THE CREEP OF STEEL AT HIGH TEMPERATURES

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PREFACE

This investigation on the creep resistance of steels was undertaken at the request of the Babcock & Wilcox Co., to provide engineering data at the higher temperatures. The work was carried out in the Department of Physics at the Massachusetts Institute of Technology.

The difficulties in the path of accurately determining the creep resistance are evidenced by the wide diversity of values obtained by different experimenters, and there is still much to be done on the development of research apparatus. The type of flow occurring in steel is not certain, even after the subject has been studied by scores of experimenters. There is need of more fundamental research. In the meantime, however, the designer requires engineering data on a large variety of steels for high temperature use. It has been attempted here to supply this data for a considerable number of materials at the higher temperatures.

The author desires to express his indebtedness to Mr. J. B. Romer for the metallographic examination of the test specimens, and to Prof. Albert Sauveur and Dr. R. S. Williams for examining the manuscript.

F. H. Norton.

Cambridge, Mass.
June, 1929.

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CHAPTER I

INTRODUCTION

It is only within a relatively few years that the engineer has realized the importance of the time element in determining the useful strength of steel at high temperatures. The working temperatures are ever rising to higher levels and at any time are limited mainly by the lack of knowledge concerning the properties of steels at high temperatures. It is safe to say that many steam installations are running today with the superheater tubes at 850°F., and plants are contemplated where the temperature will run to 900°F. or even 1000°F. In oil stills the metal reaches 900°F. and perhaps 1000°F., while the temperature in the mercury boiler runs to 1150°F.

In most structures it is, of course, desirable to increase the stresses to the highest value compatible with safety. There must always be, however, a certain reserve in strength to take care of uncertainties in calculations, properties of the material and operating conditions. This is generally called the factor of safety. Our knowledge of the properties of metals at high temperatures is comparatively inexact, and our operating experience under designed stresses is at present rather limited; so it is necessary to reduce the stresses in many cases to an unnecessary degree to secure safety. The various published values of permissible stresses for long life at high temperatures are generally so discordant that the need for more extensive and precise data is evident.

It is the object of this paper to provide the engineer with data on the safe stresses for various steels, especially at high temperatures. The methods and results of other experimenters are briefly reviewed, the Babcock & Wilcox creep testing apparatus is described, the creep results for seventeen types of steel at temperatures above 1000°F. are given, and the significance of the results is discussed. It is hoped that these results will be of value in the present and future design of high temperature structures.

CHAPTER II

THE PHYSICAL CONDITION OF STEEL AT HIGH TEMPERATURES

Above red heat, steel has yielding characteristics not usually associated with it at ordinary temperatures. We do not, as yet, have sufficient information to indicate definitely into which class of solid or fluid flow hot steel belongs. It may be either a plastic solid or a viscous fluid, or combine the properties of both.

A viscous fluid, of which pitch is a good example, has the flow characteristics shown in curve (*a*) of Fig. 1. The rate of flow is proportional to the load, even down to the smallest values, and yet a great resistance may be offered against loads acting for a short time. This class of materials has no true elasticity and therefore no yield point.

A plastic solid, such as wet clay, has flow characteristics as shown in curve (*b*) of Fig. 1. Here we have a more complicated condition. Until the load reaches a certain value there is no flow or extension, but after this point is reached the flow increases regularly in proportion to the load in excess of this value. It will be noted that the flow curve does not reach zero at a definite value of load, but approaches the axis gradually. We do not know the exact cause of this departure from a straight line at low flow rates, but it is probably due to the fact that plastic solids are made up of grains or particles of various sizes and shapes and some are less resistant to pressure than others.

The distinction between these two types of flow may be made clearer by a few examples. Glass is considered a very hard and brittle substance, yet, if a rod or tube be stressed by laying it horizontally across two supports, it will in the course of a few years, at room temperature, show a distinct

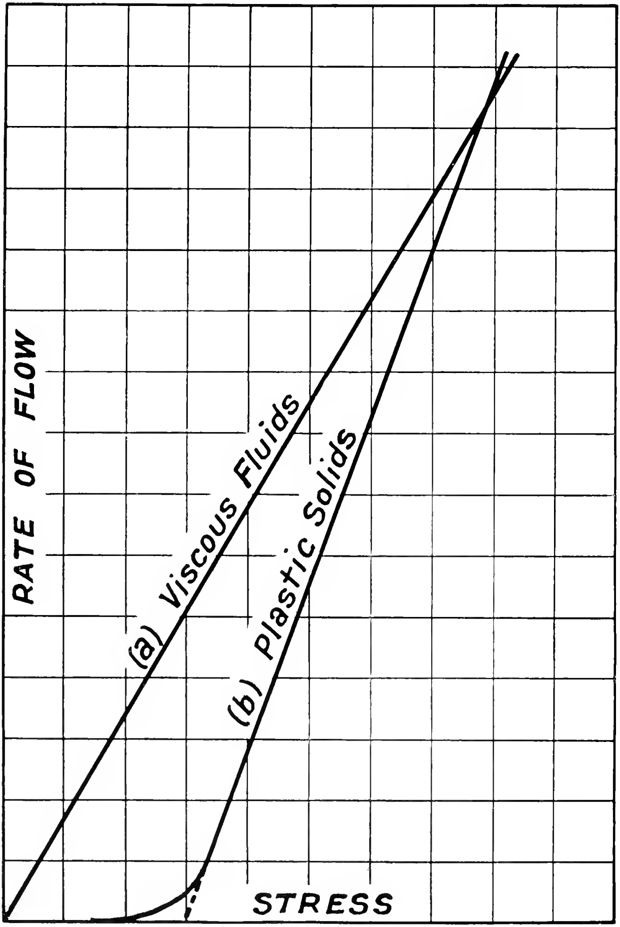


FIG. 1.

sag. Sealing wax will do the same thing much more rapidly. These viscous materials, then, will alter their form with the very smallest force if time enough is available. On the other hand, plastic solids such as a tallow candle or plasticine may be relatively soft, and yet if not stressed beyond a certain point will hold their form indefinitely.

Because of the difficulties in accurately measuring the flow of steel at high temperatures we do not know whether there is a stress below which no movement occurs. Dickenson states "The steels which the author has investigated behave very much like highly viscous fluids well below the critical range, and cannot be said to have any definite strength at red heat." He also considers the possibility of steel creeping even at room temperatures. In fact, flow in low melting point metals at room temperature has long been recognized. A number of experimenters have measured the rate of flow of the softer metals, and it has been well known that cantilever beams of lead or tin will sag at room temperatures in a few months. However, little has been done to determine whether pure metals act as fluids or solids. Such information, which can be comparatively easily obtained at room temperature would throw much light on the behavior of steel at red heat.

Turning to the mechanism of flow in hot steel we still have little real information. Steel is not a homogeneous substance, but is composed of grains more or less separated by boundary layers. The flow may be due to slippage at the grain boundaries, to deformation of the grains themselves, or perhaps to both. The evidence points to a primary yielding at the higher temperatures of the grain boundaries due to the lower softening amorphous material usually deposited there.

There is a vast amount of work to be done by the physicist in studying the fundamentals of metallic flow. Work should be carried out on the softer metals at room temperature where the experimental conditions can be controlled with great precision. The flow characteristics of a single crystal would be most interesting. The laws of flow should then be verified at high temperatures for iron and and steel. In this way we can greatly simplify our present haphazard engineering tests, and provide a sound basis for the development of superior structural materials.

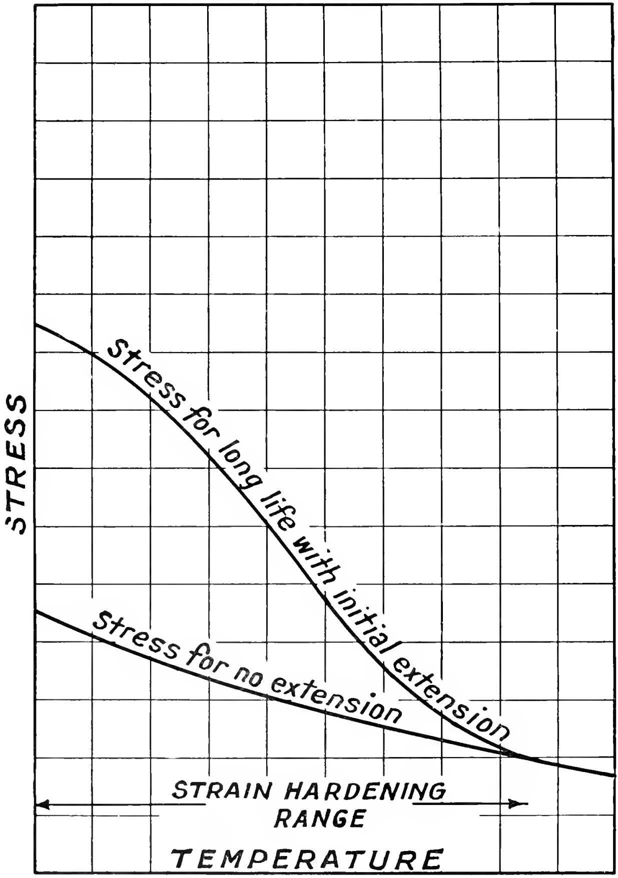


Fig. 2.

When annealed steel is stressed slightly beyond its elastic limit at temperatures below a certain point, the original proportional limit is raised until the stress is sustained apparently without further strain. This raising of the proportional limit can be carried on to a definite load value beyond which there will be a continuous yielding. This phenomenon is called strain hardening, and the temperature below which it occurs, the strain hardening range. This range varies somewhat with the kind of steel but seldom extends above 1000°F.; so we are not primarily concerned with it here. It may be well, however, to point out a few interesting facts about strain hardening. Work at the National Physical Laboratory and elsewhere has shown clearly that metal, strain hardened at a certain temperature, has the proportional limit permanently raised, and unless a higher temperature is reached no annealing takes place. The increase in proportional limit seems to be always accompanied by an increase in hardness.

In Fig. 2 are shown typical curves of load plotted against limiting creep stress and creep stress for no extension. At the lower temperatures there is a marked difference between the two curves. As the temperature increases they converge, until, at the limit of the strain hardening range, they join and continue together at higher temperatures.

In designing a structure for high temperatures we must first determine the temperature range in which it is to be used, and then decide whether a slight initial extension is permissible or not; if it is, then the allowable stress can run to the upper curve. If the temperature runs above the strain hardening range, there is but one set of values to consider.

It should be emphasized that the frequently used term "limiting creep stress" is a rather indefinite one. In fact, we are not sure there is any limiting value. All that can be accurately stated is that, at a certain load, the rate of flow is below a certain value, the latter determined by the precision of the measurement. In this paper the results are given in hours of life for a one per cent extension.

CHAPTER III

CREEP TEST METHODS

In the earliest methods of testing metals at high temperatures, the specimen was heated in a forge or furnace, and then quickly placed in a testing machine and pulled. The temperature reading was, of course, quite inaccurate, and the rate of pulling was not considered an important factor.

Perhaps the first accurate work was done at the Watertown Arsenal in 1888 by Howard. From then on a number of investigators have studied the strength of metals at high temperatures. The rate of testing was comparatively fast, and the temperature was not measured on the specimen itself, but usually in a surrounding bath. However, this work brought out the importance of high temperature tests on metals.

A number of physicists such as Ewing, Muir and Hopkinson, studied the characteristics of metals when stressed above the yield point. Some of the apparatus then used compares favorably with that used today.

All the earlier experimenters failed to recognize the full importance of the time element in the flow of steels; so that their permissible stresses were in most cases too high. It was pointed out by Atchison in 1919, and later by Chevenard, Dickenson, and Lea that steels would continuously extend, at a continuous rate, when loaded considerably below their quick breaking stress. The important fact shown clearly at this time was that the stresses in a structure must be low enough to prevent an undue change in size during its life. This meant that the stress must be set to give an extremely small extension during the usual test period of 500 to 1000 hours.

It is believed by French and others that the proportional limit, as precisely determined in a quick test, approximates in value the limiting creep stress at that temperature, provided the material is beyond the strain hardening range. A number of values substantiate this conclusion, but on the other hand, the work of Clark and White indicates that the limiting creep stress (if there is a limit) is below the proportional limit value. We need a large amount of additional data before we can draw any general conclusions. In the meantime, it is only safe to base our design on the results of long time tests.

It may be of interest to describe the more recent methods of testing in detail; as the refinements in temperature measurement, temperature control, and extension measurement are carried to a high degree. Some experimenters maintain the load for a long period of time, and others make a rapid test and determine the proportional limit with accurate extensometers.

The furnaces are all of the tubular form wound with a heating coil. The National Physical Laboratory used a platinum foil winding on a refractory tube, but most of the others are wound with wire of the nickel-chromium type on an insulated metal tube. In some cases the winding is uniform, but French used extra end coils, and Bregousky and Spring, end coils only, in order to obtain an even temperature along the specimen. Even with these precautions there may be a temperature variation along the specimen of 25° to 50°F. due to conduction along the holders.

The method used in measuring the extension varies. In most cases clamps are placed on the top and bottom of the specimens, and then brought out to a measuring device. French, Preister and Harder, and Malcolm used two indicator dials. Mochel and McVetty used an optical extensometer of great sensitivity. French, at the Bureau of Standards, also used an optical extensometer (Tuckerman-Martens) for the rapid tests. Direct reading micrometer telescopes, sighted directly on the ends of the specimen, have been used. This method eliminates any errors in bringing the readings out of the furnace with rods, but is subject to errors when there is any scaling of the specimen. In long time tests, where the extension readings need not be as precise, the extension is usually taken on the ends of the holder. It should be noted that the sensitivity of an extensometer is not a measure of the obtainable precision. For example, an instrument can be made to read a millionth of an inch, but errors caused by temperature variation, differential expansion, warping, etc., may amount to many times this value in a long test.

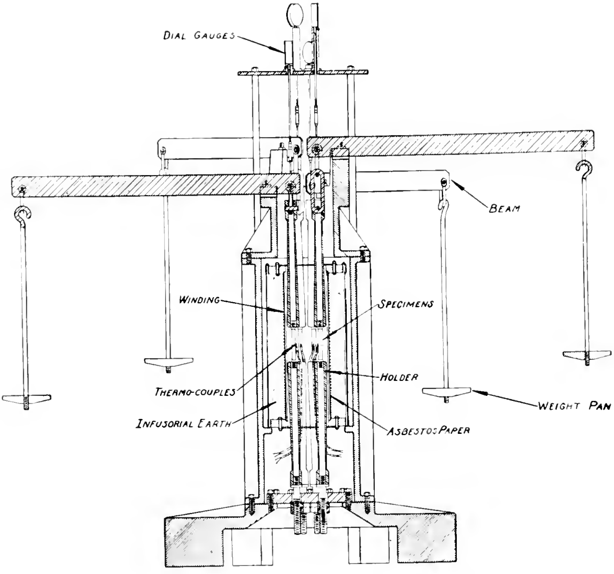
The usual method employed in making a creep test is to load the specimen at a certain value and maintain this load for a period of time and measure the rate of extension. The test is then repeated at a different load or temperature, and the extension again determined until a load is found for each temperature where the steel will just fail to show a measurable creep. Of course, the longer the time of test and the more accurate the extension determinations, the more precise will be the creep value.

In the short time tests the specimen is held very closely to the desired temperature, then pulled at a uniform rate and simultaneous readings of load and extension taken. The proportional limit is usually found graphically. It is obvious that with more precise readings the deviation from a straight line can be observed at a lower load than with less precise ones. We are not at all sure that if we could obtain results, say one hundred times as precise as at present, that there would be any limit indicated, any more than we are sure that there is a stress below which there is no creep.

CHAPTER IV

THE BABCOCK & WILCOX CREEP APPARATUS

It was desired to test a number of steel specimens simultaneously for a long period and at several temperatures.



B & W Creep Apparatus
Fig. 3.

Therefore, three furnace units, each holding six specimens were decided upon. The testing unit constructed for this purpose is shown in Figs. 3 and 4. A standard .505″

diameter[1] test specimen with a 4″ gauge length is screwed into alloy steel holders, and maintained at a given tension by a simple lever mounted on knife edges.

