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Part III

EFFECT OF PRIOR CREEP ON MECHANICAL PROPERTIES OF AIRCRAFT STRUCTURAL METALS

Part III: - C110M Titanium Alloy

Jeremy V. Gluck
Howard R. Voorhees
James W. Freeman

Engineering Research Institute
The University of Michigan

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FOREWORD

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ABSTRACT

A study was carried out of the effect of exposure to elevated temperature creep conditions on the subsequent mechanical properties of C110M, an 8 percent manganese binary titanium alloy. Exposures were conducted for times of 10, 50, or 100 hours either unstressed or at stresses causing up to 3 percent total deformation at temperatures between 650° and 800°F. Specimens were taken parallel to the sheet rolling direction.

Following the exposures, short-time tensile, compression or tension-impact tests were run at either room temperature or the temperature of exposure. Prior creep-exposure was found to have little effect on the fracture strength or ductility in either tensile tests or tension-impact tests. The original material had an abnormally high tension yield strength and a low compression yield strength. Exposure to temperature alone caused a decrease in the tensile yield strength and an increase in the compression yield strength depending on the exposure time and temperature, and on the test temperature. Plastic deformation either during loading, or principally during creep, resulted in an increase in the tensile yield strength and a decrease in compression yield strength from the values established by exposure to temperature alone. This behavior can be attributed to a Bauschinger-type effect.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

RICHARD R. KENNEDY
Chief, Metals Branch
Materials Laboratory

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[a]INTRODUCTION

The effect of prior creep-exposure at elevated temperatures on subsequent short-time mechanical properties was studied for a binary 8 percent manganese-titanium alloy, C110M. The research was conducted as a portion of a program sponsored at the University of Michigan by the Materials Laboratory, Wright Air Development Center, U. S. Air Force, under Contract AF 33(616)-3368. Previous reports issued under this contract have dealt with an aluminum alloy, 2024-T86, (Ref. 1) and a precipitation hardening stainless steel, 17-7PH (TH 1050 condition) (Ref. 2). These materials represent three different types of sheet alloys which might be applied in aircraft structures under conditions which would cause creep during part of their service life.

The general purpose of this investigation is to assess the manner by which exposure to the combined effects of high temperature and the creep process could adversely affect the properties of a material for subsequent service. Due to the paucity of information concerning these effects, sufficient background data must be accumulated on representative types of materials before an insight can be gained into the basic principles involved. The need for information of this type has increased as aircraft design and performance requirements have progressed to the point where creep conditions are attained during a portion of the operating cycle. Such creep exposures must not seriously reduce the strength, ductility, or shock resistance of the materials of construction.

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EXPERIMENTAL PROGRAM

Three exposure temperatures were selected for the studies of the C110M titanium alloy; 650°, 700°, and 800°F. The test specimens were exposed for time periods of 10, 50, or 100 hours at either zero stress or at stresses selected to give 0.5, 1.0, 2.0, or 3.0 percent total deformation in the specified time intervals. Total deformation is defined as all deformation (both elastic and short-time plastic strain) occurring during the application of the load plus the creep deformation of the specimen under the given conditions of stress and temperature. The stresses used in this investigation were those determined to give, on the average, the desired total deformation, since inherent scatter in creep properties causes actual deformations for some specimens to be greater or less than the desired nominal value. Approximately 10 creep tests at various stress levels were first run at each exposure temperature to define the stress-time for total deformation curves used to establish the exposure stresses. It was considered that more consistent data would be obtained if the exposure stresses and times were fixed rather than varying time to obtain exactly reproducible creep strain.

Time-elongation data were taken for each exposure test and all correlations of subsequent mechanical properties are presented in terms of the actual deformation. The deformation data are broken down into their various components; total loading deformation, plastic deformation during loading (if any), creep deformation, and total deformation at the end of the exposure period.

To evaluate the effects of the exposures, the following tests were carried out:

1. Tensile tests at room temperature and the exposure temperature for specimens exposed either 10 or 100 hours, and at room temperature for specimens exposed 50 hours.

2. Compression tests at room temperature and the exposure temperature for specimens exposed for either 10 or 100 hours, and at room temperature for specimens exposed 50 hours.

3. Tension-impact tests on smooth specimens at room temperature and the exposure temperature for samples exposed 100 hours and and for samples exposed 10 hours at 700°F.

4. Hardness determination at room temperature for all tensile specimens.

Test specimens were taken in the direction parallel to the sheet rolling direction, the nominally weaker direction of the material.

Properties of the specimens subjected to creep exposure were compared to the average properties established for the unexposed material by a series of from five to ten replicate tests intended to define the normal scatter in the given property. For samples subjected to unstressed exposure, duplicate tests were conducted to give more confidence in the results. In a few cases, duplicate stressed exposure tests were conducted.

TEST MATERIAL

Eleven sheets of C110M titanium alloy in the annealed condition were purchased from the Rem-Cru Titanium Corporation. The material was all from heat A1172600. The sheets were 0.064 inches thick by 30-36 inches wide by 60-90 inches long. The certified chemical analysis furnished by the producer was the following:

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

The manufacturer's reported properties for this material follow:

Ultimate Tensile Strength	149,400 psi
Tensile Yield Strength	147,200 psi
Elongation	15.0 percent
Bend	3T

TEST SPECIMENS

Of the eleven sheets of C110M received, three were arbitrarily selected for providing test specimens. The test specimens were chosen from among the three sheets to provide a measure of the variation in properties between sheets and within individual sheets. Consequently it was necessary that each specimen be readily identifiable according to its original location.

The sampling procedure adopted was designed to permit the most economical utilization of the material consistent with the specification that the specimens be tested in the direction parallel to the sheet rolling direction. The sampling scheme for an individual sheet is illustrated in Figure 1. Each sheet was divided into one-inch wide strips running the length of the sheet. Over the 90-inch length of the sheet four sections or quarters of length were laid out. One end of the sheet was arbitrarily designated the "A" end and its subsections labeled AA and AB, while the other end was designated the "C" end and its subsections labeled CC and CD. Occasionally the AA samples were merely labeled A and the CC samples labeled C. Samples for the initial tests for the determination of base properties were taken from strips 1, 5, 9, etc. as indicated in Figure 1, which were subdivided to provide a repeating sampling pattern over the width and the length of the sheet. The remainder of the strips were reserved for the 22-inch blanks of the specimens to be given creep exposure prior to testing. The individual specimens were stamped with a number sequence designating the sheet number, section number, and the strip number. Thus, the specimen labeled 2CD-17T is a tensile specimen from the CD end of strip 17 from Sheet 2.

The details of the various test specimens used in this investigation are shown in Figure 2. All specimens for the tests of mechanical properties were designed so that they could be machined from the creep specimens following the desired exposure. For exposure to creep, the width of the gage section of the specimens was machined 0.030 inches over the 0.5 inch nominal width. This was machined off after creep exposure. This procedure permitted the measurement of the properties of the material itself unaffected by the particular edge effects, if any, associated with the exposure of the specimen.

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

TEST EQUIPMENT AND PROCEDURES

Detailed discussion of the development of the test equipment and procedures has been previously given (Refs. 1 and 2) and will not be repeated in the present report. Wherever applicable, ASTM Recommended Practices were adhered to in test procedures.

The creep-exposure tests were carried out in individual creep-testing machines with heating provided by a wire wound resistance furnace fitting over the specimen assembly. Strain measurements were accomplished using a modified Martens optical extensometer system.

Tensile and compression tests were conducted in a Baldwin-Southwark hydraulic tensile machine equipped with a strain pacer. A strain rate of 0.005 inches per inch per minute was used. A recording extensometer system employing a micro-former strain gage was employed to give a continuous plot of the test results. A special compression testing fixture which included a loading ram and a pair of guide blocks to restrain lateral buckling of the specimen was constructed for use in this investigation.

An Olsen impact-testing machine was modified to permit the carrying out of tension-impact tests on sheet specimens. The modifications included construction of holding jaws to permit attachment of the specimens to the pendulum head, extension of the striking surfaces, and the construction of a small split-type furnace for heating the specimens.

Specimens prepared for metallographic examination were wet ground on rotating laps using a series of silicon carbide papers through 600 mesh. Finish polishing was accomplished with acqueous media of Linde "A" and Linde "B" polishing compound on rotating laps covered with "Microcloth." The polished samples were etched with a mixture of 1 part glycerine to 1 part hydrofluoric acid.

Hardness determinations were made using a Rockwell "C" scale. The value reported is the average of five or six impressions made on shoulders and gage sections of the exposed specimens.

EXPERIMENTAL RESULTS

The results of the exposure tests were correlated with respect to the amount of prior creep, temperature, and time of exposure. In all plots the properties of the unexposed material and the material exposed to time and temperature alone are indicated on the zero deformation axis. Consistent trends in the curves were taken as a measure of significant property changes. A knowledge of the variance of the unexposed material would permit comparisons of property changes with respect to the unexposed condition even if specific confidence limits could not be fixed to the deformation versus residual property curves themselves. This point is discussed further in Appendix I.

The complete time-deformation data obtained permitted the separation of the strain into its various components. Consequently, correlations are presented in terms of both the actual total deformations and associated creep deformation obtained in the test. In tests at 650°F, particularly, plastic deformation occurred during loading. This deformation was obtained from the total loading deformation by subtracting the normal elastic strain expected at the test stress. The creep deformation was obtained by subtracting the total loading deformation from the total deformation at the end of the test. Total plastic strain would be the sum of the creep deformation and the plastic deformation on loading.

ESTABLISHMENT OF EXPOSURE STRESSES

The results of the seven to nine creep tests at each of the three test temperatures, 650°, 700°, and 800°F, to establish stress versus total deformation characteristics between 10 and 100 hours for 0.5, 1.0, 2.0, and 3.0 percent total deformation are summarized in Table 1. None of the tests were run to rupture, the tests being discontinued once the limit of useful strain had been reached. The discontinued creep specimens were then tensile tested at room temperature in order to determine the effect of the creep on the tensile properties. The subsequent tensile test properties together with the total test time and final deformation are included in Table 1.

The stress-time for total deformation curves are presented in Figure 3. The nominal stresses for the required creep were determined from the intersection of the total deformation curves with the ordinate at 10, 50, or 100 hours. In some cases, further experience with the creep exposure tests later necessitated readjustment of the stresses.

At 650°F relatively low stresses were required so as not to exceed 0.5 percent total deformation on loading. Creep at these stresses was very slow. At higher stresses very rapid creep occurred. Estimates of the stress required to obtain 2.0 and 3.0 percent deformation on loading were used in order to draw the curves for these deformations at 650°F. At 700° and 800°F little difficulty was encountered in obtaining the desired total deformations in the time interval to be considered. Breaks in the curves apparently exist at each of the test temperatures.

Samples exposed to creep at 650° or 700°F exhibited instances of increased tensile and yield strength at room temperature, Table 1, with the effect most noticeable for the 700°F samples. The increase in strength was moderate, generally within 15 percent of the base value, and was accompanied by some decrease in ductility. Several specimens exhibited a decrease in yield strength after creep at 800°F, with a sample exposed for almost 1300 hours showing a severe loss of yield strength. The specimens with shorter exposure time periods or larger amounts of deformation suffered less drop in yield strength and even exhibited slight increases in ultimate strength.

Some increase in hardness, Table 1, over the as-produced value of Rockwell "C" 33.4 was observed in a number of the specimens.

BASE PROPERTIES BEFORE CREEP EXPOSURE

Tensile, compression, and tension-impact tests were conducted in order to establish the average strength of the as-produced material at both room temperature and at the temperatures of creep-exposure. Specimens were taken at random, generally three per sheet, and the results presented as average values within sheets and the average of all tests at the given temperature. The average of all tests was used as the basis for comparisons with properties following creep. Statistical treatment of the base property data is included in Appendix I.

Tensile Properties

The results of tensile tests at room temperature, 650°, 700°, and 800°F are summarized in Table 2. A plot of the effect of testing temperature on average short-time mechanical properties is given in Figure 4, with typical stress-strain curves from tensile tests presented in Figure 5.

Fairly good agreement in tensile and yield strengths was noted both within sheets and between sheets. Individual tests values at all test temperatures were generally within 5 percent of the average value. Both the tensile and yield strengths showed a decrease with increasing test temperature of approximately the same magnitude. Elongation underwent a slight decrease at 650°F from the room temperature value and then a substantial increase at 700° and 800°F. Reduction of area values are also reported even though such measurements on sheet specimens are not very accurate. A caution should also be added with respect to the modulus values reported in Table 2. These values were computed from the slopes of the stress-strain curves and are not considered as precise modulus determinations.

The room temperature tensile and yield strength properties reported in Table 2 were slightly lower and elongations higher than those reported by the manufacturer for the heat (see page 3). In both determinations it was apparent that the tensile yield strength was high with respect to the ultimate strength.

Compression Properties

Compression test results at room temperature and elevated temperature are presented in Table 3. A plot of the effect of test temperature on average compression yield strength is included in Figure 4 and typical stress-strain curves from these tests are plotted in Figure 6.

The compression yield strength exhibited about the same temperature dependency as did the tensile yield strength although there was some levelling-off tendency to be noted between 700° and 800°F. Indicated modulus values were about the same in both tension and compression.

Variation between tests and between sheets was slight, generally not exceeding a deviation of 5 percent from the average value at the particular test temperature.

It became apparent during the course of this work that the relationship between the tensile and compression yield strengths was not typical of that previously observed for this material. The average compression yield strengths established for the as-received material were generally about 60 percent of the tensile yield strength at the same test temperature. This was in contrast to a more normal observation of essentially equivalent tension and compression yield strengths. With the approval of the Materials Laboratory, WADC, work was initiated on a study of this discrepancy. The presently available results of this study are discussed in the section on the relations between tensile and compression yield strengths (see page 16).

Tension-Impact Properties

The results of tension-impact tests at room temperature and elevated temperature are summarized in Table 4, and the average tension-impact strength is plotted as a function of test temperature in Figure 2. Some decrease in tension-impact strength occurred with increasing test temperature. Fairly good agreement between average properties of individual sheets was noted; however, individual tests within sheets exhibited scatter. This was particularly the case for room temperature and 650°F tests of Sheet 2, and some elevated temperature tests of Sheets 1 and 3.

Hardness Properties

The hardness of the material as-received was determined to be Rockwell "C" 33.4. This value is the average of four determinations each on three coupons, each taken from a different sheet of test stock.

TENSILE PROPERTIES AFTER EXPOSURE

Unstressed Exposure

Room-Temperature Tests. Room temperature tensile tests following unstressed exposure revealed very little change in properties with the exception of the yield strength following 800°F exposure. The test data are summarized in Table 5 and plotted in Figure 7. Reference to this figure shows that the unstressed exposure had negligible effect on the ultimate tensile strength, while the 650° and 700°F exposures had minor effects on the yield strength. Following exposure at 800°F the yield strength dropped consistently with increased exposure time, reaching a value about 12 percent below the as-received strength after 100 hours of exposure. Elongation values exhibited a slight but hardly significant decline with increased exposure times and temperatures. Hardness first underwent a slight increase and then a levelling-off with longer times at each of the exposure temperatures.

Good agreement was obtained in the subsequent tensile tests for the duplicate exposures conducted.

Elevated-Temperature Tests. The results of tensile tests at the exposure temperature following unstressed exposure are summarized in Table 6 and plotted in Figure 8.

The ultimate tensile strengths were virtually unaffected by exposure to temperature alone. An apparent increase in tensile strength from 800°F exposure was within the variation noted in replicate tests to establish the base strength.

The average yield strength after 100 hours exposure at 700°F was about 9 percent below the as-produced, 10 hour, or 50 hour values. At 800°F the yield strength dropped for exposures up to 50 hours and then recovered at 100 hours -- but not to the original value. The maximum loss of yield strength at 800°F was about 19 percent of the base strength at this temperature.

The elongation values showed some decrease for exposures up to about 50 hours at each of the temperatures followed by a return to the vicinity of the base value after 100 hours exposure.

The agreement between duplicate exposure tests was generally quite good.

Creep Exposure

Room-Temperature Tests. Tensile tests at room temperature following prior creep for 10, 50, or 100 hours are reported in Table 7 and plotted as a function of both creep deformation and total deformation for each exposure time and temperature in Figures 9, 10, and 11. A summary of the test results for all temperatures is presented in Figure 12. Hardness data are summarized in Figure 13 and representative stress-strain curves from these tests are included in Figure 14. With one exception one test was made for each nominal creep deformation. Conclusions were drawn from trend lines constructed through four test points for varying deformations in each exposure time.

At 650°F, Figure 9, a major portion of the total deformation in each test was obtained during loading. Consequently the range of creep deformations covered was rather limited, generally ranging only to about 0.5 percent even though the associated total deformations were as much as 3 percent. On either a total deformation or creep deformation basis the variations in tensile strength with increased deformation were fairly slight, generally within 5000 psi deviation from a base strength level of 146,000 psi. Yield strengths tended to show an increase with prior creep with increases as much as 12,000 psi above the strength of material exposed to temperature alone. A correlation on the basis of total plastic strain would lie somewhere between the trend lines drawn on Figure 9. Ductility changes were relatively slight.

Considerably greater effects of prior creep on tensile properties at 75°F were found for exposure at 700°F (Figure 10) than were found for exposure at 650°F. Both the tensile and yield strengths showed increases with increased amounts of prior creep. At the larger amounts of deformation the increase in strength over the base condition was 10 percent or greater. At 700°F the loading deformation was a smaller proportion of the total deformation than was encountered at 650°F and the plastic component of the loading deformation was also considerably smaller. Consequently, the range of creep deformations covered was much greater than those studied at 650°F. The elongation values fell off somewhat with increased amounts of prior creep.

The results of the tests after creep exposure at 800°F (Figure 11) indicate little or no change in subsequent tensile strength and ductility. The changes in yield strength were the same as those due to the effects of temperature alone. At this temperature a great proportion of the deformation occurred during creep. A creep test specimen exposed for almost 1300 hours at 800°F (see page 7) showed a severe drop in yield strength although crept to only 0.52 percent total deformation (0.47 percent creep deformation).

The summary of the tensile test data presented in Figure 12 indicates that there was some tendency for the longer exposure times at 650° and 700°F to result in increases in tensile strength and perhaps yield strength. There appeared to be no effect of exposure at 800°F on the tensile strength, while the yield strength did appear to be a function of the exposure time rather than the amount of deformation.

Although the effect of prior creep on the tensile test elongation was not large, the 100 hour exposures tended to result in lower elongations than did the shorter exposure times.

Hardness changes as the result of prior creep were relatively minor (Figure 13) and were apparently confined to an over-all increase of some 5 points Rockwell "C" over the base condition. No particular effect could be attributed to the varying amounts of prior creep, while the only effect of exposure time appeared in the 800°F exposure data where the 100 hours exposure had a somewhat lower hardness than the 10 and 50 hours exposures.

Elevated Temperature Tests. Tensile tests at the exposure temperature were conducted for samples that had been exposed to prior creep for 10 or 100 hours. The results of these tests are summarized in Table 8. Plots of the data for each exposure temperature and time are given in Figures 15, 16, and 17, with a summary of the data included in Figure 18. Figure 19 presents representative stress-strain curves from these tests.

Prior creep at 650°F had little or no effect on the 650°F tensile and yield strengths (Figure 15). As was the case with the room temperature tests, most of the total deformation was obtained during loading and the range of creep deformation covered was quite limited. Some decrease in elongation did appear to result from increased amounts of prior creep.

The creep at 700°F did have an effect on the 700°F tensile properties (Figure 16). This consisted of some increase in the yield strength for 10 hours exposure and an increase in both the tensile and yield strengths for 100 hours exposure. In the case of the yield strength after 100 hours exposure, increased creep served to wipe out the loss that occurred from exposure to temperature alone, while the tensile strength showed an increase of almost 15 percent over the base condition. However, the increased tensile strength after the 100 hour exposures was accompanied by a substantial drop in elongation. At the highest percentage of creep studied, the subsequent tensile elongation was less than half the base value.

Prior creep for 10 hours at 800°F appeared to have little or no effect on the 800°F tensile properties, while the 100 hour prior creep had an adverse effect on the yield strength. (Figure 17). The loss of yield strength following 10 hours exposure was apparently due to temperature alone. However, the yield strength of material exposed to creep for 100 hours was reduced by 25 percent from the base value. Tensile test ductility in these tests was increased by larger amounts of prior creep.

COMPRESSION PROPERTIES AFTER EXPOSURE

The compression property evaluated was the 0.2 percent offset yield strength. Modulus values computed from the slopes of the stress-strain curves are also reported.

Unstressed Exposure

Exposure of the C110M alloy to temperature alone for periods up to 100 hours was found to cause significant increases in the compression yield strength, depending both on the exposure temperature and the test temperature.

Room Temperature. The results of room temperature compression tests on specimens subjected to exposure without stress for 10, 50, or 100 hours at 650°, 700°, or 800°F are summarized in Table 9 and plotted in Figure 20. With only one exception, that of 50 hours exposure at 700°F, the results of duplicate tests showed very good agreement.

For all exposures except that of 10 hours at 650°F, the average compression yield strength was raised from 15 percent to almost 40 percent over the base condition. The increase in yield strength was apparently both temperature and time dependent, with the greatest increase occurring between the 0 and 10 hours exposure at 700° or 800°F. At 650°F, the maximum effect apparently occurred between 10 and 50 hours. The strength after 100 hours exposure at either 700° or 800°F dropped off somewhat from the maximum value. The indicated modulus values showed no changes.

Elevated Temperature. The results of the compression tests of material exposed without stress and tested at the exposure temperature are summarized in Table 10 and plotted in Figure 21.

These data indicate than an increase in elevated temperature compression yield strength resulted from all the 700°F exposures and the 10 and 50 hours exposure at 800°F. Agreement between duplicate tests was again generally good.

Exposure at 650°F for 100 hours caused a slight but hardly significant increase in the 650°F yield strength. However, the 700°F exposure resulted in an increase in 700°F yield strength at 10 hours which leveled off as the exposure time was further increased. The 800°F tests showed an increase in yield up to 50 hours exposure followed by a drop-off that left the 100-hour results little changed from the base strength. The maximum increase for 700°F exposure was 37 percent above the 700°F base condition, while the maximum increase for the 800°F tests was 28 percent of the 800°F base condition. Modulus values again appeared to be unaffected.

Creep Exposure

Prior creep at all temperatures tended to reduce the room temperature compression yield strength of C110M from the value established by exposure to temperature alone. In most cases, however, strengths still remained above the base condition. Elevated temperature strengths following prior creep showed less clear-cut effects although some tendency existed for reduction in strength in the 650° and 700°F tests.

Room Temperature. Room temperature compression tests on samples subjected to prior creep are summarized in Table 11. Plots of the effects of exposure time and temperature are presented in Figures 22, 23, and 24 and summarized in Figure 25. Representative stress-strain curves from these tests are presented in Figure 26.

The data indicate that increased amounts of prior creep caused a general decrease in compression yield strength from the value established for exposure to temperature alone. In most cases, however, this did not result in a reduction of strength below that of the base condition of the unexposed material, since the unstressed exposures were previously shown (see page 12) to raise the yield strength by significant amounts. However, in the cases of 10 hour prior creep exposure at 650° and 700°F, the final yield strength did fall below the base value when the total deformation exceeded approximately one percent.

Although total deformations up to 3 percent were covered in the 650°F exposures, the associated creep deformations were limited to about one percent. (Figure 22). This amount of deformation served to eliminate the increase in strength for the 50 and 100 hours unexposed conditions, while for 10 hours, the strength immediately dropped below the base value. For all three times, the exposure to 0.5 percent creep deformation served to reduce the yield strength some 8-10 percent below the value established for exposure to temperature alone.

Losses in yield strength from 700°F exposure to prior creep were generally larger than those found at 650°F (Figure 23). For a given amount of deformation, the severity of the effect was diminished as the exposure time was increased. For 10 hours exposure, approximately 0.5 percent creep deformation (1.5 percent total deformation) reduced the strength to the base value for the unexposed condition. For the longer exposure times creep deformations or total deformations of from 3 to 6 percent were required to reduce the strength to the base value.

The maximum reductions in strength from the value for zero deformation following total deformations up to 3 percent were 32 percent for 10 hours creep, 22 percent for 50 hours and 14 percent for 100 hours prior creep.

In the 800°F exposures practically all the deformation obtained was due to creep (Figure 24). Creep deformations up to 3 percent reduced the yield strength from the zero deformation value. However, for all exposure times the strengths leveled off at between 118-125 percent of the base condition for unexposed material. The maximum reduction in strength from the condition of exposure to temperature alone was 10 percent for 10 hours creep, 15 percent for 50 hours, and only 7 percent for the 100 hours prior creep time. The maximum loss in strength was reached in about 0.5 percent creep deformation for 10 hours, 1 percent for 50 hours, and 1.5 percent for 100 hours.

Elevated Temperature. Compression tests at the exposure temperature of material exposed to prior creep are summarized in Table 12. As indicated previously, tests were confined to exposure times of 10 or 100 hours. The individual plots of the test data are presented in Figures 27, 28, and 29, and summarized in Figure 30. Figure 31 present typical stress-strain curves for these tests.

In general, exposure and testing at 650° or 700°F resulted in a loss of strength, while the 800°F tests showed the possibility of a slight improvement in strength over the base conditions.

In the 650°F tests (Figure 27) for both the 10 and 100 hour exposures, creep deformations of about 0.5 percent (1-2 percent total deformation) lowered the strength by some 15 percent from the base value for unexposed material.

In the 700°F tests, the reduction in strength from that of the material exposed without stress was larger. However, in the ranges of time and deformation studied, the observed minimum strength did not fall below the unexposed base material. (Figure 28). In the 10 hour tests the maximum loss of strength was reached at about 0.5 percent creep deformation and the strength appeared to level out at a value about 30 percent below that for exposure to temperature alone. The results of the 100 hour exposure tests were not as consistent and were complicated by scatter for the zero stress exposures. Up to 2 percent total deformation (1.5 percent creep deformation) the yield strength apparently fell off with increased deformation, reaching a value about 20 percent below the average value for unstressed exposure for 100 hours. However, the test point for approximately 3 percent deformation indicates a considerable increase in strength. The validity of this point is somewhat uncertain and, therefore, the trend line is indicated as questionable.

The 800°F tests (Figure 29) resulted in minor increases in yield strength for intermediate deformations. The data for both 10 and 100 hours indicate an increase averaging about 10 percent over the zero deformation value when the material was subjected to 0.5 to 1 percent creep deformation. Beyond this initial increase there appeared to be a slight tendency for the strength to drop off with increased amounts of creep deformation. However, the data for 100 hours indicate that almost 7 percent creep deformation did not reduce the yield strength below the initial value. No particular effect appears to be attributable to differing exposure times.

TENSION IMPACT PROPERTIES AFTER EXPOSURE

Tension-impact tests after unstressed exposure at 650°, 700° and 800°F were run at both room temperature and the exposure temperature. Specimens exposed to creep at 700° for 10 or 100 hours were also tested at room temperature and the exposure temperature. However, the tests of material exposed to creep at 650° and 800°F were limited to 100 hours exposure. The tension-impact tests were conducted on smooth specimens.

Unstressed Exposure

Room Temperature. Data from room temperature tension-impact tests following unstressed exposure is tabulated in Table 13 and plotted in Figure 32. In general, there was relatively little effect. A considerable amount of scatter was noted between duplicate tests of several conditions and it was not possible to fix clear trends from the data. The data indicate that 100 hours exposure at 650° or 800°F tends to raise the tension-impact strength. However, the 700°F data show an apparent intermediate effect with a maximum occurring at 10 hours. The availability of only one test point for this condition complicates the drawing of any conclusions. Ductility measurements made on the test specimens were inconclusive.

Elevated Temperature. The results of tension-impact tests conducted at the exposure temperature are summarized in Table 14 and plotted in Figure 33. In these tests the reproducibility between duplicate exposures was much better than in the room temperature tests. The data indicate slight but hardly significant increases in 100 hours at 650° and 800°F while an increase of almost 30 percent over the base condition was found at 700°F for 100 hours exposure, with an accompanying decrease in ductility. The ductilities for other exposure conditions were not affected.

Creep Exposure

Room Temperature. The test results for specimens subjected to prior creep and then tested in tension-impact at room temperature are summarized in Table 15 and plotted in Figure 34. The tests were confined to exposure to creep in 100 hours at 650°, 700°, or 800°F and for 10 hours at 700°F. Excessive scatter for the 650° exposure and the 10-hour exposures at 700°F made the interpretation of the results quite difficult. For both exposure temperatures it appears that increased amounts of deformation tend to reduce the tension-impact strength below the value for zero deformation. Some of the values for tension-impact strength following exposure at 650°F were reduced to as much as one-half the unexposed strength. On the other hand, the 100-hour creep exposure at 700°F showed an increase in tension-impact strength with an apparent maximum effect at about 1-percent creep deformation. The 100-hour exposure at 800°F resulted in a decrease in the tension-impact strength from the increase over the base condition observed for the material exposed to temperature alone. The strength appeared to level off at about the level of the base strength for deformations above 1 percent.

Elevated Temperature. Tension-impact properties for specimens tested at the temperature of prior creep are summarized in Table 15 and plotted in Figure 35. These results are limited but show more consistency than did the room-temperature tests following the same range of creep exposure.

Very little change from the base condition or the condition of exposure to temperature alone was found for the tests after 100-hour exposure at 650° or 800°F or the 10-hour exposure at 700°F.

The one condition of unstressed exposure that did result in a significant increase in tensile impact strength at elevated temperature was for 100 hours at 700°F. However, after about 0.25-percent creep deformation at 700°F, the strength was reduced to the level of the unexposed material.

RELATIONS BETWEEN TENSION- AND COMPRESSION-YIELD STRENGTHS

Comments from Republic Aviation personnel on data contained in progress reports on this contract pointed out that the reported compression yield strengths appeared to be too low in relation to the tension yield strengths. These data are summarized in the present report in Tables 2 and 3 and indicate that the compression yield strength averaged about 60-70 percent of the tension yield at each test temperature. Republic cited experience which indicated the yield strengths in tension or compression to be of the same order of magnitude.

In order to resolve this discrepancy, a study was undertaken to answer the following questions:

1. Is the compression test procedure used at the University satisfactory?
2. Could the previously reported results be reproduced?
3. Is the apparent discrepancy related to the material and not the test procedure?

The major source of information for this study was TML Report No. 43 "An Evaluation of Compression-Testing Techniques for Determining Elevated Temperature Properties of Titanium Sheet" issued by the Titanium Metallurgical Laboratory of Battelle Memorial Institute. (Ref. 4)

The compression testing procedures used at the University are in substantial agreement with the practices recommended in TML Report No. 43. These include the use of an averaging extensometer, off-set grooved guide blocks, and a consistent supporting force achieved with the use of a torque wrench. Absolute values of compression yield strength determined with this equipment were compared with data available in the literature for three alloys tested; 2024-T86, 17-7PH (TH 1050), and C110M. Good agreement with reported values was found. The accompanying sketch (Figure 36) compares the absolute values of compression yield strength of C110M determined at the University with those determined at three other laboratories (as reported in TML Report No. 43). This comparison shows the values obtained at the University fall slightly to the low side -- particularly at room temperature -- although the deviation is not excessive.

