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WADC TECHNICAL REPORT 57-150

EFFECT OF PRIOR CREEP ON MECHANICAL PROPERTIES OF AIRCRAFT STRUCTURAL METALS

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FOREWORD

This report was prepared by the Engineering Research Institute of the University of Michigan under USAF Contract No. AF33(616)-3368. The contract was initiated under Task No. 73605, with Mr. E. L. Horne acting as project engineer for the Materials Laboratory, Wright Air Development Center. The research is identified as Project No. 2498 in records of the Engineering Research Institute. This report covers work done from February 10, 1956 to January 9, 1957.

ABSTRACT

Tests have been performed on two typical aircraft structural sheet alloys in an investigation to study changes in mechanical properties brought about by prior exposure to elevated-temperature creep conditions. Specimens of 2024-T86 aluminum alloy and 17-7PH (TH 1050) precipitation hardening stainless steel were exposed for times of 10, 50, and 100 hours at stresses giving up to 3% total deformation, using temperatures of from 350° to 500°F for the 2024-T86 and 600° to 900°F for the 17-7PH.

Following the exposures, short-time tensile, compression, or tension-impact tests were run at either room temperature, the temperature of exposure, or both. The results indicate that the short-time strength of structural materials may be either raised or lowered. The changes in properties may approach as much as 50 percent of the original value. The direction of the change depends on the material, test temperature, creep exposure conditions, and property being measured.

From the standpoint of the structures designer the most important changes found to date are a large drop in strength for 2024-T86 after prior creep exposure for times of from 10 to 100 hours and an apparent decline in the room temperature ductility of 17-7PH (TH 1050 condition) after prior creep exposure for 100 hours at temperatures near 600°F.

PUBLICATION REVIEW

This report has been reviewed and is approved

FOR THE COMMANDER:

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INTRODUCTION[a.)]

This investigation under Contract AF 33(616)-3368 seeks to determine effects of elevated-temperature creep exposure on short-time mechanical properties of several aircraft sheet materials. Test conditions were chosen to produce property changes approximating those which might be induced in airframes subjected to aerodynamic heating.

In this initial phase of the study, creep stresses giving up to 3% total deformation in times from 10 to 100 hours have been considered. The properties to be measured before and after such creep exposure are tension, compression and tension-impact properties, together with hardness levels. The current testing program includes sheet materials representative of three types of alloys employed in skins of current air vehicles -- an aluminum alloy, a heat-treatable stainless steel and a titanium alloy.

[a.)] Manuscript released by the authors on 20 February 1957 for publication as a WADC Technical Report.

TESTING PROGRAM

Materials and temperature ranges to be considered during the first year of the contract were specified as follows:

1. An aluminum alloy, 2024-T86, from 350° to 500°F.
2. A titanium alloy, C110M, from 650° to 800°F.
3. A precipitation hardening stainless steel, 17-7PH (TH 1050 condition) from 600° to 900°F.

For the implementation of this program three primary test temperatures were selected to cover the range for each material:

2024-T86	350°, 400°, 500°F
C110M	650°, 700°, 800°F
17-7PH	600°, 800°, 900°F

Time periods for exposure were fixed at 10, 50, and 100 hours with the exposures to be carried out at zero stress and at those stresses resulting in 0.5, 1.0, 2.0, and 3.0 percent total deformation in the three time intervals listed. These total deformations include all deformation (both elastic and short-time plastic strain) occurring during load application plus the creep deformation of the specimen at the creep-exposure temperature and stress.

Only three of the variables time, stress, temperature and total deformation can be chosen independently. For ease of scheduling, the first three of these were fixed. The creep-exposure stresses were determined from average curves of log stress versus log time for a given total deformation. The inherent scatter in creep properties results in actual deformations for some specimens greater or less than the desired nominal value.

After the exposure period, the following tests were carried out:

1. Tensile tests including stress-strain curves at room temperature and at the exposure temperature.
2. Compression stress-strain tests at the same temperatures.
3. Tension-impact tests at the same temperatures.
4. Hardness determinations at room temperature. Where deemed useful, metallographic examination was made.

For a number of creep-exposure conditions, duplicate tests were run with specimens taken randomly from the test material. Properties of specimens with prior exposure to creep conditions were compared with average properties established for unexposed material by a series of from five to ten replicate tests designed to define the normal scatter for each material.

The aluminum and titanium alloys were specified to be tested in the conditions supplied by the manufacturers. The C110M titanium alloy was furnished hot rolled and annealed, and the 2024-T86 aluminum alloy was furnished in the cold worked and artificially aged condition. The stainless steel, 17-7PH was tested in the TH 1050 condition, a double aging treatment which was performed at the University. The aluminum and the stainless steel alloys were specified to be tested in the direction crosswise to the sheet rolling direction, while the titanium alloy was to be tested in the direction parallel to the rolling direction.

Initial testing priority was given the aluminum alloy, with no work planned on the titanium alloy for the first year beyond procurement of the material. Work with the stainless steel for the initial contract year has been limited to a survey of effects on room temperature tensile properties from prior creep to 2% total deformation in 100 hours. Temperature increments of 50°F between 600° and 900°F were used with this alloy in order to establish the temperature of maximum effect from creep exposure.

TEST MATERIALS

The test materials specified by the Materials Laboratory, WADC, were 2024-T86 aluminum alloy, C-110M titanium alloy, and 17-7PH stainless steel. The source, form, analysis, and available processing details for each material are summarized in the sections that follow.

Armco 17-7PH Stainless Steel

Sixteen sheets of the 17-7PH precipitation hardening stainless steel were received from the Armco Steel Corporation. The material was supplied in sheets 0.064-inches thick by 36 inches by 120 inches in No. 2D finish and in Condition A. (Condition A consists of an annealing treatment carried out at 1925°F followed by air cooling). The certified chemical analysis furnished by the producer was within the nominal composition limits for this alloy. These are the following:

Element	Nominal (percent)	Actual (Heat 55651)
Carbon	0.09 Max	0.072
Manganese	1.00 Max	0.55
Phosphorus	0.04 Max	0.018
Sulfur	0.03 Max	0.011
Silicon	1.00 Max	0.33
Chromium	16.00-18.00	17.03
Nickel	6.50- 7.75	7.25
Aluminum	0.75- 1.50	1.28
Iron	Balance	Balance

The TH 1050 condition was carried out at the University using the following treatment on bundles of one-inch wide specimen blanks.

1. Condition A material heated in air for 1-1/2 hours at 1400±10°F,
2. Air cool 10 minutes to approximately 500°F,
3. Quench in 60°F water,
4. Hold 8-12 hours at 60°F,
5. Age 1-1/2 hours at 1050±10°F, then air cool.

This treatment is a refinement of that specified by Armco. (See Ref. 1) It was adopted to insure a closer degree of control and uniformity than required by the usual commercial treatment specifications. The 8-12 hours holding at 60°F before the final aging treatment was largely for convenience in scheduling the use of available furnaces.

2024-T86 Aluminum Alloy

Nineteen Alclad sheets of the aluminum alloy, 2024-T86, were procured from the Kaiser Aluminum and Chemical Corporation. The sheet dimensions were 0.065-inches thick by 48 inches wide by 72 inches long.

Although the heat number of the material was not specified, a certified inspection report was received from the producer stating that the composition of the material shipped to the University was within the following nominal limits for this material:

Element	Range (percent)
Copper	3.8-4.9
Manganese	0.3-0.9
Magnesium	1.2-1.8
Silicon	0.50 Max
Iron	0.50 Max
Chromium	0.25 Max
Zinc	0.10 Max
Others	0.15 Max
Aluminum	Balance

The T86 condition of this material is a cold working and aging treatment carried out by the producer. It consists of the following steps:

1. Solution treatment: 910-930°F, quench in cold water.
2. Cold work: approximately 5.5 percent reduction.
3. Aged: 370-380°F, 10 hours.

C-110M Titanium Alloy

Eleven sheets of annealed C-110M titanium alloy were purchased from the Rem-Cru Titanium Corporation. The sheets were 0.064 inches thick by 30-36 inches wide by 60-90 inches long. The material was all from Heat Number A1172600. The chemical analysis furnished by the producer follows:

Element	Percent (by weight)
Manganese	7.9
Carbon	0.10
Nitrogen	0.02
Hydrogen	0.0093
Titanium	Balance

SPECIMEN PREPARATION

The preparation of test specimens for this investigation involved two considerations. First was the sampling of the specimen blanks from the sheets; and second, the actual design and machining of the specimens.

The sampling procedure is very important. A reliable set of base properties (or a scatter band of properties) was essential to provide a base from which any possible changes could be measured. It was also important that the exposure samples be representative of the test stock.

In material produced according to given specifications, and especially in sheet material, a number of possible sources of scatter in properties exist. For instance, variations in mill practice and in chemical analysis might result in property differences. Even in material from a single heat, differences in properties from sheet to sheet may arise from inherent variations in processing conditions and, for that matter, inhomogeneities might be encountered over a single sheet. Such variations could result from point-to-point differences in the amount of reduction, segregation carried through from the ingot, or the effects of differing thermal history. Any or all of these sources of scatter could be encountered in the testing of sheet material and must be allowed for when establishing the normal scatter in properties.

In the present investigation, it was not deemed feasible to include possible heat-to-heat variations, wherefore all test material for each alloy was taken from a single heat. However, it was felt essential that variations between sheets and within a given sheet be recognized.

Since the physical dimensions of the as-received sheets differed for the several alloys, actual details of the sampling schemes differed although the principle of selection was the same. A prime consideration was that any given test specimen be readily identified according to location.

Since both the 2024-T86 and the 17-7PH alloy were specified to be tested in the direction crosswise to the rolling direction, specimens had to be taken across the narrow direction of the as-received sheets in such a way that some idea be gained of the variation in properties across the width of the sheet. This was accomplished by setting up a basic sampling unit termed a panel. Within each panel, specimen blanks were arranged in a non-repeating pattern which represented sampling across the width of the sheet. Repetitions of the panel carried the sampling over the length of the sheet.

Three sheets of material were arbitrarily selected for tests of each alloy. Each sheet was sheared into panels five or six inches wide, and the panels themselves sheared into one-inch wide specimen blanks. Figure 1 indicates the sampling scheme for the 2024-T86 aluminum alloy while Figures 2 and 3 show the scheme for the 17-7PH stainless steel. The specimen-numbering scheme is also indicated in these figures. Thus, the code number for each specimen identifies its sheet number, panel number, and specimen position within the panel.

Dimensions of the various test specimens that were machined from the one-inch wide specimen blanks are shown in Figures 4 and 5. All specimens for the tests of the mechanical properties were designed so that they could be machined from the creep specimens following the desired exposure. For the exposure tests themselves, the width of the gage section of the specimen was machined 0.030 inches over the 0.5 inch nominal width for tensile test specimens. The gage section of all types of specimens was remachined after the prior exposure, even under zero load. This common procedure for all tests permits measurement of the properties of the sheet material itself unaffected by the particular edge effects, if any, associated with the prior exposure of a given specimen.

For ease in machining, jigs were constructed so that five or six specimens could be made at the same time. The specimens were milled to rough dimensions. The shoulder radii and gage sections were then ground to finished dimensions.

The notched tension-impact specimen was prepared to the major dimensions using standard procedures. Following this, a flat-bottomed V-groove was ground into each edge of the specimen. During this operation the specimen was held in a special fixture so that the location of the notches could be accurately controlled. Next, the center of each flat was nicked with a sharp grinding wheel. Finally, the nicked flat was lapped to the final width and root radius, using a lapping compound and a phosphor bronze wire whose radius was slightly under the final radius desired for the notch. For the notch prepared to the dimensions indicated in Figure 5 the theoretical stress concentration factor, K_t, is equal to 4.2.

The notched tension-impact test was added to the program after the dimensions for un-notched specimens had been established. The notch geometry adopted was that which had been previously chosen for notched-specimen rupture tests in another research program being conducted for the Materials Laboratory. The width was thus not the same for smooth and notched specimens used in the present program. This fact should be of little consequence since the desired comparison is not between different types of specimens, but between like specimens with different histories of prior creep exposure.

TEST EQUIPMENT

The test equipment utilized in this investigation may be divided into two categories: the creep-rupture equipment used to produce the desired exposures either with or without stress; and the equipment for the subsequent tensile, compression, or tension-impact tests.

Exposure-Test Equipment

The creep-rupture tests and elevated-temperature exposure tests, either stressed or unstressed, were carried out in individual University of Michigan creep-testing machines. In these units the stress is applied to the specimen through a third class lever system having a lever arm ratio of about 10 to 1. The specimen is held by a gripping system that includes universal joints at either end in order to provide uni-axial loading. The specimen is heated by a wire-wound resistance furnace fitting over the specimen assembly.

Strain measurements are accomplished by a modified Martens optical extensometer system. A simplified drawing of this system is presented in Figure 6. Pairs of extensometer bars are normally attached to collars which are pinned through holes in the shoulder sections of the test specimen. This method of extensometer attachment necessitates the use of correction factors in order to obtain the true deformation of the gage section of the specimen, as will be discussed in the section on test procedures.

The extensometer bars extend from the bottom of the furnace and are spring clamped (over a cylindrical pin) against machined flats on the bottom specimen holder. Sandwiched between the sets of extensometer bars are the stems of small mirrors. Differential movement of the top and bottom sets of bars causes the mirrors to rotate. A fixed illuminated scale and a telescope fitted with cross hairs are mounted about five feet from the mirrors. As the specimen elongates, a very small movement of the extensometer bars results in a large change in the reflected scale reading observed through the telescope. The factor for converting the observed movement to absolute deformation has been computed from the geometry of the system and checked experimentally. The dimensions of the system used at the University of Michigan permit detection of a specimen elongation of about 10 millionths of an inch.

Tensile and Compression Test Equipment

The tensile and compression tests were carried out in a Baldwin-Southwark hydraulic tensile machine equipped with a strain pacer. The holders for the tensile tests were the same type as used for creep testing, while a special fixture discussed in the next section was constructed for the compression tests.

For elevated-temperature tests a wire-wound resistance furnace was constructed with a 5-inch diameter core. This larger-than-usual core was necessary to accommodate the extensometer assembly and compression fixture. The difficulties in obtaining temperature distribution over the specimen gage length in such a furnace with a high ratio of core diameter to length were minimized by providing a closer spacing of furnace windings at the bottom of the furnace.

Compression Test Fixture

The basic design of the compression test fixture was adapted from that of Flanigan, et. al. (Ref. 2). It consisted of a base, a pair of adjustable guide blocks, a loading ram, and a cylindrical head to position the loading ram. The components of the fixture are shown in Figure 7, while the unit is shown in Figure 8 assembled for testing.

The base and guide blocks were made from H-40 steel and the loading ram from 17-22A(V) steel hardened to Rockwell "C" 40. The purpose of the guide blocks is to constrain the specimen from lateral buckling during the test. A pair of set screws provides the means for adjustment of the movable guide block.

The original guide blocks were smooth surfaced. However, during the initial tests of this unit, to obtain reproducible stress-strain curves with respect to both slope and proportional limit was found to be too much of an art.

The receipt of a report (Ref. 3) from the Titanium Metallurgical Laboratory at Batelle Memorial Institute on compression testing techniques led to modification of the compression guide blocks. The results of Kotchanik, et. al., were cited to show that values of compressive modulus (slope of the stress strain curve) were independent of supporting force when the guide blocks contained off-set grooves. Accordingly, a set of grooves off-set from each other were machined into the surface of the guide blocks. These can be seen in Figure 7.

This modification of the basic design proved to be successful as judged by the good consistency of data obtained with the modified unit.

Extensometer for Tension and Compression Tests

Although the Martens extensometer system could have been used for tensile and compression tests, it was not convenient for such short-time tests inasmuch as the measurement of elongation with this system requires alternate readings from the two mirrors and requires periodic interruption for resetting of the mirrors when large strains are involved. Consequently, the tensile machine was equipped with an O. S. Peters automatic stress-strain recording system to permit a continuous plot of the test results. This recording system also included a strain pacer which permitted accurate control of strain rates.

The O. S. Peters recording system employs a linear variable transformer (or microformer) to detect deformations.

To permit the use of the microformer for elevated temperature testing, an auxiliary extensometer unit was constructed to transfer specimen motion outside the furnace. In the original design (See Fig. 9) the extension was transmitted from only one side of the specimen and was sensitive to whether the sides of the specimens were parallel and to the axiality of load application. After initial experience with this equipment, the desirability of an averaging-type extensometer was recognized and the system accordingly modified. The modified system transmits the deformation of the specimen through an averaging linkage.

The revised system is shown in Figure 8 set up for a compression test. The specimen is gripped by screws made of heat-resistant alloy and tipped with tungsten carbide inserts. Motion of these screws is transmitted by pairs of flat extensometer bars made of 17-7PH alloy. At the lower ends of these bars are two cross pieces--one attached to a rod and the other containing a tube. The ends of the cross pieces are grooved to fit pins brazed to the lower ends of the extensometer bars. This joint acts in much the same manner as a knife edge. A spring maintains the seat of the pin in the cross piece. Finally, the microformer pickup is attached to the rod and tube. (See Fig. 10)

Also essential to this system is the open frame that forms the base for the compression test set-up and which is drilled and tapped at each end so that it can be included in the specimen gripping assembly for tensile tests. The purpose of this frame is to permit the attachment of the microformer to the rod and tube on the center line of the compression or tension axis.

This system has been successfully used for obtaining stress-strain curves at room temperature and at elevated temperature in both tension and compression. The extensometer was checked by comparing stress-strain curves obtained with it at room temperature against those in which the microformer was attached directly to the specimen. The results showed excellent agreement.

Tension-Impact Test Equipment

An existing Olsen impact testing machine was modified to permit carrying out tension-impact tests on sheet specimens. The modifications included construction of pairs of specimen-holding jaws that could be attached to the pendulum of the impact machine, and extension of the striking surfaces so that the impact occurred at the maximum downward point of the pendulum swing. In addition, it was necessary to re-calibrate the scale of the machine to obtain true values of impact strength under the test conditions employed.

The design of the specimen-holding jaws is shown in Figure 11 and a schematic representation of the test set-up is shown in Figure 12.

The specimen-holding jaws were modified from the design of Muhlenbruch (Ref. 4). The grip assembly was made to screw into a holding assembly fixed to the pendulum head. The specimen itself is held in the split grip sections. A cavity was machined into one side of the split grip to accommodate the specimen. The other half of the split grip has a plane surface and is fixed into position by an indexing pin located at the back end of the grip. The two halves of each grip are locked together by a snap ring. Stiffening rods fixed to the front holder and allowed to "float" in holes in the rear holder reduce the bending tendency of the assembly as the pendulum falls. The striker, which is screwed onto the rear holder provides the necessary tension impact loading as it hits the striking plates of the machine. Since the shoulder dimensions of the notched specimens were different from those of the smooth specimens a set of jaws was constructed for each type of test.

Because of the location of the specimen holding assembly, an auxiliary set of striking surfaces had to be added to the existing impact machine base. This modification is indicated in Figure 12. The location of the striking plates was fixed such that the distance L on Figure 12 was the same for the pendulum head and the striking surface in relation to the center of rotation of the pendulum arm. This arrangement permitted the impact blow to take place at the maximum downward point of the pendulum swing.

The impact data can not be read directly from the scale of the machine because of the added weight of the grips and because the rear portion of the grips falls from the head immediately after the impact blow.

The scale of the machine can be used, however, in the sense that it indicates the height to which the pendulum rises on the up-swing. An arm concentric with the pendulum arm and one-fifth of its length contacts a sine-curve rectifier that slides on a pair of vertical rods. The rectifier in turn contacts an indicating disk which provides a reference point on the scale of the machine. The height to which the indicating disk is pushed above its rest position is directly proportional to the height of the pendulum head.

A measurement of the scale showed that 0.73 inches corresponded to 20 scale divisions. It was then possible to obtain an expression that would convert scale divisions to pendulum height, since a 5:1 ratio exists between the lengths of the pendulum arm and the indicator arm. The expression follows:

$$H' = \frac{S}{20} \frac{(0.73)(5)}{(12)} = (0.0152)(S)$$

where H' is the pendulum height in feet after impact, and S is the number of scale divisions traversed by the indicating disk.

Using the terms indicated on Figure 12, the kinetic energy just before impact is $E_p = WH - \alpha F$

where E_p = initial energy, ft-lb;
H = initial height of pendulum center of gravity, ft;
W = pendulum weight, lb;
α = angle of rotation on downswing, degrees;
F = friction loss per degree

and the final energy just after impact is

$$E_f = WH' + \beta F$$

where E_f = final energy, ft-lb
H' = final pendulum height, ft
β = angle of rotation on up-swing, degrees

The difference between these terms is I, the energy absorbed by the impact. Thus,

$$I = E_p - E_f = WH - \alpha F - WH' - \beta F$$

$$I = W(H - H') - F(\alpha + \beta)$$

The calibration of the machine consisted of the determination of the friction loss and the effective initial height of the pendulum head. Because of the irregular shape of the pendulum head it was necessary that the initial height of the center of gravity of the pendulum be calculated from the characteristics of the machine.

The basis of the calibration was the fact that when no specimen is fixed onto the pendulum head, there can be no impact energy absorbed. Thus, the difference in heights would represent the friction loss of the machine. The equation then reduced to the following:

$$I = 0 = W(H - H') - F(\alpha + \beta)$$

$$W(H - H') = F(\alpha + \beta)$$

The pendulum was removed from the machine and weighed. This was found to be 57.5 pounds. The side plates and front specimen holder were found to weigh 5 pounds and the complete specimen holding assembly was found to weigh 7.7 pounds. Using these various pendulum weights, the assembly was allowed to fall from the initial height and the final height was determined.

Weight	S (avg)	H	Angle of Rotation ($\alpha + \beta$)
W = 57.5 (pendulum only)	117	1.78 ft.	151°
W + 5 = 62.5 (plus front grips)	122	1.85	153°
W + 7.7 = 65.2 (complete assembly)	123.5	1.88	154°

The angle of rotation was determined by laying out the various distances on a sheet of paper and measuring with a protractor. This procedure was approximate and possibly an average angle could have been used.

From these data, a series of three equations could be written. Since only two unknowns were present it was possible to use the third equation as a check of the accuracy of the determinations.

$$(57.5)(H - 1.78) = 151^\circ F$$
$$(62.5)(H - 1.85) = 153^\circ F$$
$$(65.2)(H - 1.88) = 154^\circ F$$

Solving these equations leads to values of $F = 0.40$ ft-lbs per degree for the friction loss, and the effective initial height $H = 2.82$ feet.

With these values known, it was then possible to compute the equation for the actual testing conditions of 65.2 pounds initial pendulum weight and 62.5 pounds final weight. (This comes about since the rear grips fall from the assembly after impact.)

With the aid of a cord attached to the rear grips it was possible to simulate the operation of the equipment without a specimen being present. Thus, the rear grips were pulled from the assembly at the maximum downward position. In this case H' was found to correspond to 124 scale units. A value of 155° was used for the angle of rotation and the calibrating equation was written as follows:

$$I = 0 = W_1 H - W_2 H' - F(\alpha + \beta)$$
$$I = (65.2)(2.82) - 62.5\,(0.0152S) - 0.40\,(155)$$
$$I = 122 - 0.95\,S \qquad (1)$$

where I is the impact energy absorbed in ft-lbs
S is the scale difference

This equation was then plotted so that the values of impact energy could be read directly for any measured scale difference.

For elevated temperature tension-impact tests a wire-wound resistance furnace was mounted horizontally on a table adjacent to the impact machine so that the specimen and its gripping assembly could be heated prior to their attachment to the pendulum head. It was originally intended that the furnace be mounted vertically so that the specimen assembly as attached to the head could be pushed up, locked into place in the furnace, and then released when temperature had been attained. The high thermal conductivity of the aluminum specimens precluded this since a portion of the grips and the pendulum head remained outside the furnace. This relatively large mass of unheated metal acting as a heat sink resulted in a large temperature gradient over the specimen when attempts were made to heat it while attached to the pendulum head.

TEST PROCEDURES

Except for elevated-temperature tension impact measurements, rather standard test procedures are available for all tests required for this program. Wherever applicable, ASTM Recommended Practices were adhered to. Other testing details followed practices developed through experience at the University of Michigan.

Specimen temperatures for all elevated-temperature tests were measured with chromel-alumel thermocouples wired to the gage section. All thermocouple beads were shielded from direct furnace radiation by a wrapping of asbestos cord.

In order to limit the holding time at the start of a test, furnaces were preheated within 50°F of the desired final temperature before specimens were placed into them. The temperature distribution over the entire gage section could be brought to within ±3°F of the nominal test temperature in a time period of no more than four hours. For the creep-exposure tests, an elapsed time of four hours between placing the specimen in the furnace and application of the load was adopted to provide uniformity of testing procedures.

Creep-Exposure Test Procedure

For each creep test, three thermocouples were used, one in the center and one at each end of the gage section. The modified Martens extensometer system described previously was used to measure the deformation both during load application and during the ensuing creep period. For the tests run to large total deformations the extensometer mirrors were reset from time to time to prevent their moving beyond the ends of the fixed scale.

At the end of the 10, 50, or 100 hour exposure period a final extensometer reading was taken and the power to the furnace turned off. Experience has shown that cooling the specimen with the load in place minimizes property changes of the type associated with creep "recovery." For the tests carried out under no load, i.e., temperature exposure only, the same general scheme was used. All the steps of a normal creep test were followed with the exception of the loading. The two duplicate specimens for each unstressed exposure were wired together and run in the same unit at the same time. The slight additional thickness of the material had no detectable effect on the temperature distribution within the furnace.

In the initial tests to determine time-deformation data of 17-7PH alloy, the extensometer bars were suspended from pins through the specimen shoulders. For later creep exposures the extensometer bars were attached to collars clamped directly onto the specimen gage section. This procedure proved to be satisfactory in tests with up to two percent total deformation.

It had been hoped that all exposure tests could be carried out with collars mounted directly on the gage sections, however, this did not prove to be practical in the case of the 2024-T86 alloy. The softness of this material and its clad coating led to the danger of inadvertently notching the specimen while clamping on the collars. In at least one case, premature failure occurred at a collar mounted on the gage section.

Tension and Compression Tests

The tensile test procedure with respect to temperature level and distribution was the same as that described for creep-exposure with the exception that two thermocouples rather than three were mounted on the gage section of the specimen. This was necessary in order not to interfere with the extensometer assembly mounted on the gage section. With reasonable care it was found possible to attain a temperature distribution of 2-3°F over the gage length of the specimen mounted in the large core diameter furnace used for these tests. At the higher temperatures it occasionally became necessary to shunt a portion of the furnace winding in order to obtain proper temperature distribution.

Due to the manner in which the specimen was gripped in the fixture, it was not possible to mount thermocouples directly on the compression specimens. For actual compression tests, the temperature measurements were taken from couples mounted at the base of the cylinder at the upper end of the fixture and the support block at the lower end of the fixture. With suitable shunting of the furnace winding it was possible to obtain a distribution of 3°F over the fixture. The validity of this method of temperature measurement was checked by comparing the readings from the external couples with the readings from a set of three couples that had been spot welded to the edges of a dummy specimen of 17-7PH alloy. The correlation between the dummy and the external couples was good.

For the room temperature tension tests the microformer strain follower was mounted directly on the specimen gage section, while at elevated temperatures the extensometer assembly was used in conjunction with the strain follower. In either case a two-inch gage length was used.

All tensile tests were run at a strain rate of 0.005 inches per inch per minute with the aid of the strain pacer. The test data were recorded in the form of a curve of load versus deformation. From this curve were calculated the 0.2 percent offset yield strength and the slope of the elastic portion (elastic modulus). The maximum load observed from the recorder trace was used to calculate the ultimate tensile strength. Measurements of elongation and reduction of area were made from the fractured specimen.

Because of the clearances that existed in the fixture, it was necessary to use a gage length of 1.7 inches for the compression tests. After accurately setting the gage length with the aid of a jig, the holding screws were tightened until it was certain that the tungsten carbide tips had achieved a tight grip on the specimen. A light coating of Molykote lubricant was applied to the specimen, the entire assembly placed in the opened compression fixture, and the top of the fixture was then set in place and screwed down.

According to Kotchanik, et. al. (Ref. 3) compressive yield strength values obtained from this type of fixture have a critical relationship to the supporting force. Consequently, a torque wrench was used to tighten the specimen guide blocks. A force of from 2 to 4 inch-pounds was found to give consistent results.

After the fixture was closed, the assembly was set on the pedestal and placed under the cross head of the tensile machine as shown in Figure 8. Finally, the strain follower was attached to the rod and tube of the extensometer and the recording system zeroed.

The load was applied at the approximate tensile machine setting that would give a strain rate of 0.005 inches per inch per minute in a tensile test. (This was necessary since the extensometer system was actually operated in the reverse direction from a tensile test and thus it was not possible to follow the strain pacer dial). The load application was continued until a marked change in slope was observed in the recorder trace. From the trace, the slope of the elastic portion (compressive modulus) and the 0.2 percent offset yield strength were determined.

Tension-Impact Test Procedure

Prior to assembling the specimen in the tension-impact test holding grips, measurements were made of the shoulder-to-shoulder distance and the cross sectional area of the specimen gage section.

The actual running of the test consisted of screwing the grip assembly to the holder at the back of the pendulum head which had been previously raised to the fixed initial height. The latch holding the specimen was then released and the head allowed to fall between the striking surfaces. The height to which the indicating disc rose after the impact was read from the scale of the machine and this value converted to energy absorbed upon impact by the use of equation (1), page 13. Measurements of specimen elongation and reduction of area after impact were made on a number of specimens. Although these data are reported, significance of reduction of area for sheet specimens is questionable.

A considerable amount of difficulty was encountered in running the elevated temperature tension-impact tests on aluminum specimens (the only material on which such tests have been run to date). It had originally been intended that the specimen in its gripping assembly would be heated in a vertical furnace while attached to the pendulum head. When proper temperature had been attained, it was planned to merely raise the furnace out of the way and release the pendulum latch. However, the high thermal conductivity of the aluminum specimen and the large unheated mass of the pendulum head combined to cause a large temperature difference over the length of the specimen gage section.

As an expedient, a procedure was adopted in which the specimen and gripping assembly were heated in a separate furnace and then attached to the pendulum head while hot. In this manner a reasonable temperature distribution could be reached over the specimen gage section.

A series of trial runs established the amount of time necessary to remove the specimen from the furnace and attach it to the head. It was necessary that this be done while the operator wore asbestos gloves and thus the operation was somewhat clumsy. Next the amount by which the specimen would cool in this time period was determined. In the actual running of the tests, the specimen assembly was heated to a temperature that much above the nominal test temperature in order that the actual impact would occur at the nominal test temperature. Fairly consistent values of impact energy were obtained after the operator had gained proficiency in the handling of the hot specimen assembly. Improvements in this procedure are to be attempted before extensive tension impact tests are conducted for the balance of the planned program.

Calculation of Effective Gage Length for Extension Measurements in Creep Tests.

Many of the creep data taken in this investigation were obtained using extensometers located between collars attached to pin holes on the shanks of the specimens. The deformation recorded included not only the extension in the gage section but also in the fillets and shanks. Consequently, it was necessary to calculate an effective gage length for these specimens that would take into account the deformation of the fillets and shanks.

Two different corrections were needed, depending on whether elastic or plastic deformation was being measured. The elastic correction was used for loading deformations or in short time tensile tests where the Martens extensometer was used, while the plastic correction was used for creep periods. No correction was necessary for tests using the automatic recording system since the extensometer attached directly to the gage section.

The effective gage length for the elastic case may be calculated from the specimen geometry alone. A sketch of a typical specimen is presented in Figure 13. This drawing defines the various terms used in the calculation of the effective gage length. The measurements made on a typical specimen were the widths at equal increments of distance from the fillet shoulder to the actual gage section. The widths are tabulated in column (b) of Table 1 for distance increments of 0.050 inches.

In the elastic case the strain in any section is inversely proportional to the area, so that the effective gage length for each short interval was simply the interval length multiplied by the ratio of the relative area of that interval to the area in the gage section. For a sheet specimen, the relative areas (column g) were merely the interval widths. The ratio between this width and the gage section width was multiplied by the interval length (column h) and summed to give the total contribution of the fillet. This was doubled to account for both fillets. The equivalent shank length was the total shank length multiplied by the ratio between the gage section width and the shank width. The shank length is the pin-to-pin distance minus the shoulder-to-shoulder distance. The effective gage length then was calculated by subtracting the actual fillet lengths from the shoulder-to-shoulder distance and adding the effective lengths of the fillets and shanks. This is indicated in Table 1 and was equal to SS + 0.45" for the particular specimen design under consideration. For a 0.530-inch wide specimen, the effective gage length for loading was SS + 0.48".

For the calculation of the plastic case, it was necessary to have information on the stress-creep rate relationships for the material at the test conditions. This information was obtained from the test data themselves. Examination of the rough time-elongation data showed that the minimum deformation rate for all specimens occurred at about 25 percent of the rupture life. A calculation was made of the minimum creep rate in scale units per hour at the time corresponding to about 25 percent of the rupture life for that particular stress.

The case illustrated in Table 1 considers a gage section stress of 110,000 psi for a test on 17-7PH at 800°F. A plot of stress versus creep rate in scale units is presented in Figure 14. From the specimen geometry, the stress was then calculated at each previously measured interval in the fillet. The stresses are tabulated in column (c). The creep rate at 800°F corresponding to each stress was obtained from Figure 14 and recorded in column (d) and finally the average creep rate was calculated for each 0.050-inch interval of fillet length. The effective length for each 0.050-inch interval was then calculated by multiplying the length by the ratio of the creep at that particular stress to the creep rate in the gage section (i.e., at 110,000 psi). This calculation, indicated in column (f), was then doubled to account for both fillets. The equivalent length of the shank was computed by multiplying the shank length by the ratio of the shank creep rate to the gage section creep rate. The effective gage length for creep at 800°F was then expressed in terms of the shoulder-to-shoulder distance by first subtracting the actual fillet lengths and then adding the calculated effective lengths of the fillets and shanks. The value obtained for 800°F was SS - 0.905". The values for 600° and 900°F obtained in a similar manner are as follows:

$$EGL_{600°F} = SS - 1.01''$$

$$EGL_{900°F} = SS - 0.83''$$

For the 2024-T86 alloy, similar calculations gave the following results:

$$EGL_{350° \text{ and } 400°F} = SS - 0.70''$$

$$EGL_{500°F} = SS - 0.90''$$

It must be emphasized that such effective gage lengths are valid only for the particular material, temperature and specimen geometry considered.

Metallographic Examinations

Conventional techniques of mounting, grinding, polishing and etching were followed in preparing specimens of the 2024-T86 and 17-7PH alloys for metallographic examination.

Initial polishing steps for the 2024-T86 alloy were carried out on a slow rotating wheel (at about 300 rpm) using 180-or 240-mesh silicon carbide paper lubricated with a few drops of oil. Polishing was started first on 400-mesh and then 600-mesh silicon carbide paper--in each case lubricated with oil. The next step consisted of hand polishing on No. 4-0 emery paper which had been lubricated with a few drops of a kerosene-liquid paraffin mixture (one part paraffin to five parts of kerosene). This step was continued until all previous polishing marks had been removed. Then the specimen was washed with benzene or isopropanol. The final polishing was started on a slow (300 rpm) wheel covered with "Broadcloth," using a polishing medium of 5 micron Alumina. The last steps were carried out on a wheel covered with "Microcloth," using a medium of 1 micron Magnesium Oxide to which had been added a small amount of liquid green soap. The specimen was polished first at 300 rpm, then the wheel was stopped and the polishing finished by hand. Care was taken that the hand polishing be carried out with a circular motion.

The polished samples were photographed in the un-etched condition and then etched with Keller's Etch in order to reveal the microstructure. The composition of this reagent follows:

HF (conc)	1 part
HCL(conc)	1
HNO_3(conc)	2.5
H_2O	95

A sample of the as-produced material was examined using the selective etching technique described by Keller (Ref. 5) in an attempt to identify its constituents. This technique involved the following etches used in successive order: 1 percent HF; 20 percent H_2SO_4; 25 percent HNO_3; and 1 percent NaOH. The differences by which these reagents attack the constituents can be used to identify them. In addition, a phosphoric acid etch (Ref. 6) was also used for identification studies.

The technique for metallographic preparation of the 17-7PH alloy was considerably simpler and easier to carry out than was the case with the much softer aluminum alloy. The samples were first mounted in bakelite and then wet ground in order to remove any disturbed metal. The rough polishing steps were carried out successively on 240-, 400-, and 600-mesh silicon carbide paper on a rotating lap. The paper was lubricated with water throughout these steps.

Finish polishing was accomplished with acqueous media of Linde "A" and Linde "B" polishing compounds on rotating laps covered with "Microcloth."

The polished samples were then etched with Marble's Reagent or with a special reagent developed at the University of Michigan for the examination of heat-resistant materials. (See Ref. 7)

The composition of Marbles' Reagent follows:

$CuSo_4$	20 gm
conc H Cl	100 ml
H_2O	100 ml

The composition of the special etch developed at the University is the following:

No. 4 Etch

29 % $CuCl_2$ in H_2O
36 % Glacial Acetic Acid
23 % HCl
5 % H_2SO_4
7 % $HCrO_4$

EXPERIMENTAL RESULTS

Testing priority in this investigation was given to the aluminum alloy. But since the 17-7PH material was received first, studies on that alloy were carried out until receipt of the aluminum. Work completed on the 17-7PH included: (1) preliminary studies of room temperature properties, (2) 600°F tensile tests, (3) definition of elevated temperature rupture and total deformation, (4) a check of the effect of remachining creep specimen prior to tensile testing, (5) studies of the effects of unstressed exposure and exposure to 2 percent total deformation in 100 hours on the room temperature tensile properties.

Experimental results for both materials tested to date are arranged together in the following general order:

(1.) Preliminary tests to establish creep deformation properties,

(2.) Short-time properties of specimens before creep exposure,

(3.) Effect of prior creep exposure on (a) tension properties, (b) compression properties, and (c) tension-impact properties.

(4.) Results of metallographic examination and special studies.

Preliminary Total Deformation Curves

Before the required stress levels could be chosen for the actual creep-exposure periods, data had to be obtained on total deformation as a function of stress and time.

Creep-rupture tests on the 17-7PH at 600°, 800°, and 900°F and on the aluminum alloy at 350°, 400°, and 500°F gave the times listed in Tables 2 and 3 for total deformations between 0.5 and 3%. The tabulated results include rupture times and fracture elongation, which are useful measures of variability of a material. At each temperature good consistency of rupture and elongation was found.

Reduction of area values for sheet specimens are difficult to measure and are often considered not worth reporting. They have been included in the present study largely because the reduction of area is the only measure of ductility applicable to the notched tension-impact specimens.

Curves of stress versus time for total deformations of 0.5, 1, 2, and 3% total deformations were established at each of the test temperatures from the data obtained. (See Figs. 15 and 16) At 600°F, none of the test stresses used for the 17-7PH alloy was low enough to give less than 0.5% loading deformation, while at 800° and 900°F results for 0.5% deformation were obtained only for time periods of a few hours or less. Consequently, additional tests will be required at lower stresses.

