planned to explore specific areas in greater depth, by factorial or other designs.

F. MULTIPLE BALANCE EXPERIMENTS

A useful modification of the random balance design involves grouping sets of inputs in balanced factorial designs, and then superimposing one set upon another. For example, Inputs A, B and C (in the previous example) could be grouped in this 5 x 2 x 3 factorial layout:

		A_1	A_2	A_3	A_4	A_5
B_1	C_1		2			3
	C_2					
	C_3			1		
B_2	C_1					
	C_2				6	
	C_3	4			5	

Test number shown in box

Each cell would be run once in the first 30 tests, and then such repeat runs would be performed as the total number of tests permitted. If limited to 50 tests, the 20 repeat runs might be selected to explore particularly interesting areas of the matrix.

Inputs D, E and F could, possibly, be arranged in the following 2 x 4 x 3 layout.

	D_1			D_2		
	F_1	F_2	F_3	F_1	F_2	F_3
E_1	2			3		4
E_2					1	
E_3				6		
E_4						5

Test numbers shown in box

These 24 combinations (assuming 50 tests in total) could all be run twice, with two to be run a third time. Each cell from this matrix would be run simultaneously with a cell from the first matrix and with cells from any other additional matrices. The analysis of these data could be handled by the use of scatter diagrams, as well as in matrix form following standard analysis of variance procedures. Multiple balance permits study of interaction effects within blocks to a greater degree than would be possible if the assignment of levels for each test were purely random. When interactions between certain factors are anticipated, it is highly desirable to design the experiment to include those factors in factorial arrays.

G. THE DESIGN OF THE SCREENING EXPERIMENT

It was proposed that a specimen of 7075-T6 be subjected to varying sequences of load, temperature and time. Four sequences were arbitrarily decided upon--each sequence to include one of four levels of time, one of four levels of temperature and one of four levels of stress.

For Sequence I, all possible combinations of time, temperature and stress can be shown in the following matrix:

Time (hr)	Temperature				Stress (%)
	200° F	250° F	300° F	350° F	
0.5					70
					75
					80
					85
1.0					70
					75
					80
					85
1.5					70
					75
					80
					85
2.0					70
					75
					80
					85

These 64 blocks represent all combinations possible for these three factors of four levels, for the initial sequence.

Considering the number of test pieces available and the desire to leave as many as possible available for subsequent exploratory and confirming test runs, it was considered desirable to run only a portion of the 64 possible. Various alternatives were considered, and a one-half replicate was selected as being the most satisfactory. Thus, 32 out of 64 possible combinations were selected, as indicated below:

Time (hr)	Temperature (°F)				Stress (%)
	200°	250°	300°	350°	
0.5	X			X	70
		X	X		75
		X	X		80
	X			X	85
1.0		X	X		70
	X			X	75
	X			X	80
		X	X		85
1.5		X	X		70
	X			X	75
	X			X	80
		X	X		85
2.0	X			X	70
		X	X		75
		X	X		80
	X			X	85

This arrangement is balanced and, although not complete, does thoroughly explore the temperature-stress-time domain. Considering that the effects are not likely to be discontinuous, and three factor interaction (i.e., one block showing unusual results) is not anticipated, the gaps in coverage are of little consequence.

In addition to these 32 tests, five repeat runs were planned, as a check on test repeatability.

For Sequences II, III and IV, each test piece is to be subjected to a different combination of time, stress and temperature. Each succeeding sequence will be a repeat of the original 32. However, each test stage is unique and the assignment of combinations to each sequence is purely random, with two qualifications:

(1) That impossible combinations, i.e., those that would result in early failures, would not be run.

(2) That the assignment of time to each sequence be so made that each time is represented only once (though the order can vary), resulting in each test running five hours.

Thus, in effect, by randomly assigning the 32 combinations to four sequences, the 32 tests are, in effect, a sample from 64^4 total possible combinations.

The final configuration of the experiment is shown in Table 1.