THE PROPERTIES OF METALS.

A STUDY OF THE INFLUENCE OF TIME EFFECTS ON THE TENSILE STRENGTH AT HIGH TEMPERATURES.

By

ALEXANDER SEIVEWRIGHT CLARK, B.Sc., A.R.T.C.

(Thesis presented in compliance with the regulations for the Degree of Doctor of Philosophy of the University of Glasgow.)

The Royal Technical College, Glasgow.

March, 1928.

INDEX.

ABSTRACT:

This is an investigation on tensile testing dealing with the serious weakening effect which occurs at elevated temperatures and which is only realized when the metal is stressed for a prolonged period. The extension of the metal in these prolonged tests has been designated "Creep" or "Flow". The rate at which the metal extends may be scarcely detectable but if it persists, it will ultimately cause failure. The stress, if any, at which this creep ceases is known as the "Creep Limit Stress". The most direct methods for estimating this stress are very tedious and an effort has been made to materially shorten the test. A consideration of evidence given by various investigators, leads to certain definite conclusions, and from these is devised a development of the "Progressive Stress Test" which reduces the time to determine the limit stress to about a fortnight. Certain prolonged tests on wires at normal temperature, supply further evidence of this time effect. They also show that there are only two phases of creep. An "Initial Creep" which represents the gradual stabilising of conditions within the metal, if the final condition is perfect stability the creep ceases, giving the creep limit; but if the final condition is instability, the second phase "Final Creep" commences, this producing continued reduction in cross sectional area till failure takes place. The creep limit stress is not yet an established fact, but in practice the acceptance of a restricted life prevides a working limit stress.

THE PROPERTIES OF METALS.

A STUDY OF THE INFLUENCE OF TIME EFFECTS ON THE TENSILE STRENGTH AT HIGH TEMPERATURES.

INTRODUCTION:-

Of recent years there has been considerable engineering development, particularly so in the generation of power and in various chemical processes. Advances in these fields have led to the use of all structural materials under increasingly severeconditions, and possible progression has been hindered by the lack of sufficiently robust material. Possibly the factor mitigating most against the desired progression has been that of temperature. The steam turbine designer in his striving for better efficiencies has pushed working pressures and temperatures higher and higher, and has simultaneously taken his materials problems into a new and difficult zone. The rapid progress in chemical engineering has created a demand for plant to withstand very severe temperatures and pressures, sometimes such, that only the acceptance of a limited life for the article provides a satisfactory solution of the difficulty.

The effect of temperature on the direct tensile strength is very well known, the metal generally maintains its normal strength up to some temperature characteristic of its class, above this temperature there is a fairly rapid decrease in strength, with increasing temperature, till the metal has no useful resistance remaining. These strength-temperature values are simply obtained, the material, when in the testing-machine, is heated to the desired temperature and broken after the usual fashion. This method has now been in vogue for many years and is merely a normal test with the refinement of being made at a high temperature.

Since it was developed from the cold test where the rate of testing had practically no significance so no heed was taken of the factor time in these tests. This time factor has probably been set aside as it was troublesome, also, as a quickly conducted test showed the material in a favourable light.

Time effects have been observed by different investigators in the last thirty years or more, but it has only been in the last seven or eight years that they have been especially investigated, and with such effect that it is clearly evident that the time factor cannot be neglected in high temperature materials testing or in plant design.

The obvious effects of time are simple and easily grasped. A stress which a heated metal might survive when tested in the usual fashion might cause it to rupture if it were applied for a sufficient time. Again, at some high temperature, some stress will cause fracture in say a fraction of a second and as the stress is reduced the time to fracture lengthens, till the time required will ultimately be measured in years. It may be observed that stress and temperature are interchangeable, an increase in temperature having the same effect as an increase in stress and vice versa.

The failure of the metal with time is apparently due to a "Creep" or "Flow" which occurs. The main creep phenomenon is that some stress and temperature will produce a continuous stretching in a material, this ultimately causing fracture. For any definite temperature it is observed that different stresses produce different continuous creep rates, the rate diminishing as the stress is reduced, generally at some stress the creep apparently ceases. It is this cessation of creep which has given rise to the idea of a Creep Limit Stress, that is, the stress at which there is no continuous creep.

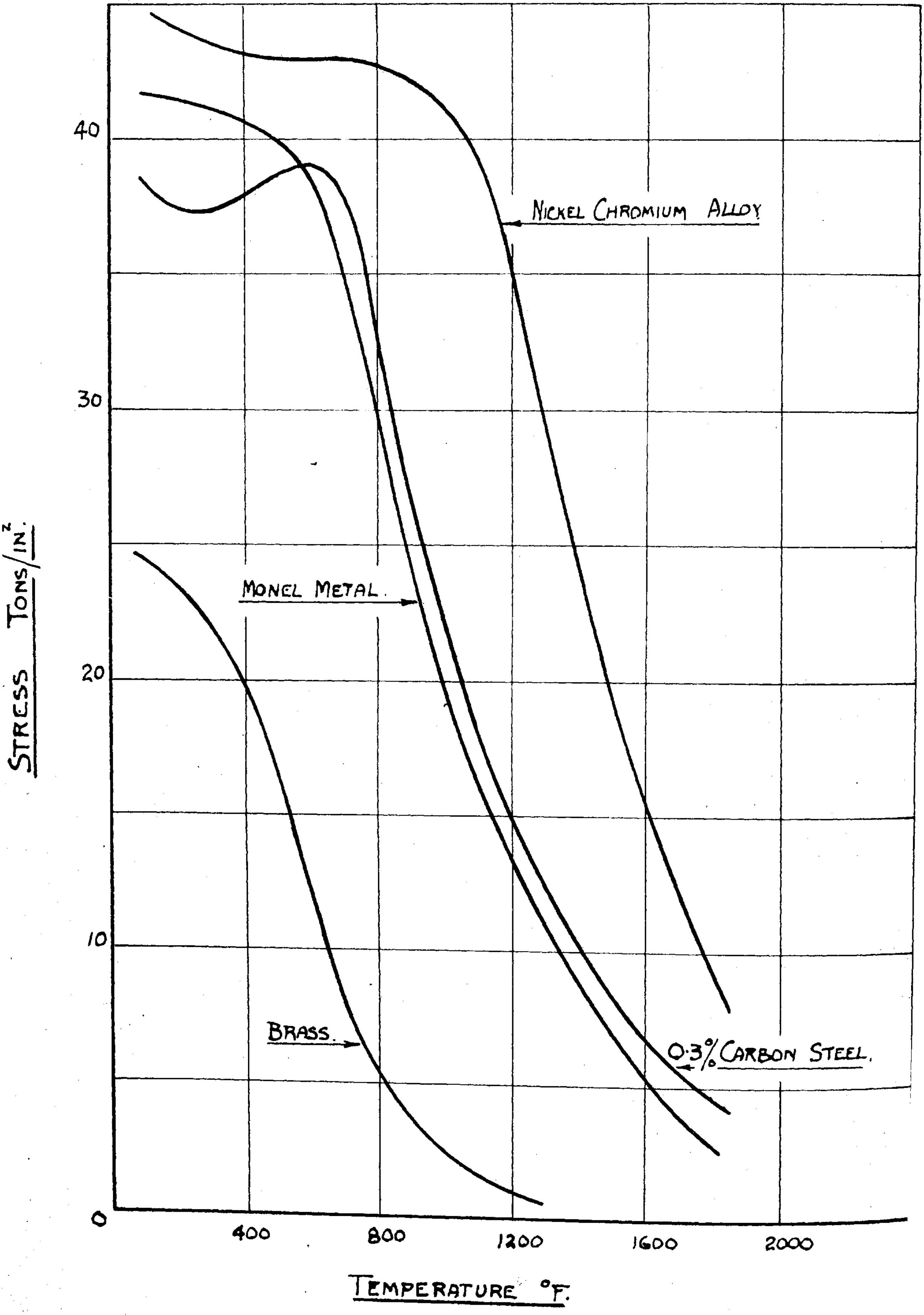
Flow is somewhat analagous to fatigue, the length of life in each case increasing as the severity of the conditions are reduced. As in designing structures subjected to fatigue actions so in the high temperature stress ranges, it is useful to have limiting values to work to. The ideal limit is one which provides for infinite life, but since this is not generally required, and in some cases is rendered impossible by other factors, it is convenient to raise the limit values and accept a restricted life. A knowledge of the change of the average creep rate with change in stress or temperature will then provide a variety of life contingencies.

Several methods have been employed for prolonged high temperature tensile tests , the combined results of which reveal the simplicity of the creep results and the complexity of the creep process. No one investigator has covered the complete field, but a survey of the various results, and also, of some of the criticisms of these results and the methods of obtaining them, supplies the main feature of the creep process. From the review a special method of making high temperature tensile tests has been devised so that the creep limit for any temperature may be estimated after about a fortnight's test, and with the expenditure of one test specimen. This method is a development of the Progressive Stress Test and the following is an account of this development worked up on a series of metals both ferrous and non-ferrous.

DIRECT STRENGTH-TEMPERATURE RELATION:-

The ordinary stress-temperature testing has provided familiar data, generally given in curve form as in Fig.(1). The same characteristics are shown by all the metals

FIG. 1.



DIRECT STRENGTH — TEMPERATURE.

considered. There is a retention of normal strength from normal temperature up to some critical temperature, beyond which the strength diminishes rapidly with increase of temperature, the material having ultimately no useful strength remaining. The test method employed to obtain these curves is very simple. The test-piece is placed in an ordinary testing machine and heated by some means, generally by an electric furnace. On the desired temperature being attained the test is proceeded with as usual.

Such tests occupy little time in actually breaking the metal, the breaking time ranging from a few seconds to about one hour depending on the testing machine and the information desired. If the ratesof loading were diminished it would be found that the strength values obtained would also diminish, so that the curves in Fig.(1) would require to be sheared down in order to show strength values which would result in prolonged life.

PROLONGED TESTS:-

It is only recently that the vital importance of the time factor has been realized, but time effects have been observed in earlier experimental work both at normal and high temperatures.

In 1899, Prof. Muir, in his paper "Recovery of Iron from Overstrain", described a time effect and made reference to forward and backward creeping. He wrote, "Iron strained beyond the yield when subjected to a small stress will elongate more than it would if in the primitive state and a slight continued elongation - a "Creeping" - may occur after the load has been applied. If this load be withdrawn a quite appreciable permanent, or semi-permanent, set will be found to have been produced; a set which diminishes slightly and, if small, may vanish provided time be allowed for backward creeping to take effect." (1).

NICKEL-CHROME STEEL.

FIG. 2.

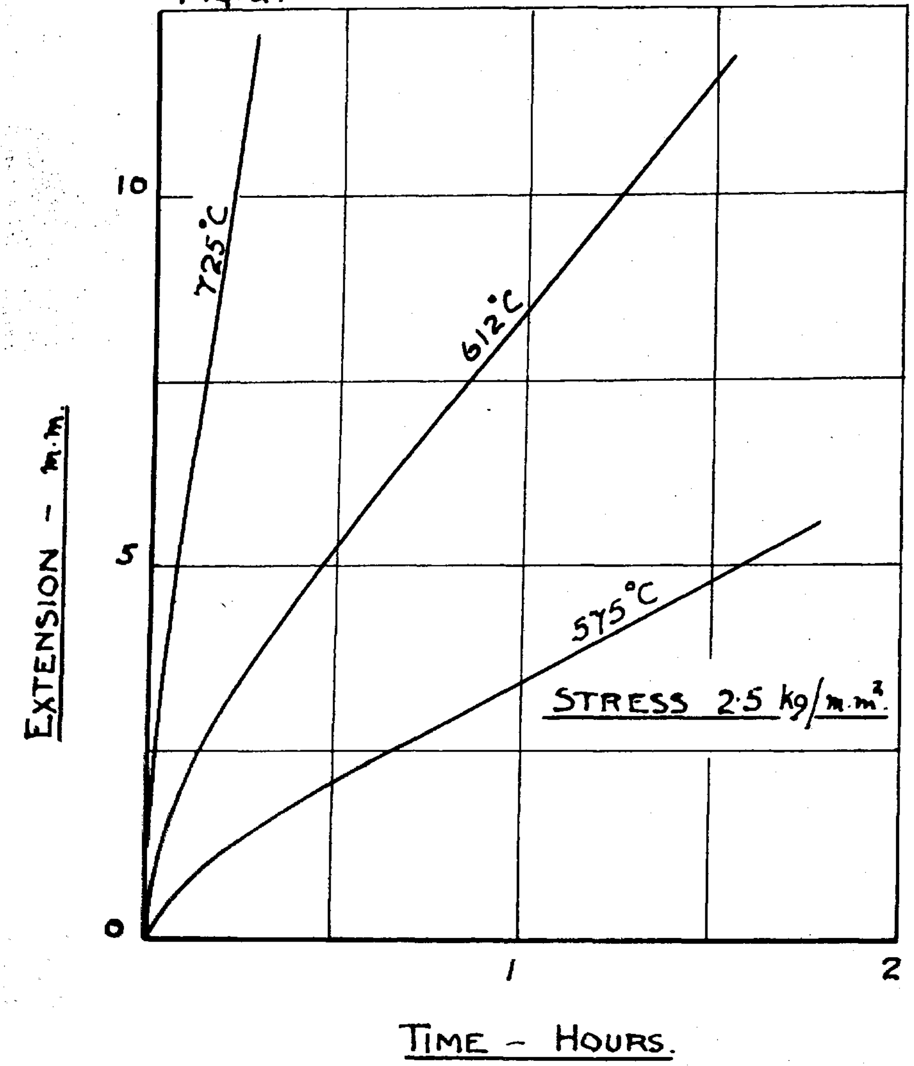
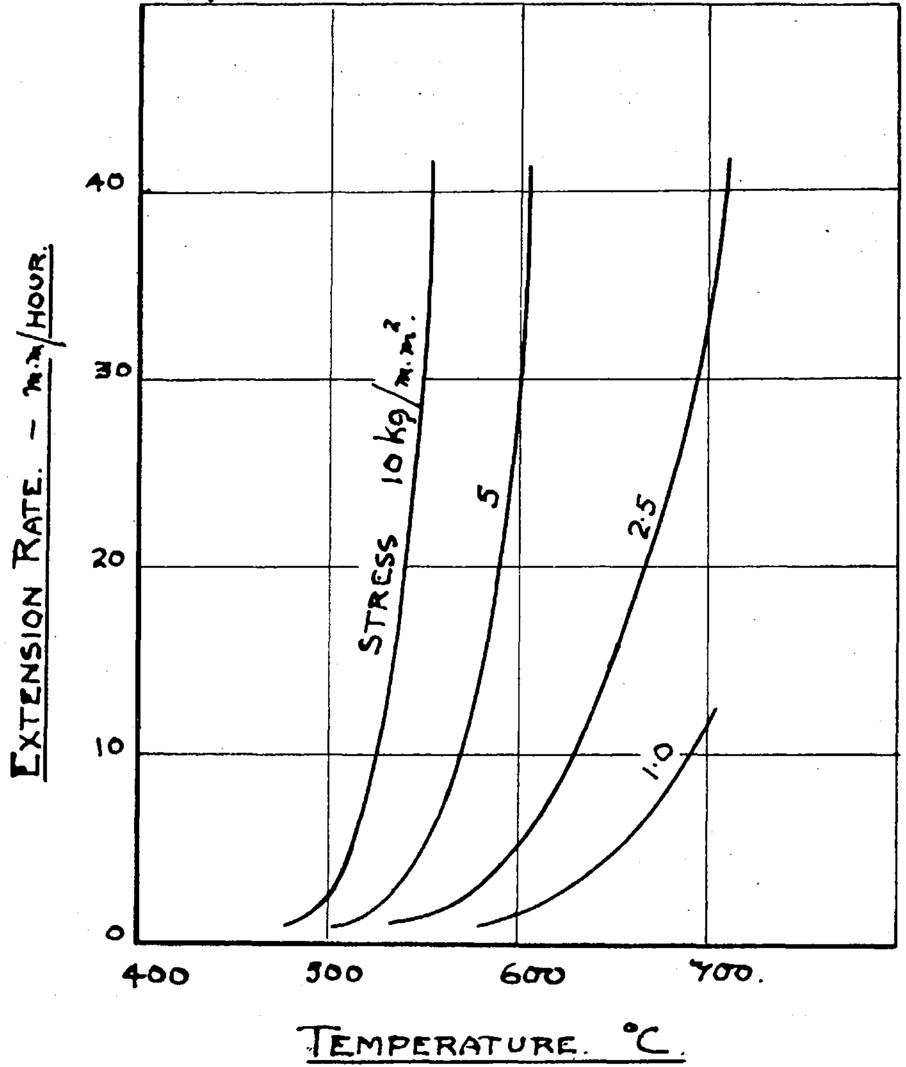


FIG. 3.



Describing elastic limit tests in 1905, Hopkinson reported forward and backward creeping, especially at high temperatures where the elastic limit is very low (2).

Some long duration tests on wires were described by Prof. Barr in 1910, (3), some of the tests being made at normal temperature on steel. Two extreme tests show that with a loading rate high enough to cause fracture in one minute the ultimate stress was 21 tons/in^2., and where the loading prolonged the test for twenty-two hours the ultimate stress was 19 tons/in^2., about 90% of the quick test value.

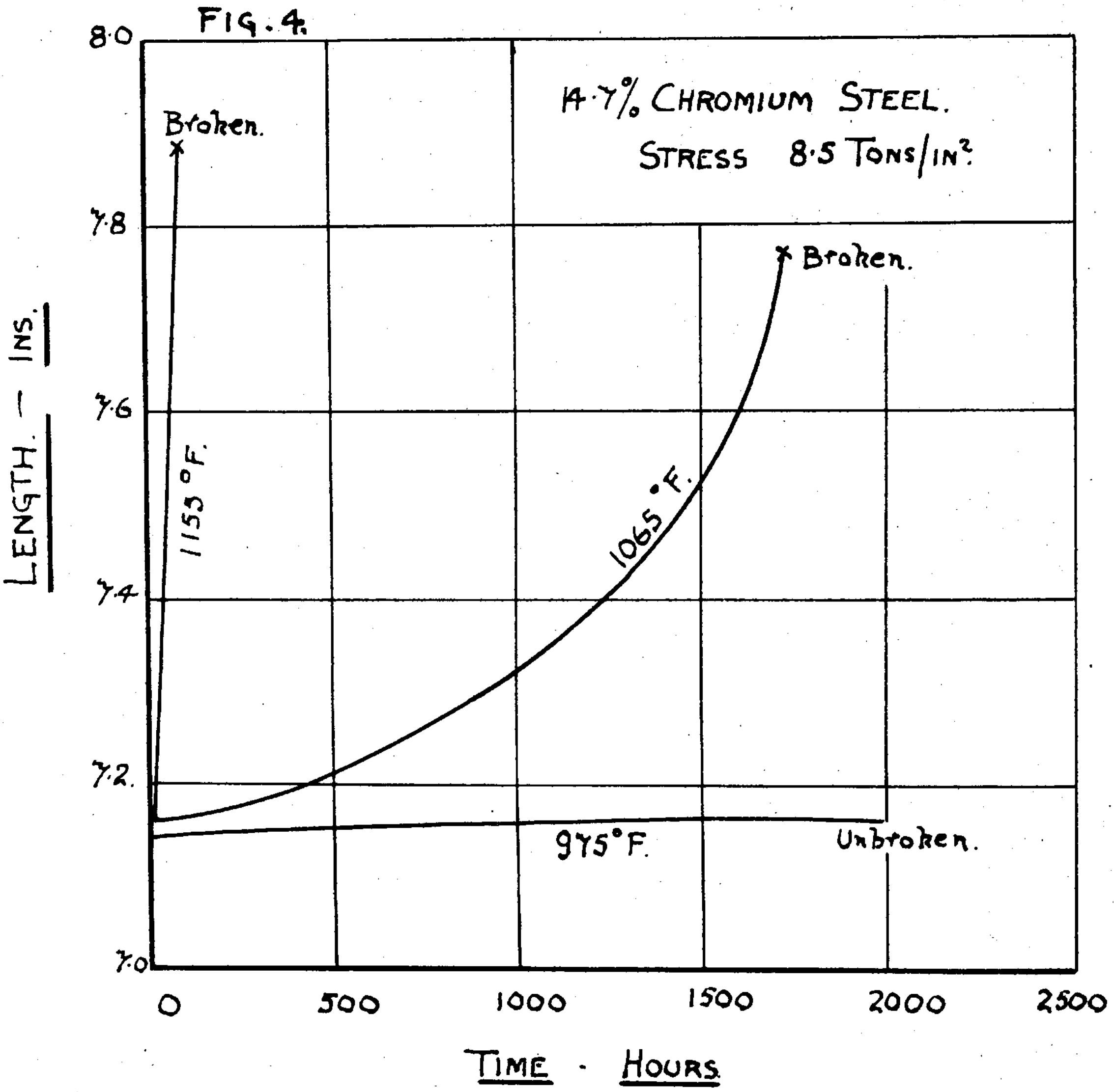
In an investigation on the deformation of soft steel at high temperatures, Rosenhain and Humfrey, 1913, observed that as the straining rate was reduced the breaking strength was lowered. (4).

Prof. P. Chevenard (5) was the first of the moderns to study the time effect, his main object being to classify certain steels according to their rigidity at elevated temperatures. The testing times were very short being of a few hours duration only, but the extension results are very distinctive. The extension or creep curves he obtained are similar to those in Fig. 2. They show a rapid initial extension which gradually slows and ultimately settles down to an apparently steady rate. Chevenard measured these final creep rates and plotted them with the corresponding temperature as in Fig. 3. These curves clearly indicate, by their approach to the axis of zero creep rate, a series of stress-temperature values which will not produce continuous creep. The accuracy of these tests is enhanced as the number and duration of the tests in the region of no continuous creep are increased. The curves also illustrate that

---

<u>Note</u>: Numbers in parenthesis refer to the bibliography.

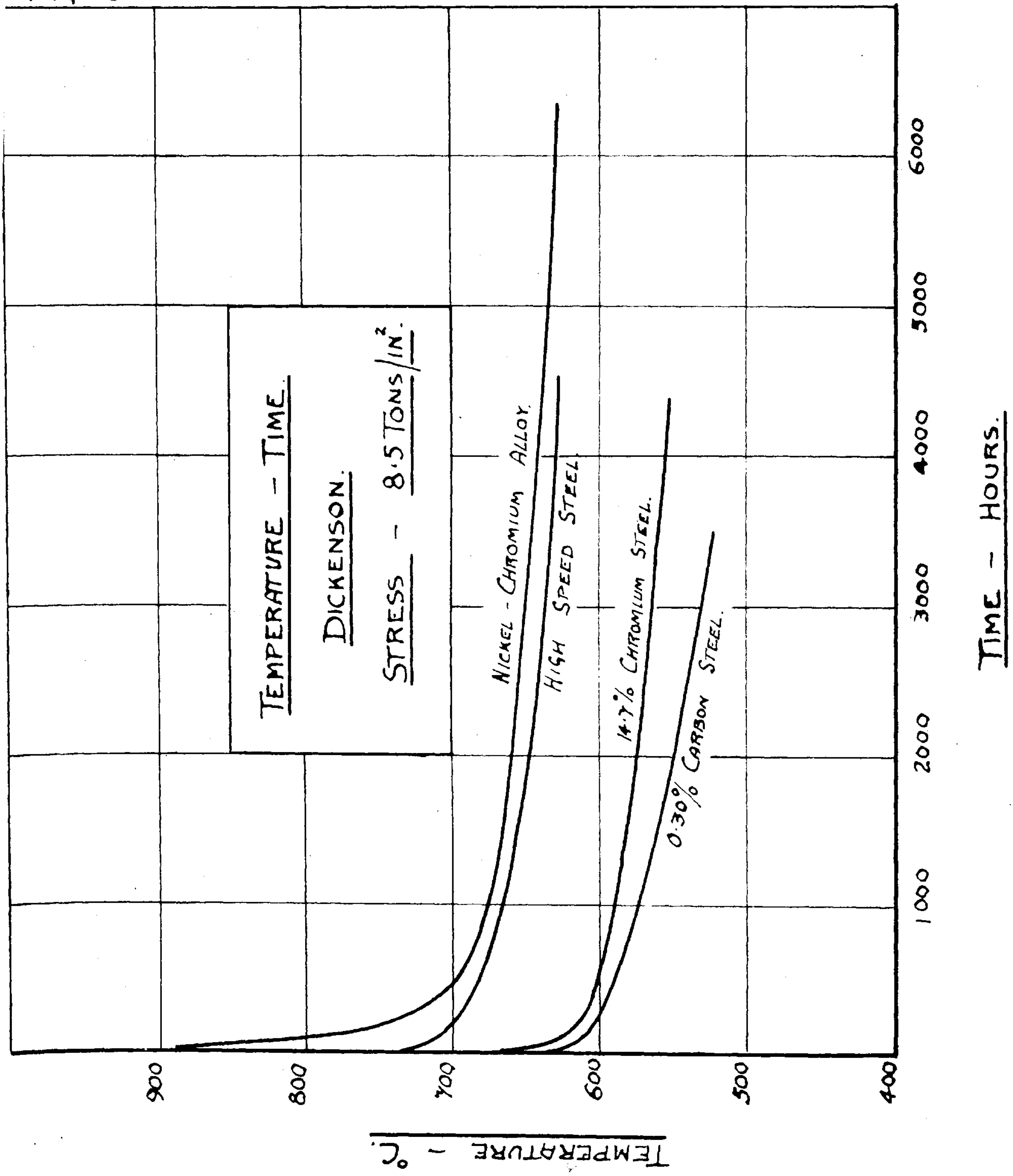
FIG. 4.



EXTENSION - TIME CURVES.

DICKENSON.

FIG. 5.


TEMPERATURE - TIME
DICKENSON.
STRESS - 8.5 TONS/IN.²
NICKEL - CHROMIUM ALLOY.
HIGH SPEED STEEL.
14.7% CHROMIUM STEEL.
0.30% CARBON STEEL.
900
800
700
600
500
400
TEMPERATURE - °C.
1000
2000
3000
4000
5000
6000
TIME - HOURS.

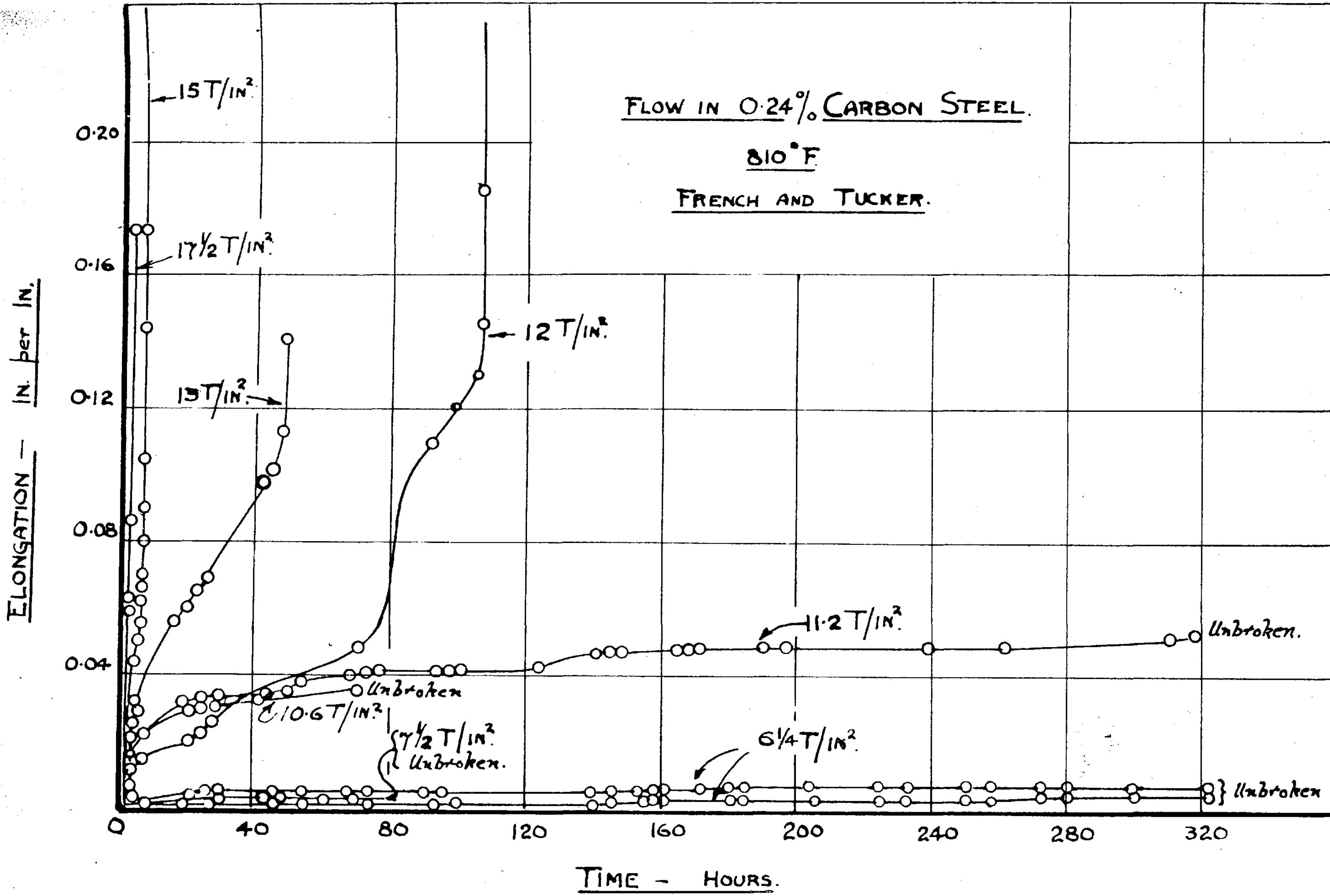
a small temperature increase has a more serious effect than a large stress increase.

Chevenard's method was employed by Prof. F.C. Lea (6) whose tests were performed in a standard testing machine using an extensometer similar to Marten's Mirror Extensometer. He made very accurate extension measurements and carried his tests for longer periods than Chevenard. Lea tested with constant temperature and varying stress. His curves show features similar to those of Chevenard, a period of initial flow or creep merging into a steady creep rate above the limit stress and giving no continuous creep below the limit stress, Fig. 10. Lea plotted the continuous creep rates against stress and took the stress at the intersection of the curve with the axis of zero creep rate as the limit stress. This limit stress he termed the Temperature Viscosity Stress.

The most direct experimental investigation at high temperatures was originally performed in 1922 by Dickenson (7). Using a simple lever machine he stressed all his test specimens at 8.5 tons/in^2., and heated them over a range of from 500 to 700 Deg. Centigrade. The testing procedure consisted in maintaining the temperature constant and noting the extension progress. The extensions gave curves of which those in Fig. 4 are typical. The temperature-time results are illustrated by Fig. 5, which indicates a longer life as the temperature is reduced. The shape of the curves suggests a limiting temperature giving infinite life or a sufficiently long one to suit practical requirements. In the case of the Nickel-Chromium alloy Dickenson estimates a life of about 10 years at 1060 Deg. Fah.

The results given by Dickenson do not establish the existence of a creep limit below which no continuous creep may occur, but the tests will determine stress and temperature

FIG. 6.



FLOW IN 0·24% CARBON STEEL.
810°F
FRENCH AND TUCKER.

values to give a sufficiently long and safe life to a structure. This test method is necessarily very slow, but it possesses the advantage of supplying very accurate stress-temperature values suitable for design purposes.

In the very comprehensive work performed at the National Physical Laboratory by Tapsell and his collaborators (8). The method originated by Dickènson was adopted, the temperature being kept constant and the stress varied for each creep limit determination. They estimated the creep limit by Chevenard's method, plotting the average steady creep rates, measured from their extension curves, with the corresponding stress; the incidence of this curve with the axis of zero creep rate giving a measure of the creep limit.

Information on elongation is also given by French and Tucker in a paper published in 1925 (9). They followed Dickènson's method with constant temperature and varying stress. Their method of measuring extensions was unique in that they observed the changes in length of the test-piece with a measuring telescope sighted through a window in the furnace wall. Their elongation-time curves, Fig. 6, show three sections which were termed - Initial Flow, Secondary Flow, and Final Flow. French and Tucker estimated the limit stresses from these curves after the fashion employed by Tapsell. They named this stress the "No Flow", in the second period, stress; this stress giving long life with deformation, this deformation being measured by the initial flow. In their published results, French and Tucker only give initial flow values taken above the limit stress so that the amount of initial flow at this stress must be estimated. It may be taken as being of the order of one per cent. and the time to produce this amount of flow is less than a day.

A testing procedure touched on by Dickenson and extensively used by Ingall is the Progressive Temperature method (10). The stressed test-piece is heated at a constant rate till fracture occurs, the temperature at fracture being taken as the limit temperature. Dickenson used only one heating rate and evidently abandoned the method in favour of his other test method, the limit temperatures shown by the heating tests being considerably higher than those obtained otherwise.

Ingall's researches, however, were very extensive. He tested a variety of pure metals and solid solutions, and used three heating rates, and the time effect was noticeably evident in that, as the heating rate was reduced the breaking temperature was also reduced.

A very simple progressive test was devised by Brown, who maintained the temperature constant while increasing the stress in steps of one ton/in^2./day till fracture occurred, the breaking stress being taken as the limit stress. (11).

That time had an effect was realized from the outcome of some tests on cast iron at high temperatures, made by Prof. Mellanby in the Royal Technical College, sometime during the late war. One test-piece showed a certain strength with the ordinary test, but a second one which had been kept at the test temperature overnight, showed a reduction in strength. Brown considered that if such a prolonged temperature treatment with no load would so affect the material as to weaken it, then if a stress were applied during the thermal treatment, the material might be more seriously affected. This method of combining the application of stress and temperature over a time interval was also recognised as being more true to working conditions than was

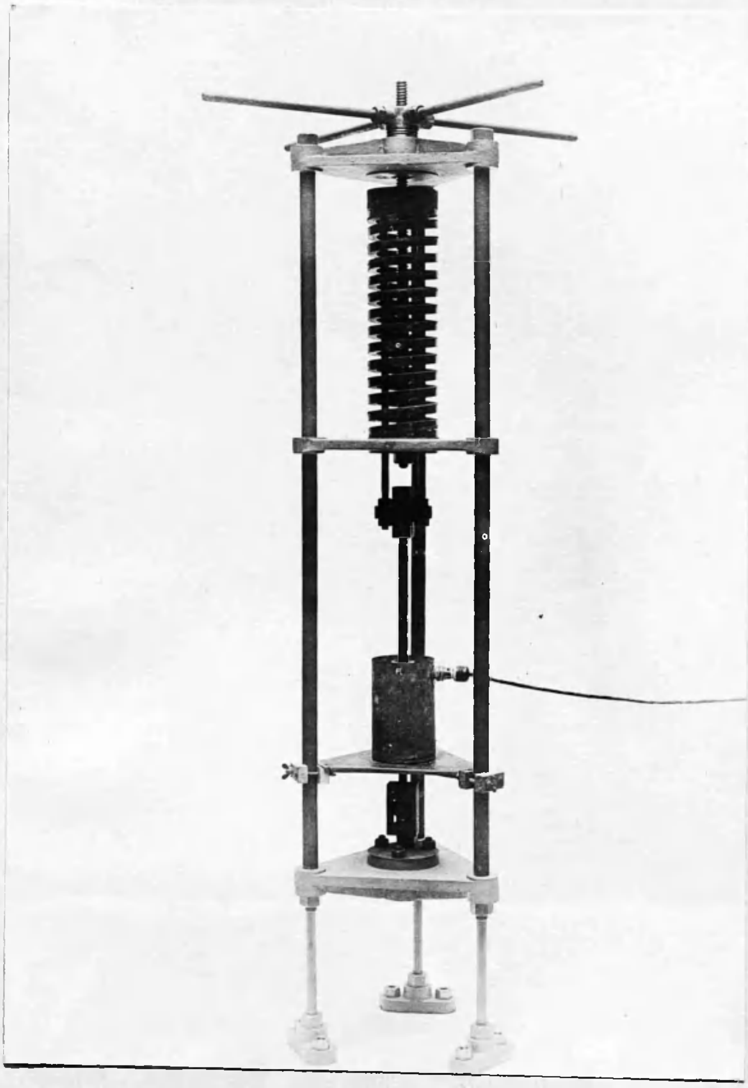


FIG. 7.

the ordinary short time test.

In order to make prolonged tests a special machine was constructed as in Fig. 7. The machine is very compact, the spring forming a neat method of loading, and is very easily controlled by means of the screw and handwheel. The compression of the spring is a measure of the applied load. The test-piece is carried between screwed straining rods, the ends of the rods being centred on balls at the fixed and straining cross-heads. Axial application of the load is in this way ensured. The straining rods run between side buffers (not shown) which prevent the furnace tube being damaged when the test-piece fractures. The furnace is constructed from a silica glass tube, 8 inches long by 2 inches diameter, wound over a length of 6 inches with nichrome wire, the wire being bound with asbestos rope and the whole insulated in the container by means of asbestos wool and kieselguhr. The heating current is taken at 250 volts., from the town supply through an adjustable lamp resistance. The test speciments made in one of two diameters 0.252 and 0.206 inches, are made to the standard dimensions of Fig. 8.

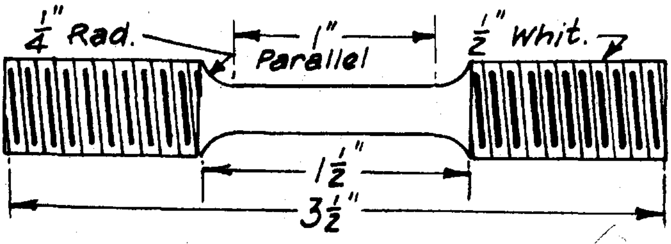
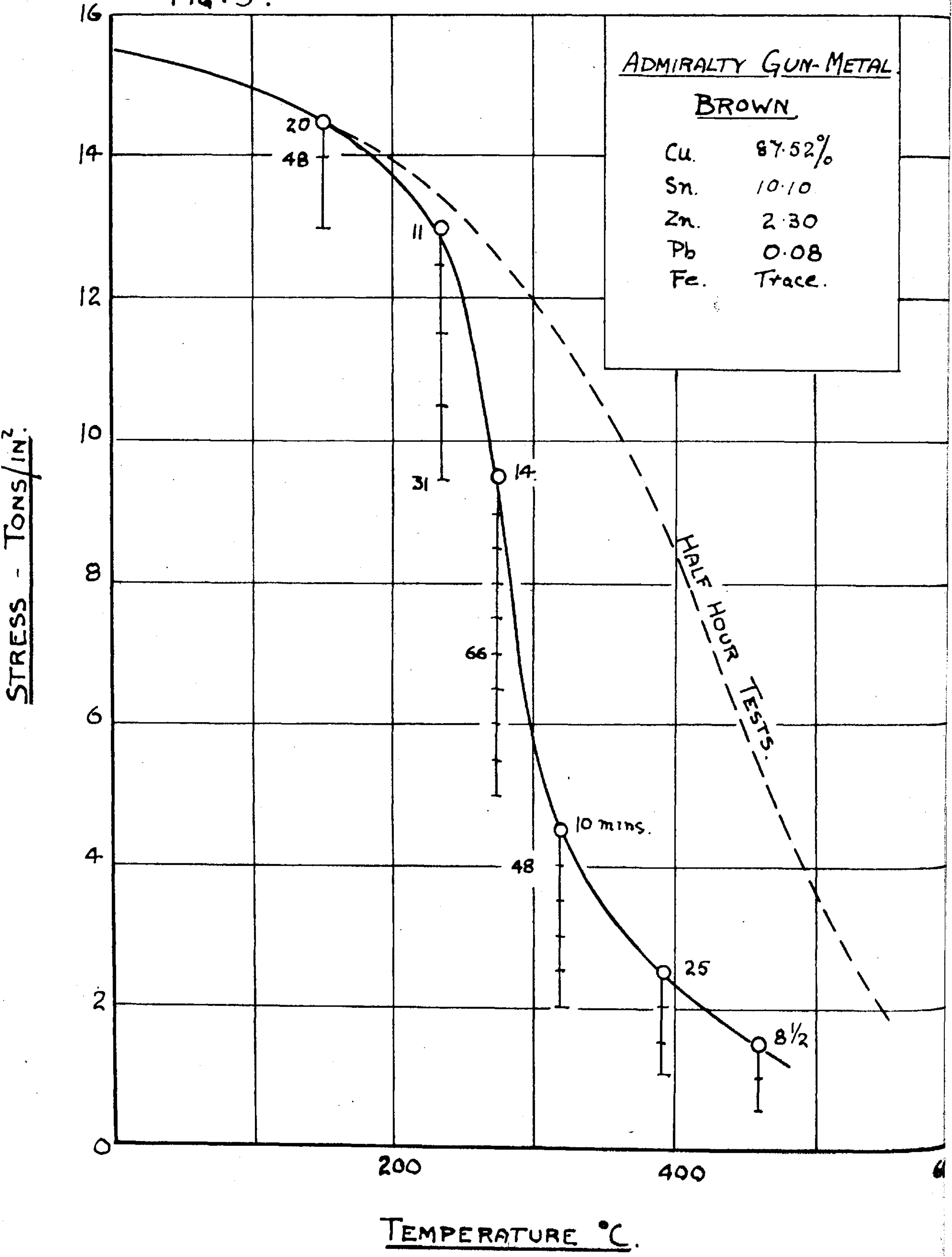


FIG. 8.

FIG. 9.


ADMIRALTY GUN-METAL
BROWN
Cu. 87·52%
Sn. 10·10
Zn. 2·30
Pb 0·08
Fe. Trace.
HALF HOUR TESTS.
16
14
12
10
8
6
4
2
0
200
400
20
48
11
31
14
66
10 mins.
48
25
8½
STRESS - TONS/IN.²
TEMPERATURE °C.

The original prolonged tests were made on cast iron. The first test-piece was maintained at a constant stress and temperature for about a fortnight and nothing happened. The stress was increased and left for another period, with again, no result. The stress was increased at various intervals till the iron failed. Brown decided that to get anywhere some definite test method was essential and he fixed on constant temperature with stress increasing at the rate of one ton/in^2./day to fracture. In this way he tested a series of cast irons and proceeded with, a high tensile brass, phosphor bronze, Monel metal, cast aluminium and Admiralty Gun-metal. The author had the pleasure of assisting with the tests on Monel metal and Admiralty Gun-metal. The results supply ordinary quick break values along with the limit or prolonged test values. Brown's curves for Admiralty Gun-metal are given in Fig. 9; these show decidedly the marked artificial strength which the ordinary quick tests give. The slow break curves supply a truer representation of the material's behaviour under working conditions.