In order to fit curves to the available time-deformation data it was necessary to allow for breaks in some of the curves. In general, these curves tend to follow the same slopes as the rupture curves at the same temperature.

A check of the 17-7PH data was possible by a comparison with the results of Hanlon, Salvaggi, and Guarnieri (Ref. 8) for tests at 800°F. Figure 17 compares the two investigations. The agreement appears to be good.

The curves for 0.5 and 1.0% total deformation were established for the 2024-T86 alloy without too much difficulty at all three temperatures, but 2.0% appeared to be a practical limit for deformation at 350° and 400°F. Even this required stresses to within 1000 psi of the rupture strength and examination of Figure 16 reveals the difficulty of stress selection inherent in trying to reach 2.0 and 3.0% deformations in 10, 50, or 100 hours. Therefore, for the time being, the attainment of 3.0% total deformation was ruled out at 350° and 400°F. Even at 500°F, stresses selected from Figure 16 to give 3% deformation resulted in fracture before the time period for creep exposure was over.

Hardness measurements taken on the 17-7PH (TH 1050) specimens after the completion of testing are included in Table 2. They show a moderate increase in hardness from exposure to time, stress, and temperature. Random hardness impressions taken on each sample, three in the shanks and three in the gage section, show no significant differences in hardness between the shanks and gage section. An analysis of the hardness data indicated that the hardness change at all test temperatures was significant with respect to the as-treated (base) condition, but that there was no significant difference between the average hardness changes for 800° and 900°F exposures, while the difference between the 600°F exposures and the other two temperatures was on the borderline of significance.

Base Properties of Material Before Creep Exposure

Sufficient tension, compression and tension-impact tests were conducted on random specimens of the 2024-T86 alloy to establish the normal scatter in properties both at room temperature and at the temperatures used for creep exposures--350°, 400°, and 500°F. Results for the three types of tests are listed separately in Tables 4 through 7.

With the 17-7PH stainless steel in the TH 1050 condition, tension tests to establish base properties have been completed only for room temperature and for 600°F. Compression and tension-impact properties were obtained only at room temperature during the first year of the contract. (See Tables 8 through 11)

2024-T86

The results of ten tension tests at room temperature and nine at each of the elevated temperatures (Table 4) shows good agreement in the ultimate and yield strengths for 2024-T86 specimens. Differences between sheets appear to be no greater than the differences within an individual sheet. Statistical analysis of the data indicate that creep exposure must result in a change in strength from the unexposed condition greater than 1500-3000 psi for the change to be significant.

At the elevated temperatures, the strengths were lower and the spread between the tensile and yield strengths decreased. Thus, at room temperature the yield strength was about 5,000 psi lower than the tensile strength, while the spread had decreased to approximately 1,500 psi at the higher temperatures tested. The elongations and reductions of area showed only a moderate increase over the room temperature values for tests up to 500°F. These effects of temperature on properties of the as-received material are brought out by Figure 18.

The room temperature compression yield strengths for 2024-T86 show perhaps a bit more scatter than did the tensile yield, however, the elevated temperature values have about the same scatter for both tension and compression. The scatter within sheets appears to be of the same order as the scatter between sheets. The compression yield strength was about 5,000 psi higher than the tensile yield strength at room temperature and about 10,000 psi higher at the three elevated temperatures, 350°, 400°, and 500°F. Thus, at room temperature the compression yield strength is about 105 percent of the tension yield strength, while at 500°F it is of the order of 125 percent of the tension yield strength.

Representative stress-strain curves in tension and in compression are shown in Figures 19 and 20. The elastic modulus, as determined from the slope of the initial portion of such curves is about the same for tension and compression in corresponding tests at room temperature or at 350°F. At 400° and 500°F the compression modulus was higher than the value for tension.

The average values for the tension-impact data in Tables 6 and 7 have been included on Figure 18.

The data for each testing temperature show a large scatter in tension impact strength within individual sheets, but the scatter between the sheet averages is fairly small and the sheet averages agree well with the average value for all tests run at a given temperature. Thus, although the reliability of an individual tension-impact value might be questionable, the average of several tests can be considered a fair measure of the impact properties.

Increasing the test temperature appeared to have little effect on the tension-impact strength. The average values showed a slight decrease in strength at 350°, an increase at 400°, and a decrease at 500°F. No explanation is offered for the hump at 400°F.

Since the smooth-bar tests appeared to show little sensitivity for tension-impact strength with temperature, two notched-bar tests were run at each of the test temperatures. These results, reported in Table 7, are also plotted in Figure 18. The notched-bar strength was almost exactly half the smooth-bar strength, while the effect of test temperature was the same as that for smooth bars--even to the occurrence of the hump at 400°F. Again, no explanation for this behavior is evident.

Statistical analysis of the room temperature data for smooth bars indicated that for a change in tension-impact properties to be significant with respect to the as-received condition, a difference of 3 ft-lbs would be necessary, while the significance limit between the averages of pairs of exposed samples would be 4 ft-lbs.

17-7PH (TH 1050)

The room temperature tension data of Table 8 indicate that the samples from 17-7PH Sheet No. 1 were somewhat stronger and less ductile than the samples from Sheets 2 and 3. There was little difference between the hardnesses of the samples from all three sheets.

The average properties at room temperature were calculated for each sheet and for all tests. Since six specimens were run from Sheet 1 and only two each from Sheets 2 and 3, a second set of averages, that of the average of the sheet averages, was calculated to reduce the bias that would result from the simple average of all ten tests. The basis for this was that an average of the three sheets should not be weighted 60 percent with values from Sheet 1.

Statistical analysis of the scatter in the room temperature data indicated that changes in tensile and yield strength after exposure would have to be about 12,000-15,000 psi in order to be significant.

The tensile tests at 600°F showed less scatter from sheet to sheet than they did at room temperature; however, large differences in strength were noted within Sheets 2 and 3. In Sheet 2, one of the three samples was quite a bit weaker than the other two, while in Sheet 3 just the opposite was the case.

The scatter from low to high in room temperature strength represented about 14 percent of the average strength, while at 600°F the scatter was about 17 percent of the average value. The drop in average tensile strength from room temperature to 600°F was about 15 percent of the room temperature strength. Elongation decreased as the testing temperature increased.

Room-temperature compressive yield strength for 17-7PH showed fair consistency. (See Table 10) The scatter between sheets and within individual sheets was slightly greater than the scatter previously encountered in tensile tests of the same material. In addition, the deviation from low to high individual values was about 22 percent of the average strength for all sheets. These results suggested that significant changes in compressive yield strength would be of the order of from 15,000 to 18,000 psi.

Both the compression yield strength and modulus were higher than those obtained in tension, with the compression yield about 12-13 percent higher. The increase in modulus for compression over tension was of the order of 4-5 percent.

The as-treated tensile and compression properties of 17-7PH determined at the University of Michigan were compared with the results available in the literature from other laboratories. Such a comparison indicates not only the possible heat-to-heat variability of the material, but the effect of heat treatment within the commercial specifications.

The data summarized in Table 12 indicate a fair correlation between the results of the various laboratories. While the Cornell values (Ref. 11) of room temperature strength were the highest, they corresponded to the higher hardness reported. The WADC results (Ref. 9) were reported for material of two hardness levels, with the University of Michigan results falling between. The Armour results (Ref. 11) were a bit lower, while the typical values given by Armco were the lowest of all. The 600°F results obtained by the University of Michigan and by Armour were somewhat higher than either the WADC or Armco data.

The compression yield strength determined at the University of Michigan was somewhat higher in absolute value than the data from other sources but were about the same percentage higher than the tensile yield strength as were compression results from other laboratories.

These data indicate that the material treated at the University of Michigan was fairly representative of the alloy, although the tensile properties were somewhat on the high side.

The results of tension-impact tests run at room temperature on both smooth and notched specimens of the 17-7PH alloy are summarized in Table 11. As mentioned in the section on specimen preparation, the notched samples had a theoretical stress concentration factor of 4.2. The notched-bar tests showed a greater degree of scatter than did the smooth-bar tests. In both cases, however, the average values of impact energy absorbed were lowest for specimens from Sheet 1. In the case of the smooth bars, Sheet 2 was intermediate in strength while Sheet 3 was intermediate in the case of the notched bars. For both types of test it appeared that the scatter between extreme values within an individual sheet was greater than the scatter between the averages of the sheets.

Based on the averages of all tests, the effect of the notch was to reduce significantly the amount of energy absorbed upon tension-impact. It should be noted, incidentally, that the cross sectional area at the base of the notch was 25 percent greater than the gage-section area of the smooth samples.

Slight and probably unaccountable differences in the notches themselves may have contributed to the scatter in the notched bar results.

Tension Properties after Prior Creep Exposure

Tables 13 and 14 list results of short-time tension tests at room temperature and at the exposure temperatures for 2024-T86 specimens exposed to 10, 50, and 100 hours at 350°, 400°, and 500°F without any applied stress. The added effect of stress to cause total deformations of 0.5, 1, 2, and 3% in the 10, 50, and 100 hour periods of creep exposure was studied in experiments reported in Table 15. On both Tables 13 and 15, hardness data have been included.

Effects of both stressed and unstressed exposures at temperatures between 600° and 900°F on room-temperature tensile properties of 17-7PH alloy are covered by the listings in Table 16.

In these tables each specimen is described by the nominal exposure conditions, the actual exposure conditions, the actual deformation obtained, and the tensile properties after completion of the exposure treatment.

The nominal exposure conditions consisted of the exposure time, temperature, and desired total deformation. The stress to produce this deformation was estimated from the total deformation data of Figure 15 and 16. The actual deformations obtained differed somewhat from the nominally specified deformation. However, every effort was made to cover the range of deformations specified to be studied and the data were correlated with respect to the actual deformation.

Measurement of specimen extension both during load application and during the following creep-exposure period permitted separation of the total deformation into its component parts. In many cases the test stresses were below the proportional limit, but in a few cases there was some plastic deformation on loading. The amount of this deformation was quite small. The major portion of the plastic deformation occurring during a test was from creep at the testing temperature and stress. This component, designated the creep deformation, was obtained by subtracting the total loading deformation from the total deformation at the end of the test.

The contract called for a study in terms of fixed total deformations, but the total plastic deformation, short-time plastic deformation (from loading), or the creep deformation may prove to offer better general correlations of the final data. For this reason the several components of the total deformation have been included on the tables of data where such entries are appropriate. In several cases, separate curves of results have been plotted in terms of total deformation and of creep deformation.

2024-T86

Representative stress-strain curves in tension have been assembled in Figures 21 and 22 to illustrate in graphical form the general effects of prior creep or of exposure to temperature alone on subsequent yielding of 2024-T86 alloy. Room-temperature yield strength was noticeably reduced by exposure to the elevated temperature, with a greater reduction as the creep-exposure temperature increased from 350° to 400° to 500°F. For the same length of the exposure period, the decline in yield strength brought about by exposure to temperature in the absence of applied stress was greater than the further decline in strength for stresses causing creep to total deformations of 0.5-3%, especially at the lower two temperatures where the stress-strain curves seemed to be rather independent of the stress at which exposure took place. The fourth set of curves for room temperature stress-strain tests after prior exposure at 400°F illustrates the progressive lowering of yield strength when the exposure time is increased from 10 to 50 to 100 hours.

Corresponding sets of representative curves in Figure 22 illustrate trends for tension stress-strain characteristics at the exposure temperature after prior periods of creep or of unstressed exposure. In contrast to the findings for room temperature tension tests, prior exposure to the elevated test temperatures under zero stress appeared to have no particular effect on the subsequent yield at 350°, 400°, or 500°F. However, creep due to an applied stress during the exposure period did measureably lower later yield strength at temperature. This lowering of strength was but slightly influenced by the amount of creep which took place. The set of curves for different times of exposure at 400°F at stresses giving about 1 percent of creep deformation suggests that the time of creep exposure may be more important than the amount of creep obtained, at least insofar as later yield strength is concerned.

The curves of Figure 23 show graphically the data of Tables 13 and 14 for tensile properties after prior exposure to elevated temperature under zero stress. Unstressed exposures at 350°F for 10 - 100 hours resulted in a slight drop of room-temperature yield or tensile strength. Decrease in room-temperature strength was progressively greater for exposure at 400° and 500°F. For all three temperatures of prior unstressed exposure, declines in room temperature strength were greater for longer exposure periods. The yield and ultimate strengths in tension for tests conducted at the exposure temperature showed no large effect of prior holding at temperature without stress. Subsequent elongation at fracture seemed to be rather independent of the prior unstressed exposures considered for tests at room or elevated temperature.

In the room-temperature tests with prior exposure at 500°F, a 20 - 30 percent drop in yield or tensile strength was observed after a 10-hour unstressed exposure. With duplicate tests, the tensile and yield strengths after 50 hours of prior exposure were about the same as for 10 hours, while a longer time exposure (100 hours) resulted in noticeable drop in strength below the values after 10 and 50 hours exposure time. This observed trend could be the result of erratic data, but could also reflect a double-peak aging reaction such as has been reported for this alloy composition (See Ref. 12).

The factor of deformation during the creep-exposure period has been added to the test data presented in Figures 24 through 26. In the first two of these figures, room-temperature strength was correlated separately against creep deformation and against total deformation, with the creep-exposure time and temperature as parameters. In all cases the creep deformation was such a predominant part of the total that the character of the curves is the same whether results are plotted against total deformation or against the creep deformation above.

Some decrease in tensile and yield strength is suggested with increased amounts of prior deformation at 350°F. It should be recognized that the points for zero deformation indicate that the loss of strength from time at temperature alone was of the same order of magnitude as the effects of creep under stress. The data of Figure 26 show the decrease of strength in tests at 350°F to be about the same as the loss of room-temperature strength after the same amount of prior creep exposure.

With prior creep at 400°F, the effect of deformation during the creep exposure on reduction in subsequent strength was greater than for creep at 350°F.

The room-temperature strength was further reduced by prior deformation by about the same amount that it was reduced by exposure to temperature alone. A condition that produced 2-percent total deformation in 100 hours at 400°F resulted in a drop in room-temperature tensile strength to 80 percent of the unexposed value and a drop in the 400°F tensile strength to about 75 percent of the unexposed value. The corresponding yield strengths were reduced to 70 and 75 percent respectively of the unexposed value. Exposure to temperature alone for the same time period reduced the room-temperature tensile and yield strengths by 15 and 25 percent respectively, while the strengths at 400°F test temperature (Fig. 26) were virtually unaffected.

The data for 500°F prior creep exposure show a severe loss in subsequent tensile strength at both room temperature or 500°F after exposure. The exposure to temperature alone resulted in a loss of about 18 - 22 percent of the room-temperature tensile strength and from 30 - 45 percent of the room-temperature yield strength, depending on the length of the prior exposure time. The effect of stressed exposure caused a further drop in the subsequent strengths. One-half percent total deformation at 500°F dropped the room-temperature strength to about 60 - 70 percent of the unexposed value and cut the yield strength almost in half. Larger amounts of total deformation accentuated the loss of strength. After the most severe condition--- 100 hours exposure to 3 percent total deformation--- the room-temperature tensile strength was 53 percent of the unexposed value and the yield strength only 33 percent of the unexposed value.

The strengths at 500°F (shown in Fig. 26) were similarly affected by exposure at 500°F. The unstressed exposure to temperature alone had little effect on the tensile properties--reducing the tensile and yield strengths by only 6 or 7 percent in the extreme case. However, stressed exposure had a severe and immediately deleterious effect on the 500°F strength. In many cases the tensile strength was reduced to 50 - 75 percent of the unexposed value. The yield strengths were reduced about the same percentage as were the tensile strengths. This was contrary to the results of room-temperature tests of the same conditions which showed the yield strength to be reduced a greater percentage than was the tensile strength. The most severe drop in both the room-temperature and elevated-temperature strengths occurred up to 1.0 percent total deformation. Thereafter the subsequent tensile and yield strengths leveled off. In the case of 10 hours creep exposure at 500°F the room-temperature strength appeared to increase slightly with amounts of prior creep deformation beyond 1.5 - 2.0 percent total deformation.

The relative effects of the various prior creep exposures on tensile strength and yield strength in tension are summarized in Table 17, with the strengths expressed as a percent of the unexposed value for the given test temperature. At 350°F the maximum loss of strength is listed as about 15 percent, at 400°F the loss of strength ranged to 25 percent, while at 500°F a loss of 50 - 60 percent of the original strength was encountered for the longer times and greater amounts of total deformation.

Hardness determinations at room temperature run on the exposed specimens were listed in the tabular data referred to earlier. These data for the 2024-T86 alloy have been plotted in Figure 27 as a function of exposure temperature and time. Effects of both unstressed and stressed exposure follow the same general course as was found for tensile and yield strengths. Hardness decreased with both longer exposure times and higher exposure temperature. For prior creep at 500°F, the curve indicated a reversal in slope at 50 hours exposure time.

The time of exposure appeared to have little influence on the elongation in tensile tests after prior creep exposure. In general, larger creep deformations at any temperature seemed to reduce the elongation measureably, especially for subsequent tests at the exposure temperature. The curves of Figure 28 for exposure at 350°F demonstrate the type of results obtained.

17-7PH (TH 1050)

Table 16 lists all data obtained to date on effects of prior exposure on subsequent short-time properties of 17-7PH. Included in the tabulation are results of room-temperature tensile tests for specimens exposed at zero stress for 10, 50, or 100 hours at 600°, 800°, or 900°F.

Two specimens from different sheets were run at each exposure condition. A plot of the average values of tensile strength, elongation, and hardness versus exposure time is presented in Figure 29.

Statistical analysis of the replicate tests of the as-treated material had indicated a change of 12,000 to 15,000 psi would have to be obtained in order to be significant. The data indicate that the unstressed exposures at 600°F had no significant effect on the tensile strength of the material. The effects were also negligible for 10 hours exposure at both 800 and 900°F. However, the longer exposures at these temperatures did result in a significant increase in the strength. At 900°F there may have been a maximum effect somewhere between 50 and 100 hours, while at 800°F, there may be a maximum effect at somewhat over 100 hours. The hardness data confirm the trends indicated by the tensile strengths. Elongation shows slight change, although moving consistently in the opposite direction from the change in strength.

The scatter in strength between replicate exposure conditions was most pronounced for the exposures carried on at 600° and for 10 hours at 800°F and ranged from 6,000 to 17,000 psi. At longer times and higher temperatures, the two values were only 500 to 4,000 psi apart.

By mutual agreement between the University and WADC an initial phase of the evaluation of the 17-7PH alloy was a survey of the effects on the room-temperature tensile properties of creep to two-percent-total deformation in 100 hours. The exposure temperatures were fixed at 50°F increments between 600° and 900°F. The stresses required were interpolated using data from the total-deformation curves of Figure 15, replotted as shown in Figure 30.

At least two tests were run for each condition chosen. Results of this preliminary study are among the data of Table 16. Plots of tensile strength, yield strength, elongation, and hardness (all taken at room temperature) are presented in Figure 31 as a function of exposure temperature.

The effects of both stressed or unstressed exposure were to raise the tensile and yield strengths over the as-treated value. Significant effects were noted for unstressed exposures at 800° and 900°F, and for stressed exposures at all temperatures above 600°F. The stressed exposure raised the strength to a greater extent than did the unstressed exposure, with the maximum effect for both occurring at about 850°F. The strengthening effect of stressed exposure over unstressed exposure appears to be greater in the case of the yield strength than for tensile strength.

The effects of the exposures on the hardness and elongation were contrary to the trends indicated by the tensile and yield strengths. At the lower end of the range of exposure temperature the elongation was greatly reduced by stressed exposure. At 800°F creep-exposure temperature the elongation of the unstressed samples also showed some reduction; elongations for both types of exposures tended to converge thereafter.

The final hardness for samples given stressed exposure tended to be slightly lower than the hardnesses of the unstressed samples, at least up to exposure temperatures of 800° - 850°F. This was contrary to the normal expectation that increased hardness would accompany the higher tensile and yield strengths of the stressed samples.

The most significant results of this initial survey appear to be the following:

1. Stressed or unstressed exposures between 600° and 900°F tend to raise the tensile and yield strengths.

2. The effect of stressed exposure is greater than that for unstressed exposure--particularly in reducing the spread between the tensile and yield strengths.

3. The temperature of maximum effect is about 800° - 850°F.

4. At the lower end of the temperature range, i.e. 600° - 750°F, stressed exposure greatly reduced the room-temperature ductility.

This low room-temperature ductility after stressed exposure at 600° to 700°F may be the most important effect noted in this survey. Extension of the testing to temperatures below 600°F would appear valuable in order to better define any adverse results from prior creep or time at temperature.

Attention is called to the variability of total deformation obtained at 600°F with 17-7PH specimens under substantially identical creep-exposure conditions--despite fairly consistent loading deformation. This behavior is perhaps not too unusual in that this alloy has a rather extensive period of relatively-rapid primary creep early in the test and since primary creep tends to be variable from test to test.

The proportion of total deformation which occurred during load application was rather high at 600°F due to the high stresses involved, but most of the loading deformation even in this case represented elastic strain. Figure 32 presents the ratio of loading deformation to total deformation and the proportion of the loading deformation due to the elastic portion. The results indicate that even at 600°F most of the total deformation is due to the creep during the exposure period.

Compression Properties after Prior Creep Exposure

To date compression tests on exposed material have been completed only for the 2024-T86 aluminum alloy. The results of such exposures in the absence of stress are listed in Tables 18 and 19 respectively for subsequent tests at room temperature and at the exposure temperature. Effects of stress during the exposure period are considered in the tests reported in Table 20.

Actual stress-strain curves for representative compression tests have been reproduced in Figures 33 and 34. At room temperature, the same period of exposure at a given temperature seems to have lowered the yield strength about the same degree regardless of the stress present during the exposure period. The greatest factor in strength after exposure appears from these curves to be the temperature of the exposure, with little further influence of the duration of exposure or the deformation during it. Tests at the elevated temperature of the prior creep exposure are similar except that now larger deformations during the exposure period resulted in lower compression yield strengths than did unstressed exposures or low prior creep deformations.

Figure 35 summarizes the effect of the exposure conditions on the room temperature compression yield strength (0.2 percent offset strength), while Figure 36 is a similar plot for the compression yield strength at the exposure temperature. The room-temperature results were somewhat similar to the effects of exposure on the tensile strength. Exposures at 350° and 400°F resulted in a progressive loss of strength with both temperature and time of exposure. At 500°F there was a severe drop in strength for 10 hours exposure and then an increase at 50 hours and an intermediate decrease at 100 hours. Ten hours exposure at 500°F reduced the room-temperature compression yield strength almost 39 percent below the unexposed value, while 50 hours exposure reduced the strength only 24 percent and 100 hours exposure reduced the strength about 29 percent. This behavior is a probable manifestation of the double aging reaction mentioned earlier. Apparently the compression properties were more sensitive to this effect than were the tensile properties.

What might be considered more normal behavior was exhibited by the effects of exposure time on the elevated temperature compression yield strength (Figure 36). In this instance, an increase in the exposure time and temperature resulted in a loss of strength throughout the range of time and temperature studied. The first ten hours of exposure had relatively the greatest effect; thereafter the strength dropped off less rapidly with time. A major loss of strength from the unexposed value--53 percent--was observed for 100 hours exposure at 500°F. The loss of strength at 350°F was slight, only about 3 percent for 100 hours exposure. One hundred hours exposure reduced the 400°F strength by about 16 percent.

Compression yield strengths after prior creep are shown in Figures 37 and 38 for tests at room temperature and at the creep temperature. Separate curves are plotted for exposure periods of 10, 50, and 100 hours, with separate presentations against creep deformation and against total deformation during the exposure period.

For exposures at 350° or 400°F, and for a fixed exposure time, the curve of room-temperature compression yield strength versus creep deformation or total deformation exhibited a peak at intermediate values in the deformation range investigated. In contrast, all curves for 500°F creep exposure and the curves of elevated-temperature strength for 350°F and 400°F exposure exhibited a steady decline from zero prior deformation to the largest deformation used. The explanation for these observations is not immediately apparent.

The percentages of the initial compression yield strength retained after specified exposure conditions are listed in Table 21. After 50 - 100 hours creep at 500°F, half or less of the original strength may remain.

Tension-Impact Strength after Prior Creep Exposure

Tension-impact tests after prior creep-exposure histories were limited to the 2024-T86 alloy. (See Tables 22 through 24 and Figures 39 and 40). From Figure 39, a possible slight drop in room temperature tension-impact strength is indicated with time and temperature of exposure. However, the results of the 100-hour exposure tests are confusing. One hundred hours at 400° or 500°F apparently raised the tension-impact strength. The scatter between the 100 hour results at 350°F was large, with the average of the two determinations indicating a drop in strength from the 50-hour value at this exposure temperature.

It will be remembered that analysis of the replicate tests on the unexposed material indicated that the significant changes in tension-impact strength between pairs of determinations would be about 4 ft-lbs. On this basis, only the 500°F exposures showed a significant change in properties with respect to the unexposed condition. Thus, it appears that the room-temperature smooth-bar tension-impact test was not as sensitive to the effects of unstressed exposure as were the tensile and compression tests.

Absolute effects of prior unstressed exposure on elevated-temperature tension-impact strength were small, possibly less than the limit of significance.

Effects of creep during the exposure period prior to tension-impact testing at room temperature appear to be quite variable from the curves plotted in Figure 40. If we disregard the point for 350°F with the largest deformation studied for 100 hours exposure, tension-impact strength at room temperature seems not to be much affected by moderate changes in conditions of prior creep exposure.

Metallographic Examinations

Samples of 2024-T86 and 17-7PH alloys were studied metallographically to establish a record of the microstructure before testing and to examine for structural changes brought about by the testing.

Photomicrographs of the aluminum alloy shown in Figure 41 include the as-received material and specimens after creep exposure at 350° and 500°F, respectively. The latter two samples were chosen to have about the same amount of total deformation from the creep exposure.

Apparently, the 500°F exposure altered the response of the material to the etchant, but possible visible precipitation had occurred in this sample. The specimen exposed at 350°F shows evidences of deformation and a variation in the overall grain size.

Using selective etching techniques, the following phases were identified: $Cu\ Al_2$; $Al_2\ Cu\ Mg$; $Al_7\ Cu_2\ Fe$. Others may be present and this list of constituents is not intended to be all-inclusive.

An incomplete metallographic examination of the 17-7PH alloy included specimens of the material as received (Condition A) and after the TH 1050 heat treatment. (See Figure 42). The effect of the heat treatment was precipitation both within the grains and at grain boundaries. A creep-test specimen examined after some 500 hours at 800°F and 90,000 psi showed evidence of over-aging of the precipitate. (See Fig. 42)

Effect of Re-Machining on Tensile Test Results

In the section on Specimen Preparation it was noted that the design of creep specimens is such that after creep exposure the edges of the gage sections could be remachined before subsequent tests of mechanical properties. This was done for two reasons. First, it was desired that the final tests measure the properties of the sheet material itself and not the particular specimen's edge effects. Second, it was desired that the practice for subsequent tensile test specimens conform to that adopted for the tension-impact and compression specimens which were designed to be machined from the gage section of an exposed creep specimen.

The question arose as to what effect, if any, the subsequent remachining operation would have on the tensile properties of an exposed specimen. A check test was run on 17-7PH specimens intended for exposure at 700°F and 120,000 psi to reach 2 percent total deformation in 100 hours. One specimen, 2R-T2, was given the standard remachining operation after exposure. Another specimen 3Q-T6 was given the identical exposure and then tensile tested without remachining; i.e., with 0.530-inch wide gage section. The results of these tests follow:

	Total Deformation (%)	Ultimate Tensile Strength (psi)	0.2% offset Yield Strength (psi)	Elong. %-2 in.	Red. of Area (%)	E, 10^6 psi	Hardness R"C"
Remachined (2R-T2)	2.54	219,000	218,000	2.2	13.7	30.6	44.0
Not Re-machined (3Q-T6)	1.95	220,000	219,000	3.5	13.8	29.6	44.2

The result of these two tests indicates that the remachining operation apparently had no significant effect on the tensile properties.

The effect of remachining on the subsequent elevated temperature tensile properties of 2024-T86 given unstressed exposure was also checked for two specimens given 100 hours exposure at 400 or 500°F. Results were checked against two specimens given the identical exposures and then remachined. The data, included in Table 15, show that the tensile strength of the un-machined samples was slightly higher than the remachined samples. However, the yield strength, elongation, and reduction of area showed good agreement with the remachined results. In any case, no cause to depart from the adopted procedure is evidenced.

DISCUSSION

To date, two results of concern to the designer have been noted to result from prior creep exposure:

(1.) A marked decline in subsequent short-time strength for the 2024-T86 aluminum alloy,

(2.) An apparent drop in subsequent ductility of 17-7PH after prior exposure to temperatures around 600°F.

The best way to present these findings for possible design application must still be resolved. For structures in which critical sections are subject to local concentrated stresses, the estimated total deformation imposed by the geometry and loading of the structure may be the preferable criterion against which to correlate strength and ductility changes. For most structures subjected to creep during service, only the permanent deformations can be measured. In this case, the strength changes would probably be desired in terms of total plastic deformation (or creep deformations if the initial plastic strains of loading are small).

Perhaps the simplest correlation for most general use would be in terms of the temperature and stress present during the period of creep exposure. Figure 43 illustrates a possible graphical presentation of subsequent tensile strength after creep exposures for 10 hours and 100 hours. In this figure the limiting exposure condition, shown in dashed lines, corresponds to the rupture strength for the exposure time and temperature under consideration.

These initial findings correspond to a rather limited range of test variables and only one type of prior history--constant-stress creep for exposure periods between 10 and 100 hours. Results obtained may or may not be the same as effects on short-time properties caused by the variable or complex stressing, alternating loads and fluctuating temperatures of actual service. Some data which were obtained indicated the direction of stressing may be important. Thus, the compression properties of the 2024-T86 alloy showed a greater reduction than did tension properties after the same prior creep in tension for the two cases.

An operating structure may be subjected to simultaneous stresses acting in different directions. Proper application of the simple-tension data of a study such as this to actual structures is as yet unaswered.

Even the two different alloys studied to date show that the direction of strength changes after prior creep varies with the particular material and conditions involved. Until such time as sufficient data are on hand to generalize the trends, test results appear to be needed for each alloy, major heat treatment and range of exposure conditions.

CONCLUSIONS

Rather complete coverage has been given to 2024-T86 aluminum alloy in a study of effects on short-time mechanical properties from total deformation up to 2% at 350°, 400°, and 500°F, in 10, 50, and 100 hours. Limited data with 17-7PH alloy in the TH 1050 condition have also been determined for creep-exposure temperatures from 600° to 900°F. Test results obtained suggest the following conclusions:

1. Short-time strengths may be either raised or lowered by prior exposure to temperature, with or without the presence of stress. Changes in strength may be as much as 50% of the original value. The direction and magnitude of the changes depends on the material, test temperature, creep-exposure conditions, and the property being measured.

2. Exposure to temperature in the absence of applied stress had approximately the same magnitude of effect on subsequent properties as did the added effect of creep during the exposure period. In most cases, longer exposure times and larger amounts of deformation during the exposure resulted in greater changes in mechanical properties.

3. For the 2024-T86 alloy tests, compression properties showed a greater sensitivity to tension exposure conditions than did tensile properties. Tension-impact strength was relatively insensitive to prior creep exposure.

4. The most important changes from a designer's standpoint are a large drop in the strength of 2024-T86 after prior creep-exposure for time periods of 10-100 hours and an apparent decline in room-temperature ductility of 17-7PH (TH 1050) after prior creep exposure for 100 hours at temperatures near 600°F.

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Table 1

Example Calculation of Effective Gage Lengths for Strip Specimens 17-7PH Alloy (TH 1050 Condition)

		Gage Length for Creep at 800°F				Elastic Gage Length			
(a) Distance from Shoulder, inches	(b) Spec. Widths, inches	(c) Stress (psi)	(d) Creep Rate, $(\Delta L + \Delta R)$/hr	(e) Avg. Creep Rate per 0.050"	(f) Avg. Creep (e) Creep at Center per 0.050"	(g) Rel. Area of Interval	(h) Area in GS (g)	x	Length of Interval
0	1.0050	55,400	0.025			1.005		0.0255	
0.050	0.9236	60,300	0.066	0.0455	0.001	0.924		0.0274	
0.100	0.8466	65,800	0.095	0.0805	0.002	0.847		0.0299	
0.150	0.7790	71,500	0.210	0.1525	0.004	0.779		0.0326	
0.200	0.7210	77,300	0.470	0.340	0.008	0.721		0.0351	
0.250	0.6707	83,100	1.1	0.785	0.019	0.671		0.0377	
0.300	0.6278	88,800	2.2	1.65	0.039	0.628		0.0403	
0.350	0.5916	94,200	4.8	3.50	0.083	0.592		0.0428	
0.400	0.5622	99,000	9.5	7.15	0.170	0.562		0.0450	
0.450	0.5387	103,500	17.0	13.25	0.316	0.539		0.0470	
0.500	0.5208	107,000	27.0	22.0	0.524	0.521		0.0485	
0.550	0.5094	109,400	38.0	32.5	0.774	0.509		0.0498	
				Sum	1.940		Sum	0.4616 = 0.46	
Center	0.5064	110,000	42.0	---		0.506			

PLASTIC CASE - 800°F

Effective Length 2 fillets = 2(1.940)(0.050)
= 0.194"

Shank Length = pin-pin minus shoulder-shoulder
= 4.82 - 3.55 = 1.27

Equivalent Length of Shank:

$$1.27\ \frac{(\text{Creep Rate in Shank})}{(\text{Creep Rate at Center})} = 1.27\ \frac{(0.025)}{(42)} = 0.0008''$$

Total Equivalent Length: Shank plus Fillets

0.0008 + 0.194 = 0.195"

ELASTIC CASE

Effective Length 2 fillets = 2(0.46)= 0.92"

Shank Length = 1.27"

Equivalent Shank Length:

$$1.27\ \frac{(\text{Gage Section Area})}{(\text{Shank Area})} = 1.27\ \frac{(0.506)}{(1.005)} = 0.63''$$

Total Equivalent Length: Shank plus Fillets

0.92 + 0.63 = 1.55"

EFFECTIVE GAGE LENGTH = SHOULDER TO SHOULDER - ACTUAL FILLET + (EFFECTIVE SHANK PLUS FILLETS)

$EGL_{800°F}$ = SS - 2(0.55) +0.195
= SS - 0.905"

$EGL_{elastic}$ = SS - 2(0.55) + 1.55
= SS + 0.45"

Similarly

$EGL_{(600°F)}$ = SS - 1.01"

$EGL_{(900°F)}$ = SS - 0.83"

And Similarly, for 2024-T86 with 0.530" gage section width

$\text{Elastic}\ EGL$ = SS + 0.48"

$\text{Plastic}\ EGL_{(350°\text{ and }400°F)}$ = SS - 0.70"; $EGL_{(500°F)}$ = SS - 0.90"

Table 2

Rupture and Total Deformation Data 17-7PH Alloy (TH 1050 Condition)

Spec. No.	Test Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 1 inch)	Reduction of Area (%)	Hardness after test (R"C")	Loading Def., %	Time to Reach Indicated Total Deformation - hours			
								0.5%	1.0%	2.0%	3.0%
1K-T5	600	180,000	0.1	4.0	13.1	44.4	---	---	---	---	---
1K-T2		180,000	broke on loading	4.0	0	42.3	---	---	---	---	---
1U-T1		175,000	15.1	10.0	17.5	45.5	0.80	---	0.05	1.6	4.1
1C-T3		170,000	11.9	7.0	15.0	44.7	0.75	---	0.4	2.5	5.7
1G-T1		170,000	42.6	9.0	20.5	45.8	0.72	---	4.0	4.6	12.0
1L-T6		165,000	98.8	12.5	20.5	44.3	0.69	---	0.6	17.5	32.0
1C-T5		160,000	661.2	16.5	26.0	47.7	0.64	---	8.5	71.0	152.0
2E-T1		150,000	stopped at 2515.2 hrs.	---	---	---	0.59	---	46.0	330.0	675.0
2E-T5		125,000	stopped at 1893.3 hrs.	---	---	---	0.52	---	2000.0*	---	---
1G-T5	800	105,000	37.3	22.0	37.0	46.3	0.47	0.05	0.3	0.8	1.3
3A-T6		100,000	61±3	43.0	44.0	46.8	0.41	0.1	1.9	6.4	10.2
1U-T3		100,000	107±5	32.0	44.0	46.0	0.41	0.1	2.3	8.5	16.0
1C-T4		95,000	179.1	26.0	36.5	47.2	0.38	0.4	4.0	14.0	25.5
1U-T4		90,000	555.6	37.5	48.5	48.2	0.35	0.5	8.0	29.0	52.0
1Q-T25		70,000	stopped at 1936.7 hrs.	---	---	---	0.26	7.0	90.0	850.0	---
1U-T5	900	75,000	19.8	31.0	46.5	46.9	0.32	0.10	1.0	2.9	4.6
1K-T4		70,000	29.1	28.0	49.0	46.1	0.29	0.20	1.2	3.4	5.7
1K-T6		70,000	56.7	38.5	52.8	45.9	0.30	0.25	1.4	4.6	7.7
1L-T5		70,000	24.5	29.8	48.6	45.6	0.31	0.15	0.8	2.4	4.3
1C-T2		70,000	28.4	32.2	47.2	46.8	0.30	0.17	1.1	3.2	5.2
1K-T3		60,000	152.2	33.0	65.0	45.7	0.26	0.8	4.4	13.5	24.4
1G-T4		55,000	323.6	43.0	51.0	46.8	0.24	1.5	5.0	23.0	45.5
1C-T2		50,000	699.1	40.0	49.5	46.4	0.21	4.0	17.0	76.0	134.0

* **Estimated**

Table 3

Rupture and Total Deformation Data 2024-T86 Aluminum Alloy

Spec. Loc.	Test Temp. (°F)	Stress (psi)	Rupture Time (hrs)	Elongation (%/2 in.)	Reduction of Area (%)	Loading Def. (%)	Time to Reach Indicated Total Deformation (hrs) 0.5%	1.0%	2.0%	3.0%
2B-T5	350	46,000	20.4	6.0	8.8	0.51	--	approx. 7		
3L-T11		45,000	24.5	4.2	9.2	0.47	0.08	--	--	--
4A-T4		40,000	82.3	4.5	6.7	0.42	1.0	40.0	71.0	--
3E-T5		37,500	171.3	3.0	4.6	0.38	6.5	76.0	approx 7	--
2C-T1		35,000	481.2	2.8	4.1	0.37	19.5	256.0	--	--
4M-T4		32,000	460.5	2.0	5.1	0.32	31.5	310.0	--	--
2F-T11		30,000	(742.5)^b	--	--	0.32	46.0	554.0	--	--
2P-T4	400	40,000	6.6	7.0	14.4	0.46	0.3	--	--	--
3D-T3		37,500	19.2	5.0	8.1	0.41	0.5	8.1	18 (est)	--
4M-T11		35,000	28.1	2.0	1.6	0.41	1.2	15.0	--	--
3E-T11		30,000	(51.5)^a	1.5	4.6	0.32	4.0	32.0	--	--
2C-T5		30,000	83.1	4.0	6.6	0.33	4.0	43.5	76.5	--
2J-T5		25,000	360.6	3.5	6.2	0.29	23.0	169.0	354.0	--
4G-T5		20,000	(1127.8)^b	--	--	0.21	160.0	825.0	--	
3L-T2	500	25,000	1.7	7.0	20.4	0.34	0.06	0.51	1.05	1.5
2J-T2		20,000	8.6 ± 1	10.5	22.0	0.26	1.1	4.0	--	--
4G-T11		20,000	7.1 ± 1.5	11.0	27.4	0.27	0.6	2.6	--	--
2J-T11		19,000	22.8	9.2	13.1	0.22	2.4	7.9	--	--
2C-T11		15,000	113.1	9.2	16.3	0.16	11.1	42.4	--	--
4A-T1		14,000	66.6	9.3	19.1	0.18	8.4	26.0	45.8	60 (est)
3D-T5		14,000	104.5	8.8	13.6	0.17	11.5	40.0	73.5	85 (est)
4A-T11		10,000	461.0	8.7	19.4	0.13	74.0	184.0	378.0	438.0

