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CREEP IN FIVE STEELS AT DIFFERENT TEMPERATURES

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CREEP IN FIVE STEELS AT DIFFERENT TEMPERATURES

By H. J. French, H. C. Cross, and A. A. Peterson

ABSTRACT

This report describes so-called creep tests in which the elongation of metal specimens is observed with time under a fixed load. Tests were made on a low-carbon structural steel, a high-chromium steel, a chromium-molybdenum structural steel, high-speed steel, and a high chromium-high nickel austenitic steel and correlated with short-time tension tests at corresponding temperatures within the range 70 to 1,350° F. (20 and 730° C.).

So-called creep charts are given in which the relations are shown between stress, temperature, elongation, and time for each of the steels. These charts enable the approximate determination of the stress permitting life of different durations with different total elongations. The application of these charts is discussed in some detail.

Correlation of creep tests with short-time tension tests show that, when using accurate equipment, the proportional limit was in the range of stresses which could be sustained for long periods with small amounts of deformation.

The best resistance to oxidation in air was shown by the high chromium-high nickel steel and the high-chromium steel. These appear to be superior to the high-speed steel, which, however, with the high chromium-high nickel steel showed the best load-carrying ability in the range 1,100 to 1,350° F. (595 to 730° C.).

The chromium-molybdenum steel was not structurally stable at 1,200° F. (650° C.). Oxidation was accompanied by decarburization and grain growth.

CONTENTS

I. INTRODUCTION

The high temperatures and pressures associated with recent developments in power-plant equipment, oil-cracking processes, and the chemical industries have shown the need for additional information on the behavior of metals at high temperatures. Attention has recently been focused in particular upon so-called "creep tests" or the flow in metals subjected to stresses for long periods at elevated temperatures.

Within the past five years many investigations have been made in this field, but the information obtained has apparently not satisfied the requirements of designing engineers who insist upon having a more nearly quantitative evaluation of the relations between stress, temperature, elongation, and time for different metals.

This report is prepared to permit selection of working stresses for five steels at temperatures between atmospheric and 1,350° F. (732° C.). Preliminary results for three of these were previously reported (8, 24).[1] Comparisons are given of the results of the creep tests with short-time tension tests at corresponding temperatures.

II. PREVIOUS INVESTIGATIONS

1. CREEP TESTS COMPARED TO SHORT-TIME TENSION TESTS

Examination of published data will create some definite, but not necessarily correct, impressions concerning safe working stresses and creep in metals. It will likewise develop seemingly inconsistent results and show differences in opinion with respect to various phases of the subject. Certain investigators, such as Dickenson (4), are convinced that short-time tension tests are useless and misleading to designing engineers and have turned their attention to creep tests. Others, such as Brearley (4) and Rosenhain (17), are either not wholly convinced that such a view is justified or maintain that useful information can be secured from carefully made tension tests. It is probably true that most of the published results of tension tests can not safely be used for determining working stresses, but some of the creep tests are likewise misleading (24). Only a few investigators, including Lynch, Mochel, and McVetty (12), the authors (8, 24), and Pomp and Dahmen (33), have attempted to refine short-time tension-test methods and correlate results with carefully made creep tests.

The latter require considerable time, are therefore expensive, and are subject to errors of appreciable magnitude, especially when attempting to determine quantitatively the relations between stress, temperature, creep, and time.

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[1] The figures given in parentheses here and throughout the text relate to the reference numbers in the bibliography given at the end of this paper.

Creep tests, unless carefully made and the results reasonably interpreted, may create a false sense of security on the part of engineers, for even with accurate determinations on a single bar, melt, or lot of steel the question remains what variations from observed numerical values may ordinarily be expected if tests are repeated on other bars, melts, or lots of the same type of steel.

Where maximum and minimum values of tensile strength (or elastic properties) are included in specifications for engineering materials for use at atmospheric temperatures, the range is seldom less than 10,000 lbs./in.^{2}, and a variation of only 3,000 to 5,000 lbs./in.^{2} for commercial steels would be considered very small and satisfactory for most practical purposes.

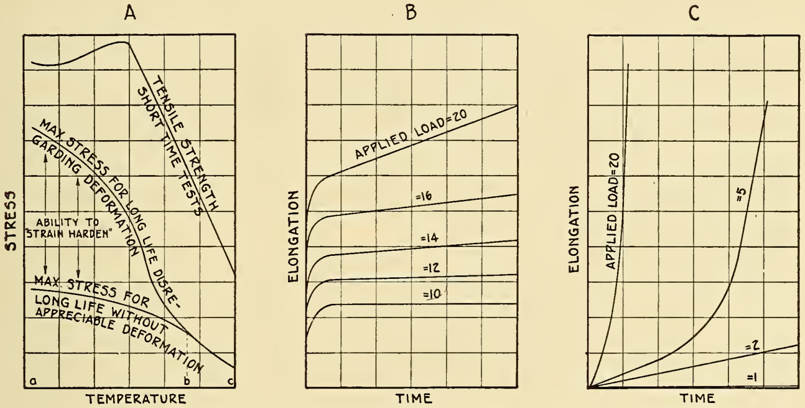


Fig. 1.—*Diagram showing the character of the relations between stress, temperature, time, and elongation in ordinary structural steel*

A, Creep chart.
B, Time elongation curves where strain hardening is observed.
C, Time elongation curves where strain hardening is not observed.

If, with the same metals and reasonably accurate test methods at high temperatures, only half this total variation is observed, the per cent variation may be enormous, as the "strength" or load-carrying ability may only be a few hundred or thousand pounds per square inch.

Under such conditions an approximate determination would offer many advantages, provided it could be secured quickly and could likewise be depended upon. Therefore, attention will be given in the latter portion of this report to methods for a quick and approximate determination of working stresses.

2. EFFECT OF TEMPERATURE ON CREEP IN STEELS

The conceptions developed from creep tests previously reported by one of the authors are illustrated in Figure 1. In the upper part of the temperature range considered (*b c*, fig. 1 *A*) any appreciable deformation initially produced by the applied load is followed by continuous creep which ultimately results in fracture of the specimen; at lower temperatures (*a b*, fig. 1 *A*) initial deformation, even of appreciable magnitude, is not necessarily accompanied by continuous creep. Due to the ability of metals to strain harden, initial changes in dimensions may be followed by a practical cessation of creep or at least a decrease to an entirely different order of magnitude.

Typical time-elongation curves upon which these conceptions are based are shown in Figure 1 *B* and *C*. However, definite information is lacking whether the creep can ever be zero at temperatures above the range in which the metal will strain harden. Even at lower temperatures there is the question whether strain hardening results in an absolute cessation of flow or a decrease in the rate of flow to very low values. It is difficult to obtain a direct answer to these questions, but the latter is, perhaps, of academic interest rather than of practical importance. It is important to know whether the rate of flow can be zero at relatively high temperatures where the metal does not show strain hardening.

TABLE 1.—*Chemical compositions and other details of the steels tested*

Mark	Chemical composition (per cent)											Hot finished to—	Heat treatment or condition in which tested	Remarks
	C	Mn	P	S	Si	Cr	Mo	Ni	W	V	Cu			
	0.24	0.37	0.021	0.028	0.01	----	----	----	----	----	----	1-inch plate.	As hot-rolled by supplier.	Ordinary boiler plate.
K3	.39	.51	.015	.029	.19	0.87	0.21	----	----	----	----	1⅛-inch rod.	1,625° F., 2 hours air; 1,550° F., 1½ hours oil; 1,300° F., 2 hours oil.	A structural alloy steel, heat treated.
A336	.77	.24	.031	.035	.42	3.9	----	0.14	13.6	1.9	----	1-inch rod.	As received from manufacturer; probably annealed after hot-working.	Low tungsten-high vanadium high-speed steel.
A340	.28	.38	.026	.013	.17	20.5	----	----	----	----	0.98	½-inch rod.	1,830° F. water; 1,200° F.	A high-chromium "stain-resisting" steel.
A347A	.24	.53	.009	.005	2.96	18.05	.005	23.3	----	----	.07	1⅛-inch rod.	1,450° F., 2 hours, furnace cool.	A high nickel-high chromium, "austenitic" steel.
A347B	.21	----	----	----	2.96	18.10	----	23.4	----	----	----	do	Annealed by supplier; probably same as for A347A.	

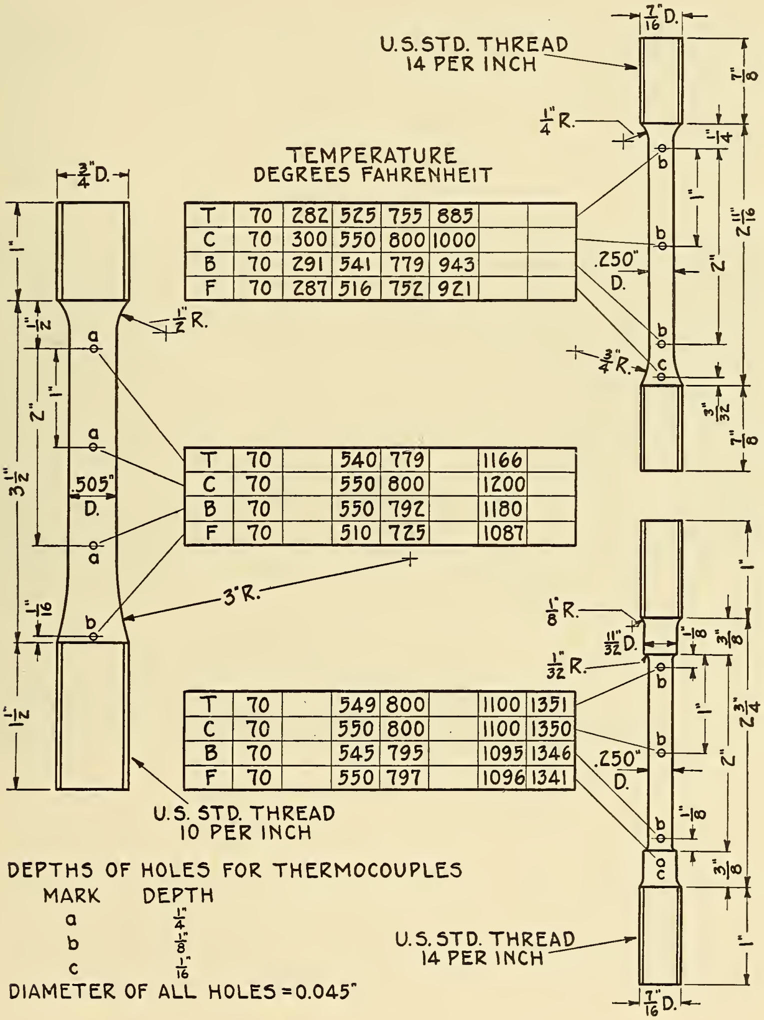
III. STEELS TESTED

The chemical compositions and other details of the five steels tested are given in Table 1. Each steel represents an important industrial type, and the group covers a wide range in composition, structure, and applications.

IV. TEST METHODS AND EQUIPMENT EMPLOYED

1. CREEP TESTS

Creep tests were made with equipment and procedure already described in some detail (8). Loads were applied to the specimens by hanging weights at the ends of levers while elongation was determined from gauge-length measurements made with an optical micrometer, with smallest direct reading on the vernier of 0.01 mm (0.00039 inch).