CONSIDERATION OF THE VARIOUS TEST METHODS:-

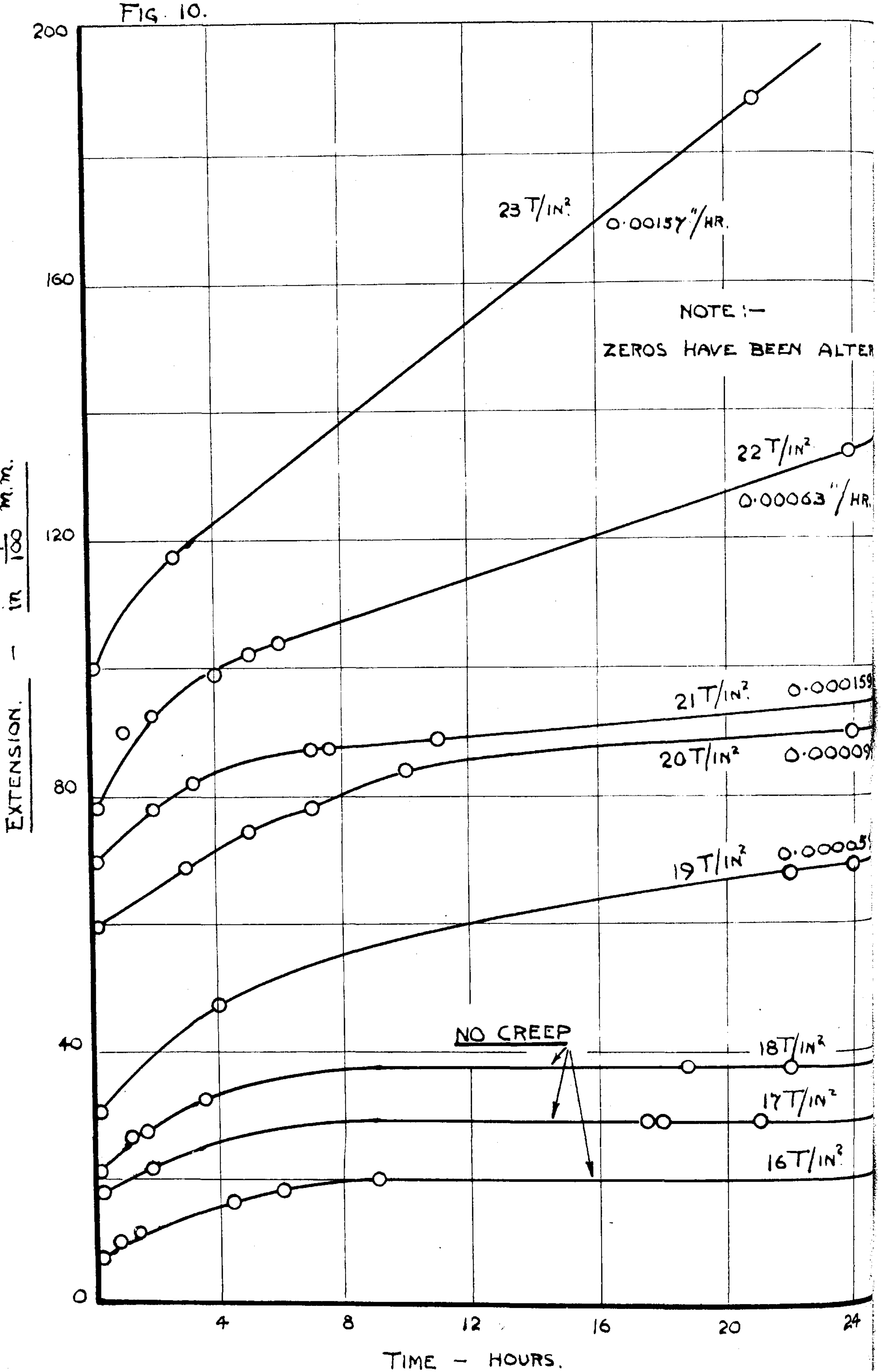
The pioneer work of Chevenard and Lea gives certain conclusions and supplies extension data which is not included in the records of long duration tests. As has already been described, their extension curves show two phases, the first of a few hours duration, during which the extension rate progressively decreases till it assumes a final steady rate - this being the second phase. The extension rate curves, derived from these steady flows, show that for reasonable accuracy in the limit estimation, it is desirable to obtain rate values in the vicinity of zero.

The direct method of making prolonged tests by maintaining the stress and temperature constant may be termed the "Absolute" method. This method is similar to the fatigue testing method and the classic examples given by Dickinson illustrate that the results closely resemble those obtained from fatigue tests, particularly in that the stress or temperature-time curves is hyperbolic in form, the stress or temperature asymptote suggesting a limit.

The position of this limit indicating asymptote is difficult to ascertain and the more accurate the desired result, the more time absorbing the test becomes. This testing time has been materially shortened by applying Chevenard's creep rate method to the extension-time curves obtained from the absolute tests.

When a metal, heated to some elevated temperature, is stressed above the creep limit three different types of flow are observed. The "Initial Flow" commences with a high rate, gradually slowing to a minimum rate. This initial flow indicates a period of unstable equilibrium, the metal initially extending at a greater rate than it can recover or harden, this hardening effect becoming gradually more pronounced and ultimately the recovery rate balances the extension rate. When this balance is struck the material elongates fairly uniformly giving the "Secondary Flow". This flow cannot be absolutely uniform as reduction in cross-sectional area will accompany elongation and so the stress will increase and accelerate the flow rate. The flow then proceeds to the second unstable condition, that of "Final Flow", where the reduction of section becomes rapidly more effective, the final extensions being of a local character. With ideal conditions of observation there would be no evidence of

FIG. 10.



LEA - EXTENSION - TIME RELATION.

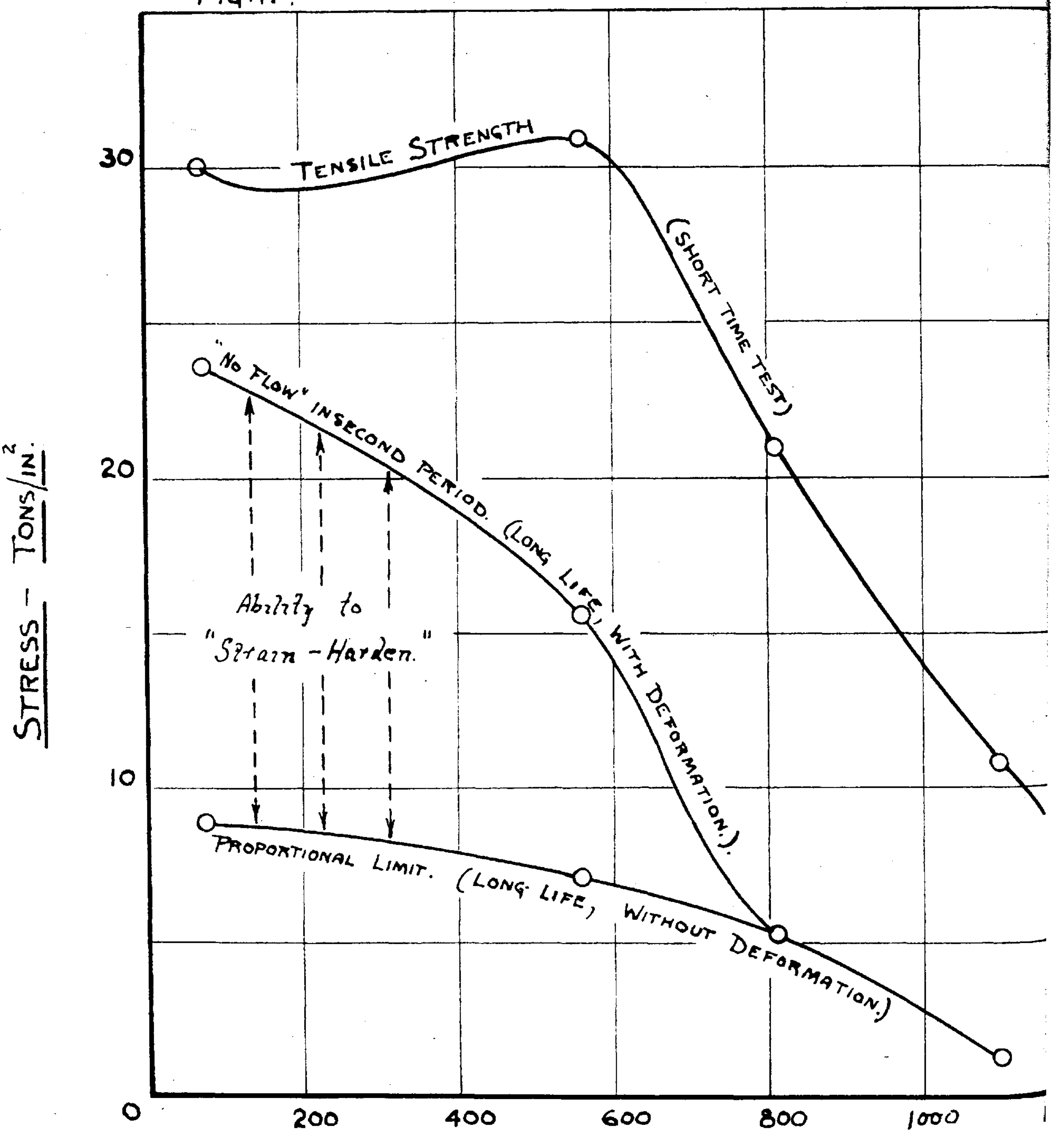
0·32% CARBON STEEL.

752 ° F.

the steady flow in the second period, since there can be no steady flow as the continued extension will carry on the stress increase, and the initial flow will merge into the final flow with no intermediate step - the extension-time curve will show a point of inflexion. These extension phenomenon are only shown if the metal is stressed sufficiently, if the stress be low it may only produce initial flow, the extension then ceasing. The determination of the actual stress at which the creep apparently ceases is best made by Chevenard's method; this was done by French and Tucker and by the National Physical Laboratory workers. Taking the average flow rate in the second period, or at the point of inflexion, and plotting with stress or temperature the limit is much more readily estimated than by the hyperbolic method.

A series of extension-time curves for a limit estimation are of similar form, but show certain distinction for different temperatures or stresses. Below the limit conditions the period of initial flow is very short, generally of a few hours duration only; this is most readily seen in Lea's curves Fig. 10. In the region of the limit this flow extends for about a day, Fig. 6, but above the limit conditions the period extends and initial flow persists for days. This prolongation of the initial flow period renders very difficult and tedious the estimation of the limit from tests performed above the limit stress. This arises from the fact that if the initial flow persists for more than a day it is very easy to plot the extension time curve so that the final portion of the initial flow stage appears as a straight line, and if this is done the limit may be artificially raised. To prevent this, the tests must be so prolonged as to ensure that the period of initial flow is safely passed before determining creep

FIG. 11.



FRENCH AND TUCKER.

0·24% C. STEEL.

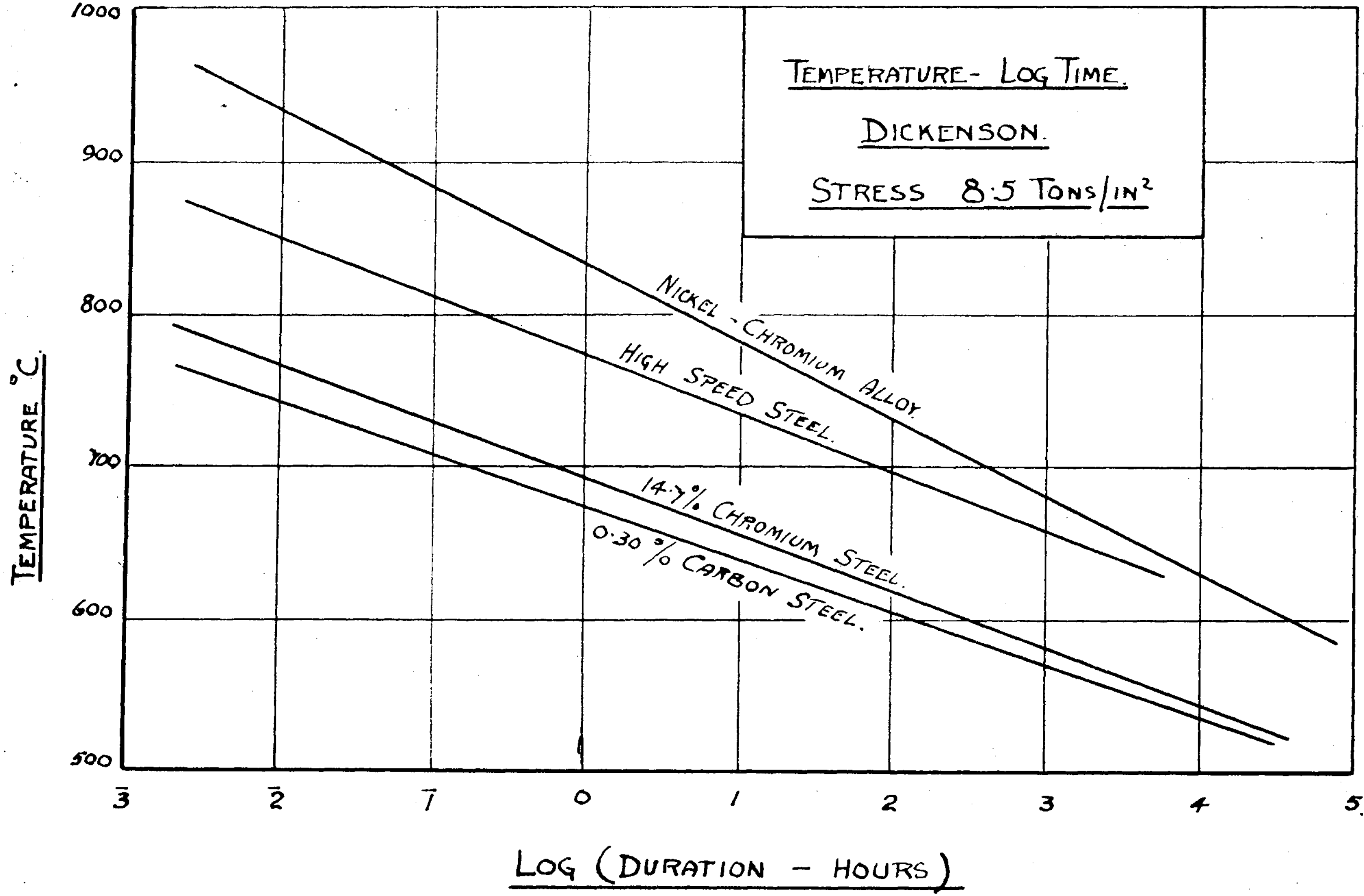
rate values.

In their published report French and Tucker include a composite diagram, which is reproduced in Fig. 11. It shows the Ultimate Strength, Creep Limit Stress, and Limit of Proportionality Stress. These curves divide the stress-temperature field into three distinct zones. The first, under the proportional limit curve covers the range of elastic deformation, conditions in this zone producing no permanent deformation in the metal. The second, between the proportional limit and the creep limit stress curves indicates a zone of initial flow, This flow, however, ceases, as the conditions are below the creep limit conditions. This second region was designated by French and Tucker as the field where the metal retained the "Ability to Strain Harden". The ability of the material to strain harden is due to the well known work hardening phenomenon, whereby the deformation of a metal results in a strengthening of the structure. Strain hardening is an after effect from deformation, within limits the strain hardening increases with deformation; at the same time it is governed to some extent thermally, strain hardening being non-existent above a certain annealing temperature. The controlling factors, deformation and temperature are portrayed in the diagram. The ability to strain harden is considerable at normal temperature and gradually diminishes to zero at about 800 Deg. Fah., in this case the annealing temperature. Above this temperature, since strain hardening is absent and non-elastic deformation would spell continuous creep and failure the creep limit stress coincides with the limit of proportionality, the limit of elastic distortion. The creep limit stress is the upper limit of temporary creep. Whenever the stress is increased into the third region, the initial flow instead of ceasing proceeds to the final flow and the metal ultimately fails. This third zone might be named the "Time Factor" area. The more the stress exceeds the creep limit stress the shorter the life of the material becomes, till it is the matter of a few seconds when the stress is the normal ultimate stress. From a knowledge of the final elongation and the average flow rate the life for a particular stress and temperature may be estimated. Expectations of life of from months to years may be determined and the corresponding lines plotted in this third region. Such curves are given by Tapsell and Bradley.(8)

The progressive heating method employed by Ingall is very interesting and illustrates the time-effect very explicitly. It has the serious drawback, in that, as practiced by Ingall, the limit temperature found is much above that observed by the absolute method. The following reasoning will make this clear. Considering creep in relation to the rate of heating, as the temperature is raised the stress temperature condition will reach the creep limit value which if maintained would ultimately cause failure. But, in the heating test the conditions do not remain constant, the temperature is steadily raised and at the same time the creep rate also rises, the test assuming the form of a race in which the temperature proceeds steadily with the creep rate following on doing its utmost. The higher the heating rate the higher the temperature attained before fracture and vice versa.

An illustration may be taken from Dickinson's extension curves Fig. 4. One piece broke after about 100 hours at 1,155 Deg. Fah. which is about 180 Deg. Fah., in excess of the limit temperature. ~~Taking Ingall's lowest~~

FIG. 12.

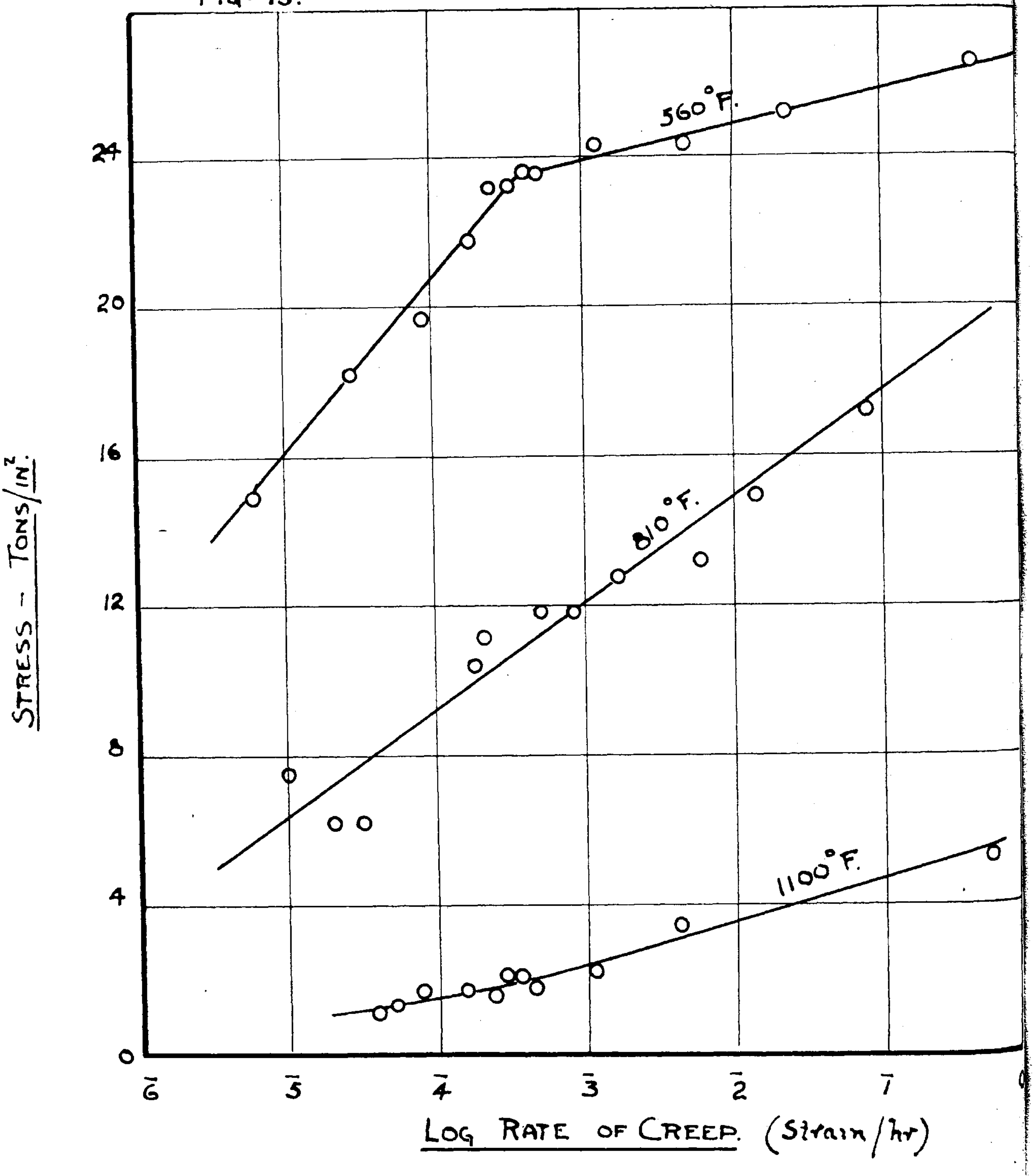

TEMPERATURE - LOG TIME.
DICKENSON.
STRESS 8·5 TONS/IN²
NICKEL - CHROMIUM ALLOY.
HIGH SPEED STEEL.
14·7% CHROMIUM STEEL.
0·30 % CARBON STEEL.
TEMPERATURE °C.
1000
900
800
700
600
500
$\bar{3}$
$\bar{2}$
$\bar{1}$
0
1
2
3
4
5.
LOG (DURATION - HOURS)

~~heating rate as 5 Deg. Fah., which is about 180 Deg. Fah.~~, ~~in excess of the limit temperature.~~ Taking Ingall's lowest heating rate as 5 Deg. Fah. per minute, his test would pass from the limit conditions to 1,155 Deg. Fah., in half an hour, so that the temperature had about 100 hours to spare before the creep could cause failure. This time margin is, of course, rapidly reduced as the temperature rises, but the temperature must advance considerably beyond 1,155 Deg. Fah., before failure occurs, so that this particular result would show a result at least 200 Deg. Fah., on the wrong side.

This manner of testing might prove more satisfactory if the temperature were progressively increased say in daily increments, extensometer measurements being made to measure the creep effects due to the periods at constant temperature.

In several of the discussions on the various papers and articles on creep the method of plotting results logarithmically has been raised. Foremost in the advocation of this method has been Bailey (12) who has analysed many results and has arrived at some very interesting conclusions. The general conclusion which Bailey draws is that there is no creep limit. He cites Dickinson's results where if the temperature is plotted with the logarithm of the time the result is a straight line, this meaning, of course, that there can be no creep limit, Fig. 12. Logarithmic plotting, however, labours under the same disability as do other methods, in that, they represent facts within the range they portray but beyond that they can show nothing. Any experimental plotting is limited to the data available and, in this case, there is none to show that

FIG. 13.



LOGARITHMIC PLOT FOR 0·24% C. STEEL.

BAILEY.

Dickenson's straight lines continue so indefinitely.

It is interesting to compare these results with the corresponding fatigue test results which they so closely resemble. About fatigue, there was a similar doubt as to the existence of a limit, normal plotting of the results suggested a hyperbola with a limit asymptote, while logarithmic plotting said there was no limit. In 1910, after a careful investigation of existing fatigue data, Basquin (13) suggested that a fatigue limit might exist. More recent work by Moore & Kommers (14) and others on a basis of 10^8 reversals has shown that there is a limit indicating discontinuity in the logarithmic curve.

Bailey also applied logarithmic plotting to extension results, an example being shown in Fig. 13, where he has used French and Tucker's results and plotted the logarithm of the creep rate in the second period with the corresponding stress. He was again rewarded with more straight lines, the natural conclusion being that flow is unceasing. If we assume that there is no creep limit and that logarithmic plotting is prophetic then we may extrapolate these lines and find that at zero stress this steel would creep or flow at rates of the order of 10^{-7} and 10^{-9} inches per hour at 810 and 560 Deg. Fah., respectively. Such a result is quite in order in so far as it shows that at a definite stress the creep rate decreases with decrease in temperature, but even at moderately high temperatures to have flow with no stress producing it is absurd. The third curve in the diagram may assist in explaining matters. This curve, for 1,100 Deg. Fah., shows a decided flattening to some stress value, suggesting a limit. That we get ~~said~~ such an evident suggestion of a limit at a high temperature, leads us to the conclusion that at lower temperatures, giving more stable conditions in the metal, the other curves will ultimately flatten out also. These three curves of Fig. 13, illustrate an interesting effect of temperature on creep rate. The higher the temperature the more marked is the distinction between cessation of creep at the limit and continuance above the limit. As the temperature is reduced the initial flow above the limit becomes more prolonged and immediately above the limit it must be practically indistinguishable from continuous flow. So with logarithmic plotting the limit indicating discontinuity occurs at higher creep rates for high temperatures than for low temperatures. To reach this discontinuity at low temperatures the testing times would require to be considerably extended. In the case of some tests on copper wires at normal temperature, with a stress of 11.56 tons/in.^{2} producing a creep rate of the order of 0.00007 cm./hour, after 7,000 hours the metal is still in the initial flow stage, this stress is very close to the limit stress if it is not the actual limit stress.

The essential conclusions from this consideration may be shortly summed up. The absolute method forms a logical and straightforward test, but it is very laborious. The time involved may be shortened and the accuracy probably unimpaired by combining with it Chevenard's extension rate method. In certain respects the logarithmic investigation of the available evidence casts some doubt on the idea of a creep limit stress, but in others, it leads to the belief that there may be a creep limit stress. The problem may be definitely solved at some date, which must needs be in the distant future; but no matter the outcome, the present day creep limit stresses, if used discreetly, will be found eminently satisfactory.

PROGRESSIVE STRESS METHOD:-

The progressive stress method has already been described, but since it forms the basic test in the experiments to be described, it will now be considered in detail.

In the original tests described by Brown, a series of brittle metals were tested, these comprising cast irons and several non-ferrous alloys which are ductile at low temperatures, but exhibit brittleness at higher temperatures.

Brown's conception of his test was, if a metal would sustain a stress and temperature for twenty-four hours it would remain indifferent indefinitely. This conclusion was deduced from some of the initial experiments when a cast iron withstood a series of increasing stresses for considerable periods. The cast iron showed little or no elongation so it was considered unnecessary to employ an extensometer. Ultimately the search for the limit stress was reduced to the simple method of subjecting the metal under test to daily stress advances, the rate of increase being generally taken as 1 ton/in.^{2}/day. The stress immediately preceding fracture was considered the limit stress.

This method may be quite legitimate with brittle material which shows practically no distortion, but it is open to question when ductile metals are under test. Under certain conditions a ductile metal might creep for days before fracturing, and , in such a case when testing by the progressive method the stress would have been increased beyond the limit value before the creep had advanced sufficiently to cause fracture.

Since the present research was to be performed mainly on steels, the author decided that extension measurements were essential if reliable results were to be

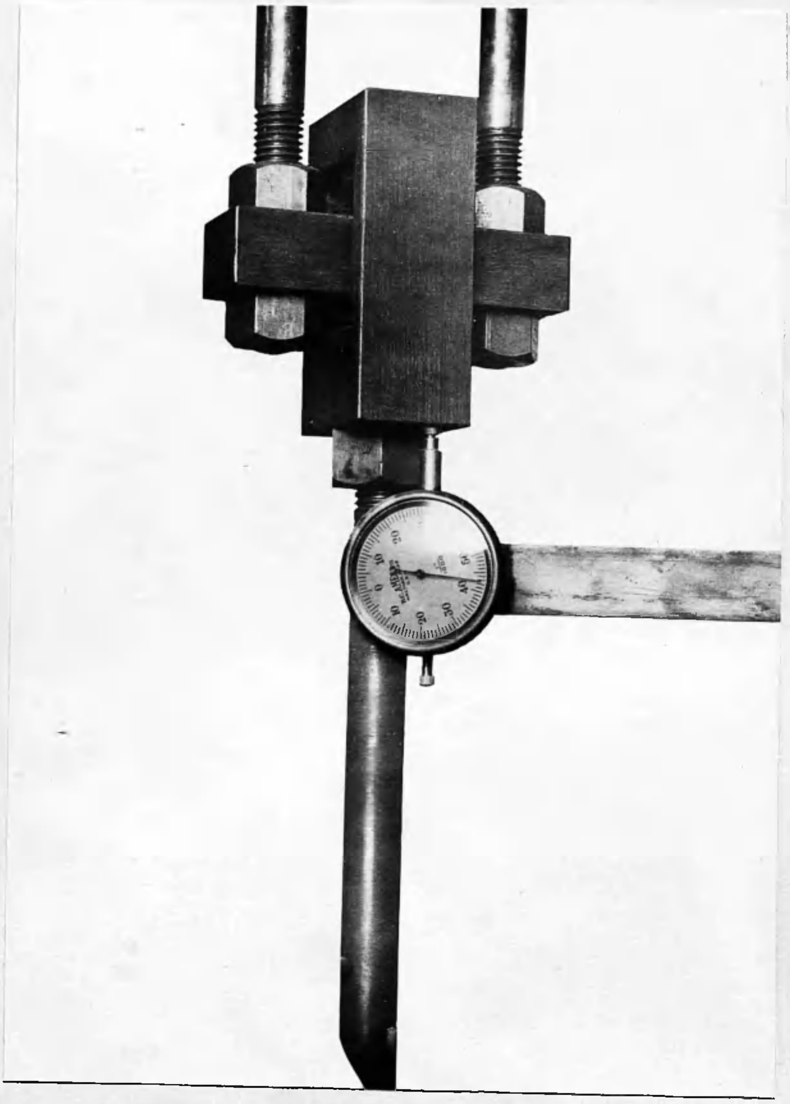


FIG. 14.

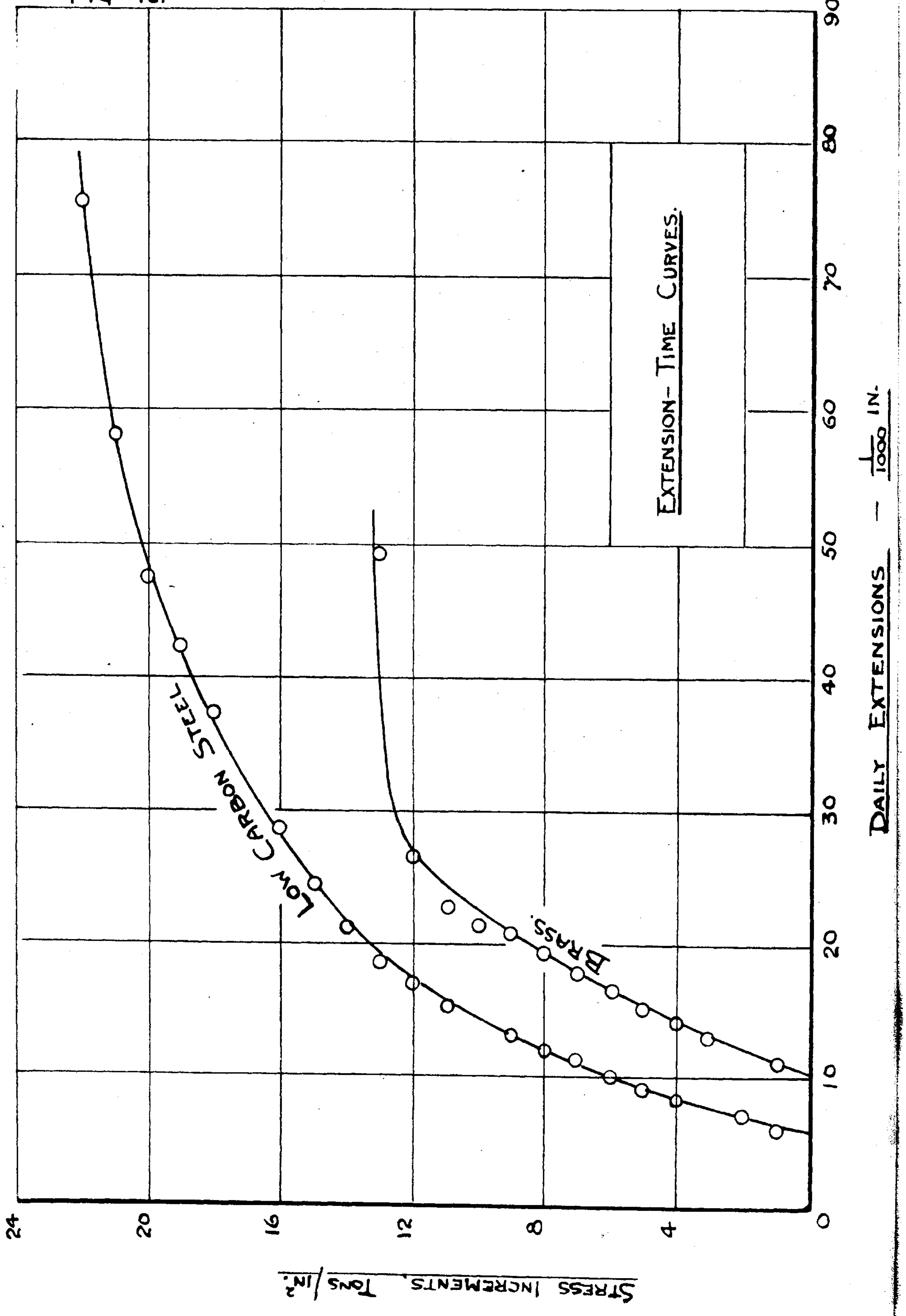
obtained. The simplest means of obtaining extension records was to measure the displacement of the straining crosshead relative to the fixed frame of the machine, the crosshead moving upwards as the test-piece elongated.

The first measurements were taken with an"Unique Test Indicator", reading from zero to fifteen thousandths of an inch. The indicator was clamped rigidly to the machine frame with its moving head touching the underside of the straining crosshead, the pointer showed the relative motion. This arrangement was very crude and the indicator required frequent resetting, but it was used throughout a progressive test and served to show that there was a definite extension process. In the subsequent tests an "Ames Micrometer Dial" Fig. 14 was substituted for the test indicator. The micrometer dial reads in thousandths of an inch with a range of three tenths of an inch; this range was found to be sufficient for a complete test.

To follow the extension process in the progressive stress test the creep evidence already discussed must be considered. It has been shown that in the range from the limit of proportionality to the creep limit stress there is only one creep - initial or temporary - this creep exists for a time and ultimately ceases. When the creep limit stress is exceeded, this temporary creep still occurs but instead of ceasing it passes off into continuous creep.

Since the progressive stress test proceeds in stages of twenty-four hours, the duration of these creep effects are important. An examination of various extension curves supplies these durations. In general, in a set of extension curves, as the variable factor, stress or temperature, is reduced the duration of initial flow is also reduced, and this reduction continues through the limit

FIG. 15.



EXTENSION- TIME CURVES.
LOW CARBON STEEL
BRASS.
DAILY EXTENSIONS — 1/1000 IN.
STRESS INCREMENTS, TONS/IN.²
0
10
20
30
40
50
60
70
80
90.
4
8
12
16
20
24

value. In Dickenson's and Tapsell and Bradley's curves the minimum initial flow proceeds for about twenty-four hours, so that in the range below the limit it will exist for a shorter time. French and Tucker's curves show similar values and in some cases the duration of the initial flow is only a few hours. Lea's curves show temporary creep as lasting from eight to sixteen hours. Generally, in the field between the limit of proportionality and the creep limit stress temporary creep occurs, and its duration varies with the applied stress. In the lower portion of the field this creep is of a very short duration and probably even for a short range above the creep limit stress (depending on the temperature) it does not exceed twenty-four hours.

Applying to the progressive stress test, employing daily stress increments, the fact that temporary creep exists for less than a day at stresses up to the creep limit stress, each loading produces an immediate elastic extension followed by a temporary creep extension, both these extensions are included in the daily extension measurements. On passing the creep limit stress these two extensions still occur, but the initial flow instead of ceasing, either continues or passes off into continuous creep depending on the existing conditions. Such phenomena are graphically portrayed by the set of Lea's curves shown in Fig. 10. The particular features observed are, below the creep limit stress the amount of temporary creep, or permanent deformation, increases fairly steadily with increase in stress, and above the creep limit stress the creep increase over each daily period becomes progressively greater.

Plotting extensions from a progressive stress test with either stress or time, the two being interchangeable,

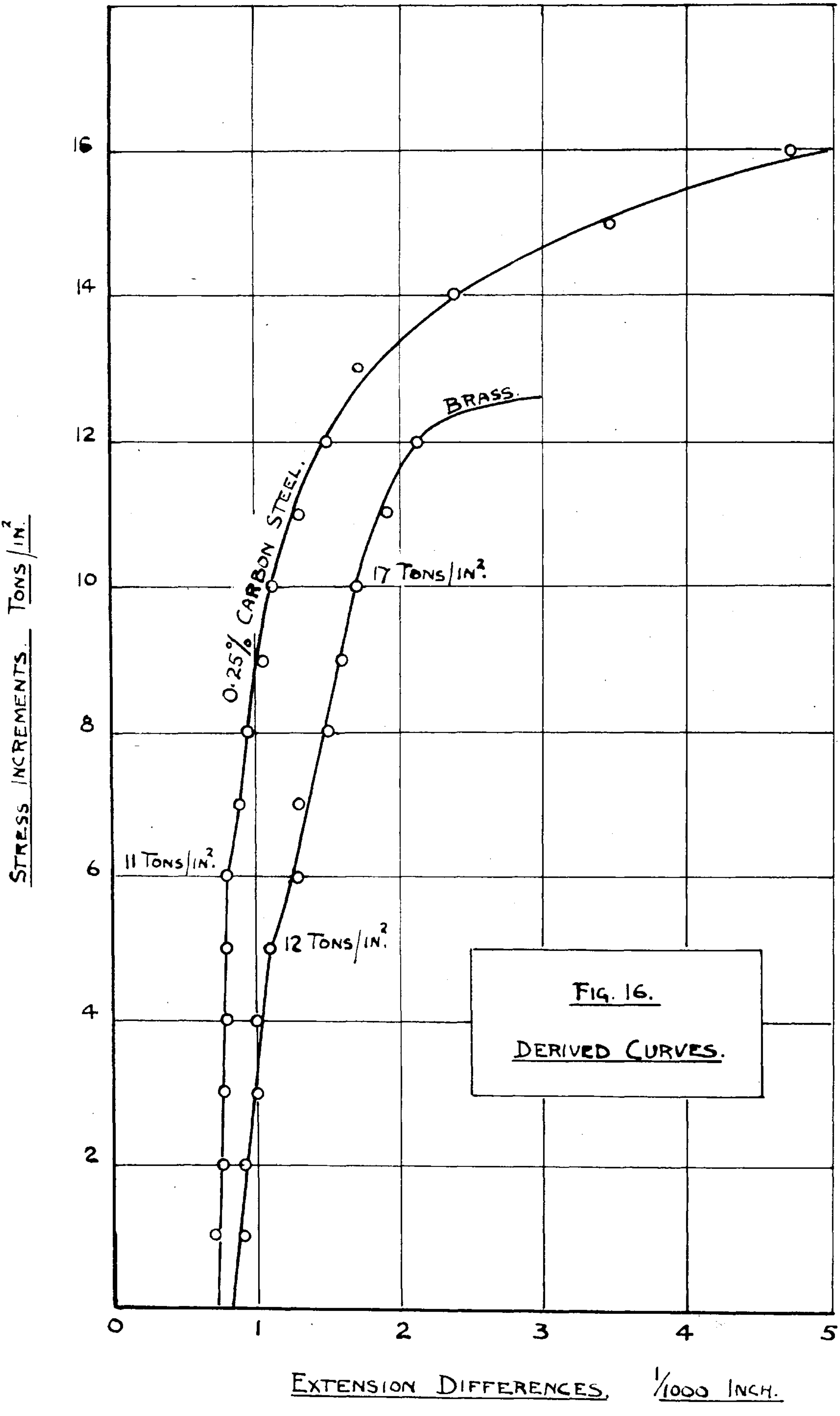


FIG. 16.

DERIVED CURVES.

curves as in Fig. 15 are obtained. These commence with a very flat curve passing through a sharp curve to a second flat curve. The first flat portion represents the zone of initial flow below the creep limit stress, while the remaining portions represent the flow above the creep limit stress. In this curve the point of divergence representing the creep limit stress is not clear. Lea's curves show that temporary creep increases fairly steadily with intensified stress; so that considering only extension increases, a better idea of the position of the divergence corresponding to the creep limit stress will be obtained. This is done by taking extension differences from the extension curves and replotting on the same base. The new derived curves Fig. 16, are composed of straight lines passing off into curves. The straight line corresponds to the steady increases of temporary flow and the curve corresponds to continuous flow, the limit of the straight line indicates the creep limit stress.

In making these tests, the twenty-four hour period is followed as far as possible but each week-end there is a forty-eight hour period. This increase in time has no effect as below the limit conditions all the extension for a particular stress is finished in less than twenty-four hours, and the metal remains dormant for the succeeding day. Above the creep limit stress, increasing the time interval increases the corresponding creep extension, but this need not be considered as the extension measurements taken after the limit has been passed, have nothing whatever to do with the creep limit estimation.

It is appreciated that there are several objections to the method of measuring extensions by the Ames Gauge as used here; this not being done directly on the gauge length. Actually the gauge records changes in length

TABLE N° 1.

COMPARISON OF AMES GAUGE WITH 2" CAMBRIDGE EXTENSOMETER.

DIAMETER OF TEST-PIECE 0·360" LENGTH OF TEST-PIECE $3\frac{1}{2}$"

DIAMETER OF STRAINING RODS 0·75" LENGTH OF STRAINING RODS. $16\frac{1}{2}$".

$$\text{YOUNG'S MODULUS OF TEST-PIECE} = \frac{9 \times 2240 \times 2}{\cdot 00124} = 32{\cdot}5 \times 10^6 \text{ lb/in}^2.$$

$$\text{STRETCH OF } 16\tfrac{1}{2}\text{" OF STRAINING ROD / TON/IN}^2\text{ STRESS} = \frac{2240 \times 16{\cdot}5}{32{\cdot}5 \times 10^6} = 0{\cdot}00114\text{"}.$$

STRESS TONS/IN².	CAMBRIDGE EXTENSOMETER.		AMES GAUGE.		TOTAL EXTENSION OF 3½" OF TEST-PIECE. INCH.	STRESS ON STRAINING RODS TONS/IN².	EXTENSION OF 16½" OF STRAINING RODS. INCH	EXTENSION OF T.P. + EXTENSION OF S.R. A. INCH.	ERROR. R – A INCH.
	READING.	EXTENSION INCH.	READING.	EXTENSION. R. INCH.					
1	38·5	0	0	0	0	·226	·000258	·000258	–·000258
2	39·8	·00013	2	·002	·00023	·45	·000514	·000744	·001256
3	1·0	·00025	4	·004	·00044	·68	·000775	·001215	·002785
4	2·5	·00040	6·3	·0063	·0007	·90	·00103	·00173	·00457
5	4·0	·00055	8·3	·0083	·00096	1·13	·00129	·00225	·00605
6	5·2	·00067	10·3	·0103	·00117	1·35	·00154	·00271	·00759
7	6·6	·00081	12·0	·0120	·00142	1·58	·0018	·00322	·00978
8	8·0	·00095	14·3	·0143	·00166	1·80	·00205	·00371	·01059
9	9·3	·00108	16·0	·0160	·00189	2·03	·00231	·00420	·01180
10	10·8	·00123	18·0	·0180	·00215	2·26	·00258	·00473	·01327
11	12·1	·00136	19·8	·0198	·00248	2·48	·00294	·00542	·01438
12	13·5	·00150	21·8	·0218	·00262	2·71	·00309	·00571	·01609
13	149	·00164	23·0	·0230	·00287	2·93	·00334	·00621	·01679
14	16·4	·00179	25·4	·0254	·00313	3·16	·0036	·00673	·01867
15	17·8	·00193	27·6	·0276	·00338	3·38	·00385.	·00723.	·02037.