(a) failed at collar; collar on gage section in this instance

(b) Test discontinued without failure

Table 4

Tensile Test Data for 2024-T86 Alloy

Test Temp (°F)	Spec. No.	Ult. Tensile Strength (psi)	0.2% offset Yield Strength (psi)	Elongation (% - 2 inch)	Reduction of Area (%)	E (10^6 psi/in./in.)	Hardness (R"B")
room	2P-T5	75,000	70,100	10.2	12.9	10.7	82.5
	2C-T2	75,800	70,900	7.2	12.7	10.9	82.0
	2J-T3	76,100	70,800	8.0	8.9	11.0	79.7
	Average	75,633	70,600	8.5	11.5	10.9	81.4
	3E-T1	74,500	69,400	8.0	19.0	10.4	79.5
	3L-T3	75,400	70,800	7.2	13.6	11.3	79.1
	3L-T5	76,000	70,600	6.2	8.9	11.0	80.8
	3E-T2	76,400	70,600	7.5	11.3	10.6	80.0
	Average	75,575	70,350	7.2	13.2	10.8	79.8
	4A-T5	75,200	70,000	8.0	8.6	10.7	79.9
	4M-T3	77,500	72,000	7.5	10.6	10.9	78.9
	4G-T2	75,000	70,400	8.0	12.2	10.7	80.8
	Average	75,900	70,800	7.8	10.4	10.7	79.9
Average - 10 tests		75,690	70,560	7.8	11.9	10.8	80.3
350	2B-T55	57,100	55,700	9.5	15.9	10.5	
	2F-T3	58,300	56,400	9.8	20.6	10.2	
	2M-T2	59,400	58,500	8.5	17.9	10.5	
	Average	58,267	56,867	9.3	18.1	10.4	
	3A-T11	56,900	55,500	9.5	20.3	10.6	
	3G-T3	58,100	56,900	9.0	19.1	10.0	
	3K-T2	57,500	56,700	10.0	20.0	9.9	
	Average	57,500	56,367	9.5	19.8	10.2	
	4C-T11	56,800	55,600	7.0	13.1	10.6	
	4H-X11	58,500	56,900	9.5	18.2	9.8	
	4Q-T1	58,100	56,900	9.5	17.4	10.3	
	Average	57,800	56,467	8.7	16.2	10.2	
Average 9 tests		57,854	56,456	9.2	18.0	10.3	
400	2D-T11	51,800	50,000	9.5	19.2	9.5	
	2F-T5	52,100	50,300	8.5	16.6	9.3	
	2M-T3	54,900	53,000	9.5	21.9	9.8	
	Average	52,933	51,100	9.2	19.2	9.5	
	3A-T2	54,600	52,300	10.8	20.4	9.0	
	3G-T1	51,700	50,000	9.0	19.6	9.4	
	3K-T1	51,700	49,600	8.0	18.6	9.3	
	Average	52,667	50,633	9.3	19.5	9.2	
	4C-T55	51,400	49,500	7.0	(9.0)*	9.3	
	4N-T2	52,300	50,700	10.0	18.3	9.1	
	4P-T3	54,400	53,900	8.8	18.8	9.5	
	Average	52,700	51,700	8.6	18.6	9.3	
Average 9 tests		52,784	51,033	9.0	19.2	9.4	
500	2D-T4	37,600	35,200	9.5	23.9	7.3	
	2H-T3	38,900	38,000	9.5	21.6	7.7	
	2M-T11	43,200	42,000	9.0	19.3	7.9	
	Average	39,900	38,400	9.3	21.6	7.6	
	3B-T1	38,400	36,900	8.8	23.1	7.4	
	3F-T3	40,200	39,100	8.5	25.1	7.7	
	3N-T5	40,300	38,400	9.5	20.7	7.6	
	Average	39,633	38,133	8.9	22.6	7.6	
	4B-T1	42,600	42,000	7.5	20.5	7.5	
	4E-T2	42,900	42,100	8.5	24.0	7.6	
	4N-T4	44,400	43,400	9.0	20.1	7.9	
	Average	43,300	42,500	8.3	21.5	7.7	
Average - 9 tests		40,944	39,677	8.8	21.9	7.7	

* **omitted from average - broke at gage point**

Table 5

Compression Test Data for 2024-T86 Alloy

Test Temp. (°F)	Spec. No.	0.2% offset Yield Strength (psi)	Elastic Modulus (10^6 psi/in./in.)
room	2P-C4	74,100	10.7
	2C-C1	77,800	10.2
	2J-C4	76,000	10.5
	2J-C3	73,000	10.2
	Average	75,250	10.4
	3E-C1	77,800	10.6
	3E-C4	75,800	10.4
	3L-C4	79,600	11.1
	Average	77,730	10.7
	4M-C3	69,200	10.6
	4A-C2	72,600	10.1
	4G-C3	76,100	10.1
	Average	72,630	10.3
Average - 10 tests		75,200	10.4
350	2D-X4	63,900	10.6
	2M-X1	66,600	10.2
	2F-X1	70,800	10.2
	Average	67,100	10.3
	3A-X1	65,600	10.2
	3K-X5	69,800	10.2
	3P-X5	67,600	10.3
	Average	67,667	10.2
	4N-X5	68,000	10.3
	4H-X5	64,200	10.6
	4C-X1	65,800	10.7
	Average	66,000	10.5
Average - 9 tests		66,922	10.3
400	2M-X5	61,500	10.7
	2K-X1	60,300	9.9
	2B-X5	59,400	10.2
	Average	60,400	10.3
	3B-X5	60,200	10.3
	3J-X5	60,500	9.9
	3N-X1	61,200	10.4
	Average	60,667	10.2
	4Q-X1	61,800	10.0
	4F-X1	60,000	9.8
	4D-X1	61,400	10.2
	Average	61,067	10.0
Average - 9 tests		60,711	10.2
500	2E-X1	51,500	8.8
	2L-X1	49,800	8.8
	2N-X1	48,400	8.6
	Average	49,900	8.7
	3D-X1	48,100	9.3
	3G-X5	50,800	8.6
	3H-X1	49,700	8.9
	Average	49,533	8.9
	4B-X5	51,500	9.0
	4J-X1	52,700	9.2
	4P-X1	50,800	9.4
	Average	51,667	9.2
Average - 9 tests		50,734	9.0

Table 6

Smooth-Bar Tension-Impact Test Data for 2024-T86 Alloy

Test Temp. (°F)	Spec. No.	Energy Absorbed a) (ft-lb)	Elongation (% - 2 inch)	Reduction of Area (%)
room	2C-M22	20	7.5	7.0
	2J-M2	19	6.5	13.7
	2P-M22	16	5.5	9.3
	Average	18.3	6.5	10.0
	3E-M2	18	6.5	12.4
	3E-M44	21	5.0	11.7
	3L-M4	18	5.8	16.3
	Average	19.0	5.8	13.4
	4A-M2	20	4.5	11.6
	4G-M22	14	4.0	6.2
	4G-M4	20	7.5	13.7
	4M-M4	16	5.2	9.2
	Average	17.5	5.3	10.2
Average - 10 tests		18.2	5.8	11.2
350	2P-M5	14		
	2F-X2	19		
	Average	16.5		
	3L-M44	20.5		
	3E-M5	16	4.8	
	Average	18.2		
	4G-M5	16		
	4M-M5	16	4.0	
	4A-M5	17	4.5	
	Average	16.3		
350° - Average		16.9	4.4*	
400	2C-M44	16	4.2	
	2N-X44	27		
	2P-M4	18		
	Average	20.3		
	3G-X2	24	6.2	
	4B-X44	16		
	4G-M2	14		
	4M-M44	20	4.2	
	Average	16.7		
400° - Average		19.2	4.9*	
500	2C-M2	14	5.0	
	2M-X44	18	5.5	
	2Q-M2	16		
	Average	16		
	3K-X44	15		
	4G-M44	17		
	4M-M2	18		
	4M-M22	16	4.8	
	Average	17		
500° - Average		16.2	5.3*	

* Average of 3 tests only

a) Specimen gauge section 0.200 in. wide x 0.064 in. thick.

Table 7

Notched-Bar Tension-Impact Data for 2024-T86 Alloy

Temp (°F)	Spec. No.		Energy Absorbed a) (ft - lb)
room	2C-X3		9
	3M-X33		8
	4L-X3		10
		Average	9
350	2J-X3		8
	4N-X3		8
		Average	8
400	3E-X3		12
	2C-X33		8
		Average	10
500	4D-X3		8
	3L-X3		7
		Average	7.5

a) Minimum Cross Section at Notch 0.250 in. wide x 0.064 in. thick. Theoretical Stress Concentration factor, $K_t = 4.2$.

Table 8

Room-Temperature Tensile Data for 17-7PH Alloy (TH 1050 Condition)

Spec. No.	Ult. Tensile Strength (psi)	0.2% offset Yield Strength (psi)	Elongation % in 2 inch	Reduction of Area (%)	E (10^6 psi/in./in.)	Hardness (R"C")
1C-T1	212,000	208,000	4.2	16.9	29.0	43.9
1L-T1	209,000	196,000	6.0	13.9	28.8	42.8
1L-T2	214,000	196,000	5.5	14.3	29.0	43.5
1L-T3	216,000	210,000	5.6	9.8	28.7	43.8
1L-T4	215,000	208,000	4.5	13.4	28.6	44.9
1U-T2	211,000	207,000	4.0	17.9	28.6	43.4
Average	212,833	204,160	5.0	14.4	28.8	43.7
2J-T3	197,000	186,000	9.0	19.4	27.6	43.4
2N-T3	187,000	173,500	8.8	21.7	29.3	42.3
Average	192,000	179,750	8.9	20.6	28.4	42.8
3G-T1	201,000	195,500	7.8	18.7	28.2	45.1
3Q-T1	202,000	195,000	7.2	20.8	29.2	44.3
Average	201,500	195,250	7.5	19.8	28.7	44.7
Average of 10 Tests	206,400	197,500	6.3	16.7	28.7	43.7
Average of Sheet Average	203,100	193,050	7.1	18.2	28.6	43.7

Table 9

Tensile Test Data at 600°F for 17-7PH (TH 1050 Condition)

Spec. No.	Ult. Tensile Strength (psi)	0.2% offset Yield Strength (psi)	Elongation % - 2 inch	Reduction of Area (%)	Elastic Modulus (10^6 psi/in./in.)
1G-T3	179,600	168,500	4.0	12.6	28.1
1P-T22	175,300	169,500	5.8	17.2	28.2
1P-T26	163,600	158,900	5.0	15.0	27.9
Average	172,833	165,633	4.9	14.9	28.1
2E-T2	183,000	168,700	4.5	16.1	29.3
2J-T4	156,900	148,000	5.2	14.8	27.4
2S-T4	186,900	179,000	5.2	16.1	27.2
Average	175,600	165,233	5.0	15.7	28.0
3A-T3	157,100	147,900	2.5	16.4	29.4
3F-T3	186,000	178,600	6.2	15.2	27.9
3P-T4	159,200	150,000	4.5	12.5	28.6
Average	167,433	158,833	4.4	14.7	28.6
Average 9 tests	171,989	163,233	4.8	15.1	28.2

Table 10

Room Temperature Compression Test Data 17-7PH Alloy (TH 1050 Condition)

Spec. No.	0.2% offset Compression Yield Strength (psi)	Compression Modulus (10^6 psi/in. /in.)
1C-C44	242,000	29.5
1C-C4	235,000	30.1
1C-C22	228,000	29.6
1U-C4	226,000	29.6
Average	232,750	29.7
2J-C44	195,000	29.6
2E-C2	206,000	30.1
Average	200,500	29.8
3L-C6	205,000	29.8
3L-C4	234,000	29.6
3L-C44	216,000	30.3
Average	218,333	29.6
Average 9 tests	220,777	29.8
Average of sheet averages	217,194	29.8

	0.2% offset Tension Yield Strength (psi)	Tension Modulus (10^6 psi/in. /in.)
Average of sheet 1	204,160	28.8
Average of sheet 2	179,750	28.4
Average of sheet 3	195,250	28.7
Average of 3 sheets	193,050	28.6

Table 11

Room-Temperature Tension-Impact Data 17-7PH Alloy (TH 1050 Condition)

Notched Specimens		Smooth Specimens	
Specimen No.	Energy Absorbed (ft-lb)	Specimen No.	Energy Absorbed (ft-lb)
1G-M5	32	1C-M5	35
1G-M2	8	1C-M6	37
1U-M2	16	1C-M1	45
1U-M4	12		
Average	17	Average	39
2E-M6	36	2J-M1	48
2N-M4	45	2J-M2	41
2N-M5	9	2E-M1	62
Average	30	Average	50.3
3F-M5	36	3L-M2	52
3F-M6	49	3L-M5	52
3L-M1	46	3F-M4	33
Average	47	Average	45.6
Average of 10 tests	28.9	Average of 9 tests	45.0
Average of sheet averages	31.3	Average of sheet averages	45.0

Note: Notched Specimens 0.250 inch wide at minimum section. Theoretical stress concentration factor $K_t = 4.2$.

Smooth Specimens 0.200 inch wide in gauge section.

Table 12

Comparison of Tensile and Compression Properties Determined at the University of Michigan or Elsewhere for 17-7PH Given the TH 1050 Treatment

Tensile Properties

Test Temp (°F)	Source of Data	Ult. Tensile Strength (psi)	0.2% offset Yield Strength (psi)	Elongation (% - 2 inch)	Hardness (Rockwell "C")
room	University of Michigan	203,100	193,050	7.1	43.7
600		171,989	163,233	4.8	----
room	Armco Steel Corporation (ref. 1)	Typical 200,000	185,000	9.0	43
room		Minimum 180,000	150,000	6.0	
600		157,500	132,500	6.0	
room	Armour Research Foundation (ref. 10)	195,900	183,200	8.8	43-44
600		177,700	166,600	3.8	
room	WADC (ref. 9)	209,200	197,000	6.5	45.5
room		193,000	177,400	8.5	43.0
600		155,200	164,900	5.0	
room	Cornell Aero. Lab. (ref. 11)	219,500	209,000	5.0	47-48

Compression Properties

Test Temp (°F)	Source of Data	0.2% offset Yield Strength (psi)	Compression Yield Str. / Tensile Yield Strength (%)
room	University of Michigan	219,194	112.3
room	Armco Steel Corporation	110% of Tensile Yield	-----
room	Armco Research Foundation	195,000	106.8
room	WADC	195,800	110.0

Table 13

Effect of Unstressed Exposure on Room-Temperature Tensile Properties of 2024-T86 Alloy

Temp (°F)	Time (hr)	Spec. No.	Ult. Tensile Strength (psi)	0.2% offset Yield Strength (psi)	Elongation (% - 2 inch)	Reduction of Area (%)	E (10^6 psi/in./in.)	Hardness (Rockwell "B")
350	10	2J-T1	74,900	69,000	7.5	9.2	10.9	79.3
	10	4A-T2	75,400	69,500	8.2	13.8	10.1	80.7
			75,150	69,250	7.8	11.8	10.5	80.0
	50	2P-T1	73,300	66,100	7.5	9.9	11.0	77.8
	50	4G-T3	74,500	65,900	7.5	8.1	10.8	77.2
			73,900	66,000	7.5	9.0	10.9	77.5
	100	2P-T3	71,600	63,500	7.5	11.1	10.8	75.8
	100	3M-T1	71,500	63,200	7.0	11.0	10.8	75.8
			71,550	63,350	7.2	11.0	10.8	75.8
400	10	2P-T2	71,600	63,900	6.5	15.3	11.0	75.8
	10	4G-T1	71,200	63,300	6.5	12.3	11.0	74.7
			71,400	63,600	6.5	13.8	11.0	75.2
	50	3E-T4	67,000	56,900	7.5	12.9	11.0	72.0
	50	4M-T2	66,600	56,500	7.5	11.4	11.3	71.3
			66,800	56,700	7.5	12.2	11.2	71.6
	100	2C-T3	64,500	53,800	7.5	12.1	10.7	68.2
	100	3L-T1	64,300	53,800	7.5	13.0	11.3	68.7
			64,400	53,800	7.5	12.6	11.0	68.4
500	10	2P-T11	62,500	50,100	7.0	10.0	10.6	65.3
	10	3E-T3	61,500	49,300	7.0	12.6	10.4	66.8
			62,000	49,700	7.0	11.3	10.5	66.0
	50	2C-T4	62,400	50,300	7.5	10.0	10.8	68.0
	50	4G-T4	59,900	48,500	7.0	11.7	10.6	66.1
			61,150	49,400	7.2	10.8	10.7	67.0
	100	3L-T4	51,500	37,000	7.0	13.0	10.9	54.3
	100	4A-T3	52,100	38,800	6.5	13.6	10.6	54.7
			51,800	37,900	6.8	13.3	10.8	54.5

Table 14

Effect of Unstressed Exposure on Elevated-Temperature Tensile Properties of 2024-T86 Alloy

Exposure Conditions		Tensile Test Results						
Temp (°F)	Time (hrs)	Tensile Test Temperature (°F)	Spec. No.	Ult. Tensile Strength (psi)	0.2% offset Yield Strength (psi)	Elongation (% - 2 inch)	Reduction of Area (%)	E (10^6 psi/in./in.)
350	10	350	3G-T4	59,800	57,900	9.0	17.3	10.2
350	10	350	2B-T2	59,600	58,600	8.8	14.2	10.4
			Average	59,700	58,250	8.9	15.8	10.3
350	50	350	3K-T4	57,000	55,000	6.5	11.4	10.1
350	50	350	4C-T1	57,200	56,000	10.5	21.2	10.1
			Average	57,100	55,500	8.5	16.3	10.1
350	100	350	3D-T1	56,900	56,000	7.5	15.0	9.9
350	100	350	4Q-T11	58,300	56,800	9.8	16.4	10.1
			Average	57,600	56,400	8.6	15.7	10.0
400	10	400	3A-T55	53,500	51,000	9.5	18.1	9.3
400	10	400	4P-T1	55,100	53,400	9.5	19.0	9.4
			Average	54,300	52,200	9.5	18.5	9.4
400	50	400	2D-T1	52,500	50,600	8.5	21.9	9.8
400	50	400	3N-T3	54,300	53,700	10.0	17.6	9.6
			Average	53,400	52,150	9.2	19.8	9.7
400	100	400	2H-T4	52,100	50,500	10.0	17.8	9.0
400	100	400	4E-T1	54,700	54,000	10.0	23.6	9.7
			Average	53,700	52,250	10.0	20.7	9.4
400	100	400	a)5B-T3	55,400	52,100	9.2	18.9	9.1
500	10	500	2D-T2	39,800	38,000	9.0	26.4	7.6
500	10	500	4N-T55	40,400	38,300	8.8	20.2	7.8
			Average	40,100	38,150	8.9	23.3	7.7
500	50	500	3B-T2	39,600	38,300	9.0	23.9	7.8
500	50	500	4B-T11	38,600	37,300	8.0	23.9	8.3
			Average	39,100	37,800	8.5	23.9	8.0
500	100	500	3F-T55	39,500	38,300	9.0	23.6	7.8
500	100	500	2L-T11	37,700	35,600	10.5	26.0	7.5
			Average	38,600	36,950	9.8	24.8	7.6
500	100	500	a)5H-T5	44,000	35,400	8.2	21.5	8.1

a) Specimens Not Remachined Prior to Tensile Test

Table 15

Effect of Prior Creep-Exposure on Tensile Properties and Hardness of 2024-T86 Alloy

Nominal Exposure Conditions			Actual Exposure Conditions				Deformation Obtained (%)				Tensile Properties After Exposure						
Temp (°F)	Time (hr)	Total Deformation (%)	Spec. No.	Time (hr)	Temp (°F)	Stress (psi)	Loading (Total)	Loading (Plastic)	Creep	Total	Test Temp (°F)	Ult. Tensile Strength (psi)	0.2% offset Yield Strength (psi)	Elongation (% - 2 inch)	Reduction of Area (%)	Modulus, E (10^6 psi/in. /in.)	Hardness Rockwell "B"
350	10	0.5	4H-T5	10.1	350	36,000	0.36	0.01	0.16	0.52	room	74,800	68,600	8.5	13.8	10.7	78.2
	10	0.5	3A-T1	10.1	350	36,000	0.40	0.01	0.15	0.55	room	74,500	68,200	9.0	9.3	10.6	79.0
	10	1.0	2F-T4	10.4	350	44,500	0.51	0.03	0.62	1.13	room	73,600	68,000	7.0	14.2	10.7	80.2
	10	1.0	4C-T2	10.3	350	44,500	0.49	0.03	0.38	0.87	room	74,500	68,800	7.0	10.5	10.9	79.7
	10	2.0	3K-T11	10.1	350	47,000	0.53	0.04	1.09	1.62	room	74,300	69,200	10.0	12.6	10.8	79.3
	10	2.0	4B-T3	10.2	350	47,000	0.55	0.04	1.35*	1.90*	room	73,100	68,300	5.8	9.4	10.9	80.8
	10	0.5	4C-T5	10.4	350	36,000	0.37	0.01	0.16	0.53	350	57,500	56,500	9.0	19.9	10.6	80.2
	10	0.5	3D-T22	10.0	350	36,000	0.38	0.01	0.15	0.53	350	57,600	56,500	10.5	17.2	10.1	80.3
	10	1.0	3N-T1	10.1	350	44,500	0.48	0.03	0.44	0.92	350	56,100	55,600	9.5	19.2	10.0	----
	10	2.0	2L-T55	10.0	350	47,000	0.55	0.04	1.35*	1.90*	350	56,200	56,100	3.5	10.1	10.2	----
	50	0.5	3A-T4	50.2	350	30,000	0.33	0	0.21	0.54	room	72,900	65,600	8.0	11.1	11.0	79.0
	50	0.5	2N-T55	50.0	350	29,000	0.30	0	0.15	0.45	room	72,900	66,100	6.8	11.4	11.4	79.7
	50	1.0	3G-T55	50.0	350	39,500	0.42	0.02	0.68	1.10	room	69,800	62,400	8.5	10.8	10.7	76.8
	50	1.0	4P-T11	50.1	350	39,500	0.41	0.02	0.43*	0.84*	room	71,900	64,900	7.5	9.2	10.8	77.7
	50	2.0	3G-T1	50.3	350	41,000	0.47	0.02	1.05	1.52	room	71,200	63,900	5.5	8.1	11.0	77.5
	50	2.0	4J-T3	50.2	350	41,500	0.46	0.02	1.35	1.81	room	69,800	63,300	5.0	5.9	10.8	77.5
	50	0.5	2Q-11	50.0	350	29,000	0.29	0	0.15	0.44	350	56,300	54,600	9.0	19.6	9.9	77.7
	50	1.0	2E-T3	53.3	350	39,500	0.42	0.02	0.66	1.08	350	54,500	53,600	9.2	18.1	10.5	----
	50	2.0	2A-T2	50.1	350	41,500	0.47	0.02	1.06	1.53	350	53,800	53,000	7.0	15.5	9.8	80.2
	100	0.5	2M-T5	100.1	350	28,000	0.29	0	0.24	0.53	room	69,800	61,500	7.0	9.2	10.4	76.0
	100	0.5	4F-T4	102.5	350	28,000	0.28	0	0.18	0.46	room	72,600	64,600	8.0	11.9	10.8	79.0
	100	1.0	4P-T4	100.0	350	37,500	0.42	0.01	0.71*	1.13*	room	71,700	62,900	8.5	10.8	10.7	76.8
	100	1.0	2H-T1	100.2	350	37,500	0.41	0.01	0.70	1.11	room	70,800	62,600	7.0	9.1	11.0	76.5
	100	2.0	3K-T5	100.1	350	39,000	0.43	0.02	1.52	1.95	room	65,100	60,000	5.0	4.7	10.9	78.3
	100	2.0	2E-T2	100.0	350	39,000	0.42	0.02	1.55*	1.97*	room	67,400	60,500	4.0	4.7	10.6	78.5
	100	0.5	3H-T3	100.0	350	28,000	0.27	0	0.19	0.46	350	53,400	51,500	11.0	18.8	9.9	77.3
	100	1.0	3B-T3	99.8	350	37,500	0.39	0.01	0.68	1.07	350	53,000	51,900	8.2	13.2	10.1	----
	100	2.0	2N-T3	100.0	350	39,000	0.40	0.02	2.04	2.44	350	48,300	48,000	2.0	6.5	9.8	79.0

* Estimated

Table 15 (continued)

Effect of Prior Creep-Exposure on Tensile Properties and Hardness of 2024-T86 Alloy

Nominal Exposure Conditions			Actual Exposure Conditions				Deformation Obtained (%)				Tensile Properties After Exposure						
Temp (°F)	Time (hr)	Total Deformation (%)	Spec. No.	Time (hr)	Temp (°F)	Stress (psi)	Loading (Total)	Loading (Plastic)	Creep	Total	Test Temp (°F)	Ult. Tensile Strength (psi)	0.2% offset Yield Strength (psi)	Elongation (% - 2 inch)	Reduction of Area (%)	Modulus, E (10^6 psi/in./in.)	Hardness Rockwell "B"
400	10	0.5	2B-T1	10.0	400	28,000	0.32	0.01	0.34	0.66	room	68,800	59,300	7.5	11.3	10.6	74.3
	10	0.5	3A-T3	10.0	400	28,000	0.32	0.01	0.27	0.59	room	70,000	61,200	7.8	12.5	10.9	76.5
	10	0.5	4C-T3	12.4	400	28,000	0.57	0.26	0.25	0.82	room	70,500	60,900	8.0	14.8	10.5	76.1
	10	1.0	3D-T11	10.7	400	36,000	0.40	0.04	0.73	1.13	room	69,000	60,000	8.0	14.2	10.9	75.0
	10	1.0	4Q-T2	10.0	400	36,000	0.40	0.04	0.81	1.21	room	68,800	60,400	5.5	11.1	10.6	77.7
	10	1.0	4C-T4	12.3	400	36,000	0.42	0.04	0.97	1.39	room	68,600	59,200	8.5	12.3	10.9	74.3
	10	2.0	2N-T11	10.2	400	37,000	0.44	0.04	0.83	1.27	room	70,100	61,500	8.0	11.8	10.9	----
	10	2.0	2E-T55 rupt.	10.0	400	37,500	0.47	0.05		2.23 at 9.8 hrs.		--	--	--	--	--	----
	10	0.5	2D-T44	10.2	400	28,000	0.31	0.01	0.22	0.53	400	48,000	46,700	10.0	22.4	9.2	78.2
	10	1.0	2M-T5	10.5	400	36,000	0.42	0.04	0.73*	1.15*	400	46,000	45,600	7.8	17.9	9.3	----
	10	2.0	4K-T2	10.0	400	37,000	0.40	0.04	1.29	1.69	400	47,000	46,400	7.8	15.3	9.4	76.2
	50	0.5	4H-T1	50.1	400	23,000	0.24	0	0.29	0.53	room	65,300	55,100	8.0	9.6	10.8	71.3
	50	0.5	3K-T3	50.3	400	23,000	0.26	0	0.32	0.58	room	66,600	56,000	8.5	10.6	10.7	73.2
	50	1.0	3K-T55	50.1	400	29,000	0.34	0.01	0.62	0.96	room	65,900	56,000	7.5	8.6	11.3	72.1
	50	1.0	2D-T5	52.5	400	29,000	0.34	0.01	0.88	1.22	room	64,300	53,000	7.0	10.9	10.8	69.5
	50	1.0	2B-T4	50.1	400	30,000	0.35	0.01	1.08	1.43	room	64,500	53,800	7.0	10.6	10.7	70.8
	50	2.0	2M-T4	49.2	400	31,500	0.33	0.02	1.02	1.35	room	64,100	53,600	5.8	8.2	10.8	74.3
	50	2.0	4D-T11	50.0	400	31,500	0.35	0.02	0.79	1.14	room	65,400	55,200	7.5	11.4	10.5	71.8
	50	2.0	3F-T1 rupt.	42.2	400	32,000	0.36			1.38 at 34 hrs.		--	--	--	--	--	----
	50	0.5	2E-T11	50.1	400	23,000	0.25	0	0.34	0.59	400	44,800	42,700	10.0	22.9	9.1	----
	50	1.0	4N-T3	50.4	400	29,000	0.33	0.01	1.03	1.36	400	42,500	41,000	8.0	15.1	9.5	----
	50	2.0	5C-T2	50.0	400	31,500	0.30	0.02	1.34	1.64	400	42,900	41,700	4.5	8.4	9.3	72.3
	100	0.5	3D-T4	100.0	400	21,000	0.24	0	0.25	0.59	room	64,500	53,100	9.0	14.6	10.9	70.0
	100	0.5	4H-T55	100.2	400	21,000	0.22	0	0.33	0.55	room	64,500	53,900	8.5	11.7	11.0	68.9
	100	1.0	4H-T3	100.3	400	27,000	0.29	0.01	0.78	1.07	room	61,800	50,800	11.0	11.7	10.4	69.0
	100	1.0	3B-T11	100.1	400	27,000	0.30	0.01	0.77	1.07	room	63,800	52,000	7.0	10.4	10.8	70.7
	100	2.0	3A-T5	100.0	400	29,000	0.28	0.01	1.25	1.53	room	60,600	50,900	5.5	7.5	10.9	71.0
	100	2.0	4D-T3	100.0	400	29,000	0.33	0.01	1.27	1.60	room	62,200	23,800	6.5	7.3	10.6	70.5
	100	2.0	2K-T11 rupt.	82.8	400	29,500	0.30	0.01		1.60 at 72 hrs.		--	--	--	--	--	----
	100	0.5	2H-T2	100.0	400	21,000	0.23	0	0.37	0.60	400	41,900	39,800	10.7	23.9	9.3	----
	100	0.5	3F-T5	100.4	400	21,000	0.22	0	0.35	0.57	400	43,600	41,000	11.0	24.6	9.6	----
	100	1.0	3F-T2	99.6	400	27,000	0.30	0.01	0.98	1.28	400	41,800	39,800	9.0	15.9	9.8	71.3
	100	1.0	2M-T55	100.0	400	27,000	0.30	0.01	0.94	1.24	400	40,800	38,500	7.0	12.9	9.4	71.3
	100	2.0	5G-T5	100.2	400	29,000	0.30	0.01	1.85	2.15	400	37,600	37,100	2.2	3.1	8.5	----

* Estimated

Table 15 (concluded)

Effect of Prior Creep-Exposure on Tensile Properties and Hardness of 2024-T86 Alloy

Nominal Exposure Conditions			Actual Exposure Conditions				Deformation Obtained (%)				Tensile Properties After Exposure						
Temp (°F)	Time (hr)	Total Deformation (%)	Spec. No.	Time (hr)	Temp (°F)	Stress (psi)	Loading (Total)	Loading (Plastic)	Creep	Total	Test Temp (°F)	Ult. Tensile Strength (psi)	0.2% offset Yield Strength (psi)	Elongation (% - 2 inch)	Reduction of Area (%)	Modulus, E (10^6 psi/in./in.)	Hardness Rockwell "B"
500	10	0.5	2F-T55	10.2	500	14,500	0.17	0	0.30	0.47	room	53,500	38,900	7.8	10.6	10.5	60.2
	10	1.0	4N-T5	10.0	500	17,000	0.20	0	0.89	1.09	room	48,100	33,700	8.0	14.2	10.5	----
	10	1.0	4P-T5 rupt.	7.4	500	18,000	0.23	0		2.00 at 6 hrs.		--	--	--	--	--	----
	10	1.0	4H-T4	10.0	500	18,000	0.22	0	1.34	1.56	room	48,900	33,400	8.0	13.9	10.7	50.3
	10	2.0	2D-T3	10.4	500	19,000	0.24	0	2.75*	3.00*	room	50,300	35,700	7.2	14.2	10.7	57.7
	10	3.0	4E-T11	10.0	500	19,500	0.23	0	3.25*	3.50*	room	51,400	36,200	7.8	12.1	10.4	58.2
	10	3.0	4N-T11 rupt.	10.2	500	19,800	0.25	0		0.89 at 3.75 hrs.		--	--	--	--	--	----
	10	0.5	4B-T5	10.2	500	14,500	0.23	0	0.40	0.63	500	28,200	26,300	7.2	29.6	7.9	57.2
	10	1.0	2N-T2	10.4	500	17,000	0.22	0	0.57	0.79	500	27,900	26,200	10.0	24.4	8.2	58.3
	10	2.0	4L-T11	10.0	500	19,000	0.26	0	2.67	2.93	500	23,100	22,800	6.0	13.8	8.3	54.3
	50	0.5	4P-T55	53.6	500	11,000	0.12	0	0.68*	0.80*	room	42,200	25,000	10.2	18.4	10.7	35.3
	50	0.5	3Q-T2	50.0	500	11,000	0.12	0	0.63*	0.75*	room	47,500	30,900	10.0	13.3	11.3	48.7
	50	1.0	2H-T11	50.0	500	13,000	0.14	0	0.85	0.99	room	45,800	31,100	8.0	14.2	10.4	45.8
	50	1.0	3G-T5 rupt.	9.5	500	14,000	0.17	0	--	--	--	--	--	--	--	--	----
	50	1.0	3G-T2	50.3	500	14,000	0.17	0	1.42	1.59	room	46,100	29,400	10.0	15.7	10.6	45.0
	50	2.0	3J-T1	50.0	500	14,000	0.16	0	0.98	1.14	room	48,700	32,400	9.5	13.1	11.0	50.2
	50	3.0	3B-T5	50.1	500	15,000	0.20	0	3.23	3.43	room	42,100	27,400	7.2	18.0	10.5	45.0
	50	3.0	3P-T4 rupt.	47.2	500	15,500	0.18	0		3.35 at 42 hrs.		--	--	--	--	--	----
	50	3.0	2K-T2 rupt.	39.2	500	15,250	0.18	0		1.27 at 22 hrs.		--	--	--	--	--	47.2
	50	0.5	5G-T1	50.0	500	11,000	0.14	0	0.46	0.60	500	22,100	20,100	13.0	28.7	9.7	----
	50	1.0	4B-T55	50.1	500	13,000	0.17	0	1.09	1.26	500	20,600	18,900	10.8	28.7	7.7	46.8
	50	2.0	5M-T2	50.0	500	14,000	0.16	0	2.15	2.31	500	20,800	19,500	10.0	30.6	7.7	45.0
	50	3.0	5G-T4	53.2	500	15,000	0.17	0	2.94	3.11	500	20,500	19,900	11.5	33.0	8.1	49.3
	100	0.5	3D-T55	100.0	500	9,000	0.11	0	0.51	0.62	room	44,400	28,200	9.8	17.5	10.7	38.8
	100	0.5	4J-T4	100.0	500	9,000	0.11	0	0.75	0.86	room	38,000	21,600	12.0	23.6	10.3	30.3
	100	1.0	2M-T1	99.9	500	12,000	0.14	0	0.95	1.09	room	44,100	28,700	8.0	14.1	10.8	43.5
	100	1.0	4F-T2	100.0	500	12,000	0.15	0	3.20	3.35	room	39,600	22,800	10.0	14.7	10.4	30.5
	100	2.0	4B-T2	100.0	500	12,500	0.17	0	1.72	1.89	room	42,300	25,900	9.0	14.3	10.7	42.0
	100	3.0	3N-T4	100.0	500	13,000	0.15	0	3.10	3.25	room	41,000	23,100	8.5	15.6	10.9	37.3
	100	3.0	2L-T5 rupt.	80.5	500	13,700	0.17	0		3.43 at 72 hrs.		--	--	--	--	--	----
	100	3.0	3P-T55 rupt.	91.1	500	13,400	0.16	0		3.05 at 82.5 hrs.		--	--	--	--	--	42.7
	100	0.5	2N-T2	100.0	500	9,000	0.12	0	0.76	0.88	500	20,800	18,200	16.5	38.8	8.0	32.8
	100	1.0	3B-T55	100.0	500	12,000	0.14	0	1.24	1.38	500	22,100	19,800	13.8	35.3	8.0	37.5
	100	2.0	2A-T4 rupt.	59.0	500	12,500	0.16	0		2.68 at 58 hrs.		--	--	--	--	--	40.0
	100	3.0	4D-T1 rupt.	91.9	500	13,000	0.14	0		2.67 at 89 hrs.		--	--	--	--	--	42.0

* Estimated

Table 16

Effect of Stressed and Unstressed Exposure on Room-Temperature Tensile Properties of 17-7PH Alloy in the TH 1050 Condition

	Exposure Conditions							Room Temperature Tensile Properties					
Spec. No.	Temp (°F)	Stress (psi)	Time (hr)	Total Def. (%)	Plastic Loading Def., %	Total Loading Def., %	[a] LD/TD (%)	Ult. Tensile Strength (psi)	0.2% offset Yield Strength (psi)	Elongation (% in 2 inch)	Reduction of Area (%)	E (10^6 psi/in./in.)	Hardness (R"C")
Average Properties - 3 sheets - As treated								203,000	193,050	7.1	18.2	28.6	43.7
2E-T4	600	None	10	None				192,000	183,000	8.5	20.0	30.2	40.9
3P-T3	600	None	10	None				209,000	203,000	6.5	19.7	30.4	43.4
			Average					200,500	193,000	7.5	19.8	30.3	42.2
1P-T21	600	None	50	None				193,000	186,000	10.5	18.3	30.4	42.0
3L-T5	600	None	50	None				187,000	180,000	9.0	22.6	31.2	41.6
			Average					190,000	183,000	9.8	20.5	30.8	41.8
2N-T4	600	None	100	None				192,500	184,200	8.0	18.4	29.4	42.5
3A-T1	600	None	100	None				212,000	206,000	7.5	19.4	29.8	45.8
			Average					202,250	195,100	7.8	18.9	29.1	45.3
2N-T1	600	157,000	100.5	1.89	0.09	0.60	31.8	223,000	(223,000)	1.5	13.7	29.4	45.3
3Q-T7	600	157,000	100.4	3.82		0.72	18.9	209,000	--	2.0	8.6	30.3	41.1
1P-T24	600	157,000	99.9	5.30		0.75	14.1	217,500	(188,500)	2.0	5.8	28.9	42.8
			Average	3.67				216,500	(205,750)	1.8	9.7	29.5	43.1
2S-T3	650	137,000	105.0	1.87		0.50	26.8	215,000	215,000	2.5	12.5	30.4	43.5
3B-T4	650	137,000	100.1	2.71	0.05	0.63	23.2	206,000	206,000	2.5	14.0	31.8	41.7
			Average	2.29				210,500	210,500	2.5	13.2	31.1	42.6
2R-T6	700	118,000	100.2	1.82		0.47	25.8	211,000	210,000	4.0	17.7	29.6	42.8
3G-T3	700	118,000	100.7	1.60	0.015	0.42	26.2	218,500	218,000	3.0	16.0	30.8	44.9
			Average	1.71				214,750	214,000	3.5	16.8	30.2	43.8
2R-T2	700	120,000	100.1	2.54		0.50	19.7	219,000	218,000	2.2	13.7	30.6	44.0
3Q-T6	700	120,000	100.1	1.95		0.43	22.1	220,000	219,000	3.5	13.8	29.6	44.2
			Average	2.24				219,500	218,500	2.8	13.8	30.1	44.1
2J-T5	750	101,000	100.0	1.94		0.42	21.6	222,000	220,000	3.0	17.0	29.7	44.2
3B-T3	750	101,000	100.0	1.62		0.25	15.4	218,000	217,000	4.5	16.7	30.0	46.1
			Average	1.78				220,000	218,500	3.7	16.8	29.8	45.2
3H-T1	800	None	10	None				201,000	195,000	7.5	18.7	30.8	43.8
2R-T3	800	None	10	None				192,000	187,000	5.0	16.9	29.8	41.9
			Average					196,500	191,000	6.2	17.8	30.3	42.8
2S-T2	800	None	50	None				218,000	213,000	4.9	15.1	31.2	43.6
1Q-T23	800	None	50	None				220,000	215,000	6.0	17.9	30.4	45.5
			Average					219,000	214,000	5.4	16.5	30.8	44.6
3G-T6	800	None	100.0	None				222,000	216,000	4.0	17.9	29.8	47.4
2N-T2	800	None	100.0	None				222,500	216,000	5.0	17.3	30.2	48.2
			Average					222,250	216,000	4.5	17.6	30.0	47.8
3P-T1	800	81,000	102.6	2.12		0.31	14.6	232,000	229,000	3.5	12.1	29.9	46.7
2S-T6	800	81,000	102.1	1.88		0.32	17.0	227,000	222,000	4.2	15.8	30.2	46.7
			Average	2.00				229,500	225,500	3.8	14.0	30.1	46.7
2R-T5	850	66,000	100.0	1.99		0.26	13.1	235,000	230,000	5.0	13.4	30.8	46.4
3H-T3	850	66,000	100.1	2.09	0.008	0.29	13.9	231,000	228,000	4.2	14.3	30.0	47.6
			Average	2.04				233,000	229,000	4.6	13.8	30.4	47.0
1P-T23	900	None	10	None				205,500	200,000	6.5	17.2	30.2	43.1
3A-T5	900	None	10	None				206,500	201,000	5.0	18.2	30.8	44.2
			Average					206,000	200,500	5.8	17.7	30.5	43.6
2S-T1	900	None	50	None				230,000	224,000	3.5	14.1	30.9	46.2
3H-T6	900	None	50	None				234,000	228,500	5.0	13.7	30.6	47.0
			Average					232,000	226,500	4.2	13.9	30.8	46.6
3P-T6	900	None	100.0	None				222,000	215,000	4.5	8.4	30.4	46.2
2N-T5	900	None	100.0	None				220,000	213,000	6.0	17.1	28.8	47.0
			Average					221,000	214,000	5.2	12.8	29.6	46.6
2R-T1	900	49,000	100.0	1.55		0.19	12.2	214,000	209,000	6.5	16.7	29.9	45.3
3G-T2	900	50,000	100.0	2.04	0.005	0.22	10.8	224,000	219,000	4.0	15.2	29.7	46.8
1Q-T22	900	50,000	100.0	2.33		0.20	8.6	235,000	230,000	4.0	13.1	30.0	48.1
			Average	1.97				224,333	219,333	4.8	15.0	29.5	46.7

* gage section not remachined before tensile test

[a] L.D.= Total Loading Deformation; T.D.= Total Deformation at end of Creep-Exposure period.