TEMPERATURE
DEGREES FAHRENHEIT

T	70	282	525	755	885		
C	70	300	550	800	1000		
B	70	291	541	779	943		
F	70	287	516	752	921		

T	70		540	779		1166	
C	70		550	800		1200	
B	70		550	792		1180	
F	70		510	725		1087	

T	70		549	800		1100	1351
C	70		550	800		1100	1350
B	70		545	795		1095	1346
F	70		550	797		1096	1341

DEPTHS OF HOLES FOR THERMOCOUPLES

MARK	DEPTH
a	1/4"
b	1/8"
c	1/16"

DIAMETER OF ALL HOLES = 0.045"

Fig. 2.—*Test specimens used for temperature calibration in both short-time and long-time tension tests and the temperature variations encountered with the original equipment*

Temperatures were controlled by make-and-break type temperature controllers acting through base-metal thermocouples located in the test specimens. Three commercial recorder controllers were used for the 10 high temperature creep test units by connecting the furnaces in parallel in groups of either 2 or 4. The resistance of the windings and also the insulation of the individual furnaces of each group were first carefully balanced, and in subsequent operation the current was regulated by auxiliary resistances to give practically the same temperatures in the respective test specimens. The controller was then attached to one furnace in each group and frequent measurements were made to insure comparable temperatures in the specimen in the "key" furnace and the bars in the others of the group.

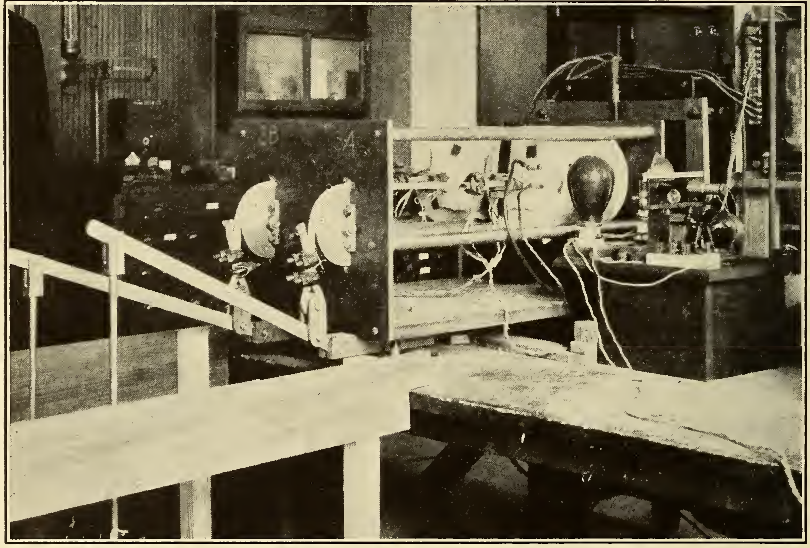


Fig. 3.—*One of the completely assembled creep test units*

Optical micrometer used in measuring creep is shown in the foreground at the right.

The controllers operated within a range of about plus or minus 20° F. (±11° C.), but this range was frequently much smaller and has since been decreased by relocating the thermocouple for temperature control close to the furnace windings. Maximum temperature variations throughout the gauge length of the specimens are shown in Figure 2, while a photograph of one of the completely assembled horizontal test units is given in Figure 3. Four of these have recently been replaced by vertical units and furnaces wound to give smaller temperature variations throughout the test specimens.

2. TENSION TESTS

A description has already been published of the equipment used in the tension tests (24), which were made with a hydraulic testing machine and a modified Martens' extensometer, with smallest direct reading in the Tuckerman optical lever system equal to four-millionths of 1 inch. In compliance with many requests for the details of construction, detailed drawings of this extensometer and of the optical system have been included in Letter Circular 238 of the Bureau of Standards which will be supplied on request. A photograph of the assembled equipment for the tension tests is shown in Figure 4.

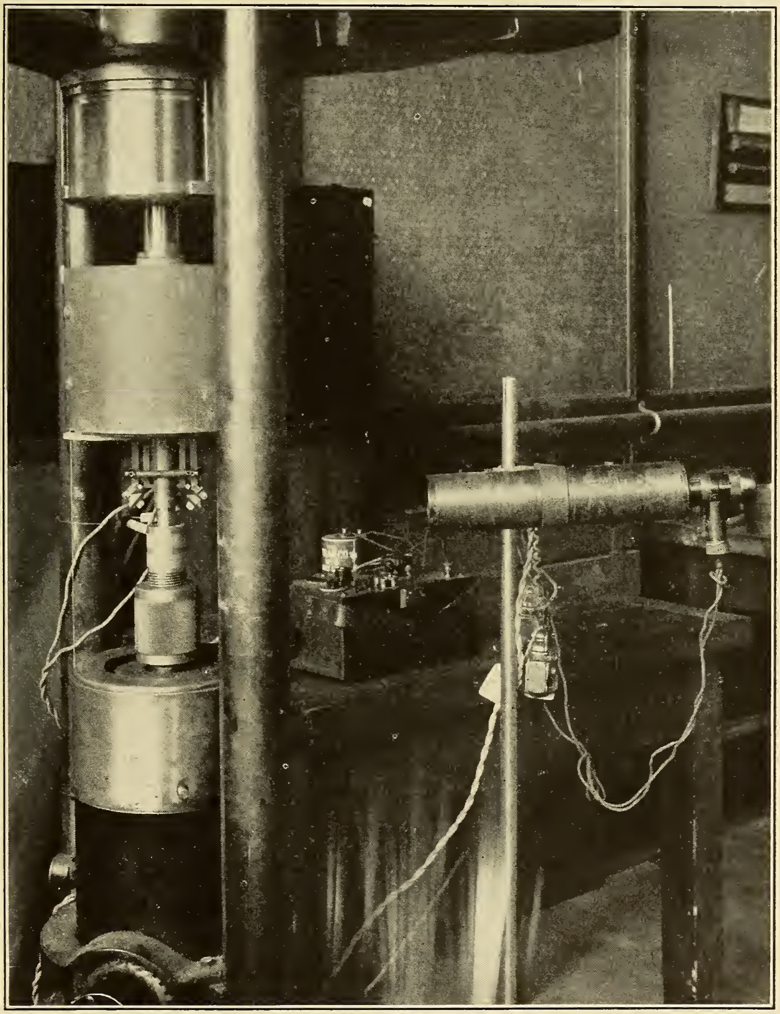


FIG. 4.—*Assembled equipment for the tension tests*

The limited space between the movable head and base of the testing machine made it necessary to use a relatively short furnace. The temperature variations observed under such conditions are shown in Figure 2. Care was taken to reach thermal equilibrium before applying the stress and measuring the strain, and with the practice employed smooth stress-strain curves were secured. The need for reaching thermal equilibrium is shown by the fact that steels, with an expansion coefficient of about 0.000008 parts per unit of length per degree Fahrenheit, will elongate four-millionths of 1 inch with a temperature rise of one-half of 1° F. Temperature control within such limits is very difficult to obtain in tension tests if temperature fluctuations must be avoided for any appreciable time. It is fortunate that under ordinary conditions determination of the stress-strain relations requires only from 5 to 15 minutes, and the electrical circuits can frequently be balanced manually so that during such an interval fluctuations in temperature of the control thermocouple may be kept within 2 or 3° F. (about 1 or 2° C.). Where variations in temperature take place slowly in one direction, there will be a progressive change in the observed elastic modulus but no marked irregularities in the stress-strain curves. However, such changes may have an important effect upon the observed proportional limits. Hence, improvements in furnace construction and methods for close temperature control are greatly to be desired.

The need for an accurate extensometer for high-temperature tension tests was discussed in a previous report (24). With a proportional limit at high temperatures of the order of 1,000 lbs./in.^{2}, and an assumed modulus of elasticity of 10,000,000 lbs./in.^{2}, the total deformation in a 2-inch specimen at the proportional limit will be of the order of 0.00002 inch. It is obviously not practicable to determine proportional limits with certainty under such conditions when using instruments which permit readings of strain only to the nearest one-thousandth or ten-thousandth of 1 inch.

V. EXPERIMENTAL RESULTS

1. TIME-ELONGATION CURVES

The time-elongation curves obtained for each of the five steels when subjected to stresses at different temperatures are summarized in Figures 5 to 9, inclusive. These are similar to the curves shown in Figures 1 *B* and *C* and may be divided into two groups, depending upon whether the temperature of test is above or within the range in which the steel strain hardens. The maximum temperature at which strain hardening is observed varies with the composition of the steel as will be seen by comparison of Figures 5 to 9.

2. CREEP CHARTS

The time-elongation curves may be summarized in the manner illustrated in Figure 1 *A* to show the stresses which can be sustained for long periods at different temperatures with different degrees of deformation. Such terms as "long life," "freedom from appreciable

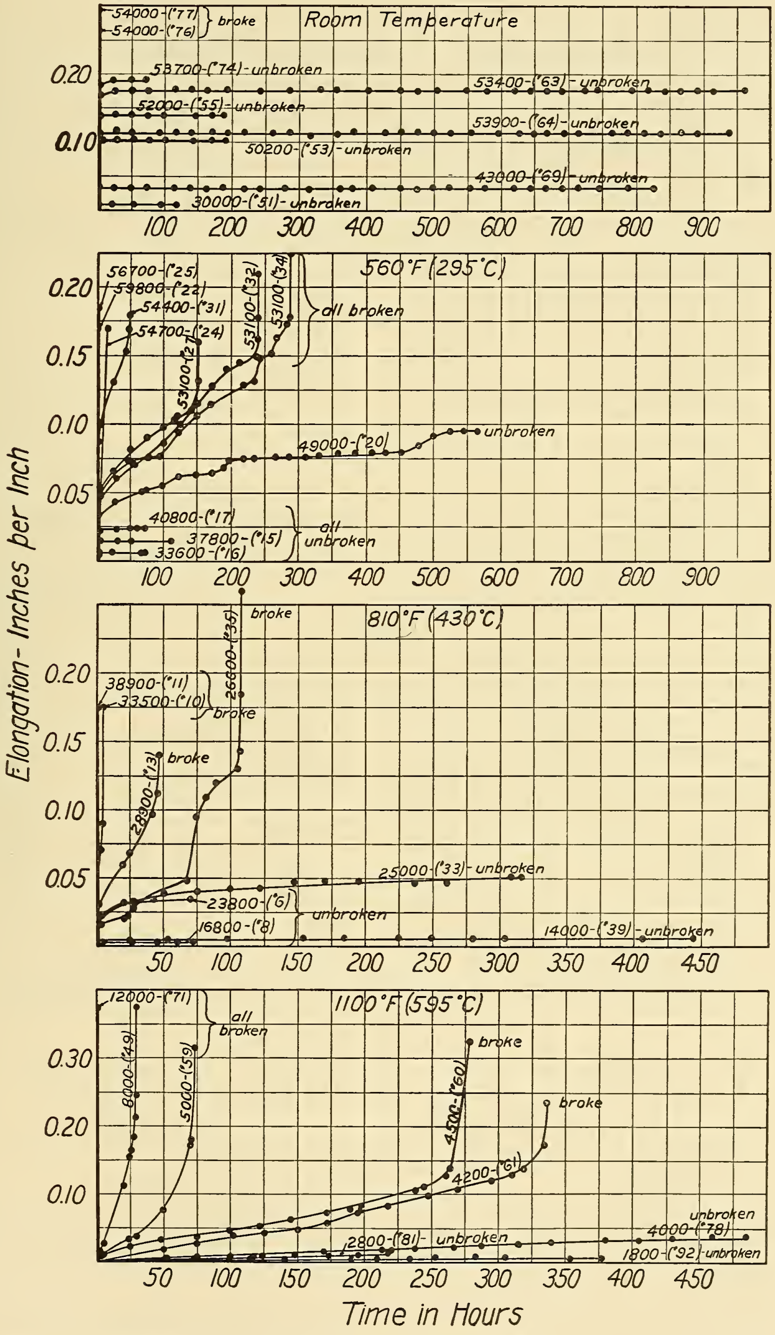


FIG. 5.—*Time-elongation curves for hot-rolled 0.24 per cent carbon steel under stress at different temperatures*

The numerical values given above the curves refer to the applied load expressed in pounds per square inch of original cross section. Test specimen numbers are in brackets.

