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TENSILE ELASTIC PROPERTIES OF 18:8 CHROMIUM-NICKEL STEEL AS AFFECTED BY PLASTIC DEFORMATION

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SUMMARY

The relationship between stress and strain, and between stress and permanent set, for 18:8 alloy as affected by prior plastic deformation is discussed. Hysteresis and creep and their effects on the stress-strain and stress-set curves are also considered, as well as the influence of duration of the rest interval after cold work and the influence of plastic deformation on proof stresses, on the modulus of elasticity at zero stress (E_0), and on the curvature of the stress-strain line. A constant (C_1) is suggested to represent the variation of the modulus of elasticity with stress.

Curves of variation of proof stress with prior plastic deformation often have many oscillations between high and low values. Causes of the most abrupt of these oscillations are: Variation in the duration of the rest interval, and variation in the distribution of the experimental points throughout the range of extension. These oscillations probably are due in part to variations of internal stress. Variations in the rest interval generally have opposite effects on the slopes of the stress-set and the stress-strain curves. When E_0, C_1, and the corresponding stress-set curve are known, a fairly good picture is available of the elastic strength. Slight prestretching, to the extent of a small fraction of 1 percent, generally causes considerable improvement in elastic strength. Whether most of the improvement is permanent can be established only by further experiment.

Comparison is made between values of E_0 and C_1 for 18:8 alloys and for other typical metals and alloys.

INTRODUCTION

This report deals with some phases of an investigation, which was sponsored by the National Advisory Committee for Aeronautics, of the elastic properties of high-strength aircraft metals. The tensile elastic properties of a widely used corrosion-resisting steel containing about 18 percent chromium and 8 percent nickel were investigated. In the annealed condition, this alloy is relatively soft. It can be strengthened by cold work but not (to an important extent) by heat treatment. As its strength and elastic properties depend on the degree of cold work, the investigation considered the influence of cold work on these properties.

The elastic properties of a metal, as considered in this report, comprise the modulus of elasticity and the elastic strength. The elastic strength is generally expressed, for technical purposes, by one or more indices intended to represent the stress that causes the metal to reach, or even slightly to surpass, the boundary between elastic and inelastic deformation. This boundary was at one time considered to be definite and technically determinable. Below this boundary, the metal was assumed to behave in accordance with the mathematical theory of elasticity. The stress was assumed, in accordance with Hooke's law, to be proportional to the strain. On removal of stress the metal was assumed to return to the exact form that it had before the stress was applied. These properties were also assumed to be unchanged by subdivision or by variation of the size of the solid.

For some years, however, the meaning attached to the term "elastic strength" has been gradually changing. It has been found that the estimated proportional limit depends on the sensitivity of the method of measurement; the greater the sensitivity, the lower is the estimated proportional limit. Sayre (references 1 and 2) has shown, by an extremely sensitive method of measurement applied to ordinary steels and to some nonferrous metals, that the stress-strain line is probably curved throughout its entire length. Such curvature, moreover, is not necessarily due to a combination of elastic and plastic deformation. Mathematical studies of the probable variation of the attractive and repulsive forces with distance between the atoms of a space lattice seem to indicate that a curvilinear relationship between stress and strain is to be expected (reference 3). According to this view, Hooke's law is only an approximate representation of the stress-strain relationship within certain limits. A continuously curved stress-strain line obviously could not be utilized to find a definite boundary between elastic and inelastic deformation.

With development of knowledge of the microstructure of metals, it became evident that metals in general commercial use do not conform to another of the postulates of the mathematical theory of elasticity. These metals, which are made up of crystallites of varying orientation, are not unchanged by subdivision. Because of the varying orientation, the crystallites vary greatly in modulus of elasticity and elastic strength in any given direction in a polycrystalline body. In such a metal there could be no definite, technically determinable boundary between elastic and inelastic deformation. With increase in mean stress, the transition from elastic to plastic deformation is gradual.

It is conceivable, however, that a body could exhibit a curvilinear stress-strain relationship and a gradual transition from elastic to plastic deformation and yet be perfectly elastic below a certain stress. (By "perfect elasticity" is here meant the ability to resume at once its exact original form after removal of stress or after return, by any route, to the original stress.) The investigations of Hopkinson and Williams (reference 4) and Rowett (reference 5), however, have shown the existence of mechanical hysteresis at ranges of stress far below the elastic range. The investigations of Sayre (references 1 and 2) have confirmed these conclusions and have led to the view that hysteresis exists within any stress range. Such hysteresis, although it is generally called "elastic hysteresis," is evidence of imperfect elasticity, if perfect elasticity be defined as previously stated. According to the evidence, therefore, metals probably are not perfectly elastic at any stress.

Even the technically determined limits of elasticity are altered by slight surpassing of these limits (overstress). (See references 6 and 7.) Although the stress-strain relationship may be approximately linear before overstress, the relationship becomes curvilinear when the metal is retested immediately after release of the overstress. Rest of some overstressed metals at room temperature restores the stress-strain line to its original form. Restoration is hastened, however, by heating to 80°–100° C. (reference 7) or slightly higher. Among the metals that are thus restored to an approximately linear stress-strain relationship are the low-carbon steels. For some overstressed metals, however, complete restoration does not result from rest at room temperature or at 80°–100° C. but may result from heating at considerably higher temperatures.

As shown by Bauschinger (reference 6), overstress in tension causes immediate lowering of the elastic limit and yield point in compression, and vice versa. The stress-strain line is thus lowered more for stresses in the reverse direction than for stresses in the direction of the prior overstress. The elastic strength, in the direction opposite to the previous overstress, is not restored to its primitive value, even after rest or slight heating.

All these effects of overstress vary with the amount of the overstress (degree of prior plastic deformation). Study of the elastic properties of metals should therefore include study of the effects of slight overstress and of more severe cold work.

Even at stresses below the technically determined elastic limit, deformation may increase with time at constant load. A prevalent designation for such increase is "drift." After release of load, deformation generally continues for a time in the reverse direction to that of the loading. Such deformation is often termed "elastic after effect," although such a term is not generally appropriate. After fairly rapid increase or removal of load, a considerable part of the subsequent change of dimension may be due to "thermal creep." This effect is a purely elastic one caused by change of temperature. The phenomenon was first described and explained by Kelvin (reference 8). The importance of thermal creep has been exphasized more recently by Sayre (references 9, 10, and 11) and is discussed in more detail in a later section of this paper. The changes of dimensions under constant load or after removal of load, however, generally are not due entirely to thermal creep. They frequently consist almost entirely of a slower change of dimension, which may be discernible for hours, days, or even weeks. Both this slow creep and thermal creep proceed at rapidly decreasing rate. As the long-continued deformation after release of load is a type of inelastic action, such deformation is not appropriately termed "elastic" after effect.

There is evident need for clarification of the nomenclature for the elastic and the inelastic properties of metals. A general term is needed to designate any type of deformation occurring without increase of load. The word "creep," frequently used with this meaning, will be so used in this report. A fairly sharp distinction can be made between thermal creep and other types of creep. If there is a real difference in kind between the so-called drift and other types of slow deformation under constant load, however, the authors are not able to make such distinction in discussion of the data of this report.

The stress-strain line tends to be more curved for the 18:8 alloy steel than for carbon steels and ordinary alloy steels. The absence of a technically determinable proportional limit for this alloy, and for some other stainless steels, led to the specification of "proof stresses" as indices of elastic strength. A proof stress, as thus specified, must be endured without causing more than a designated amount of permanent deformation (permanent set) after release of the load. Such a test does not give a value for the elastic strength of a specimen but is merely intended to insure that the elastic strength is not below a certain limit. In the investigation of the elastic strength of metals, however, good use can be made of proof stresses determined

from stress-set curves; i. e., curves representing the influence of stress on permanent set (deformation remaining after release of load).

The investigation herewith reported has considered both the stress-set and the stress-strain relations. These two relations present complementary views of the elastic properties of a metal. The interrelationship between a stress-strain curve, hysteresis, creep, and permanent set, is discussed in part II. The method of obtaining correlated stress-set and stress-strain curves is illustrated and discussed in part III. The variations of the stress-set relationship and of the derived proof stresses with prior plastic extension, with the duration of the rest interval, and with the "extension spacing," are discussed in part IV. The variations of the stress-strain relationship with prior plastic extension, with duration of the rest interval, and with the extension spacing, as well as the variation of the modulus of elasticity with stress, are discussed in part V. Although this report is confined to results obtained with 18:8 chromium-nickel steel, results already obtained with other metals (to be discussed in a supplementary report) indicate that the conclusions are not limited (in qualitative application) to 18:8 alloy.

I. MATERIALS, APPARATUS, AND METHODS

MATERIALS AND SPECIMENS

The 18:8 corrosion-resistant alloy steels used in this investigation were of several compositions and had received various degrees of cold work. One of these steels, in two different degrees of hardness, is the same that was used in a previous investigation (results unpublished) for the Bureau of Aeronautics, Navy Department. The other steels were generously supplied by the Allegheny Ludlum Steel Corporation. They were some of the same materials that had been used by Dr. V. N. Krivobok of that company in investigating the effects of composition and cold work on some of the mechanical properties (reference 12). These steels were of four compositions, differing slightly in the proportions of chromium and nickel and in carbon content. They were supplied in three different degrees of hardness. Table I gives the compositions of all the materials and the mechanical properties of the materials as received.

In the serial designation given to each specimen, the first numeral represents the composition of the steel, and the numeral following the letter is the specimen number. The letter represents the degree of hardness; A represents annealed material, B represents half-hard material, and C represents hard material.

Only tension-test specimens were used in this investigation. The diameters of these specimens over their gage length and the corresponding bar diameters are given in table II. In order to obtain maximum accuracy in the determination of stresses, for the loading device used, the gage diameters were made as large as possible. In other respects, the specimens were according to the standard of the American Society for Testing Materials, for threaded specimens with 2-inch gage length. The ratio of gage length to diameter was not important in this investigation, because the investigation of elastic properties never required extension beyond the point of beginning local contraction.

APPARATUS

A pendulum hydraulic testing machine of 50,000-pound capacity was used. (The accuracy of this machine is discussed later.) The specimens were held in grips with spherical seats. The extensometer used in some of the preliminary stress-strain measurements was a Ewing extensometer with 2:1 lever ratio. In later experiments, a Ewing extensometer with ratio 5:1 was used. The smallest scale division on this instrument corresponded to a change of length of 0.00008 inch, and readings could be estimated to about ± 0.000008 inch; this sensitivity corresponds to a strain sensitivity of $\pm 4 \times 10^{-4}$ percent for the 2-inch gage length used. The Ewing extensometer measures the average of the extensions on two opposite sides of the specimen. In some of the later experiments, a pair of Tuckerman optical strain gages were used; these gages were attached to the opposite sides of the specimens. The smallest scale division on this extensometer corresponds to a change in length of 0.00004 inch. By means of a vernier on this instrument, it is possible to estimate changes of length to within about 0.000002 inch; this sensitivity corresponds to a strain sensitivity of 1.0×10^{-4} percent for the 2-inch gage length used.

METHOD OF INVESTIGATION

The experiments consisted in determining the total strains at various stresses and the corresponding permanent extensions after release of load. The results thus obtained were used in plotting correlated stress-strain and stress-set curves. From the stress-set curves, proof stresses were obtained corresponding to permanent sets of 0.001, 0.003, 0.01, 0.03, and 0.10 percent. From the stress-strain curves, values were obtained for the modulus of elasticity.

As one object of the investigation was to determine the variation of elastic properties with plastic deformation, the previously mentioned correlated information was obtained with specimens that had received various degrees of cold work. Considerable information about the influence of prior plastic deformation could be obtained by comparing the results obtained with the annealed, the half-hard, and the hard steels. In order to investigate the effects of numerous smaller variations in prior plastic deformation, however, tests were not confined to specimens of the various steels as received.

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By tension, specimens were extended by numerous short stages, and stress-strain and stress-set curves were obtained after each of these stages. With the same specimen, it was thus possible to obtain a sequence of curves representing the variation of elastic properties with plastic deformation.

ACCURACY OF DETERMINATION OF STRESS-SET CURVES

Permanent set was not measured at zero load, but at a load of 200 pounds. In order to determine the error in setting at this load, a series of extensometer readings were taken (with the same specimen) involving repeated increase of the load to a maximum (the selected

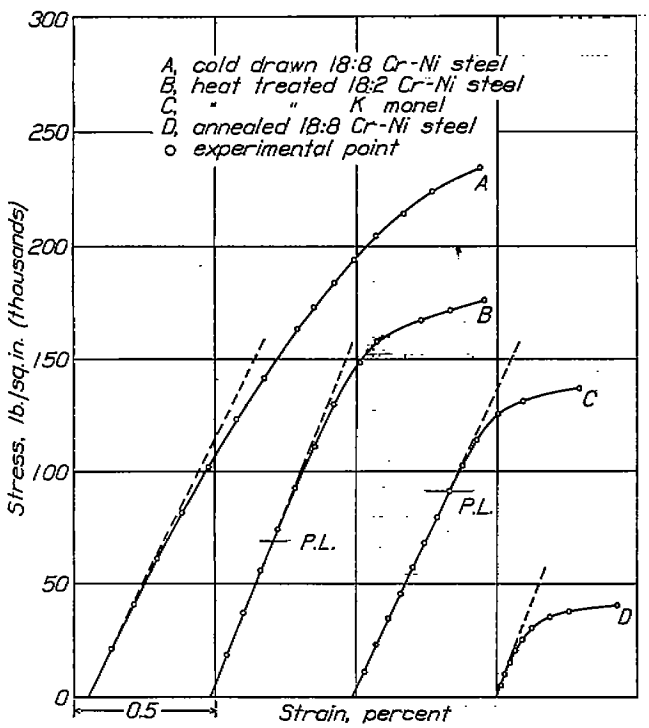

FIGURE 1.—Tensile stress-strain curves for four different metals.

value of this maximum being low enough to avoid permanent set) and reduction again to the minimum. The maximum difference between two successive readings at the minimum was equivalent to a load change of 6 pounds. This value corresponds to a stress error of 30 to 120 pounds per square inch, depending on the gage diameter of the specimen used. This stress error corresponds to a strain error of 0.0001 to 0.0004 percent, assuming a modulus of 30 million pounds per square inch. The effect of this error would be most important in determination of the lower part of a stress-set curve. As proof stresses in this report are based on permanent sets of 0.001, 0.003, 0.01, 0.03, and 0.10 percent, the corresponding maximum errors in these proof stresses would be 10 to 40 percent, 3 to 12 percent, 1 to 4 percent, 0.3 to 1.2 percent, and 0.1 to 0.4 percent, respectively.

When a stress-set curve was plotted, however, a number of determinations of permanent set were made and the curve was faired through all these points. The probable error involved in determining proof stresses, therefore, would be somewhat less than those for single measurements. The percentage error in determining values for the lowest proof stress, 0.001 percent, evidently is rather large. The error, nevertheless, is insufficient to invalidate the results; as shown in a number of figures to be discussed later, variations of the 0.001-percent proof stress (with the various factors) are qualitatively similar to variations of the proof stresses corresponding to the higher values of permanent set.

II. STRESS-STRAIN RELATIONSHIP, HYSTERESIS, AND CREEP

TYPICAL STRESS-STRAIN CURVES

Typical stress-strain curves, for annealed and for cold-drawn 18:8 steel, and for two alloys strengthened by heat treatment, are shown in figure 1. With the strain scale used in this figure, stress-strain lines *B* and *C* (representing the heat-treated alloys) appear straight, up to the indicated proportional limits. No proportional limit, however, can be found for either the cold-worked or the annealed 18:8 alloys. Even with this strain scale, it appears probable that the stress-strain lines for the 18:8 alloys are curved from the origin. With a more sensitive strain scale, the curvature would become prominent. For the heat-treated alloys, a more sensitive scale would cause the apparent proportional limits to be lower and less definite. Extremely sensitive strain measurements, such as those used by Sayre (references 1 and 2), probably would cause all the resultant stress-strain lines to be curved from the origin; all qualitative distinction between the curves for these four alloys would thus disappear.

GENERAL DESCRIPTION OF EXPERIMENTS ON HYSTERESIS AND CREEP

The stress-strain measurements indicated in figure 1 were made with gradually increasing load. If from some point on any of these curves the load had been gradually reduced to zero, the stress-strain relationship during this decrease would have followed a different curve. Even when the maximum stress is well below the technical elastic limit, the ascending and the descending curves generally do not coincide. The cycle of stress thus causes a hysteresis loop, which may or may not be closed at the bottom. The width of the loop and the degree of separation of the ascending and the descending curves at the bottom depend on the stress range, on the rate of loading, and on the number of previous cycles.

The interrelationship between stress, strain, and permanent set cannot be satisfactorily discussed without considering the influence of hysteresis and creep. In this report, some consideration will therefore be

given to hysteresis, its variation with cyclic repetition, and its relationship to positive and negative creep. Several series of hysteresis loops are shown in figures 2 and 3. In each of these series, the nominal stress range was between two constant tensile values; the lower value was only sufficient to facilitate reproducibility of strain measurement. With the stress range used for each specimen, considerable permanent set was obtained with the first cycles. The stresses were calculated by dividing the load by the cross-sectional area at the beginning of each cycle; this area was calculated from the original area by taking account of the prior plastic extension. The stresses so defined are termed "true stresses," to distinguish them from the nominal stresses based on the original cross-sectional area of the specimen.

In figure 2, the two rows of loops represent results of experiments with two specimens of one of the annealed 18:8 alloys. In order to avoid confusion, the origin of each loop has been shifted forward, by a constant abscissa interval, from the origin of the preceding loop. In each series, the experiments started with the material in its original condition. The number of each cycle in the series is given at the top. The cycle time, in minutes, is given at the top of each loop of the upper row and inside each loop of the lower row. The total plastic extension prior to each cycle is also given inside each loop. The time interval between cycles is indicated by the symbol at the beginning of each cycle. Each cycle, with one exception, was started immediately after the preceding cycle; one of the cycles was started a day after the preceding cycle. The abscissa scales for both rows are the same and are indicated at the bottom of the figure.

Because of the greater stress range in the cycles of the upper row, the plastic extension in the first few cycles was much greater in this row than in the lower row. Nevertheless, the permanent set per cycle evidently decreased more rapidly in the upper row than in the lower row. This difference in behavior doubtless is due to the much greater work-hardening obtained in the first few cycles of the upper row. Because of accidental overstressing, only 29 cycles could be obtained with the stress range represented by the lower row. A new specimen of the same material, therefore, was given 30 rapid cycles of the same stress range without observation of the strains, and the experiment was continued as represented in figure 3. The upper row of cycles in figure 2 will be discussed first. The lower row of figure 2 will then be discussed in connection with figure 3.

HYSTERESIS EXPERIMENTS WITH SPECIMEN 1A-5, FIGURE 2

The first four cycles in the upper row of figure 2 are represented by ordinary stress-strain curves. The first cycle, because of the relatively high stress applied to this annealed material, caused an extension of 15 percent. The solid line represents the variation (with strain) of the nominal stress, that is, stress based on the original sectional area; the broken line represents the variation of the stress based on the actual cross section corresponding to the strain. Each of the other loops of the upper row is a plot of the true stress as previously defined.

Comparison of loops 1 to 4, with allowance for the fact that the abscissa scale is much more sensitive for loops 2, 3, and 4 than for loop 1, showed that each of these loops (both at the middle and at the bottom opening) is considerably narrower than the preceding loop. With continued cyclic repetition, however, the difference in form between any two adjacent loops gradually becomes smaller. In order to study these further variations, therefore, it is necessary to use a still more sensitive abscissa scale. This necessity suggests representation by stress-deviation curves. For loops 5 to 161, consequently, abscissas represent deviations, differences in strain from that corresponding to an assumed initial modulus line. The nearer this assumed modulus line is to tangency with the stress-strain curve at the origin, the more sensitive can the abscissa scale be made. With the assumption of an initial modulus of 31×10^{6} pounds per square inch, it has been possible to make the abscissa scale in figure 2 much more sensitive for loops 5 to 161 than for loops 2, 3, and 4.

During studies of the variations of the hysteresis loop with cyclic repetition, consideration may be given to the width of the loop at the middle, the width of the opening at the bottom, the deviation range of the loop, and the negative creep at the bottom. These deformation values, for the series of cycles represented by the upper row of figure 2, are listed in table III. This table contains information not only about the cycles represented in figure 2 but also about the other cycles not shown in the figure. For some of the cycles that are not represented in figure 2, stress-strain measurements were made; for other cycles, such as cycles 141 to 145, inclusive, no stress-strain measurements were made but the stress range was the same as for the measured cycles. The time for an unmeasured cycle, as shown in table III, was much less than for a measured cycle. The net plastic extension per cycle, consequently, was much less for the unmeasured than for the measured cycles.

With cyclic repetition, as shown in figure 2 and table III, the width of the loop at the middle and the width of the opening at the bottom, tend to decrease. The deviation range of the loop (abscissa range in fig. 2) also tends to decrease. This general trend of each of these values, however, is sometimes interrupted or masked by the effect of any marked variation of the cycle time or of the time interval between cycles. Each cycle represented in the upper row of figure 2 generally started immediately after the end of the pre-

ceding cycle. (The negative creep at the end of a cycle was viewed as part of that cycle.) After the 11 short cycles 141 to 154, however, there was a rest interval of 1 day. Loop 155, which immediately followed this rest interval, is much wider than loop 140. This widening effect, however, is only temporary; during several subsequent loops, the width rapidly decreases and the general trend is resumed.

The net permanent extension per cycle (width of the opening at the bottom of the loop) is the difference between the total positive and the total negative creep during the cycle. Most of the positive creep occurs at and near the top of the loop, and most of the negative creep occurs at and near the bottom. The bulging of the hysteresis loop in the first part of the descent from the top often gives qualitative evidence of positive creep. The amount of creep thus revealed, however, is somewhat less than the actual positive creep, because the descending stress-deviation line would curve rapidly to the left, if there were no positive creep. In the absence of direct measurement made during the cycle, the total positive or the total negative creep cannot be estimated for any of the cycles. Values for positive creep based on the bulging of the loop below the top, however, are listed in column 13 of table III. These values evidently have only qualitative significance.[1]

Positive creep during the first part of the descent from the top may have its counterpart in negative creep during the first part of the ascent from the bottom of the loop. In other words, if time is not given for negative creep at the bottom of a loop, the next loop may show evidence of negative creep during the first part of the ascent. This negative creep reduces the positive strain and thus increases the steepness of the first part of the ascent. Sometimes this negative creep is sufficient to cause actual deviation to the left in this part of the loop. In an investigation of stress-strain or stress-set relationship, therefore, care is necessary to eliminate or minimize the disturbing effect of negative creep, near the end of a cycle, on the form of the following stress-strain or stress-set curve. In the cycles represented in figure 2, and in most of the experiments represented in the following figures, the disturbing influence of negative creep was minimized by allowing a rest interval (indicated at the bottom of each cycle in fig. 2) before beginning the next cycle. Time was thus given for completion of important thermal creep and the most rapid part of the inelastic creep. As will be shown later, however, much longer time is necessary to eliminate entirely the influence of inelastic negative creep.

[1] The amount of positive creep during descent from the top depends on the time available for creep at and near the top of the ascent. It also depends on the rate of descent from the top. In the experiments represented in figs. 2 and 3, time was not given for completion of the fairly rapid creep at the top of the loop; after each reading, the cycle was immediately resumed. If even a few minutes had been allowed for creep at the top, the most rapid portion of the positive creep would have been completed. Forward creep during descent, therefore, would have been much less and probably would have had no discernible effect on the form of the loop.

In the series of cycles represented in the upper row of figure 2, and in the other measured cycles represented in table III, negative creep was determined 1 and 3 minutes after the end of the descent to the bottom of the loop. The positions after negative creep for 3 minutes are indicated in figure 2, and the amounts of creep during 1 and 3 minutes are listed in columns 11 and 12 of table III. That the rate of negative creep decreases rapidly with time is indicated by the fact that the creep during the first minute generally was greater than the additional creep during the next 2 minutes. In spite of the rapid decrease in rate, however, negative creep may sometimes be discernible for hours, days, or even weeks (reference 10).

HYSTERESIS EXPERIMENTS WITH SPECIMEN 1A-3, FIGURE 2

In the lower row of figure 2 the loops represent a series of 29 cycles obtained with another specimen of the same material but with a much smaller range of stress. Information about these cycles, and about the other cycles of the series, is given in table IV. The first four loops in the lower row represent variation of stress with strain; the other loops represent the variation of stress with deviation from an assumed initial modulus line. For some of the cycles not represented in figure 2, stress-strain measurements were made; for the others, stress-strain measurements were not made, but the stress range was the same as for the measured cycles. The unmeasured cycles were in two groups: cycles 14 to 19, inclusive, and cycles 22 to 27, inclusive. The time of an unmeasured cycle was much shorter than that of a measured cycle, and no time was allowed for negative creep between unmeasured cycles.

With cyclic repetition, the deviation range, the loop width, and the width of the opening at the bottom (net positive creep) tend to decrease. As in the upper row of loops, the decrease in these deformation values is greatest during the first cycles; with cyclic repetition, the rate of decrease tends to become gradually less, although this general trend is sometimes interrupted owing to changes in cycle time. In the lower row the loops are more irregular than in the upper row. Positive creep during descent from the top of the loop also is more prominent in the lower than in the upper row. This difference may be due to the fact that the stress range during the first cycle represented in the upper row was sufficient to carry the metal through the stage of most rapid work-hardening with deformation.

HYSTERESIS EXPERIMENTS WITH SPECIMEN 1A-4, FIGURE 3

Because of accidental overstress of specimen 1A-3, the series represented by the lower row of figure 2 and in table IV consisted of only 29 cycles. In order to study the effect of a larger number of cycles, with the same material and with the same stress range, another series was started with a new specimen, designated

1A–4. This series, consisting of 388 cycles, is represented by the hysteresis loops in figure 3; the corresponding numerical values are listed in table V. The first 30 cycles (not represented in fig. 3) were unmeasured cycles, intended merely to carry the specimen quickly through the stages that had already been studied by means of specimen 1A–3 (lower row of fig. 2). The total extension caused by the 30 initial rapid cycles applied to specimen 1A–4 unfortunately was not measured. This extension, however, doubtless was less than the extension caused by the 29 cycles, with much longer cycle time, applied to specimen 1A–3. Comparison of widths of loops in the two series indicates that the extension caused by the 30 rapid cycles applied to specimen 1A–4 was about 3.5 percent. Assuming a value of 3.5 percent, corresponding values for total permanent set at the end of the other cycles of the series have been estimated, and are listed in column 10 of table V.

For convenient arrangement of the symbols and legend in figure 3, it is assumed that the end of the measured negative creep is the end of the cycle. An interval of unmeasured creep is treated as an interval between cycles. The time allowed for negative creep at the end of a cycle, as indicated by the symbols and legend of figure 3, generally was either 2 or 3 minutes. When the total time for negative creep was 2 minutes, the amount of creep was measured at the end of the 2 minutes, and this time was assumed to be the end of the cycle; the next cycle was started immediately. When the total time for negative creep was 3 minutes, the amount of creep was measured at the end of 1 minute but not at the end of the 3 minutes. Although the next cycle was started at the end of the 3 minutes, the time interval between such cycles was assumed to be 2 minutes. Between cycles 80 and 81, the interval was 45 hours; between cycles 115 and 116, the interval was 3 days. In this series, as shown in table V, there were four groups of consecutive rapid cycles: cycles 48 to 78, inclusive; cycles 84 to 113, inclusive; cycles 119 to 273, inclusive; and cycles 276 to 375, inclusive.