Table 16 summarizes the results of additional tests run at room temperature and 700°F to check the reproducibility of the data. These tests were run at normal support force -- about 2-4 inch-pounds -- with an additional test at each temperature run with a supporting force of 50-60 inch-pounds. The purpose of this was to see if a substantial increase in support force would significantly increase the compression yield strength. The results of all check tests showed excellent agreement with the data originally reported. Increased support force had a slight effect on yield strength. The effect, if any, was certainly not enough to account for the apparent discrepancy with the tensile yield strength. Premature buckling was thus ruled out as a factor in producing low compression strengths.

Since the study of the procedures and reproducibility of the test data did not resolve the discrepancy, attention was directed towards the test material itself. Examination of available data indicated that the particular heat of C110M received for testing had an abnormally high ratio of tensile yield strength to ultimate tensile strength. For heat A1172600 the ratio varied from 88-98 percent, while data indicated the ratio to vary from 70-90 percent over the temperature range up to 700°F. (TML Report No. 43)

This observation led to the suspicion that the low ratio between the tensile and compression yield strengths was due more to an abnormally high tensile yield strength of this heat than to any faults in the compression testing procedures. Partial confirmation of this has been obtained from tests run on samples of RC 130A sheet remaining from the experimental work reported in WADC TR 54-54 "A Study of Creep of Titanium and Two of Its Alloys." The sheet tested was from heat A5036 and was received in the spring of 1952. Thus, it is over 5 years old and may not be representative of current production.

The tensile strength of heat A5036 was originally determined to be 129,000 psi and the yield strength 110,000 psi. The check tests just run indicated a tensile strength of 133,000 psi and a yield strength of 114,500 psi. The ratio of yield strength to tensile strength was thus about 0.85 which compares favorably with the Armour and Rem-Cru data. The compression strength of this heat was found to be 118,500 psi. For this heat, therefore, the ratio of the compression yield strength to the tensile yield strength shows excellent agreement with the data from TML Report No. 43. The results also increase the confidence placed in the compression testing procedures used at the University.

Comparative analyses of the two heats tested follow :

		C	Mn	N	H_2	Ten. YS/Ten. Ult.	Comp. YS/Ten. YS
C110M	Heat A1172600	.10	7.0	.028	.0093	.98	.76
RC130A	Heat A5036	.10	6.9	.018	.0083	.85	1.03

Apparently the disparity between the tensile and compression yield strengths is an anamoulous one associated with the particular heat of C110M (A1172600) received for testing.

In the absence of obvious compositional effects (the oxygen contents are unknown) it appears that the differences between heat A1172600 and the other heats -- that is heat A5036 and the data reported in TML Report No. 43 -- could be related to processing conditions. It should be noted that heat A1172600 was received in early October 1956 while TML Report No. 43 is dated June 8, 1956 and presumably deals with material produced much earlier than that. Thus, unknown differences in processing conditions, presence of residual stresses, etc. might be present in the latest heat.

Arrangements were made with approval of the Materials Laboratory, WADC for Republic Aviation and the University to cooperate to exchange test stock of C110M in order to check the other's test results and procedures.

A supply of blank strips from Heat A1172600 was shipped to Republic and strip stock from another heat, A50089, was furnished by Republic. Tests were conducted at room temperature in both tension and compression.

The results of tests conducted at the University on heat A50089 follow:

	Tensile Properties					Compression Properties	
Strip No.	Ultimate Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%)	Reduction of Area (%)	E (10^6 psi)	0.2% Offset Yield Strength (psi)	E (10^6 psi)
1	127,100	110,800	26.8	32.4	14.8	115,800	15.3
2	126,900	111,800	25.8	31.2	14.7	112,200	15.3
3	124,800	111,000	24.0	29.6	14.9	111,900	15.3
Avg.	126,267	111,200	25.5	31.1	14.8	113,033	15.3

Close agreement was obtained between replicate tests, with the strength values falling well within ± 2 percent from their respective average values. The agreement between tension and compression yield strengths was also close, with the former about 1-1/2 percent higher on the average. These results agree well with what might be termed "normal" properties and the relationships between tension and compression yield strengths.

To date the results of the tests run by Republic on heat A1172600 have not been received. It does, however, appear that the compression yield/tension yield ratio of the stock from heat A1172600 purchased by the University is considerably less than that normally expected for this alloy.

Further, unstressed exposure of this material at 800°F for times up to 100 hours increased the compression yield strength and decreased the tensile yield strength. (These data are reported in Tables 5 and 9 of the present report and plotted on Figures 7 and 20. Particularly striking were the data for the 100-hour exposure which resulted in an almost complete reversal of the ratio between the tensile and compression yield strengths.

Specimens taken from heats A5036 and A50089 were also subjected to 100 hours unstressed exposure at 800°F and then tested in tension or compression at room temperature with the following results:

Check Tests on Effect of Unstressed Exposure on C110M

	Room Temp. Tensile Properties			Room Temp. Compression Properties		
Exposure Condition	Ultimate Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%)	Yield Strength (psi)	Elongation (%)	Heat No.
As. Rec.	133,000	114,500	14.8	118,000	15.9	A5036
+800°F-100 hr	120,000	101,000	15.2	110,000	15.7	
As Rec.	126,300	111,200	14.8	113,000	15.3	A50089
+800°F-100 hr	141,200	109,200	15.3	115,000	16.1	

The accompanying bar graph (Figure 37) illustrates the relation between the room temperature tension and compression properties of material from the three heats of C110M both in the as-received condition and after exposure to 800°F for 100 hours. This figure makes evident that only the as-received condition of heat A1172600 exhibited the "abnormal" relationship between the tensile and compression yield strengths and suitable heat treatment of this condition would change the relationship.

Plotting the tension and compression stress-strain curves for the as-received material from heats A5036 and A1172600 on the same graph (Figure 38) shows a marked difference in the shape of the stress-strain curve between the tension and compression portions for the material from heat A1172600. These curves show a remarkable resemblance to those presented by Templin and Sturm (Ref. 5) which show the effects of unidirectional or polydirectional cold work on 52S aluminum rod. The aluminum rod given unidirectional cold working exhibited a tension curve with a rather sharp "knee" at a stress slightly below the yield strength, while the compression half was much more gradually rounded. The rod given polydirectional work exhibited curves of the same shape for both testing directions. Similar results were obtained by Templin and Sturm for 99.5% pure aluminum and 24ST aluminum.

Such results are a common manifestation of the Bauschinger effect whose very definition in the ASM Metals Handbook (Ref. 6) is "the phenomenon by which plastic deformation of a metal raises the yield strength in the direction of plastic flow and decreases the yield strength in the opposite direction."

Very strong evidence exists of the presence of a Bauschinger-type effect in the as-received stock of C110M.

In view of the above findings, analysis was made of the effects of creep-exposure on the relationships between the tension and compression yield strength. Figure 39 presents simultaneous plots of the tension and compression yield strengths at room temperature following prior creep while Figure 40 presents a similar series of plots for the tensile and yield strengths at the exposure temperature. In these figures the strengths were plotted as a function of creep deformation, although total plastic strain could also have been used.

The intersection of these curves with the zero deformation axis indicates the effect of exposure to temperature alone. Also indicated are the strengths of the unexposed material. Examination of these data shows that exposure at the higher temperatures and longer times caused an increase in the compression yield strength relative to the tensile yield strength.

The changes in the relative magnitudes of the yield strengths are indicated in the following tabulation:

Exposure Conditions		Test Temp. (°F)	Ratio: Compression Yield / Tensile Yield
Temp. (°F)	Time (hr)		
As Produced		Room	0.75
650	10	Room	0.79
	50	Room	0.88
	100	Room	0.92
700	10	Room	0.99
	50	Room	1.00
	100	Room	0.96
800	10	Room	1.12
	50	Room	1.14
	100	Room	1.13
As Produced		650	0.64
650	10	650	0.64
	100	650	0.68
As Produced		700	0.61
700	10	700	0.85
	100	700	0.92
As Produced		800	0.66
800	10	800	0.88
	100	800	0.75

This behavior suggests that relief of residual stresses probably occurred during the unstressed exposures.

The effects of the unstressed exposures were completely eliminated by the application of tensile creep at either 650° or 700°F. As both Figure 39 and 40 show, increased amounts of tensile creep at 650° or 700°F tend to raise the subsequent tensile yield strength and lower the subsequent compression yield strength. Approximately 1 percent creep deformation was sufficient in most cases to restore the compression yield/tension yield ratio to that exhibited by the unexposed material. The yield strengths of material subjected to creep at 800°F tended to become equal after about 1 percent creep deformation and thereafter were little affected by further creep.

It is evident that the application of tensile creep to this material caused a decrease in the compression yield strength relative to the tension yield strength for all the conditions investigated. Such behavior appears to be quite consistent with the definition of the Bauschinger effect quoted previously. Recovery effects also appear to operate at 800°F, but the general effect is the same for all temperatures of creep-exposure.

It should be realized, of course, that the foregoing test results and discussion apply to material tested in the direction parallel to the sheet rolling direction. The directionality of the effect was further studied by tests on specimens taken transverse to the sheet rolling direction. These additional tests consisted of room temperature tension and compression tests of as-produced material or material exposed at 800°F for 100 hours without stress. The material tested was from Heats A5036 and A1172600. The samples from Heat A1172600 were taken from a fourth sheet of test stock in order that the longitudinal and transverse specimens could be taken from adjacent portions of the sheet. The longitudinal properties of sheet 4 show good agreement with the average properties determined from sheets 1 - 3.

The test results are summarized on page 22 and presented in the form of a bar graph in Figure 41.

These data indicate that the transverse strengths of C110M tend to be about the same as or somewhat higher than the corresponding longitudinal properties. The compression yield/tensile yield ratio underwent no significant change in either heat as the result of unstressed exposure, and the transverse properties were "normal" for heat A1172600, although there appears to be a tendency for the transverse compression yield strength to be somewhat higher relative to the tension yield strength than was the case for the longitudinal value. The ratio of tensile yield to ultimate tensile strength appeared to be normal for all conditions of transverse testing. The Bauschinger-type effect, therefore, does not appear to be present in the transverse direction of heat A1172600.

The available evidence points very strongly to the presence of residual tensile stress in the longitudinal direction of the material. Such stress probably resulted from a straightening operation and, as indicated previously on page 20, should be removable by stress relief treatments.

The effect of creep-exposure on the subsequent mechanical properties of transverse specimenswas not determined. The data for longitudinal tests, Figures 39 and 40, indicated that tensile creep caused changes in mechanical properties consistent with the definition of the Bauschinger effect (see page 21) and it is not unlikely that similar behavior would be encountered in the transverse direction.

Longitudinal and Transverse Tensile and Compression Properties of C110M

at Room Temperature

Test Direction*

As-Produced	Longitudinal			Transverse		
Heat A1172600	Ult. Strength (psi)	Yield Strength (psi)	Modulus, E (10^6 psi)	Ult. Strength (psi)	Yield Strength (psi)	Modulus, E (10^6psi)
Tensile	147,000	141,000	15.5	145,500	131,000	16.0
	143,500	139,500	15.3	149,000	134,000	15.8
Avg. (Sheet 4)	145,250	140,250	15.4	147,250	132,500	15.9
Avg. (Sheets 1, 2, 3)	(146,211)	(142,889)	(16.5)			
Compression		107,000	16.0		153,000	16.9
		112,000	16.3		162,000	16.3
Avg. (Sheets 1, 2, 3)		109,500	16.2		157,500	16.6
		(108,000)	(16.2)			
Heat A5036						
Tensile	130,000	113,000	14.4	128,500	124,000	15.7
	136,000	116,000	15.1	133,000	128,500	15.8
Avg.	133,000	114,500	14.8	130,750	126,250	15.8
Compression		116,500	16.1		147,000	16.5
		119,500	15.7		142,000	16.6
Avg.		118,000	15.9		144,500	16.6
Exposed 100 hours at 800°F						
Heat A1172600						
Tensile	147,000	130,000	15.4	151,000	137,500	16.0
	145,500	127,000	15.2	153,000	139,000	16.6
Avg.	146,250	128,500	15.3	152,000	138,250	16.3
Compression	135,000	135,000	17.3		157,500	15.8
		137,000	16.7		155,000	16.7
Avg.		136,000	17.0		156,250	16.2
Heat A5036						
Tensile	120,000	101,000	15.2	141,000	120,000	16.0
				139,000	122,000	17.6
Avg.	(120,000)	(101,000)	(15.2)	140,000	121,000	16.6
Compression		110,000	15.7		131,000	16.6
					130,000	17.8
Avg.		(110,000)	(15.7)		130,500	17.2

* with respect to sheet rolling direction

METALLOGRAPHIC EXAMINATION

Metallographic examination was made of several representative specimens of C110M following creep-exposure. Photomicrographs of these specimens are presented together with a photomicrograph of the as-produced material in Figures 42-45. Included with the photomicrographs are the room temperature tensile and compression strengths following the specified exposure.

The as-produced structure consisted of alpha grains in a beta matrix (Figure 42). Very little change at 1000X magnification was discernable in the microstructures of the material after creep-exposure. Figure 45 indicates a possible slight tendency for the alpha grains to become equi-axed during exposure at 800°F.

The mechanical-property data included with these figures indicate that increases in strength or significant changes in interrelation between the tensile and compression yield strength occurred without any microstructural change visible using light microscopic techniques at 1000X.

In earlier work conducted at the University on another heat of this alloy (Ref. 3) examination was made of as-received or heat-treated structures that had been creep tested for as much as 1000 hours at 600°F. This previous examination also indicated no change visible at magnifications up to 1000X.

DISCUSSION

The results of this investigation indicate that prior creep-exposure had relatively little effect on the fracture strength or ductility of C110M in the longitudinal direction to rolling in either normal strain rate tensile tests or tension-impact tests. Exposure of the material either to temperature alone or to temperature and stress did cause significant changes in the manner by which it underwent plastic deformation in short-time tension or compression tests.

The behavior can be attributed to the susceptibility of the material to a Baushinger-type effect and was manifested by an abnormally high tensile yield strength and a low compression yield strength in the as-received stock. It was found that the effect could be modified or eliminated by exposure to temperature alone (in the manner of a stress relief treatment) or could be re-introduced by the application of plastic strain in tension. The plastic strain was composed of creep deformation and, depending on the temperature and stress level, short-time plastic strain obtained during loading.

The maximum effects found followed creep-exposure at 700°F. The study of effects resulting from creep-exposure at 650°F was limited because of the small range of creep deformation that accompanied total deformations of up to 3 percent. Increases in tensile and yield strength following creep at 700°F were as much as 10-20 percent above the base strengths. Exposure to temperature alone at 800°F caused a decrease in the tensile yield strength of as much as 25 percent. This decrease was not eliminated by the introduction of stress to the exposure conditions. Fragmentary data indicate that exposure at 800°F for times up to 1000 hours might cause the room temperature yield strength to drop as much as 50 percent.

The compression yield strength was generally found to be increased above the strength of the as-produced material by exposure to temperature alone. The increase in strength was lost when the material was subjected to tension creep. Generally, creep did not cause the yield strength to drop below the original value for the as-produced material. As the exposure time was increased, a larger amount of deformation was required in order to result in the same loss of compression yield strength.

Very little could be interpreted from the results of the tension-impact tests. Excessive scatter masked what may have been a slight tendency for the strength to decrease following larger amounts of prior deformation. The tension-impact tests at elevated temperature showed little or no effect of prior creep on subsequent properties.

The test data were studied in an attempt to determine the main factor affecting properties. Correlations were presented in terms of either creep deformation or total deformation versus mechanical properties following exposure. In the circumstance where creep represented the major part of the deformation, i.e., creep-exposures at 800°F, the creep deformation can be safely said to be the governing factor. At 650°F and in some cases at 700°F, a substantial amount of plastic deformation occurred during loading. Under these circumstances it is difficult to ascertain whether plastic loading deformation, creep deformation, or total plastic strain was the principal contributor to changes in properties. The effect of varying the proportions of loading deformation to creep deformation was studied by comparing the mechanical properties following constant amounts of total deformation, independent of the time required to reach them. Thus, three different loads, representing three different loading deformations, were required to reach a given total deformation in 10, 50, or 100 hours.

Such an analysis was complicated by the effects due to exposure to temperature alone and, consequently, no clear cause could be fixed to explain the results of 650° or 700°F creep-exposures on the basis of the presently available data. To explain these effects completely would require additional experimentation designed to separate the effects of short-time plastic strain, creep deformation, aging, and recovery effects. Such exposures should be directed to reach a specified final amount of plastic strain through a number of different paths involving combinations of pre-strain or post-strain.

A limited number of room temperature tensile and compression tests on transverse samples indicated that the Bauschinger-type effect was not present in the transverse direction of the as-produced material. No information was obtained on the effects of creep-exposure on transverse specimens.

It does appear to be fairly well established that exposure of C110M to plastic strain and/or temperature can cause marked changes in certain short-time mechanical properties of interest to the designer of aircraft structure. The alterations in the absolute values of tension and compression yield strengths and their ratio would certainly be an example of how service conditions could affect subsequent load-carrying ability.

CONCLUSIONS

Exposure of C110M sheet to temperature and stresses resulting in total deformations of up to 3 percent in 100 hours at temperatures of 650°, 700°, or 800°F caused little change in the fracture strength or ductility in tensile tests or tension-impact tests at either room temperature or the temperature of exposure.

The as-received material exhibited an abnormally high tensile yield strength and a low compression yield strength in the directional longitudinal to the sheet rolling direction. Exposure to temperature alone caused a decrease in the tensile yield strength and an increase in the compression yield strength. These changes were dependent on the exposure time and temperature and the test temperature.

Plastic deformation occurring during loading in tension, or mainly as a result of creep in tension, caused increases in the tensile yield strength and decreases in the compression yield strength. Again, these changes were dependent on both the exposure conditions and the test temperature.

The behavior of the tension and compression yield strengths may be attributed to a Bauschinger-type effect.

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TABLE 1

TOTAL DEFORMATION DATA AND RETAINED TENSILE PROPERTIES

AT ROOM TEMPERATURE FOR C110M

Test Temp (°F)	Spec. No.	Stress (psi)	Loading Deformation (%)	Time to Reach Indicated Total Deformation (hrs) 0.5%	1.0%	2.0%	3.0%	Test Time (hrs)	Total Deformation (%)	Subsequent Room Temperature Tensile Properties: Ult. Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%/2 inches)	Reduction of Area (%)	Modulus, E 10^6 (psi)	Hardness (R"C")
650	1C-32T	105,000	3.88	--	--	--	--	43.3	5.49	166,000	147,000	10.0	30.0	15.8	33.6
	1C-36T	100,000	2.24	--	--	--	0.03	91	5.95	173,000	169,000	11.5	13.7	15.1	40.4
	2C-31C	97,000	1.60	--	--	41	134*	165.9	3.45*	162,000	162,000	7.3	--	15.4	36.1
	3A-28T	95,000	0.84	--	13.5	125.5	--	166	2.63	165,000	160,000	12.2	23.9	15.9	39.0
	1A-36T	85,000	0.68	--	110	--	--	142	1.10	144,000	141,500	20.0	32.6	15.0	38.4
	2A-32T	75,000	0.60	--	125	--	--	142	1.05	164,000	159,000	14.5	22.8	16.8	--
	3C-5T	70,000	0.56	--	290	--	--	307	1.03	151,000	145,000	19.7	27.9	15.4	--
	1A-5T	60,000	0.48	5	--	--	--	216	0.68	152,000	145,000	19.3	29.8	15.6	--
	2A-1T	55,000	0.42	66.5	--	--	--	142	0.53	146,000	140,000	15.8	31.2	15.8	36.1
700	3C-24T	90,000	0.86	--	0.4	12.9	25*	51	5.0*	--	--	--	--	--	--
	3AB-17T	80,000	0.65	--	22.2	47*	68*	71	3.1*	164,000	158,000	13.0	22.0	15.2	39.2
	2A-13T	75,000	0.63	--	17	46	64	147	6.0*	174,200	164,800	7.3	17.3	16.5	--
	2C-32T	65,000	0.52	--	41	94	127	143	3.49	170,000	151,000	16.8	26.0	16.1	--
	3A-5T	60,000	0.43	5	49	102	142	210	4.8*	169,000	149,000	16.5	21.2	16.1	--
	1C-5T	50,000	0.36	28	108	220	--	242	2.18	167,000	151,000	15.7	25.6	16.9	--
	2C-9T	40,000	0.30	63	193	--	--	193	1.10	158,000	140,000	17.5	27.0	16.6	--
	1A-1T	35,000	0.21	110	--	--	--	139	0.58	149,000	134,000	18.0	27.4	15.5	--
800	3C-13T	35,000	0.30	1	3.2	7.6	12.2	46	6.60	151,000	140,000	19.3	25.2	15.9	--
	2A-20T	30,000	0.24	3	8.5	17.5	26	117	10*	151,000	138,000	20.3	28.6	15.0	--
	1A-24T	25,000	0.18	4	11	27.5	46.5	123	6.40	158,000	137,000	24.0	31.4	17.2	--
	3C-32T	20,000	0.18	11	29	87	160	169	3.10	145,000	130,000	19.8	21.4	16.2	--
	3A-32T	15,000	0.07	20	64	314	--	358	2.11	143,000	125,000	23.0	25.2	15.2	33.2
	2C-1T	10,000	0.09	52.5	296	--	--	307	1.02	150,000	132,000	30.0	25.5	16.5	--
	1C-20T	5,000	0.05	1140	--	--	--	1292	0.52	135,000	67,700	23.8	33.5	16.3	35.9

* Estimate by extrapolation.

TABLE 2

TENSILE TEST DATA FOR

C110M AS PRODUCED

Test Temp (°F)	Spec. No.	Ult. Tensile Strength (psi)	0.2% offset Yield Strength (psi)	Elongation (%/ 2 inches)	Reduction of Area (%)	Modulus, E 10^6 (psi)
room	1A-9T	145,000	140,000	22.0	35.2	16.8
	1AB-17T	144,000	139,000	24.0	32.4	16.0
	1C-13T	152,000	144,000	21.5	30.2	16.8
	Average	147,000	141,000	23.5	32.6	16.5
	2C-5T	146,000	144,000	22.3	29.6	16.8
	2C-20T	147,000	143,000	21.7	31.6	16.4
	2A-28T	146,000	142,000	20.5	32.0	16.9
	Average	146,333	143,000	21.5	31.1	16.7
	3C-20T	146,000	142,000	22.7	26.4	15.8
	3A-13T	147,000	145,000	21.5	30.8	16.4
	3A-34T	151,000	147,000	22.5	33.3	16.6
	Average	148,000	144,667	22.2	30.1	16.3
	Average - 9 tests	146,211	142,889	22.4	31.3	16.5
650	1C-24T	108,000	92,000	19.5	28.0	13.4
	1A-32T	109,000	95,000	21.0	33.3	13.8
	1C-9T	107,000	--	15.1	31.6	13.6
	Average	108,000	93,500	18.5	31.0	13.5
	2A-24T	112,000	97,000	14.5	29.0	13.6
	2C-13T	111,000	97,000	17.5	24.7	13.5
	2A-5T	112,000	94,500	16.0	24.0	13.9
	Average	111,667	96,167	16.0	25.9	13.7
	3C-9T	114,000	100,000	17.0	21.6	13.8
	3C-34T	111,000	96,700	17.7	26.6	13.0
	3A-1T	112,000	98,600	16.7	24.8	13.6
	Average	112,333	98,433	17.1	24.3	13.5
	Average - 9 tests	110,667	96,033	17.2	27.1	13.6
700	1C-1T	94,900	83,500	17.2	36.4	12.3
	1A-13T	106,000	91,000	19.0	34.1	13.7
	1A-28T	105,000	92,700	21.2	31.4	13.6
	Average	101,967	89,067	19.1	33.9	13.2
	2C-36T	107,000	95,700	16.1	32.7	13.6
	2C-24T	107,000	91,400	17.0	32.8	13.3
	2AB-17T	106,000	91,500	15.8	29.6	13.5
	Average	106,667	92,867	16.3	31.8	13.5
	3C-17T	107,000	97,500	16.0	32.4	12.8
	3A-24T	109,000	96,700	18.7	29.2	13.4
	3A-9T	108,000	94,000	19.0	28.0	12.7
	Average	108,000	96,067	17.9	29.9	13.0
	Average - 9 tests	105,545	92,667	17.8	31.9	13.2
800	1C-28T	90,000	83,000	39.7	51.0	11.8
	1C-17T	90,000	85,000	25.4	47.3	11.8
	1A-20T	90,600	82,000	29.0	49.5	12.0
	Average	90,200	83,333	31.4	49.3	11.9
	2A-9T	91,000	79,700	30.0	48.7	12.0
	2A-36T	93,000	84,500	46.5	51.0	12.3
	2C-28T	93,200	85,500	32.0	49.7	11.3
	Average	92,400	83,233	36.2	49.8	11.9
	3C-1T	95,000	84,800	24.7	45.3	11.2
	3C-28T	95,300	85,700	30.8	47.2	11.1
	3A-20T	94,000	87,000	21.3	43.4	11.2
	Average	94,766	85,833	25.6	45.3	11.2
	Average - 9 tests	92,455	84,133	31.1	48.1	11.7

TABLE 3

COMPRESSION TEST DATA

FOR C110M AS PRODUCED

Test Temp (°F)	Spec. No.	0.2% offset Yield Strength (psi)	Compression Modulus, E 10^6 (psi)
room	1C-24C	108,000	15.8
	1A-5C	107,000	16.2
	1A-13C	108,000	16.0
	Average	107,667	16.0
	2C-24C	107,000	16.7
	2C-9C	109,000	15.9
	2A-28C	105,000	16.4
	Average	107,000	16.3
	3A-24C	108,000	16.0
	3C-32C	110,000	16.4
	3A-9C	111,000	16.1
	Average	109,667	16.2
	Average - 9 tests	108,111	16.2
650	1A-24C	63,000	12.9
	1C-32C	58,400	12.6
	1C-5C	57,600	12.8
	Average	59,667	12.8
	2C-28C	58,400	12.9
	2A-9C	55,800	13.2
	2A-5C	68,400	13.2
	Average	60,800	13.1
	3A-13C	58,600	13.2
	3C-24C	71,000	13.3
	3C-5C	57,800	12.8
	Average	62,400	13.1
	Average - 9 tests	61,000	13.0
700	1A-28C	57,900	12.7
	1C-13C	53,800	12.5
	1A-9C	55,400	12.3
	Average	55,700	12.5
	2C-13C	60,600	12.9
	2A-24C	--	12.5
	2C-5C	59,400	12.5
	Average	60,000	12.6
	3A-32C	54,600	12.7
	3C-28C	59,000	12.5
	3C-6C	--	12.4
	Average	56,800	12.5
	Average - 7 tests	57,243	12.5
800	1C-28C	53,900	11.8
	1C-9C	55,100	11.8
	1A-32C	53,800	11.6
	Average	54,300	11.7
	2C-32C	62,500	12.0
	2A-32C	55,400	11.7
	2A-13C	55,600	11.9
	Average	57,800	11.9
	3A-28C	59,800	12.1
	3C-13C	--	--
	3A-5C	54,600	11.7
	Average	57,200	11.9
	Average - 8 tests	56,337	11.8

TABLE 4

TENSION-IMPACT TEST DATA (SMOOTH BAR)

FOR AS-PRODUCED C110M

Test Temp (°F)	Spec. No.	Tension-Impact Strength (ft-lb)
room	1A-5M	48
	1A-13M	50
	1C-24M	69
	Average	55.6
	2A-28M	67
	2C-5M2	64
	2C-9M	37
	Average	56.0
	3A-9M	50
	3A-29M	62
	3C-28M	58
	Average	56.6
	Average - 9 tests	56
650	1A-24M	47
	1C-5M1	50
	1C-13M	50
	Average	49
	2A-5M2	47
	2A-9M	59*
	2C-24M	44
	Average	46
	3A-5M1	45
	3C-5M2	44
	3C-9M	43
	Average	44
	Average - 8 tests	46
700	1A-5M2	53*
	1A-28M	48
	1C-9M	47
	Average	48
	2AB-24M	43
	2C-5M1	41
	2C-13M	45
	Average	43
	3A-5M2	33*
	3A-13M	43
	3C-24M	43
	Average	43
	Average - 7 tests	44
800	1C-5M2	57*
	1C-28M	41
	Average	
	2A-5M1	41
	2A-13M	47
	2C-28M	45
	Average	44
	3A-28M	45
	3C-5M1	52*
	3C-13M	41
	Average	43
	Average - 6 tests	43

*** Omitted from Average.**

TABLE 5

EFFECT OF UNSTRESSED EXPOSURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF C110M

Exposure Conditions			Tensile Properties After Exposure						
Temp (°F)	Time (hrs)	Spec. No.	Test Temp (°F)	Ult. Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%)	Reduction of Area (%)	Modulus, E 10^6 (psi)	Hardness (R"C")
650	10.0	2A-31A	room	144,000	136,000	25.3	31.4	15.1	35.3
	50.0	1C-26C	room	147,500	140,000	23.3	35.6	15.4	37.2
	100.0	2A-21A	room	143,400	136,800	24.0	32.2	15.5	35.8
	105.5	1A-B26	room	145,000	135,000	20.5	34.8	15.0	36.5
	Average			144,200	135,900	22.2	33.5	15.2	36.2
700	10.0	1C-D15	room	143,000	140,000	23.8	34.0	15.4	39.1
	10.0	3C-D33	room	146,000	---	24.0	27.9	15.4	38.7
	Average			144,500	140,000	23.9	30.9	15.4	38.9
	50.0	2C-21C	room	149,000	137,500	23.0	33.2	16.1	35.8
	100.0	1A-3A	room	146,500	140,000	19.5	32.0	15.4	38.5
800	10.0	1A-15A	room	146,000	133,000	24.0	35.7	15.1	35.1
	50.0	1C-D3	room	144,000	129,000	23.3	31.8	15.0	34.9
	50.0	3C-33C	room	146,000	130,000	22.5	29.8	15.8	36.3
	Average			145,000	129,500	22.9	30.8	15.4	35.6
	100.0	2C-D31	room	147,000	125,000	19.3	29.2	15.7	34.1

TABLE 6

EFFECT OF UNSTRESSED EXPOSURE ON ELEVATED TEMPERATURE

TENSILE PROPERTIES OF C110M

Exposure Conditions			Tensile Properties After Exposure						
Temp (°F)	Time (hrs)	Spec. No.	Test Temp (°F)	Ult. Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%)	Reduction of Area (%)	Modulus, E 10^6 (psi)	Hardness (R"C"*)
650	10.0	3C-11C	650	112,700	94,900	20.5	26.0	13.7	35.4
	50.0	2A-B21	650	111,500	94,500	17.5	27.6	12.9	34.5
	100.0	2A-B7	650	114,000	97,000	22.5	26.3	12.9	35.8
	105.5	3C-D11	650	109,000	97,500	15.0	26.4	13.1	37.2
	Average			111,500	97,250	18.8	26.4	13.0	36.5
700	10.0	2C-D7	700	107,000	91,000	17.5	31.6	13.5	36.5
	50.0	3A-11A	700	108,000	90,000	13.8	16.9	13.1	35.5
	100.0	3C-18C	700	109,000	84,400	17.3	30.2	11.5	35.8
	100.0	1C-D26	700	104,000	79,800	22.0	33.6	12.2	37.2
	Average			106,500	82,100	19.7	31.9	11.8	36.5
800	10.0	3A-B33	800	91,600	74,400	22.3	48.6	11.3	34.7
	10.0	1C-15C	800	87,400	67,300	33.0	49.0	11.5	36.0
	Average			89,500	70,850	27.2	48.8	11.4	35.4
	50.0	2A-B31	800	92,200	68,000	23.5	45.0	11.4	32.8
	100.0	3A-18A	800	96,500	78,200	29.5	43.4	11.2	37.0