Table 17

Tensile and Yield Strengths of 2024-T86 after Specified Exposure, Expressed as Percentage of Unexposed Value at Test Temperature

Exposure Temp (°F)	Exposure Time (hr)	Total Def. (%)	Test Temp (°F)	Percent of Unexposed Tensile Strength	Percent of Unexposed Yield Strength
none	none	none	room	75,690 psi	70,800 psi
none	none	none	350	57,854 psi	56,456 psi
350	10	none	room	99.5%	98.0%
		0.5	room	97.5	97.5
		1.0	room	97.0	97.2
		2.0	room	95.8	96.5
	10	none	350	103.0	103.9
		0.5	350	98.6	100.2
		1.0	350	97.6	99.8
		2.0	350	96.8	98.4
	50	none	room	97.8	93.2
		0.5	room	96.2	92.3
		1.0	room	94.9	91.0
		2.0	room	91.9	89.0
	50	none	350	99.3	100.0
		0.5	350	97.0	96.8
		1.0	350	94.8	95.2
		2.0	350	90.3	93.5
	100	none	room	94.4	89.5
		0.5	room	94.2	89.0
		1.0	room	94.0	89.0
		2.0	room	87.0	84.7
	100	none	350	99.3	100.0
		0.5	350	92.4	91.5
		1.0	350	91.4	91.3
		2.0	350	85.7	87.0
none	none	none	room	75,690 psi	70,800 psi
none	none	none	400	52,784 psi	51,033 psi
400	10	none	room	94.0%	93.2%
		0.5	room	92.9	86.1
		1.0	room	91.8	85.2
		2.0	room	89.4	84.4
	10	none	400	102.2	100.8
		0.5	400	91.5	91.0
		1.0	400	88.2	91.0
		2.0	400	90.0	96.9
	50	none	room	88.5	80.4
		0.5	room	87.5	78.9
		1.0	room	86.2	77.6
		2.0	room	83.5	74.9
	50	none	400	101.2	100.9
		0.5	400	87.2	86.1
		1.0	400	82.5	82.0
		2.0	400	82.3	83.0
	100	none	room	85.3	75.6
		0.5	room	85.0	74.8
		1.0	room	83.6	73.4
		2.0	room	79.8	69.8
	100	none	400	100.3	102.3
		0.5	400	84.3	82.2
		1.0	400	79.5	77.5
		2.0	400	75.4	74.9
none	none	none	room	75,690 psi	70,800 psi
none	none	none	500	40,944 psi	39,677 psi
500	10	none	room	82.0%	70.0%
		0.5	room	70.6	53.6
		1.0	room	64.7	48.1
		2.0	room	65.0	48.1
		3.0	room	66.7	50.2
	10	none	500	97.5	96.2
		0.5	500	78.4	75.6
		1.0	500	66.8	64.3
		2.0	500	61.2	59.2
		3.0	500	55.5	54.2
	50	none	room	79.9	69.2
		0.5	room	67.4	52.3
		1.0	room	61.4	43.0
		2.0	room	58.8	41.0
		3.0	room	56.5	38.8
	50	none	500	96.4	94.5
		0.5	500	74.7	70.5
		1.0	500	53.9	48.4
		2.0	500	50.4	49.1
		3.0	500	50.2	49.4
	100	none	room	68.0	53.6
		0.5	room	60.1	42.4
		1.0	room	54.9	36.2
		2.0	room	54.2	34.9
		3.0	room	53.5	33.2
	100	none	500	94.2	93.4
		0.5	500	74.7	70.5
		1.0	500	53.9	48.4
		2.0	500	50.4	49.1
		3.0	500	50.2	49.4

Table 18

Effect of Unstressed Exposure on Room-Temperature Compression Properties of 2024-T86 Alloy

Exposure Conditions Temp (°F)	Exposure Conditions Time (hrs)	Spec. No.	Compression Test Results 0.2% offset Compression Yield Strength (psi)	Compression Test Results Compression Modulus (10^6 psi/in./in.)
350	10	2C-X2	74,100	10.3
	10	4A-X44	74,500	10.6
		Average	74,300	10.4
	50	3E-X2	72,000	10.9
	50	4A-X2	71,500	11.0
		Average	71,750	11.0
	100	2J-X44	66,900	10.5
	100	4G-X33	69,900	10.9
		Average	68,400	10.7
400	10	3L-X33	65,400	11.0
	10	4G-X44	65,200	10.8
		Average	65,300	10.9
	50	2P-X44	59,500	10.7
	50	4G-X2	59,700	10.8
		Average	59,600	10.8
	100	2P-X2	53,900	10.6
	100	4A-X33	57,300	10.3
		Average	55,600	10.4
500	10	2J-X2	47,300	10.5
	10	4M-X2	45,500	11.3
		Average	46,400	10.9
	50	3L-X2	57,500	11.2
	50	4A-X22	56,500	10.6
		Average	57,000	10.9
	100	2J-X33	51,500	10.5
	100	3E-X44	51,300	10.6
		Average	51,400	10.6

Table 19

Effect of Unstressed Exposure on Elevated-Temperature Compression Properties of 2024-T86 Alloy

Exposure Condition		Compression Test Results			
Temp. (°F)	Time (hrs)	Compression Test Temp (°F)	Spec. No.	0.2% offset Compression Yield Strength (psi)	Compression Modulus (10^6 psi/in./in.)
350	10	350	2L-X5	64,300	10.0
350	10	350	3D-X5	64,500	10.4
				64,500	10.2
350	50	350	4N-X1	64,600	10.2
350	100	350	3J-X1	65,000	10.3
350	100	350	4D-X5	65,000	10.5
				65,000	10.4
400	10	400	3G-X1	58,100	9.8
400	10	400	4E-X5	55,800	9.7
				56,950	9.8
400	50	400	3P-X1	51,600	9.9
400	50	400	4N-X5	52,400	9.8
				52,000	9.8
400	100	400	2N-X1	50,600	9.6
400	100	400	3L-X44	50,600	9.9
				50,600	9.8
500	10	500	2B-X1	36,600	9.3
500	10	500	4M-X44	35,200	9.1
				35,900	9.2
500	50	500	2H-X1	30,800	9.0
500	50	500	3A-X5	32,400	8.5
				31,600	8.8
500	100	500	4H-X1	22,900	9.1
500	100	500	2D-X1	24,600	9.1
				23,750	9.1

Table 20

Effect of Prior Creep Exposure on Compression Properties of 2024-T86 Alloy

Nominal Exposure Conditions			Actual Exposure Conditions				Deformation Obtained				Subsequent Compression Properties		
Temp. (°F)	Time (hr)	Total Deformation (%)	Spec. No.	Time (hr)	Temp (°F)	Stress (psi)	Loading (Total) %	Loading (Plastic) %	Creep (%)	Total (%)	Test Temp. (°F)	0.2% offset Yield Strength (psi)	Compression Modulus (10^6 psi/in./in.)
350	10	0.5	2E-T5	10.0	350	36,000	0.36	0.01	0.15	0.51	room	78,000	10.9
	10	0.5	4L-T55	9.9	350	36,000	0.37	0.02	0.15	0.52	350	61,800	10.4
	10	1.0	3H-T55	9.9	350	44,500	0.48	0.04	0.36	0.84	room	74,800	10.7
	10	1.0	4L-T2	10.1	350	44,500	0.47	0.03	0.48	0.95	350	58,800	10.3
	10	2.0	2L-T2	10.2	350	47,000	0.50	0.03	1.07	1.57	room	73,000	10.6
	10	2.0	3C-T5	9.9	350	47,000	0.53	0.06	1.47	2.00	350	52,000	9.9
	50	0.5	4K-T5	50.0	350	29,000	0.29	0	0.16	0.45	room	73,600	11.0
	50	0.5	5C-T1	50.0	350	29,000	0.29	0	0.18	0.47	350	59,000	10.6
	50	1.0	4E-T55	50.1	350	39,500	0.40	0.01	0.61	1.01	room	71,000	11.1
	50	1.0	2A-T5	51.0	350	39,500	0.43	0.04	0.53	0.96	350	54,500	10.2
	50	2.0	3C-T11	50.1	350	41,500	0.47	0.06	0.49	1.06	room	69,600	10.8
	50	2.0	4L-T3	50.0	350	41,500	0.46	0.05	0.50	1.06	350	53,600	10.1
	100	0.5	3N-T2	103.0	350	28,000	0.22	0	0.23	0.45	room	73,100	10.6
	100	0.5	2N-T1	100.0	350	28,000	0.30	0	0.19	0.49	350	57,000	10.1
	100	1.0	3F-T11	100.4	350	37,500	0.40	0.01	0.57	0.97	room	68,500	11.1
	100	1.0	3C-T1	100.0	350	37,500	0.38	0.01	0.66	1.04	350	52,800	9.8
	100	2.0	4F-T1	100.3	350	39,000	0.42	0.02	0.35	1.77	room	64,800	11.0
	100	2.0	5M-T4		350	39,000	0.40	0.02	0.51	0.91			
400	10	0.5	3H-T11	10.2	400	28,000	0.33	0.01	0.22	0.55	room	72,900	10.9
	10	0.5	4L-T1	10.0	400	28,000	0.30	0.01	0.24	0.54	400	53,600	9.6
	10	1.0	2H-T55	9.9	400	36,000	0.41	0.04	0.82	1.23	room	65,000	10.9
	10	1.0	3C-T4	9.0	400	36,000	0.40	0.04	0.38	0.78	400	53,100	9.9
	10	2.0	4K-T55	10.1	400	37,000	0.37	0.04	0.60	0.97	room	62,400	10.6
	10	2.0	5G-T3	9.0	400	37,000	0.43	0.04	1.02	1.45	400	46,000	----
	50	0.5	4E-T5	50.1	400	23,000	0.25	0	0.30	0.55	room	62,100	11.0
	50	0.5	2A-T3	50.0	400	23,000	0.24	0	0.30	0.54	400	49,100	9.5
	50	1.0	3B-T4	50.9	400	29,000	0.29	0.01	0.47	0.76	room	63,000	10.8
	50	1.0	2A-T11	50.0	400	29,000	0.30	0.01	0.67	0.97	400	47,100	9.8
	50	2.0	3M-T1	50.0	400	31,500	0.34	0.02	1.20	1.54	room	56,100	10.4
	50	2.0	5C-T4	50.0	400	31,500	0.36	0.02	1.20	1.56	400	45,200	9.5
	100	0.5	4J-T2	100.2	400	21,000	0.24	0	0.42	0.66	room	60,200	10.7
	100	0.5	3C-T55	100.0	400	21,000	0.24	0	0.33	0.57	400	45,600	9.7
	100	1.0	2K-T1	100.4	400	27,000	0.28	0.01	1.07	1.35	room	62,500	11.1
	100	1.0	4L-T5	100.4	400	27,000	0.29	0.01	0.58	0.87	400	48,200	10.0
	100	2.0	4D-T4	100.2	400	29,000	0.32	0.01	1.86	2.18	room	50,400	10.5
	100	2.0	4F-T3 rupt.	87	400	29,000	0.29	0.01		1.87 at 82 hrs.	--	--	----
500	10	0.5	4D-T2	10.2	500	14,500	0.19	0	0.41	0.60	room	45,000	11.2
	10	0.5	5M-T11	10.0	500	14,500	0.19	0	0.46	0.65	500	31,300	8.8
	10	1.0	2Q-T2	10.0	500	17,000	0.18	0	0.43	0.61	room	43,000	11.0
	10	1.0	3C-T3	10.0	500	17,000	0.21	0	0.35	0.56	500	30,700	9.3
	10	2.0	5M-T1	10.0	500	19,000	0.25	0	1.26	1.51	room	40,400	10.2
	10	2.0	5C-T5	10.0	500	19,000	0.23	0	1.18	1.41	500	28,600	9.6
	50	0.5	3M-T5	50.2	500	11,000	0.20	0.06	0.56	0.76	room	36,100	10.7
	50	1.0	2Q-T1	50.1	500	13,000	0.17	0	0.80	0.97	room	34,800	10.5
	50	1.0	5G-T4	50.0	500	13,000	0.16	0	1.44	1.60	500	19,000	----
	50	3.0	2G-T2	50.0	500	15,000	0.18	0	3.93	4.11	room	26,800	10.8
	100	0.5	2L-T3	100.5	500	9,000	0.12	0	0.63	0.75	room	38,500	10.7
	100	0.5	3M-T11	100.1	500	9,000	0.11	0	0.50	0.61	500	21,200	9.3
	100	1.0	3H-T1	100.4	500	12,000	0.14	0	1.94	2.08	room	31,000	10.7
	100	1.0	5G-T2 rupt.	75.9	500	12,000	0.15	0		2.57 at 70 hrs.	--	--	----
	100	2.0	2A-T55 rupt.	99.3	500	12,500	0.14	0		3.29 at 90 hrs.	--	--	----
	100	2.0	5M-T3	100.0	500	12,500	0.16	0	1.27	1.43	500	21,800	9.1
	100	3.0	4K-T11 rupt.	58.2	500	13,000	0.16	0		2.12 at 48 hrs.	--	--	----

Table 21

Compression Yield Strength of 2024-T86 after Specified Exposure Expressed as Percentage of Unexposed Value at Test Temperature

Exposure Temp. (°F)	Exposure Time (hrs)	Total Def. (%)	Test Temp. (°F)	Compression Yield Strength (% of Unexposed Value)
none	none	none	room	75,200 psi
none	none	none	350	66,922 psi
350	10	none	room	98.9%
		0.5	room	102.9
		1.0	room	101.0
		2.0	room	90.5
		none	350	96.5
		0.5	350	92.5
		1.0	350	87.5
		2.0	350	77.5
	50	none	room	95.4
		0.5	room	97.5
		1.0	room	93.8
		2.0	room	83.8
		none	350	96.6
		0.5	350	88.4
		1.0	350	81.6
		2.0	350	----
	100	none	room	91.0
		0.5	room	95.8
		1.0	room	92.5
		2.0	room	81.8
		none	350	97.4
		0.5	350	85.4
		1.0	350	79.6
		2.0	350	----
none	none	none	room	75,200 psi
none	none	none	400	60,711 psi
400	10	none	room	87.0%
		0.5	room	96.4
		1.0	room	88.1
		2.0	room	----
		none	400	95.5
		0.5	400	88.5
		1.0	400	83.0
		2.0	400	----
	50	none	room	79.1
		0.5	room	83.4
		1.0	room	82.5
		2.0	room	----
		none	400	85.6
		0.5	400	81.9
		1.0	400	78.2
		2.0	400	----
	100	none	room	73.9
		0.5	room	79.2
		1.0	room	82.5
		2.0	room	71.6
		none	400	82.5
		0.5	400	79.1
		1.0	400	74.9
		2.0	400	----
none	none	none	room	75,200 psi
none	none	none	500	50,734 psi
500	10	none	room	61.9%
		0.5	room	59.2
		1.0	room	56.5
		2.0	room	51.9
		none	500	71.0
		0.5	500	62.8
		1.0	500	58.3
		2.0	500	52.0
	50	none	room	75.5
		0.5	room	56.5
		1.0	room	45.3
		2.0	room	38.4
		none	500	62.3
	100	none	room	67.8
		0.5	room	55.6
		1.0	room	49.2
		2.0	room	41.3
		none	500	47.0
		0.5	500	42.9
		1.0	500	42.4
		2.0	500	43.3

Table 22

Effect of Unstressed Exposure on Room-Temperature Tension-Impact Properties of 2024-T86 Alloy

Exposure Temp (°F)	Exposure Time (hr)	Spec. No.	Energy Absorbed a)(ft - lb)	Elongation (% - 2 inch)	Reduction of Area (%)
Unexposed		Average	18.2	5.8	11.2
350	10	4A-X3	15	3.0	7.9
	10	3E-X22	21	5.0	9.9
		Average	18	4.0	8.9
	50	4M-X4	17	5.0	11.4
	50	2C-X22	19	6.0	9.4
		Average	18	5.5	10.4
	100	3L-X4	10	6.0	8.5
	100	2C-X4	16	6.0	6.1
		Average	13	6.0	7.3
400	10	4M-X3	18	6.5	8.6
	10	2J-X4	17	6.0	11.6
		Average	17.5	6.2	9.1
	50	4A-X4	11	8.0	13.0
	50	3E-X33	21	6.5	7.7
		Average	16.0	7.2	10.3
	100	2J-X22	18	9.0	12.7
	100	4M-X33	19	7.5	9.2
		Average	18.5	8.2	10.9
500	10	4G-X22	13	5.5	10.2
	10	3E-X4	14	6.0	11.0
		Average	13.5	5.8	10.6
	50	4G-X4	11	4.0	11.5
	50	2P-X33	14	4.5	9.2
		Average	12.5	4.2	10.4
	100	2P-X4	15	6.0	13.8
	100	3L-X22	14	6.0	13.9
		Average	14.5	6.0	13.8

a) Specimen gauge section 0.200 inch wide x 0.064 inch thick.

Table 23

Effect of Unstressed Exposure on Elevated-Temperature Tension-Impact Properties of 2024-T86 Alloy

Exposure Conditions		Test Results		
Temp (°F)	Time (hrs)	Test Temp (°F)	Spec. No.	Energy Absorbed a) (ft - lb)
350	10	350	3J-X44	18
350	10	350	4M-X22	19
				18.5
350	50	350	2N-X2	19
350	50	350	4H-X44	19
				19
350	100	350	2E-X44	20
350	100	350	4M-X44	17
				18.5
400	10	400	2J-M4	20
400	10	400	3B-X44	19
				19.5
400	50	400	2M-X2	20
400	50	400	3N-X44	16
				18
400	100	400	3F-2	17
400	100	400	4D-X44	17
				17
500	10	500	2P-X22	15
500	10	500	4P-X44	14
				14.5
500	50	500	2B-X2	14
500	50	500	3L-M4	13
				13.5
500	100	500	3A-X44	12
500	100	500	4C-X2	13
				12.5

a) Specimen Cross Section 0.200 in. wide x 0.064 in. thick.

Table 24

Effect of Prior Creep Exposure on Room-Temperature Tension-Impact Strength of 2024-T86

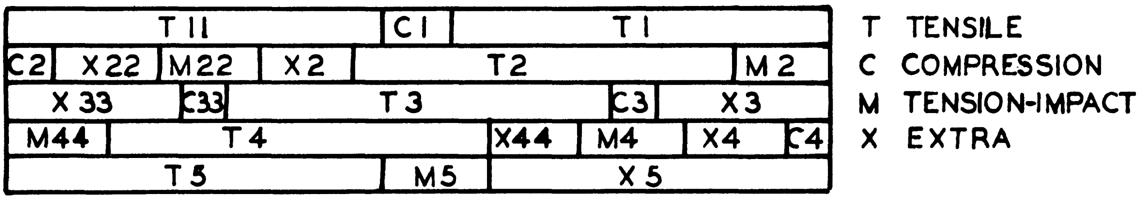
Nominal Exposure Conditions			Actual Exposure Conditions				Deformation Obtained				Subsequent Tension Impact Strengths
Temp. (°F)	Time (hr)	Total Deformation (%)	Spec. No.	Time (hr)	Temp (°F)	Stress (psi)	Loading (Total) %	Loading (Plastic) %	Creep (%)	Total (%)	a) (ft - lb.)
350	10	0.5	3F-T4	10.0	350	36,000	0.36	0.01	0.12	0.48	26
	10	0.5	4J-T1	10.0	350	36,000	0.34	0.01	0.17	0.51	23
	10	1.0	3Q-T1	10.0	350	44,500	0.48	0.03	0.60	1.08	22
	10	1.0	2L-T4	10.2	350	44,500	0.46	0.03	0.62	1.08	22
	10	2.0	3H-T4	10.2	350	47,000	0.51	0.04	0.95	1.46	24
	10	2.0	2G-T11	10.0	350	47,000	0.49	0.04	0.81	1.30	23
	10	2.0	4F-T55	rupt. 7.2	350	47,000	0.55	0.04		1.44 at 4.5 hrs.	--
	50	0.5	5M-T55	50.3	350	29,000	0.36	0	0.16	0.52	20
	50	1.0	2K-T4	50.1	350	39,500	0.39	0.02	0.50	0.89	27
	50	1.0	3P-T2	50.0	350	39,500	0.42	0.02	0.52	0.94	23
	50	2.0	4L-T4	50.1	350	41,500	0.43	0.02	1.18	1.61	18
	100	0.5	2K-T5	100.0	350	28,000	0.30	0	0.20	0.50	22
	100	0.5	4D-T55	100.0	350	28,000	0.28	0	0.18	0.46	20
	100	1.0	2E-T1	100.1	350	37,500	0.39	0.01	0.83	1.22	16
	100	1.0	3P-T5	100.1	350	37,500	0.39	0.01	0.50	0.89	19
	100	2.0	3H-T5	100.0	350	39,000	0.40	0.02	0.56	0.96	25
	100	2.0	2N-T4	rupt. 97.5	350	39,000	0.41	0.02		1.81 at 96 hrs.	--
	100	2.0	4K-T3	100.2	350	39,000	0.43	0.02	1.61	2.04	6
400	10	0.5	4D-T5	10.1	400	28,000	0.32	0.01	0.22	0.54	21
	10	0.5	2G-T3	10.1	400	28,000	0.31	0.01	0.21	0.52	21
	10	1.0	4J-T55	10.0	400	36,000	0.37	0.04	0.77	1.14	21
	10	1.0	3M-T2	10.0	400	36,000	0.40	0.04	0.84	1.24	17
	10	2.0	3M-T4	10.2	400	37,000	0.42	0.04	0.78	1.20	21
	10	2.0	5C-T11	9.0	400	37,000	0.42	0.04	0.62	1.04	19
		Note	2E-T5	rupt. 10.0	400	37,500	0.47	0.04		2.23 at 9.8 hrs.	--
	50	0.5	3P-T1A	50.0	400	23,000	0.23	0	0.26	0.49	21
	50	0.5	4F-T11	50.0	400	23,000	0.24	0	0.30	0.54	33
	50	1.0	2K-T3	50.0	400	29,000	0.32	0.01	0.84	1.16	16
	50	1.0	4J-T11	50.1	400	29,000	0.34	0.01	0.68	1.02	18
	50	2.0	2N-T5	rupt. 43.0	400	31,500	0.36			0.92 at 24 hrs.	--
	50	2.0	4K-T1	rupt. 50.0	400	31,500	0.31			1.74 at 46 hrs.	--
	100	0.5	2L-T1	100.0	400	21,000	0.24	0	0.36	0.60	17
	100	0.5	4K-T4	100.3	400	21,000	0.21	0	0.31	0.52	21
	100	1.0	4F-T5	100.2	400	27,000	0.30	0.01	0.79	1.09	13
	100	1.0	3P-T1	100.1	400	27,000	0.29	0.01	0.62	0.91	17
	100	2.0	2K-T55	100.0	400	29,000	0.31	0.01	1.03	1.34	16
	100	2.0	3M-T3	100.1	400	29,000	0.33	0.01	1.23	1.56	18
500	10	0.5	3P-T3	10.1	500	14,500	0.15	0	0.36	0.51	17
	10	0.5	2G-T55	10.1	500	14,500	0.14	0	0.35	0.49	17
	10	1.0	4B-T4	10.0	500	17,000	0.21	0	0.51	0.72	18
	10	1.0	2G-5	10.0	500	17,000	0.20	0	0.56	0.76	18
	10	2.0	5G-T55	10.0	500	19,000	0.22	0	0.80	1.02	14
	50	0.5	5M-T5	50.0	500	11,000	0.12	0	0.57	0.69	15
	50	1.0	4J-T5	50.0	500	13,000	0.15	0	3.35 *	3.50*	16
	50	1.0	3C-T2	50.0	500	13,000	0.16	0	0.90	1.06	16
	50	3.0	4N-T1	rupt. 32.2	500	15,000	0.16	0		2.74 at 29 hrs.	--
	100	0.5	4E-T4	100.0	500	9,000	0.10	0	0.66	0.76	19
	100	0.5	3M-T55	100.1	500	9,000	0.09	0	0.49	0.58	13
	100	1.0	2E-T4	100.2	500	12,000	0.14	0	1.86	2.00	18
	100	1.0	3Q-T11	100.2	500	12,000	0.14	0	1.28	1.42	16
	100	2.0	5C-T3	100.0	500	12,500	0.17	0	2.54	2.71	12
	100	3.0	2G-T1	rupt. 84.0	500	13,000	0.16	0		3.88 at 83.5 hrs.	--

a) Specimen Cross Section 0.200 in. wide x 0.064 in. thick.

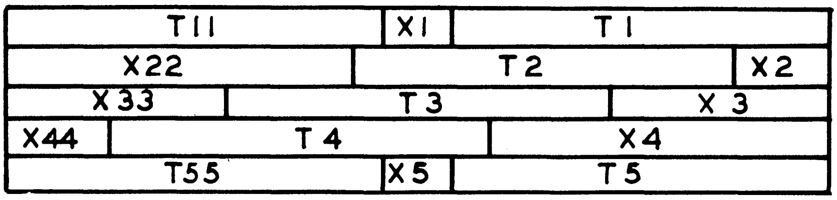
* **Estimated**

SHEET 2	SHEET 3	SHEET 4	PANEL NO.
R	R	Q	A
R	R	R	B
Q	R	R	C
R	R	R	D
R	Q	R	E
R	R	R	F
R	R	Q	G
R	R	R	H
Q	R	R	J
R	R	R	K
R	Q	R	L
R	R	Q	M
R	R	R	N
Q	R	R	P

SHEET SAMPLING SCHEME 2024-T86 SCALE 0 20 INCHES



PANEL SAMPLING SCHEME Q



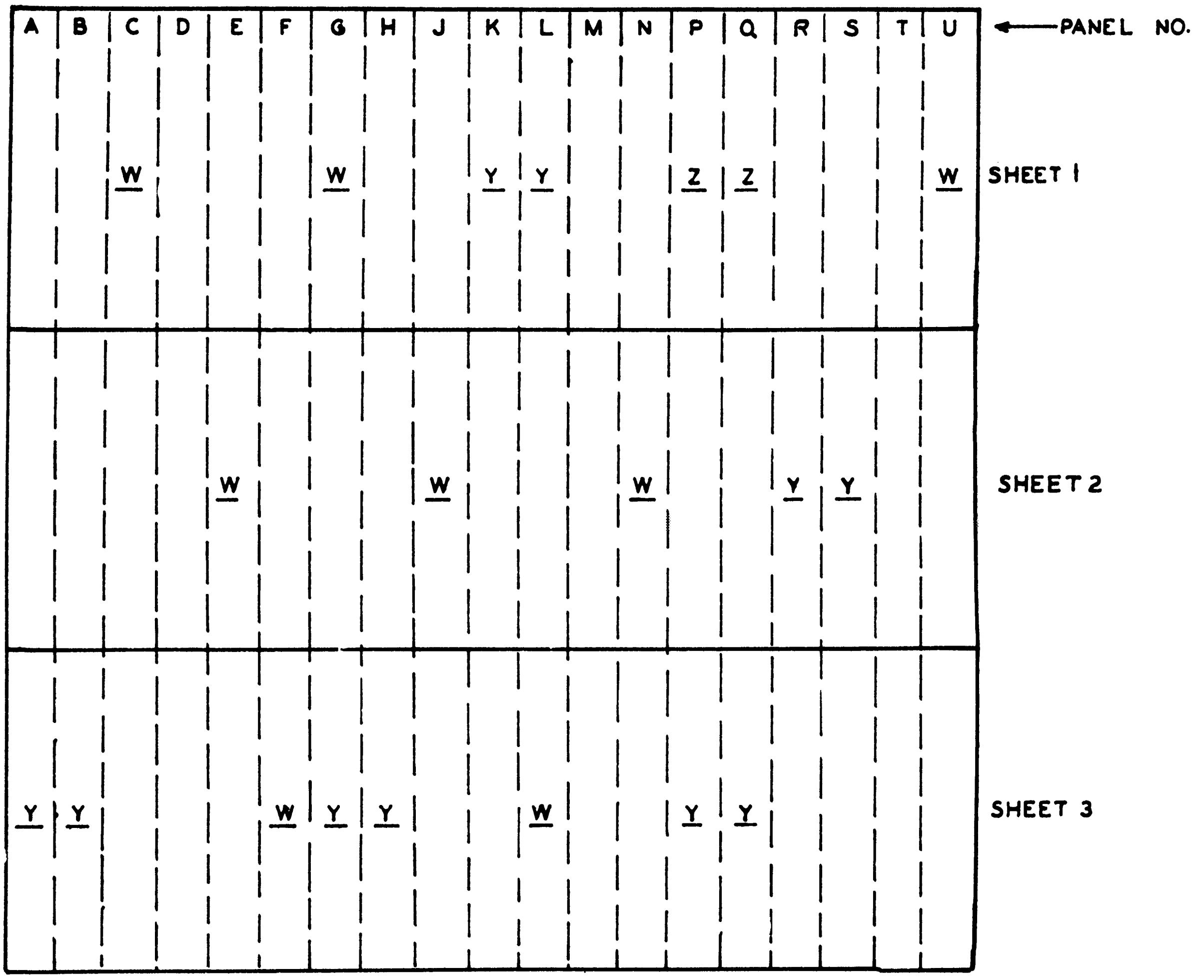
ALL BLANKS
1 INCH WIDE

PANEL SAMPLING SCHEME R

SHEET SIZE 48 × 72 ×.065 - INCHES
PANEL SIZE 48 × 5–5-1/2 INCHES
SAMPLE CODE -(EXAMPLE) 4C-T2, I.E., SHEET 4-
PANEL C - TENSILE SPEC. NO. 2

SCALE 0 10 INCHES
LENGTH ONLY

Figure 1 - Sampling Procedure for Sheets of 2024-T86 Aluminum Alloy.