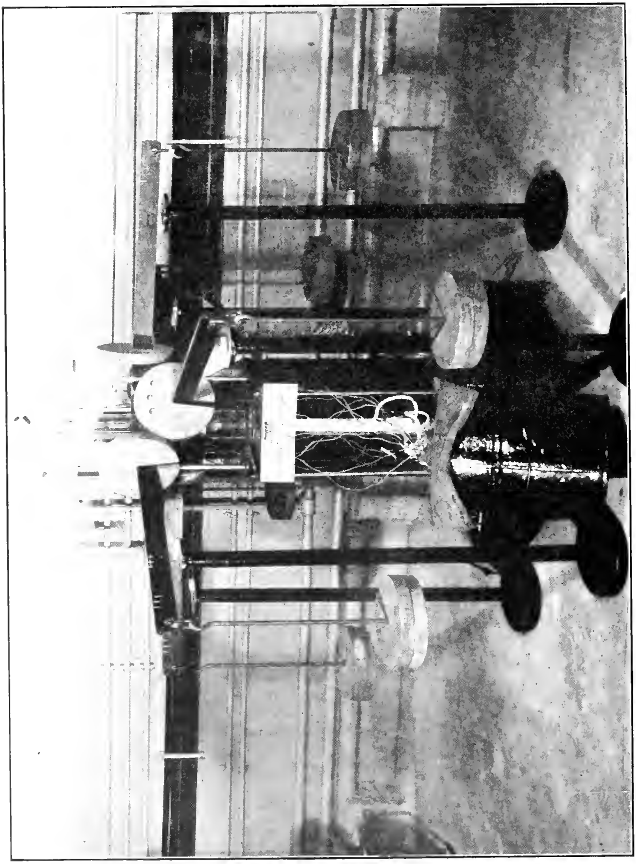


FIG. 4.

The holders are so proportioned that they will have a section decreasing in area as it approaches the cool end,

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[1] For lower temperatures and high creep resisting steels this diameter is slightly reduced.

where higher stresses are permissible, in order to reduce the heat conduction along the holder to a minimum.

The weighing lever has a 10 to 1 ratio, and has sufficient length so that no leveling adjustment is necessary during the run. This greatly reduces the cost of the apparatus and makes a very compact and simple arrangement.

Six specimens are arranged symmetrically inside of the heating furnace which consists of a 5″ iron pipe wound with asbestos paper and a heating coil. The furnace is sufficiently long to give a uniform heating effect, and is carefully insulated to prevent loss of heat. A thermocouple is tied tightly to the inner side of each test specimen so that the individual temperatures can be measured, although no variation among the six was found in the first test. As the thermo-couple is on the side of the specimen away from the furnace wall, it is shielded from the radiation and should read the true temperature of the specimen with precision. Asbestos fiber is packed around the holders at the top of the furnace to prevent any hot gases from escaping.

The temperature of the furnace is maintained at a constant value by connecting a thermo-couple, fastened to the heater winding, to a potentiometer recorder, which operates a rheostat for regulating the current through the furnace at the proper value. The controlling couple is placed on the winding to prevent lag and hunting, and is, of course, higher than the specimen couples. A set of these controllers is shown in Fig. 5. In general the temperature of the specimens is maintained constant within ±5°F. The wires from the couples on the individual specimens are carried out to a set of switches and potentiometer as shown in Fig. 6.

It is as necessary to keep the room temperature uniform as it is the specimen temperature, because of the expansion of the frame work of the testing unit. This temperature regulation is carried out by circulating the air around the room by fans and by controlling the amount of air drawn in from the basement corridor. The room temperature

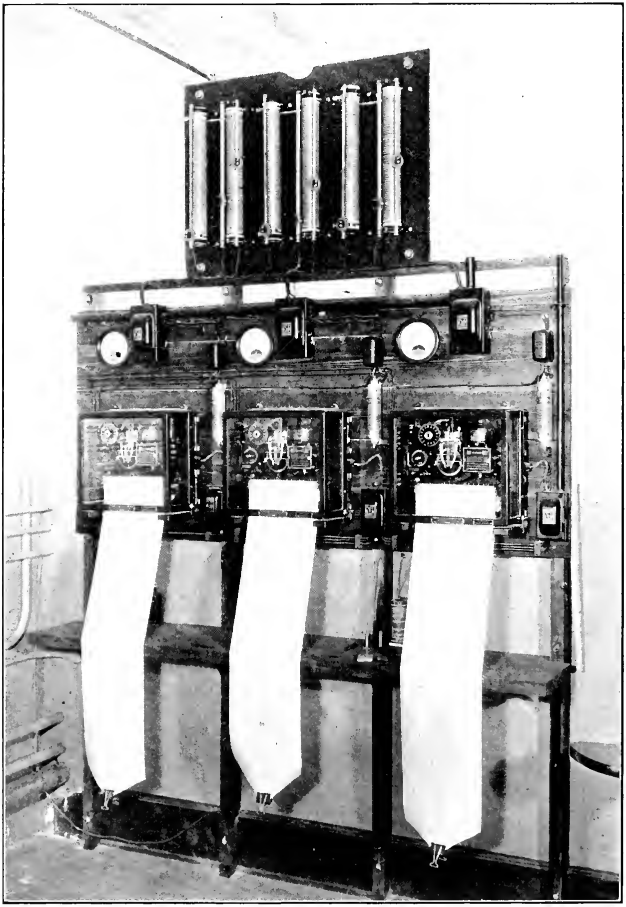

Fig. 5.

during the test is constant to within ±2°F. The cold junction of the controller couple is mounted on the cast

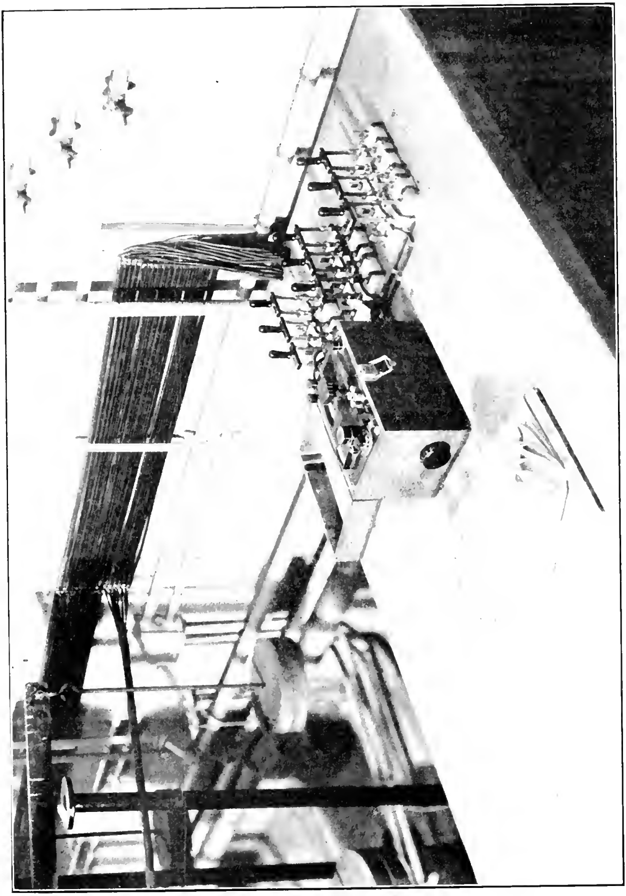

Fig. 6.

iron frame which gives a constant difference between the frame and the specimens.

The extension of the specimens is read directly by dial gauges, reading to .0001 of an inch. These gauges are mounted on the top of the apparatus, and are connected by steel struts to the lever arms directly in line with the specimens.

In order to prevent oxidation of the specimens a stream of dry nitrogen is supplied to the bottom of the apparatus during the test. The complete installation is shown in Fig. 7. It was not found that nitrogen has any appreciable effect on the steels even after long periods of heating.

The tests are made by bringing the unloaded specimens up to the desired temperature and then applying a load somewhat below the supposed creep stress. This load is maintained steadily for about 400 hours, and a record of the extension made twice a day. The load is then increased about 10 per cent and maintained for another 400 hours, and so on until the rate of creep becomes large. In Fig. 8 is shown the extension readings taken from a test of one of the steels. It will be noted that the rate of elongation is approximately constant for each load, and this will be true until there is a reduction in area, when the rate for a given load will increase. In these tests, however, the load was not carried to such high values. At the lower temperatures some of the specimens elongated for 50 to 100 hours after a load increase, but due to strain hardening this elongation ceased if the stress was below the limiting creep value.

The slope of the curves in Fig. 8 are determined graphically and plotted as rate of elongation against corresponding load and temperature on log sheets as shown in Figs. 50 to 54. It is clear that in all cases the most representative curve through the points is a straight line. Whether it will continue a straight line down to lower rates of creep or have a bend as indicated by French cannot be determined without more precise data. This method of plotting is convenient as it is not difficult to draw a representative line through a few points and read off the safe load for any extension rate or life. Even with two values a line can be drawn with fair precision.

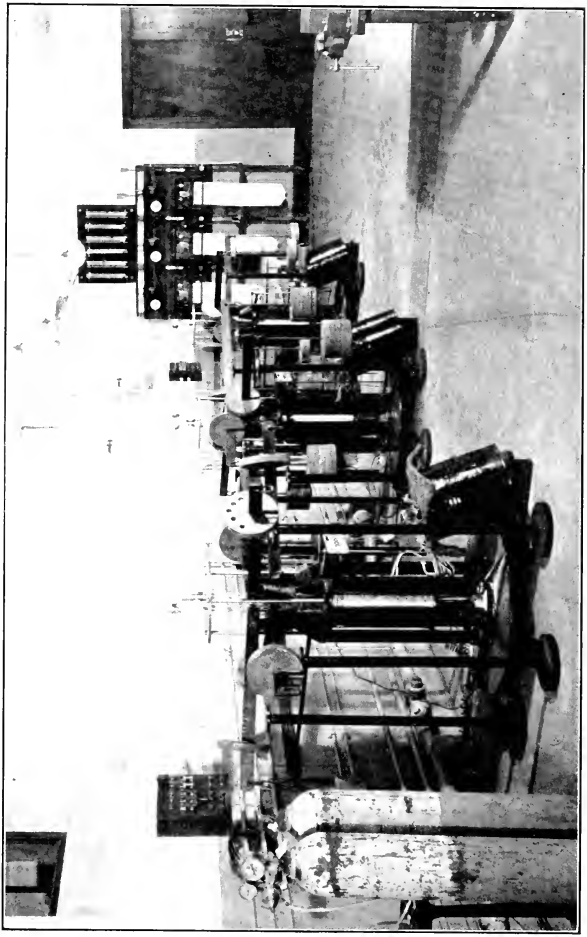

Fig. 7.

Values are taken from these curves representing a life of 100,000 and 10,000 hours with a permissible extension of one per cent.

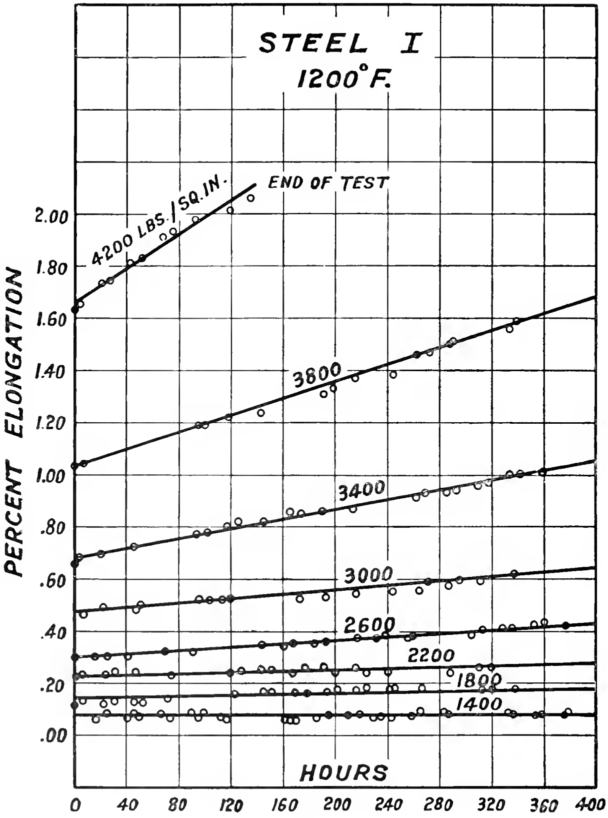

Fig. 8.

In a number of cases the load on the specimens was gradually decreased after a definite rate of creep was established. In all cases the rate of creep for a given load was the same when decreasing as when increasing. This information will allow us in future tests to put on at once sufficient load to produce a small creep and then reduce this until the rate of creep is very small. The length of time required to make a test will be considerably shortened by using this method. It cannot be used, however, in the strain hardening range when it is desired to obtain the creep stress with no initial extension.

CHAPTER V

DESCRIPTION OF THE STEELS TESTED

This section of the report has been prepared by the metallurgical laboratory of the Babcock & Wilcox Company at Bayonne, N. J., and gives a complete description of the original steels as well as the changes occurring during the test.

In selecting steels for creep analysis, an effort was made to cover a wide and comprehensive field. The steels selected fell into three distinct groups. The first, and as far as creep at high temperatures is concerned, the most important group, is made up of five steels whose composition is such that they are austenitic at room temperatures. The second group also contains five steels which differ from the preceding group in that the amount of alloying element added, although not sufficient to produce an austenitic structure at room temperature, is sufficient to distinctly change many of their characteristics. The third group consists of a plain carbon steel and six steels in which the amount of alloying element is just sufficient to bring about distinct changes in the properties at room and slightly elevated temperatures.

Austenitic Steels.

In Table I will be found the symbol letter, reference name and complete chemistry of the five austenitic steels of the first group.

The complete history of these five steels is not known. Probably they were hot finished, unannealed bars, although the last point is uncertain.

These steels are not hardened by heat treatment; on the other hand, quenching from about 1850°F. develops a condition of maximum softness and ductility. This is a characteristic of austenite.

TABLE I

Symbol	Reference Name
A	18–8–½ Chrome Nickel Silicon
B	19–6–1 Nickel Chrome Silicon
C	25–20–1 Chrome Nickel Silicon
D	20–7–1½ Chrome Nickel Silicon
E	18–8–½ Chrome Nickel Silicon

	A	B	C	D	E
Carbon	.14%	.14%	.12%	.43%	.09%
Silicon	.32	1.09	.76	1.35	.43
Manganese	.45	.43	.53	.52	.38
Phosphorus	.008	.017	.008	.004	.026
Sulphur	.014	.023	.026	.012	.030
Nickel	8.23	19.01	19.67	6.99	8.12
Chromium	18.15	6.37	24.90	20.16	18.11
Tungsten	None	None	None	.60	None
Vanadium	.13	None	.18	.23	None

The effect of mechanical work is quite pronounced; in particular, the temperature at which the mechanical work is performed is very important. The lower the finishing temperature, the higher will be the yield point and to a certain extent the tensile strength, but at the same time, there is a distinct loss in the ductility. A comparison of the physical properties, shown in Table II of hot rolled bars and fully softened bars, brings out this point.

TABLE II

	Hot rolled bars	Softened bars
Tensile strength, lb. per sq. in.	110,000	90,000
Yield point, lb. per sq. in.	82,000	35,000
Proportional limit, lb. per sq. in.	67,500	30,000
Elongation in 2″	36%	61%
Reduction of area	52%	75%
Brinell hardness	223	135
Rockwell hardness	B-95	B-85

In considering the microstructure of these steels, a comparison will be made between samples of the original materials and the specimens after they have been subjected to the creep tests referred to in the earlier chapters.

It has been our experience that a solution of aqua regia in glycerine develops, to best advantage, the general structural characteristics of the high chrome alloys. Murakami's reagent is resorted, for observing carbides. This corresponds, in its action, to boiling sodium picrate as used on plain carbon steels.