* Rockwell "C" hardness at room temperature

TABLE 7

EFFECT OF PRIOR CREEP-EXPOSURE ON ROOM TEMPERATURE

TENSILE PROPERTIES AND HARDNESS OF C110M

Nominal Exposure Conditions			Actual Exposure Conditions								Room Temperature Tensile Properties After Exposure					
Temp (°F)	Time (hrs)	Total Def. (%)	Spec. No.	Time (hrs)	Temp (°F)	Stress (psi)	Load. Def. (Total) (%)	Load. Def. (Plastic) (%)	Creep Def. (%)	Total Def. (%)	Ult. Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%/2 inches)	Reduction of Area (%)	Modulus E x 10^6(psi)	Hardness R"C"
650	10	0.5	2CD3	10.0	650	59,000	0.42	nil	0.06	0.48	145,500	141,000	21.0	29.4	15.9	36.6
		1.0	1AB11	10.0	650	95,200	1.61	0.90	0.22	1.83	145,000	145,000	20.5	31.4	16.2	36.1
			3AB20	10.0	650	96,605	0.94	0.24	0.18	1.12	144,500	141,500	22.3	33.4	15.0	37.3
		2.0	3A29	10.0	650	97,500	1.30	0.60	0.30	1.60	148,000	148,000	20.0	27.5	15.7	36.8
		3.0	1A17A	10.0	650	98,000	2.51	1.80	0.35	2.86	148,000	148,000	22.3	31.7	15.5	38.5
	50	0.5	3CD8	50.0	650	56,000	0.32	nil	0.08	0.40	147,000	144,000	19.5	32.0	16.9	37.9
		1.0	1C4	50.0	650	86,000	0.89	0.28	0.19	1.08	141,000	139,000	22.5	33.2	14.9	36.8
		2.0	2AB26	50.3	650	96,800	1.49	0.76	0.55	2.04	151,000	148,000	24.3	30.2	16.0	37.2
		3.0	2C15C	50.0	650	97,300	1.74	1.01	0.60	2.34	148,000	148,000	--	25.7	15.7	38.4
	100	0.5	1A30	100.0	650	54,000	0.41	nil	0.10	0.51	145,000	130,500	22.0	32.0	15.0	37.0
		1.0	3A8	100.0	650	82,000	0.74	0.14	0.26	1.00	151,000	147,000	21.0	28.3	15.4	37.5
		2.0	2C3	100.0	650	95,200	0.80	0.10	0.47	1.27	152,000	148,000	18.8	28.2	16.0	37.9
		3.0	2AB20	100.0	650	95,800	1.48	0.80	0.84	2.32	148,000	145,000	18.3	30.5	15.4	37.6
700	10	0.5	1A4	10.0	700	56,000	0.43	nil	0.12	0.55	138,000	135,000	21.0	30.0	14.7	38.5
		1.0	3AB8	10.0	700	79,000	0.62	0.10	0.17	0.79	149,000	144,000	23.2	31.4	15.5	36.6
		2.0	2A16	10.0	700	93,000	1.77	1.07	0.96	2.73	150,500	149,500	21.0	31.2	15.2	37.9
		3.0	3CD14	10.0	700	100,000	3.76	3.00	5.44	8.80	177,000	175,000	7.8	18.2	15.6	34.2
	50	0.5	1CD30	50.1	700	43,000	0.34	nil	0.21	0.55	146,000	141,000	22.0	32.1	17.0	37.7
		1.0	3AB14	50.0	700	62,000	0.46	nil	0.38	0.84	152,000	145,000	20.5	28.8	15.7	37.5
		2.0	2A26	50.3	700	75,000	0.64	nil	0.98	1.62	149,000	144,000	17.8	23.4	15.2	37.3
		3.0	1A11	50.2	700	82,000	0.68	0.05	2.19	2.87	164,000	158,000	17.0	27.5	15.0	40.4
	100	0.5	3A33A	100.0	700	36,000	0.25	nil	0.26	0.51	148,000	136,500	20.5	28.8	16.5	38.0
		1.0	2A7A	100.1	700	51,000	0.36	nil	0.32	0.68	149,000	138,000	21.7	32.9	15.2	34.7
		2.0	1A26A	100.0	700	63,000	0.50	nil	1.78	2.28	162,000	149,000	17.3	26.2	16.1	39.4
		3.0	3AB11	117.7	700	69,000	0.51	nil	1.89	2.40	162,000	152,000	15.0	23.8	15.2	38.3
800	10	0.5	1CD11	10.0	800	21,000	0.18	nil	0.33	0.51	144,000	134,000	22.5	33.2	15.2	36.0
		1.0	2AB2	10.0	800	28,000	0.21	nil	0.58	0.79	141,400	132,300	25.0	31.4	16.2	35.8
		2.0	2CD16	10.0	800	34,000	0.29	nil	1.76	2.05	147,000	135,000	20.5	30.6	15.3	35.8
		3.0	1AB4	10.0	800	37,000	0.29	nil	2.08	2.37	146,000	137,500	22.7	30.8	15.5	37.2
	50	0.5	2CD21	50.0	800	11,000	0.08	nil	0.40	0.48	142,000	125,000	23.5	31.1	16.0	36.7
		1.0	1CD4	50.0	800	17,000	0.14	nil	0.92	1.06	143,500	128,000	21.0	31.4	15.4	36.7
		2.0	3CD18	50.1	800	22,500	0.16	nil	2.16	2.32	149,000	130,500	20.0	25.5	15.8	35.1
		3.0	1AB15	50.0	800	25,000	0.20	nil	2.44	2.64	146,000	131,000	21.3	30.3	15.7	36.1
	100	0.5	1AB3	100.0	800	9,500	0.11	0.03	0.45	0.56	142,000	121,000	22.3	30.3	15.9	33.7
		1.0	3AB18	100.0	800	14,000	0.13	0.03	1.11	1.24	145,000	129,000	21.8	29.6	16.1	36.5
		2.0	2C7C	100.1	800	19,500	0.17	0.02	2.04	2.21	146,000	130,000	20.5	25.8	16.5	34.3
		3.0	1C3C	100.0	800	22,000	0.17	nil	2.67	2.84	145,000		19.5	28.7	16.3	33.1

TABLE 8

EFFECT OF PRIOR CREEP-EXPOSURE ON ELEVATED TEMPERATURE

TENSILE PROPERTIES OF C110M

Nominal Exposure Conditions				Actual Exposure Conditions							Tensile Properties After Exposure							
Temp (°F)	Time (hrs)	Total Def. (%)	Spec. No.	Time (hrs)	Temp (°F)	Stress (psi)	Load. Def. (Total) (%)	Load. Def. (Plastic) (%)	Creep Def. (%)	Total Def. (%)	Test Temp. (°F)	Ult. Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%/2 inches)	Reduction of Area (%)	Modulus, E x 10⁶ (psi)	Hardness R"C" *
650	10	0.5	1CD1	10.1	650	59,000	0.43	nil	0.05	0.48	650	106,000	89,400	17.5	32.2	13.7	37.0
		1.0	2A36A	10.1	650	95,200	1.86	1.15	0.27	2.13	650	109,000	98,800	14.5	30.9	13.6	37.8
	100	0.5	3A15	100.1	650	54,000	0.37	nil	0.11	0.48	650	110,000	91,500	12.5	29.4	13.6	37.9
		1.0	1C7	100.0	650	82,000	0.68	0.12	0.24	0.92	650	107,000	88,500	17.7	30.5	12.8	37.5
		2.0	2C25	100.0	650	95,200	1.62	0.94	0.69	2.31	650	115,000	102,000	11.3	34.5	13.6	36.8
		3.0	3A21A	100.0	650	98,000	1.15	0.45	1.13	2.28	650	113,000	102,000	--	33.8	13.7	38.7
700	10	0.5	3CD27	10.0	700	56,000	0.38	nil	0.10	0.48	700	107,000	--	16.5	35.5	--	36.0
		1.0	1AA36	10.0	700	82,000	0.69	0.05	0.25	0.94	700	103,000	93,000	17.3	33.6	12.5	37.8
		2.0	2C17C	10.0	700	90,500	0.93	0.24	0.50	1.43	700	112,000	98,400	17.5	33.6	12.1	35.0
		3.0	1AB1	10.0	700	92,000	1.04	0.33	0.74	1.78	700	106,500	96,300	15.8	33.8	12.3	35.4
	100	0.5	2CD25	100.0	700	36,000	0.36	0.24	0.41	0.67	700	112,500	82,000	15.5	33.2	12.0	37.5
		1.0	1A7	100.0	700	51,000	0.34	nil	0.74	1.08	700	112,000	78,300	13.0	25.0	12.6	38.0
		2.0	2C10	100.0	700	63,000	0.46	nil	1.09	1.55	700	119,500	93,600	14.3	32.9	12.8	38.7
		3.0	3AB3	100.0	700	70,000	0.56	0.02	1.86	2.42	700	119,000	98,400	8.0	20.9	12.9	36.9
800	10	0.5	3A27	10.0	800	21,000	0.17	0.04	0.44	0.61	800	93,000	64,200	36.5	53.0	12.2	37.0
		1.0	3C8	10.0	800	28,000	0.25	nil	0.77	1.02	800	93,100	70,100	25.0	36.0	11.5	34.2
		2.0	1AB20	10.0	800	34,000	0.26	nil	1.23	1.49	800	90,700	78,200	38.5	36.6	12.8	36.6
		3.0	2A17A	10.0	800	38,000	0.30	0.02	1.69	1.99	800	92,500	69,400	33.0	51.5	11.5	36.9
	100	0.5	1AB33	100.0	800	9,500	0.08	nil	0.51	0.59	800	88,000	73,400	29.3	49.3	12.8	36.4
		1.0	3C15	100.3	800	14,000	0.11	nil	0.94	1.05	800	87,500	57,500	47.0	57.0	12.2	36.1
		2.0	1AB7	100.0	800	19,500	0.17	nil	1.91	2.08	800	87,000	56,700	43.8	50.8	12.7	36.8
		3.0	2A25	100.0	800	22,000	0.15	nil	3.04	3.19	800	90,000	59,800	32.8	50.0	11.8	36.9

* Rockwell "C" hardness at room temperature

TABLE 9

EFFECT OF UNSTRESSED EXPOSURE ON ROOM TEMPERATURE COMPRESSION PROPERTIES OF C110M

Exposure Conditions			Compression Properties After Exposure		
Exposure Temp (°F)	Exposure Time (hrs)	Spec. No.	Test Temp (°F)	0.2% Offset Yield Strength (psi)	Compression Modulus, E 10^6 (psi)
650	10	1AB13	room	115,000	15.9
	10	2C32	room	105,000	16.1
		Average		110,000	16.0
	50	2CD9	room	126,000	16.2
	50	3CD13	room	124,000	16.5
		Average		125,000	16.4
	100	1AA28	room	128,000	15.9
	100	3AB9	room	119,000	15.4
		Average		123,500	15.6
700	10	1CD24	room	147,000	16.1
	10	3CD9	room	136,000	15.7
		Average		141,500	15.9
	50	1AB24	room	127,000	15.6
	50	3C32	room	152,000	16.6
		Average		139,500	16.1
	100	2CD32	room	134,000	15.7
	100	3AB13	room	132,000	15.0
		Average		133,000	15.4
800	10	1CC32	room	149,000	16.5
	10	2CD24	room	151,000	16.3
		Average		150,000	16.4
	50	2AB9	room	147,000	16.1
	50	3CD24	room	153,000	16.2
		Average		150,000	16.2
	100	1AB32	room	135,000	16.6
	100	3C28	room	142,000	16.8
		Average		138,500	16.7

TABLE 10

EFFECT OF UNSTRESSED EXPOSURE ON ELEVATED TEMPERATURE COMPRESSION PROPERTIES OF C110M

Exposure Conditions			Compression Properties After Exposure		
Exposure Temp (°F)	Exposure Time (hrs)	Spec. No.	Test Temp (°F)	0.2% Offset Yield Strength (psi)	Compression Modulus, E 10^6 (psi)
650	10	1CD13	650	61,000	13.2
	10	3AA32	650	58,400	13.2
		Average		59,700	13.2
	50	1CD32	650	59,100	13.7
	50	2AB13	650	---	--
		Average		(59,100)	(13.7)
	100	2A24	650	63,700	13.6
	100	3CD32	650	65,300	13.4
		Average		64,500	13.5
700	10	2CD13	700	82,700	13.4
	10	3A28	700	73,900	12.8
		Average		83,300	13.1
	50	1CC28	700	67,800	12.7
	50	2AA32	700	76,500	13.1
		Average		72,150	12.9
	100	1AA32	700	62,000	12.5
		2AA28	700	88,000	13.3
		Average		75,000	12.9
800	10	2CC28	800	62,500	12.6
	10	3AB24	800	63,800	11.2
		Average		63,150	12.2
	50	1AB9	800	67,800	11.8
	50	3AB32	800	72,500	12.5
		Average		70,150	12.2
	100	1CD9	800	60,800	12.2
	100	2AB32	800	58,800	11.8
		Average		59,800	12.0

TABLE 11

EFFECT OF PRIOR CREEP-EXPOSURE ON ROOM TEMPERATURE COMPRESSION PROPERTIES OF C110M

Nominal Exposure Conditions				Actual Exposure Conditions							Compression Properties After Exposure		
Temp (°F)	Time (hrs)	Total Def. (%)	Spec. No.	Time (hrs)	Temp (°F)	Stress (psi)	Load. Def. (Total) (%)	Load. Def. (Plastic) (%)	Creep Def. (%)	Total Def. (%)	Test Temp (°F)	0.2% Offset Yield Strength (psi)	Compression Modulus E x 10^6 (psi)
650	10	0.5	3CD15	10.0	650	59,000	0.44	nil	0.05	0.49	room	115,000	15.8
		1.0	2AB10	10.0	650	95,000	1.54	0.85	0.22	1.76	room	107,500	15.3
		2.0	1A18	10.0	650	97,520	2.66	1.95	0.55	3.21	room	98,300	15.2
		3.0	3CD10	10.0	650	98,000	1.06	0.35	0.20	1.26	room	101,000	15.9
	50	0.5	1CD18	50.0	650	56,000	0.44	0.03	0.07	0.51	room	118,000	15.2
		1.0	2AB25	50.0	650	88,929	0.72	0.06	0.27	0.99	room	114,000	16.9
		2.0	3CD3	50.0	650	96,800	0.85	0.15	0.85	1.70	room	104,000	15.2
		3.0	1AB29	50.1	650	97,500	2.25	1.55	0.85	3.10	room	108,000	16.1
	100	0.5	3C3	100.0	650	54,000	0.36	nil	0.08	0.44	room	127,000	16.7
		1.0	1C18	100.0	650	82,000	0.72	0.13	0.38	1.10	room	114,000	15.7
		2.0	2A10	101.0	650	95,200	2.24	1.53	0.86	3.10	room	108,000	15.3
		3.0	1CD6	100.0	650	95,900	2.19	1.50	1.24	3.43	room	102,000	16.0
700	10	0.5	1CD33	10.0	700	56,000	0.43	nil	0.11	0.54	room	125,000	16.4
		1.0	2A2	10.0	700	82,000	0.62	nil	0.32	0.94	room	115,000	15.3
		2.0	3C27	10.0	700	90,500	1.27	0.58	0.66	1.93	room	94,400	16.8
		3.0	1AB18	10.0	700	92,000	2.16	1.45	1.43	3.59	room	103,000	16.6
	50	0.5	2C2	50.6	700	43,000	0.33	nil	0.19	0.52	room	130,000	15.0
		1.0	1A33	50.0	700	64,000	0.53	0.03	0.60	1.13	room	120,000	16.3
		2.0	3AB15	50.0	700	75,000	0.61	0.03	1.54	2.15	room	106,500	16.0
		3.0	2CD10	50.0	700	82,000	0.73	0.10	5.72	6.45	room	110,000	15.9
	100	0.5	2CD26	100.1	700	36,000	0.27	nil	0.31	0.58	room	136,000	16.4
		1.0	3AB29	100.0	700	51,000	0.38	nil	0.67	1.05	room	131,000	16.2
		2.0	3C14	99.9	700	63,000	0.51	0.02	0.84	1.35	room	121,000	16.2
		3.0	1C30	100.1	700	70,000	0.61	0.07	2.91	3.52	room	114,000	16.1
800	10	0.5	3C29	10.0	800	21,000	0.15	nil	0.42	0.57	room	131,000	16.3
		1.0	2A3	10.0	800	28,000	0.22	nil	0.64	0.86	room	136,000	15.7
		2.0	3A14	10.0	800	34,000	0.27	nil	1.44	1.71	room	136,000	16.5
		3.0	2C26	10.0	800	38,000	0.32	nil	2.30	2.62	room	136,000	16.4
	50	0.5	3A3	50.0	800	11,000	0.06	nil	0.32	0.38	room	140,000	15.6
		1.0	1C33	50.0	800	17,000	0.12	nil	0.97	1.09	room	129,000	16.8
		2.0	2CD2	50.0	800	22,500	0.17	nil	1.71	1.88	room	123,500	16.5
		3.0	3AB27	50.0	800	25,000	0.20	nil	2.78	2.98	room	129,000	16.2
	100	0.5	2AB16	100.0	800	9,500	0.09	nil	0.44	0.53	room	132,500	15.5
		1.0	3CD29	99.9	800	14,000	0.10	nil	0.97	1.07	room	135,200	15.8
		2.0	2C16	99.9	800	19,500	0.14	nil	1.37	1.51	room	128,000	15.5
		3.0	1AB30	100.0	800	22,000	0.19	nil	2.87	3.06	room	130,000	15.2

TABLE 12

EFFECT OF PRIOR CREEP-EXPOSURE ON ELEVATED TEMPERATURE COMPRESSION PROPERTIES OF C110M

Nominal Exposure Conditions			Actual Exposure Conditions								Compression Properties After Exposure		
Temp (°F)	Time (hrs)	Total Def. (%)	Spec. No.	Time (hrs)	Temp (°F)	Stress (psi)	Load. Def. (Total) (%)	Load. Def. (Plastic) (%)	Creep Def. (%)	Total Def. (%)	Test Temp (°F)	Yield Strength (psi)	Compression Modulus, E 10^6 (psi)
650	10	0.5	2CC4	10.0	650	59,100	0.40	0.02	0.05	0.45	650	67,800	13.5
		1.0	3CD21	10.0	650	95,100	0.79	0.08	0.15	0.94	650	53,600	13.5
		2.0	2C36C	10.1	650	97,500	2.16	1.45	0.26	2.42	650	51,700	13.7
			3AB30	10.0	650	97,500	1.15	0.45	0.17	1.32	650	49,600	14.7
	100	0.5	3AB1	100.0	650	54,000	0.37	nil	0.11	0.48	650	66,000	13.2
		1.0	1C17C	100.0	650	82,000	0.70	0.12	0.35	1.05	650	67,600	14.1
		2.0	3A34A	100.0	650	95,200	0.76	0.06	0.68	1.44	650	53,800	13.6
		3.0	2AB27	100.0	650	96,000	1.13	0.44	0.57	1.70	650	54,700	13.3
700	10	0.5	3C10C	10.0	700	56,000	0.39	nil	0.09	0.48	700	63,800	12.8
		1.0	2A15A	10.0	700	82,000	0.70	0.06	0.29	0.99	700	56,100	12.2
		2.0	2CD4	10.0	700	90,500	0.88	0.20	0.46	1.34	700	58,700	13.2
		3.0	1AA23	10.0	700	92,000	1.08	0.38	1.57	2.65	700	55,500	12.5
	100	0.5	1C36C	100.0	700	36,000	0.27	nil	0.31	0.58	700	78,300	12.6
		1.0	2AB1	100.0	700	51,000	0.37	nil	0.66	1.03	700	67,000	13.0
		2.0	2CD20	100.0	700	63,500	0.43	nil	1.55	1.98	700	59,500	13.6
		3.0	3A17A	100.0	700	70,000	0.51	nil	2.70	3.21	700	91,800	12.8
800	10	0.5	2CD15	10.0	800	21,000	0.16	nil	0.45	0.61	800	64,800	11.8
		1.0	3C21C	10.0	800	28,000	0.22	nil	0.57	0.79	800	70,100	11.6
		2.0	1AA16	10.0	800	34,000	0.26	nil	1.35	1.61	800	67,300	12.5
		3.0	1C31C	10.0	800	38,200	0.31	0.02	2.27	2.58	800	64,600	12.4
	100	0.5	2A27A	100.0	800	9,500	0.08	nil	0.51	0.59	800	71,000	11.8
		1.0	1C14C	100.0	800	14,000	0.10	nil	0.99	1.09	800	64,600	11.7
		2.0	3AB21	100.0	800	19,500	0.15	nil	2.19	2.34	800	69,000	12.3
		3.0	2AB15	100.0	800	22,000	0.17	nil	3.05	3.22	800	64,600	11.9
			2CD1	100.0	800	28,000	0.19	nil	6.66	6.85	800	62,200	12.4

TABLE 13

EFFECT OF UNSTRESSED EXPOSURE ON ROOM TEMPERATURE TENSION-IMPACT PROPERTIES OF C110M

Exposure Conditions			Tension-Impact Properties After Exposure			
Temp (°F)	Time (hrs)	Spec. No.	Test Temp (°F)	Tension-Impact Strength (ft-lb)	Elongation (%/2 inches)	Reduction of Area (%)
650	10	1CD5	room	65	6.0	27.7
	10	2CD24	room	53	8.0	24.5
		Average		59	7.0	26.1
	50	1A13A	room	46	5.0	16.7
	50	3CD24	room	52	7.5	22.4
		Average		49	6.2	19.6
	100	2A24	room	86	15.0	35.3
	100	3A5	room	50	6.0	36.7
		Average		68	10.5	36.0
700	10	1CC32	room	95	15.5	29.6
	50	2CC28	room	76	8.5	27.4
	50	3AB9	room	44	5.0	17.5
		Average		60	6.8	22.4
	100	1C13C	room	53	4.0	21.0
	100	2C32	room	57	11.0	28.3
		Average		55	7.5	24.6
800	10	1CC28	room	64	10.5	37.3
	10	3AA32	room	66	13.0	27.8
		Average		65	11.8	32.6
	50	2AA28	room	69	6.0	26.5
	50	3AB24	room	34	4.0	13.6
		Average		52	5.0	20.0
	100	2AA13	room	83	16.5	30.1
	100	3A28	room	78	15.0	30.4
		Average		80	15.8	30.2

TABLE 14

EFFECT OF UNSTRESSED EXPOSURE ON ELEVATED TEMPERATURE TENSION-IMPACT PROPERTIES OF C110M

Exposure Conditions			Tension-Impact Properties After Exposure			
Temp (°F)	Time (hrs)	Spec. No.	Test Temp (°F)	Tension-Impact Strength (ft-lb)	Elongation (%/2 inches)	Reduction of Area (%)
650	10	2CD5	650	45	11.0	34.5
	10	3C32	650	46	12.0	29.3
		Average		46	11.5	31.9
	50	1CD24	650	49	13.5	37.7
	50	2CD9	650	44	12.0	30.0
		Average		46	12.8	33.8
	100	1AB5	650	50	12.0	37.5
	100	3CD9	650	42	10.0	36.0
		Average		46	11.0	36.8
700	10	1AA28	700	47	13.0	41.2
	10	2AB5	700	49	11.0	30.7
		Average		48	12.0	36.0
	50	1AB9	700	47	12.5	35.8
	50	2AA32	700	46	12.0	32.1
		Average		46	12.2	34.0
	100	2AB9	700	68	8.5	20.2
	100	3C5	700	56	8.5	23.7
		Average		62	8.5	22.0
800	10	1AA32	800	35	12.0	34.4
	10	2CC13	800	44	12.5	28.6
		Average		40	12.2	31.5
	50	1AB24	800	46	13.5	35.5
	50	3C13C	800	52	10.8	31.3
		Average		49	12.2	33.4
	100	1CD9	800	46	12.0	32.2
	100	3A13	800	50	10.0	31.3
		Average		48	11.0	31.8

TABLE 15

EFFECT OF PRIOR CREEP ON SMOOTH SPECIMEN TENSION-IMPACT PROPERTIES OF C110M

Nominal Exposure Conditions			Actual Exposure Conditions								Tension-Impact Properties After Exposure			
Temp (°F)	Time (hrs)	Total Def. (%)	Spec. No.	Time (hrs)	Temp (°F)	Stress (psi)	Load Def. (Total) (%)	Load Def. (Plastic)(%)	Creep Def. (%)	Total Def. (%)	Test Temp (°F)	Tension-Impact Strength (ft-lbs)	Elongation (%/2 inches)	Reduction of Area (%)
650	100	0.5	1C6C	100.0	650	54,000	0.35	nil	0.08	0.43	room	27	2.5	30.0
		1.0	3CD2	100.0	650	82,000	0.62	0.02	0.29	0.91	room	55	6.5	29.2
		2.0	2C27C	100.0	650	95,200	1.41	0.74	0.86	2.27	room	82	10.5	23.9
		3.0	1A31A	100.0	650	95,900	1.91	1.23	1.14	3.05	room	41	5.0	27.0
		1.0	2AB34	100.0	650	82,000	0.64	0.04	0.24	0.88	650	46	12.0	35.0
		3.0	1CD14	100.0	650	95,900	0.81	0.13	0.99	1.00	650	50	11.5	32.6
700	10	0.5	1AB6	10.0	700	56,000	0.40	nil	0.08	0.48	room	62	9.5	18.2
		1.0	2CD34	10.0	700	82,000	0.75	0.11	0.50	1.25	room	49	5.5	16.0
		2.0	3AB10	10.0	700	91,000	0.88	0.18	0.38	1.26	room	79	14.0	35.3
		3.0	1CD31	10.0	700	92,000	1.00	0.30	0.53	1.53	room	70	10.0	40.3
		0.5	3CC2	10.0	700	56,000	0.39	nil	0.07	0.46	700	43	12.0	41.1
		1.0	1AB14	10.0	700	82,000	0.74	0.10	0.21	0.95	700	50	12.0	36.8
		2.0	2CD27	10.0	700	90,800	0.86	0.09	0.59	1.45	700	45	9.0	36.9
		3.0	3A30A	10.0	700	92,000	0.78	0.07	0.50	1.28	700	45	9.5	28.9
	100	0.5	2AB4	100.0	700	36,000	0.25	nil	0.19	0.44	room	64	11.0	25.7
		1.0	3C30C	100.0	700	51,000	0.34	nil	0.41	0.75	room	77	10.0	21.9
		2.0	1AB31	100.0	700	63,000	0.42	nil	1.06	1.48	room	73	12.5	30.5
		3.0	2CC34	100.0	700	70,000	0.54	nil	1.70	2.24	room	59	9.5	21.3
		0.5	3AA2	100.0	700	36,000	0.25	nil	0.22	0.47	700	48	10.0	28.5
		1.0	2AA4	100.0	700	51,000	0.39	nil	0.35	0.74	700	47	12.0	34.2
		2.0	1CD23	100.0	700	63,000	0.45	nil	1.64	2.09	700	45	6.0	26.7
		3.0	3AA10	100.0	700	70,000	0.51	nil	2.33	2.84	700	44	7.5	23.8
800	100	0.5	2A34A	100.0	800	9,500	0.06	nil	0.43	0.49	room	61	10.0	31.3
		1.0	3CD30	100.0	800	14,000	0.10	nil	0.87	0.97	room	62	10.0	26.6
		2.0	1AA14	100.0	800	19,500	0.15	nil	2.32	2.47	room	57	9.5	31.6
		3.0	1CD20	100.0	800	21,000	0.15	nil	2.79	2.94	room	71	10.5	27.4
		1.0	1C23C	100.0	800	14,000	0.10	nil	0.89	0.99	800	41	10.0	40.0
		3.0	3AB2	100.0	800	22,000	0.15	nil	2.85	3.00	800	39	11.0	30.9

TABLE 16

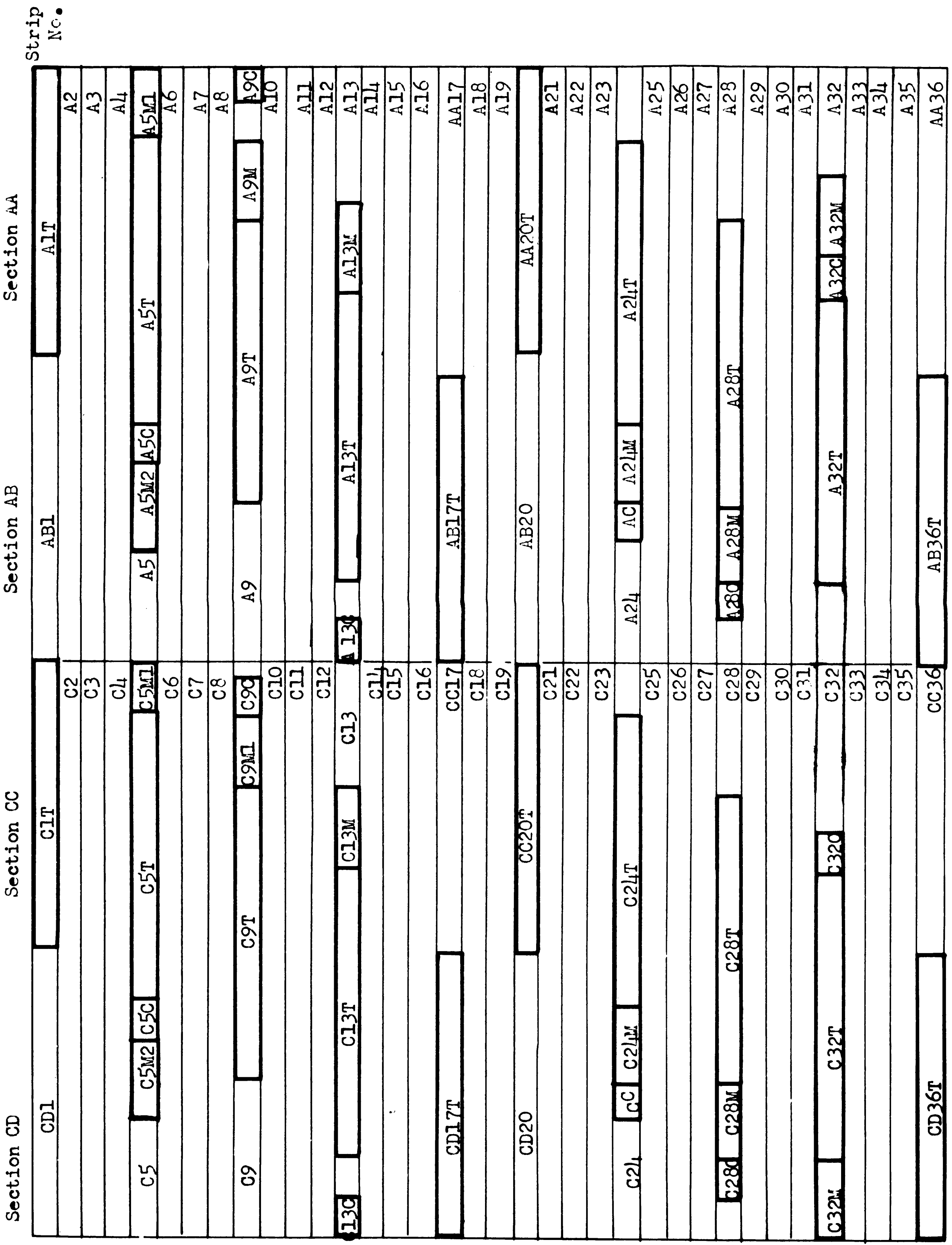
COMPARISONS OF ORIGINAL AND CHECK TEST TENSILE AND COMPRESSION DATA FOR TWO HEATS OF C110M TITANIUM ALLOY