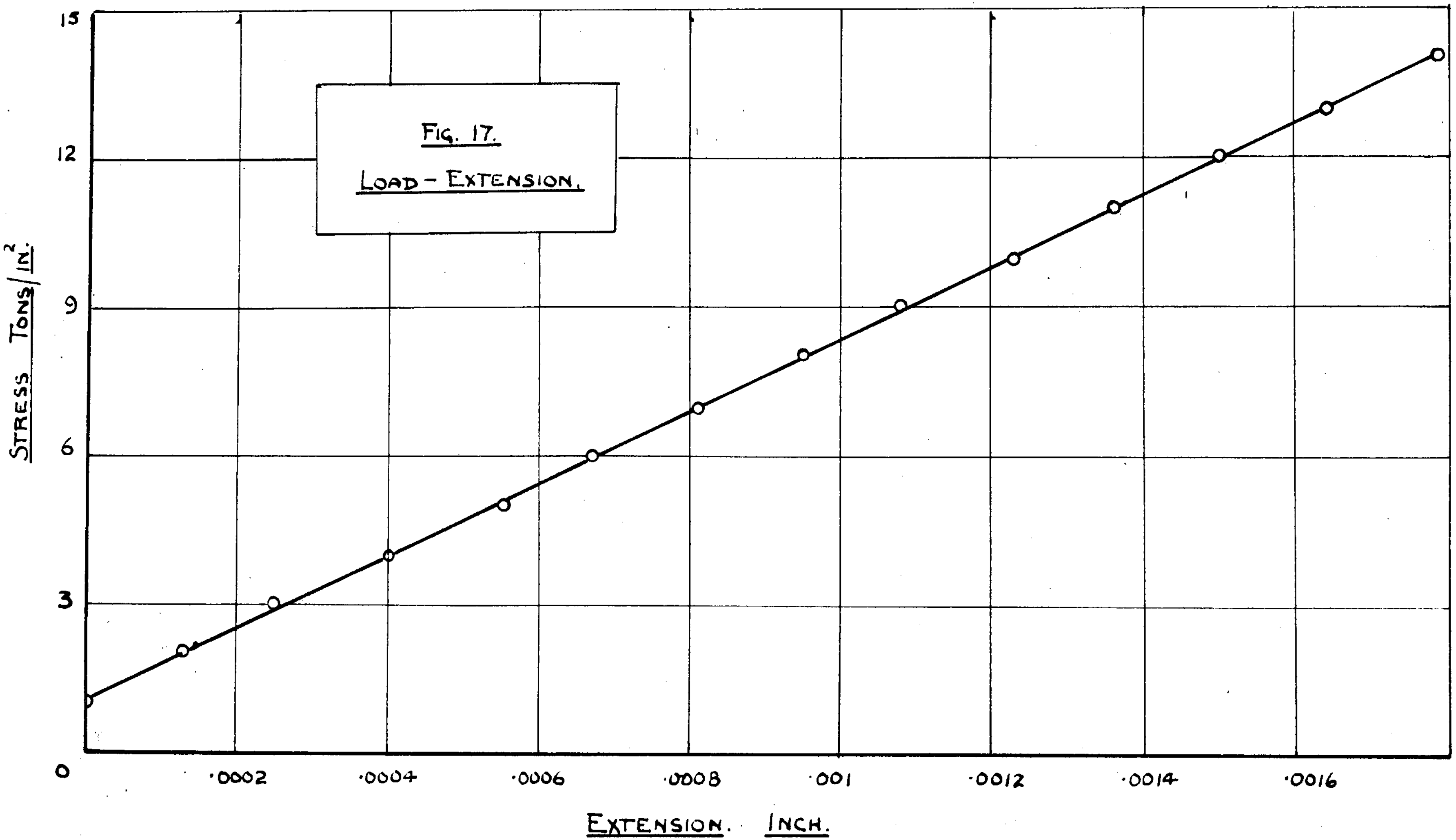


FIG. 17.

LOAD - EXTENSION.

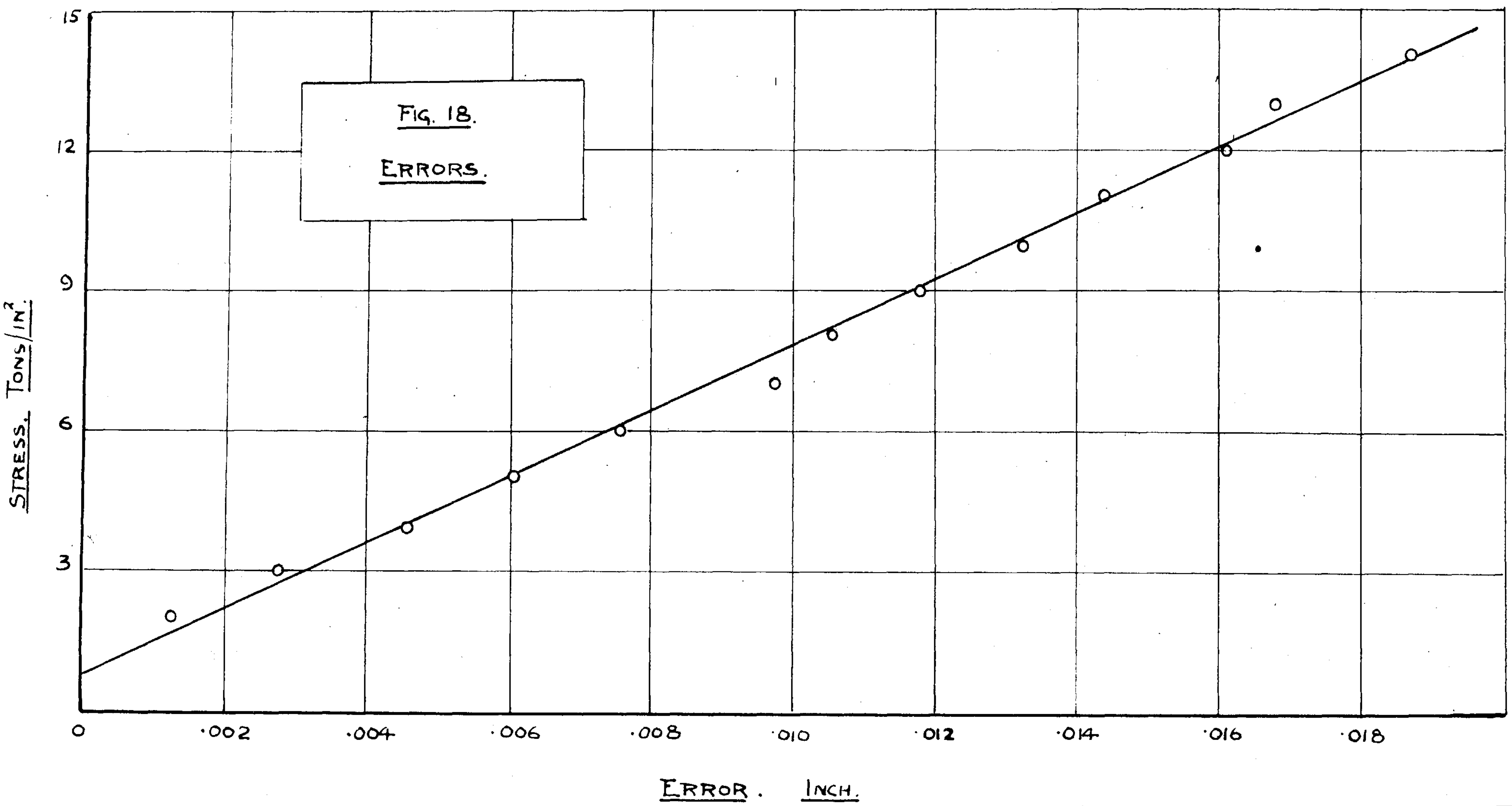


FIG. 18.

ERRORS.

both of the test-piece and of the straining members of the machine under the combined influence of stress and temperature. It also shows the results of buckling in the base plate and the side rods.

To study the effect of the extension of the straining rods and frame distortion, the clock gauge was compared with a Cambridge Extensometer fitted directly on a test-piece. The test-piece was loaded to the capacity of the machine the stress induced being below that of the limit of proportionality. The extensions noted are detailed in table No. 1. Fig. 17, is the stress extension curve for the test-piece, the Young's Modulus of which was 32.5 x 10^6 lb/in^2. Taking the straining rods to have this elasticity, their extensions under the test loading were determined, and reducing the test-piece, extensions to a basis of extension of a 3.5 inch parallel length, the actual error due to frame distortion was found and plotted in Fig. 18. This error follows a straight line law. This error alters the shape of the extension-time curves, and also the shape of the straight portion of the derived curve, but since the necessary correction would be the subtraction of a straight line, the limit estimation is not affected if this adjustment is not made.

On making the daily stress increase, the gauge records immediate extensions which are constant throughout a test. This elastic extension is made up of the elastic extension of the test-piece, of the straining rods and of the frame distortion. This is tabulated in the test results as "Stretch on Loading" Table No. 2. It is also included in the "Final Gauge Reading" which is plotted in the extension-stress increment curves, but as has been shown it does not affect the limit estimation.

Errors due to temperature fluctuation are more insidious than those due to stress variation. Variations in temperature produce different creep rates and this error is unfortunately very difficult to assess. The temperature varies with the mains voltage which fluctuates with the City and the College load, it reaches a maximum and remains fairly constant at this value overnight, the conditions existing in the morning being those which have been imposed on the metal for the major portion of the complete day. The occurrence of this constant period helps considerably to minimise the detrimental effects of temperature variation, the serious fluctuations only accur at the beginning of initial flow and tend to reduce the flow. The flow rate comes to its proper value with the increase of temperature to the proper test value and the final stages of initial flow occur under the correct conditions. In this way, at the limit conditions the flow will pass on to the continuous stage at the correct temperature; and further, since below the creep limit stress the initial flow stage occupies less than twenty-four hours, the loss of extension, due to the low initial flow rate, will be made up within the day when the temperature rises to its normal value.

Changes in temperature show themselves in changes in length of the test-piece and the heated members of the testing machine, these variations being read on the micrometer dial. This effect may be corrected by observing gauge changes for definite temperature changes and applying this to correct for fluctuations on either side of the mean temperature. The average correction is 1/1 0,000inch./Deg. Fah.; this alters with the temperature, as the temperature is increased a greater length of the straining rods is subjected to temperature influence so the correction will

Table. N°2.

Progressive Stress Test on Brass at 340°F.

Test-Piece. N°. 205. 0·252" Dia.					Gauge Readings Thousandth of an Inch.						
Stress Tons/in²	Temperature °F.	From. 9.30 A.M.	Till 9.30 A.M.	Total Time Hours.	Before Loading	After Loading.	Stretch on Loading.	Final.	Temperature Corrected.	From Curve.	Difference
10	344	28·1·27	29·1·27	24	0	10·5	10·5	11·0	11·0	10·1 11·0	0 0·9
11	342	29·1·27	31·1·27	48	11·0	12·0	1·0	12·6	12·8	12·9	1·0
12	344	31·1·27	1·2·27	24	12·6	13·6	1·0	14·0	14·0	13·9	1·0
13	342	1·2·27	2·2·27	24	14·0	14·9	0·9	14·8	15·0	15·0	1·1
14	345	2·2·27	3·2·27	24	14·8	15·7	0·9	16·4	16·3	16·3	1·3
15	340	3·2·27	4·2·27	24	16·4	17·1	0·7	17·3	17·7	17·6	1·3
16	337	4·2·27	5·2·27	24	17·3	18·4	1·1	18·4	19·1	19·1	1·5
17	339	5·2·27	7·2·27	48	18·4	19·4	1·0	20·7	21·2	22·4	1·7
18	338	7·2·27	8·2·27	24	20·7	21·6	0·9	22·0	22·6	24·3	1·9
19	344	8·2·27	9·2·27	24	22·0	25·0	3·0	26·4	26·4	26·4	2·1
20	351	9·2·27	10·2·27	24	26·4	35·6	9·2	50·0	49·3		
20·5		10·2·27			50·0						

be greater accordingly.

Table No. 2 shows the method of recording the various extensions and other observations throughout a progressive stress test; these results are from a test on brass at 340 Deg. Fah. Stress and temperature are entered in conjunction, the temperature being taken at the end of each twenty four hours. The readings are all made in the morning so that overnight conditions are observed. The time under each stress and temperature is shown along with the starting and finishing times of each stress step. In making a test, when the test-piece is at the required temperature the load is set to zero and the micrometer dial set accordingly. The stress is then brought to the first value and immediately after loading the micrometer and temperature are measured. These first dial readings are entered under "Before and After Loading" and the initial temperature is set at the head of the temperature column, to be used to correct the initial after loading reading if necessary. The difference between before and after loading is entered as "Stretch on Loading". At the end of the twenty-four hour period the micrometer gauge is again read, entry being made under "Final Gauge", and the corresponding temperature is measured. The stress is increased by a further ton/in^2., the gauge again read. This procedure is carried through each morning. Under "Temperature Corrected" gauge readings the initial after loading reading and each final reading are entered, after being corrected for temperature. These corrected readings are plotted with the number of the corresponding stress increment, giving the extension-stress increment curve, Fig. 14. From the smoothed curve extension values are entered under "From Curve", the successive differences from these are put under "Difference". Differences plotted with stress increments give the derived curve, Fig. 16, and the limit stress value.

To obtain ductility records, the test-length is marked by two transverse scratches one inch apart. After fracture the broken pieces are put carefully together and held firm by placing on a sheet of plasticine. The distance between the scratches is measured with a measuring microscope. The reduced diameter is also more conveniently measured in this way than with a screw micrometer.

Throughout all the tests performed, the greatest number of fractures occurred within the gauge length, the scratches never inducing a fracture. This may be attributed to the use of a full-wound furnace for heating the test-pieces, this type of furnace giving an uneven temperature distribution over the test-length, the centre of the length always being hottest and consequently weakest, so that fracture will perforce take place there, unless some inherent weakness or flaw locates it elsewhere.

There are certain distinctive differences between the progressive stress test and the absolute method. In the absolute method the creep limit stress is approached by reduction through the field of continuous creep, while with the progressive test the limit stress is approached via the field of temporary creep. The tendency with the absolute method is to estimate the limit on the high side, while with the progressive test it tends to the low side; this, of course, is a decided advantage from the safety point of view, though it means more material if the metal is to be worked just on the limit. Since in the progressive stress test, the initial flows exist for less than a day, then with a stress increment rate of one ton/in^2.,/day, there is no time effect and the creep limit stress may be very accurately determined in about ten days. This compares very favourably with the absolute method which requires months to complete and uses several test-pieces.

FURNACE TESTS WITH CAST IRON:-

In the course of this research the author had occasion to participate in the discussion on a paper on the subject of "Failure of Metals by Creep" by Kerr (15). Kerr referred to the work of two American experimenters (16), which appeared to raise important issues regarding the accuracy of the standard procedure. The Americans had made temperature surveys on similar test-pieces heated in full and gap-wound furnaces; the gap-winding being so arranged as to give a uniform temperature along the test-length. They also made comparative tensile tests using both furnaces. Their stress-temperature diagrams showed that the full-wound furnace produced results which were false by about 100 Deg. Fah. This increase in temperature they attributed to the fact that full-winding in a furnace has the effect of concentrating the heat towards the centre of the test-piece and leaving the ends cool.

An examination of the American's temperature variations for full-winding was made and the results compared with a survey made in the author's plant. A considerable discrepancy was found and it was concluded that this and the abnormal results from their full-wound furnace tests could probably be explained by poor shielding of their thermo-couple from the furnace wall radiation and hot air currents. To finally settle the problem it was decided to carry out a complete furnace investigation and compare strength values of cast iron when tested in either type of furnace, special care to be taken with the measurement of temperature.

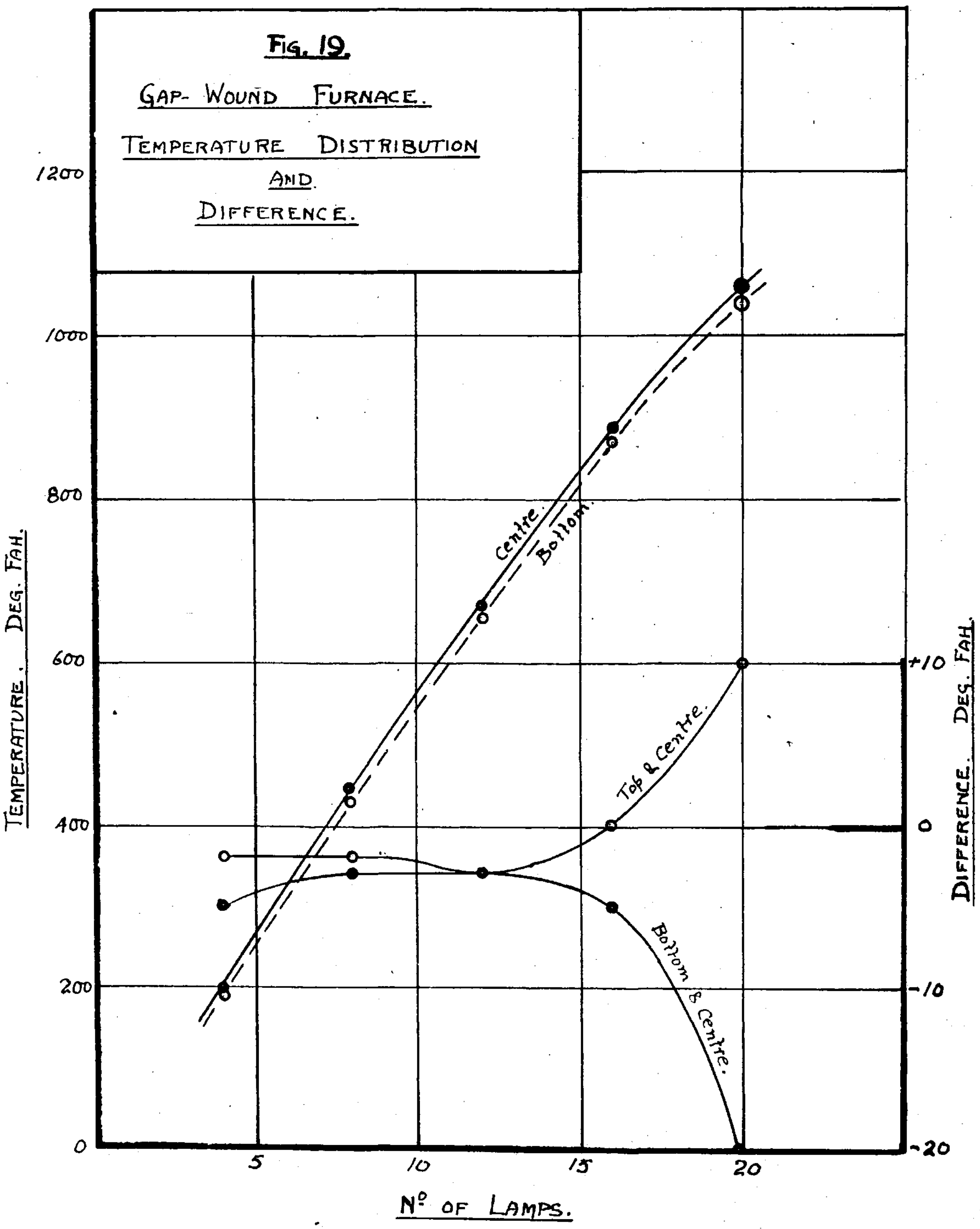


Fig. 19.

Gap-Wound Furnace.

Temperature Distribution and Difference.

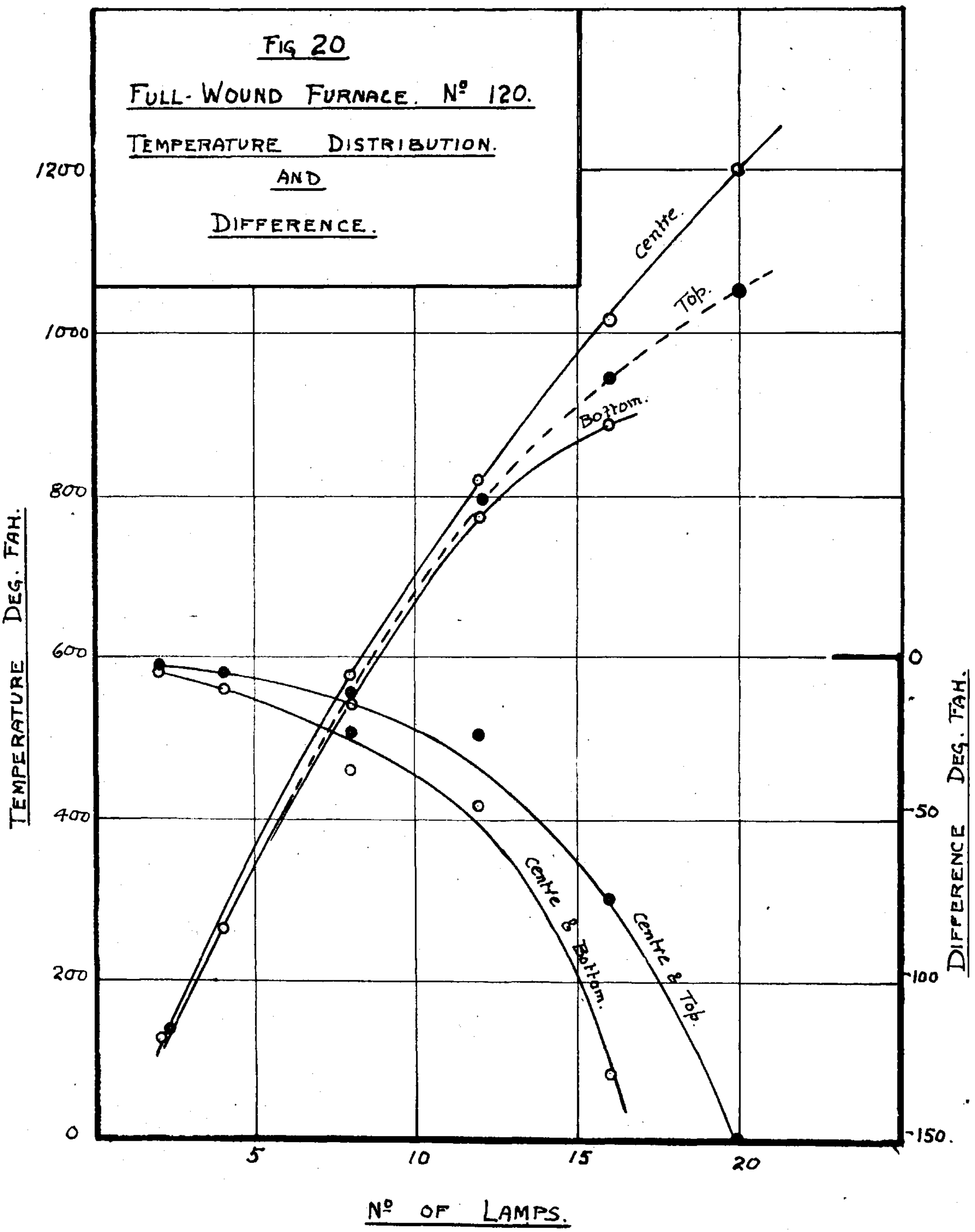


Fig 20

Full-Wound Furnace. No 120.

Temperature Distribution and Difference.

Two new furnaces were constructed, one full and the other gap-wound and the temperature surveys proceeded with. Three thermo-couples were employed, the hot junctions being located one at either end and one on the centre of the test-length. For purposes of checking the uniformity of the temperature distribution additional couples were sometimes inserted in a variety of intermediate positions. Each couple was carefully bound to the test-piece by means of a strand of asbestos cord. The cord shielded the junction from radiation and the surrounding hot air, so that the actual metal temperature was obtained. The electro-motive force generated by the couples was measured with a milli-volt meter using the "Null" method, thus ensuring that any resistance in the couple leads was cancelled.

The full-wound furnace remained as it had been wound, 120 turns on a six-inch length, but the gap-wound one had to be rewound several times before a uniform temperature along the test-length was attained. The final winding was - 29 turns on 1½ inches at the top, 11 turns for 2½ inches, 40 turns on 2 inches at the bottom, making 80 turns in all. The test-piece was located at the centre of the furnace length.

The results of the surveys are given in Figs. 19 and 20, gap-winding Fig. 19, and full-winding Fig. 20. The temperatures are plotted on a base of the number of lamps used in the control resistance panel.

For gap-winding, two curves are given connecting temperature with lamp resistance; these are for the centre and bottom couples, that for the top is not shown as it was practically coincident with the centre curve. The other two curves show differences between the top and the centre, and between the bottom and the centre temperatures.

The temperature distribution is fairly uniform up to 700 Deg. Fah., after which it gradually becomes less regular, the top becoming hotter and the bottom cooler there being a temperature gradient from the top to the bottom. The deviations are small, the greatest being 20 Deg. Fah., low, at about 1,100 Deg. Fah.

The corresponding curves for the full-wound furnace are shown in Fig. 20. Three temperature curves are given, for the centre, top and bottom couples, at all temperatures the centre is always the warmest portion and the bottom is always coolest. The differences in this case are very considerable being 150 Deg. Fah., and more at 1,200 Deg. Fah.; similarly with the gap-wound furnace, they are within reasonable bounds up to 700 Deg. Fah.

For any given number of lamps in the circuit resistance there is no fixed temperature, but rather some range, as the packing at the top of the furnace cannot be made always in the same state of tightness. For this reason, in making the surveys, it was essential to make good and well shielded thermo-junctions and to commence with a low temperature so that any danger of a couple burning through would be confined to the finish of a survey. In one case there was a burnt couple, the bottom couple in the full-wound furnace burning through at the end of the range. This couple was made of copper and constantin wires, and it was found that the copper wire burned through very readily. In later tests, iron was substituted for copper, the couples thereafter giving every satisfaction.

Both sets of temperature curves are initially nearly straight, showing a direct relation between temperature and furnace current. In the higher temperature ranges there is a falling off in temperature; this is due

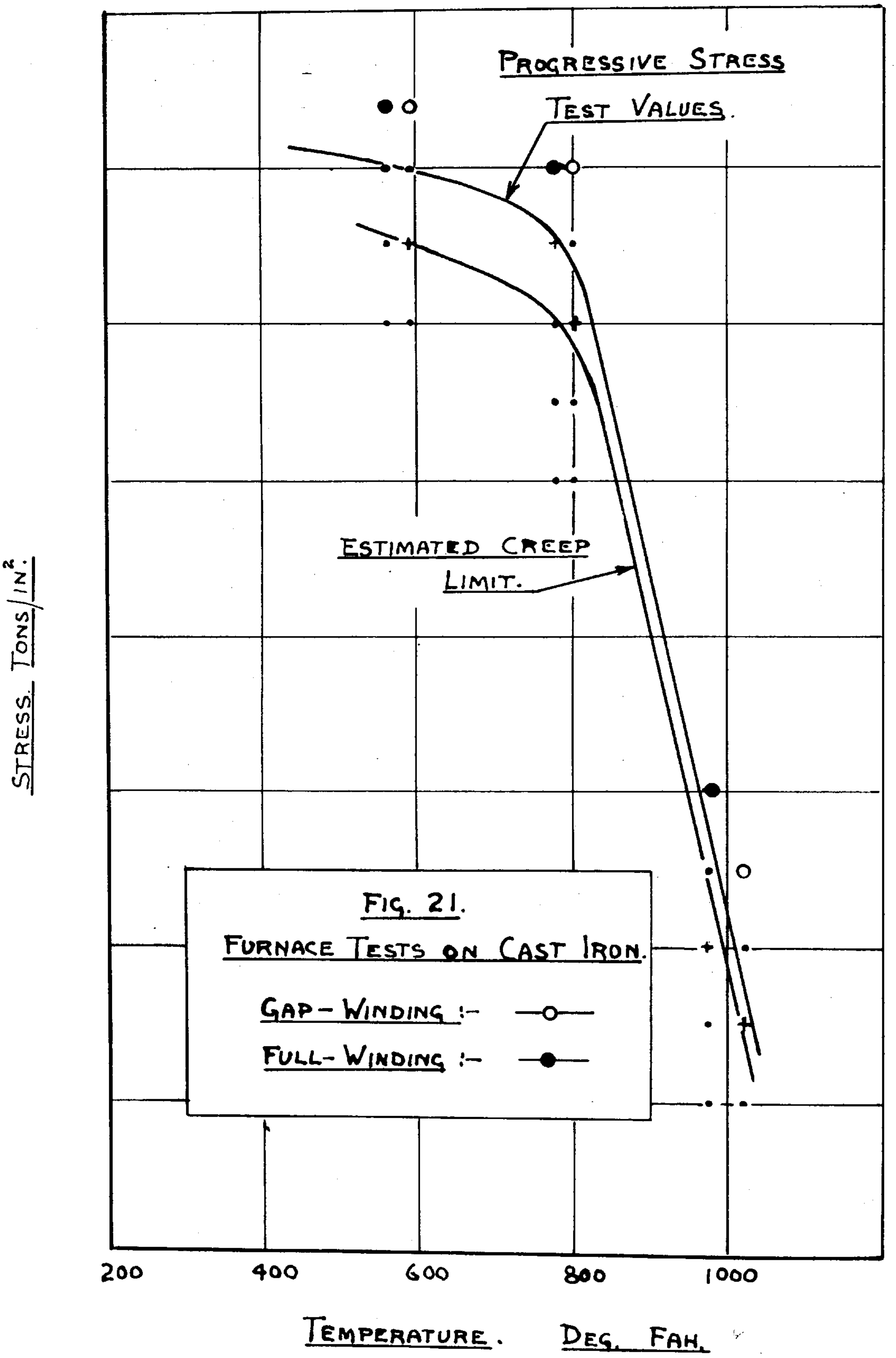


Fig. 21.

Furnace Tests on Cast Iron.

to greater heat losses by conduction and convection.

The full-wound furnace gives uniform radiation, so that in heating a test-piece, the relatively small specimen receives heat at the same rate as do the more massive grips. When steady conditions occur, there is a heat flow from the test-piece through the straining rods to the rest of the machine, giving a temperature gradient from the centre of the test-piece outwards. Closing the top of the furnace reduces the heat loss due to convection and the hottest region is in consequence moved upwards; so to obtain the highest temperature at the centre of the test-length the furnace is set off centre relative to the test-piece. With gap-winding the heating effect is concentrated about the grips, and heat flows into the test-piece until steady conditions are attained, when the temperature distribution along the test length is uniform. With the top closed the upper portion of the specimen tends to become warmer than the rest, due to restriction of convection, and for this reason the gap-wound furnace has uneven end windings.

On the completion of the furnace tests, experiments were carried out on cast-iron, using the two forms of furnace construction. Six cast iron test-pieces of known general properties were selected. The tests were made at approximately 600, 800 and 1,000 Deg. Fah., two tests being made at each temperature, one with full-winding and the other with gap-winding. This choice of temperatures was made to give a good disposition of the resulting strength values on the stress-temperature diagram. This diagram is given in Fig. 21.

It is very apparent that there is no difference in the strength values obtained by using the different types of furnace winding, the small differences shown on

TABLE N^{o}. 3.

CAST IRON.

DETAILS.	STRESS. TONS/IN^{2}.	TEMP.^{E} DEG. FAH.	FINAL GAUGE. 1/1000"	TEMP^{E} CORR^{D} 1/1000"	FROM CURVE 1/1000"	DIFF^{E} 1/1000"
TESTS N^{OS}. 2, 3 & 4 MADE IN GAP-WOUND FURNACE. N^{o} 2 AV. TEMP. 800 °F.	10	806	21·9 22·5	21·9	19·6 22·0	2·4
	11	798	24·6	24·8	24·6	2·6
	12	793	26·8	27·5	27·5	2·9
	13	795	31·0	31·5	31·5	4·0
	14	—				
N^{o} 3. AV. TEMP. 1020 °F.	2	1020	1·4 3·0	3·0	1·4 3·0	
	3	1023	4·8	4·5	4·5	
	4	1018	14·2	14·4	14·4	
	5	1018				
BROKE ON LOADING AT APPROXIMATELY 14 3/4 TONS/IN^{2}. N^{o} 4. AV. TEMP. 590 °F.	12	583	15·0 15·2	15·9	14·5 15·9	1·4
	13	590	17·7	17·7	17·6	·7
	14	590	20·0	20·0	20·0	2·4
TESTS N^{OS}. 1, 5 & 6 MADE IN FULL-WOUND FURNACE. N^{o} 1. BREAKING LOAD 6 TONS/IN^{2}. AV. TEMP. 974 °F.	2	995	14·0 15·2	13·1	12·2 15·7	3·5
	3	975	19·8	19·7	19·7	4·0
	4	975	24·3	24·5	24·4	4·7
	5	975	30·8	30·7	30·7	6·3
BROKE ON LOADING AT APPROXIMATELY 14 3/4 TONS/IN^{2}. N^{o} 5. AV. TEMP. 562 °F.	12	543	14·9 15·0	16·9		
	13	568	16·6.	16·0		
	14	575	18·5	17·2		
N^{o} 6. AV. TEMP. 775 °F.	10	760	10·2 9·8	11·3	10·0 10·9	0·9
	11	760	10·3	11·8	12·0	1·1
	12	775	13·4	13·4	13·7	1·7
	13	777	16·3	16·1	16·0	2·3
	14.	775.	19·0	19·0	19·3.	3·3

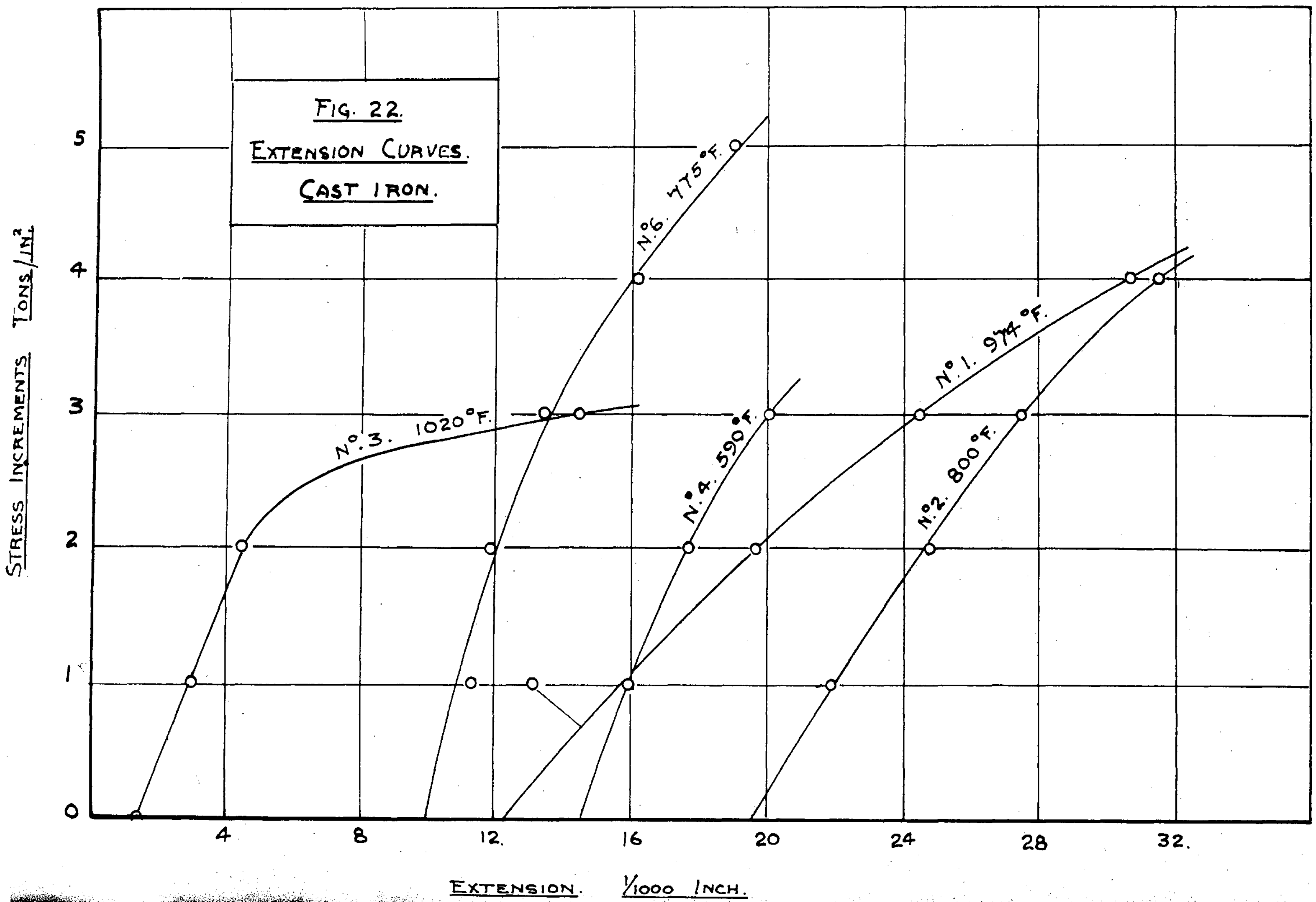


Fig. 22.
Extension Curves.
Cast Iron.

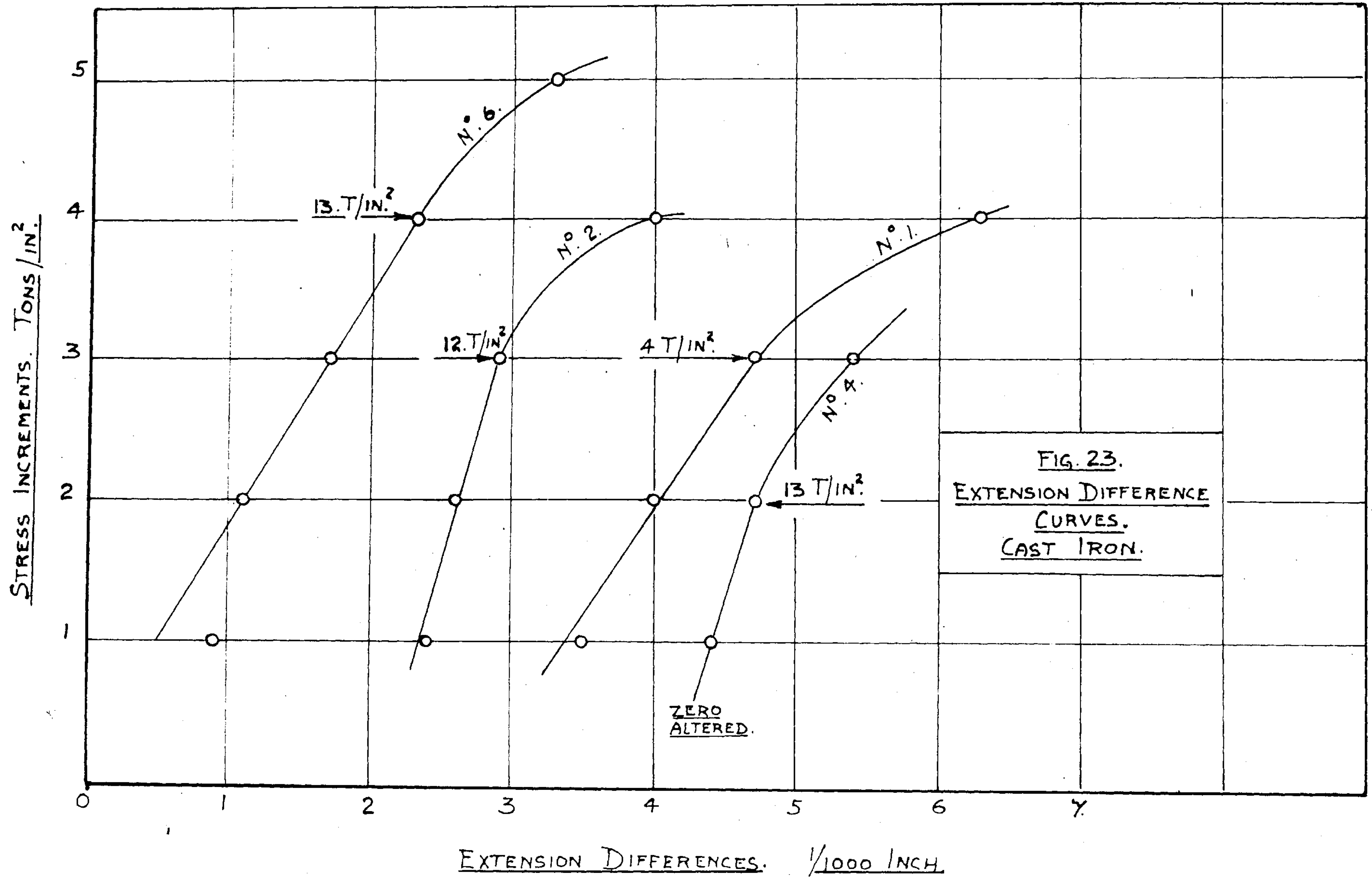


FIG. 23.
EXTENSION DIFFERENCE CURVES.
CAST IRON.

the curve being within the range of experimental error. It is thus shown that for this type of tensile test at elevated temperatures a full-wound furnace is just as satisfactory as a furnace which produces a uniform temperature along the test length, subject to the thermo-junction being located at the hottest point of the specimen.

During these tests the Ames micrometer gauge was employed to follow the extension of the cast iron. These measurements are given in Table No. 3 along with the other test information. The final gauge readings after having the temperature correction applied were plotted as extension curves in Fig. 22, that for Test No. 5 being omitted as the temperature had varied very erratically. The curves are typical but are very short since the tests were kept short after the fashion of the original progressive stress test. Considering the paucity of stress increments before the limit value, the derived curves Fig. 23 are very clear, the straight portion and the divergence being well marked. At the points of divergence the corresponding limit stresses have been entered. The derived curve No. 3 is not plotted, but the limit stress is easily estimated from an inspection of the values taken from the extension curve. The estimated creep limit values are plotted with the slow break stresses in Fig. 21. The estimated creep limit stresses are about one ton/in^2 lower than the progressive stress test curve over the range of 600 to 1,000 Deg. Fah., the ordinary progressive stress values being too high to the extent of one stress increment.

On measuring the test-pieces for elongation after fracture only a small increase in length could be detected, but so small that probably most of it was due to bad fitting of the fractured ends. No reduction in cross-section could be detected.

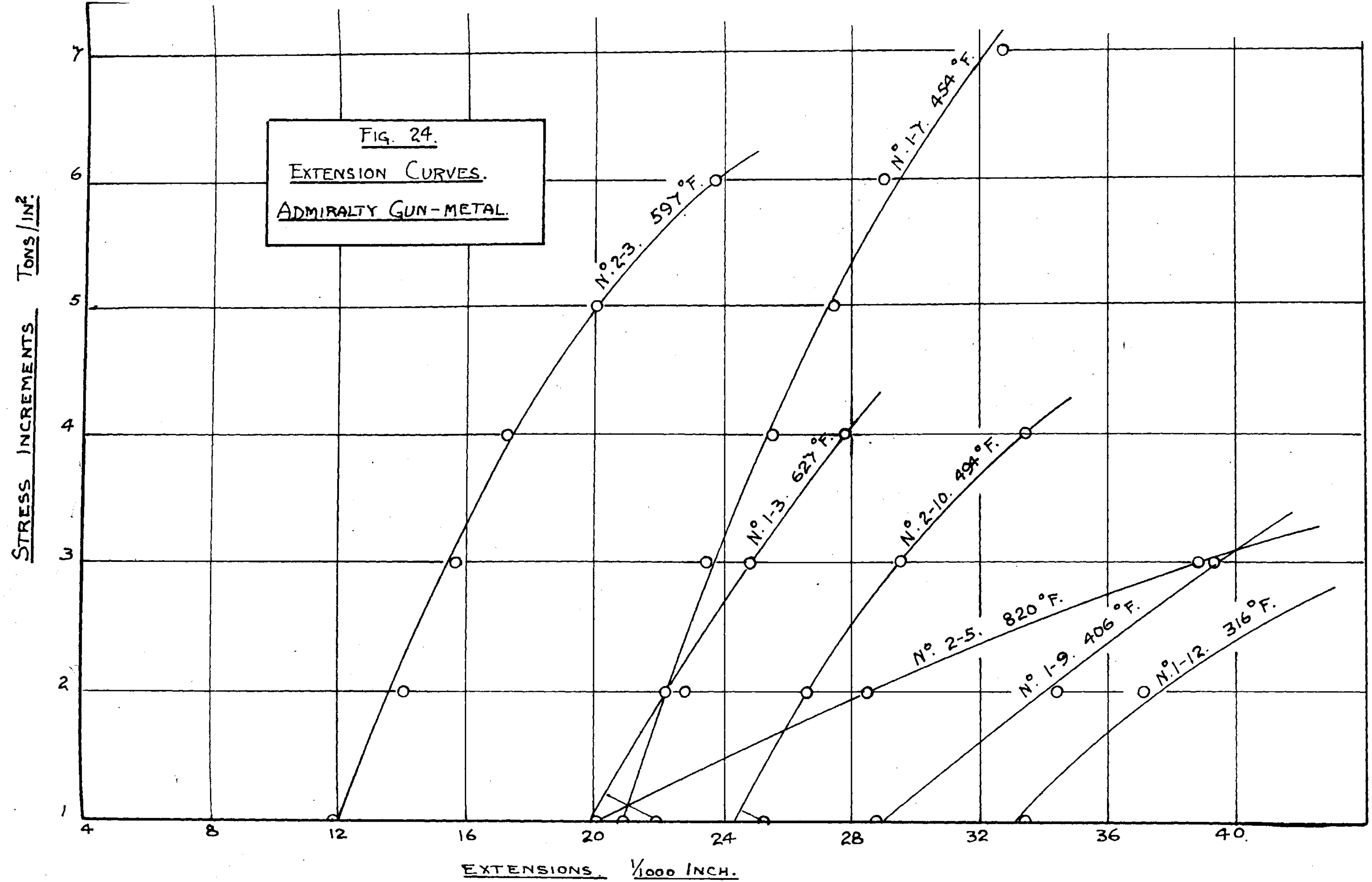


FIG. 24.