STEEL A

18-8-½ Chrome Nickel Silicon

	Per Cent
Carbon	.14
Silicon	.32
Manganese	.45
Nickel	8 23
Chromium	18 15
Vanadium	.13

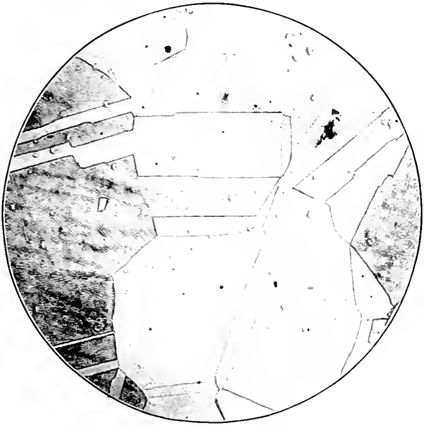

Fig. 9.—Original. 1496-1. 100 ×. Etchant—aqua regia and glycerine.

The original material is extremely large grained austenite, indicating that it was finished at a relatively high temperature. During the tests, a specimen of this steel was heated to 1200°F. and held at this temperature for a period of

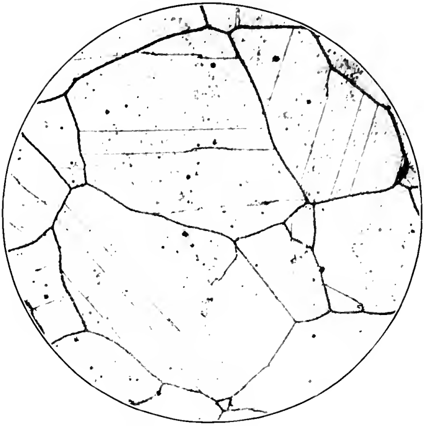

Fig. 10.—5900 hours at 1200°F. 1496-2. 100 ×. Etchant—aqua regia and glycerine.

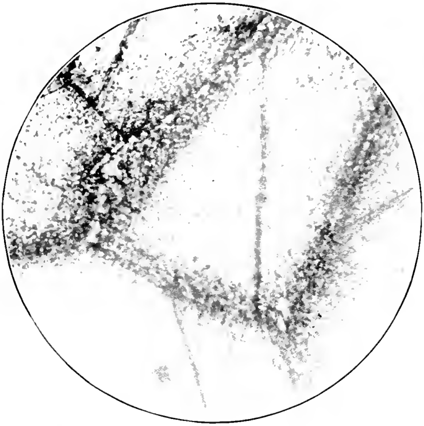

Fig. 11.—1496-3. 100 ×. Etchant—aqua regia and glycerine.

5900 hours (under stress) and, as will be noted in Fig. 10, a distinct change has occurred at the grain boundaries. Even though the magnification is only 100 diameters, it can be readily seen that carbides are precipitating at the boundaries. Further proof of this statement is to be had by observing Fig. 11, where the magnification is 1000 diameters.

The original material was strictly non magnetic and etching with Murakami's reagent failed to develop evidence of carbides. After the long time tests at 1200°F., the material was distinctly magnetic and Murakami's reagent showed the presence of considerable carbide. It is evident that this material is unstable at this temperature.

The instability of this material is not verified by Rockwell hardness determination. The large grain structure noted in the original material is reflected in the low hardness number.

	ROCKWELL B
Original value	74.0
After heating at 1200°F.	75.3

STEEL B

19–6–1 Nickel Chrome Silicon

	Per Cent
Carbon	.14
Silicon	1.09
Manganese	.43
Nickel	19.01
Chromium	6.37
Vanadium	None

In this steel the amount of nickel and chromium is reversed, as compared with material A. In addition, the silicon content is higher. In the original sample, indications are that considerable carbide was present both at the boundaries and within the grains. The material is virtually non magnetic. Murakami's reagent shows a small amount of carbides at the boundaries in the form of a chain, as well as some carbide within the grains. The large masses are not entirely carbides, instead they are partially a second constituent.

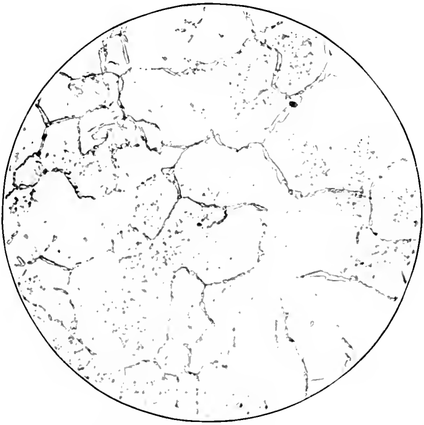

Fig. 12.—Original. 1496-4. 500 ×. Etchant—aqua regia and glycerine.

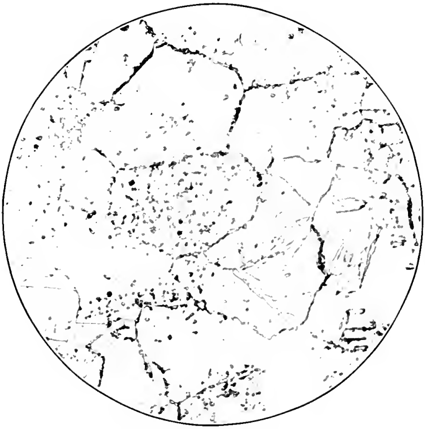

Fig. 13.—4600 hours at 1000°F. 1496-5. 500 ×. Etchant—aqua regia and glycerine.

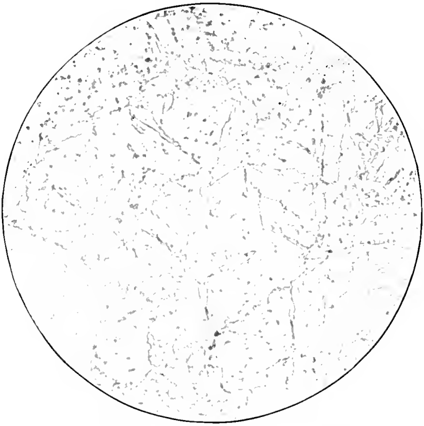

FIG. 14.—5500 hours at 1100°F. 1496-6. 500 ×. Etchant—aqua regia and glycerine.

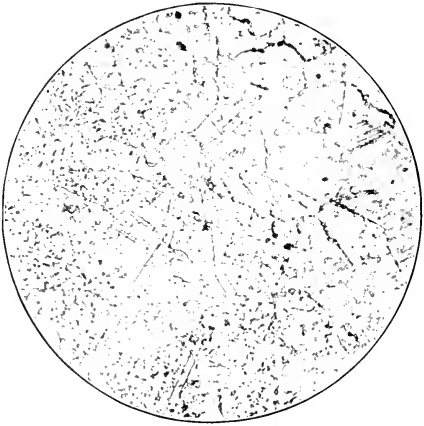

FIG. 15.—5900 hours at 1200°F. 1496-7. 500 ×. Etchant—aqua regia and glycerine.

The effect of heating this material at 1000°F. for 4600 hours has been to develop carbide formation, as can be observed in Fig. 13. As can be observed in Fig. 14, the effect of heating at 1100°F. is to increase the second constituent. The effect of heating at 1200°F. for 5900 hours is to absorb the second constituent that was present in the original material. As far as can be observed, the carbides have not changed. When the structure developed by 3300 hours at 1500°F. is noted, it becomes apparent that the maximum temperature for carbide precipitation is in the neighborhood of 1200°F. and re-solution begins at or before 1500°F. This is confirmed by Murakami's reagent which disclosed the reabsorption of the previously precipitated carbides. The higher temperature develops a larger size grain.

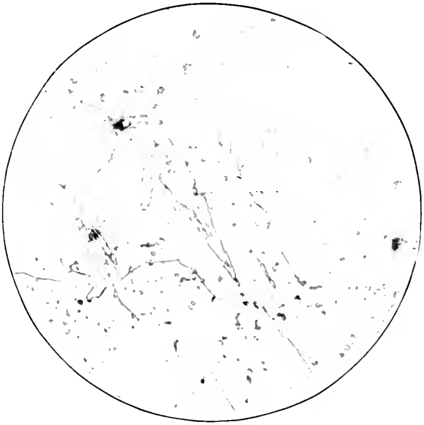

Fig. 16.—3300 hours at 1500°F. 1496-S. 500 ×. Etchant—aqua regia and glycerine.

Heating at 1000, 1100 and 1200°F. steadily reduced the Rockwell number, whereas, the 1500°F. heating raised the value above the original.

Rockwell B

Original value	79.0
After heating at 1000°F	73.3
After heating at 1100°F	72.3
After heating at 1200°F	69.8
After heating at 1500°F	82.0

The absorption of the second constituent, at and below 1200°F., is accompanied by a decrease in hardness. The absorption of carbides at 1500°F. is accompanied by an increase in hardness.

STEEL C

25–20–1 Chrome Nickel Silicon

	Per Cent
Carbon	12
Silicon	.76
Manganese	.53
Nickel	19 67
Chromium	24 90
Vanadium	.18

In this instance, both nickel and chromium are high, and there is considerable silicon present. The grain structure, in the "as received" condition, was small, thus indicating a relatively low finishing temperature. The sample was non magnetic. When this material was etched with aqua regia, a number of small particles were observed. Murakami's reagent developed a number of large carbides within the grains. After heating for 5900 hours at 1200°F., the etching characteristics are quite different. Aqua regia develops a number of black particles, as can be noted in Fig. 18, which quite likely are carbides. There is also an increase in the carbides at the boundaries. Evidently this material is somewhat unstable at 1200°F.

The original material had a relatively high Rockwell hardness, confirming the belief that the finishing temperature was low. Long heating at 1200°F. had little effect on the hardness.

Rockwell B

Original value	93.7
After heating at 1200°F	92.1

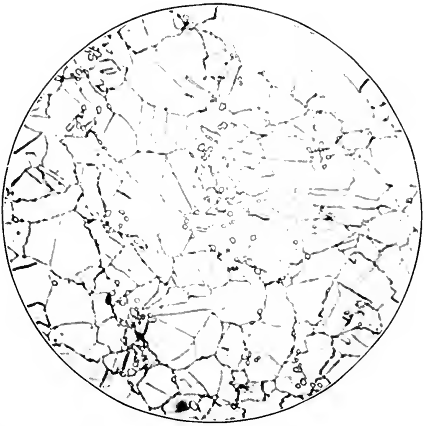

FIG. 17.—Original. 1496-9. 500 ×. Etchant aqua regia and glycerine

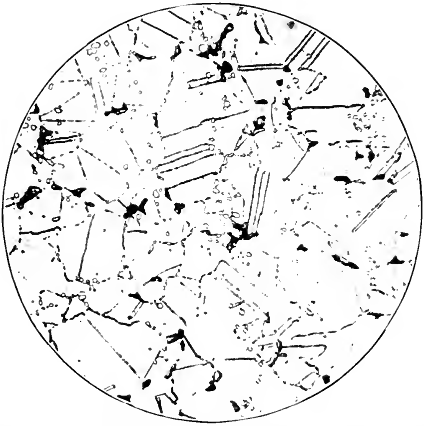

FIG. 18.—5900 hours at 1200°F. 1496-10. 500 ×. Etchant—aqua regia and glycerine.

STEEL D

20–7–1½ Chrome Nickel Silicon

	Per Cent
Carbon	.43
Silicon	1.35
Manganese	.52
Nickel	6.99
Chromium	20.16
Vanadium	.23
Tungsten	.60

Here we have a steel that differs from the others in that the chromium and silicon are on the high side, and in addition, both vanadium and tungsten are present. This composition will increase the tensile strength and lower the ductility when tested at room temperatures; however, the following sections will show that the permissible creep stress at high temperatures is not improved. The original material, of small grain size, contained carbide particles within the grains and only traces at the grain boundaries. Fig. 19 depicts these conditions.

As a result of heating for 4600 hours at 1000°F. or 5900 hours at 1200°F., the carbide particles have become smaller and more numerous. The conditions in the two samples are so similar that only one photomicrograph, Fig. 20, of the 1200°F. specimen, is shown. The condition of the carbide particles, coupled with the fact that a slight degree of magnetism developed, is indicative of the instability of this material at these temperatures.

The original material was small grained and evidently finished at a low temperature as is confirmed by the high Rockwell value.

The specimen heated at 1000°F. showed a lower hardness than did the original or the 1200°F. specimen.

Rockwell B

Original value	102.7
After heating at 1000°F	95.0
After heating at 1200°F	102.7

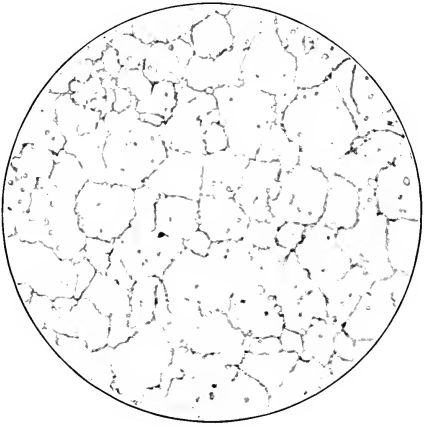

FIG. 19.—Original. 1496-11. 500 ×. Etchant—aqua regia and glycerine.

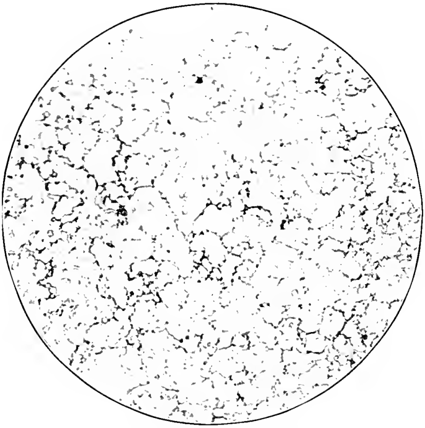

FIG. 20.—5900 hours at 1200°F. 1496-12. 500 ×. Etchant—aqua regia and glycerine.

STEEL E

18-8-½ Chrome Nickel Silicon

	Per Cent
Carbon	.09
Silicon	.43
Manganese	.38
Nickel	8.12
Chromium	18.11
Vanadium	None

Chemically, this material is quite similar to material A. The structure in the "as received" condition is smaller grained, thus indicating a lower finishing temperature. In the "as received" condition, no indications of magnetism were observed; heating, however, tended to develop magnetism. At and below 1200°F., even after long time heating, the magnetism was quite slight, whereas 3000 hours at 1500°F. produced sufficient alpha iron to give the sample strong magnetic characteristics.

The original material is virtually free from carbides as is shown in Fig. 21. The effect of 4600 hours at 1000°F. plus 2200 hours at 900°F. has, as is shown in Fig. 22, developed distinct evidence of carbide precipitation, which is confirmed by Murakami's reagent.

The conditions depicted in Fig. 23 are different than those shown in Fig. 22, therefore, we feel that these changes occurred at 1200°F. during the 5900 hours. Increased carbide precipitation and grain growth occurred, indicating instability. As a result of heating at 1500°F., a few scattered carbides were developed along the grain boundaries. The general grain structure changed materially with considerable magnetism developing. The evidence leads to the belief that this material is somewhat unstable.

Reference was made in the preceding pages to the similarity of steels E and A and to the fact that material E was smaller grained and finished at a lower temperature. This is reflected in the hardness.

Although heating increased the carbide precipitation, the re-equiaxing more than offset this and as a net result, we have a slight lowering of the hardness value.

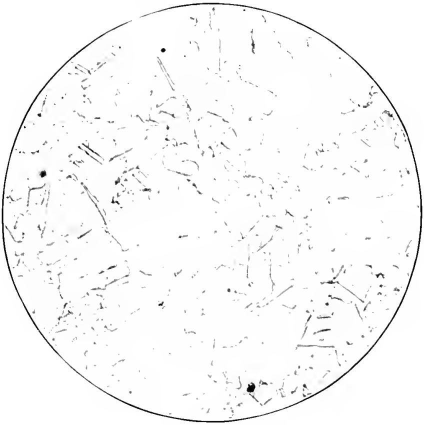

FIG. 21.—Original. 1496–13. 500 ×. Etchant—aqua regia and glycerine.

