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REGULARITIES IN CREEP AND HOT FATIGUE DATA

PART II

by

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Regularities in creep and hot-fatigue data - Part II

- by -

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SUMMARY

A previously-given theory, which was extended in Part I, suggests that (for a single form of loading) strain ε is related to stress σ, time t, and temperature T by a sum of terms of the form

$$C\,\sigma^{\beta}\phi^{\kappa} \qquad \text{where} \qquad \phi = t(T' - T)^{-A},$$

that the constant A is the same for all terms and a range of materials, and that the ratios β/κ take values from the sequence 2^n. In the present Part II, the theory is compared with 103 sets of published creep-rupture, creep-rate, and hot-fatigue data relating mainly to alloys of the Fe, Ni, Cr, Co, system of 44 different compositions. The results of all analyses are given in detail in the figures and tables. A statistical assessment of the extent of agreement of the theory with the data is given with reference to the number of free constants used.

Data of the kind considered, which is that most readily available, contains virtually no direct information on strain, and can be analysed only with certain assumptions in this regard. The assumptions made reduce the general formula to two alternative simpler forms, and one or other of these was found to hold to within the apparent scatter for all but a few sets of data.

The standard ratios 2^n are confirmed by at least 40 sets of data relating to the creep and hot fatigue of widely different materials, and are not denied by the remainder. Support is given for use of the time-temperature parameter ϕ in the manner indicated in preference to others that have been proposed. The values of T' appear to follow a systematic scheme, and use of the common value of A = 20 is justified. The only clear cases of disagreement with the formula as fitted were in respect of parts of the data for 3 materials for which variations of creep strength with temperature were irregular.

The figures and tables, which appear to confirm the theory to within the discrimination of the data, provide a convenient source of reference to the mean properties and their probable deviations for many materials. They should provide reliable interpolations between directly measured points. The graphical methods used are indicated, but are set out more fully in an accompanying Memorandum.

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For Figures 11 to 97, which contain the results of analysis, reference should be made to Tables II and IIA.

1.0 Introduction

1.1 Scope of Report

In the present Part II, creep-rupture, creep-rate, and hot-fatigue data for 44 materials taken from published sources are presented in a form convenient for reference in terms of a previously given theory[1,2] and experimental results given and discussed in Part I of the Report[3]. Relevant parts of the theory are summarised below and in Paras. 2.1 and 3.1. Materials, chemical compositions and references to the sources of data are given in Table I; the main results are presented in Figures 11 to 97 and in Tables II, V, VI and VII. Tables V and VI give estimates of the random scatter in the data, and Table VII gives the number of freely adjustable constants used when fitting the theory. Self explanatory examples of the Figures with detailed legends are given in Figures 2, 3, 8 and 7. The graphical methods of analysis used* are described in detail in References 4 and 5. Reference should also be made to Section 9 of Part I.

The data selected for analysis was primarily that which was readily available. It comprises that in the extensive compilations of the "Timken Digest", the Mond Data Books for the Nimonic Alloys, "Fox Steels Design Data", and an Admiralty summary, and a number of published papers including unclassified N.P.L. and R.A.E. reports. In order thoroughly to check the theory without introducing bias by selection of data, all the data in the Timken, Mond, Fox and Admiralty publications that were sufficiently extensive to warrant attention have been examined and are presented. Much of the detailed discussion in the Report is due to an attempt to make the best use of fragmentary sets of data, and to the indirect and incomplete nature of the evidence concerning fulfilment of conditions necessary in order that data of the kind considered should be amenable to analysis. Although details are rather fully given for those to whom they are of interest, the essential content of the Report should be obtainable from the first and last sections and the Figures and Tables.

1.2 Outline of theory

Equations (2) and (3) of Part I are contained in a general formula which was stated in References 1 and 2 where a special case was used. The general formula represents strain ε as the sum of a number of terms in stress σ viz.

$$\varepsilon = C_1 \sigma^{\beta_1} \phi_1^{\kappa_1} + C_2 \sigma^{\beta_2} \phi_2^{\kappa_2} + \ldots\ldots \qquad \ldots \quad \ldots \qquad (1)$$

in which time t and temperature T are combined in the relations

$$\phi_1 = t(T_1' - T)^{-A_1}$$

$$\phi_2 = t(T_2' - T)^{-A_2}$$

..... etc.

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*The Figures are reproduced at approximately half the linear scale of the working drawings.

The C β κ T' A are constants. It was found for the materials considered in Part I that all the A had effectively the same value 20 and that the ratios κ/β had the common values $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, $\frac{1}{16}$ ..... For the present analysis, this formula, together with the standard values of A and κ/β are assumed, while the C and T' are taken to be adjustable constants for each material and term. The characteristics of the formula with these values of A and κ/β are examined in detail in Paras. 2.1 and 3.1.

The formula can be fully applied only when complete sets of creep curves are available, but, provided certain conditions are fulfilled, it may be applied in part to creep-rupture or creep-rate data like that considered which contain less information. In practice, one or other of the conditions appears to be nearly always effectively fulfilled, and formula 1 may then be simplified.

For creep at constant stress and temperature (1) becomes

$$\varepsilon = at^{\kappa_1} + bt^{\kappa_2} + \ldots\ldots \quad \ldots \quad \ldots \quad (1a)$$

and for cross plots of creep curves at constant temperature and strain ε_c it becomes

$$\varepsilon_c = A\sigma^{\beta_1}t^{\kappa_1} + B\sigma^{\beta_2}t^{\kappa_2} + \ldots\ldots \quad \ldots \quad \ldots \quad (1b)$$

Analysis of experimental data shows that several terms of (1b) may have effectively the same value of κ (cf. Paras. 2.2, 2.3). If the only terms concerned have a common value of κ, (1b) becomes

$$\varepsilon_c = (A\sigma^{\beta_1} + B\sigma^{\beta_2} + \ldots\ldots)t^{\kappa}, \quad \ldots \quad \ldots \quad (1c)$$

and this is the simplified form that satisfactorily represents nearly all the creep-rupture and hot-fatigue data examined. A similar equation (Para. 3.1) with creep rate $\dot{\varepsilon}$ in place of t represents the majority of the creep-rate data. For the two most extensive sets of data, only 4 terms were required, usually 3 or 2 were sufficient.

The applications of (1c) fall into two classes according to the relative magnitudes of the separate terms. In one class, which comprises some of the creep-rupture data and all the hot-fatigue data, different single terms show a virtual predominance, each separately in a different part of the range, so that each part may be separately fitted in the appropriate log/log plot by a straight line of one of the standard slopes. In the other class, which comprises the remaining rupture data and all the creep-rate data, two or more terms are usually of comparable significance, and the data is fitted by the appropriate curves. In view of the standard values of κ/β, application of (1c) may then be reduced to the fitting of curves of predetermined form. These are shown in Figures 5 and 9.

Sections 2, 3 and 4 give a detailed study of the data on these lines.

1.3 Conditions for analysis; presentation of data

Conditions that the creep must fulfil in order that data may be analysed in accordance with Equations (1c) (or (2a)) are that there must be either

(i) a stage of markedly accelerating creep preceding rupture as in Figure 1a (rupture data),

(ii) a long stage of steady-state creep as in Figure 1b (creep-rate data),

(iii) a stage of steady-state creep extending effectively to rupture as in Figure 1b, together with a substantially constant strain at rupture (rupture data).

To each of these corresponds a particular method of analysis and presentation.

When the first condition is satisfied, terms in Equation (1) with large κ (apparently $\kappa \geq 3$) predominate, and when the second and third, terms with $\kappa = 1$ predominate. The first and third conditions lead to different methods, say (i) and (iii), of presentation of rupture data, and the second to a method, say method (ii), of presentation of creep-rate data.

Method (i) finally presents creep-rupture data as plots of log stress versus log ϕ. When condition (i) is satisfied, rupture data for a particular temperature, initially plotted as log stress versus log time, is found to fall upon a curve indistinguishable in practice from a segmental curve made up of straight lines with standard slopes as in Part I, and also as in Figure 2a of which the details are referred to in Para. 2.2. For other temperatures the data fall upon other segmental curves, as predicted by formula (1c), made up of the same standard slopes separately displaced along the log time axis (Figure 2a). Such data is presented for convenience upon plots of log stress versus log ϕ_1, log ϕ_2, etc., in which a set of points, for various temperatures, associated with a single standard slope then combine to fall about a single line (Figure 2c). Each such set of points has in general its own scale of ϕ, dependent upon the value of T'. The data is therefore summarised by one, two or three lines with standard slopes, as in Figure 2c or Figure 8 of Part I.

Method (ii) presents creep-rate data as log stress versus log creep rate. When condition (ii) is satisfied, creep-rate data for any one material and temperature plotted as log stress versus log creep rate is found to fall about a continuous curve whose predetermined form, according to Equation (2a), is governed (see Para. 3.1) by the same standard slopes. For any other temperature, the data is fitted by a similar curve but now displaced along both horizontal and vertical axes, as shown in Figure 3c where the locus of displacement according to (2a) is indicated. Superposition of curves for different temperatures after the manner of the creep-rupture segments is only possible when no more than two terms are concerned, and even then does not lead to a convenient presentation; the data is therefore given as plots of log stress versus log rate for each temperature separately, each fitted with a curve whose relation to the other curves is calculated in accordance with the several ϕ (Figure 3c).

Method (iii) presents creep-rupture data as log stress versus log time. When condition (iii) is satisfied, rupture data may be presented similarly to creep-rate data as plots of log stress versus log time fitted with curves of predetermined form (cf. Para. 2.3).

The hot-fatigue data considered is co-ordinated by method (i), attention being given to time to rupture rather than number of cycles.

2.0 Creep rupture (Methods (i) and (iii))

2.1 General properties of formula for constant strain

For a given stress and temperature, the equation to the creep curve yielded by (1) takes the form (1a), in which constant-rate creep is represented by terms with $\kappa = 1$, and accelerating creep by terms with $\kappa > 1$: where direct experimental evidence is available, the latter terms appear to have $\kappa \geq 3$. When the curve of log stress versus log time for given strain and temperature is controlled by terms with a common value of κ, the formula for this curve, irrespective of the value of κ, takes the form (1c), and into this the previously-determined ratios κ/β of ... $\frac{1}{4}$, $\frac{1}{8}$, $\frac{1}{16}$ ... may be introduced. In (1c) the constants A, B,... are of the form $C(T' - T)^{-A}$.

At a fixed strain and a single temperature, Equation (1c) has the following features. A single term on a log stress versus log time plot yields a straight line whose slope is $-\kappa/\beta$, while several terms yield a continuous curve. For the data here examined, the greatest number of terms that are effective at a single temperature is three.

In the many cases in which only two terms are effective, the continuous curve has asymptotes of standard slope, each defined by a single term. The form of the curve is dependent only upon the values of κ/β and κ. Since only a few predetermined values of these constants are relevant, the few two-term standard curves shown in Figures 4 and 5 are common to all sets of data. Curves for the cases in which three terms are effective are readily built up (cf. Reference 5) from these curves.

At the same fixed strain and another temperature, the single-term straight line is displaced along the log-time axis in accordance with its ϕ; each of the components of the multiple-term curve is similarly but separately displaced along the log-time axis, each in accordance with its own ϕ.

In the present context, κ only affects the abruptness of the transitions between asymptotes, the abruptness becoming more marked with increase of κ. For values of κ of say unity (cf. condition (iii)) or less, the transitions are gradual and may cover the whole of the experimental range; while for κ say ≥ 3 (cf. condition (i)), they are so sharply curved that they are indistinguishable, within the scatter, from abrupt transitions. Examples are given in Figures 5 and 4 respectively which are considered in the next Paragraphs.

2.2 Method (i)

For data that fulfils condition (i) of Section 1

(a) the time to rupture is determined almost entirely by terms with large κ;

(b) a variation in the strain at rupture produces a smaller relative variation in the time to rupture, so that for moderate variations it is reasonable to treat rupture plots as constant strain plots to which the results of Para. 2.1 apply;

(c) the transitions on a log stress versus log time graph are sharply curved so that the graph reduces effectively to a number of linear segments each dependent on a single term of (1c);

(d) in view of (c) the precise value of κ is unimportant.

Figures (1a), (2a) and (4) illustrate these points: thus Figure (1a) shows a creep curve in which the term with $\kappa = 3$ predominates at large strains, and for this curve a typical strain variation of $\pm 1.5/1$ involves a time variation of $\pm 1.24/1$, which, as will be seen in Section 6.0, is within the scatter of all but the best data: for larger κ the time variation would be smaller still. Figure 4 provides standard curves for pairs of terms with $\kappa = 3$ and various κ/β; the curvature of the calculated transitions is seen to cover only a small part of the range of stress commonly encountered, and the difference between the curve and the straight-line asymptotes is within the scatter of most of the data (cf. Figure 2a). The range of the transition, and the difference between curve and straight lines, becomes smaller for larger κ, so that with $\kappa > 3$ the precise value need not be known since the curve can in all cases be approximated by the same straight-line asymptotes. This "independent term approximation" is equivalent to treating each term in (1c) separately, the chosen term for any particular stress range being that which makes the largest contribution to ε_c for that range.

Data that fulfils the condition is conveniently presented in the form of a graph (cf. Figure 2c) in which, as in Part I, Figure 8, each group of points for various temperatures but associated with a particular segment (and hence with a particular term of Equation (1)) is separately plotted as log stress versus log ϕ with its own scale of ϕ, but in which all groups share a common scale of log stress. In the diagrams relating to this method, each group of points is fitted with a mean line of standard slope; the cycles of the log stress scale are chosen for graphical accuracy to be larger (conveniently 3.75 times larger) than those of log ϕ; the points of each group are plotted with distinctive shapes; the temperatures are indicated by tagging; and the occasional bracketed points are those that fall too near a transition between two slopes to be assigned uniquely to either group, and hence are plotted on both. The legends on these graphs are given in more detail in Figure 2c: the common scales are given with closer graduations in Figure 6. Details of the procedure by which these graphs were built up are illustrated in Figure 2 and described in References 4 and 5.

This presentation enables values of stress to be read directly from the log stress scale, while values of time and temperature separately may be obtained by calculation from the log ϕ scale in which both are combined. For a fixed temperature, a log ϕ scale may be regarded as a scale of log time, and, for a fixed time, as a scale of A log (T' - T): accordingly, to enable time and temperature to be determined from the Figures without recourse to calculation, two auxiliary scales of this kind are provided which are separately labelled with time and temperature. The first is a sliding logarithmic scale of time; the second is a fixed scale constructed for the value of T' appropriate to the scale of log ϕ, and graduated in temperature.

All the figures have the common sliding logarithmic scale of time shown in Figure 6, while each line in each figure has in general its own fixed scale corresponding to the T' for that line. The latter, termed the T_{100} scale, has been arranged to give the value of log ϕ (namely log ϕ_{100}) for the fixed time of 100 hours and the labelled temperature T°C. In use, the sliding scale of time is set with its 100 hour mark opposite that for the temperature T of interest on the fixed scale; then,

$$\begin{aligned}\log \phi &= \log t - A \log (T' - T)\\ &= \log t - \log 100 + \log 100 - A \log(T' - T),\\ &= \log t - \log 100 + \log \phi_{100}\end{aligned}$$

so that

$$\log \phi - \log \phi_{100} = \log t - \log 100$$

Thus the log ϕ for time t and temperature T is distant (log t - log 100) from the graduation for T°C on the T_{100} scale, and any time t hours on the log time scale corresponds to the value of log ϕ on the adjacent log ϕ scale for that time and temperature (cf. Para. 2.8 and Figure 7). Where, owing to lack of space, the T_{100} scale has not been given in full range, it may be extended from the scales of log(T' - T) in Figure 6 (cf. Reference 5).

To indicate directly the fit of the time-temperature variable ϕ to the experimental data, auxiliary graphs of Δ log t versus temperature (cf. Figure 2) are provided, together with the best-fitting curves from Equation (1) with A = 20. The measured displacements Δ log t associated with each slope are separately plotted with points of distinctive shapes (cf. Figure 2b). The fitted curves provide the smoothed displacements used for superposition of points on the log stress/log ϕ plots (e.g. Figure 2c) in the present method (i) and for spacing the sets of curves on the log stress-log time plots in method (iii) below.

2.3 Method (iii)

For data that fulfils condition (iii):

(a) the time to rupture is determined almost entirely by terms with $\kappa = 1$;

(b) the time to rupture is considerably dependent upon the strain at rupture, so that only when the rupture strain is sufficiently constant may the rupture plots be treated as constant-strain plots;

(c) the transitions on log σ/ log t graphs are gradual (cf. Figure 5) so that the independent-term approximation is inadequate;

(d) since fulfilment of condition (iii) implies that $\kappa = 1$, the form of the transition curve is determined by formula (1c).

Figures (1b), (8a) and (5) illustrate these points and their contrast with those of Para. 2.2. The first shows a typical creep curve in which terms with $\kappa = 1$ predominate: for this curve the time variation appropriate to a strain variation of ±1.5/1 may be seen to be about ±1.6/1, a variation which (cf. Section 6.0) is comparable with the scatter of the more scattered data. The curved transitions of Figure 5 commonly extend over the entire experimental range, so that, as shown e.g. in Figure 8a, the straight-line asymptotes are not a good approximation. If Equation (1c) applies, the curves of Figure 5 should be common to all the data for which $\kappa = 1$.

Such data is conveniently presented as direct plots of log stress versus log time for each of the testing temperatures separately, to each of which the appropriate curve is fitted. In regions where only two terms are effective, the general shape of the curve is independent of the constants C, and the curve has one of the standard forms shown in Figure 5. For another temperature, each of the component terms is separately displaced along the log time axis in accordance with its own T', and the complete two-term curve is displaced, without tilt or change of form, both horizontally and vertically (cf. Figure 8a). Thus the standard curve for the particular κ/β generates a family of curves, one for each temperature, spaced according to the T'. When more than two terms are effective the form of the curve depends upon the relative magnitudes of the constants C and must be individually calculated for each case[5], the calculation being based on the two-term curves.

In the log stress versus log time plots presented according to this method, the component terms of each fitted curve for a particular temperature are shown as straight lines of standard slope. When only two terms are effective, these are asymptotes to the curve. The line of a given slope for a particular temperature passes through the graduation marked with that temperature on a spacing-scale T_s, which corresponds to the T_{100} scale of Para. 2.2: the spacings between graduations for temperatures T_1 and T_2 are of the amount $A \log(T' - T_2) - A \log(T' - T_1)$. Auxiliary $\Delta \log t$ versus temperature plots are also presented, as for method (i). Each set of $\Delta \log t$, T points, with its fitted curve, corresponds to a term with a particular ratio κ/β: the fitted curves are used to determine the spacings between the lines for that term on the T_s scale.

2.4 Δ log t and Δ log rate plots - determination of A and T'

The values of A and T' used in the construction of log stress versus log ϕ plots and in the fitting of log stress versus log time or log stress versus log rate curves, are indicated for any one term by the displacement $\Delta \log t$ (or $\Delta \log$ rate), with temperature, of the position of a line of the appropriate standard slope along the log time axis. In the example of Figure 2a for method (i), the spacing is measured between parallel segments, and plotted in Figure 2b; in the examples of Figures 3a and 8a, it is measured between parallel asymptotes of the two-term curves, and plotted in Figures 3b and 8b.

When adequate data at three or more temperatures are available to define two or more values of $\Delta \log t$, both A and T' are uniquely determined in principle. In practice, the scatter is such that in most cases a range of values of A, with corresponding values of T', will fit the experimental data equally well. For reasons discussed in Section 7.0 of Part I, and Para. 5.4 of the present Report, the constant A has been chosen to have the common value 20, and with this common value the T' for an extensive set of data is closely defined. The curvature of the plot of $\Delta \log t$ versus T decides whether T' is above or below the experimental range of temperature: an upward curvature ($\Delta \log t/\Delta T$ increasing with T) indicates a T' above, and a downward curvature a T' below this range.

In many cases the data, particularly if it refers to two temperatures only, does not of itself determine whether T' is above or below the experimental range (the "sense" of T'). However, the choice can often be made on other evidence, and, when made, a numerical value can be determined. Thus in the case of a material whose rupture data satisfies condition (iii) and whose creep-rate data satisfies condition (ii), the terms with $\kappa = 1$ control both rate and rupture, and the value of T' should be the same for both. Where there was direct evidence on this point, the sense of T' was found to be the same, although the numerical value, owing apparently to scatter, was not (cf. **Para.** 5.2). Hence, when evidence was lacking for one set the sense was if possible determined from the other. Failing such evidence, the sense was determined from data on similar materials. In all cases the numerical value was determined directly from the data concerned: each value whose sense was chosen in one of these ways is starred in Table II.

Where, for a particular slope, data at only one temperature is available, no value of T' can be determined: in such cases a value is usually adopted from an adjacent slope (such values are bracketed in Table II). For one set of data however, namely that for DM2 steel which satisfies condition (i), these values were not suitable: hence the data for the slopes for which T' was not defined were plotted simply as log stress versus log time, and fitted with standard slopes.

Some data do not establish all points on the Δ log t plot with equal certainty; thus in the example of Figure 2a the lines of slope $-\frac{1}{4}$ are firmly established at 750°C and 815°C, but only an extreme position is obtained at 700°C: the corresponding point in Figure 2b is therefore arrowed, and the fitted curve may pass below it but not above it by more than the scatter. In other cases, e.g. Figure 8a, the slope at a particular temperature may be poorly defined because only one or two experimental points are available: the corresponding Δ log t point is queried in Figure 8b, and given less weight than the others in fitting the curve (cf. Reference 5).

2.5 Nature of evidence for fulfilment of conditions (i) and (iii)

Independent evidence on the fulfilment of conditions (i) and (iii) is obtainable from data such as that given in the headings below which is often supplied in conjunction with creep-rupture and creep-rate data. The evidence is given in some detail in Table III, and the general manner in which it was used is as follows:-

(a) Creep curves: if these extend to rupture they will show directly whether the creep accelerates strongly or is of constant-rate at rupture, and will also show the strain at rupture* (cf. Figures 1a, 1b).

(b) Times to a fixed strain: if at a particular stress the time to a fixed strain of e.g. 0.5 per cent is not less than say half the time to a rupture strain of several per cent, condition (i) is probably fulfilled. The

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*If the available creep curves are sufficient in number and cover a sufficient range, it is preferable to analyse them fully in terms of Equation (1) (cf. Reference 4). Creep curves are seldom published in adequate detail however.

converse, when the time to a fixed strain is much less than the time to rupture, suggests but does not necessarily establish that condition (iii) holds.

(c) Stress for a fixed strain: if the stress for a fixed strain in a given time is little less than the stress for rupture in the same time, condition (i) is probably fulfilled. If it is appreciably less, condition (iii) is suggested but not established.

(d) Strain from constant-rate terms: if the strain that would result if the specified creep-rate acted for the period of the rupture time is a small proportion of the recorded rupture strain, condition (i) is probably fulfilled (cf. Figure 1a). If it is a large proportion, condition (iii) is probably fulfilled (cf. Figure 1b). Use of this evidence is complicated by the fact that, in a conventional constant-load test, the increase in true stress with decrease in cross-section produces accelerating creep from even a constant-rate term.

The choice between method (i) or (iii) was based upon the above criteria when the evidence was sufficient. Otherwise the method chosen was that which led to the best fit; thus data that showed abrupt transitions was analysed by method (i) and that showing gradual transitions was analysed by method (iii). Table V, (last column) shows that the independent evidence when available was usually in agreement with the observed form of transition.

2.6 Presentation of rupture data

The sources listed in Table I provide 65 sets of creep-rupture data. Of these, 3 (for HGT3, R20, Rex 326 F) are insufficient to define any log stress versus log time curve, 3 (for Nimonic 80, 80A and 90) have been presented in Part I, and one (for N155) is reserved for future detailed study. The remaining 58 sets, of which all but 2 tabulated sets (for Nimonic 95 and 100) represent direct experimental, as distinct from interpolated data, are presented in Figures 11 to 64. Tables I and IA give materials, compositions, heat treatments and sources of data; Table II gives figure numbers and values of T' where determined. Figure numbers from data where T' was not determined are given in Table IIA.

Of these 58 sets, 49 were sufficiently extensive to define both log stress-log time and Δ log t versus T curves, and of the 49, 48 sets relating to materials of 36 different compositions have been analysed by the above methods and are presented in Figures 11 to 59; the remaining set, for DM steel (Figure 60) is discussed in Para. 2.7. The 9 less extensive sets of rupture data, for materials in tube form, namely for Rex 337A, G18B, FCB(T) solid drawn, FCB(T) seam welded, and Nimonic 75 (all in Figure 60), and for Nimonic 95 (Figure 19), D4C, G18B, and Fortiweld, (Figures 62 to 64), defined log stress versus log time curves but gave no information as to the Δ log t versus T curves and hence on the value of T': data for the first 6 is available at only one temperature, and for the remaining 3, owing to the comparatively small range of stress covered and an unfortunate placing of this range, the standard slopes appear each only at a different single temperature. The Nimonic 95 data is presented (Figure 19) in a plot of log stress versus log ϕ according to method (i), since other data on this material provides a suitable value of T'; the other 8, for which no external evidence is available, are presented in plots of log stress versus log time with curves fitted for each temperature separately.

Nine sets of rupture data (Figures 16, 26, 27, 28, 39, 45, 47, 51, 53) provided plots of Δ log t (and hence values of T') for some slopes but not for others, and the undetermined value of T' (indicated in brackets in Table II) was taken, in all but Figure 47 for C-Mo steel, to be the same as that for an adjacent slope. The data for C-Mo steel does not define the T' for slope $-\frac{1}{32}$, but rejects the values used for other slopes. One set of data, for Rex 448, (Figure 37) has a very marked irregularity in its Δ log t versus T plot (Figure 37a) and has been presented both by the normal application of method (i), with T' = 1200°C; and also by a double application of method (i) separately to the data at 500°C to 550°C, and data at 600 to 650°C. The second method, using a common value of T' = 975°C, yields two parallel log stress versus log ϕ lines.

2.7 Detailed discussion of rupture data

Of the 49 sets of rupture data presented in Figures 11 to 59, 36 were analysed by method (i): these included one set for which, as mentioned in Para. 2.4, values of T' were indicated for one standard slope but not for others. Of the 36, 15 sets were shown by criteria (a) and (b), 2 sets by criterion (c), and 3 sets by criterion (d) unambiguously to fulfil condition (i) - details are in Table III. As required by Equation (1c), all showed abrupt transitions where the transition range was spanned by the data, all exhibited the standard slopes, and all but one was fitted to within the scatter by the time-temperature relation ϕ. Independent evidence as to the fulfilment of the criteria was not available for 3 sets, namely 2 of Nimonic data and one of Inconel X, but these were expected to satisfy condition (i) since data on similar alloys are known to satisfy it; they also showed abrupt transitions and standard slopes. The remaining 13 rupture sets of Table II for which independent evidence was absent or inadequate (Table III), were analysed by method (i) merely because they had abrupt transitions; these were found to exhibit the standard slopes and to be fitted satisfactorily by the time-temperature relation.

Thirteen sets of rupture data were analysed by method (iii) (Figures 47 to 59). Adequate evidence as the fulfilment of condition (iii) was available only for the extensive data for 18-8 steel (Figure 57, criterion (a)) which was generally well-fitted by the curves. Of the other 12 sets (which were analysed by method (iii) because they had curved transitions), 11 fitted to within the scatter of the data and one (2 per cent Cr Mo, Figure 48), while fitting well to the standard curves for each temperature separately, did not fit satisfactorily to the time-temperature relation. This and the similar example of Rex 448 in Para. 2.6 present the Δ log t/T anomaly mentioned in that paragraph. There was limited evidence for the 13 materials that the strain at rupture varied irregularly, and some scatter may be due to this cause (cf. Para. 5.4).

The set of data for D.M. steel (Figure 61), for which there was little independent evidence concerning the criteria, was found to have sharp transitions at low temperatures but gradual transitions at high temperatures: Equation (1c) is thus an oversimplification for this material. Data of this kind requires consideration in terms of the complete formula (1).

The log stress/log time plots of method (iii) are direct plots of experimental data, and the log stress/log ϕ plots of method (i) are immediately reducible to direct plots by use of the sliding scales of log time provided. The self-consistency of the points for any one temperature, and their correlation by the standard slopes, can be immediately assessed from the plots: the correlation of sets of points at different temperatures can also be estimated from the plots, but is more immediately seen from the auxiliary Δ log t/temperature plots. The latter represent derived data, depending to some extent on the assumption of standard values for the slopes $-\psi/3$, but these slopes appear to be sufficiently well established not greatly to affect the assessment. As an illustration, in the typical example of G.32 presented by method (i), Figure (22a) indicates that results at temperatures from 750°C to 1000°C are regular and adequately co-ordinated by the time-temperature curve derived from Equation (1), while Figure 22 shows that, for stresses between 16 t.s.i. and 2 t.s.i., the experimental results at all temperatures are well co-ordinated by the two straight lines of slope $-\frac{1}{8}$ and $-\frac{1}{4}$. Outside this stress range, other slopes (e.g. $-\frac{1}{16}$ and $-\frac{1}{2}$) may be required, but the data is inadequate to define them.

Similarly, in the typical example of 4 to 6 per cent Cr Mo + Ti steel, Figure 52a indicates that results at different temperatures are reasonably well correlated by the time-temperature curve, while Figure 52 shows that the experimental data is well co-ordinated by the set of common curves spaced in accordance with ϕ. With the exception of the two sets of data which have markedly irregular Δ log t versus T plots (cf. Para. 2.4) and four sets which exhibit the partial discrepancies discussed in Para. 5.5, all the 48 sets of creep-rupture data appear to be adequately fitted by the lines or curves provided by Equation (1c).

2.8 <u>Use of rupture plots</u>

For data plotted according to method (i), interpolated values of the time to rupture for a given stress and temperature may be readily obtained from the appropriate log stress versus log ϕ line by means of the auxiliary scales. Where two or more lines each with a separate scale of log ϕ are present, each will give a different value of the time to rupture, and the appropriate line is that which gives the shortest time. This feature is due to the change in relative predominance of terms with temperature and its explanation may be seen from Figure 2. The experimental points in Figure 2a always follow the lower line when two lines of standard slope cross. Similarly, if time and temperature are given, the lowest of the stresses to rupture given by the several lines is adopted. If time and stress are given, the lowest temperature is adopted.

As an illustration of interpolation for method (i), let it be required to determine the time to rupture for G.32 at 8 t.s.i. and 800°C. At this stress, some experimental points fall upon the line of slope $-\frac{1}{8}$, others on that of slope $-\frac{1}{4}$. In Figure 7, in which the data of Figure 22 is replotted, the sliding scales of log time from Figure 6* are set for each slope with their 100 hour graduations opposite the required temperature of 800°C, and the times on these scales corresponding to 8 t.s.i. are indicated. The time of 2900 hours for slope $-\frac{1}{8}$ is less than the 10000 hours for slope $-\frac{1}{4}$, and the former value, being the smaller, is adopted as the time to rupture.

For data plotted according to method (iii), the curves immediately yield values of interpolated stresses or times to rupture for any of the testing temperatures. If however, it is required to determine a value for an intermediate temperature, the appropriate log stress/log time curve must be constructed. When only two terms are present, as in the example of 4

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* An extra copy of Figure 6 is provided for cutting into sliding scales

to 6 per cent Cr Mo + Ti (Figure 52 and Figure 8c), it is only necessary to set the standard curve so that each of its asymptotes passes through the appropriate temperature graduation in the spacing scales. As an illustration let it be required to determine the time to rupture at 630°C and 5 t.s.i. In Figure 8c the common curve for slopes $-\frac{1}{8}$ and $-\frac{1}{4}$ has been set so that the asymptotes pass through the required graduations, and the time to rupture is seen to be 32 hours. When three or more terms are operative, the same method applied to two predominating terms will give approximate results, but for more accurate results the method to use is given in Reference 5.

Extrapolation is similar in principle to interpolation, but raises the problem of whether terms in Equation (1) not revealed by the experimental data become important. Each line or asymptote of standard slope is considered in principle to extend indefinitely in both directions.

3.0 Creep rate

3.1 Properties of formulae for constant-rate creep

The equation for creep rate, obtained by differentiating (1) with respect to time, is

$$\dot{\varepsilon} = D_1\sigma^{\beta_1}t^{\kappa_1-1} + D_2\sigma^{\beta_2}t^{\kappa_2-1} + \ldots \qquad \ldots \qquad (2)$$

in which the D at any one temperature are constants. When an extensive range of steady-state creep occurs, terms for which $\kappa \neq 1$ may be neglected. Graphs of log σ versus log $\dot{\varepsilon}$ often appear to have several distinct slopes (magnitudes $1/\beta$ since $\kappa = 1$) as asymptotes to the continuous curves, and this suggests that several terms with $\kappa = 1$ and different values of β may be present. Creep-rate data, because of the curvature of the log stress versus log rate plots, provides little direct evidence as to the values of β, but economy of hypothesis suggests use of the standard values of κ/β derived from creep rupture; this step is generally confirmed by the fit to the data.

For $\kappa = 1$ and the above values of κ/β the formula reduces to 2a, viz.

$$\dot{\varepsilon} = D_1\sigma^{\beta_1} + D_2\sigma^{\beta_2} + \ldots \qquad \ldots \quad \ldots \quad \ldots \qquad (2a)$$

This equation is similar to (1c) when in (1c) ε is constant, and it provides, since log $\dot{\varepsilon}$ = constant - log t, a log stress versus log rate curve which is the mirror image of the log stress versus log time curve of **Para. 2.3** and Figure 5.

The log stress versus log rate curves for different temperatures are derived from common curves displaced both horizontally and vertically, exactly as for rupture data analysed by method (iii): the common curves appropriate to creep rate are given in Figure 9. The slopes of the component terms are given by the standard values of κ/β, now $1/\beta$, of $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$ ...., and are mirror images of the creep-rupture slopes. Formula (2a) is fitted to the data by fitting calculated families of curves to the complete set of points.

3.2 Evidence for creep-rate condition

Creep-rate data can only be fitted by Equation (2) when condition (ii) is adequately satisfied; for if the "steady" creep rate is due to an accidental combination of accelerating and decelerating terms, as in the "apparently constant-rate creep" of Figure 1a, the relative proportions of the terms may vary at different stresses; also the values of κ, which determine the form of the log stress versus log rate curve, would be unknown.

Criteria (a) and (d) of Para. 2.4 may be expected to provide evidence as to the constancy of rate, but for most of the data presented, evidence only in respect of (d) was available (cf. Table III). Thus for example a certain test upon S.590 gave a steady creep-rate of 0.001 per cent per hour with a time to rupture of 4000 hours. The strain due to this term would therefore be at least 4 per cent at rupture owing to the increase in true stress with strain during this constant load test. Terms with high κ, although probably present, do not therefore predominate at rupture since they contribute no more than half the observed 9.6 per cent of rupture strain. Their contribution at strains below 1 per cent where creep-rates are commonly measured will be negligible. Any constant-rate creep is therefore likely to be due to terms with $\kappa = 1$.

In constrast, materials like 25-20 steel, for which the strain due to the constant-rate creep is less than 0.5 per cent out of say 5 per cent, cannot reliably be analysed on the assumption that the constant rate quoted is due to $\kappa = 1$ terms (cf. Para. 5.5).

3.3 Presentation of data - method (ii)

For reasons similar to those given in Para. 2.3 for method (iii), it is convenient to present creep-rate data, selected as in Para. 3.2, in the form of direct log stress versus log creep-rate plots for each temperature separately. The best-fitting families of curves from formula (2a) are shown, together with the component-term lines and the spacing scales T_s, one for each term, graduated in temperature.

The fit of the rate versus temperature curve, calculated from Equation (2a), to the experimental values of the spacings Δ (log rate) is shown in auxiliary graphs (cf. the Δ log t versus T graphs of Para. 2.2). In these graphs, the spacings for each term are separately plotted as points with distinctive shapes, and to each set of points the master rate versus temperature curve is fitted. The fitted curve provides the spacings on the scale T_s.

3.4 Δ log rate plots - determination of T'

The constant T' which determines the spacing on the T_s scale between the component-term lines for different temperatures is determined from the Δ log rate versus temperature plot, the construction and use of which is similar to that of the Δ log t versus T plots discussed in Para. 2.4. A is again chosen to have the value 20 which, as in the case of creep rupture, satisfactorily co-ordinates all the creep-rate data presented. The choice of T' above or below the working temperature is if necessary made in conjunction with the method (iii) creep-rupture data (Para. 2.4). Terms which appear at one temperature only, for which T' is not determinable, are if possible plotted on a T_s scale with the T' adopted from an adjacent term;

such T' are bracketed in Table II; otherwise they are plotted on a scale of rate only, and no value of T' is quoted.

3.5 Creep-rate data presented

Of the 23 sets of creep-rate data available, 4 were indicated by criterion (d) not to satisfy condition (ii), and although presented in Figures 84 to 87 their fitted curves are not considered to give a reliable indication of behaviour (see Para. 5.5).

Of the remaining 19 sets, 17 were independently shown by criterion (d) to satisfy condition (ii), and the other two could be assumed to satisfy the condition because similar materials did so: all 19 have been presented by method (iii) in Figures 65 to 83. One set (2 per cent Cr - Mo), has a very irregular Δ log rate versus T curve (Figure 69a) (cf. Rex 448, Section 2), and the data for slope $\frac{1}{2}$ has been treated in two parts, to which the two T_s scales shown refer, one relating to temperatures 482 to 538°C, the other to temperatures 593 to 649°C.

3.6 Discussion of creep-rate data

The points on the log stress-log rate plots represent direct experimental data to which immediate return may be made from the tags and scales. As in the case of creep rupture, the consistency of the points for any one temperature, and their correlation by a common curve, may be assessed from the parallelism of points with the curve: the correlation of sets of points at different temperatures may be estimated from the fit to the family of curves (whose spacing is determined by the ϕ), but is more immediately made from the Δ log rate versus temperature plots. In the typical example of Timken Sicromo 5S steel, Figure 77a indicates that results at temperatures 538°C to 704°C are adequately co-ordinated by the curve derived from the time-temperature relation, while Figure 77 shows that for stresses between 6 t.s.i. and 0.5 t.s.i. the experimental creep-rate data is co-ordinated to within the scatter by the fitted curves with use only of terms with $\kappa/\beta = \frac{1}{8}$ and $\frac{1}{4}$.

For some materials e.g. Sicromo 5 MS (Figure 78) the creep-rate data is adequately fitted with terms of slope $\frac{1}{8}$ and $\frac{1}{2}$ only, the terms of intermediate slope $\frac{1}{4}$ apparently not contributing significantly to the creep rate. However, most of the data is inadequate to show unambiguously that this term is absent, and it may make significant contributions outside the experimental range.

Of the 19 sets analysed (Figures 65 to 83), 17 are seen to show satisfactory agreement with formula (2a), the remaining 2 for 2 per cent Cr Mo (Figure 69) and S 816 (Figure 82) have irregular Δ log rate curves and are discussed in Para. 5.5.

The 4 sets that did not satisfy the condition are also discussed in Para. 5.5.

3.7 Use of creep-rate plots

Interpolated values of stress or strain rate at any of the testing temperatures may be read directly from the appropriate log stress-log rate curve exactly as for rupture data plotted by method (iii). The method of extrapolation is similar, but, as in the case of creep rupture, additional terms may need to be taken into account.

An example of interpolation is given in Figure 3c, in which the standard curve of slopes $\frac{1}{8}$ and $\frac{1}{4}$ is fitted for 600°C, and the creep rate for 2 t.s.i. at 600°C determined as 9×10^{-7}.