EXTENSION CURVES.

ADMIRALTY GUN-METAL.

ADMIRALTY GUN-METAL:-

Two sets of very carefully prepared Admiralty gun-metal test-bars were supplied by Messrs. Dewrance and Co., of the following compositions:-

Metal.	Set No. 1.	Set No. 2.	Admiralty Specification.
Copper	87.8%	87.4%	88%
Tin	10.24	10.28	10
Zinc	1.76	1.63	2
Lead	-	0.50	-

The first set was approximately to Admiralty Specification, while the second had the addition of half a per cent of lead. The addition of the lead content was made in order to observe the effect of lead on the high temperature properties.

These tests being made upon relatively weak material the stress increments were reduced from 1 ton/in^2., to ½ Ton/in^2, so as to limit stress errors to ½ Ton/in^2. A record of the extensions as shown on the micrometer gauge was noted. In conjunction with the slow tests ordinary quick break tests were performed, the test-piece was heated as usual and the stress was increased in steps till fracture occurred, extensions were noted on the micrometer gauge.

Eleven progressive tests were made, six being on the normal alloy and five on the leaded one. The extension curves are given in Fig. 24. With two exceptions, No. 2-3 at 597 Deg. Fah., and No. 1-7 at 454 Deg. Fah., they are very poor, their extent being only three or four stress increments, four other tests were not plotted.

Considering those which were not plotted. Of the non-leaded alloy, No. 1-5 tested at 788 Deg. Fah., gave only three stress increments commencing at 1 Ton/in^2., and breaking with a stress of 2 Tons/in^2. This test-piece crept about

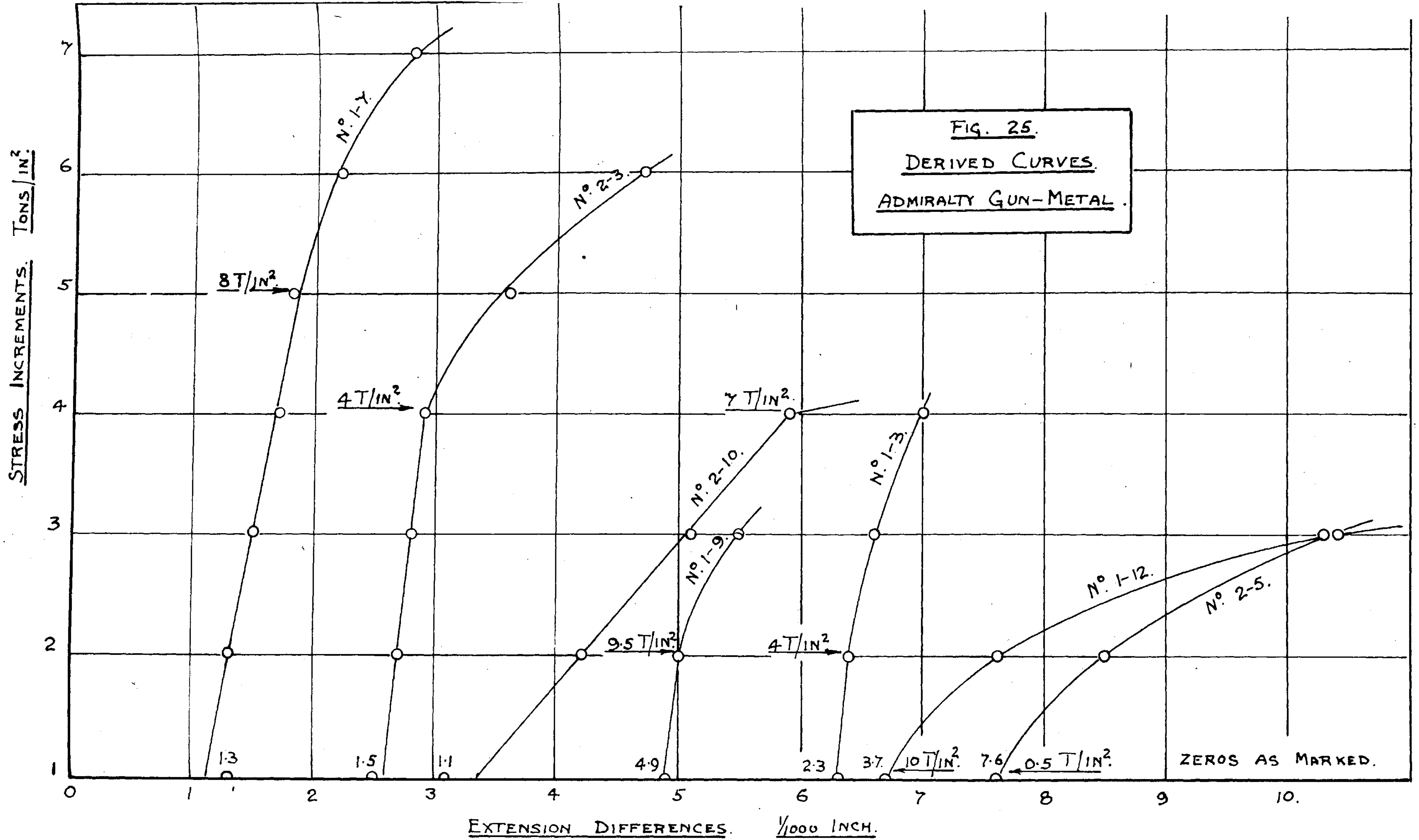


FIG. 25.

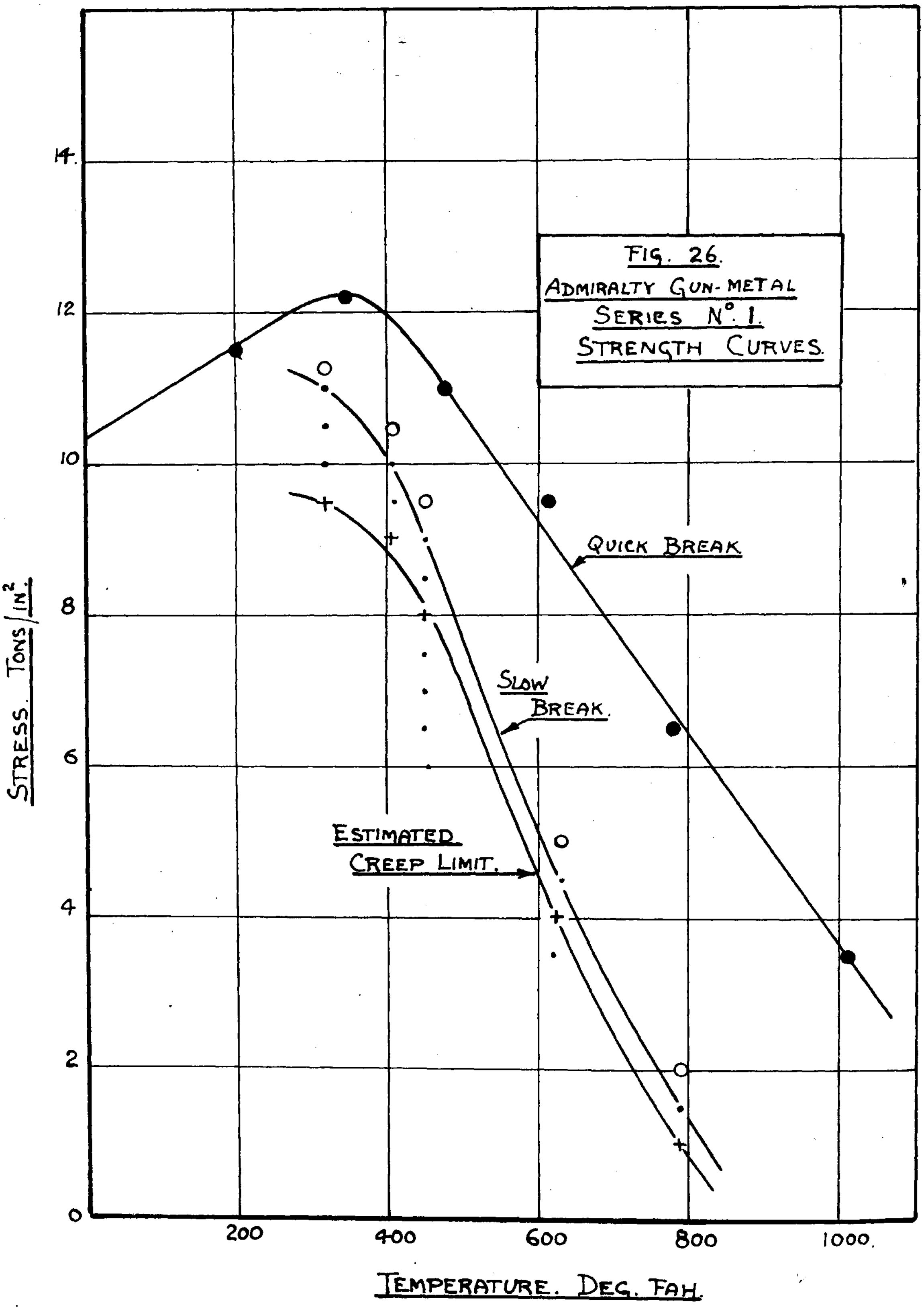
DERIVED CURVES.

ADMIRALTY GUN-METAL.

11/1000 inch at 1.5 Tons/in^2., and about 3/1000 inch at 1 Ton/in^2., so that the limit is probably 1 Ton/in^2. Test-piece No. 1-10 broke on loading with the second stress increment, 10 Tons/in^2., at 305 Deg. Fah., the test being practically valueless. Of the leaded alloy, No. 2-7 tested at 405 Deg. Fah., gave only three stress increments, from 7 Tons/in^2. to fracture at 8 Tons/in^2. It was evidently not a representative sample as can be seen from its low position on the stress-temperature diagram Fig. 27. Test No. 2-12 suffered from extension irregularities, the micrometer gauge had evidently stuck several times during the test. From the creep values and a consideration of the course of the stress-temperature curve the limit stress was estimated at about 9.5 Tons/in^2. at 300 Deg. Fah.

The remaining seven tests gave a variety of forms of extension difference curves. The curves for tests Nos. 1-7 and 2-3 are normal and show a reasonable length of straight. Tests Nos. 1-12 and 1-9 were probably commenced on or just above the limit stress as their difference curves show only the upper curved range so that the limit values have been taken as No. 1-12 - 9.5 Tons/in^2 at 316 Deg. Fah., and No.1-9 - 9 Tons/in^2 at 406 Deg. Fah. Test No. 2-5 has apparently also been commenced above the limit stress, in fact, at the temperature of the test, 820 Deg. Fah. there is the possibility that there is no limit stress, continuous creep commencing with a very low stress. The limit, however, has been estimated at ½ Ton/in^2. In the case of test No. 2-10, the difference curve is a straight line up to the last extension reading. The breaking stress is in agreement with the others, but there is no guide to the position of the limit value other than interpolation from the other limit stresses.

The majority of these tests have been too short to

FIG. 26.
ADMIRALTY GUN-METAL
SERIES N°. 1.
STRENGTH CURVES.
QUICK BREAK
SLOW BREAK.
ESTIMATED CREEP LIMIT.
STRESS. TONS/IN.²
TEMPERATURE. DEG. FAH.
14
12
10
8
6
4
2
0
200
400
600
800
1000.

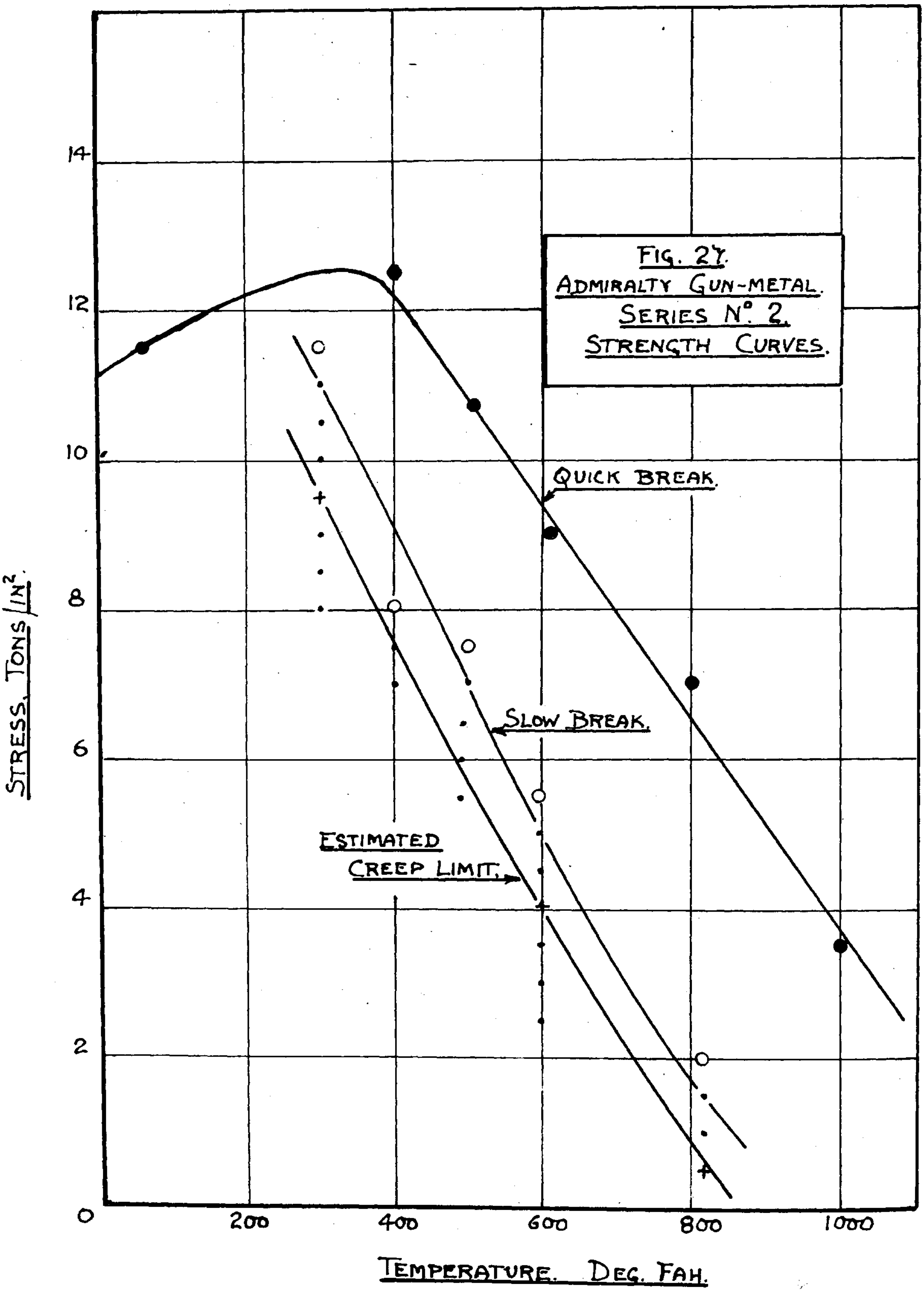


FIG. 27.
ADMIRALTY GUN-METAL.
SERIES Nº 2.
STRENGTH CURVES.
QUICK BREAK.
SLOW BREAK.
ESTIMATED CREEP LIMIT.
STRESS. TONS/IN².
14
12
10
8
6
4
2
0
200
400
600
800
1000
TEMPERATURE. DEG. FAH.

make proper estimations of the creep limit stress, but reckoning from the definite results from the two long tests Nos. 1-7 and 2-3 the plotted creep limit stress values combine very well Figs. 26 and 27. The strength curves in these figures are typical of this class of non-ferrous alloy, though their strengths are somewhat lower than is general for Admiralty Gun-metal.

The gap, between the ordinary quick break stress-temperature curve and the progressive stress test curve, which was demonstrated by Brown, is in evidence in these diagrams; but there is also a further gap between the progressive stress test curve and the estimated creep limit stress curve. This difference due to creep effects, is of the order of 1½ tons/in^2., to the critical temperature of about 400 Deg. Fah., beyond this the difference is reduced to 1 ton/in^2.

The slow break and estimated creep limit curves for the leaded alloy are rather straight; this is probably due to the lack of test values between 300 and 500 Deg. Fah., where in this range for the normal alloy there are distinct rounded shoulders to these curves. Test-piece No. 2-7 which fractured at the low stress of 8 tons/in^2., at 405 Deg. Fah., should probably have broken at about 10½ Tons/in^2., when the curves for both alloys would have been practically identical.

The quick break and creep limit curves for both metals have been combined in Fig. 28. So far as the quick break curves show, there is little difference between the metals, the leaded alloy has the advantage of about 1 ton/in^2., from normal to the critical temperature, but both are similar beyond this temperature. Allowing for the difference between the creep limit curves already discussed, there is little difference in them also, the

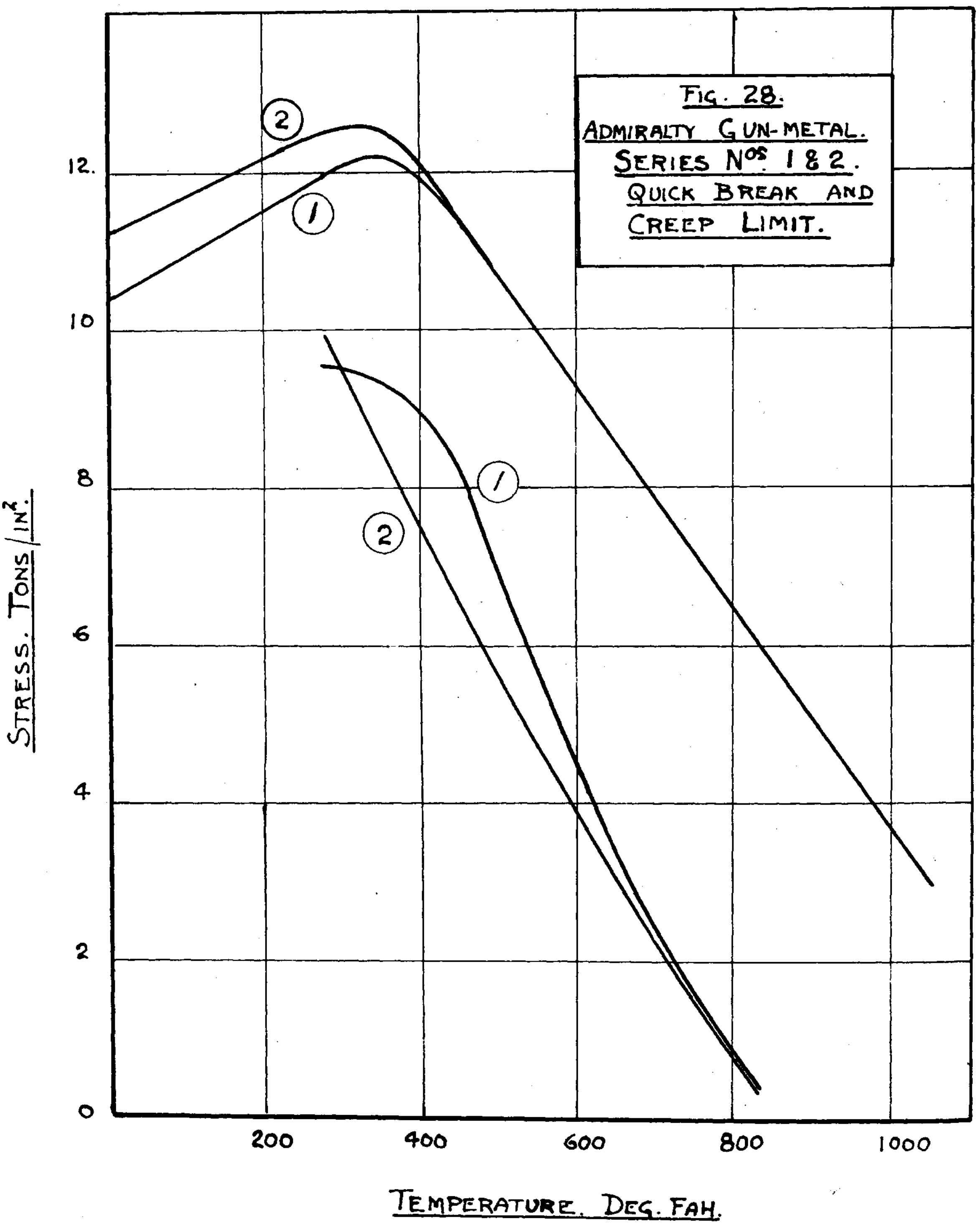


FIG. 28.
ADMIRALTY GUN-METAL.
SERIES N^{OS} 1 & 2.
QUICK BREAK AND CREEP LIMIT.

leaded alloy being apparently weaker. This weakness may be due to a slight weakening effect caused by the lead addition, this weakness only appearing during prolonged tests.

During the quick break tests the clock gauge was used to record extensions. The stress-extension readings gave fair straight lines over the elastic range, the remaining range showing smooth curves. No definite determinations could be made so the curves are not shown. The elastic extensions include those of the testing-machine itself and even correcting for this the gauge readings are not sufficiently accurate to allow modulus determinations to be made. This same consideration also rules out the limit of proportionality values.

On examining the surface of the test-pieces after fracture, the rough marks, resembling hammer blow indentations peculiar to some of the non-ferrous alloys, could be seen covering the gauge length.

The surface was also cracked, the cracks being widest in the region of the fracture. Fracture always appeared to be located at one of these cracks, the crack apparently widening and proceeding through the metal, the structure tore through to the opposite side. This progressive tearing apart produced a badly tumbled fracture and the test-piece sometimes appeared to have been bent, the fracture in every case was so disturbed as to prevent the two portions being fitted together. These badly fitting fractures prevented any elongation measurements being made and the section was too distorted to determine reductions in area.

BRASS:-

A series of eleven tests were made on a brass of the following composition:-

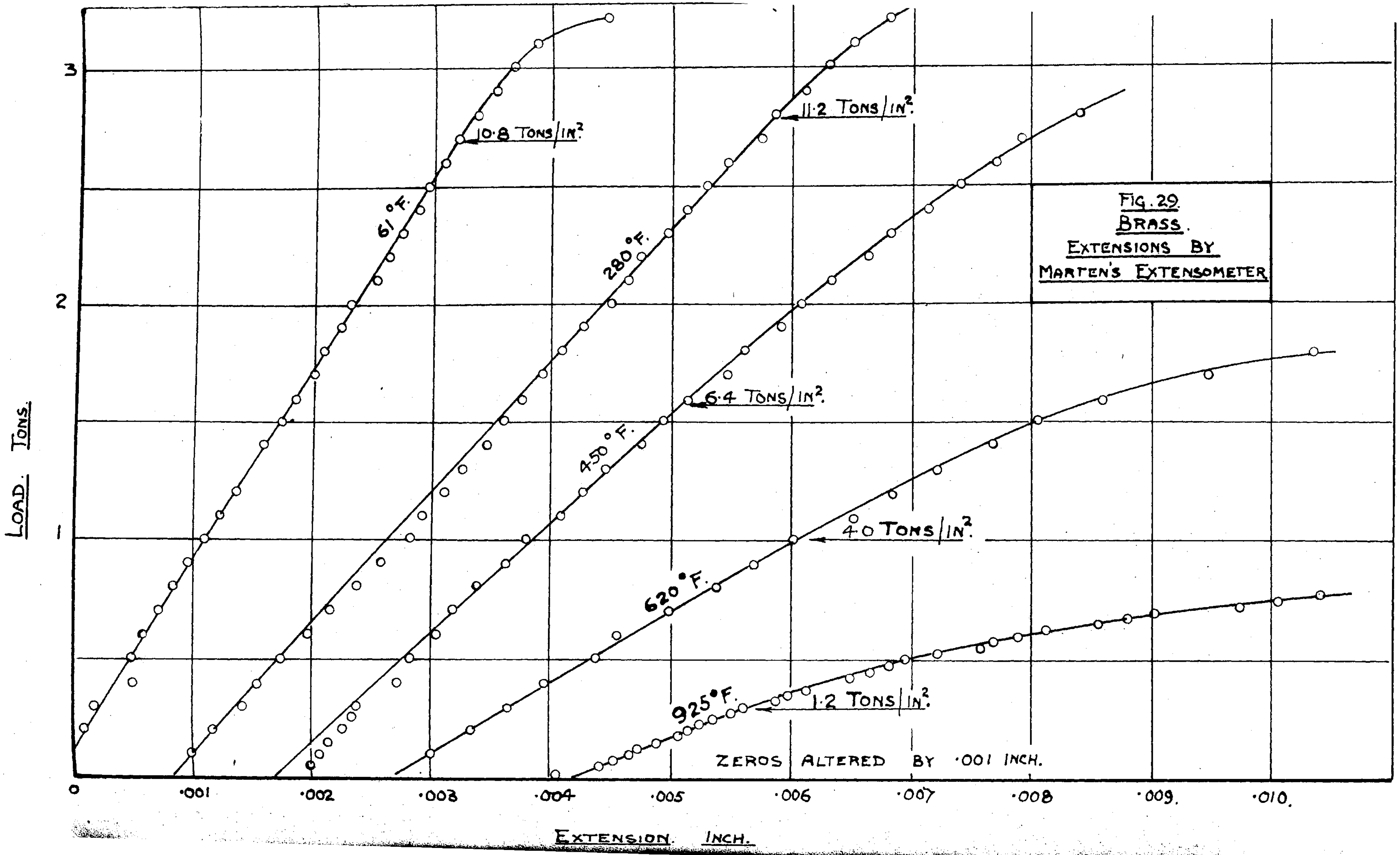


Fig. 29
Brass.
Extensions by
Marten's Extensometer

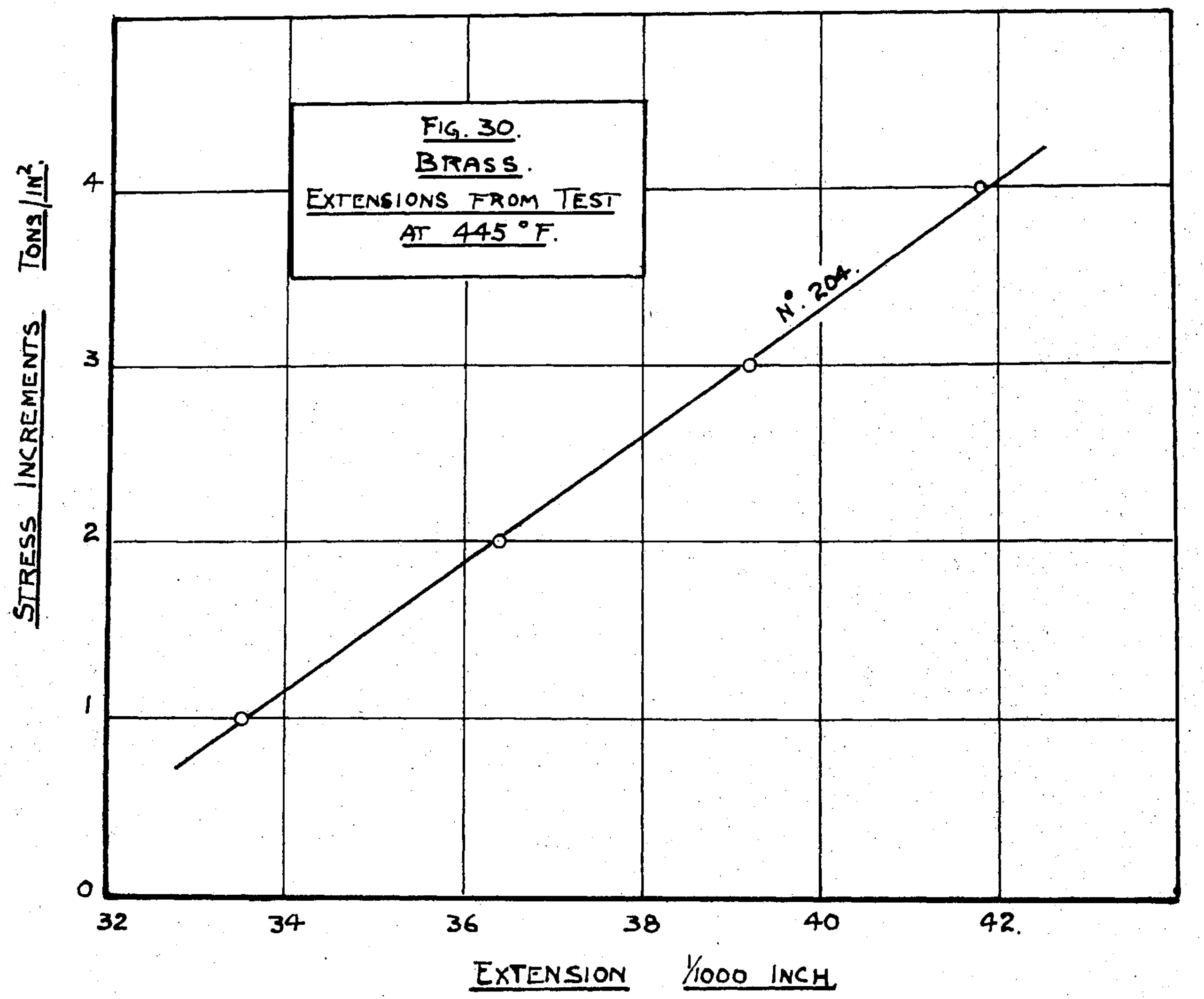


Fig. 30.

Brass.

Extensions from Test at 445 °F.

Copper	67.7%
Zinc	30.8
Iron and Aluminium	1.4
Manganese	A trace.

The analysis was made by the Metallurgical Department of the College.

Six quick break tests were made in the Avery 100 ton Testing Machine in the Materials Testing Laboratory of the College. The test-pieces were heated in an electric furnace, and the extensions produced during the tests were measured by a specially adapted Marten's Extensometer. This modified extensometer was devised by the late Prof. Longbottom (17).

The extensometer measurements are plotted as load-extension curves in Fig. 29. The curves are arranged in order of increasing temperature, the reduction of the modulus and limit of proportionality values being in this way very clearly illustrated.

The remaining five specimens were tested by the progressive test method, using the micrometer gauge. In the first three tests all above 550 Deg. Fah., the gauge was of little value the tests being only of from two to three stress increments duration. In the final two tests at 445 and 340 Deg. Fah., it was more useful, the tests being of four and eleven increments respectively. The extension-stress increment curve for the test at 445 Deg. Fah., is shown in Fig. 30 and is a very good straight line, showing no sign of a limit other than that given by the progressive stress test value of 11 tons/in^2. The curve for 340 Deg. Fah., is very good and is typical of the progressive stress test; it is shown in Fig. 15 plotted with a similar curve for a low carbon steel. The curve for

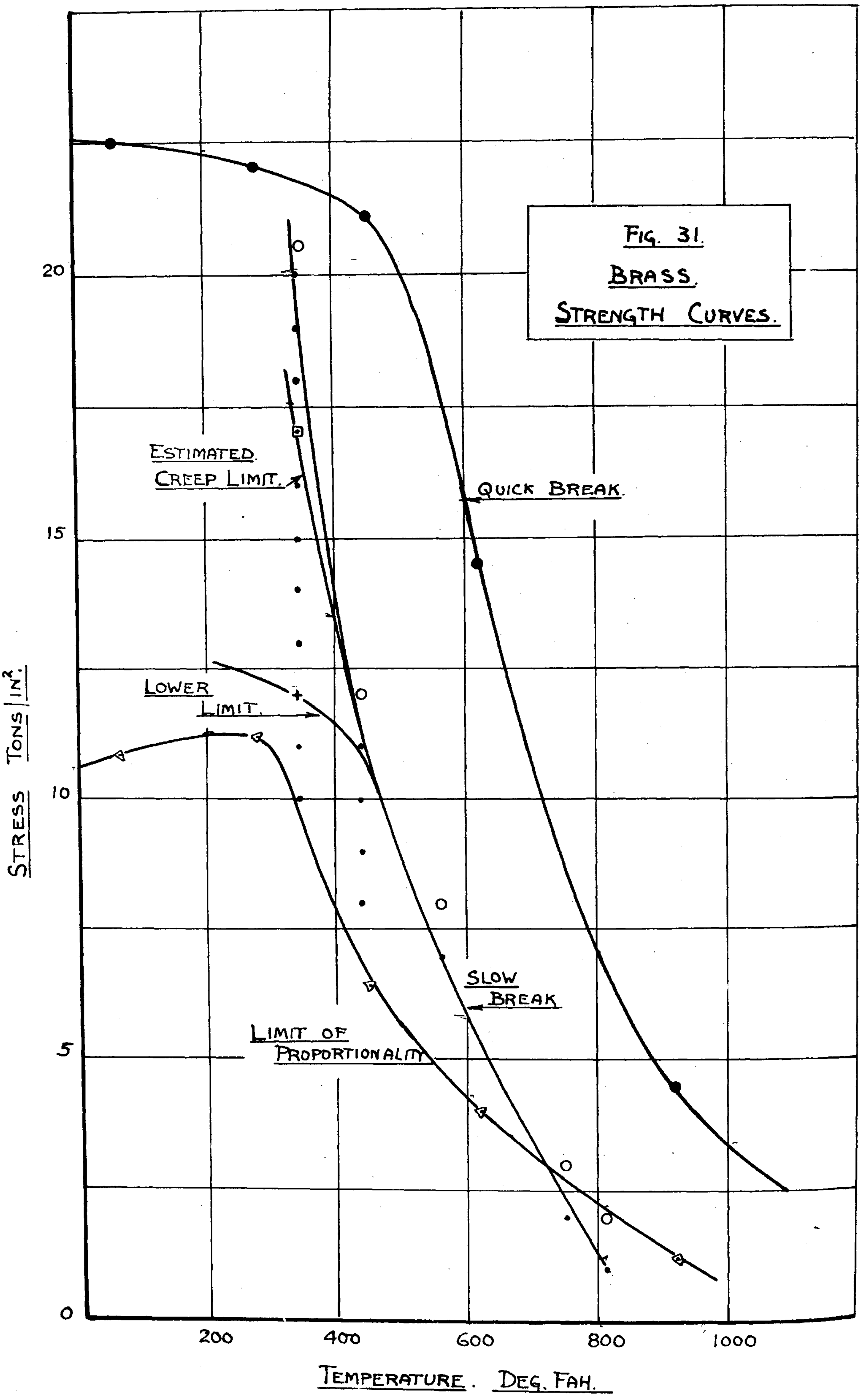


FIG. 31.

BRASS.

STRENGTH CURVES.

brass is initially much flatter and changes its direction very rapidly immediately before fracture. The extension difference curve is given in Fig. 16, along with that for steel; there is again a resemblance. The brass curve, however, shows two limits and proceeds very quickly from the upper limit to fracture. These limits are at 12 and 17 tons/in^2. The extension results from this test are shown in Table No. 2. Towards the end of this test some slipping of the test-piece was observed. One slip was noticed on loading from 19 to 20 tons/in^2., and on going from 20 to 20½ tons/in^2., there were three distinct slips, one being of the order of fifty thousandths. These slips were readily felt as pulses.

The quick and slow break values are combined in Fig. 31, which shows, quick break, slow break, estimated creep limit and limit of proportionality curves. The quick break curve indicates a change or critical point at about 450 Deg. Fah., the strength thereafter diminishing rapidly to about 3 tons/in^2., at 1,000 Deg. Fah. The slow break curve shows a similar rapid decrease in strength between the temperatures of 350 and 900 Deg. Fah. The limit of proportionality curve crosses the slow break curve at about 700 Deg. Fah. According to the conception of the limits of proportionality and creep the limit of proportionality can never exceed the creep limit stress, then in this case the limit of proportionality values must be too great, since if there is an error in the creep limit stress it will tend to be on the high side. The error in the limit of proportionality values is probably caused by a time effect, the tensile test being carried through too quickly to allow the slow creeps, which will occur after the actual limit of proportionality is passed, to show themselves in the extensions.

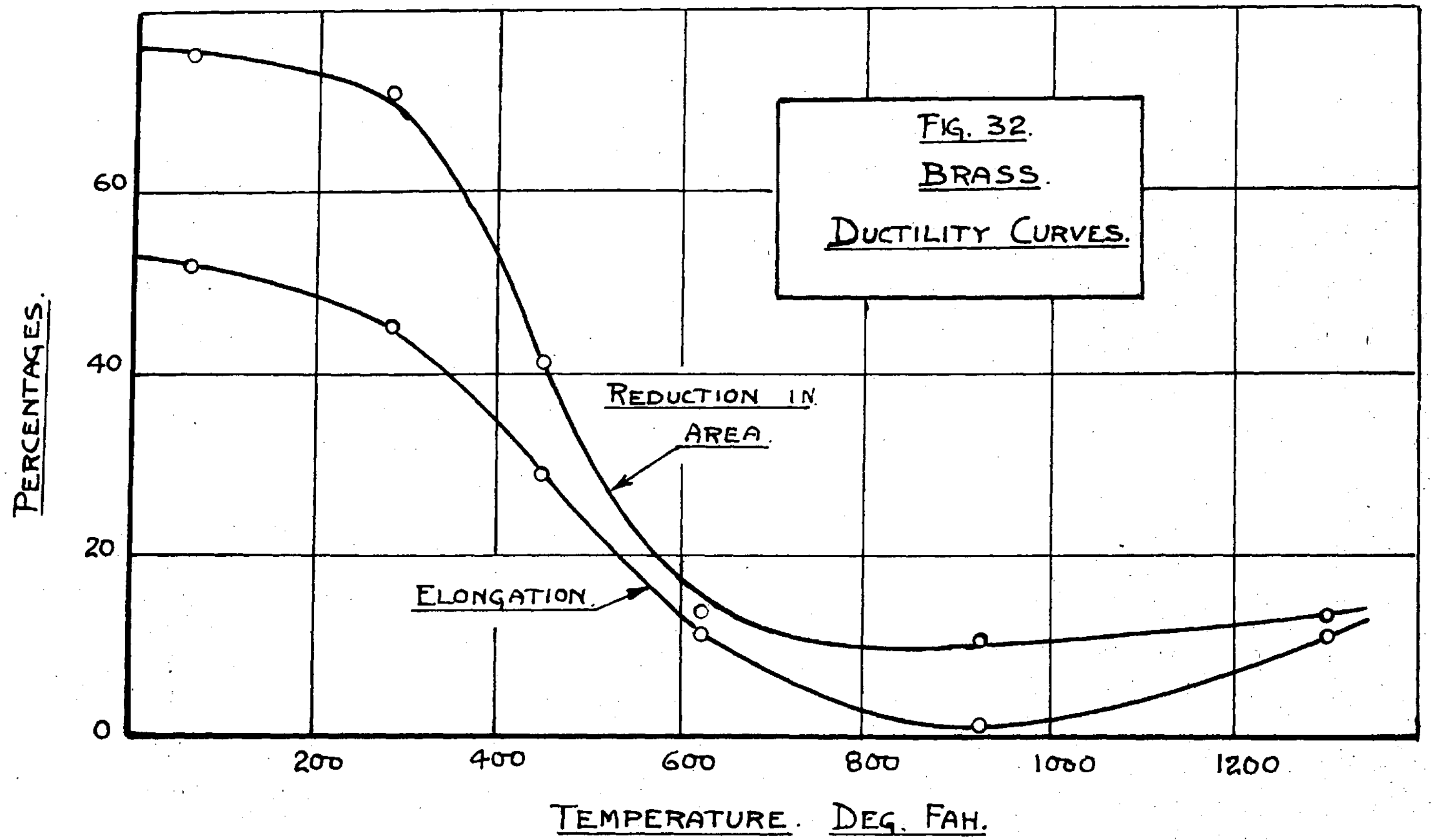


Fig. 32.
Brass.
Ductility Curves.

Of the two limits shown by the extension difference-stress increment curve of Fig. 16, the upper limit is the creep limit stress and the lower limit corresponds to the ordinary yield stress. This lower limit curve is defined by only two test points and apparently coincides with the slow break curve at about 450 Deg. Fah. The only direct evidence for this meeting is the creep extension curve for the test at 445 Deg. Fah., there is no evidence from the tests at higher temperatures as they were too short. A full consideration of the relation between this lower limit and the yield stress will be given later when an 0.25% carbon steel is dealt with.

Considering the ductility curves, Fig. 32, there is a very considerable drop in the reduction of area values between 300 and 600 Deg. Fah., and to a lesser extent with the elongations. So at the critical point of 450 Deg. Fah., as on the quick break curve, we have other two phenomena, loss of ductility and merging of the lower limit or yield values with the slow break values. The alterations in ductility evidently affect the creep process. When the ductility is very low the initial flow values are reduced so that the extension-stress increment curve is nearly straight, and since the final elongation is low the amount of final flow must also be small and is apparently completed in about the period of one stress increment. The test on brass at 345 Deg. Fah., shows the change from brittleness to ductility, the creep affects in this case resembling those for steel, the brass at this temperature being quite ductile. This test-piece showed considerable necking down, while the others at higher temperatures showed none.

Considering these results from cast iron, Admiralty Gun-metal and brass. These metals are either wholly brittle, or they have a ductile range at low temperatures followed by a brittle or low ductility range. In the majority of cases these tests have been carried through when the metals have been in the upper range, the brass example cited above being the one exception. Certain of the gun-metal tests were within the ductile range, but these have been shown to be rather unsatisfactory as the tests were commenced on the creep limit value. The results show that if a material is brittle then the original progressive stress test will give a close approximation to the estimated creep limit stress. In the cases of cast iron and gun-metal these two values were within one or two stress increments of each other, and with brass they coincided over the brittle temperature range at least.

Generally, for brittle materials or metals having a range of brittleness,the original progressive stress test will be a satisfactory substitute for the estimated creep limit method, provided a small stress allowance is made. In the ductile range or with ductile metals, extensometer measurements must be made.

0.5% CARBON STEEL:-

It was on this steel that the first elongation measurements were made, commencing with an "Unique Test Indicator"; this indicator was discarded in favour of an "Ames Micrometer Gauge" having a much wider range. Twelve tests were made; these included five ordinary quick break tests and of the remaining seven, two were tentative experiments yielding negative results.