Loop 31 of figure 3 is about as wide as loop 4 of the lower row of figure 2. The narrowing effect of the first four measured cycles applied to specimen 1A–3, therefore, was about equal to the effect of the first 30 rapid cycles applied to specimen 1A–4. That the relatively great width of loop 31 represents an unstable condition induced by the previous 30 rapid cycles is indicated by the greatly decreased width of loop 32. The effect on cycle 31 was as if some of the unpermitted creep of the first 30 cycles were transferred to cycle 31.

With cyclic repetition, the maximum width of the loop and the width of the opening at the bottom (net positive creep) gradually decrease. The positive creep during descent from the top of the loop, as indicated by the form of this part of the loop, also gradually decreases. The decrease in these deformation values is rapid during the first few measured cycles but becomes slower with cyclic repetition. The general trend, however, is sometimes interrupted, owing to changes in cycle time or in the interval between cycles. The 31 rapid cycles following loop 47, for example, were followed by the slightly widened loop 79. This increased width, however, was only temporary; loop 80 is only about as wide as loop 47 and loop 81 is considerably narrower. That this difference in width between loops 80 and 81 probably is not due to the 2-day interval is indicated by the fact that rest between cycles generally causes the loop width to increase. The 3-day interval between cycles 115 and 116 caused loop 116 to be wider than loop 115. That loop 116 represents an unstable condition induced by the long prior rest interval is indicated by the fact that loops 117 and 118 are much narrower than loop 116 and are even narrower than loop 115. The 30 rapid cycles following loop 83 and without subsequent rest interval, and the 155 rapid cycles between loops 118 and 274, caused little change in the loop width.

After the 10 rapid cycles between loops 377 and 388, loop 388 is much wider (both at the middle and at the bottom opening) than loop 377. This increased width of loop 388, however, is due not to the preceding rapid cycles but to the great difference in cycle time. The greater time of cycle 388 gave opportunity for a much greater amount of positive creep. If additional cycles had been applied with the shorter cycle time generally used in this series, even the first of such cycles possibly would have given a loop no wider than loop 377; with further cyclic repetition, the loop width probably would have slowly decreased.

VARIATION OF CREEP WITH CYCLIC REPETITION

The negative creep at the bottom of the loop, as shown in tables III, IV, and V, decreased rapidly during the first few cycles, and changed little during further cyclic repetition. If negative creep at the end of each cycle had been measured for a much longer period, however, the results probably would show that cyclic repetition caused the negative creep to decrease at a generally decreasing rate (reference 13). Both net positive creep and negative creep, with repetition of cycles of constant stress range, probably approach zero. The width of the loop at the middle, however, probably does not approach zero but approaches a limiting value. With a completely closed loop, the form and the size probably would be independent of cycle time. The hysteresis represented by such a loop is sometimes termed "elastic hysteresis." A better name in frequent use is "statical hysteresis."

That the 388 cycles (applied to specimen 1A–4) have not caused the hysteresis to be entirely statical is demonstrated by the previously mentioned difference

between loops 377 and 388 of figure 3, and by the fact that these loops, unlike a loop representing statical hysteresis, are far from complete closure. Thousands, possibly millions, of cycles probably would have to be applied to this specimen to cause complete closure of the loop and to make the hysteresis entirely statical (reference 13). With much shorter cycle time (high cycle frequency), the number of cycles necessary to reach a condition of statical hysteresis would be still greater.

THERMAL CREEP

Negative creep frequently is called "elastic after effect." The probable reason for this name is that negative creep represents approach to the initial form and dimensions. One kind of negative creep, however, probably is due to plastic deformation of some parts of the microstructure, caused by internal stresses in the elastic portions of the microstructure. As a general name for the phenomenon, "elastic after effect" is therefore less suitable than "negative creep."

One kind of negative creep undoubtedly represents a truly elastic change of form due to the thermal influence of change of stress. Kelvin (reference 8) showed that elastic extension of a metal tends to cause slight lowering of temperature and that elastic compression (or removal of elastic tension) tends to cause slight elevation of temperature, provided that the temperature coefficient of expansion of the metal is positive. The opposite temperature changes occur if the coefficient of expansion is negative. After abrupt change of tensile or compressive stress, therefore, metal tends to absorb heat from its surroundings or to give up heat to its surroundings and thus tends to change in length until the difference in temperature between the metal and its surroundings disappears. This type of creep has been investigated by Sayre (references 9, 10, and 11) and by others and has been called "thermal creep."

As shown by Sayre, consideration should be given to the probable amount and duration of thermal creep after any abrupt change of stress. The total amount of thermal creep, which can be determined approximately by means of equations based on the mathematical investigation by Kelvin, depends on the temperature coefficients of expansion and of the modulus of elasticity as well as on the change of stress (reference 10). Consideration of these equations has led to the conclusion that, in the specimens of 18:8 alloy used in this investigation, the total thermal creep was 0.003 times the preceding abrupt elastic change of length. A value of about 0.0025 was obtained by Sayre for ordinary steel. For 18:8 alloy, however, the ratio would be somewhat greater, because the temperature coefficients of expansion and of the modulus of elasticity are greater for this alloy than for ordinary steel. Assuming that the ratio is 0.003 for 18:8 alloy, the total thermal creep probably amounts to about 0.00001 percent per 1,000 pounds per square inch prior adiabatic change of stress.

The rate and the duration of thermal creep, because they depend on the rate of change of temperature of the metal, depend on the thermal conductivity of the metal, and on other factors affecting the rate of transfer of heat to and from the surroundings. With a relatively long wire, the rate of equalization of temperature depends almost entirely on the rate of radiation and convection and very little on the conduction of heat along the wire. Under such conditions, the duration of thermal creep, as stated by Sayre (reference 10), is nearly proportional to the diameter of the wire. With the relatively short, thick specimen used in the investigation, most of the heat transfer would be by conduction through the ends. Very little quantitative information is available about the duration of thermal creep under these conditions. Results mentioned by Farren and Taylor (reference 14) are somewhat contradictory. The impression gained from their paper, however, is that the thermal change (with the form of specimen used in this investigation) would generally be completed within about a minute. In order to minimize the effects of thermal creep, therefore, most of the readings of permanent set, described in the following sections, were made after a rest interval of at least 1 minute. The time needed for the rest interval obviously depends on the amount of the prior change of stress.

In a specimen under bending stress, change of stress causes opposite changes in temperature on opposite sides of the specimen. The resultant steep transverse temperature gradient thus causes the equalization to be much faster, and consequently causes the duration of thermal creep to be much shorter for bending than for tension or compression. For torsion, the amount of thermal creep is generally negligible because torsion causes practically no change in volume.

The stress range for the previously described loops of figures 2 and 3 was not great enough to cause important thermal creep. Even if the stress had been lowered rapidly from the maximum value of the cycle, the total negative thermal creep would have been less than 0.001 percent. The time required for the descent from the top to the bottom of each loop, moreover, was sufficient to allow completion of most of the thermal creep during the descent. The negative creep observed at the bottom of each loop was therefore almost entirely inelastic creep.

III. STRESS-SET CURVES, STRESS-DEVIATION CURVES, AND PROOF STRESSES

Stress-strain (or stress-deviation) curves alone give incomplete information about the elastic properties of 18:8 alloy. This information needs to be supplemented

by study of the relationship between stress and resultant slight plastic deformation (permanent set). The method of obtaining correlated stress-set and stress-deviation curves is illustrated by the diagram at the right of the lower row of figure 3.

This diagram consists essentially of a series of hysteresis loops of gradually increasing range. Each experimental point in this diagram, with one exception, was obtained with merely enough delay to permit observation of the stress and the strain. The rate of variation of the load, however, was so slow that the influence of thermal creep probably was negligible. With the one exception mentioned, no time was allowed for negative creep at the bottom of a loop; the next loop was started immediately. (In most of the experiments to be described later, there was a time interval between any two loops.) The one exception in this series of loops is at the end of loop 4. After the immediate reading, represented by point E, there was a delay of 70 minutes before the beginning of loop 5. (Loop 5 has been shifted to the right as indicated by the scale at the bottom of the figure.) The rather large amount of negative creep during the 70-minute interval has shifted the beginning of loop 5 from E to F. As thermal creep was negligible, the negative creep from E to F was almost entirely inelastic.

The total permanent set after each loop is indicated by the abscissa of the corresponding point at the bottom of the loop. If the stress at the top of each loop is plotted against the total permanent set at the bottom of the loop, a curve is obtained representing the variation of permanent set with stress. Curves thus obtained are shown in the lower rows of figures 6, 8, 12, and 16 and in both rows of figure 20. They will be presented and discussed in part IV. In the obtaining of a stress-set curve, time was generally allowed for the most rapid part of the negative creep at the bottom of the loop. The amount of this creep generally increases with the previously applied stress.

The curve drawn through the tops of the series of gradually increasing loops in figure 3, is a stress-deviation curve. Such a curve, although it is obtained by a series of cycles, differs little in form and position from a stress-deviation curve obtained with continuous increase of load. From a series of gradually increasing loops, therefore, it is possible to obtain both a stress-set and a stress-deviation curve. Stress-deviation curves so obtained are shown in the upper rows of figures 6, 8, 12, and 16, discussed in part V.

Various proof stresses may be derived from a stress-set curve. By "proof stress" is meant the stress corresponding to an indicated value of permanent set. The values of permanent set utilized in establishing proof stresses in this report are 0.001, 0.003, 0.01, 0.03, and 0.10 percent. For any of these values of permanent set, the proof stress may be determined from a stress-set curve by estimating the ordinate at the corresponding abscissa. The steeper the slope of the stress-set curve, the higher are the corresponding proof stresses.

IV. THE INFLUENCE OF PRIOR PLASTIC DEFORMATION AND OF DURATION OF THE REST INTERVAL ON THE STRESS-SET CURVE AND ON THE DERIVED PROOF STRESSES

THE INFLUENCE OF PRIOR PLASTIC EXTENSION ON THE STRESS-SET CURVE AND ON THE DERIVED PROOF STRESSES. SPECIMEN 1B-1

In order to investigate the effect of prior plastic deformation on the stress-set curve and on the derived proof stresses, tension-test specimens of the various materials have been extended by numerous small stages to the point of beginning local contraction or even somewhat further. After each of these small stages a stress-set and generally a stress-deviation curve have been obtained. With a single specimen, therefore, it has frequently been possible to obtain a series of stress-set and stress-deviation curves. With the specimens of the less ductile materials, however, fewer of these curves could be obtained, and results from several specimens have sometimes been assembled in a single figure.

Attention will first be given to the stress-set curves in the lower row of figure 6 and to the derived diagram of figure 7. The results shown in these two figures were obtained with the same specimen of half-hard metal, 1B–1. This specimen was stretched in numerous short stages. Each of these stages consisted of a group of cycles of increasing range, similar to the previously described group shown at the right of figure 3. From each of these groups, a stress-set curve and a stress-deviation curve were obtained. Most of the stress-set curves are shown in the lower row of figure 6, and the corresponding stress-deviation curves are shown in the upper row.

In each of the cycles of a group, readings were taken without a rest interval. (In later experiments, with other specimens, readings in each cycle were taken after a rest interval, generally 1 minute.) The rate of increase or decrease of stress, however, was never faster than about 75,000 pounds per square inch per minute. For the smaller cycles of each group, the rate was only about 30,000 pounds per square inch per minute. In the last (largest) cycle of a group, in which the range of stress generally was considerably greater than any of the values indicated in the stress-set curves of figure 6, the plastic extension was relatively large. In this cycle, therefore, the reduction of stress from the maximum to the minimum was made very slowly; the time required for this reduction was 6 to 7 minutes. Between the last reading for each group of cycles and the first reading for the next group, there was a rest interval.

No time was given for negative creep before the readings, except before the initial reading for each group of cycles. Negative creep, however, would chiefly affect the positions of experimental points representing the effects of the higher stresses. The effect of allowance for negative creep on the form of the stress-set curve and on the proof stresses would probably be relatively small. Because of the slow rates of loading and unloading, moreover, the reproducibility of results probably was sufficiently good to permit a study of the influence of prior plastic extension and of the rest-interval.

The rest interval between determinations of successive stress-set curves (or stress-deviation curves) varied from a few minutes to several days. The duration of the rest intervals is indicated, in figures 6 and 7 and in other diagrams, by various symbols, whose meaning is explained in the key of figure 7. In the experiments represented in figures 6 and 7, the rest interval generally was 2 to 6 minutes; a few of the intervals were much longer. The extensions indicated by the experimental points of figure 7 consisted entirely of groups of cycles like the group at the right of figure 3, with no extensions between these groups.

Comparison between the experimental points in figure 7 and the corresponding stress-set curves in figure 6 was facilitated by numbering consecutively the points in figure 7, and these numbers have been used to identify the corresponding curves of figure 6.

The initial stress-set curve, curve 1 of figure 6, shows permanent set at very low stress. With increase of stress, moreover, the permanent set increases very rapidly. The corresponding proof stresses, as indicated (for 0.001, 0.003, and 0.01 percent permanent set) by the short projecting lines at the left of figure 7, are low. The proof stresses for 0.10 percent permanent set cannot be obtained from any of the curves shown in this report but have been obtained from curves drawn with a less sensitive scale of abscissas. Curve 2 of figure 6 is much steeper than curve 1; the nearly vertical portion, moreover, is much greater in curve 2 than in curve 1. The slight plastic extension required to obtain curve 1 evidently has caused considerable improvement in elastic strength.

During several succeeding cycles, the improvement in elastic strength generally continues, as illustrated by curves 3, 4, and 5 of figure 6, and by the corresponding points in figure 7. With still more prior plastic extension, there is practically no further general improvement in the nominal proof stresses corresponding to permanent sets of 0.001 and 0.003 percent, and only slight improvement in the proof stress for 0.01 permanent set. The proof stresses corresponding to permanent sets of 0.03 percent and 0.10 percent, however, show continuous general improvement with increase in prior extension.

In the discussion of proof stress-deformation curves such as those of figure 7, chief attention will be given to the curves representing the 0.001 percent and 0.003 percent proof stresses. In the consideration of elastic strength, more attention probably should be paid to these indices than to the 0.01, 0.03, and 0.10 percent proof stresses. The 0.01 percent proof stresses probably should be viewed as indices of resistance to yield rather than as indices of elastic strength.

The most conspicuous characteristic of the proof stress-deformation diagram (fig. 7) is the wide scatter of experimental points. This wide scatter cannot be attributed to experimental error but is due to the influence of several variables inseparably associated with investigation of the variation of proof stresses with plastic extension. In order to study the influence of plastic extension and of the associated variables on proof stresses, consecutive experimental points have been connected by straight lines. The graphs thus obtained, as will appear in the following discussion of this and other figures, should be viewed not as continuous "curves" of variation of proof stress with deformation but as a sequence of experimental points connected by straight lines. In the graphs so drawn in figure 7, there is tendency to zigzag oscillation between high and low values. A wide swing sometimes comprises several experimental points; for example, the swings between 20 and 23 and between 33 and 42. A few wide swings, however, are between adjacent points. An exceptionally high point tends to be followed immediately or shortly by an exceptionally low point, and vice versa. Examples of wide swing between adjacent points are 77–78, 102–103, 113–114

These wide oscillations are superposed on a less abrupt wavelike oscillation of mean values. This wavelike oscillation is represented approximately by the broken curve for 0.001 percent proof stress in figure 7. Similar curves could be drawn for the 0.003 percent and the 0.01 percent proof stresses. Maxima and minima for all these curves would be at about the same abcissas. For the 0.001 percent proof stress, the highest wave crest is at prior plastic extension of about 0.4 percent. For the 0.003 percent proof stress, the wave crests are at about the same height at prior plastic extensions of 0.2 and 6 percent; with further extension, the heights of the wave crests evidently change very little. For the 0.01, 0.03, and 0.10 percent proof stress, the wave crests increase in height with increase in prior extension.

If the curves were drawn with ordinates representing true stress (stress based on the sectional area at the beginning of each stress-set determination), the curve for 0.001 percent proof stress would still have its highest maximum at about 0.4 percent prior extension but the maxima for the curves for other proof stresses would increase in height with increase in prior extension.

The oscillations in the proof stress-deformation curves of figure 7 correspond to variations in the stress-set curves. In the consideration of possible causes of

these variations, attention is attracted to the influence of the rest interval prior to the determination of each stress-set curve. This interval was 2 to 6 minutes for all the curves except three. For three curves, 98, 103, and 108, the prior rest interval ranged from about 80 minutes to 21 hours. These three curves are much less steep than the curves immediately preceding, and they correspond to exceptionally low points in figure 7. This fact suggests that the slope of the stress-set curve is greatly influenced by the prior rest interval.

In the literature, practically no reference has been made to the influence of the prior rest interval on the form of the stress-set curve. References 1, 5, 7, 9, 10, 11, 15, and 16 discuss the influence of rest interval on the form of the stress-strain curve. These references all report that overstress lowers (increases the rate of deviation of) the stress-strain curve. Before the overstress, the curve (for many metals) may have a long, nearly straight portion; after the overstress, the graph is curved from the origin. Rest after overstress, as generally reported (references 7, 15, and 16), tends to elevate the stress-strain curve in such a way as to restore the original nearly straight portion. With some metals, restoration of "elasticity" is complete after a rest interval at room temperature; with other metals, complete restoration requires a slight temporary elevation of temperature. On a stress-set curve, however, a rest interval evidently tends to have the opposite effect. With increase in the duration of rest, according to the evidence in figures 6 and 7, the stress-set curve becomes less steep. As some exceptionally low points in figure 7 were obtained after very short rest intervals, however, they must have been influenced by some factor other than the duration of the rest interval. This subject was further investigated, therefore, by additional experiments made with special attention to the influence of the rest interval.

THE INFLUENCE OF PRIOR PLASTIC EXTENSION AND OF DURATION OF THE REST INTERVAL ON THE STRESS-SET CURVE AND ON THE DERIVED PROOF STRESSES, SPECIMEN 1B-3

Another specimen of the same half-hard material was similarly extended by groups of cycles of application and removal of load. Results thus obtained are shown in figures 8 to 11. For these extensions, as for those represented in figures 6 and 7, there was a rest interval, but no extension interval, between successive groups of cycles.

In the determination of each stress-set curve (fig. 8) from a group of cycles, such as that shown at the right of the lower row of figure 3, the time schedule was different from that used in determining the stress-set curves of figure 6. Each reading of permanent set, represented by each experimental point in the lower row of figure 8, was obtained after a rest interval of 1 minute, after the stress had been reduced to the minimum value (about 1,500 pounds per square inch). The time required for the reduction of stress from the maximum to the minimum value was about 1 minute for the smallest (first) cycle of a group, and 1½ to 2 minutes for the largest (last) cycle. The rest interval before reading probably was not enough for completion of negative creep induced by the large cycles. This creep, however, probably was small in comparison with the permanent set. Variations in form of the stress-set curves, therefore, can be attributed largely to the influence of prior plastic deformation and to varying duration of the rest interval.

A rest period intervened also between adjacent groups of cycles (adjacent stress-set curves). The duration of this rest interval is indicated approximately by the symbols in figures 8 and 9, which are explained by the key in figure 9. Further information about the influence of the rest interval was obtained by interspersing a number of intervals ranging from ½ hour to more than 48 hours among the much shorter intervals, 2 to 6 minutes.

The influence of duration of the rest interval is clearly shown by comparison of the stress-set curves in the lower row of figure 8 and by comparison of the heights of the corresponding experimental points in figure 9. Every relatively long prior rest interval resulted in a stress-set curve less steep than the curves immediately preceding and following. As some of the stress-set curves of this series are not shown in figure 8, the relative steepness of curves 8 to 27 of that figure can be deduced only from the relative heights of the corresponding experimental points in figure 9. As shown in figure 9, every experimental point representing a relatively long prior rest interval is lower in the diagram than the points immediately preceding and following. Of the exceptionally low points in figure 9, only one or two represent results obtained after a short rest interval, 2 to 6 minutes. The most conspicuous of these is 33, which appears to represent a recoil from the exceptionally high point 32.

The evidence appears conclusive, therefore, that the steepness of the tensile stress-set curve for this material tends to decrease with increase in the duration of the preceding rest period. In a consideration of the possible causes of this effect of the rest interval, attention is naturally directed to the effect of negative creep. A specimen in which negative creep had been permitted probably would exhibit more positive creep (permanent set) on reloading than would a specimen that had not been given opportunity for negative creep. In this connection, it is worthy of note that the effect of a 56-minute rest interval (curve 54) on the steepness of the stress-set curve was nearly as great as the effect of a longer interval. This fact appears to be consistent with the opinions of various investigators (reference 11) that the relationship between rate of creep and time is exponential.

The fact that the initial proof stresses are exceptionally low may not be attributable entirely to the long time that has been available for negative creep. To what extent these low initial values are attributable to prior negative creep or to other effects of a long rest period can be decided only after further investigation.

The wide zigzag oscillations so noticeable in figure 7 are again conspicuous in figure 9. Not all of the wide oscillations in this figure are attributable to differences in rest interval. The steep descent between 32 and 33, for example, evidently is due to some other cause. Differences in the rest interval evidently may be so interspersed as to intensify the oscillations and influence their spacing. A low point representing a long rest interval tends to be followed immediately by an abrupt rise to an exceptionally high point. This high point is followed by a descent, which is influenced considerably in steepness (of the straight connecting lines as drawn) by the position of the next point representing a long prior rest interval. This influence of the relative positions of the low points that represent long rest intervals is illustrated by the following examples. Between low points 19 and 24, which are relatively far apart, there is a steep rise and less steep descent. Between low points 31 and 37, which are still farther apart, there are two oscillations. Between low points 40 and 43, 43 and 46, 46 and 48, and 48 and 51, which are near together, there is a steep rise and an equally steep descent. Point 28 apparently is so placed that it shortens the rebound from point 27. The extension spacing of the interspersed points representing long rest intervals, evidently has much influence on the range of oscillation.

The initial stress-set curve of figure 8, like the initial curve of figure 6, is much less steep than the next succeeding curve. The form of curve 1 of figure 8 apparently indicates that permanent set is induced in this material by any stress, however small. Curve 2 shows that the elastic strength has been greatly improved because of the slight plastic extension in determining curve 1. Further plastic extension caused general further improvement of elastic strength, as shown by the stress-set curves of figure 8 and by the increase in height of the corresponding points in figure 9. This improvement continues at a generally decreasing rate until point 5 is reached. At this point begins the first important descent to a minimum. The position and height of this minimum is affected only slightly by point 7 representing a relatively long prior rest interval. The range of oscillation apparently tends to increase with prior plastic extension, at least to an extension of 12 to 18 percent. (A similar increase in range of oscillation with prior extension may be seen in fig. 7.)

The zigzag oscillations are superposed on a less abrupt wavelike curve. The curve for 0.001 percent proof stress, as in figure 7, reaches its first maximum at prior extension of about 0.4 percent and its first minimum at an extension of about 2 or 3 percent. Even if the ordinates in figure 9 represented true stresses, the curve for 0.001 percent proof stress would show no continuous tendency to increase in height with increase in prior plastic extension beyond about 0.4 percent.

THE INFLUENCE OF PRIOR PLASTIC EXTENSION AND OF DURATION OF THE REST INTERVAL ON THE STRESS-SET CURVE AND ON THE DERIVED PROOF STRESSES, SPECIMEN 2A-1

In order to obtain further information about the influence of prior plastic extension and of duration of the rest interval on the stress-set curve and on the derived proof stresses, another series of experiments was made with a specimen of annealed material, 2A–1. Stress-set curves obtained in these experiments are shown in the lower row of figure 12, and the derived proof stresses are shown in figure 13. In these figures, ordinates represent "true stress," stress based on the sectional area at the beginning of determination of a stress-set curve.

In the previously described experiments, with specimens 1B–1 and 1B–3, extension was by a continuous series of stages, each comprising a group of cycles involved in the determination of a stress-set curve. In the experiments with specimen 2A–1, however, there were numerous pairs of adjacent short extensions separated by relatively long single extensions. Each pair of adjacent short extensions consisted of two adjacent groups of cycles involved in the determination of two stress-set curves. In each pair in figure 13, therefore, the experimental points are separated only by the extension involved in determining the first stress-set curve of the pair. As the first stress-set curve of each pair was obtained after a relatively long extension, the determination of this curve should be preceded by a relatively long rest interval. This rest interval, as shown in figure 13, was at least 20 minutes, often much longer. The second experimental point of a pair was obtained after a rest interval that varied from a few minutes to 20 minutes or more. From the relative positions of the experimental points of a pair, information may be obtained about the influence of duration of the rest interval.

In many instances, the stress-set curves of a pair were separated by a small intervening cycle (insufficient to cause important permanent extension but sufficient to influence the lower part of the following stress-set curve). The nominal maximum stress of this intervening cycle was 40,000 pounds per square inch. The second point of each pair with such an intervening cycle is indicated in figures 12 and 13 by a small diamond shaped symbol.

After the intervening cycle, the second stress-set curve of the pair was immediately determined. Although a rest interval of varying duration immediately preceded the intervening cycle, this cycle prevented the

rest interval from affecting the second stress-set curve of the pair.

With the annealed material used in these experiments, the range of oscillation in figure 13 does not attain the high values noted for half-hard material in figures 7 and 9. The range of oscillation, however, evidently tends to increase with the prior extension. The influence of duration of the rest interval on these oscillations is again conspicuous in figures 12 and 13. As shown in figure 12, stress-set curves obtained after relatively long rest intervals, generally are less steep than the curves immediately preceding and following. As shown in figure 13, the low point of each oscillation (with a few exceptions) represents a result obtained after a relatively long rest interval. Increase in duration of the rest interval, therefore, evidently tends to lower the stress-set curve and the derived proof stresses. The effect of increase in the rest interval appears to be large for the first hour; further increase in duration appears to have somewhat less effect.

The effect of the (previously described) small cycle intervening between two consecutive stress-set curves is clearly revealed in figure 12. A stress-set curve immediately following such a cycle always extends vertically for a considerable distance, which evidently tends to increase with the prior plastic extension. In figure 13, all the corresponding points are at the tops of oscillations. Oscillation tops not occupied by such points are occupied by points obtained with short prior rest intervals; they are also the second points of pairs.

An intervening small cycle, therefore, probably tends to accentuate the rebound from the low point of an oscillation, and a long rest interval tends to accentuate the recoil from the high point of an oscillation. There is need, however, for investigation of the effect of a rest interval after an intervening cycle. Only part of the improvement in elastic properties caused by such a cycle may be permanent.

Although oscillations such as those shown in figure 13 are influenced by duration of the rest interval and by an intervening cycle, they probably are influenced by other factors, which are yet to be considered. The general impression gained from a study of figures 7, 9, and 13 is that an exceptionally low point, due to any cause, tends to be followed by an abrupt rise to an exceptionally high point. The spacing and the range of these oscillations evidently can be influenced by interspersing relatively long rest intervals among short rest intervals and also by interspersing other procedures that tend to influence the steepness of the stress-set curve.