See Table 1 for the chemical composition of this steel.

deformation," etc., which are used in Figure 1 are not definite but may be justified by the fact that differences in mechanical properties may ordinarily be expected in different melts of the same type of steel. They may equal or exceed the differences in working stresses which are based on various conceptions of "long life"; that is, whether 1,000 hours, 5,000 hours, or more, etc.

An illustration of such differences is found in Figure 9 in which two bars, marked *A* and *B*, from one shipment were tested under similar conditions. The proportions of carbon, nickel, chromium, silicon, etc., found in the two bars were identical for ordinary purposes, but one was annealed at the factory while the other was treated in supposedly a similar manner in the laboratory. There is, as shown in Figure 9 (lower right corner), an appreciable difference in the creep characteristics of these two bars.

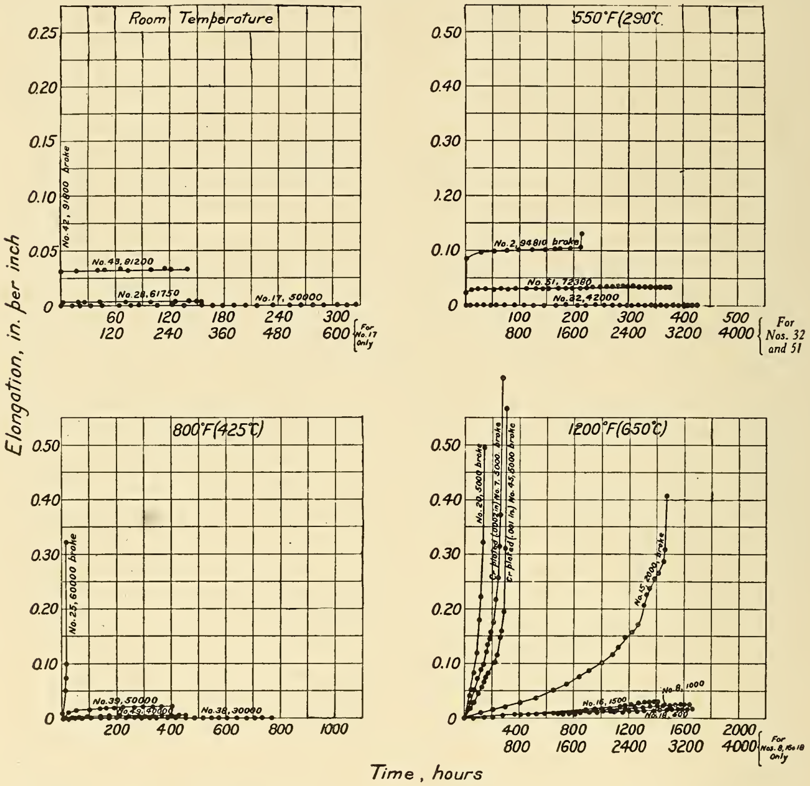


FIG. 6.—*Time-elongation curves for a quenched and tempered chromium-molybdenum structural steel under stress at different temperatures*

The numerical values given above the curves refer to the applied load expressed in pounds per square inch of original cross section.
See Table 1 for details of composition and treatment of this steel.

Creep charts of the type illustrated in Figure 1 *A* may likewise be justified by reference to load-life curves. These, as is shown in Figure

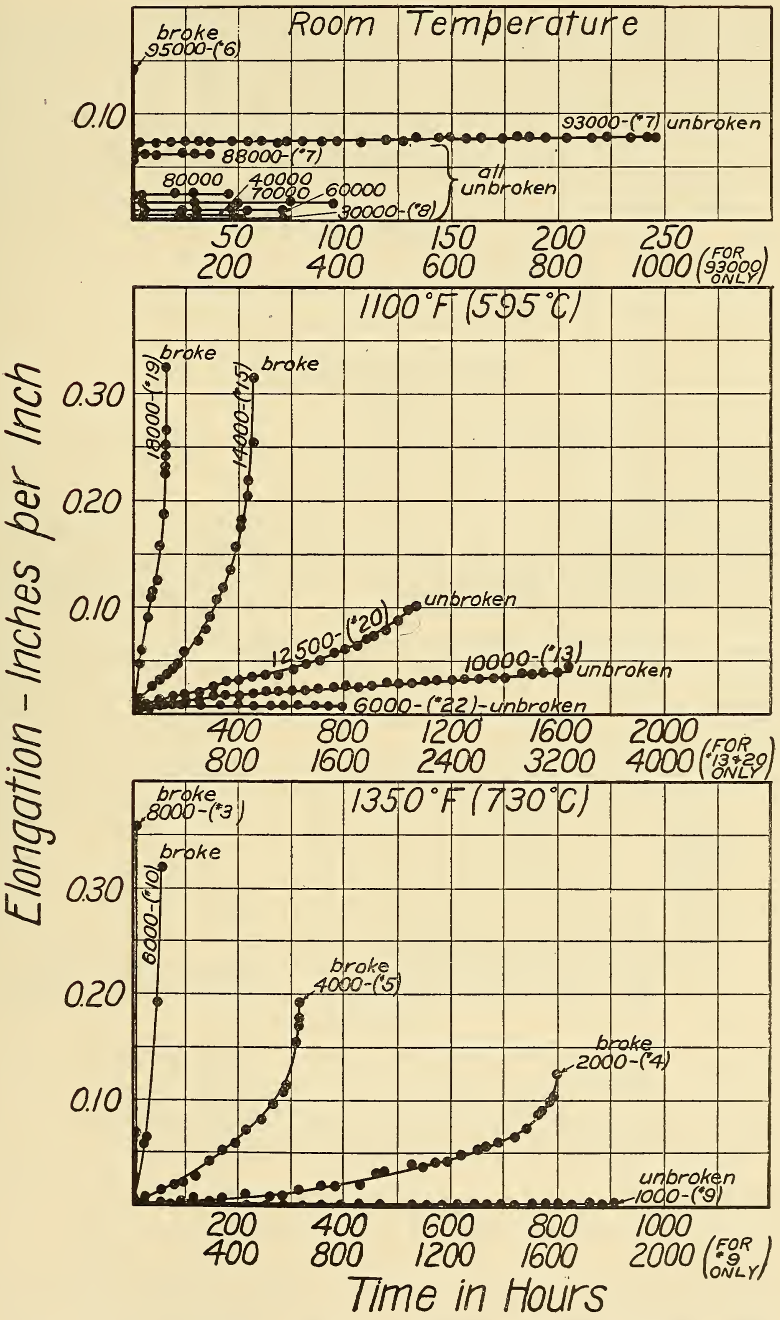


FIG. 7.—*Time-elongation curves for hot-finished high-speed tool steel under stress at different temperatures*

The numerical values given above the curves refer to the applied load expressed in pounds per square inch of original cross section. Test specimen numbers are given in brackets. See Table 1 for details of composition and treatment of this steel.

10, may be similar to stress-cycle graphs of fatigue tests at atmospheric temperatures and show a more or less sharp bend or "knee," indicating a limit of "static endurance," or they may appear to take the form of a hyperbola. Curves of the latter type do not always approach the horizontal coordinate within the range of life included in the tests and are found mostly in tests at the higher temperatures.

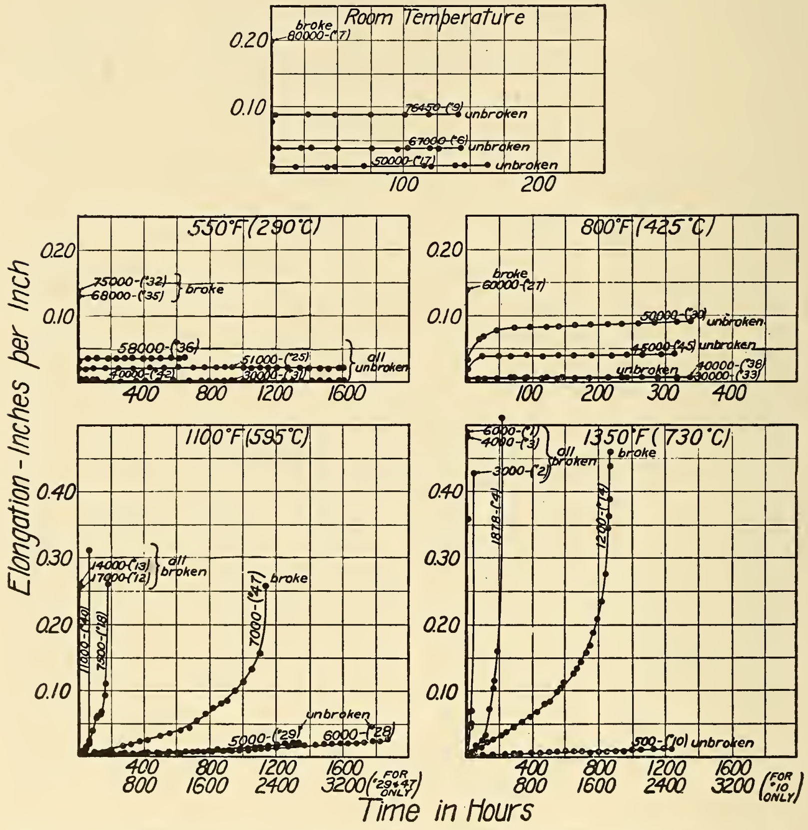


FIG. 8.—*Time-elongation curves for quenched and tempered 20 per cent chromium steel under stress at different temperatures*

The numerical values given above the curves refer to the applied load expressed in pounds per square inch of original cross section. Test specimen numbers are given in brackets.
See Table 1 for details of composition and treatment of this steel.

Similar effects are shown by the relation of stress and the time to produce 1 per cent elongation, likewise summarized in Figure 10.

However, the point has been made that allowable working stresses in practice are frequently restricted by the permissible deformation and that a more useful summary for many engineers would include evaluation of life in hours and the per cent deformation during this life. Creep charts giving such information are probably much to be desired, but little data are available upon which such summaries may be based. The tests described in this report, which have been continued generally for longer periods than similar tests made by earlier investigators and which have likewise included determinations at more temperatures under a greater range of stresses, do not give sufficient data upon which to base such detailed comparisons without estimation of some of the values sought. The reasons for this can be explained by considering what has been called initial and secondary flow.