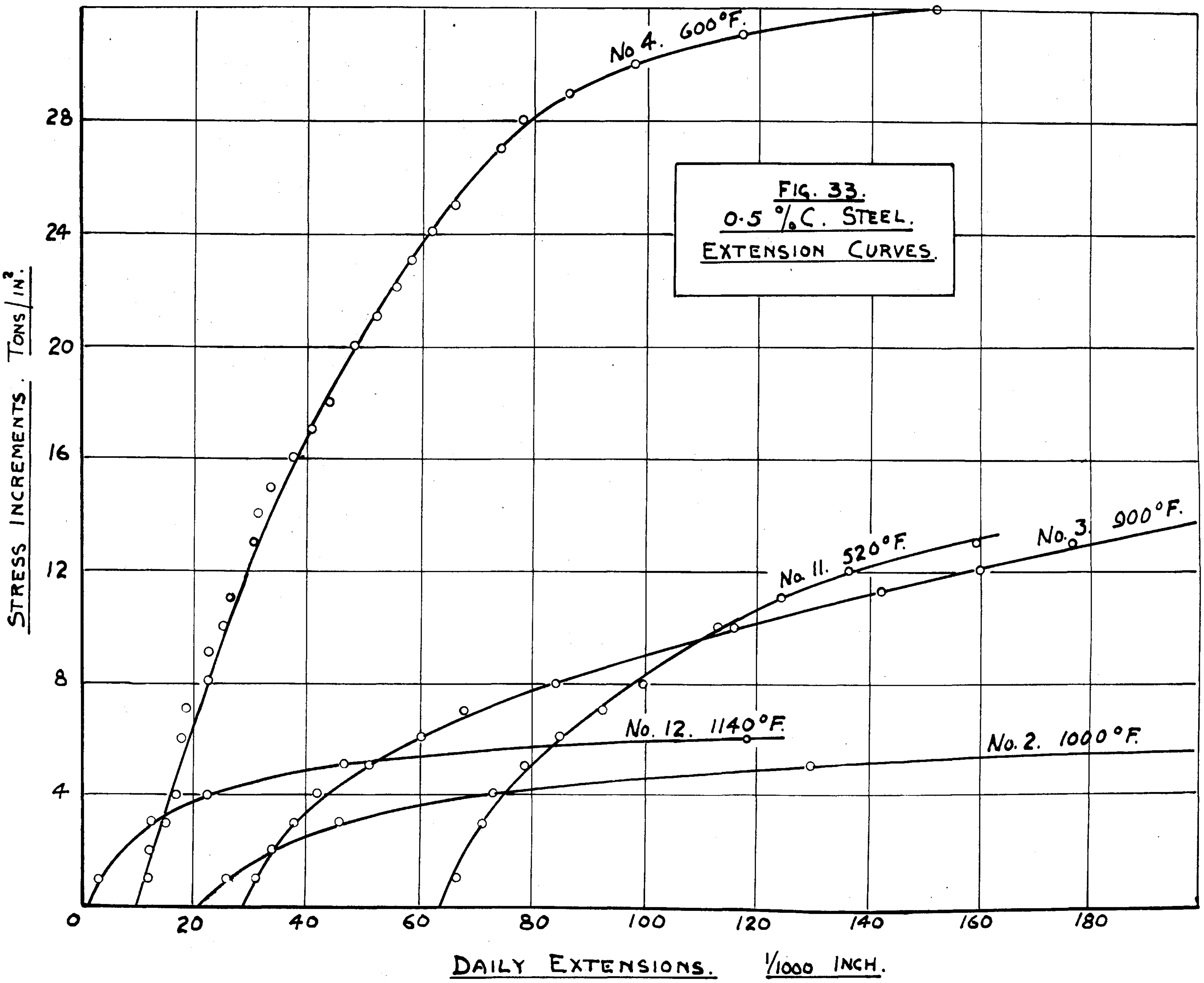


FIG. 33.
0·5 %C. STEEL.
EXTENSION CURVES.

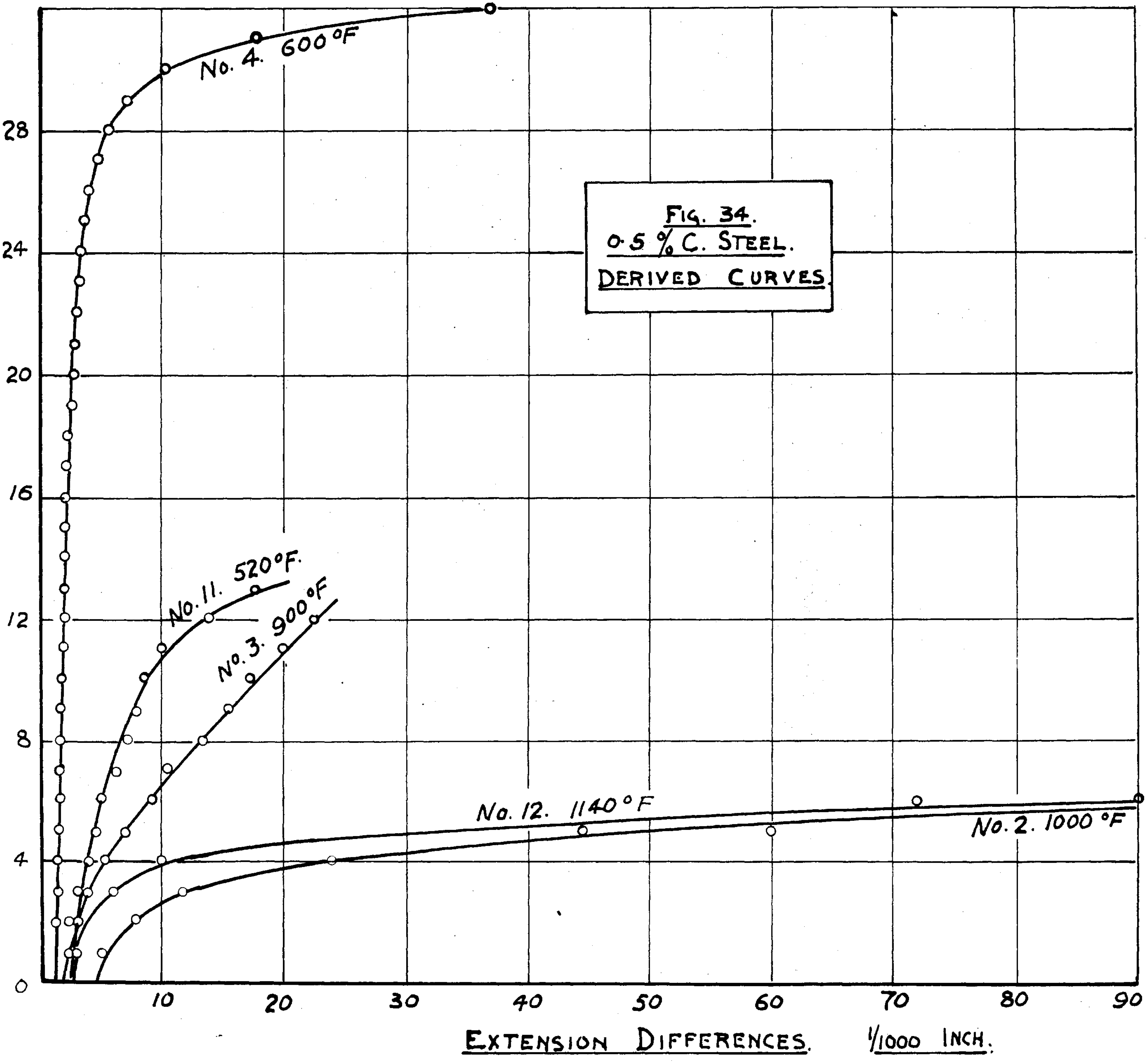


FIG. 34.
0·5 % C. STEEL.
DERIVED CURVES.
STRESS INCREMENTS. TONS/IN.²
EXTENSION DIFFERENCES. 1/1000 INCH.
No. 4. 600°F
No. 11. 520°F.
No. 3. 900°F
No. 12. 1140°F
No. 2. 1000°F
0
4
8
12
16
20
24
28
10
20
30
40
50
60
70
80
90

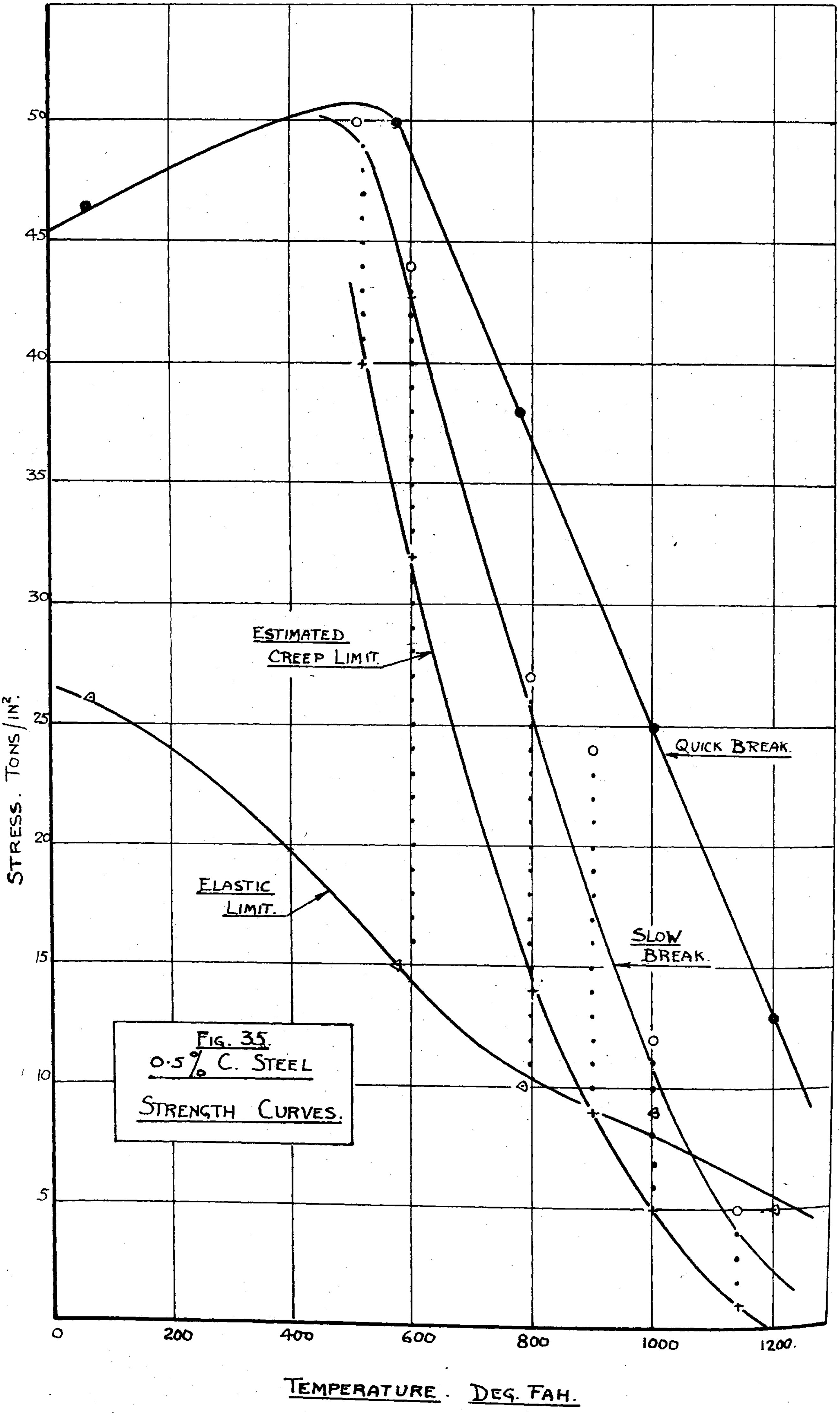


FIG. 35.
0·5% C. STEEL
STRENGTH CURVES.

The extension and extension difference - stress increment curves from the slow tests are shown in Figs. 33 and 34. The second figure is the most directly informative, showing at a glance that tests Nos. 2, 3 and 12 were commenced above the creep limit stress, there being no initial straight portion to these curves. The curve for No. 11 is very nearly straight at the beginning, the test probably having been commenced just on the creep limit stress. Curve No. 4 has a very long straight portion, this extending for sixteen stress increments, the test commenced at 16 tons/in^2., and the estimated creep limit stress is 32 tons/in^2. The limit stresses for tests Nos. 2, 3 and 12 were roughly estimated from the difference curves and from a consideration of the slow break strength curve. Considering the approximate extensions given by the unique test indicator, the limit stress for the first test was estimated as 14 tons/in^2., at 800 Deg. Fah.

The strength curves are given in Fig. 35, showing quick break, slow break, estimated creep limit and limit of proportionality values. Their principal feature is the wide separation between the estimated creep limit and the slow break curves. Unlike cast iron and brittle non-ferrous alloys, when a ductile steel is tested by the original progressive stress test, this test gives an entirely false impression of the strength of the metal. The error ranges from 25% at 500 Deg. Fah., to 400% at 1,100 Deg. Fah., the errors being based on the estimated creep limit values. In testing ductile metals the extensometer method must be applied to the progressive stress test and care must be taken to commence all tests well below the estimated creep limit values.

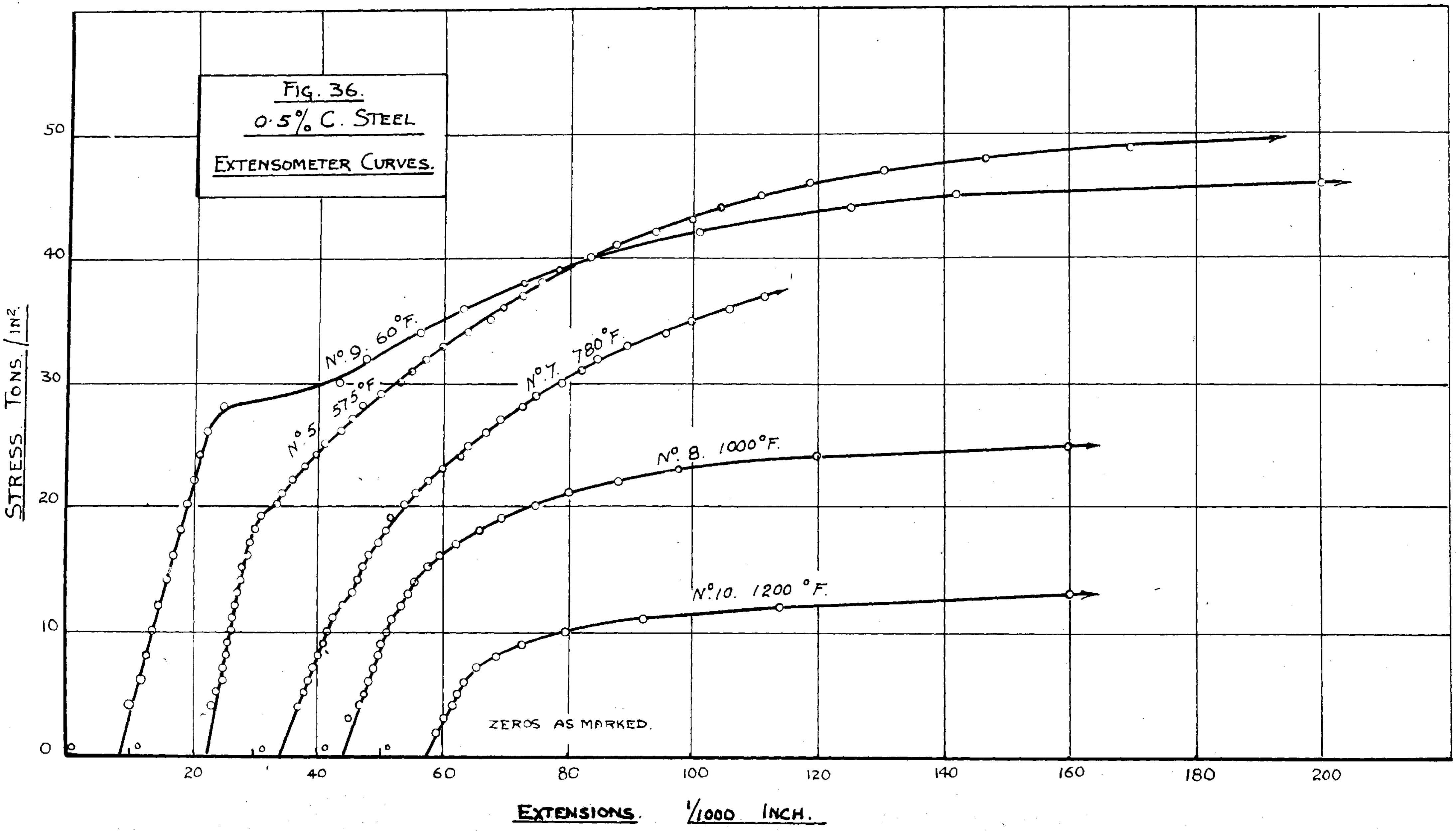


Fig. 36.
0·5% C. Steel
Extensometer Curves.

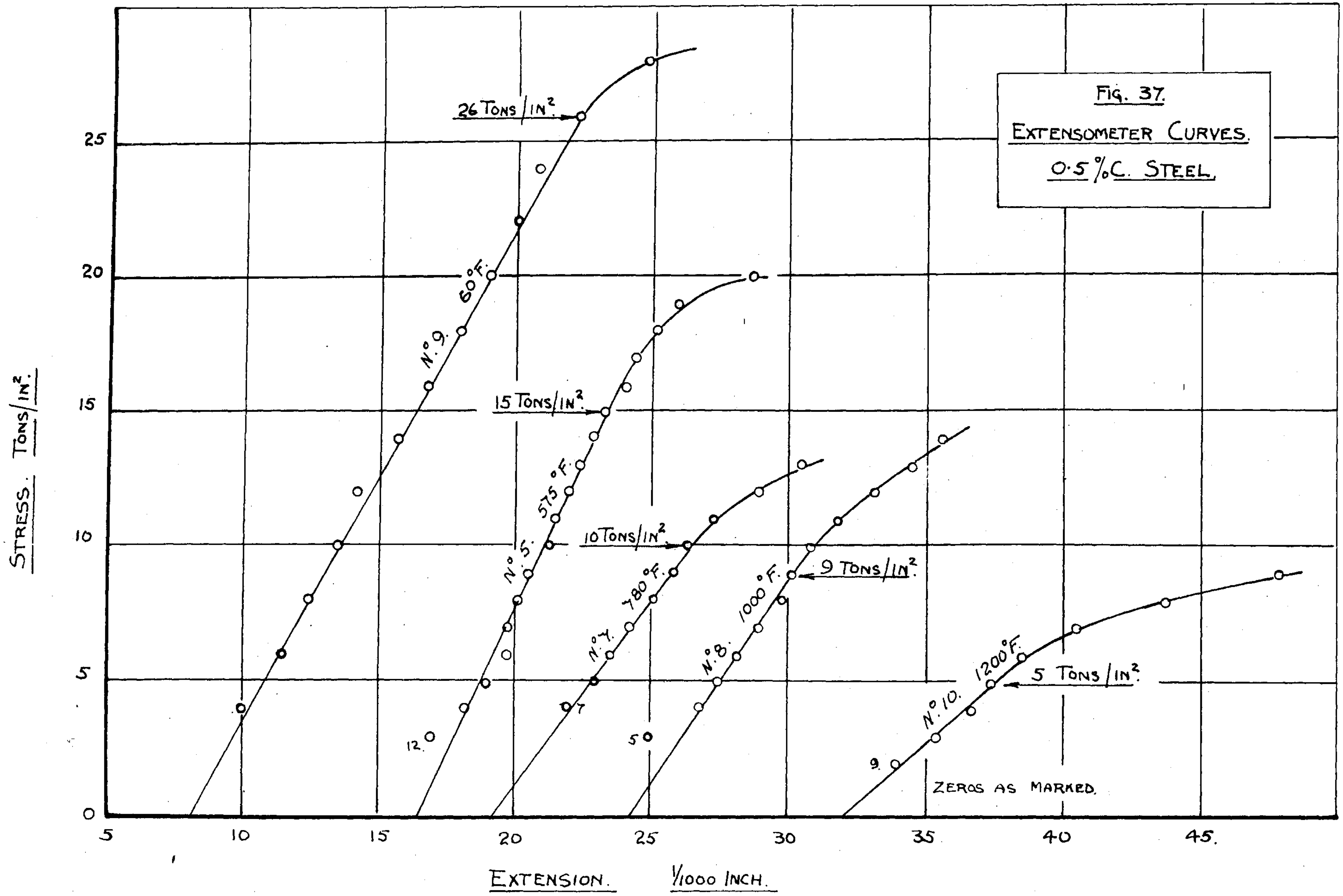


Fig. 37.

Extensometer Curves.

0·5%C. Steel.

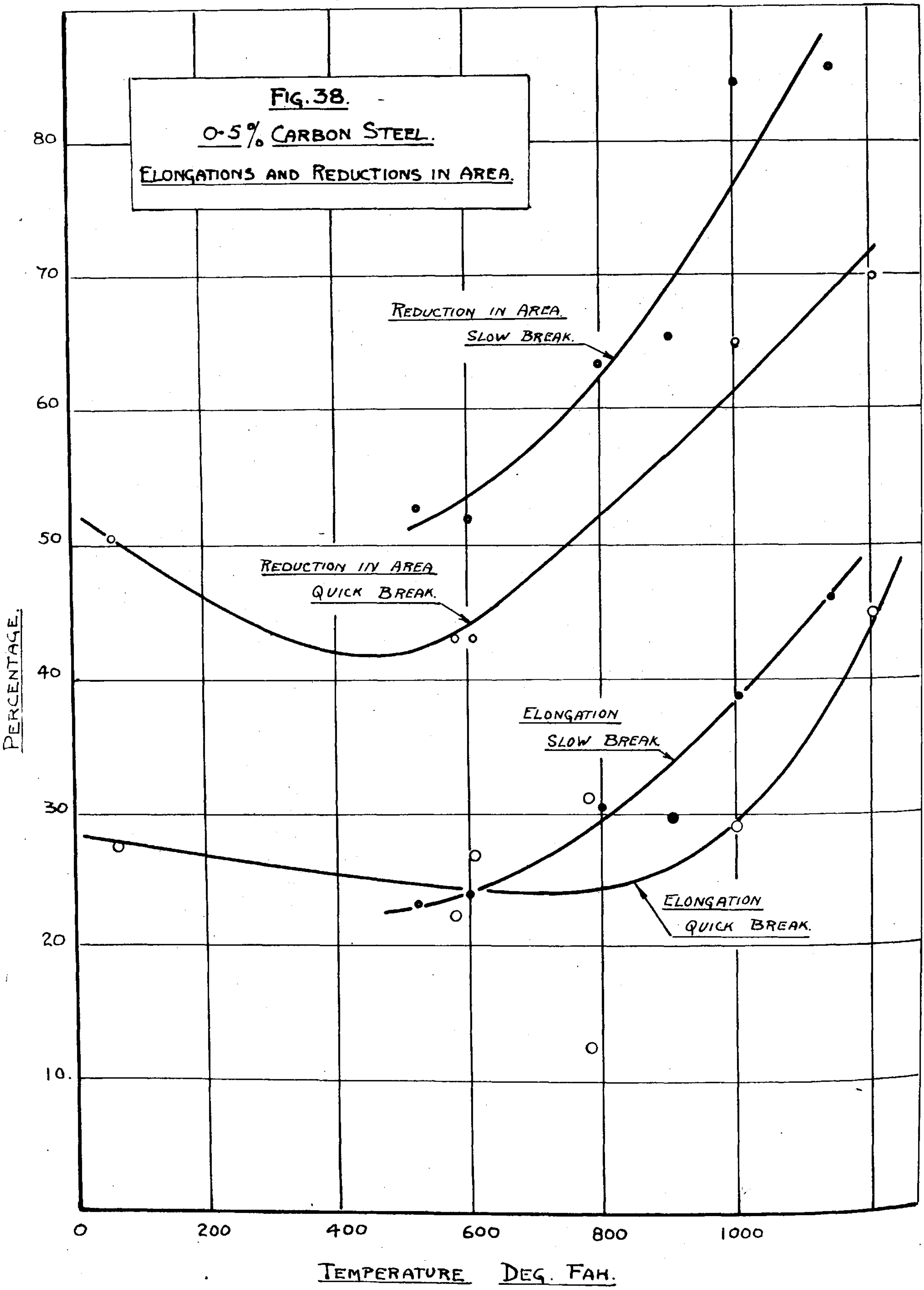


FIG. 38.

0·5% CARBON STEEL.

ELONGATIONS AND REDUCTIONS IN AREA.

The extensometer records for the quick break tests are given in Figs. 36 and 37. They resemble the usual load-extension curves for steel, having a straight elastic portion, a yield and a final plastic portion. The yield is well defined at normal temperature, this definition becoming less sharp as the temperature increases till the yield is no longer evident at 1,200 Deg. Fah., and is barely noticeable at 1,000 Deg. Fah. The values of the limits of proportionality were approximately determined from these curves, Fig. 37 and were plotted on Fig. 35 with the other strength curves. The limits of proportion: :ality give a fair curve which crosses the estimated creep limit curve at 900 Deg. Fah. The values for the limits of proportionality are most probably high due to the crudeness of the extension measurements, this causing the crossing of these limit curves.

The percentage elongations and reductions in area are shown in Fig. 38. The ductility values for the slow creep tests are slightly higher than for the quick break tests. The ductility reaches its lowest value about 600 Deg. Fah., but the steel never becomes brittle.

0.25%CARBON STEEL:-

This steel was supplied by Messrs. David Colville & Sons, Ltd., Motherwell. Great care is taken with the manufacture of this steel which is of a quite normal composition, the manufacturing process accounting for the good qualities which it shows. No details of manufacture are available, but the composition is as follows:-

Carbon	0.25%
Silican	0.10
Manganese	0.15
Sulphur and Phosphorus	0.03.

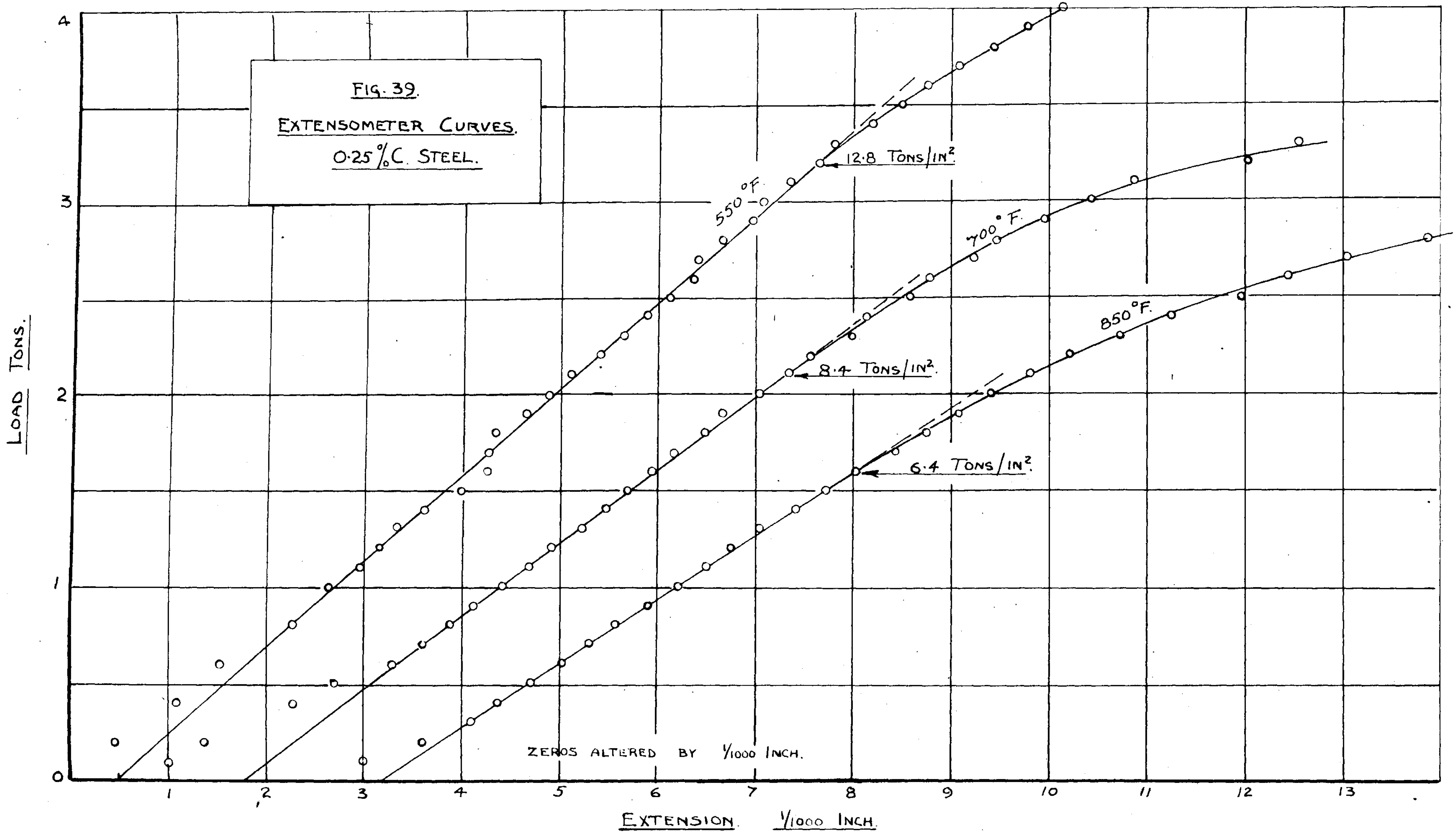


Fig. 39.

Extensometer Curves.

0·25 % C. Steel.

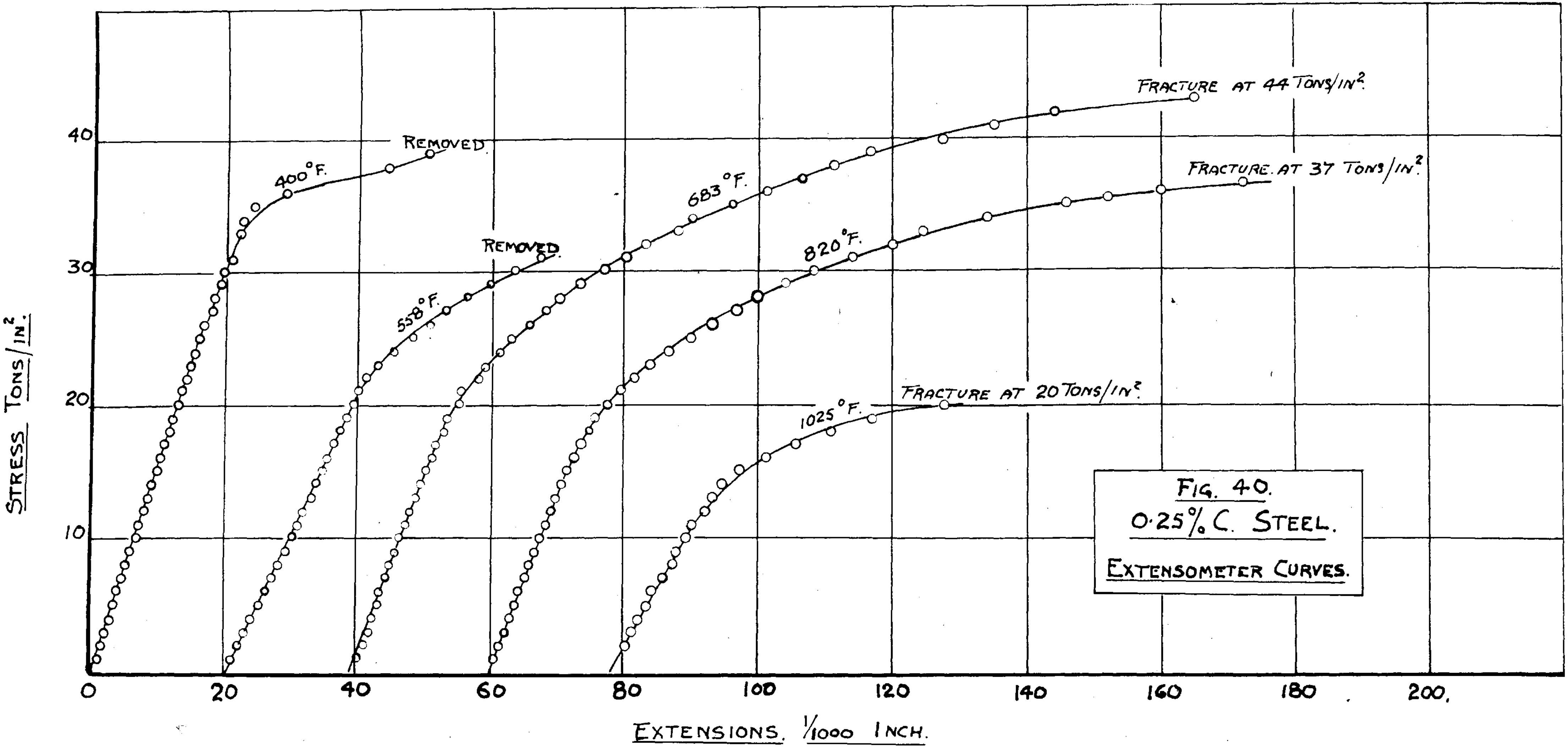


Fig. 40.
0·25% C. Steel.
Extensometer Curves.

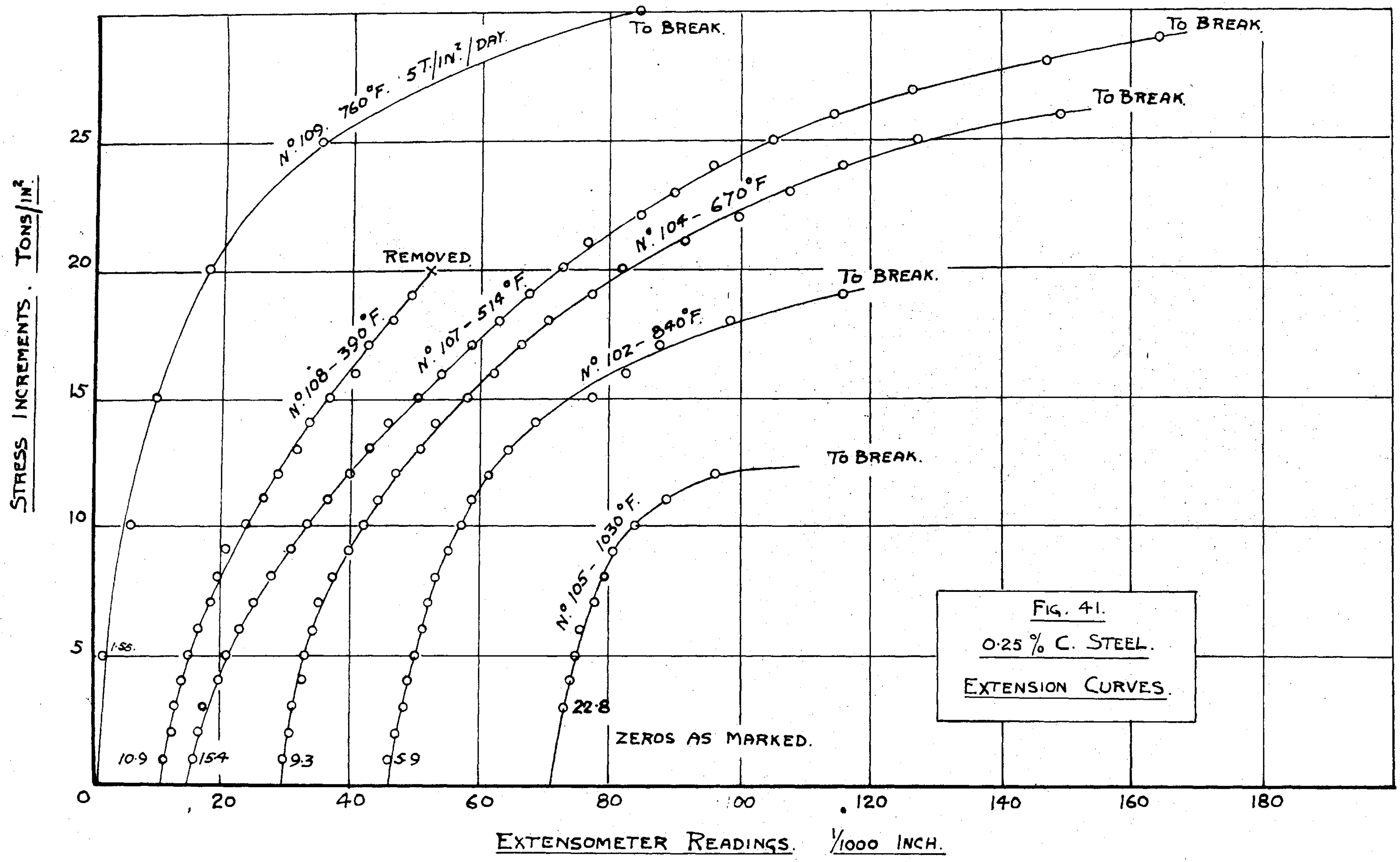


Fig. 41.
0.25 % C. Steel.
Extension Curves.

Three quick break tests were made in the 100 Ton Testing Machine using the Martèn's type extensometer. The test temperatures were 550,700 and 850 Deg. Fah. The extensometer results are given in Fig. 39, the limits of proportionality being 12.8, 8.4 and 6.4 tons/in^2., respectively.

A series of five quick tests were made in the spring machine, to obtain an approximation to the yield stress and to determine the ultimate strengths. The stress-extension results are given in Fig. 40, which shows also the yield and ultimate stresses. The elastic limits were not determined as the dial gauge is not sufficiently sensitive and the values are shown high.

The slow break tests were very carefully made, great care being taken to commence the tests well below the estimated creep limit stresses so as to give long straight portions to the extension difference - stress increment curves. In one case the test was discontinued shortly after the limit stress was passed. The stress increments were varied for two tests. At 1,030 Deg. Fah. the increment was reduced to ½ ton/in^2., to enable a more accurate estimation to be made. At 760 Deg. Fah., a stress increment of 5 tons/in^2., was used, this in order to see the effect of increasing the increment on the estimation of the limit. The extension curves are given in Fig. 41.

These curves are normal, those for varied increments being little different from the others. For the five ton increments, each increment is plotted as five, unit or one ton, increments, the resulting curve being initially steeper than the others and after the limit region the decrease in slope is much more rapid than with the others. The low initial slope is due to cummulative initial flows, over a large number of small stress increments,

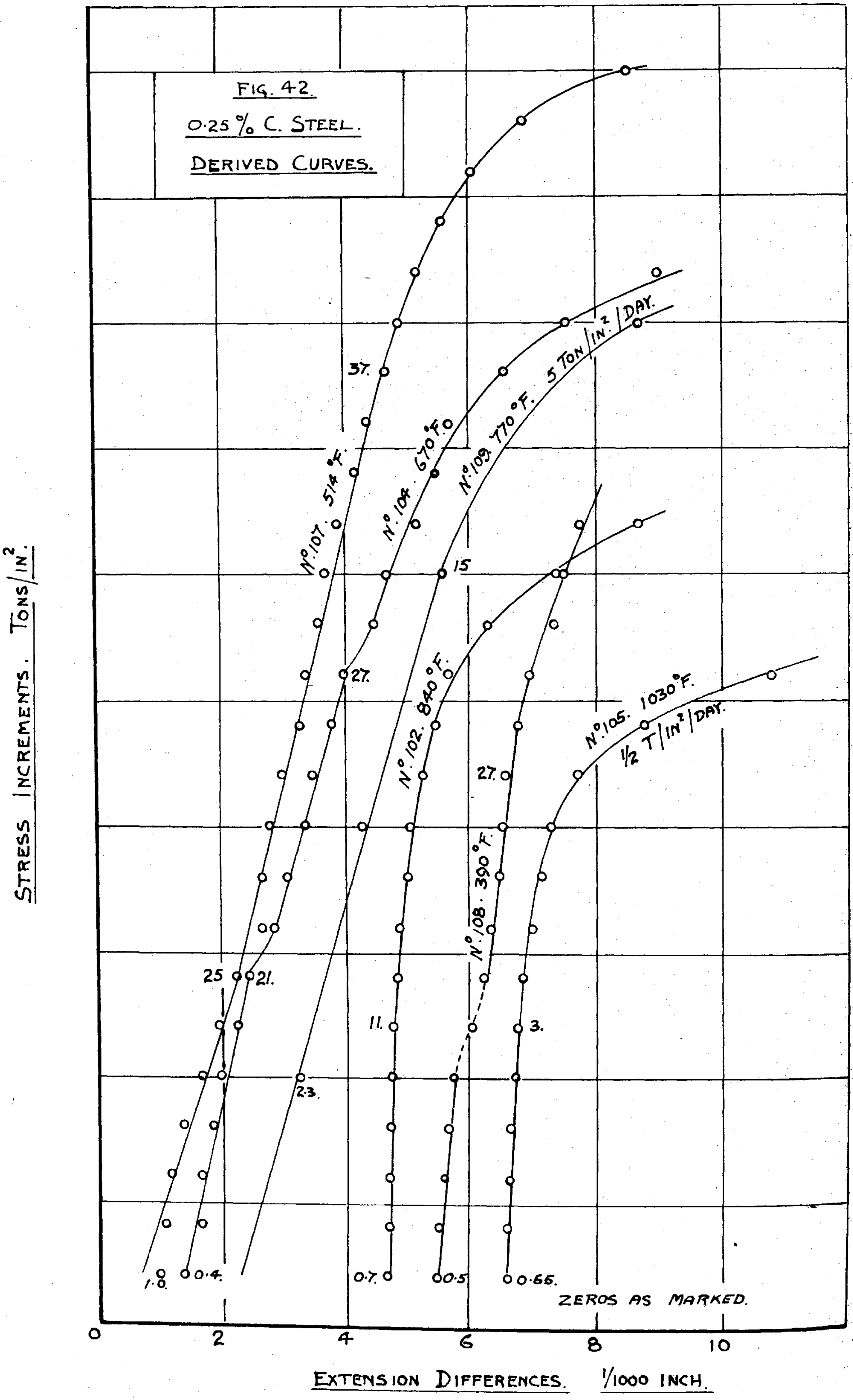


FIG. 42.

0·25 % C. STEEL.

DERIVED CURVES.

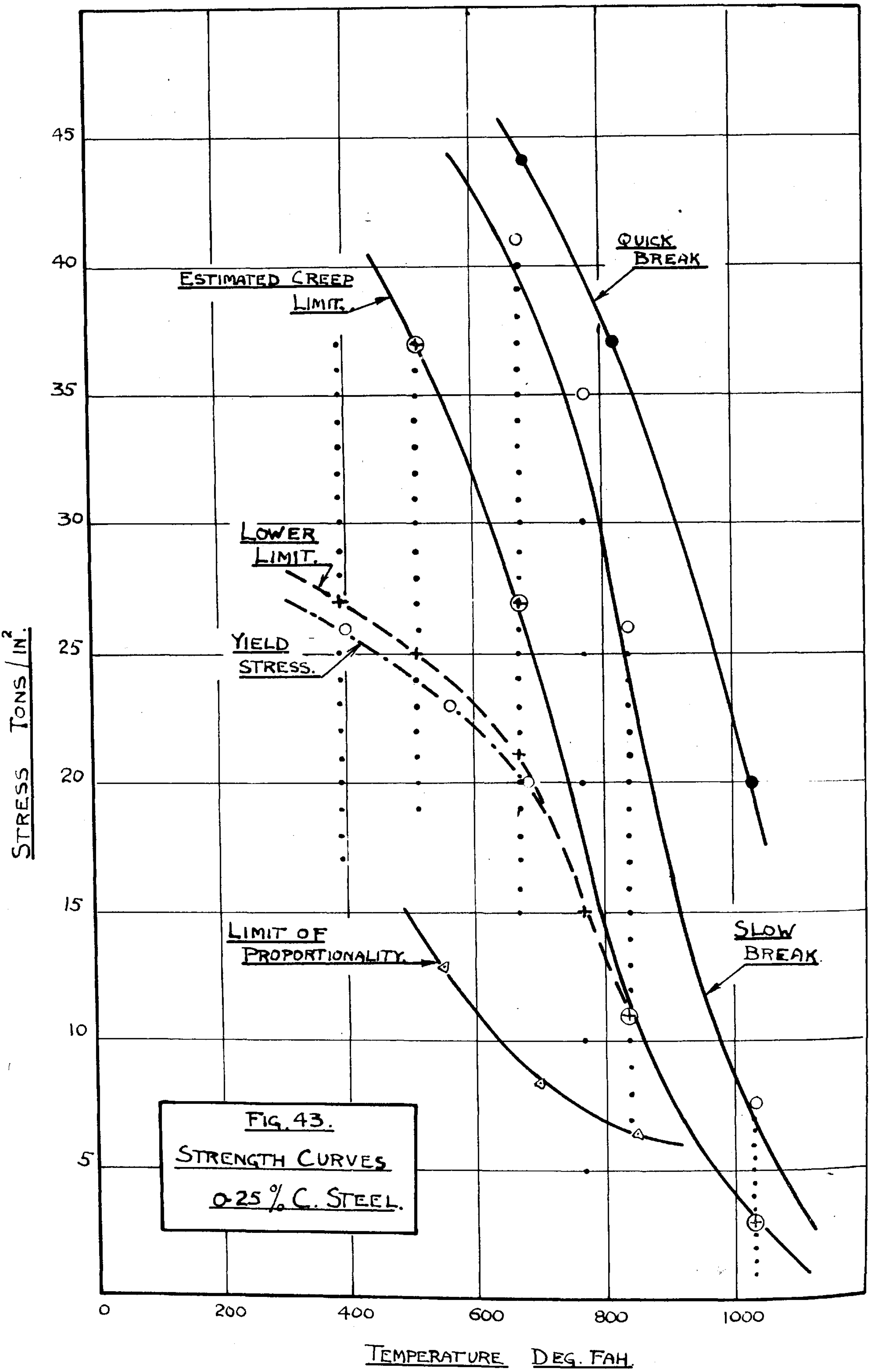


FIG. 43.
STRENGTH CURVES
0·25 % C. STEEL.

producing more distortion for a given stress, when for the same stress with larger increments the individual initial flows will be larger but they will sum up to a smaller distortion. Above the creep limit region these effects are reversed, with the large increment the creep rate increases more rapidly than with the small increment. Also for the half ton increments the initial slope is lower than for one ton increments. When considering this half ton stress increment curve it should be noticed that the increment scale has been doubled, each test increment being plotted as 1 ton/in^2. This increase in scale displays the curve to better advantage.