The oscillations shown in figure 13 may be viewed as superposed on a less abrupt wavelike curve. For both the 0.001 percent and the 0.003 percent proof stresses, the first wave maximum probably is at a prior extension of 5 or 6 percent, and the first minimum is at about 10 percent. These extensions are much greater for this annealed specimen than for the half-hard specimens represented in figures 7 and 9. For the 0.01, 0.03, and 0.10 percent proof stresses, the general trend (with prior extension) is continuously upward.

THE INFLUENCE OF PRIOR PLASTIC EXTENSION AND OF DURATION OF THE REST INTERVAL ON THE STRESS-SET CURVE AND ON THE DERIVED PROOF STRESSES, SPECIMENS 2C-1, 3C-1, 4C-1, AND 5C-1

The extension experiments previously described were made either with annealed material or with half-hard material that could be extended greatly before beginning to contract locally. The extension experiments now to be described were made with hard material, which could not be extended far before reaching maximum load condition. Results obtained with four specimens of hard material, differing slightly in composition, are shown in figures 16 and 17.

The initial stress-set curve for each specimen shows no vertical portion. Even the smallest stresses evidently caused permanent set. These curves, like the corresponding curves for annealed and half-hard metal, show no evidence of a real elastic limit of the metal as received. As shown by the increased steepness of curves 2, however, considerable improvement in elastic strength was caused by even the slight permanent extension made in determining curves 1. That most of this improvement is not due to the shortness of the rest interval between curves 1 and 2 will become evident in discussion of subsequent experiments in which the rest intervals between curves 1 and 2 were much longer.

With further plastic extension, as illustrated by the other curves of figure 16 and by the other experimental points in figure 17, the improvement in elastic strength continues more slowly. This improvement consists chiefly in elevation of the upper part of the stress-set curve, thus causing general continuing rise of the 0.03 percent and the 0.10 percent proof stress curves in figure 17. The curves for 0.001 and 0.003 percent proof stresses, however, reach maxima at extensions of 0.15 to 0.4 percent. Beyond this maximum in each curve, there are alternate descents and rises qualitatively similar to the oscillations shown in figures 7, 9, and 13.

Most of the rest intervals in these experiments were short, 2 to 6 minutes. A few results, however, were obtained with relatively long prior rest intervals. These occasional points evidently have much influence on the oscillations of the curves in figure 17. Such points, with a few exceptions, are low points of wide oscillations. Two of the exceptions are points 3 and 4 obtained with specimen 5C–1. Because these points are located on the abrupt rise due to the first slight plastic extensions, the depressing effect of the relatively long rest interval was not sufficient to interrupt the rise. Point 6 representing about the same rest

interval, however, is near the bottom of the recoil from the first rise. The relatively long rest interval here accentuates the recoil and gives an exceptionally low point.

Although the duration of the rest interval generally has considerable influence on the slope of the stress-set curve and on the derived proof stresses, the examples just cited (and others still to be discussed) seem to indicate that the oscillations of the proof stress-deformation curve are due in part to other factors.

INFLUENCE OF PRIOR PLASTIC EXTENSION ON THE PROOF STRESS-DEFORMATION CURVES, SPECIMENS 2B-3, 2B-4, 3B-4, 2C-4, 5C-3, AND 5C-4

It seemed desirable to investigate further the influence of duration of the rest interval and other factors, and especially to ascertain the form of the proof stress-deformation curve with the influence of variations in the rest interval eliminated or at least minimized. In the obtaining of the previously described proof stress-deformation curves, most of the rest intervals were short. When the proof stress-deformation curves now to be described were obtained, nearly all of the rest intervals were either medium (20 to 70 minutes) or long (17 or more hours). Typical stress-set curves thus obtained are shown in figure 20, and the corresponding proof stress-deformation curves are distributed among figures 21 to 24. With any one of the specimens represented in figure 20, nearly all of the rest intervals were of the same order. With specimens 2B–3, 3B–4, and 5C–3, nearly all of the intervals were of medium length, 30 to 70 minutes; a few intervals were about 1 day. With specimens 2B–4, 2C–4, and 5C–4, nearly all of the rest intervals were about 1 day; a few intervals were about 2 days.

The initial stress-set curve for each specimen represented in figure 20, like the initial stress-set curves obtained with previously described specimens, shows permanent set at all stresses. Comparison of curves 1 and 2 shows that even the slight plastic extension required for determining curves 1 caused considerable improvement in elastic strength. The fact that the rest intervals between curves 1 and 2 were relatively long appears to indicate that much of the improvement caused by this slight tensile extension is permanent. The permanence of the improvement, however, can be determined definitely only by additional experiments with much longer rest intervals.

PROOF STRESS-DEFORMATION CURVES OBTAINED WITH REST INTERVALS OF A DAY OR MORE AT ROOM TEMPERATURE OR WITH REST INTERVALS OF 30 MINUTES IN BOILING WATER

The results represented by the stress-set curves in figure 20 are typical of a number of results obtained with specimens of annealed, half-hard, and hard materials. From these stress-set curves are derived the proof stress-deformation curves of figures 21 to 29, inclusive. The stress-set curves from which figures 25 to 29 are derived are not included in the report.

Extension of each of the specimens represented in figures 21 to 29 generally was by the previously described alternate long and short stages. The short stage consisted of a pair of adjacent groups of cycles involved in determination of a pair of adjacent stress-set curves. Each pair was separated by a relatively long extension interval from the pairs immediately preceding and following. The rest interval prior to the first stress-set curve of a pair was always at least 20 minutes, often much longer.

When the forms of the proof stress-deformation curves in figures 21 to 29 are studied, it is convenient to consider first the forms of the curves that are as free as possible from the influence of duration of the rest interval. With such curves as a basis of comparison, it should be possible to discern the modifying influence of the rest interval. For this reason, many of the diagrams of figures 21 to 29 were obtained with consistently long rest intervals, 18 hours or more. Such diagrams were obtained with specimens 2B–4 of figure 22, 2C–4 and 5C–4 of figure 24, and 4B–4 of figure 25.

Numerous experiments, by various investigators, have shown that restoration of "elasticity" after overstress is greatly accelerated by even a short rest interval at the temperature of boiling water (reference 7). A rest interval of 30 minutes or less in boiling water was found to have as much effect as days of rest at room temperature. Most of the effects described in the literature, however, were obtained with carbon steels. The observed "restoration of elasticity," moreover, consisted in elevation of the stresss-strain curve. Such experiments apparently give no assurance that treatment with boiling water would accelerate the effect of a rest interval on the stress-set curve of 18:8 alloy. Nevertheless, the effect of boiling water was tried, as a possible means of shortening the time required for obtaining a proof stress-deformation curve free from the influence of varying rest interval. Experiments were made with rest intervals of 30 minutes in boiling water interspersed with long rest intervals at room temperature. Proof stress-deformation curves, based on these experiments, were obtained with specimens 5B–3 of figure 25, 5B–4 of figure 26, and 3C–4 of figure 27.

The points obtained with a rest interval of 30 minutes in boiling water generally are no higher in the diagram than the points obtained with a rest interval of a day or more at room temperature. In each of the three diagrams, therefore, a single curve has been drawn to represent the results obtained with both of these rest conditions. A very different relationship is found when both medium and long rest intervals are at room temperature. As shown in the diagrams for specimens 3B–4 of figure 23, 4B–3 of figure 25, and 2C–3 of figure

27, points representing a rest interval of a day or more at room temperature are consistently below the points representing a rest interval of 20 to 70 minutes at room temperature. The changes occurring during the rest interval, therefore, evidently are much faster at 100° C. than at room temperature. The evidence indicates that a rest interval of 30 minutes in boiling water has practically the same effect as an interval of about 1 day at room temperature.

In the discussion of the form of the basic proof stress-deviation curve, attention will therefore be directed first to curves obtained either with rest intervals of 30 minutes in boiling water or entirely with long rest intervals at room temperature. Diagrams of this kind were obtained with seven specimens, 2B–4 of figure 22, 2C–4 and 5C–4 of figure 24, 4B–4 and 5B–3 of figure 25, 5B–4 of figure 26, and 3C–4 of figure 27. If some irregular oscillations between high and low values be disregarded, the results obtained with each of these specimens may be represented by a curve of about the same form. The first part of each curve, like the first part of the proof stress-deformation curves previously described, is a steep rise to a maximum, reached at a small prior plastic extension. Each curve then descends to a minimum, and again gradually ascends.

PROOF STRESS-DEFORMATION CURVES OBTAINED WITH MEDIUM REST INTERVAL (20-70 MINUTES)

Seven diagrams, distributed among figures 21, 23, 24, 25, 27, and 29, are based largely on experimental points obtained with medium rest intervals, 20 to 70 minutes. The six diagrams obtained with half-hard and hard material will be considered first. Each curve has the usual initial rise to a maximum, reached at a small prior extension, and the usual steep descent. The oscillations, however, are much more prominent in these curves than in the curves based entirely on long rest intervals. One of the oscillations generally involves a rebound from the first minimum to a second maximum at an extension of 1 to 2 percent. A few of the experimental points in these diagrams were obtained with a long rest interval (a day or more); each of these points generally is the first point of one of the previously described pairs, based on adjacent stress-set curves. The second point of a pair generally was obtained with a medium rest interval. Each point representing a long rest interval, with one exception, is at the bottom of an oscillation. The second point of such a pair, again with one exception, is much higher than the first, and sometimes is the high point of an oscillation. The interspersed points representing long rest intervals, therefore, generally tend to accentuate the oscillations between high and low values of proof stresses.

Even when both experimental points of a pair were obtained with medium rest intervals, the second point frequently is much higher than the first. Examples of this relationship are points 5–6, 7–8, and 11–12, obtained with specimen 2B–3 of figure 21; points 4–5, obtained with specimen 5C–3 of figure 24; and points 11–12 obtained with specimen 4B–4 of figure 25. Frequently, also, the opposite relationship is found. A relatively low second point of a pair, however, generally is located somewhere in the recoil from the high point of an oscillation. Examples of such location in the recoil from a previous high point are pair 9–10 obtained with specimen 2B–3 of figure 21, pairs 7–8 and 11–12 obtained with specimen 3B–4 of figure 23, and pair 9–10 obtained with specimen 4C–3 of figure 27. When a pair of points follows a long single extension, the second point of the pair tends to be higher than the first. When the extension interval prior to a pair of points is rather short, the combined influence of variations in the rest interval and of the extension spacing of the preceding points may cause the second point of the pair to be no higher than the first. A short extension, when it is the first extension of a specimen or when it follows a long extension interval, evidently tends to increase the proof stresses.

The range of oscillation tends to be especially wide when alternate medium and long rest intervals occur within the extension range usually occupied by the first rapid rise and descent. An example of this is seen in the diagram for specimen 4B–3 of figure 25. The difference in rest interval between points 2–3 has caused premature and abrupt recoil from the first peak of the curve. This recoil is followed by an equally abrupt rebound, which causes point 5 to occupy an unusually high position, for a point representing a long rest interval. Another, less conspicuous, example of the influence of duration of the rest interval within this extension range, is found in the diagram for specimen 2C–3 of figure 27. These examples are additional illustrations of the previously mentioned fact that an exceptionally low point, however it may be caused, tends to be followed immediately or shortly by an exceptionally high point.

A curve drawn so as to follow approximately the first rise and descent, and then so as to follow the low points of oscillations in each of the six diagrams would be similar in form to the previously described basic curve obtained either with long rest intervals at room temperature or with rest intervals of 30 minutes in boiling water. The curve would first rise rapidly to a maximum, reached at small extension, would then descend rapidly, and again rise slowly to an extension of about 5 percent. The evidence appears to indicate that the basic curve for all these diagrams is of the same general form, but that the form may be obscured or masked by the influence of variations in the duration of the rest interval and in the extension spacing of the experimental points.

A diagram obtained with annealed specimen 5A–3 is shown in figure 29. In addition to the experimental points within the range of the first rapid rise and descent, there are four widely separated pairs of points. In three of these pairs, the first point represents a long rest interval. Every other point of the diagram, with one exception, represents a medium rest interval. The first point of each of the four pairs, whether it represents a long or medium rest interval, is lower than the second point. This fact tends to confirm the previously expressed view that the difference in height between the points of a pair depends not only on difference in the rest interval but also on the extension spacing. When a pair follows a relatively long single extension, the general tendency is for the second point of the pair to be higher than the first.

The range of oscillation obtained with annealed material tends to be smaller than the ranges obtained with half-hard or hard materials. The range evidently tends to increase with increase in the prior plastic deformation, whether the deformation is by tensile extension, by rolling, or by drawing.

A basic curve drawn to represent the points in this diagram would be of the wavelike form mentioned in connection with previously described diagrams. Because of the great range of extension, the curve would have several maxima and minima. The curve for 0.001 percent proof stress evidently would reach its first maximum at an extension of about 2 to 5 percent. All of the other basic curves, probably because of the great work-hardening rate for annealed material, evidently have a general upward tendency. The upward tendency is slight, however, for the curve representing 0.003 percent proof stress.

PROOF STRESS-DEFORMATION CURVES OBTAINED WITH INTERSPERSED LONG AND SHORT REST INTERVALS

Four diagrams, obtained with half-hard material, are based on experiments with both long and short rest intervals. These diagrams were obtained with specimens 2B–2 of figure 21, 3B–3 of figure 22, 4B–2 of figure 23, and 5B–2 of figure 26. The experimental points of each of these diagrams are arranged in pairs. The first point of each pair was obtained after a relatively long rest interval, 17 hours or more; the second point of each pair, with one exception, was obtained after a rest interval of 2 to 6 minutes. The exception is point 2 of 2B–2, which was obtained after a rest interval of 20 minutes.

Even with this wide difference in duration of the rest interval, the second point of a pair is not always higher than the first. In the diagram for specimen 2B–2 of figure 21, point 4 is no higher than point 3. These points, however, are at the bottom of the recoil from the first maximum. Every other second point of a pair, in this diagram, is considerably higher than the first. The second points of pairs 5–6 and 9–10, owing to the great effect of the difference in rest interval, are much higher than the maximum of the initial rise.

In the diagram for specimen 3B–3 of figure 22, points 3 and 4 (belonging to the same pair) are at the same height. This pair, however, is at the crest of the initial rise. (The difference between points 1 and 2 is unusually small.) Every other second point of a pair is considerably higher than the first. The effect of the difference in rest interval is so great for pair 5–6, that point 6 is nearly as high as the initial maximum.

In the diagram for specimen 5B–2 of figure 26, every second point of a pair, with one exception, is higher than the first. The recoil from the initial maximum is so great that the first minimum is exceptionally low. The rebound from this minimum carries pair 5–6 to a considerably greater height than pair 3–4, and thus places point 6 at a second maximum.

In the diagram for specimen 4B–2 of figure 23, three of the second points of a pair are below the corresponding first points. The spacing, however, is such that point 3 is at the first maximum and point 4 is far down in the following descent. Point 7 is at the second maximum and point 8 is on the following descent. In this diagram, the extension spacing evidently is such as to overcome, in the instances mentioned, the effect of the difference in rest interval.

If curves were drawn in each of these four diagrams, so as to follow the initial rise and descent and then so as to follow the low points of the oscillations, the curves would be qualitatively similar to the previously described basic curves. In the diagram for specimen 4B–2, the extension spacing evidently is such that superposed oscillations are minimized, and a curve drawn in accordance with the experimental points would be similar in form to the basic curve.

In figures 28 and 29 are four diagrams obtained with four specimens of annealed material. In three of these diagrams, the first point of each pair generally was obtained after a long rest interval and the second point generally was obtained after a rest interval of 2 to 6 minutes. Almost invariably the second point of each pair is considerably higher than the first. A curve drawn so as to follow the initial rise and descent and then so as to follow the low points of the oscillations would have the previously described wavelike form. This curve, for each proof stress, would have a generally ascending course, passing through successively higher maxima, and minima. In this respect, the curves for 0.001 and 0.003 percent true proof stresses for annealed material differ from the corresponding curves for half-hard and hard materials. This difference probably is due to the much greater work-hardening rate for the annealed material.

FACTORS INVOLVED IN THE FORM OF THE PROOF STRESS-DEFORMATION CURVE

In the previous discussion, it has been shown that the proof stress-deformation curve generally consists of abrupt oscillations superposed on a wavelike curve. It has also been shown that these oscillations are due in part to variations in the prior rest interval and in part to the extension spacing of the experimental points; also that an exceptionally low point tends to be followed immediately or shortly by an exceptionally high point, and vice versa.

The most probable cause of the wavelike form of the basic curve, of the influence of the extension spacing, and of the recoil and the rebound from high and low points, respectively, is variation of internal stress. Tensile internal stress tends to lower the proof stresses, especially the proof stresses corresponding to very small amounts of permanent set. Relief of internal stress by suitable tempering or annealing tends to elevate the proof stresses, especially the 0.001- to 0.003-percent proof stresses. Internal stress can also be relieved considerably by mechanical treatment. "Springing" (slight alternate bending) treatment tends to reduce internal stress in rolled or drawn rods. It has been suggested also that internal stress may be successfully relieved by slight prestretching by tension; some experiments have been made at the National Bureau of Standards to investigate the possibilities of this method. The use of mechanical methods of relief of internal stress would have certain advantages over the thermal method. One disadvantage of the thermal method is that the temperature necessary for relief of internal stress, as shown by investigation at the Bureau, tends to decrease the corrosion resistance of 18:8 alloy.

The suggested use of prestretching for relief of internal stress would imply that internal stress induced by severe rolling or drawing may be largely eliminated by slight tensile extension. The general impression has been that moderate tensile extension does not introduce important internal stress. Different views, however, have been expressed by a few investigators. Kuntze (references 16 and 17), after investigation with copper, concluded that tensile extension, up to 3 percent, increases internal stress in cold-rolled copper. Further information evidently is needed about the variation of internal stress with tensile extension.

The evidence presented as to the form of the proof stress-deformation curve for 18:8 alloy suggests that the form of the basic curve and also the superposed oscillations may be due largely to variations in internal stress. The variation of internal stress corresponding to the basic curve possibly is as follows: The first slight extension causes decrease of internal stress to a minimum, and thus causes a corresponding increase in proof stresses. Further extension, however, causes general increase of internal stress, with wavelike variations and with corresponding opposite variations in proof stresses. These variations of internal stress probably are due to repeated increase of the internal stress to a limit, at which there is partial relief of internal stress by local flow in regions of highest tensile stress. Each relief of stress proceeds until a minimum is reached, at which the stress again begins to build up. Such variations of internal stress obviously would be influenced by the spacing of interspersed groups of cycles such as those used in determining stress-set curves. They would also be influenced by varying duration of the rest interval, because varying duration of the rest interval permits varying amounts of negative creep. The upper limit of internal stress, at which relief by local flow begins, evidently would increase with the increase in hardness due to plastic extension. This increase of internal stress would account for the increase in range of oscillation with increase in hardness.

The information obtained by means of the proof stress-deformation curves should be of practical application in the effort to obtain high elastic strength in cold-worked 18:8 alloy. In an attempt to relieve internal stress by slight tensile extension, especially in hard material, the amount of this extension probably should be slight and be carefully controlled. Additional evidence obviously is needed to establish the effects of slight plastic extension followed by a long rest interval on proof stresses and on positive and negative creep.

V. THE STRESS-STRAIN RELATIONSHIP FOR 18:8 CHROMIUM-NICKEL STEEL

STRESS-DEVIATION CURVES

An incomplete view of the elastic properties of a metal is obtained by considering only the relation between the stress and the deformation that remains after the stress has been released. Consideration should be given not only to the influence of stress on permanent set but also to the influence of stress on the accompanying total strain. In a structure or a machine, the greater part of the total strain is elastic strain. Part may be plastic strain. The plastic part of the total strain has been discussed in part IV. Attention will now be directed to the total strain and especially to the elastic component.

The incompleteness of the view obtained by considering only the stress-strain relationship is illustrated by the previously mentioned fact that the literature contains results of many investigations on the influence of a rest interval (after overstress) on the stress-strain curve but practically no information about the influence of a rest interval on the stress-set curves. The incompleteness of the view obtained by considering only the stress-set relationship will become apparent after consideration of the data now to be presented.

The relationship between a stress-set curve and the corresponding stress-strain curve has been illustrated and discussed in part III. In the determination of the

stress-set curves discussed in part IV, measurements were generally made of the corresponding total strains. The stress-strain relationship thus determined has been represented by stress-deviation curves. (The method of deriving a stress-deviation curve from a stress-strain curve has been described in pt. II.) Typical stress-deviation curves are shown in the upper rows of figures 6, 8, 12, and 16. Each stress-deviation curve is directly above the corresponding stress-set curve.

The deviations obtained directly from the measured strains are total deviations. These deviations are represented by the experimental points in the upper rows of figures 6, 8, 12, and 16, and each broken-line curve represents the variation of total deviation with stress. As total strain is the sum of the elastic strain and the corresponding permanent set, the stress-set curve directly below each stress-deviation curve can be used in making allowance for the permanent set, and in thus obtaining a curve representing more nearly the influence of stress on elastic strain. Each solid-line curve in the upper rows of figures 6, 8, 12, and 16 has been thus obtained from the corresponding broken-line curve, by deducting values of permanent set indicated by the stress-set curve immediately below.

The corrected stress-deviation curves of figures 6, 8, 12, and 16 will now be compared with the corresponding stress-set curves. It is of interest to observe whether the wide variations in the slope of the stress-set curve, variations that cause the wide oscillations in the proof stress-deformation curves (described in pt. IV), are accompanied by either similar or opposite variations in slope of the stress-deviation curve.

The initial stress-set curve, for each of the specimens tested (as shown in pt. IV), generally gives evidence of permanent set at even the lowest stresses, and the slope decreases rapidly with increase of stress. Stress-set curve 2 of each series generally shows great superiority, in these respects, over curve 1. The corresponding stress-deviation curves, however, show a quite different relationship. Uncorrected stress-deviation curve 1 in each of the four figures (figs. 6, 8, 12, and 16) differs little from curve 2 in initial slope, but the curvature is greater in curve 1 than in curve 2. Uncorrected stress-deviation curves 1 and 2 in each figure, therefore, differ much less than the corresponding stress-set curves.

The corrected stress-deviation curves 1 in these figures are initially steeper than curves 2. In this respect, therefore, the difference between stress-deviation curves 1 and 2 is opposite to the difference between the corresponding stress-set curves. The curvature, however, is greater in stress-deviation curve 1 than in stress-deviation curve 2.

It has also been shown in part IV that the stress-set curve varies greatly in steepness with prior plastic extension and that the steepness tends to oscillate between high and low values. Also these oscillations are due in part to varying duration of the rest interval, and in part to the spacing of the stress-set curves throughout the total range of plastic extension. Comparison will now be made between these variations in steepness of the stress-set curve and the corresponding variations in steepness of the stress-deviation curve. In this comparison, consideration will be given first to some of the stress-set curves representing extremes of steepness.

In figure 6, stress-set curve 56 is much steeper and stress-set curve 57 is much less steep than the average, although each was obtained with a short rest interval. The corresponding stress-deviation curves, however, differ little in slope. Stress-set curve 77, which is steeper than the average, is followed by a curve that is much less steep than the average. The corresponding uncorrected stress-deviation curves, however, differ little in slope or curvature. Corrected stress-deviation curve 78, consequently, is much steeper than curve 77. The difference between the corrected stress-deviation curves, therefore, is opposite to the difference between the corresponding stress-set curves. The three stress-set curves 98, 103, and 108, obtained with relatively long rest intervals, are much less steep than the preceding curves. Uncorrected stress-deviation curves 98, 103, and 108, however, differ little in slope from the preceding curves. Corrected curves 98, 103, and 108, consequently, are steeper than the preceding curves. The evidence in figure 6 therefore suggests that variations in steepness of the stress-set curves, especially variations due to the duration of the rest interval, generally are accompanied by opposite variations in steepness of the elastic stress-deviation curve.

In figure 8, stress-set curves 31, 37, 40, 43, 46, 48, 51, and 54, obtained with relatively long rest intervals, are less steep than the curves immediately preceding. The corresponding corrected stress-deviation curves (with the exception of curves 31 and 54), however, are steeper than the curves immediately preceding.

As figure 12 was obtained with annealed material, the differences in steepness between the curves representing relatively long rest intervals and the curves immediately preceding, are generally less prominent than in figures 6 and 8 representing half-hard material. These differences in steepness generally tend to increase with the prior plastic extension. Inasmuch as consecutive curves corresponding to the larger prior extensions are few in figure 12, the evidence as to the comparative influence of duration of the rest interval on stress-set and stress-deviation curves is less conclusive in this figure than in figures 6 and 8. Four curves, nevertheless, will be used in comparison. Stress-set curves 7, 10, 13, and 19 are much less steep than the curves immediately preceding. Of the four corresponding corrected stress-deviation curves, curves 7 and 13 are slightly less steep than the preceding curves. Curves

10 and 19, however, are much steeper than the preceding curves, thus tending to confirm the evidence in figures 6 and 8: that the effect of duration of the rest interval on the corrected stress-deviation curve is opposite to the effect on the stress-set curve.

Figure 12 contains a number of pairs of stress-set curves that were obtained with an intervening small cycle in lieu of a rest interval (pt. IV). Consideration will now be given to the comparative effect of this small intervening cycle on the corresponding stress-set and stress-deviation curves. A stress-set curve following such a cycle, as shown in figure 12, invariably is steeper than either of the two adjacent curves. The influence of the small cycle on a stress-deviation curve can be determined by comparison of the curve with the following curve and not by comparison with the preceding curve, which has been influenced by the prior relatively long rest interval. The corrected stress-deviation curve following a small cycle evidently tends to be slightly steeper than the following curve. The effects of the small intervening cycle on both the stress-set and the corrected stress-deviation curve, therefore, were qualitatively the same. The effect of this small cycle (with no following rest interval), therefore, differed greatly from the effect of duration of the rest interval. This subject, however, needs further investigation, with introduction of a rest interval after the small cycle.

In figure 16, 6 stress-set curves were obtained with medium or long rest interval. Four of these stress-set curves, 8 of specimen 2C–1, 4 of specimen 3C–1, 5 of specimen 4C–1, and 6 of specimen 5C–1, are much less steep than the preceding curves. Of the corresponding corrected stress-deviation curves, curve 8 of specimen 2C–1 and curve 5 of specimen 4C–1 are slightly steeper than the preceding curves; the other two curves are about as steep as the preceding curves.

The evidence presented in figures 6, 8, 12, and 16 therefore indicates that conclusions as to the stress-strain curve cannot be drawn with certainty from the form of the stress-set curve. Neither can conclusions as to the stress-set curve be drawn from the form of the stress-strain curve. Duration of the rest interval, however, generally has opposite effects on the steepness of the stress-set and elastic stress-strain curves. Results obtained with other metals, to be included in a supplementary report, indicate that these conclusions are not limited in application to 18:8 chromium-nickel steel.

CURVES OF VARIATION OF THE MODULUS OF ELASTICITY WITH STRESS

A curved stress-strain relationship is much more clearly revealed and more readily studied by means of a stress-deviation curve than by means of a stress-strain curve. The stress-deviation curves of figures 6, 8, 12, and 16 all show prominent curvature. Curvature is nearly as prominent in the correctedas in the uncorrected curves.