	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R	S	T	U
SHEET 1			W				W			Y	Y			Z	Z				W
SHEET 2					W				W				W			Y	Y		
SHEET 3	Y	Y				W	Y	Y			W			Y	Y				

Sheet Dimensions: 36 x 120 x 0.064 inches
Panel Width: 6-1/4 to 6-1/2 inches
Sheet Designation: 1, 2, 3, etc.
Panel Designation: A, B, C, etc.
Panel Location Code: 1A, 3L, etc. (Sheet No. - Panel No.)
Specimen Blank Sampling Scheme: W, Y, or Z **(see Figure 3)**

Figure 2. - Panel Sampling Scheme for Sheets of 17-7PH Stainless Steel Sheet

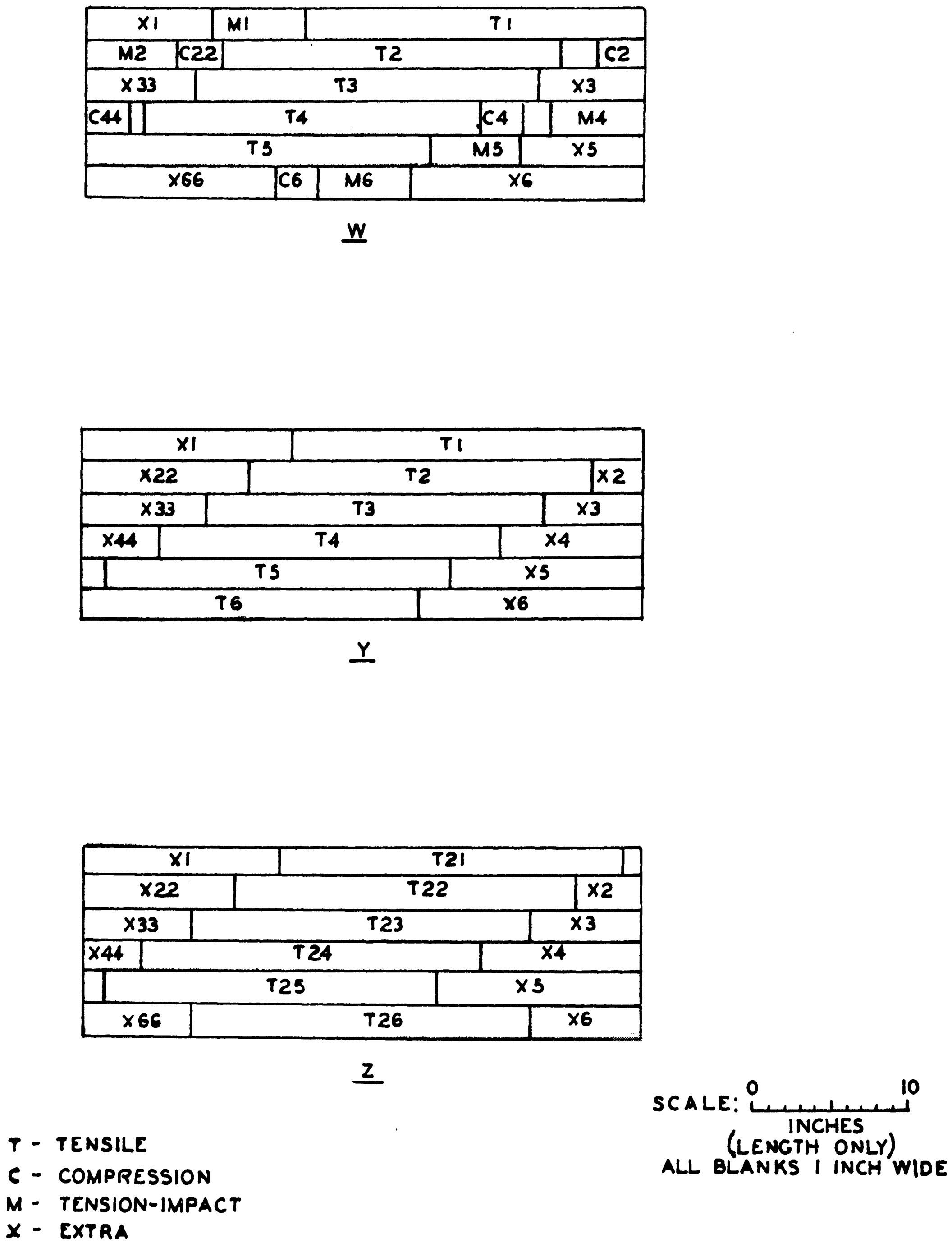
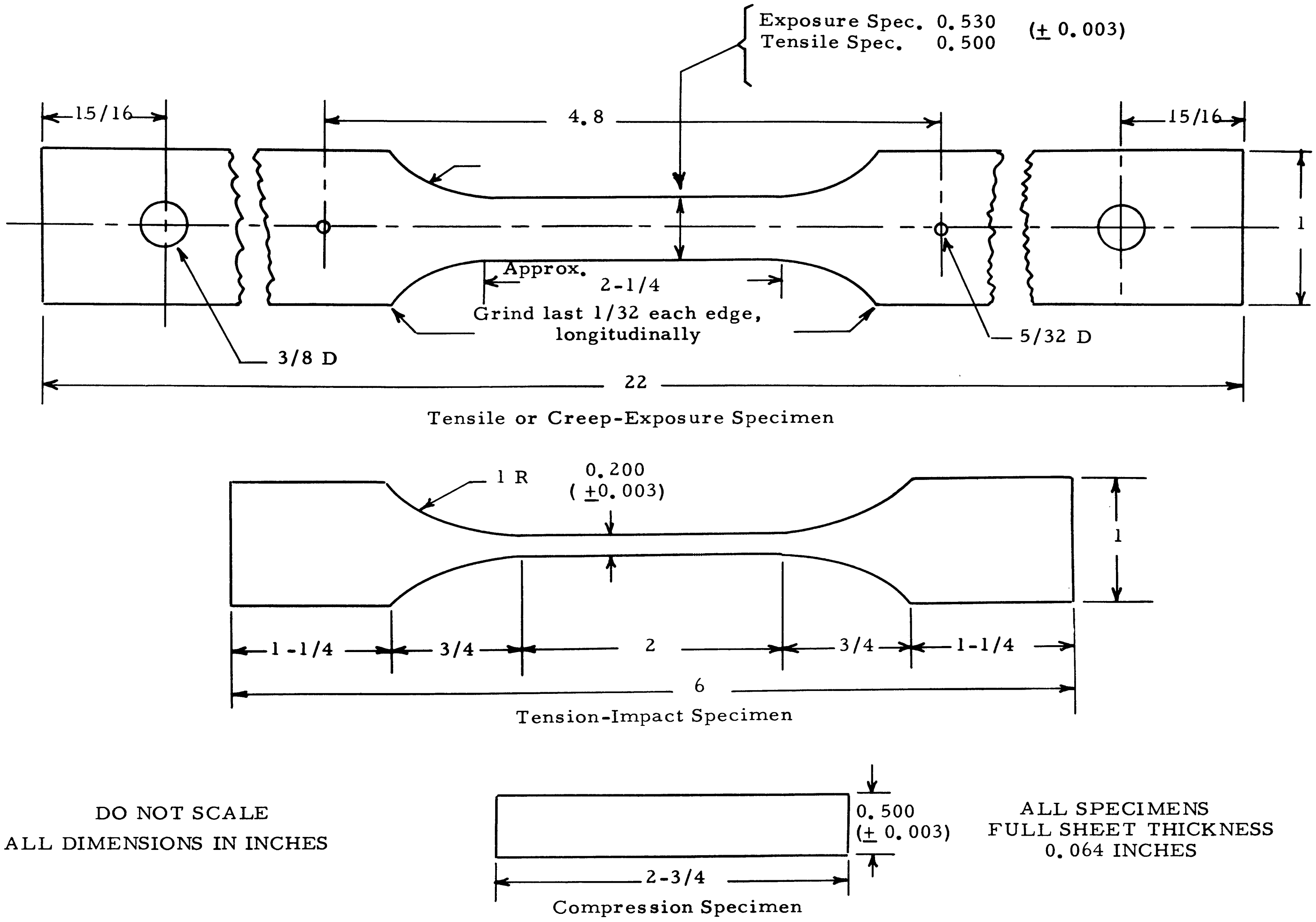


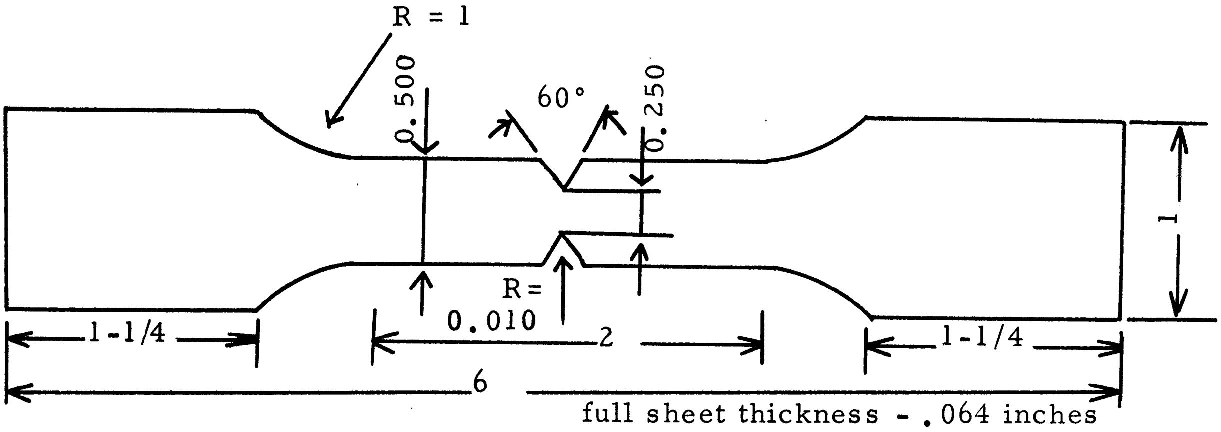
Figure 3. - Specimen Blank Sampling Schemes for Panels of 17-7PH Stainless Steel Sheet



DO NOT SCALE
ALL DIMENSIONS IN INCHES

ALL SPECIMENS
FULL SHEET THICKNESS
0.064 INCHES

Figure 4. - **Details of Test Specimens (**Tension-Impact and Compression Specimens Designed to be Cut **from Creep Specimens after Exposure).**



All Dimensions in Inches.

full sheet thickness - .064 inches

Figure 5. - Design of notched tension-impact specimen

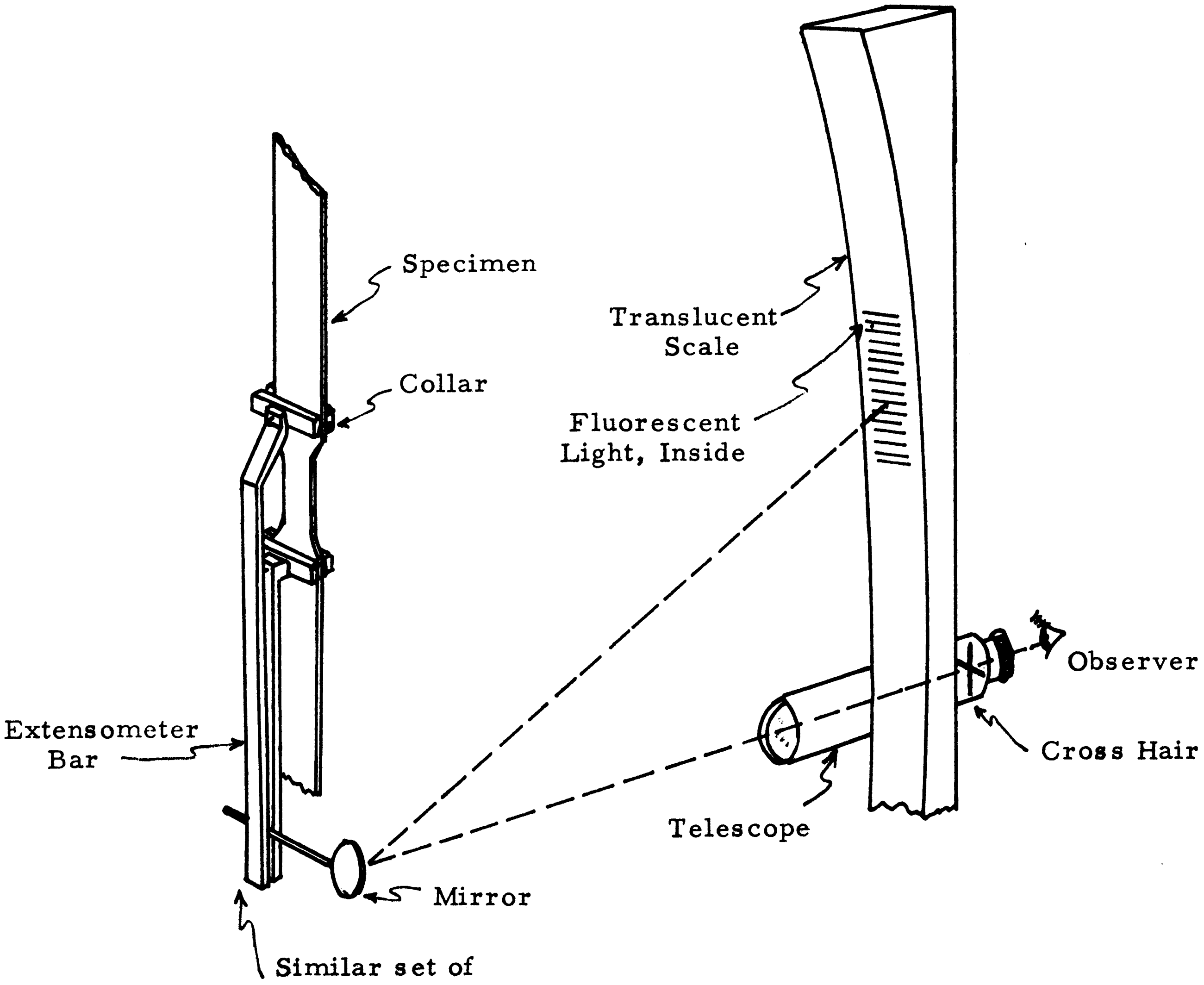


Figure 6. - Simplified Drawing of Modified Martens Extensometer System Used for Deformation Measurement in Creep Tests.

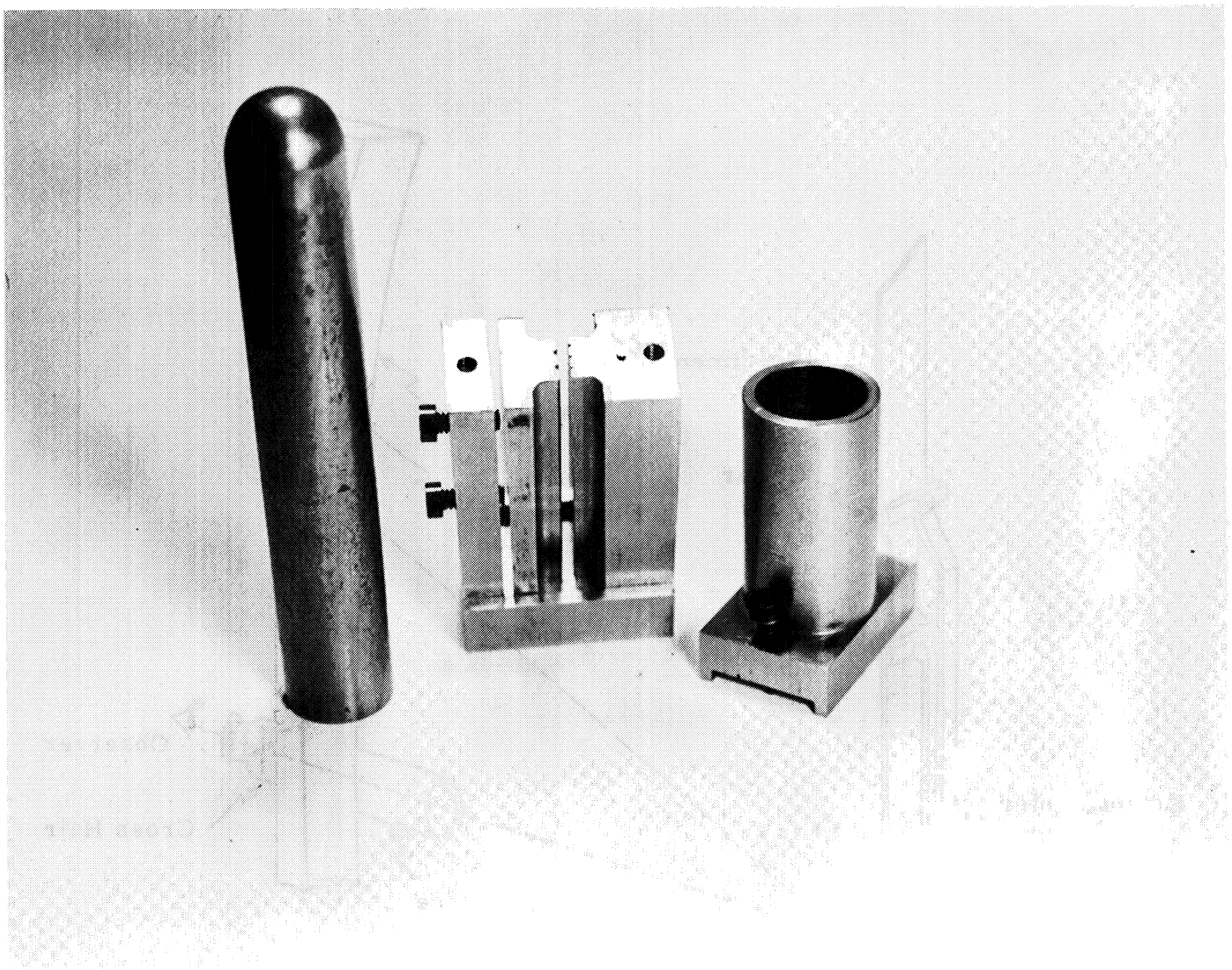


Figure 7. - Components of Compression Fixture - Note the Off-set Grooves in Guide Blocks.

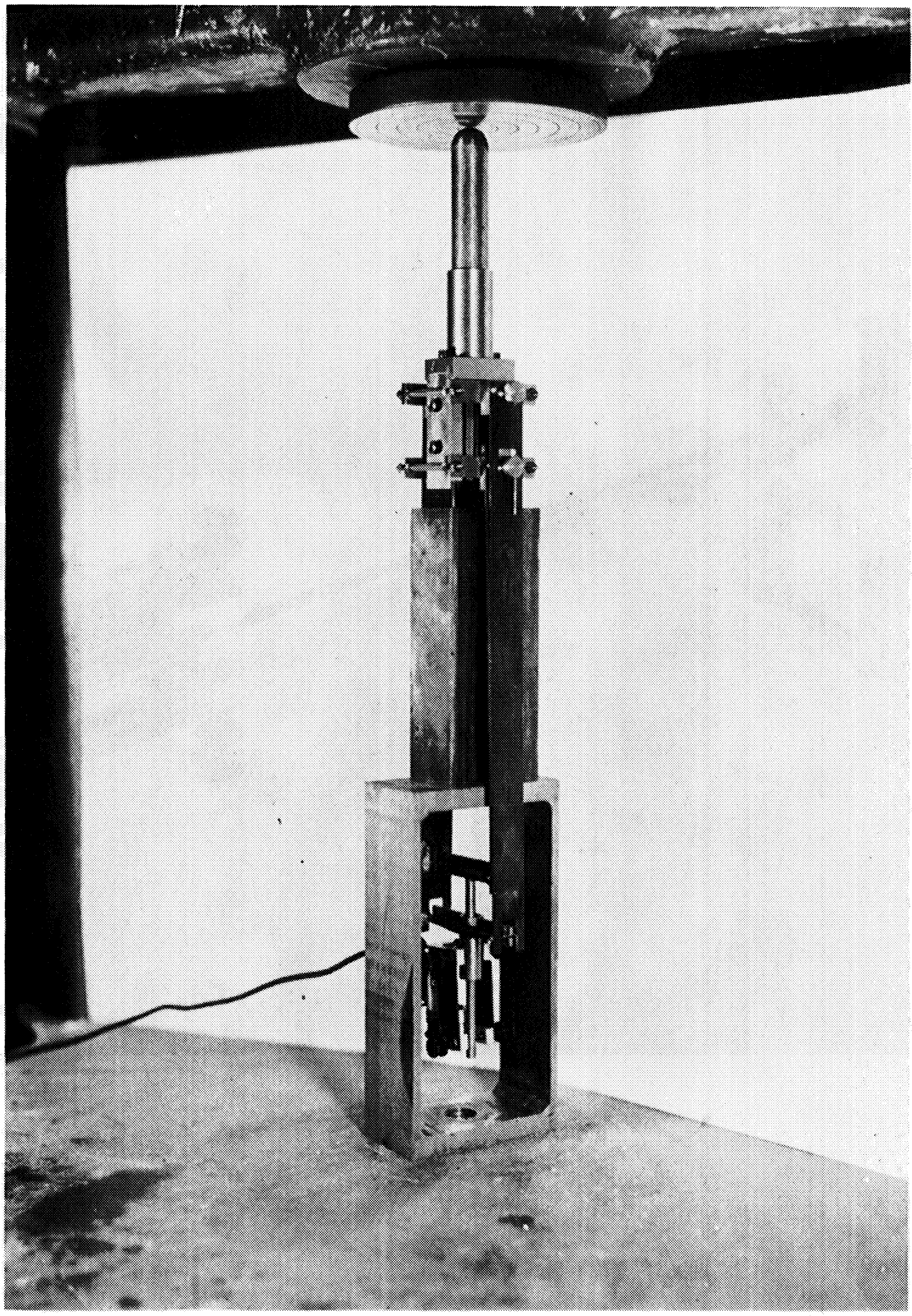


Figure 8. - Compression Fixture Assembled for Testing with Averaging Extensometer in Place.

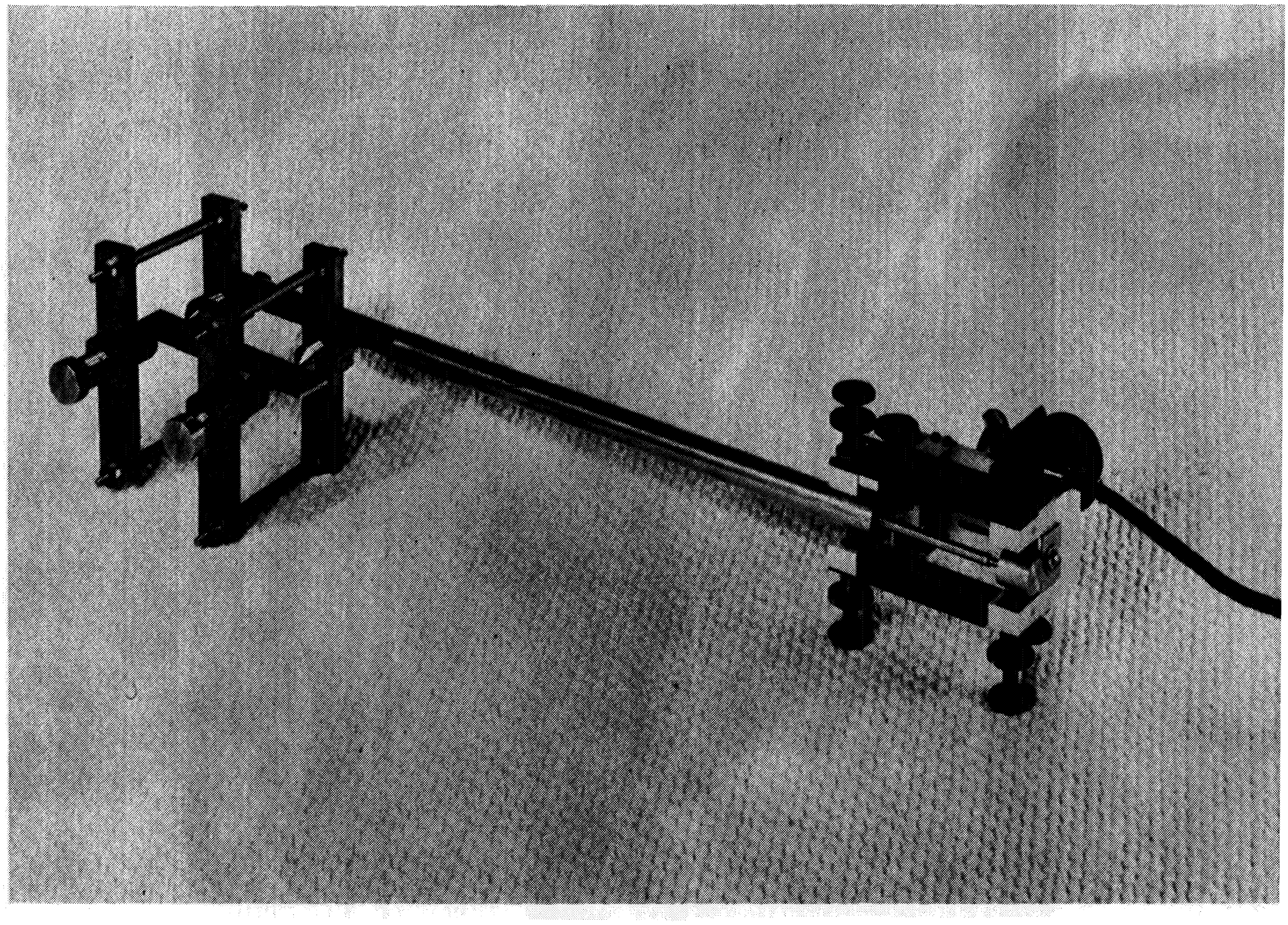


Figure 9. - Original Rod and Tube Extensometer Fixture with O. S. Peters Microformer Strain Follower Attached.

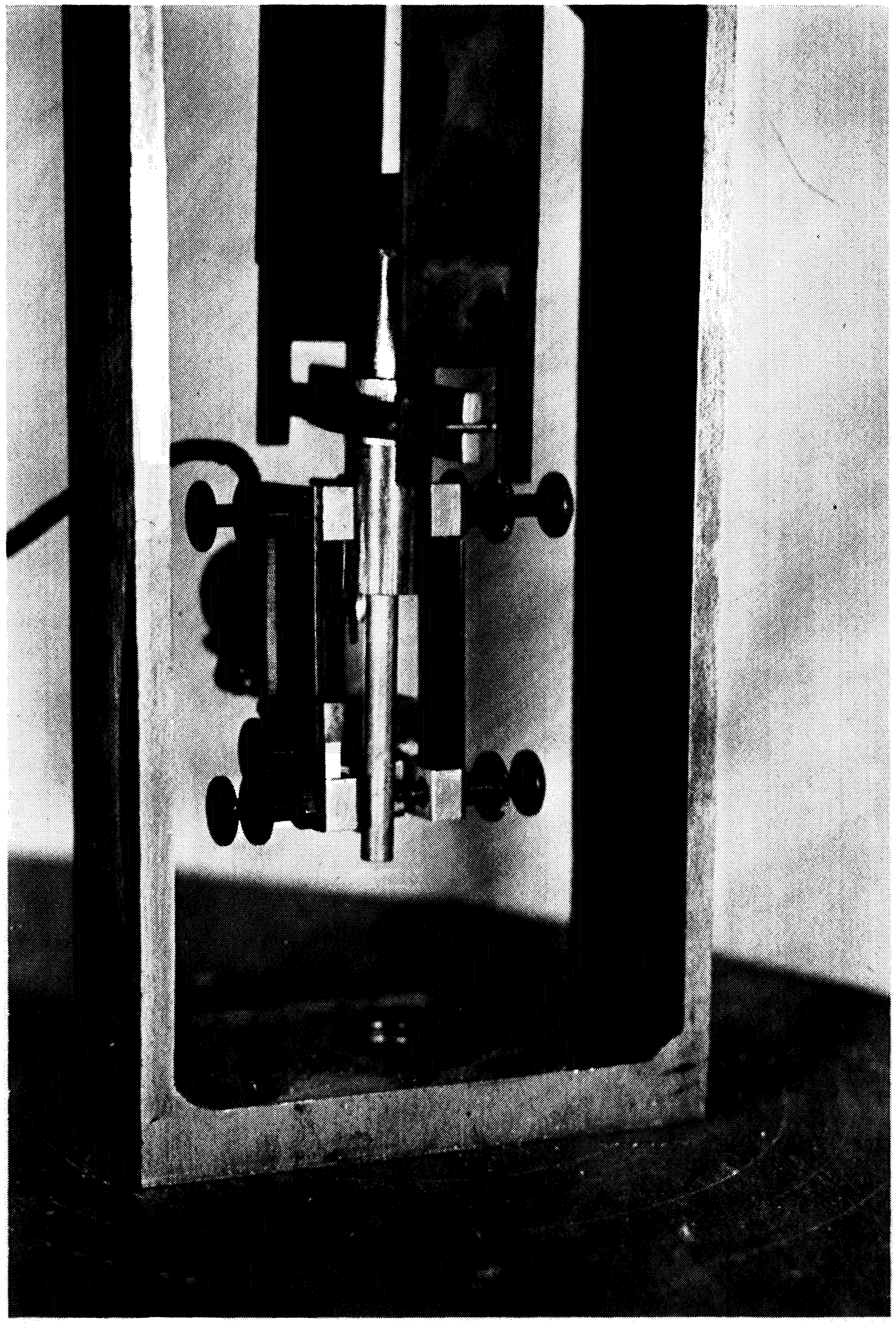


Figure 10. - Detail of Lower End of Revised Extensometer System.

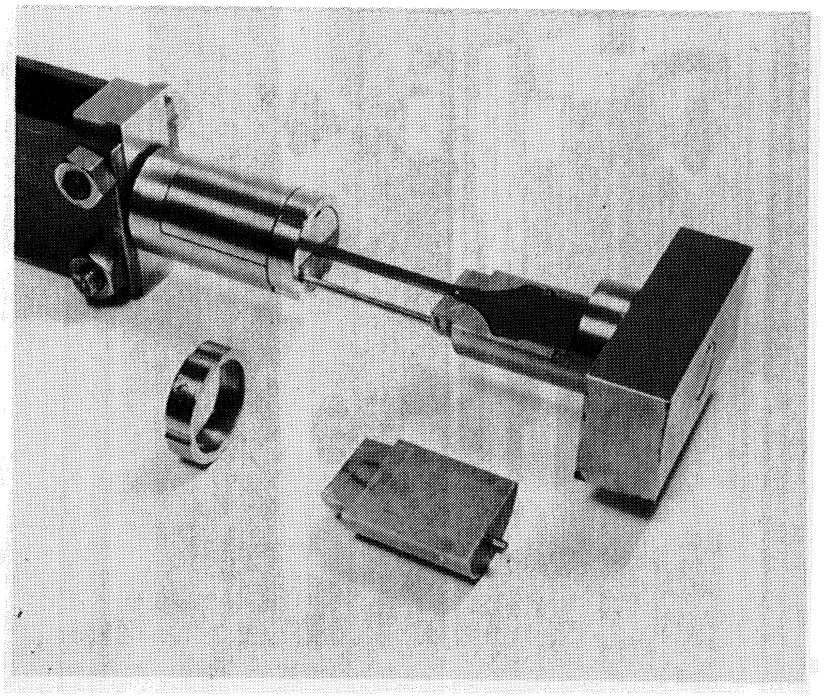


Figure 11. - Tension-Impact Specimen and Gripping Assembly for Smooth Specimens. The Plates at Far Left Fit Over the Impact Machine Pendulum Head.

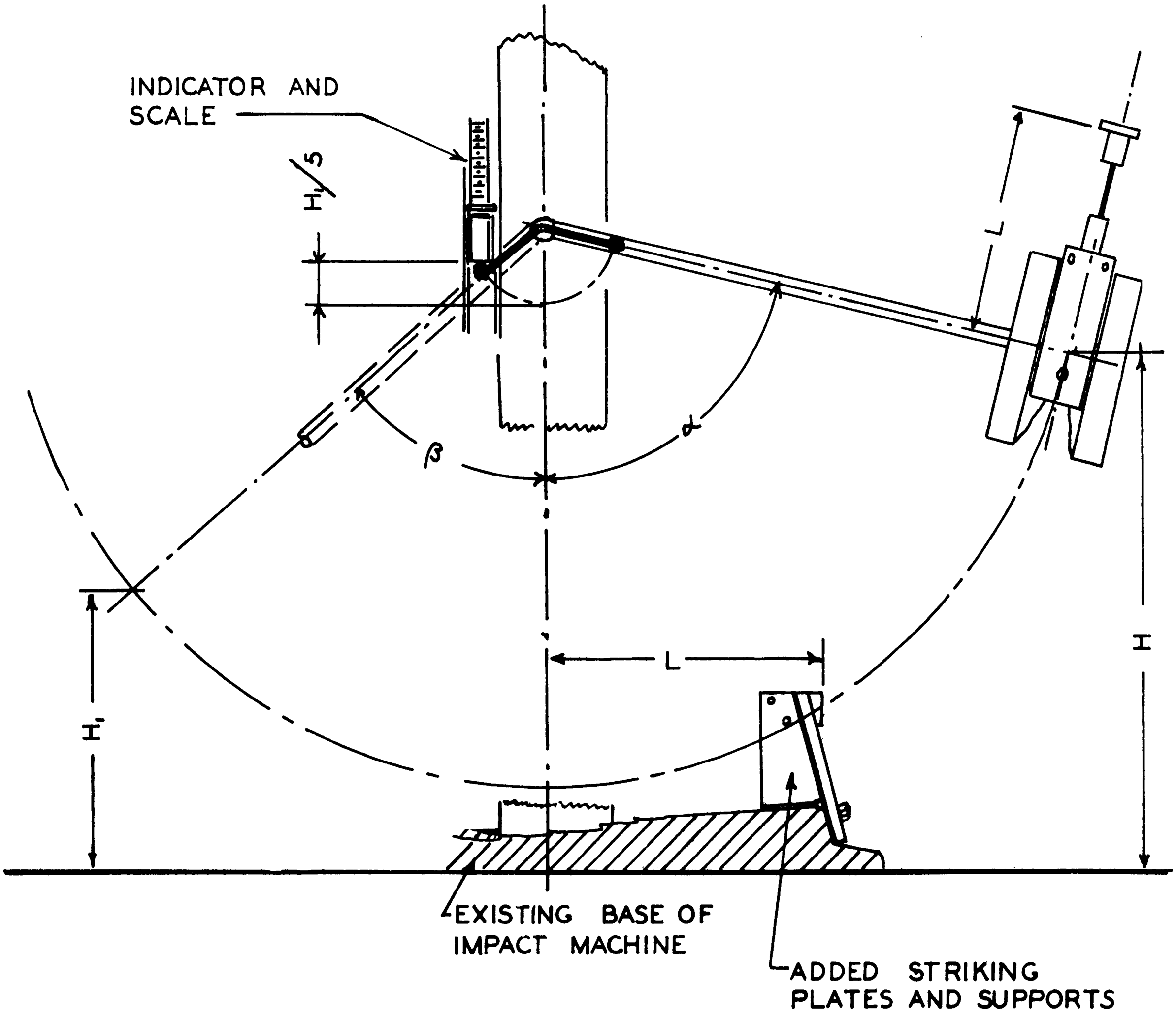


Figure 12. - Geometry of Olsen Impact Machine as Modified for Tension-Impact Testing

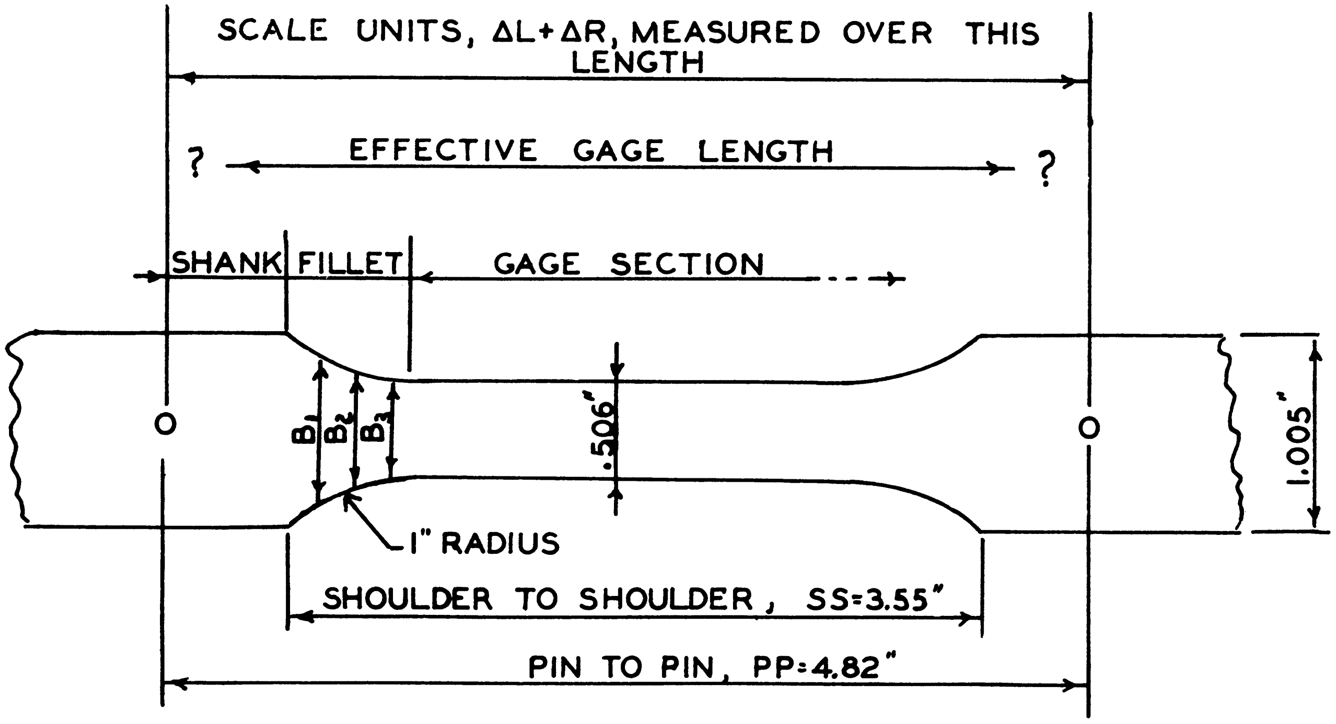


Figure 13. - Gage Section of Typical Strip Specimen for Illustration of Calculation of Effective Gage Length

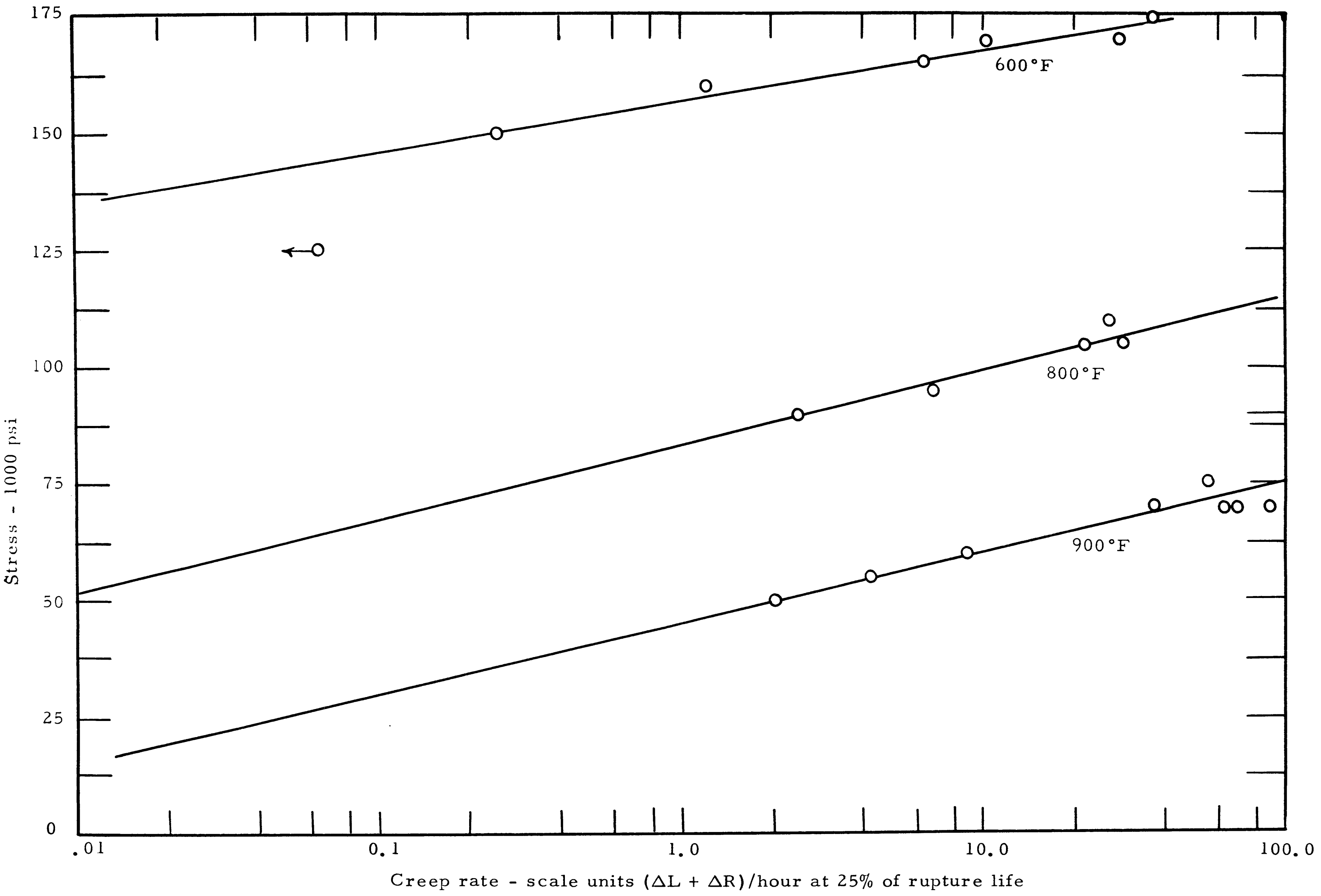


Figure 14. - Stress Versus Relative Creep Rate at 600°, 800°, 900°F for 17-7PH Alloy in TH 1050 Condition

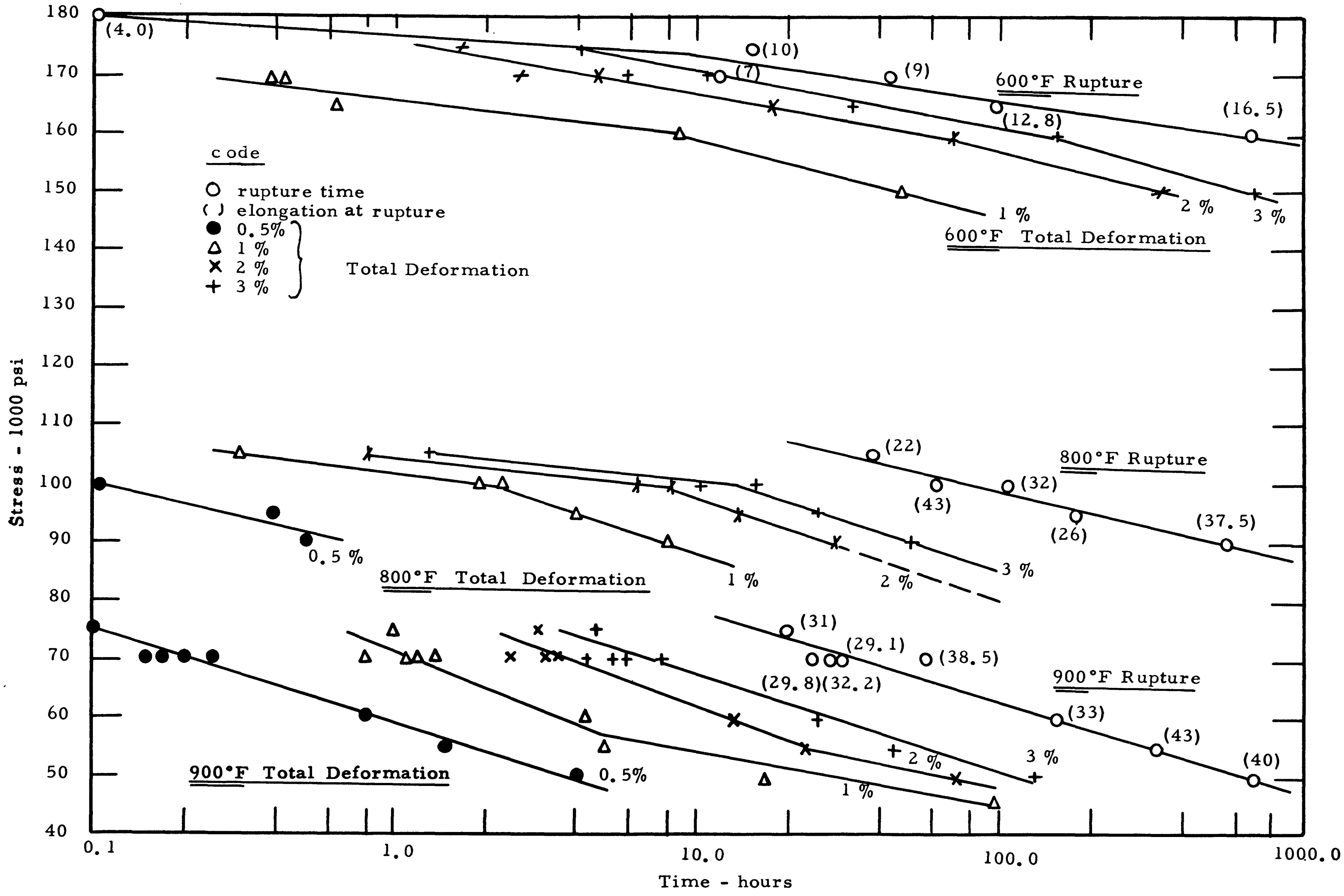


Figure 15. - Time for Rupture and Specified Total Deformations Versus Stress for 17-7PH Alloy in TH 1050 Condition