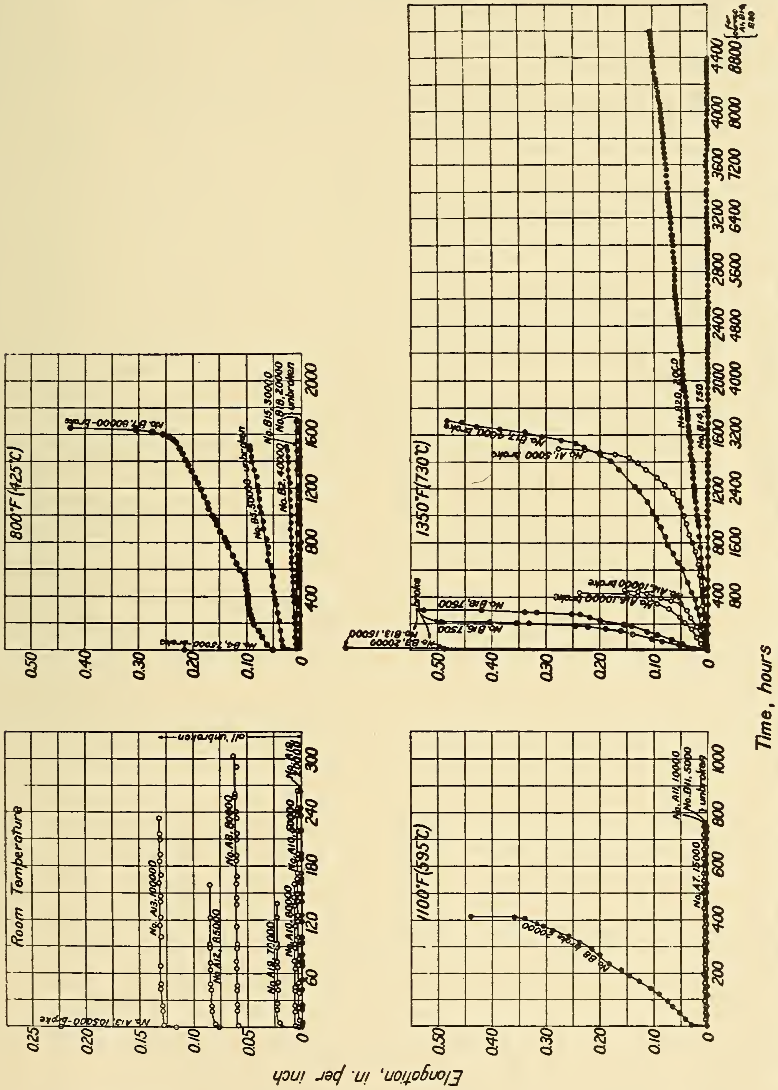


FIG. 9.—*Time-elongation curves for annealed high nickel-high chromium steel under stress at different temperatures*

The numerical values given above the curves refer to the applied load expressed in pounds per square inch of original cross section. See Table 1 for details of composition and treatment of this steel.

As already pointed out, creep is not continuous at temperatures at which strain hardening takes place, but ceases, for most practical purposes, after a variable initial period. At such temperatures the determination of the working stress is a function of the permissible initial creep.

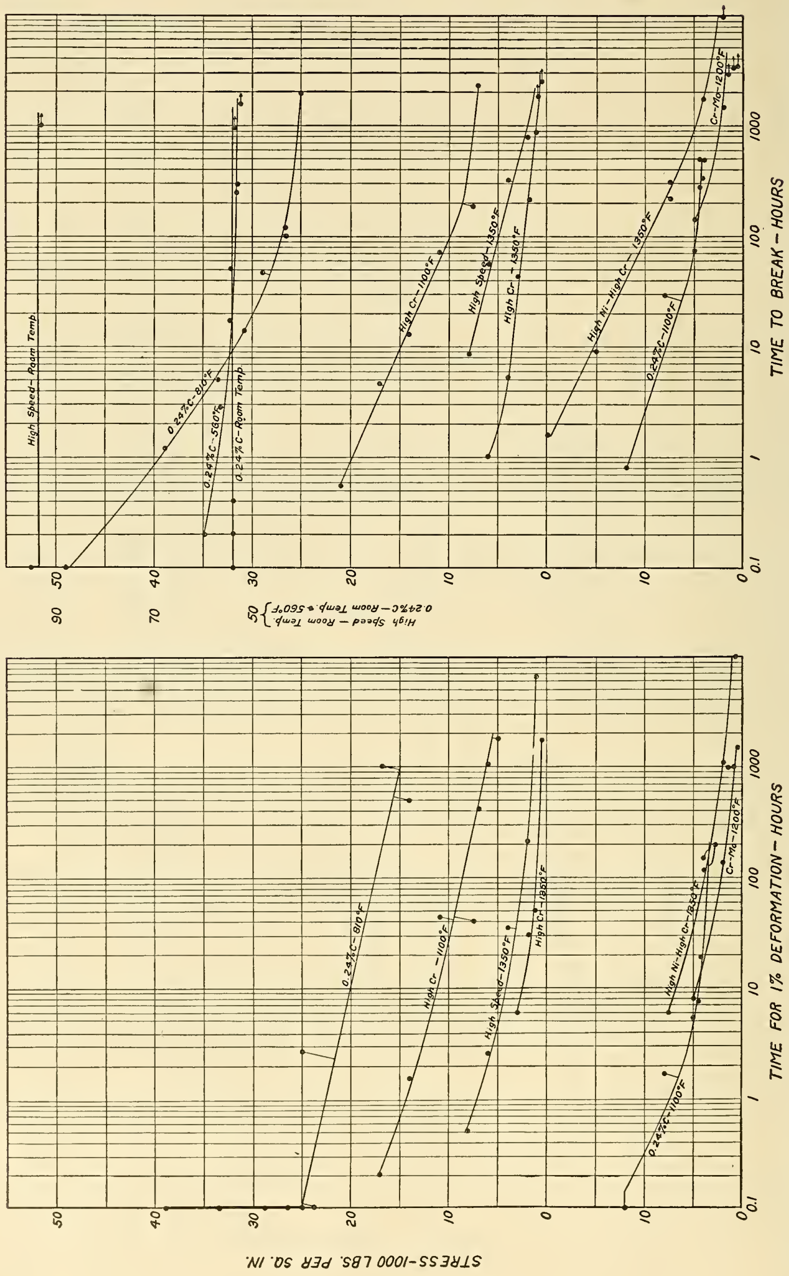


FIG. 10.—*Relation between applied load and the time to fracture or the time to produce 1 per cent deformation in different steels at different temperatures*

At temperatures above those at which the metal strain hardens the initial creep is followed by further and continuous deformation which may take place at approximately the same rate, a higher or a lower rate, depending upon the exact conditions of the test. Long life of any selected duration with no more than some selected deformation can only be obtained if the flow rate in this second period (secondary flow rate) is low. Hence, at temperatures above those at which the metal will strain harden the criterion is the secondary flow rate.

It will be evident from examination of Figures 5 to 9, inclusive, that there is no sharp division between the several stages of creep, and that the exact magnitude of the initial flow is frequently in doubt. Likewise, the rate of creep in the second stage is not necessarily uniform.

The selection of maximum stresses for any selected life and allowable deformation is further complicated by the character of the relations between stress and initial flow or secondary flow rate, as will be evident from Figures 11 and 12. It is seldom practicable in advance of a set of tests to select the conditions so that a selected deformation will be obtained in a certain length of time. Applied loads must be selected which cover a wide range, and the stresses producing no more than certain allowable deformation in any selected interval must be secured by interpolation or extrapolation on curves of the type shown in Figures 11 and 12.

In few cases are there sufficient points to permit exact location of the desired stress values despite the fact that the tests from which these curves were plotted are more extensive than those reported by most other investigators. In addition, there is some reasonable doubt as to the exact location of many of the points due to the fact that there is not always a sharp ending of the initial flow and not necessarily a uniform rate of flow in the second period.

Under such conditions it is only possible to estimate the maximum stresses which will permit certain selected life with certain deformation, but this estimate is the best that can be secured at this time and is based upon tests which are more extensive than most others which have so far reached the stage of publication. Presentation of the creep charts reproduced in Figures 13a and 13b is made with this discussion to avoid misunderstanding concerning the accuracy of the data or the methods of arriving at the given numerical values.

Since the criterion of life of any selected duration with some selected deformation is based on the initial flow at temperatures within the strain-hardening temperature range of the metal and upon the secondary flow rate at higher temperatures two sets of curves appear in each diagram in Figures 13a and 13b. Where these curves cross, the lowest for any selected deformation should be used.

In selecting stress values from such charts it should be kept in mind that appreciable differences may be observed in duplicating the tests on other melts of the same metals and a factor of safety applied.

The creep charts are based on the assumption of a uniform rate of flow in the second period, and on this basis curves representing 0.1 per cent deformation in 1,000 hours are the same as those for 1 per cent deformation in 10,000 hours, etc.

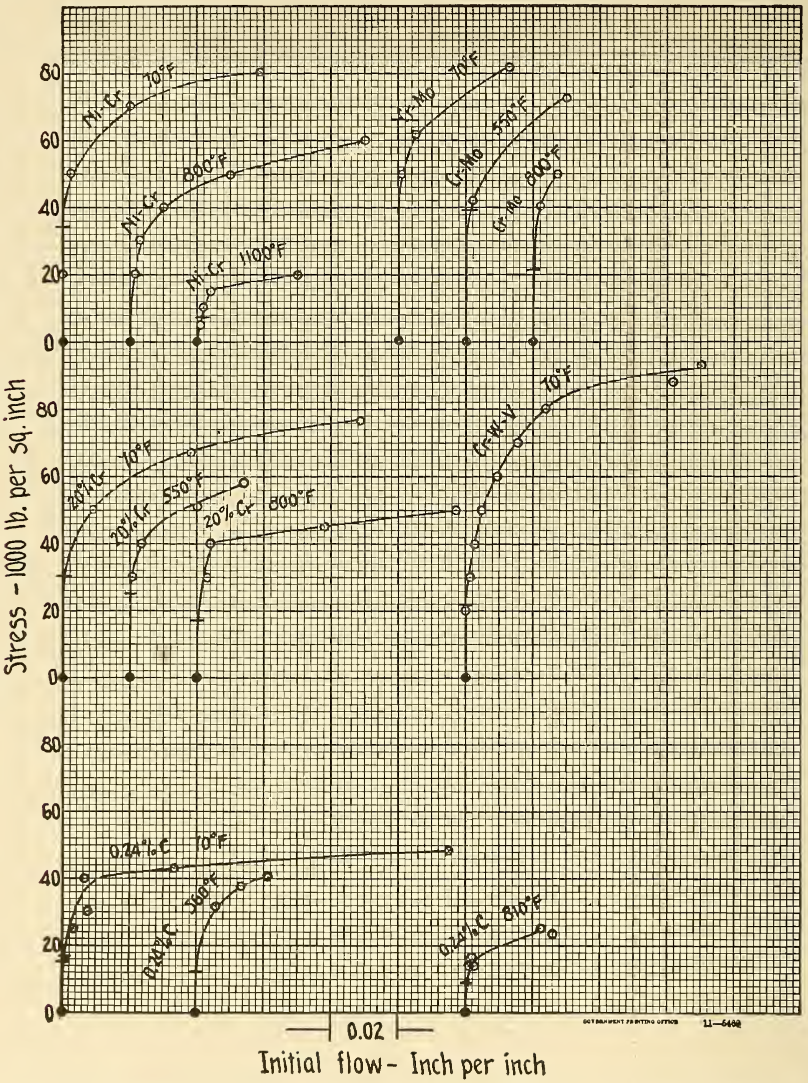


FIG. 11.—*Relation between applied load and initial flow in different steels at different temperatures*

See text for discussion.