The fact that the slope of each curve decreases continuously from the origin evidently means that the modulus of elasticity decreases continuously with increase in stress. The modulus of elasticity at zero stress could be derived from the angle of slope of the tangent to the curve at the origin, allowance being made for the modulus of the assumed line from which the deviations are estimated. For any stress, the modulus could be derived similarly from the slope of the tangent to the stress-deviation curve at the corresponding point. It is generally more convenient, however, to derive the modulus from the slope of the secant drawn from the origin to the point (on the stress-deviation curve) corresponding to the given stress. This modulus, known as the "secant" modulus,[2] was used (in this investigation) to study the variation of the modulus with stress and with prior plastic extension.

Curves of variation of the modulus with stress have been derived from all the corrected stress-deviation curves and from a few of the uncorrected stress-deviation curves, of figures 8, 12, and 16, also from the ascending portions of many of the hysteresis loops of figures 2 and 3. The stress-modulus lines derived from the stress-deviation curves of figures 8, 12, and 16 are shown in figures 10, 14, and 18. Each stress-modulus line has been shifted to the right from the preceding line and has been given a separate abscissa scale. Abscissas, increasing from left to right, represent values of the secant modulus of elasticity. The scale of abscissas is indicated at the left of the upper row. Ordinates represent true stress, stress based on the cross section at the beginning of the determination of the curve.

The values for E_0, the modulus at zero stress, are merely extrapolated values, obtained by extending the stress-modulus line to zero ordinate. In figures 10 and 18, representing half-hard and hard material, respectively, nearly all the stress-modulus lines are straight, either throughout the entire represented extent or throughout all but the upper part of the extent. In figure 10, "corrected" line 1 is much less steep than any of the other corrected lines. Although this line is straight, the following two lines (and to a less extent line 4) are curved. With a few exceptions, all of the other lines of this figure are practically straight. In figure 18, lines 1 and nearly all the other lines are practically straight. In figure 14, representing annealed material, stress-modulus lines 1 to 12 are curved; the curvature decreases generally from line 1 to line 12. The other lines in this figure, with a few exceptions, are practically straight.

[2] It should be noted that this modulus differs from a frequently used "secant modulus," based on the variation of total strain with stress.

A linear relationship between stress and the secant modulus may be represented by the equation $E=E_0-kS$. In this equation, E represents the modulus at any stress S; E_0 represents the modulus at zero stress; and k represents the cotangent of the angle of slope of the stress-modulus line. (This equation evidently indicates that the corresponding stress-strain line is a parabola.) An equation of this form was found by Sayre (references 1 and 2) to represent the stress-modulus relationship for ordinary steels and for a number of nonferrous metals. Sayre's equation, however, represented the influence of stress on the tangent modulus. The tangent modulus obviously decreases more rapidly, with increase of stress, than the secant modulus. Values of k reported by Sayre for various metals, therefore, are not directly comparable with values obtained from the stress-modulus lines in figures 10, 14, and 18.

Bridgman (reference 18) found linear decrease in compressibility (linear increase in the volume modulus of elasticity) for many metals, with increase in hydrostatic compressive stress. As the constants published by Bridgman to represent this relationship are based on variation of the secant modulus, they are comparable with the values obtained from figures 10, 14, and 18.

Some years earlier, the authors of references 16 and 17 presented evidence of linear relationship between tensile stress and the "Dehnungszahl" (α), the reciprocal of the secant modulus of elasticity. As k is small, such a relationship evidently implies a nearly linear relationship between stress and the secant modulus throughout a considerable range of stress.

The constant k is a dimensionless index of the curvature of the stress-strain line. It is not entirely satisfactory, however, as an index of the influence of stress on the modulus of elasticity. For such an index, it appears desirable to use a constant that represents the fractional change of the modulus with stress although such a constant is not dimensionless. A suitable constant for this purpose may be obtained from the equation $E=E_0(1-CS)$. In this equation, E, E_0, and S have the same significance as in the previous equation, and C is the new constant. This constant is equal to k/E_0, and is a small decimal fraction.

Stress-modulus lines for annealed steel 2A–1, obtained with prior extensions up to about 11 percent (compare figs. 14 and 15), are curved from the origin. A few of the lines obtained with harder material are similarly curved. For the curved lines, an equation representing the variation of the modulus with stress needs an additional term containing a second constant. Addition of such a term to each of the preceding two equations, gives the following equations:

$$E=E_0-k_1S-k_1k_2S^2$$

and

$$E=E_0[1-C_1\ S(1+C_2S)] \text{ or } E=E_0(1-C_1S-C_1C_2S^2)$$

(Instead of using both constants in the third term on the right of each equation, a single constant could be used.)

For nearly all the corrected stress-modulus lines obtained with half-hard and hard material (figs. 10 and 18), and for most lines obtained with annealed material (fig. 14), C_2S is either zero or so small that it may be neglected. For curves 1 to 12 of figure 14 and for a few curves of figures 10 and 18, C_2S is not negligible. Values of C_1 and C_2 are indicated in figures 10, 14, and 18 by the numbers adjacent to the corrected stress-modulus lines. Values of C_1 for the curved lines are based on the slopes of the tangents at the origin.

In figures 4 and 5 are stress-modulus lines obtained from the ascending portions of many of the hysteresis loops of figures 2 and 3. The stress-deviation lines in these hysteresis loops are based on total strain, because the loops could not be corrected for permanent set. As most of the plastic component for the ascending part of each curve is near the top, however, stress-modulus curves derived from the ascending curves of some of the hysteresis loops should give approximately correct values of E_0 and C_1. Hysteresis loops suitable for such a purpose are loops obtained after so many cycles that the positive and negative creep per cycle is small.

All the hysteresis loops previously described (figs. 2 and 3) were obtained with annealed material. The loops in the upper row of figure 2 were obtained with a relatively large stress range, which caused about 15 percent plastic extension in the first loop. The derived stress-modulus lines, shown in the upper row of figure 4, are nearly straight. The loops in the lower row of figure 2 and in figure 3 were obtained with a much smaller stress range, which caused only about 3-percent plastic extension in the first loop. The derived stress-modulus lines, shown in the lower row of figure 4 and in figure 5, are curved. The great difference in plastic extension in the first loop probably is the cause of the great difference in curvature between the stress-modulus lines shown in the upper row of figure 4 and those shown in the lower row of figure 4 and in figure 5. This relationship between prior plastic extension and degree of curvature of the stress-modulus line is similar to that illustrated in figure 14. With increase in prior plastic extension, the curvature of this line (for annealed material) evidently tends to decrease, and the line generally is straight for extensions beyond about 10 percent.

Values of E_0 and C_1, estimated from the stress-modulus lines in figures 4 and 5, are listed in tables III, IV, and V. Although these values were obtained from uncorrected stress-deviation curves, they generally fall within the range of values obtained from corrected stress-deviation curves for annealed material, as represented by the numbers adjacent to the solid-

line curves of figure 14. That values obtained from uncorrected stress-deviation lines generally differ little from values obtained from corrected lines is illustrated in figures 10, 14, and 18 by a few broken lines obtained from uncorrected stress-deviation curves of figures 6, 12, and 16. The broken lines in figures 10, 14, and 18 generally differ little, in position, slope, and curvature, from the corresponding solid lines. Under these conditions, values of E_0 and C_1 obtained with uncorrected stress-deviation lines evidently differ little from values obtained with corrected lines. The initial broken line for each of the steels represented in the three figures, however, differs considerably from the corresponding solid line. Values of E_0 and C_1, obtained with initial uncorrected stress-modulus lines, therefore, may differ considerably from values obtained with corrected lines. Uncorrected lines generally give lower values of E_0 and higher values of C_1 than those obtained from corrected lines. The difference between values of C_1 obtained from corrected and uncorrected lines is less than it would be if the stress-set curve and the corrected stress-strain curve were similar in form. As shown in figures 6, 12, and 16, the lower part of the stress-set line tends to be nearly straight, whereas the corrected stress-strain line generally is uniformly curved.

In table VI are listed the ranges of values for E_0, k_1, and C_1 obtained with the 18:8 alloy, for comparison with values similarly obtained with other metals. Three of these metals, an annealed steel containing 14 percent chromium and 2 percent nickel, a cold-drawn alloy containing about 13 percent chromium, 5 percent iron, and 82 percent nickel, and cold-drawn K-monel metal (heat-treatable), have been studied in connection with the general investigation of elastic properties of high-strength aircraft metals sponsored by the National Advisory Committee for Aeronautics. The curves upon which these values are based will be included in a supplementary report. Other values listed in the table were obtained from the previously mentioned data published by Sayre (references 1 and 2) and by Bridgman (reference 18). The values published by Sayre have been corrected to allow for the fact that his data represent the influence of stress on the tangent modulus.

The values of C_1 for 18:8 alloy, given in table VI, range from 6 to 55. As illustrated by the curve for C_1 in figure 30, to be discussed later, the upper limit of this range represents annealed, and the lower limit represents severely cold-worked metal. Even for severely cold-worked 18:8 alloy, the value of C_1 is considerably higher than values obtained from Sayre's data, except the range listed for aluminum alloy. For the aluminum alloy, the upper limit of the listed range of C_1 is about the same as the value for severely cold-worked 18:8 alloy. The values obtained with annealed 14:2 chromium-nickel steel, however, fall within the range of values for 18:8 alloy. The ranges for cold-drawn Inconel and cold-drawn K-monel metal overlap the lower part of the range for 18:8 alloy.

The value for annealed 18:8 alloy is much higher than any other value listed in the table. This table, however, contains no value for an annealed pure metal or for any annealed single-phase alloy except 18:8 alloy. (The aluminum "hard-drawn and annealed" probably was merely heated for relief of internal stress.) Annealed pure metals and single-phase alloys generally give strongly curved stress-strain lines. This fact implies a high value of C_1. Some data published in reference 17 appear to indicate that C_1 for annealed copper may be as high as about 360.

No quantitative information is available as to the influence of heat treatment on C_1. The steels used by Sayre were all of spring temper. It seems probable that higher values for C_1 would be obtained with annealed steels than with quenched-and-tempered steels. It is worthy of note that his next highest range of C_1 listed in table VI was obtained with an annealed steel. The influence of heat treatment on C_1 evidently needs further investigation.

INFLUENCE OF PRIOR PLASTIC EXTENSION AND OF THE PRIOR REST INTERVAL ON E_0 AND C_1

For specimen 1B–3, the initial value of E_0 (curve 1 of fig. 10) is about 32 million. As illustrated by curve 2, the slight plastic extension involved in the determination of curve 1 has decreased E_0 from 32 to 25 million. Accompanying this decrease in E_0 is a decrease in C_1 from 43.9 to 9.4×10^{-7}. Similar though smaller differences exist between curves 1 and 2 obtained with specimens 2C–1, 3C–1, 4C–1, and 5C–1 of figure 18. (These differences for specimens 4C–1 and 5C–1 possibly are within the limits of experimental error.) These examples are not mentioned to imply that similar differences will be found between curves 1 and 2 obtained with every specimen. They are mentioned as illustrations of the fact that variations of E_0, with prior plastic extension and with duration of the rest interval generally are accompanied by similar variations of C_1. Numerous illustrations of this parallel variation of E_0 and C_1 may be found in figures 10, 14, and 18. The higher the modulus at zero stress, the less steep usually is the stress-modulus curve; that is, the higher is the index (C_1) of variation of the modulus with stress. This relationship is clearly revealed in diagrams of a different type, now to be described.

In figures 11, 15, and 19 are shown curves derived from the stress-modulus curves of figures 10, 14, and 18. Abscissas in these curves represent prior plastic extension; ordinates represent values of E_0 and C_1 and of the secant modulus corresponding to an arbitrarily selected tensile stress, whose value is indicated by a subscript

number with the last three ciphers omitted. Attention will be directed first to the curves of variation of E_0 and C_1.

Comparison of these two curves in each of the three figures shows that variations of E_0 generally are accompanied by qualitatively similar variations of C_1. The most conspicuous example of this is the initial steep drop in the curves for E_0 and C_1 in figure 11. Qualitatively similar descent of both curves is found also in the diagrams of figure 19. An exception, however, is found in figure 15; the initial course of the curve for C_1 in this figure is a steep rise instead of the usual initial steep descent. The initial value of C_1 in figure 15 is lower than any of the values obtained with prior plastic extensions between zero and about 45 percent. This abnormally low initial value, however, possibly is not correct. The curve from which the low value was derived, curve 1 of figure 12, obviously is based on so few experimental points that its course is not well established. To a less extent, the same criticism applies to several of the curves following curve 1 of figure 12. There is considerable doubt, therefore, as to the reality of an initial increase of C_1 with prior plastic extension. The doubt is accentuated by a study of figure 30, to be described later.

In figure 19, representing hard material, the initial trend of each curve, for both E_0 and C_1, is downward. After the initial descent, the course of the curves gives no clear indication of a general trend for either E_0 or C_1. The numerous irregularities probably are due to the influence of the variables previously discussed. For these materials, severely cold-worked prior to test, E_0 and C_1 evidently do not change much with further plastic extension. A broader view of the evidence, shown in figure 30 (to be discussed later), indicates that the general trend of C_1, with plastic extension, is downward at a gradually decreasing rate.

The curves for E_0 and C_1 in figures 11, 15, and 19 will now be compared with the corresponding curves of variation of proof stresses (figs. 9, 13, and 17). In this comparison, particular attention will be given to the influence of duration of the rest interval. It has been shown in part V that variation in the rest interval has opposite effects on the stress-deviation and stress-set curves. It is not surprising, therefore, to find that points representing relatively long rest intervals tend to be at the tops of oscillations in the curves of variation of E_0 and C_1, whereas the corresponding points in the proof stress-deformation curves tend to be at the low points of oscillations. The range of oscillations, however, generally is much less in the curves of variation of E_0 and C_1 than in the curves of variation of proof stresses.

From corresponding values of E_0 and C_1, the secant modulus may be calculated for any stress. The intermediate curves in figures 11, 15, and 19 represent the variations of the moduli corresponding to some arbitrarily selected stresses. In figures 11 and 13, these curves (E_{100}) show the variations of the modulus corresponding to a tensile stress of 100,000 pounds per square inch. In figure 15, the intermediate curve (E_{50}) shows the variation of the modulus corresponding to a stress of 50,000. Modulus values corresponding to stresses between zero and either 50,000 or 100,000 could readily be estimated from these diagrams by interpolation.

THE VARIATION OF E_0 AND C_1 WITH ULTIMATE TENSILE STRENGTH

The evidence presented in figures 11, 15, and 19 indicates that E_0 and C_1 generally decrease with increase in plastic extension, whether the experiments are made with annealed, half-hard, or hard material. The evidence suggests that E_0 and C_1, for 18:8 alloy, generally tend to decrease with increase in the hardness due to cold work, whether the cold work is applied by rolling or by prestretching. It appeared possible, therefore, that values for E_0 and C_1 obtained with all the specimens tested could be combined in one diagram by use of some property that indicates, at least qualitatively, the amount of cold work applied either in rolling or prestretching. As the tensile strength generally is a good qualitative index of the amount of prior cold work, use has been made of this property in constructing a single diagram (fig. 30) to represent the variations of E_0 and C_1 with work-hardening.

Abscissas in figure 30 represent "true" tensile strength, based on the cross section at the beginning of the determination of each stress-modulus curve. (See p. 21.) The experimental points in this figure representing annealed, half-hard, and hard material are at the left, in the middle, and at the right, respectively.

The values for C_1 will be considered first. Although there is considerable scatter of the experimental points representing values of C_1, the composite curve as drawn represents fairly well all of the experimental values except the initial values. With one exception, the points representing initial values are above the composite curve. This corresponds to the observation made in part II that, either because of some effect of the long prior rest interval or because of internal stress, the data based on the initial stress-set and stress-strain curves generally cannot readily be correlated with the data obtained after slight plastic extension. The inherent properties of the material apparently are best revealed by a second determination of stress-set and stress-deviation curves soon after the initial determinations made with the material as received.

With increase in tensile strength, as shown by the composite curve, C_1 decreases. For annealed material the value evidently is many times the value for hard material, which means that the curvature of the stress-deviation line is much greater for annealed than for hard material. Although C_1 generally tends to be less for hard than for half-hard material, the difference is slight.

The variation of E_0 with increase in tensile strength is much more irregular than the variation of C_1. The general tendency is for E_0 to decrease with increase in tensile strength. The effect on E_0 of increase in tensile strength above about 150,000 pounds per square inch, however, is slight. The effect may be masked by other variables, such as differences in composition and microstructure. These variables evidently have more effect on E_0 than on C_1.

Values of the modulus of elasticity corresponding to some arbitrarily selected tensile stresses have also been included in figure 30. Variation of these values with tensile strength is generally less than the variation of E_0.

CONCLUSIONS

1. An incomplete view of the tensile elastic properties of 18:8 alloy is obtained by considering either the stress-strain or the stress-set relationship alone. Consideration should be given to both relationships.

2. In a study of the elastic properties, consideration should be given to the influence of hysteresis and of positive and negative creep.

3. Both the stress-set relationship and the stress-strain relationship are much influenced by duration of the rest interval. The influence of duration of the rest interval is due, in part at least, to the influence of negative creep.

4. Increase in the rest interval generally decreases the slope of the stress-set curve and thus decreases the proof stresses. Increase in the rest interval generally increases the slope of the "corrected" stress-strain curve.

5. Curves of variation of proof stresses with prior plastic extension often have many wide, abrupt oscillations superposed on a gradual wavelike mean curve. The wide oscillations generally are associated with varying duration of the rest interval and with variation in the extension spacing of the experimental points. The complexity of form of the proof-stress deformation curve possibly may be attributed in part to variation of internal stress with plastic extension.

6. With prior plastic extension, the proof stresses corresponding to small percentages of permanent set (0.001 to 0.003 percent) generally increase considerably to a maximum, reached at a small percentage of prior plastic extension, and then decrease to a minimum. Further extension causes irregular oscillations in the proof stresses.

7. From corresponding stress-strain and stress-set curves may be derived corrected stress-strain curves to represent approximately the variation of elastic strain with stress. From the corrected stress-strain curves may be derived curves of variation of the secant modulus (for these curves) with stress.

8. The stress-modulus line for annealed material that has received no prior plastic extension is strongly curved. With prior plastic extension, the curvature decreases and generally is negligible for extensions of more than about 10 percent. For half-hard and hard materials, the stress-modulus lines generally are straight.

9. Straightness of the stress-modulus line indicates that the corresponding stress-strain lines are parabolas. The cotangent k_1 of the angle of slope of the stress-modulus line is a dimensionless index of the degree of curvature of the stress-strain line. As an index of the fractional change of the secant modulus with stress, a suitable constant is C_1, which is equal to k_1/E_0. The modulus at zero stress E_0 is obtained by extrapolating the stress-modulus line to zero stress.

10. When the stress-modulus line is curved from the origin, C_1 may be based on the slope of the tangent at the origin, and a second constant C_2 may be used to represent the curvature of the stress-modulus line. The second constant C_2 is not generally necessary except for material that has been annealed and afterward has not been extended more than about 10 percent.

11. When E_0, C_1, and the corresponding stress-set curve are known, as a function of the prior extension and the rest interval, a fairly good picture is available of the elastic strength.

12. With prior plastic extension, both E_0 and C_1 generally decrease. Variations in E_0 generally are accompanied by similar variations in C_1.

13. In a practical estimation of the elastic strength of 18:8 alloy, the best procedure now available consists in determining the corrected stress-set and stress-deviation curves. From these may be estimated proof stresses and values of E_0 and C_1. Much further information, however, may be obtained by determining (with the same specimen) a second stress-set curve and the corresponding stress-deviation curve and by deriving from these a second set of indices.

14. In specifications for elastic strength, possible use could be made of a specified lower limit for E_0 and a specified upper limit for C_1 to apply throughout a specified range of stress. Such a requirement, based on these indices, would have some advantages over the more arbitrary requirements now in use in some specifications. In addition to the suggested limitation of the form of the elastic stress-strain curve, specifications should include a proof-stress requirement for limitation of permanent set.

15. As indicated by conclusion 6, slight prestretching generally causes considerable improvement in elastic strength. Most of this improvement persists for at least a day. Whether most of the improvement is permanent can be determined only by further experiment. Slight prestretching, however, may prove to be of practical use as a means of improving the elastic strength of severely cold-worked material.

Although these conclusions apply specifically only to the tensile elastic properties of the bar material used in the investigation, it appears probable that they are applicable qualitatively to many other metals, in other shapes and sizes, and stressed in other ways. The

same methods of investigation, applied to several other alloys (previously mentioned), one of them a pearlitic alloy steel, show that these conclusions are applicable qualitatively to those alloys as well as to 18:8 alloy.

Now that some understanding has been obtained of the influence of plastic deformation and of accessory factors on the elastic strength of 18:8 alloy, it is desirable that an investigation be made of the superimposed influence of thermal treatment to reduce internal stress. Additional investigation of the various other factors, however, evidently is much needed.

NATIONAL BUREAU OF STANDARDS,
WASHINGTON, D. C., *November 22, 1938.*

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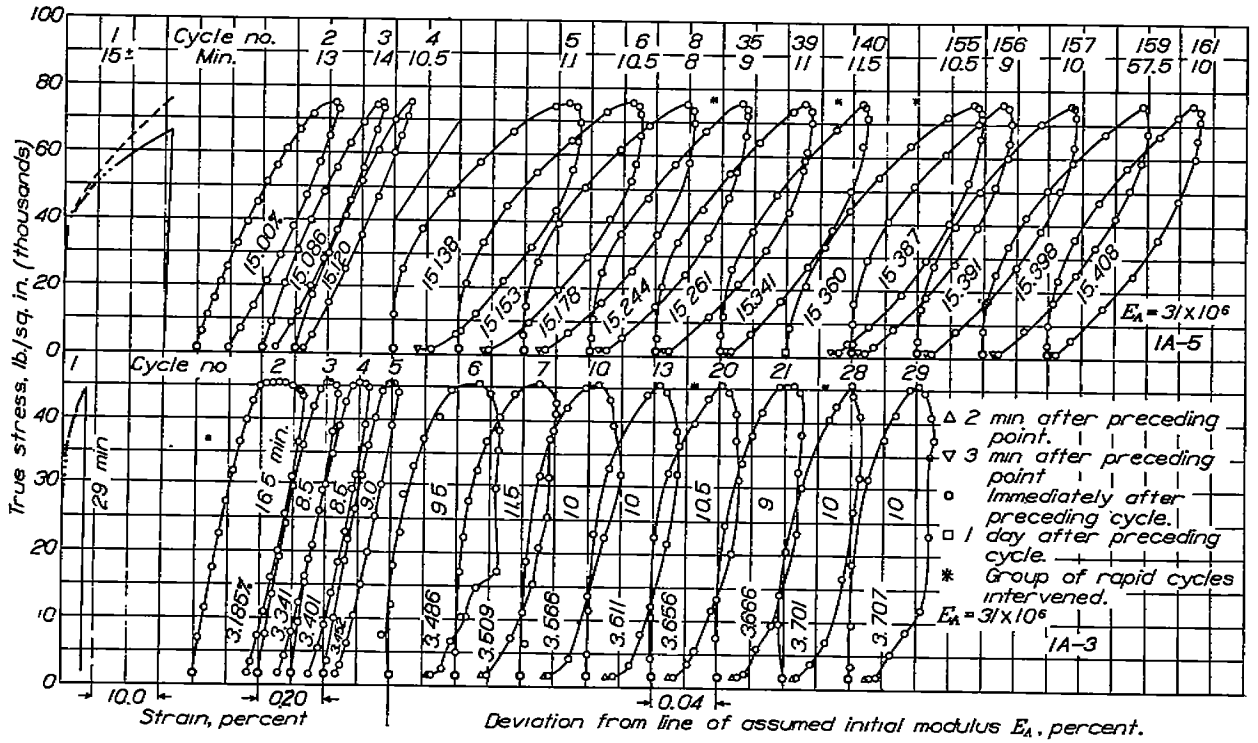

FIGURE 2.—Variation in form of hysteresis loops with cyclic repetition.

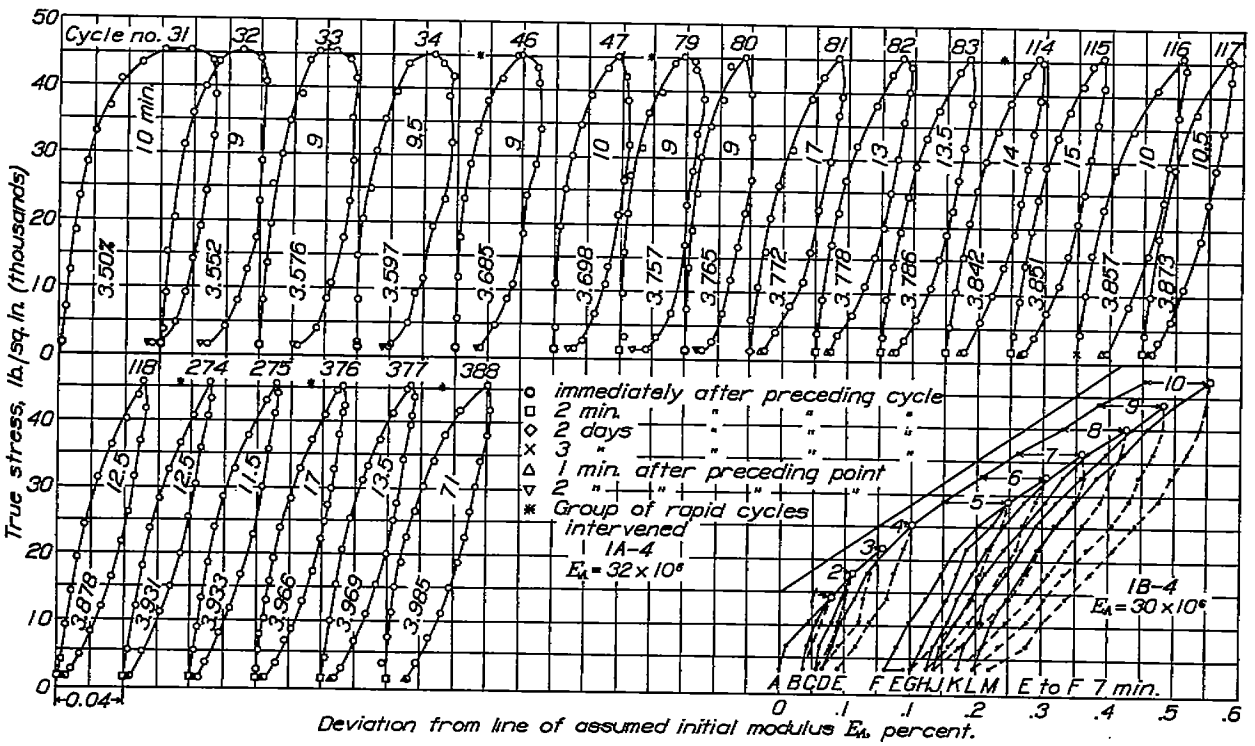

FIGURE 3.—Variation in form of hysteresis loops with cyclic repetition. Interrelationship between a stress-set and a stress-deviation curve.