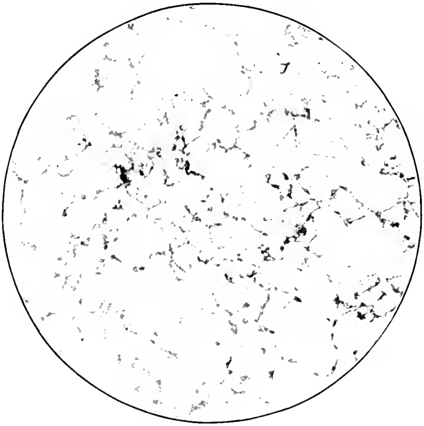

FIG. 22.—4600 hours at 1000°F. and 2200 hours at 900°F. 1496-14. 500 ×. Etchant—aqua regia and glycerine.

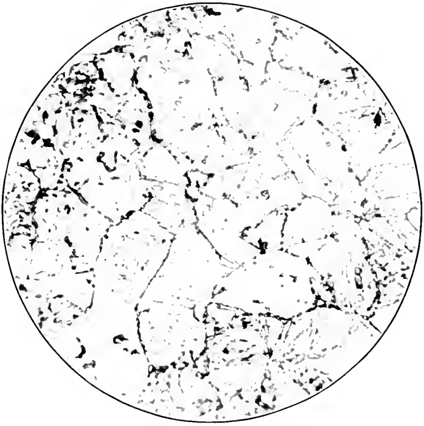

Fig. 23.—5900 hours at 1200°F. plus 1700 hours at 1000°F. 1496-15. 500 ×. Etchant—aqua regia and glycerine.

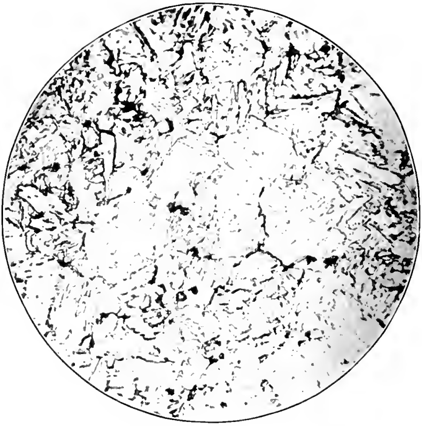

Fig. 24.—3000 hours at 1500°F. 1496-16. 500 ×. Etchant—aqua regia and glycerine.

Rockwell B

Original value	92.7
After heating at 1000°F	89.0
After heating at 1200°F	87.8
After heating at 1500°F	87.8

The general situation, with respect to the five austenitic steels, is that variations in chemistry, provided the material remains austenitic, have less effect on the physical properties than do variations of the temperature at which the material is mechanically worked. On heating, the above effects are more or less overcome, and by the time the temperature approaches the transformation point for alpha iron, the materials of this group, as far as load carrying ability is concerned, become of about equal value. However, their stability at high temperature varies materially.

Stainless Steels and Irons.

The steels in the second group, are for the most part low carbon irons or steels, to which sufficient chromium has been added to give them their desired corrosion resistant properties, and they are accordingly known as stainless irons or stainless steels. At room temperature they are not austenitic, instead, they have distinct air hardening properties and readily become martensitic.

Table III gives the reference name and chemistry of the five members of this group.

Table III

Symbol	Reference Name
F	Low Chrome Stainless Iron
G	High Chrome Stainless Iron
H	Stainless Steel
I	Low Chrome High Silicon Steel
J	27 Per Cent Chrome Iron

	F	G	H	I	J
Carbon	.11%	.10%	.09%	.39%	.20%
Silicon	.30	.86	.47	3.51	.36
Manganese	.45	.31	.47	.35	.80
Phosphorus	.020	.010	.022	.010	.025
Sulphur	.028	.011	.019	.011	.019
Nickel	.14	.23	.18	.22	.51
Chromium	13.22	17.60	12.40	2.25	26.94

In the above table, we have given the analysis of each individual bar that was used for making the test coupons for the creep investigation. In practice, it is customary to regulate a number of these elements between certain minimum and maximum values. As a result, different heats will analyze quite differently, and as would be expected, the physical properties will vary quite materially. Furthermore, the previous thermal or mechanical treatment will again alter the physical properties. Material J, for example, has an ultimate tensile strength, in the fully softened condition, between the limits of 75,000 and 100,000 pounds per square inch. By suitable heat treatment, the ultimate tensile strength of material F can be raised as high as 210,000 pounds per square inch. In Table IV we are showing the approximate minimum values in the fully softened state, of these five materials.

Table IV

	F & H	G & J	I
Tensile strength, lbs. per sq. in.	100,000	75,000	105,000
Yield point, lbs. per sq. in.	80,000	50,000	85,000
Elongation in 2″	25%	30%	45%
Reduction of area	62%	65%	55%

STEEL F

Low Chrome Stainless Iron

	Per Cent
Carbon	.11
Silicon	.30
Manganese	.45
Nickel	.14
Chromium	13.22

The original bar of this material showed a very fine pseudo martensitic structure as illustrated below. Apparently this is a hot finished, air cooled bar. The carbides are present in the form of a network.

The specimen that was held at 1100°F. for 5500 hours showed the same type of structure after this treatment

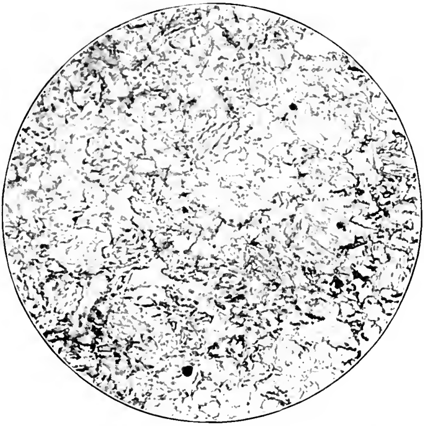

Fig. 25.—Original. 1496-17. 500 ×. Etchant—aqua regia and glycerine.

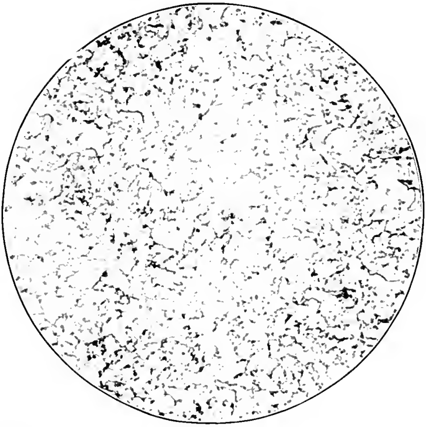

Fig. 26.—4600 hours at 1000°F. 1496-18. 500 ×. Etchant—aqua regia and glycerine.

as did the specimen held at 1000°F. for 4600 hours. Fig. 26 taken from the latter specimen, indicates that a certain amount of annealing and carbide solution has been brought about by this long time heating. After heating at 1200°F., the change is very pronounced and is in the nature of a recrystallization and a solution of the carbide network.

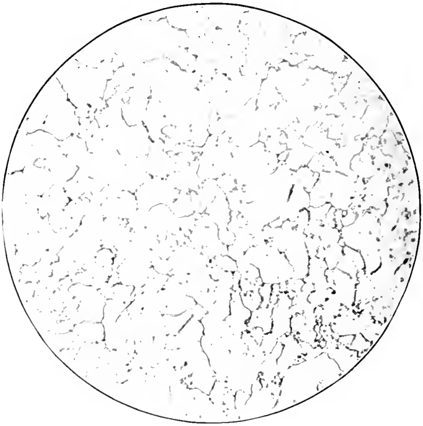

Fig. 27.—5900 hours at 1200°F. 1496-19. 500 Etchant—aqua regia and glycerine.

Aqua regia developed a pseudo martensitic structure in this Low Chrome Stainless Iron and we would, therefore, expect a high Rockwell value. As the test temperature was raised, the carbides went into solution and the matrix was steadily re-equiaxed—this is reflected in the Rockwell hardness.

Rockwell B

Original value	102.9
After heating at 1000°F	95.7
After heating at 1100°F	92.2
After heating at 1200°F	82.0

STEEL G

High Chrome Stainless Iron

	Per Cent
Carbon	.10
Silicon	.86
Manganese	.31
Nickel	.23
Chromium	17.60

The original condition of this material, as shown in Fig. 28, is that of a large grained chromiferrous iron matrix containing many elongated pearlitic or carbide areas and a few distinct carbides at the boundaries of these areas. As a result of heating for 4600 hours at 1000°F. or 5500 hours at 1100°F., these areas break up and many free carbides are absorbed. This condition, as found in the 1100° F. specimen, is well shown by Fig. 29.

The changes brought about by long time heating of this material lowered the Rockwell hardness.

Rockwell B	
Original value	86.3
After heating at 1000°F	85.7
After heating at 1100°F	82.5

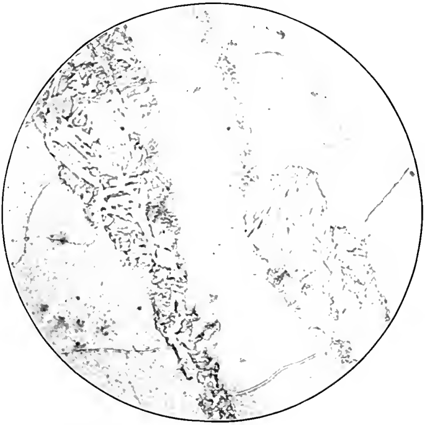

FIG. 28. Original. 1496-20. 500 ×. Etchant—aqua regia and glycerine.

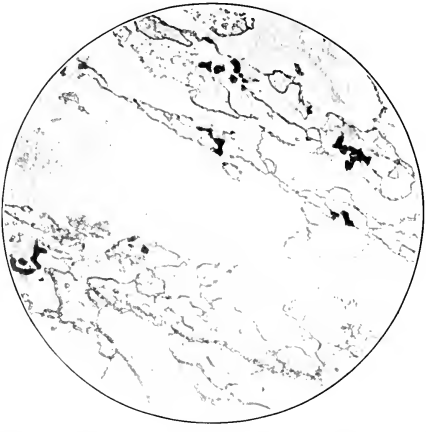

FIG. 29.—5500 hours at 1100°F. 1496-21. 500 ×. Etchant—aqua regia and glycerine.

STEEL H

Stainless Steel

	Per Cent
Carbon	.09
Silicon	.47
Manganese	.47
Nickel	.18
Chromium	12.40

Unfortunately none of the original material was available for microscopic examination. Chemically, this is very similar to steel F, and there is little doubt but that under the same conditions of previous mechanical and thermal treatment, the two structures would be identical. It is also to be expected that the effects of long time heating would be to produce structures of the same order. This is borne out by comparing Fig. 30, which illustrates the typical structure noted in the specimen of steel H, which had been heated at 1100°F. for 5500 hours, with Figs. 26 and 27, which show the typical structures of steel F after similar heating. Higher temperature tends to develop larger grains and almost complete solution of the carbides. This is to be noted in Fig. 31, which represents the structure present in the specimen heated at 1350°F. for 4300 hours.

The same softening was noted in this material as in material F.

Rockwell B

Original value	
After heating at 1100°F	92.7
After heating at 1350°F	71.5

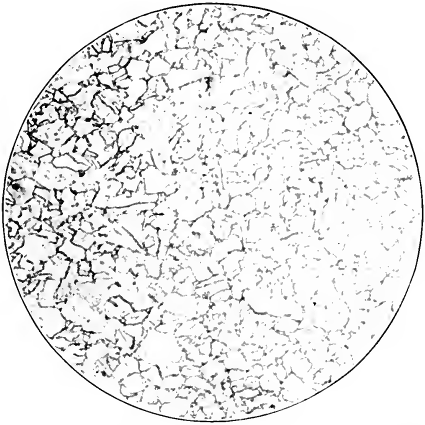

FIG. 30.—5500 hours at 1100°F. 1496-22. 500 ×. Etchant—aqua regia and glycerine.

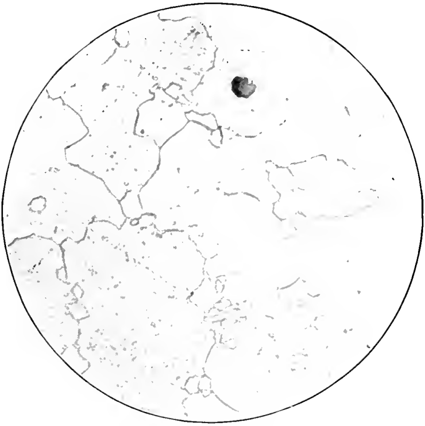

FIG. 31.—4300 hours at 1350°F. 1496-23. 500 ×. Etchant—aqua regia and glycerine.

STEEL I

Low Chrome High Silicon Steel

	Per Cent
Carbon	.39
Silicon	3.51
Manganese	.35
Nickel	.22
Chromium	2.25

The presence of 3.5 per cent silicon, with only a little over 2 per cent of chromium, places this material in a somewhat different class from the other members of this group, and judging from Figs. 32 and 33, this material is quite stable.

Specimens of this material, after 4600 hours at 1000°, 5500 hours at 1100°, and 4000 hours at 1200°F. respectively, were examined and no observable change was noted in them. In a fourth specimen, after 4300 hours at 1350°F., there is a slight indication of a small change, as can be noted in Fig. 33. All of these samples show innumerable small spheroidal carbide particles at the boundaries, as well as within the grains.

As noted, this material was not affected by heating and the changes in the Rockwell hardness are correspondingly small.

Rockwell B	
Original value	98.7
After heating at 1000°F	98.3
After heating at 1100°F	98.2
After heating at 1350°F	96.7

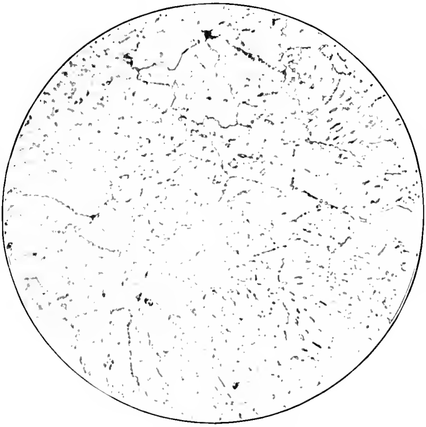

FIG. 32.—Original. 1496-24. 500 ×. Etchant—aqua regia and glycerine.

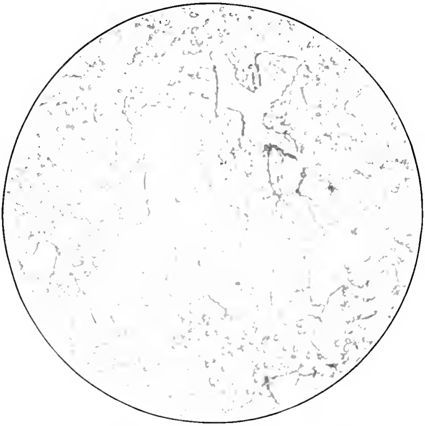

FIG. 33.—4300 hours at 1350°F. 1496-25. 500 ×. Etchant—aqua regia and glycerine.

STEEL J

27 Per Cent Chrome Iron

	Per Cent
Carbon	.20
Silicon	.36
Manganese	.80
Nickel	.51
Chromium	26.94

The large amount of chromium present in this material has such a marked effect on the transformation point that the gamma phase is completely eliminated. On heating, this material passes directly from alpha to delta iron.

We do not have any of the original material, and therefore we are unable to state whether the black masses noted after 4000 hours at 1200°F. were precipitated by this heating or whether they were in the material originally and only partly redissolved. Fig. 34 illustrates this condition at 100 diameters, and Fig. 35 illustrates the detail of the black particles when viewed at 1000 diameters.

Heating this material for 4300 hours at 1350°F. brings about an entirely different condition. The black masses have entirely disappeared, thus indicating that they were present in the original material. In place of these masses, we find a number of rather thin elongated envelopes which probably represent small pools of austenite formed around carbide particles where the carbon content is sufficiently high to permit of such a condition. This would indicate that they are not dissolved, instead, they have simply changed their characteristics so that they etch differently. Murakami's reagent shows uniform carbide distribution throughout all specimens.

On heating this material at 1500°F., we find that the black masses, as well as the envelopes, have completely disappeared and the matrix is now a uniform polyhedral grain, with the carbides uniformly dispersed as in the other specimens. As far as can be noted, no change has occurred in the carbides in any of these samples.