4.0 Hot fatigue

4.1 Relation to formula

It was shown in Part I of the Report that data for the time to rupture in hot fatigue, for zero mean stress, could be co-ordinated by formula (i), and fitted by standard slopes from the same sequence as for creep-rupture data. In the present Report, available hot-fatigue data is analysed in greater detail. No independent criteria are available (contrast Para. 2.5), but method (i) appears adequate since all data show standard slopes with abrupt transitions.

4.2 Hot-fatigue data presented

Of the 15 sets of hot-fatigue data available, 5 have not been presented, namely one very extensive set for N.155 which is reserved for future study, and 4 sets from the Mond booklets which provided only one log stress versus log time point at each temperature.

The remaining 10 are presented in Figures 88 to 97; of these, four provided both log stress versus log time and Δ log t versus temperature plots, and were analysed by method (i); the remaining 6 defined the log stress versus log time slope at only one temperature. These 6 were plotted as log stress versus log time and are fitted with lines of standard slope in Figures 92 to 97.

4.3 Discussion of hot-fatigue data - use of plots

The 4 sets of data analysed by method (i), Figures 88 to 91, indicate a fit to within the scatter to the standard slopes, the scatter appearing to be of the same order as for creep rupture of these materials. The time-temperature relation is not severely tested by this data, since only for Nimonic 90, Figure 89a, did the same slope appear at three different temperatures: in this case the Δ log t versus T curve fits the points closely.

The log stress versus log ϕ plots, as in the case of creep rupture, serve to summarize the data, and provide a basis for interpolation and possibly extrapolation. The method is identical with that of Para. 2.8.

5.0 Discussion of data as a whole

5.1 Evidence on form of time-temperature relationship

The graphs of Sections 2, 3 and 4 may be considered to establish the validity of the assumption of standard slopes. This result together with the more extensive Δ log t or Δ log rate plots provides evidence to discriminate between various proposed time-temperature relationships of which several, particularly those of Larsen and Miller[17], Manson and Haferd[18], and Dorn[19] have been extensively used to correlate creep data.

The Larsen and Miller relationship that, at constant stress and strain,

$$T\,(C + \log t) \;=\; \text{constant} \;\equiv\; \log \phi_L \text{ (say)}$$

is at variance with the standard slopes of log stress versus log time (or log rate) established by the present work. For, under these conditions, $\Delta(\log \phi_L) = 0$,

$$\text{i.e.} \qquad \Delta \log t/\Delta T \;=\; -\,(C + \log t)/T \qquad \ldots \quad \ldots \quad \ldots \qquad (3a)$$

so that, for given ΔT and T, Δ log t varies with t. Thus the lines of log stress versus log time for different temperatures are represented as being not parallel.

The remaining two relations are not inconsistent with the standard slopes, but predict forms of Δ log t versus T curve at variance with most of the data presented. Thus the Manson and Haferd relation, effectively

$$\log t + BT \;=\; \text{constant} \;\equiv\; \log \phi_M \text{ (say)}$$

provides
$$\Delta \log t/\Delta T \;=\; -\,B, \text{ a constant,} \qquad \ldots \quad \ldots \quad \ldots \qquad (3b)$$

so predicting that the graph of Δ log t versus T is a straight line; while the Dorn relation

$$t\, e^{-(\Delta Hr/RT)} \;\equiv\; \phi_D \text{ say,}$$

can be written

$$\log t - (\Delta Hr)/RT \;=\; \log \phi_D,$$

which provides
$$\Delta \log t/\Delta T \;=\; -(\Delta Hr/RT^2), \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (3c)$$

thus predicting that the slope of the Δ log t versus ΔT graphs decreases with temperature.

The relation of the present Report

$$t(T' - T)^{-A} \;\equiv\; \phi$$

provides
$$\Delta \log t/\Delta T \;=\; -\,\frac{A}{(T' - T)}$$

predicting that the slope increases or decreases with T according as T' is above or below the experimental range of T.

Table IV below summarizes the evidence from the figures on the curvature of the Δ log t and Δ log rate plots, the latter being similar in form to the Δ log t plots. The column headings are as in Table II.

TABLE IV

Curvature of Δ log t and Δ log rate plots

Change of slope with temperature	Number of Δ log t or Δ log rate plots				
	R(i)	R(iii)	$\dot{\varepsilon}$(ii)	F(i)	Total
Increasing	20	2	2	1	25
Decreasing	9	15	11	0	35
Constant	1	2	1	0	4
Undefined or ambiguous	28	9	25	3	65

The plots in the last row are mostly those that contain only two points and therefore give no information as to curvature. In the remaining rows, only 4 plots support the straight line of the Manson and Haferd relation; the 35 plots with decreasing slope favour the Dorn relation and that of the present Report equally since the difference in the curvature predicted by these relations is within experimental error; while the 25 plots of the first row with increasing slope support the relation ϕ alone. Thus if a common form of time-temperature relationship is to be used for all materials and slopes, then there will be many fewer discrepancies if the ϕ of the present Report is used.

5.2 Probable errors in the T'

The use of ϕ having been justified, it remains to discuss the significance of the experimental values of T'.

An independent estimate of the error in T' can be obtained for those materials for which both creep-rupture and creep-rate data relate to $\kappa = 1$ (i.e. both conditions (ii) and (iii) appear to be fulfilled) so that each provides an independent value of the same T' (cf. Para. 2.4). Differences are observed which provide evidence as to systematic and random errors in T'.

A difference in T' for a solitary material provides virtually no evidence; but on the assumption that all experimental points are equally liable to error, the combination of all available differences provides enough values for statistical study. Such combination must take account of the widely differing amounts of evidence for establishing the individual T': it is assumed that the probable error in T' is inversely proportional to the square root of the number of experimental points and to the range of experimental temperature, and is directly proportional to the difference between T' and the mean experimental temperature T_m. On the assumption of a Gaussian distribution of the error in the individual T', the distribution of errors in the difference (T'_r (rupture) - T'_ε (rate)) was found by computation to be Gaussian, with a probable error s_d related to the errors s_r and s_ε of the individual T' by the approximate formulae

$$s_d = s_r \left(1 + 0.31\, {}^{s_\varepsilon}/_{s_r}\right), \quad s_r > s_\varepsilon$$

$$s_d = s_\varepsilon \left(1 + 0.31\, {}^{s_r}/_{s_\varepsilon}\right), \quad s_\varepsilon > s_r \quad .. \quad (4)$$

Each experimental value of $(T'_r - T'_\varepsilon)$ was therefore assigned a weighting factor $1/s_d$, and the weighted ogival distribution curve is shown in Figure 10. It is seen to be closely Gaussian, thus both confirming the assumptions and indicating no appreciable systematic differences between the T'.

By combining the individual weighting factors for each set of data with the standardised experimental error (i.e. error for unit weighting factor) from Figure 10, estimates of the standard deviations in Table V were made. The table relates only to those materials for which comparison was possible for at least one slope, but for these materials includes values for all slopes for which a T' was determined. The table gives for each material and slope separately the experimental values of T'_r and T'_ε taken from Table II, the standard deviations s_r and s_ε, the most probable mean value of T', and its standard deviation s.

5.3 Significance of differences between the T'

In order to test the significance of differences between the most probable T' for a particular slope but different materials, the individual T' are compared in the last column of Table V with the weighted mean T' for all materials that have that slope: the departure of the T' for each material from this mean is shown as a fraction of the standard deviation of the T' for that material. This column suggests that the T' for slope $\frac{1}{8}$ are significantly different for different materials, but that the differences for the other slopes (for which however there is less evidence) are not significant. For any one material, the T' for different slopes are in general significantly different. The weighted mean T' for a particular slope, taken over all the materials, differs markedly from the weighted mean for any other slope.

Direct comparison of the T' in the above manner is only possible for the materials for which two independent estimates of the value were available; for the remaining materials, the error in T' can be assessed either by assuming that the scatter in each experimental point is the same as for the material of Table V, or directly from the Δ log t versus T plots, as in Figure 8 of Part I. The scatter in the graphs of log stress versus log time, log rate, or log ϕ, suggests that the first assumption is probably safe for the remaining data. The scatter in the best of the method (ii) graphs is appreciably less than that for the data of Table V (see Section 6.0 and Table VI), and these graphs confirm that the T' are in general different for different slopes and, for the same slopes, for different materials.

There are five materials (18-8-Cb, DM2, $2\frac{1}{4}$Cr - 1Mo, killed carbon and Silmo steels) for which a T' was obtainable for the same standard slope both for terms with $\kappa = 1$ (creep rate) and $\kappa \geq 3$ (creep rupture): these T' differ markedly, suggesting that terms in Equation (1) with the same κ/β but different κ have in general different T'.

Although the T' for a given slope are in many instances clearly different for different materials, the scatter is such that for a group of related materials the differences are barely distinguishable, so that the use of common values may be considered (cf. the common "activation energy" of Reference 19). There were however very few instances of extensive data for which common values could be used for different slopes.

5.4 The common value of A, and interpretation of the T'

No individual set of data is adequate in range and consistency to determine both A and T' directly. Since the values of T' obtained depend markedly on the chosen value of A, the evidence for the choice of A = 20 rests mainly on the physical reasonableness of the T' as a whole.

The values listed in Table II, which are based on A = 20, are seen to fall between the absolute zero and the melting point, except for those from three sets of data which were independently shown (Para. 5.5) not to satisfy the conditions for the analysis.

A further indication of the reasonableness of the T' is provided by the correspondence, for the Nimonic alloys, between the T' for slope $\frac{1}{8}$ and the solution treatment temperatures. This correspondence was noted in Part I for 4 sets of tabulated data: a comparison of Tables I and II of the present Report extends this to 7 sets of direct experimental data, and also shows that, for Nimonic 90, when the solution-treatment temperature was changed from 1080°C to 1150°C, there was a corresponding change in the T'.

For the other slopes of the Nimonic alloys and for the other solution treated materials of the table, the indications are fragmentary and inconclusive, and for two materials (S590 and S816) the T' are below the working range. Such values in Table II are usually associated with materials that have a normalizing or annealing treatment rather than a solution-treatment. All low values of T' are outside the range of nominal heat-treatment temperatures, but it appears from Table II that most of those for slopes $\frac{1}{8}$ and $\frac{1}{4}$ fell within the range of temperature over which "blue brittleness" may be observed.

On the present evidence there appears no need to consider a value of A other than 20.

5.5 Departures from Equations (1c) and (2a)

It remains to consider the 13 sets of data which depart from Equations (1c) or (2a) by more than the experimental scatter. Departures are of two kinds: firstly, those probably due to incomplete fulfilment of the conditions under which the approximate Equations (1c) and (2a) hold, but where the data are qualitatively in agreement with Equation (1), and secondly those for which the Δ log t/T or Δ log rate/T plots are not in accordance with ϕ, and where the data are therefore not in accordance with Equation (1) as fitted.

As a general comment, but especially in regard to rupture data controlled by terms with κ = 1, disagreement would arise from systematic changes in the strain at rupture with stress or temperature; for Equation (1c) relates to constant strain. No clear evidence of a systematic bias due to these changes is however provided either by the graphs of Figures 47 to 59 (which contain the only available strains for all the data considered), or by the analysis of Para. 5.2. Random changes presumably contribute to the random scatter, and the observed scatter (cf. Section 6.0 and Table VI) is, as would be expected from this cause, greater for rupture data with κ = 1 than for the other data.

The five examples of the first kind comprise the rupture data for DM steel and the creep-rate data for this steel and 16-13-3, 25-20 and 18-8 steels. For each of these there is evidence that terms with more than one value of κ are present. Thus, in the data for the creep rupture of DM steel, while the limited independent evidence of Table III favours condition (i), the transitions in the log stress versus log time plot Figure 61 change from abrupt at low temperatures to gradual at high temperatures, so that Equation (1c) is an over-simplification. The complete Equation (1) is able to account for this effect if terms with the same slope $-\kappa/\beta$ but different κ have different T' (cf. Para. 5.3): but the rupture data alone is insufficient to determine the required constants, and so the figure has only been fitted for each temperature separately with standard slopes or a standard curve as appropriate. For the creep-rate data for this and for the other three steels which is presented in Figures 84 to 87 and 84a to 87a, the independent evidence of Table III shows that condition (ii) is not satisfied: the creep rate is presumably contributed, not mainly by the t^1 term as in Figure 1b but by a combination of all terms as in Figure 1a. The creep rate would be expected to follow the standard curves of log stress versus log rate, or log rate versus temperature, only in the unlikely event that all terms were present in the same proportions at different stresses and temperatures. The curves in fact fit the data poorly, and for the first three materials a fit is only obtained with a T' above the melting point. The broken lines (obtained from Equation (2a)) are intended only to indicate the degree of misfit and not to give a reliable summary of the properties.

There are eight instances of apparent systematic departure of the second more serious kind from Equations (1c) and (2a). The departures for two, however, (Inconel X (Figure 23) and 16-13-3 (Figure 35)) fall within the limits of apparently random scatter exceeded by about 10 per cent of all the data considered (i.e. within category B of Table VI, Section 6). All comprise departures from the time-temperature relation ϕ and relate each to one term only of Equation (1c) or (2a). They may be seen on the Δ log t/T plots for each of Inconel X, Rex 448, 2 per cent Cr Mo, 16-13-3, Sicromo 3, and Sicromo 5S, (Figures 23a, 37a, 48a, 35a, 54a), and on the Δ log rate plots for 2 per cent Cr Mo and S816 (Figures 69a, 82a). The Δ log t or Δ log rate plots for the remaining terms were all in accordance with ϕ. Three of the discrepant plots (for rupture of Rex 448 and 2 per cent Cr Mo, and for creep-rate of 2 per cent Cr Mo) were sufficiently irregular (cf. Paras. 2.6, 2.7 and 3.5) not to be immediately fitted by any available time-temperature relation: four (for rupture of 16-13-3, Sicromo 3 and Sicromo 5S, and for the creep rate of S816) were those that showed no curvature (cf. Table IV), and would be better fitted by the Manson and Haferd parameter. Discrepancies might conceivably be explained by systematic changes with temperature in the strain at rupture as mentioned above, and for Rex 448 there is some evidence (cf. Reference 20) for this view; but the evidence as a whole does not appear adequate to account for the observed discrepancies which are up to 4:1 in time. The data for S816 may be biased by the different heat treatments used for different temperatures of testing (see Table 1). The remaining plot (Figure 23) for rupture of Inconel X shows a rather large discrepancy at the highest temperature and draws attention to a possible explanation of these effects within the framework of Equation (1). For the discrepancy appears to be associated with the fact that the T' for one term (950°C for the term with $\kappa/\beta = \frac{1}{16}$; Table II) lies within the experimental range. For temperatures in the immediate neighbourhood of a T', a term is represented by Equation (1) as passing through an indefinitely large value with possibly a change of sign. Thus a term may be effective near a T' that makes contributions, at temperatures well away from a T', too small to be directly resolved by the data. Although there is no direct evidence like that for Inconel X for any other material, this possibility is present for all. Behaviour at temperatures in the neighbourhood of a T' is to be a matter for further study.

6.0 Summary and conclusions

One hundred and three sets of creep-rupture, creep-rate and hot-fatigue data have been considered in this Report, including all the data (92 sets) in the 4 compilations. Of these, 96 and 85 sets respectively were sufficiently extensive to define a relationship between stress and time or creep rate, 2 (for N 155) being so extensive as to justify separate detailed study. The remaining 94 (83) have all been analysed, as far as the extent of the data warranted, in terms of Equation (1), and have been presented; these totals include the 3 sets of tabulated data for Nimonics 80, 80A and 90 considered only in Part I.

Of those analysed, only 5 (5) were clearly shown by independent evidence not to fulfil the requirements for analysis by the simplified forms (1c) and (2a) of Equation (1); when these 5 sets were nevertheless analysed they were all found to deviate from (1c) or (2a) in ways that could in principle be covered by the complete Equation (1).

The 89 (78) sets that did fulfil the requirements were analysed by Equation (1c) or (2a) as appropriate. The scatter in time of the points from the calculated lines may readily be estimated from the Figures because a given percentage discrepancy in time is represented by a parallel displacement of a standard line or curve along the log time axis. The displacements corresponding to ±0.1 and ±0.2 in log time are indicated in Figure 6 with examples in Figures 2c, 3c and 8c. These ranges are equivalent to +25 to -20 and +60 to -40 per cent in time respectively. The 89 (78) sets concerned have been classified into groups A, B and C respectively according to whether half* or more of the points fall within ±0.1, within ±0.2, or outside these limits, in log time. For each set of data the classification is noted in the appropriate Figure while the numbers of sets in the different categories are summarised in Table VI. It was found by inspection that for a particular set of data the error in log time tended to be constant for different slopes while the error in log stress varied with the slope. The errors have, therefore, been quoted in log time rather than in log stress, but the corresponding stress errors for any particular slope may be obtained from Table VI(b).

Of the above 89 (78) sets of data, 75 (64) were sufficiently extensive to define both log stress versus log time or rate, and log time or rate versus temperature graphs. Table VI(a) shows that for 46 sets the time errors were within +25 to -20 per cent and the stress errors generally less than ±5 per cent, and for 23 (18) sets the time errors were within +60 to -40 per cent and stress errors generally not more than ±10 per cent. The 6 (6) sets relating to 5 materials that fall outside this range all show systematic departures (cf. Para. 5.5) from the time temperature variable but not from the standard slopes. They are discussed in detail in Para. 5.5.

Fourteen (14) sets were too restricted to establish the time temperature variable, and so were fitted with standard slopes for each temperature

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* For a Gaussian distribution, half the points would be expected to fall within ±0.68 of the standard deviation from the mean line.

separately: of these, 9 (Table VI (a)) fitted to within +25 or -20 per cent in time, 2 to within +60 or -40 per cent, and 3 were outside this range but gave no indication of systematic bias. The above figures include the 4 extensive sets of hot-fatigue data. Of these, one fell in Category A and the other 3 only just outside it.

When it is remembered that only for the most consistent of materials is the (statistically ill-defined) claim made that creep is consistent to within ±5 per cent in stress or ±50 per cent in time, it may be inferred that the data studied are adequately represented by Equation (1) with the standard values of κ/β and n. This representation is not obtained by taking the liberty of an undue number of freely-adjustable constants. With the standard ratios κ/β regarded as non-adjustable, each term of Equation (1c) or (2a) involves no more than 2 adjustable constants, namely the T' and the multiplying factor represented by the free choice of the height at which the line of standard slope is drawn. Where a term appears at only one temperature it involves only the free choice of the height. For the 75 sets of data which were fully analysed, the numbers of free constants used, which are indicated by the Figures, are given in Table VII. It is seen that 53 of these required no more than 4 adjustable constants. These numbers need to be considered in relation to the fact that in addition to the many variables of composition and treatment, 3 independent variables, namely stress, time or rate, and temperature are concerned.

TABLE VII

Numbers of free constants required for fitting data

Number of free constants	Number of sets of data				
	R(i)	R(iii)	$\dot{\varepsilon}$(ii)	F(i)	Totals
2	12	0	0	0	12
3	2	0	0	2	4
4	15	8	14	2	39
5	5	1	1	0	7
6	4	3	3	0	10
7	1	0	0	0	1
8	0	1	1	0	2

The graphs Figures 11 to 97 form a convenient and accessible summary of the direct experimental data, and the curves in full line should give a reliable indication of the mean properties, and their scatter, of the materials. They afford an immediate means for obtaining information for temperatures, times, and stresses, between those covered by direct experiment, and, to the extent that accurate extrapolation depends upon accurate knowledge of the basis from which extrapolation is made, they also offer a firm basis for extrapolation. The results clearly show that reliable extrapolations are not to be expected from use of a single overall time-temperature parameter in the manner often attempted, and they also discredit the use, except in special circumstances, of the

Larson-Miller, Dorn and Manson Haferd parameters. The present formula (1) offers a method free from these objections that may be worthy of trial.

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REFERENCES

No.	Author(s)	Title, etc.
1	A. Graham K. F. A. Walles	Relationships between long and short-time creep and tensile properties of a commercial alloy. J. Iron and Steel Inst. Vol. 179, p.105, February, 1955.
2	K. F. A. Walles A. Graham	The relationship between the creep and tensile properties at elevated temperatures of Nimonic 80 - II. N.G.T.E. Report No. R.137, June, 1953.
3	A. Graham K. F. A. Walles	Regularities in creep and hot-fatigue data - Part I. C.P. 379. December, 1956.
4	K. F. A. Walles	Methods for reduction of high temperature data in terms of a theory of deformation. N.G.T.E. Memorandum No. M.242, December, 1956.
5	K. F. A. Walles	Addendum to M.242: Convenient graphical methods for reduction of data with predetermined slopes. November, 1956.
6	Anon	Digest of steels for high temperature service 5th Edition 1946. The Timken Roller Bearing Company.
7a	Anon	The Nimonic alloys. Henry Wiggin and Co. Ltd.
7b	Anon	Supplement to the Nimonic series of alloys. The Mond Nickel Co. Ltd.
7c	Anon	Wiggin nickel alloys No. 35. Henry Wiggin and Co. Ltd., 1955.
8	Anon	Fox steels for high temperature service-data on creep and heat resisting steels. Samuel Fox and Co. Ltd.
9	H. J. J. Redwood	Creep and fatigue tests for Admiralty gas turbine development projects. F in C/BWS/3, May, 1954.
10		Private communication - creep data obtained at N.P.L. upon an early heat (OKW) of Nimonic 80.
11	L. W. Larke Mrs. R. A. Whittaker	Some creep properties of Nimonic 95 at 850°C and Nimonic 80A (special process) at 750°C and 815°C. R.A.E. Technical Note No. Met.217, March, 1955.

REFERENCES (cont'd)

No.	Author(s)	Title, etc.
12	E. D. Ward	Discussion on creep. J. Iron and Steel Inst. Vol. 182, p.187, February, 1956.
13	Anon	Inconel X. International Nickel Company.
14	R. W. Ridley	The creep properties of cast G.34 over the temperature range 850 to 1000°C for periods up to 1000 hours. N.P.L. H.T. 40/53, April, 1953.
15	N. J. Grant A. G. Bucklin	On the extrapolation of short-time stress rupture data. Trans. A.S.M. Vol. 42 p.720, 1950.
16	G. V. Smith E. J. Dulis E. G. Houston	Creep and rupture of several chromium nickel austenitic steels. Trans. A.S.M. Vol. 42 p.935, 1950.
17	F. R. Larson J. Miller	A time-temperature relationsip for rupture and creep stresses. A.S.M.E. Trans. Vol. 74 No. 5 p.65, 1952.
18	S. S. Manson A. M. Haferd	A linear time-temperature relation for extrapolation of creep and creep-rupture data. N.A.C.A. Technical Note No. 2890, March, 1953.
19	R. L. Orr O. D. Sherby J. E. Dorn	Correlation of rupture data for metals at elevated temperatures. Trans. A.S.M. Vol. 46 p.113, 1954.
20	N. H. G. Daniels L. W. Larke	The creep properties of Rex.448 Ferritic turbine disc steel at 500°C, 550°C, 600°C and 650°C. R.A.E. Tech. Note No. Met.169, April, 1953.

TABLE I

Chemical composition, heat treatments, and sources, of more extensive data

Material	Condition	C	Cr	Ni	Co	Mo	Cb	Ti	Fe	Al	Si	Mn	Other	Ref
		Composition per cent												
Nimonic 80 - I														10
Nimonic 80 - II	8 hr 1080°C A.C. 16 hr 700°C	[illegible]	20.4	Bal.				2.48	0.39	0.57	0.48	0.32		9
Nimonic 80A - I	8 hr 1080°C A.C. 16 hr 700°C		[illegible]	Bal.				2.31	0.27	1.33				9
Nimonic 80A - II	"Special Process"	0.03	19.7	Bal.	1.0			2.4	0.30	1.18	0.60	0.06	Cu 0.05	11
Nimonic 80A - III	8 hr 1080°C A.C. 16 hr 700°C													12
Nimonic 90 - I	8 hr 1080°C A.C. 16 hr 700°C													12
Nimonic 90 - II	8 hr 1150°C A.C. 16 hr 700°C	0.04	20.38	Bal.	20.07			2.48	0.42	0.96	0.57	0.39		9
Nimonic 90 - III	8 hr 1080°C A.C. 16 hr 700°C A.C.	0.07	19.4	Bal.	19.1			2.56	0.38	1.54	0.48	0.13	Cu 0.1	9
Nimonic 95 - I	1½ hr 1200°C 8 hr 1080°C 16 hr 700°C	0.08	19.8	Bal.	17.8			2.98	0.31	1.74	0.36	0.08	Cu 0.06	11
Nimonic 95 - II	4 hr 1150°C A.C. 6-8 hr 1080°C A.C. 16 hr 700°C	0.15 max	18-21	Bal.	15-21			2.3-3.5	5.0 max	1.4-2.[illegible]	1.0 max	1.0 max	Cu 0.5 max	7b
Nimonic 100	1½ hr 1200°C A.C. 16 hr 850°C	0.3 max	10-12	Bal.	18-22	4.5-5.5		1.0-2.0	2.0 max	4.0-6.0	0.5 max			7c
G.32	10 min 1250°C, O.Q. 46 hr 750°C	0.30	19.5	11.3	47.9	2.28	1 28		13.2		0.38	0.78	V 2.55	9
Inconel X	Annealed 1150°C A.C. 24 hr 840°C 20 hr 700°C	0.04	15.0	73.0			1.0	2.5	7.0	0.7	0.40	0.50		13
G.34	As cast	0.39	13.2	12.4	46.6	2.2	1.33				0.56	0.71	V 2.92	14
35-15	W.Q. from 1090°C	0.04	16.0	35.76					Bal.		1.00	0.59		6
H.46	(not known)	0.2	1.0			0.5	0.15		Bal.		0.3	0.4	V 0.7	9

TABLE II

Figure numbers, and values of T', for data of Table I

Material	Fig. No. R	Fig. No. $\dot{\varepsilon}$	Fig. No. F	Slope $\frac{1}{16}$ R(i)	R(iii)	$\dot{\varepsilon}$(ii)	F	Slope $\frac{1}{8}$ R(i)	R(iii)	$\dot{\varepsilon}$(ii)	F	Slope $\frac{1}{4}$ R(i)	R(iii)	$\dot{\varepsilon}$(ii)	F	Slope $\frac{1}{2}$ R(i)	R(iii)	$\dot{\varepsilon}$(ii)	F
Nimonic 80 - I	11							1080											
Nimonic 80 - II	12		88				1300*	1080				1200			(1300)				
Nimonic 80A - I	13		92					1080				1220							
Nimonic 80A - II	14							[1080]				1220*							
Nimonic 80A - III	15							1080				1240							
Nimonic 90 - I	16			(1080)				1080				1240							
Nimonic 90 - II	17		89				1150	1150				1250			(1150)				
Nimonic 90 - III	18							1080				1275				1400			
Nimonic 95 - I	19											[1330]							
Nimonic 95 - II	20							1150				1350							
Nimonic 100	21											1370							
G.32	22		90					1250			1350*	1350							
Inconel X	23			950				1050				500							
G.34	24							1275											
33-15	25											75							
H.46	26			(400)				400*				(400)							

Notes to Table II

R, $\dot{\varepsilon}$, and F refer to creep rupture, creep rate, and fatigue respectively; numbers (i), (ii) and (iii) refer to the corresponding methods of reduction of data.

[ ] Indicates T' adopted from similar material.
( ) Indicates T' adopted from adjacent slope
* Indicates sense of T' (Para. 2.4) not determined by data.
† Indicates markedly irregular Δ log t (or Δ log rate) graph.

TABLE I (cont'd)

Chemical compositions heat treatments, and sources of more extensive data

Material	Condition	Composition per cent C	Cr	Ni	Co	Mo	Cb (Nb)	Ti	Fe	Al	Si	Mn	Other	Ref
18-8 + Cb	A.C. from 925°C	0.08	18.25	12.93			0.88				0.58	1.72		6
Red Fox 36	A.C. from 1050°C	0.10 max	17-20	11-13			0.75-1.2				0.8 max	2.0 max		8
FCB (T) - I	1 hr 850°C A.C.	0.15	20.06	12.36			1.52		Bal.		0.80	1.17		9
FCB (T) - II	1 hr 1050°C A.C.	0.15	20.06	12.36			1.52		Bal.		0.80	1.17		9
DM 2	Annealed 840°C	0.10	0.97			0.55			Bal.		0.25	0.36		6
25-20	W.Q. from 1180°C	0.11	23.60	20.65					Bal.		0.75	0.58		6
G.19	As cast	0.34	19.9	13.0	10.1	1.57	2.97		Bal.		0.84	0.67	W 2.87	9
25-12	W.Q. from 1200°C	0.06	24.96	13.40					Bal.		0.42	1.55		6
16-13-3	W.Q. from 1090°C	0.08	16.42	13.44		2.81			Bal.		0.45	1.40		6
Rex 337A	Soln treat 1230°C aged 700°C	0.19	13.75	18.25	6.83	3.84		0.81	Bal.		0.63	0.61	Cu 3.35	9
		0.23	14.66	17.85	6.82	3.75		0.82	Bal.		0.91	0.74	Cu 3.55	9
Rex 448	O.Q. 1150°C tempered 650°C	0.22	10.50	1.29		0.69	0.62		Bal.		0.39	0.87	V 0.19	9
Red Fox 31	W.Q. 1100°C	0.10-0.25	24.0-27.0	14.0-17.0							1.25-2.0	1.0 max		8
2¼ Cr Mo	Annealed 840°C	0.15	2.24			0.90					0.33	0.39		6
CML - I	Normalized 940°C	0.12 max	0.75-1.25			0.40-0.70					0.60 max	0.30-0.70		8
CML - II	Annealed 940°C													8
CRM.2 I	Tube annealed 930°C	0.15 max	2.0-2.5			0.90-1.10					0.50 max	0.30-0.60		8
CRM.2 II	Normalised 900°C tempered 730°C													8
CRM.2 III	Annealed 930°C													8

TABLE II (cont'd)

Figure numbers, and values of T', for data of Table I

Material	Fig. No. R	Fig. No. $\dot{\varepsilon}$	Fig. No. F	Slope $\frac{1}{16}$ R(i)	Slope $\frac{1}{16}$ R(iii)	Slope $\frac{1}{16}$ $\dot{\varepsilon}$(ii)	Slope $\frac{1}{16}$ F	Slope $\frac{1}{8}$ R(i)	Slope $\frac{1}{8}$ R(iii)	Slope $\frac{1}{8}$ $\dot{\varepsilon}$(ii)	Slope $\frac{1}{8}$ F	Slope $\frac{1}{4}$ R(i)	Slope $\frac{1}{4}$ R(iii)	Slope $\frac{1}{4}$ $\dot{\varepsilon}$(ii)	Slope $\frac{1}{4}$ F	Slope $\frac{1}{2}$ R(i)	Slope $\frac{1}{2}$ R(iii)	Slope $\frac{1}{2}$ $\dot{\varepsilon}$(ii)	Slope $\frac{1}{2}$ F
18 - 8 + Cb	27	81		(310)				310		470		(310)						90	
Red Fox 36	28			(250)				250				200*							
FCB(T) - I	29											170*							
FCB(T) - II	30		93									110*							
DM.2	31	67								390		290		870					
25-20	32	(86)						240				110		1200				1800	
G.19	33							1050											
25-12	34	75				330*		300				300						50	
16-13-13	35	(85)						350*				300		1400				1750	
Rex 337A	36		91				1300*	1080*			1100*								
Rex 448	37											975‡ or 1200							
Red Fox 31	38											30				-250			
GIL - I	39							(925)				925*							
2¼ Cr + 1 Mo	40	72						945		850		1050*		-20*				-20	
CML - II	41											870							
CRM.2 - I	42							330				1300							
CRM.2 - II	43			320				210				1000							
CRM.2 - III	44							360				960							

Notes to Table II

R, $\dot{\varepsilon}$, and F refer to creep rupture, creep rate, and fatigue respectively; numbers(i), (ii) and (iii) refer to the corresponding methods of reduction of data.

[ ] Indicates T' adopted from similar material
( ) Indicates T' adopted from adjacent slope
* Indicates sense of T' (Para. 2.4) not determined by data
‡ Indicates markedly irregular Δ log t (or Δ log rate) graph.

TABLE I (cont'd)

Chemical compositions, heat treatments, and sources, of more extensive data

Material	Condition	C	Cr	Ni	Co	Mo	Cb (Nb)	Ti	Fe	Al	Si	Mn	Other	Ref
		Composition per cent												
Killed carbon	Annealed 840°C	0.15							Bal.		0.28	0.46		6
Silmo	Annealed 840°C	0.11				0.50			Bal.		1.35	0.30		6
C-Mo	Annealed 840°C	0.13				0.52			Bal.		0.25	0.49		6
2% Cr Mo	Annealed 840°C	0.11	2.08			0.50			Bal.		0.42	0.45		6
Sicromo 2	Annealed 840°C	0.09	2.06			0.51			Bal.		1.32	0.41		6
Sicromo 3	Annealed 840°C	0.12	3.25			0.50			Bal.		1.40	0.43		6
4-6% Cr Mo	Annealed 840°C	0.10	5.09			0.55					0.18	0.45		6
4-6% Cr Mo + Ti	Annealed 870°C	0.10	4.98			0.50		0.51	Bal.		0.38	0.44		6
Sicromo 5S	Annealed 840°C	0.10	4.83			0.51			Bal.		1.55	0.38		6
Sicromo 5MS	Annealed 840°C	0.10	5.16			0.91			Bal.		1.37	0.37		6
Sicromo 7	Normalized 950°C., drawn 815°C	0.11	7.33			0.59			Bal.		0.92	0.43		6
Sicromo 9M	Normalized 950°C., drawn 815°C	0.12	9.50			0.95			Bal.		0.67	0.44		6
18-8	W.Q., 1090°C	0.06	17.75	9.25					Bal.		0.61	0.50		6
S.816	Soln treat 1290°C: aged 16-24 hr at 760 for tests at 650 to 760; aged at 815°C for tests at 815°C	0.40	20.58	19.60	43.86	3.98	3.85	2.54				1.01	W 3.70	15
		0.32	19.80	20.34	44.00	4.30	3.23	2.53				1.16	W 3.92	

TABLE II (cont'd)

Figure numbers, and values of T', for data of Table I

Material	Fig. No. R $\dot{\varepsilon}$ F	Slope 1/16 R(i)	Slope 1/16 R(iii)	Slope 1/16 $\dot{\varepsilon}$(ii)	Slope 1/16 F	Slope 1/8 R(i)	Slope 1/8 R(iii)	Slope 1/8 $\dot{\varepsilon}$(ii)	Slope 1/8 F	Slope 1/4 R(i)	Slope 1/4 R(iii)	Slope 1/4 $\dot{\varepsilon}$(ii)	Slope 1/4 F	Slope 1/2 R(i)	Slope 1/2 R(iii)	Slope 1/2 $\dot{\varepsilon}$(ii)	Slope 1/2 F
Killed Carbon	45 65					(220)		140*		220		320				100	
Silmo	46 68	760*								225*		950				1120*	
C-Mo	47 66						380	90*			240	200			(240)		
2% Cr Mo	48 69						350	310			240					150*	
Sicromo 2	49 70		280				280	260			200					-100	
Sicromo 3	50 73						360?	260			200					-250	
4-6% Cr Mo	51 74						300	100			300	200			(300)		
4-6% Cr Mo + Ti	52 76						420?	440*			190					90*	
Sicromo 5S	54 77						960?	865			190	[illegible]					
Sicromo 5MS	53 78						410	420			410*					-200	
Sicromo 7	55 79						350	300			310					-200	
Sicromo 9M	56 80						370				350	300				-200	
18-8	57(87)						330	-200			200	-200				-250	
S.816	58 82		340	410			340	390									

Notes to Table II

R, $\dot{\varepsilon}$, and F refer to creep rupture, creep rate and fatigue respectively; numbers (i) (ii) and (iii) refer to the corresponding methods of reduction of data.

[ ] Indicates T' adopted from similar material

( ) Indicates T' adopted from adjacent slope

* Indicates sense of T' (Para. 2.4) not determined by data

† Indicates markedly irregular Δ log t (or Δ log rate) graph

TABLE I (cont'd)

Chemical compositions, heat treatments, and sources of more extensive data

Material	Condition	Composition per cent												Ref
		C	Cr	Ni	Co	Mo	Cb (Nb)	Ti	Fe	Al	Si	Mn	Other	
S.590	Soln treat 1245°C 1 hr W.Q. For tests at 649-760°C aged 16-24 hr at 760°C. For tests at 815°C, aged at 815°C. For tests at 870°C-1038°C aged at 732°C.	0.39	20.84	19.62	19.24	3.79	4.17		Bal.			1.37	W 3.95	15
DM	Annealed 840°C	0.07	1.24			0.54			Bal.		0.72	0.42		6
Sicromo	Annealed 840°C	0.11	2.50			0.50			Bal.		0.78	0.41		6

TABLE II (cont'd)

Figure numbers, and values of T', for data of Table I

Material	Fig. No. R	Fig. No. $\dot{\varepsilon}$	Fig. No. F	Slope $\frac{1}{16}$ R(i)	Slope $\frac{1}{16}$ R(iii)	Slope $\frac{1}{16}$ $\dot{\varepsilon}$(ii)	Slope $\frac{1}{16}$ F	Slope $\frac{1}{8}$ R(i)	Slope $\frac{1}{8}$ R(iii)	Slope $\frac{1}{8}$ $\dot{\varepsilon}$(ii)	Slope $\frac{1}{8}$ F	Slope $\frac{1}{4}$ R(i)	Slope $\frac{1}{4}$ R(iii)	Slope $\frac{1}{4}$ $\dot{\varepsilon}$(ii)	Slope $\frac{1}{4}$ F	Slope $\frac{1}{2}$ R(i)	Slope $\frac{1}{2}$ R(iii)	Slope $\frac{1}{2}$ $\dot{\varepsilon}$(ii)	Slope $\frac{1}{2}$ F
S.590	52	83			420	410			350	330			1340	1330*					
DM	(61)	(84)								1800				1020				1250	
Sicroma 2½		71								(110)				110				(110)	

Notes to Table II

R, $\dot{\varepsilon}$, and F refer to creep rupture, creep rate and fatigue respectively, numbers (i), (ii) and (iii) refer to the corresponding methods of reduction of data.