Test Temp. (°F)	Spec. No.	Compression Yield Strength (psi)	Modulus $E \times 10^6$	Remarks
	Original Results - Heat A1172600			
Room	Average	108,111	16.2	Average Tensile Test Results Ultimate Strength - 146,211 psi Yield Strength - 142,889 psi Modulus - 16.5 x 10^6 psi
	Check Test Results - Heat A1172600			
Room	1A9A	103,000	15.0	Normal Support Force
	2A24A	108,000	15.2	Normal Support Force
	2C9C	104,000	15.7	Normal Support Force
	3A24A	108,000	16.0	Normal Support Force
	3C2C	114,500	15.5	Support Force= 50 in-lb.
	Original Results - Heat A1172600			
700	Average	56,800	12.5	Average Tensile Test Results Ultimate Strength - 105,545 psi Yield Strength - 92,667 psi Modulus - 13.2 x 10^6 psi
	Check Test Results - Heat A1172600			
700	1C9C	54,800	13.2	Support Force = 60 in-lb.
	2C24C	58,500	13.0	Normal Support Force
	3C9C	50,300	13.3	Normal Support Force

Check Test Results - Heat A5036

Room	Tensile	Ultimate	Yield	Modulus
		130,000	113,000	14.4
		136,000	116,000	15.1
	Average	133,000	114,500	14.8
	Compression		Yield	Modulus
			116,500	16.1
			119,500	15.7
	Average		118,000	15.9

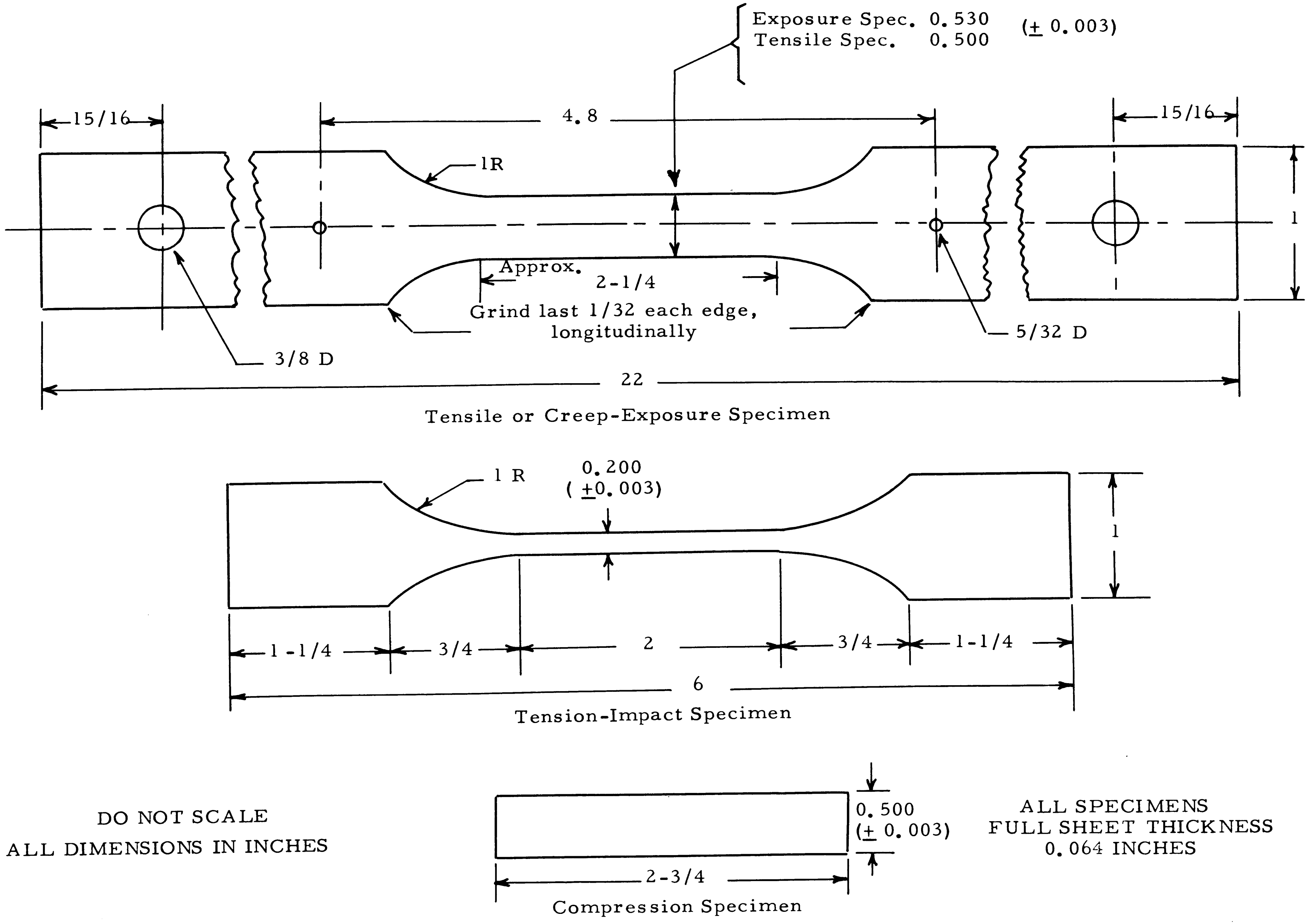
Heat No.	Test Temp.	Ratio ; Compression Yield/Tension Yield	
A1172600	Room	0.76	
	700°	0.61	
A5036	Room	1.03	
Boeing Data	Room	0.97-1.08	Data from TML Report No. 43
Armour Data	Room	1.02-1.09	Data from TML Report No. 43
	700°	0.98-1.20	Data from TML Report No. 43



Sheet Dimensions: 36 x 90 x .064 inches
Strip Width: 1 inch

Scale: 0 inches 10
(Length only)

Figure 1. - Sampling Procedure for Sheets of C110M Titanium Alloy.



Tensile or Creep-Exposure Specimen

Tension-Impact Specimen

Compression Specimen

DO NOT SCALE
ALL DIMENSIONS IN INCHES

ALL SPECIMENS
FULL SHEET THICKNESS
0.064 INCHES

Figure 2. - Details of Test Specimens (Tension-Impact and Compression Specimens Designed to be Cut from Creep Specimens after Exposure).

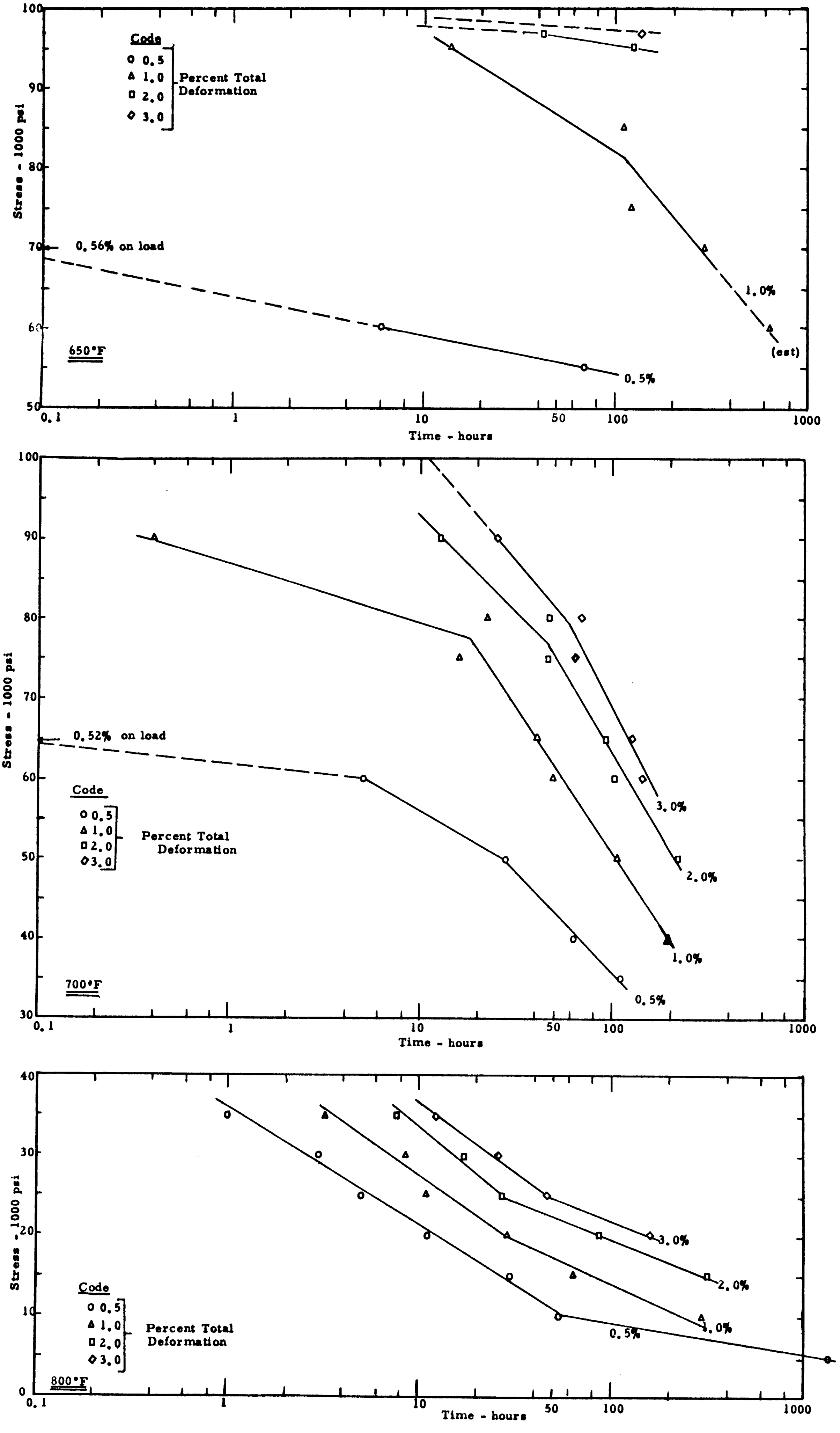


Figure 3. - Stress Versus Time to Reach Indicated Total Deformation for C110M at 650°, 700° and 800°F.

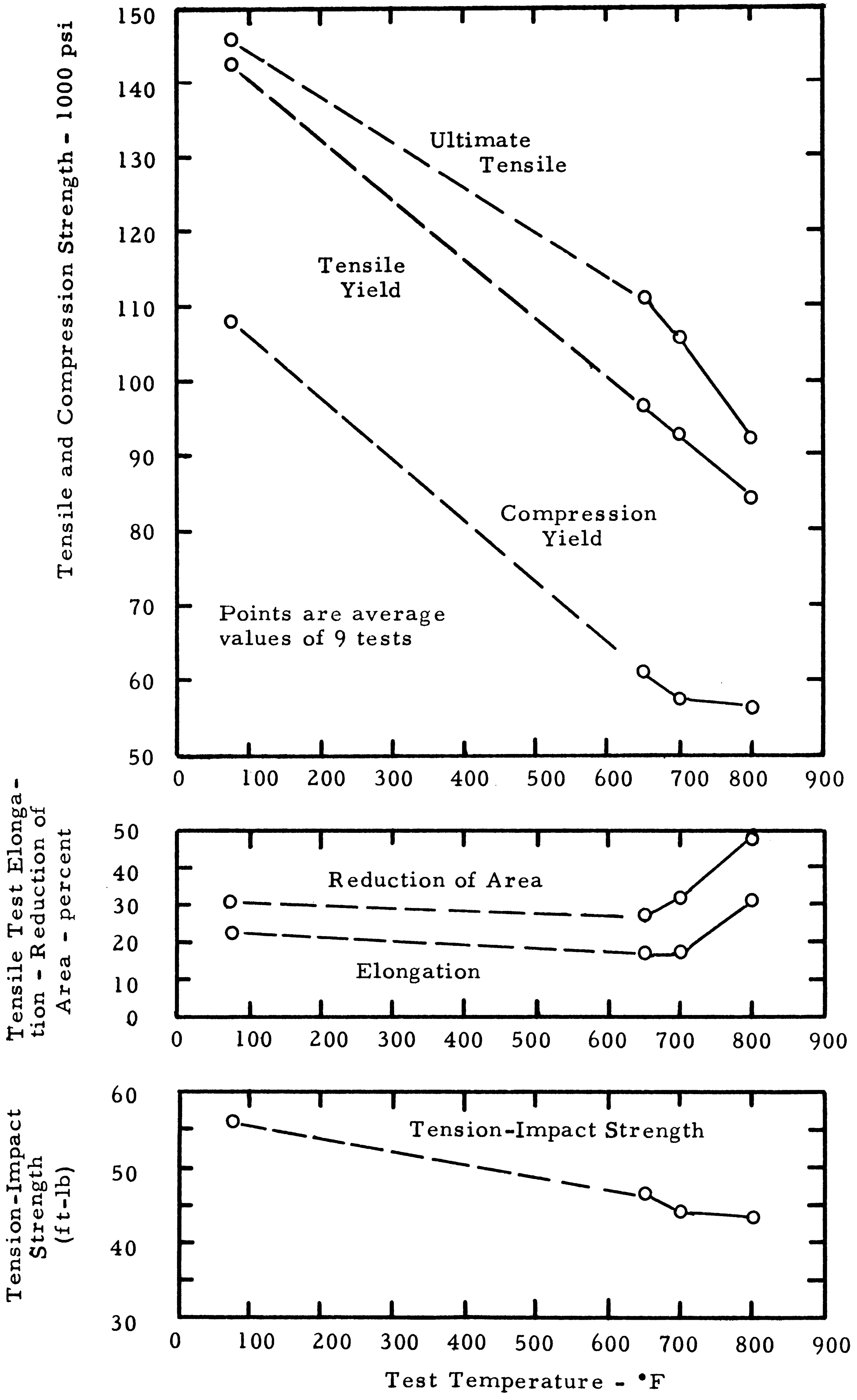


Figure 4. - Effect of Test Temperature on Short-Time Mechanical Properties of As-Produced C110M (Heat A1172600).

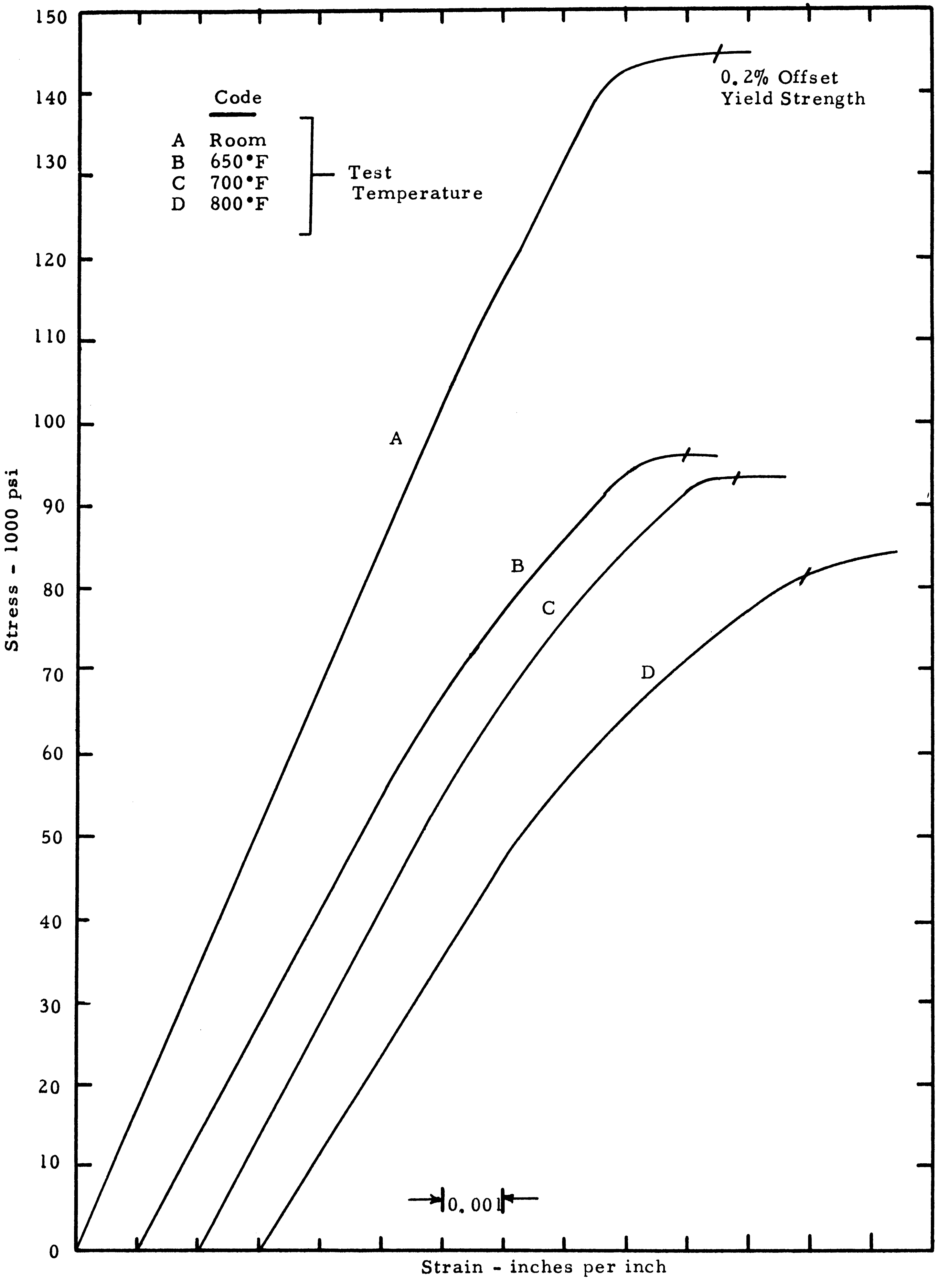


Figure 5. - Tensile Test Stress-Strain Curves for As-Produced C110M.

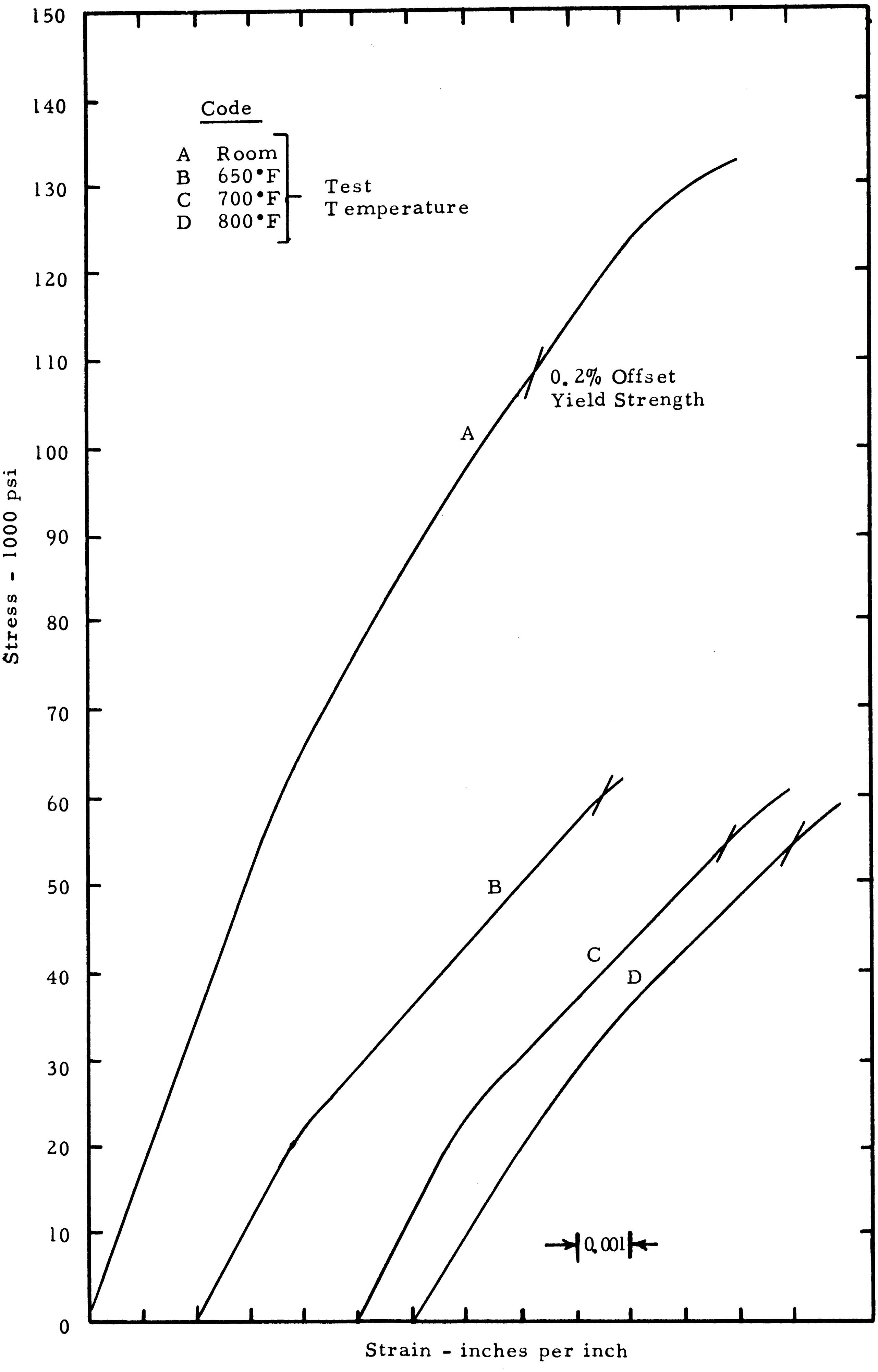


Figure 6. - Compression Test Stress-Strain Curves for As-Produced C110M.

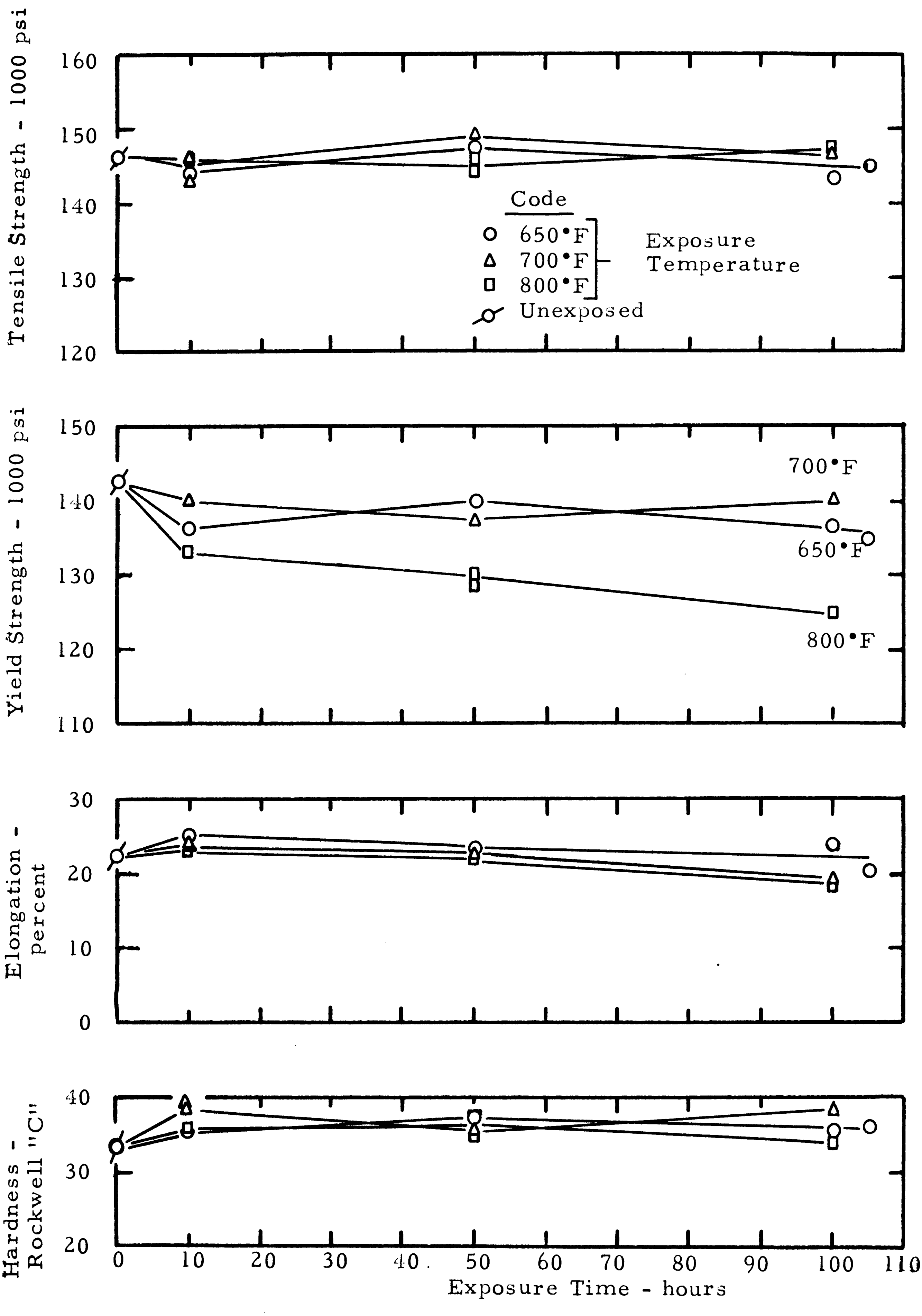


Figure 7. - Effect of Unstressed Exposure at 650°, 700°, or 800°F on Room Temperature Tensile Properties of C110M.

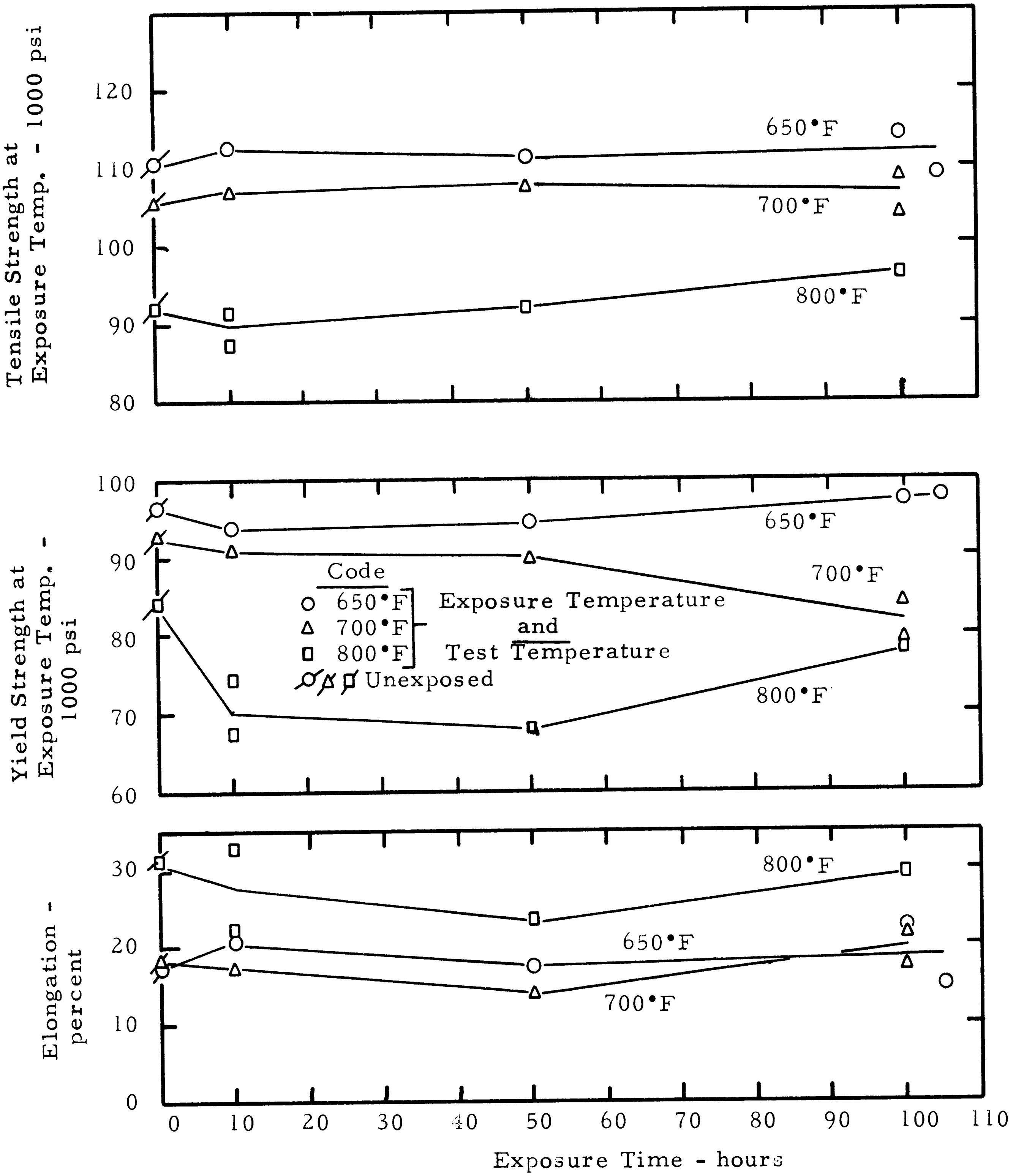


Figure 8. - Effect of Unstressed Exposure at 650°, 700°, or 800°F on Elevated Temperature Tensile Properties of C110M

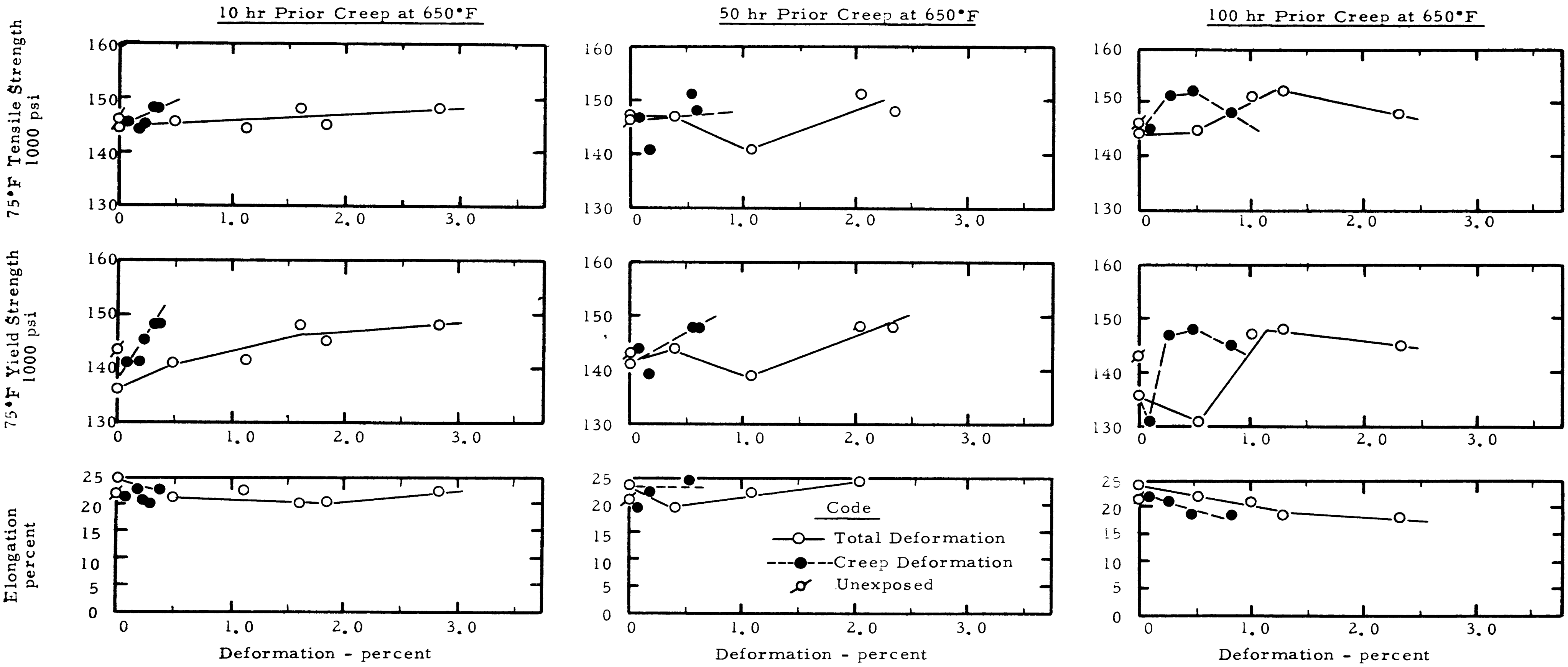


Figure 9. - Effect of Prior Creep Exposure at 650°F on Room Temperature Tensile Properties of C110M.