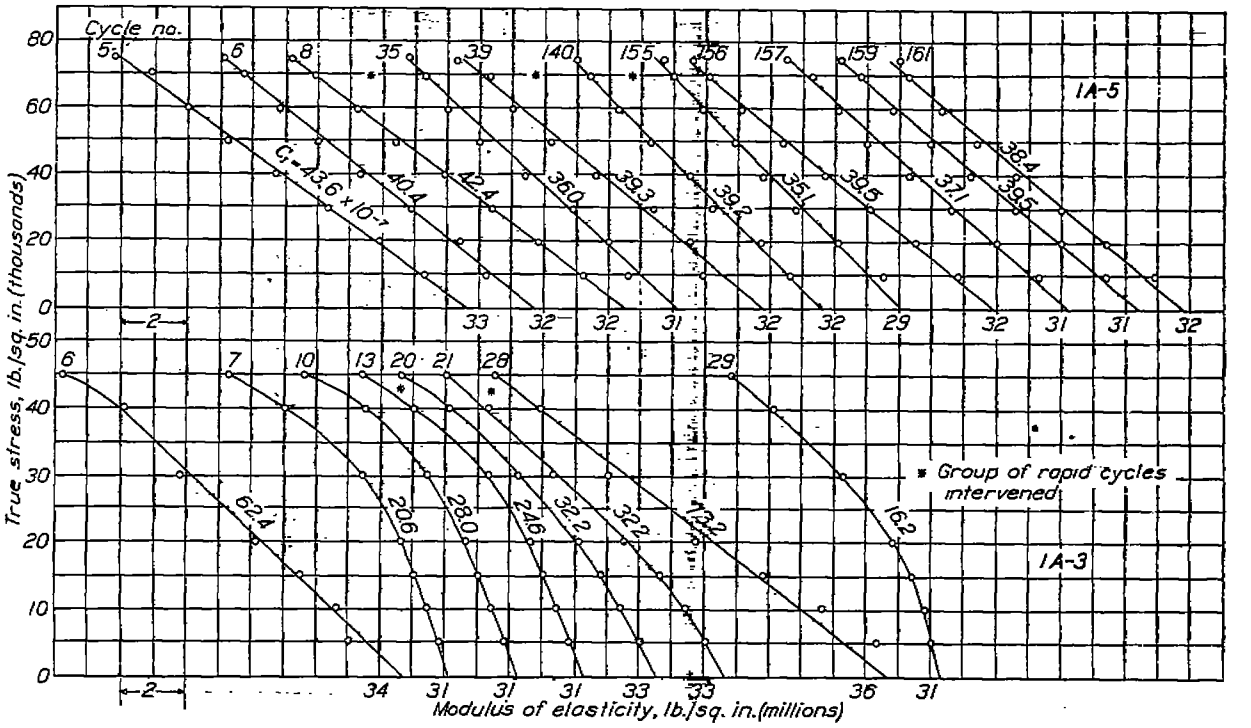

FIGURE 4.—Stress-modulus curves derived from the ascending portions of hysteresis loops of figure 2.

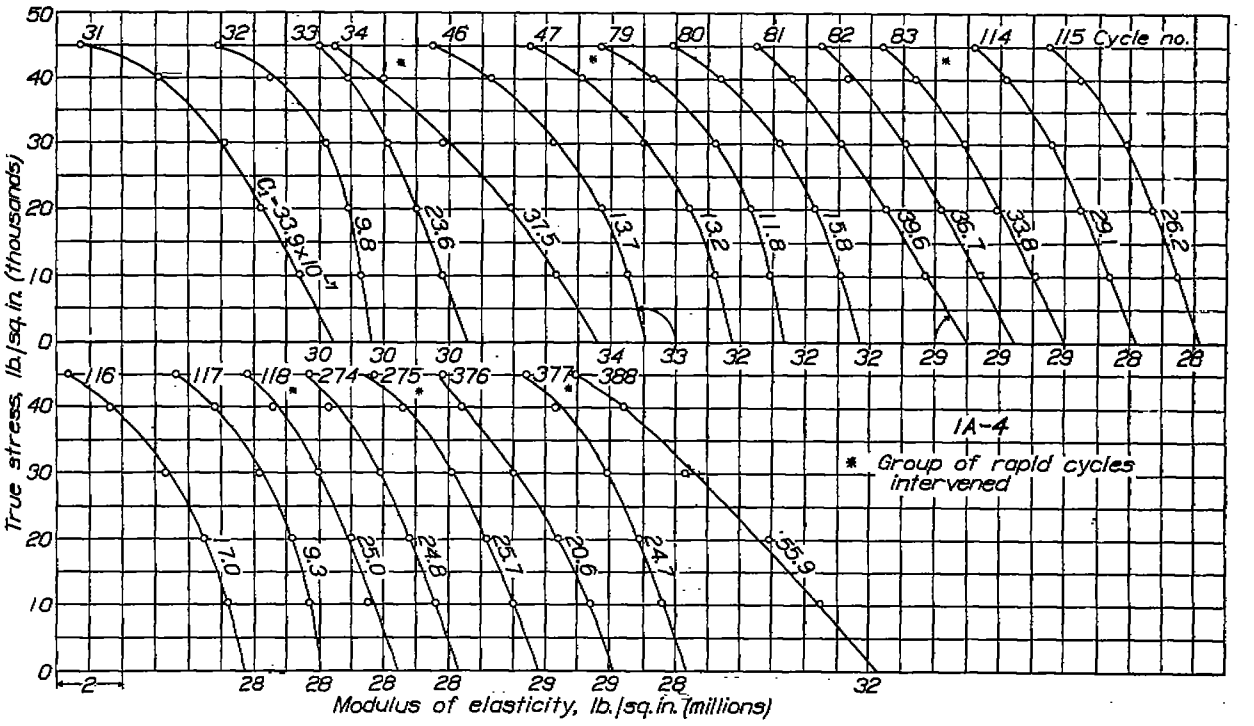

FIGURE 5.—Stress-modulus curves derived from the ascending portions of hysteresis loops of figure 3.

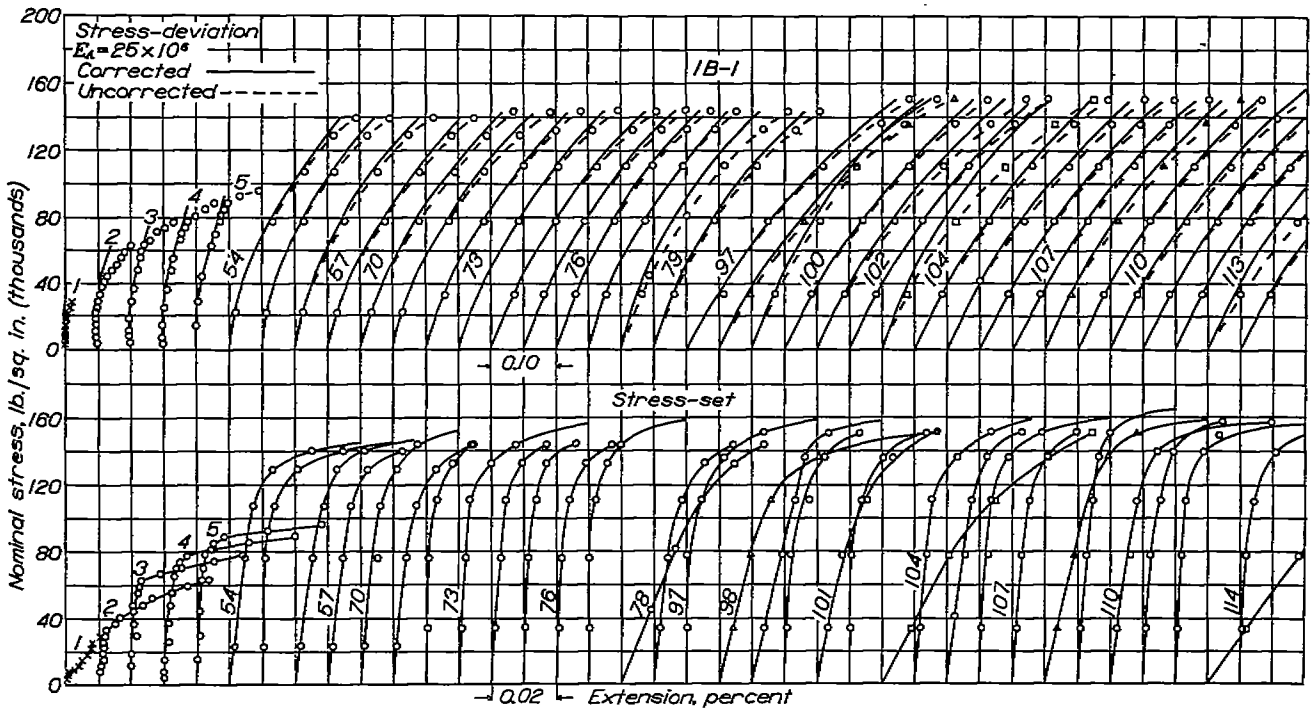

FIGURE 6.—Stress-set and stress-deviation curves obtained with a specimen of half-hard material (1B-1, table I).

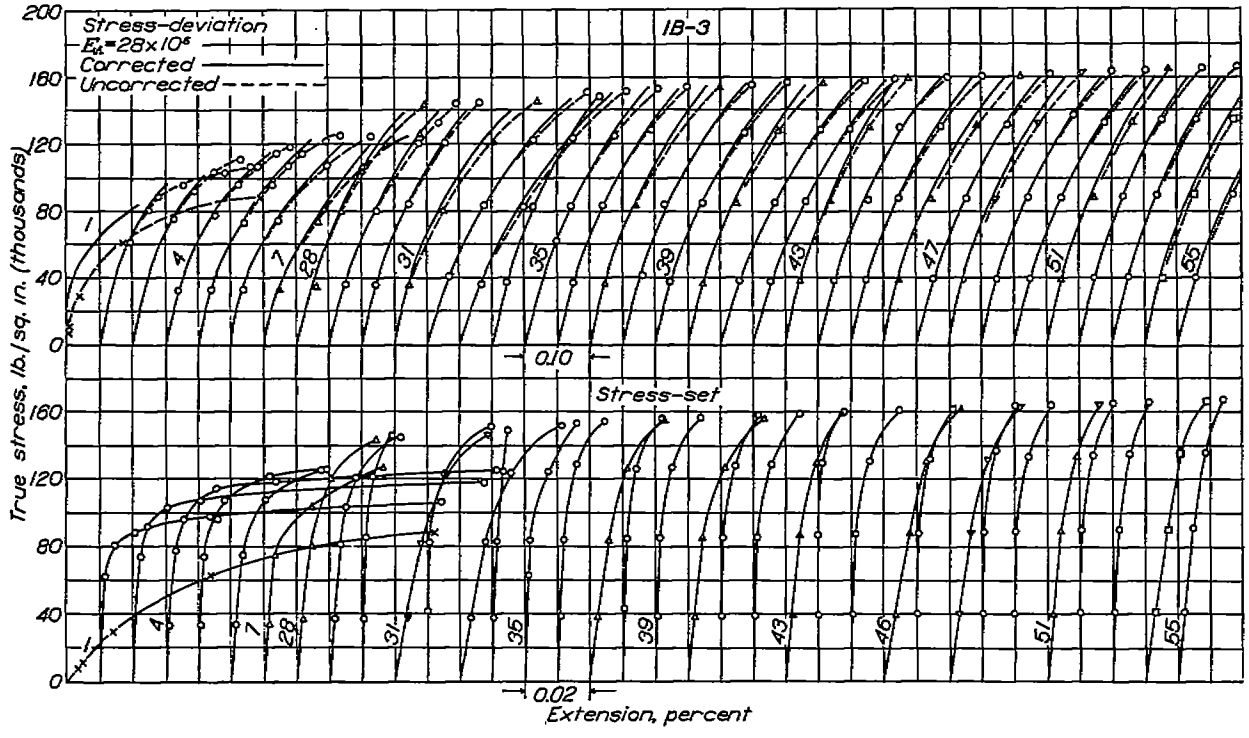

FIGURE 8.—Stress-set and stress-deviation curves obtained with a specimen of half-hard material (1B-3, table I).

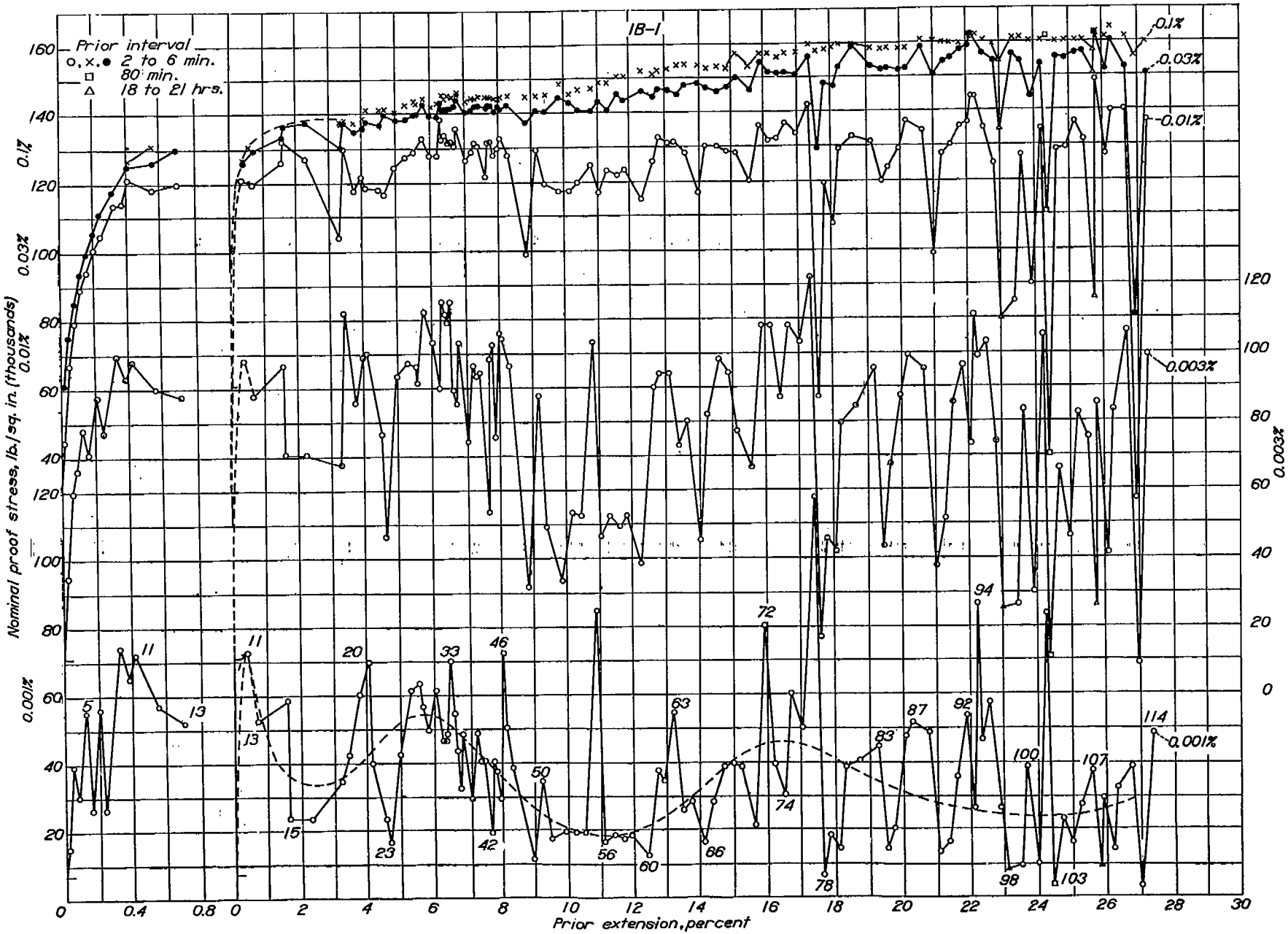

FIGURE 7.—Variation of proof stresses with prior plastic extension. Half-hard material (1B-1, table I).

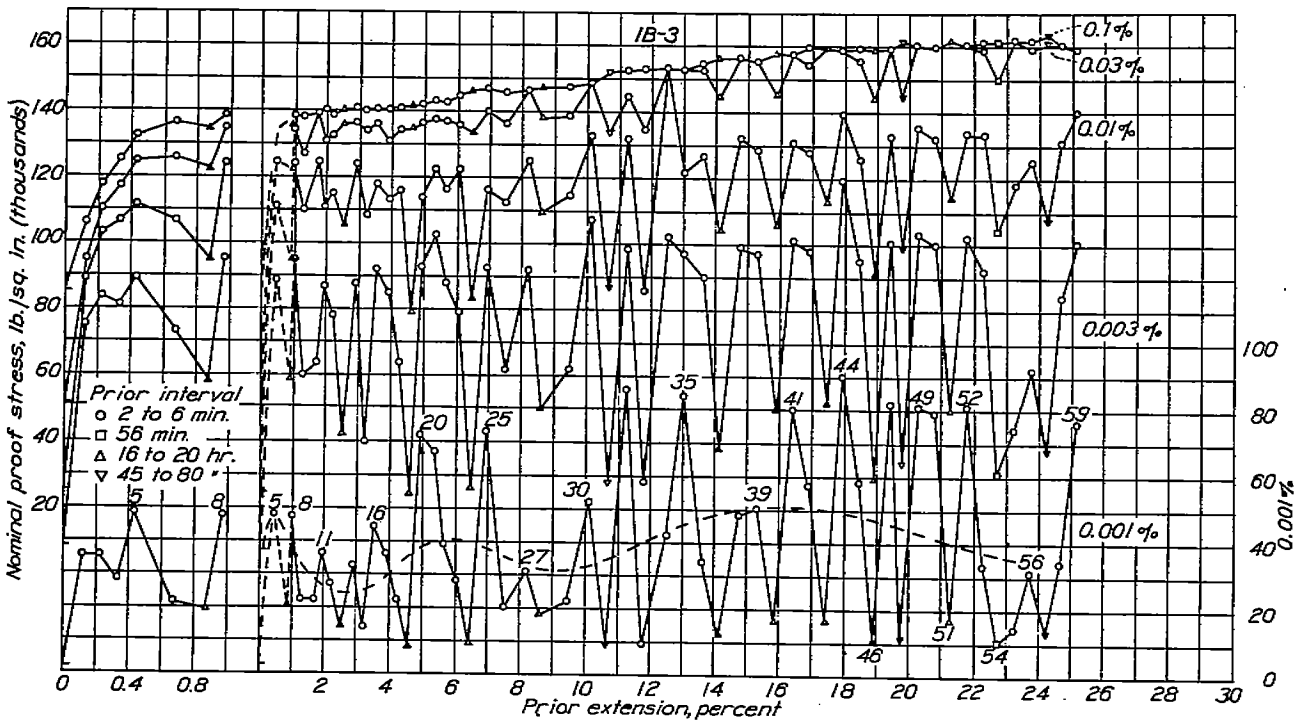

FIGURE 9.—Variation of proof stresses with plastic extension. Half-hard material (1B-3, table I).

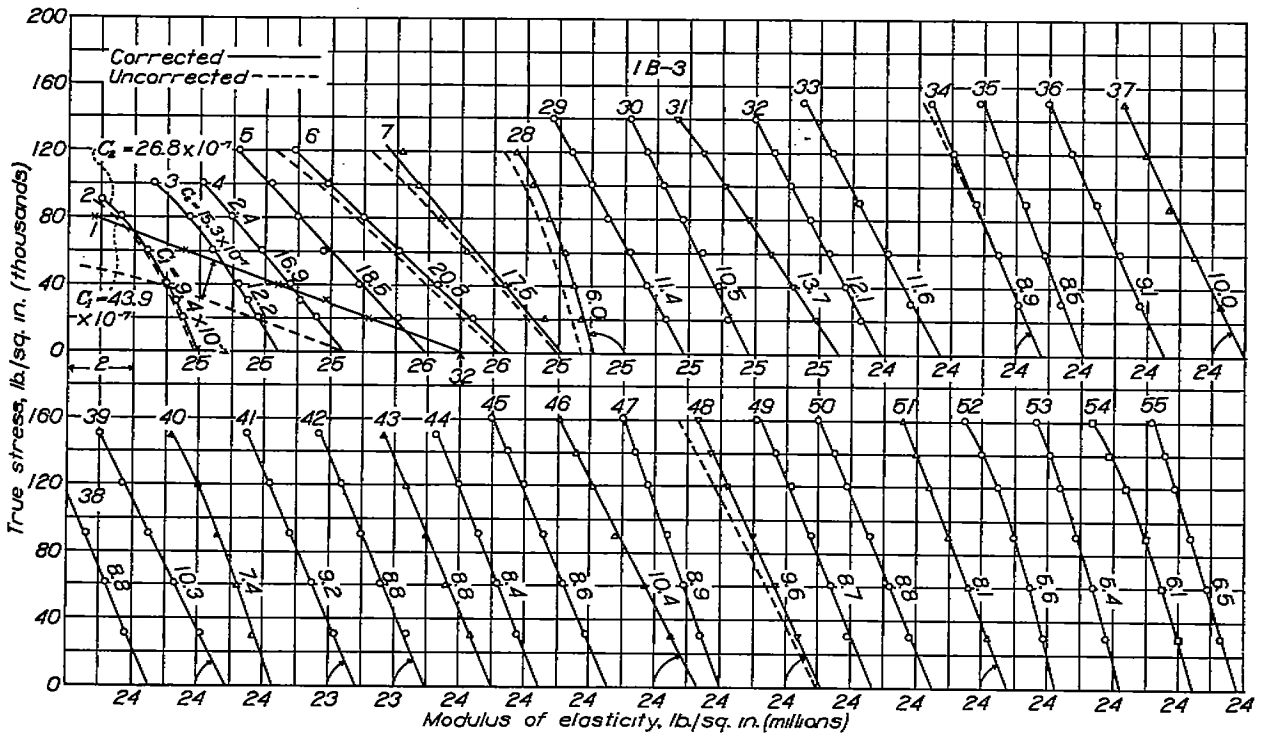

FIGURE 10.—Stress-modulus curves for half-hard material, derived from stress-deviation curves of figure 8.

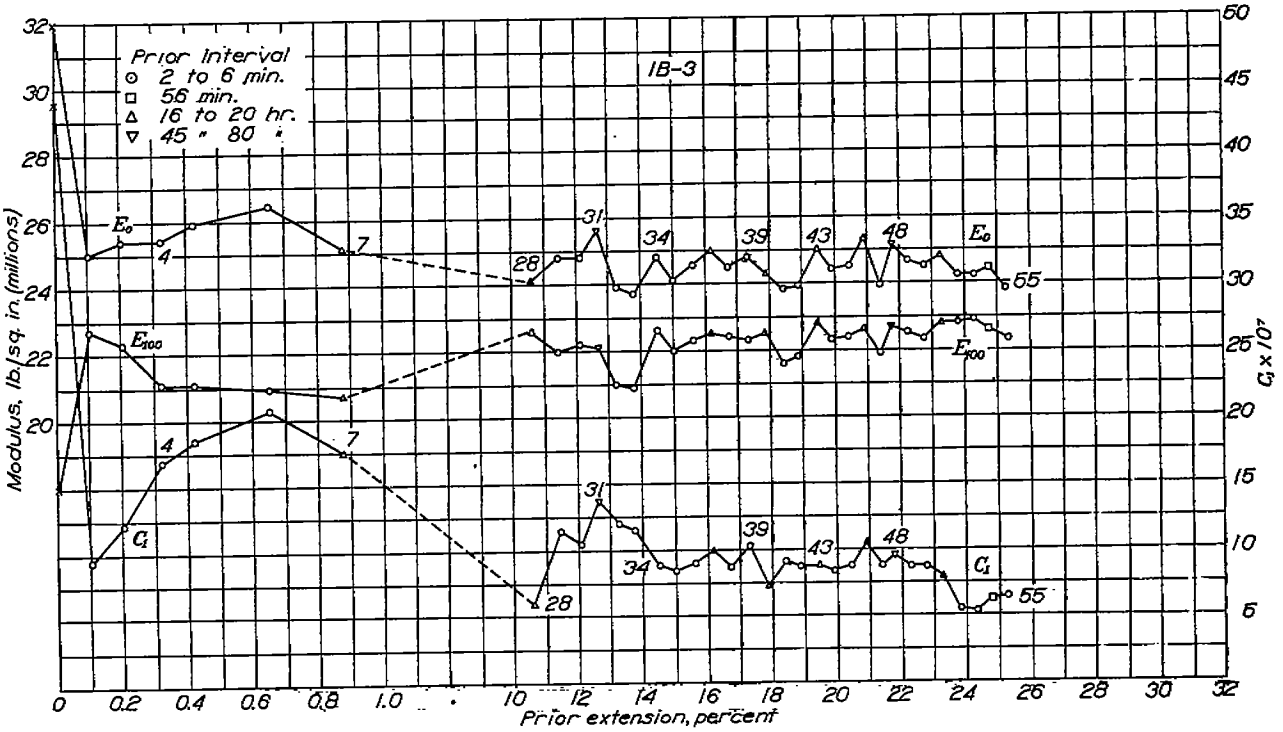

FIGURE 11.—Variation of the modulus of elasticity and of the index C_1 with prior plastic extension. Half-hard material (1B-3, table I).

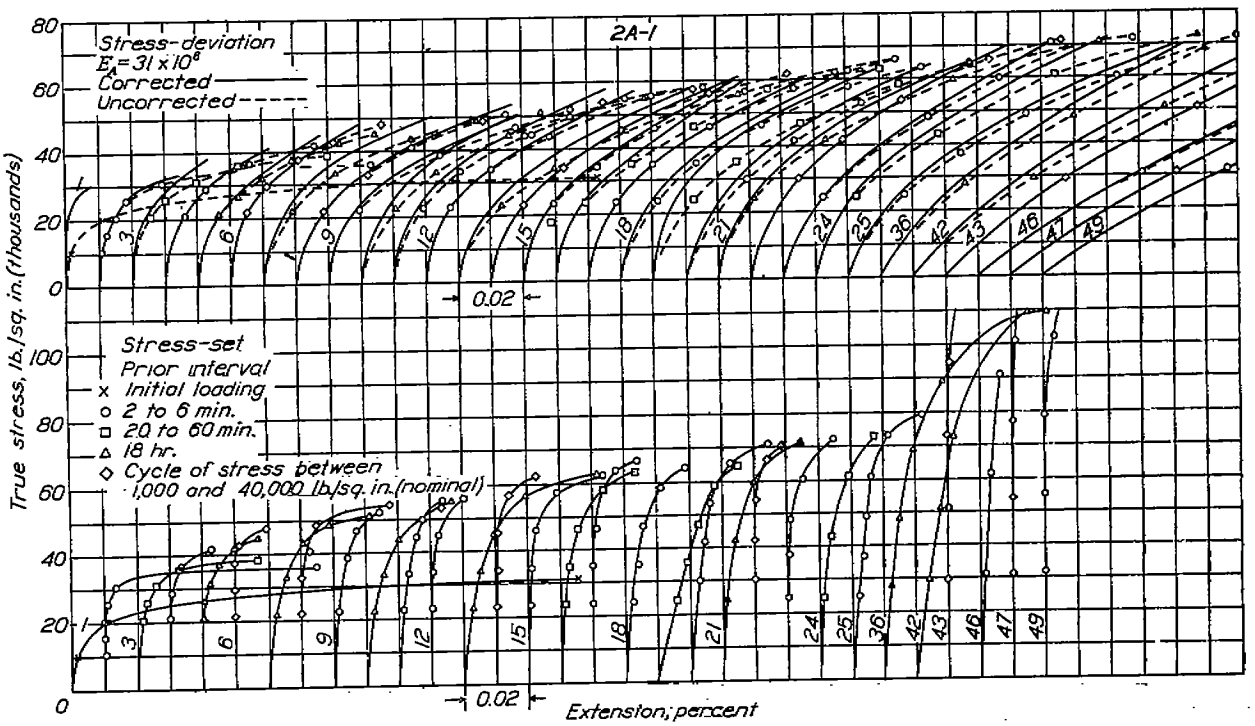

FIGURE 12.—Stress-set and stress-deviation curves obtained with a specimen of annealed material (2A-1, table I).