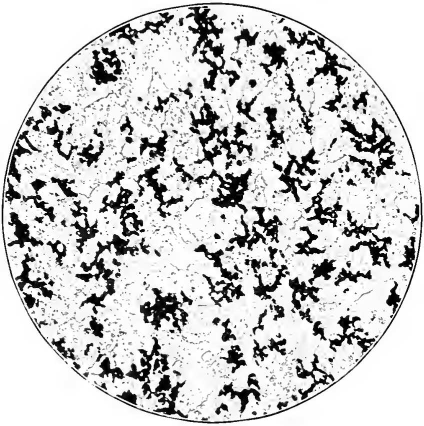

Fig. 34.—4000 hours at 1200°F. 1496-26. 100 ×. Etchant—aqua regia and glycerine.

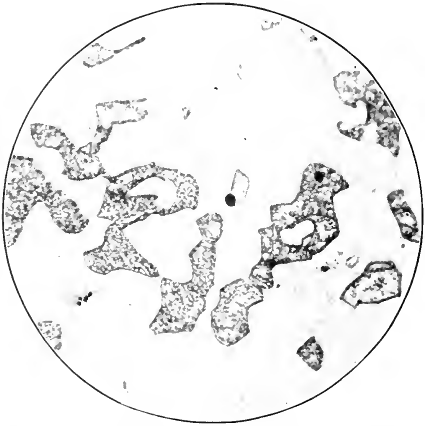

Fig. 35.—4000 hours at 1200°F. 1496-27. 1000 ×. Etchant—aqua regia and glycerine.

FIG. 36.—4300 hours at 1350°F. 1496-28. 500 ×. Etchant—aqua regia and glycerine.

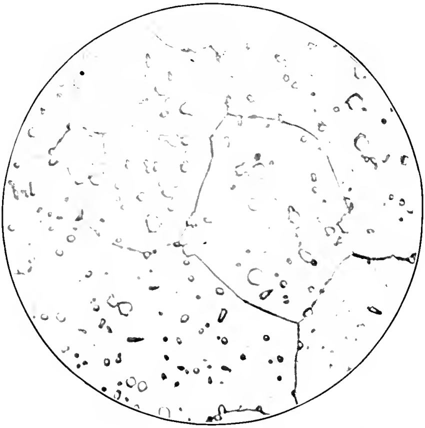

FIG. 37.—3000 hours at 1500°F. 1496-29. 500 ×. Etchant—aqua regia and glycerine.

The disappearance of the black masses is accompanied by a lowering of the hardness value, and as the grains are re-equiaxed, this value falls off a few more points.

	ROCKWELL B
Original value....................................	
After heating at 1200°F............................	95.5
After heating at 1350°F............................	88.3
After heating at 1500°F............................	86.8

Carbon and Alloy Steels.

The essential character of all the members of the third group is that they are pearlitic when in the annealed condition. This is due to the fact that the amount of alloying elements and carbon are too low to sufficiently change the temperature or rate of the transformation and, therefore, the carbon has an opportunity to become entirely pearlitic on slow cooling.

From the data included in Table V it can be noted that the seven steels making up this group cover a wide range of commercial pearlitic steels.

TABLE V

Symbol	Reference Name
K	.45 Per Cent Carbon Steel
L	3.5 Per Cent Nickel Steel
M	Chrome Nickel Steel
N	Chrome Vanadium Steel
O	.75 Per Cent Tungsten Steel
P	Special Pearlitic Steel
Q	2 Per Cent Tungsten Steel

	K	L	M	N	O	P	Q
Carbon........	.45%	.34%	.40%	.40%	.34%	.40%	.25%
Silicon........	.20	.19	.20	.25	.17	.25	.25
Manganese.....	.42	.57	.59	.62	.46	2.22	.57
Phosphorus....	.020	.039	.025	.023	.015	.020	.011
Sulphur........	.030	.031	.031	.035	.022	.021	.018
Nickel.........	.....	3.46	1.30	.....	.....	......	.22
Chromium......	.....	......	.66	.79	.....	......	.38
Tungsten......	.....	.....	......	.....	.74	....	1.95
Vanadium......	...	.....	.....	.57			

All of these materials were made by the acid open hearth process and were annealed by heating above the upper critical point followed by furnace cooling, and it was in this condition that they were subjected to the creep tests. The physical properties of these seven steels vary in the annealed condition. In the following table will be found the values obtained on a standard .505″ × 2″ gauge length coupon made from each bar of the original material.

TABLE VI

Symbol	Tensile strength, lbs. per sq. in.	Yield point	Elong. in 2″, per cent	Red. of area, per cent
K	77,550	41,330	28.5	40.3
L	89,600	57,500	26.5	47.5
M	98,690	57,000	26.0	57.8
N	97,250	65,500	28.0	59.6
O	80,100	48,500	23.0	34.3
P	97,090	59,000	20.0	60.4
Q	95,050	65,750	26.0	52.5

In the annealed state, the microstructure of these seven steels is, to all intents and purposes, thoroughly interspersed with grains of ferrite. The ratio of pearlite to ferrite grains varies with the individual samples, this, of course, being controlled by the carbon content and the amount of alloying element present. After the heating, irrespective of whether the temperature was 1000, 1100 or 1200°F., the only change to be noted is that of a thorough spheroidization of the pearlite. The exceptions noted being in the Chrome Nickel Steel, M, which was slightly spheroidized in the annealed condition. Long time heating failed to increase this spheroidization. Another exception is that of Chrome Vanadium Steel, N, where the carbides have coalesced into larger globules rather than remaining dispersed as very small particles, as in the other steels.

In Table VII will be found a record of the number of hours and the temperature at which the various specimens were tested, and on the following pages will be shown a series of photomicrographs representative of the conditions just discussed.

TABLE VII

Symbol	Temperature, °F.	Total time of test-hours
K	1000	1500
	1100	1700
	1200	1600
L	1000	1500
	1100	1700
M	1000	1500
	1100	1700
	1200	1600
N	1000	1500
	1100	1700
	1200	1600
O	1000	1500
	1100	1700
	1200	1600
P	1100	1700
	1200	1600
Q	1200	4000

STEEL K

FIG. 38.—Original. 1496-30. 500 ×. Etchant 4 per cent nital.

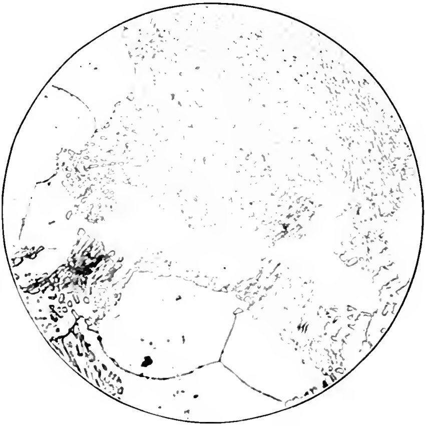

FIG. 39.—1700 hours at 1100°F. 1496-31. 500 ×. Etchant 4 per cent nital.

STEEL L

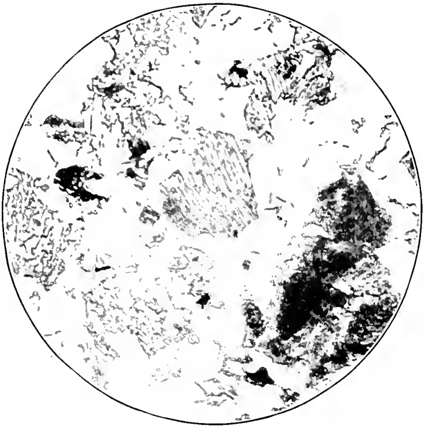

FIG. 40.—Original. 1496-32. 500 ×. Etchant 4 per cent nital.

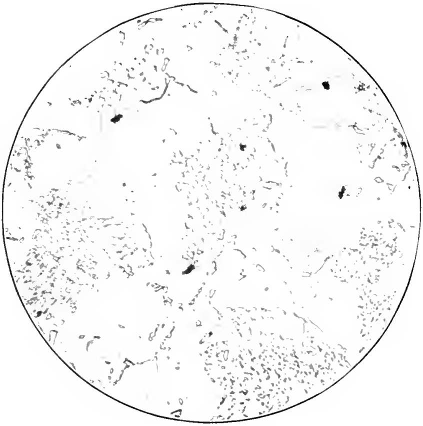

FIG. 41.—1700 hours at 1100°F. 1496-33. 500 ×. Etchant 4 per cent nital.

STEEL M

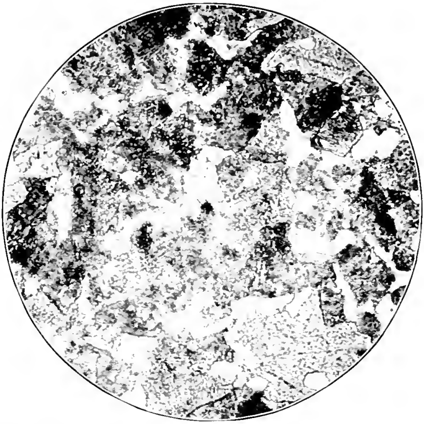

FIG. 42.—Original and heated condition. 1496-34. 500×. Etchant 4 per cent nital.

STEEL N

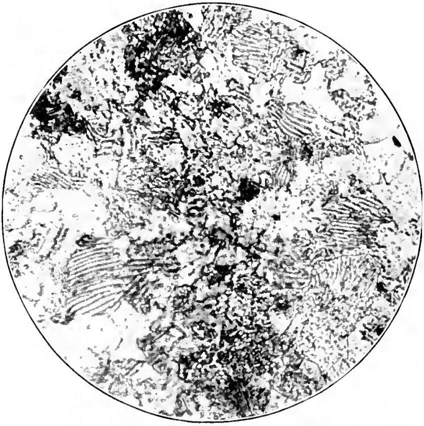

FIG. 43.—Original. 1496-35. 1000 ×. Etchant 4 per cent nital.

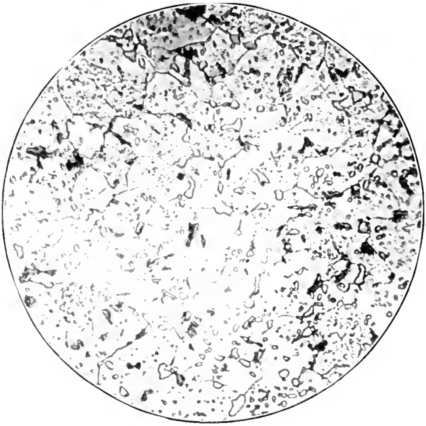

FIG. 44.—1600 hours at 1200°F 1496-36. 1000 × Etchant 4 per cent nital.

STEEL O

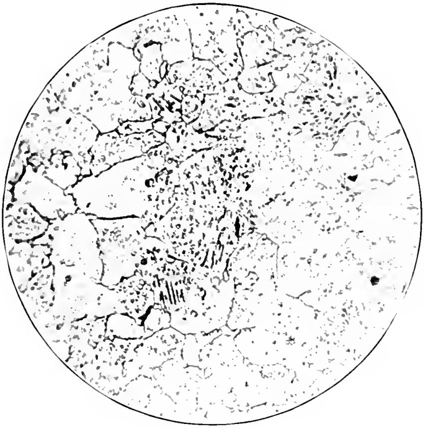

FIG. 45.—1700 hours at 1100°F. 1496-37. 1000 ×. Etchant 4 per cent nital.

STEEL P

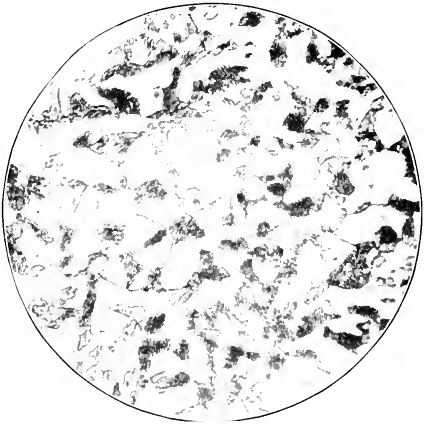

FIG. 46.—Original. 1496-38. 1000 ×. Etchant 4 per cent nital.

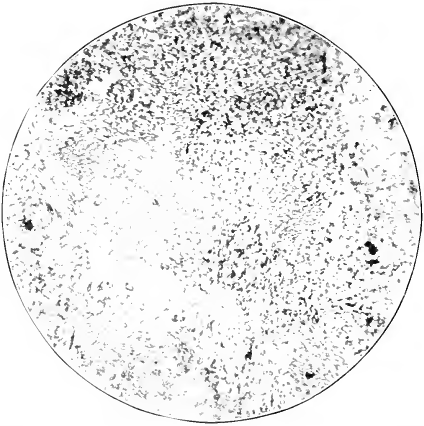

FIG. 47.—1700 hours at 1100°F. 1496-39. 1000 ×. Etchant 4 per cent nital.

Steel Q

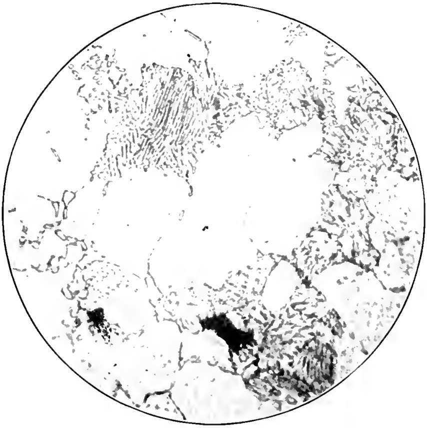

Fig. 48.—Original. 1496-40. 1000 ×. Etchant 4 per cent nital.

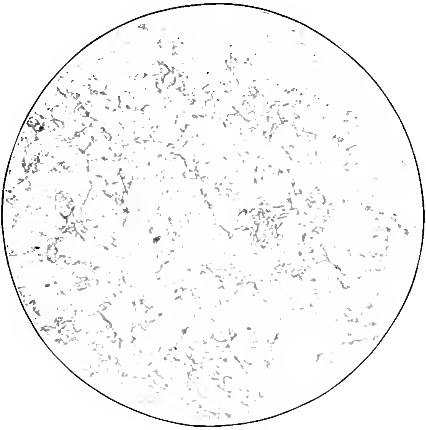

Fig. 49.—4000 hours at 1200°F. 1496-41. 1000 ×. Etchant 4 per cent nital.

CHAPTER VI

RESULTS

The rate of flow for the various specimens is shown in Figs. 50 to 54. As previously stated straight lines seemed to be the best representative curves.

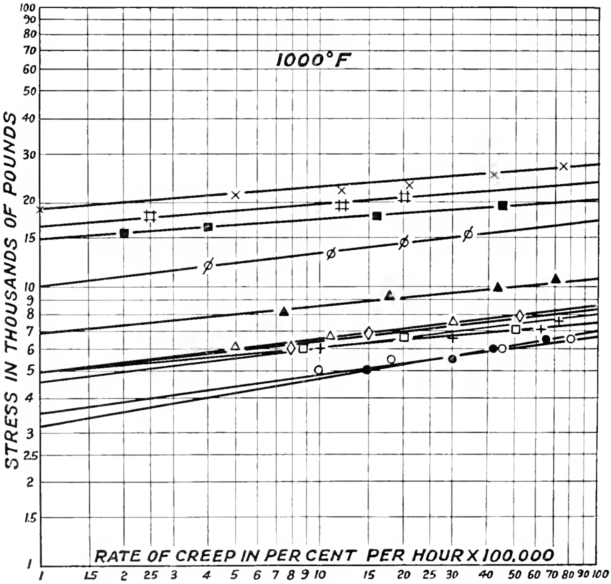

Fig. 50.

The stresses for a life of 100,000 and 10,000 hours with 1 per cent elongation, as taken from the preceding curves, are shown in Table VIII. These values are plotted in Figs. 55 and 56.