The curves for 514 and 670 Deg. Fah., show a flattening over the centre portions; this is reproduced in the extension difference curves Fig. 42, where a distinct discontinuity is shown in the corresponding curves. In these cases there are two limiting values for each temperature. In the case of the test at 390 Deg. Fah., there is a break at 22 tons/in^2., but the slope remains the same; this discontinuity being most probably due to some disturbance which altered the micrometer gauge. The other difference curves are self explanatory, giving limiting values as shown.

The limit values are plotted along with the ultimate strengths, limits of proportionality and slow break values in Fig. 43. From the test with 5 tons/in^2 increments, the estimated limit is practically that shown by the curve for the creep limit. This result is very favourable, but it will presently be seen from tests on cast steel that the accuracy of the test is of the order of plus or minus the stress increment.

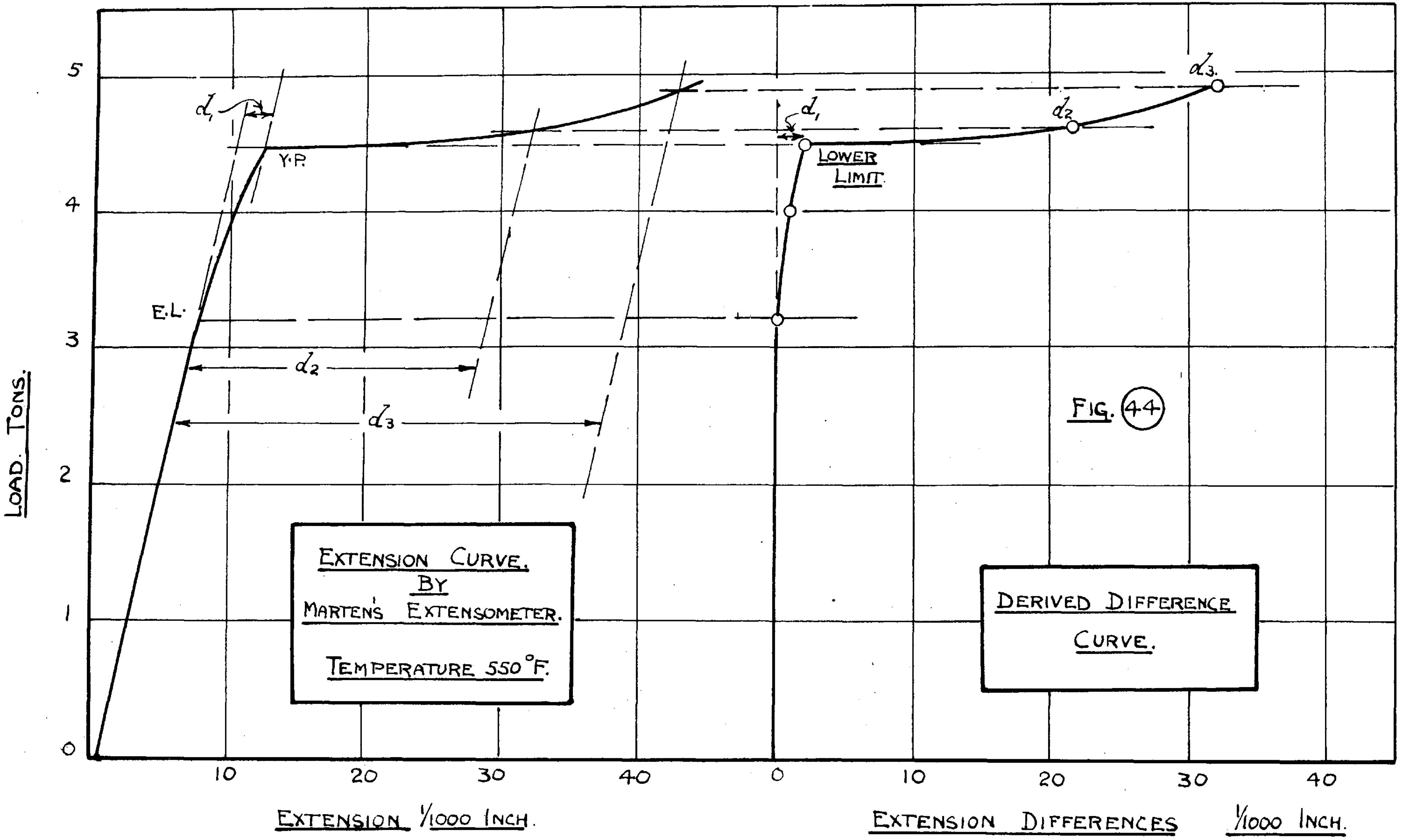


FIG. 44

Extension Curve.
By
Marten's Extensometer.
Temperature 550°F.
Derived Difference Curve.
Load. Tons.
5
4
3
2
1
0
10
20
30
40
Extension 1/1000 Inch.
0
10
20
30
40
Extension Differences 1/1000 Inch.
Y.P.
E.L.
Lower Limit.
d_1
d_2
d_3
d_1
d_2
d_3.

In making these tests the order was from high to low temperature so that at 670 Deg. Fah., the test-piece was broken but the limit estimation was made so as only to show the lower limit. Similarly at 514 Deg. Fah., only the lower limit was determined, and that at 390 Deg. Fah., was used only as a check and the test not continued so far as the upper limit. In this way the lower limit curve was obtained and although it was considered peculiar, it was only when the complete extension curves were drawn that the actual creep limit curve was determined. This creep limit stress curve was found to follow the usual course from maximum strength at the lower critical temperature to practically no strength at 1,100 Deg. Fah.

On the strength characteristics diagram, Fig. 43, it is noticeable that the curves for lower limit and yield stress are practically coincident, the evident conclusion being that they are one and the same curve. This occurrence is readily explained with the aid of Fig. 44.

Here is plotted a load-extension curve taken at 550 Deg. Fah., on the 100 Ton Testing Machine with the Martin's Type Mirror Extensometer. The elastic limit and the yield point are clearly marked. If this test were carried through in daily stress stages, then if the elastic limit were correct there would be no change up to this point and possibly little to the yield point. After the yield point the extensions would be greater due to the effect of initial flow. Probably initial flow would be observable before the yield point, depending on the sensitivity of the extensometer. In any case the form would be the same, so that this load-extension curve is essentially the same as a progressive stress test stress increment - extension curve.

Taking extension differences, these are zero up to the elastic limit, have the value d_1 at the yield point and at two succeeding stresses above the yield stress they are d_2 and d_3. These differences give the derived curve shown, which again is practically identical with the derived curve by the progressive stress test. Here two limits are indicated, the elastic limit and the lower creep limit. The lower creep limit is the yield point of the short time test. The differences going to make up d_1 are very small so that the elastic limit escapes detection by the Ames gauge in the progressive stress test. Also the resemblance between the extension results finishes with the yield point, the time factor altering the aspect of the tests. This lower limit is a better measure of the yield stress than that given in the quick test, since it can be detected by less sensitive extensometer apparatus and is not liable to artificial elevation due to high straining rates.

The lower limit or yield curve merges with the creep limit curve at about 800 Deg. Fah., also in the quick break curves, Fig. 40, there is no yield indication at 820 Deg. Fah., and over. At about 800 Deg. Fah., the time effect wipes out the yield point and substitutes the creep limit. With a small temperature advance of from 100 to 150 degrees the limit of proportionality merges with the estimated creep limit.

In order to check the progressive stress method of estimating the creep limit stress a set of long duration tests was made, with varying stress at approximately 820 Deg. Fah. Seven tests were carried through with

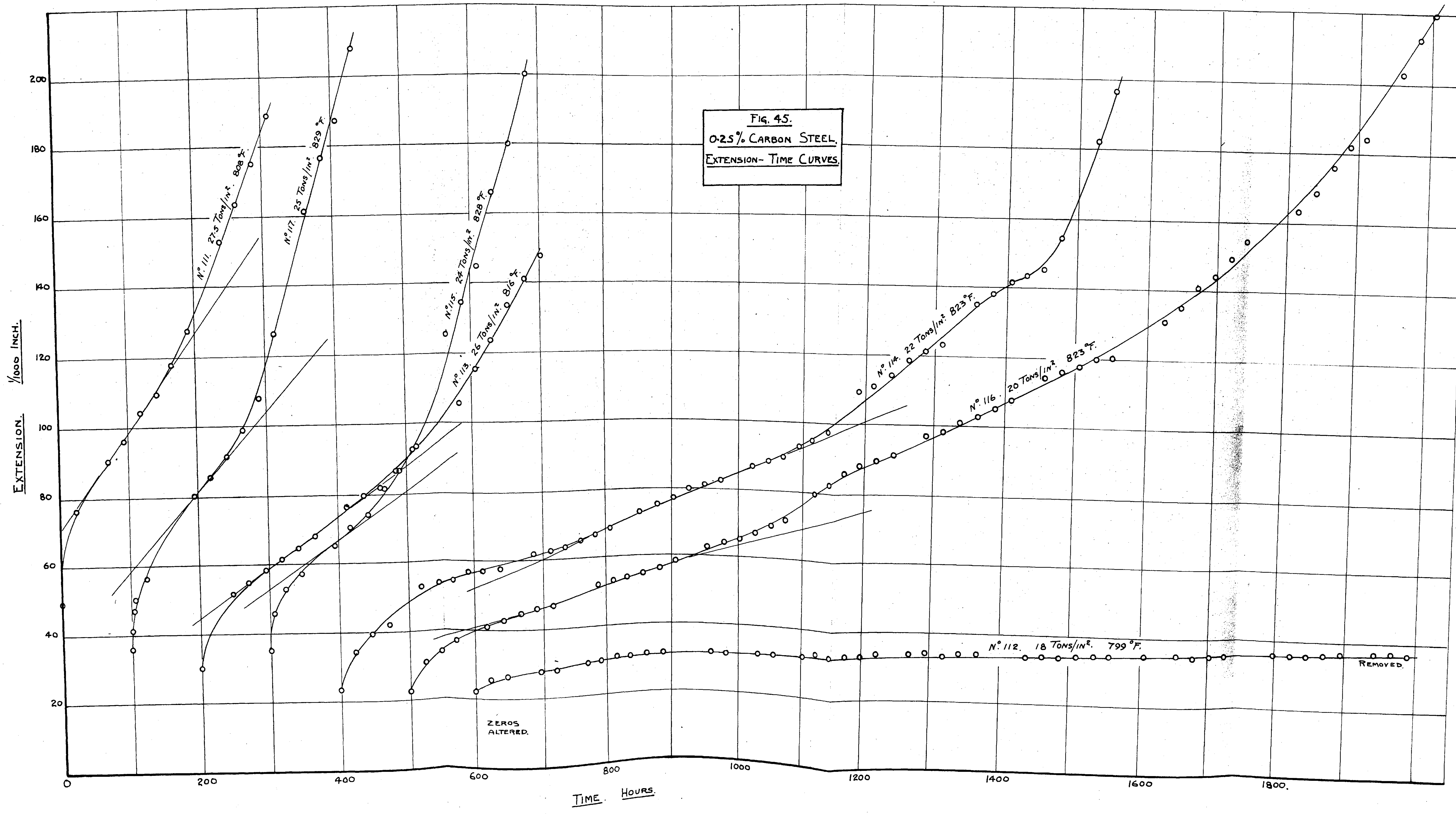


Fig. 45.

0.25% Carbon Steel.

Extension–Time Curves.

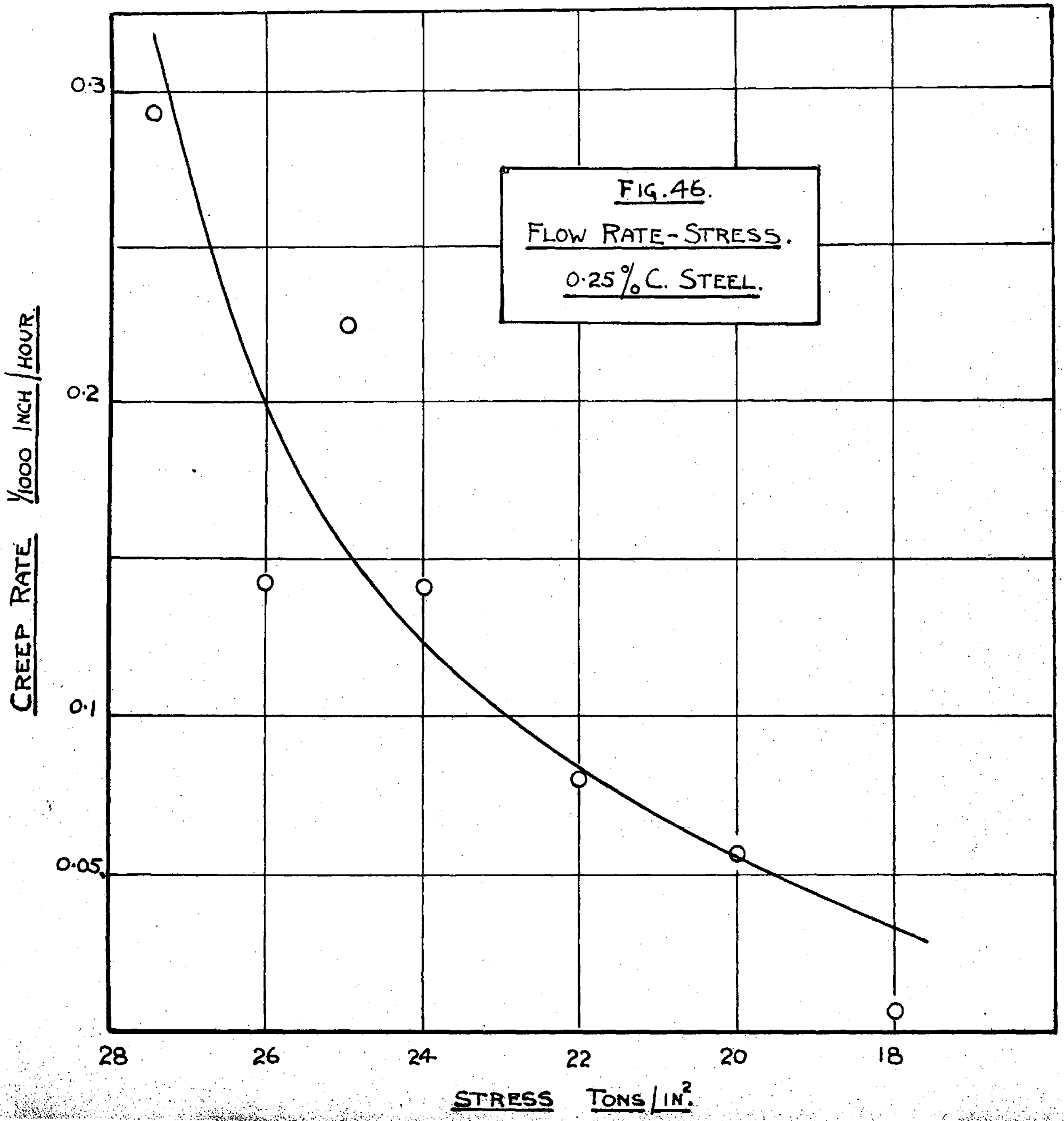


FIG. 46.

FLOW RATE - STRESS.

0·25% C. STEEL.

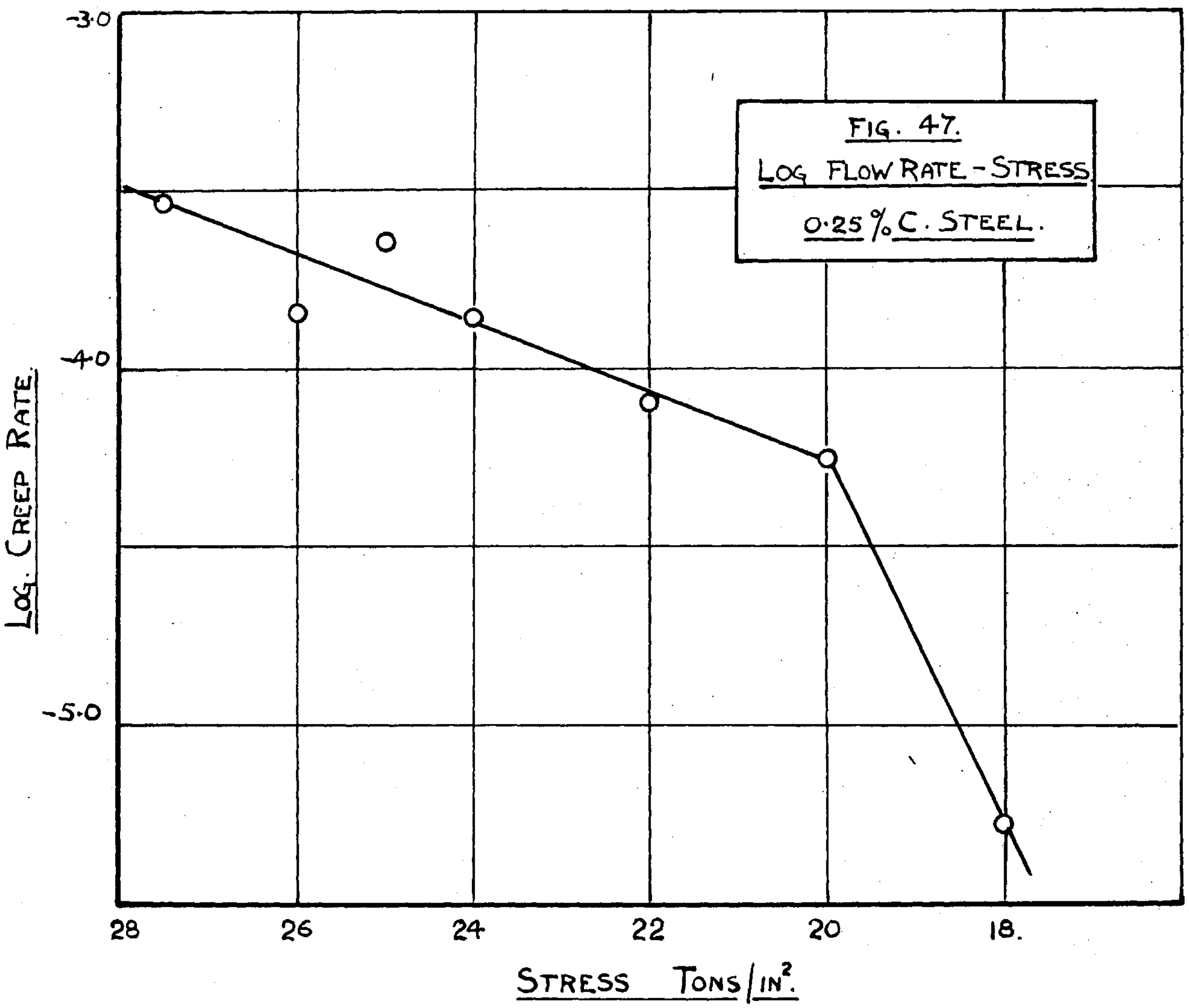


FIG. 47.

LOG FLOW RATE - STRESS

0·25 % C. STEEL.

TABLE. N°. 4.

0·25% CARBON STEEL.

FLOW RATES.

STRESS TONS/IN^2.	TEMPERATURE. DEG. FAH.	MINIMUM CREEP RATE. 1/1000" / HOUR.	MINIMUM CREEP RATE. INCH / HOUR.	LOG. CREEP RATE.
27·5	808	0·293	·000293	−3·5360
26·0	816	0·142	·000142	−3·8478
25·0	829	0·224	·000224	−3·6500
24·0	828	0·140	·000140	−3·8540
22·0	823	0·080	·000080	−4·0970
20·0	823	0·056	·000056	−4·2518
18·0	799	0·0053	·0000053	−5·2757

stresses ranging from 27½ tons/in^2., to 18 tons/in^2., the temperature being maintained as constant as possible. Daily extension readings were noted till the metal fractured or till sufficient extension measurements had been made. The extension-time curves are given in Fig. 45. Due to temperature fluctuations the curves are somewhat erratic, but their general shape shows an initial creep portion followed by final creep to fracture. With high stresses creep rates are high and initial flow passes quickly into final flow. At lower stresses the creep rates are reduced and the change from initial to final flow is more gradual there being apparently a range of constant creep. At 18 tons/in^2., this intermediate portion is very pronounced, the creep rate being very low, and after about 80 days test there is no sign of increase in the creep rate, so that 18 tons/in^2., must be close on the creep limit stress.

To estimate the creep limit stress the intermediate or minimum flow rates were measured and plotted with the corresponding stresses in Fig. 46. The resulting curve is somewhat hyperbolic in form tending to tangency with the axis of zero creep rate at a stress of about 13 to 14 tons/in^2. Further the logarithm of the creep rate was plotted with stress the result being as in Fig. 47, where the plot is a straight line to 20 tons/in^2., and there changing direction. The reduction in log. creep rate for stresses below 20 tons/in^2., being much greater than for those above 20 tons/in^2. These flow values are tabulated in table No. 4.

That the log. creep rate curve shows such a discontinuity may be taken as additional evidence that the creep or flow will cease at some limiting stress. The graphical evidence in Figs 45, 46 and 47 indicates a

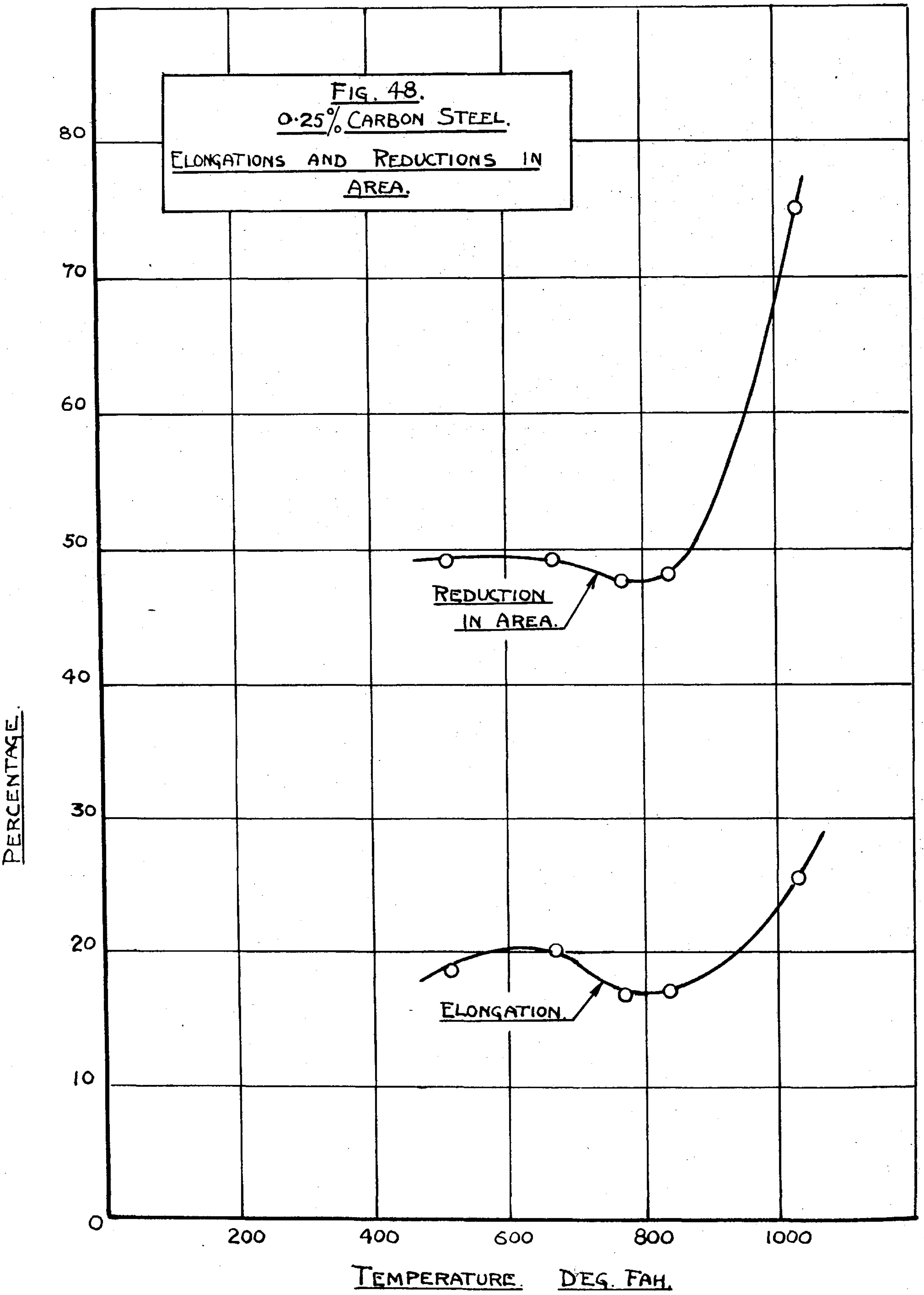


FIG. 48.

0·25% CARBON STEEL.

ELONGATIONS AND REDUCTIONS IN AREA.

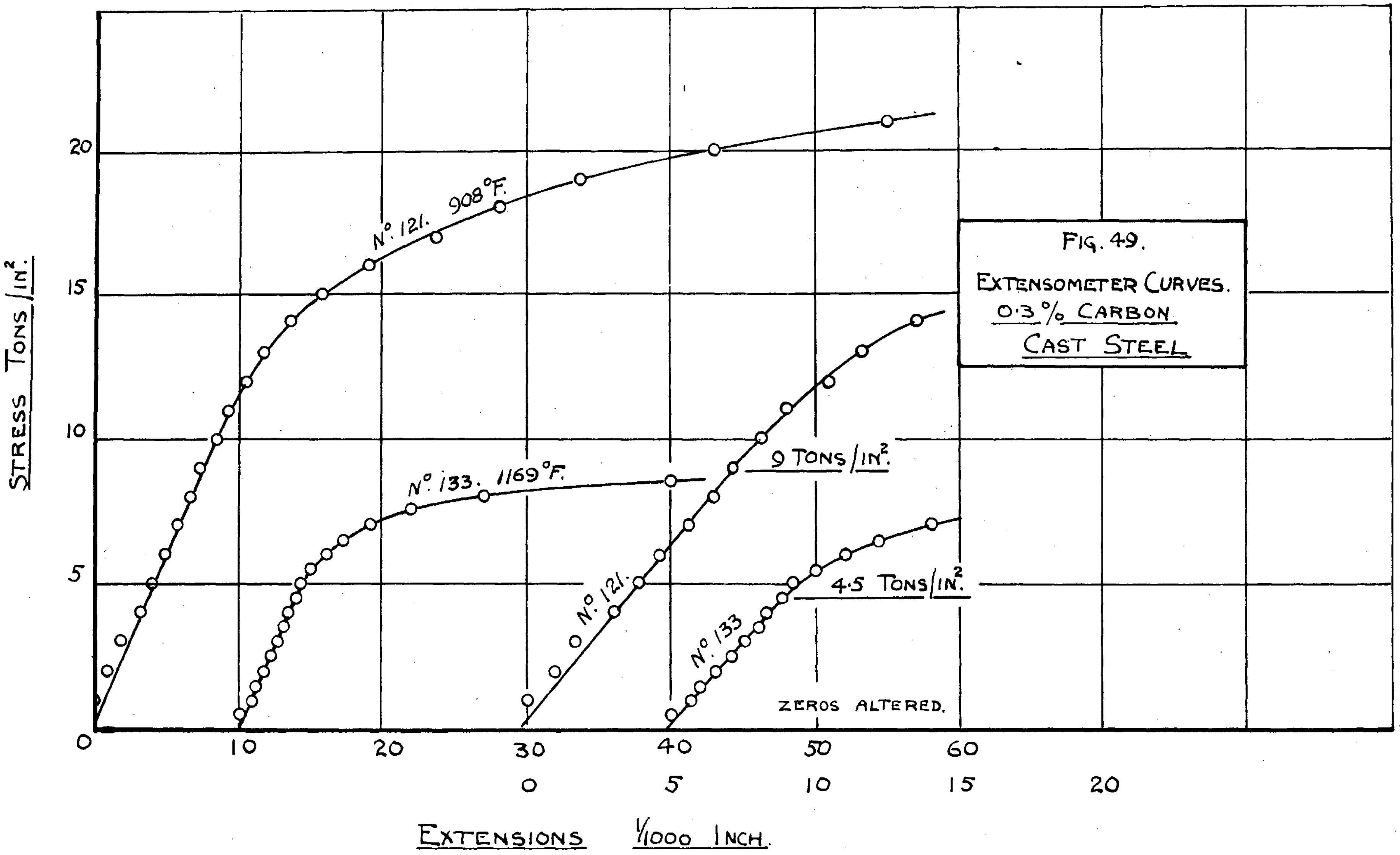


FIG. 49.

EXTENSOMETER CURVES.
0·3% CARBON
CAST STEEL

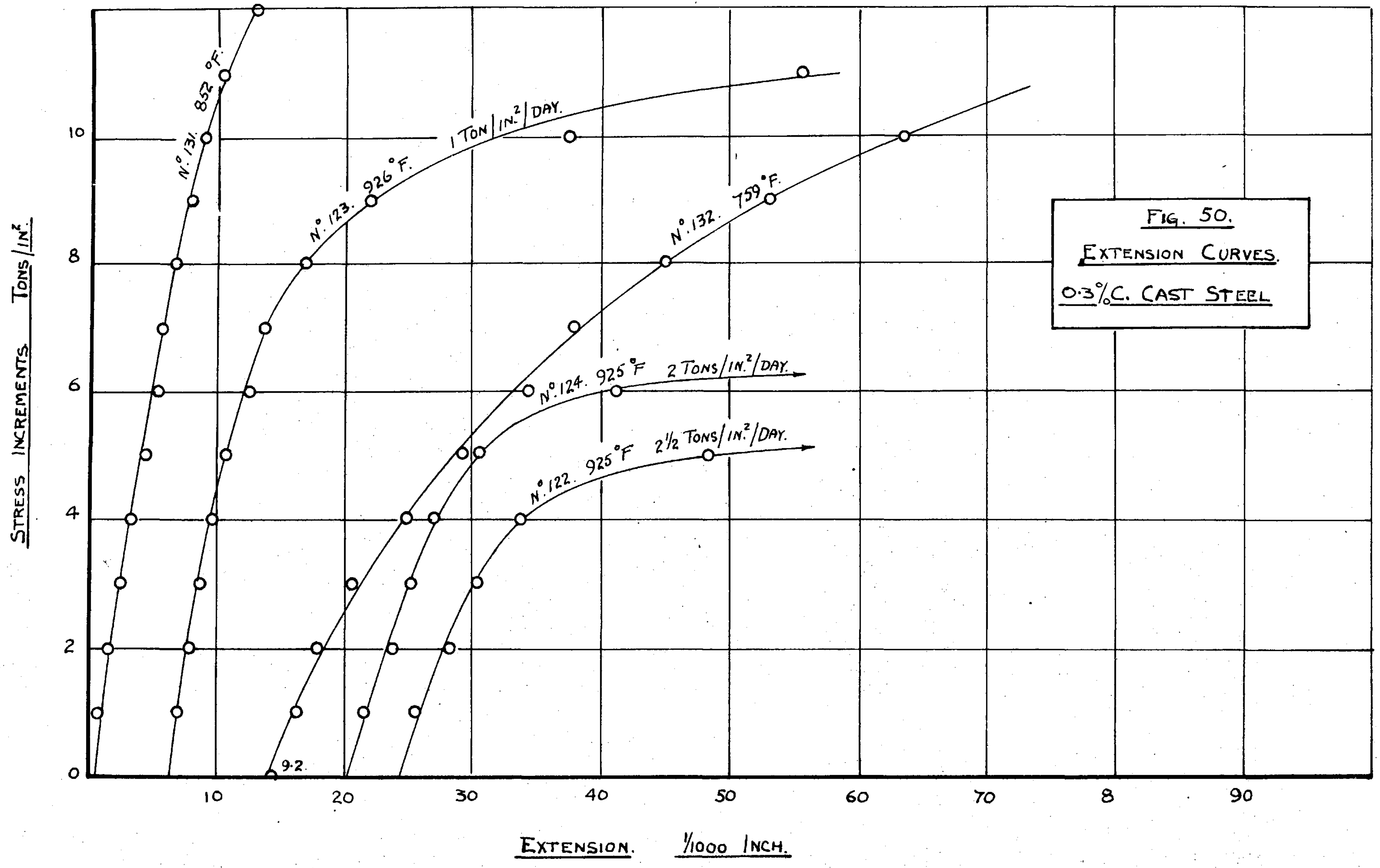


FIG. 50.

EXTENSION CURVES.

0·3%C. CAST STEEL

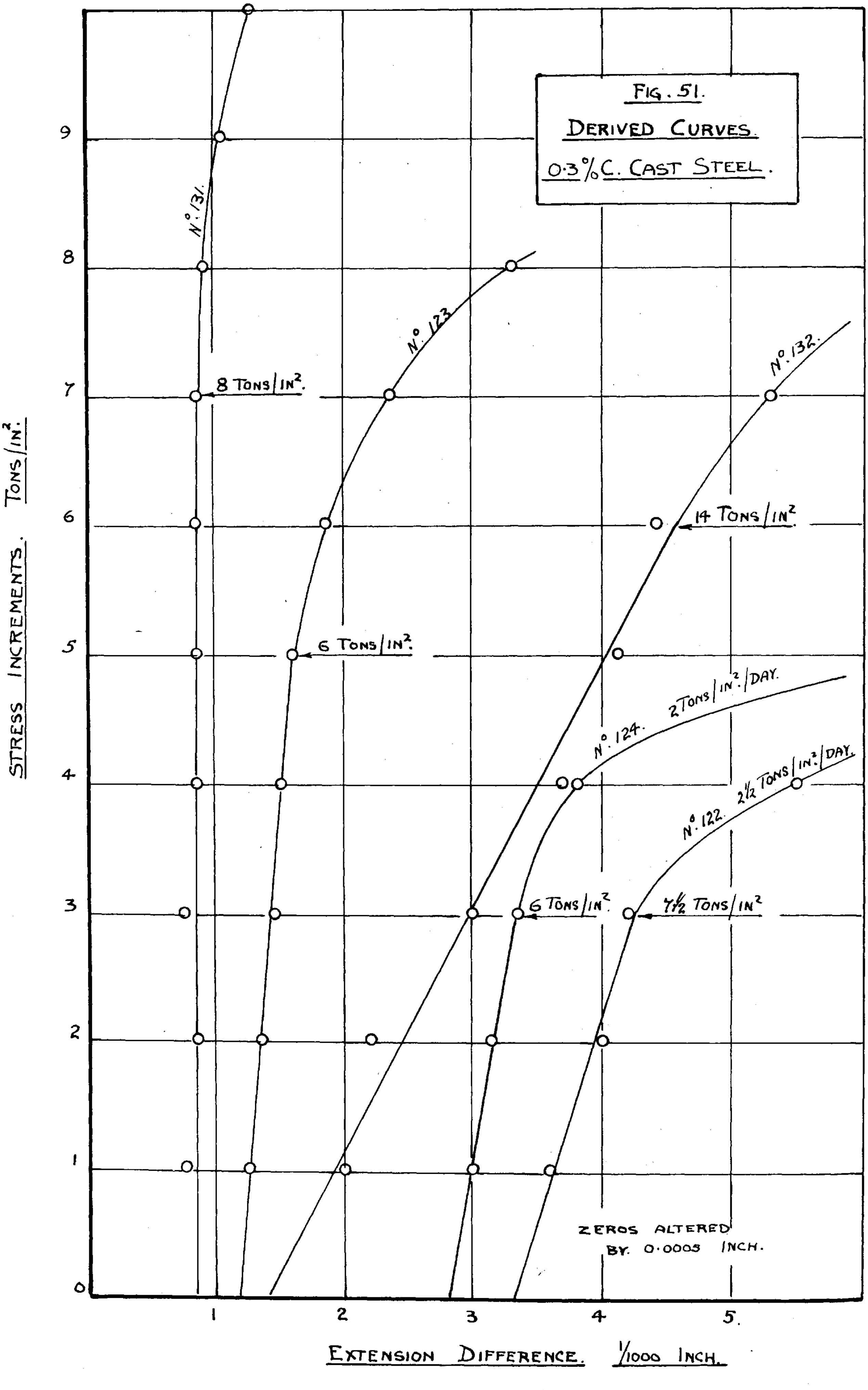


FIG. 51.

DERIVED CURVES.

0·3 % C. CAST STEEL.

limit of 13 to 14 tons/in^2., at 820 Deg. Fah. This value falls on the estimated creep limit curve, so that in this case the progressive stress method of making a limit stress estimation gives the same result as does the more laborious and time absorbing absolute method.

The ductility results from the slow tests are given in Fig. 48. The ductility is fairly constant up to 800 Deg. Fah., it then rises rapidly as a red temperature is approached.

CAST STEEL:-

A piece of material cut from the turbine casing of an Ex-German Cruiser supplied the cast steel used in the following experiments. The scrap was approximately 3½ inches by 1½ inches and had a chord of 20 inches, the diameter of the casing had been approximately 7 feet. The test-pieces were cut out circumferentially. The carbon content was found to be practically 0.3 per cent.

Two quick break tests were first made at 908 and 1,169 Deg. Fah., the resulting extension curves are given in Fig. 49. The limit of proportionality values were approximately 9 and 4½ tons/in^2. respectively. The metal is very ductile the percentage reductions in area being 67 and 89 and the percentage elongations 30 and 47 respectively.

Three progressive stress tests with stress increments of 1 ton/in^2 were made at 759,852 and 926 Deg. Fah. With an increment of 2 tons/in^2., a test was made at 925 Deg. Fah., and with an increment of 2½ tons/in^2., another was made at 925 Deg. Fah. Thus at 925 Deg. Fah., three progressive stress tests were made with three different increments. The extension and extension difference-stress increment curves are in Figs. 50 and 51, each stress increment being plotted as a unit. The lower limit, only,

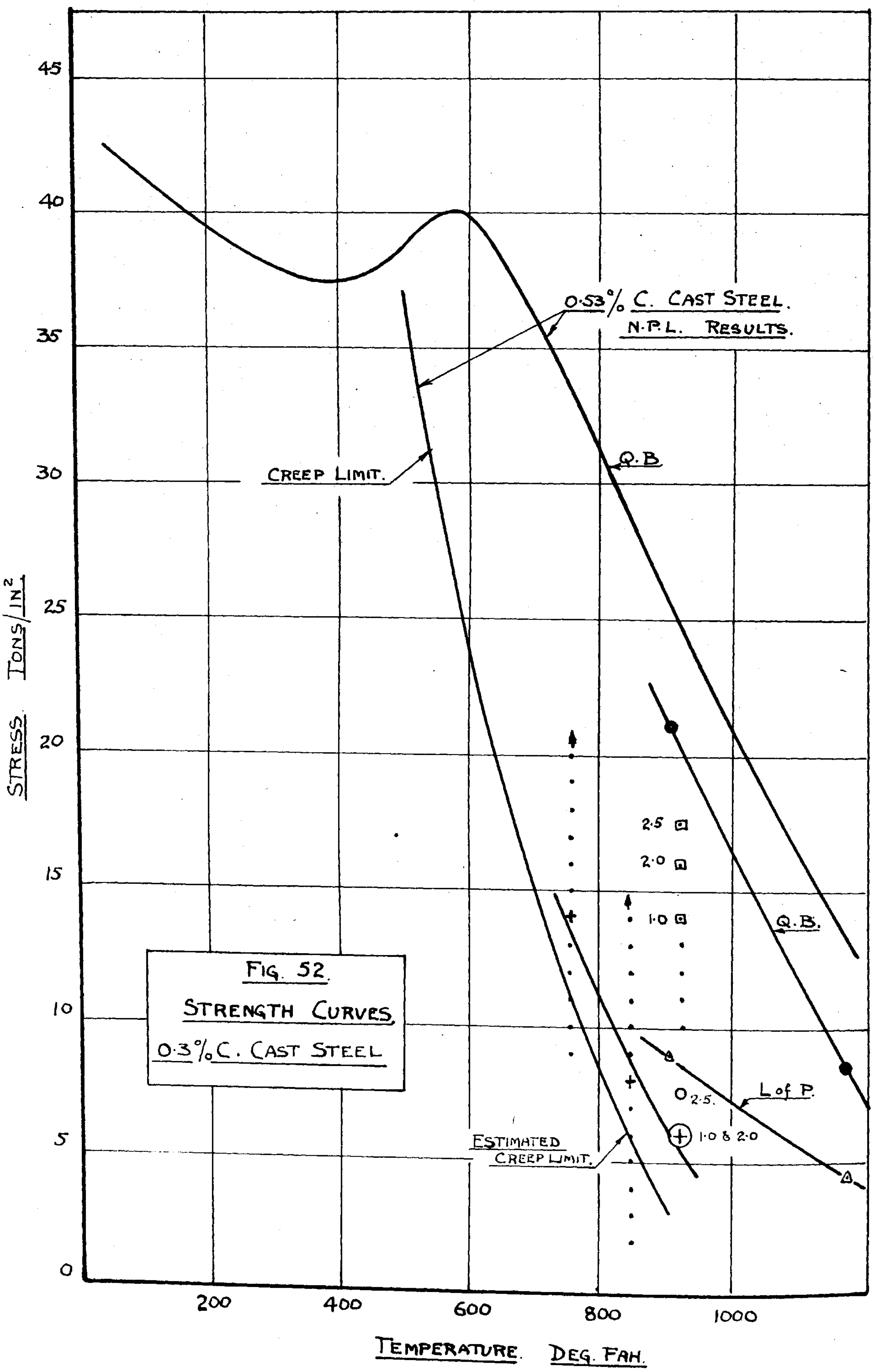


FIG. 52.
STRENGTH CURVES,
0·3% C. CAST STEEL

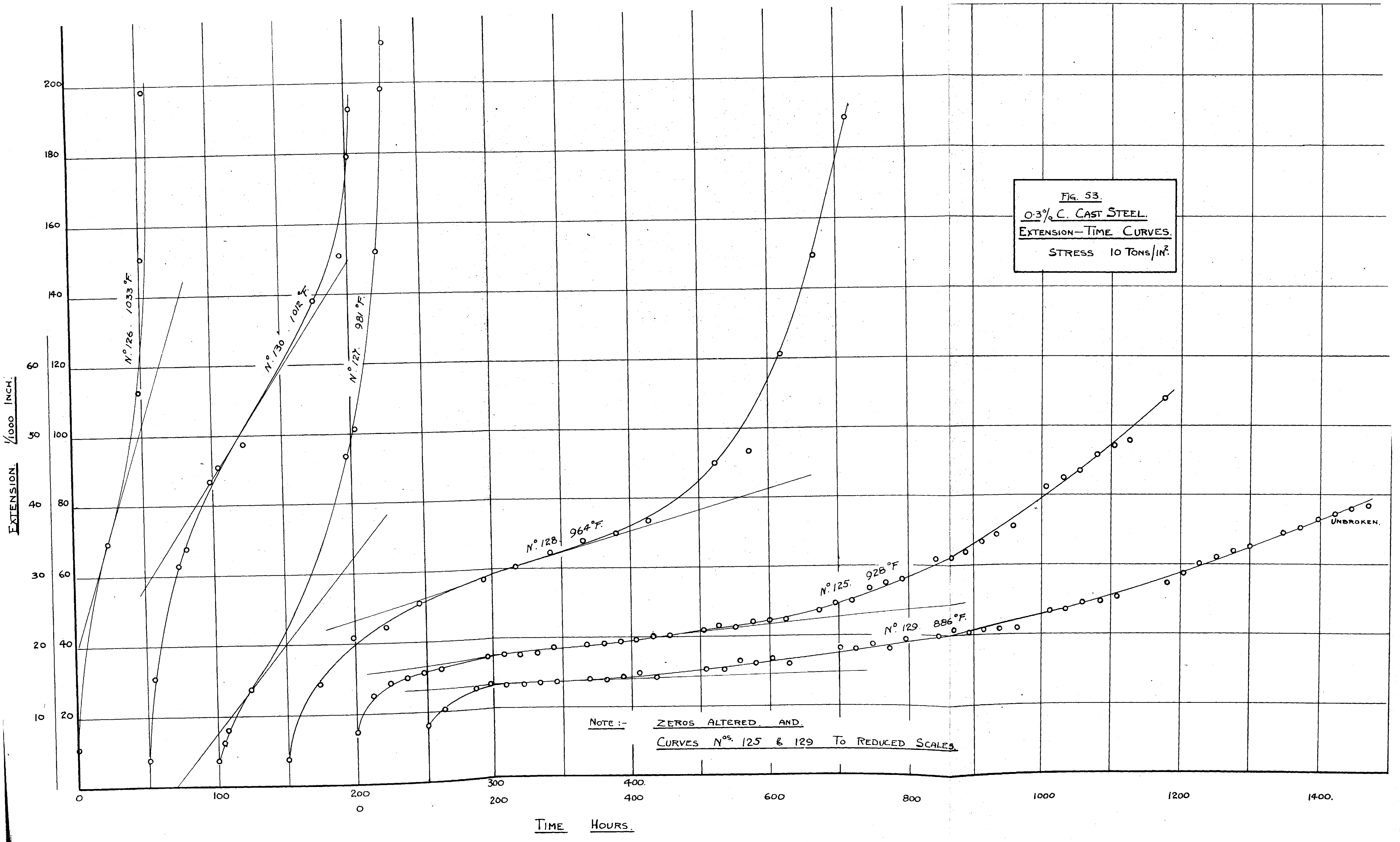


FIG. 53.