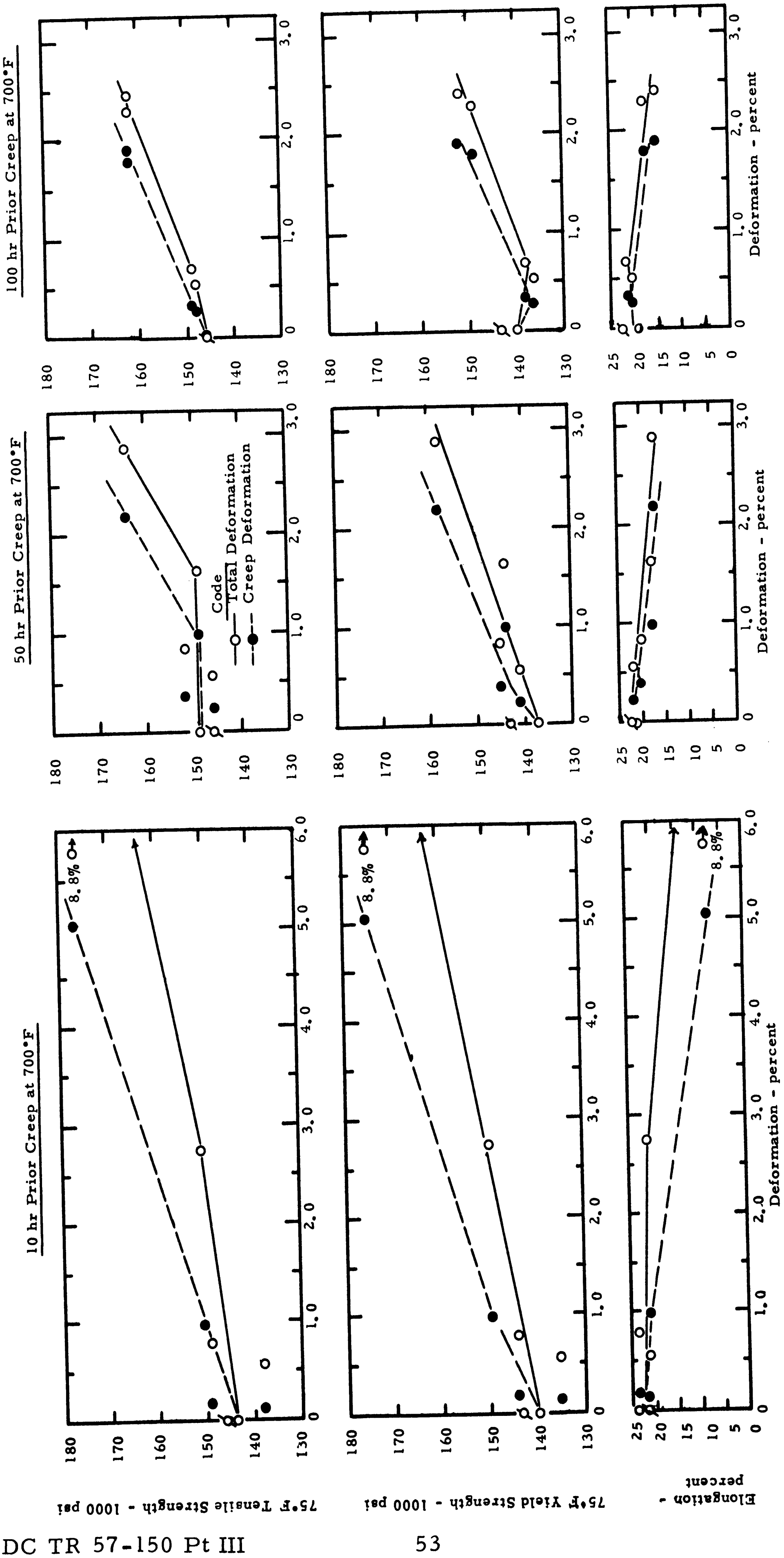


Figure 10. - Effect of Prior Creep Exposure at 700°F on Room Temperature Tensile Properties of C110M.

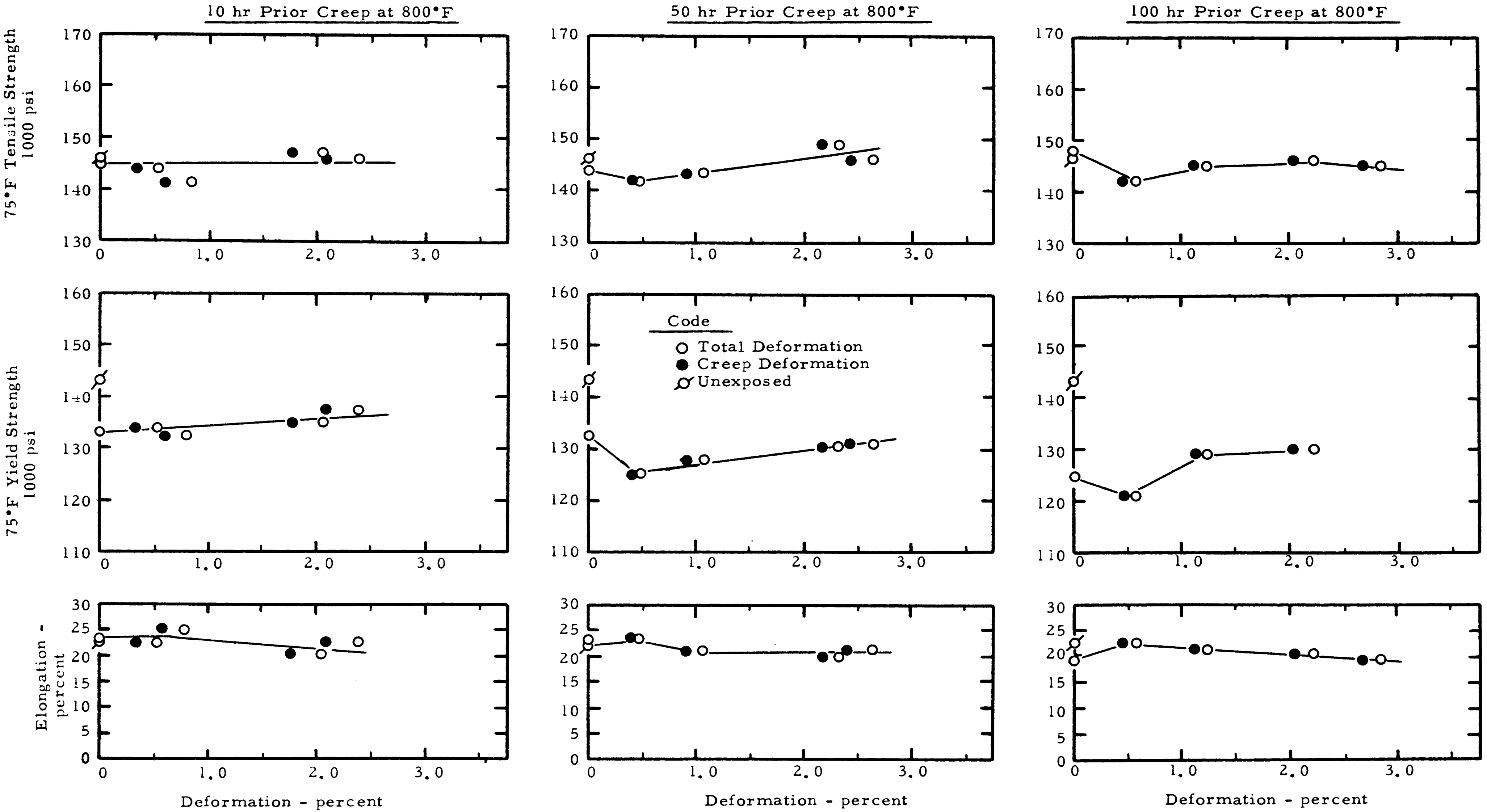


Figure 11. - Effect of Prior Creep Exposure at 800°F on Room Temperature Tensile Properties of C110M.

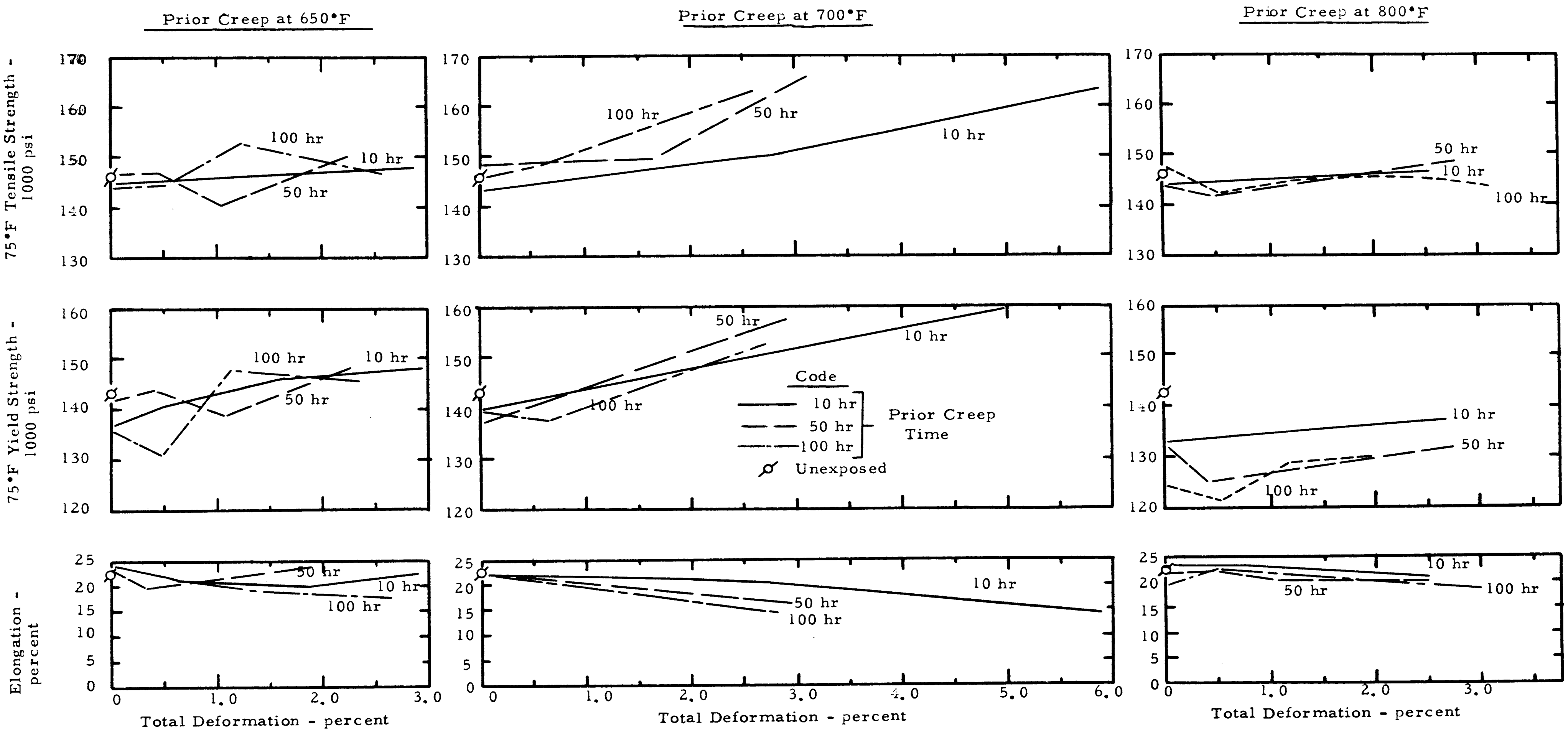


Figure 12. - Summary of Effect of Prior Creep Exposure on Room Temperature Tensile Properties of C110M.

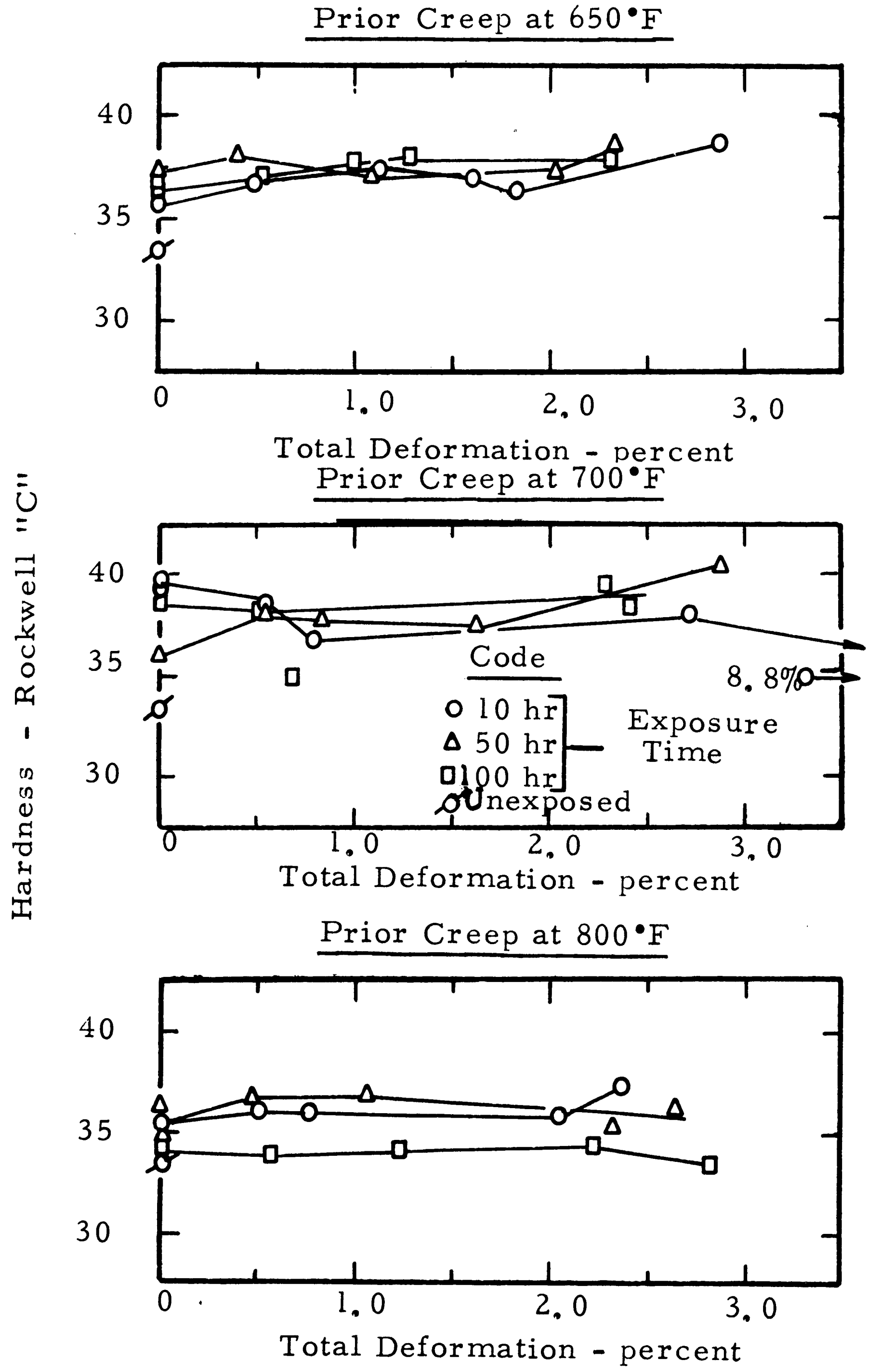
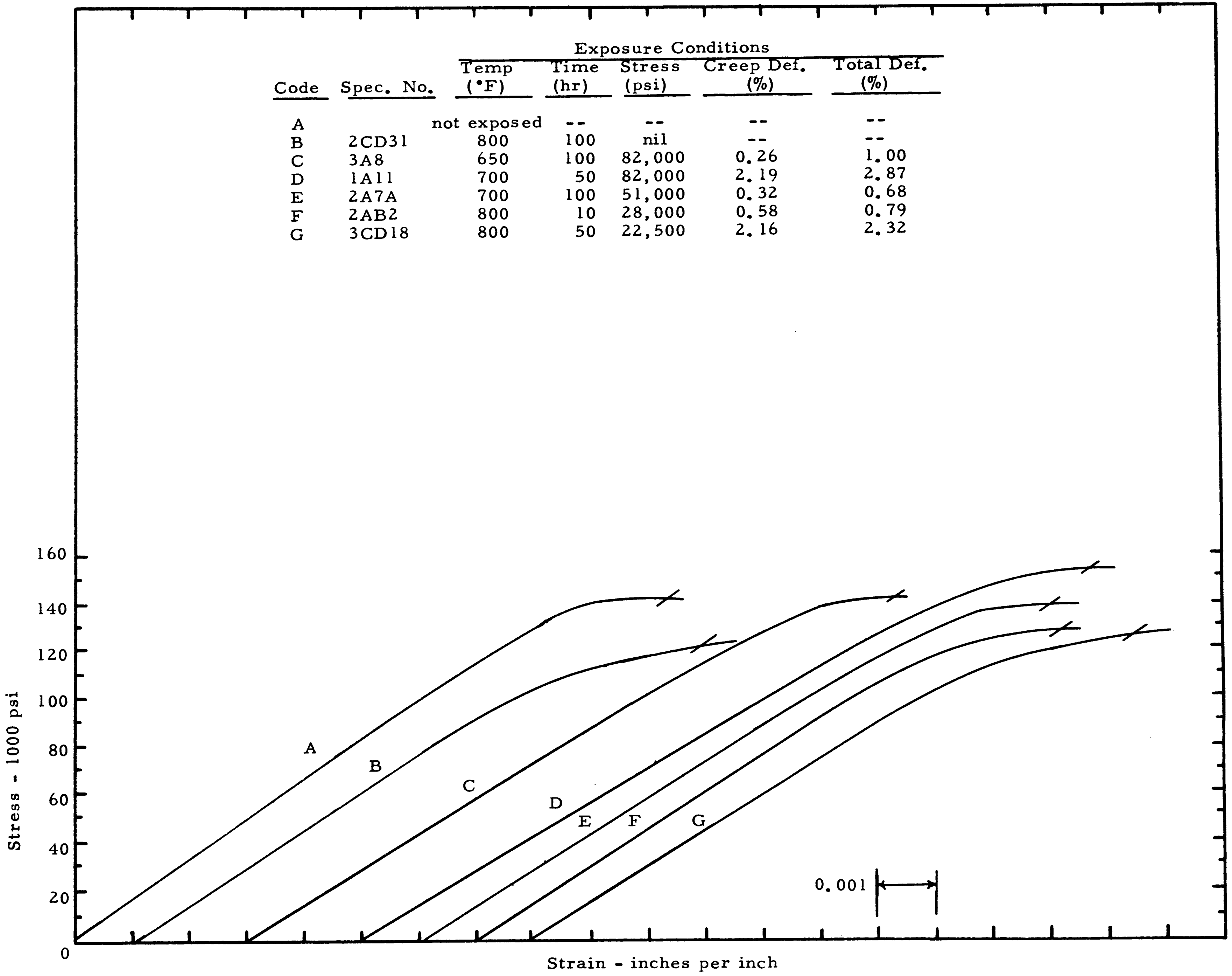


Figure 13. - Effect of Prior Creep Exposure in Hardness of C110M.



Code	Spec. No.	Exposure Conditions Temp (°F)	Time (hr)	Stress (psi)	Creep Def. (%)	Total Def. (%)
A		not exposed	--	--	--	--
B	2CD31	800	100	nil	--	--
C	3A8	650	100	82,000	0.26	1.00
D	1A11	700	50	82,000	2.19	2.87
E	2A7A	700	100	51,000	0.32	0.68
F	2AB2	800	10	28,000	0.58	0.79
G	3CD18	800	50	22,500	2.16	2.32

Figure 14. - Representative Room Temperature Tensile Test Stress-Strain Curves of C110M after Prior Creep Exposure.

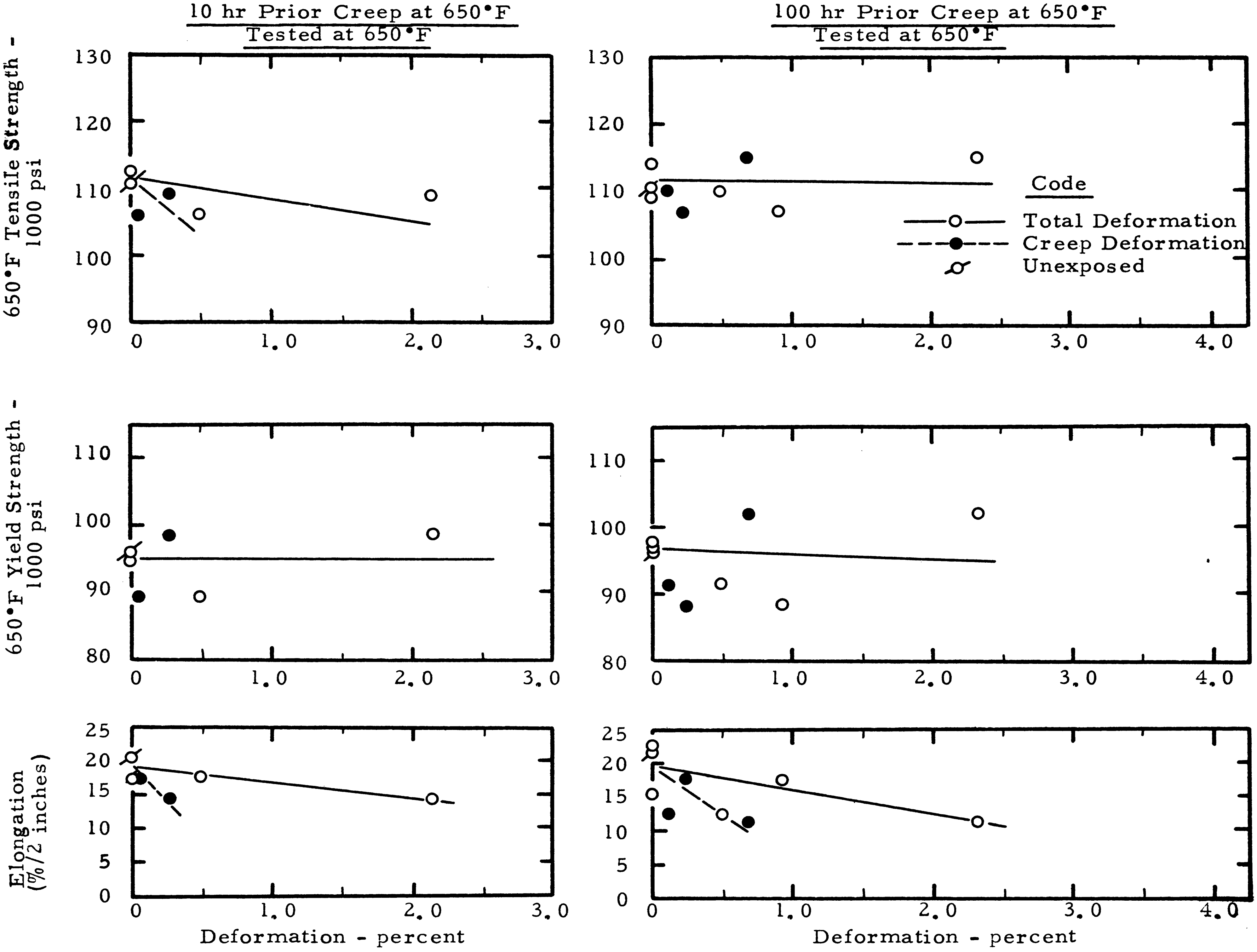


Figure 15. - Effect of 650°F Prior Creep Exposure on 650°F Tensile Properties of C110M

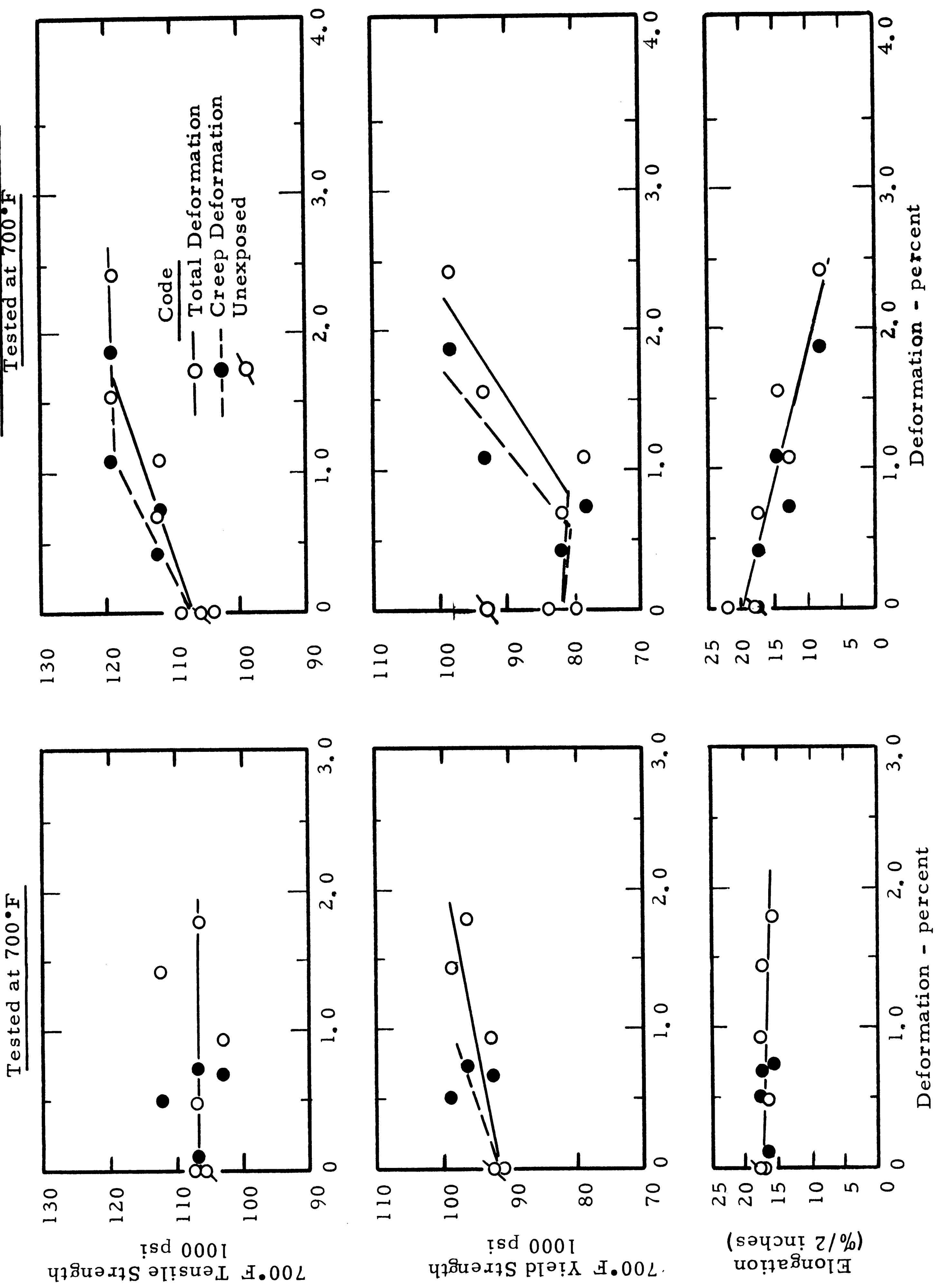


Figure 16. - Effect of 700°F Prior Creep Exposure on 700°F Tensile Properties of C110M.