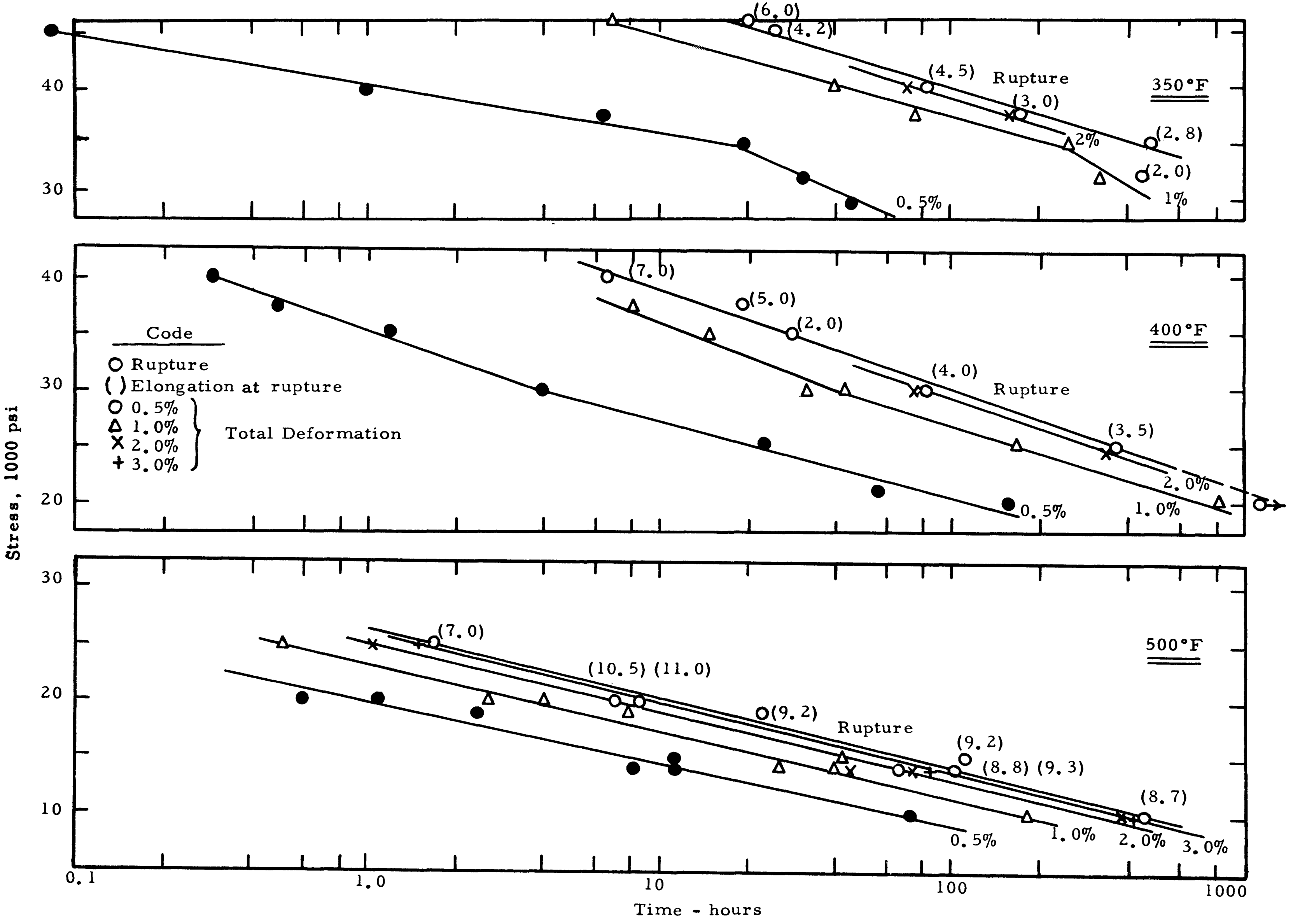


Figure 16 - Stress Versus Time for Rupture and Specified Total Deformations for 2024-T86 Aluminum Alloy at 350°, 400°, 500°F. **(Original Survey Data).**

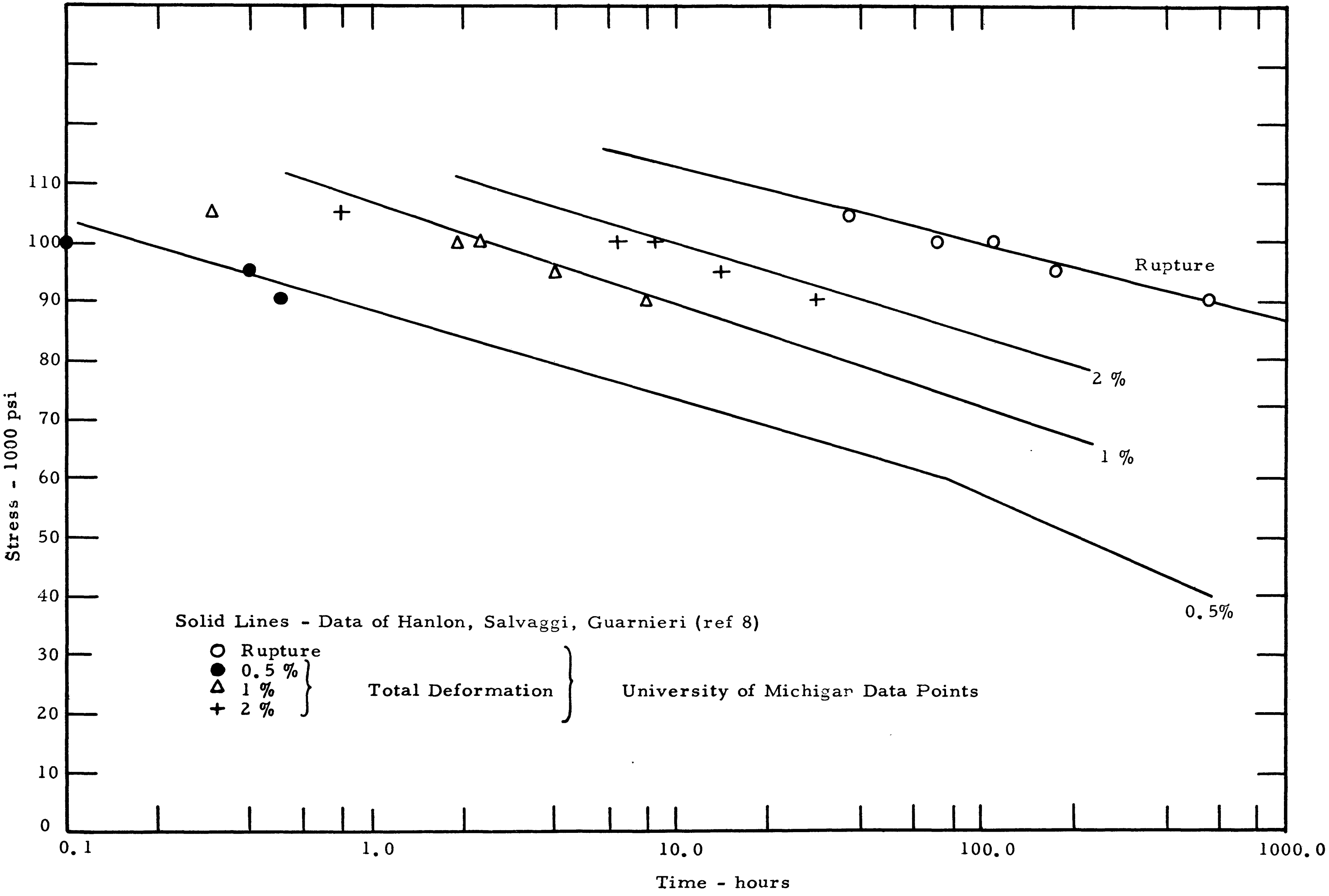
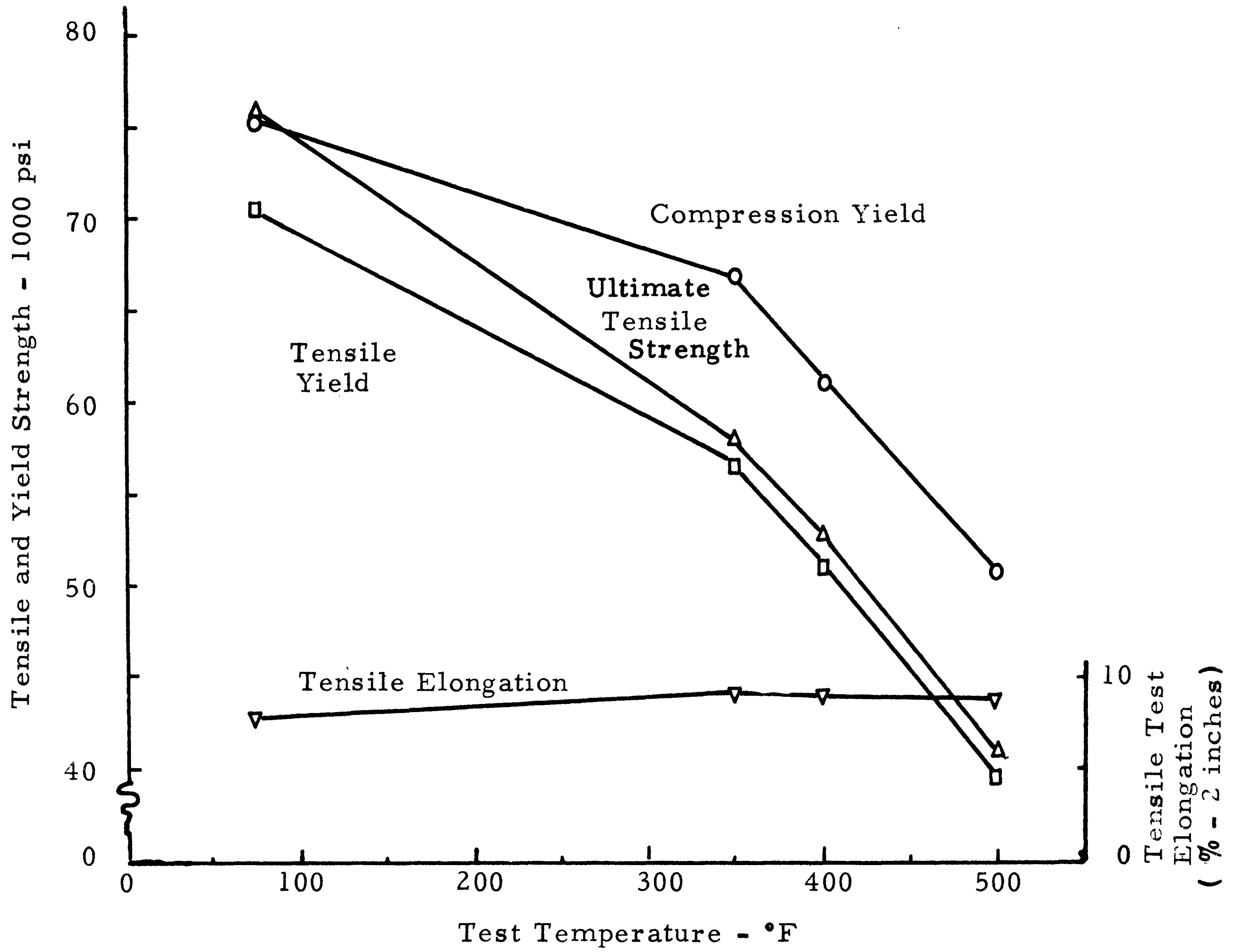


Figure 17. - Comparison of University of Michigan Data Points with Rupture and Total Deformation Curves of Hanlon, Et Al for 17-7PH at 800°F



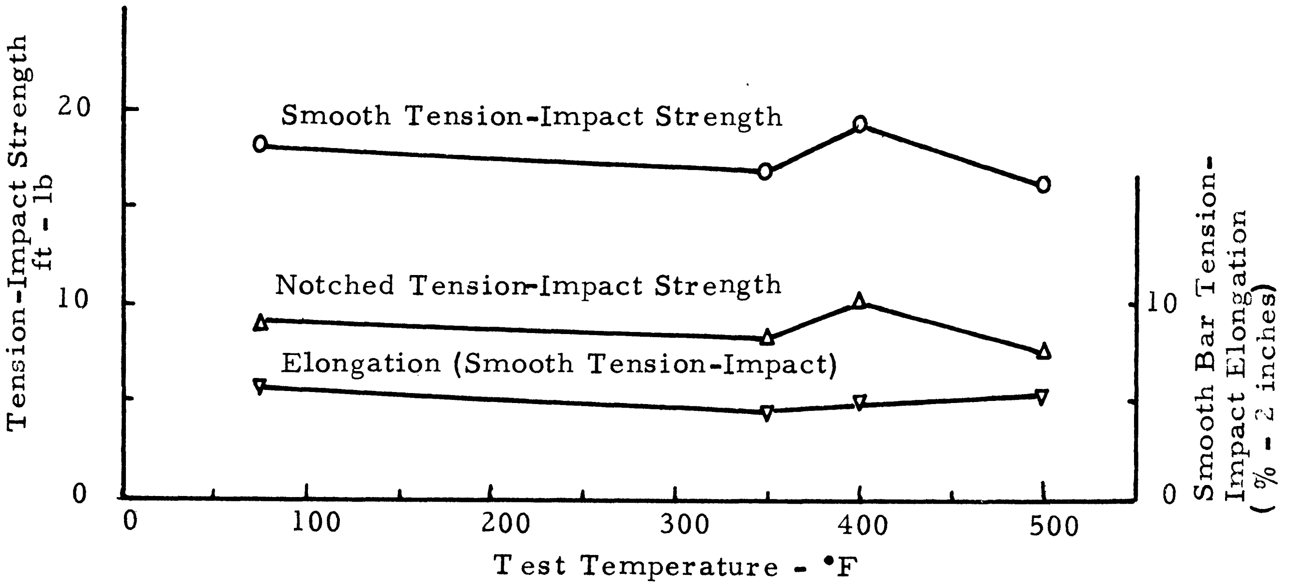


Figure 18. - Effect of Temperature on Short-Time Properties of As-Received 2024-T86 Aluminum Alloy.

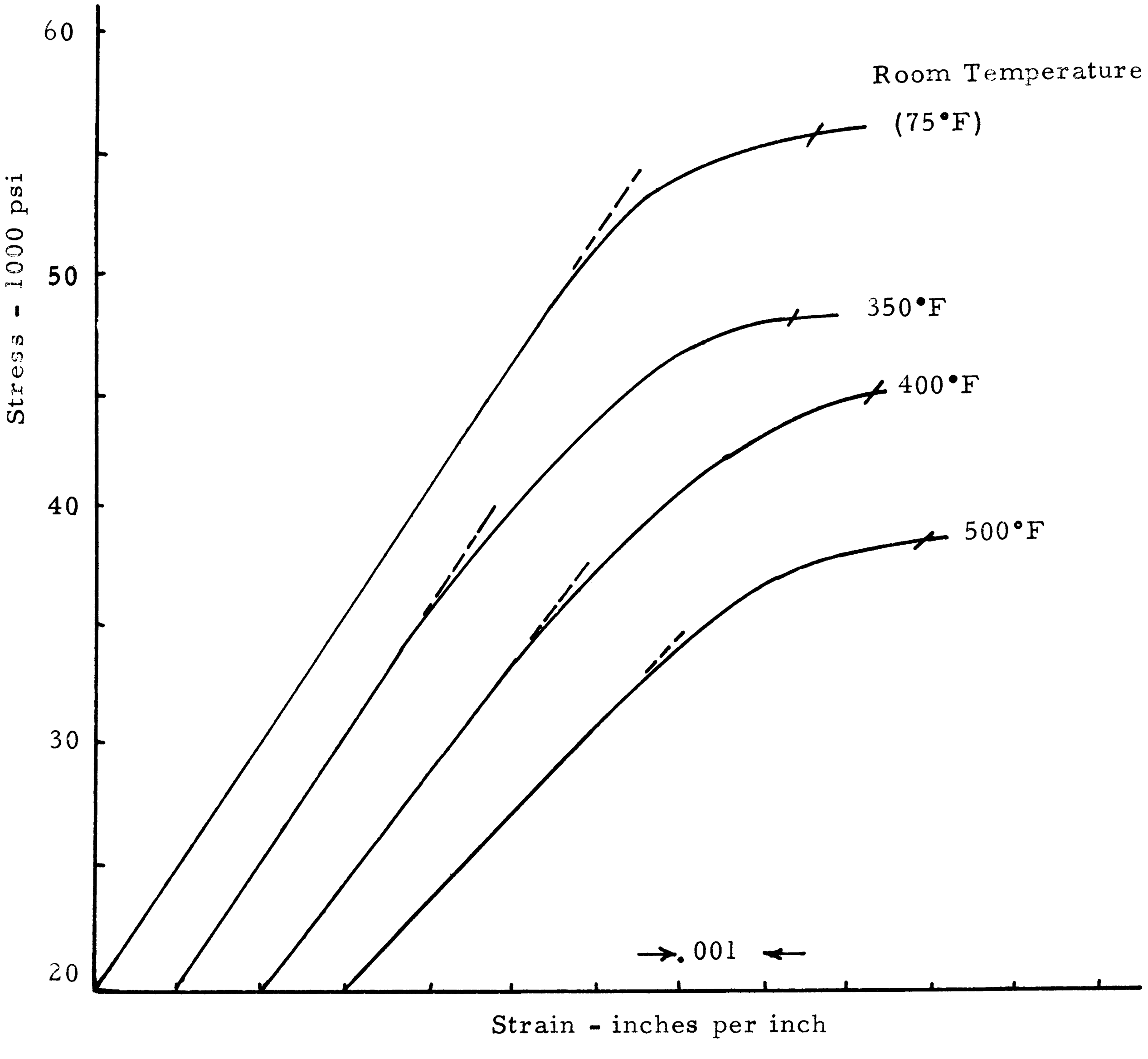


Figure 19. - Representative Tensile Test Stress-Strain Curves for As Received 2024-T86

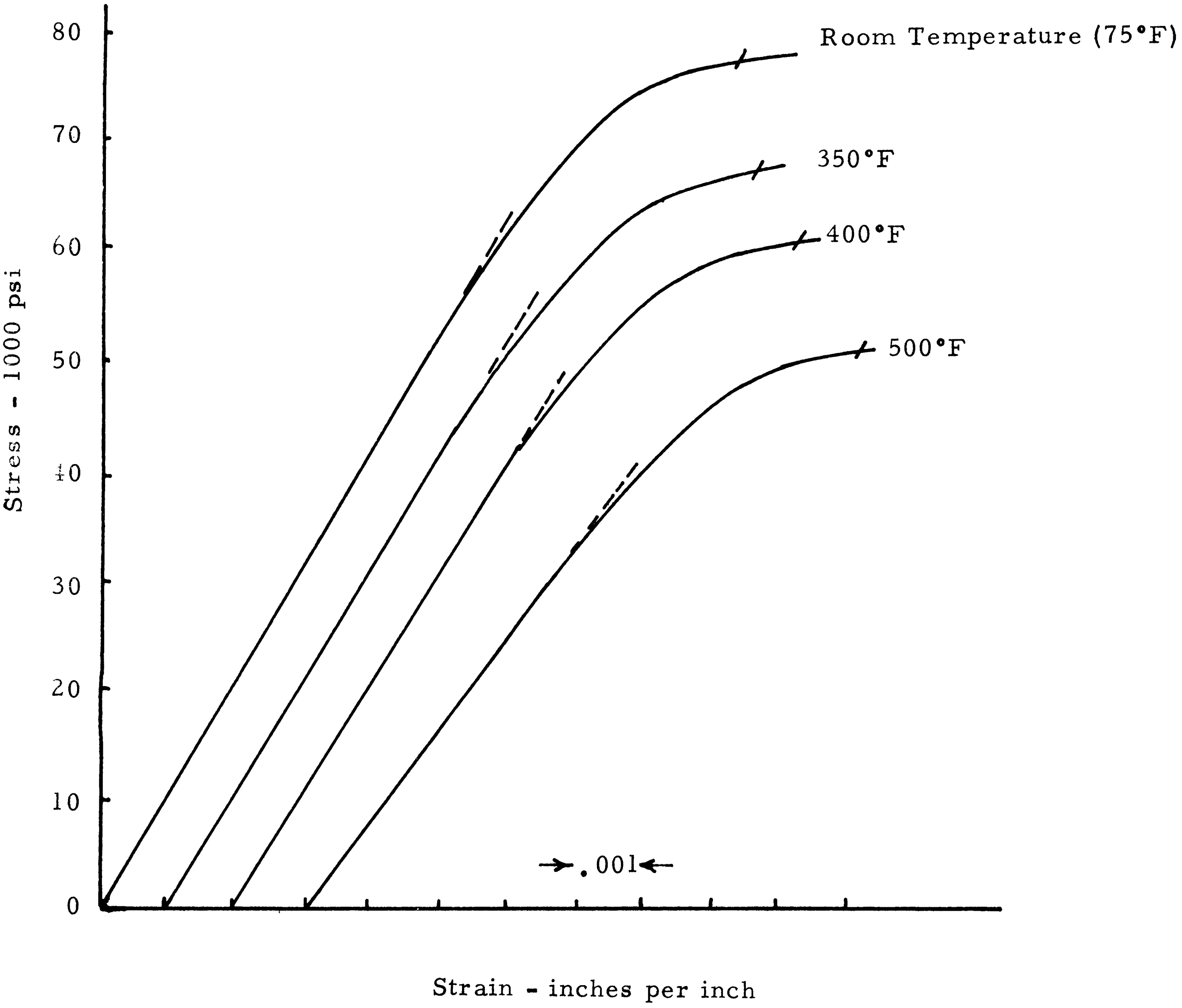
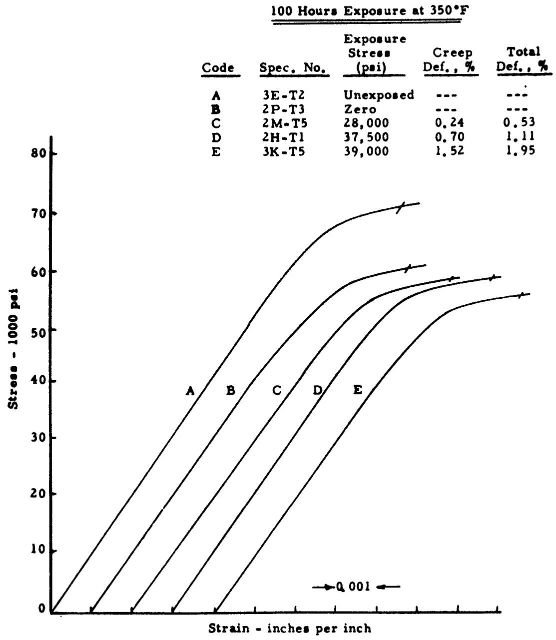
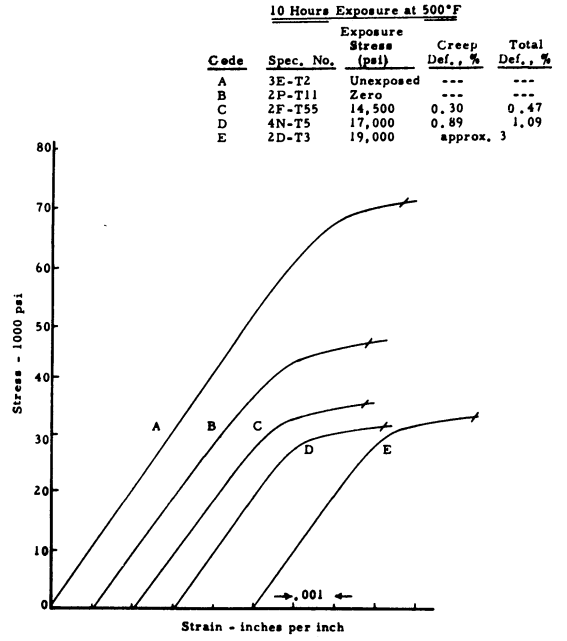


Figure 20. - Representative Compression Test Stress-Strain Curves for As Received 2024-T86



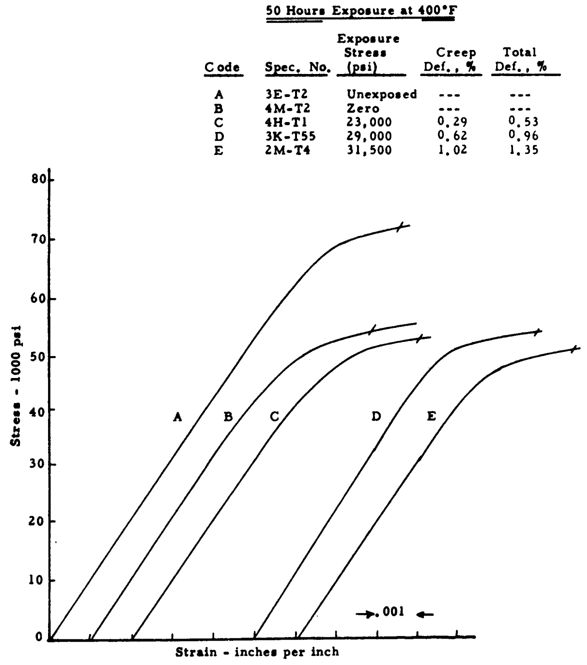
100 Hours Exposure at 350°F

Code	Spec. No.	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	3E-T2	Unexposed	---	---
B	2P-T3	Zero	---	---
C	2M-T5	28,000	0.24	0.53
D	2H-T1	37,500	0.70	1.11
E	3K-T5	39,000	1.52	1.95



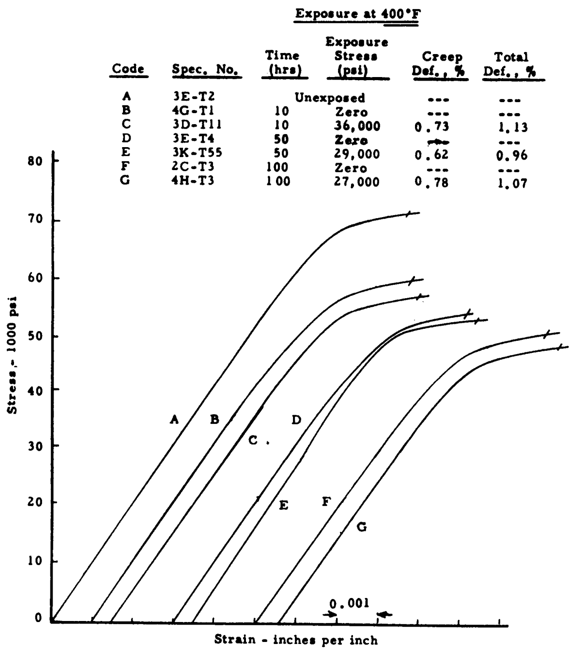
10 Hours Exposure at 500°F

Code	Spec. No.	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	3E-T2	Unexposed	---	---
B	2P-T11	Zero	---	---
C	2F-T55	14,500	0.30	0.47
D	4N-T5	17,000	0.89	1.09
E	2D-T3	19,000	approx. 3	



50 Hours Exposure at 400°F

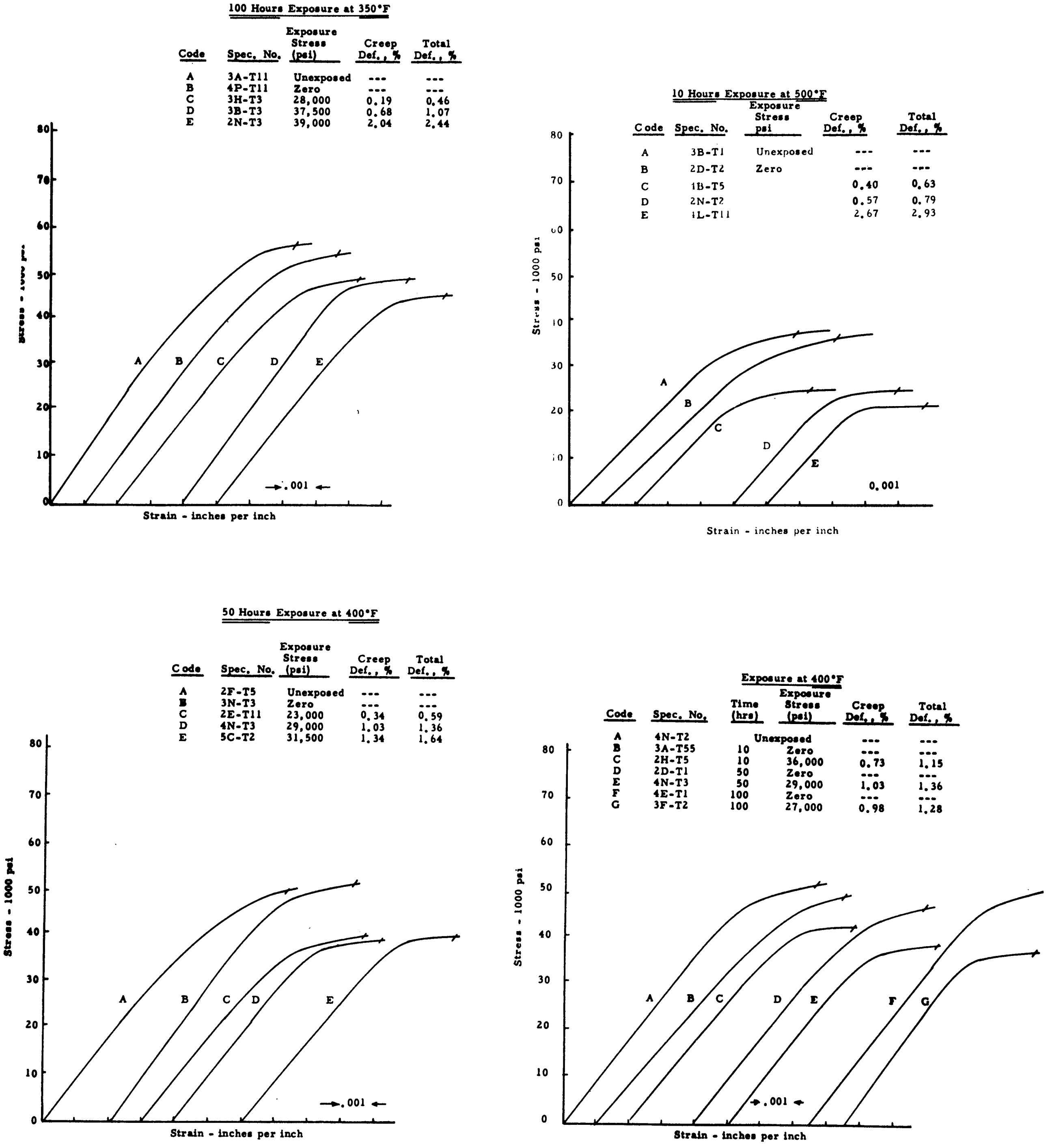
Code	Spec. No.	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	3E-T2	Unexposed	---	---
B	4M-T2	Zero	---	---
C	4H-T1	23,000	0.29	0.53
D	3K-T55	29,000	0.62	0.96
E	2M-T4	31,500	1.02	1.35



Exposure at 400°F

Code	Spec. No.	Time (hrs)	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	3E-T2	Unexposed		---	---
B	4G-T1	10	Zero	---	---
C	3D-T11	10	36,000	0.73	1.13
D	3E-T4	50	Zero	---	---
E	3K-T55	50	29,000	0.62	0.96
F	2C-T3	100	Zero	---	---
G	4H-T3	100	27,000	0.78	1.07

Figure 21. - Representative Stress-Strain Curves in Tension at Room Temperature for 2024-T86 Alloy after Exposure to Various Amounts of Prior Creep at 350°, 400°, or 500°F



100 Hours Exposure at 350°F

Code	Spec. No.	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	3A-T11	Unexposed	---	---
B	4P-T11	Zero	---	---
C	3H-T3	28,000	0.19	0.46
D	3B-T3	37,500	0.68	1.07
E	2N-T3	39,000	2.04	2.44

10 Hours Exposure at 500°F

Code	Spec. No.	Exposure Stress psi	Creep Def., %	Total Def., %
A	3B-T1	Unexposed	---	---
B	2D-T2	Zero	---	---
C	1B-T5		0.40	0.63
D	2N-T2		0.57	0.79
E	1L-T11		2.67	2.93

50 Hours Exposure at 400°F

Code	Spec. No.	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	2F-T5	Unexposed	---	---
B	3N-T3	Zero	---	---
C	2E-T11	23,000	0.34	0.59
D	4N-T3	29,000	1.03	1.36
E	5C-T2	31,500	1.34	1.64

Exposure at 400°F

Code	Spec. No.	Time (hrs)	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	4N-T2		Unexposed	---	---
B	3A-T55	10	Zero	---	---
C	2H-T5	10	36,000	0.73	1.15
D	2D-T1	50	Zero	---	---
E	4N-T3	50	29,000	1.03	1.36
F	4E-T1	100	Zero	---	---
G	3F-T2	100	27,000	0.98	1.28

Figure 22. - Representative Stress-Strain Curves in Tension at 350°, 400°, or 500°F after Prior Exposure to Various Amounts of Creep at the Same Temperature

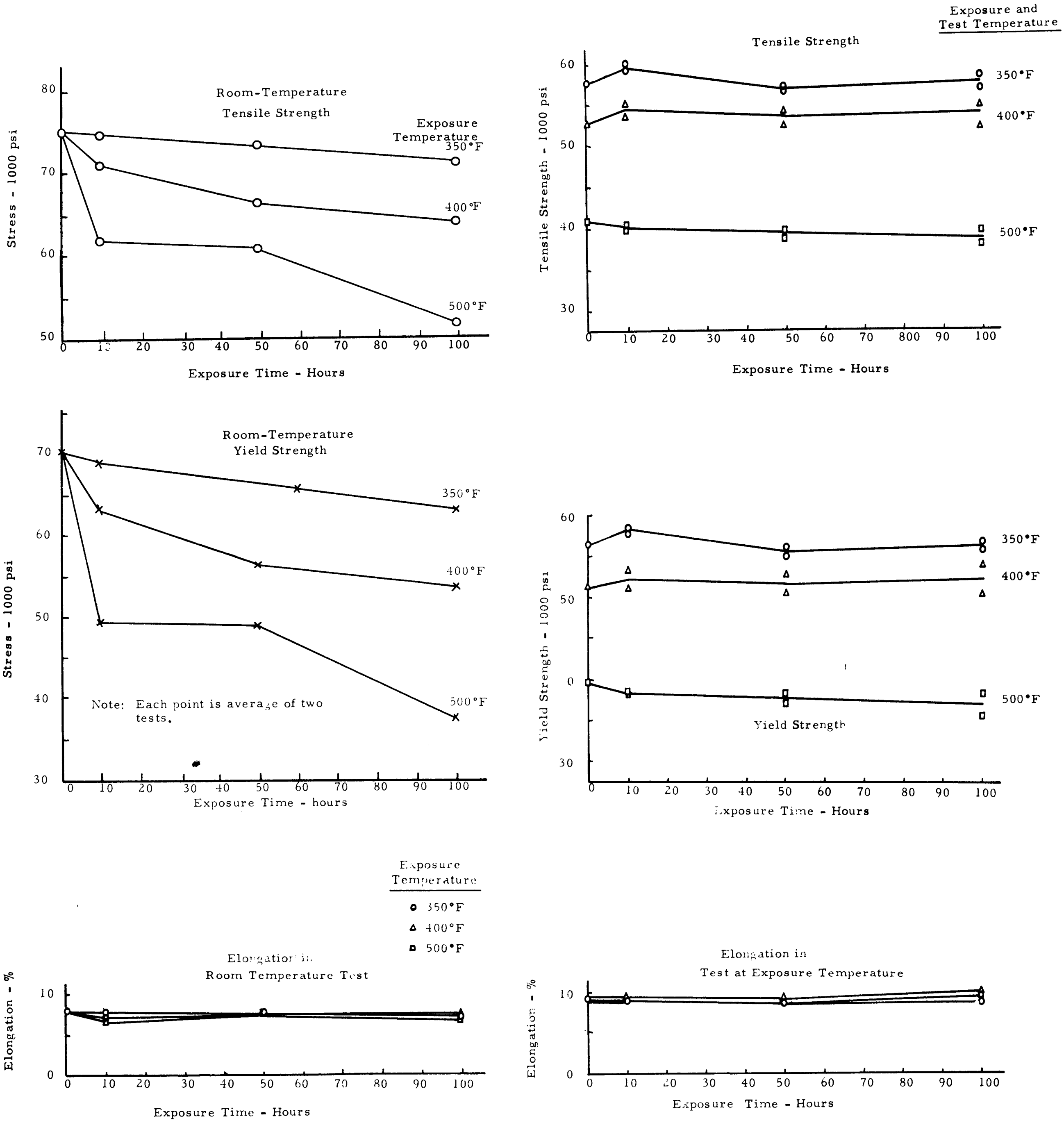


Figure 23. - Effect of Prior Unstressed Exposures of 2024-T86 on Tensile Properties at Room Temperature and at the Temperature of Exposure