0·3% C. CAST STEEL.

EXTENSION—TIME CURVES.

STRESS 10 TONS/IN^2.

NOTE :- ZEROS ALTERED AND CURVES N$^{os.}$ 125 & 129 TO REDUCED SCALES.

TABLE N° 5.

0·3 % C. CAST STEEL.

FLOW RATES.

STRESS TONS / IN^2.	TEMPERATURE DEG. FAH.	MINIMUM CREEP RATE. 1/1000" / HOUR.	MINIMUM CREEP RATE. INCH / HOUR.	LOG. CREEP RATE.
10	1033	1·27	·00127	−2·8960
"	1012	0·61	·00061	−3·2144
"	981	0·495	·000495	−3·3050
"	964	0·119	·000119	−3·9245
"	928	0·011	·000011	−4·9585
"	886	0·0028.	·0000028.	−5·5250.

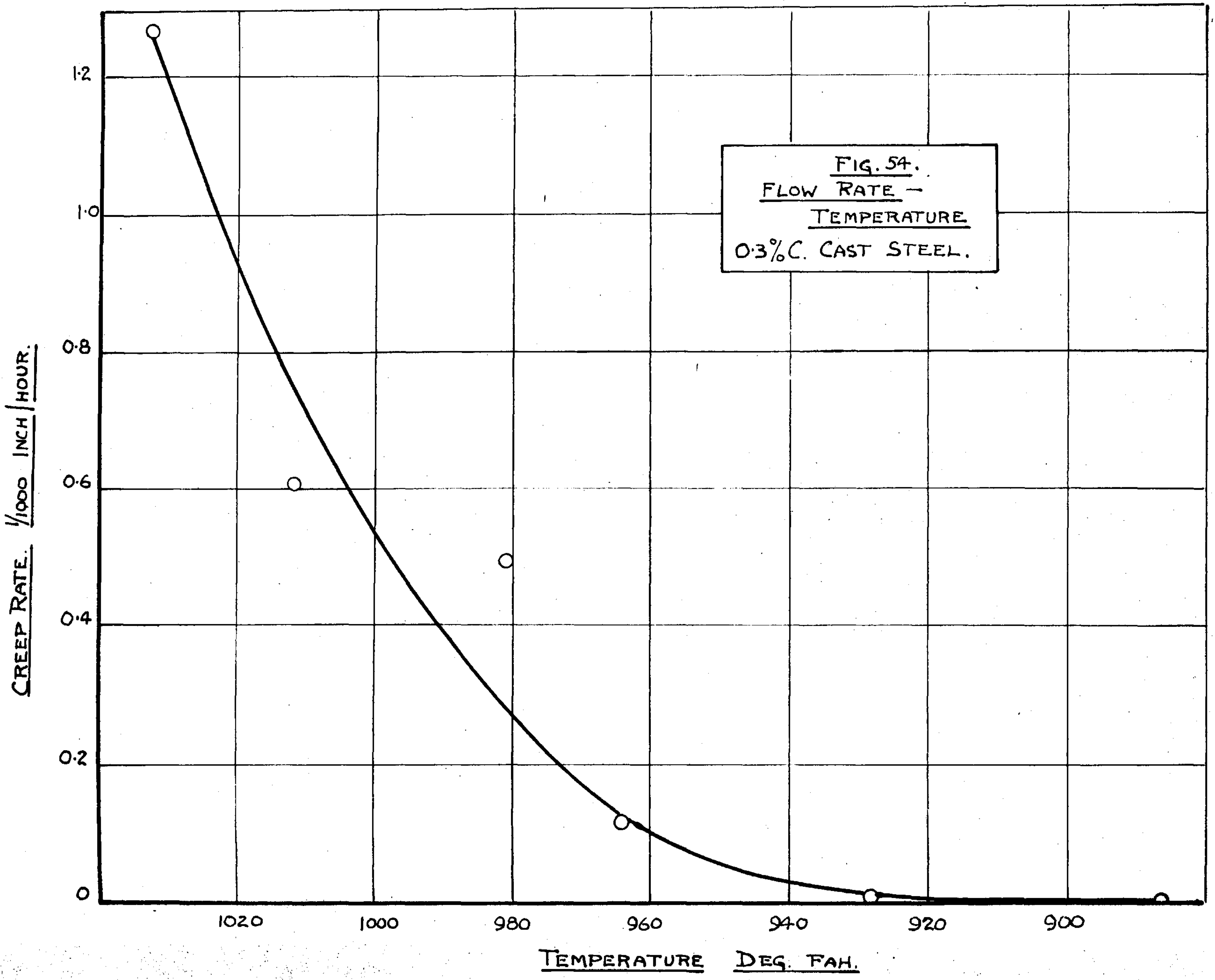


Fig. 54.
Flow Rate – Temperature
0·3% C. Cast Steel.

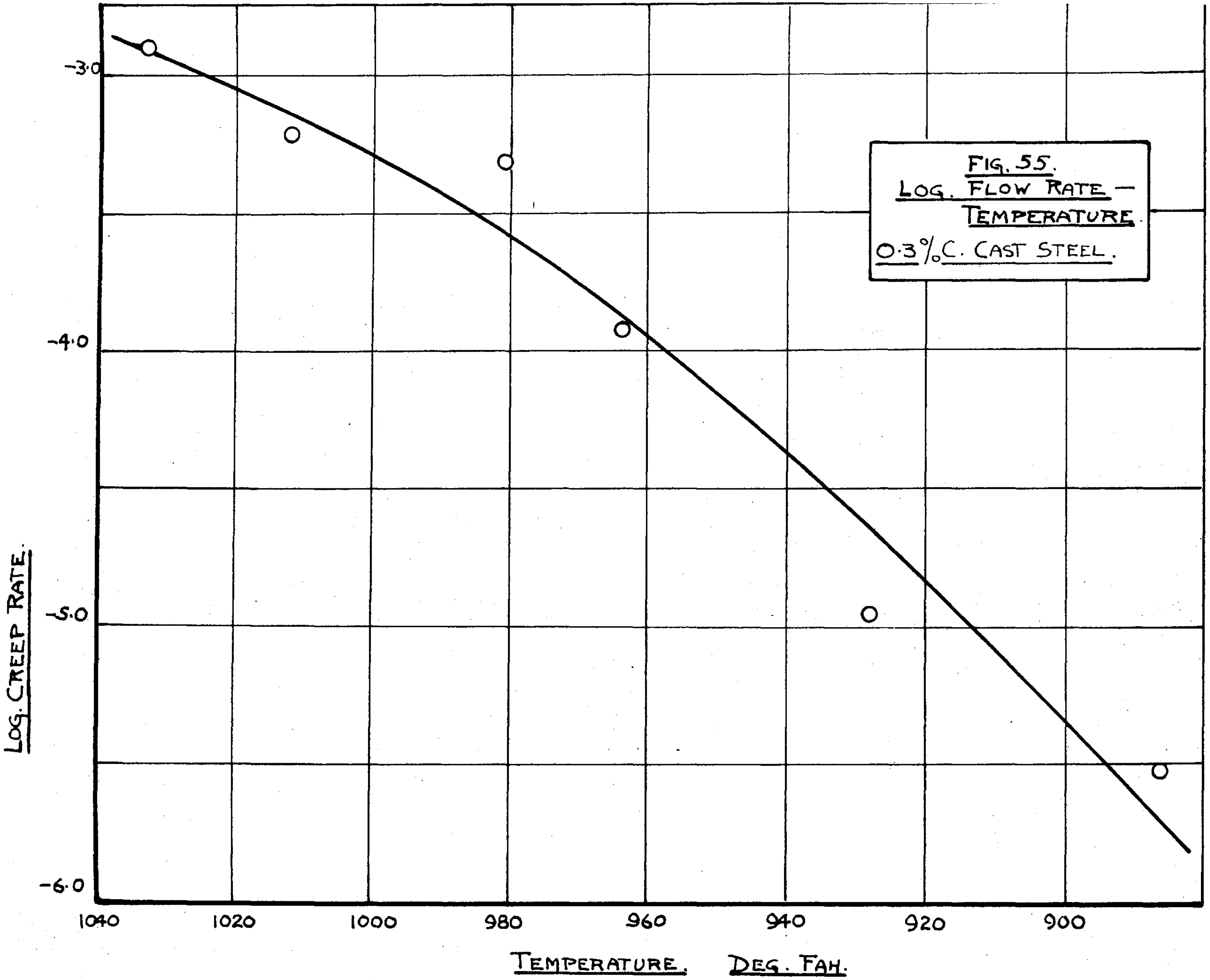


Fig. 55.
Log. Flow Rate — Temperature.
0·3% C. Cast Steel.

has been found in each case, as at the temperatures considered both limits have merged.

At 925 Deg. Fah., the creep limit stress is given as 6 tons/in^2., by the one and two tons/in^2., increment tests, while for the increment of 2½ tons/in^2. the limit is 7½ tons/in^2. The accuracy of the test is limited by the stress increment, the result always being within an increment of the correct value. Thus any advantage in increasing the stress increment to hasten the test, results in a loss of accuracy.

These characteristic values are shown in Fig. 52 along with results from an 0.53% carbon cast steel, tested at the National Physical Laboratory.(8). The limit of proportionality values lie above the creep limit stress values. As with the previous steel the measurements made with the clock gauge tend to give high results in the elastic limit determination.

As a second check on the progressive stress method of creep limit estimation a second series of absolute tests were made, this time with constant stress, 10 tons/in^2. and varying temperature. Six tests were made over a temperature range from 1,033 to 886 Deg. Fah. The extension-time curves are shown in Fig. 53, and these are very similar to those for 0.25% carbon steel.

The minimum creep rates were determined and plotted with the corresponding temperatures in Fig. 54, the creep rates are given in Table No.5. The resulting curve is again of a hyperbolic form becoming tangential to the axis of zero creep rate at about 860 to 880 Deg. Fah. The logarithmic plot, Fig. 55, in this case, is not so definite, the form being a flat curve which might tend to an asymptote somewhere below 880 Deg. Fah. The limit temperature

TABLE No. 6.

0·3% C. CAST STEEL.

DUCTILITY DATA.

MARK.	TEST.	TEMPERATURE. DEG. FAH.	FINAL GAUGE LENGTH. Cm.	EXTENSION. Cm.	% AGE EXTENSION ON 2.52 Cm.	DIAMETER. INCH.	DIAMETER. Cm.	REDUCED DIAMETER. Cm.	% AGE REDUCTION IN AREA.
121	QUICK.	908	3·274	0·754	30·0	0·2065	0·525	0·301	67·0
122	2·5 T/in². SLOW	925·	3·202	0·682	27·0	0·206	0·523	0·314	63·0
123	1 T/IN². SLOW	926	3·327	0·807	32·0	0·2065	0·525	0·278	72·0
124	2 T/IN² SLOW	925	3·257	0·737	29·2	0·206	0·523	0·304	66·0
126	ABSOLUTE	1033	3·395	0·875	34·7	0·2065	0·525	0·250	77·5
127	ABSOLUTE	981	3·200	0·680	27·0	0·2065	0·525	0·275	72·5
128	ABSOLUTE	964	3·255	0·735	29·1	0·2065	0·525	0·265	74·5
130	ABSOLUTE	1012	3·396	0·876	34·7	0·206	0·523	0·210	84·0
133	QUICK.	1169.	3·717.	1·197	47·5.	0·206.	0·523.	0·167.	89·5.

for 10 tons/in^2. as estimated by the progressive stress method is 820 Deg. Fah.; this is lower than that given by the absolute method but it shows that the progressive stress method is safe and short.

On account of the varied nature of these tests no ductility curves could be drawn, but the ductility results are shown in Table No. 6.

DISCUSSION OF TEST RESULTS:-

The furnace experiments were very interesting although somewhat lengthy. The greatest time was spent in adjusting the windings of the gap-wound furnace to give a satisfactory temperature distribution. This involved about half a dozen winding alterations and a variety of tests with each winding for different furnace positions.

In these tests, using a vertical furnace with the top closed in with asbestos wool packing, an evenly distributed gap-winding is useless, and the final gap-winding was such as to concentrate more heat at the bottom than at the top.

Due to this variable top packing it was found to be impossible to repeat a previous temperature with the same furnace current. But, the variable packing was useful, in that, with a little practice a fine temperature control could be obtained by making a hole in this packing and varying the hole to suit temperature fluctuations.

The strength tests in these furnaces show that no special type of furnace is required to give correct stress-temperature values. Care must be taken to heat the test-piece properly, either uniformly, or with a temperature gradient out from the centre. If the second method is used the hottest temperature of the test-piece must be measured. Also the thermo-junction must not be held against the test-piece in any haphazard fashion, but must be tightly in contact with the metal and must be shielded from the furnace wall radiation and from hot air currents. There are various ways of fixing the couple, but that of carefully binding it to the test-piece with asbestos cord is both simple and effective.

The tests on cast iron, Admiralty gun-metal and brass may be considered together as their results are similar in many respects. Cast iron over normal testing temperatures is a brittle metal, the gun-metals and the brass are ductile up to certain temperatures and thereafter they become brittle. This brittleness leads to an interesting test result. This is shown in its effect on the creep or flow of the metals, when it results in the creep extension-stress increment curves being nearly straight lines up to practically the last increment, after which a fair stretching takes place. The low ductility has already been shown to result in reduced initial flow values, so straightening out the creep extension curve. Also since the actual elongation of the test-piece is small, when continuous flow sets in it produces fracture in one, or at most, two days. In this way the estimated creep limit stress is always just one or two stress increments below the progressive stress test breaking stress.

When a metal is brittle, to obtain the creep limit stress all that is required is to perform an original progressive stress test without an extensometer and reduce the breaking stress by one or two stress increments depending on the accuracy required.

The different effects of ductility and lack of ductility are strikingly displayed in the tests on brass.

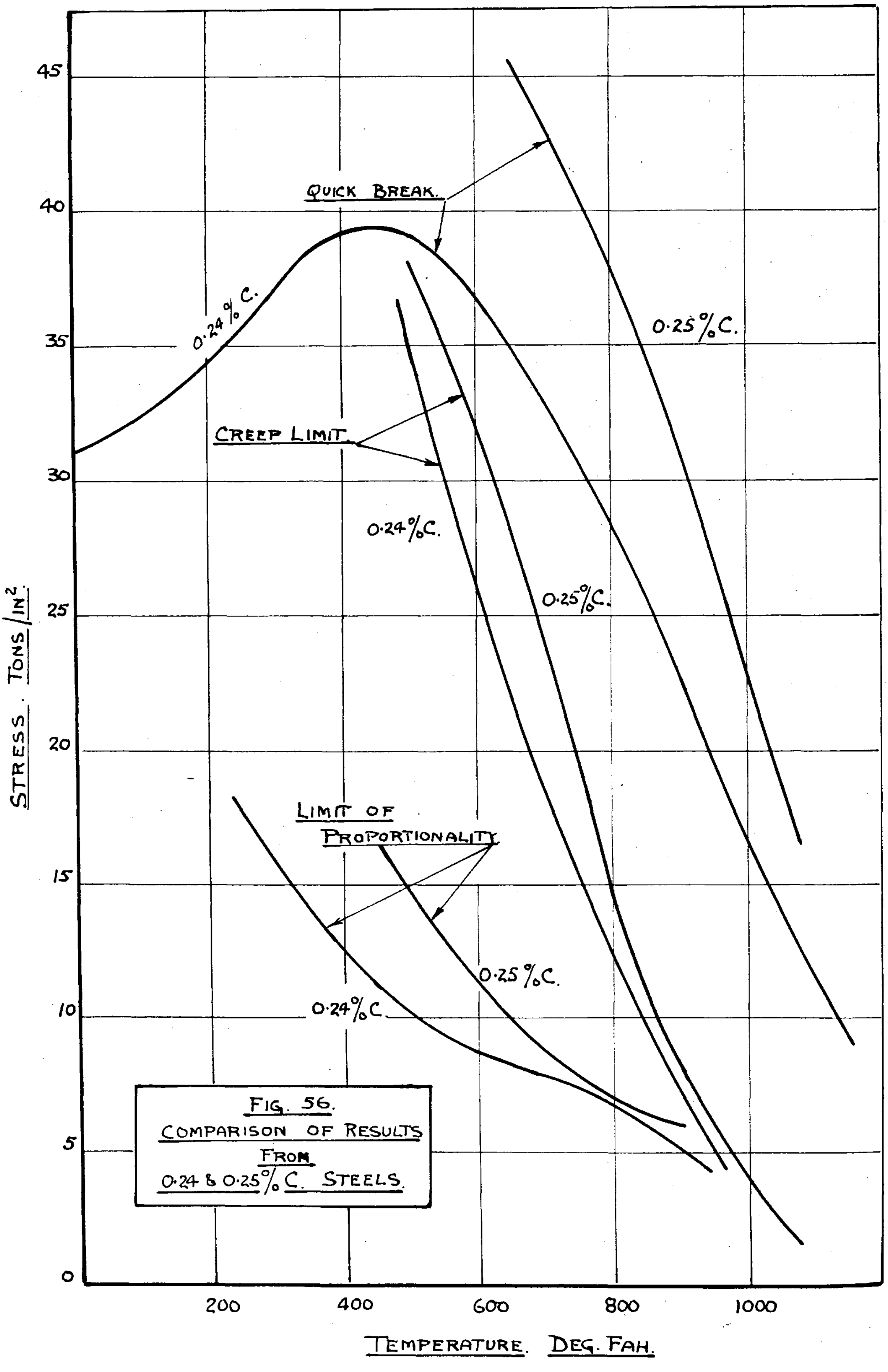


FIG. 56.
COMPARISON OF RESULTS
FROM
0·24 & 0·25 % C. STEELS.

This metal is so brittle above the critical temperature as to give perfectly straight creep extension curves. But, just below the critical temperature it aquires considerable ductility and in addition we have an introduction to the two limits, the lower - or yield stress and the upper - the estimated creep limit stress. The brass in this condition behaves very like steel, although it does not have the same range between the creep limit stress and the slow break stress.

This double limit estimation is very interesting. It provides a new method of finding the yield stress and at the same time defines the yield. It also suggests a very comprehensive test which will be economical in time, labour and material. Using an extensometer of the sensitivity required for elastic limit determinations with a progressive stress test, three limit discontinuities would appear in the extension difference-stress increment curve these being, elastic limit, yield and creep limit stress. The accuracy attained would be of the order of the stress increment used, and the testing time would vary with the increment and the creep limit stress.

Taking such a test on the 0.25% carbon steel and repeating the five tests shown with the same increments and commencing each test at zero stress, the total testing time required would be about 130 days. This would provide limit values for each of a comprehensive range of five temperatures. With the absolute test, to make one creep limit determination at least five test-pieces are required and fully 100 days testing time is needed. The difference is obvious.

By checking the progressive stress method with absolute tests it has been shown that the progressive stress method is emminently satisfactory.

Another comparison check is given in Fig. 56,

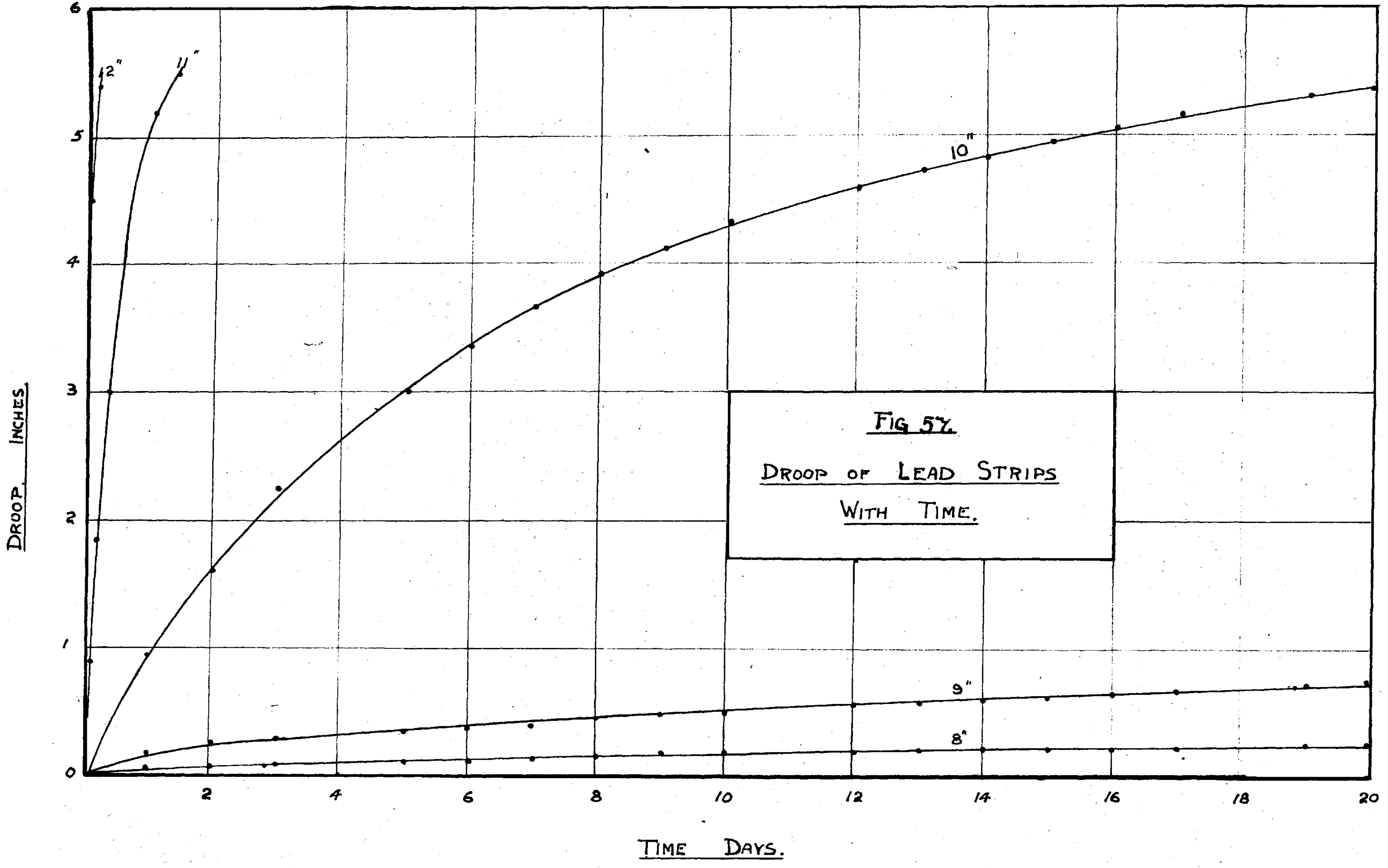


Fig 57.

Droop of Lead Strips With Time.

which shows results from the 0.25% carbon steel, along with results from an 0.24% carbon steel which was tested at the National Physical Laboratory (8). On the basis of ultimate strength and elastic limit values the 0.25% carbon steel is superior. This superiority is shown by the creep limit stress also, the improvement in this case is not greater than in the other. The 0.24% carbon steel creep limit curve was determined by the absolute method, so that again we have the progressive stress method giving results similar to those by the absolute method.

PROLONGED TESTS AT NORMAL TEMPERATURE:-

The greater portion of the researches into the behaviour of metals under prolonged stress application has been concerned with elevated temperature conditions, and has mostly dealt with steels and the hard metals. There are several soft metals, such as would be expected to flow readily under the action of low stresses at normal temperature, which could be easily tested and might provide further evidence towards the solution of the creep problem.

(a) LEAD:-

When soft metals are thought of, lead immediately suggests itself and since it is easily procurable, tests were commenced with this metal.

A piece of lead sheeting was cut into strips half an inch wide and of a variety of lengths. These strips were held at cantilevers and the free ends were allowed to droop under their own weight. They were supported over a table and the droop of each free end was taken each day with the table as datum. A set of droop-time curves are given in Fig. 57, the length of each strip is marked against each curve. The longer strips drooped rapidly, the 12 inch strip falling in a little under three hours, that strip 11 inches long falling in about 30 hours. The 10 inch strip drooped fairly rapidly to begin with but the rate became slower, becoming fairly steady after a fortnight. The rate showed signs of increasing again in the fourth week, but here the test ceased as the lead had drooped into contact with the support. Strips 9 and 8 show very flat curves to begin with, developing later into straight lines of apparently constant slope. They might have continued so indefinitely but after about a month the experiment had to be discontinued, as the apparatus was inadvertently subjected to a shock which displaced the strips.

(b) CANTILEVER TESTS ON COPPER AND STEEL:-

Further cantilever tests were proceeded with using heavy gauge copper wire and steel knitting needles each length being uniform and loaded at each free end with various loads to produce definite maximum stresses. The deflections of the free ends were measured from a datum base with a stand micrometer gauge. These tests were persevered with for some time but the results were very unsatisfactory and accurate measurements were difficult to make without disturbing the test-lengths. In the case of steel no tendency to develop continuous creep was observed.

(c) DIRECT TENSILE TESTS:-

Tinned Copper.

From the experience of these bending tests it was decided that the best results would be obtained from direct tensile tests which could be most conveniently made on wires loaded with weights.

Tests were commenced on tinned copper wire of 0.0125 inch diameter, which on test in a standard Barr's

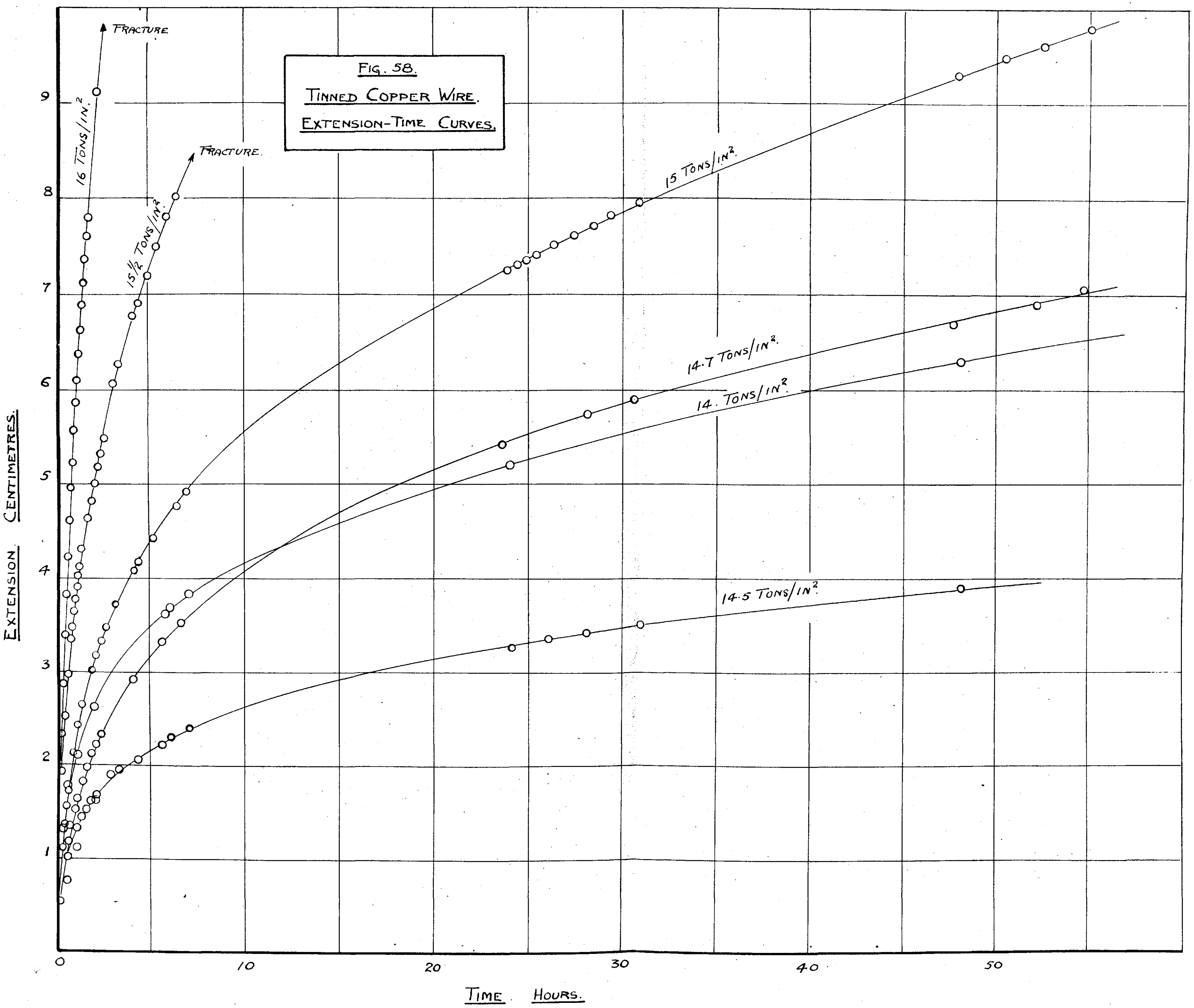


Fig. 58.

Tinned Copper Wire.

Extension-Time Curves.

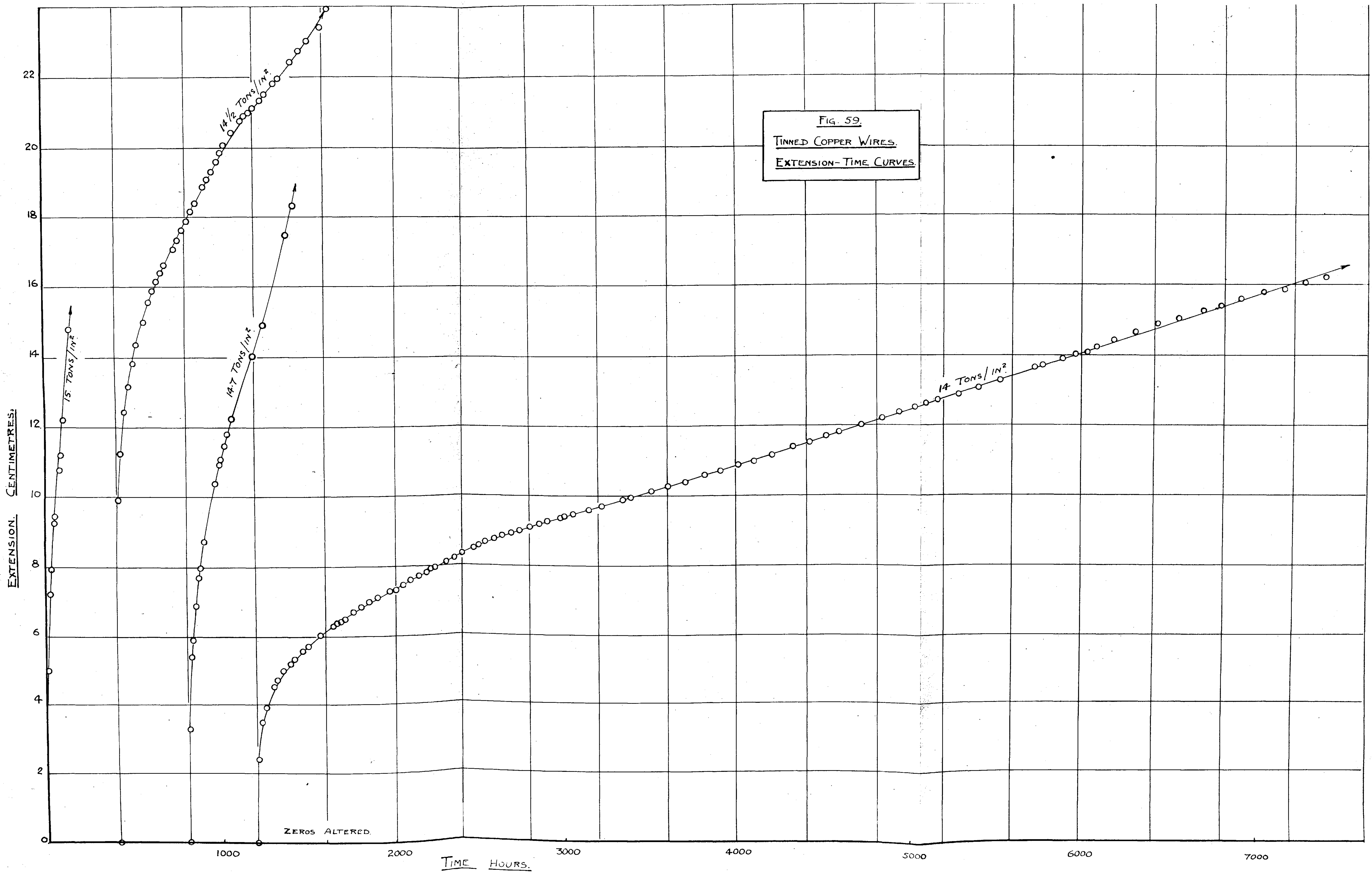


Fig. 59.

Tinned Copper Wires.

Extension-Time Curves.

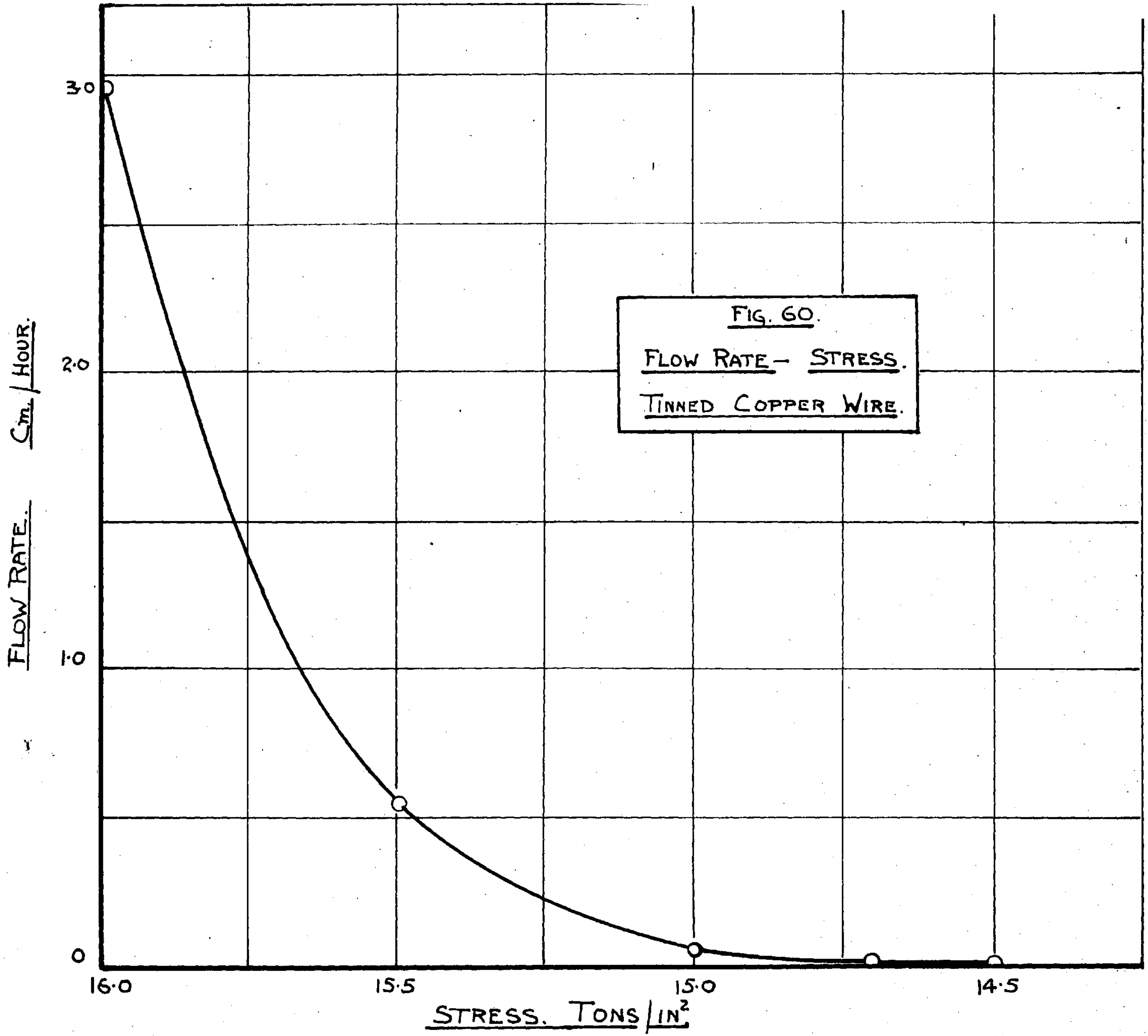


FIG. 60.

FLOW RATE – STRESS.

TINNED COPPER WIRE.

TABLE N° 7

TINNED COPPER WIRE.

FLOW RATES.

STRESS Tons/in^2	FLOW RATE Cm/Hour.	LOG. FLOW RATE.
16.0	2.966	0.472
15.5	0.54	−0.268
15.0	0.05625	−1.250
14.7	0.01445	−1.840
14.5	0.00596	−2.2245
14.0.	0.00144.	−2.8415.

TABLE N° 8.

ANNEALED COPPER WIRE.

FLOW RATES.

LOAD lb.	STRESS Tons/in^2.	FLOW RATE Cm/Hour.	LOG. FLOW RATE.
32.	14.82	0.344	−0.4634
31	14.35	0.276	−0.5591
30	13.53	0.00956	−2.0195
29	13.41	0.00386	−2.4134
28.5	13.2	0.000283	−3.5482
27.5	12.72	0.000376	−3.4248
27	12.49	0.000117	−3.9318
26	11.72	0.0000733	−4.1349
25.	11.56	0.000070	−4.1549.

Wire Tester showed a breaking strength of 17.1 tons/in^2. The test wires of 100 cm., gauge length were attached to a wall fixture and loaded at the free end. A pointer on the lower gauge gave indications on a metre stick set in a clamp which was fixed on the floor., Daily extension readings were made. No account was taken of any deflection of the upper gauge which lowered slightly due to the unwinding of the twist where the wire was taken round the support.

The first test was made with a stress of 15 tons/in^2. the wire breaking after about 144 hours. With a stress of 14 tons/in^2. the time occupied in fracturing was 6288 hours.

The extension-time curves are shown in Figs. 58 and 59. The first series show the initial period over three days, to an extended scale, the second series give the complete curves to fracture. These curves show the characteristic creep phases, initial and final flow, the change from the one to the other forming a point of inflexion on the curve.

The minimum creep rates, measured at these points of inflexion, were taken and plotted with the corresponding stresses in Fig. 60. The resulting curve shows a rapid decrease in flow rate to 15 tons/in^2. thereafter the reduction is much slower. The curve shape suggests that it either becomes tangential to the axis of zero creep rate at some stress below 14 tons/in^2., or it becomes asymptotic, in which case the wire would ultimately fail no matter to what stress it was subjected. The flow data are given in Table No. 7.

In such a case, a change to another method of plotting may help towards a decision, and logarithmic plotting has been used. The stress-log. creep rate curve

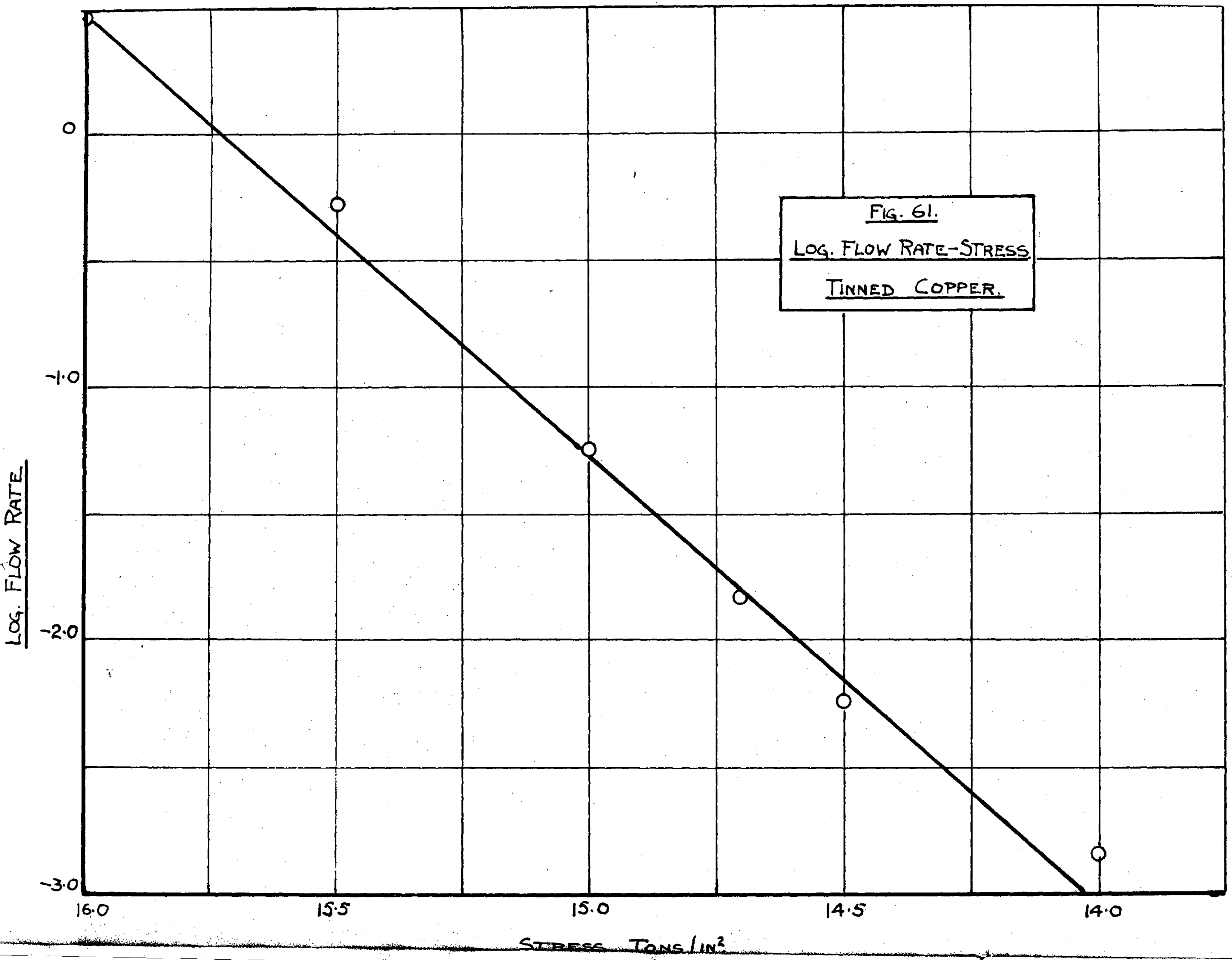


Fig. 61.