[ ] Indicates T' adopted from similar material
( ) Indicates T' adopted from adjacent slope
* Indicates sense of T' (Para. 2.4) not determined by data
‡ Indicates markedly irregular Δ log t (or Δ log rate) graph

TABLE IA

Chemical compositions, heat treatments and sources of less extensive data

Material	Condition	C	Cr	Ni	Co	Mo	Cb, Nb	Ti	Fe	Aℓ	Si	Mn	Other	Ref.
		COMPOSITION PER CENT												
Rex 337A	Not given. Materials tested in tube form.	Not given												9
G 18B														9
FCB(T)														9
Nimonic 75														9
Esshete D4C	Normalized 940°C	0.12 max				0.45-0.65					0.35 max	0.40-0.70		8
G 18B	Soln treated 1300°C A.C.	0.38	12.9	13.0	10.3	1.6	2.98	-	Bal.	-	1.14	0.81	2.66W	9
Fortiweld	Normalized 940°C	0.16 max				0.40-0.60					0.40 max	0.60 max	B 0.001-0.005	8
0.3% carbon steel	Not given	Not given												9

Material	Condition	Aℓ	Ni	Fe	Mn	Si	Sn	Zn	Cu	Ref.
Hidurax - I/12A	As rolled	10.93	4.82	4.76	0.27				Bal.	9
Hidurax - I	As rolled	9.58	4.6	4.56	0.19	0.10	0.16	0.09	Bal.	9
Hidurax - IV	Annealed 2 hr 600-650°C	10.69	5.31	5.49	0.32	0.10	0.08	0.07	Bal.	9

T A B L E IIA

Figure numbers for data of Table IA

Material		Fig. No. R	Fig. No. F
Rex 337A	in tube form	60	
G18B	in tube form	60	
FCB(T)	in tube form	60	
Nimonic 75	in tube form	60	
Esshete D4C		62	
G18B		63	
Fortiweld		64	
0.3% C Steel			94
Hidurax I/124			95
Hidurax I			96
Hidurax IV			97

TABLE III

Evidence of criteria for creep-rupture and creep-rate data

Material	Criterion	Nature of evidence	Data and method	Form of transitions	Agreement or disagreement
Nimonic 80-I	(a)	Upturning creep curves above 0.3 per cent.	R(i)	none	-
Nimonic 80-II	(a)	Upturning creep curves above 0.3 per cent.	R(i)	sharp	A
Nimonic 80A-I	(a)	Upturning creep curves above 0.3 per cent.	R(i)	sharp	A
Nimonic 80A-II	(a)	Upturning creep curves above 0.3 per cent.	R(i)	sharp	A
Nimonic 80A-III	(b)	Time to 0.2 per cent more than 30 per cent of time to rupture.	R(i)	sharp	A
Nimonic 90-I	(-)	None.	R(i)	sharp	-
Nimonic 90-II	(a)	Upturning creep curves above 0.3 per cent.	R(i)	sharp	A
Nimonic 90-III	(a)	Mostly upturning creep curves above 0.3 per cent.	R(i)	sharp	A?
Nimonic 95-I	(a)	Upturning creep curves above 0.3 per cent.	R(i)	none	-
Nimonic 95-II	(c)	Stress to rupture no more than 10 per cent greater than stress for 0.5 per cent strain.	R(i)	sharp	A
Nimonic 100	(-)	None.	R(i)	none	-
G 32	(a)	Upturning creep curves above 0.3 per cent.	R(i)	sharp	A
Inconel X	(-)	None.	R(i)	sharp	-
G 34	(a)	Upturning creep curves above 0.5 per cent.	R(i)	none	-
35 - 15	(-)	None.	R(i)	none	-
H 46	(a)	Upturning creep curves above 2 per cent.	R(i)	sharp	A?

No evidence	-	Disagreement	D
Ambiguous	?	Favourable	A?
Agreement	A	Unfavourable	D?

T A B L E III (con't)

Material	Criterion	Nature of evidence	Data and method	Form of transitions	Agreement or disagreement
18 - 8 + Cb	(d)	Extrapolated creep rate 3×10^{-5}, acting for rupture time 3,400 hr gives 10 per cent out of total 44 per cent strain. Condition (ii) satisfied, (i) doubtful.	R(i) ε(ii)	sharp gradual	D? A
Red Fox 36	(c)	Stress to rupture is on average 10 per cent greater than stress to 1 per cent strain.	R(i)	sharp	A
FCB(T)-I	(a)	Upturning creep curves above 0.2 per cent.	R(i)	none	-
FCB(T)-II	(a)	Upturning creep curves above 0.2 per cent.	R(i)	none	-
DM 2	(d)	Extrapolated creep rate 6×10^{-5} for 1500 hr gives 9 per cent out of 33 per cent total strain. Condition (ii) satisfied, condition (i) probably not.	R(i) ε(ii)	sharp gradual	D? A
25 - 20	(d)	Creep rate 2.2×10^{-6} gives 0.4 per cent out of 3 per cent total strain. Condition (i) satisfied, condition (ii) not.	R(i) ε	sharp gradual	A A? (T' above m.p.)
G 19	(a)	Upturning creep curve above 2 per cent strain.	R(i)	none	-
25 - 12	(d)	Extrapolated creep rate 1×10^{-5} for 1400 hr gives strain of 1.4 per cent out of 12 per cent total strain. Condition (i) satisfied, condition (ii) doubtful.	R(i) ε	sharp (little data)	A ?
16 - 13 - 3	(d)	Creep rate 1.6×10^{-5} for 2800 hr gives strain of 0.45 out of 18.5 per cent total. Condition (i) satisfied, condition (ii) not.	R(i) ε	sharp? gradual	A? A? (T' above m.p.)
Rex 337A	(a)	Upturning creep curves above 1 per cent strain.	R(i)	sharp	A
Rex 448	(a)	Upturning creep curves above 1 per cent strain.	R(i)	none	-

No evidence	-	Disagreement	D
Ambiguous	?	Favourable	A?
Agreement	A	Unfavourable	D?

TABLE III (cont'd)

Material	Criterion	Nature of evidence	Data and method	Form of transitions	Agreement or disagreement
Red Fox 31	(c)	Stress for rupture 20 per cent greater than stress for 1 per cent strain: evidence doubtful.	R(i)	sharp	?
Esshete CML-I	(-)	None.	R(i)	sharp	-
2¼ Cr - 1 Mo	(d)	Extrapolated creep rate 4×10^{-5} in 1500 hr gives strain 6 per cent out of 45 per cent total. Condition (ii) satisfied, condition (i) probably satisfied.	R(i) $\dot{\varepsilon}$(ii)	sharp gradual	A? A
Esshete CML-II	(c)	Stress to rupture 20 per cent greater than stress for 1 per cent strain. Condition (i) doubtful.	R(i)	none	-
Esshete CRM2-I	(-)	None.	R(i)	sharp?	-
Esshete CRM2-II	(c)	Stress for rupture 20 per cent greater than stress for 1 per cent strain. Condition (i) doubtful.	R(i)	sharp	?
Esshete CRM2-III	(c)	Stress to rupture 50 to 10 per cent greater than stress for 1 per cent strain. Condition (i) doubtful.	R(i)	sharp	?
Killed carbon	(d)	Creep rate 1.2×10^{-6} for 14,000 hr gives 1.7 per cent strain out of 10 per cent total; 3.5×10^{-5} for 1,350 hr gives 4.7 per cent out of 27 per cent total. Condition (ii) satisfied, condition (i) doubtful.	R(i) $\dot{\varepsilon}$(ii)	sharp gradual	? A
Silmo	(d)	Creep rate 8×10^{-6} for 3,700 hr gives 3 per cent strain out of 5 per cent total. Condition (ii) satisfied, condition (i) not.	R(i) $\dot{\varepsilon}$(ii)	sharp gradual	D A

No evidence	-	Disagreement	D
Ambiguous	?	Favourable	A?
Agreement	A	Unfavourable	D?

TABLE III (cont'd)

Material	Criterion	Nature of evidence	Data and method	Form of transitions	Agreement or disagreement
C-Mo	(d)	Creep rate 6×10^{-6} for 4000 hr gives 2.4 per cent out of 5 per cent total strain; 3×10^{-6} for 3,900 hr gives 1.2 per cent out of 15 per cent total strain; 1.3×10^{-5} for 3,200 hr gives 4.2 per cent out of 13.5 per cent total strain. Condition (ii) satisfied. Strains to rupture 6, 5, 15, 13.5, 8, 17 per cent. Condition (iii) partly satisfied.	R(iii) $\dot{\varepsilon}$(ii)	gradual gradual	A? A
2% Cr-Mo	(d)	Extrapolated creep rate 4×10^{-5} for 4,600 hr gives 10.4 per cent out of 54 per cent total strain. Condition (ii) satisfied. Rupture strain 60, 42, 54, 60 per cent. Condition (iii) satisfied.	R(iii) $\dot{\varepsilon}$(ii)	gradual gradual	A A
Sicromo 2	(d)	Extrapolated creep rate 8×10^{-5} for 900 hr gives 7.2 per cent out of 63 per cent strain. Condition (iii) doubtful (but poor evidence). Rupture strains 42, 51, 62, 63 per cent.	R(iii) $\dot{\varepsilon}$(ii)	gradual gradual	? A
Sicromo 2½	(-)	None.	$\dot{\varepsilon}$(ii)	gradual	-
Sicromo 3	(d)	Extrapolated creep rate 2×10^{-5} for 3,600 hr gives 7.2 per cent out of 50 per cent total strain. Condition (ii) satisfied, condition (iii) doubtful. Rupture strains 52.5, 59.5, 50.7, 27.5.	R(iii) $\dot{\varepsilon}$(ii)	gradual gradual	? A?
4 to 6% Cr-Mo	(d)	Extrapolated creep rate 1.8×10^{-6} for 5,400 hr gives 1 per cent strain out of 22 per cent total; 3×10^{-5} for 2,700 hr gives 8 per cent out of 33.5 per cent total. Condition (ii) probably satisfied, condition (iii) doubtful. Rupture strains 48, 20, 33, 22, 51 per cent.	R(iii) $\dot{\varepsilon}$(ii)	gradual? gradual	? A?

No evidence	-	Disagreement	D
Ambiguous	?	Favourable	A?
Agreement	A	Unfavourable	D?

TABLE III (cont'd)

Material	Criterion	Nature of evidence	Data and method	Form of transitions	Agreement or disagreement
4 to 6% Cr-Mo + Ti	(d)	Extrapolated creep rate 10^{-4} for 2,000 hr gives 20 per cent strain out of 56 per cent total. Condition (ii) satisfied. Rupture strains 20, 45, 56, 40 per cent. Condition (iii) satisfied.	R(iii) $\dot{\varepsilon}$(ii)	gradual gradual	A A
Sicromo 5S	(d)	Extrapolated creep rate 10^{-4} for 900 hr gives 9 per cent out of 75 per cent total strain. Condition (ii) satisfied, condition (iii) probably satisfied. Rupture strain 55, 63, 75, 44, 74 per cent.	R(iii) $\dot{\varepsilon}$(ii)	gradual gradual	A? A
Sicromo 5MS	(d)	Extrapolated creep rate 2×10^{-5} for 2,700 hr gives 5.4 per cent strain out of 50 per cent total. Condition (ii) satisfied, condition (iii) probably satisfied. Rupture strains 56, 46, 50, 85 per cent.	R(iii) $\dot{\varepsilon}$(ii)	gradual? gradual	A? A
Sicromo 7	(d)	Extrapolated creep rate 2×10^{-5} for 1,200 hr gives 2.4 per cent out of 56 per cent (but poor evidence). Condition (ii) probably satisfied, condition (iii) probably not. Rupture strains 44, 44, 56, 86 per cent.	R(iii) $\dot{\varepsilon}$(ii)	gradual gradual	D? A
Sicromo 9M	(d)	Extrapolated creep rate 7×10^{-5} for 2,500 hr gives 13.5 per cent total strain. Conditions (ii) and (iii) satisfied, except for changing rupture strain 31, 43, 52, 98 per cent.	R(iii) $\dot{\varepsilon}$(ii)	gradual gradual	A? A
18-8	(a)	Abnormal form of creep curve given for a steel of similar composition in Reference 16, Figure 2, indicates condition (ii) <u>not</u> satisfied, condition (iii) satisfied.	R(iii) $\dot{\varepsilon}$	gradual gradual	A A? (poor fit)

No evidence	-	Disagreement	D
Ambiguous	?	Favourable	A?
Agreement	A	Unfavourable	D?

TABLE III (cont'd)

Material	Sample of evidence, criterion (d): Creep rate per cent/hr	Time to rupture	Strain from K = 1	Total strain	Data and method of plotting	Form of transition	Agreement or disagreement
S816	10^4	10^{-3}	10	19.7	R(iii)	gradual	A
	0.10	20.9	2.09	8.1			
	0.002	652	1.3	5.6			
	120	0.092	11	15.[illegible]			
	1.6	5.9	9.5	7.1	δ(ii)	gradual	A
	7.6×10^{-4}	2,619	1.59	7.1			
	3,000	0.0055	16.5	18.[illegible]			
	15	0.37	5.5	3.8			
	0.01	112	1.12	4.0			
	Condition (ii) satisfied, condition (iii) generally satisfied except for changing strain at rupture						
S590	330	0.045	16.4	25.3	R(iii)	gradual	A
	1.0	[illegible]	6.3	[illegible]			
	0.001	[illegible]	4	9.6			
	5,000	0.0014	7	22.8			
	1.0	9.90	9.9	26.4	δ(ii)	gradual	A
	0.0003	[illegible]	3.2	>13.7			
	260	0.029	7.5	18.[illegible]			
	0.0014	1,112	1.56	15.8			
	2,000	0.008	15	24.[illegible]			
	0.027	100.5	2.7	42			
	170	0.086	14.6	2[illegible].3			
	0.0032	550	1.76	25.5			
	22	0.33	7.5	35.5			
	0.073	61.3	5.9	20.5			
	Condition (ii) satisfied, condition (iii) generally satisfied except for changing strain at rupture						
DM	1.2×10^{-6}	5,151	0.74	28.5	R	some abrupt some gradual	?
	2.1×10^{-6}	4,000	0.82	46.2			
	2.5×10^{-6}	1,352	0.34	20.0			
	4.8×10^{-6}	950	0.47	17.6	δ	gradual	A?
	Condition (i) satisfied, condition (ii) not satisfied						(T' above m.p.)

TABLE V

Values of T' with calculated errors

	Material	Rupture		Rate		Mean		Deviation of mean T' from overall mean
		T'_r	s_r	T'_ε	s_ε	T'	s	
Slope $\frac{1}{16}$	Sicromo 2	280	82			280	82	1.5
	S816	340	45	410	37	380	30	0.77
	S590	420	24	410	13	410	15	0.47
	Overall weighted mean T' = 403°C							
Slope $\frac{1}{5}$	C Mo	380	40	90	84	350	37	+0.38
	2% Cr Mo	350	31	310	24	330	21	-0.29
	Sicromo 2	280	30	260	25	270	21	-3.1
	Sicromo 3	360	15	260	43	340	14	+0.29
	4-6% Cr Mo	300	18	100	87	275	17	-3.6
	4-6% Cr Mo + Ti	420	50	440	42	430	39	+2.4
	Sicromo 5ME	410	30	420	108	410	28	+2.6
	Sicromo 7	350	23	300	270	350	22	+0.64
	S816	340	26	390	35	360	21	+0.67
	S590	360	13	330	13	345	10	+0.90
	Overall weighted mean T' = 336°C							
Slope $\frac{1}{4}$	C Mo	240	16	200	33	230	14	+0.43
	2% Cr Mo	240	75			240	75	+0.21
	Sicromo 2	200	87			200	87	-0.28
	Sicromo 3	200	47			200	47	-0.51
	4-6% Cr Mo	300	48	200	37	260	32	+1.12
	4-6% Cr Mo + Ti	190	36			190	36	-0.94
	Sicromo 5S	190	37	130	38	160	29	-2.2
	Sicromo 5MS	410	114			410	114	+1.6
	Sicromo 7	310	140			310	140	+0.61
	Overall weighted mean T' = 224°C							
Slope $\frac{1}{2}$	Sicromo 2			-100	113	-100	113	+0.18
	Sicromo 3			-250	170	-250	170	-0.70
	4-6% Cr Mo	300	130			300	130	+3.3
	4-6% Cr Mo +Ti			90	113	90	113	+1.3
	Sicromo 3MS			-200	112	-200	112	-0.62
	Sicromo 7			-200	112	-200	112	-0.62
	Overall weighted mean T' = -110°C							

TABLE VIa

Numbers of sets of data falling within various ranges of error in time

Extent of analysis	Category	Range in time or rate	Number of sets of data R(i)	R(iii)	$\dot{\varepsilon}$(ii)	F(i)	Total
Data fully analysed	A	-20 to +25 per cent	30(24)	3(3)	12(12)	1(1)	45(40)
in accordance with	B	-40 to +60 per cent	8(7)	7(5)	5(3)	3(3)	23(18)
Equations (1c) or (2a)	C	< -40 to > +60 per cent	1(1)	3(3)	2(2)	0	6(6)
Data only analysed	A	-20 to +25 per cent	(6)	(0)	(0)	(3)	(9)
in respect of stress	B	-40 to +60 per cent	(2)	(0)	(0)	(0)	(2)
and time or rate	C	< -40 to > +60 per cent	(0)	(0)	(0)	(3)	(3)

TABLE VIb

Stress errors corresponding to specified time errors

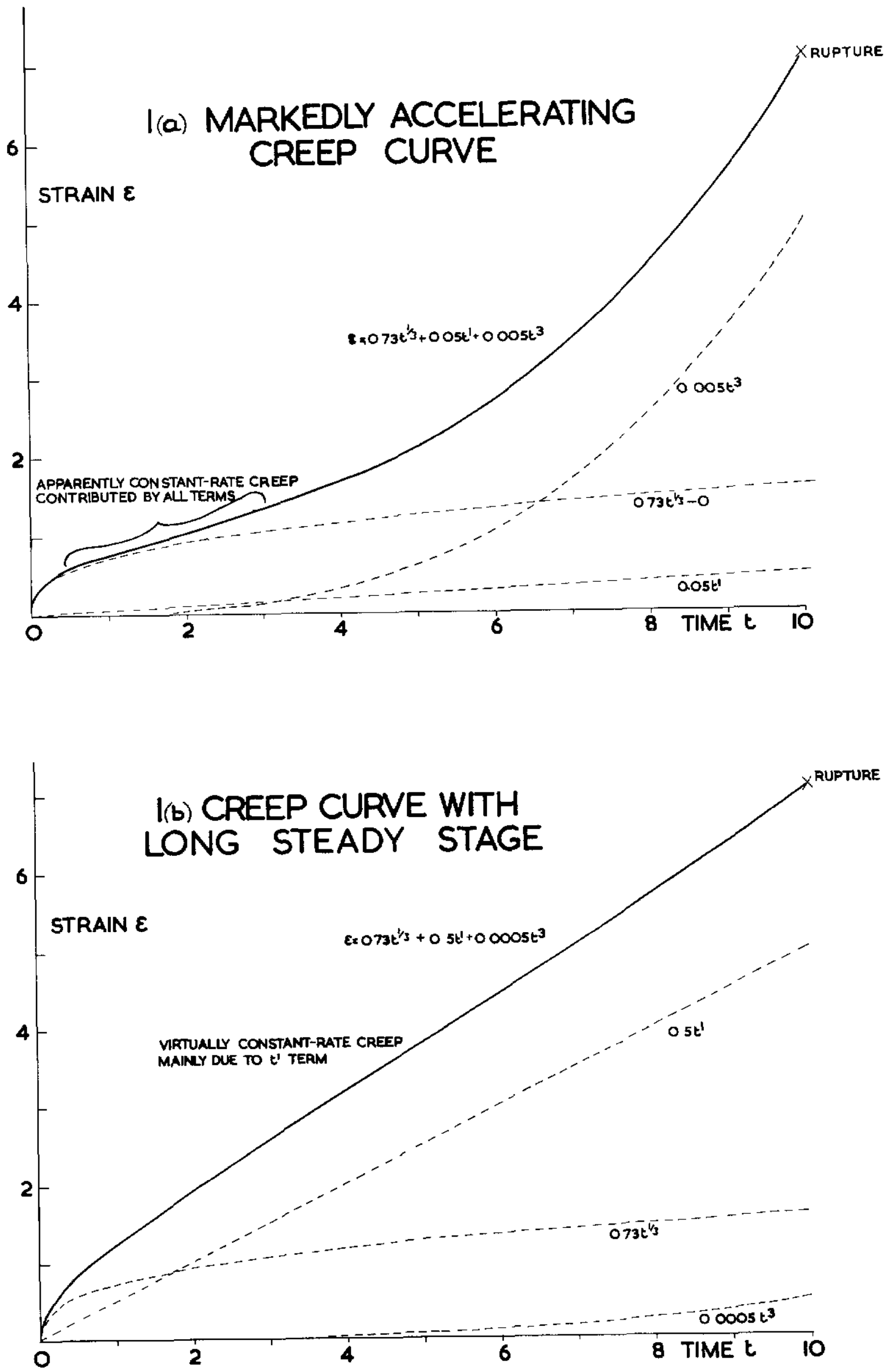
		Slope $\frac{1}{32}$	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$
Log time error	Time error	Stress error per cent				
±0.1	-20 to +26 per cent	±0.7	±1.4	±3	±6	-11 to +13
±0.2	-37 to +58 per cent	±1.4	±3	±6	-11 to +13	-20 to +25
±0.3	-50 to +100 per cent	±2	±4	-8 to +9	-16 to +19	-29 to +41

Notes: (i) Time ranges are those which include at least half the experimental points.

(ii) For headings see Table II.

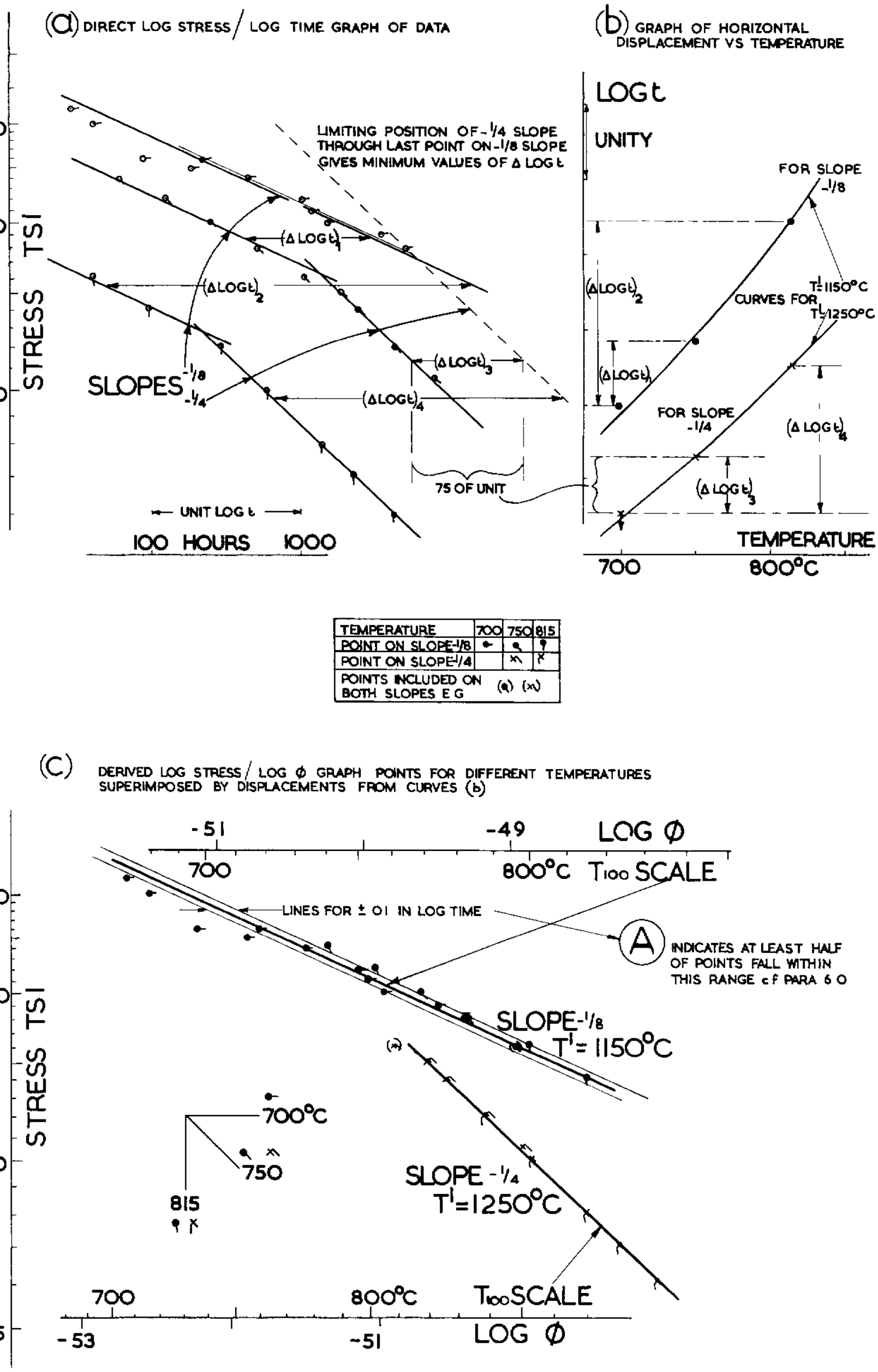
(iii) Bracketed figures refer to data from the four compilations References 6 to 9.

FIG. 1



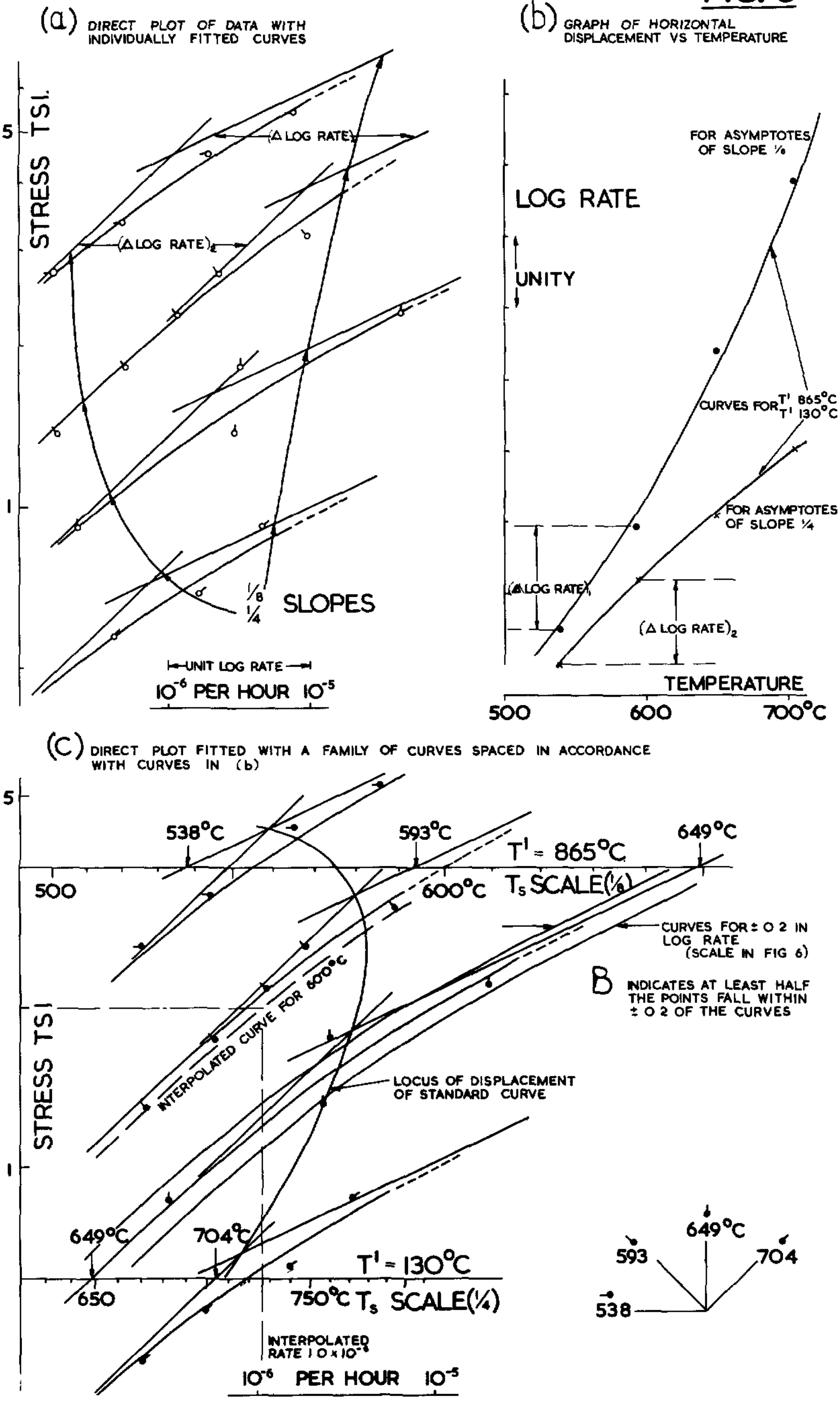
TYPES OF CREEP CURVES TO WHICH REPORT REFERS

FIG. 2



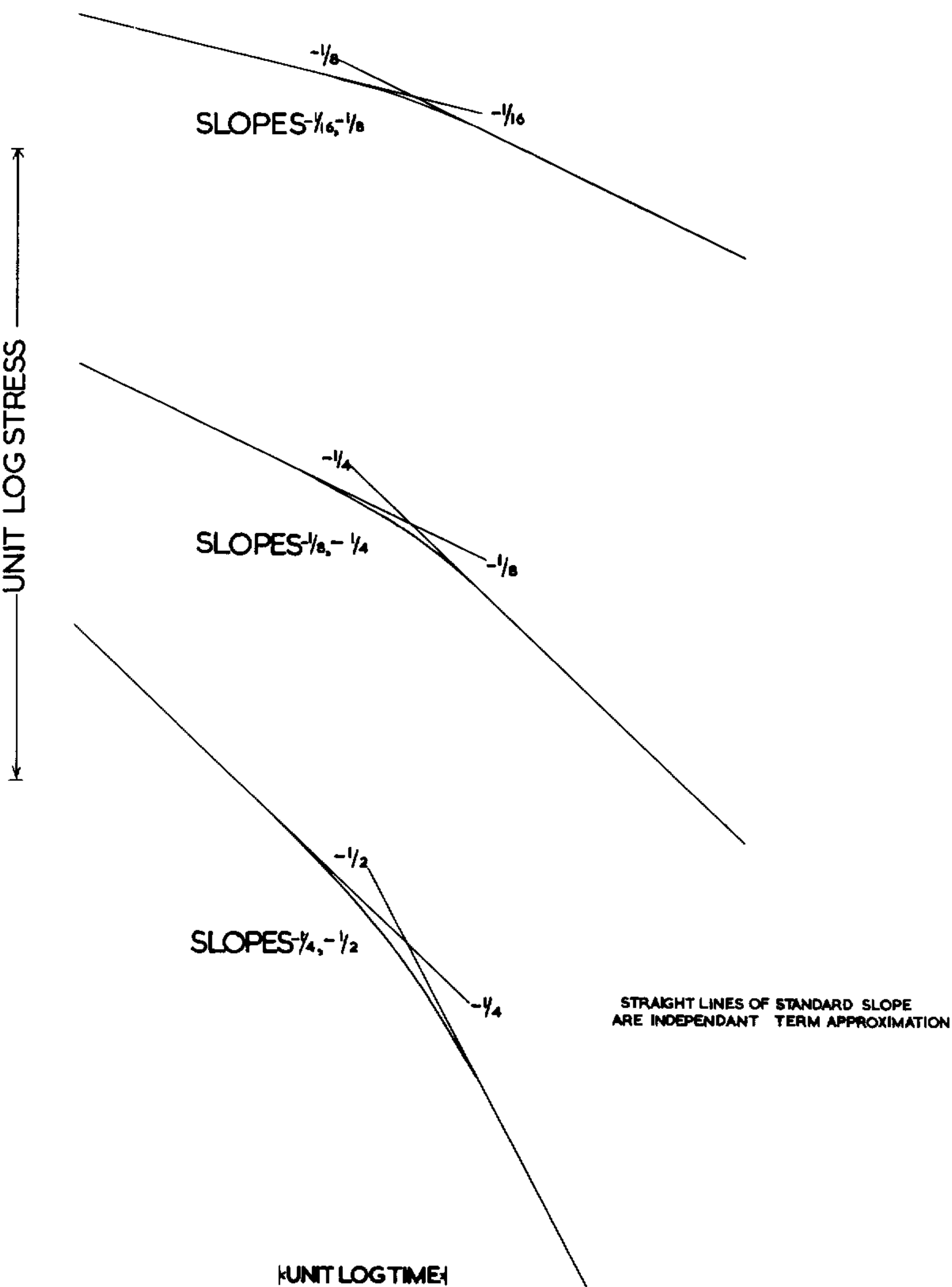
REDUCTION OF DATA BY METHOD (i)

FIG. 3



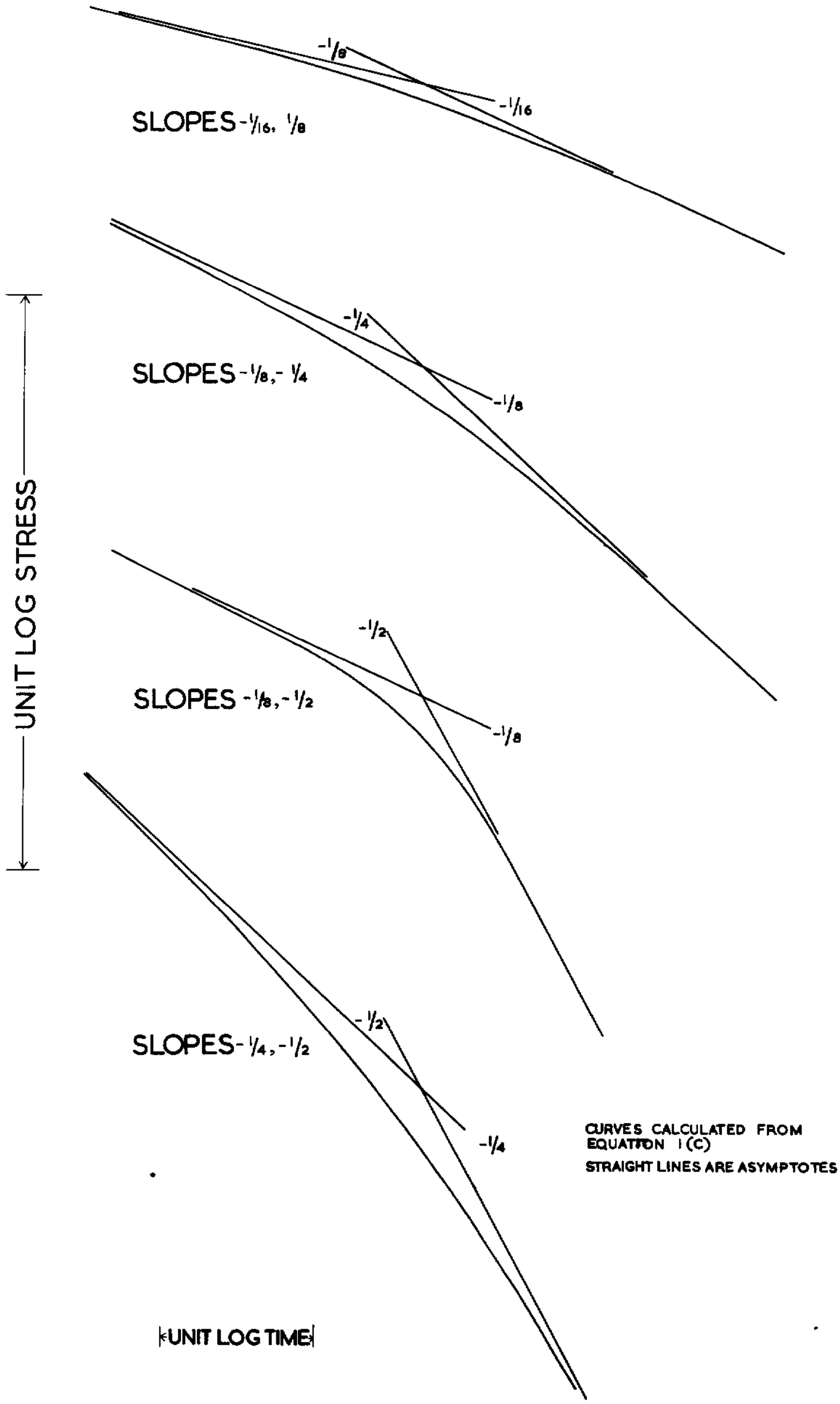
REDUCTION OF DATA BY METHOD (ii)