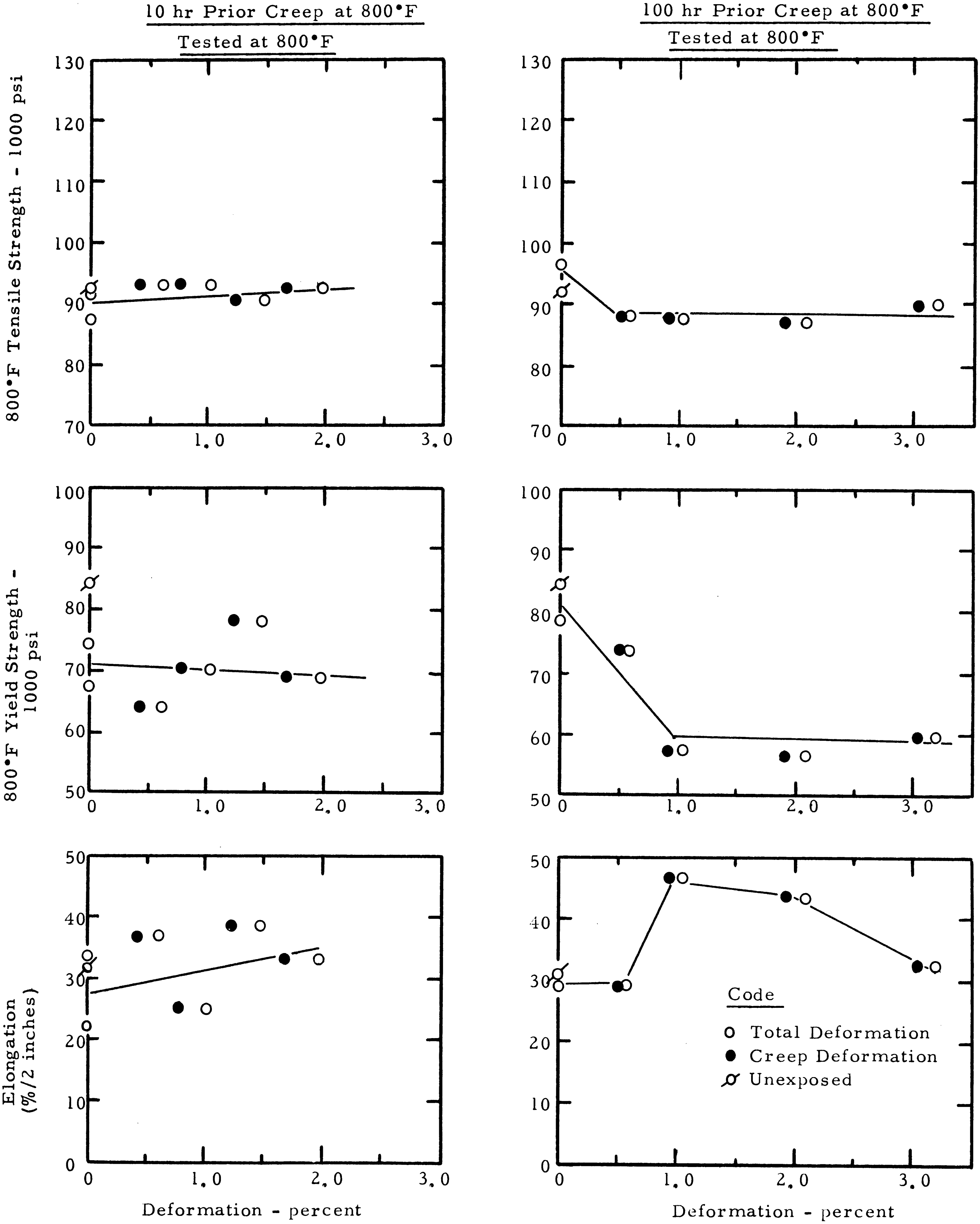


Figure 17. - Effect of 800°F Prior Creep Exposure on 800°F Tensile Properties of C110M.

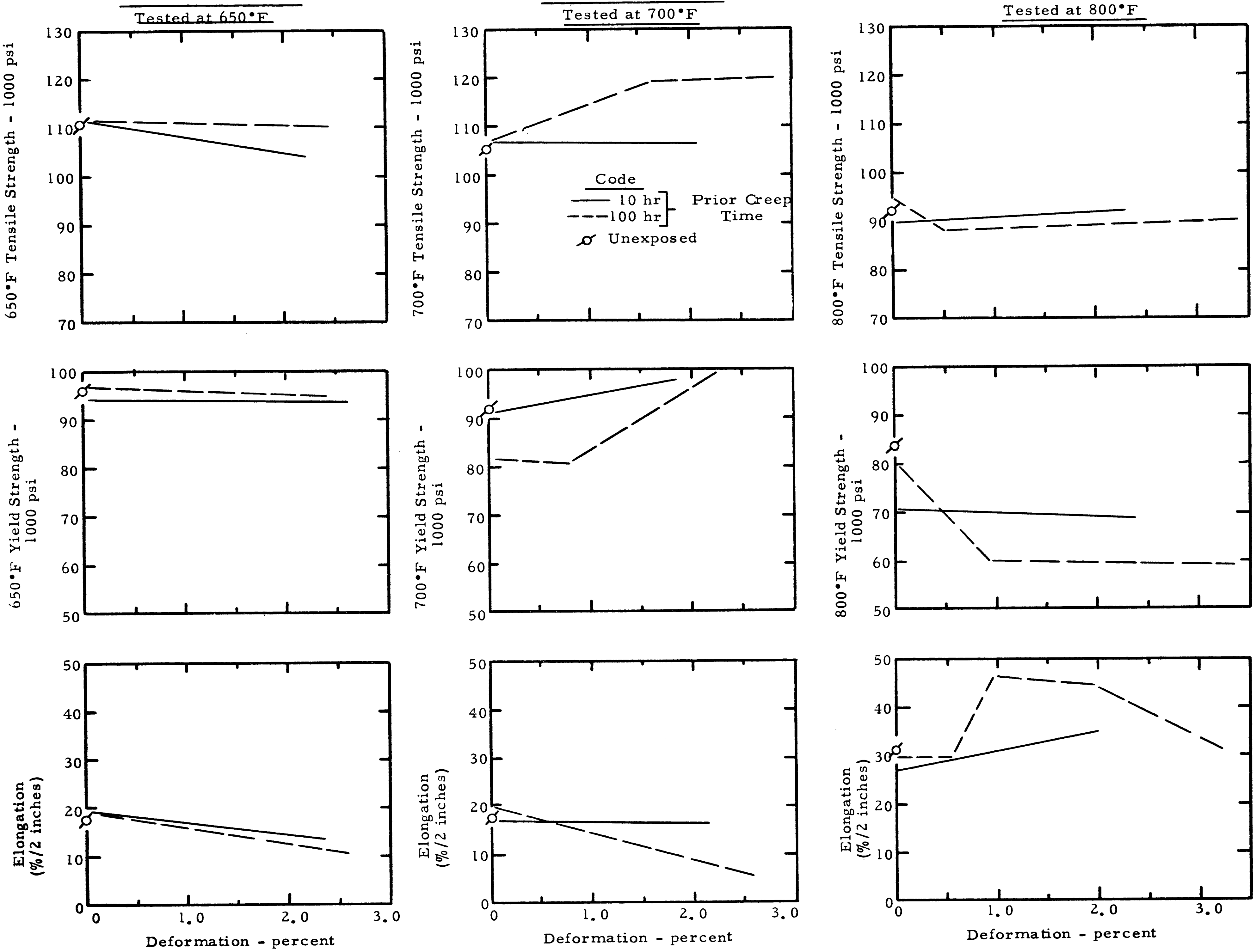
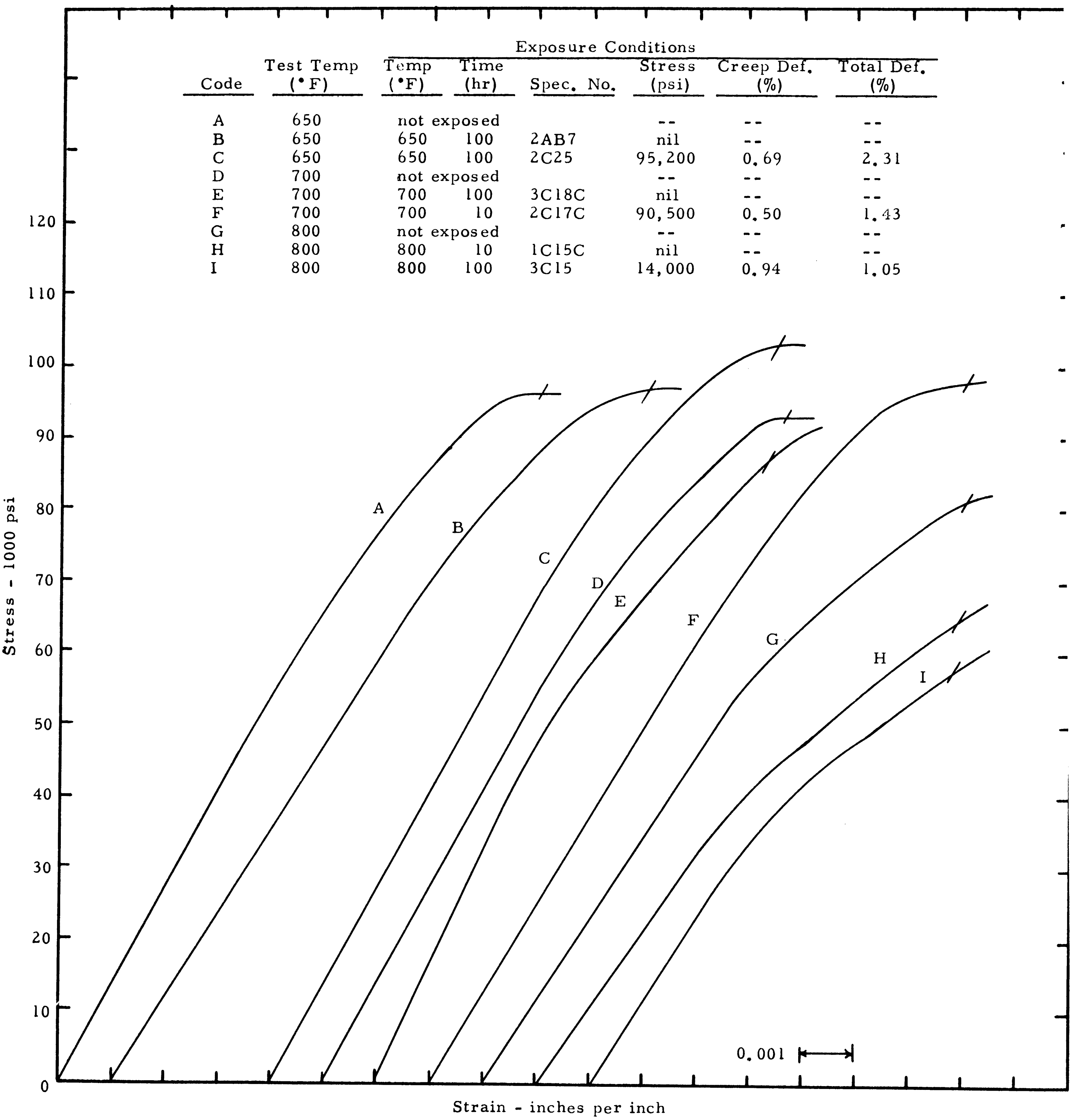


Figure 18. - Summary of Effect of Prior Creep Exposure on Elevated Temperature Tensile Properties of C110M.



Code	Test Temp (°F)	Exposure Conditions Temp (°F)	Time (hr)	Spec. No.	Stress (psi)	Creep Def. (%)	Total Def. (%)
A	650	not exposed			--	--	--
B	650	650	100	2AB7	nil	--	--
C	650	650	100	2C25	95,200	0.69	2.31
D	700	not exposed			--	--	--
E	700	700	100	3C18C	nil	--	--
F	700	700	10	2C17C	90,500	0.50	1.43
G	800	not exposed			--	--	--
H	800	800	10	1C15C	nil	--	--
I	800	800	100	3C15	14,000	0.94	1.05

Figure 19. - Representative Tensile Test Stress-Strain Curves at Elevated Temperature for C110M after Prior Creep Exposure

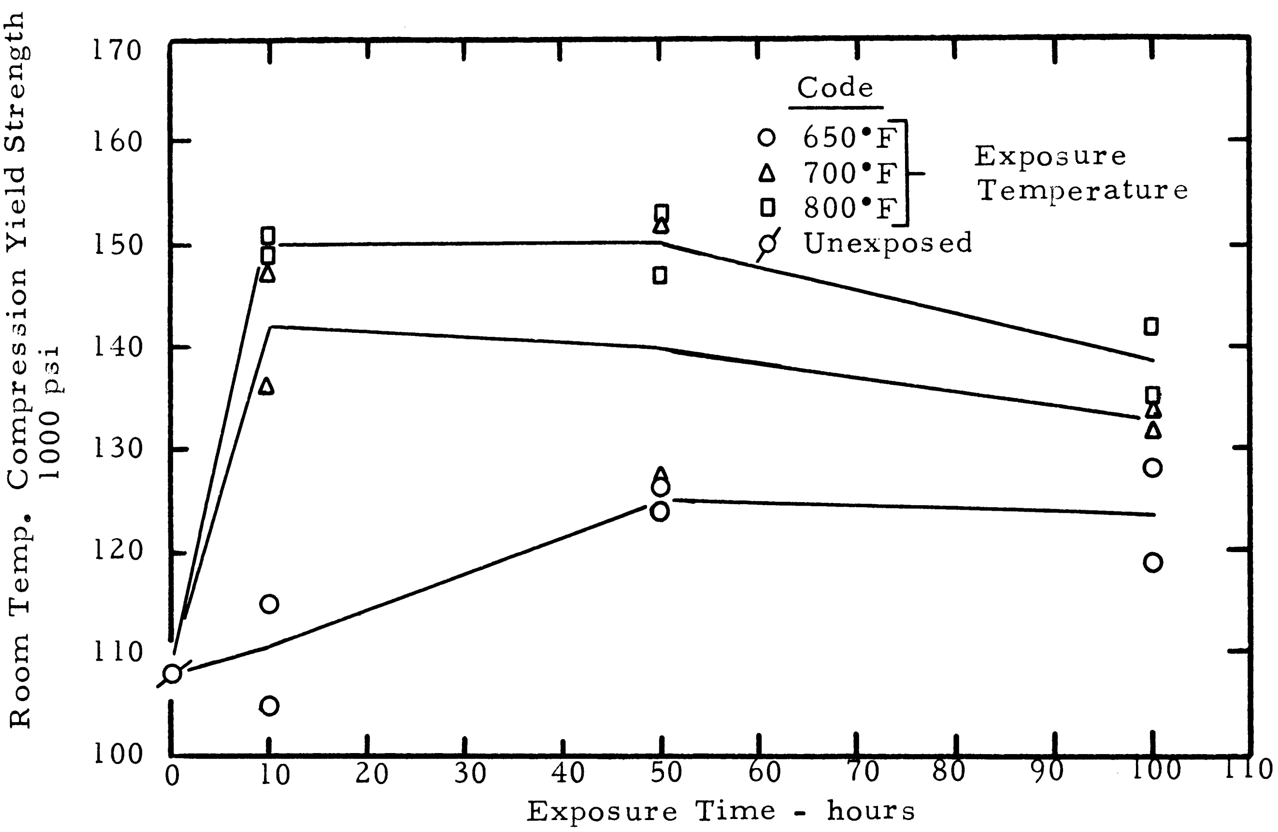


Figure 20. - Effect of Unstressed Exposure at 650°, 700°, or 800°F on Room Temperature Compression Yield Strength of C110M.

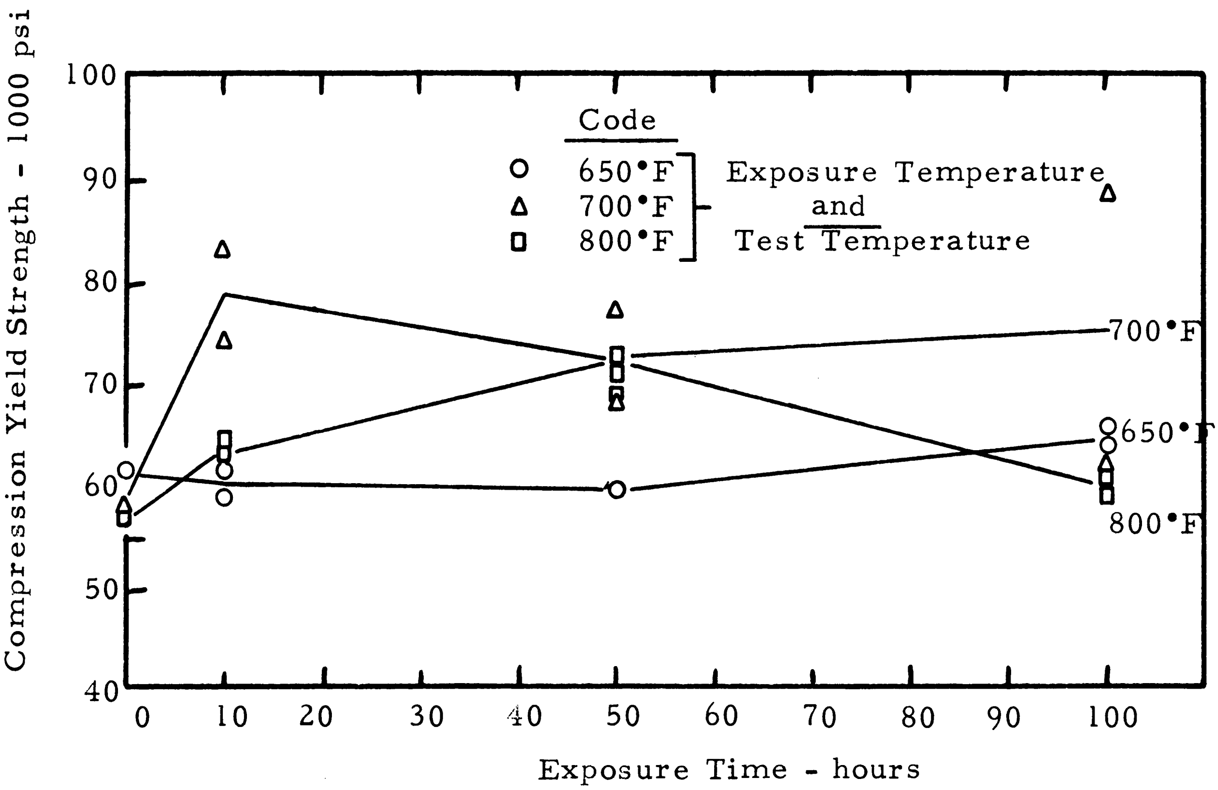


Figure 21. - Effect of Unstressed Exposure at 650°, 700°, or 800°F on Elevated Temperature Compression Yield Strength of C110M.

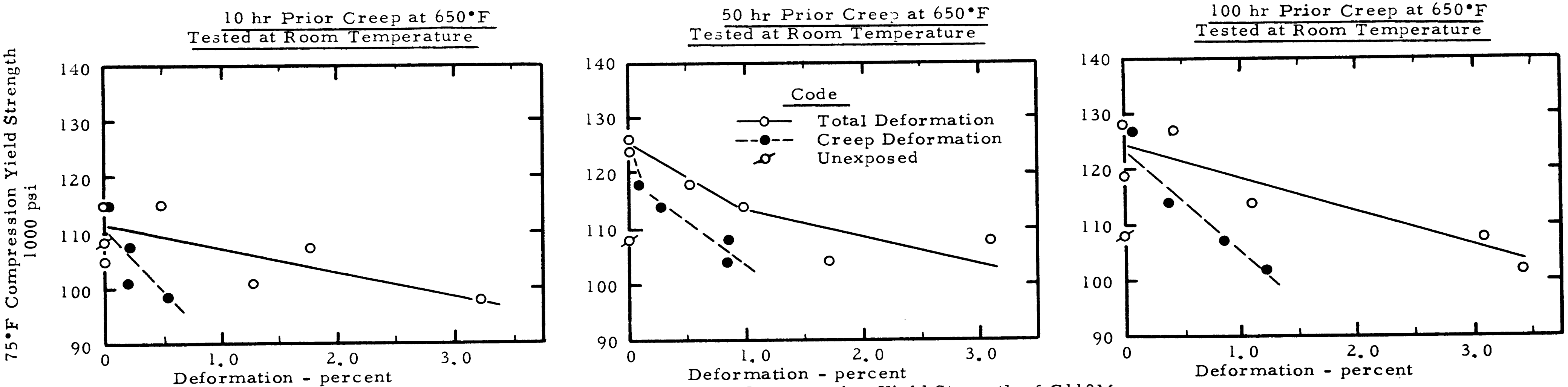


Figure 22. - Effect of Prior Creep at 650°F on Room Temperature Compression Yield Strength of C110M.

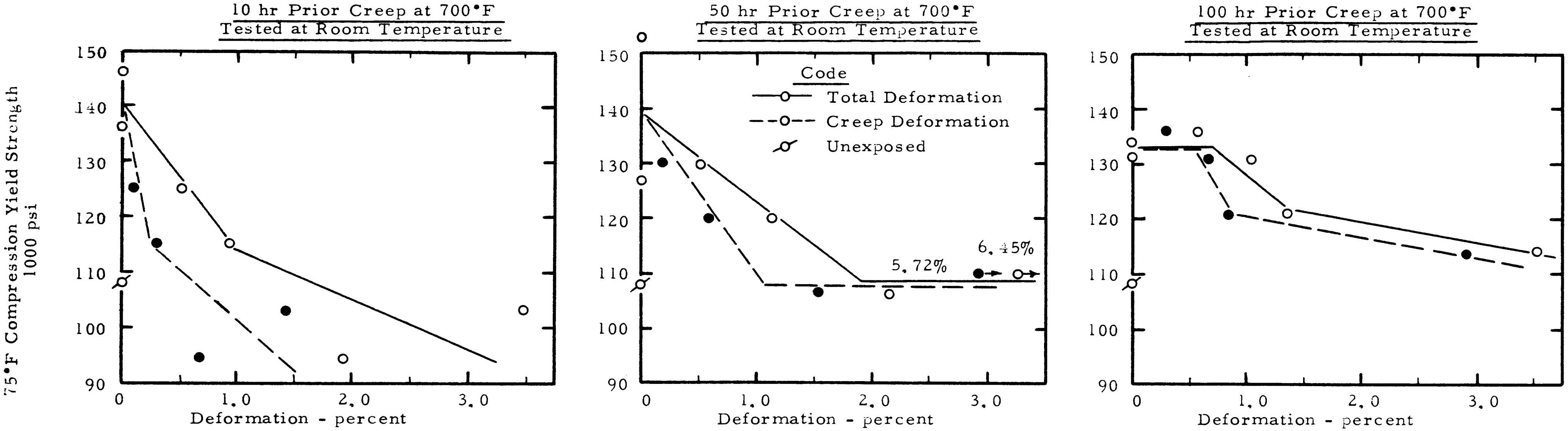
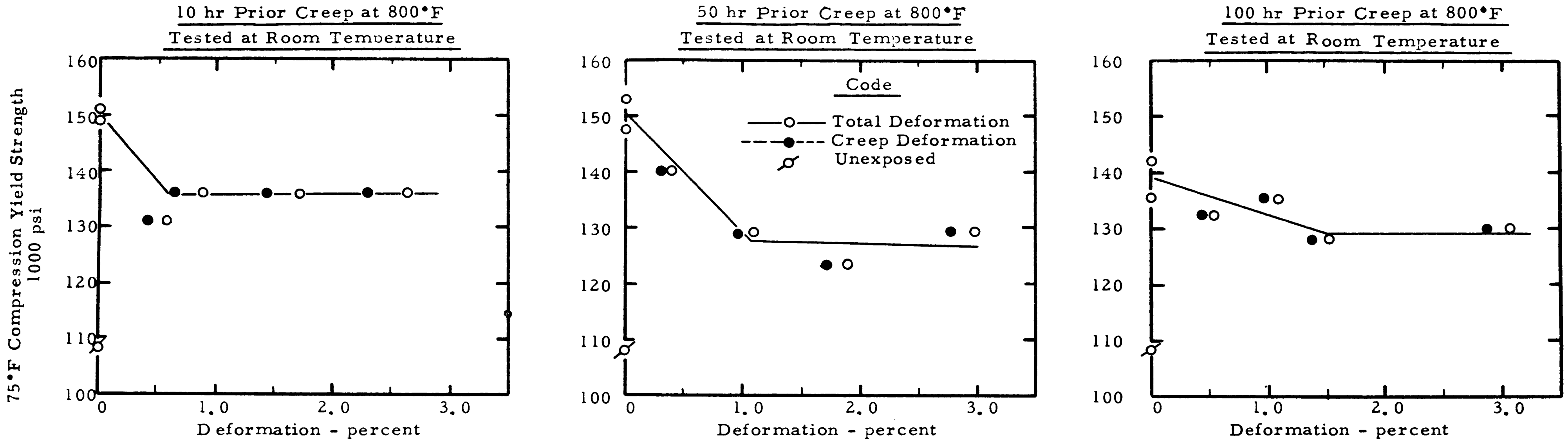


Figure 23. - Effect of Prior Creep Exposure at 700°F on Room Temperature Compression Yield Strength of C110M.



10 hr Prior Creep at 800°F
Tested at Room Temperature

50 hr Prior Creep at 800°F
Tested at Room Temperature

100 hr Prior Creep at 800°F
Tested at Room Temperature

Figure 24. - Effect of Prior Creep Exposure at 800°F on Room Temperature Compression Yield Strength of C110M.

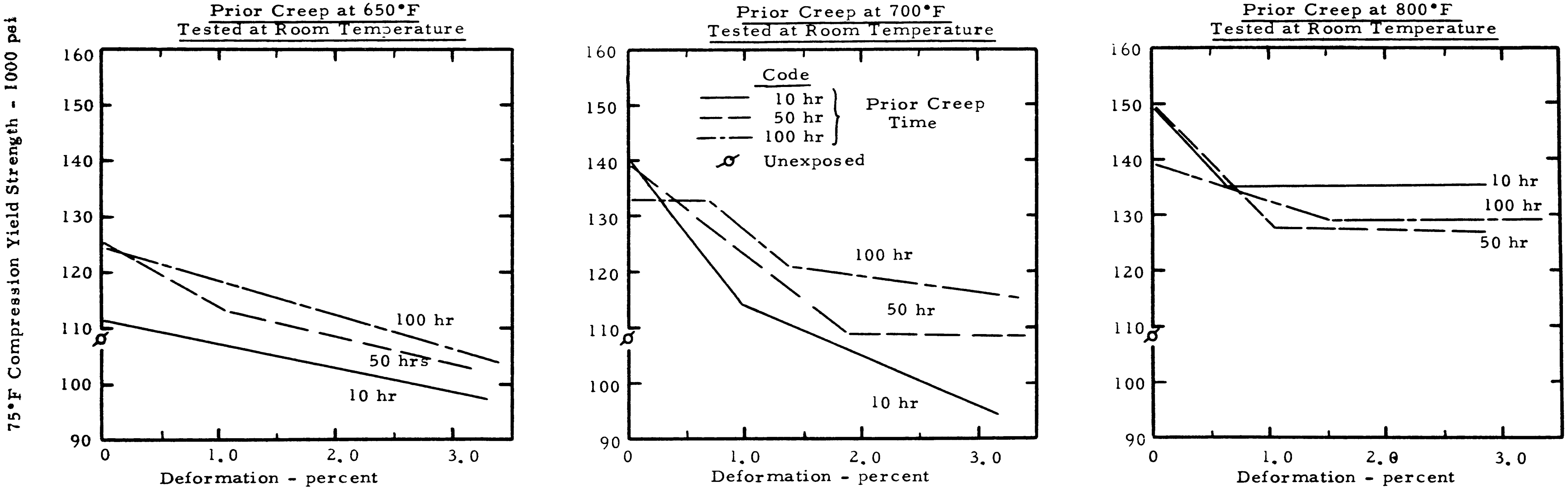
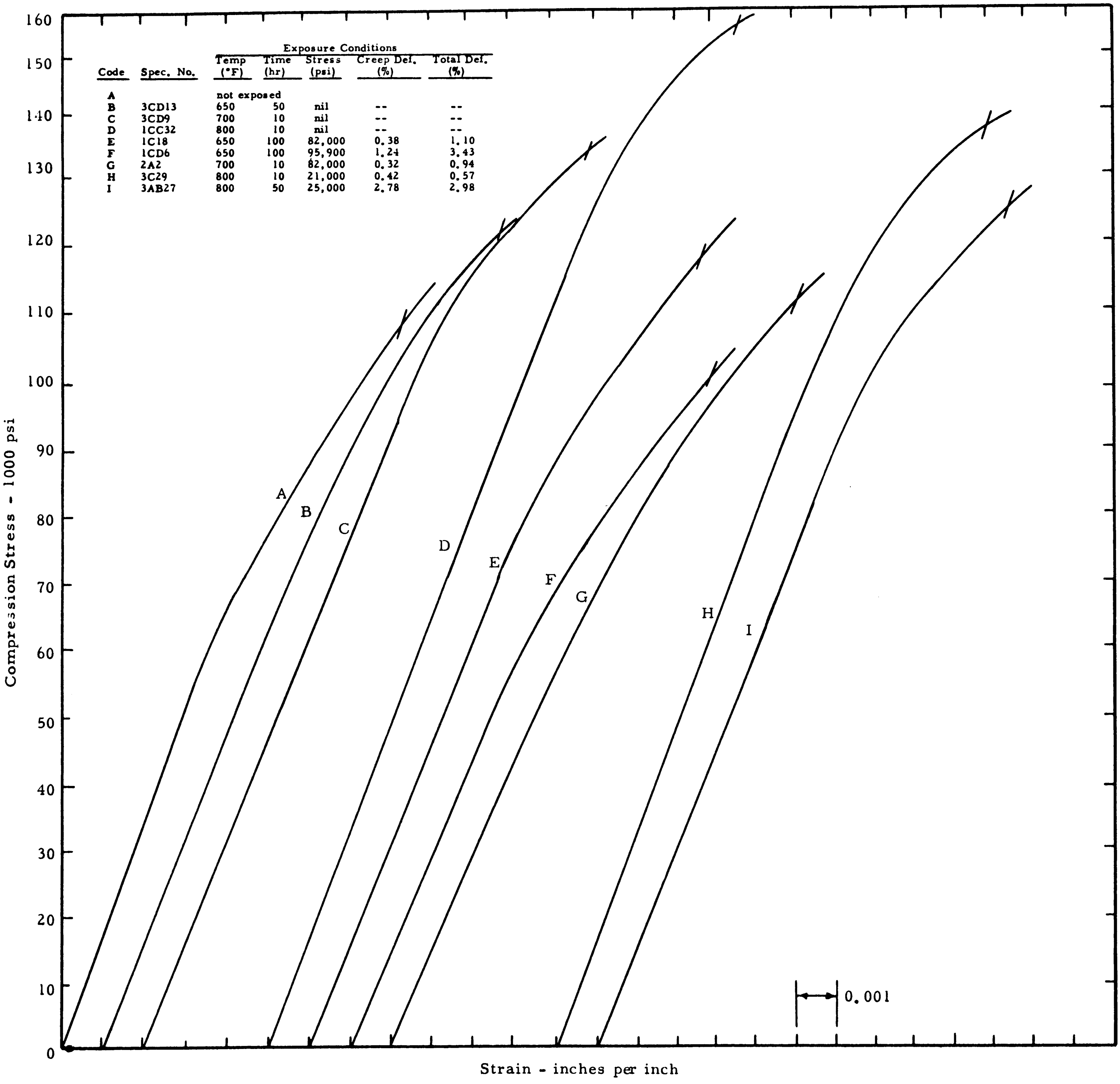


Figure 25. - Summary of Effect of Prior Creep Exposure at 650°, 700° or 800°F on Room Temperature Compression Yield Strength of C110M.