3. CORRELATION OF CREEP TESTS WITH SHORT-TIME TENSION TESTS

Evidence was presented in previous reports (8, 24) that stresses permitting long life with freedom from appreciable deformation in the creep tests were close to the proportional limits of the short-time tension tests at corresponding temperatures provided the stress-strain relations were determined with accurate equipment. Comparison of creep-test data with the proportional limits of the different steels is included in Figures 13a and 13b, and in only one of the five is there doubt of an approximate relationship. The proportional limit-temperature curve for the chromium-molybdenum steel crosses the curve representing 0.1 per cent deformation in 1,000 hours in the creep tests. The proportional limit is above the creep-test curve at atmospheric temperatures and shows a similar tendency at

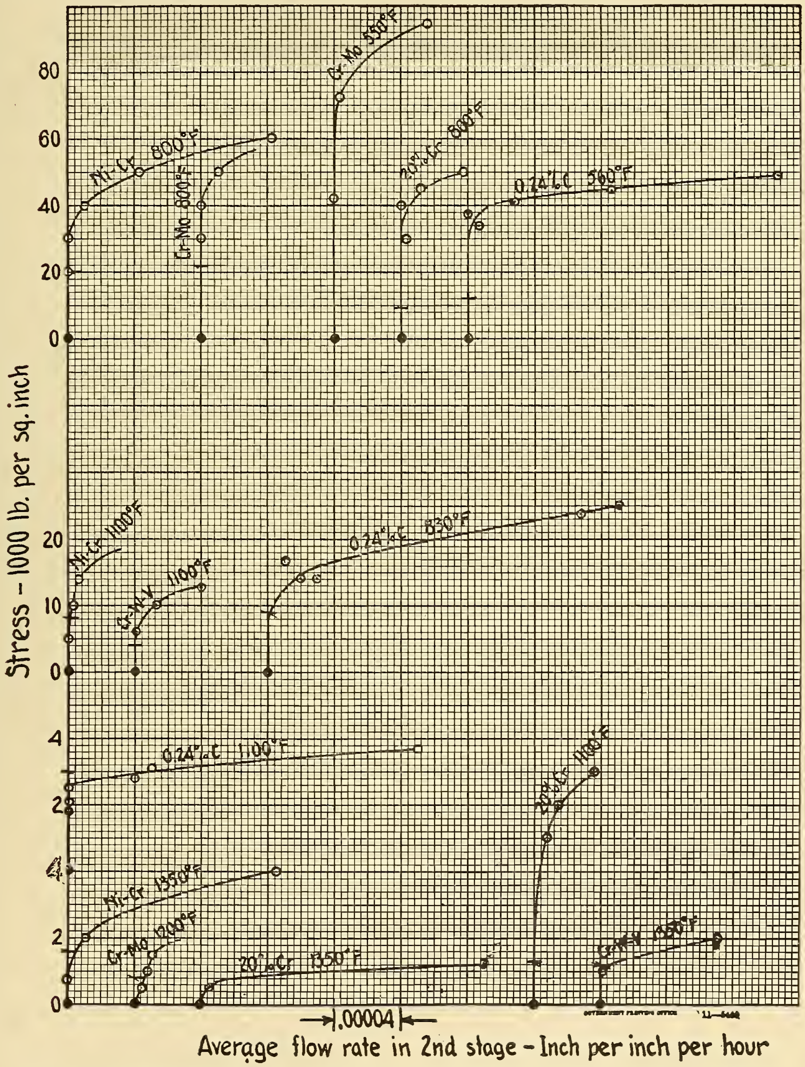


FIG. 12.—*Relation between applied load and secondary flow rate in different steels at different temperatures*

See text for discussion.

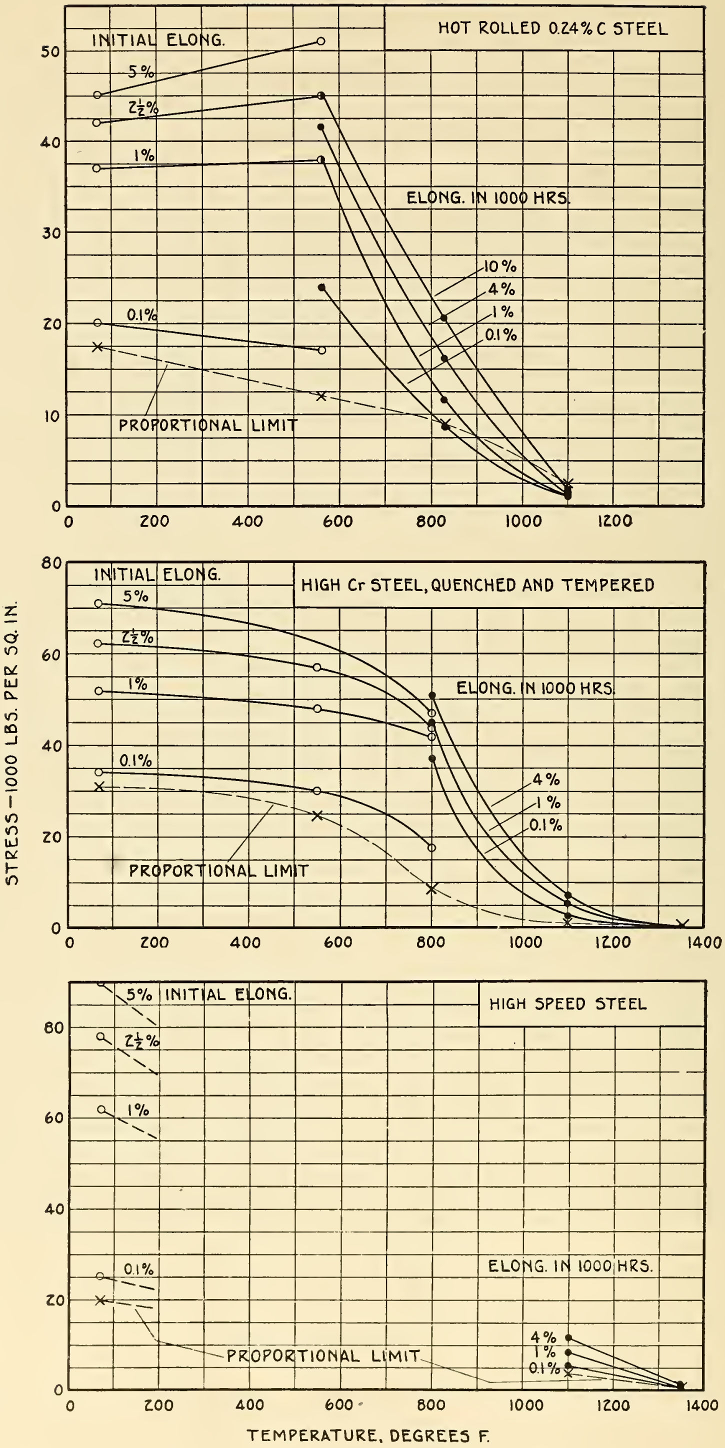


Fig. 13a.—*Creep charts of three of the steels tested*

These give the relations between stress, temperature, elongation, and time. See text for the manner of application of data and other details. Proportional limits were obtained in short-time tension tests.

1,350° F. (732° C.). Stress-strain curves used in determining proportional limits are summarized in Figures 14 to 17, inclusive.

A more detailed comparison between the short-time and long-time tests is shown in Figure 18, in which the stresses giving different deformations in 1,000 hours in the creep tests are compared to different deviations from the assumed proportionality between stress and strain in the short-time tension tests. Such comparison shows effects equivalent to changing the sensitivity of the strain-measuring devices in both the long-time and short-time tests.

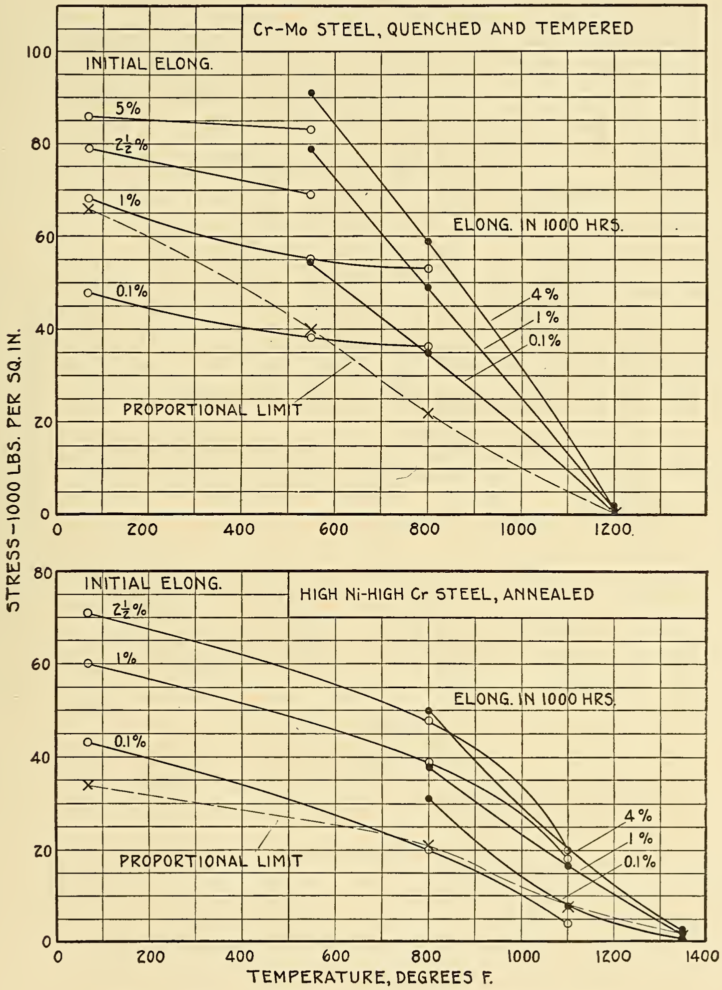


FIG. 13b.—*Creep charts of two of the steels tested*

These give the relations between stress, temperature, elongation, and time. See text for the manner of application of data and other details. Proportional limits were obtained in short-time tension tests.

It will be observed that the maximum allowable stress decreases materially as the permissible deformation decreases. Since the permissible deformation determined in such tests is affected by the accuracy of the strain-measuring devices, the maximum allowable stress in the creep tests is dependent also upon the accuracy of the strain measurements. This condition is also reflected in the short-time tension tests where a decrease in the deviation from the assumed proportionality between stress and strain causes a lowering of the observed values of proportional limit.

A deviation of 0.1 per cent from the assumed proportionality between stress and strain in the tension tests is generally observed at a stress which is higher than that producing a similar deformation in 1,000 hours in the creep tests at corresponding temperatures. In other words, for a given accuracy of strain measurement the short-time test gives somewhat higher values than the long-time test, but the proportional limit determined by accurate equipment is in the range of stress which may be sustained for long periods with small amounts of deformation. Quantitative comparisons vary, depending upon the steel tested, the accuracy of equipment, and the manner of making the tests and interpreting data. In general, however, there seems to be a tendency for the proportional limit of the short-time test to become progressively higher than allowable creep stresses as the temperature of test is raised. This is not always evident, but is shown in many cases in Figure 19, in which are plotted the results obtained by the authors as well as those reported by Pomp and Dahmen (33).