FIG. 4



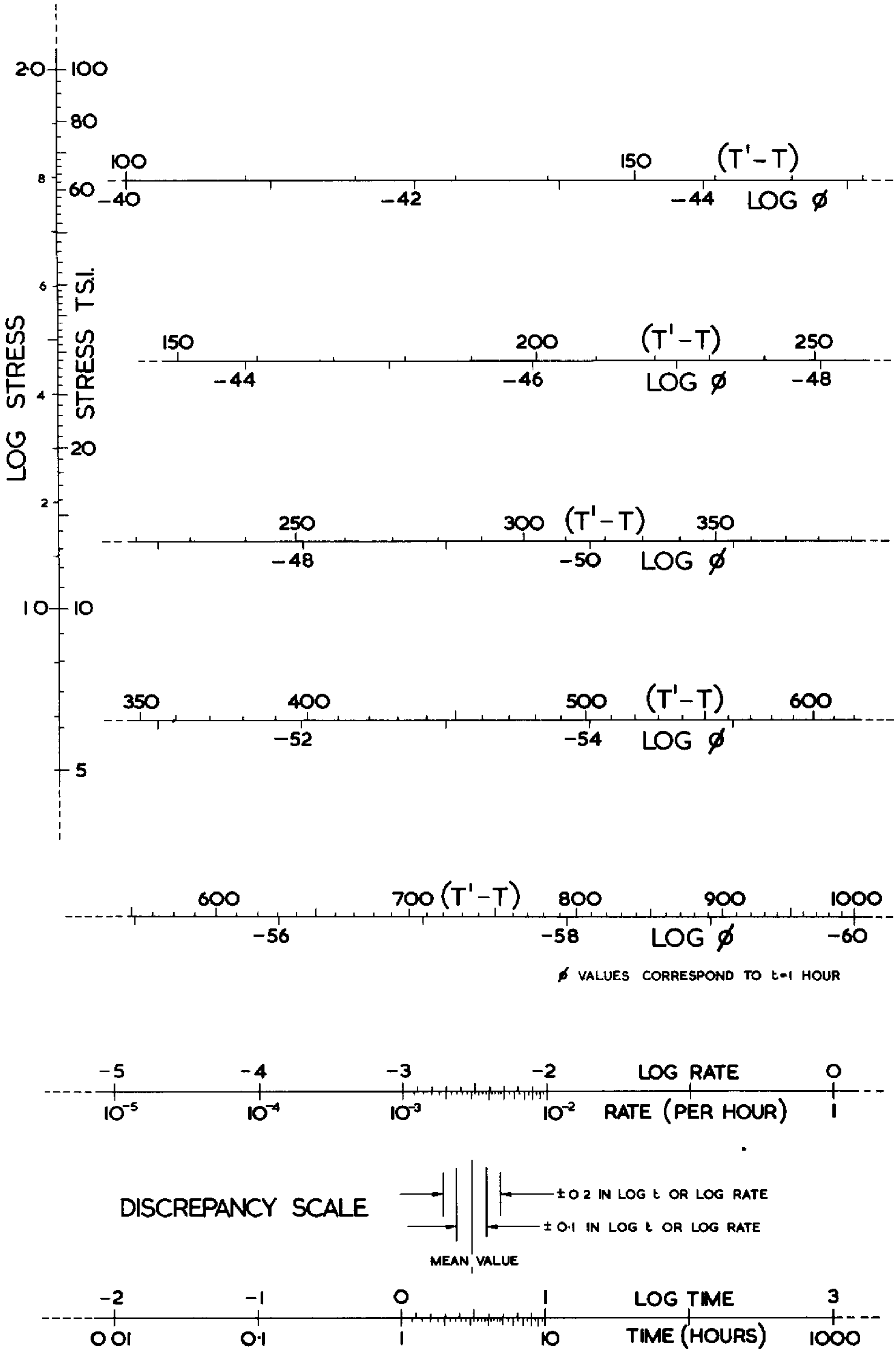
TWO TERM STANDARD CURVES OF LOG STRESS vs LOG TIME FOR K=3

FIG. 5



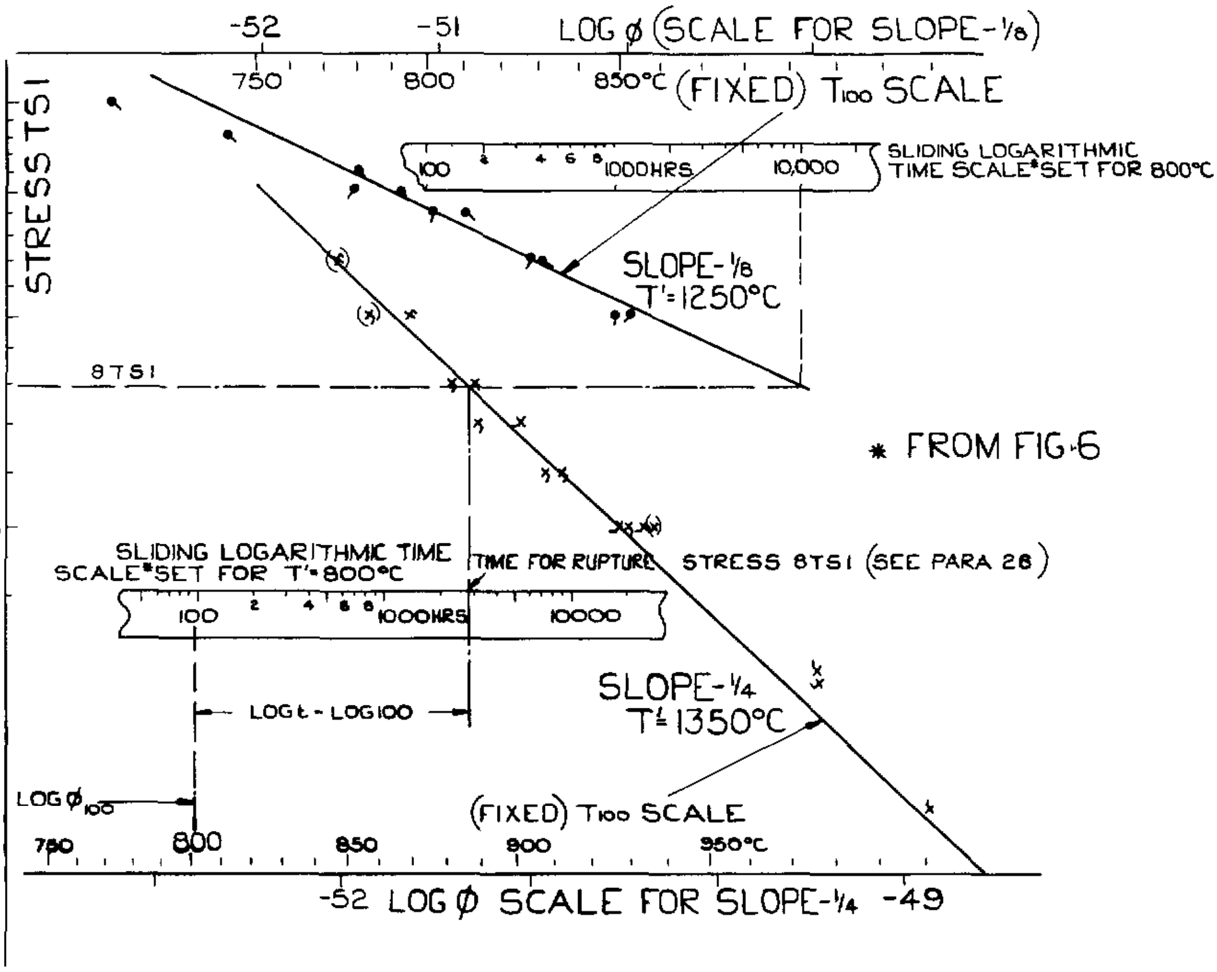
TWO-TERM STANDARD CURVES OF LOG STRESS vs LOG TIME FOR K=1

FIG. 6

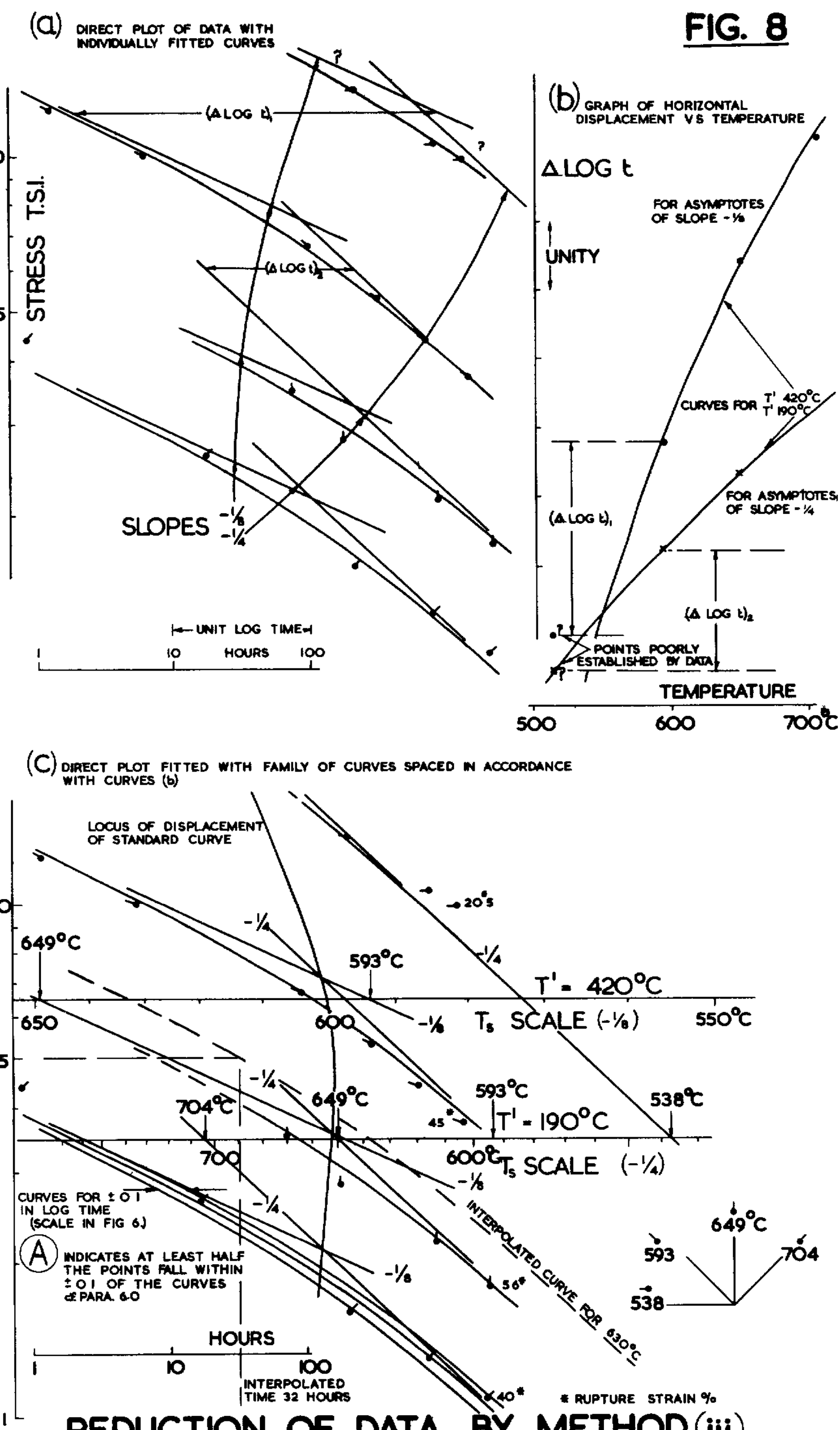


DETAILED SCALES COMMON TO ALL FIGURES

FIG. 7

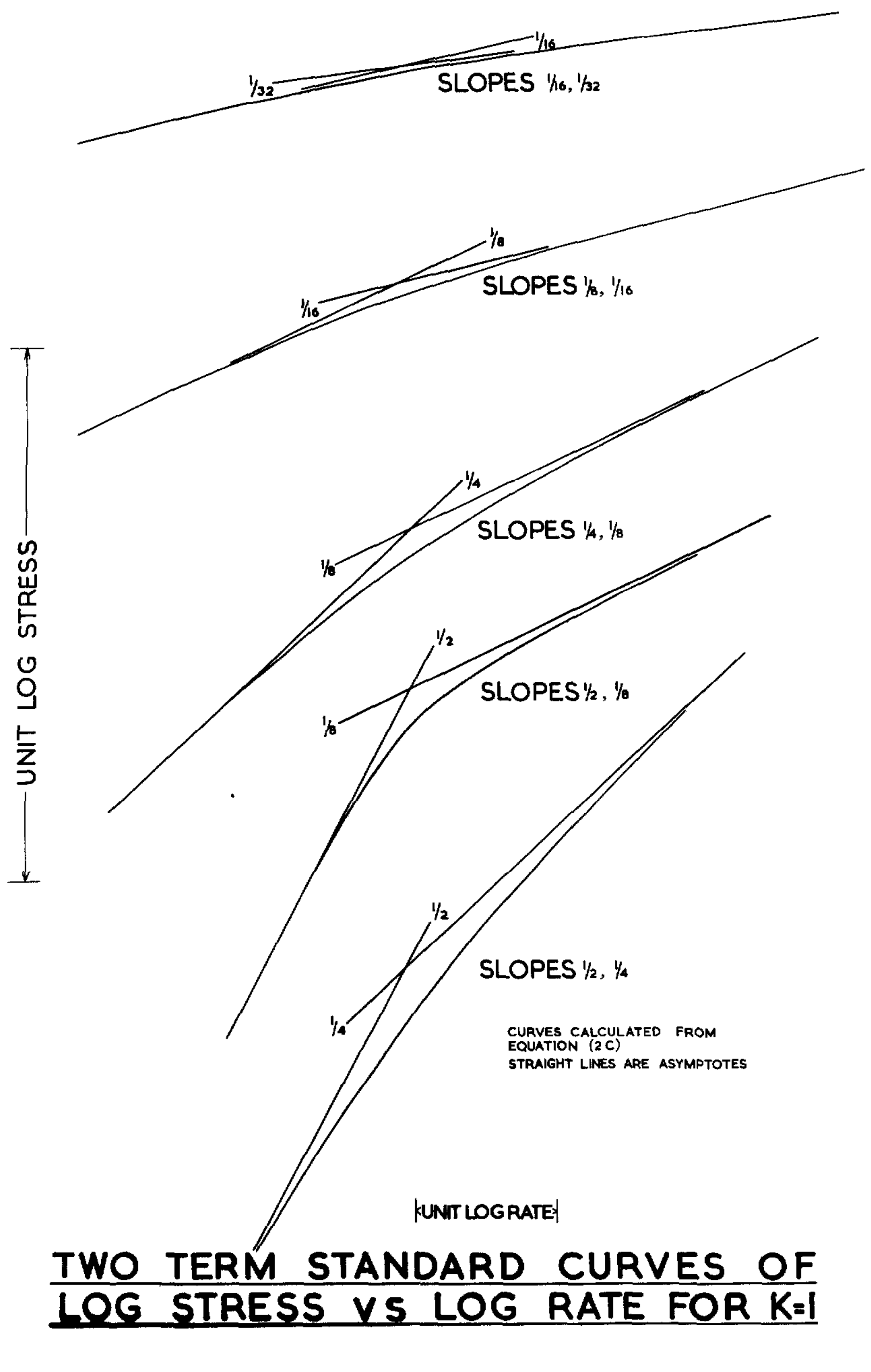


USE OF METHOD (I) RUPTURE PLOTS



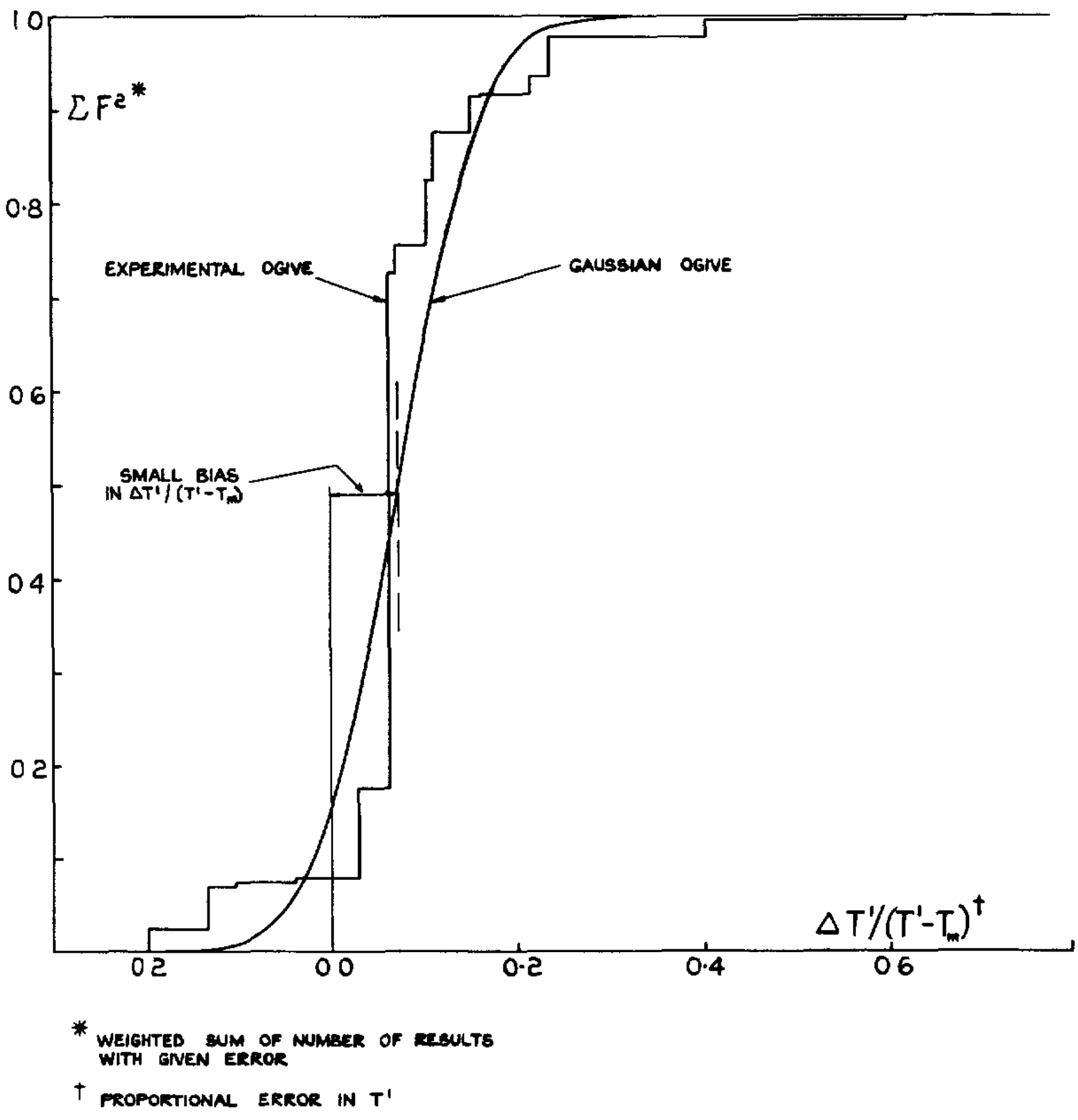
REDUCTION OF DATA BY METHOD (iii)

FIG.9

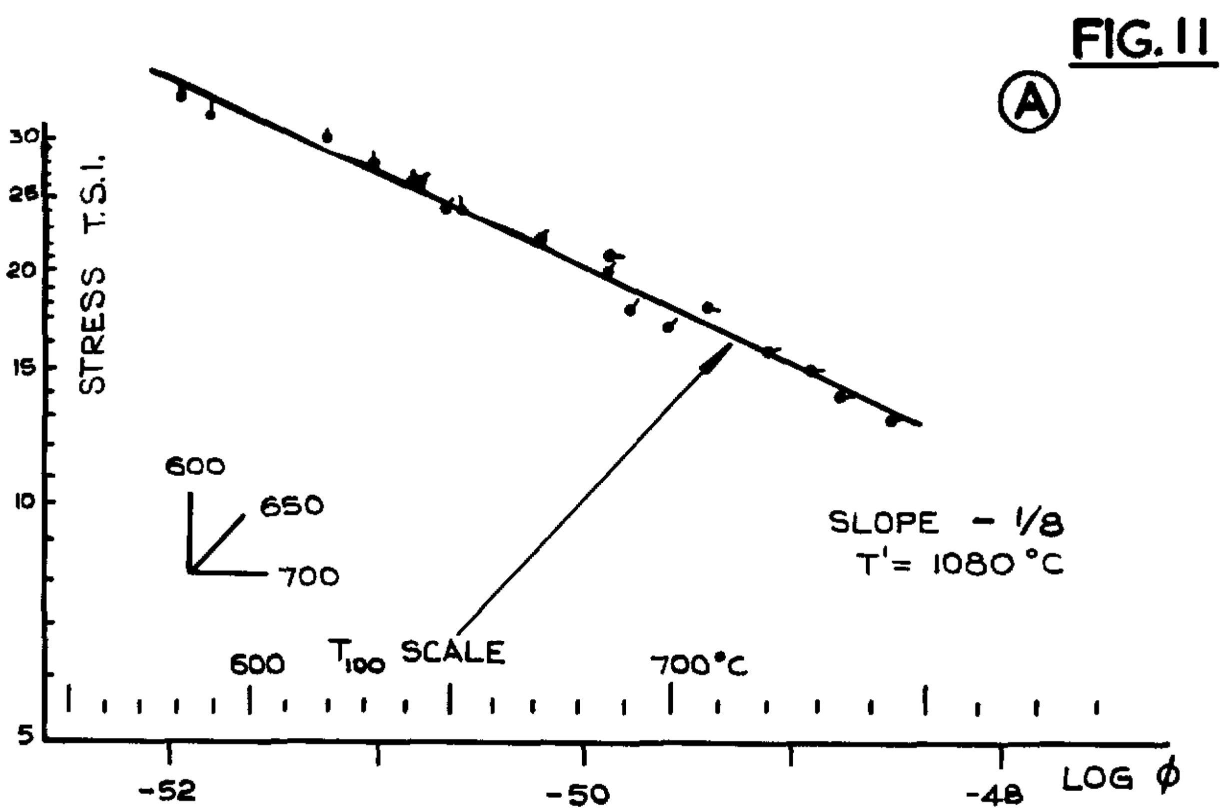


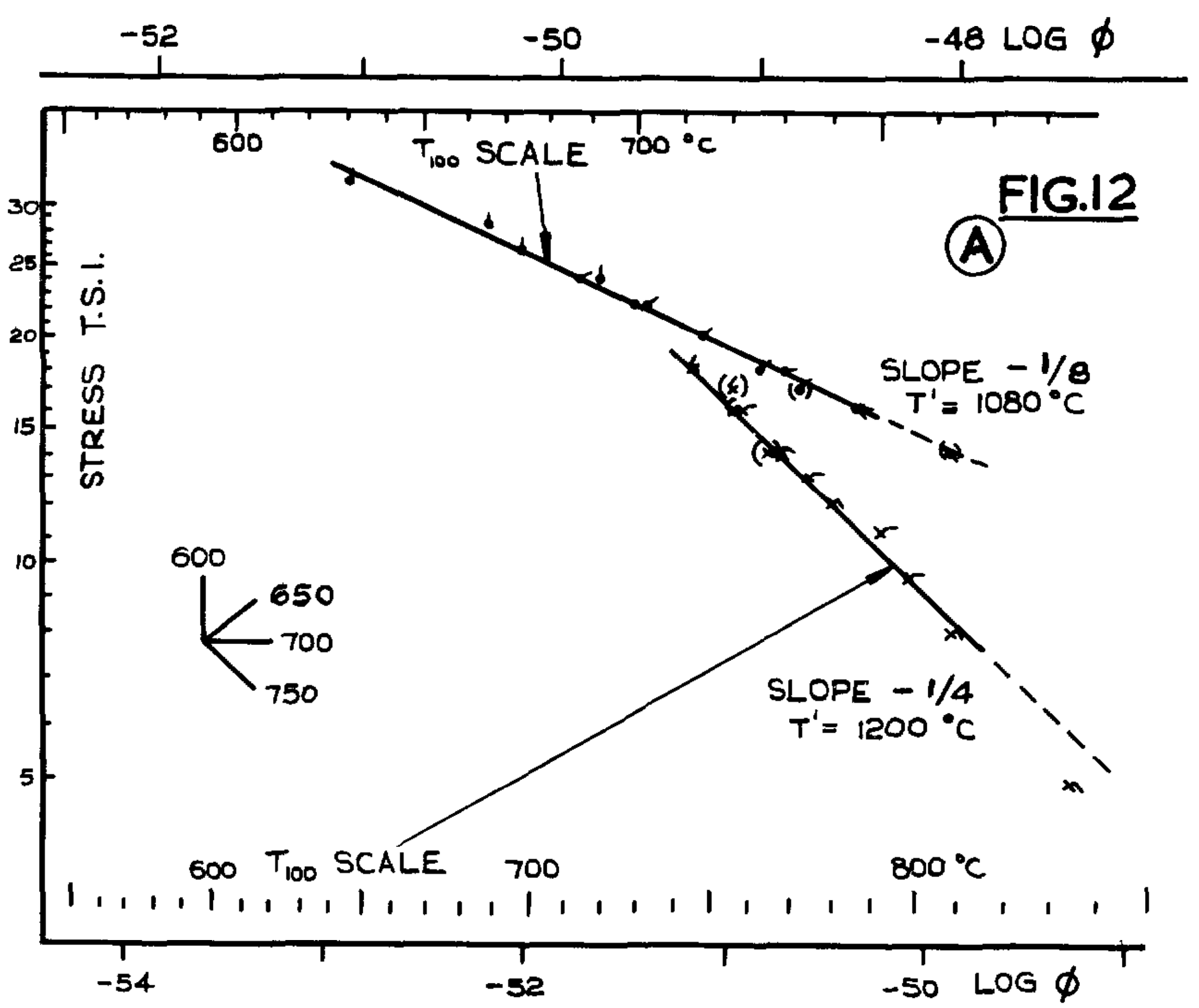
TWO TERM STANDARD CURVES OF LOG STRESS VS LOG RATE FOR K=1

FIG. 10



STATISTICAL DISTRIBUTION OF OBSERVED DIFFERENCES IN T'





CREEP RUPTURE
NIMONIC 80

FIG. 11a

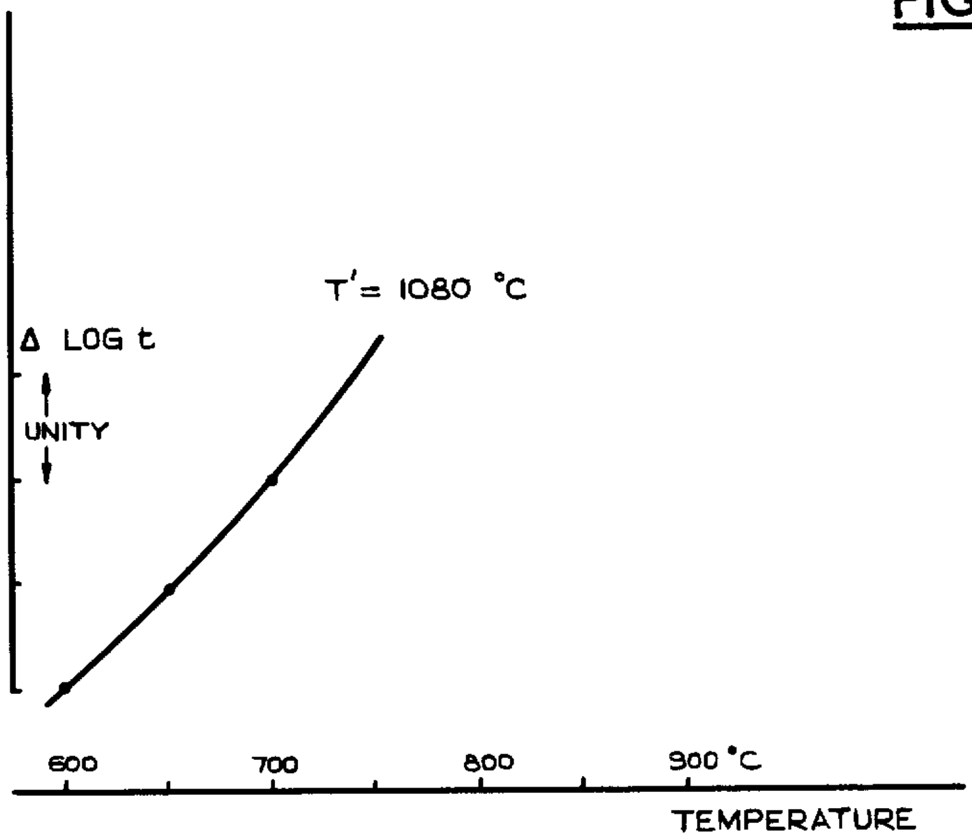
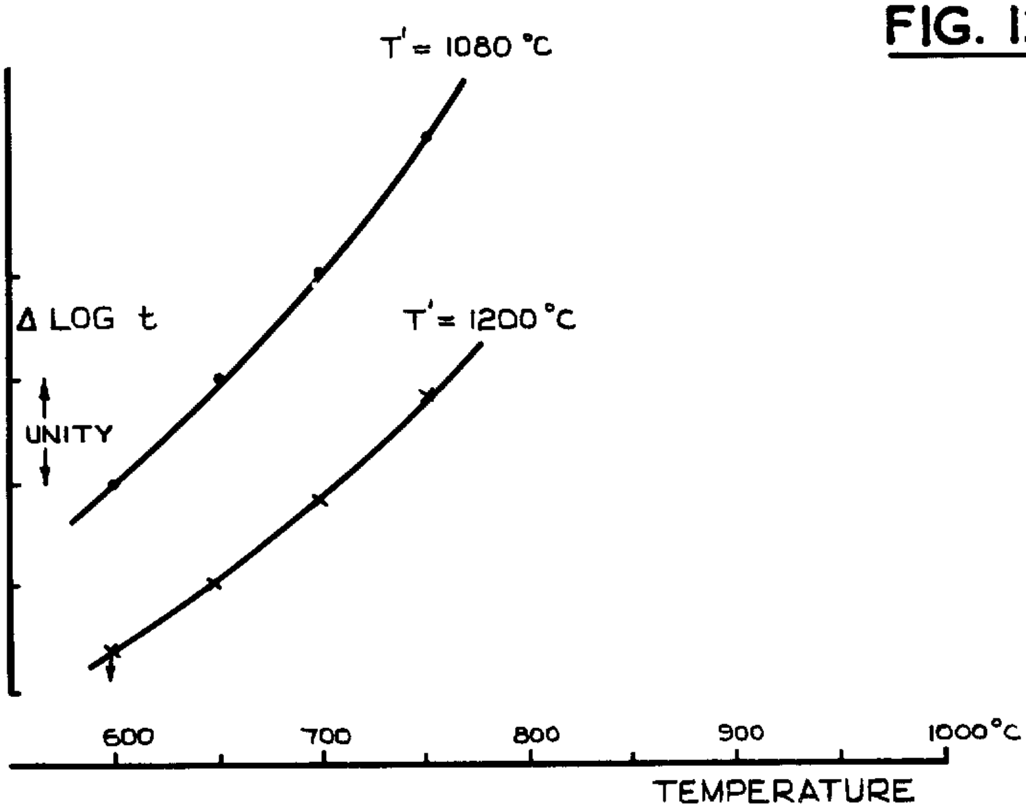


FIG. 12a



Δ LOG t/T PLOTS
NIMONIC 80

FIG. 13

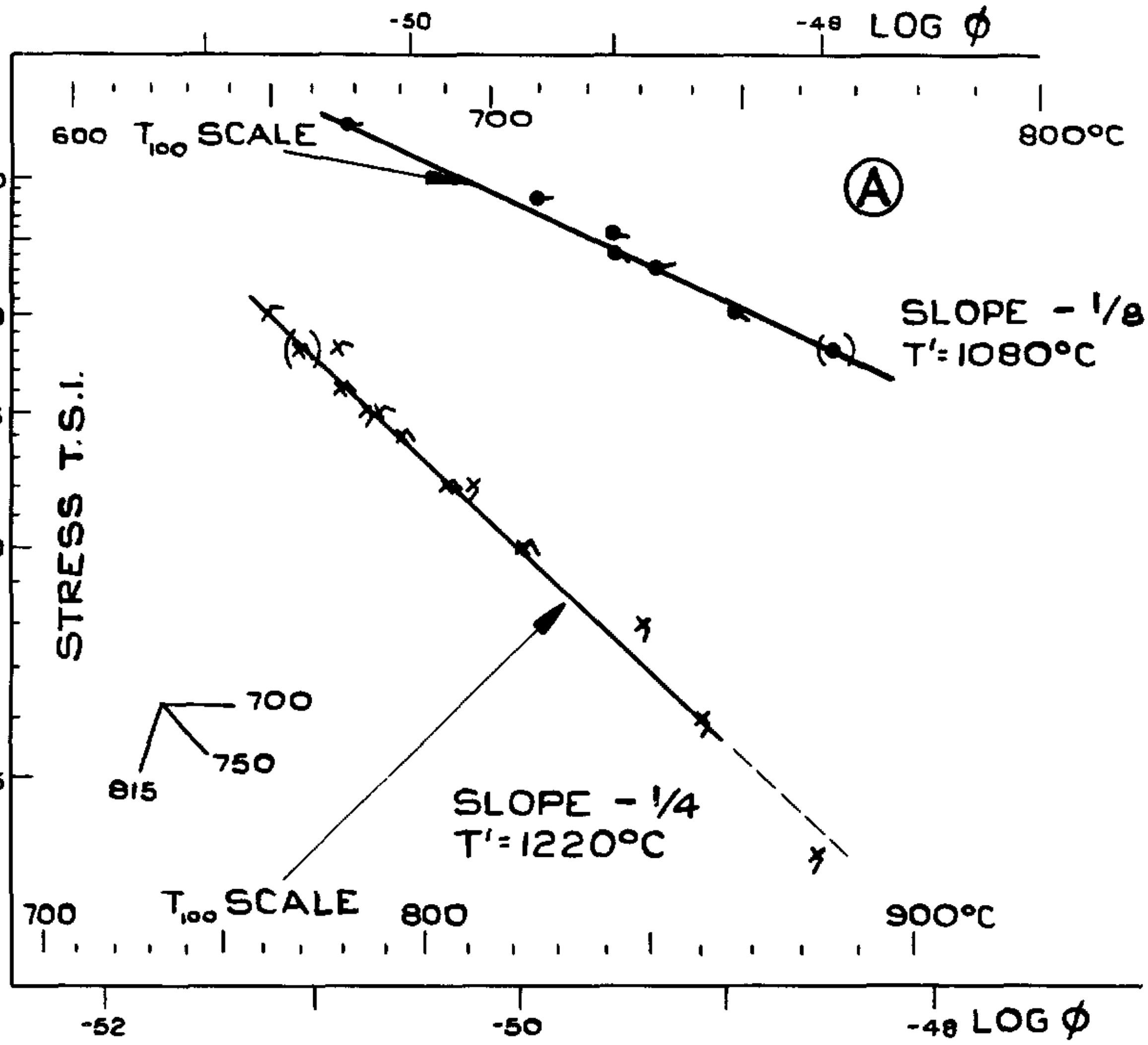
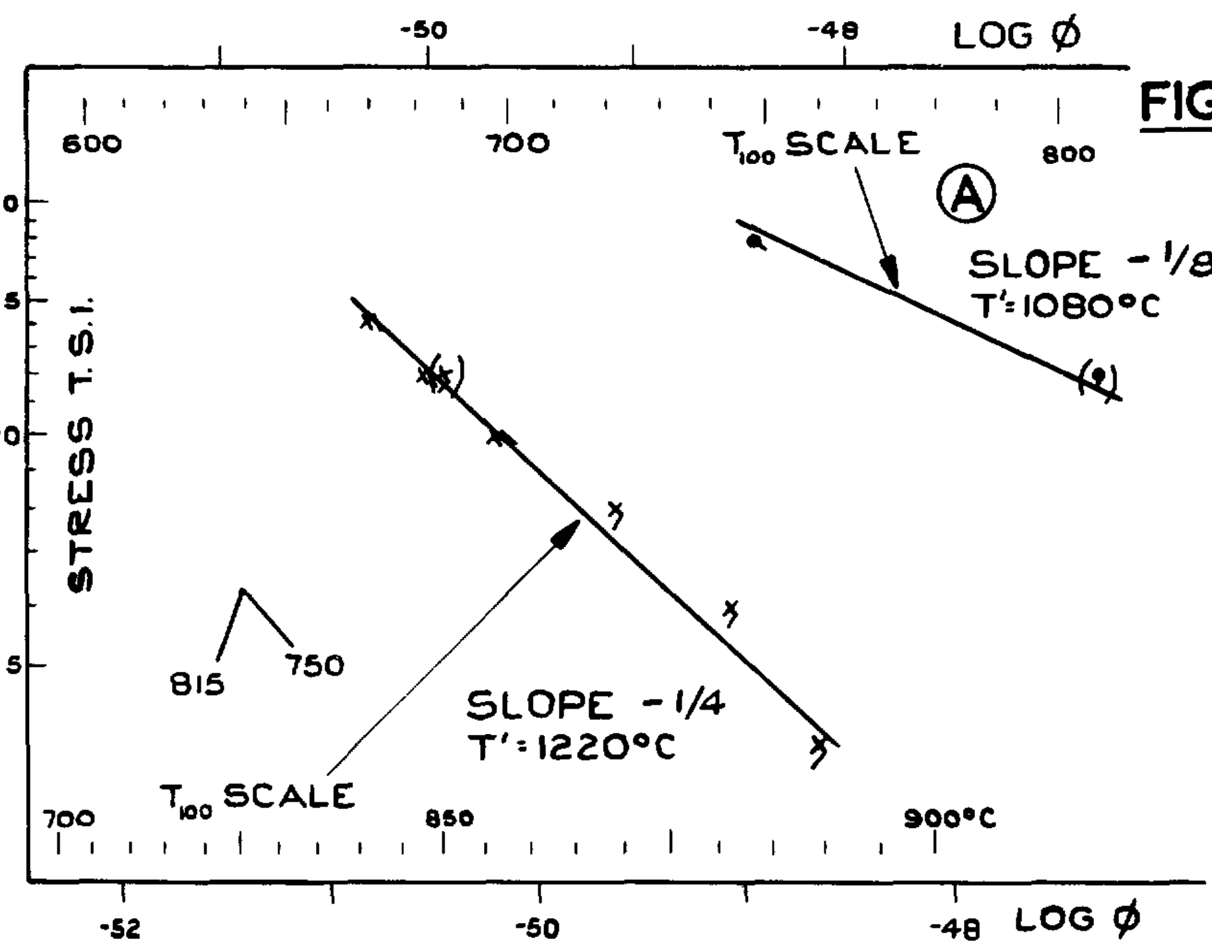


FIG. 14



CREEP RUPTURE

NIMONIC 80A

FIG. 13 a

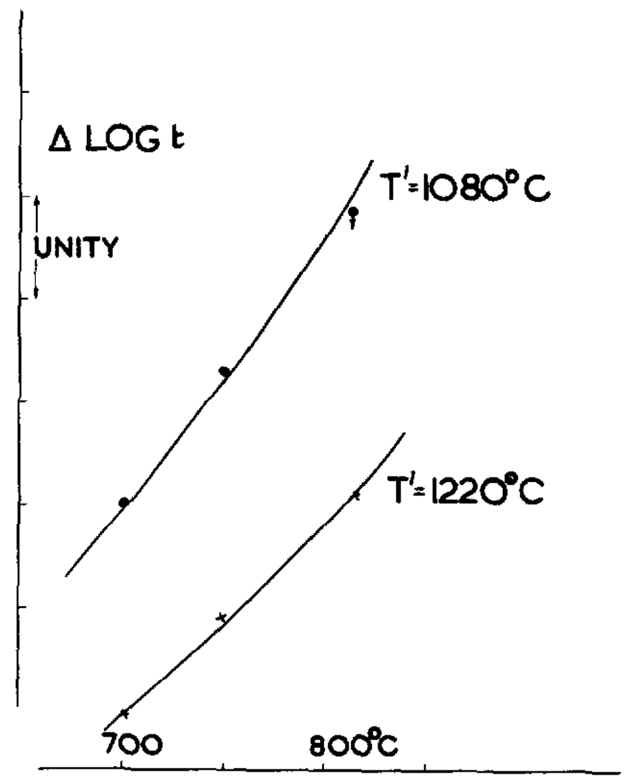
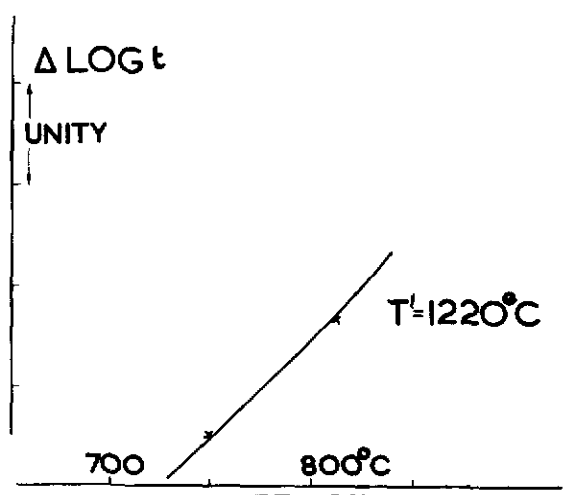