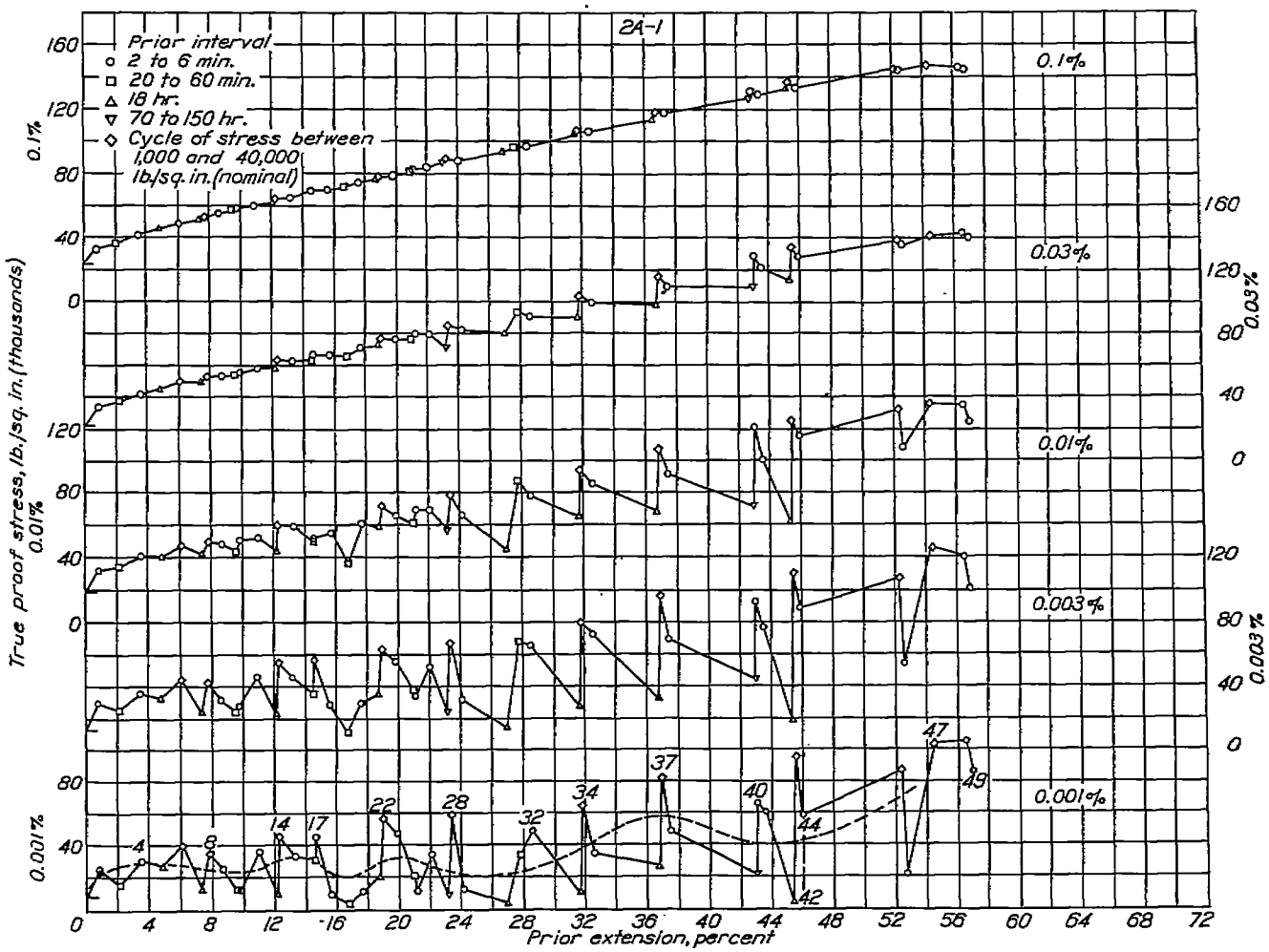

FIGURE 13.—Variation of proof stresses with prior plastic extension. Annealed material (2A-1, table I).

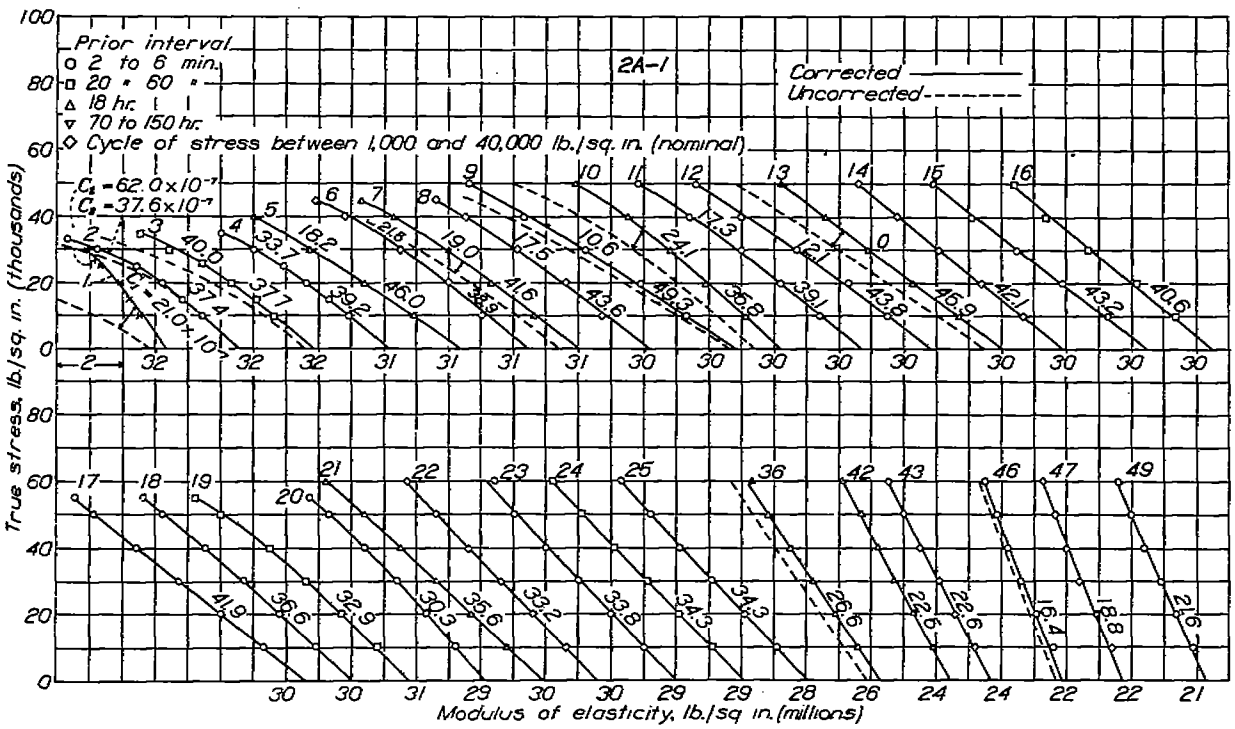

FIGURE 14.—Stress-modulus curves for annealed material, derived from stress-deviation curves of figure 12.

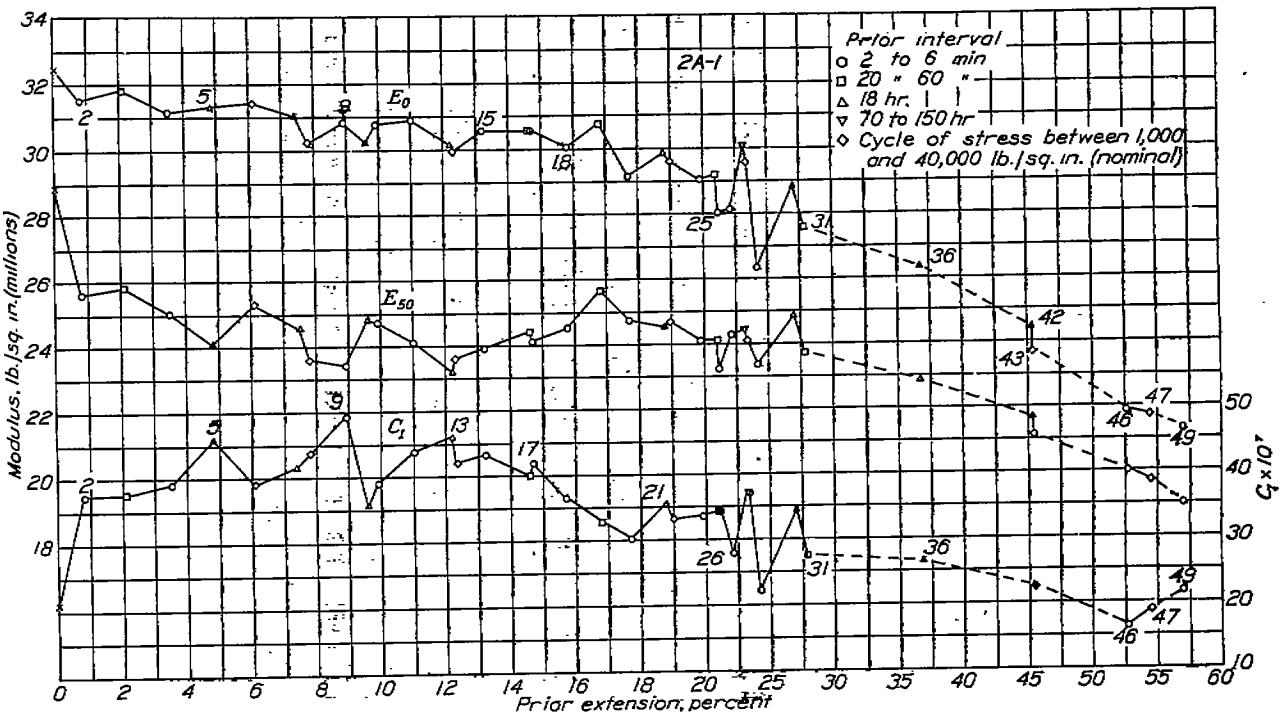

FIGURE 15.—Variation of the modulus of elasticity and of the index C_1 with prior plastic extension. Annealed material (2A-1, table I).

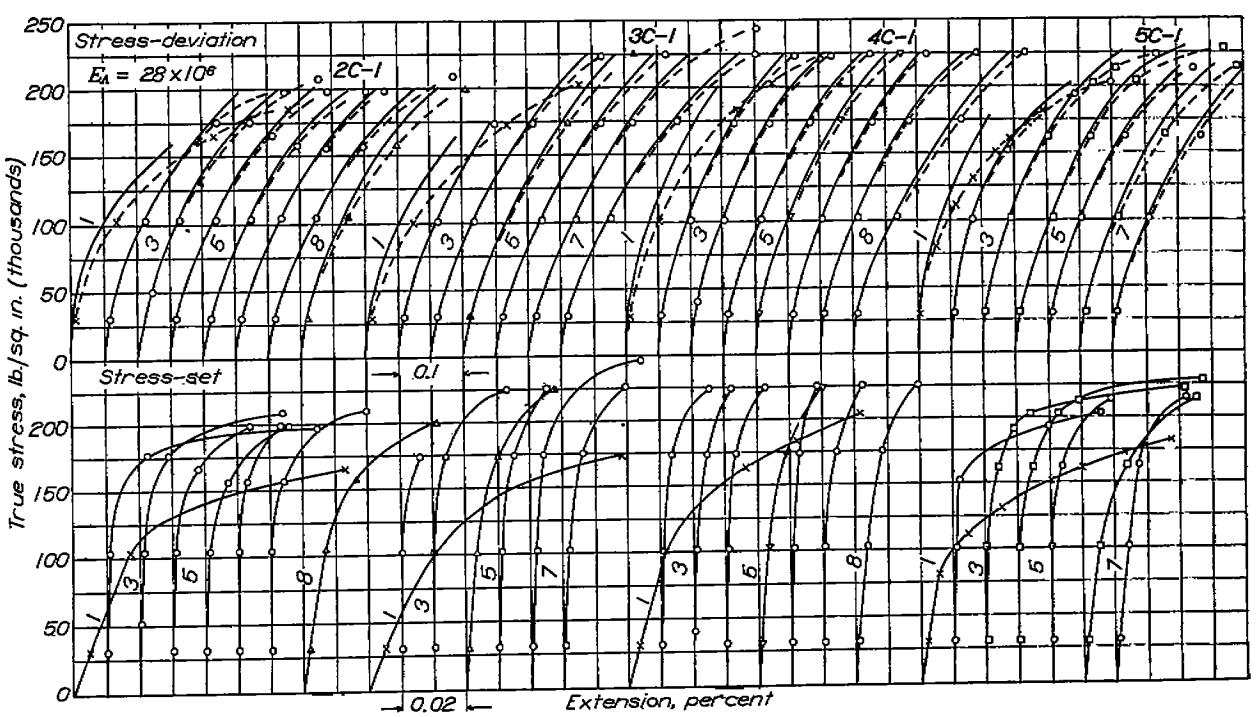

FIGURE 16.—Stress-set and stress-deviation curves obtained with four specimens of hard material (2C-1, 3C-1, 4C-1, 5C-1, table I).

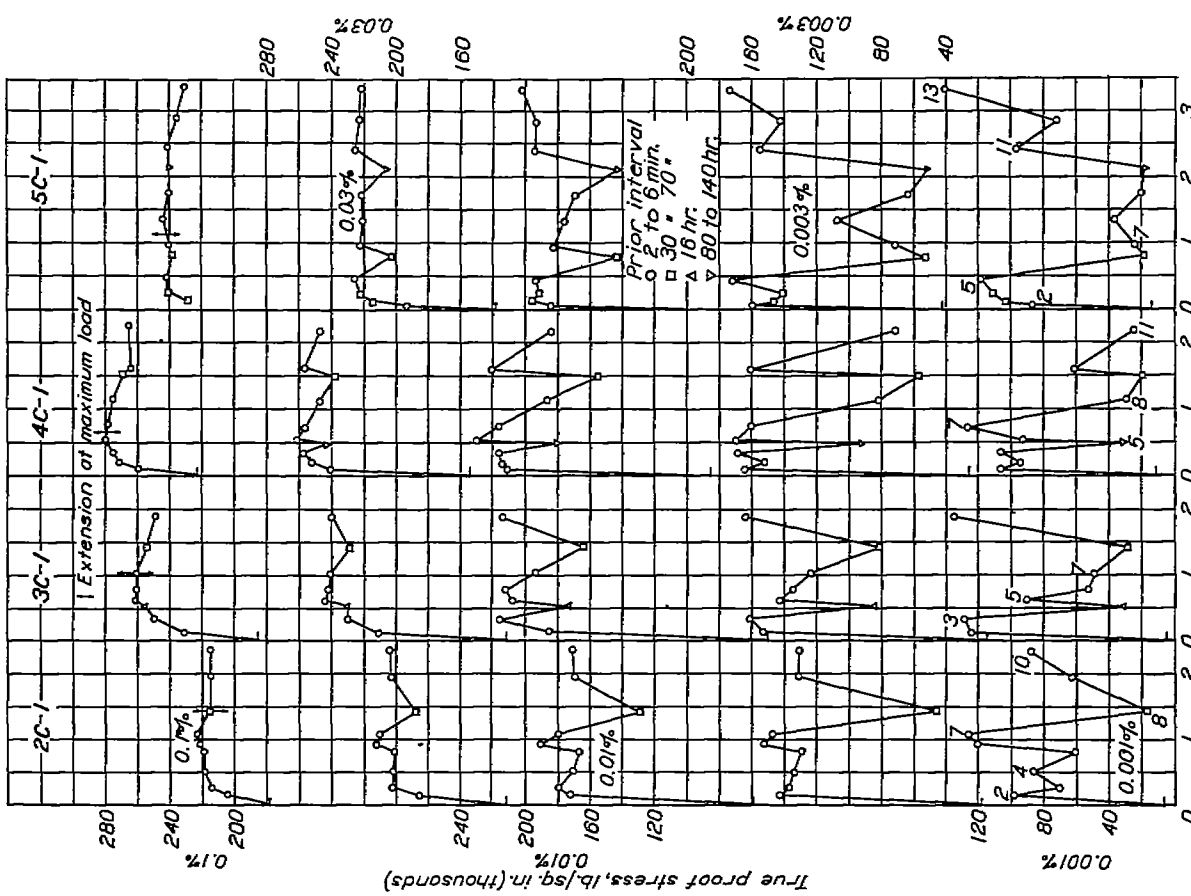

FIGURE 17.—Variation of proof stresses with prior plastic extension. Four specimens of hard material (2C-1, 3C-1, 4C-1, 5C-1, table 1).

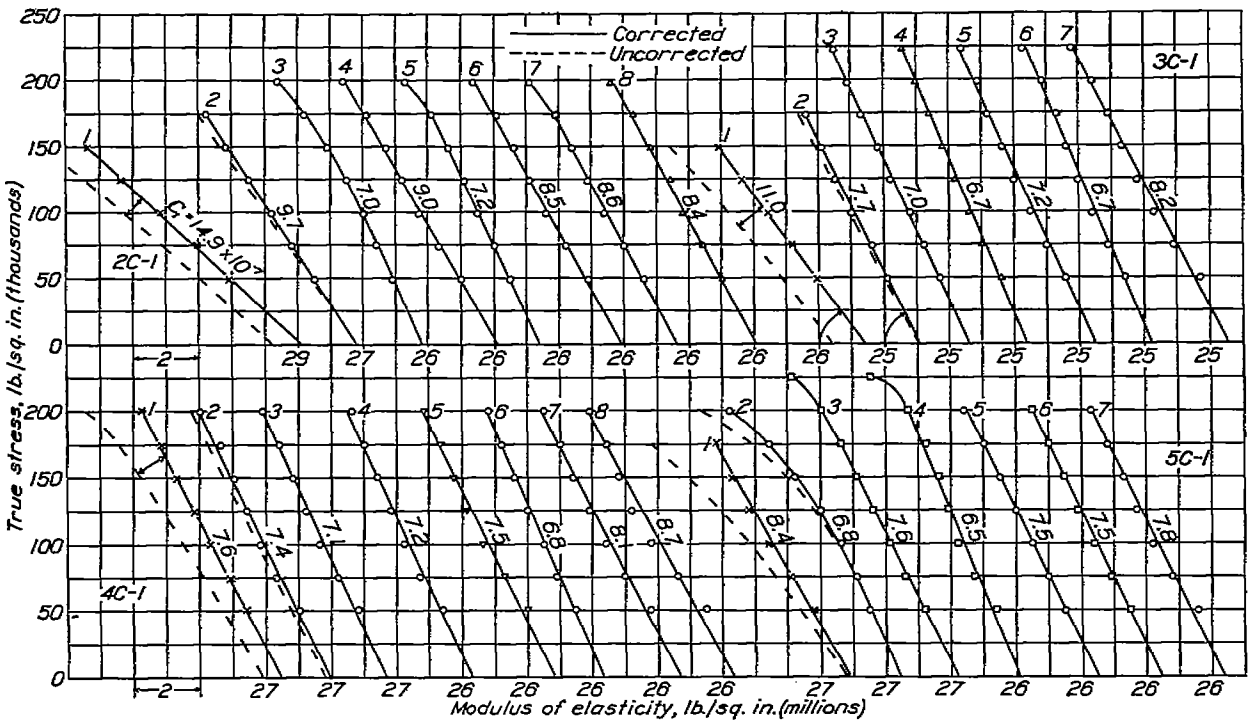

FIGURE 18.—Stress-modulus curves for hard material, derived from stress-deviation curves of figure 16.

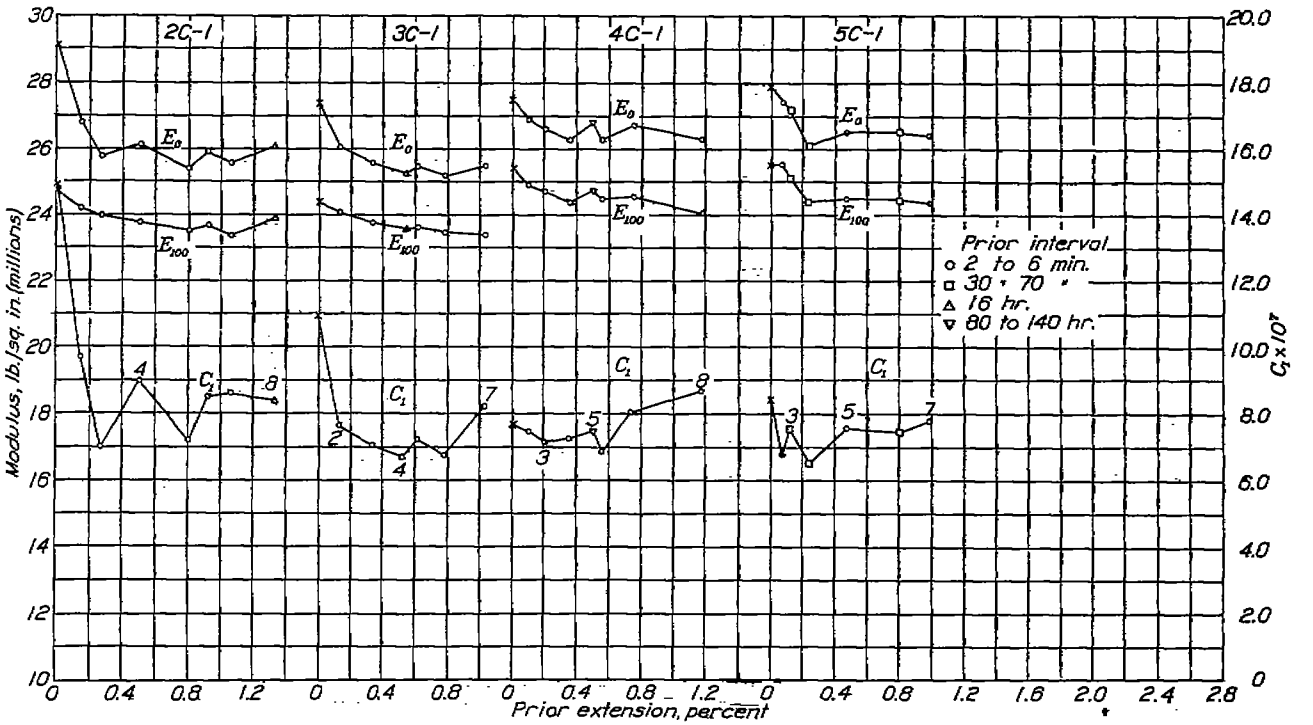

FIGURE 19.—Variation of the modulus of elasticity and of the index C_1 with prior plastic extension. Four specimens of hard material (2C-1, 3C-1, 4C-1, 5C-1, table I).

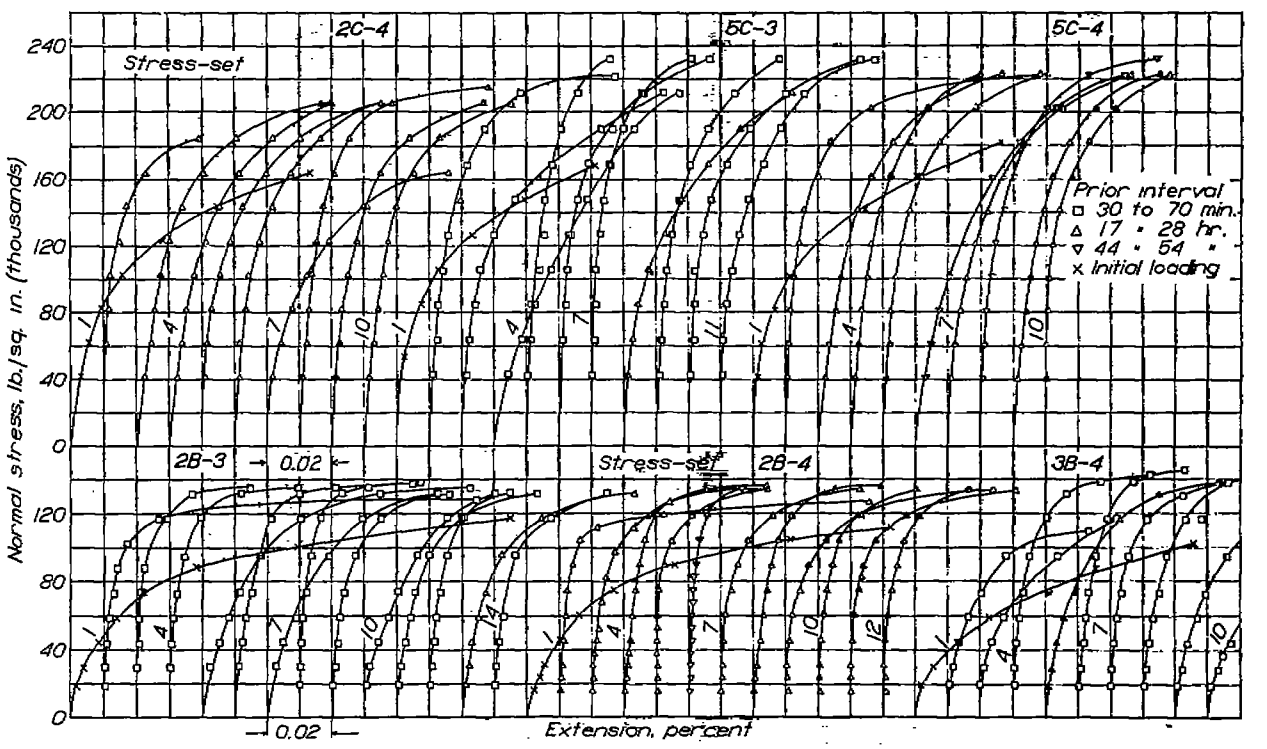

FIGURE 20.—Stress-set curves obtained with medium and long rest intervals. Three specimens each of half-hard and hard materials (2B-3, 2B-4, 3B-4, 2C-4, 5C-3, 5C-4, table I).