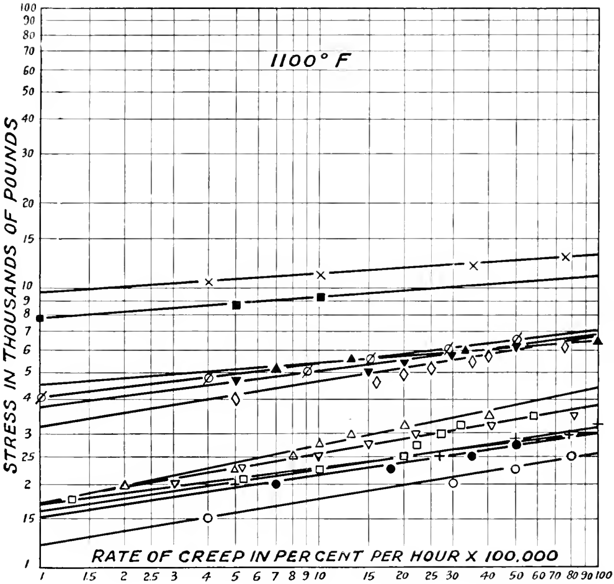
1100° F
STRESS IN THOUSANDS OF POUNDS
RATE OF CREEP IN PER CENT PER HOUR X 100,000
100
90
80
70
60
50
40
30
20
15
10
9
8
7
6
5
4
3
2.5
2
1.5
1
1
1.5
2
2.5
3
4
5
6
7
8
9
10
15
20
25
30
40
50
60
70
80
90
100

FIG. 51.

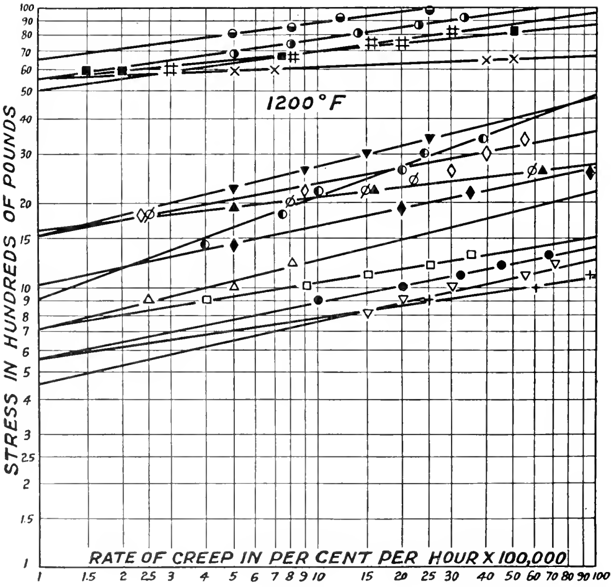
1200 °F
STRESS IN HUNDREDS OF POUNDS
100
90
80
70
60
50
40
30
20
15
10
9
8
7
6
5
4
3
2.5
2
1.5
1
RATE OF CREEP IN PER CENT PER HOUR X 100,000
1
1.5
2
2.5
3
4
5
6
7
8
9
10
15
20
25
30
40
50
60
70
80
90
100

FIG. 52.

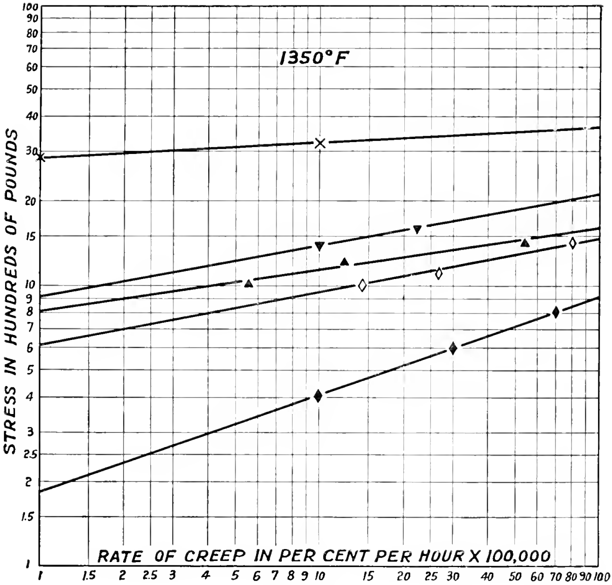
1350° F
STRESS IN HUNDREDS OF POUNDS
RATE OF CREEP IN PER CENT PER HOUR X 100,000
100
90
80
70
60
50
40
30
20
15
10
9
8
7
6
5
4
3
2.5
2
1.5
1
1
1.5
2
2.5
3
4
5
6
7
8
9
10
15
20
25
30
40
50
60
70
80
90
100

Fig. 53.

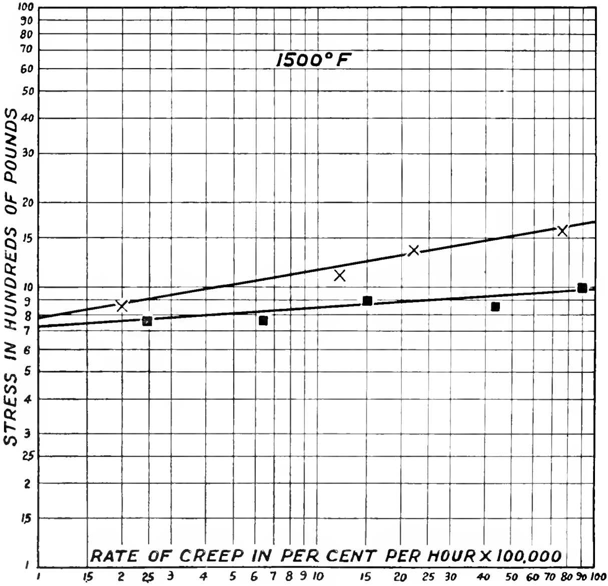
1500° F
STRESS IN HUNDREDS OF POUNDS
100
90
80
70
60
50
40
30
20
15
10
9
8
7
6
5
4
3
25
2
15
1
RATE OF CREEP IN PER CENT PER HOUR X 100,000
1
15
2
25
3
4
5
6
7
8
9
10
15
20
25
30
40
50
60
70
80
90
100

Fig. 54.

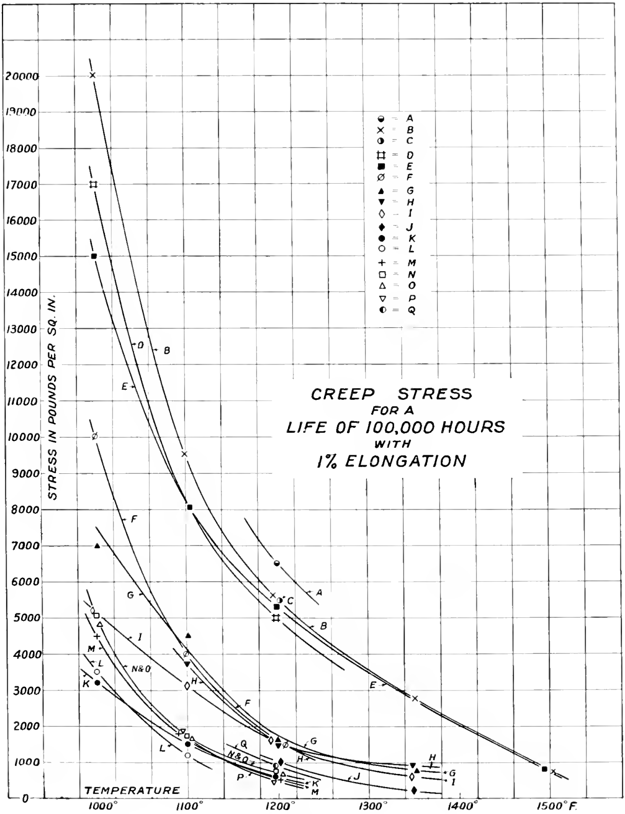
CREEP STRESS
FOR A
LIFE OF 100,000 HOURS
WITH
1% ELONGATION
STRESS IN POUNDS PER SQ. IN.
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
TEMPERATURE
1000°
1100°
1200°
1300°
1400°
1500° F.
◒ = A
× = B
◑ = C
⌗ = D
■ = E
Ø = F
▲ = G
▼ = H
◊ = I
♦ = J
● = K
○ = L
+ = M
□ = N
△ = O
▽ = P
◐ = Q
A
B
C
D
E
F
G
H
I
J
K
L
M
N&O
P
Q

Fig. 55.

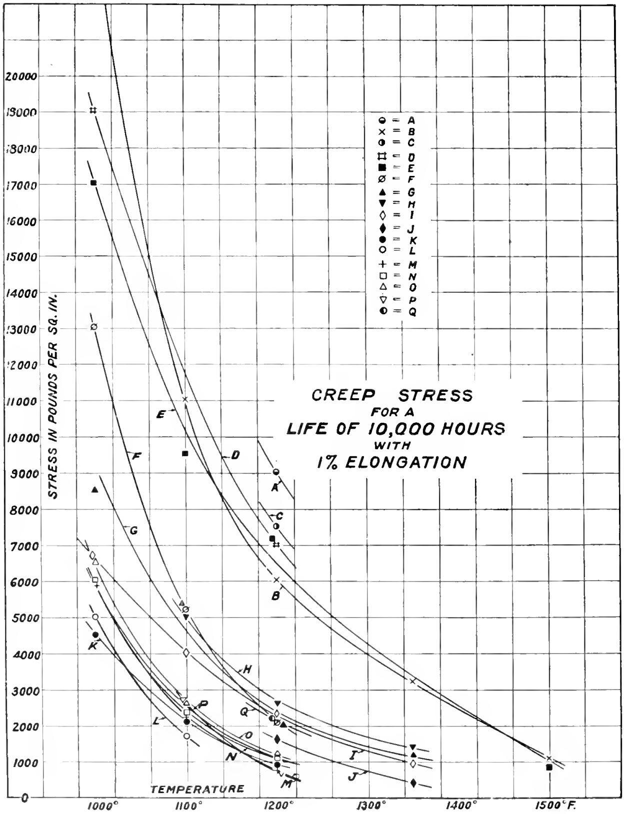
CREEP STRESS
FOR A
LIFE OF 10,000 HOURS
WITH
1% ELONGATION
⊖ = A
× = B
◑ = C
⌗ = D
■ = E
Ø = F
▲ = G
▼ = H
◊ = I
♦ = J
● = K
○ = L
+ = M
□ = N
△ = O
▽ = P
◐ = Q
STRESS IN POUNDS PER SQ. IN.
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
TEMPERATURE
1000°
1100°
1200°
1300°
1400°
1500°F.
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q

Fig. 56.

Table VIII.—Creep Stress in Pounds for a Life of 100,000 and 10,000 Hours with 1 Per Cent Elongation

Steel	1000°F.		1100°F.		1200°F.		1350°F.		1500°F.	
	100,000	10,000	100,000	10,000	100,000	10,000	100,000	10,000	100,000	10,000
A	......	......	.....	......	6,500	9,000				
B	20,000	25,000	9,500	11,000	5,500	6,000	2,800	3,200	750	1 100
C	.....	......	.....	.....	5,500	7,500				
D	17,000	19,000	.....	......	5,009	7,000				
E	15,000	17,000	8,000	9,500	5,500	7,000	.....	.....	750	850
F	10,000	13,000	4,000	5,200	1,600	2,100				
G	7,000	8,500	4,500	5,200	1,600	2,100	900	1,200		
H	......	......	3,700	5,000	1,500	2,600	900	1,400		
I	5,000	6,500	3,200	4,000	1,500	2,300	600	950		
J	......	......	.....	......	1,000	1,600	180	400		
K	3,200	4,500	1,500	2,100	550	900				
L	3,500	5,000	1,200	1,700						
M	4,500	6,000	1,600	2,200	550	750				
N	5,000	6,000	1,700	2,300	700	1,100				
O	5,000	6,500	1,700	2,600	700	1,200				
P	......	.....	1,700	2,600	450	750				
Q	......	......	......	.....	900	2,100				

CHAPTER VII

PRECISION OF THESE CREEP VALUES

It is somewhat difficult to give a definite figure for the precision of the creep results reported here because there are so many factors contributing to it. These may be enumerated as follows:

1. Uneven temperature distribution over the specimen.
2. Error in temperature readings.
3. Error in extension measurements.
4. Variation in specimens of same make of steel due to slight differences in composition, manufacture, etc.
5. Errors in plotting best representative curves.
6. Errors in assuming uniform flow throughout the life.

In several cases duplicate specimens were run and the agreement was better than 5 per cent. This does not, however, include any errors listed under (1), (4), and (6), and possibly under (3). It would seem safe to say that the creep loads can be relied on to within ±25 per cent, and that the relative values would be somewhat closer. It would not be advisable, however, to apply these results too rigorously to design until data is available from longer tests and from actual installations.

CHAPTER VIII

DISCUSSION OF RESULTS

The curves of flow rate in Figs. 50 to 54 show some interesting facts. While there are not a great many values actually showing a life of more than 10,000 hours, it would seem reasonable to extend the curves down to a life of 100,000 hours, because in the cases where values are available, the curves continue in a straight line. Whether or not these logarithmic curves will continue as straight lines to the lowest values of load or whether they become horizontal at some definite load, we are unable to determine from these data. However, it is thought that up to a life of 10,000 hours we have unquestionably a straight line when plotted on the logarithmic scale. If the straight line did continue indefinitely, we would have creep even at the lowest loads, as Dickenson has pointed out, but the life would be measured in thousands or millions of years.

The straight line on logarithmic paper represents an exponential function. If y is the flow rate in per cent per hour, x the stress in lbs. per sq. in. and m and n constants, the relation will be:

$$y = mx^n$$

m is represented by the intercept of the line on the y axis or the unit flow rate, while n is given by the tangent slope of the line. The values of n average 5 but range from 3 to 17. This indicates how enormously the rate of creep runs up with a slight increase in load.

If we were to make tests similar to the ones reported here, but with a testing time at one load of 4000 hours, instead of 400 hours, the rate of creep could be measured with ten times the present precision; and values could be obtained for much lower rates of creep, allowing the type of flow to be known much more accurately. The assumption is made in stating a value for maximum life under a given load, that the rate of creep remains constant throughout the life. This assumption is true where the creep rate is low for a testing time of perhaps as much as 1000 hours, and it seems reasonable to suppose that the same rate of creep would still continue for 10,000 or 100,000 hours if the maximum extension is limited to one per cent, which is the figure arbitrarily taken here.

It will be noticed that the straight lines in Figs. 50 to 54 have the same general slope. However, a few of the lines have a somewhat different slope from the average. For example, the tungsten steels at 1200°F. have a considerably greater slope than the average, whereas one of the austenitic steels at the same temperature has a comparatively low slope. There does not seem to be any particular significance in the change of slope, and no consistency can be traced between the different curves. Some of this change is undoubtedly due to errors in values and errors in plotting, but this will not account for the few cases where the change in slope is considerable. More data will be required before we can draw any conclusions concerning this. It seems reasonable that some steels would have different flow characteristics from others, and this would be shown by the slope of these curves.

There is little strain hardening shown at temperatures over 1000°F., although in some cases it occurs. With the apparatus used here the extension is not taken directly on the specimen itself so that we cannot determine the exact extent of the strain hardening, for the elastic elongation of the apparatus as a whole comes into the extension readings when the load is changed. That is, these tests show us the rate of creep, but not the exact amount of extension.

It will be noticed that the curves in Fig. 55 fall roughly into three groups: the lowest is carbon and alloy steels; the second, high chrome stainless steels; and the third and highest, austenitic steels. It is clearly evident that at temperatures above 1000°F. the so-called alloy steels are little superior to plain carbon steel although this statement of course would not apply to lower temperatures.

The steels of high chromium content show two to three times the creep resistance of low carbon steel, although there is a decrease in their resistance with a very high chromium content. This type of steel probably has no transformation point which may account for the unusual behavior.

The austenitic steels seem to be approximately alike in creep resistance, and have values about ten times that of low carbon steel at these temperatures. The fact is very striking, however, that the austenitic steels tested are entirely in a group by themselves in regard to creep resistance. This is an interesting point, and it is believed that it has not been brought out before.

At room temperatures austenitic steels are generally soft and ductile, but have the property of being easily work hardened. This is the reason why they are so difficult to machine and why they resist abrasion. At high temperatures this type of steel offers great resistance to plastic flow (compared with other steels) which would be quite unexpected when considering the properties at room temperature. The reason for this high temperature rigidity may be due to strain hardening even at the higher temperatures, or to the fact that the face-centered atomic structure gives more rigid crystals than the body-centered structure in the martensitic steels.