FIG. 14 a



Δ LOG t/T PLOTS NIMONIC 80A

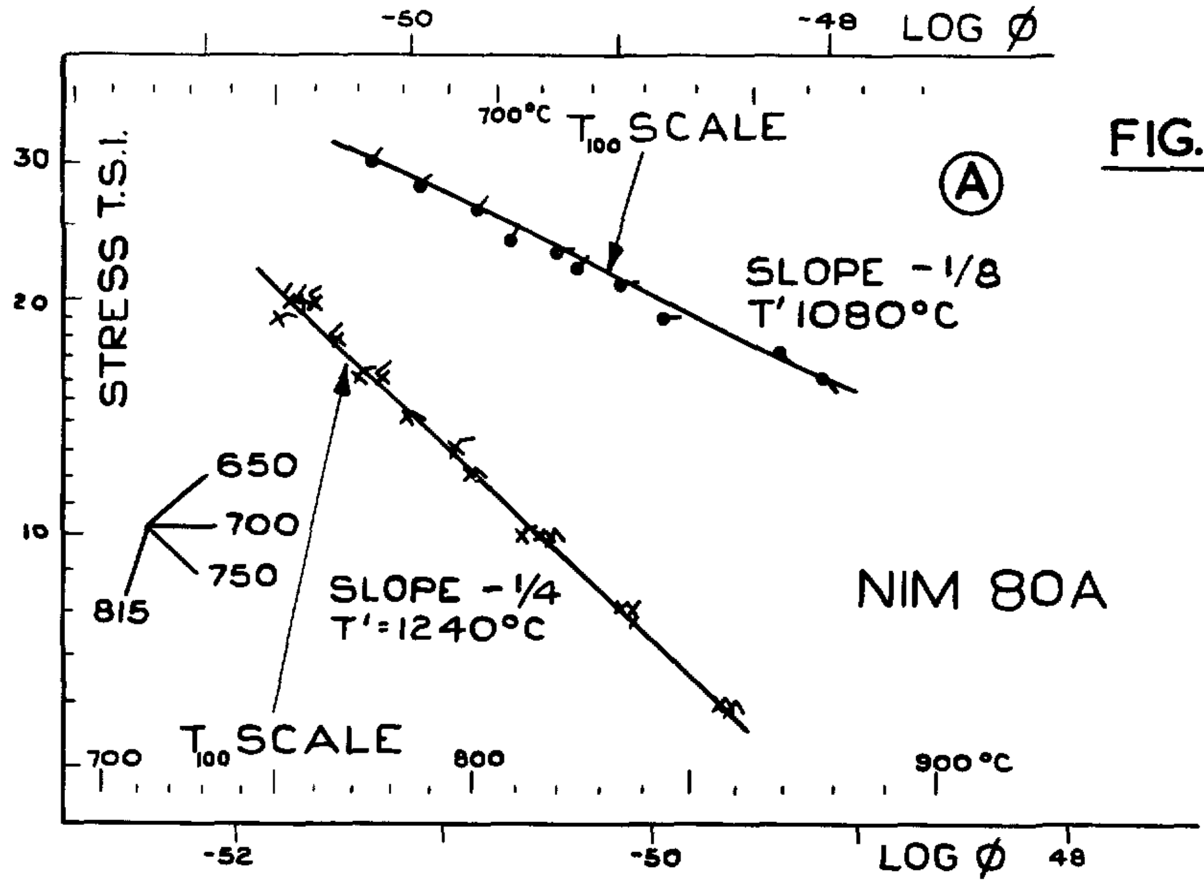
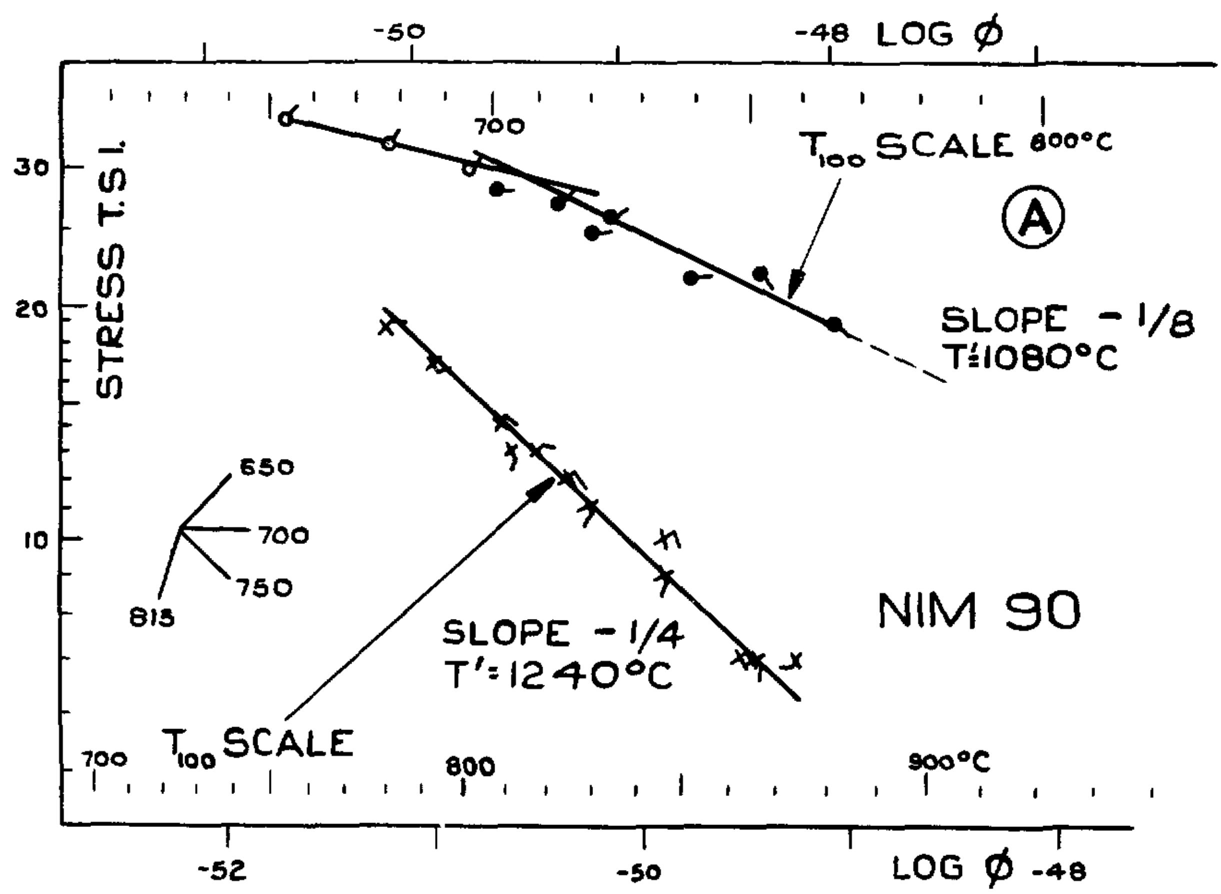


FIG. 15

FIG. 16



CREEP RUPTURE NIMONIC 80A AND NIMONIC 90

FIG. 15a

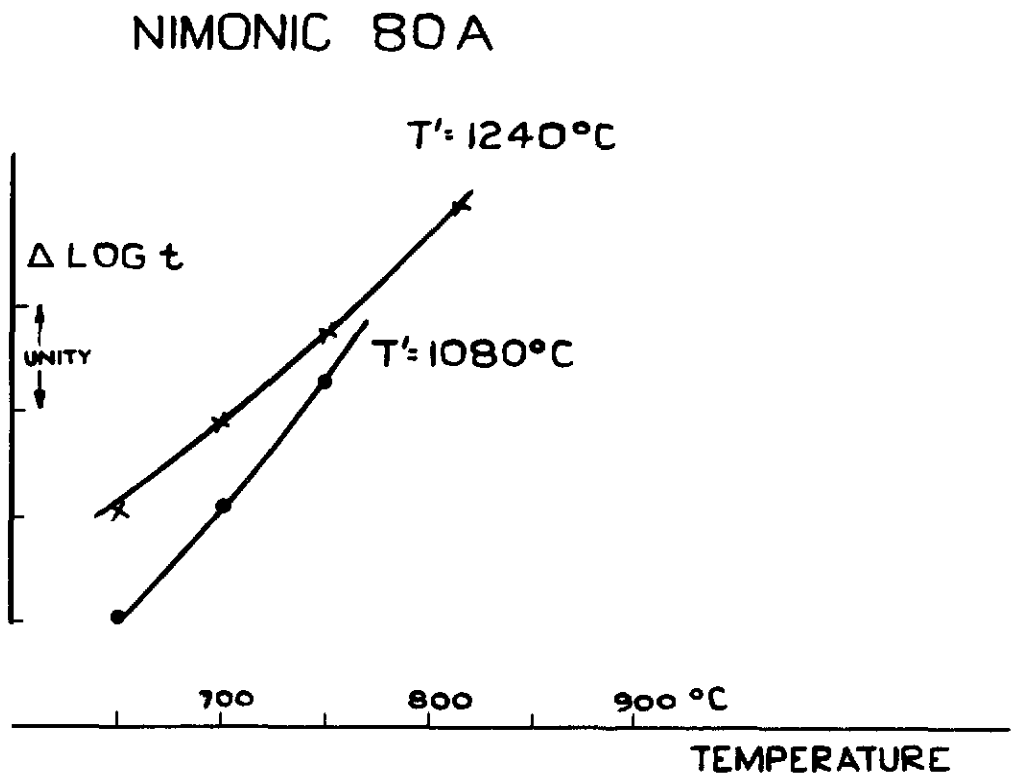
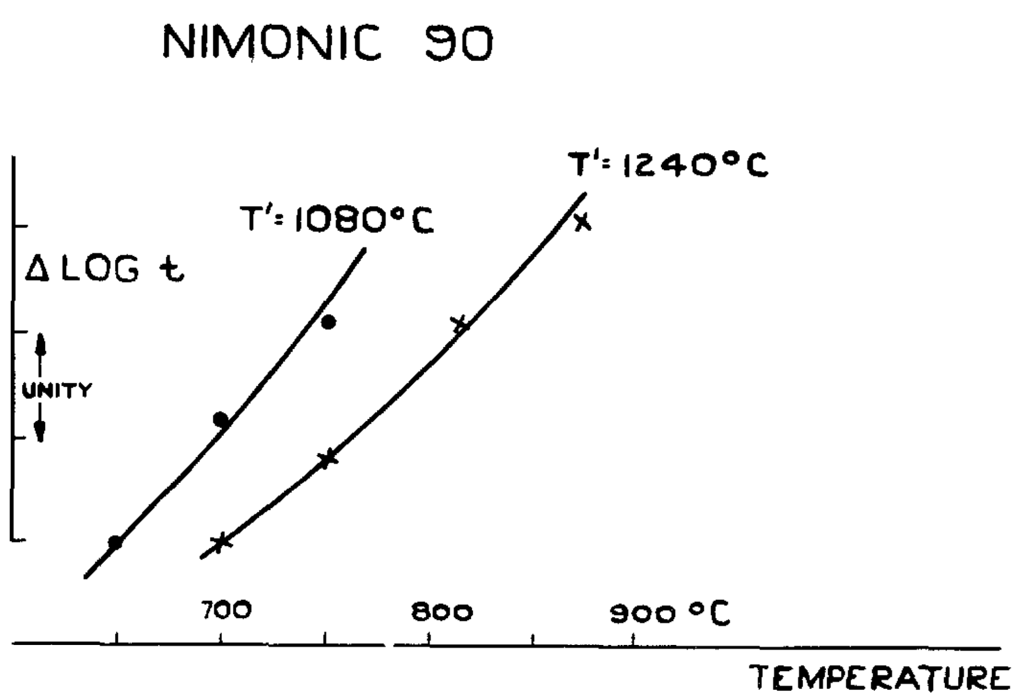


FIG. 16a



Δ LOGt / T PLOTS NIMONICS 80A AND 90

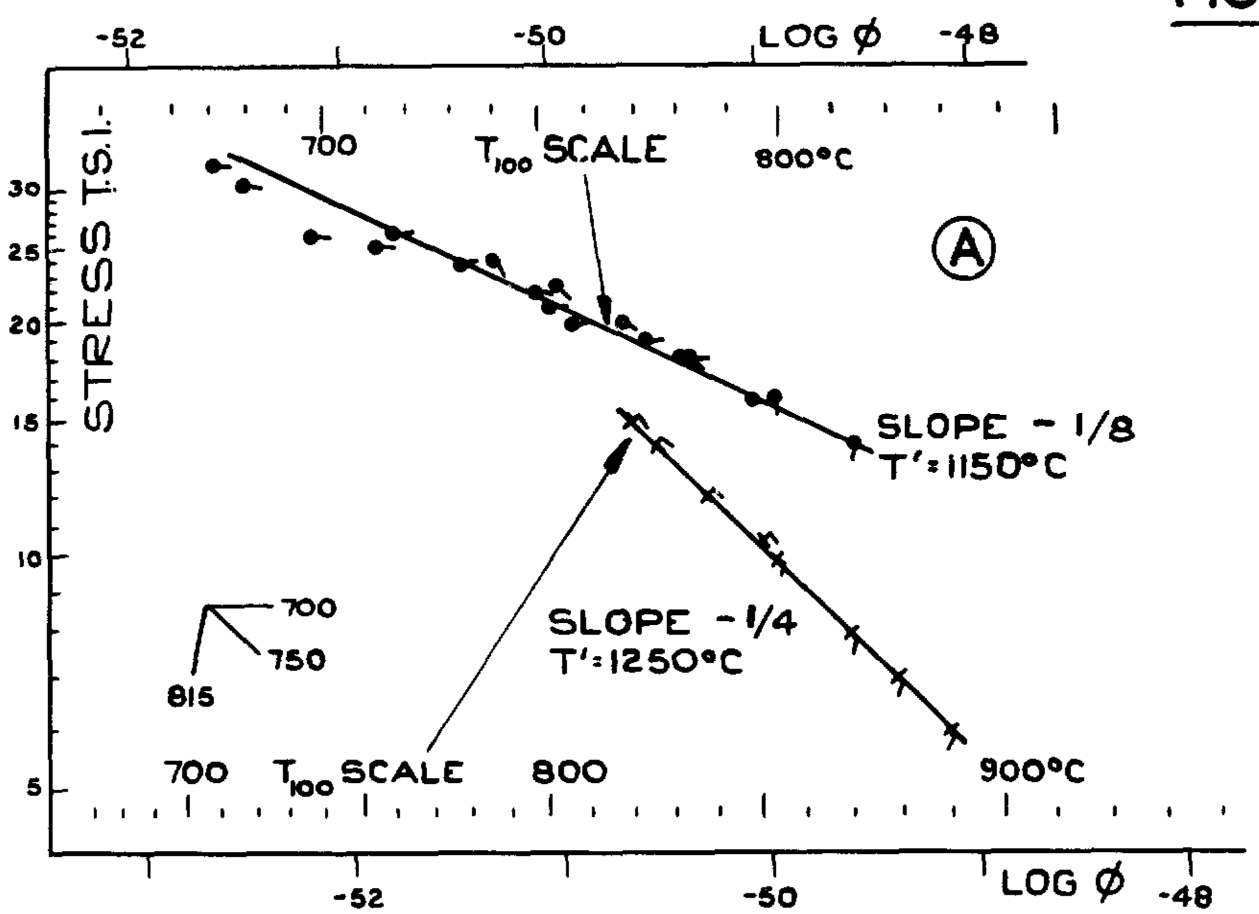


FIG. 17

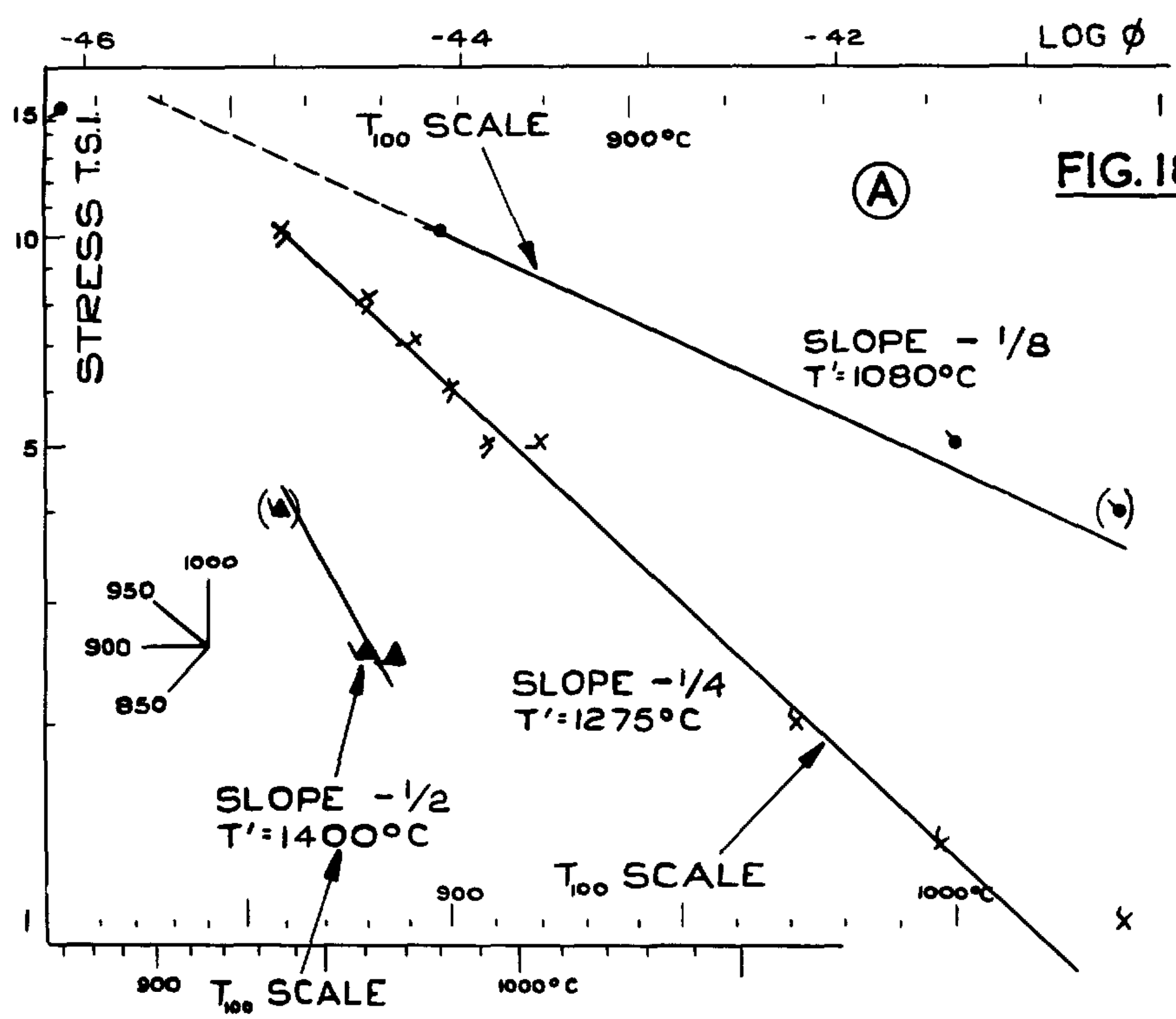


FIG. 18

CREEP RUPTURE
NIMONIC 90

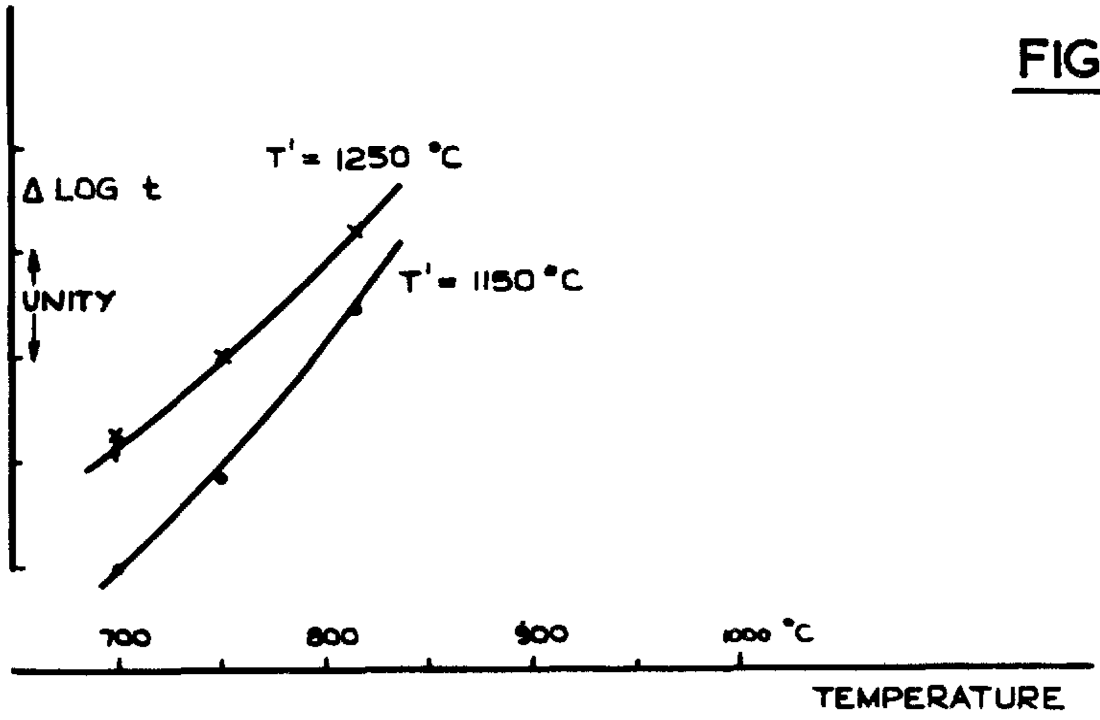
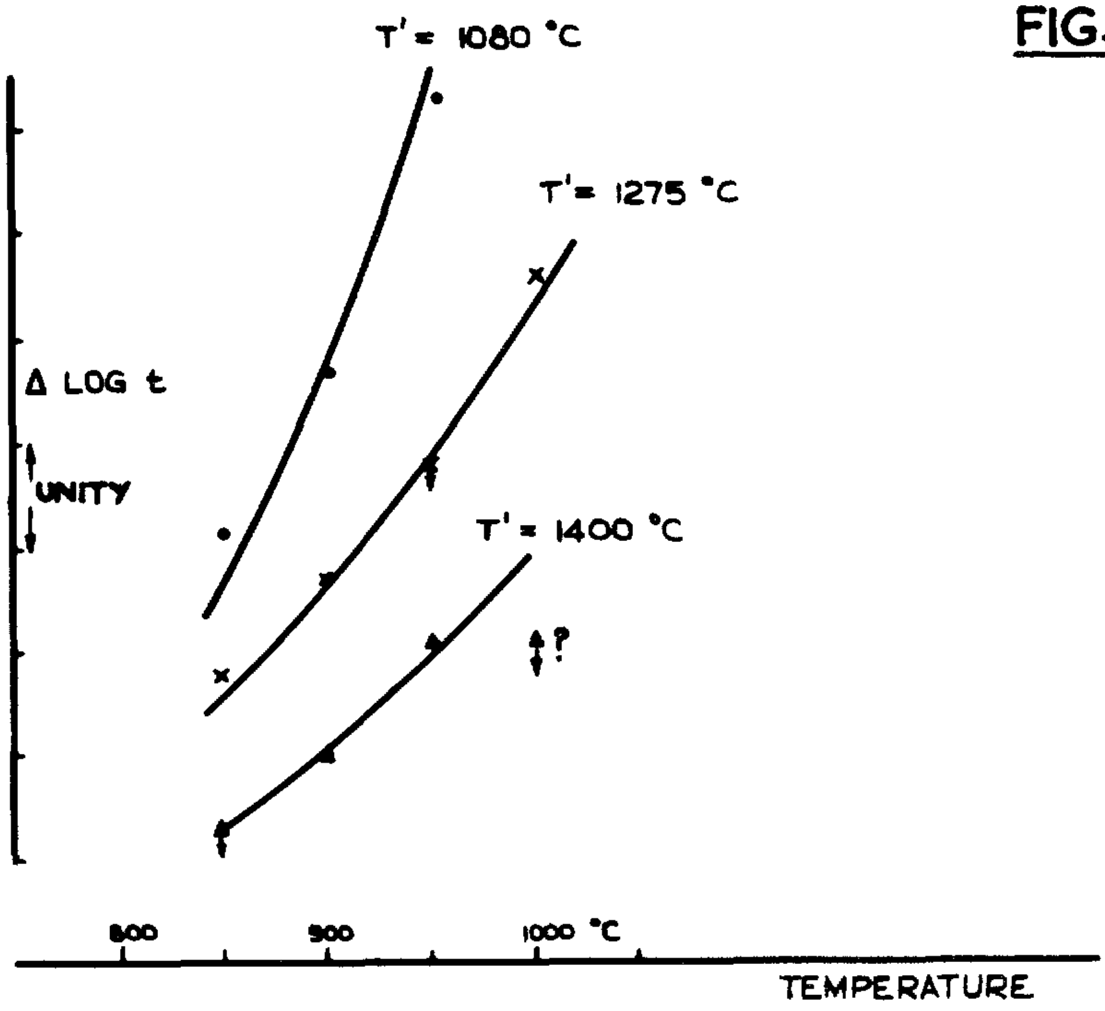


FIG. 17a

FIG. 18a



Δ LOG t/T PLOTS
NIMONIC 90

FIG. 19

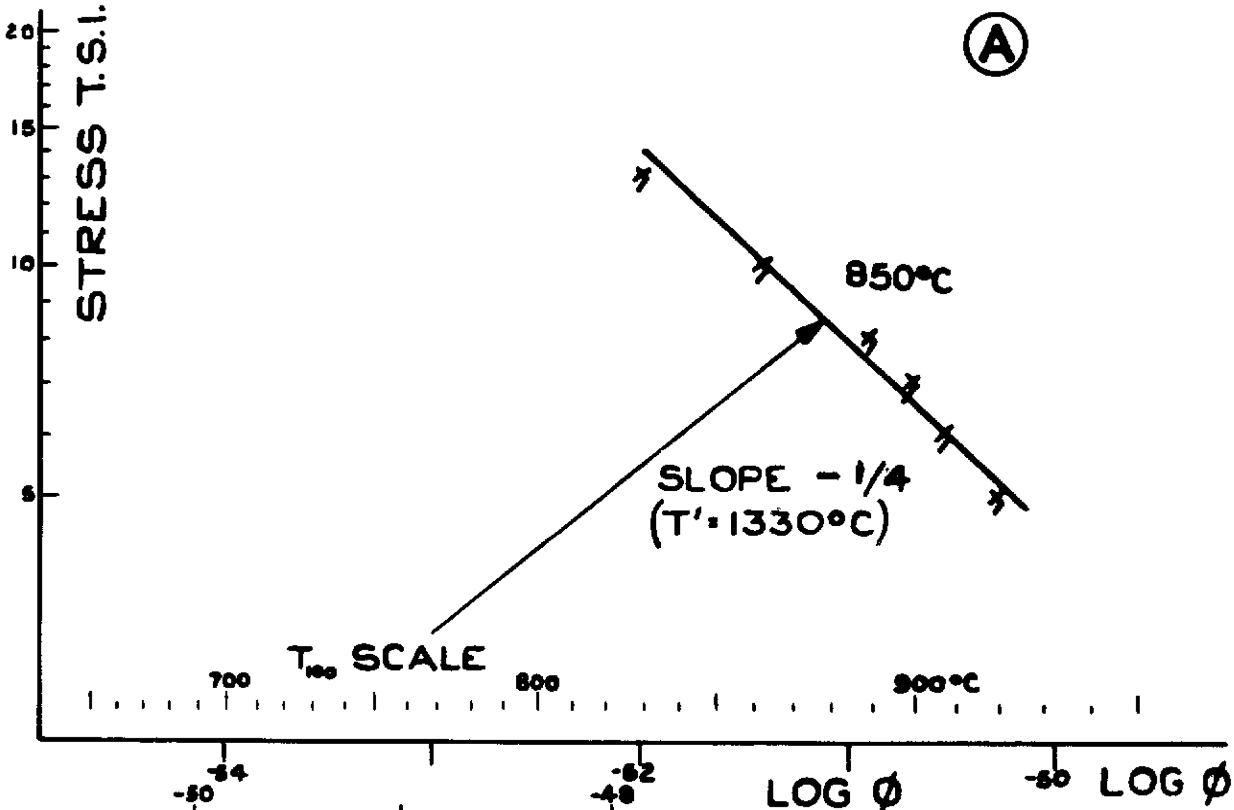
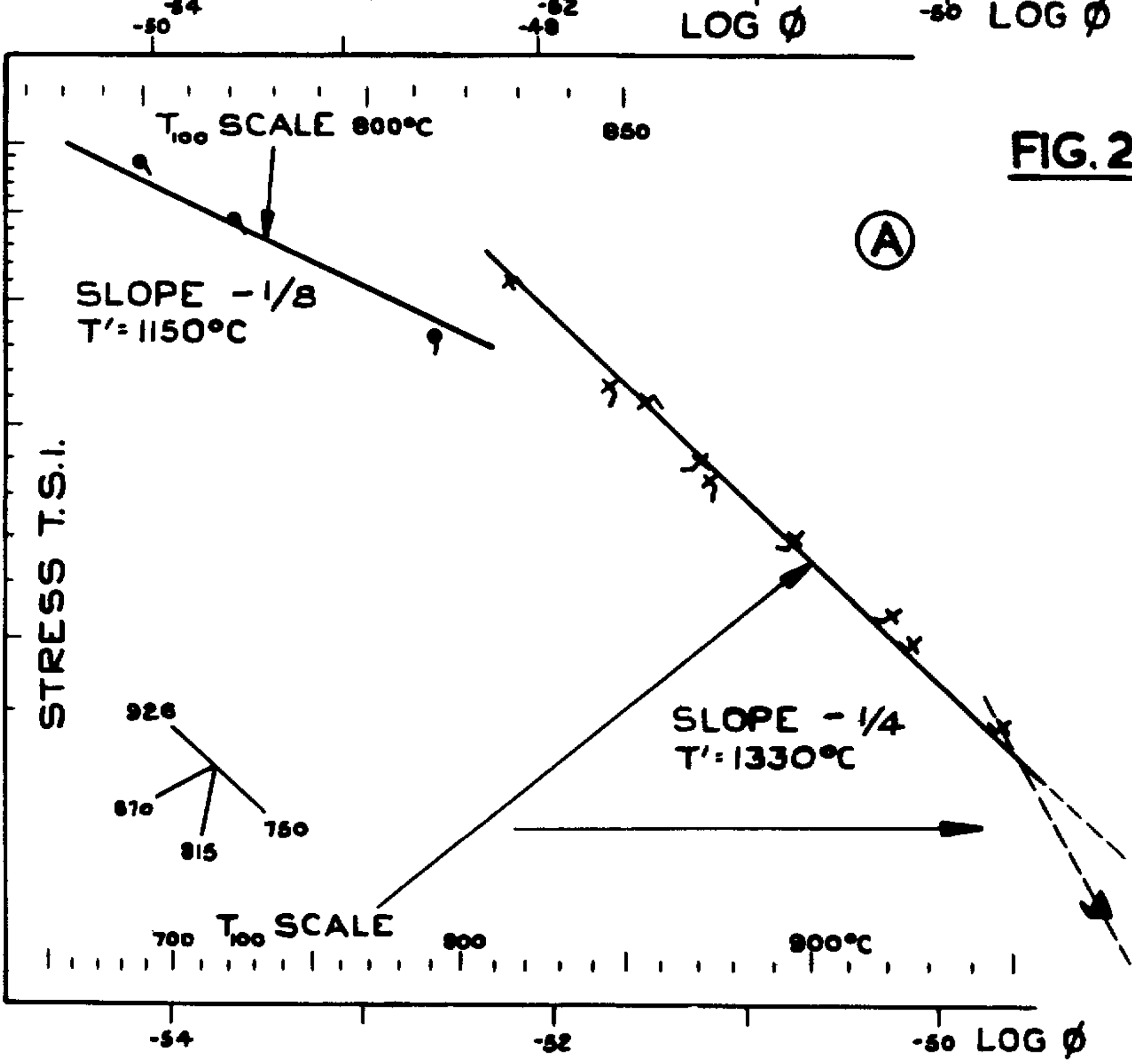


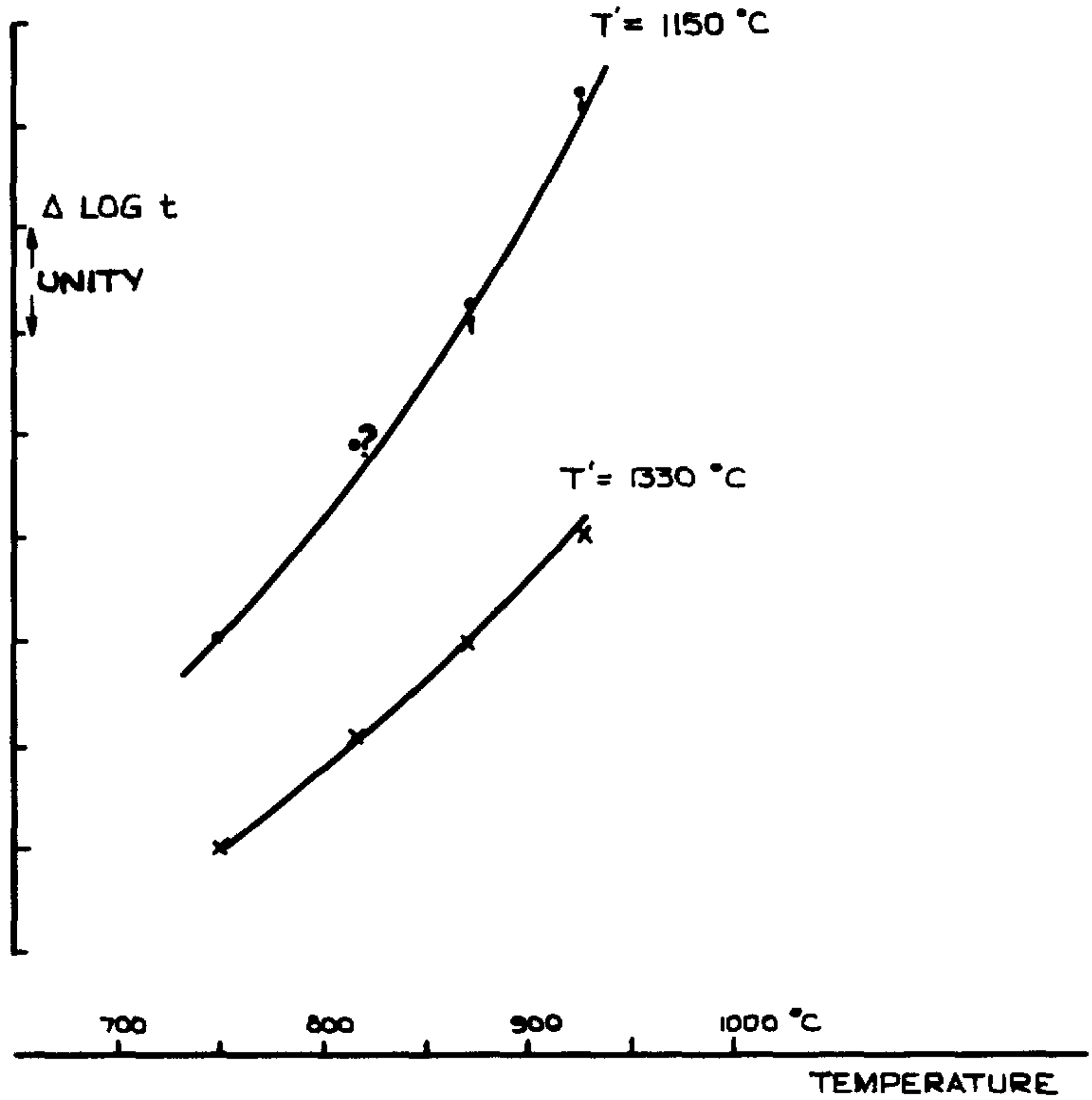
FIG. 20



CREEP RUPTURE

NIMONIC 95

FIG. 20a



Δ LOG t/T PLOT
NIMONIC 95

FIG. 21

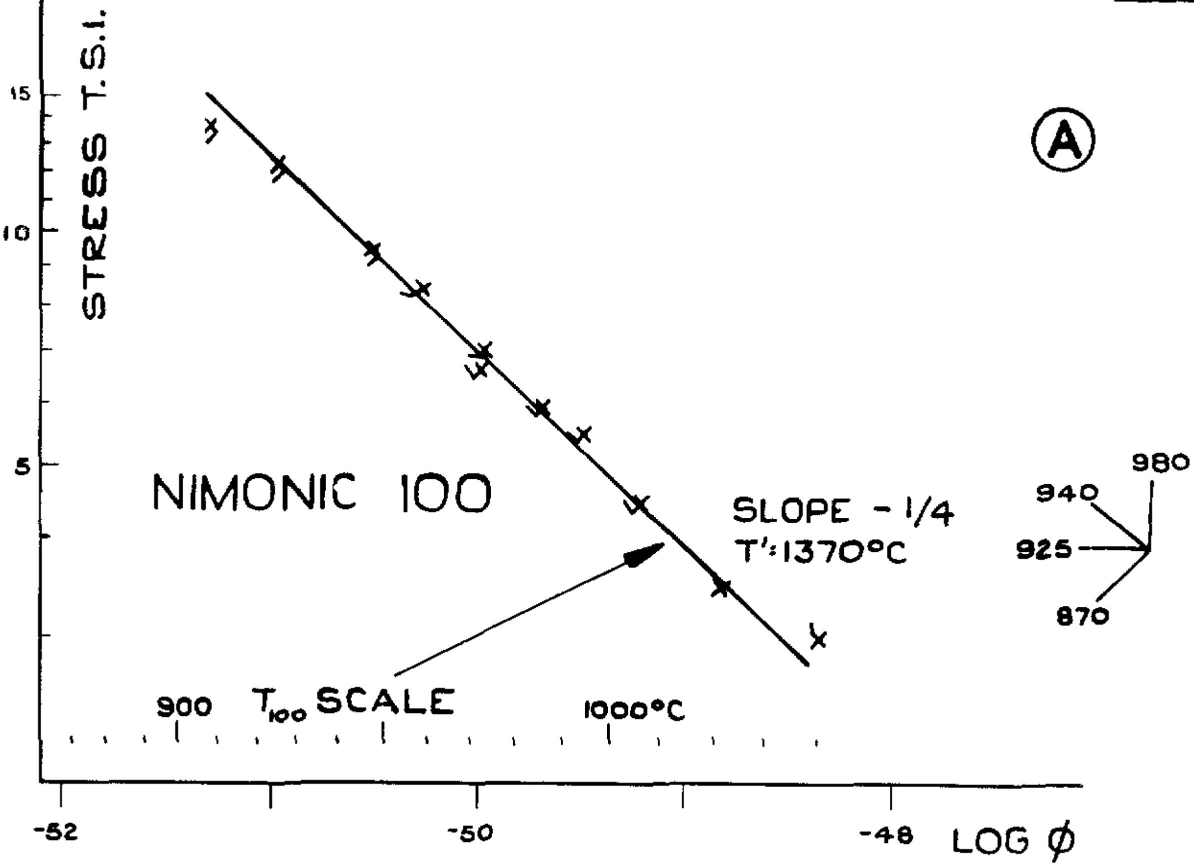
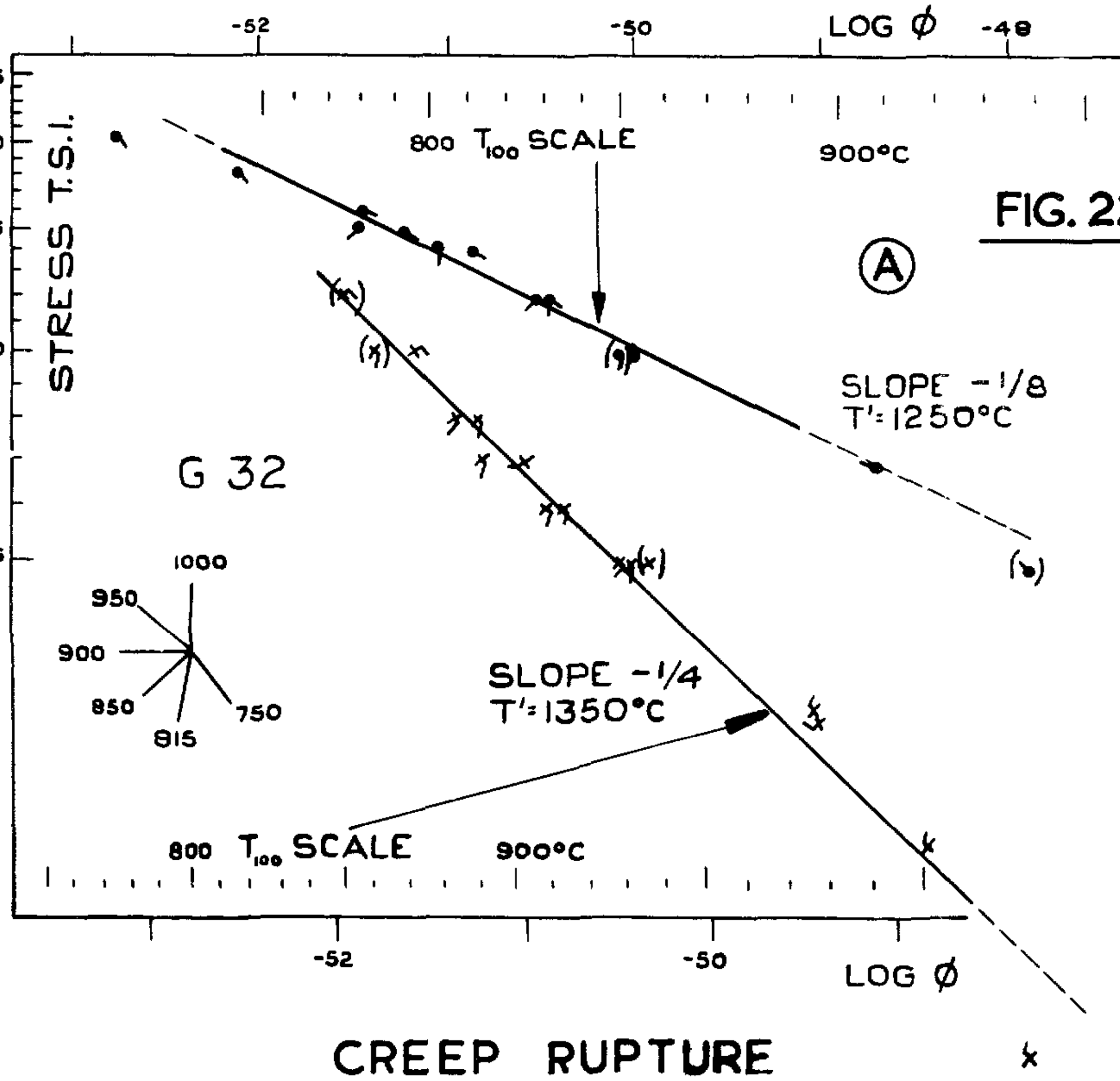