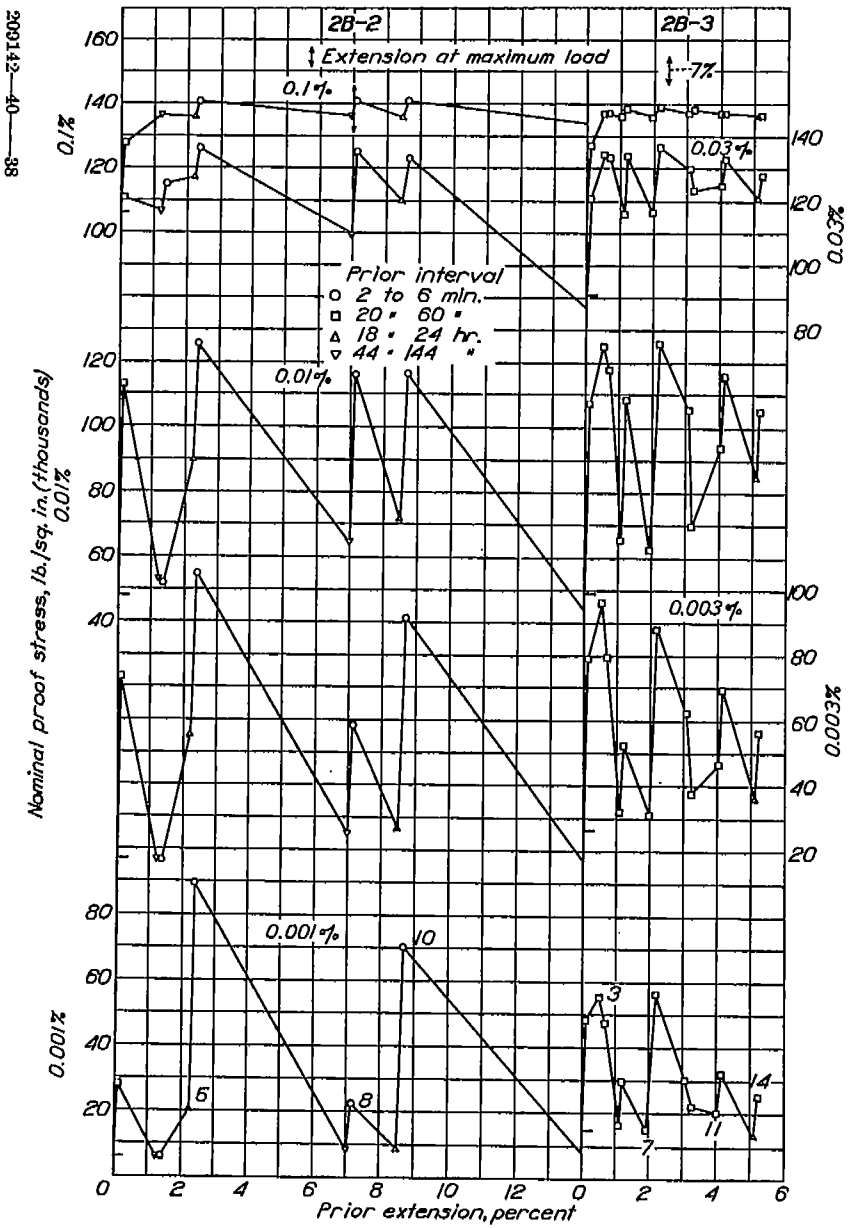

FIGURE 21.—Influence of duration of the rest interval on curves of variation of proof stress with plastic extension. Half-hard materials (2B-2, 2B-3, table I).

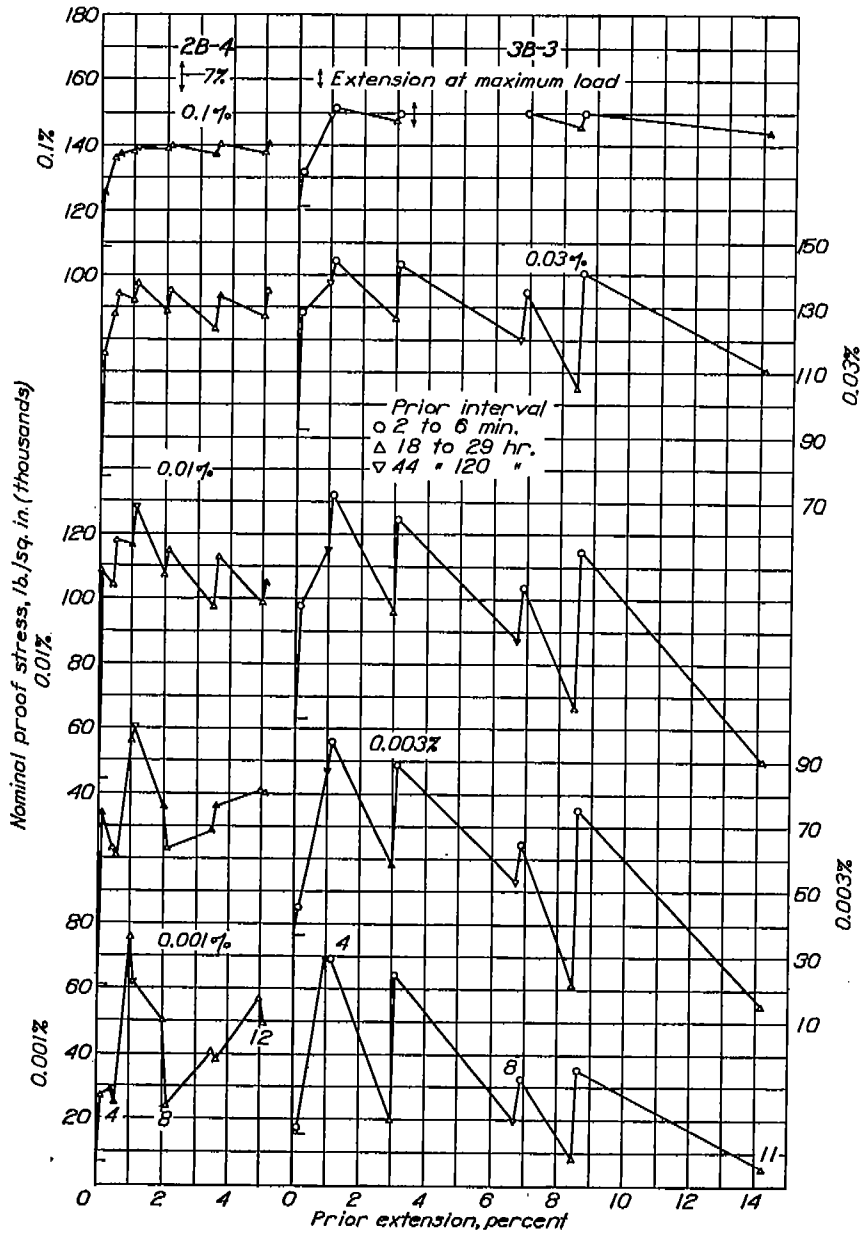

FIGURE 22.—Influence of duration of the rest interval on curves of variation of proof stress with plastic extension. Half-hard materials (2B-4, 3B-3, table I).

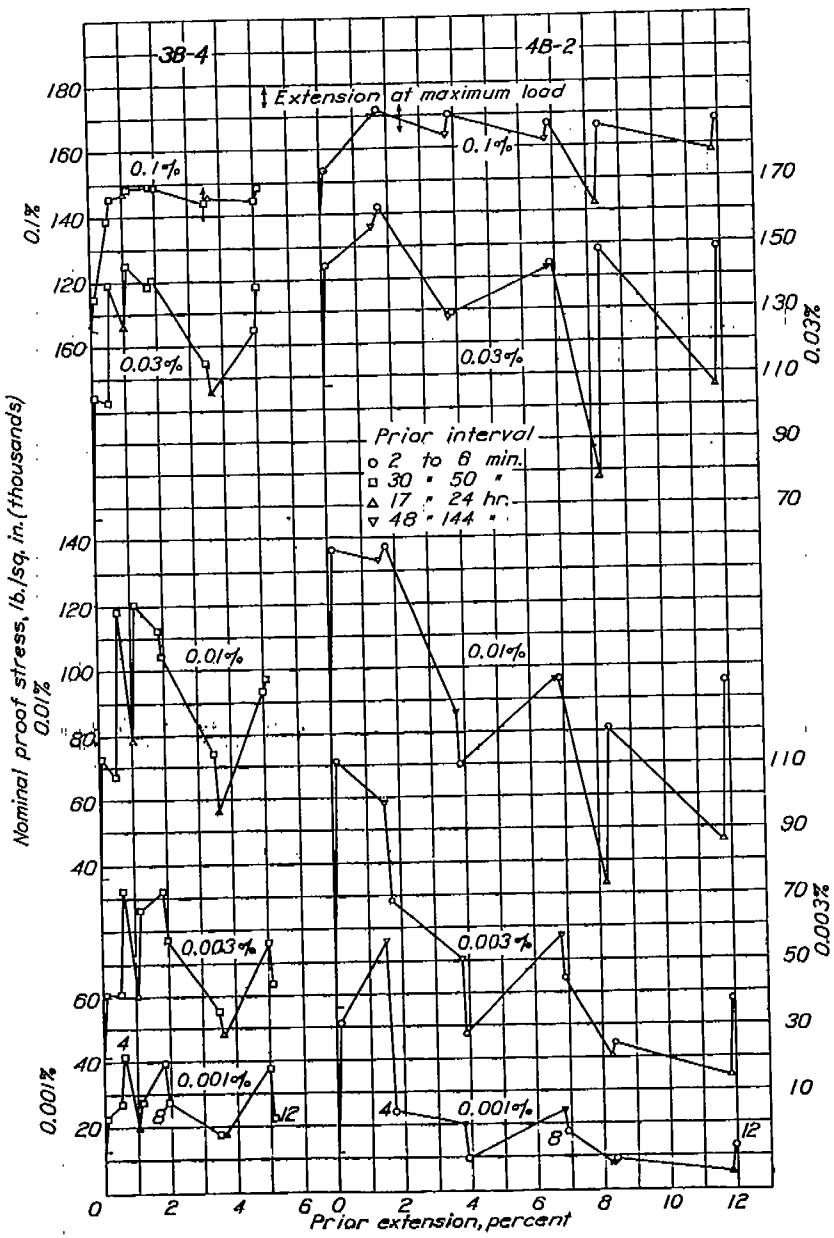

FIGURE 23.—Influence of duration of the rest interval on curves of variation of proof stress with plastic extension. Half-hard materials (3B-4, 4B-2, table I).

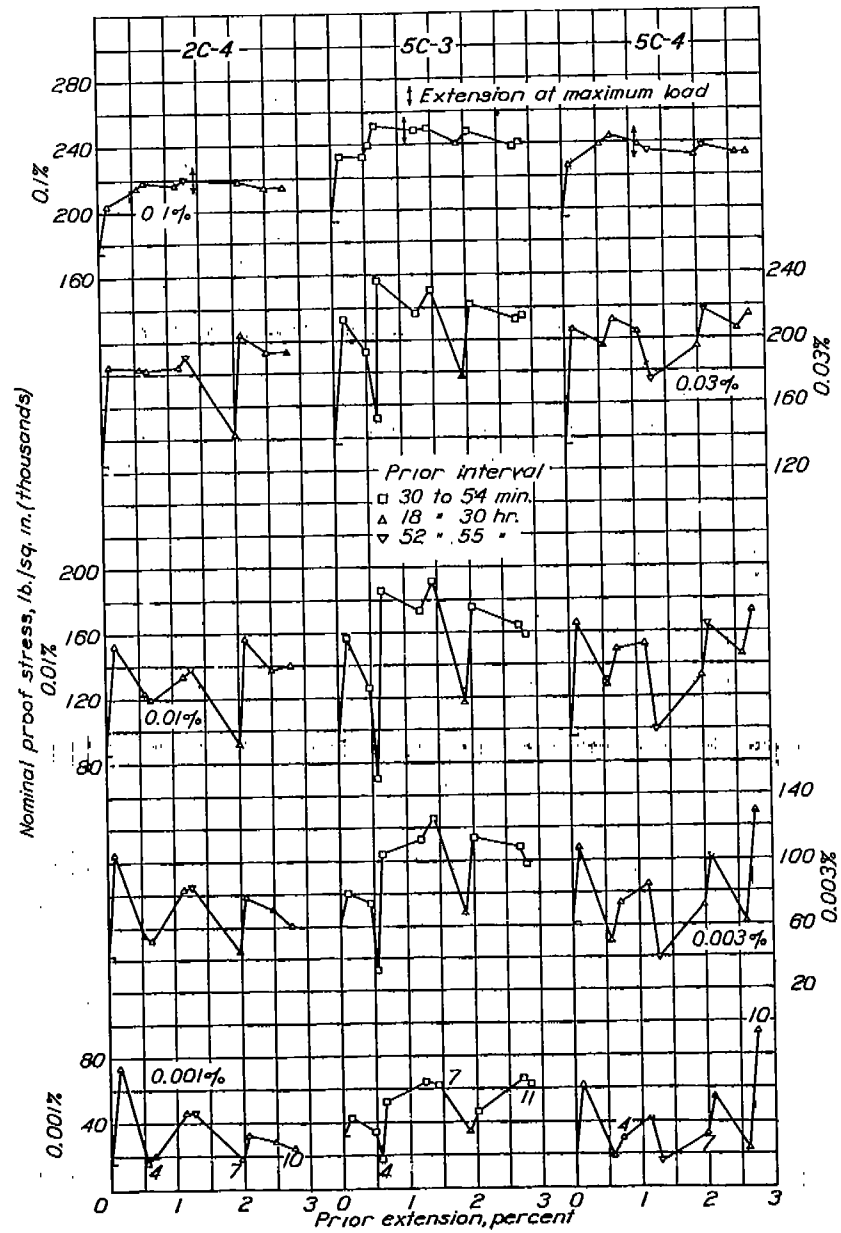

FIGURE 24.—Proof stress-deformation curves obtained entirely with either medium or long rest interval. Hard materials (2C-4, 5C-3, 5C-4, table I).

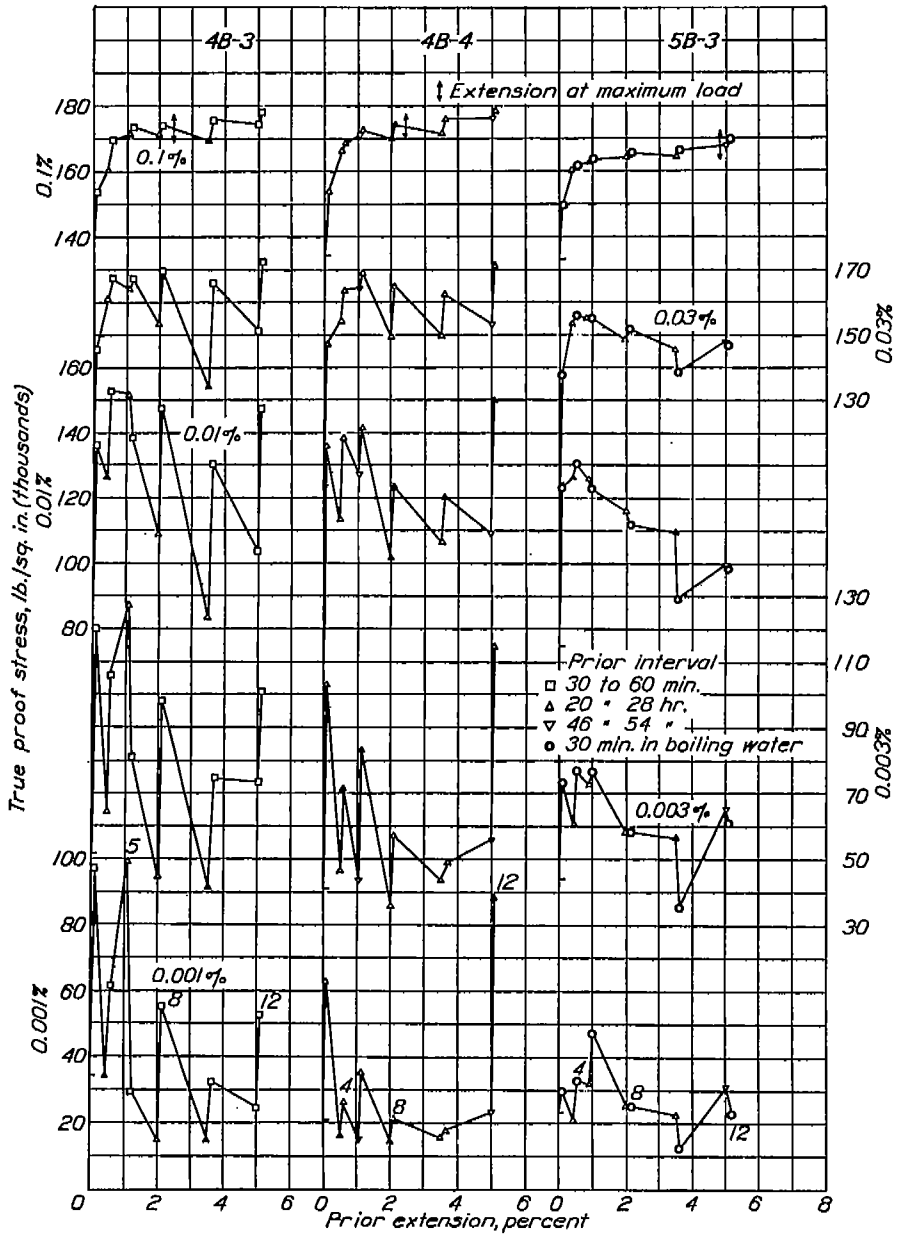

FIGURE 25.—Influence of medium and long rest intervals at room temperature and of 30 minutes at 100° C. on the proof stress-deformation curves. Half-hard materials (4B-3, 5B-4, 5B-6, table I).

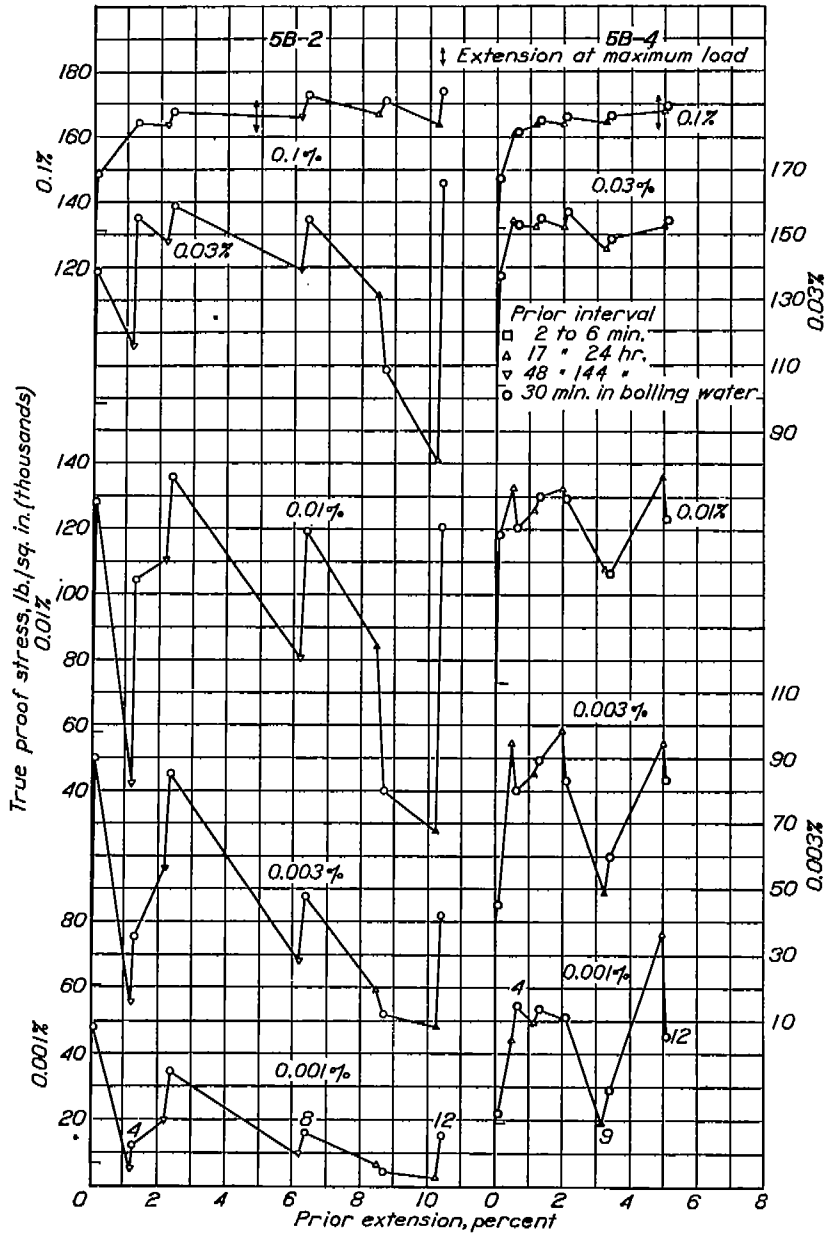

FIGURE 26.—Influence of short and long rest intervals at room temperature and of 30 minutes at 100° C. on the proof stress-deformation curves. Half-hard materials (5B-2, 5B-4, table I).

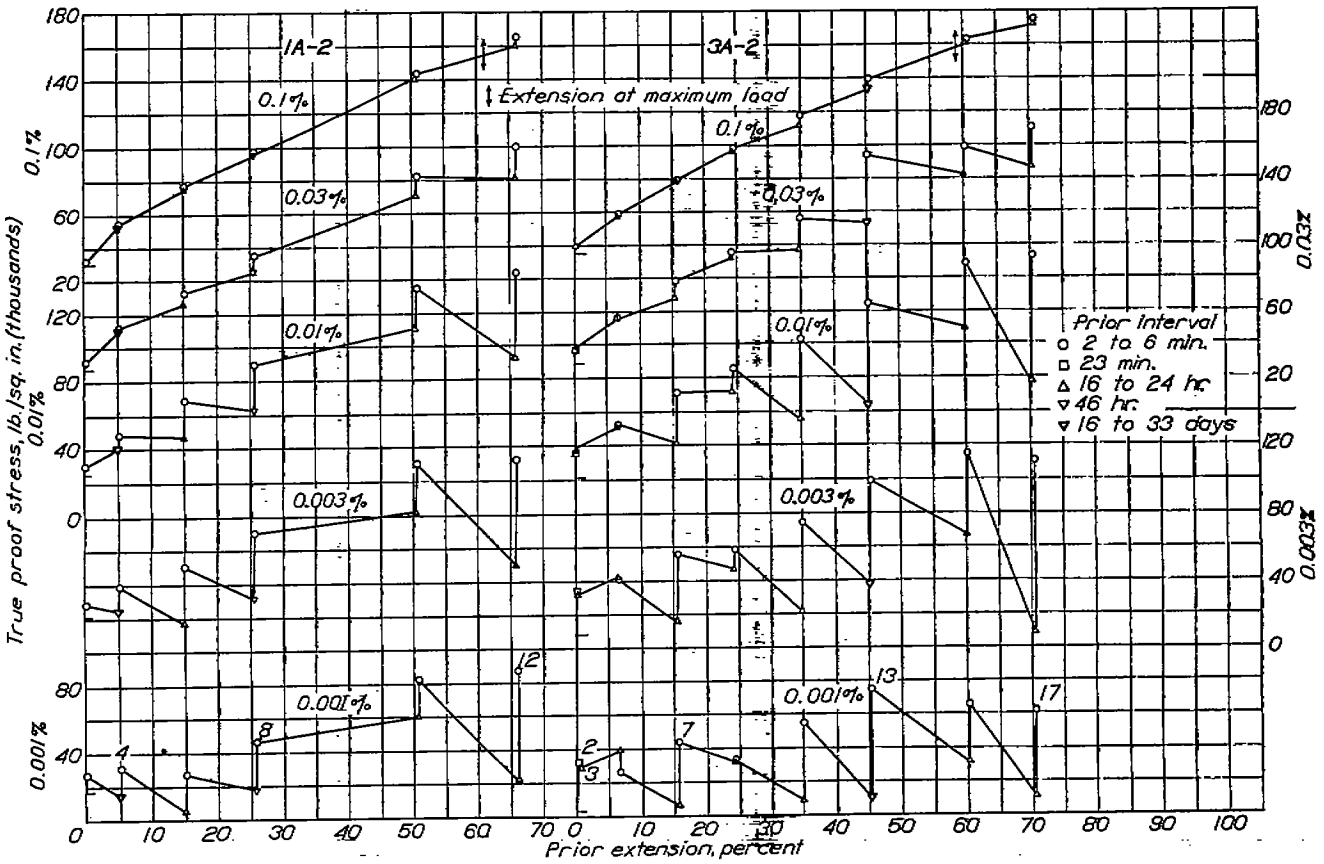

FIGURE 28.—Influence of short and long rest intervals on the proof stress-deformation curves. Annealed materials (1A-2, 3A-2, table I).

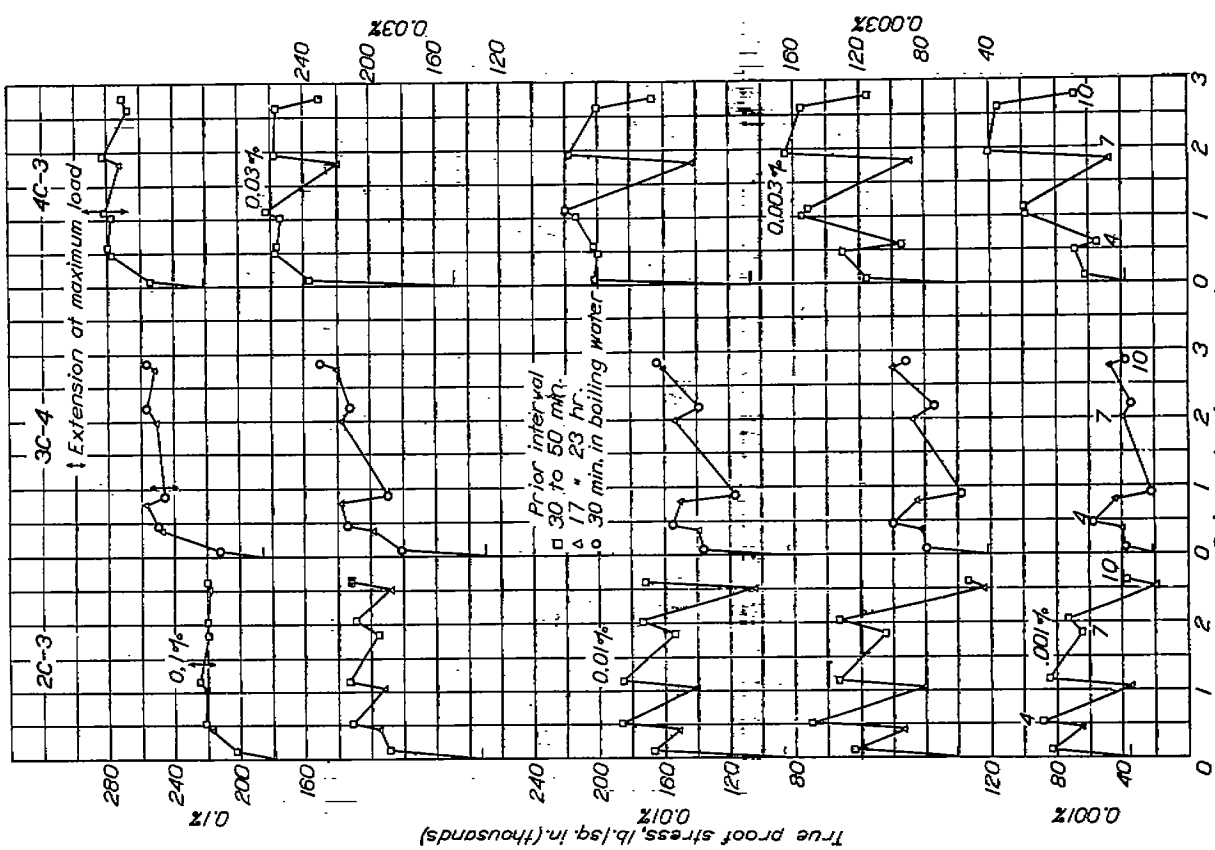

FIGURE 27.—Influence of medium and long rest intervals at room temperature and of 30 minutes at 100° C. on the proof stress-deformation curves. Hard materials (2C-3, 3C-4, 4C-3, table I).