		Exposure Conditions				
Code	Spec. No.	Temp (°F)	Time (hr)	Stress (psi)	Creep Def. (%)	Total Def. (%)
A		not exposed				
B	3CD13	650	50	nil	--	--
C	3CD9	700	10	nil	--	--
D	1CC32	800	10	nil	--	--
E	1C18	650	100	82,000	0.38	1.10
F	1CD6	650	100	95,900	1.24	3.43
G	2A2	700	10	82,000	0.32	0.94
H	3C29	800	10	21,000	0.42	0.57
I	3AB27	800	50	25,000	2.78	2.98

Figure 26. - Representative Compression Test Stress Strain Curves at Room Temperature for C110M after Prior Creep Exposure.

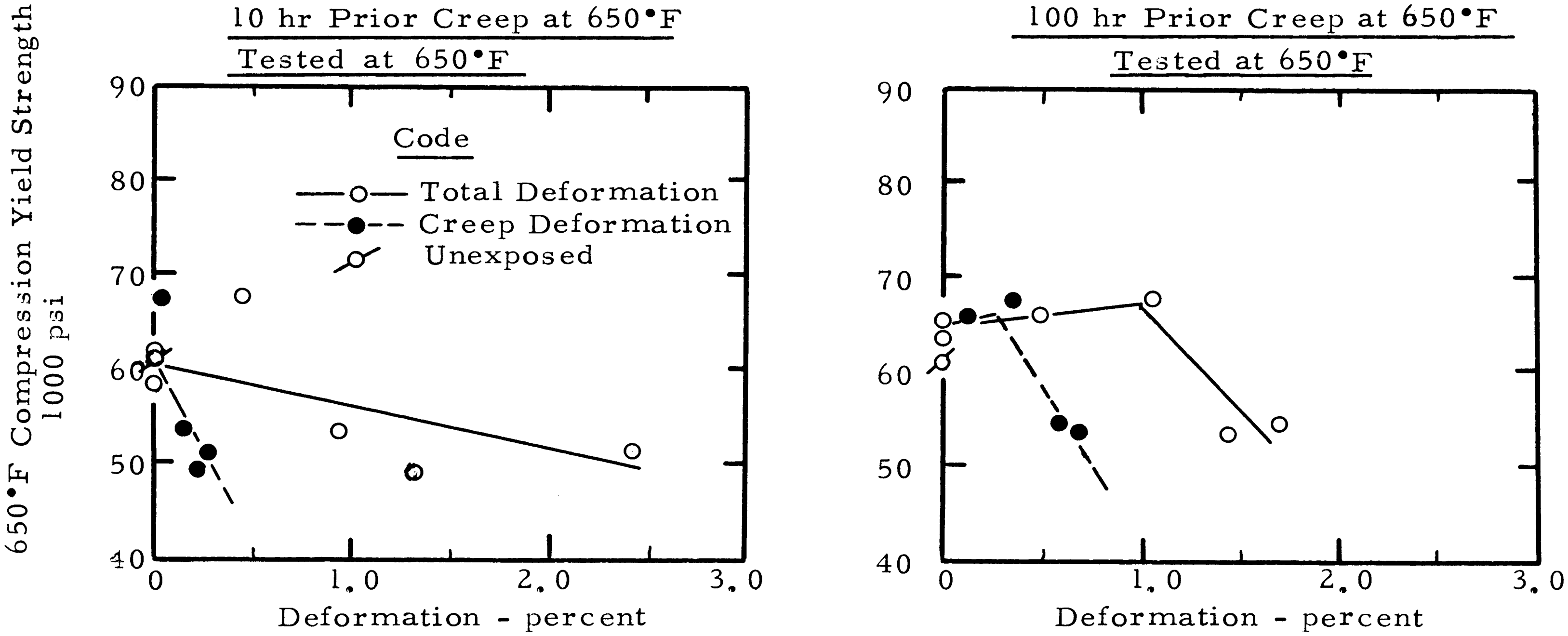


Figure 27. - Effect of Prior Creep Exposure at 650°F on 650°F Compression Yield Strength of C110M.

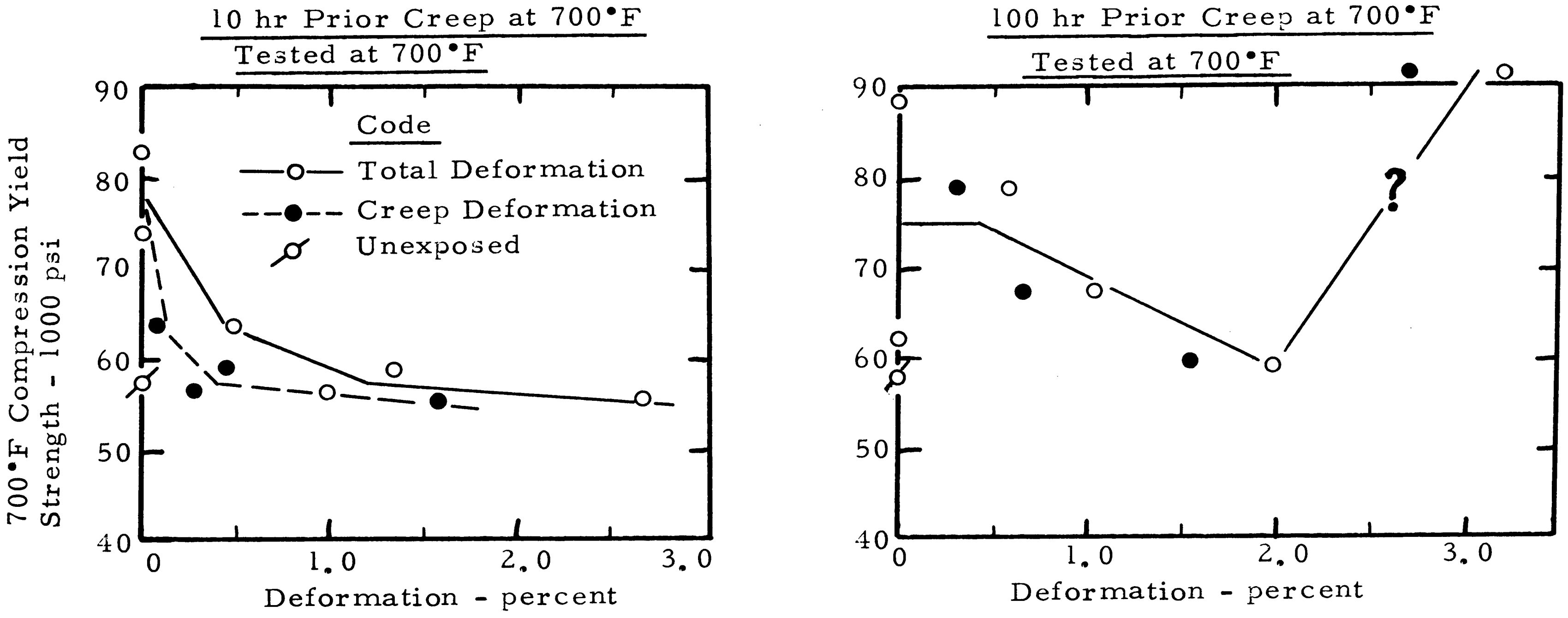


Figure 28. - Effect of Prior Creep Exposure at 700°F on 700°F Compression Yield Strength of C110M.

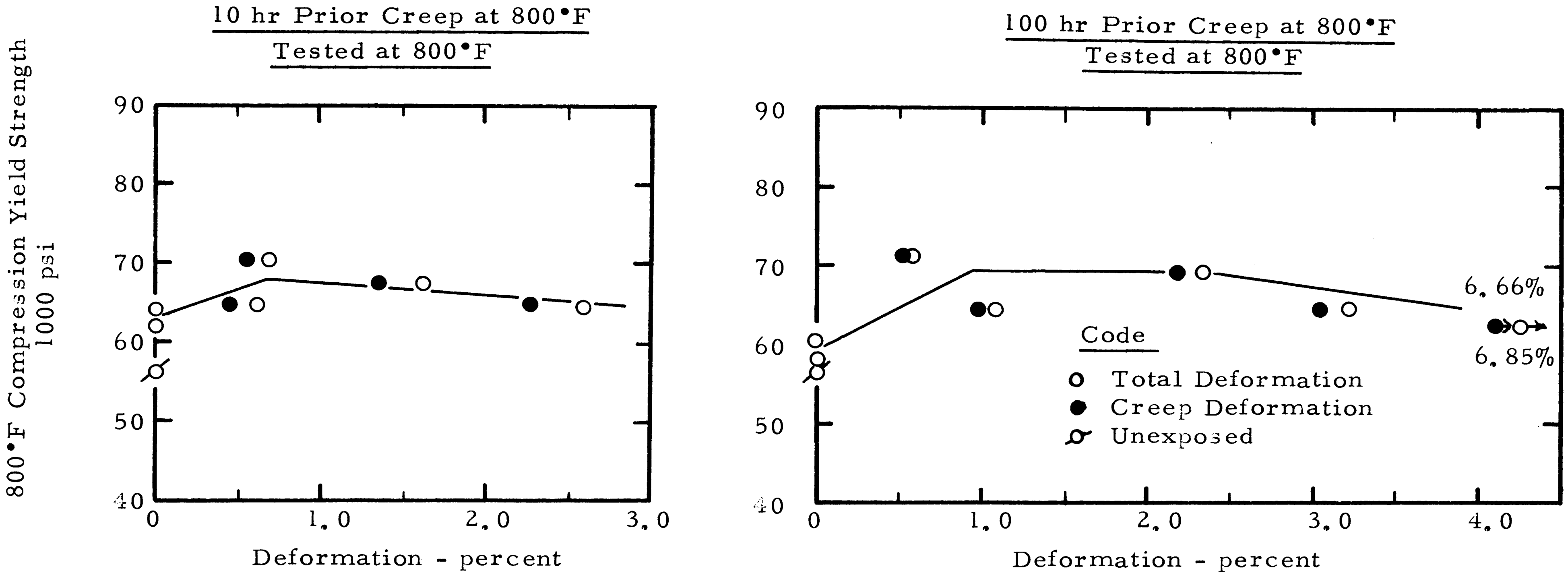


Figure 29. - Effect of Prior Creep Exposure at 800°F on 800°F Compression Yield Strength of C110M.

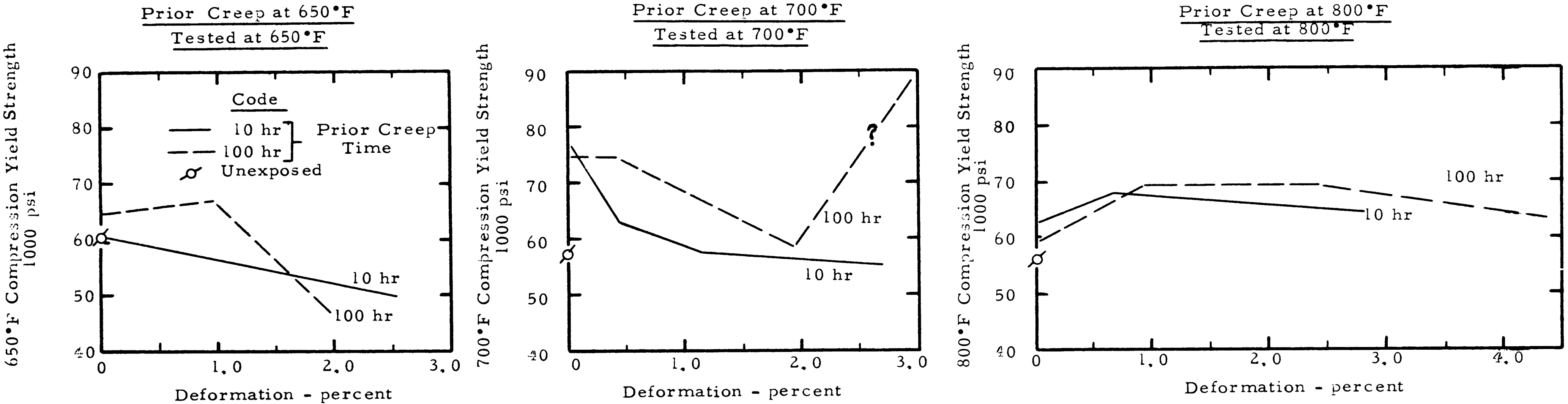
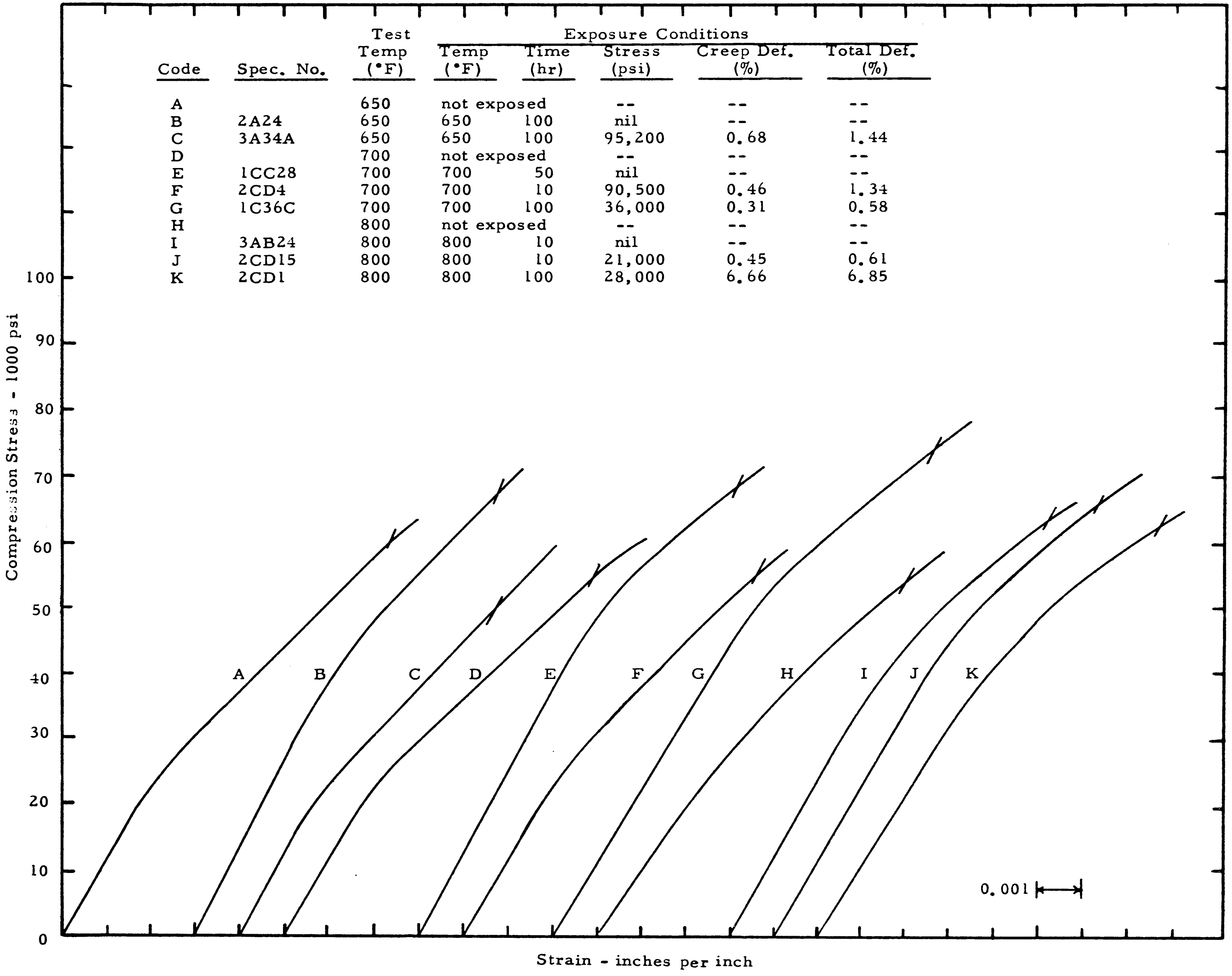


Figure 30. - Summary of Effect of Prior Creep Exposure at 650°, 700°, or 800°F on Elevated Temperature Compression Yield Strength of C110M.



Code	Spec. No.	Test Temp (°F)	Exposure Conditions Temp (°F)	Time (hr)	Stress (psi)	Creep Def. (%)	Total Def. (%)
A		650	not exposed		--	--	--
B	2A24	650	650	100	nil	--	--
C	3A34A	650	650	100	95,200	0.68	1.44
D		700	not exposed		--	--	--
E	1CC28	700	700	50	nil	--	--
F	2CD4	700	700	10	90,500	0.46	1.34
G	1C36C	700	700	100	36,000	0.31	0.58
H		800	not exposed		--	--	--
I	3AB24	800	800	10	nil	--	--
J	2CD15	800	800	10	21,000	0.45	0.61
K	2CD1	800	800	100	28,000	6.66	6.85

Figure 31. - Representative Compression Test Stress-Strain Curves at Elevated Temperature Following Prior Creep Exposure.

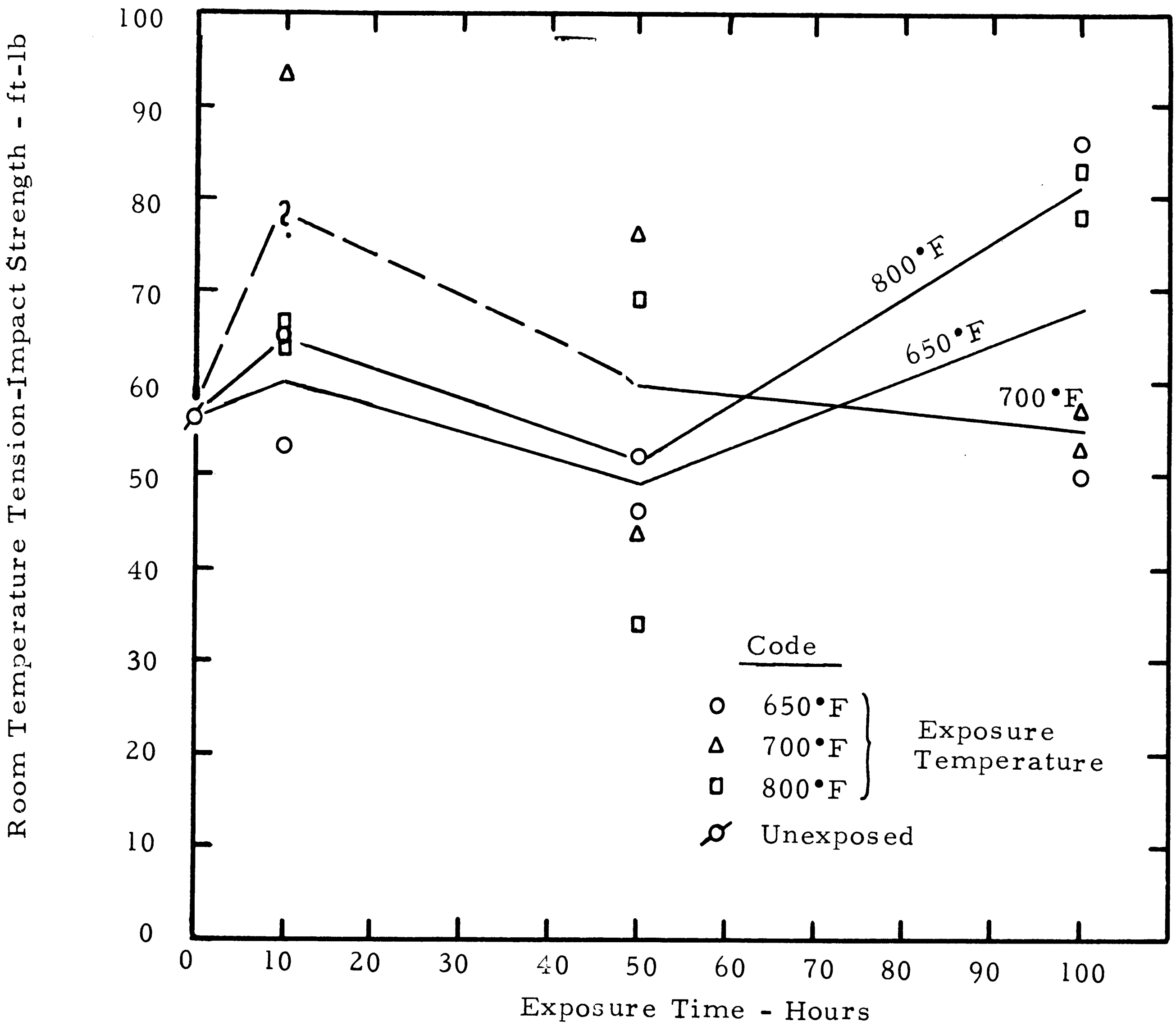


Figure 32. - Effect of Unstressed Exposure on Room Temperature Tension-Impact Strength of C110M.

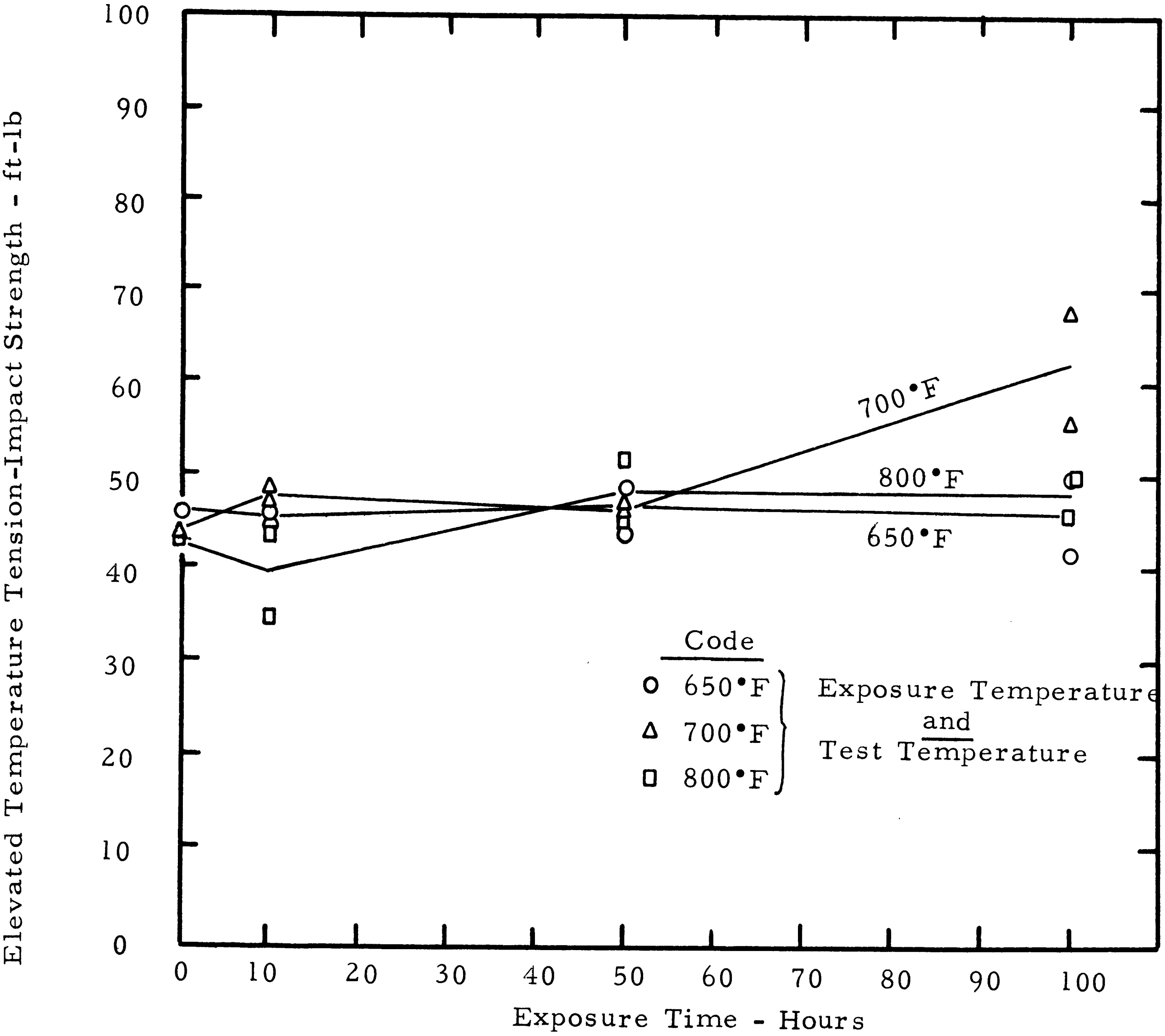


Figure 33. - Effect of Unstressed Exposure on Elevated Temperature Tension-Impact Strength of C110M.

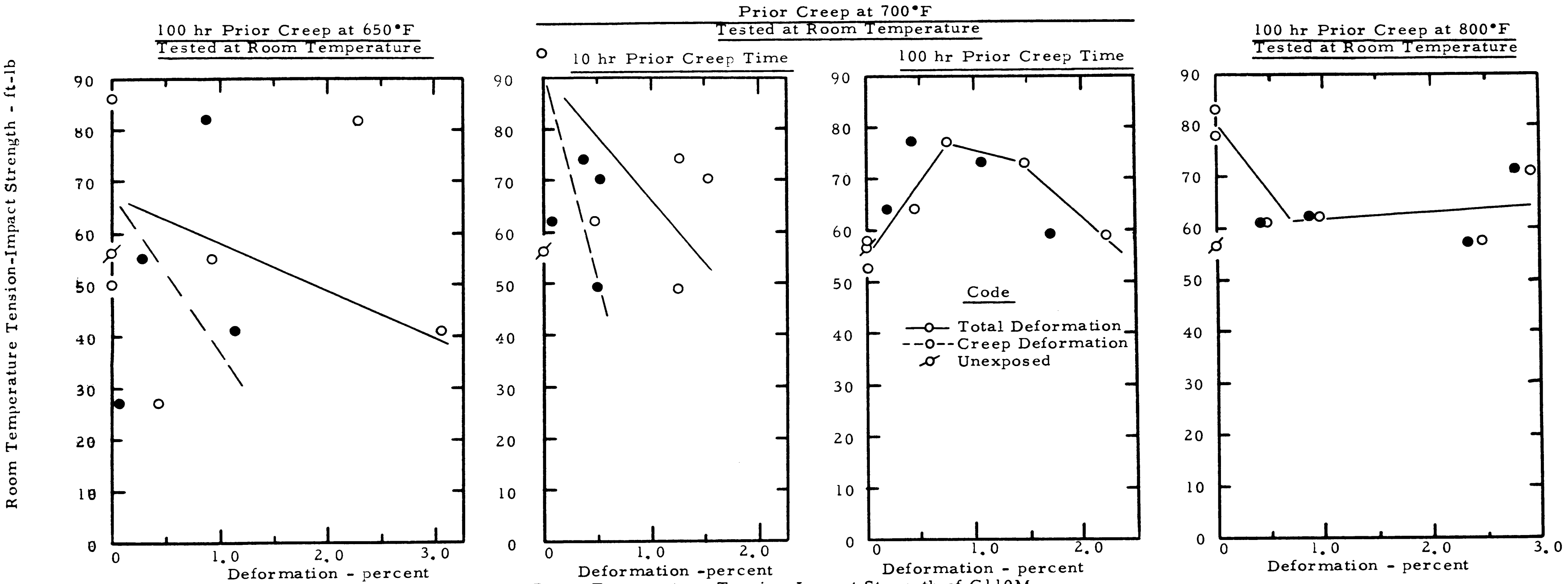


Figure 34. - Effect of Prior Creep Exposure on Room Temperature Tension-Impact Strength of C110M.

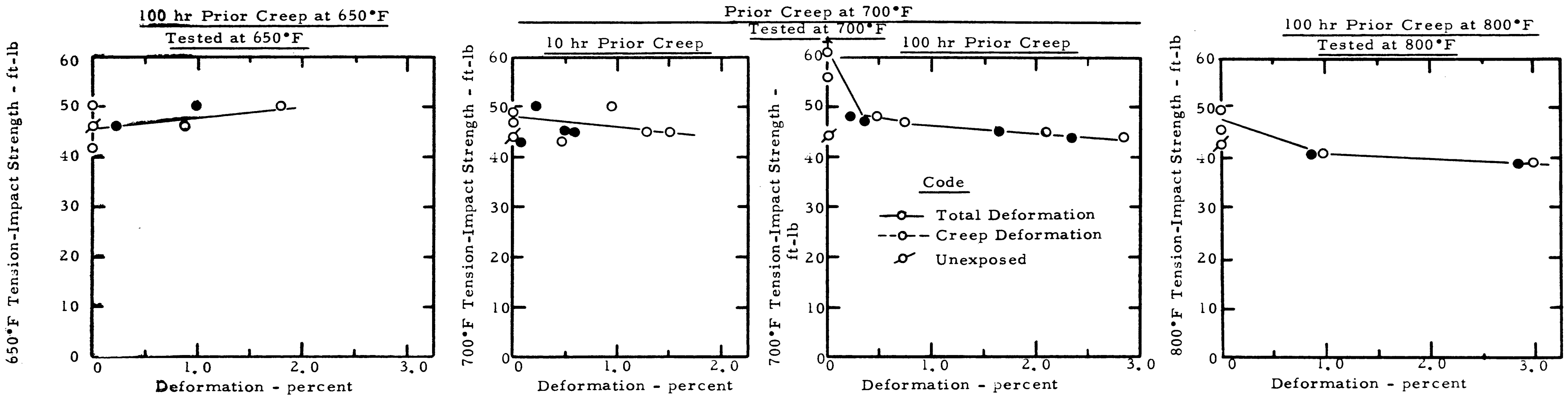


Figure 35. - Effect of Prior Creep Exposure on Elevated Temperature Tension-Impact Strengths of C110M.