Log. Flow Rate-Stress

Tinned Copper.

is given in Fig. 61 and appears to be a straight line. This method is really useful as it opens out the flow scale at the lower end of the stress range. So far as it goes, however, it remains a straight line and gives no indication of a limit.

To reach a satisfactory conclusion, the tests would require to be extended to lower stresses, and the actual testing times would be increased to several years. If we assume that the log. curve is a straight line for all stresses, then with a stress of 13 tons/in^2. the wire would fracture in a little under 200 years. This is on the basis that the wire extends about 20% before fracture, which was the average elongation shown by the various test-lengths.

Though a definite creep limit has not been demonstrated by these results, it is evident that any desired expectation of life may be obtained from a consideration of the log. plot which will give the corresponding stress value.

(d) ANNEALED COPPER:-

During the testing of the tinned copper wires, a simple apparatus was constructed for making flow tests on wires. The general arrangement of the apparatus is given in Fig. 62. Essentially a metre stick carries two clamps one at either end. Both clamps are shown in detail in Fig. 63. The top clamp rests in a wire loop which is suspended from a roof beam, this wire is held between the front of the metre stick and the forward limb of the clamp. At the rear there is a brass plate between the metre stick and the rear limb, and between this plate and the clamp is held the test wire. The clamp serves the dual purpose of supporting the loaded wire and the metre stick. The test wire is taken over the round top of the

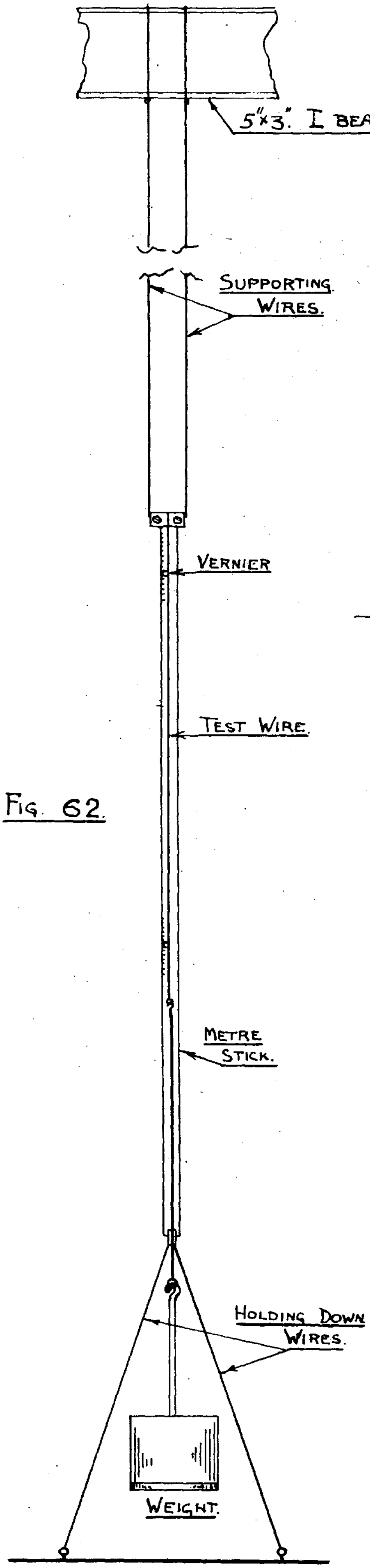
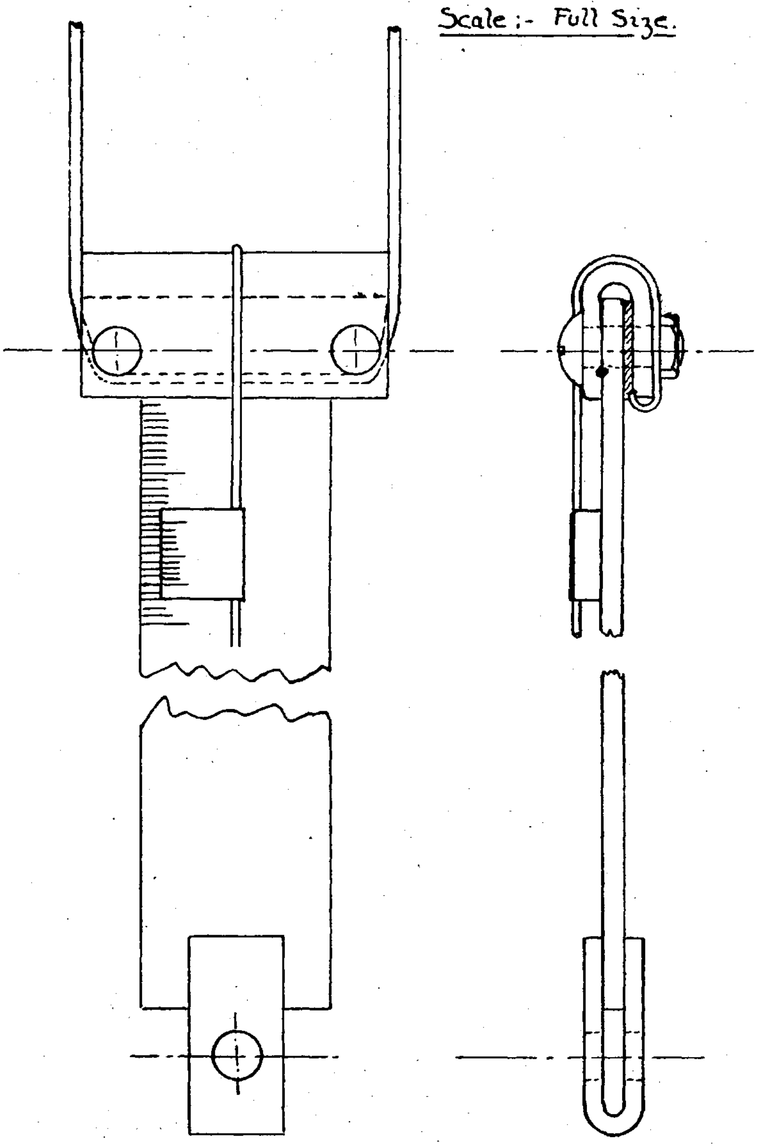


FIG. 62.

FIG. 63.

Scale :- Full Size.



clamp and passes over the face of the metre stick. The lower front edge of the clamp is also rounded, these fillets prevent nipping of the test wire which results in undesirable local stresses causing fracture at the support. The metre stick is held vertical by two wires which are strained between the lower clamp and two eyebolts in the floor.

The test wires were cut from pure copper wire, obtained from the British Drug Houses. The complete coil was annealed at 300 Deg. Centigrade before use. The test-lengths were cut 70 cm. long and cleaned. A small centimetre vernier, made in thin sheet brass, was soft soldered to the wire 10 cm. from one end and a second at 50 cm. from the first. The free end was looped and twisted, the twist being then soft soldered. This method of making an eye was found to be very satisfactory provided the load did not exceed 40 lb. Further, this load was about the limit which could be applied to the metre stick as it bent under load and had to be pulled straight with the holding down wires, too excessive a load here drawing the stick from the top clamp. The load was applied through a wire stirrup hooked to the eye of the test wire; the stirrup carried a weight carrier at the lower end. The apparatus was so set up as to have the wire parallel to the stick with the verniers in proper conjunction with the centimetre scale.

During the preparation of the test-wires they received considerable handling and to remove any strain effects they were boiled in water for an hour before testing.

The complete test plant comprised twelve such units.

FIG. 64.

ANNEALED COPPER WIRE.

LOWER GAUGE EXTENSIONS.

Fig. 65.

Annealed Copper Wire.

Upper Gauge Extensions.

FIG. 66.

ANNEALED COPPER WIRE.

EXTENSION - TIME CURVES.

The copper wire used was 20 S.W.G., 0.035 inch diameter. On testing in the Barr's Wire Tester, it gave an ultimate strength of 16 tons/in^2. The tests were performed over a load range of 32 to 25 lb., corres:ponding to stresses 14.82 to 11.56 tons/in^2.

The complete extension records are given in Figs. 64, 65 and 66; ~~they are contained in a pocket at the end of this thesis~~. Fig. 64 records the lower vernier readings and Fig. 65 those for the top vernier. From these curves, readings were taken at definite intervals, numerous or sparse as the curve demanded, and the corresponding differences, or the extensions on 50 cm. length, taken out and plotted as the final extension-time curves Fig. 66.

These are typical flow curves. It is noticeable that at the lower loads the wires are still in the initial flow stage, and may possibly remain so for some considerable time. In these cases it is impossible to determine the minimum creep rate, so that only the final rate shown has been measured, tabulated in Table No. 8 and plotted in Fig. 67. In this figure only the lower creep rates are shown. This curve is similar to Fig. 60, showing the same tendency to become tangent or asymptotic to the axis of zero creep rate. Due to the incompleteness of the extension curves the logarithms of the minimum creep rates plot very erratically and do not lie in any order, so this curve is not given.

An estimation of life expectancy may be made from the extension curves. That curve for 27 lb. load, 12.49 tons/in^2. stress shows a present creep rate of 0.000117 cm./hour. Assuming that it will extend 12 cm. before fracturing, that is, after about 6 cm. at the said creep rate, then it

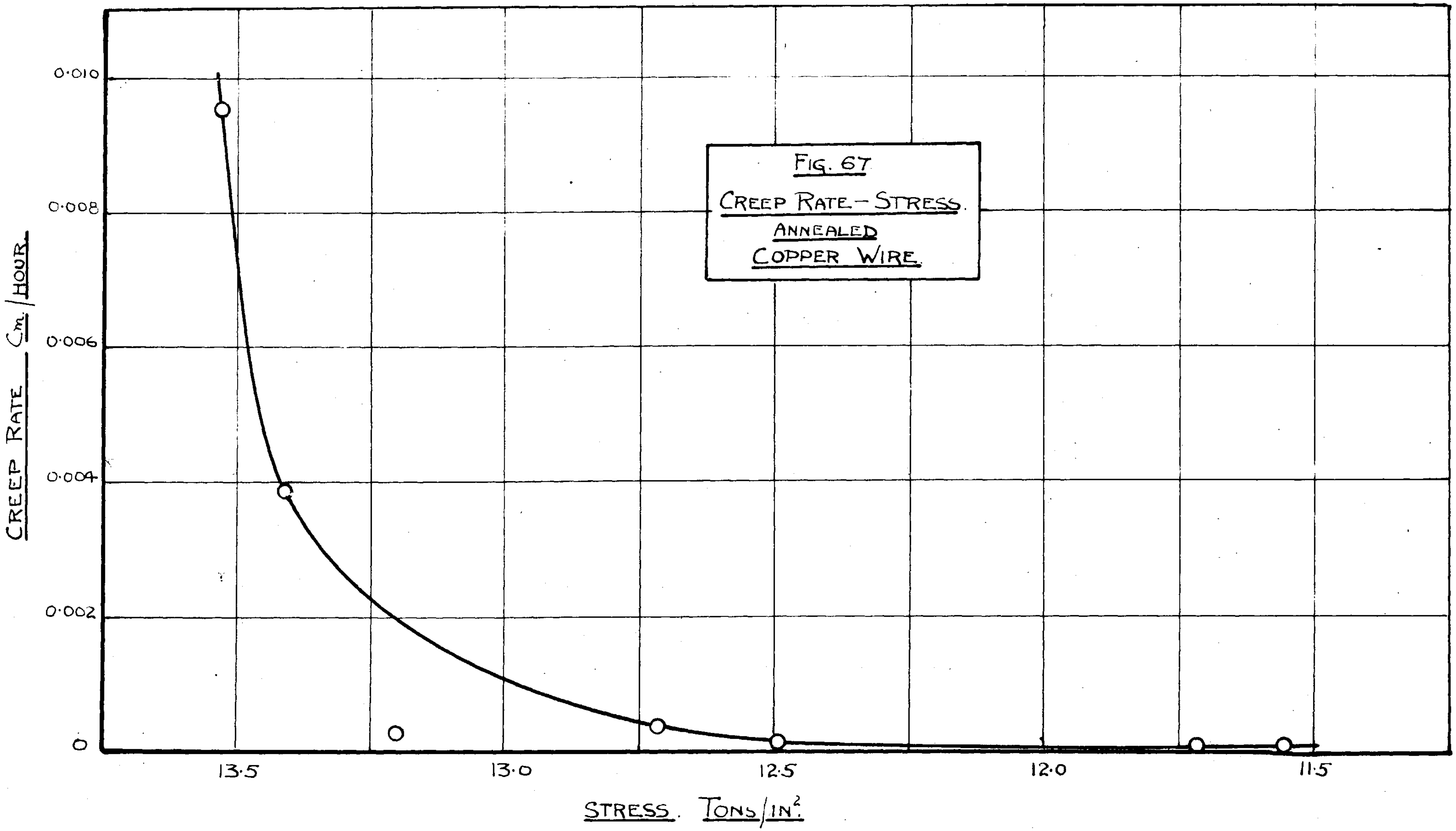


Fig. 67

Creep Rate – Stress.

Annealed

Copper Wire.

will break about seven years hence. This estimation is of course on the high side as no account has been taken of the shortening of life due to the increasing creep rate in the second flow period. On the same basis, reducing the stress by 1 ton/in^2. the life would be increased somewhere about fourteen times. Thus even with imcomplete test data, which provides no evidence of a creep limit, a desired life may be decided upon and the corresponding stress readily determined.

(e) IRON AND STEEL:-

Pure iron wire was annealed at 900 Deg. centigrade and after-cleaning was made up into test-lengths complete with verniers and each wire was boiled to remove overstrain effects. The wire was 0.024 inch diameter. On making a normal test the ultimate strength was 36½ tons/in^2. Two prolonged tests were made at 34½ and 35½ tons/in^2. Both gave initial flow lasting for about 50 days and thereafter flow apparently ceased, since no further extension could be detected after another 100 days. The amounts of initial flow were 0.105 and 0.175 cm. respectively, these extensions are 0.21% and 0.35% of the original lengths.

Two tests were made on hard drawn steel wire, the wire being tested as received. These showed initial flow of about 200 days duration the extension then ceasing. The testing loads were 23 and 24 lb. respectively, the ultimate breaking load was 24½ lb.

These tests on iron and steel show that at normal temperature the creep limit for ferrous metals is just a few per cent. below the ordinary ultimate strength. Also, just at this limit stress the initial flow is very small and is only completely produced after a very considerable period.

RESULTS:-

Prolonged tests on wires at normal temperature are very easily made and for the soft non-ferrous metals the apparatus described is sufficiently accurate. For harder metals such as iron and steel a more accurate extension measuring method is required.

The extension-time curves show clearly that there are two stages of creep extension, an initial and then a final which results in fracture. The rate of production of initial flow is reduced as the stress intensity is lowered and with this speed reduction, the time to complete the initial flow is lengthened. This necessary prolongation of the test-time is very awkward for stress determination, but it may be dispensed with if a limit based on a definite life is considered sufficient.

Finally, the existence or non-existence of a limit has not been settled, but sufficient evidence has been produced to show that the problem would require years to solve, this time necessarily being of the same order as the life required from any structure to be designed.

FAILURE:-

This is an attempt to explain the form of the creep limit curves by means of a few experimental observat::ions and conclusions which have been drawn from them.

On stressing a metal it developes slip planes, gliding on these planes produces extension and with a sufficient stress intensity fracture ultimately occurs. It is generally accepted that this slipping is accompanied by a strengthening action which can even stop slipping on a series of planes so stiffening them as to cause slip to transfer to a less favourably oriented set of planes. What this "Strain Hardening" is due to has been explained by a variety of theories which still leave it somewhat of a mystery.

Turning to thermal effects, after certain plastic deformation a metal will respond to special thermal treatment by recrystallizing which under certain conditions leads to crystal growth. This has been the subject of considerable investigation, but particularly work by Chappell (18) and Carpenter and Elam (19) has shown that this thermal action has a definite minimum temperature. There is, also, a lower temp. range which apparently affects the internal structure of the crystal, but has no annealing effect. For iron and steel this structure change occurs about 650 to 700 Deg. Fah., and the recrystallization or annealing about 1,000 Deg. Fah.

From normal to this first critical temperature there is no thermal action so that failure depends on the relation between the applied stress and strain hardening. As the extension proceeds the stress is increased and the amount of strain hardening increases. Initially the extension rate is high so that the amount of strain hardening is also high, this results in the metal stiffening and the extension rate gradually slows. This complicated interworking of effects produces the typical initial flow portion of the creep extension curve. When the applied stress is the limit stress the strain hardening produced is ultimately just sufficient to resist the stress and the extension ceases. When the applied stress exceeds the limit, the interaction of stress, extension and strain hardening proceeds till strain hardening is no longer produced (at the limit of cold work), extension still continues and with the resulting stress increase the metal ultimately fails.

The value of the limit stress apparently varies with the atomic structure of the metal. From the normal temperature tests, for iron, body centred cubic structure, the limit stress was about 3% below the ultimate stress; while for copper, face centred cubic structure, the limit stress was 25% below the ultimate stress.

Above the annealing temperature, when the metal is stressed above the elastic limit it undergoes immediate deformation, this causing recrystallization so that the metal ultimately fails. In the tests on steels the elastic limit was seen to coincide with the creep limit at about 1,000 Deg. Fah. the approximate recrystallization temperature for steel.

Over the intermediate range from 650 to 1,000 Deg. Fah., there is a very rapid diminution in strength, this indicating a rapidly increasing temperature effect. At the lower temperature we have no thermal effect and at the upper temperature we have what might be termed maximum thermal effect, this being the lowest temperature at which recrystallization occurs. From this temperature upwards recrystallization may be practically instantaneous but removal of the effects of strain hardening cannot be so, as then, failure would occur shortly after the creep limit stress was exceeded by a small amount, whereas actually, a stress slightly in excess of the limit may take years to cause fracture.

If just above the lower critical temperature the thermal treatment could totally remove strain hardening, then the creep limit would be denoted by a vertical line between the creep limit at the lower temperature down to the elastic limit value at the slightly higher temperature, and the creep limit through the succeeding temperatures would be the elastic limit. It is much more likely that the creep limit curve between the two limits is a smooth curve as shown by the test results. This curve is a measure of the actual bond strength of the internal structure. This strength is the difference between the strength at the lower limit and a stress which is a measure of the weakening effect of temperature, this effect varying from zero at the lower limit to a maximum at the annealing temperature. Otherwise this primitive or limit strength is the sum of the elastic limit and a stress value due to strain hardening, this second stress being zero at the upper temperature.

Finally the complete range of creep limit stress values may be considered based on the elastic limit, strain hardening and thermal effects being superimposed. Up to about 650 Deg. Fah., the additional stress is entirely due to strain hardening effects. Over the intermediate range the addition is due to strain hardening progressively diminished to zero by the increasing influence of temperature. Above the annealing temperature strain hardening ceases to be permanently effective and the creep and elastic limits become one.

CONCLUSION:-

The primary object of this research was to develop the Progressive Stress Test; to make it a simple and accurate method of obtaining creep limit stresses in the shortest possible time. This has been successfully accomplished. Comparing the method adopted with the Absolute Method, they give similar results, but with the progressive stress method a complete temperature range can be covered for the same time and material expenditure as will give one limit value by the absolute method.

The apparatus used was not all that could be desired and might be improved in many respects. To increase the accuracy the extension of the test-piece should be measured directly on the test length with a sensitive extensometer say of the mirror type. Such an extensometer would require steady temperature conditions and so to simplify the extension measurements, the heating current should be automatically controlled to give as steady a temperature as possible. A longer test-piece would reduce extension errors, though, if it were kept to the present standard diameters, it would be difficult to machine.

This new method is suited to testing all classes of metals, but if any particular metal is brittle at the test temperature then the testing time may be materially shortened by a return to the original method when a reduction of the slow break stress by one or two stress increments will give the creep limit stress.

A plain, evenly wound heating furnace leads to correct strength values provided the hottest temperature of the test-length is measured. To ensure that the actual metal temperature is measured the hot-junction of the thermo-couple should be firmly bound to the test-piece and shielded from furnace wall radiation and from the surrounding hot atmosphere.

In conclusion, I desire to acknowledge my indebtedness to Professor A. L. Mellanby, D.Sc., for his encouragement throughout the research and for the many facilities provided. I have also to thank Mr. J.S. Brown, M.B.E., A.R.T.C., for helpful advice and for his keen interest in the work.

BIBLIOGRAPHY:-

1. Muir, J. "Recovery of Iron from Overstrain". Phil. Trans. Roy. Soc., Vol. 193, A.p.1., 1899.

2. Hopkinson, B. "On the Elastic Properties of Steel at High Temperatures". "Engineering." Sept. 1905.

3. Barr. West of Scotland Iron and Steel Inst. 1910.

4. Rosenhain and Humfrey. "Tenacity, Deformation and Fracture of Soft Steel at High Temperatures." Iron and Steel Inst. Vol. LXXXVII., No.1, 1913.

5. Chevenard, P. Compt. rend., 1919, 169, 712 and 1922, 175, 486.

6. Lea, F.C. "The Effect of Low and High Temperatures on Materials." Proc. Inst. Mech. Eng., Dec. 1924. Vol. II.

7. Dickenson, J.H.S. "Some Experiments on the Flow of Steels at a Low Read Heat, with a note on the Scaling of Heated Steel." Journ. Iron and Steel Inst. 1922, 106, p.103.

8. (a) Tapsell and Bradley, (b) Tapsell and Clenshaw. "Properties of Materials at High Temperatures." Department of Scientific and Industrial Research. Engineering Research. Special Reports Nos. 1 and 2.

9. French and Tucker. "Flow in a Low Carbon Steel at Various Temperatures." U.S. Bur. Stand., Tech. Paper No. 296, 1925.

10. Ingall, D.H. Journ. Inst. of Metals. Sept. 1924 and Sept. 1925.

11. Brown, J.S. "The Influence of the Time Factor on Tensile Tests Conducted at Elevated Temperatures. Journ. Inst. of Metals. Vol. XXXIV, No. 2. 1925.

12. Bailey, R.W. Discussion. W. Kerr. Eng. & Ship. in Scotland. 1925-26, and Tapsell & Bradley, Journ. Inst. of Met. No. 1. 1926.

13. Basquin, O.H. "The Exponential Law of Endurance Tests". Proc. Amer. Soc. Test. Mat., Vol. X. 1910.

14. Moore, H.F. and Kommers, J.B. "An Investigation of The Fatigue of Metals." Bulletin, No.124. Eng. Exp. Stat., Univ. Illinois., U.S.A.

15. Kerr, Wm. "Failure of Metals by Creep." Inst. of Eng. & Ship. in Scotland, 1925-1926.

16. Spring and Kanter. "Power", 1923. Sept. 1.

17. Longbottom, J.G. "Influence of Various Temperatures on the Properties of Admiralty Gun-Metal." Eng. & Ship. in Scotland 1913-1914.

18. Chappell. Jounr. Iron and Steel Inst. 1914, No.1 pp. 460-496.

19. Carpenter and Elam. "Recrystallization in Metals". Jounr. Inst. of Metals. Vol. XXIV. No. 2. 1920.

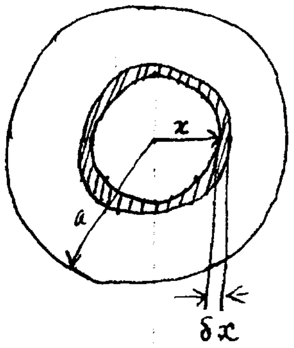
Notes on the Passage of Hot gases through narrow tubes.

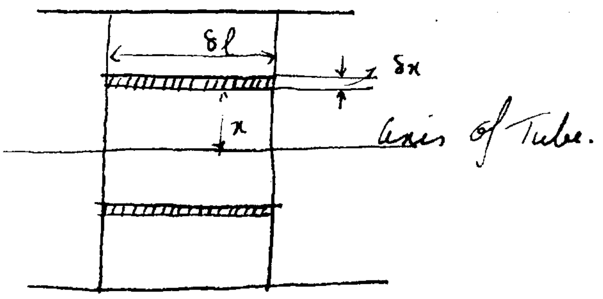
G. Hibberd

"Properties of Matter" McEwan pp170.

On the Flow of Fluids through Tubes. (Circular Section)

I Incompressible Fluids.





The volume Q of a liquid which flows in ~~unit time~~ across a section of tube in unit time may be calculated as follows. Consider the liquid bounded by two coaxial cylinders of radii x and $x+\delta x$ and by two planes at right angles to the axis of the tube and distant δl apart. The tangential viscous force on the curved surface of the cylinder of rad. x and length δl is :- $K\,\delta l\,2\pi x \frac{dv}{dx}$ (K: coeff of viscosity)

Similarly the tangential force on the curved surface of the cylinder of rad. ~~X~~ $x+\delta x$ and length δl is :-

$$K\,\delta l\,2\pi\left[x\frac{dv}{dx}+\frac{d}{dx}\left(x\frac{dv}{dx}\right)\delta x\right]$$

Consequently the difference in the tangential forces over the two curved surfaces is :-

$$-K\,\delta l\,2\pi\left(\frac{d}{dx}\left(x\frac{dv}{dx}\right)\right)\delta x.$$

If further the pressure gradient along the tube be $\frac{dp}{dl}$ the force due to the difference in the pressures ~~over~~ the two planes ends of the liquid ring is :-

$$2\pi x\,\delta x\,\frac{dp}{dl}\,\delta l$$

When the liquid has attained a steady state of flow this force must be equal and opposite to the resultant tangential viscous force opposing the motion of the liquid ring. Hence $2\pi x\,\delta x\frac{dp}{dl}\delta l = -K\,\delta l\,2\pi\frac{d}{dx}\left(x\frac{dv}{dx}\right)\delta x$

ie $x\frac{dp}{dl} = -K\frac{d}{dx}\left(x\frac{dv}{dx}\right)$

The pressure is sensibly the same over a given cross section of the tube and also the velocity of the flow v. at a distance x from the axis of the tube must be the same for all cross-sections. Thus the pressure gradient $\frac{dp}{dl}$ is independent of x, whereas for any given liquid under the conditions of the experiment, the right hand side of last equation is dependent merely upon x. Consequently the pressure gradient $\frac{dp}{dl}$ must be constant and equal to $\frac{p_1 - p_2}{l}$ i.e. P/l. Therefore integrating the last equation we have.

p_1 & p_2 = pressures at planes.
$P = p_1 - p_2$.

$$\frac{x^2}{2}\frac{P}{l} + C = -Kx\frac{dv}{dx}$$ Dividing by x

and integrating again, we have

$$\frac{x^2}{4}\frac{P}{l} + c\log_e x + c' = -Kv$$ where c' is another constant

If $x = 0$ (i.e. along the axis of the tube)

$$c\log_e 0 + c' = -Kv.$$ But $\log 0 = -\infty$

and therefore C must be zero for otherwise the vel. v would be infinite along the axis of the tube.

Again if $x = a$ (i.e. at the internal surface of the tube where $v = 0$) we have

$$\frac{a^2}{4}\cdot\frac{P}{l} + c' = 0 \quad \therefore c_1 = -\frac{a^2}{4}\frac{P}{l}.$$

Whence $$Kv = \frac{P}{4l}(a^2 - x^2)$$

Thus $$Q = \int_0^a v\, 2\pi x\, dx = \frac{\pi P a^4}{8Kl}.$$

Compressible Fluids.

In the above consideration of viscous flow of a fluid through a cylindrical cap. tube, the fluid was regarded as incompressible, but an important difference arises in the case of gaseous transpiration owing to variation in the density of the gas at different parts of the tube due to variation in the pressure. Thus the volume flowing in unit time in across a given cross-section of the tube will not be the same as the volume flowing out across a cross-section further down the tube and in consequence the velocity V of the gas parallel to the axis of the tube at a fixed distance x from the axis will vary as we move along the tube. Since however when a steady state of flow has been attained equal masses of the gas flow across each cross section in unit time it follows that ρV must be constant at a fixed distance x from the axis, where ρ is the gaseous density. But the density varies directly as the pressure 'p' of the gas and consequently the product pV of pressure and velocity at a distance x from the axis must remain constant as we move along the tube. Since then the velocity V at a distance x from the axis varies along the tube – due to variation in pressure p – relative motion will arise between portions of the gas which are equidistant from the axis. The viscous forces brought into play by this relative motion may however be treated as negligible, for if the maximum velocity of the gas be V the velocity gradient along the tube is of the order V/l and the velocity gradient across the tube is of the order V/a and since 'a' is much less than 'l' the second gradient is correspondingly greater than the first. In consequence the viscous forces arising from the first gradient of velocity may be neglected in comparison with those due to the second gradient. Therefore as before we have

$$x\frac{dp}{dl} = -K\frac{d}{dx}\left(x\frac{dV}{dx}\right)$$

but in this case the pressure gradient $\frac{dp}{dl}$ is no longer constant.

Since the pressure 'p' may be considered constant over a given cross section of the tube, we have on multiplying both sides of last equation by 'p'

$$xp\frac{dp}{dl} = -K\frac{d}{dx}\left(x\frac{d(Vp)}{dx}\right)$$

$$\therefore x\frac{dp^2}{2\,dl} = -K\frac{d}{dx}\left(x\frac{d(pV)}{dx}\right)$$

Now we have seen that pV is independent of 'l' and consequently the right hand side of the eqn is independent of l $\therefore \frac{dp^2}{dl}$ is constant and equal to $\frac{p_1^2 - p_2^2}{l}$.

Integrating the eqn $\frac{x}{2}\frac{dp^2}{dl} = -K\frac{d}{dx}\left(x\frac{d(pV)}{dx}\right)$

we get $\frac{x^2}{4}\frac{dp^2}{dl} + c = -Kx\frac{d}{dx}(pV)$ where c is a constant.

Dividing by x and again integrating we have

$$\frac{x^2}{8}\frac{dp^2}{dl} + c\log_e x + c' = -KpV$$ where c' is another constant.

When $x = 0$ (ie along axis of tube) $c\log_e 0 + c' = -KpV$ and since the velocity is not infinite c must be zero

If $x = a$ the velocity is zero whence

$$\frac{a^2}{8}\frac{dp^2}{dl} + c' = 0 \quad \therefore c' = -\frac{a^2}{8}\frac{dp^2}{dl}.$$

Substituting these values found for c and c' we find

$$KpV = \frac{1}{8}\frac{dp^2}{dl}(a^2 - x^2) = \frac{1}{8}\frac{(p_1^2 - p_2^2)(a^2 - x^2)}{l}$$

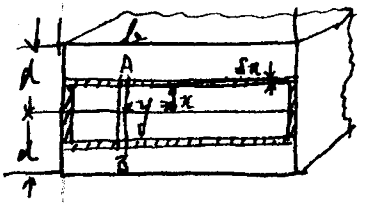
Whence if Q_1 be volume of gas entering the tube in unit time at press. p_1 and Q_2 be the vol. of gas leaving the tube in unit time at press. p_2 we have

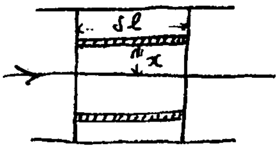
$$p_1Q_1 = p_2Q_2 = \int_0^a 2\pi x\,dx\,Vp.$$

$$= \int_0^a 2\pi x\,dx\frac{(p_1^2 - p_2^2)(a^2 - x^2)}{8Kl}$$

$$= \frac{\pi(p_1^2 - p_2^2)a^4}{16Kl}.$$

Consideration of the case of laminar (steady stream line flow) through a small rectangular tube. (Compressible fluid)





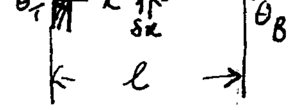
By assuming an average velocity in direction of y and a velocity gradient in direction of x for laminar flow it may be shown by a method similar to that in the preceding pages that:-

$$p_1 Q_1 = p_2 Q_2 = \left(\frac{p_1^2 - p_2^2}{24Kl}\right) d^2 (8bd + 6b^2 + 3d^2)$$

I adopted the above procedure to avoid the confusion that results from the mixture of gradients in direction of x and y. I am fully aware that in doing so I have assumed the viscous resistance at the sides to be $K\frac{dv}{dx}$ when in all probability it ought to be $K\frac{dv}{dy}$. But I could not follow it out with velocity gradients in direction of x and y.

See Royds Heat Transmission

The temperature of discharge of hot gases through small rectangular passages



Let T_1 = temp of explosion, T_2 = temp. of gas at outlet.
T = temp. of gas at x.
θ_T = temp. of flanges at inside
θ_B = temp of flanges at outlet.
θ = " " " " x.
s = Specific heat of gas (c.p.)
w = weight of gas discharged / sec.
dh = heat to flanges / □" / sec / °C.

over.

Then $-ws\,dT = dh_1\,2(b+2d)\,dx\,(T-\theta)$

Now $\frac{d\theta}{dx} = \frac{\theta_T - \theta_B}{l} = c \therefore \theta = \theta_T - cx$

$\therefore -ws\,dT = dh_1\,2(b+2d)\left[T - (\theta_T - cx)\right]dx$

$\therefore -\frac{dT}{dx} = \frac{dh_1\,2(b+2d)}{ws}T - \frac{dh_1\,2(b+2d)}{ws}(\theta_T - cx)$

and putting $\frac{dh_1\,2(b+2d)}{ws} = a$

we have $\frac{dT}{dx} + aT = a(\theta_T - cx)$

ie $al = \log_e \frac{T_1 - \theta_T - \frac{c}{a}}{T_2 - \theta_B - \frac{c}{a}}$ or $e^{al} = \frac{T_1 - \theta_T - \frac{c}{a}}{T_2 - \theta_B - \frac{c}{a}}$

ie $\underline{T_2 = \left(T_1 - \theta_T - \frac{c}{a}\right)e^{-al} + \theta_B + \frac{c}{a}}$

A simpler deduction in which inlet and outlet temps. of flanges is not considered is as follows:-

$dh = -ws\,dT$

$dh = c(T-\theta)dx$ where $c = dh_1\,2(b+2d)$

ie $-ws\,dT = c(T-\theta)dx$ or $-\frac{ws\,dT}{T-\theta} = c\,dx$

ie $-ws\log_e(T-\theta) = cx + c'$

Now when $x = 0$, $T = T_1$ $\therefore c' = -ws\log_e(T_1 - \theta)$

ie $-ws\log_e(T-\theta) = cx - ws\log_e(T_1 - \theta)$

ie $\log_e\left(\frac{T-\theta}{T_1-\theta}\right) = -\frac{cx}{ws}$ or $\frac{T-\theta}{T_1-\theta} = e^{-\frac{cx}{ws}}$

ie $T = \theta + (T_1 - \theta)e^{-\frac{cx}{ws}}$

when $x = l$ $T = T_2$ $\therefore T_2 = \theta + (T_1 - \theta)e^{-\frac{cl}{ws}}$

now $\frac{c}{ws} = \frac{dh_1\,2(b+2d)}{ws} = a$ $\therefore T_2 = \theta + (T_1 - \theta)e^{-al}$

In each of the above considerations dh_1 is taken as constant. It has been shown to vary enormously with the velocity of the gas, so that in this particular case calculations based on the assumption that dh_1 is constant, are probably incorrect.

In each of the preceding deductions steady stream line flow is assumed in which case viscosity must be considered. Since however the discharge is explosive turbulent flow is more likely to be the order of discharge, and if this is so viscosity effects will be negligible. Turbulent flow may not obtain throughout any particular cross-section, as probably a thin film of gas will be present in contact with the metal surface, and heat lost to the flanges will be by conduction through this film. On account of this, very involved calculations will be required to estimate the heat lost to the flanges, and the results obtained will be approximate only since certain assumptions will have to be made. I believe a more satisfactory method is to regard the 'gaps' as nozzles and base calculation on nozzle ~~the~~ discharges. In support of this I append the following deductions.

The drop in temperature produced by the passage of Hot Gas through apertures

The following rough calculations are given by way of extension to the paragraph at the foot of page 119 of the 4th Number of the Journal of the Royal Technical College [Paper on Preventing Electrical Apparatus from Starting Explosions]. The paragraph is as follows :- "The cooling of hot gases, by passing through a gap may be regarded as being effected in two ways (i) naturally by the sudden expansion from high pressure to low, and (ii) by passing over the cold surface of the metal flanges. The heat absorbed by a cold metal surface from a hot gas passing over it, is proportional to the area of the surface, to the density of the gas, to the speed with which the gas sweeps over the surface, and to the difference in temperature between the surface and the hot gases. When a 'gap' is short, deep, and of small area the first cause of cooling possibly predominates, with long narrow gaps cooling is probably accomplished mainly by the large metal surface swept over"

In considering the passage of hot gases (such as steam) through nozzles, it is found that the passage of the gas may be regarded as being a "reversible adiabatic expansion". This may be a large assumption if applied to the passage of flames from an explosion, but it will be made. [Combustion is not adiabatic]

For the reversible adiabatic expansion of ideal gas, $pv^n = \text{constant}$ and $pv = RT$, hence if the expansion through the gap be from P_1, T_1 to P_2, T_2, $T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$. Taking n (the ratio of the specific heats of the gas at constant pressure and constant volume) as 1.4 and $r = P_2/P_1$

then $T_2 = T_1 r^{0.286}$.

If the 'gap' is a convergent or a parallel one, the outlet pressure is always 0.53 of the initial pressure (if the final pressure is not above this). If the passage is divergent full expansion can take place within its boundary.

Should the velocity of the stream at any point in the gap be required it is given by the equation $v = \sqrt{\frac{2gn}{n-1} P_1 V_1 \left(1 - r^{\frac{n-1}{n}}\right)}$

Where P_1 is in lbs/sq.ft.

V_1 the specific volume in cub. ft/lb.

r the pressure ratio at the point (referred to P_1)

g the acceleration due to gravity.

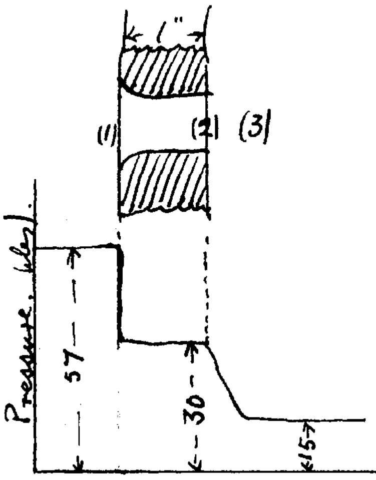
or the flow is given by. $w = a\sqrt{\frac{2gn}{n-1} \frac{P_1}{V_1}\left(r^{\frac{2}{n}} - r^{1+\frac{1}{n}}\right)}$

where w is the flow in lb/sec.

and a is the area to flow in sq.ft.

Case I The extreme case of the gap $\frac{1}{10}'' \times \frac{3}{8}'' \times 1''$

The form of the passage is of the same order as in nozzle work; the heat transference through the limited surface of metal is negligible when the quantity of gas flowing is considered; the expansion being regarded as adiabatic we have.



$$T_2 = T_1 \, r^{0{\cdot}286}$$

$$r = \frac{P_2}{P_1} = 0{\cdot}53 \text{ so } \underline{T_2 = 0{\cdot}83 T_1}$$

If say $T_1 = 3{,}700°F$ (abs) [c1800°C]

$T_2 = 3{,}070°F$ a drop of $\underline{\underline{630°F}}$

But for this case Fig 5. p 112 of the Journal paper gives a maximum Pressure $P_1 = 57$ lb/in² abs.

So $P_2 = 0{\cdot}53 \times 57 = 30$ lb/in²

and $P_3 = 15$ lbs/in² (atmospheric).

There is thus expansion from 30 to 15 lbs/in² after leaving the 'gap'. This expansion takes place <u>very</u> close to the gap and produces further cooling which is <u>probably of importance</u>.

Case II Another extreme case – the gap 0·03" × 2q" × 1".

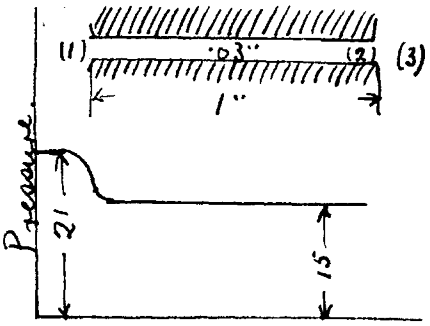


Fig 5. p 122. gives $P_1 = 21$ lbs/in² (abs).

$P_2 = P_3 = 15$ lb/sq. inch (= atmosph).

Cooling due to adiabatic expansion

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

$$= 0{\cdot}91 \, T_1$$

If $T_1 = 3.700°F$ (absol) $T_2 = 3370°F$

a drop of $\underline{\underline{330°F}}$.

Now consider the heat lost by transmission to the cold metal sides of the gap.

Reynolds laws of heat transmission stated in the paragraph quoted at the beginning of this note may be expressed by the equation

$H = B\rho v t_m$ [$H = A + B\rho v t_m$ - the term A for gases at rest being negligible

where t_m is the mean temperature difference between hot gas and metal; v is the speed of gas, ρ density, B a constant, H is the heat transmitted per unit area per second.

If w = total weight of gas passing per second, and

a = cross section area of flow, $w = a v \rho$ and

$H = \frac{w}{a} B t_m$ (Heat transmitted per sq ft per sec)

For ordinary transmission thro' boiler plates $B \doteqdot \frac{1}{1200}$ to give B in B.T.U. per sq ft per sec., w being in lb per sec. a in sq ft, t_m in °F.

Now T_1, T_2, being the temperatures of gas on entering and on leaving respectively then (ignoring natural drop of temp. due to expansion) we have:-

Heat taken from gas = $w s (T_1 - T_2)$ where s is the specific heat of the gas (pressure constant)

So $w s (T_1 - T_2) = \frac{w}{a} B A t_m$ where A = surface area of metal which is independent of flow of gas as expt. corroborates

$$\therefore T_1 - T_2 = \frac{B A t_m}{s a}$$

Substituting numbers and taking $s = 0{\cdot}24$ and the temperature of the hot gases somewhere over 3000°F (abs) and the temp of the metal over 500°F (abs) so that t_m = 2500°F we get.

$$(T_1 - T_2) = \frac{(29 \times 2) \times 2500}{1200 \times {\cdot}24 \times {\cdot}03 \times 29}$$ (A and a both being put in sq. ins)

$$\doteqdot 580\,°F$$

The total drop in temp. might thus be about 910°F - 330°F due to natural cooling (expansion) and 580°F due to transmission to the metal.

over.

Of course the various assumptions made render the calculations of very doubtful value. The experiments might lead one to expect that the drop of 630°F got in Case I should be more nearly equal to the 910°F got in Case II (both gaps were flame-proof), but the further cooling in Case I just after the gas leaves the gap could reasonably be taken to account for this difference, without having regard to a possible difference in the internal temperatures [in one case pressure attained 57, in the other 21 lb/in^2 abs]. But 900°F seems too small a drop in temperature, even taking into account the "lag on ignition" phenomenon. If so, then it can only be suggested that calculations based on adiabatic expansion of ideal gases do not apply to gases in a state of combustion.