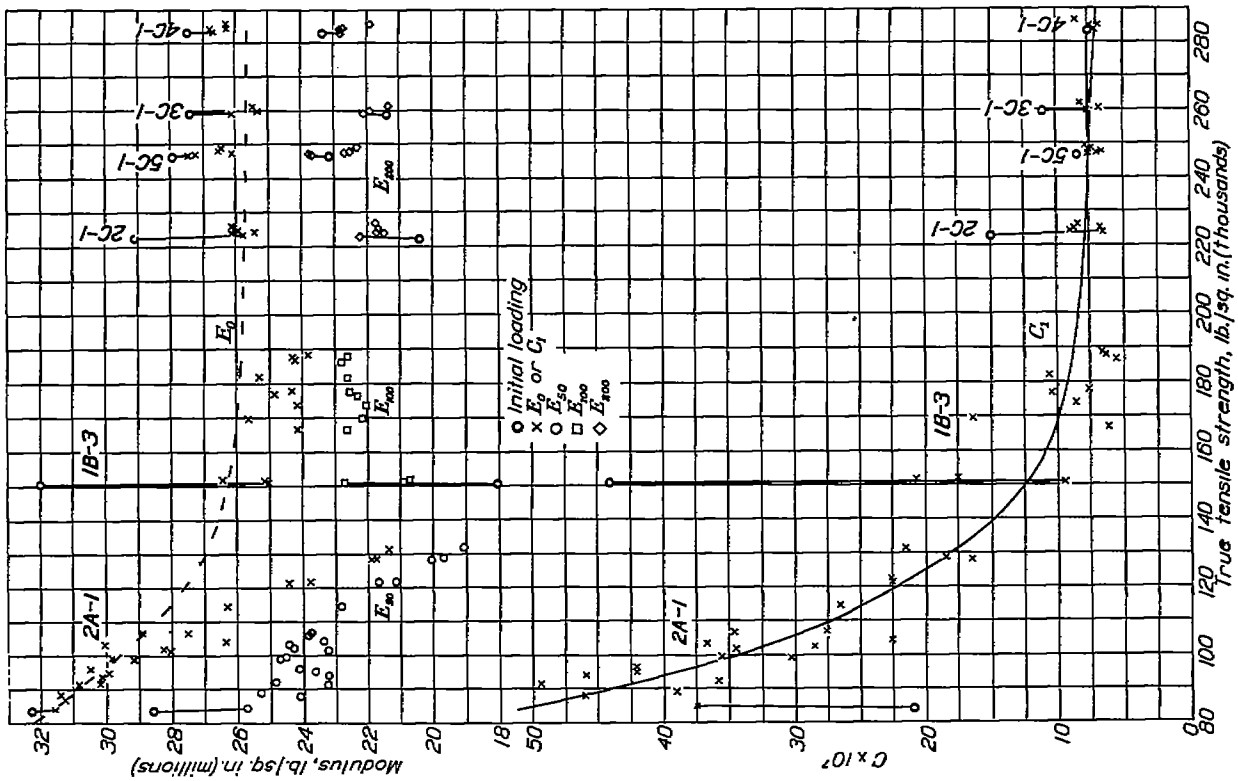

FIGURE 30.—Variation of the modulus of elasticity and of index C_1 with tensile strength. 18:8 Cr-Ni steels.

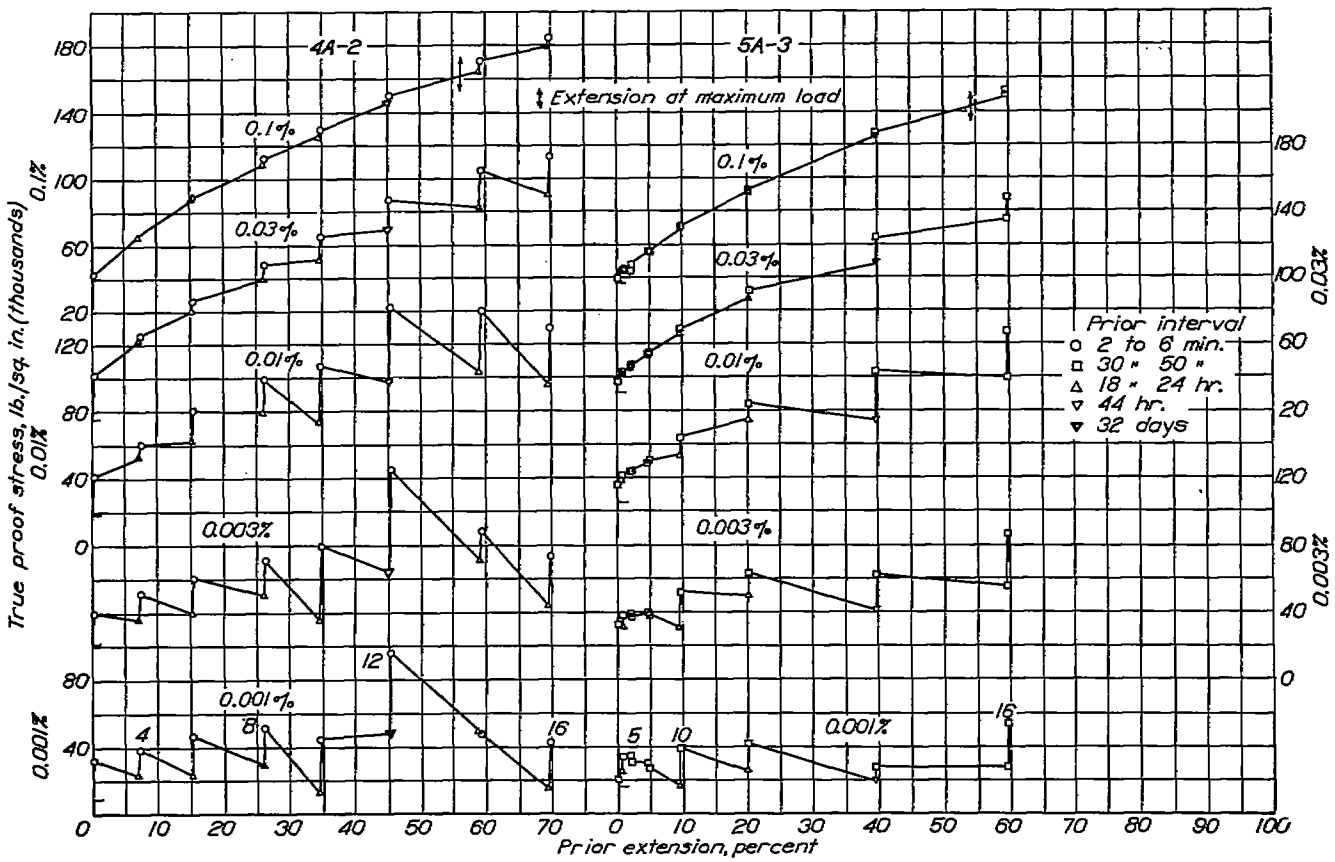

FIGURE 29.—Influence of short, medium, and long rest intervals on the proof stress-deformation curves. Annealed materials (4A-2, 5A-3, table I).

TABLE I.—CHEMICAL AND MECHANICAL PROPERTIES OF MATERIALS AS RECEIVED

Material [a]	Specimen	Condition	Chemical composition (percent)			Elongation in 2 inches (percent)		Reduction of area (percent)	Tensile strength (lb./sq. in.)	Initial proof stress (lb./sq. in.)					Initial proof ratio [b] (percent)				
			Cr	Ni	C	Maximum load	Total			0.10 percent	0.030 percent	0.010 percent	0.003 percent	0.001 percent	0.10 percent	0.030 percent	0.010 percent	0.003 percent	0.001 percent
1A	1A-2	Annealed	18.22	8.63	0.07	61.1	72.0	78.7	92,150	30,400	27,100	24,800	21,300	17,000	33.0	29.3	27.0	22.0	18.7
2A	2A-1	Annealed	18.7	9.5	.06	66.1	70.0	76.4	83,630	28,200	24,000	19,500	13,300	8,200	33.7	28.7	23.3	15.9	9.8
	2A-4									30,600	25,500	20,700	16,250	13,400	36.6	30.5	24.8	19.4	16.0
	Average									29,400	24,750	20,100	14,775	10,800	35.6	29.6	24.5	17.7	12.9
3A	3A-2	Annealed	18.4	8.9	0.7	58.7	66.3	74.8	90,630	35,800	28,900	22,200	8,200	2,500	39.6	31.9	24.3	9.1	2.8
	3A-3									35,050	30,200	25,100	19,400	15,000	38.7	33.3	27.7	21.4	16.5
	3A-4									35,250	30,800	25,700	21,000	16,200	38.0	34.0	28.4	23.2	17.9
	Average									35,370	29,970	24,330	16,200	11,230	39.0	33.0	26.8	17.8	12.3
4A	4A-2	Annealed	18.2	8.2	.11	56.2	66.0	71.7	98,630	40,500	35,300	29,000	22,000	9,000	41.1	35.8	29.4	22.3	9.1
	4A-3									41,900	36,000	30,500	25,950	21,800	42.5	36.5	30.9	26.3	22.1
	Average									41,200	35,650	29,750	23,970	15,400	41.8	36.1	30.2	24.3	15.6
5A	5A-2	Annealed	19.2	9.2	.11	54.1	66.0	74.7	91,360	36,600	30,400	25,300	20,000	12,500	40.0	33.2	28.2	21.9	13.7
	5A-3									36,600	31,100	25,500	21,200	15,500	40.1	34.0	27.9	23.2	17.0
	Average									36,600	30,750	25,650	20,600	14,000	40.05	33.6	28.1	22.5	15.4
1B	1B-1	Half hard	18.22	8.63	.07	24.2	28.5	78.7	150,630	------	------	29,300	10,780	6,850	------	------	19.5	7.1	4.5
	1B-3									85,200	50,900	24,400	7,900	2,600	56.4	33.8	16.2	5.2	1.7
	1B-5									89,900	61,300	39,100	22,000	13,800	59.7	40.7	25.9	15.1	9.2
	1B-6									89,800	62,300	42,300	26,500	16,200	59.6	41.3	28.1	17.6	10.7
	1B-7									89,400	61,000	41,700	25,100	16,500	59.3	40.4	27.7	16.7	10.9
	Average									88,580	58,880	35,270	18,580	11,200	59.0	39.1	23.4	12.3	7.4
2B	2B-2	Half hard	18.8	9.5	.06	7.03	18.5	61.1	143,130	106,500	76,400	48,500	17,000	6,000	74.4	52.7	33.9	11.9	4.2
	2B-3									110,000	81,300	49,200	26,500	14,500	76.8	56.8	34.4	17.8	10.1
	2B-4									108,500	77,500	44,000	21,000	7,000	75.7	54.9	31.1	14.7	4.9
	Average									108,330	78,400	47,730	21,500	9,170	75.6	54.8	33.4	15.1	6.4
3B	3B-2	Half hard	18.6	8.9	.07	3.46	16.3	61.6	153,800	120,900	93,500	63,200	34,800	18,700	78.6	60.8	41.1	22.6	12.1
	3B-3									121,000	92,300	63,500	36,500	15,500	78.7	60.0	41.3	23.7	10.1
	3B-4									105,300	66,500	38,100	21,300	12,000	68.8	43.2	24.8	13.8	7.8
	Average									115,900	84,100	54,930	30,870	15,400	75.3	54.7	35.7	20.1	10.1
4B	4B-2	Half hard	18.2	8.2	.11	2.42	14.3	55.1	173,690	139,300	107,000	72,500	36,600	11,500	80.1	61.8	41.7	20.4	6.6
	4B-3									140,000	109,500	77,400	51,500	34,000	80.6	63.0	45.7	29.7	19.6
	4B-4									136,400	104,200	70,000	41,000	21,000	78.5	60.0	40.3	23.6	12.1
	Average									138,530	106,900	73,300	42,830	22,170	79.8	61.5	42.6	24.7	12.8
5B	5B-2	Half hard	19.1	9.3	.12	4.80	15.8	56.8	164,830	131,200	98,000	58,000	21,000	7,000	79.6	59.5	35.2	12.7	4.2
	5B-3									132,800	104,300	75,000	44,000	24,000	80.6	63.3	45.5	26.7	14.6
	5B-4									132,200	104,000	73,000	40,000	19,000	80.2	63.1	44.3	24.3	11.5
	Average									132,100	102,100	68,670	35,000	16,670	80.1	61.9	41.6	21.2	10.1
2C	2C-1	Hard	18.8	9.4	.06	1.43	6.5	51.0	223,180	170,000	132,500	58,000	18,200	6,300	76.2	59.3	26.0	8.2	2.8
	2C-3									178,600	131,600	95,000	61,000	35,000	80.0	58.9	42.6	27.3	15.7
	2C-4									176,700	126,000	86,000	42,000	16,000	78.9	56.4	38.5	18.8	7.2
	Average									175,100	130,030	79,670	40,400	19,100	78.5	58.3	35.7	18.1	8.6
3C	3C-1	Hard	18.4	8.9	.07	1.03	5.5	52.9	259,380	184,700	131,000	50,000	15,000	5,000	71.3	50.5	19.3	5.8	1.9
	3C-4									185,000	130,200	85,000	43,000	22,000	71.6	50.2	32.7	16.7	8.5
	Average									185,350	130,600	67,500	29,000	13,500	71.45	50.35	26.0	11.2	5.2
4C	4C-1	Hard	18.3	8.1	.11	1.15	4.5	46.8	283,690	223,000	154,000	85,000	26,000	9,000	78.9	54.3	30.0	9.2	3.2
	4C-3									222,000	147,500	97,200	60,000	38,000	78.2	52.0	34.3	21.2	13.4
	Average									222,500	150,750	91,000	43,000	23,500	78.5	53.1	32.1	15.2	8.3
5C	5C-1	Hard	19.1	9.2	.14	1.12	5.75	55.3	246,830	------	138,000	100,000	42,000	14,000	------	55.6	40.4	16.9	5.6
	5C-3									192,800	136,000	94,300	60,000	32,000	77.7	54.9	38.1	24.2	12.9
	5C-4									194,200	135,500	95,000	62,500	20,800	78.4	54.7	38.4	25.2	8.4
	Average									193,500	136,500	96,430	54,830	22,270	78.05	55.1	39.0	22.1	9.0

[a] A represents annealed material; B represents half-hard material; C represents hard material.

[b] Proof ratio is given as ratio of proof stress to tensile strength in percent.

TABLE II.—DIMENSIONS OF ROD MATERIAL AS RECEIVED AND OF TEST SPECIMENS

All specimens machined to standard 2-inch gage length. Fillets and reduced section machined with aid of templet designed for 0.505 inch gage diameter standard A. S. T. M. tensile specimen]

Material	Condition	Bar diameter [1] (inches)	Nominal gage diameter (inches)	Diameter of threaded ends (inches)
1A	Annealed	5/8	0.417	0.625
2A	do	1/2	.505	.750
3A	do	1/2	.505	.750
4A	do	1/2	.505	.750
5A	do	1/2	.505	.750
1B	Half hard	5/8	.417	.625
2B	do	5/8	.417	.625
3B	do	5/8	.417	.625
4B	do	5/8	.417	.625
5B	do	5/8	.417	.625
2C	Hard	3/8	.250	.375
3C	do	3/8	.250	.375
4C	do	3/8	.250	.375
5C	do	3/8	.250	.375

[1] As received.

TABLE III.—HYSTERESIS

SPECIMEN 1A-5

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cycle	True stress range (lb./sq. in.)	Total cycle time (min.)	Time interval after preceding cycle (hr.)	Strain range (percent)	Deviation range (percent)	Loop width (percent)	Permanent set due to cycle (percent)		Total permanent set (percent)	Negative creep at bottom (percent)		Positive creep below top (percent)	Modulus E_c (lb./sq. in.)	C_1[a] (sq. in./lb.)
							Before negative creep	Net		1 min.	3 min.			
1	1.4–75.5×10³			15.3				15.00	15.00					
2	1.7–75.5	13.0	0	0.424		0.145	0.094	0.086	15.086	0.006	0.008			
3	1.7–75.5	14.0	0	.366		.092	.038	.034	15.120	.003	.004			
4	1.7–75.6	10.5	0	.349		.076	.022	.018	15.138	.002	.004			
5	1.7–75.6	11.0	0	.346	0.113	.074	.023	.015	15.153	.004	.008	0.008	32.6×10⁶	43.6×10⁻⁷
6	1.7–75.6	10.5	0	.345	.110	.069	.018	.015	15.168	.001	.003	.005	31.7	40.4
7	1.7–75.6	9.5	0	.338		.064	.013	.010	15.178	.002	.003			
8	1.7–75.6	8.0	0	.337	.103	.065	.013	.009	15.187	.003	.004	.005	32.5	42.2
9	1.7–50.8	10.0	0	.194		.025	.003	.000	15.187	.002	.003			
10–34	1.7–75.7	.6	0					.0023	15.244					
35	1.7–75.8	9.0	0	.329	.095	.055	.010	.005	15.249	.003	.005	.003	31.1	36.0
36	1.7–75.8	8.0	0	.330		.051	.008	.005	15.254	.002	.003			
37	1.7–75.8	8.5	0	.331		.054	.009	.003	15.257	.005	.006			
38	1.7–75.8	7.5	0	.330		.056	.009	.004	15.261	.003	.005			
39	1.7–75.8	11.0	0	.329	.095	.057	.008	.005	15.266	.002	.003	.005	31.8	39.3
40–139	1.7–75.9	.5	0					.0008	15.341					
140	1.7–75.9	12.0	0	.325	.089	.049	.006	.003	15.344	.002	.003	.003	31.6	39.2
141	1.7–75.9	12.0	0	.324		.049	.004	.002	15.346	.001	.002			
142	1.7–75.9	11.5	0	.325		.049	.006	.002	15.348	.003	.004			
143	1.7–75.9	12.0	0	.324		.050	.005	.002	15.350	.002	.003			
144–154	1.7–75.9	[b] (1.0)	24					[b] (.0009)	15.360					
155	1.7–75.9	10.0	24	.353	.119	.067	.032	.027	15.387	.004	.005	.005	29.1	35.1
156	1.7–75.9	9.0	0	.331	.097	.054	.008	.004	15.391	.002	.004	.005	31.95	39.5
157	1.7–75.9	10.0	0	.333	.096	.054	.009	.005	15.396	.003	.004	.003	31.25	37.1
158	1.7–75.9	9.5	0	.332		.052	.006	.002	15.398	.003	.004			
159	1.7–75.9	57.5	0	.335	.100	.055	.010	.006	15.404	.002	.004	.003	31.4	39.5
160	1.7–75.9	11.0	0	.330		.051	.007	.004	15.408	.002	.004			
161	1.7–76.0	10.0	0	.328	.092	.050	.005	.001	15.409	.003	.004	.004	31.8	38.4

[a] Values of C_1 are given as fractional change of modulus per pound per square inch.

[b] Estimated value is indicated by parentheses.

TABLE IV.—HYSTERESIS

SPECIMEN 1A-3

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Cycle	True stress range (lb./sq. in.)	Total cycle time (min.)	Time interval after preceding cycle (hr.)	Strain range (percent)	Deviation range (percent)	Loop width (percent)	Permanent set due to cycle (percent)		Total permanent set (percent)	Negative creep at bottom (percent) 2 min.	Positive creep below top (percent)	Modulus E_c (lb./sq. in.)	C_1[a] (sq. in./lb.)
							Before negative creep	Net					
1	1.4–45.5×10³	29.0		3.36		3.20		3.185	3.185				
2	1.5–45.5	16.5	0	0.329		0.187	0.166	0.156	3.341	0.010			
3	1.5–45.5	8.5	0	.232		.092	.061	.060	3.401	.001			
4	1.5–45.5	8.5	0	.230		.083	.054	.051	3.452	.003			
5	1.5–45.6	9.0	0	.221	0.088	.084	.036	.034	3.486	.002	0.030		
6	1.5–45.6	9.5	0	.197	.066	.064	.025	.023	3.509	.002	.013	34.6×10⁶	62.4×10⁻⁷
7	1.5–45.6	11.5	0	.192	.060	.049	.019	.016	3.525	.003	.010	31.1	20.6
8	1.5–45.6	9.0	0	.198		.055	.025	.022	3.547	.003			
9	1.5–45.6	10.0	0	.193		.051	.021	.019	3.566	.002			
10	1.5–45.6	10.0	0	.188	.060	.050	.017	.015	3.581	.002	.014	31.2	28.0
11	1.5–45.6	11.0	0	.189		.045	.018	.016	3.596	.002			
12	1.5–45.6	11.0	0	.189		.047	.018	.015	3.611	.003			
13	1.5–45.6	10.0	0	.186	.054	.044	.016	.012	3.623	.004	.012	31.25	24.6
14–19	1.5–45.6	[b] 15.0	0					[b] .033	3.656				
20	1.5–45.6	10.5	0	.184	.050	.048	.013	.010	3.666	.003	.011	33.5	32.2
21	1.5–45.6	9.0	0	.182	.050	.045	.012	.009	3.675	.003	.004	33.55	32.2
22–27	1.5–45.6	[b] 15.0	0					[b] .026	3.701				
28	1.5–45.6	10.0	0	.183	.046	.038	.008	.006	3.707	.002	.005	36.6	73.2
29	1.5–45.6	10.0	0	.184	.049	.046	.012	.010	3.717	.002	.010	31.3	16.2

[a] Values of C_1 are given as fractional change of modulus per pound per square inch.

[b] 6 cycles.

TABLE V.—HYSTERESIS

SPECIMEN 1A-4

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Cycle	True stress range (lb./sq. in.)	Total cycle time (min.)	Time interval after preceding cycle (hr.:min.)	Strain range (percent)	Deviation range (percent)	Permanent set due to cycle (percent)		Total permanent set (percent)	Negative creep at bottom (percent)		Positive creep below top (percent)	Modulus E_0 (lb./sq. in.)	C_1 [a] (sq. in./lb.)
						Before negative creep	Net		1 min.	2 min.			
1-30	1.5-45.5×10³	[b] (1.0)					[b](3.50)	(3.50)					
31	1.5-45.6	10.0	0:0	0.224	0.093	0.055	0.052	3.552		0.003	0.015	30.4×10⁶	33.9×10⁻⁷
32	1.5-45.6	9.0	0:0	.194	.063	.028	.024	3.576		.004	.014	29.6	9.8
33	1.5-45.6	9.0	0:0	.189	.058	.023	.021	3.597		.002	.013	30.55	22.6
34	1.5-45.6	9.5	0:0	.184	.057	.019	.016	3.613		.003	.012	33.55	37.5
35-45	1.5-45.6	3.0	0:0				.0065	3.685					
46	1.5-45.7	9.0	0:0	.181	.051	.015	.013	3.698		.002	.012	32.0	13.7
47	1.5-45.7	10.0	0:0	.176	.045	.012	.009	3.707		.003	.007	31.7	13.2
48-78	1.5-45.7	.8	1:20				.0016	3.757					
79	1.5-45.7	9.0	0:0	.180	.050	.016	.008	3.765		.008	.012	31.3	11.8
80	1.5-45.7	9.0	0:0	.174	.040	.010	.007	3.772		.003	.004	31.65	15.8
81	1.5-45.7	17.0	45:0	.1925	.0598	.0085	.0064	3.778	0.0021		.007	29.95	39.6
82	1.5-45.7	13.0	0:02	.1909	.0574	.0094	.0072	3.786	.0022		.0036	29.4	36.7
83	1.5-45.7	13.5	0:02	.1915	.0552	.0095	.0069	3.793	.0026		.0022	29.0	33.8
84-113	1.5-45.7	.2	0:0				.0016	3.842					
114	1.5-45.7	14.0	0:02	.1934	.0580	.0109	.0088	3.851	.0021		.0027	28.2	29.1
115	1.5-45.7	15.0	0:02	.1932	.0555	.0081	.0066	3.857	.0015		.0004	28.2	20.2
116	1.5-45.7	10.0	72:0	.2025	.0654	.0189	.0159	3.873	.0030		.0016	27.7	17.0
117	1.5-45.7	10.5	0:02	.1899	.0540	.0065	.0046	3.878	.0019		.0025	28.1	9.3
118	1.5-45.7	12.5	0:02	.1882	.0525	.0059	.0036	3.881	.0023		.0025	28.4	26.0
119-273	1.5-45.7	.4	0:02				(.0003)	(3.931)					
274	1.5-45.8	12.5	0:02	.1888	.0513	.0039	.0023	3.933	.0016		.0013	28.3	24.8
275	1.5-45.8	11.5	0:02	.1892	.0522	.0053	.0026	3.936	.0027		.0012	28.8	25.7
276-375	1.5-45.8	(.4)	18:00				(.0003)	(3.966)					
376	1.5-45.8	17.0	0:02	.1883	.0530	.0057	.0033	3.969	.0024		.0030	29.1	20.6
377	1.5-45.8	13.5	0:02	.1905	.0560	.0083	.0061	3.975	.00.2		.0011	28.35	24.7
378-387	1.5-45.8	(1.0)	18:00				(.001)	3.985					
388	1.5-45.8	71.0	0:02	.1985	.0614	.0129	.0120	3.997	.0009		.0012	32.2	55.9

[a] Values of C_1 are given as fractional change of modulus per pound per square inch.

[b] Estimated values are indicated by parenthe.ses.

TABLE VI.—VARIATION OF THE SECANT MODULUS OF ELASTICITY WITH STRESS

[Values of E_0 are given in million pounds per square inch. $C_1=k_1/E_0$]

1	2	3	4	5	6
Material	Source	Modulus of elasticity, E_0	Type of modulus	k_1	C_1
18:8 Cr-Ni steel	This paper	21.0-32.0	Tension	15.6-172.0	6.0-55.0×10⁻⁷
Annealed 14:2 Cr-Ni steel	To be reported	29.3-32.4	do	35.0- 77.0	10.4-24.6
Cold-drawn Inconel		30.5-34.2	do	5.0- 25.3	1.6- 7.4
Cold-drawn K monel metal		24.2-25.6	do	13.3- 24.5	5.2- 9.8
Carbon steels	Sayre [1]	28.8-30.17	do	[2] 2.7- 4.0	[2] .90- 1.60
3½ percent nickel steel		28.95-29.2	do	[2] 2.6- 6.5	[2] .90- 2.23
Copper, cold-drawn		19.12	do	[2] 3.6	[2] 1.9
Brass, spring temper		14.3 -15.5	do	[2] 2.8- 3.0	[2] 1.8- 2.0
Phosphor bronze, spring temper		14.70-15.58	do	[2] 3.2- 6.5	[2] 2.1- 4.4
17 SRT aluminum-alloy wire		10.28-10.29	do	[2] 3.7- 6.5	[2] 3.6- 6.4
Armco iron, annealed	Bridgman [3]	19.14	Volume	10.1	5.3
99 percent nickel, drawn and annealed		26.05-26.24	do	14.7- 15.0	5.6- 5.7
Copper, cold-drawn		18.81-19.14	do	10.1- 10.2	5.3- 5.4
Aluminum, hard-drawn and annealed		10.32	do	3.9	3.8

[1] From references 1 and 2.

[2] Calculated from values given for tangent moduli.

[3] From reference 18.