If the temperature is raised high enough nearly all steels will convert to the gamma form. It may be of interest to see if any of the steels tested here, while not austenitic at room temperature, are so under the conditions of test. The only specimen of the carbon and alloy steel group that might approach the transformation point at 1200°F. is Q with 2 per cent W. It is probable that these conditions would not produce an austenitic structure, but it is significant that this steel is the highest of the group.

As chromium raises the critical point, it is doubtful if any of the stainless steels are austenitic at 1350°F., the highest test temperature. In fact steel J with 28 per cent chromium, has creep values distinctly lower than others of the group, which may be due to the lack of any transformation temperature. It may be concluded that the only steels in the austenitic form, at the temperatures of test, were the stable high chromium nickel type. It may be mentioned, however, that a high speed steel tested at the Bureau of Standards had the same high temperature creep values as a high chromium nickel austenite. High speed steel would probably be austenitic at these temperatures.

While more data is necessary before conclusive statements can be made, it is fairly certain that creep resisting steels must be of the face-centered type (austenitic). Whether all austenites will give the same creep values, as indicated here, or whether other types will give somewhat lower or higher values cannot be decided until more work has been completed.

The selection of a steel for creep resistance above 1000°F. (not considering other factors such as corrosion, etc.) will be guided mainly by the creep value and the cost. An examination of the curves in Figs. 55 and 56 will lead at once to the conclusion that alloy steels, at perhaps twice the cost of carbon steels, are by no means proportionally better. Again, the stainless steels with a creep resistance of two to three times that of carbon steel cost ten to fifteen times as much. The austenitic steels (high chromium and nickel) have a creep resistance at high temperatures of about ten times that of carbon steel, and cost little more than the stainless steels. From the evidence we have here, there is little question but what the most economical materials to use from the point of view of creep are carbon and high chromium nickel steel, and when other factors such as scaling are considered, the latter is the only practical material.

CHAPTER IX

CREEP RESULTS OF OTHER EXPERIMENTERS

In Table IX are listed a number of steels on which creep data have been published, and in Figs. 57 to 59 these data are plotted.

One is struck at once with the great diversity of values for the same material. This is due for the most part to differences in method of test and inaccuracy in estimating a limiting value from too short a testing time. In a number of cases the testing time was so short that a uniform creep rate had probably not been established at the end of the test. In others the temperature and extension measurements have not had the precision of later tests. For these reasons it is difficult to make any direct comparisons. In general the more accurate the experimentation, the lower will be the estimated "limiting creep stress."

In the case of carbon steel there are a few values above 1000°F. to compare with the results obtained here. The values reported by French, as well as those of White and Clark, are in good agreement with ours. The results of Tapsell and Clenshaw, although at a lower temperature range, also appear in agreement. Other values are higher. In the case of other steels there is a fair agreement with the results of French. The results of other experimenters are in general higher. In some cases the difference is of the order of 10 to 1.

In most cases the stresses given are stated to be for an infinite life, but the precision of testing makes it impossible to really determine such a value. It is therefore attempted to give the life for an elongation of 1 per cent which is really represented by the stresses shown. These times can only be estimated from the data and methods of each experimenter and are only approximate.

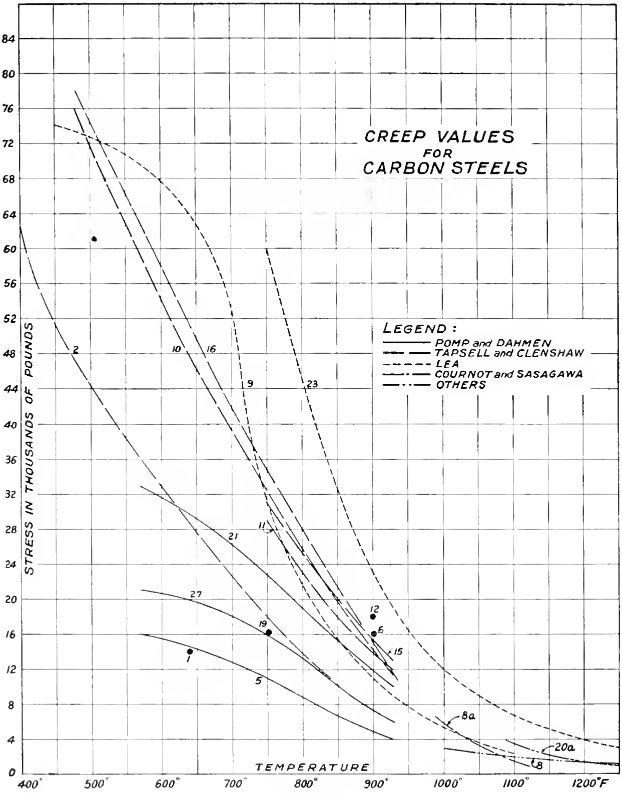
CREEP VALUES
FOR
CARBON STEELS
LEGEND:
POMP and DAHMEN
TAPSELL and CLENSHAW
LEA
COURNOT and SASAGAWA
OTHERS
STRESS IN THOUSANDS OF POUNDS
TEMPERATURE
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
400°
500°
600°
700°
800°
900°
1000°
1100°
1200°F
1
2
5
6
8
8a
9
10
11
12
15
16
19
20a
21
23
27

Fig. 57.

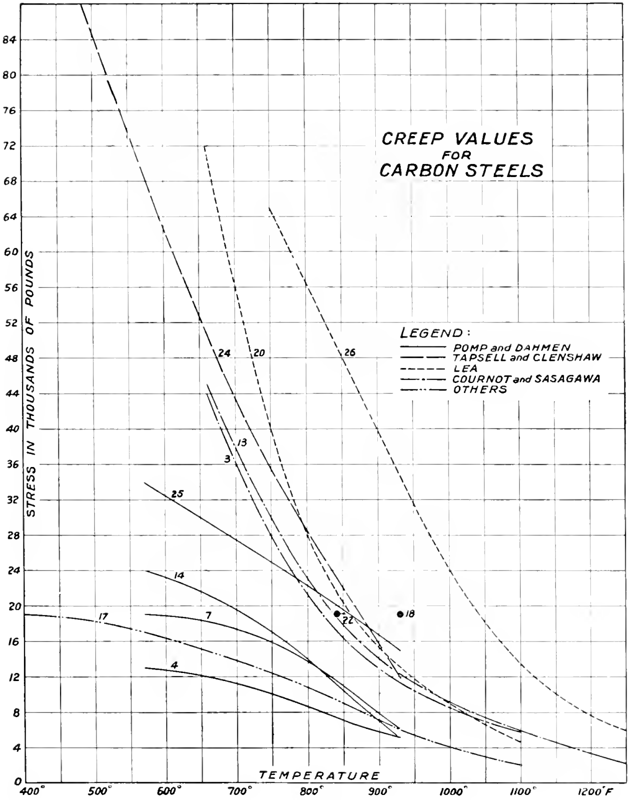
CREEP VALUES
FOR
CARBON STEELS
LEGEND:
POMP and DAHMEN
TAPSELL and CLENSHAW
LEA
COURNOT and SASAGAWA
OTHERS
STRESS IN THOUSANDS OF POUNDS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
TEMPERATURE
400°
500°
600°
700°
800°
900°
1000°
1100°
1200°F
24
20
26
13
3
25
14
17
7
4
22
18

Fig. 58.

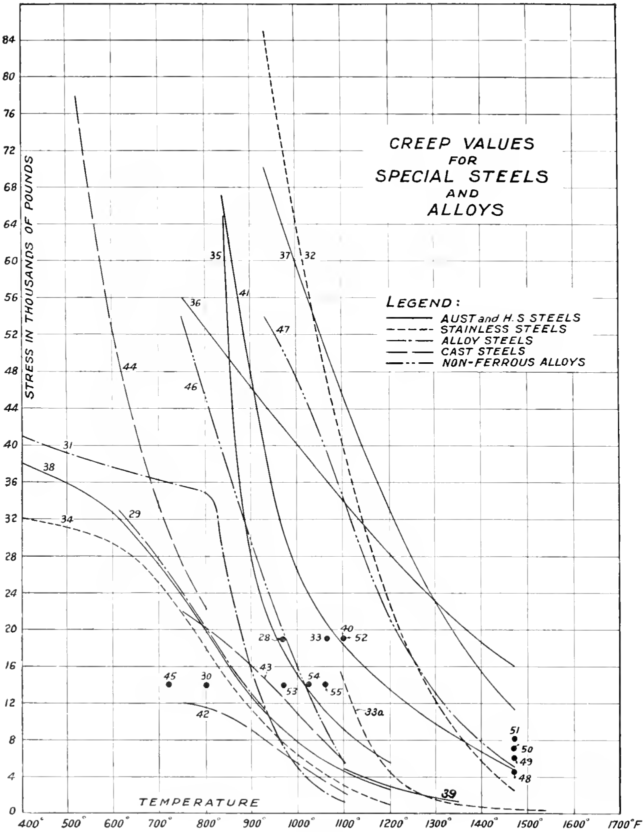
CREEP VALUES
FOR
SPECIAL STEELS
AND
ALLOYS
LEGEND:
AUST and H. S STEELS
STAINLESS STEELS
ALLOY STEELS
CAST STEELS
NON-FERROUS ALLOYS
STRESS IN THOUSANDS OF POUNDS
TEMPERATURE
84
80
76
72
68
64
60
56
52
48
44
40
36
32
28
24
20
16
12
8
4
0
400°
500°
600°
700°
800°
900°
1000°
1100°
1200°
1300°
1400°
1500°
1600°
1700°F
35
37
32
41
36
47
44
46
31
38
29
34
28
33
40
52
43
45
30
54
53
55
33a
42
39
51
50
49
48

Fig. 59.

Tapsell and Clenshaw	10,000 to 100,000 hrs.
French.	10,000 hrs.
Cournot and Sasagawa.	5,000 hrs.
Pomp and Dahmen.	2,000 hrs.
Dickenson.	2,000 to 10,000 hrs.

TABLE IX

No.	Composition	Authority	Reference
	CARBON STEELS		
1	Electrolytic Iron	Chevenard	2
2	Armco Iron	Tapsell	55
3	.04 C. Steel	Cournot & Sasagawa	10
4	.05	Pomp & Dahmen	41
5	.06	Pomp & Dahmen	41
6	.08–.12	Jasper	52
7	.11	Pomp & Dahmen	41
8	.13	White & Clark	30
8a	.13	Clark & White	57
9	.14	Lea	6
10	.17	Tapsell & Clenshaw	45
11	.20	Tapsell & Clenshaw	45
12	.20–.30	Jasper	52
13	.22	Cournot & Sasagawa	10
14	.23	Pomp & Dahmen	41
15	.23	Tapsell & Clenshaw	45
16	.24	Tapsell & Clenshaw	45
17	.24	French	51
18	.30	Dickenson	3
19	.32	Lea	6
20	.37	Lynch et al.	14
20a	.38	Clark & White	57
21	.40	Pomp & Dahmen	41
22	.45	Dickenson	3
23	.45	Lea	6
24	.51	Tapsell & Clenshaw	46
25	.58	Pomp & Dahmen	41
26	.75	Lea	6
27	1.00	Pomp & Dahmen	41
	Alloy Steels		
28	3.6% Ni	Dickenson	3
29	3.2% Ni	Pomp & Dahmen	41
30	4.2% Ni, 1.6% Cr	Chevenard	2
31	.2% Ni, .87 Cr	French Et. Al.	51

TABLE IX.—(*Continued*)

Stainless Steels

32	10.3% Cr, 2.6% Si	Cournot & Sasagawa	10
33	14.7% Cr	Dickenson	3
33a	Enduro Metal	Clark & White	57
34	20.5 Cr	French Et. Al.	51

No.	Composition	Authority	Reference
	Austenitic Steels		
35	Hadfield "Hecla"	....	31
36	High Nickel Chromium	Lea	6
37	63% Ni, 14% Cr	Cournot & Sasagawa	10
38	23% Ni, 18% Cr	French Et. Al.	51
	High Speed Steels		
39	13.6% W, 1.9% Va	French Et. Al.	51
40	17.4% W	Dickenson	3
41	13.6% W	Cournot & Sasagawa	10
	Cast Steels		
42	Cast Carbon Steel	Malcolm	15
43	Cast Ni-Cr Steel	Malcolm	15
44	Cast Carbon Steel (0.53)	Tapsell & Clenshaw	46
	Non Ferrous Alloys		
45	99% Ni	Chevenard	2
46	70% Ni, 30% Cu (rolled)	N.P.L.	28
47	80% Ni, 20% Cr (rolled)	N.P.L.	45
48	90% Ni, 10% Cr (cast)	N.P.L.	45
49	80% Ni, 20% Cr (cast)	N.P.L.	45
50	70% Ni, 30% Cr (cast)	N.P.L.	45
51	60% Ni, 40% Cr (cast)	N.P.L.	45
52	Ni-Cr alloy (cast)	Dickenson	3
53	85% Ni, 15% Cr	Chevenard	2
54	77% Ni, 23% Cr	Chevenard	2
55	9% Cr, 6% W, 86% Ni	Chevenard	2

CHAPTER X

APPLICATION OF CREEP VALUES TO DESIGN

When designing a structure for use at the higher temperatures, the usual theories of stress determination based on the assumption of perfect elasticity do not apply. There is need of more complete methods of computing stresses in plastic materials. The chief difference between the conditions in elastic and plastic materials is that the points of highest stress concentration are less in the latter due to an equalization by gradual flow. As far as our present knowledge goes, stresses determined in the usual manner will be on the safe side.

Creep values may be applied to design by selecting a value corresponding to the desired life and extension. In view of the variation in creep values, due to the sources of error previously discussed, it is suggested that two-thirds of the experimental value be used. As our data becomes more precise a higher figure can be taken, especially if the laboratory data can be correlated with service results. Great care must be taken to determine accurately the actual maximum temperature of use. In some cases the rate of flow for a given stress is doubled for a rise of 25°F.

In cases where the metal under stress is hotter on one side than on the other it is obviously unnecessary to reduce the stress to the value safe for the hot side, for the cooler metal is comparatively rigid. Unfortunately, we have very little information concerning problems of this nature although they are somewhat analogous to the design of high temperature refractory walls and crowns, where the inner face is in a plastic condition and the load is taken by the rigid outer face.

The selection of a suitable steel for high temperature requires the consideration of properties other than creep resistance. In practically every case the metal must be resistant to furnace gases and oxidizing conditions. While certain coatings offer increased resistance to oxidation, it has been found that, for structures assembled from a number of parts, an unbroken coating is difficult to maintain, which makes it necessary to have a resistant material. Another essential quality is permanence of structure. Excessive grain growth or temperature hardening must be guarded against. Resistance to wear, coefficient of expansion, and ease of working are desirable but less important properties.

Although there may be some exceptions that we do not know of, it seems quite clear at present that no previous treatment will alter the long time properties of steel above 1000°F. A long heating above this temperature will efface any previous history. The material, therefore, can be used in the condition best suited for manufacture.

CHAPTER XI

CONCLUSIONS

The results obtained on steels at temperatures over 1000°F. lead to the following conclusions:

1. The face-centered structure of the austenitic steels seems to offer a distinctly greater resistance to creep than the body-centered type.
2. The high chromium, high nickel type of austenitic steel seems to offer by far the most advantages in regard to creep resistance, heat resistance, and permanency of structure.
3. The so-called alloy steels offer little advantage in creep resistance over carbon steel.
4. The high chromium stainless steels have distinctly inferior creep resistance as compared with austenitic steels.
5. An increase in chromium content in stainless steel above 18 per cent seems to decrease the creep resistance.
6. No evidence is found for a cessation of creep as the load is decreased, and the flow rate seems to decrease with the load in an exponential manner.

CHAPTER XII

BIBLIOGRAPHY

The following bibliography abstracts the more important articles concerning the flow of metals. There are many early articles by physicists dealing with this subject, but they are not included here because they would not be of primary interest to the engineer and because the earlier tests were not continued for a sufficient length of time to give accurate flow rates.

1921

1. E. L. Dupuy, An experimental investigation of the mechanical properties of steels at high temperatures. J. Iron and Steel Inst., 104, II, p. 91. This article discusses rapid tests on steels up to high temperatures, but contains no creep values.