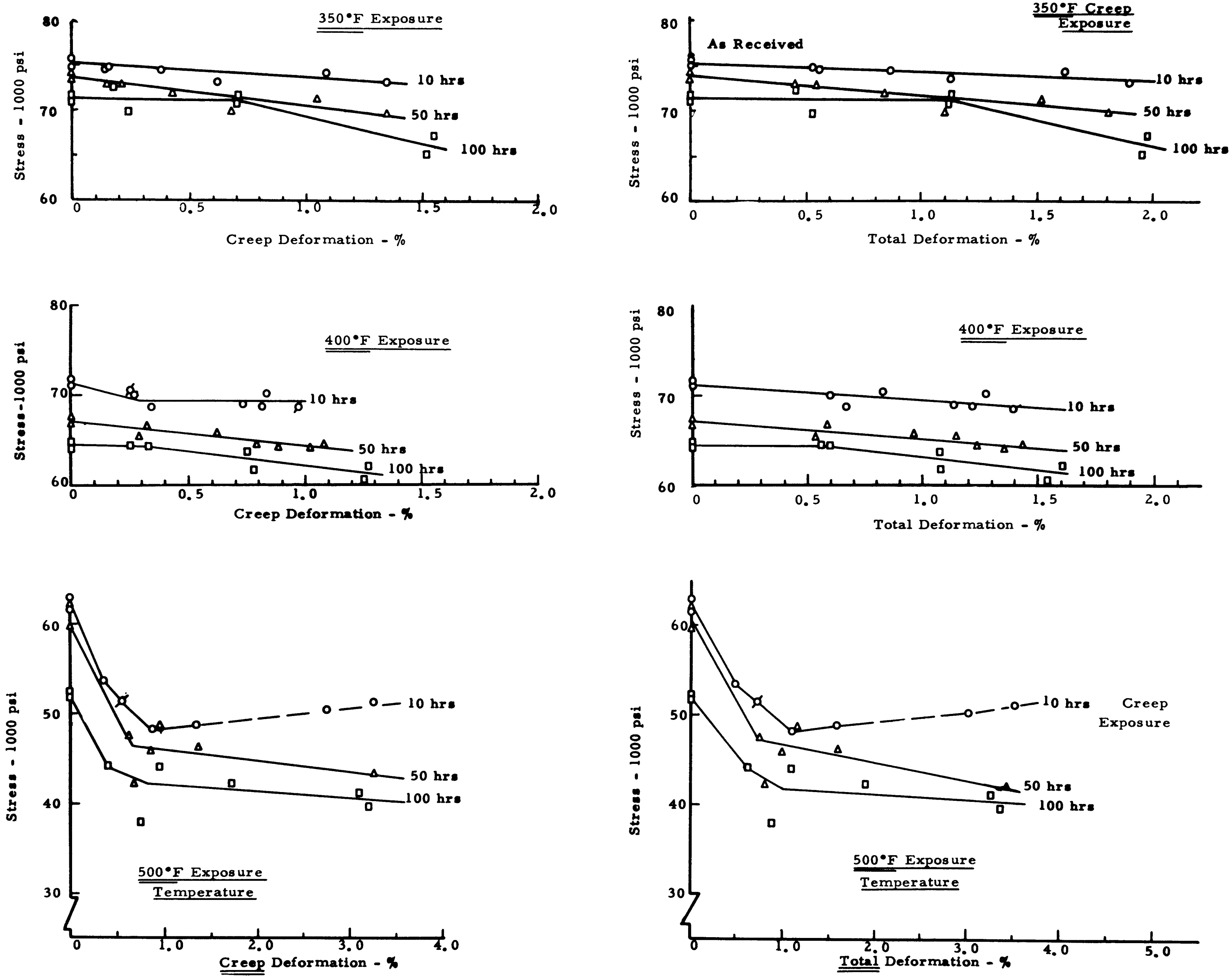


Figure 24. - Room-Temperature Tensile Strength of 2024-T86 Alloy after Prior Creep at 350°, 400°, or 500°F

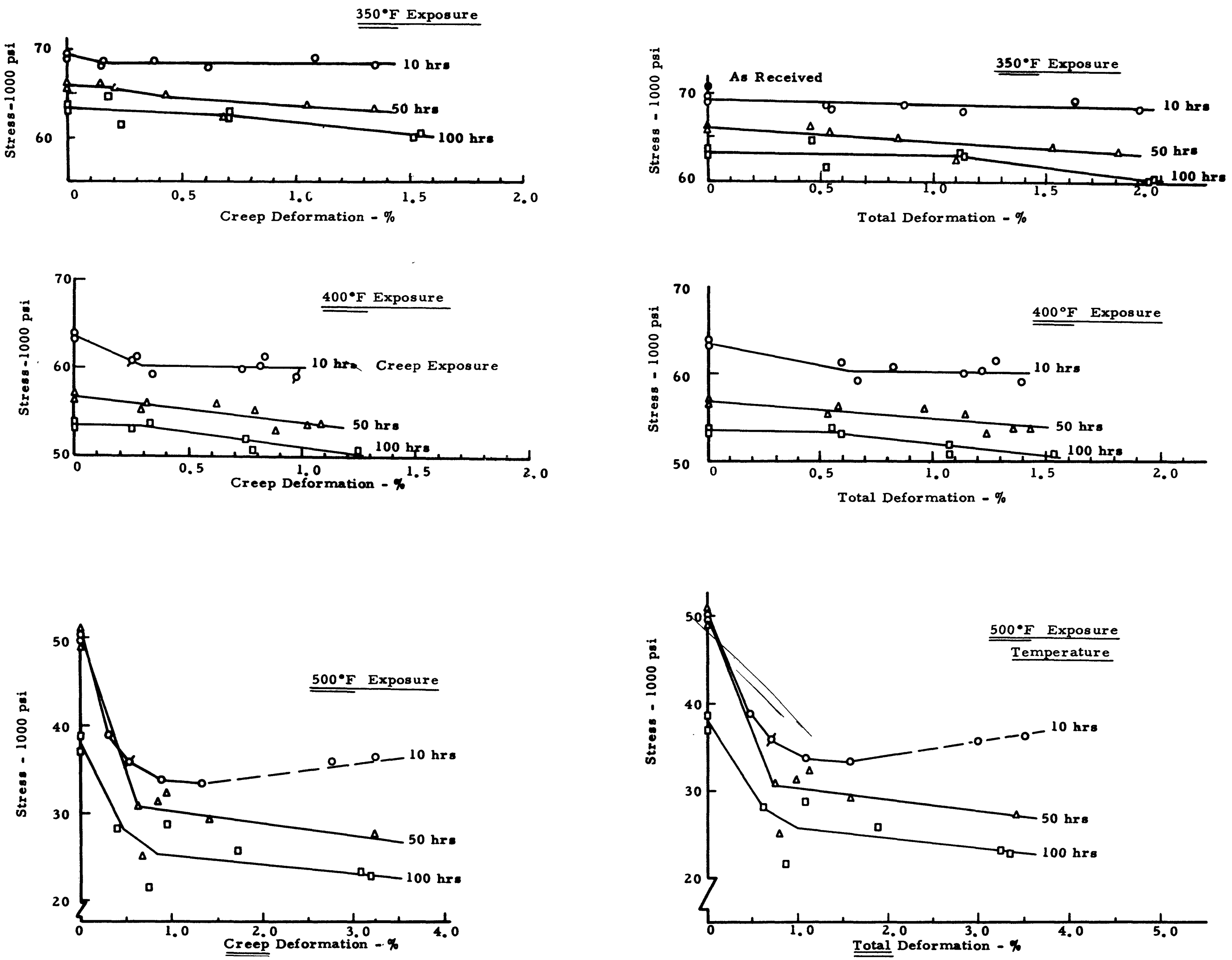


Figure 25. - Room-Temperature Tension Yield Strength of 2024-T86 Alloy after Prior Creep at 350°, 400°, or 500°F

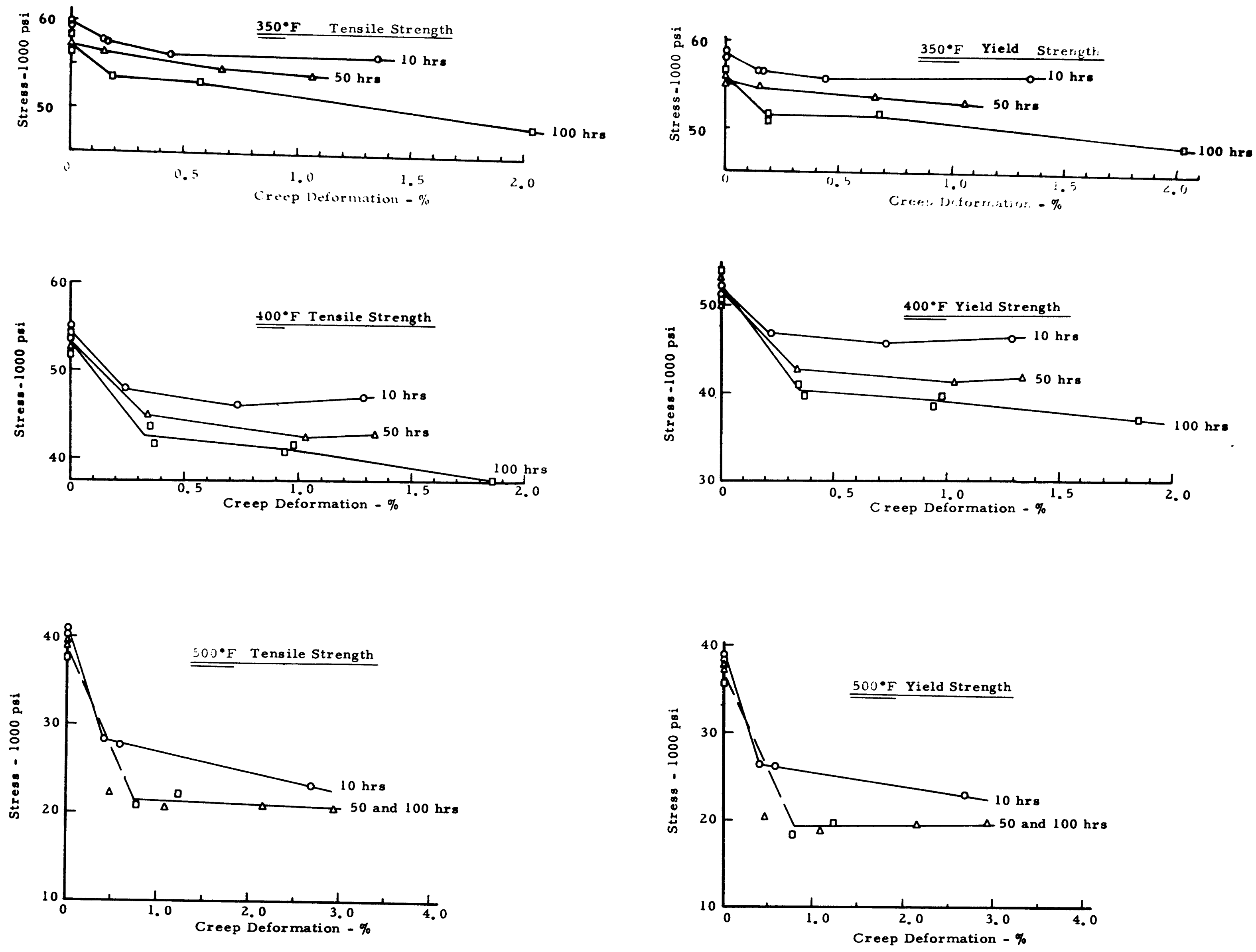


Figure 26. - Tensile Strength and Tension Yield Strength of 2024-T86 Alloy at Exposure Temperature after Prior Creep for 10, 50, or 100 Hours at 350°, 400°, or 500°F

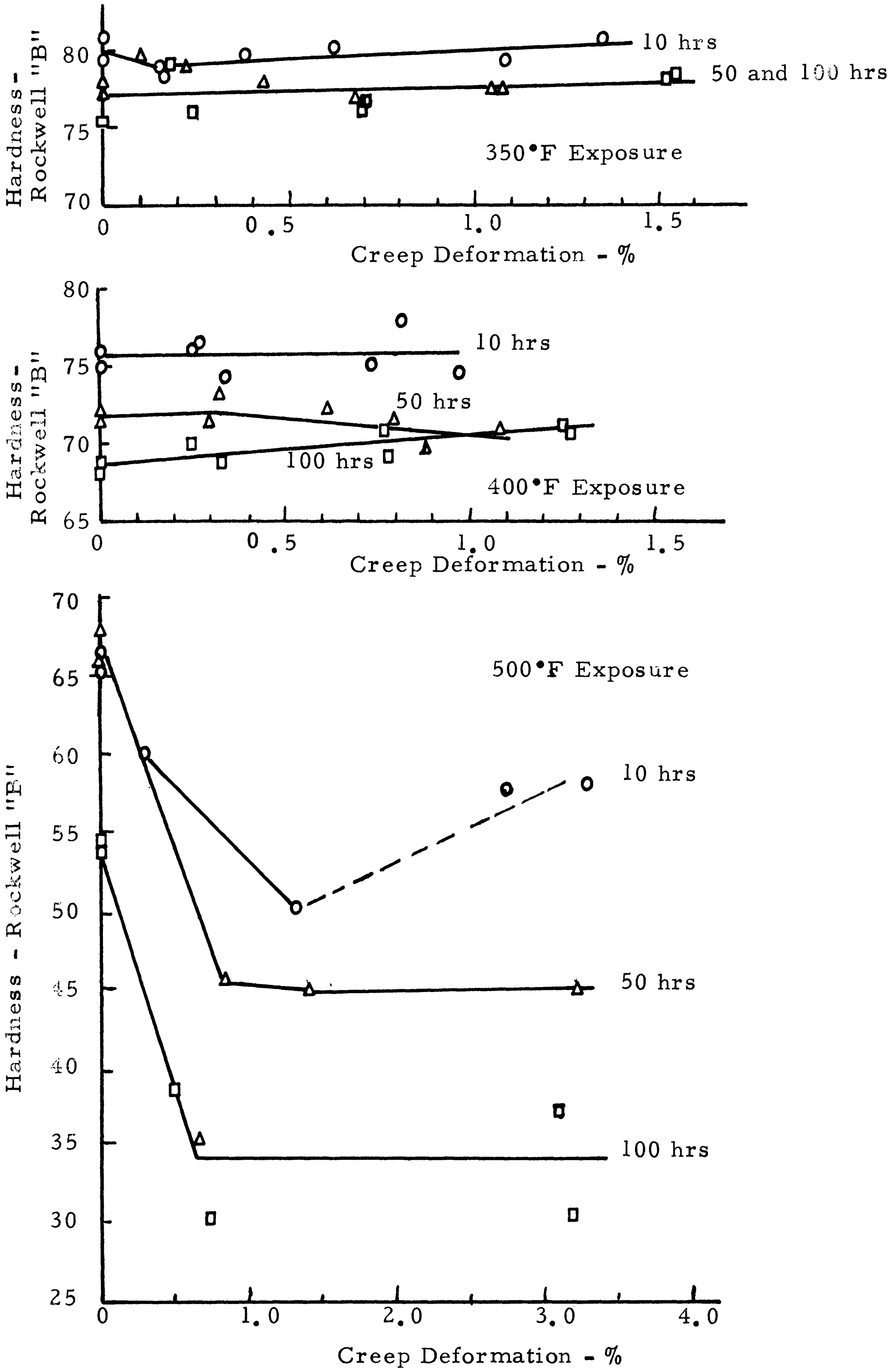


Figure 27. - Effect of Prior Creep Deformation for 10, 50, or 100 Hours at 350°, 400°, or 500°F on the Rockwell "B" Hardness of 2024-T86 Aluminum Alloy

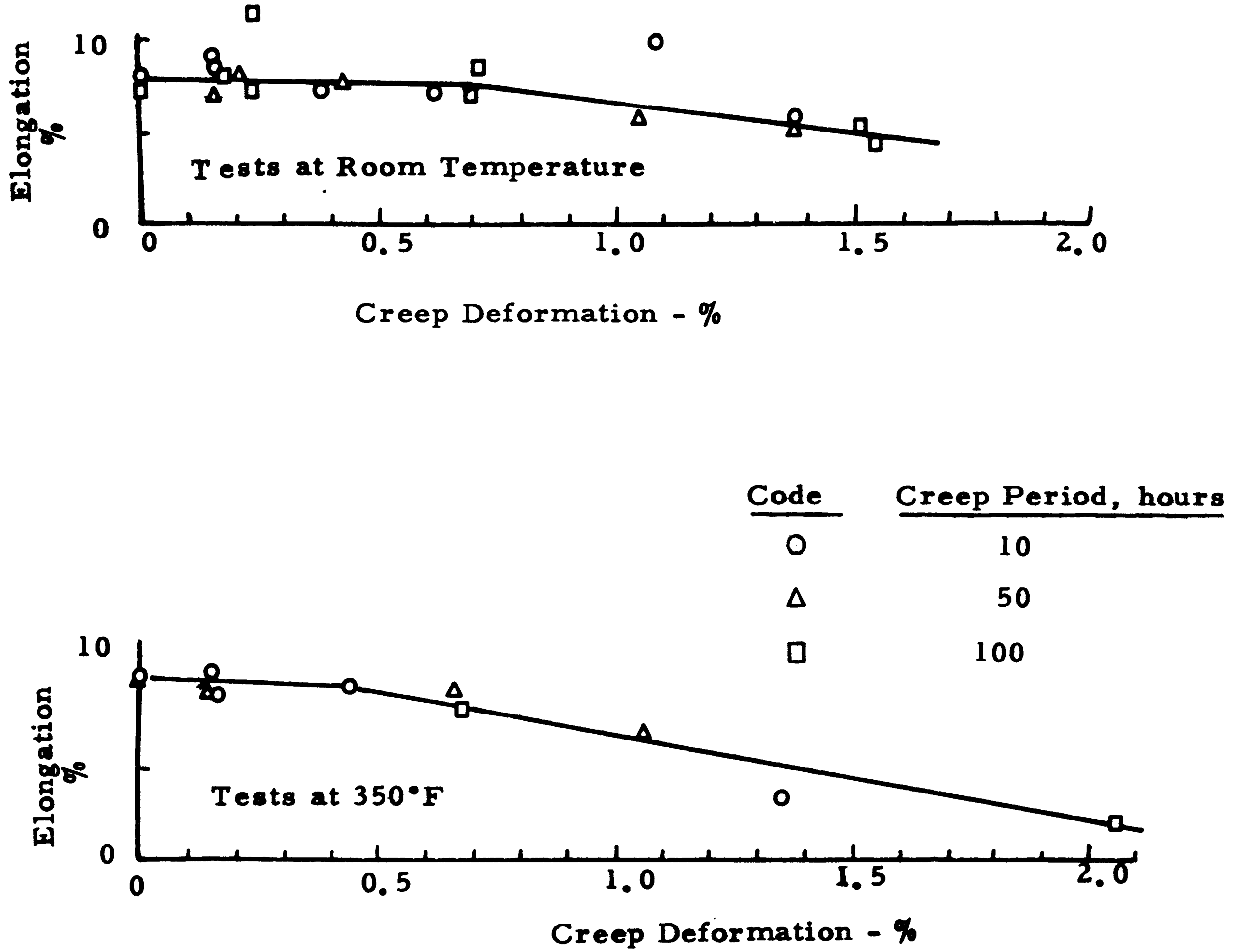


Figure 28. - Elongation of 2024-T86 in Tensile Tests at Room Temperature and at 350°F after Prior Creep at 350°F for 10, 50, or 100 Hours.

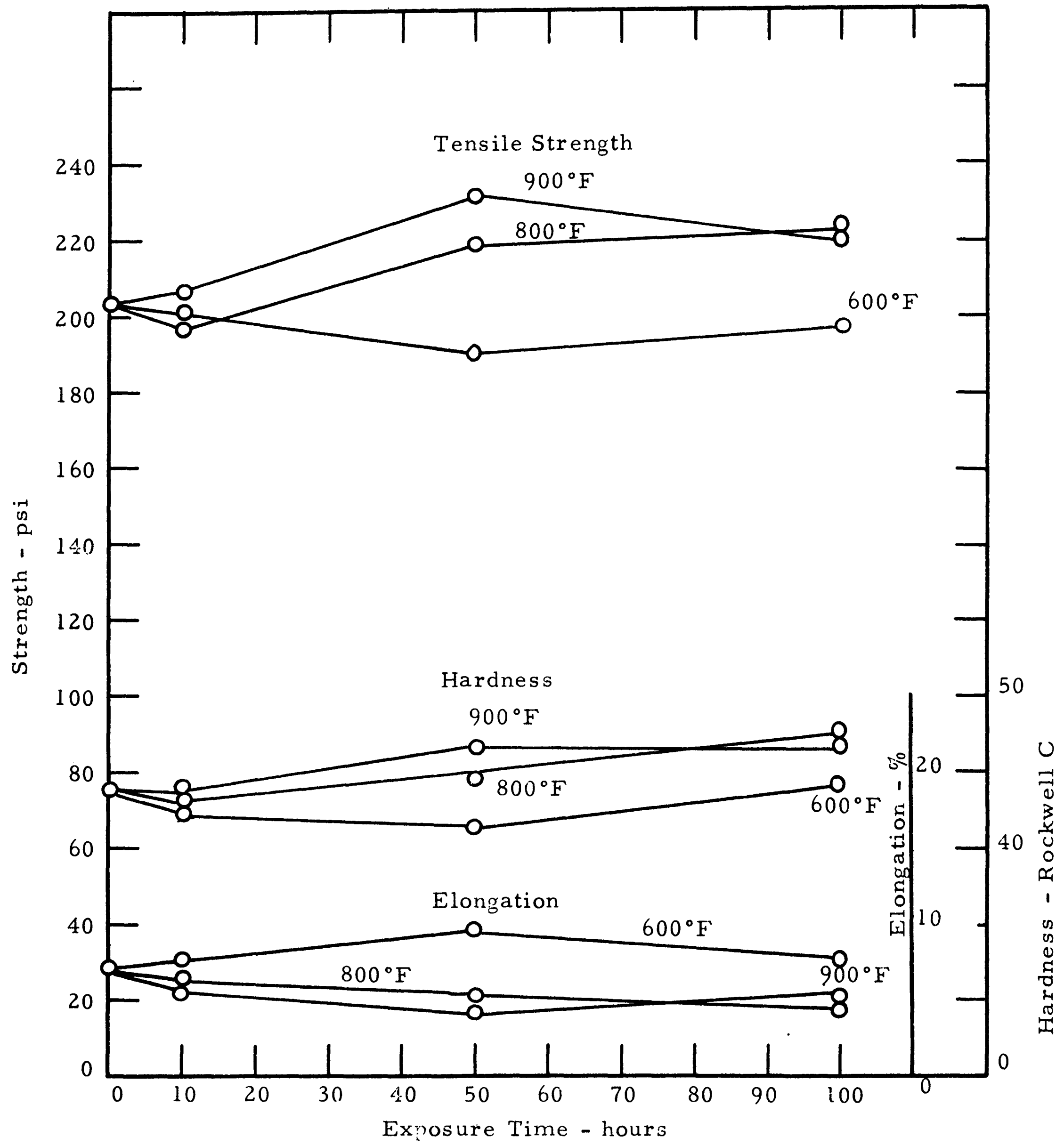


Figure 29. - Effect of Unstressed Exposure at Indicated Conditions on Tensile Strength, Elongation, and Hardness of 17-7PH Alloy in TH 1050 Condition

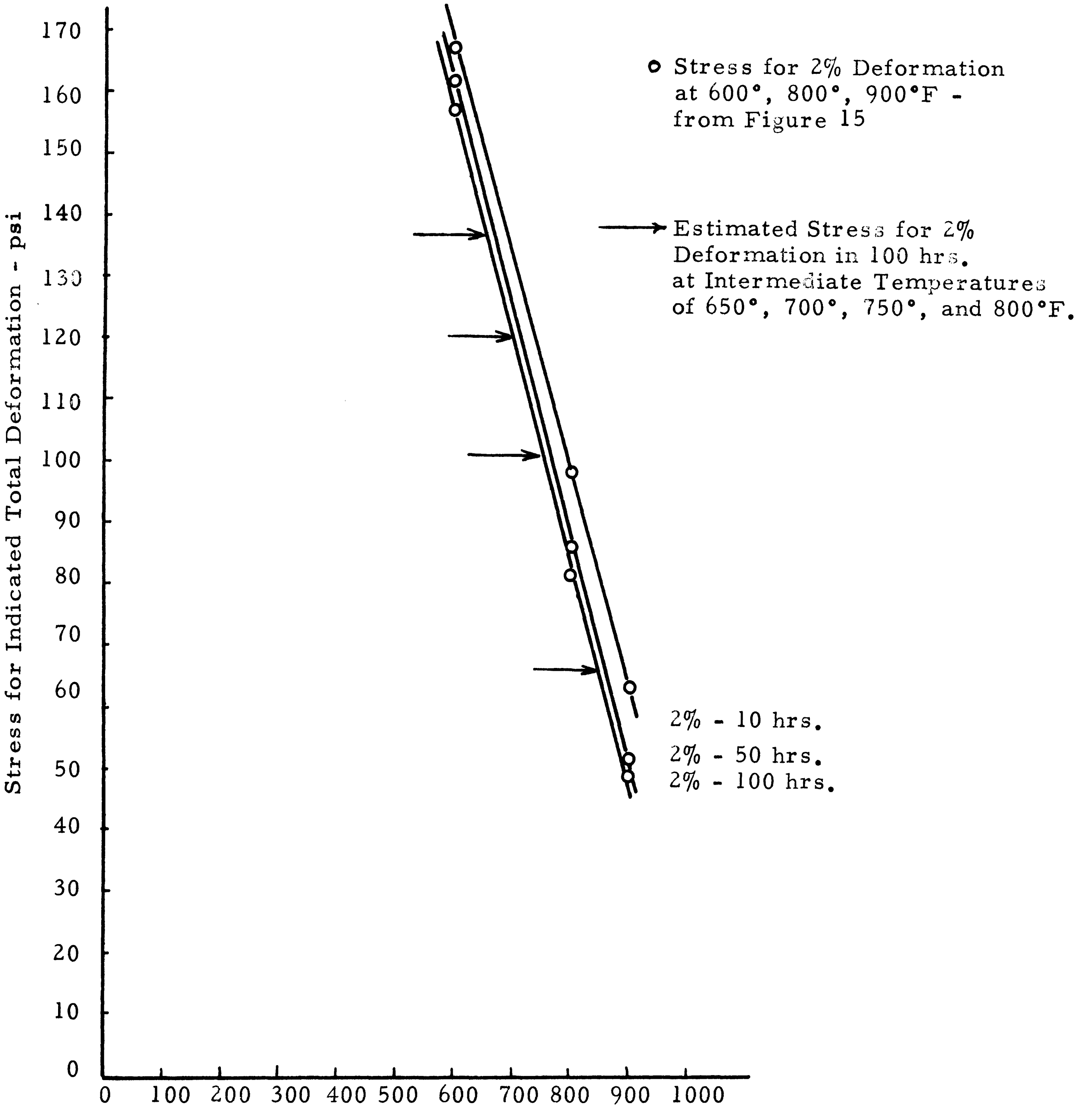


Figure 30. - Stress for 2% Total Deformation in Various Time Periods Versus Test Temperature for 17-7PH Alloy (TH 1050 Condition)

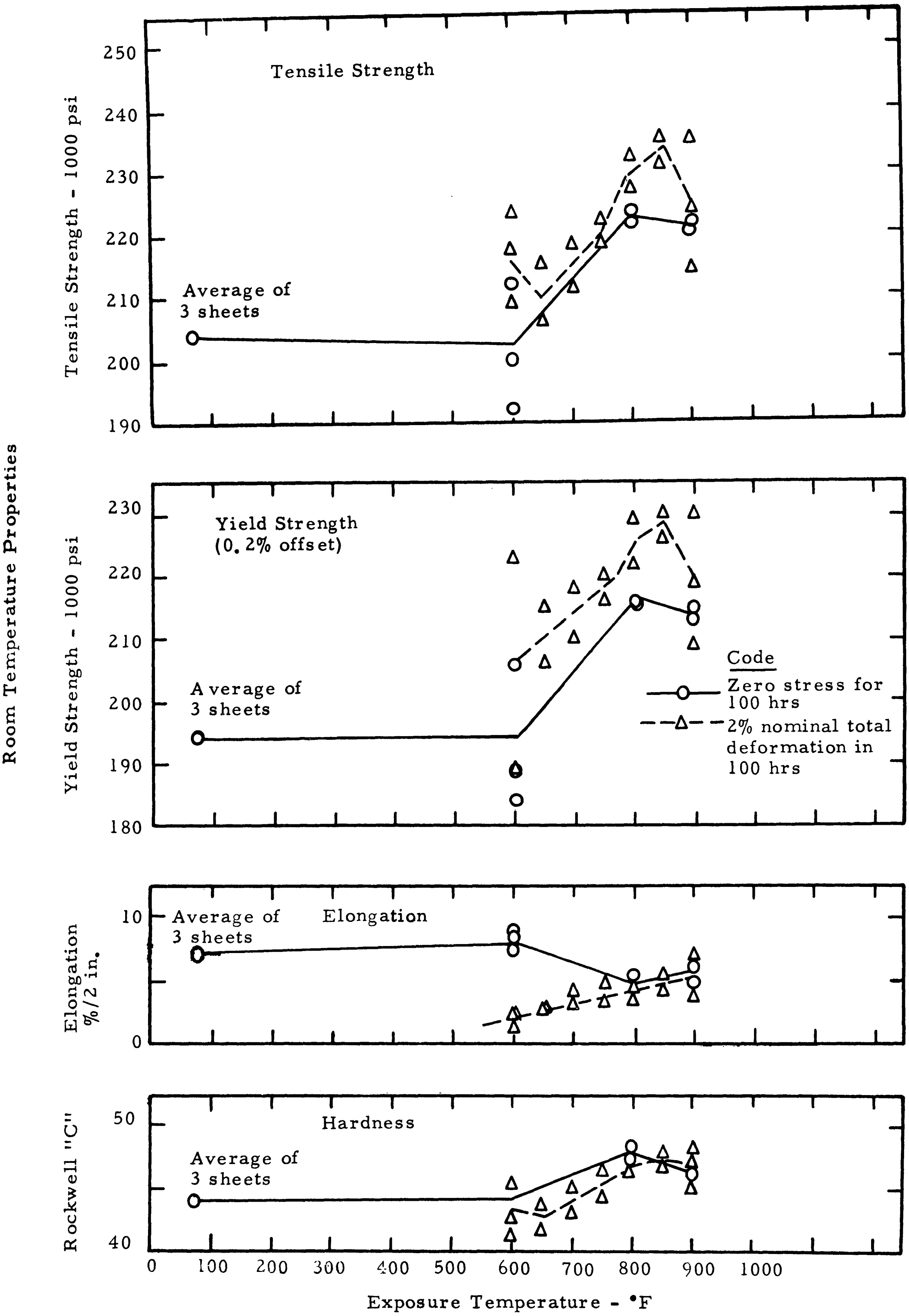


Figure 31.- Effects of 100 Hours Unstressed Exposure or 100 Hours Stressed Exposure to 2% Total Deformation at Indicated Temperatures on Room Temperature Tensile Properties of 17-7PH Alloy (TH 1050 Condition).

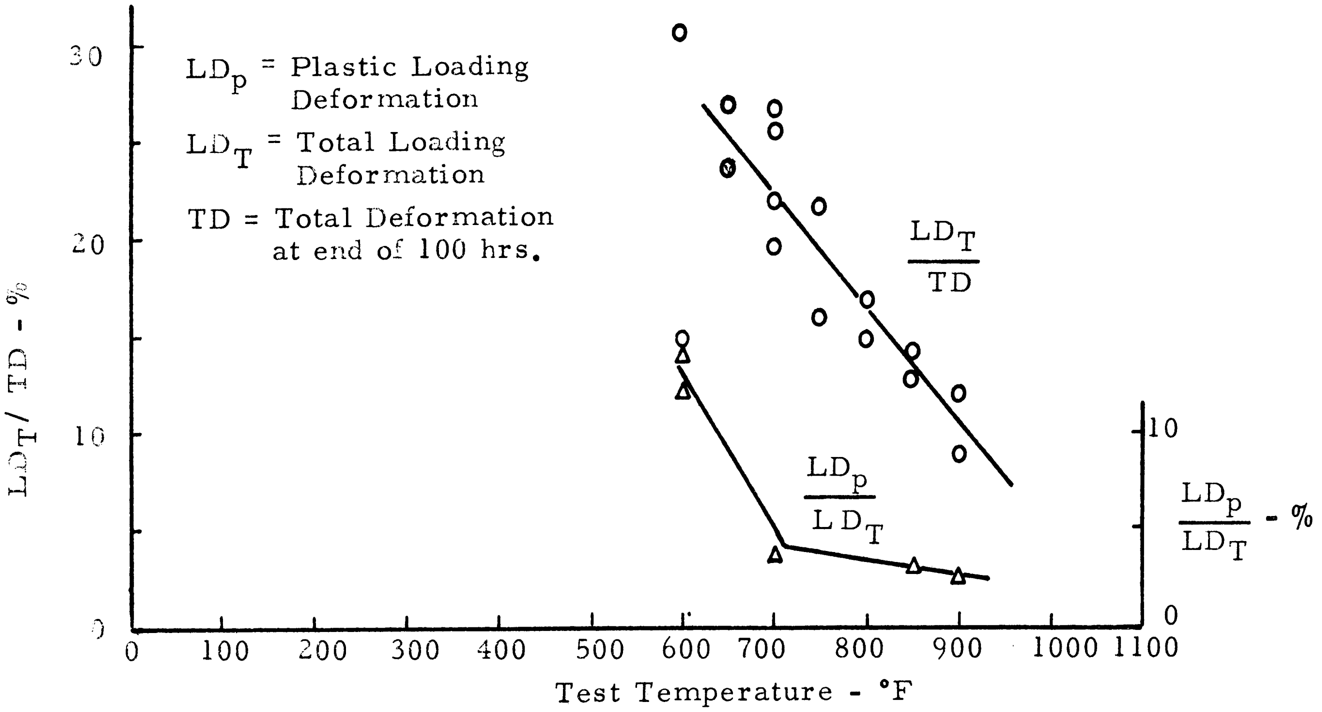
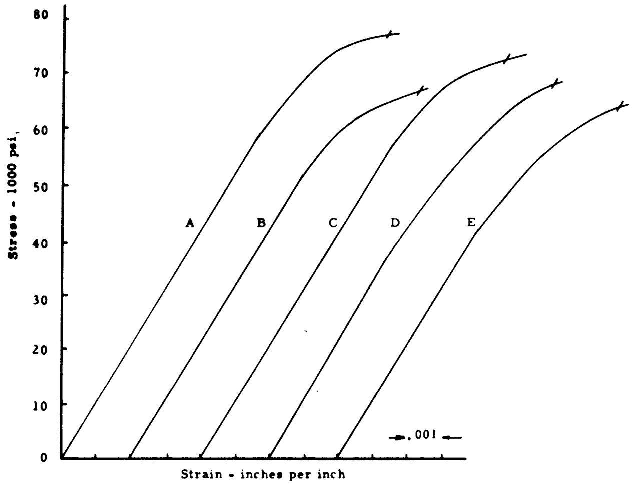


Figure 32. - Proportion of Total Loading Deformation or Plastic Loading Deformation to Total Deformation for 17-7PH (TH 1050) Stressed to 2% Nominal Total Deformation in 100 Hours at Indicated Temperature.