FIG. 22



CREEP RUPTURE

NIMONIC 100 AND G 32

FIG. 21a

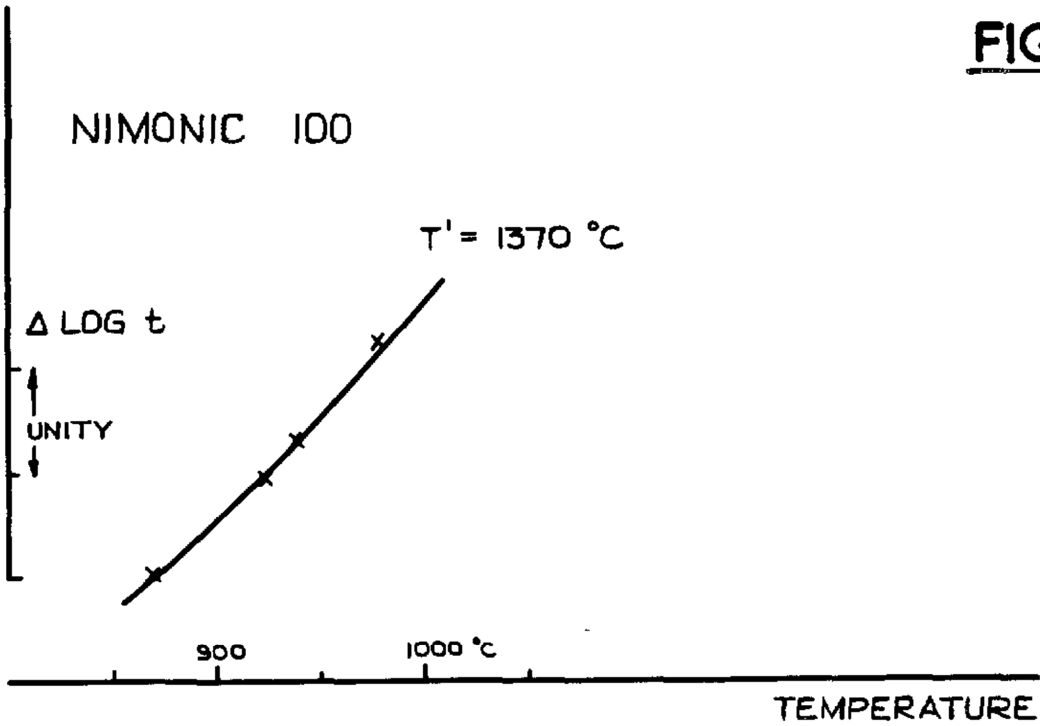
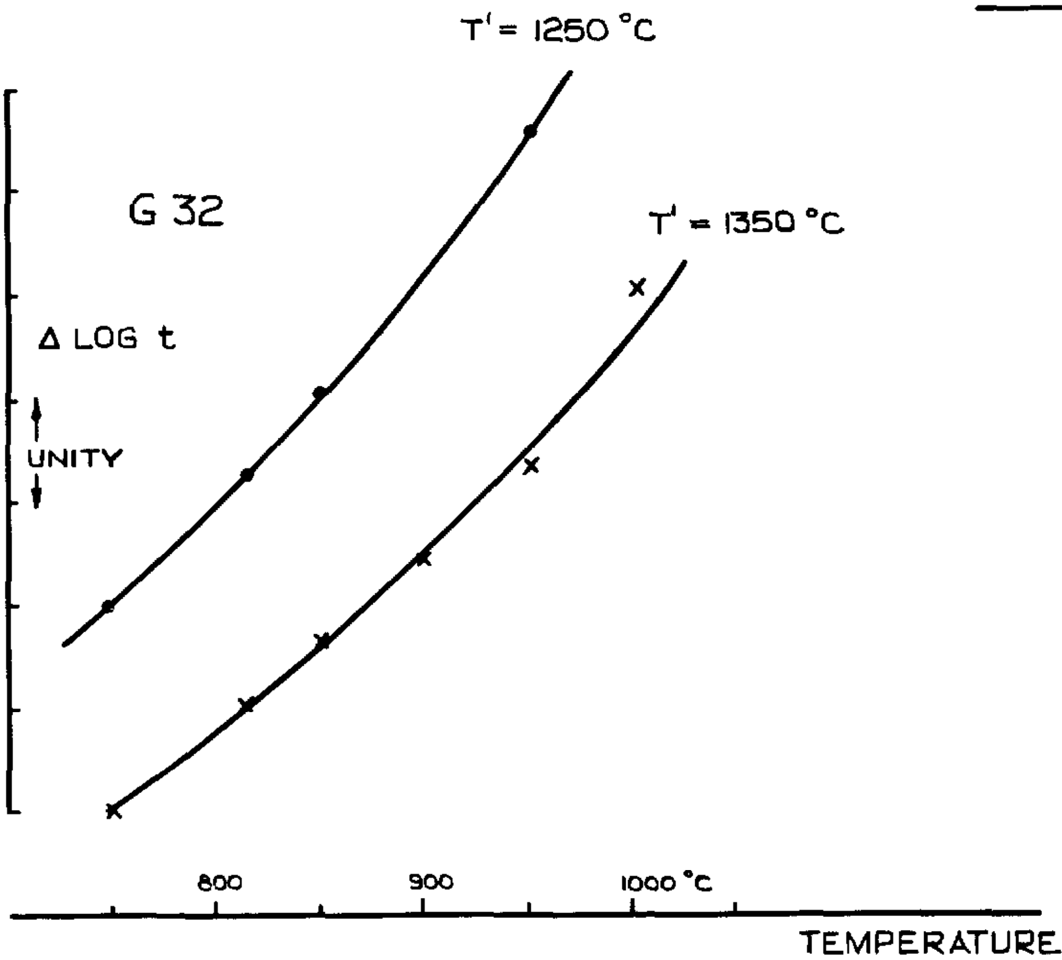


FIG. 22a



Δ LOG t/T PLOTS
NIMONIC 100 AND G 32

CREEP RUPTURE INCONEL X

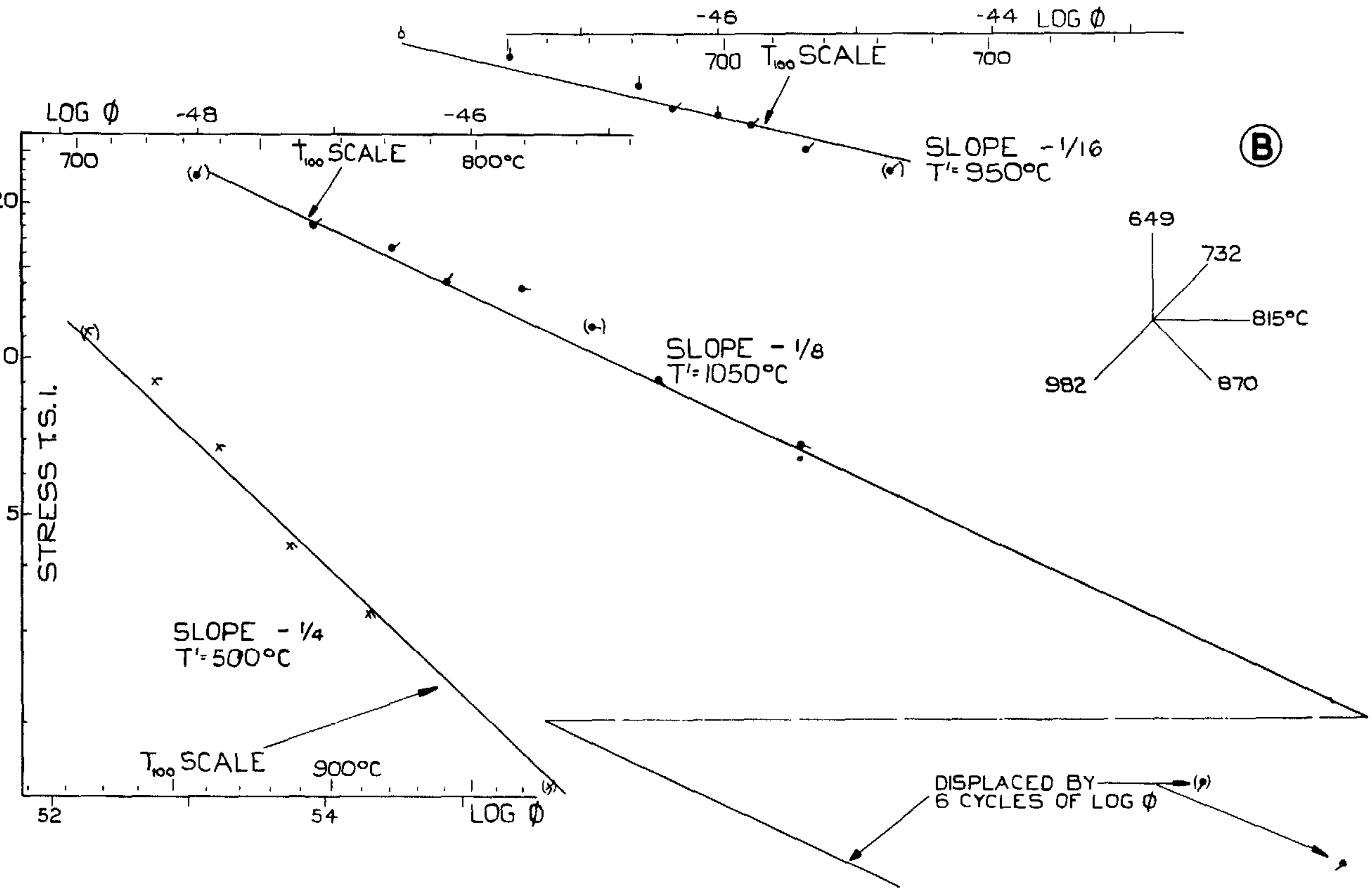
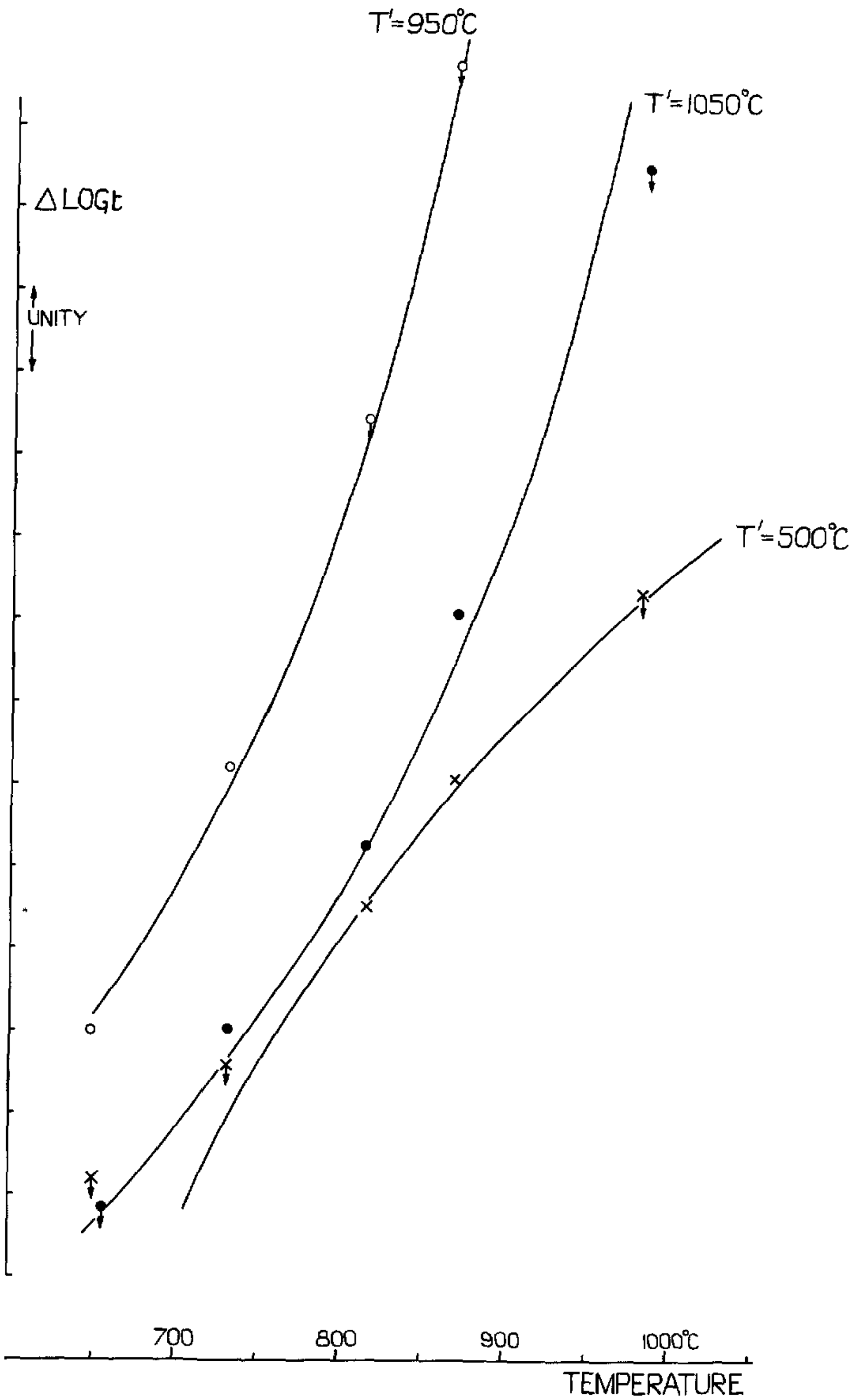


FIG. 23

FIG. 23a



Δ LOGt /T PLOT INCONEL X

FIG. 24

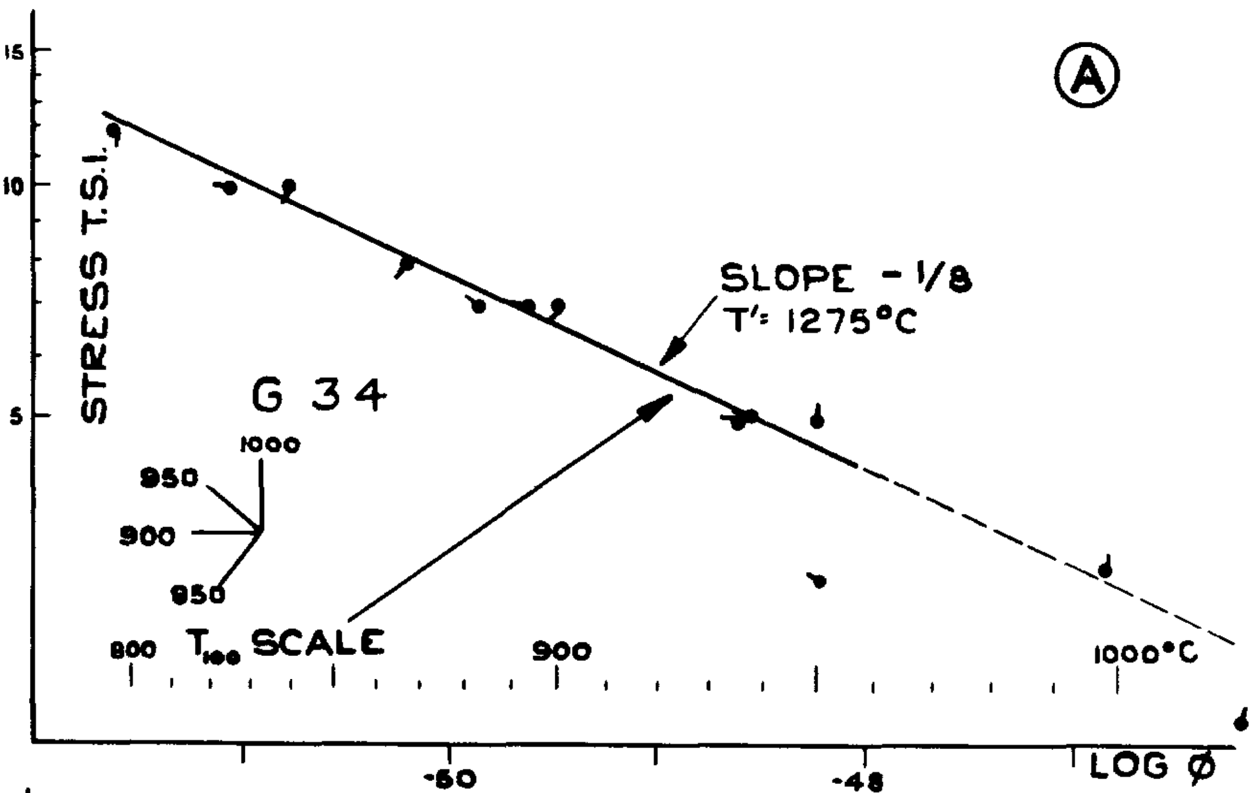
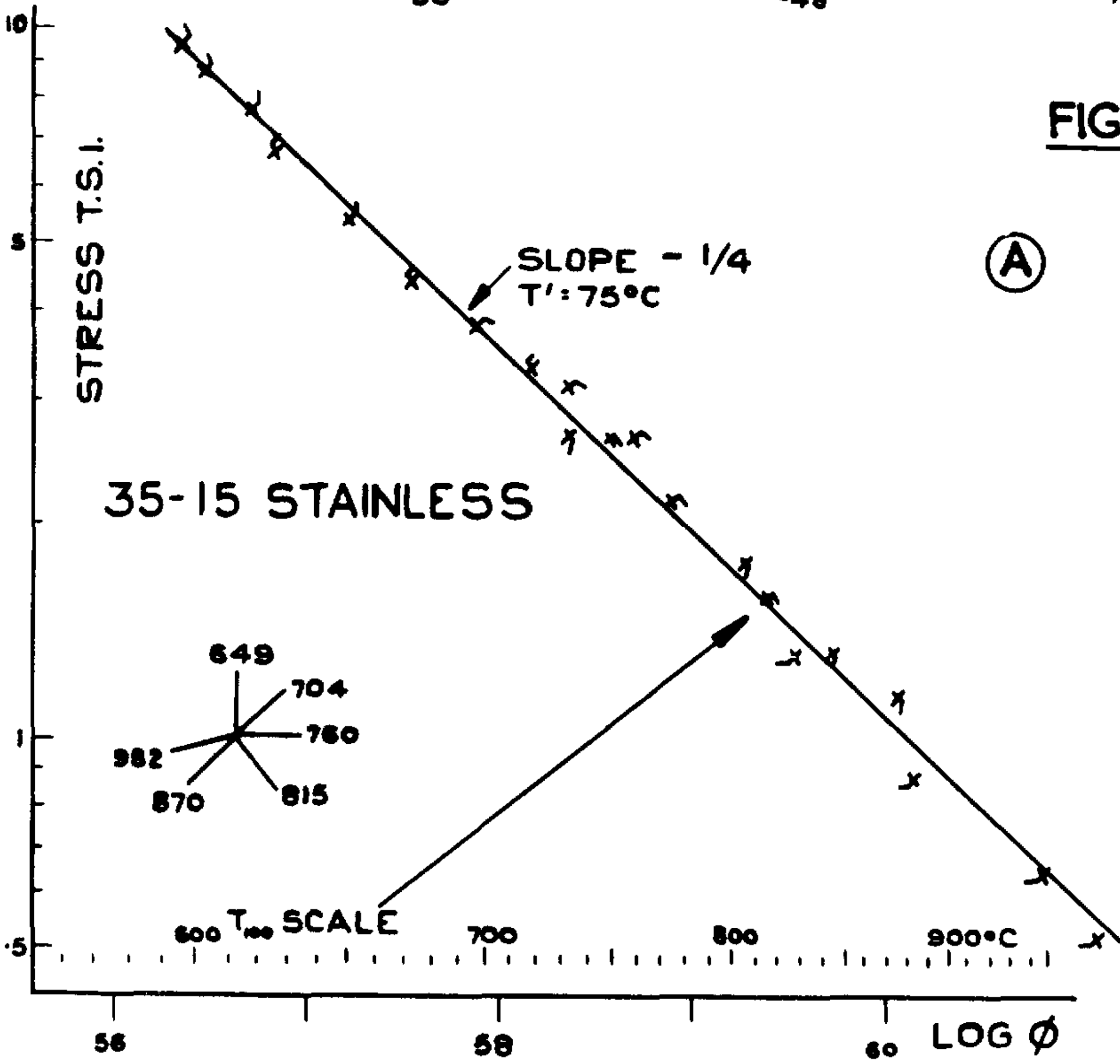


FIG. 25



CREEP RUPTURE
G 34 AND 35-15 STAINLESS

FIG. 24a

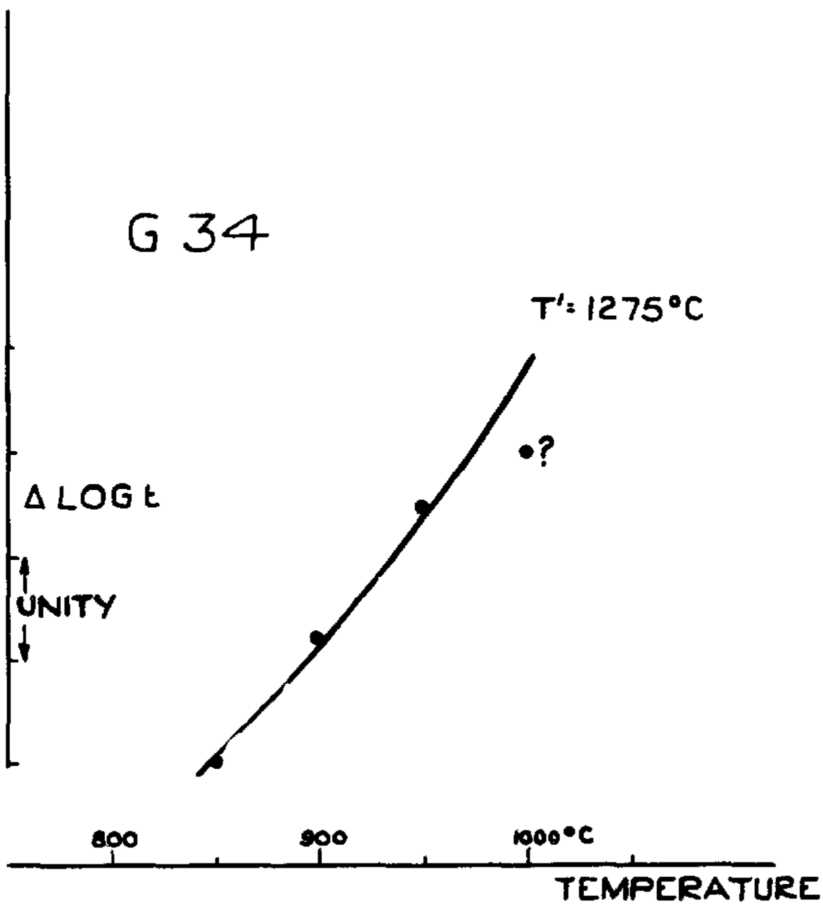
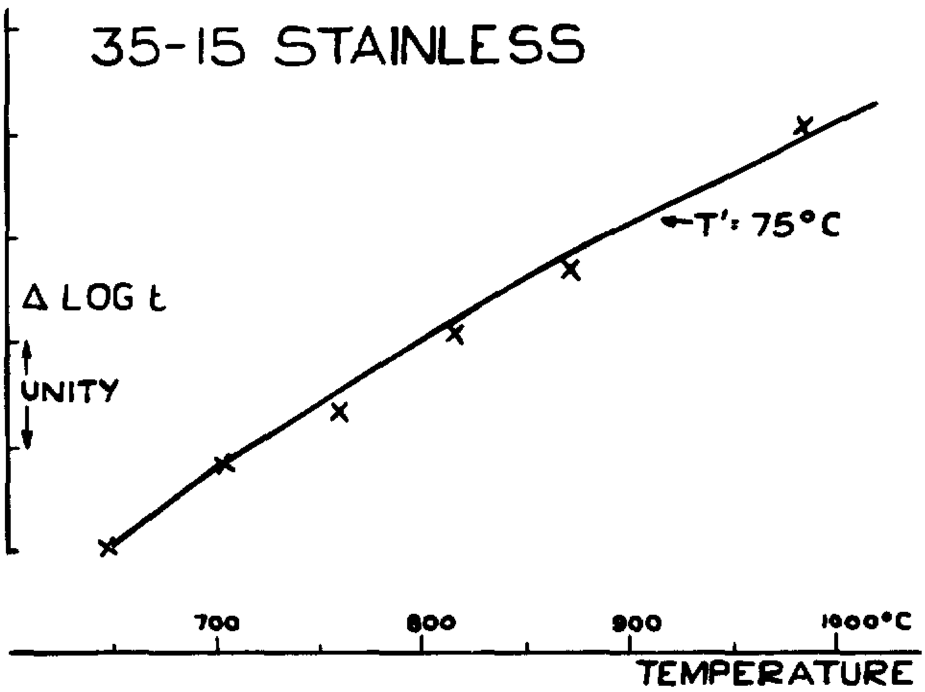