1922

2. P. Chevenard, Comptes Rendus, 175, p. 486.—This short article gives creep data on nickel and its alloys at one temperature.
3. J. H. S. Dickenson, The flow of steels at a red heat, Engrn., 114, p. 326, p. 378.—The above paper considers the creep of steels, giving a description of the apparatus used and data at one stress on a number of steels.

1924

4. F. A. Fahrenwald, Some principles underlying the successful use of metals at high temperatures. Proc. A.S.T.M., 24, II, p. 310.—The author discusses the composition and use of metals at high temperatures as well as the flow of metal under long continued loads. Some data from service tests are included.
5. H. J. French and W. A. Tucker, Available data on the properties of irons and steels at various temperatures. Proc. A.S.T.M., 24, II, p. 56.—This paper is a compilation of data on the properties of iron and steel at high temperatures with some creep values.
6. F. C. Lea, Effect of low and high temperatures on materials. Proc. Inst. Mech. Engrs., 2, p. 1053.—Very complete tests are made on the various mechanical properties of steel over a wide range of temperatures. This is one of the first investigations where the value of long time tests is realized. The influence of strain hardening is also discussed.
7. V. T. Malcolm, Methods of testing at various temperatures. Proc. A.S.T.M., 24, II, p. 14.—This is a summary of the history of high

temperature testing and considers the apparatus as well as the methods used. It contains no creep values.

1925

8. R. W. Bailey, Creep of metals at high temperatures. Eng., 119, p. 518.—This is a discussion of flow in steel and its relation to steam power plant design.
9. J. S. Brown, The influence of the time factor in tensile tests conducted at elevated temperatures. J. Inst. Metals, 34, p. 21, also Engr., 120, p. 297, p. 461.—This paper describes creep tests on several non-ferrous metals.
10. J. Cournot and K. Sasagawa, Contribution à l'ètude de la viscosite des alliages à temperature élevèe. Rev. Met. Mem., 22, p. 753, also Comptes Rendus, 181, p. 661.—The flow of several steels is studied at various temperatures. The specimens are in the form of wires and the duration of the test is not long, but the extension is measured precisely. The apparatus and method of test is fully described.
11. H. J. French and W. A. Tucker, Flow in a low carbon steel at various temperatures. B.S. Tech. Papers, No. 296.—The apparatus and methods used at the Bureau of Standards for creep testing are fully described. Results are given on a carbon steel and the flow characteristics are discussed.
12. R. H. Greaves and J. A. Jones, J. Iron and Steel Inst., 112, p. 123.—A careful investigation is made on the effect of temperature upon impact values. A few slow speed tension values are given.
13. T. McLean Jasper, Typical static and fatigue tests on steel at elevated temperatures. Proc. A.S.T.M., 25, II, p. 27.—This paper discusses methods of testing but little creep data are given.
14. T. D. Lynch, N. L. Mochel and P. G. McVetty, The tensile properties of metals at high temperatures. Proc. A.S.T.M., 25, II, p. 5.—Data on the tensile properties of various materials at temperatures up to 930°F. are collected. Some data on long time tests are given.
15. V. T. Malcolm, Metallurgical developments in the valve and fitting industry. Journ. A.S.M.E., 47, p. 1141.—The apparatus of a certain company is described and the importance of creep tests pointed out. Values are given for two cast steels.
16. A. L. Mellanby and W. Kerr, Trans. N. E. Coast Inst. of Engrs. and Shipbuilders, V. 41, P. 243.—The authors bring out clearly the effect of temperature and time on the useful strength of metals. They also go fully into the possibilities of steam plant design using the best available materials.
17. H. F. Moore and T. McLean Jasper, An investigation of the fatigue of metals. Bull. 152, Eng. Expt. Sta., Univ. of Ill.—Fatigue and tensile data are given for a number of materials up to 1200°F. but includes no actual creep values.
18. L. W. Spring and J. Kanter, Accuracy in high temperature testing of materials. Power, 62, p. 325.—Testing methods are described with particular reference to temperature uniformity in the specimen.

19. A. Pomp, strength properties of steel castings at higher temperatures. Giesserei-Zeitung, 22, 5, p. 124.—Tensile tests on steel castings at temperatures from 20 to 500°C.

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20. R. W. Bailey, Note on the softening of strain hardened metals and its relation to creep. J. Inst. Metals, 35, p. 27.—The author points out the relation between rate of softening of work hardening by heat and the rate of creep.
21. H. J. French, Methods of test in relation to flow in steels at various temperatures. Proc. A.S.T.M., 26, II, p. 7.—Long time tests are made on low carbon, stainless and high speed steel, and the data correlated with short time tests. The limiting creep stress above the strain hardening range is shown to coincide with the proportional limit at the same temperature.
22. S. H. Inberg and P. D. Sale, Compressive strength and deformation of structural steel and cast-iron shapes at temperatures up to 950°C. Proc. A.S.T.M., 26, II, p. 33.—Tests are described on structural steel and cast-iron shapes at high temperatures. The proportional limit and the effect of duration of loading is described but no actual creep data are included.
23. W. Kerr, Failure of metals by creep. Trans. Inst. of Engrs. and Shipbuilders in Scotland, 69, p. 319.—This is a most interesting paper. The author first reviews carefully the work of the experimenters in the creep field, and compares and interprets their results. Then he considers the theory of flow and attempts to set up an equation so that the creep limit can be found by substituting the values from two short time tests. The discussion of this paper is also of interest.
24. P. G. McVetty and N. L. Mochel, The tensile properties of stainless iron and other alloys at elevated temperatures. Trans. A.S.S.T., 11, No. 1, p. 73.—The tensile properties of annealed stainless iron at temperatures up to 500°C. are discussed and compared with similar properties of seven other materials. Requirements of apparatus are discussed with special reference to the necessity of refinement of stress and strain measurements.
25. W. Rosenhain, The use of metals at high temperatures. Metallurgist, 2, Jan. 29, 1926, p. 2.—The application of creep data to design is considered, with special reference to the allowable stresses in structures where the temperature varies from one side of the metal to another.
26. H. Shōji, On the plasticity of metals. Science Reports, Tôhoku Imp. Univ., 15, p. 427.—Plastic flow is defined and the flow characteristics of a number of the softer metals are studied at room temperature.
27. H. Shōji and Y. Mashiyama, On the plasticity of metals at high temperatures. Science Reports, Tôhoku Imp. Univ., 15, p. 442.—The flow characteristics of cadmium, tin and lead are studied up to their melting point.
28. H. J. Tapsell and J. Bradley, The mechanical properties at high temperatures of an alloy of nickel and copper with special reference to creep.

J. Inst. Metals, 35, p. 75.—Creep and other data are given for a copper-nickel alloy.

29. G. Welter, Statische Dauerfestigheit von Metallen und Legierungen. Zeit. Metallkunde, 18, Mar. and Apr. 1926, p. 75 and p. 117.—A large number of tests are described on the long time strength of metals and alloys at atmospheric temperatures and the results compared with the ordinary mechanical properties.
30. A. E. White and C. L. Clark, Properties of boiler tubing at elevated temperatures determined by expansion. Trans. A.S.S.T., 11, No. 1, p. 73.—The object of this investigation was to determine the safe working loads for low carbon steel tubes from 900° to 1500°F., but the data are rather incomplete. It is pointed out that at the higher temperatures creep occurs much below the proportional limit.
31. Some special steels. Engr., 141, p. 407.—This article discusses two special steels and their adaptations. Some creep data are included.
32. Furnace Steels. Engineering and Boiler House Review, 39, p. 430.—This paper has one creep value.
33. Modern heat resisting steels. Mech. World, 80, p. 59.—A description is given of recent developments with regard to some heat resisting steels with some data on creep stress.
34. Safe stresses at high temperatures. Metallurgist, 2, July 30, 1926, p. 104.—An anonymous article gives creep data on a number of steels tested by others.

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35. R. W. Bailey, Design at plant for high temperature service. Engrn., 124, p. 44.—The author believes, and offers proof from the results of others, that there is no limiting creep stress but that creep continues at the lowest loads but at an immeasurably small rate. He then applies this conclusion to design and shows that in many cases a plastic condition is more favorable than an elastic one.
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41. A. Pomp and A. Dahmen, Entwicklung eines abgekurtzten prufverfahrens zur ermittlung der dauerstandtfestigheit von stahl bei erhöhten temperaturen. Mitt. a. d. Kaiser-Wilhelm-Inst. f. Eisenforchung zu Dussel., IX, No. 3.—This is an extensive article on creep measurements. The work of others is reviewed with a description of their testing apparatus. Creep data on several steels are given although the length of test at one load was only a few hours. The limiting creep stress is compared with the elastic limit.

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43. F. Schleicher, Tension conditions at flow limits. Zeit. Angewandte Mathematik U. Mechanik, 6. No. 3, p. 199.—The author surveys previous hypotheses for flow state and shows lack of accord with actual conditions. He proposes a new hypothesis which he says is in better agreement with recent data.

44. L. W. Spring, H. W. Maack and J. Kanter, Testing flow in metals at various temperatures. Power, 65, p. 205.—The creep test apparatus used by one investigator is described. The methods of testing and the theory of flow are discussed.

45. H. J. Tapsell and W. J. Clenshaw, Properties of metals at high temperatures—I, Mechanical properties of Armco Iron, 0.17 per cent carbon steel, and 0.24 per cent carbon steel with special reference to creep. Dept. of scientific and industrial research, Engineering Research, special report No. 1, published under authority of His Majesty's Stationery Office—Comprehensive tests are described on the mechanical properties of low carbon steels. The value of creep tests is discussed and considerable data are given. A good list of references and creep results by other experimenters are given.

46. H. J. Tapsell and W. C. Clenshaw, Properties of metals at high temperatures—II, Mechanical properties of 0.51 per cent carbon steel and 0.53 per cent carbon cast steel. Dept. of scientific and industrial research, Engineering Research, special report No. 2, published under authority of His Majesty's Stationery Office.—The mechanical properties are discussed and some creep data are included.

47. A. E. White and C. L. Clark, Properties of ferrous metals at elevated temperatures as determined by short-time tensile and expansion tests. A.S.M.E. advance paper for December meeting.—Discusses short-time tests on high chrome as well as carbon steels.

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49. J. L. Cox, Some effects of heat on the physical properties of steel. Trans. A.S.S.T., 14, p. 225.—This paper describes the phenomena occurring in tensile tests of steel with rising temperatures, together with the appearance and effects of creep. It discusses the application to design of experimental results and gives a short description of manufacturing methods.
50. F. B. Foley, On the significance of the proportional limit at elevated temperatures. Trans. A.S.S.T., 13, p. 813 and p. 822.—A study to establish some definite relation between the proportional limit at room temperature and at high temperature. The strain at the proportional limit and the thermal expansion are used.
51. H. J. French, H. C. Cross, and A. A. Peterson, Creep in five steels at different temperatures. B.S. Tech. Papers, No. 362.—Creep tests are made on five types of steel up to 1350°F. with more than the usual understanding of the difficulties involved. The creep results were compared with the proportional limit values on the same steels and the agreement was good up to temperatures of 1000°F. Thereafter the creep stress for long life tends to become lower than the proportional limit.
52. T. McLean Jasper, Strength of steels at elevated temperatures with particular reference to factor of safety. Power, 67, p. 446.—This article discusses safety factors and design for high temperature steel structures. Creep values for two low carbon steels are given.
53. F. Kërber, Ermittlung der dauerstandfestigkeit von stahl bei erhéhlen temperaturen. Zeit. für Metallkunde, 20, Feb. 1928, p. 45.—The flow of various metals is described with particular reference to strain hardening and rate of flow. Most of the tests were run but a few hours. A creep test apparatus is described.
54. A. Pomp, Das verhalten von stahl gegenüber dauerbelastungen bei erhöhten temperaturen. Chemische Fabrik (Berlin), No. 5, Feb. 1, 1928, p. 53.—A brief article on the flow of steel at high temperatures is given.
55. H. J. Tapsell, Properties of materials at high temperatures, 3—Note on the "creep" of Armco iron. Dept. of scientific and industrial research, Engineering Research, special report No. 6 published under authority of His Majesty's Stationery Office.—The creep of iron is studied particularly at temperatures below 400°F. Strain hardening and temperature softening are discussed in relation to creep.
56. G. Welter, Ermüdung durch kritische statische dauerbelastung. Zeit. für Metallkunde, 20, Feb. 1928, p. 51.—The flow of several metals is studied when loaded for long periods at stresses about equal to the yield point and the elastic limit. Most of the work is done at room temperature but some interesting results are obtained. The testing apparatus is described
57. C. L. Clark and A. E. White, The stability of metals at elevated temperatures. Eng. Res. Bull., Univ. of Michigan.—The authors compare the creep stress in long time tests with the proportional limit in short

tests. At low temperatures the agreement is good, but at high temperatures they find no definite limiting creep value. They believe that at a certain temperature the strength of the crystals is equal to that of the boundaries. Above this temperature the amorphous boundaries are the weaker and below it the crystals yield first.

APPENDIX

Since the preparation of the text of this book additional creep values have become available, and it is thought that it might be advisable to include them here. The values mainly consist of runs at 900° and 1000°F. on some of the specimens previously tested. In addition, three carbon

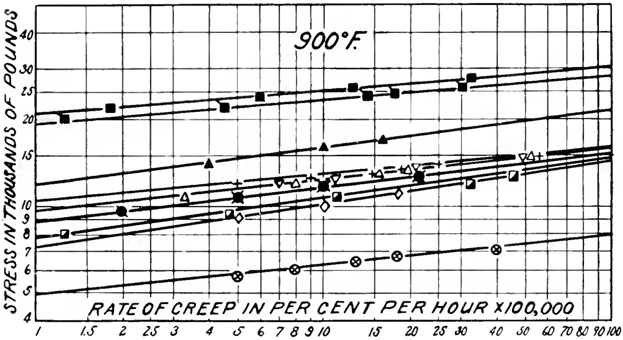

Fig. 60.

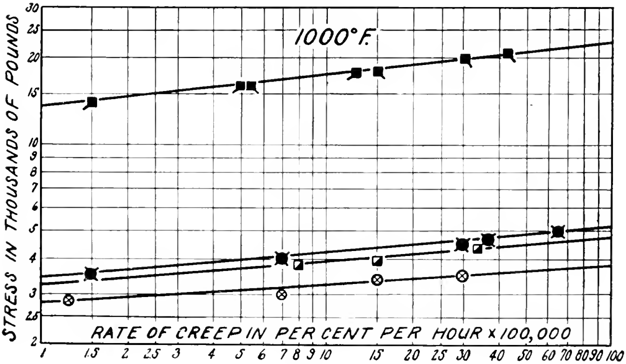

Fig. 61.

steels with varying carbon content were tested at these two temperatures. Specimens of steel E in three cases were re-run at a lower temperature than the initial test in order to see if the long maintained condition of temperature and stress had influenced their resistance to creep.

The curves of rate of creep are shown in Figures 60 and 61. and the results are summarized in the following table:

TABLE X.—CREEP STRESS

Life with 1% elongation		100,000 hrs.		10,000 hrs.	
Steel	Symbol	900°F.	1000°F.	900°F.	1000°F.
E	■	20,500	....	25,000	
E (rerun at 1000°F.)	▜	19,500	....	23,500	
E (rerun at 1100°F.)	▛	....	13,500	....	17,500
E (rerun at 1200°F.)	▟	....	13,500	....	17,500
G	▲	12,000	....	16,000	
M	+	10,500	....	13,000	
P	▽	9,600	....	12,500	
O	△	9,600	....	12,500	
.42% Carbon Steel	✖	8,800	3,500	11,500	4,200
.20% Carbon Steel	◩	7,800	3,200	10,500	3,900
.08% Carbon Steel	⊗	4,900	2,800	6,300	3,300
I	◇	7,200	....	10,000	

The results show, as would be expected, a considerable increase in strength at 900°F. over the results obtained at 1000°F. Even at this temperature the alloy steels have little advantage over the carbon steels. In agreement with other experimenters the results show that increasing the carbon content increases the creep resistance, at least up to .42 carbon. Specimens of steel E, which were re-run, show slightly lower creep resistance than originally, but the difference is small enough to be included in the experimental error.

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