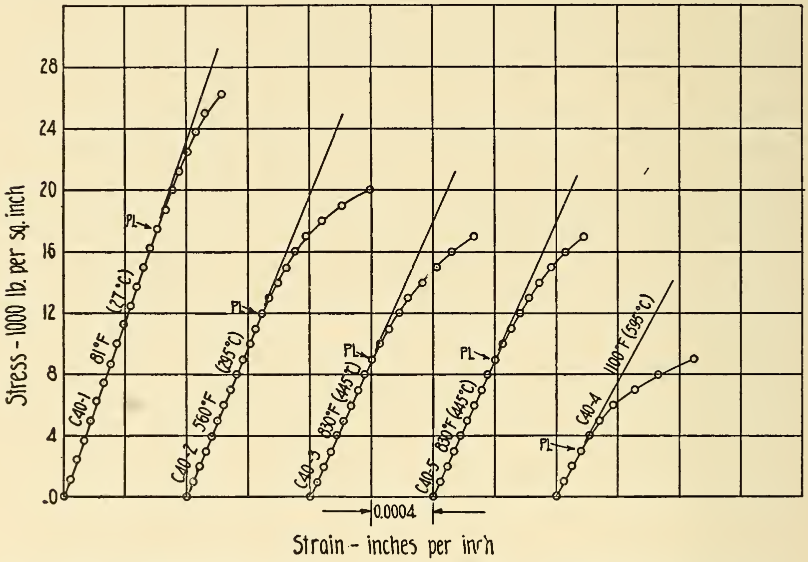


FIG. 14.—*Stress-strain relations in tension tests at different temperatures on the 0.24 per cent carbon steel*

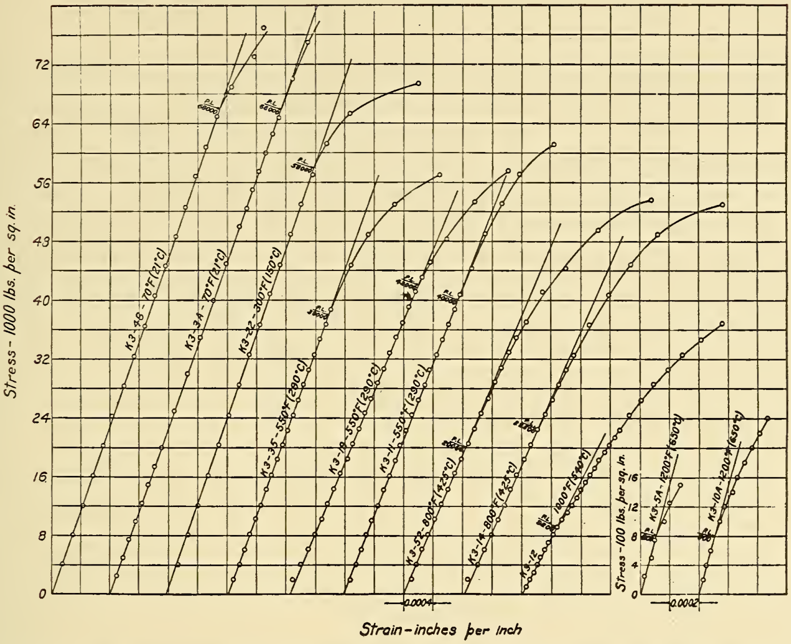


FIG. 15.—*Stress-strain relations in tension tests at different temperatures on the chromium-molybdenum steel*

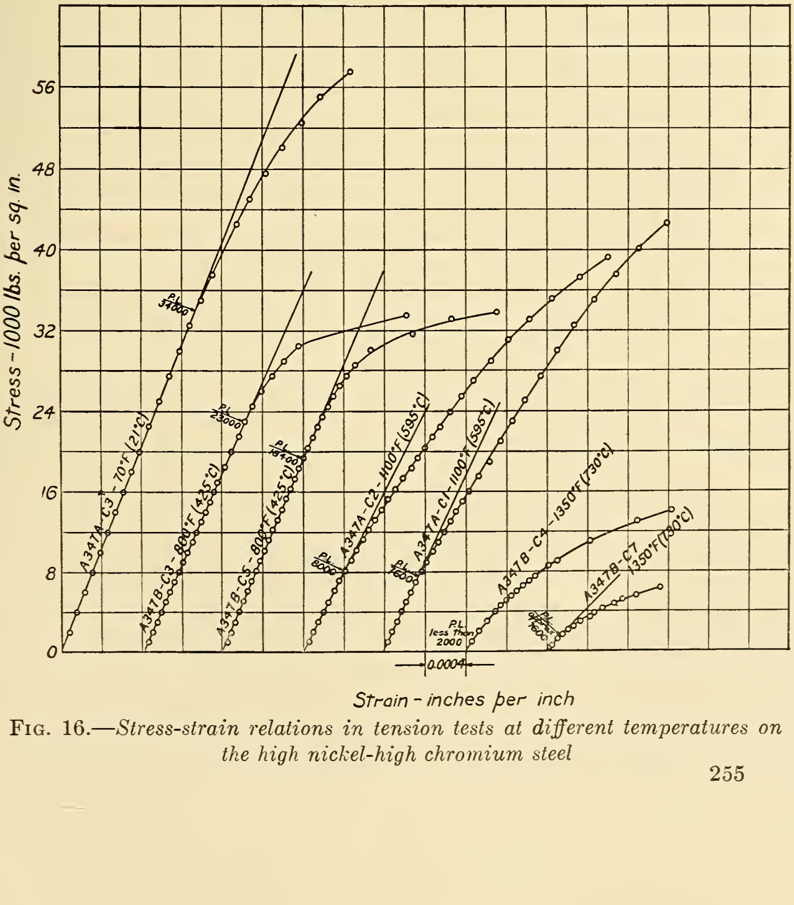


FIG. 16.—*Stress-strain relations in tension tests at different temperatures on the high nickel-high chromium steel*

The stress-strain relations observed in the short-time tension tests made with accurate equipment reflect much of the information given by the creep tests. The results obtained in both types of test are dependent upon the accuracy of equipment and procedure employed and methods of plotting and interpreting data, but for comparable results a somewhat higher order of accuracy seems to be required in the short-time tension tests than in the creep tests. This is more marked for some steels than for others and generally becomes more noticeable with increase in the temperature of test. It is unfortunate that the proportional limit of the short-time tension test is dependent not only upon the accuracy of equipment and procedure, but upon methods of plotting results and interpretation of data; but it has been a sufficiently close criterion of load-carrying ability in tests of the five steels investigated, so that it and the stress-strain relations in tension tests should continue to receive consideration.

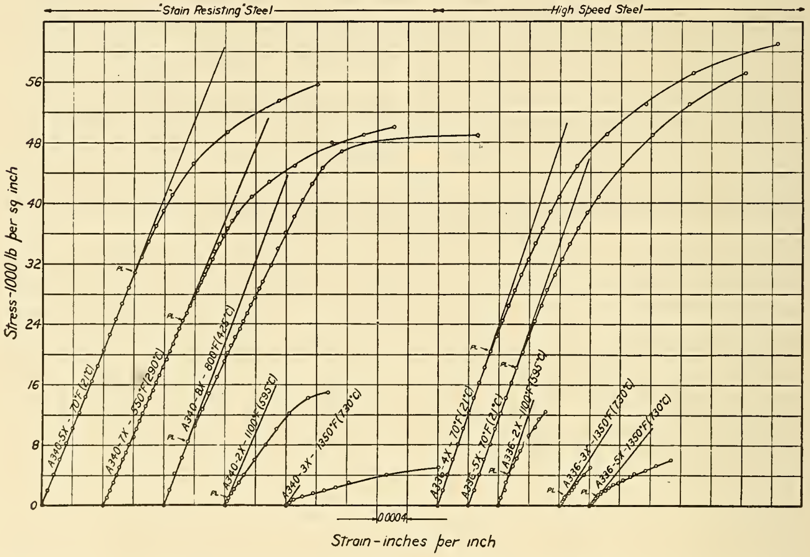


FIG. 17.—*Stress-strain relations in tension tests at different temperatures on the high-chromium and the high-speed steels*

4. COMPARISONS OF DATA FROM DIFFERENT SOURCES

Variations in equipment and procedure used in creep tests of different investigators, together with differences in the methods of interpreting data, make comparisons difficult. In Figure 20 are summarized data obtained from a number of sources for low-carbon steels, high-chromium steels, and high-speed steels. The majority of the results were taken by interpolation from experiments which were never intended to be the basis for comparison of deformation during a life as long as 1,000 hours. Furthermore, the comparisons are based on the assumption of a uniform creep rate, at least subsequent to an initial period, and can only be approximate determinations, at best, for other reasons previously explained.

As shown in Figure 20, the stress-temperature curves described in this report are quite similar, at temperatures above 600° F. (315° C.), to those based on work of Cournot and Sasagawa (14). The latter curves are located at the right in the diagram for each of the three steels so that a selected rate of creep is obtained at a higher stress or temperature or both than in the authors' tests. This is probably due to the fact that the tests of Cournot and Sasagawa were made under constant stress, obtained by reducing the load as the specimen

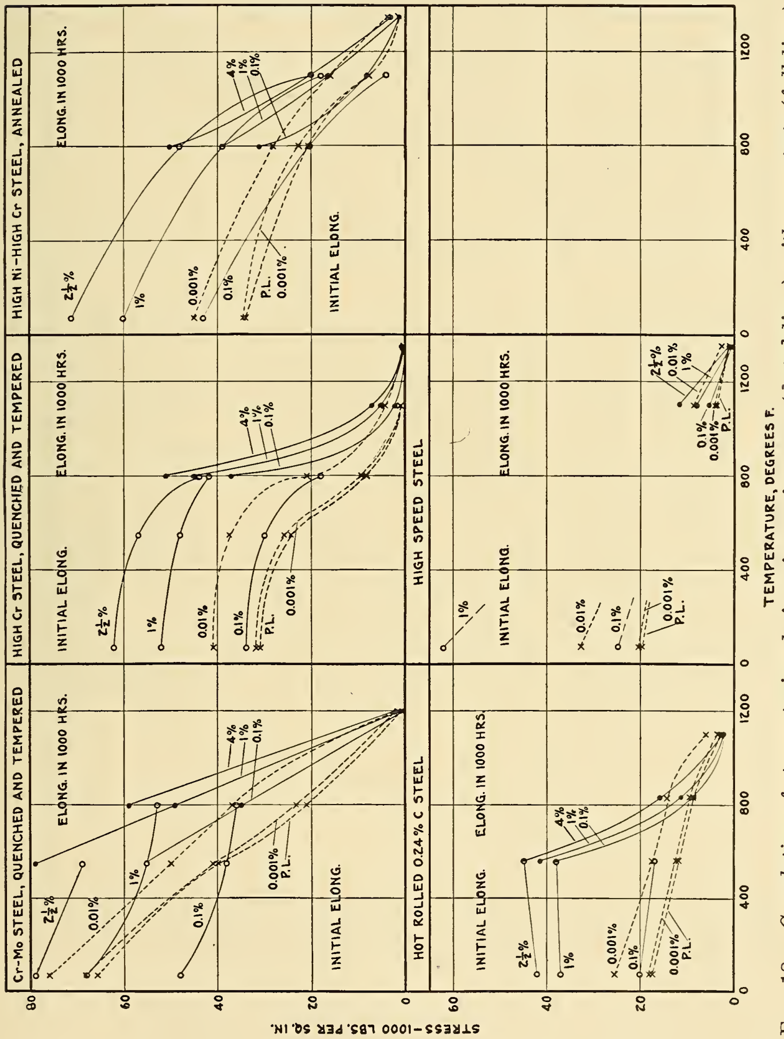


FIG. 18.—*Correlation of stress-strain relations in tension tests (dotted lines) with creep tests (full lines) at corresponding temperatures*

P. L. refers to the smallest detectable deviation from the proportionality between stress and strain using the described equipment. Other deviations are indicated by numerical values above the dotted lines. Initial elongation or elongation in 1,000 hours in the creep tests are indicated by full lines.

stretched and decreased in cross section, whereas other investigators maintained the applied load constant.