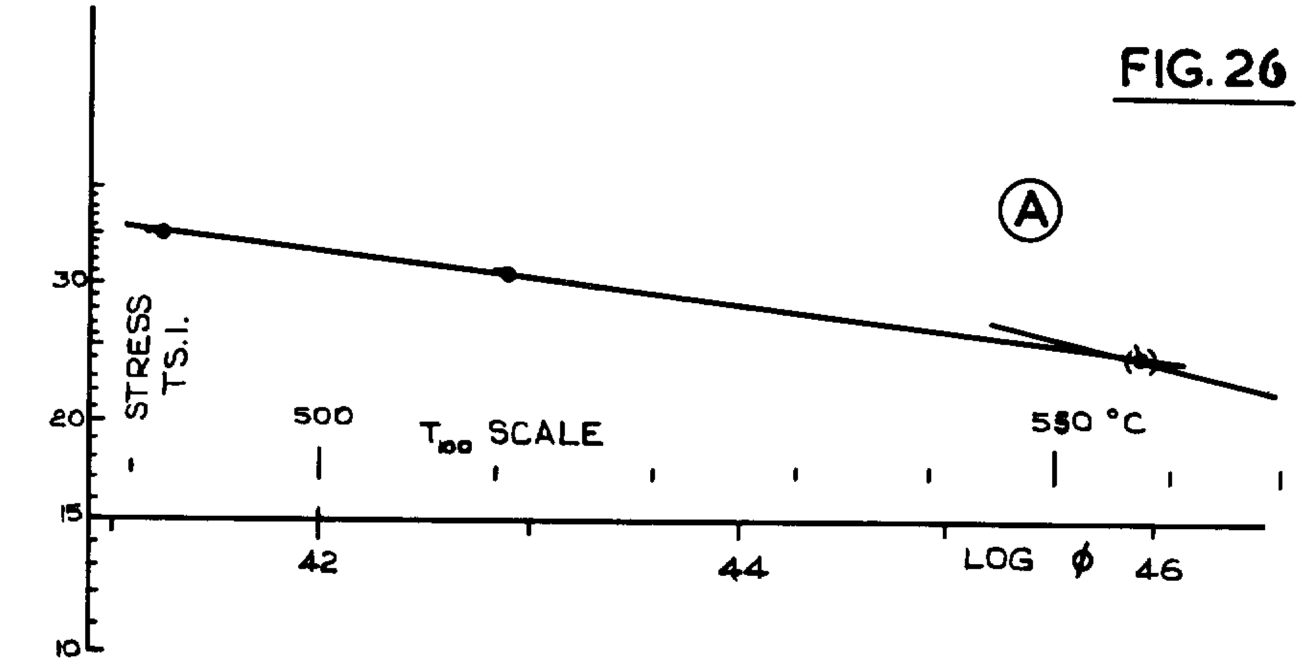
FIG. 25a

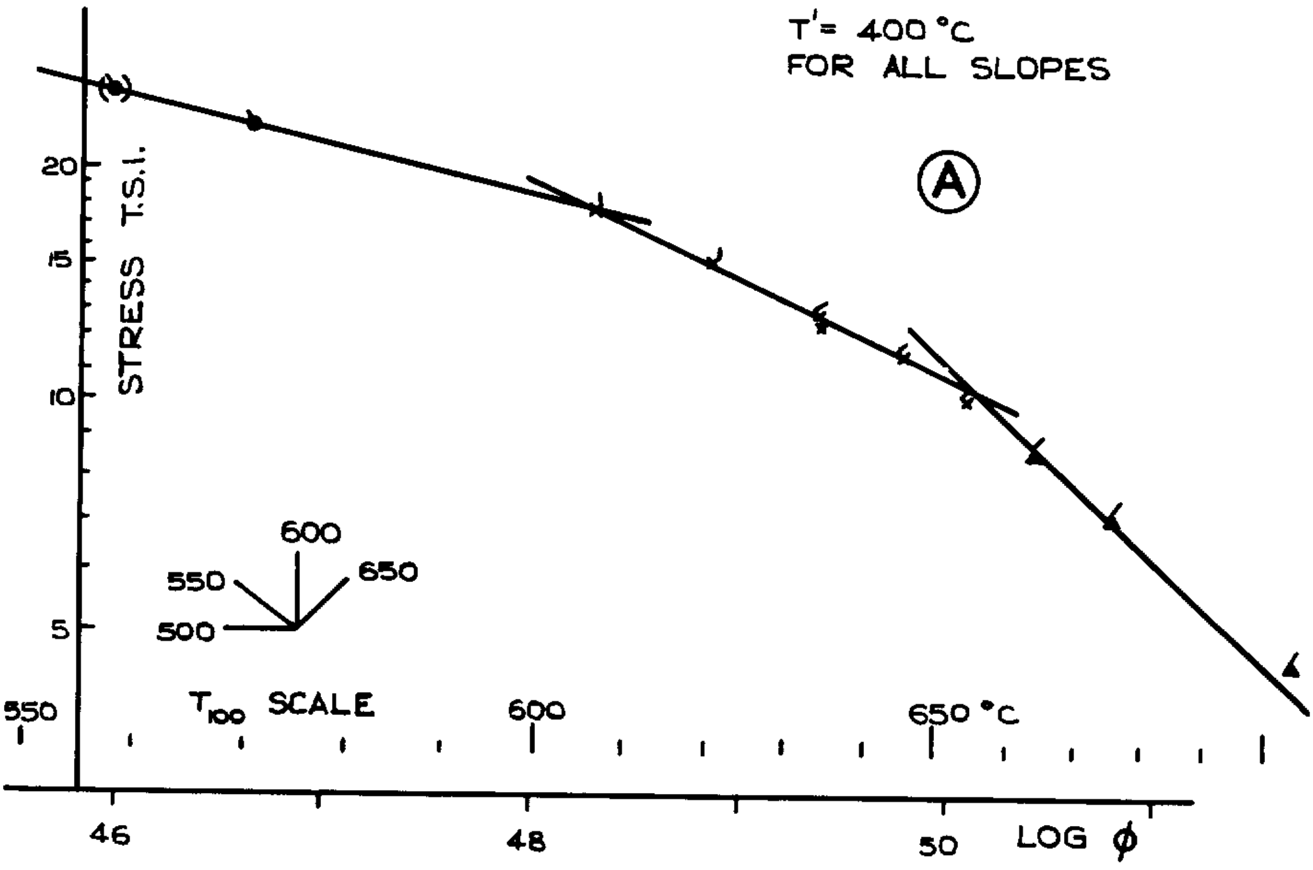


Δ LOG t/T PLOTS

G 34 AND 35-15 STAINLESS

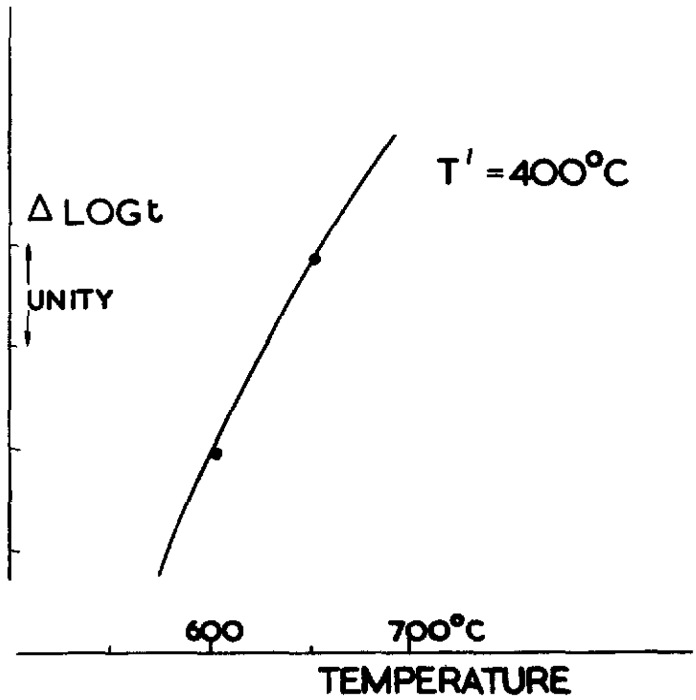
FIG. 26





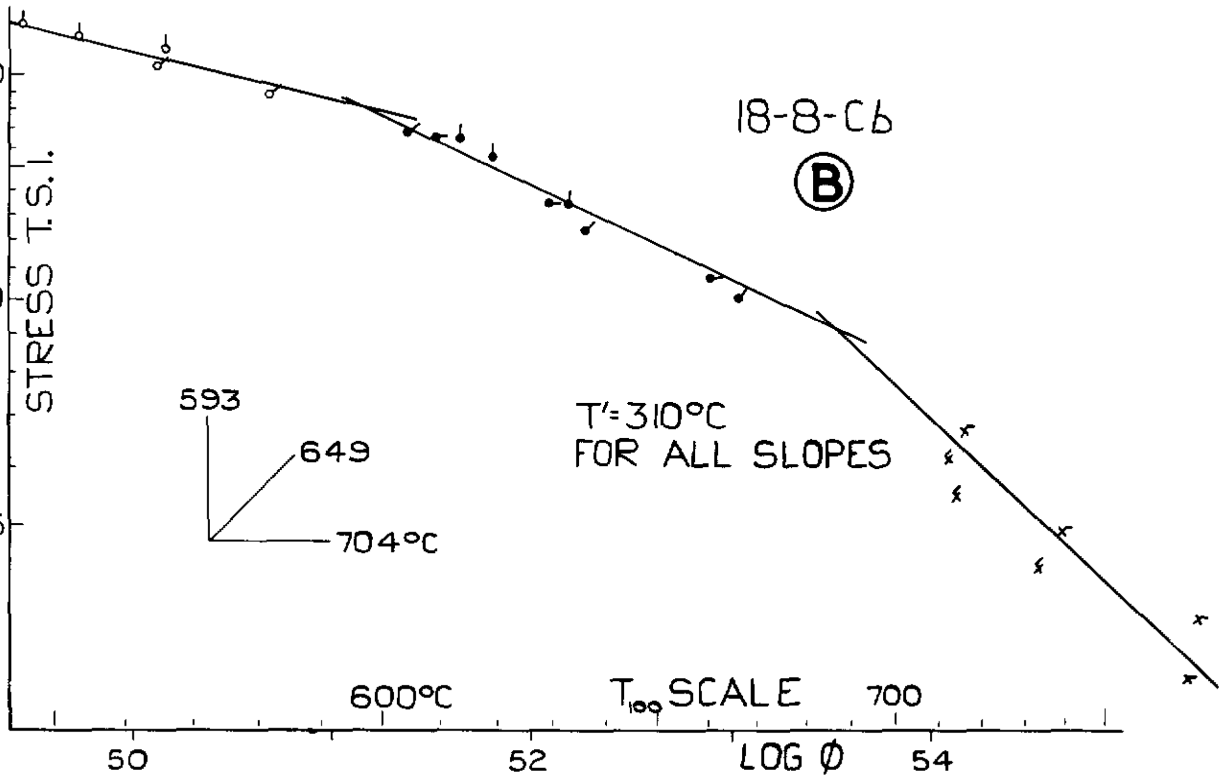
CREEP RUPTURE H46

FIG 26a



Δ LOG t/T PLOT H46

FIG. 27



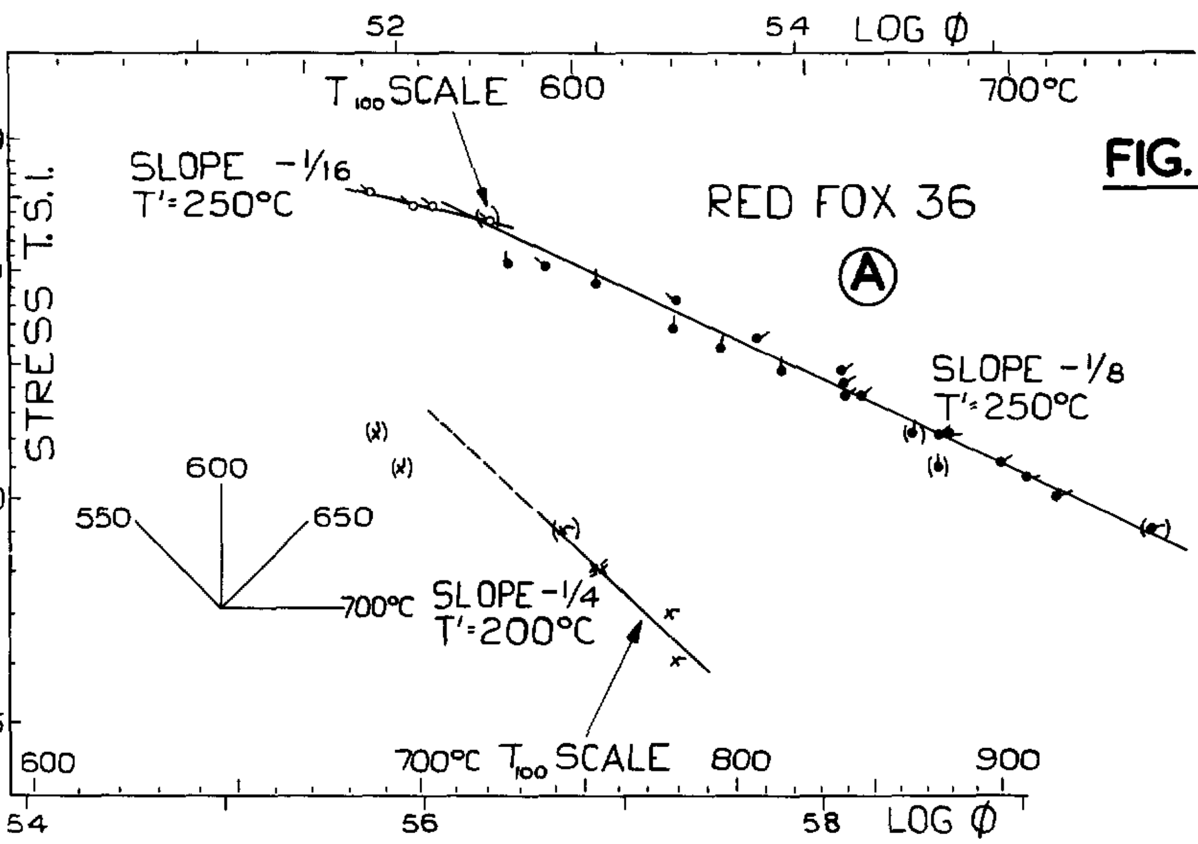


FIG. 28

CREEP RUPTURE 18-8-Cb AND RED FOX 36

FIG. 27a

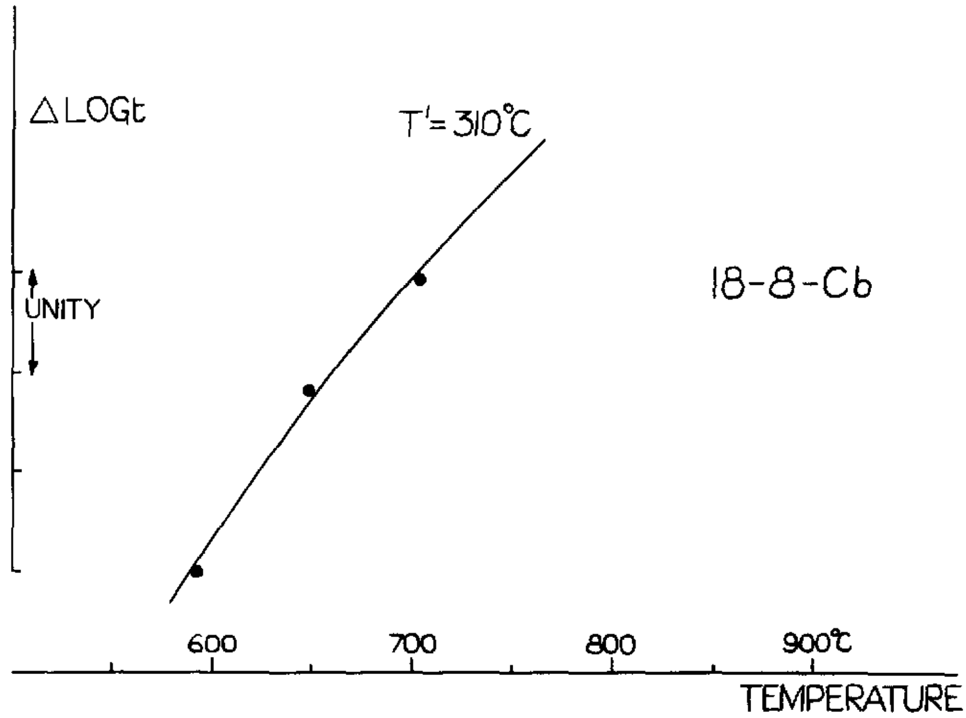
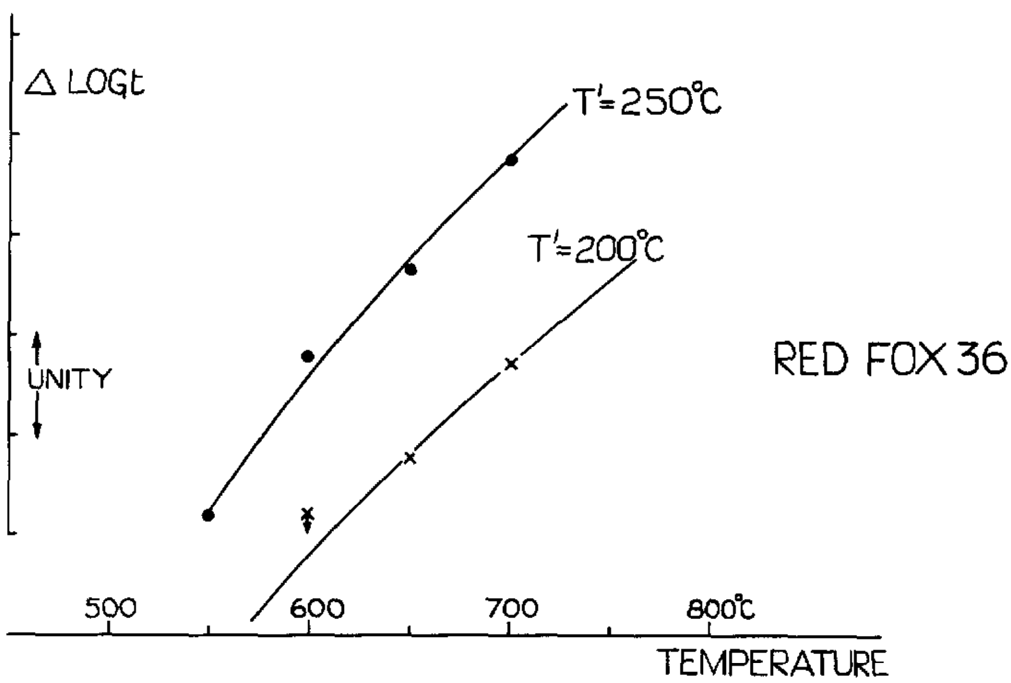


FIG. 28a



△LOGt /T PLOTS 18-8-Cb AND RED FOX 36

FIG.29

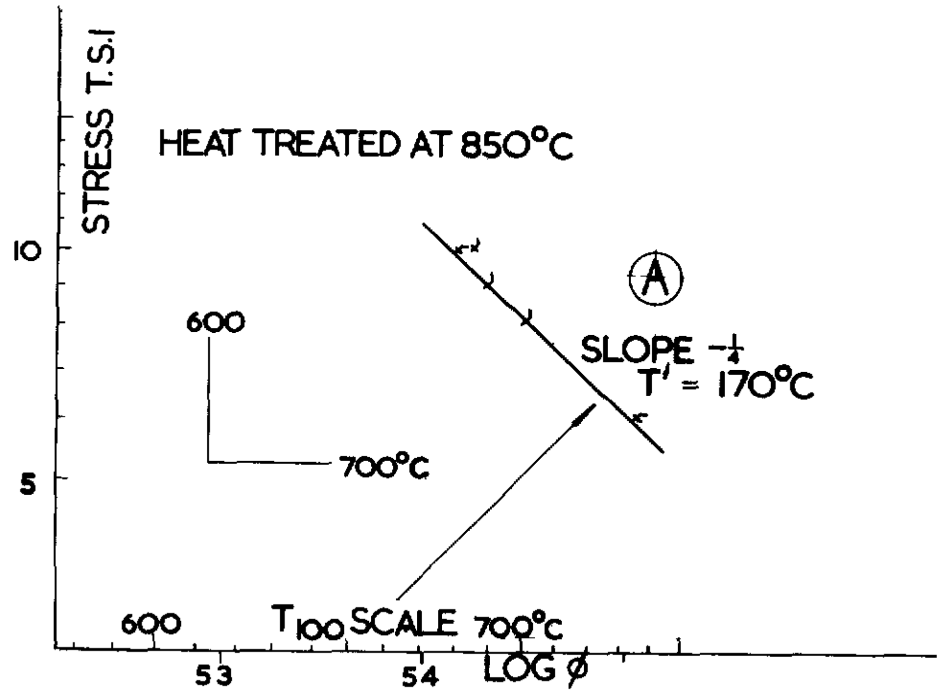
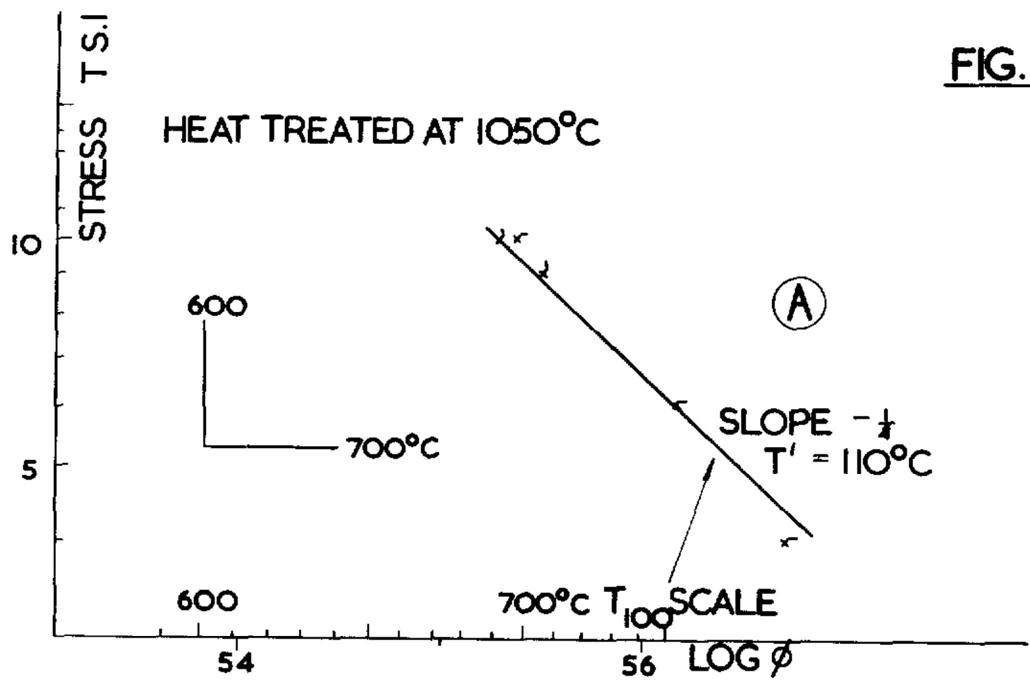


FIG.30



CREEP RUPTURE FCB (T)

FIG. 29a

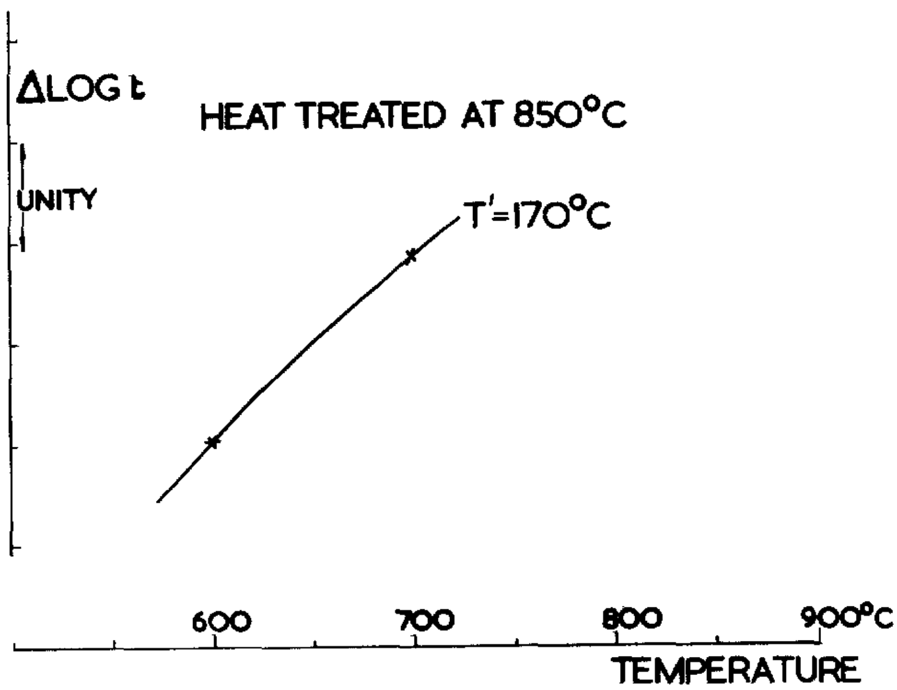
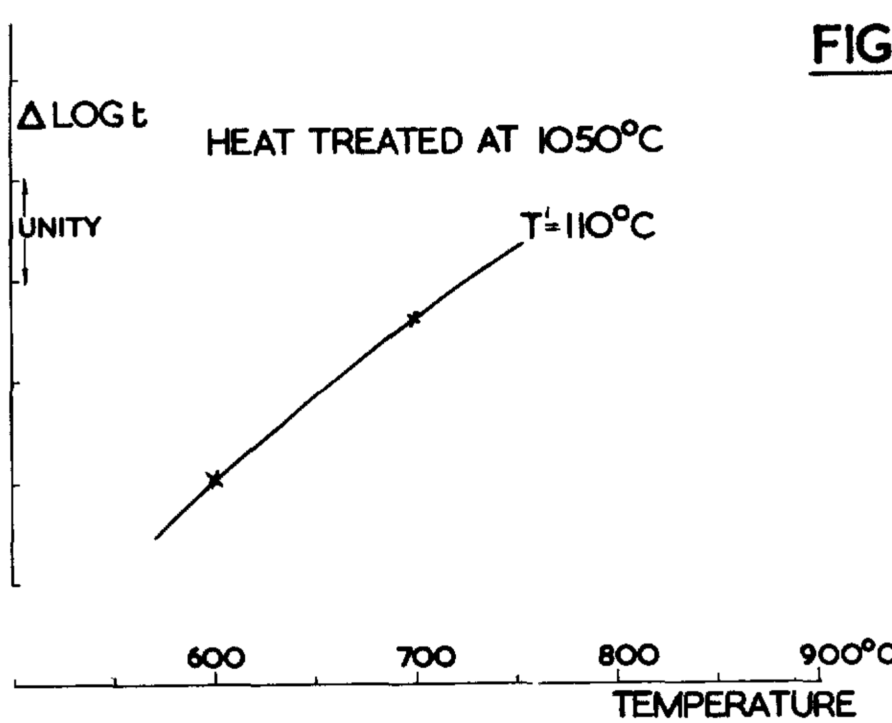


FIG. 30a



Δ LOG t /T PLOTS FCB(T)

FIG. 31

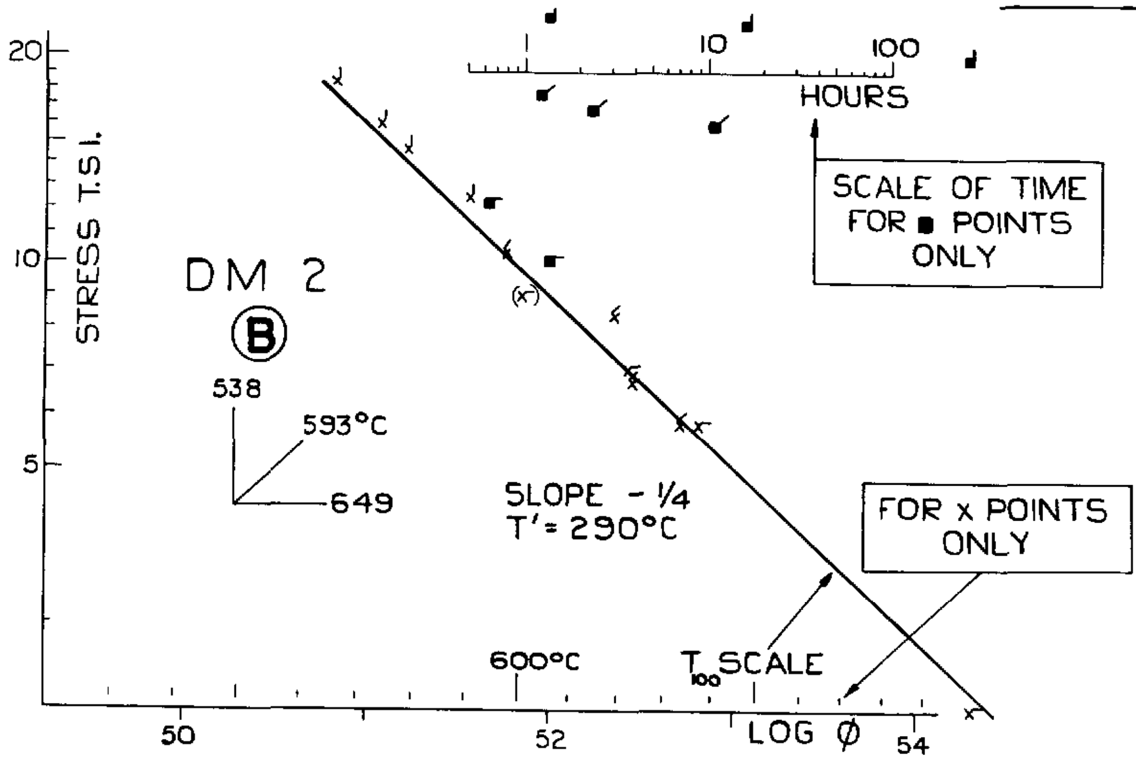
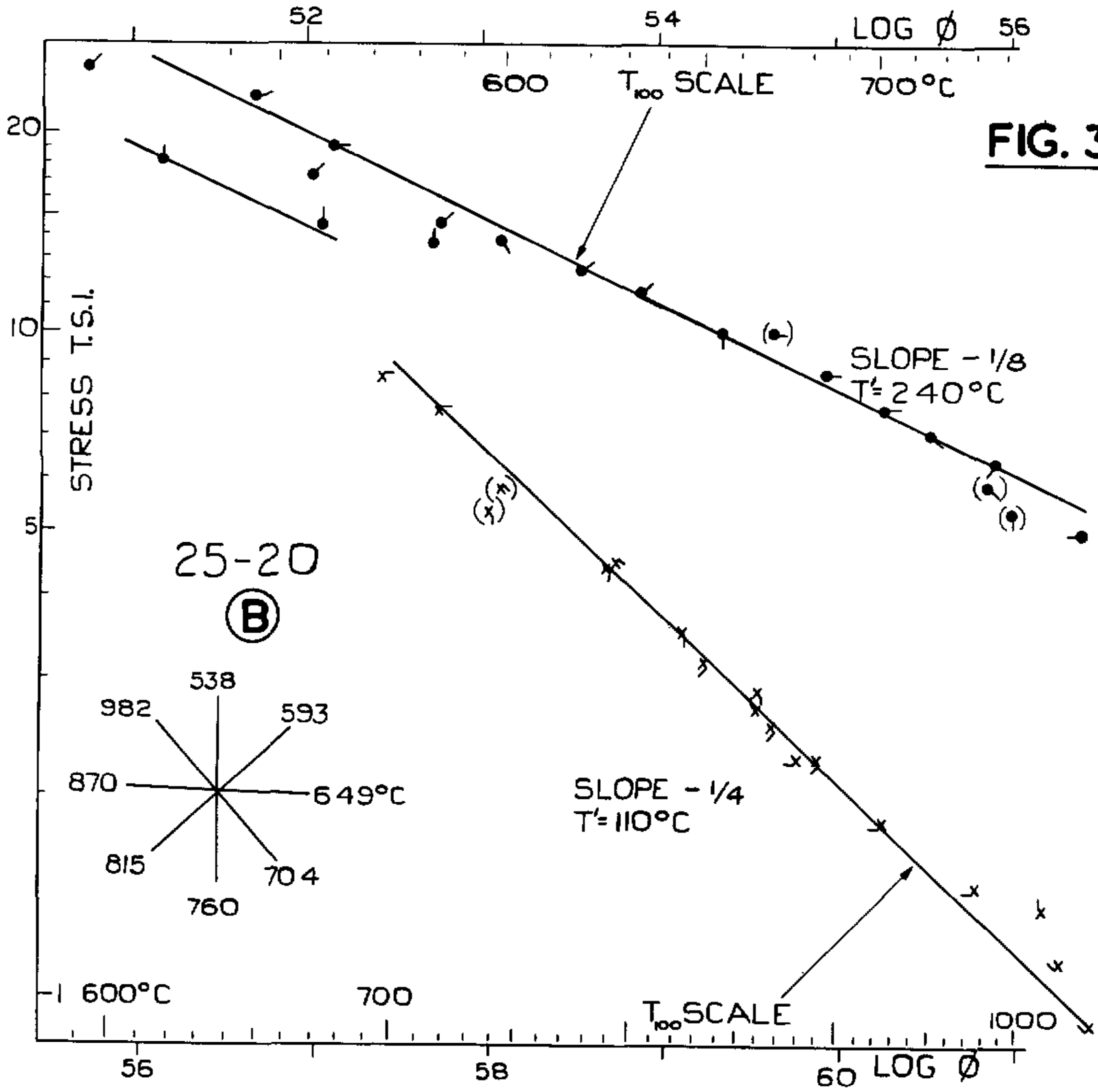


FIG. 32



CREEP RUPTURE DM 2 AND 25-20

FIG. 31a

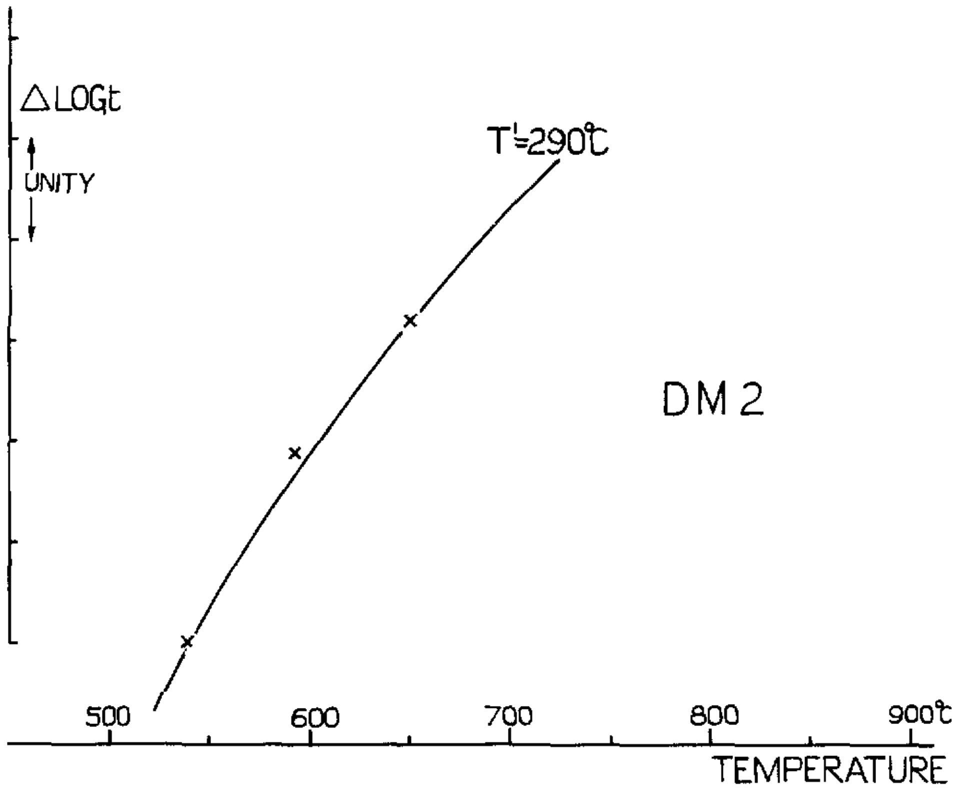
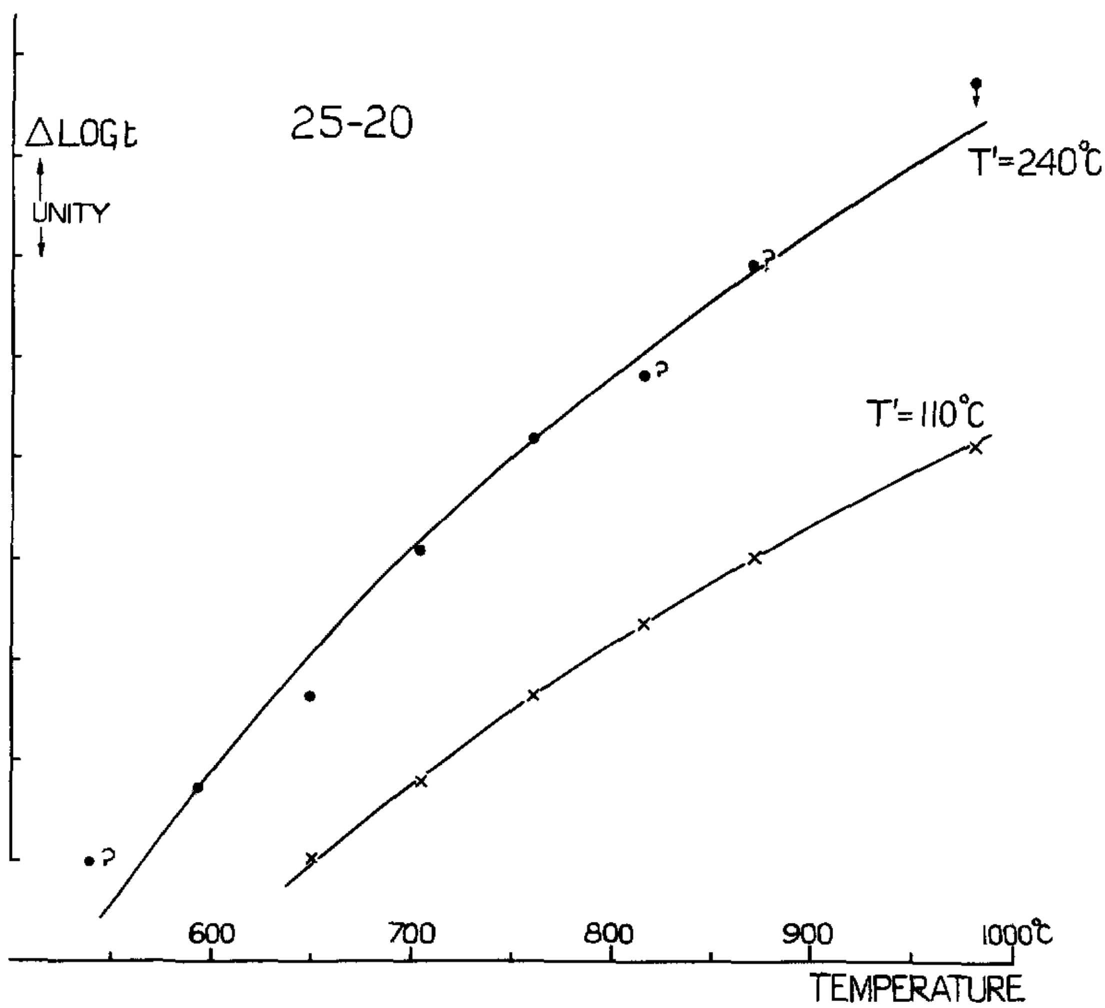


FIG. 32a



△ LOGt /T PLOTS DM 2 AND 25-20

FIG. 33

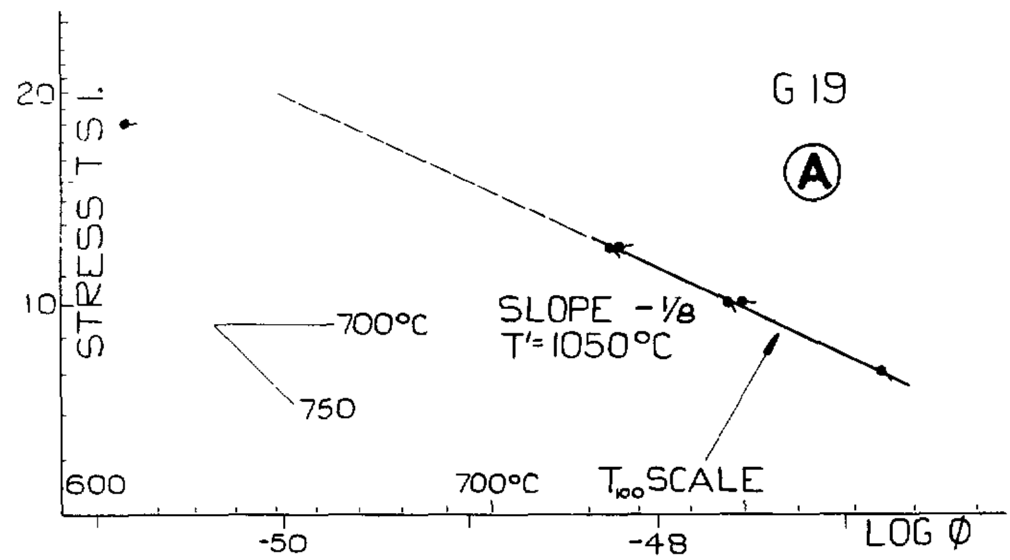
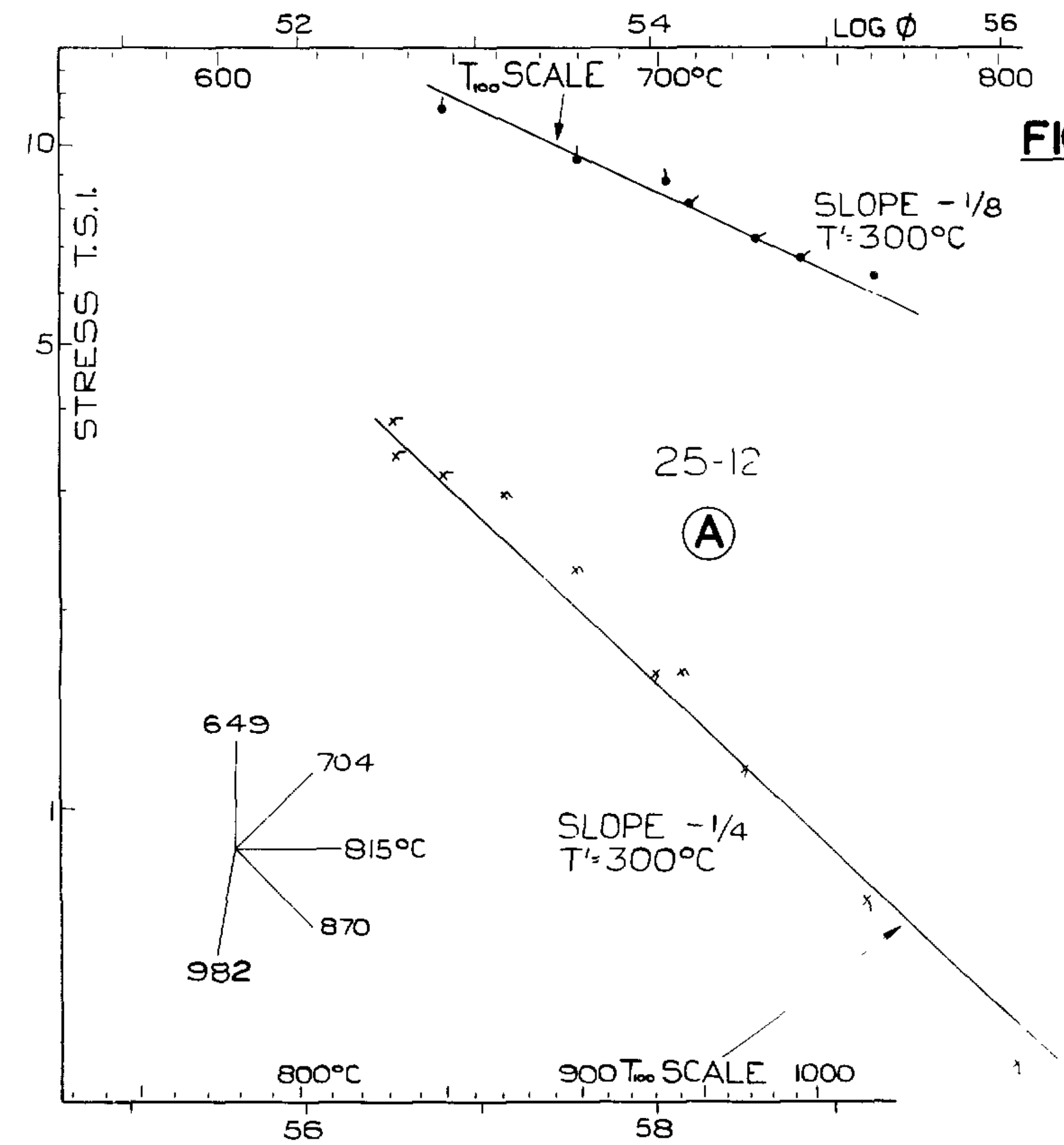


FIG. 34



CREEP RUPTURE G 19 AND 25-12

FIG. 33a

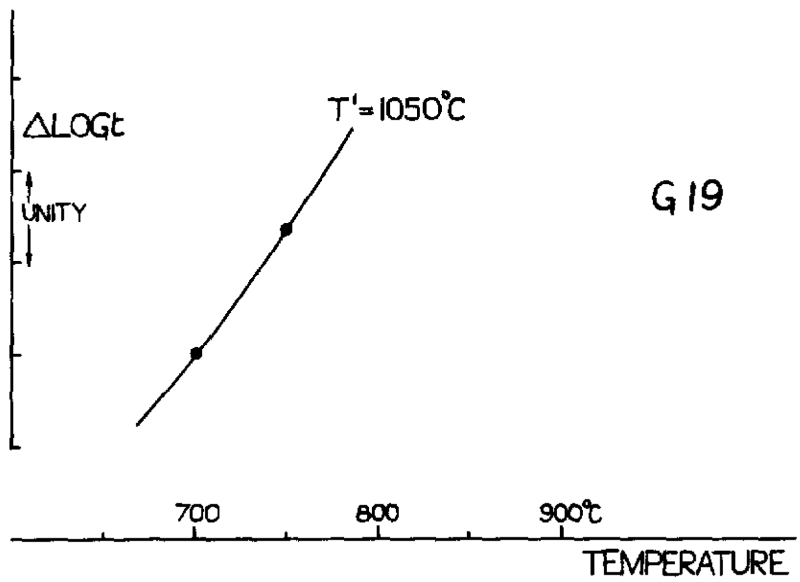
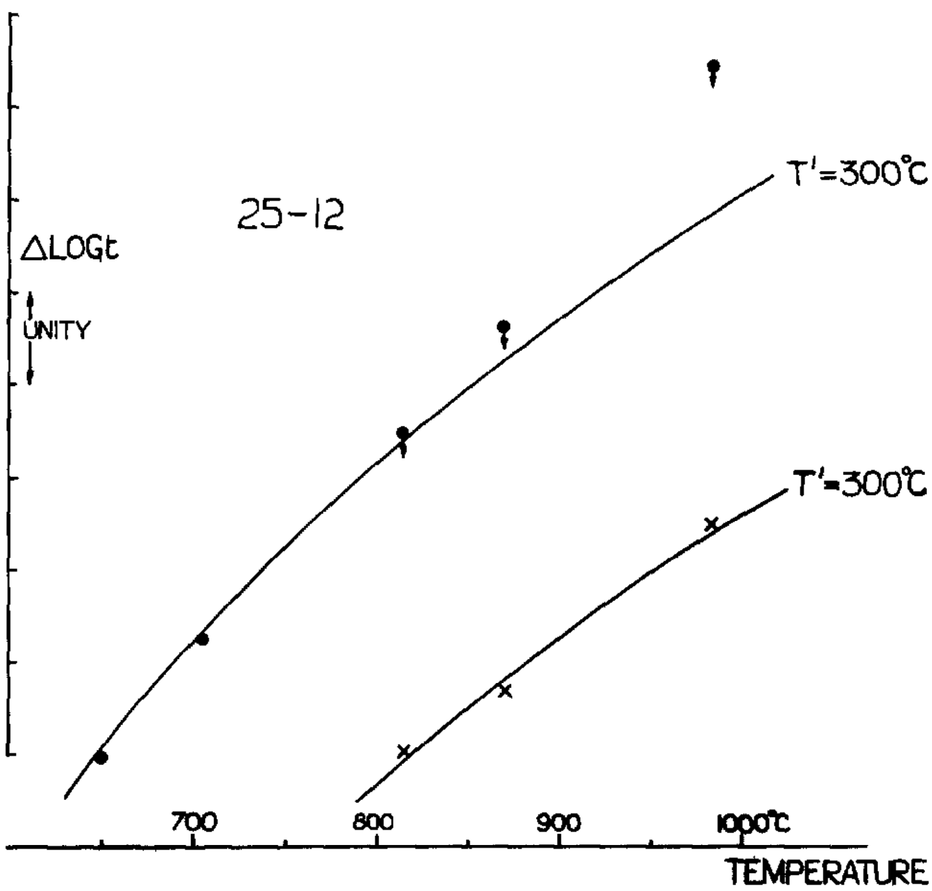


FIG. 34 a



Δ LOGt /T PLOTS G 19 AND 25-12

FIG. 35

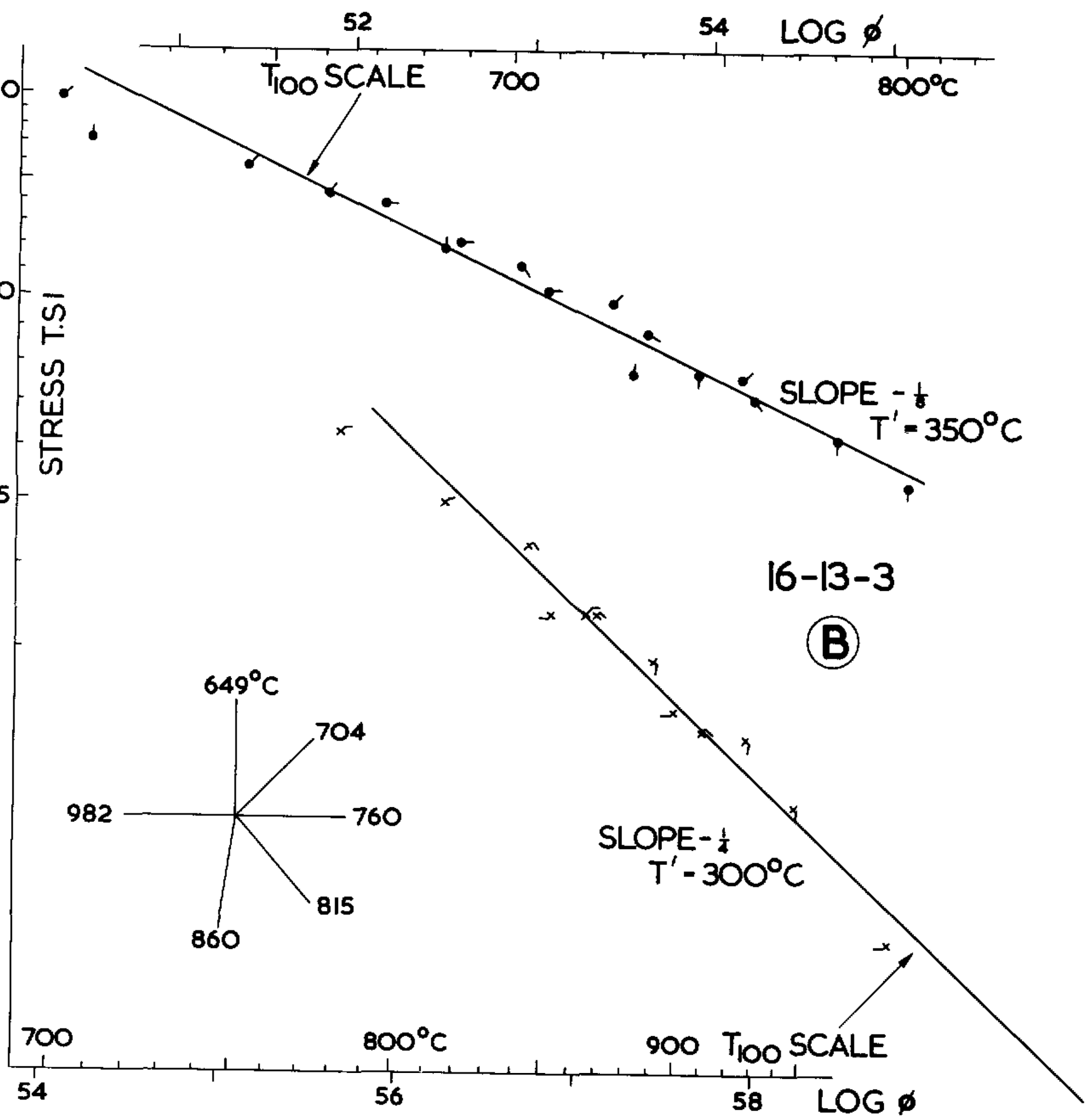
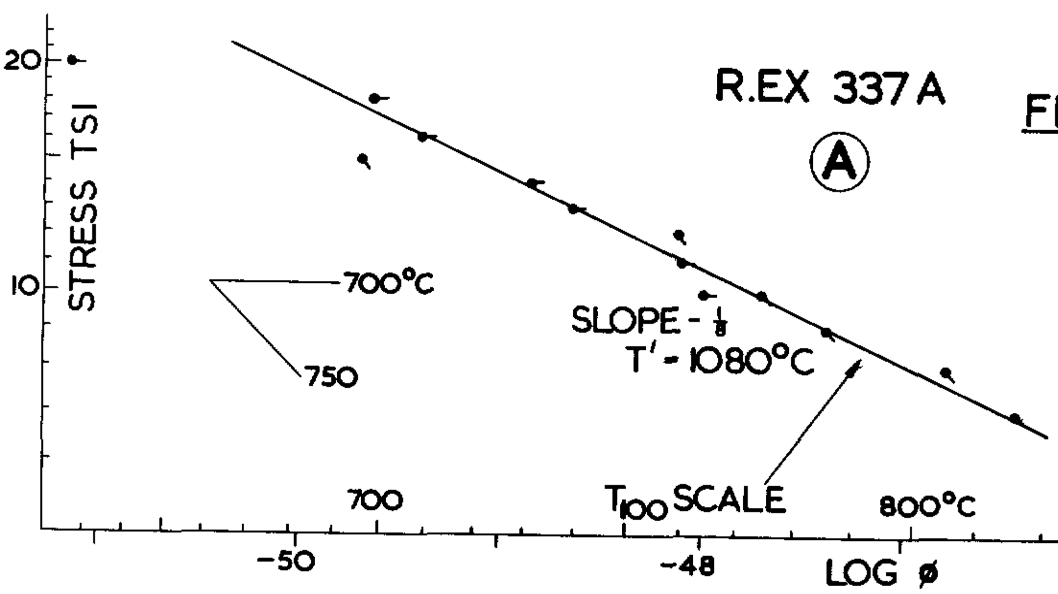


FIG. 36



CREEP RUPTURE 16-13-3 AND R.EX 337 A

FIG. 35a.