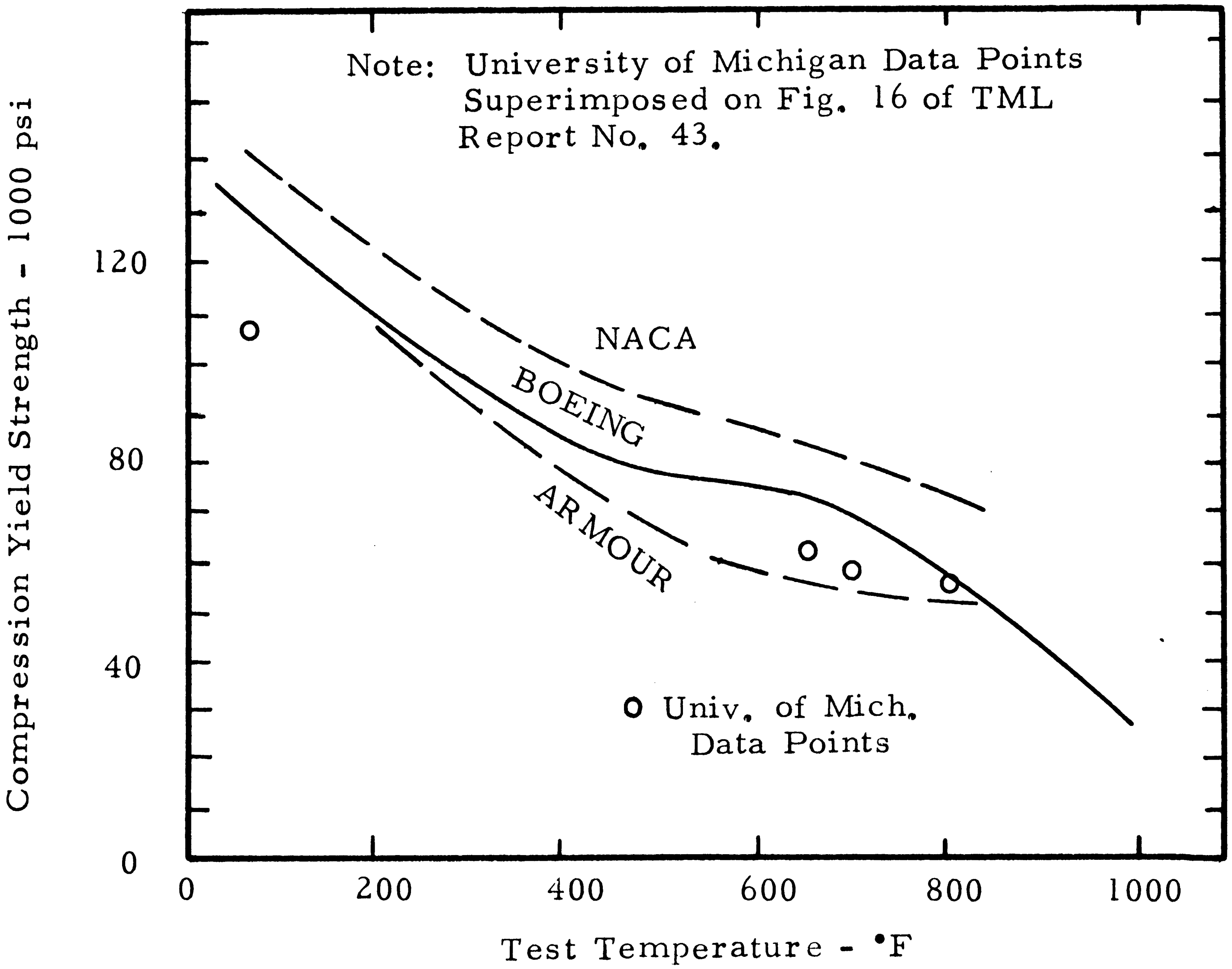


Figure 36. - Effect of Temperature on Compression Yield Strength of C110M -- Comparison of University of Michigan Data for C110M With Data from the Literature.

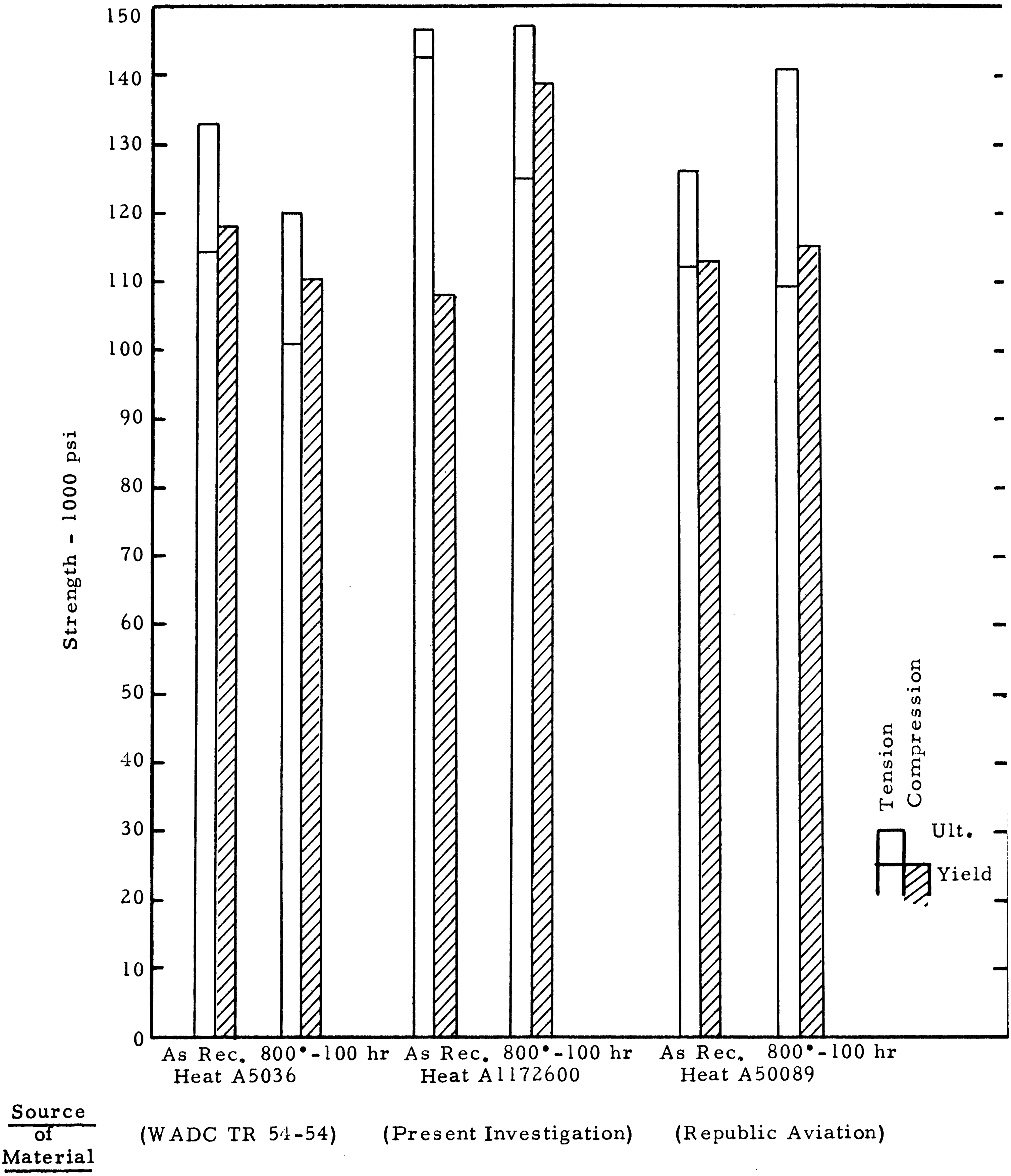


Figure 37. - Effect of 100-Hour Unstressed Exposure on Room Temperature Tension and Compression Properties of Three Heats of C110M.

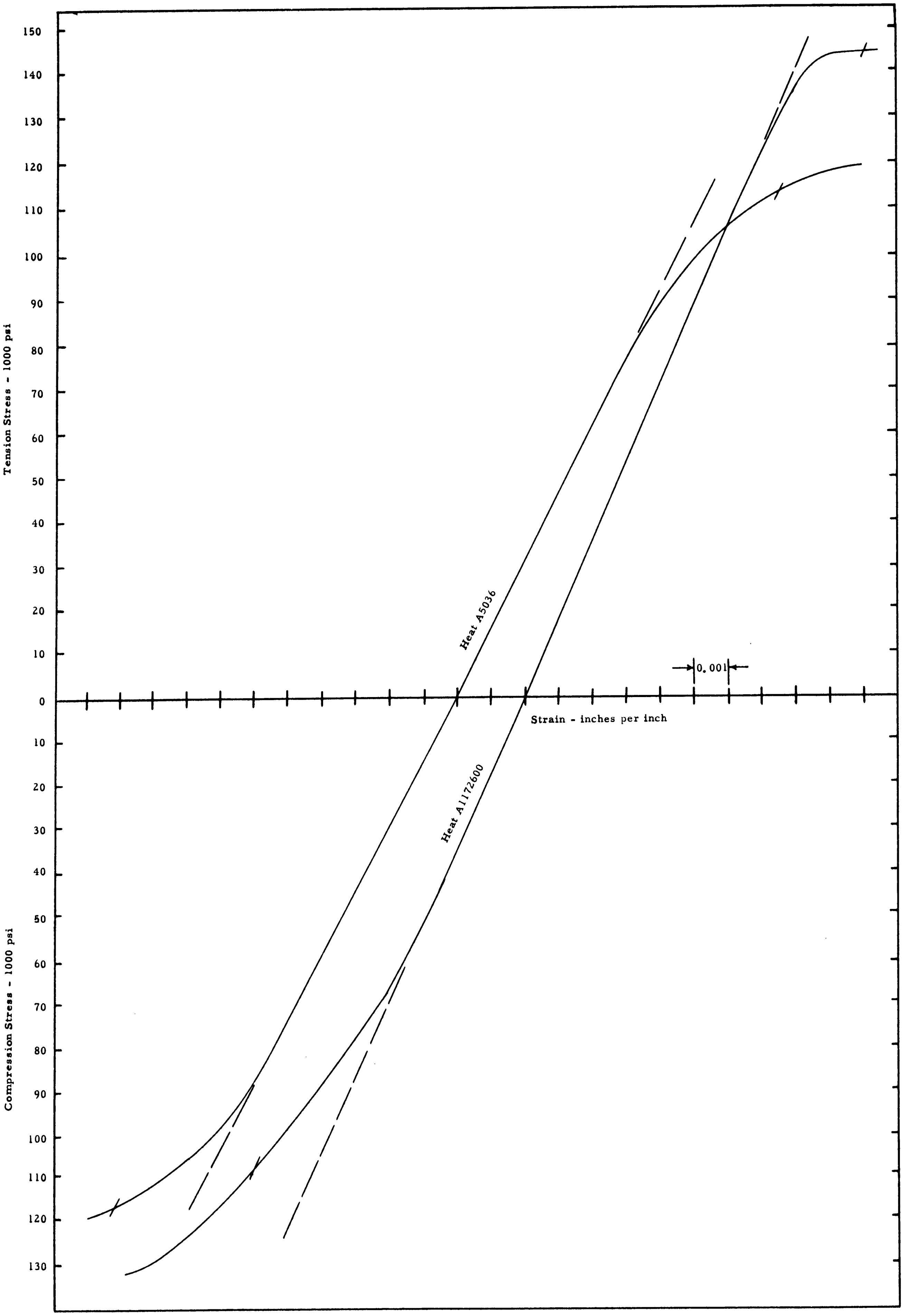


Figure 38. - Tension and Compression Stress-Strain Curves at Room Temperature for Two Heats of C110M -- Specimens taken longitudinal to the sheet rolling direction.

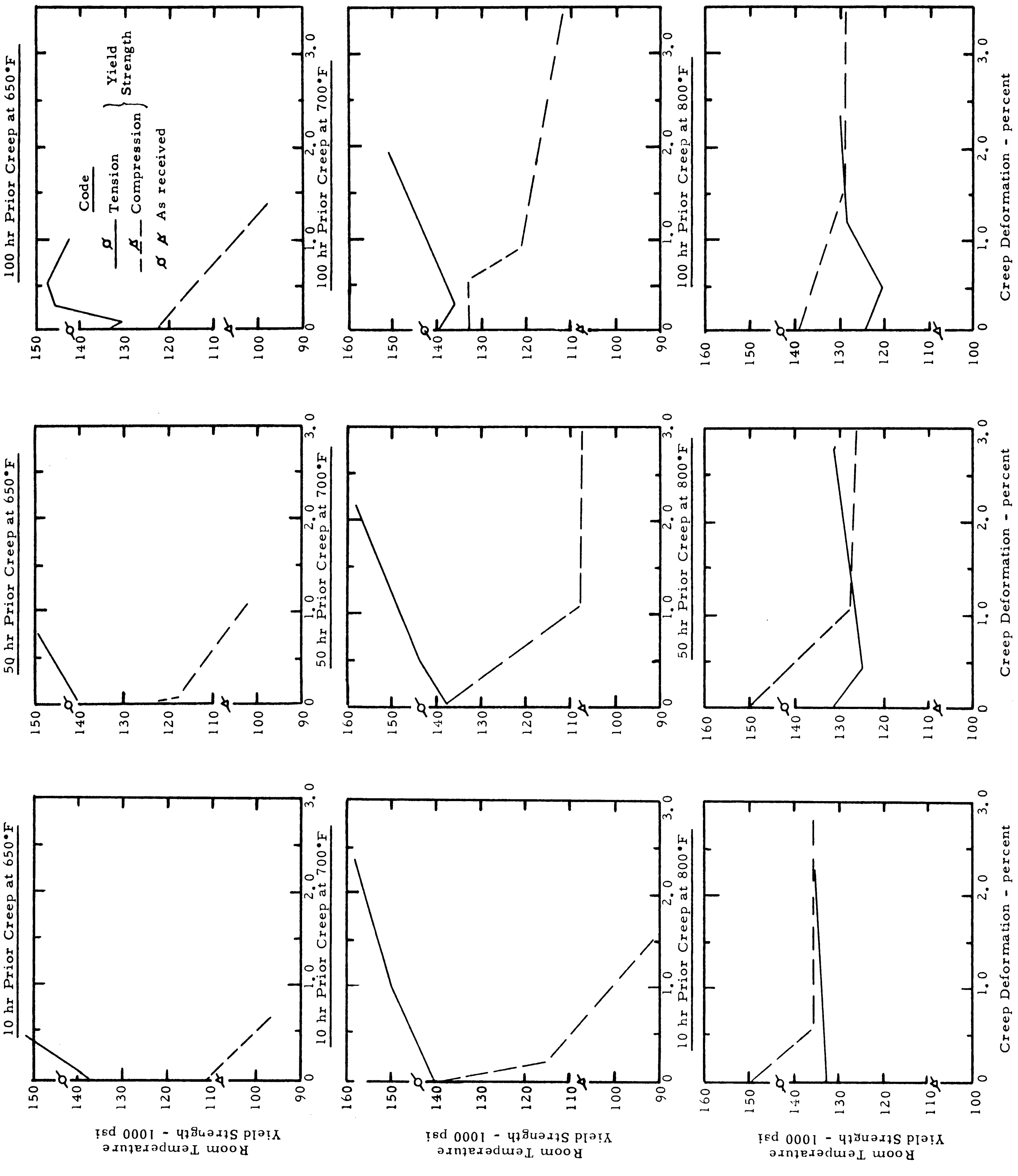


Figure 39. - Tensile and Compression Yield Strengths of C110M at Room Temperature Versus Creep Deformation for Indicated Exposure Conditions.

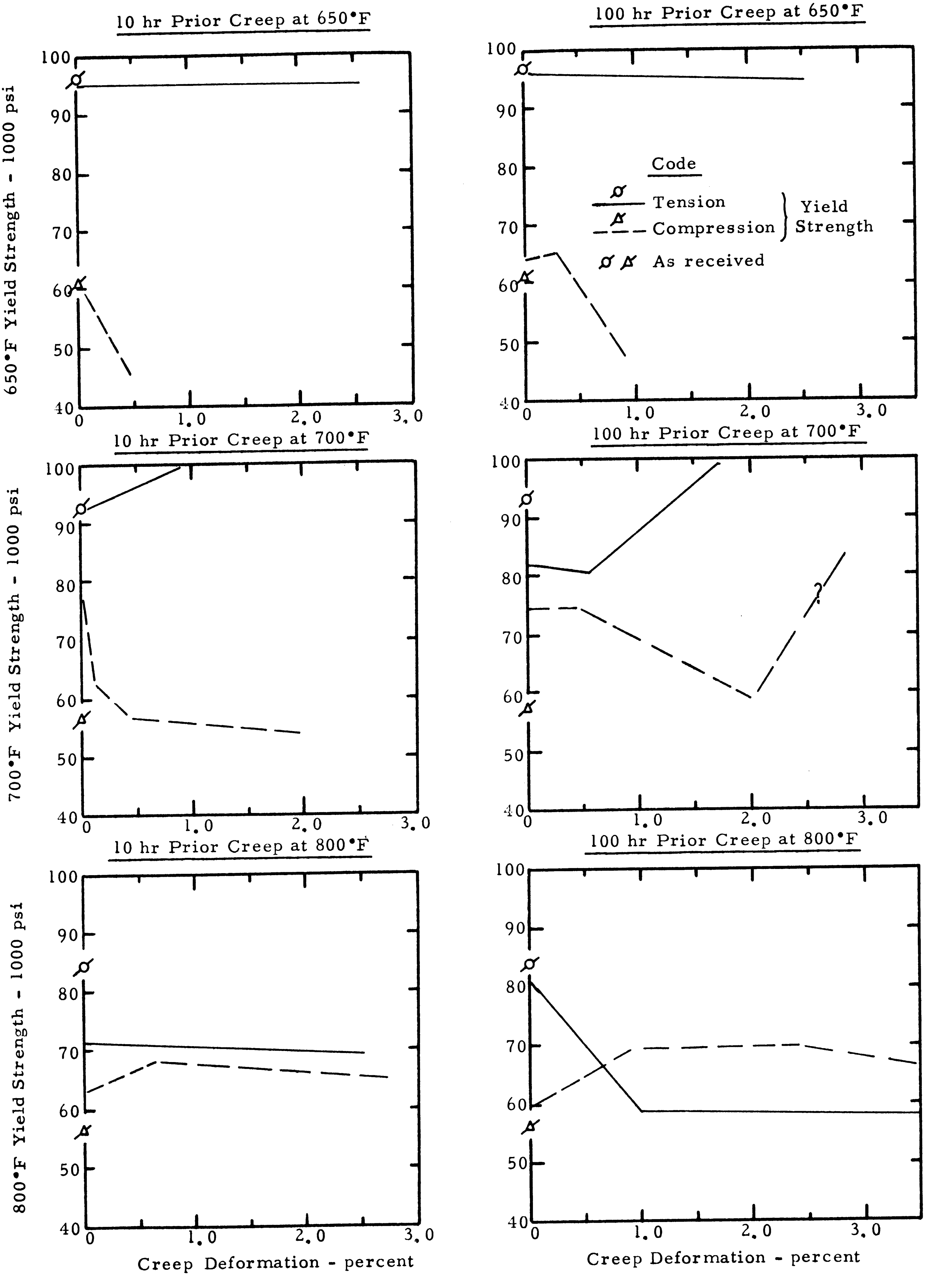


Figure 40. - Tensile and Compression Yield Strengths of C110M at Elevated Temperature After Indicated Prior Creep Exposure.

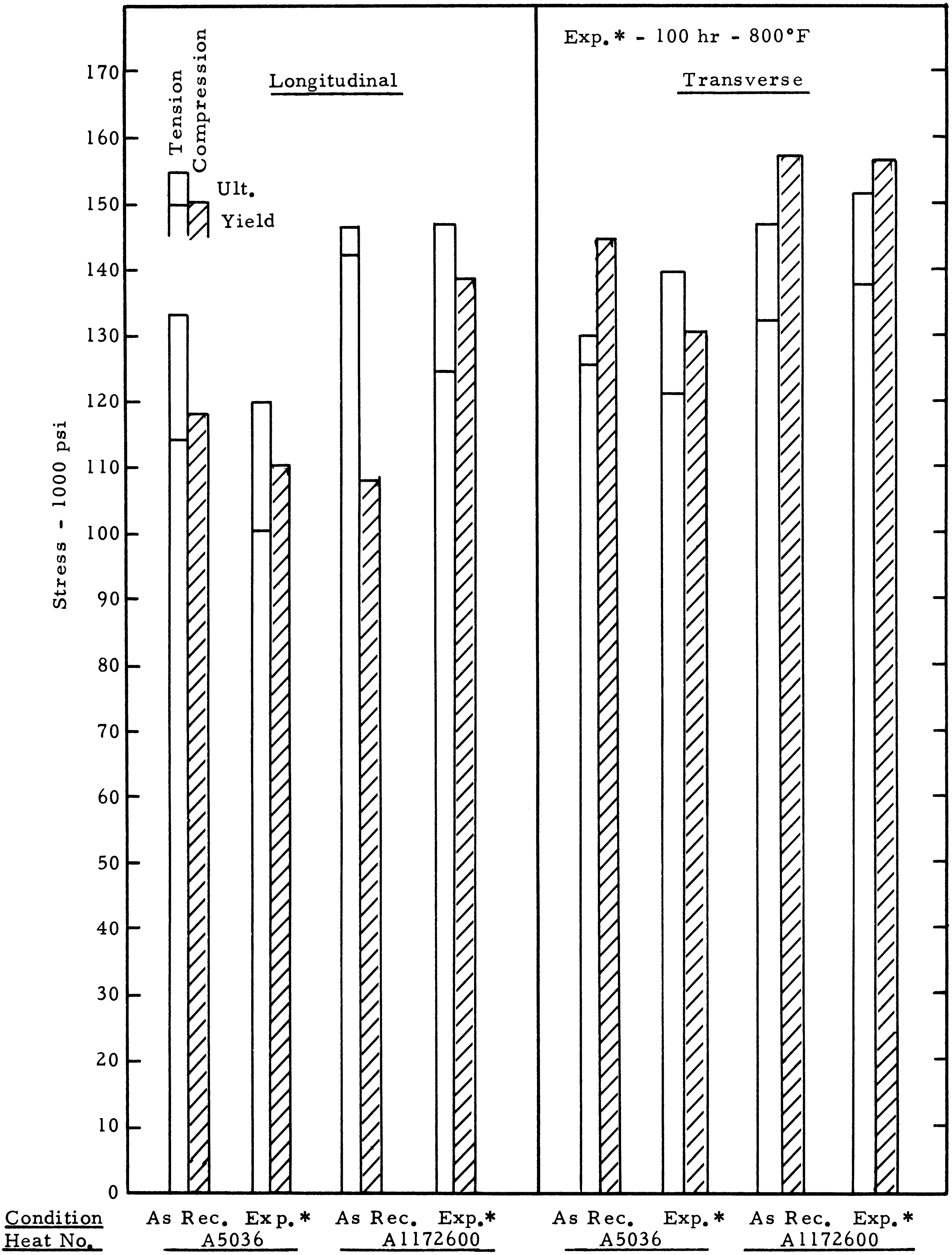


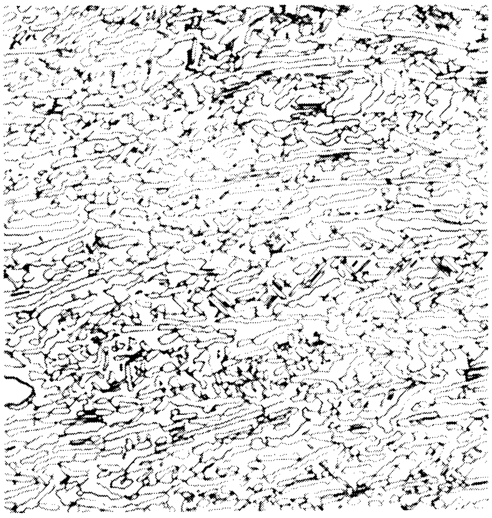
Figure 41. - Effect of 100-Hour Unstressed Exposure at 800°F on Longitudinal or Transverse Tension and Compression Strengths of Two Heats of C110M Tested at Room Temperature.

X1000

Figure 42. - C110M As-Produced

Room Temp. Properties

Ult. Tensile	146,200 (avg)
Tensile Yield	142,900 (avg)
Compression Yield	108,100 (avg)

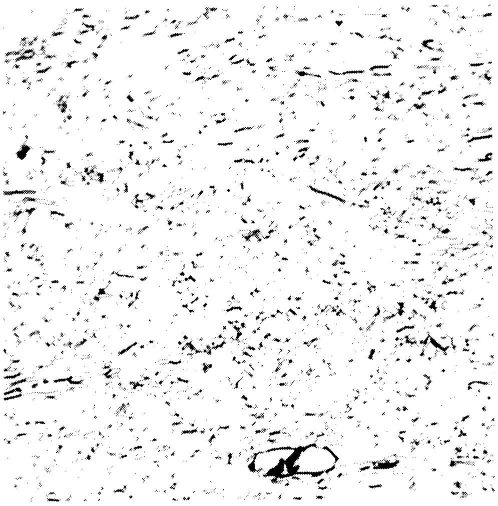


X1000

Figure 43. - C110M Exposed 100 hours at 650°F and 82,000 psi (0.26% Creep Def.)

Room Temp. Properties

Ult. Tensile	150,000
Tensile Yield	147,000
Compression Yield	114,000 (est)

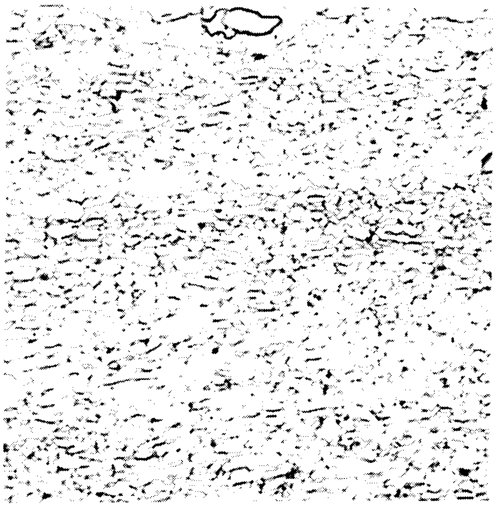


X1000

Figure 44. - C110M Exposed 10 hours at 700°F and 100,000 psi (5.44% Creep Def.)

Room Temp. Properties

Ult. Tensile	177,000
Tensile Yield.	175,000
Compression Yield	80-90,000 (est)



X1000

Figure 45. - C110M Exposed 10 hours at 800°F and 21,000 psi (0.33% Creep Def.)

Room Temp. Properties

Ult. Tensile	144,000
Tensile Yield	134,000
Compression Yield	130,000 (est)

APPENDIX I

STATISTICAL INVESTIGATION OF TEST DATA*

The short-time mechanical property data for the base (unexposed) condition of heat A1172600 were analyzed to establish the variance in normal properties. Such information is useful in evaluating the signficance of changes in properties with creep exposure.

In the present investigation, the normal properties were generally evaluated by nine duplicate tests at each temperature. Three tests each were run from the three sheets selected for study from among the eleven purchased. The properties reported in Tables 2, 3, and 4 included the average of tests within a sheet and the average of all tests. The effect of creep exposure on subsequent properties was evaluated with respect to the average of all tests.

Generally the variance of a set of data is the square of the standard deviation of the data, however, where samples sizes are small, i.e., less than about 30 observations, variance is given by the following formula

$$s^2 = \frac{\sum (X - \bar{X})^2}{N - 1}$$

where

s^2 = variance of test results
X = test result
$\bar{X}$ = average of all results
N = number of tests

For the number of samples studied in these tests "s" has almost the same properties as does sigma in a normal distribution and thus 95% of all points will fall between limits of $\pm 2s$ from the mean value.

The following tabulation gives the results of calculations of the variance of the various mechanical properties evaluated in this investigation: (It should be noted that because of the small sample size studied, one value having a large deviation from the average can greatly affect the calculated variance.)

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* The nomenclature used in this section is taken from "Quality Control and Industrial Statistics" by A. J. Duncan, Richard D. Irwin, Inc., Homewood, Illinois, 1952.

Variance Computation for Mechanical Properties of C110M (Heat A1172600)

Property	Temp. (°F)	(Av'g)	"s"	2 s (95% conf)	$\frac{s}{(\text{Av'g.})}$ (%)
Ult. Tensile	room	146,200 psi	2840 psi	5680 psi	1.94
	650	110,700	2240	4480	2.02
	700	105,500	4160*	8320	3.92
	800	92,500	2105	4210	2.28
Tensile Yield	room	142,900	2480	4960	1.74
	650	96,000	2520	5040	2.62
	600	92,700	4180*	8360	4.53
	800	84,100	2220	4440	2.64
Compression Yield	room	108,100	1760	3520	1.63
	650	61,000	5320	10640	8.74
	700	57,200	2640	5280	4.61
	800	56,300	3120	6240	5.54
Tension-Impact	room	56 ft-lb	13.	26.	23.2
	650	46	2.7	5.4	5.86
	700	44	2.5	5.	5.68
	800	43	2.4	4.8	5.58

* high value of "s" because one test had large deviation from average.

Bartlett Test Results — 95% confidence

1. Ult. Tensile - variance is homogeneous for all temp., therefore ±2s avg. = 5.08%
2. Tensile Yield - variance is homogeneous for all temp., therefore ±2s avg. = 5.72%
3. Comp. Yield - variance is homogeneous for all temp., therefore ±2s avg. = 10.26%
4. Tension-Impact - variance is homogeneous only for 650°, 700°, 800°F, therefore ±2s avg. = 11.40%

In all cases, the calculated "s" was also expressed as a percentage of the base value at the given test temperature. The effect of testing temperature on the variance was determined using the Bartlett test for homogeniety of variances. The results of this analysis showed that the variances in the ultimate tensile strength, tensile yield, and compression yield were homogeneous for all test temperatures, and the elevated temperature tension-impact variances were homogeneous but the room temperature results were not.

Consequently, the variances calculated for each temperature were expressed as a percentage of the base value and average ±2s limits were computed for each mechanical property.

The results indicate that the 95 percent confidence limits of the tensile ultimate and yield strengths fall between approximately ±5 percent of the base value, while the limits for the compression yield strength and elevated temperature tension-impact strengths fall at about ±10 percent. Room temperature tension-impact tests were considerably more subject to scatter, with a ±46 percent limitation on the 95 percent confidence limit.

These confidence limits form a rough means for the evaluation of the effects of creep-exposure and enable a better understanding to be gained of the scatter in test points from the trend lines drawn expressing the relationship between prior deformation and residual properties. This is particularly evident in the case of Figures 34 and 35, the plots of tension-impact properties. It should be realized, however, that the variance of the unexposed condition does not necessarily apply to conditions of exposure to stress and/or temperature for varying amounts of time. If the variance changes as a result of such exposure, a statistical treatment of the significance of exposure becomes a complicated analysis of the difference between the means of two small independent samples with unequal values of sigma. If the sigmas can be assumed equal and the universes are normal, then the results can be analyzed with confidence. Any deviation from these conditions must necessarily limit the effectiveness of statistical analysis.

If the assumption could not be made that exposure conditions had no effect on the variance then a sufficient number of samples would have to be evaluated at a given set of exposure conditions to permit calculation of the variance.

Assuming that the variance was constant, a computation was made of the change in ultimate tensile strength that would be required in order to be significant with respect to the base condition. This consisted of a comparison of one test point versus the nine base points. The average change required was about 4.9 percent of the base strength, a value that compares quite well with the ±5 percent computed for the 95 percent confidence limits of this property. It was then assumed that the confidence limits were an adequate expression of range of strengths to be normally expected. Test points and trend lines falling outside these limits probably represent significant changes.