The results obtained by Pomp and Dahmen on low-carbon steel are very close to those obtained in the tests described in this report; likewise the results credited to Tapsell and Clenshaw (37) for a similar steel agree closely with those of Cournot and Sasagawa in constant stress tests, but the two latter sets do not so closely agree with the former. Dickenson's results on quenched and tempered medium-carbon steel are higher than those of the other investigators.

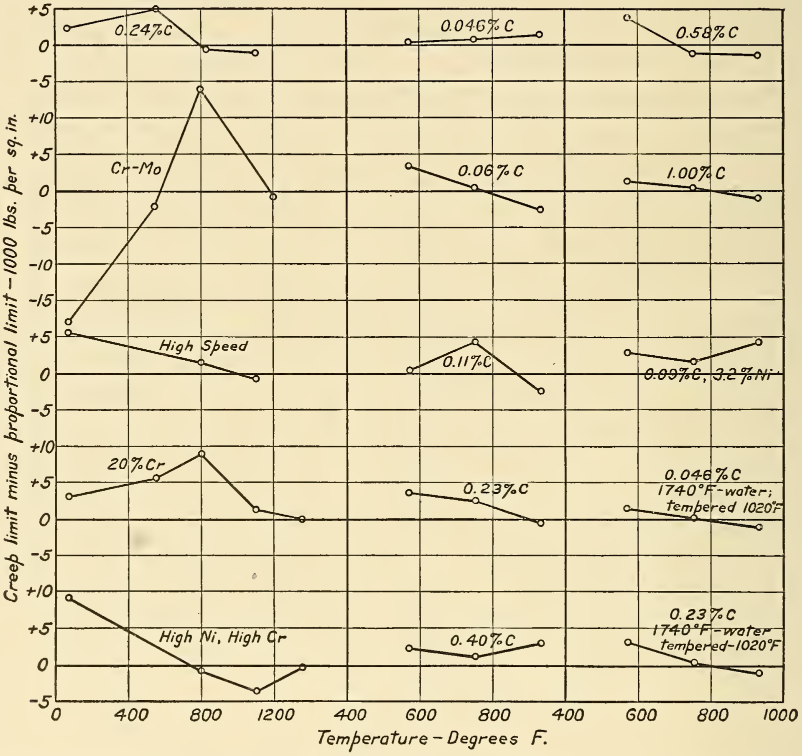


FIG. 19.—*Differences between the proportional limits in tension tests and the stress giving a selected elongation in 1,000 hours in the creep tests*

The tests made in this investigation are summarized in the column at the left; those made by Pomp and Dahmen (33) are given in the columns at the center and right side of the chart. "Creep limit" refers to 0.1 per cent elongation in 1,000 hours in the authors' tests and less than 0.0001 per cent elongation per hour in the third to sixth hours in tests of Pomp and Dahmen. "Proportional limit" is the stress giving the smallest detectable deviation from the assumed elastic modulus in the authors' tests and 0.02 per cent deformation in tests of Pomp and Dahmen.

On the whole, there is quite a scatter in the results obtained on similar metals by the different investigators. The character of the relations between stress, temperature, elongation, and time shown in Figures 18 and 20 indicates that important factors contributing to such differences are the accuracy of the tests and the manner of

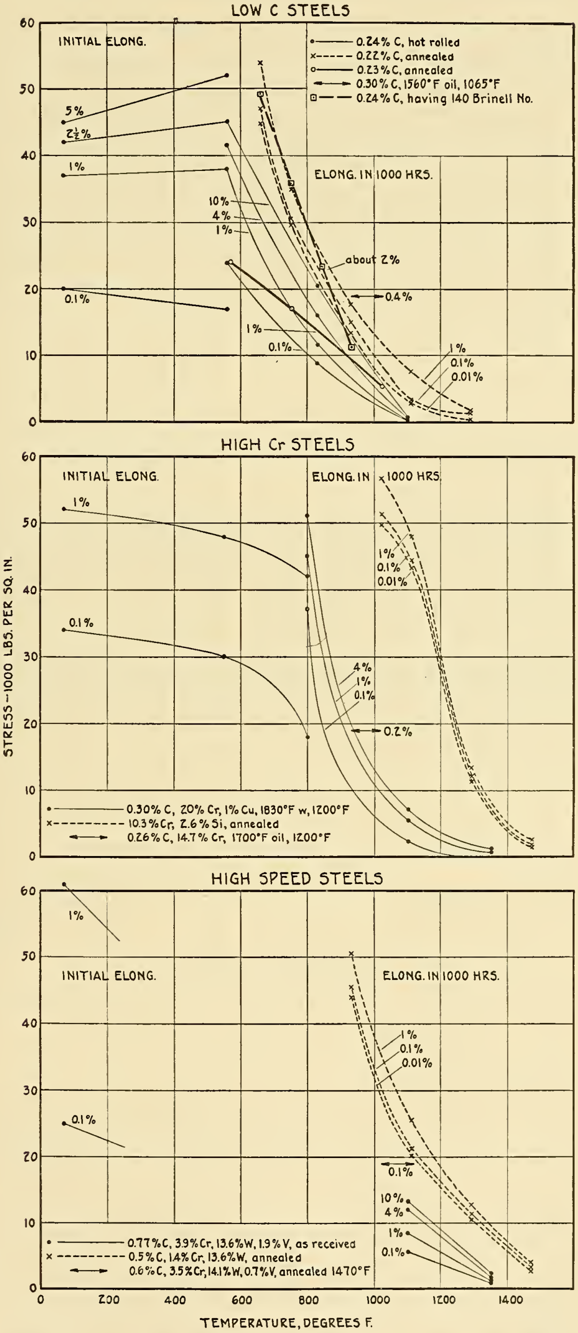


FIG. 20.—*Comparisons of the results of creep tests made on similar metals by different investigators*

●———— The authors.
× - - - - - - Cournot and Sasagawa.
○▬▬▬ Pomp and Dahmen.
←————→ Dickenson.
⊡ ▬ ▬ ▬ Tapsell and Clenshaw.

interpreting results and that these are as important in creep tests as in the short-time tension tests.

5. COMPARISONS OF THE DIFFERENT STEELS

Comparison of the different steels, based on the stress producing 0.1 per cent elongation in 1,000 hours, is made graphically in Figure 21. The steels which withstand the highest stresses at atmospheric and slightly elevated temperatures do not necessarily show superiority at higher temperatures. The range between about 600 and 800° F. (315 and 425° C.) marks the beginning of a rapid drop in load-carrying ability, and at 1,000° F. (540° C.) none of the steels tested can withstand a stress of 10,000 lbs./in.^{2} with 0.1 per cent or less elongation in 1,000 hours.

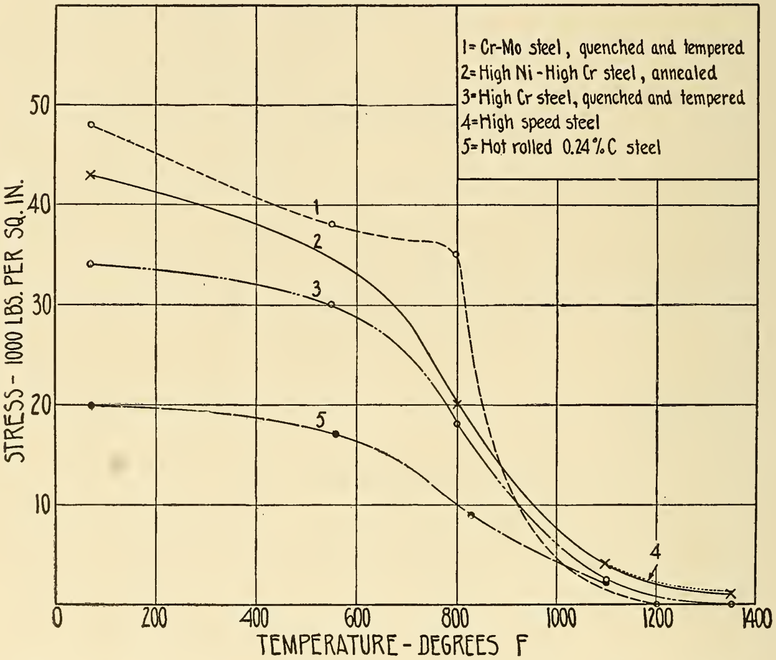


FIG. 21.—*Comparison of the five steels on the basis of the stress producing 0.1 per cent or less elongation in 1,000 hours*

See text for application of data.

At somewhat higher temperatures, between 1,100 and 1,350° F. (595 and 730° C.), the high-speed steel and the high chromium-high nickel steel have better load-carrying ability than the three other alloys. The high-chromium steel appears to be about the same as the low-carbon structural steel in its ability to withstand stress producing 0.1 per cent elongation in 1,000 hours, while the chromium-molybdenum steel gave the poorest results. This latter steel scaled very badly at 1,200° F. (650° C.), as will be evident in Figure 22, and showed measurable creep at this temperature under very low loads, as is illustrated in Figure 6. This poor load-carrying ability is probably due in part to poor resistance to oxidation in air. Coating the chromium-molybdenum steel samples with electrodeposited gold or chromium or even sprayed metallic coatings increased the life and decreased the rate of creep. Some of these results are included in Figure 6 (sample Nos. 20, 7, and 45 tested at 1,200° F. (650° C.).

The chromium-molybdenum steel was not stable structurally at 1,200° F. (650° C.). Oxidation was accompanied by what appeared to be decarburization and likewise by grain growth throughout the entire mass, although the latter effect was most marked in the decarburized outer areas, as is shown in Figure 23.

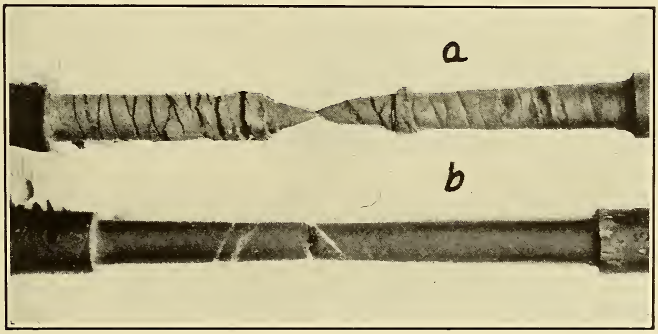


Fig. 22.—*Comparison of the oxidation of the chromium molybdenum and high chromium-high nickel steels*

a, Chromium molybdenum steel after 140 hours under 5,000 lbs./in.^{2} at 1,200° F. (650° C.).

b, High chromium-high nickel steel after 2,992 hours under 5,000 lbs./in.^{2} at 1,350° F. (730° C.).

It is possible that the low-carbon structural steel would show similar effects under similar test conditions, but samples were not available for examination. However, no evidence of grain growth was found in the low-carbon steel after 125 hours at 1,100° F. (595° C.). (Fig. 24.) There was likewise no evidence of marked structural change in the high-chromium steel, the high-speed steel, or the high chromium-high nickel steel after 1,000 to 2,000 hours under load at 1,350° F. (730° C.), as is illustrated in Figure 25.

The best resistance to oxidation in air was shown by the high chromium-high nickel steel and the high-chromium steel. They appeared to be superior in this respect to the high-speed steel which, however, with the high chromium-high nickel steel showed the best load-carrying ability in the range 1,100 to 1,350° F. (595 to 730° C.).