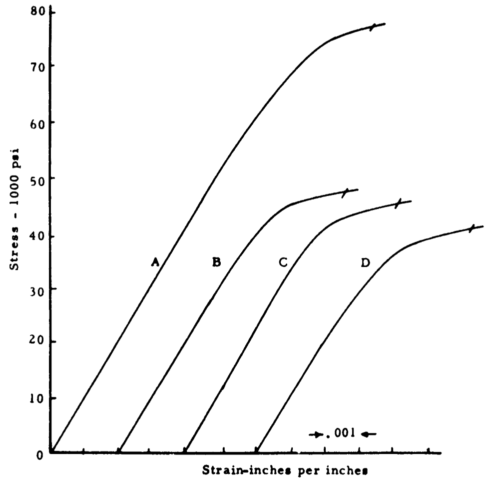
100 Hours at 350°F

Code	Spec. No.	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	2C-C3	Unexposed	---	---
B	2J-X44	Zero	---	---
C	3N-T2	28,000	0.23	0.45
D	3F-T11	37,500	0.57	0.97
E	4F-T1	39,000	1.35	1.77



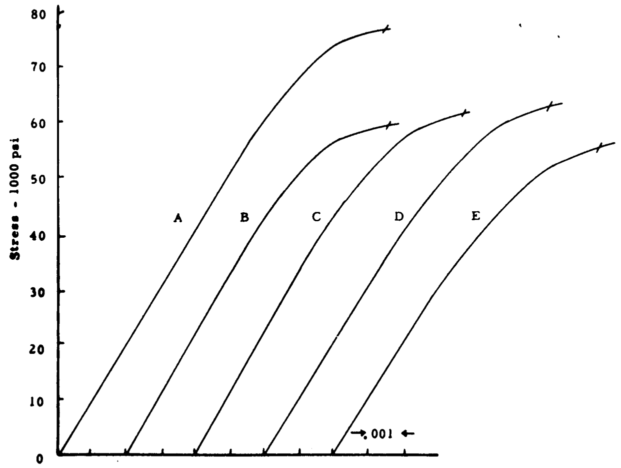
10 Hours Exposure at 500°F

Code	Spec. No.	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	2C-C3	Unexposed	---	---
B	2J-X2	Zero	---	---
C	4D-T2	14,500	0.41	0.60
D	5M-T1	19,000	1.26	1.51



50 Hours Exposure at 400°F

Code	Spec. No.	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	2C-C3	Unexposed	---	---
B	4G-X2	Zero	---	---
C	4E-T5	23,000	0.30	0.55
D	3B-T4	29,000	0.47	0.76
E	3M-T1	31,500	1.20	1.54



Exposure at 400°F

Code	Spec. No.	Time (hrs)	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	2C-C3	Unexposed		---	---
B	3L-X33	10	Zero	---	---
C	2H-T55	10	36,000	0.82	1.23
D	2P-X44	50	Zero	---	---
E	3B-T4	50	29,000	0.47	0.76
F	4A-X33	100	Zero	---	---
G	2K-T1	100	27,000	1.07	1.35

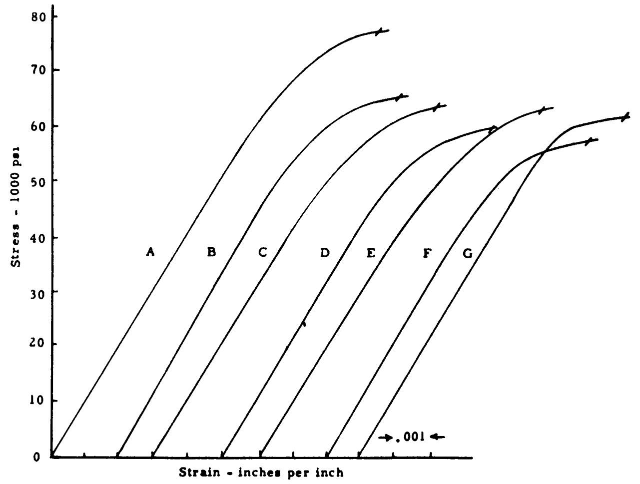
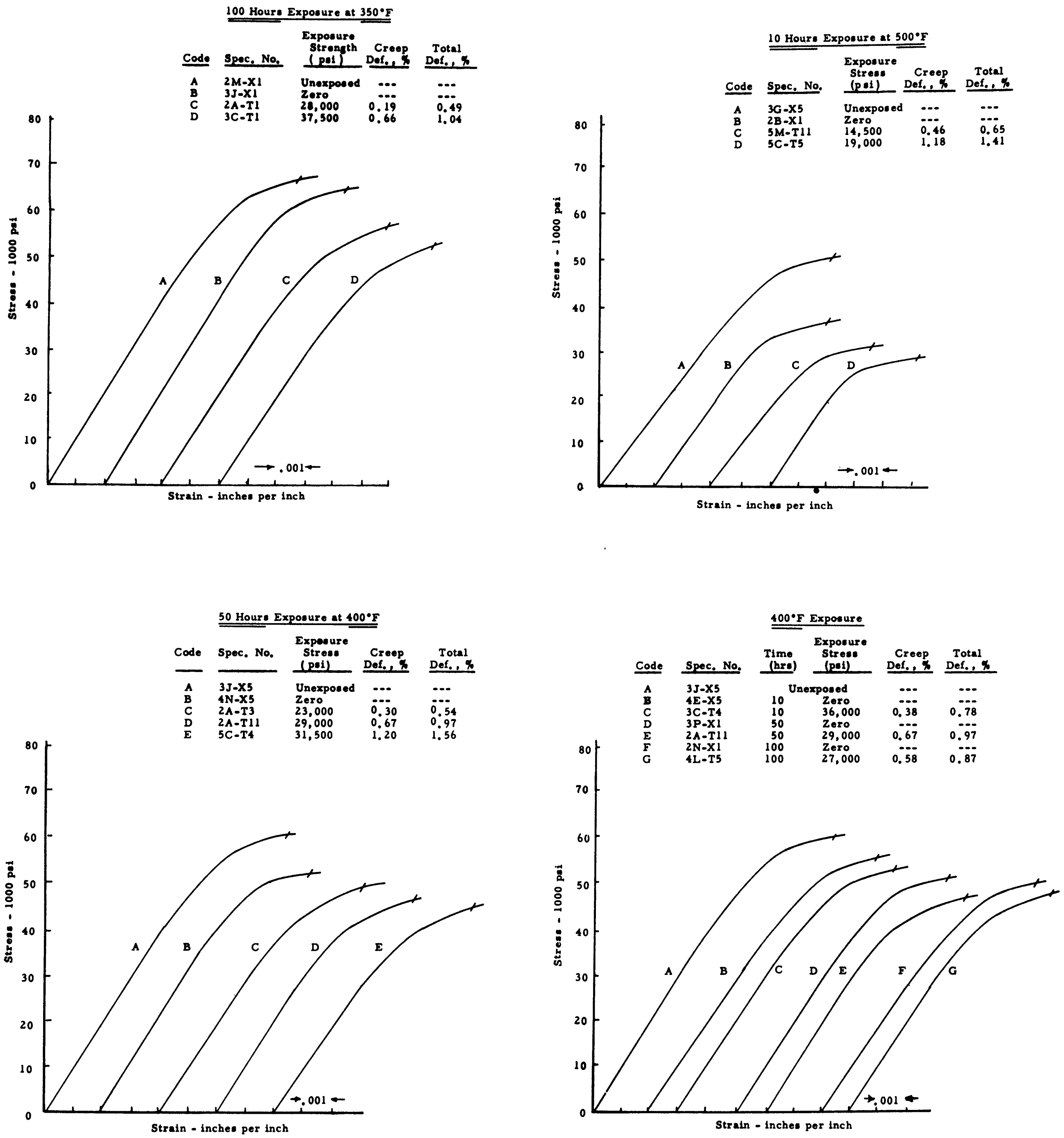


Figure 33. - Representative Stress-Strain Curves in Compression at Room Temperature for 2024-T86 Alloy after Exposure to Various Amounts of Prior Creep at 350°, 400°, or 500°F



100 Hours Exposure at 350°F

Code	Spec. No.	Exposure Strength (psi)	Creep Def., %	Total Def., %
A	2M-X1	Unexposed	---	---
B	3J-X1	Zero	---	---
C	2A-T1	28,000	0.19	0.49
D	3C-T1	37,500	0.66	1.04

10 Hours Exposure at 500°F

Code	Spec. No.	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	3G-X5	Unexposed	---	---
B	2B-X1	Zero	---	---
C	5M-T11	14,500	0.46	0.65
D	5C-T5	19,000	1.18	1.41

50 Hours Exposure at 400°F

Code	Spec. No.	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	3J-X5	Unexposed	---	---
B	4N-X5	Zero	---	---
C	2A-T3	23,000	0.30	0.54
D	2A-T11	29,000	0.67	0.97
E	5C-T4	31,500	1.20	1.56

400°F Exposure

Code	Spec. No.	Time (hrs)	Exposure Stress (psi)	Creep Def., %	Total Def., %
A	3J-X5	Unexposed		---	---
B	4E-X5	10	Zero	---	---
C	3C-T4	10	36,000	0.38	0.78
D	3P-X1	50	Zero	---	---
E	2A-T11	50	29,000	0.67	0.97
F	2N-X1	100	Zero	---	---
G	4L-T5	100	27,000	0.58	0.87

Figure 34. - Representative on Stress-Strain Curves in Compression at 350°, 400°, or 500°F after Prior Exposure to Various Amounts of Creep at the Same Temperature

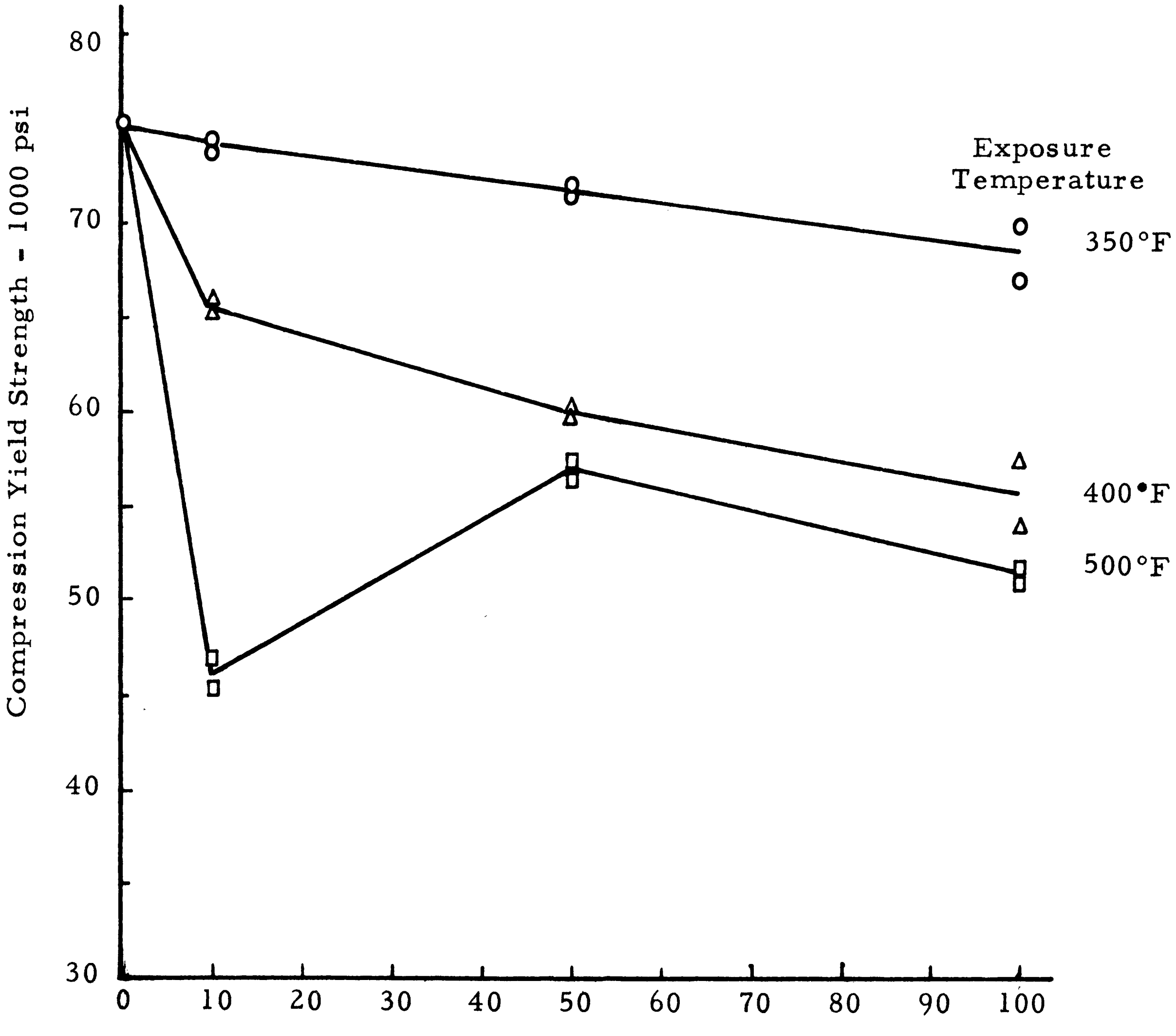


Figure 35. - Effect of Unstressed Exposure on Room-Temperature Compression Yield Strength (0.2% offset) of 2024-T86 Alloy

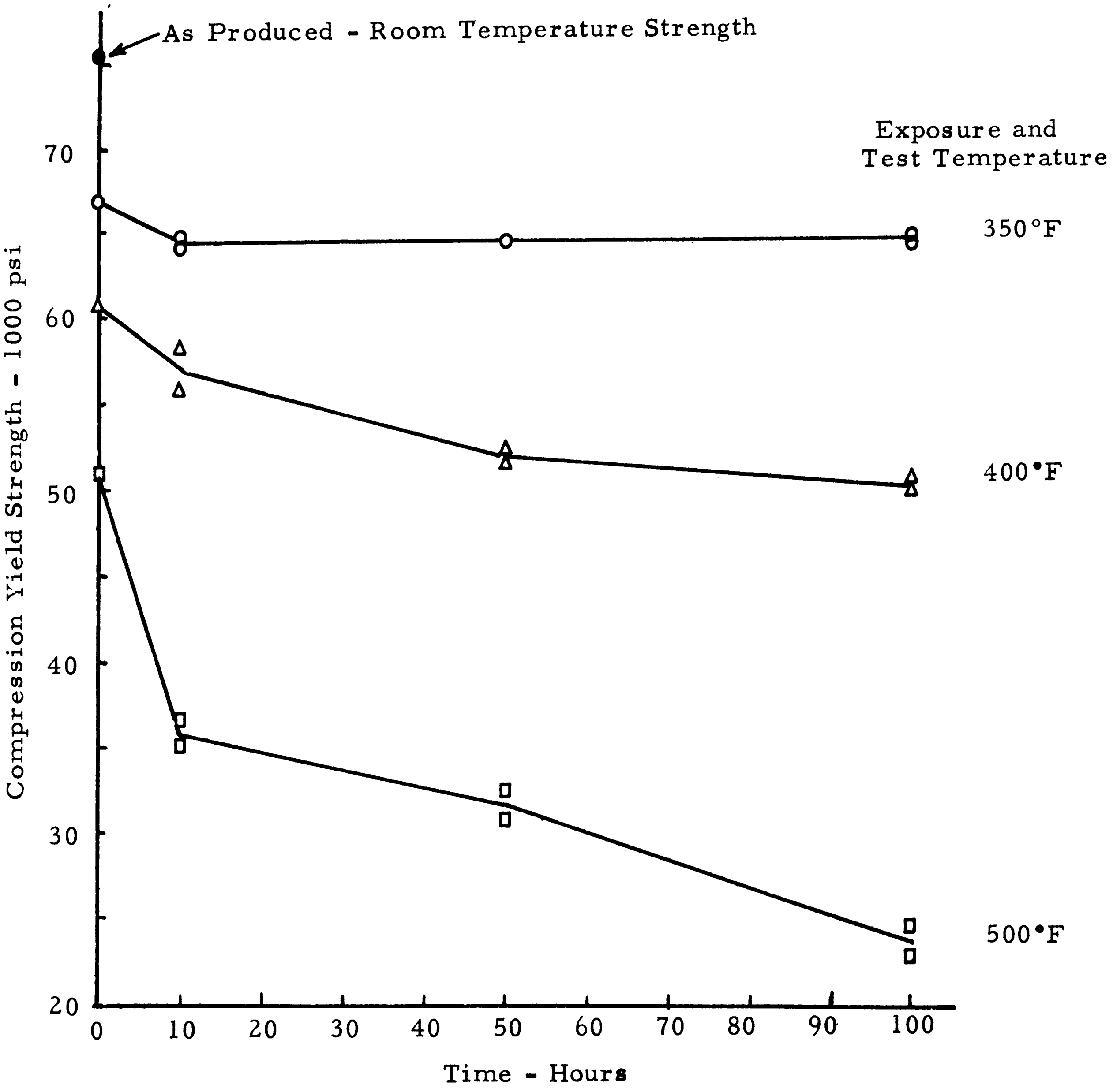


Figure 36. - Effect of Unstressed Exposure on Elevated Temperature Compression Yield Strength (0.2% offset) of 2024-T86 Alloy.

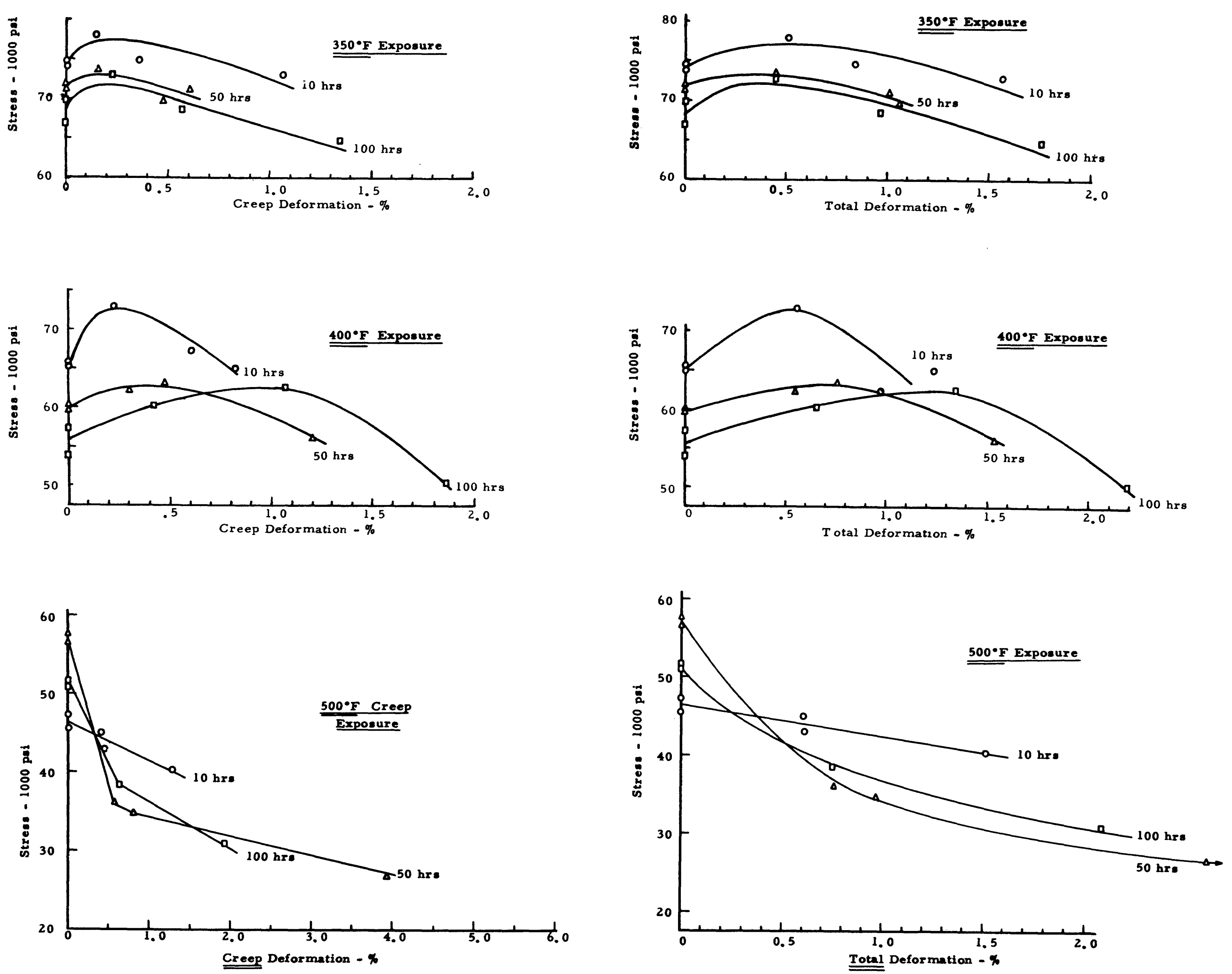


Figure 37. - Compression Yield Strength of 2024-T86 Alloy at Room Temperature after Prior Creep for 10, 50, or 100 Hours at 350°, 400°, or 500°F

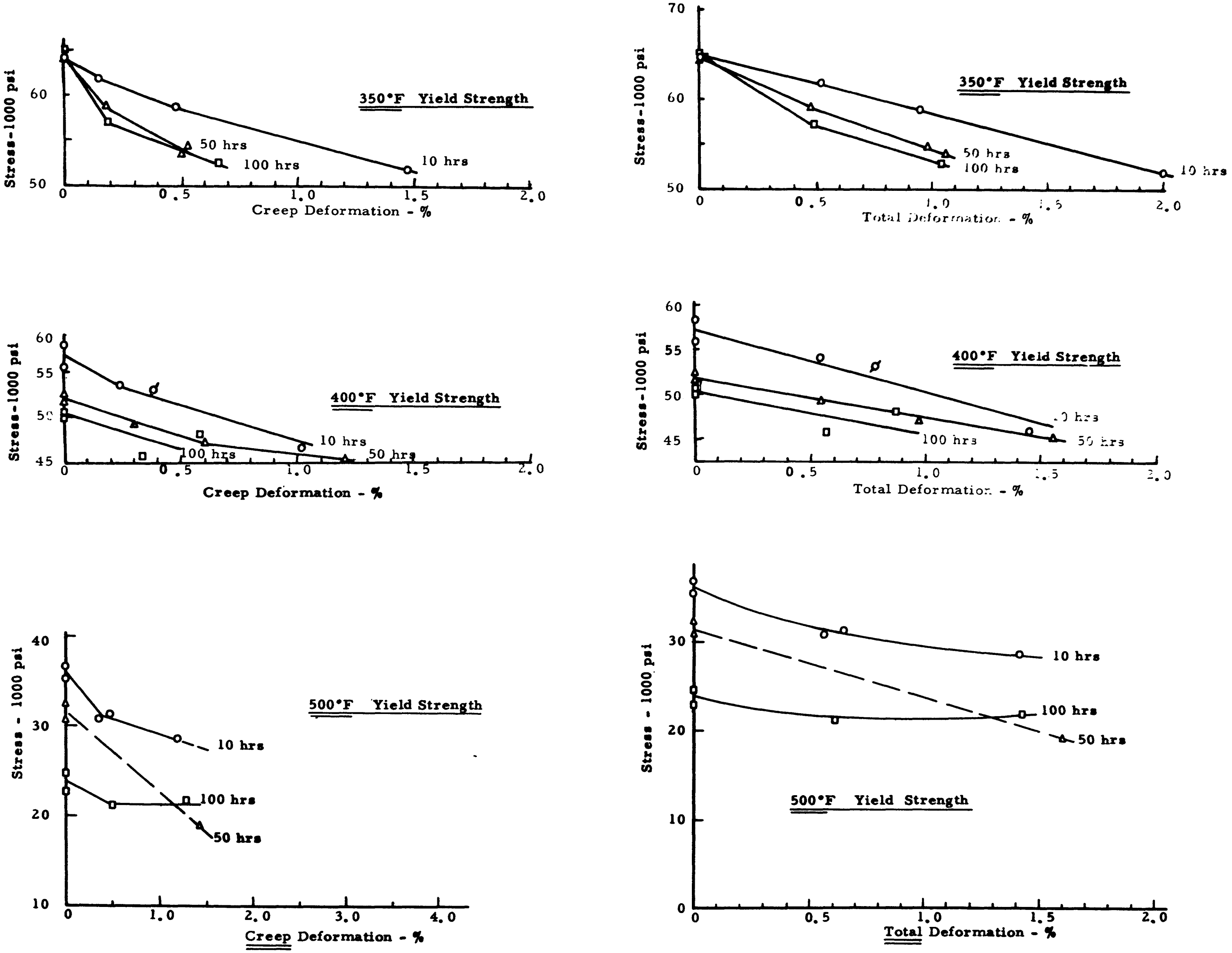
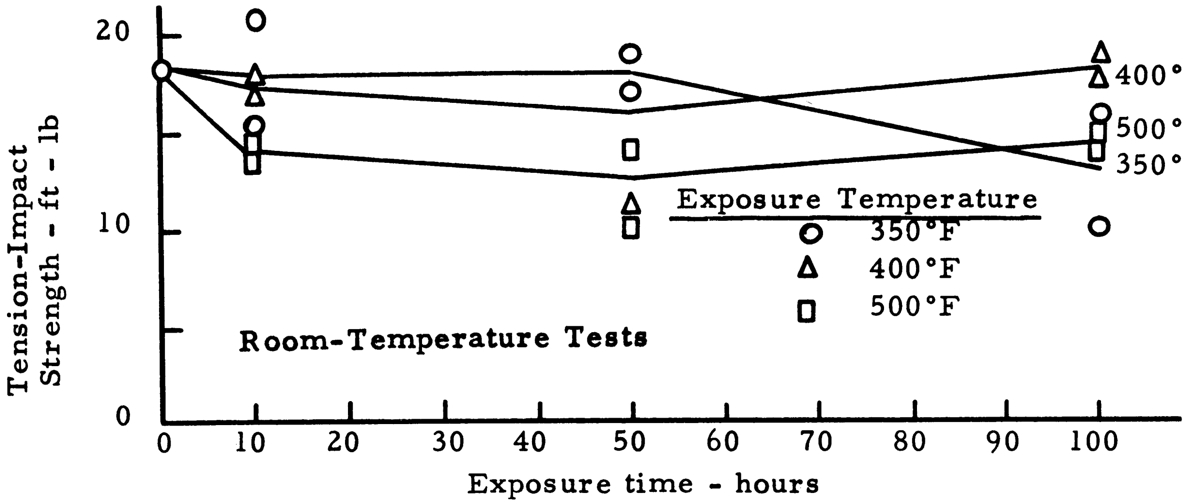


Figure 38. - Compression Yield Strength of 2024-T86 Alloy at Exposure Temperature after Prior Creep for 10, 50, or 100 Hours at 350°, 400°, or 500°F



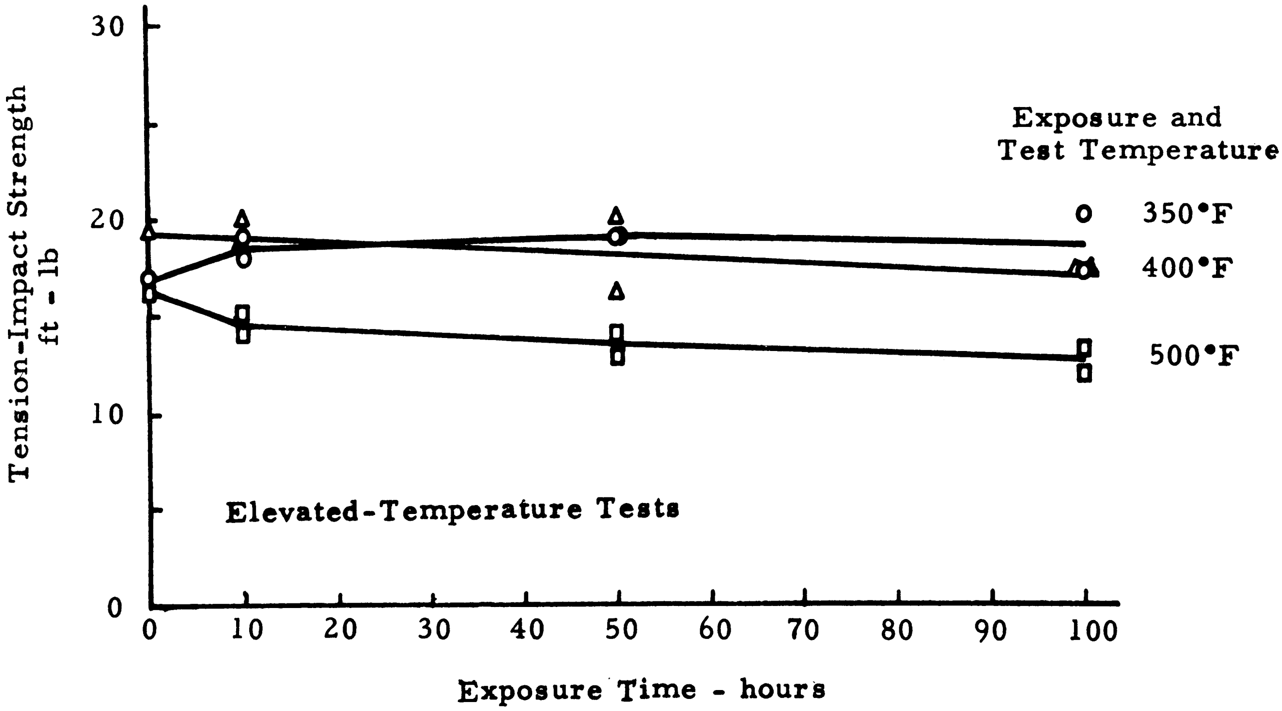


Figure 39. - **Effect of Unstressed Exposure on Tension Impact Strength of 2024-T86 Alloy.**

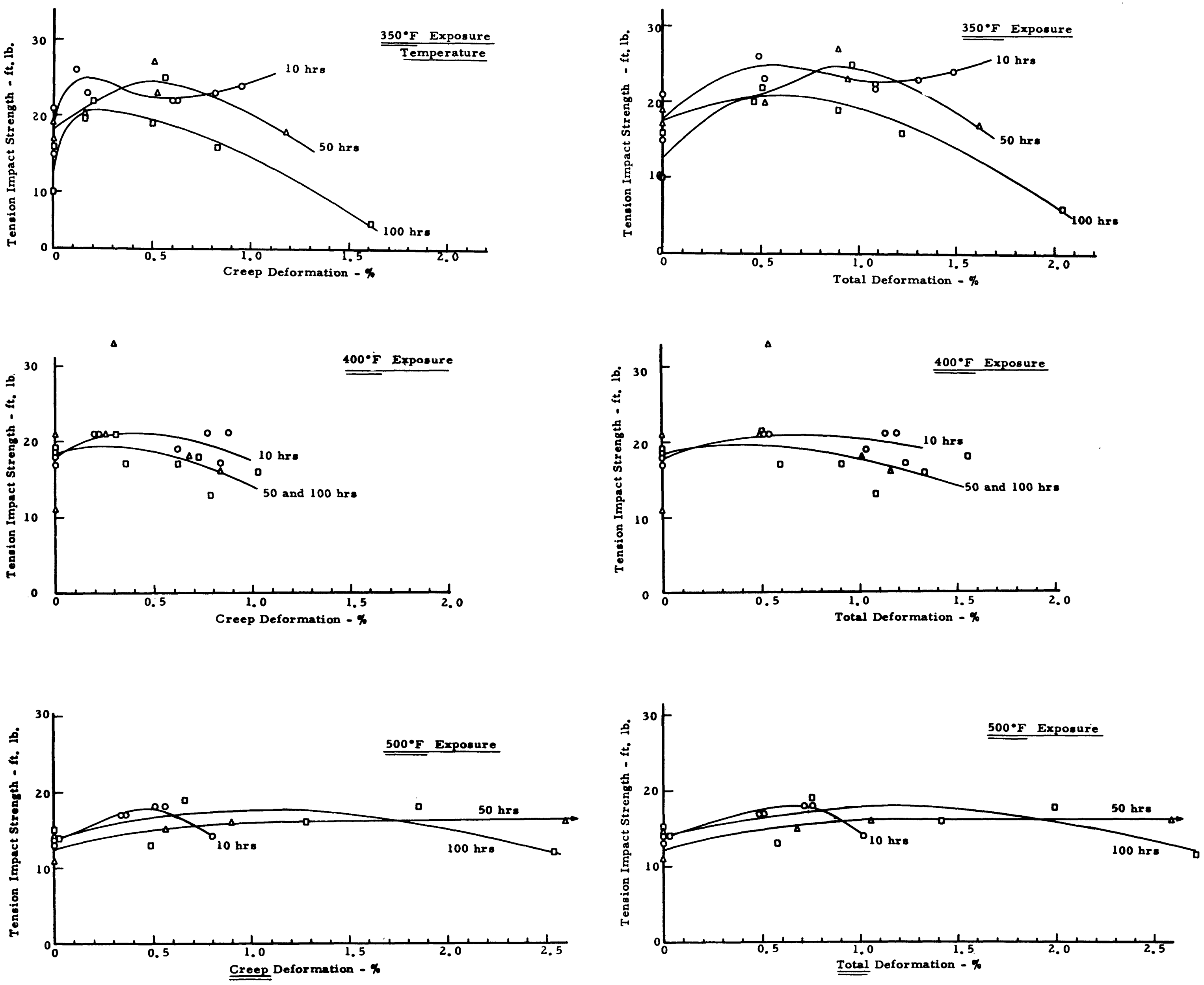
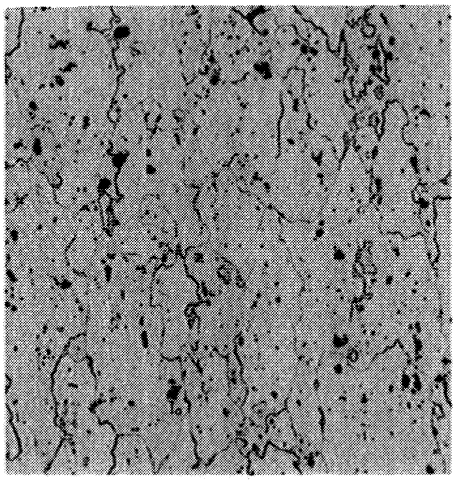
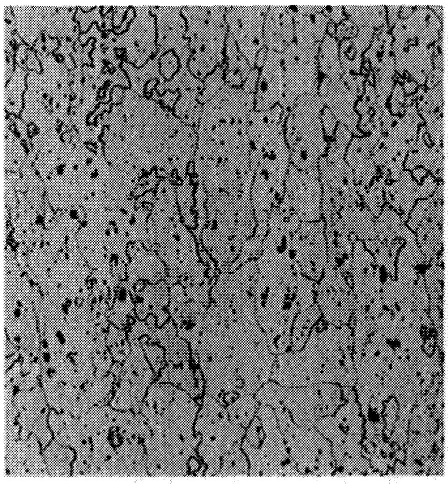


Figure 40. - Room-Temperature Tension-Impact Strength of 2024-T86 after Prior Creep Exposure at 350°, 400°, or 500°F

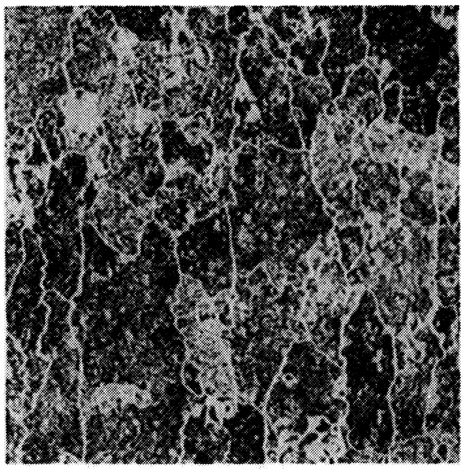


Keller's Etch X100
As Received
(Cold Rolled and Artificially Aged)



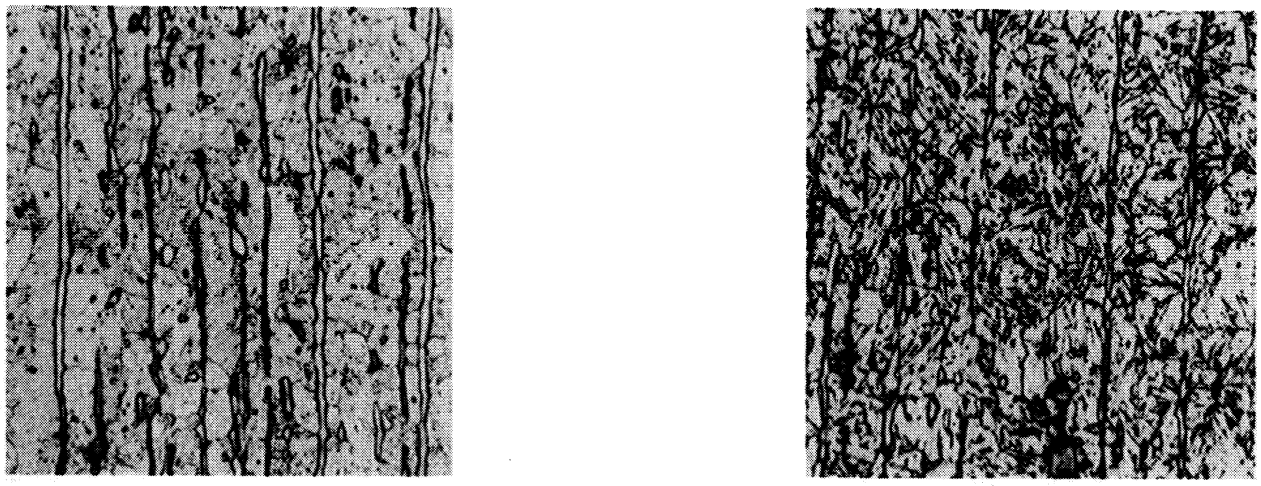
Keller's Etch X100

Spec No. 2M-T5 Exposed 100 hrs at 350°F and 28,000 psi; Total Deformation 0.52%



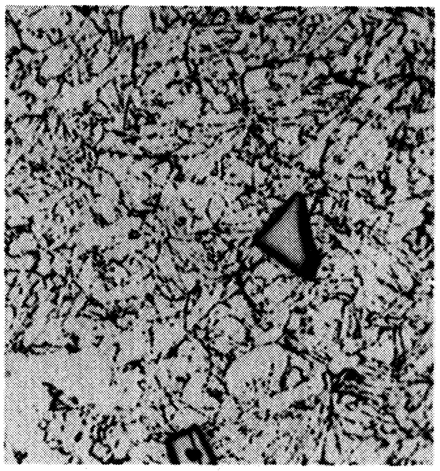
Keller's Etch X100
Spec. No. 3D-T55 Exposed 100 hrs at 500°F and 14,500 psi; Total Deformation 0.62%

Figure 41. - Representative Photomicrographs of the 2024-T86 Alloy



Marble's Reagent X1000
Condition A
(Annealed at 1925°F + Air Cool)

Marble's Reagent X1000
TH 1050 Condition (see page 4)



No. 4 Etch X1000
(TH 1050) Spec. No. 1U-T4
Tested 555 hrs at 800°F and
90,000 psi

Figure 42. - Representative Photomicrographs of the 17-7PH Alloy

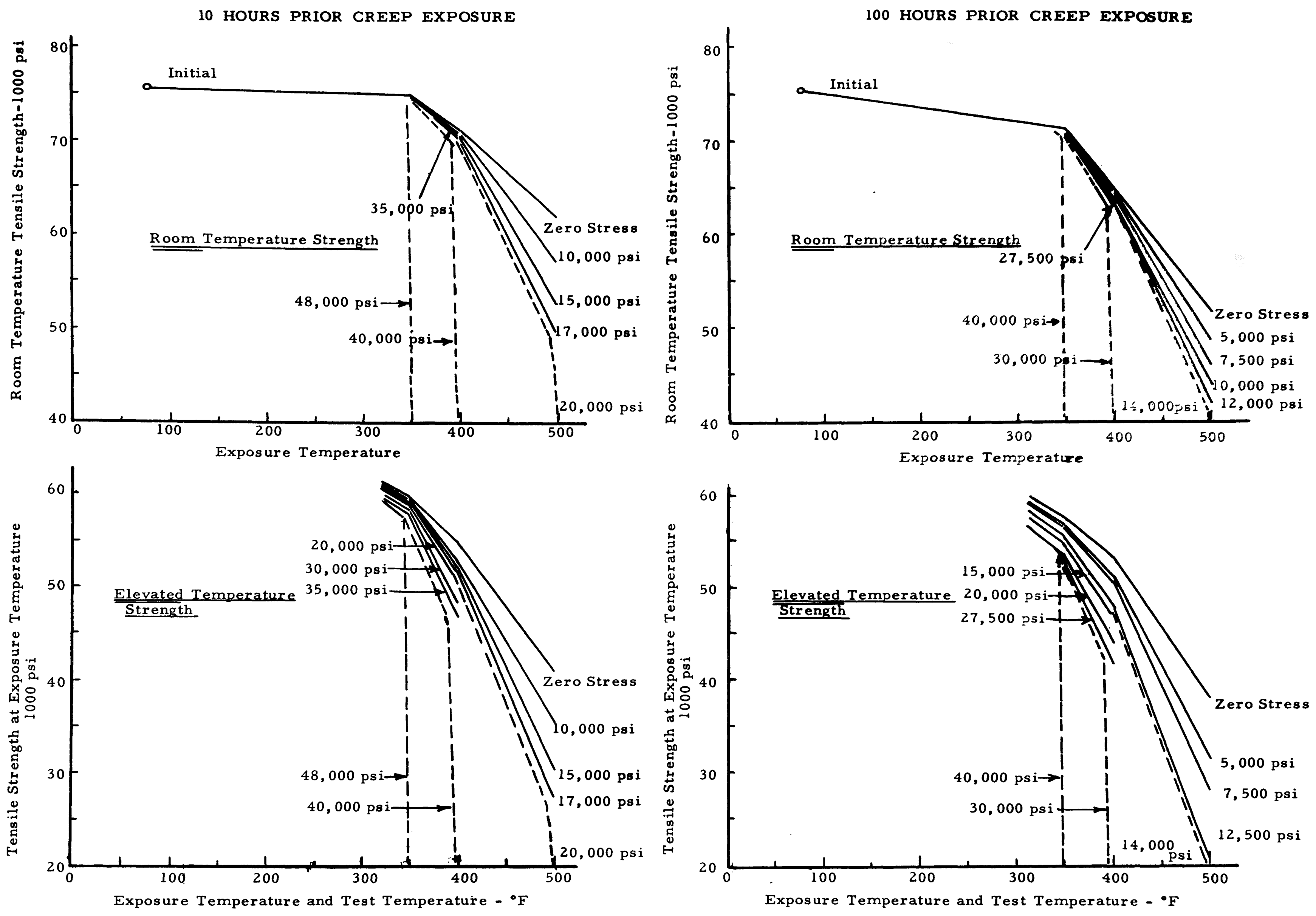


Figure 43. - Effect of Exposure Temperature and Stress on Subsequent Room-Temperature and Elevated-Temperature Tensile Strengths of 2024-T86 Aluminum Alloy Subjected to 10 or 100 Hours of Prior Creep Exposure.