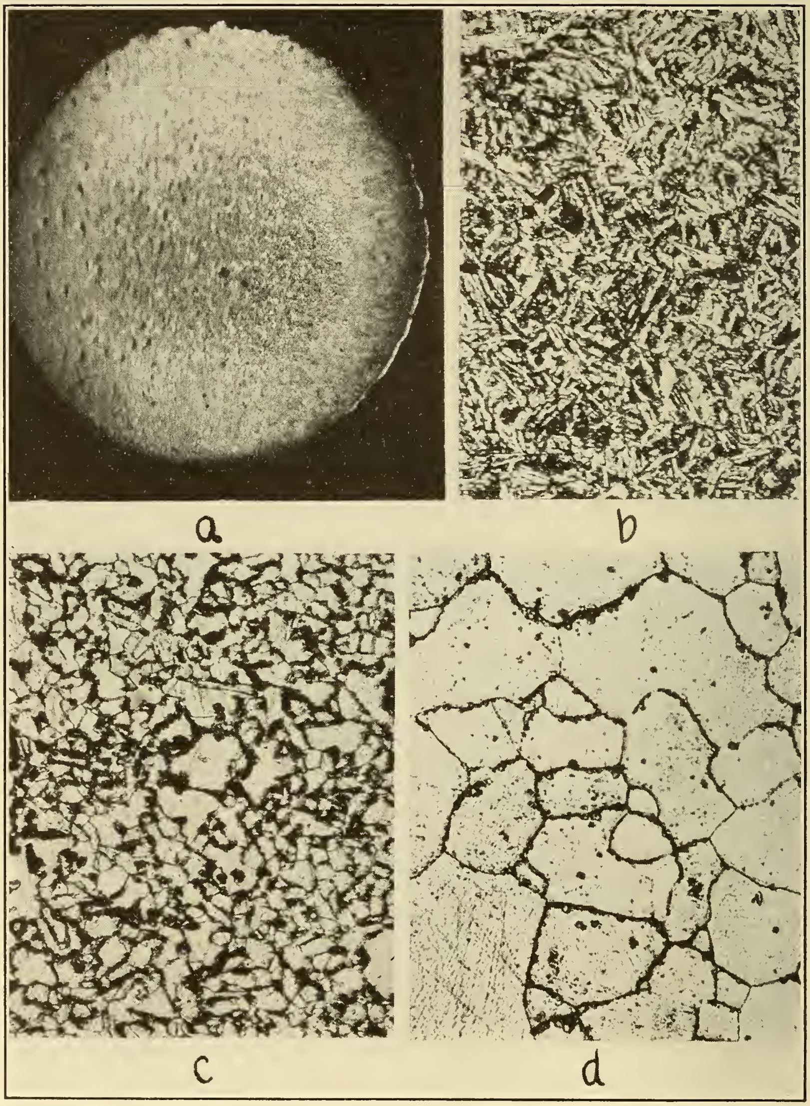


FIG. 23.—*Structure of the chromium molybdenum steel before and after test at 1,200° F. (650° C.)*

a, After 2,800 hours under 1,500 lbs./in.^{2} × 12.
b, Microstructure of steel before test. × 250.
c, Microstructure of specimen "a" at center. × 250.
d, Microstructure of specimen "a" near edge. × 250.
Samples etched with 2 per cent nitric acid in alcohol.

VI. SUMMARY AND CONCLUSIONS

The creep charts included in this report constitute the best summary of results obtained in the investigation. In these are shown the relations between stress, temperature, elongation, and time for each of the five steels at temperatures within the range 70 to 1,350° F. (20 to 730° C.).

In the temperature range within which strain hardening of the steel is observed the relation is shown between the temperature and the stresses producing different initial elongations which are followed by practical cessation of creep. At temperatures above those at which strain hardening is an important factor the relation is shown between temperature and the per cent elongation in 1,000 hours.

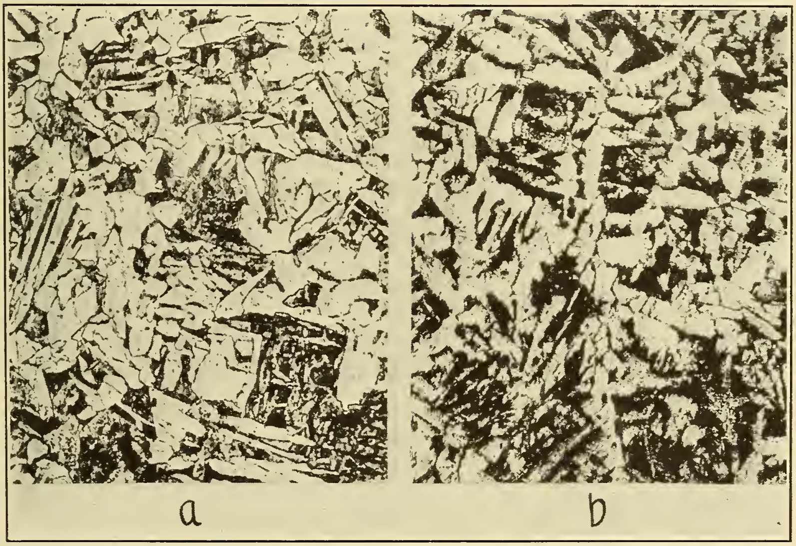


Fig. 24.—*Microstructure of the low-carbon structural steel before and after test at 1,100° F. (595° C.)*

a, Before test. ×100.
b, After 125 hours under 4,000 lbs./in.^{2} ×100.
Specimens etched for from five to six hours in cold 5 per cent picric acid in alcohol.

These charts enable the approximate determination of the stresses, permitting life of different durations with different total elongations. However, the values so obtained must not be applied too rigorously for reasons described in detail in the report. Other bars, lots, or melts of any one of the types of steel considered will probably show somewhat different numerical values from those obtained in the described tests. Furthermore, the creep charts are based on the assumption of a uniform creep rate, at least subsequent to an initial period, and the relations between stress, temperature, elongation, and time are of such a character that accurate interpolations of

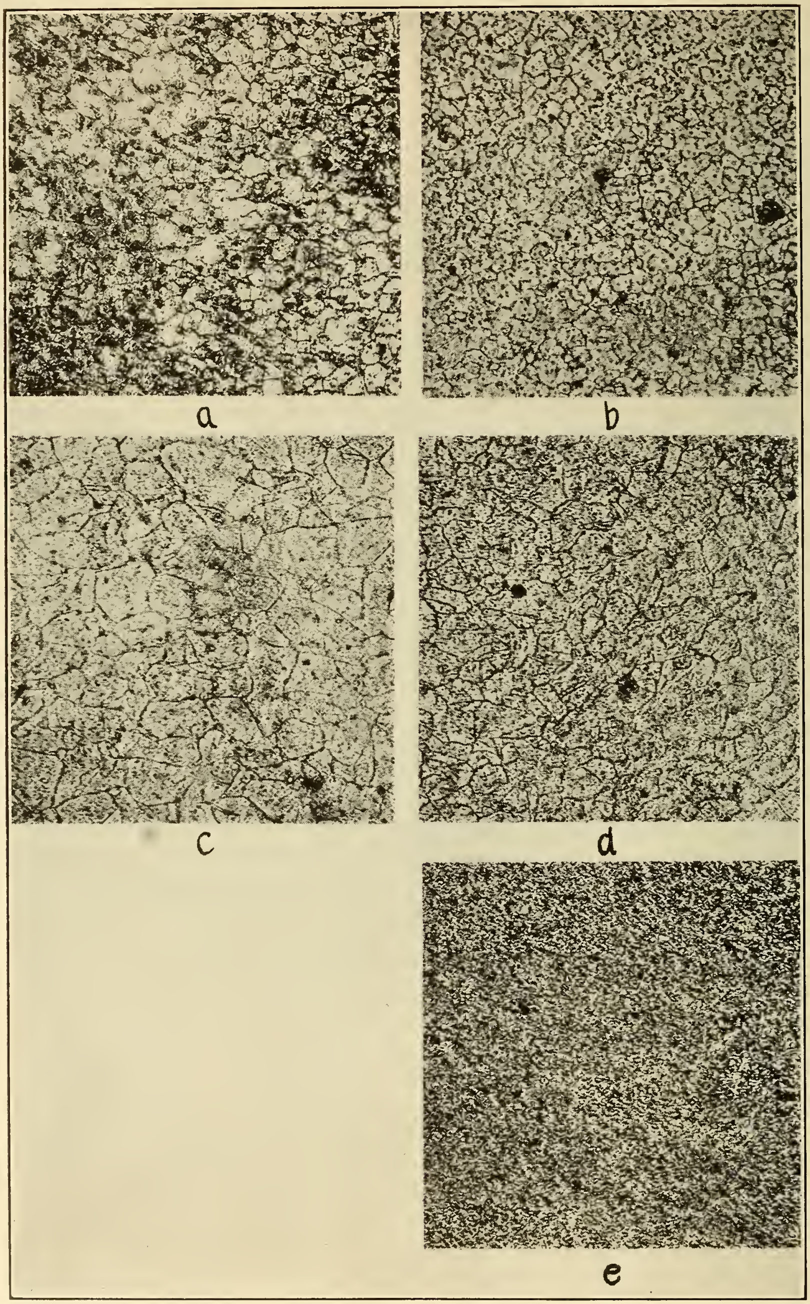


Fig. 25.—*Structures of the high chromium-high nickel steel, the high chromium steel and the high-speed steel before and after test*

a, High Cr steel before test.
b, High Cr steel after 2,500 hours under 500 lbs./in.^{2} at 1,350° F. (730° C.).
c, High Cr-high Ni steel before test.
d, High Cr-high Ni steel after 750 hours at 1,100° F. (595° C.) under 15,000 lbs./in.^{2}
e, High-speed steel after 1,800 hours under 1,000 lbs./in.^{2} at 1,350° F. (730° C.).

All specimens × 100. Etchants for *a* and *b* were 15 per cent sulphuric acid in water; for *c* and *d* were 15 per cent sulphuric acid plus a few drops of nitric acid in water; for *e*, 2 per cent nitric acid in alcohol.

numerical values was not possible even with the extended tests described.

There has, however, been a demand for the type of chart reproduced in the report and these are the best that can be prepared at this time. They should be useful if employed with an understanding of the manner of their preparation. Careful comparisons with the work of other investigators are included to show the magnitude of variations in results from different sources for similar metals.

In creep tests, as in short-time tension tests at different temperatures, the results are dependent upon the equipment and procedure employed in the tests and the manner of interpreting the results. A deviation of 0.1 per cent from an assumed proportionality between stress and strain in the tension tests was generally observed at a stress which was higher than that producing a similar deformation in 1,000 hours in the creep tests at corresponding temperatures. In other words, for a given accuracy of strain measurement the short-time test gave somewhat higher values than the long-time tests, but the proportional limit determined by accurate equipment—such, for example, as was used in the described tests—was in the range of stresses which could be sustained for long periods with small amounts of deformation. However, there appeared to be a tendency for the proportional limit to become higher than the allowable creep stresses as the temperature of the test was raised.

The best resistance to oxidation in air was shown by the high chromium-high nickel steel and the high-chromium steel. They appeared to be superior in this respect to the high-speed steel, which, however, with the high chromium-high nickel steel showed the best load-carrying ability in the range 1,100 to 1,350° F. (595 to 730° C.).

The chromium-molybdenum steel was not structurally stable at 1,200° F. (650° C.); it showed decarburization and grain growth.

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