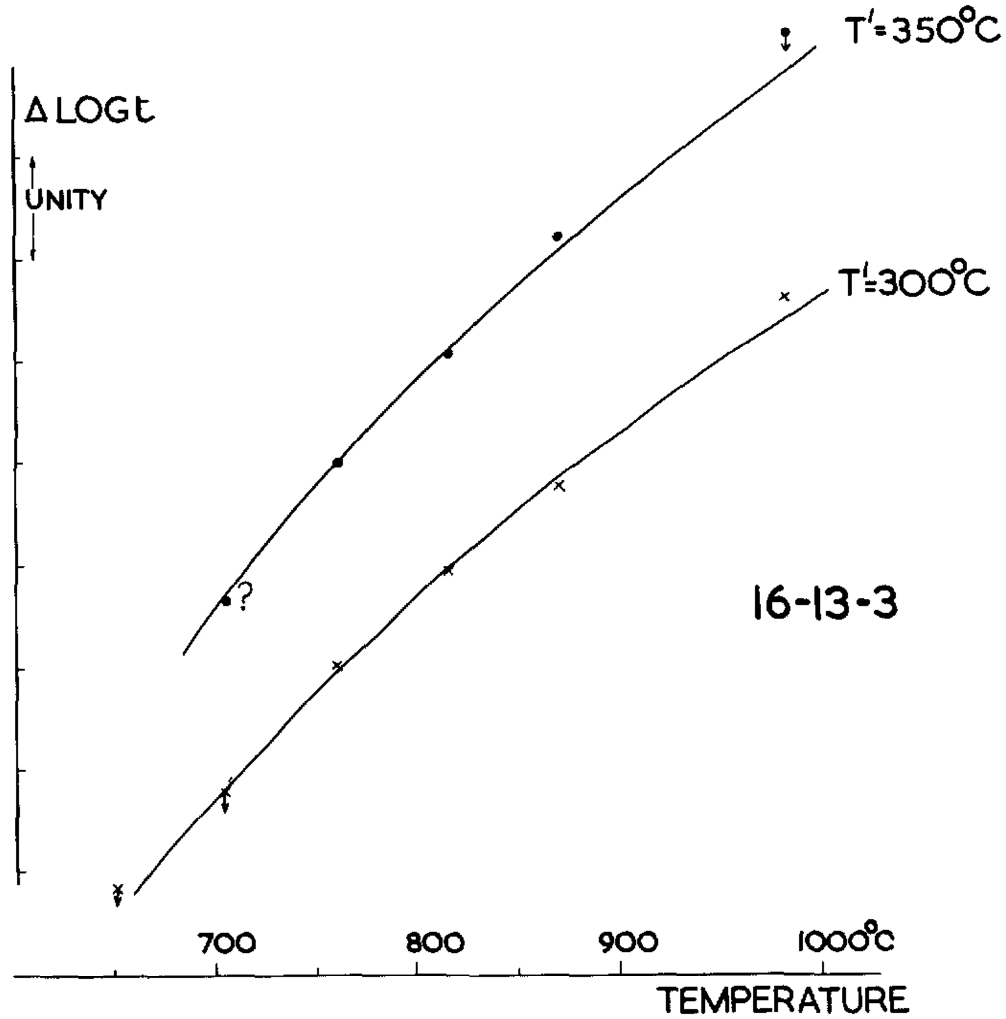
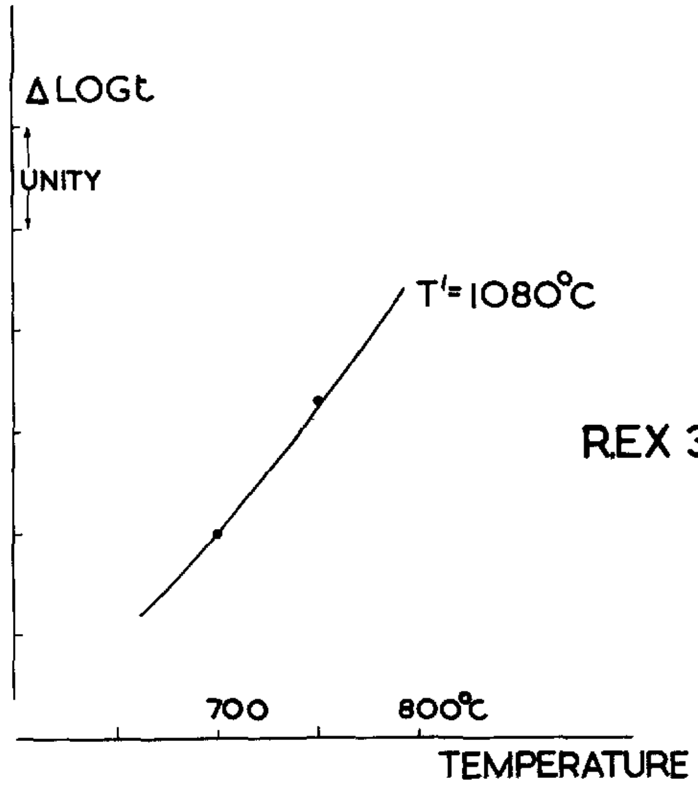


FIG. 36a.



Δ LOG t/T PLOTS 16-13-3 AND REX 337A

FIG. 37

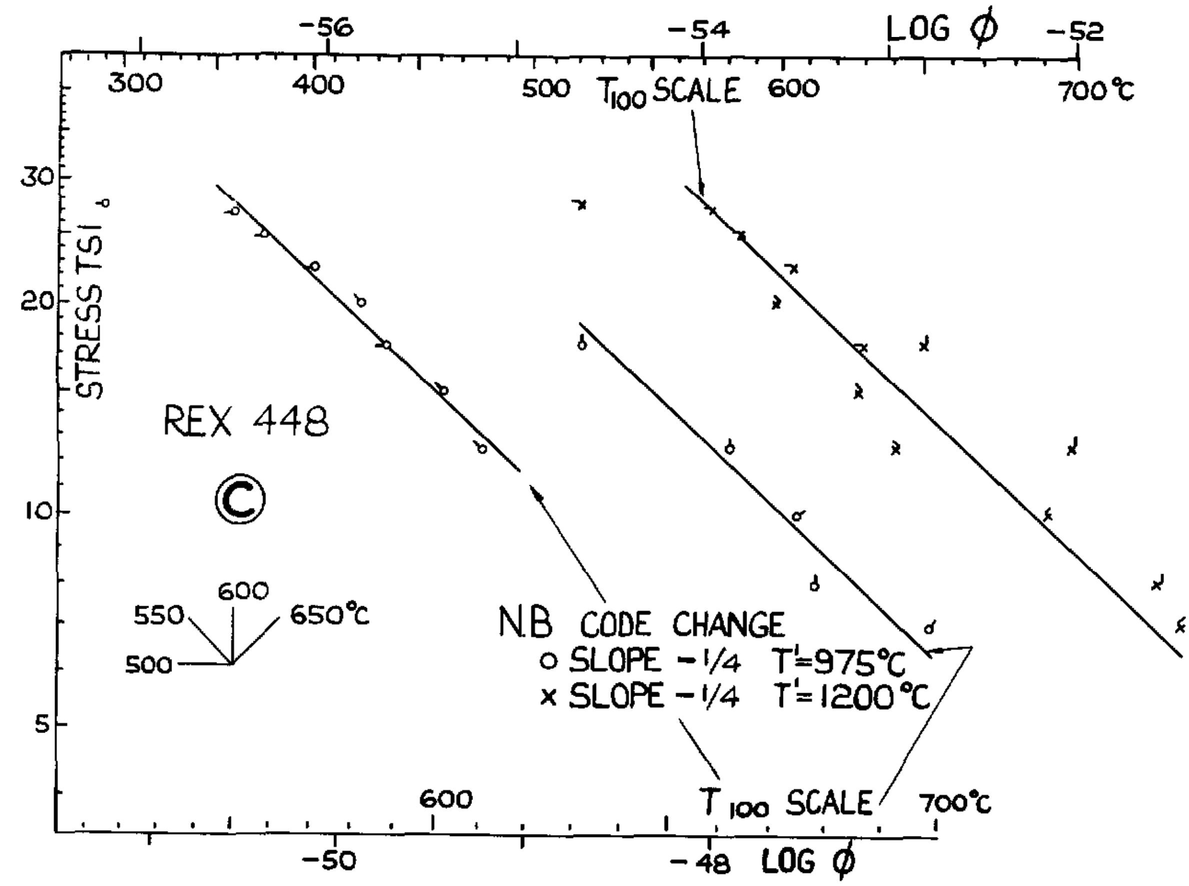
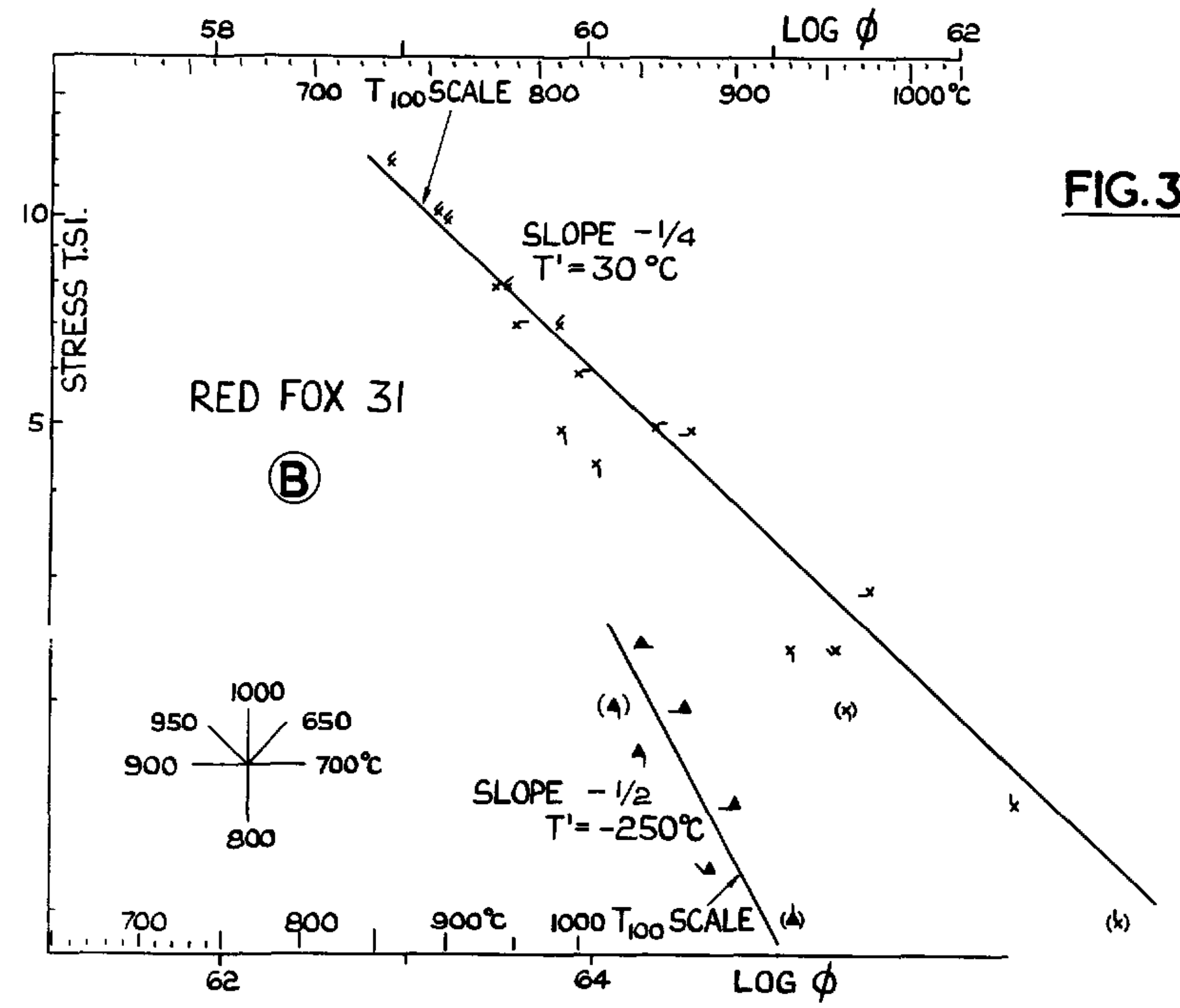


FIG. 38



CREEP RUPTURE R.EX 448 AND RED FOX 31

FIG. 37a

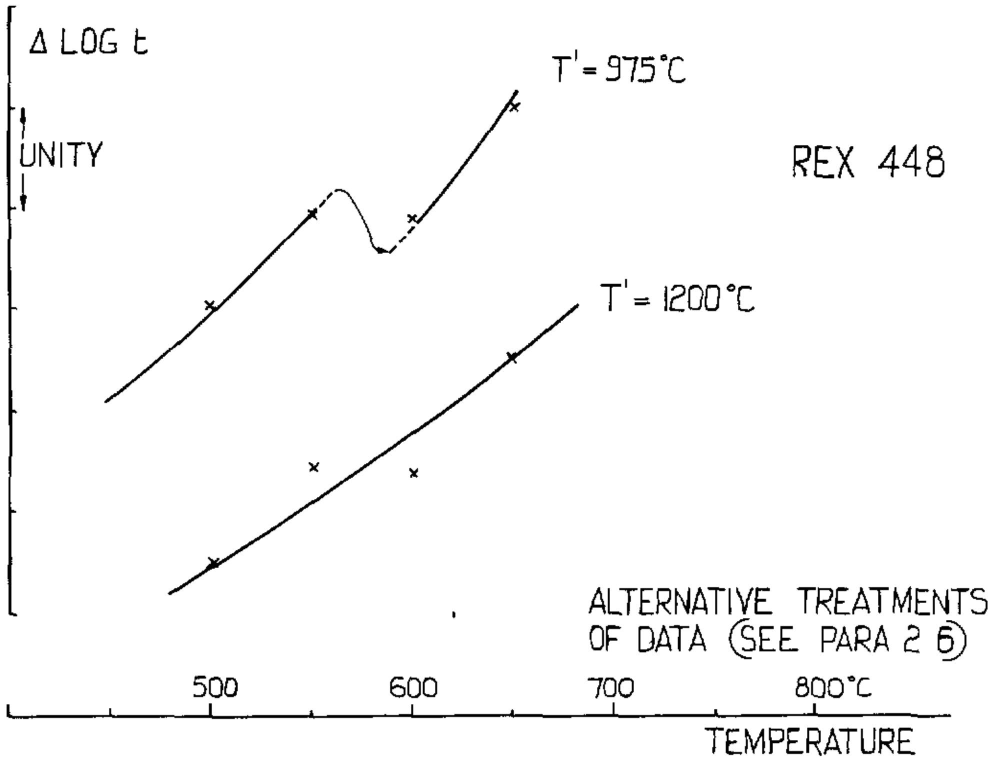
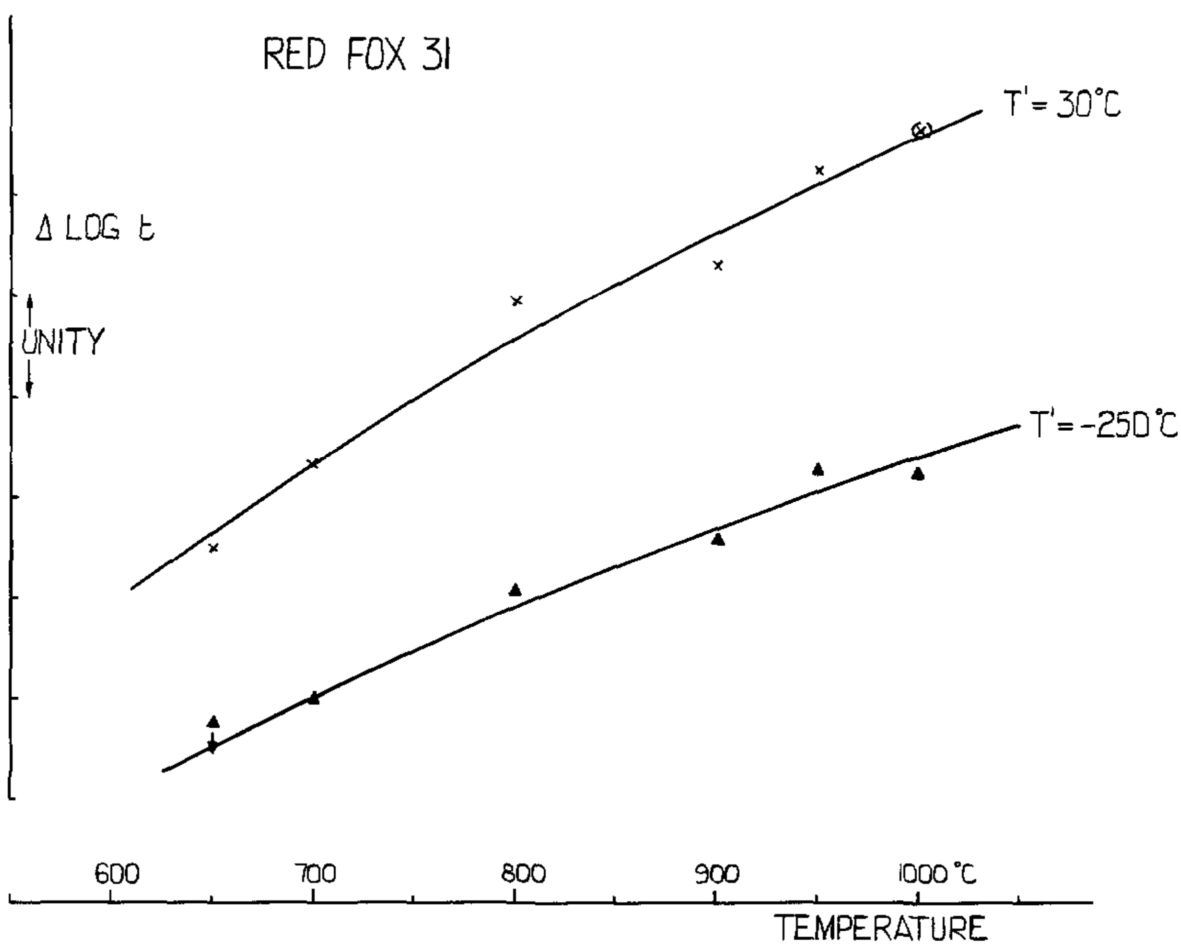


FIG. 38a



Δ LOG t/T PLOTS R.EX 448 AND RED FOX 31

FIG. 39

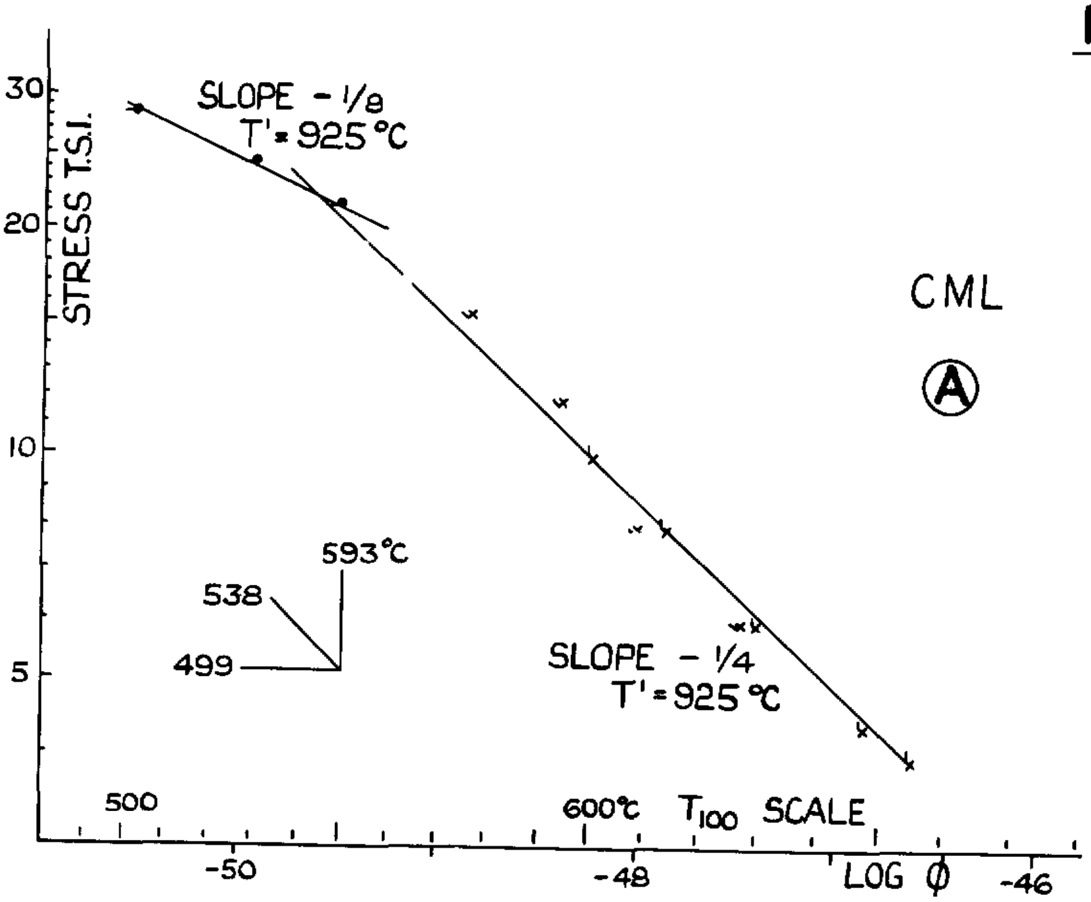
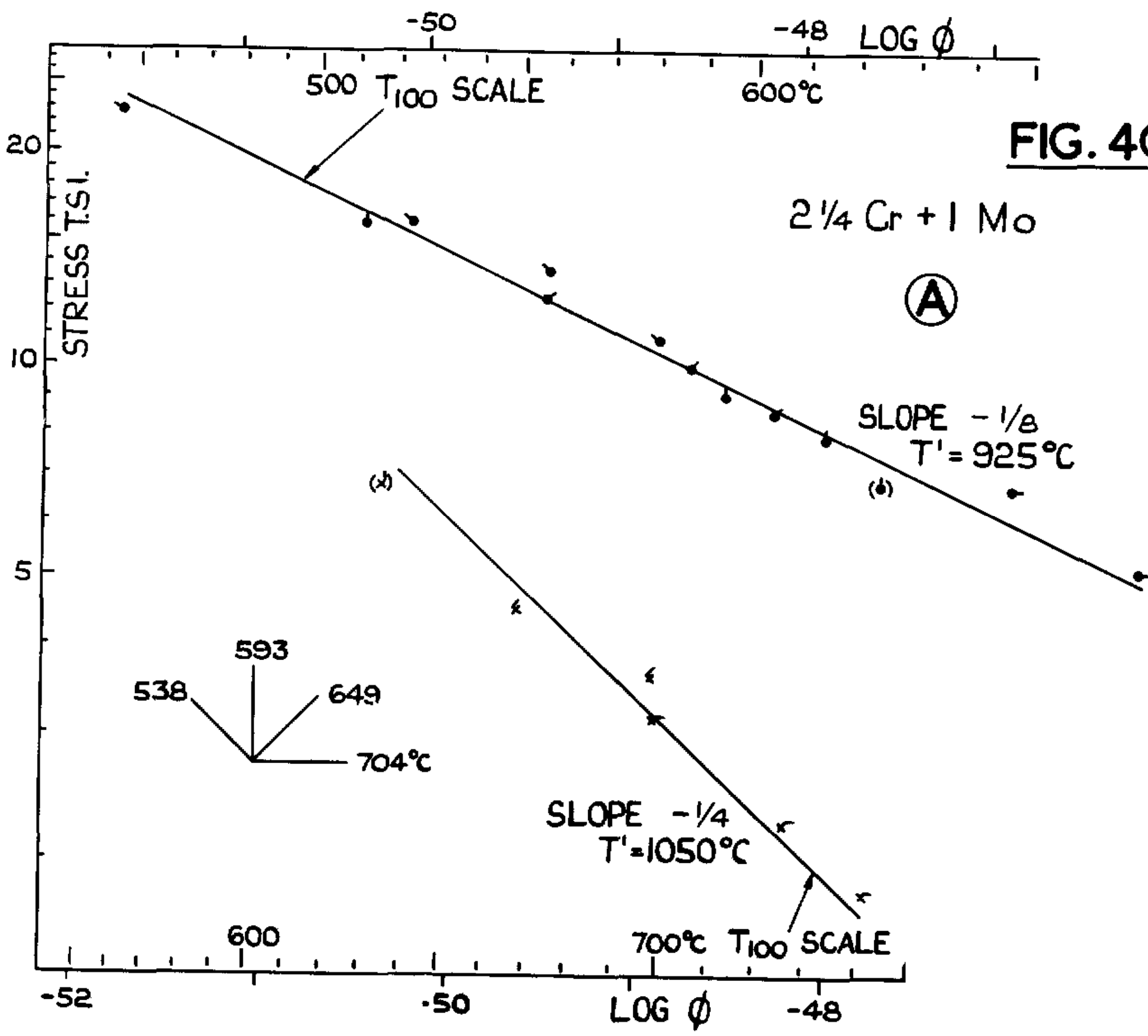


FIG. 40



CREEP RUPTURE ESSHETE CML
AND TIMKEN 2 1/4 Cr+1 Mo STEELS

FIG. 39a

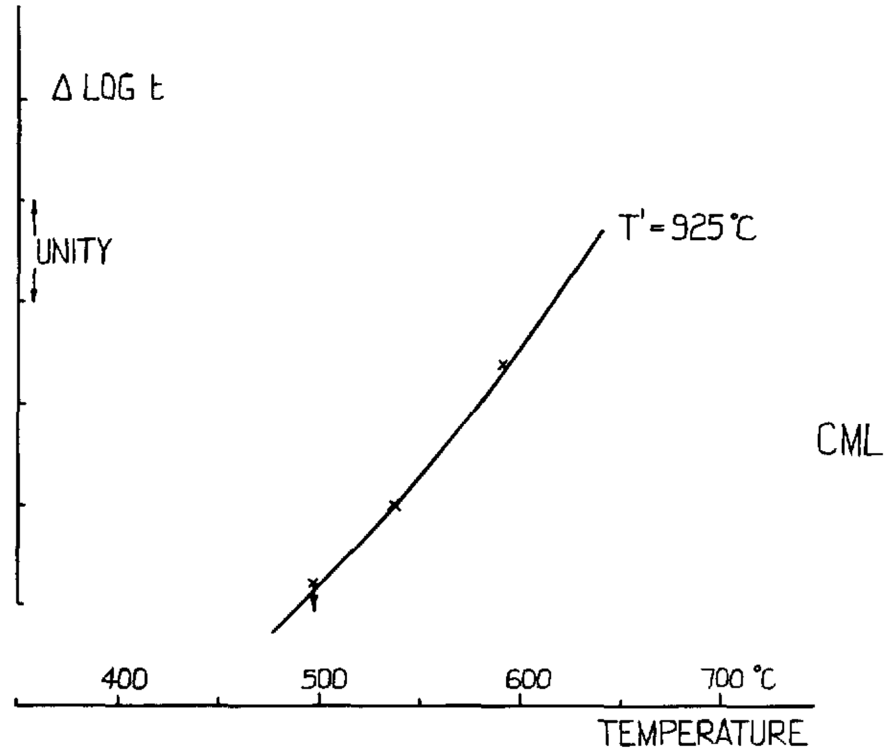
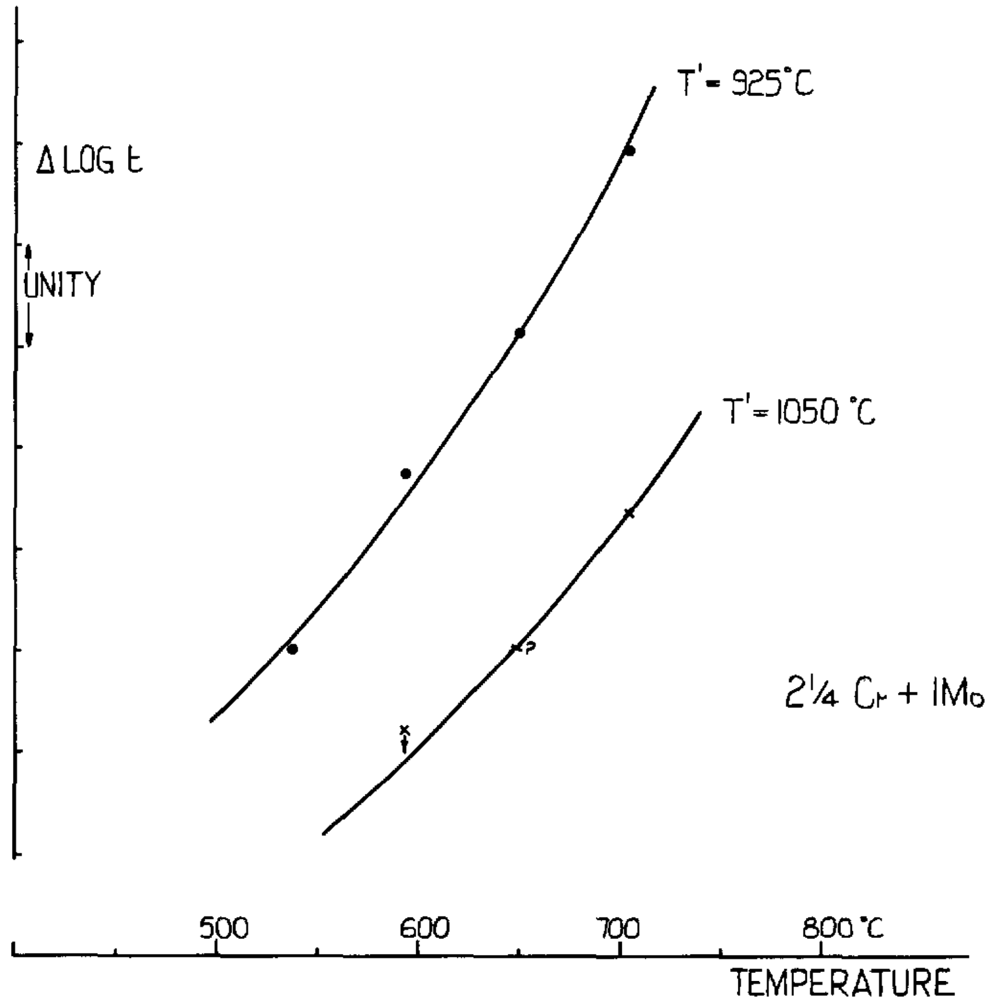


FIG. 40a



Δ LOG t/T PLOTS
ESSHETE CML AND TIMKEN 2¼ Cr+1Mo STEELS

FIG. 41

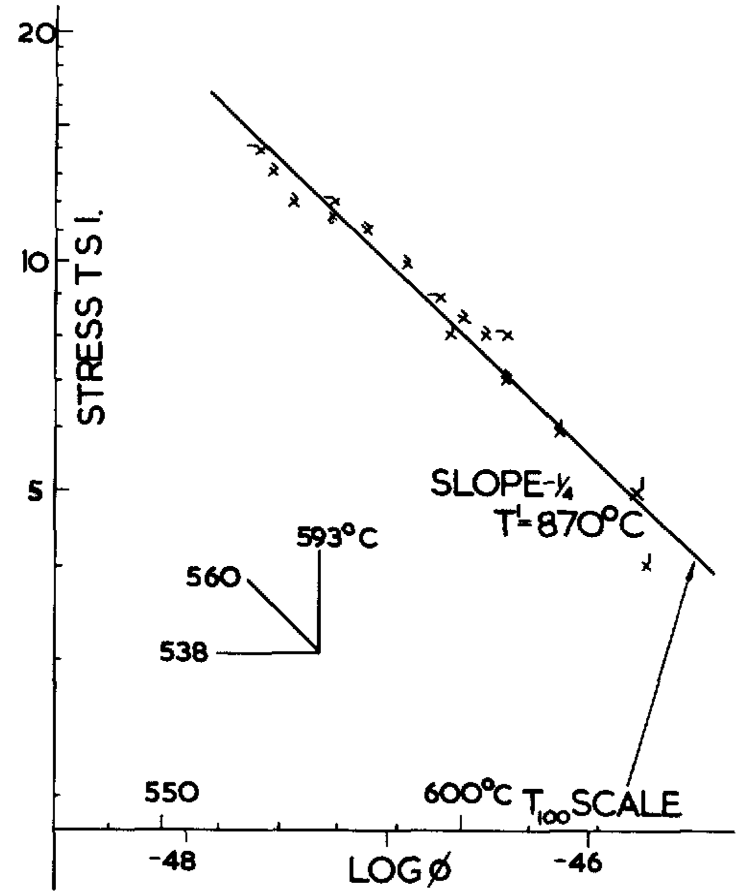
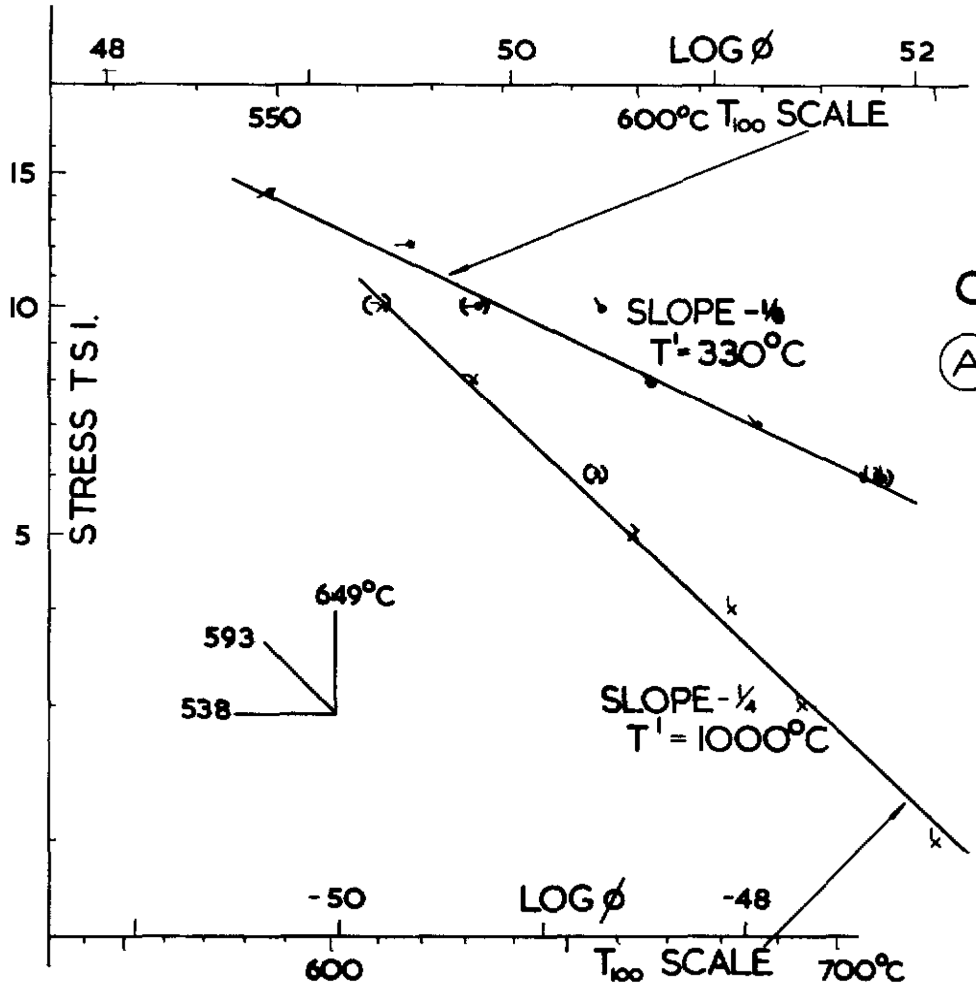


FIG. 42



CREEP RUPTURE ESSHETE CML AND CRM 2

FIG. 41a

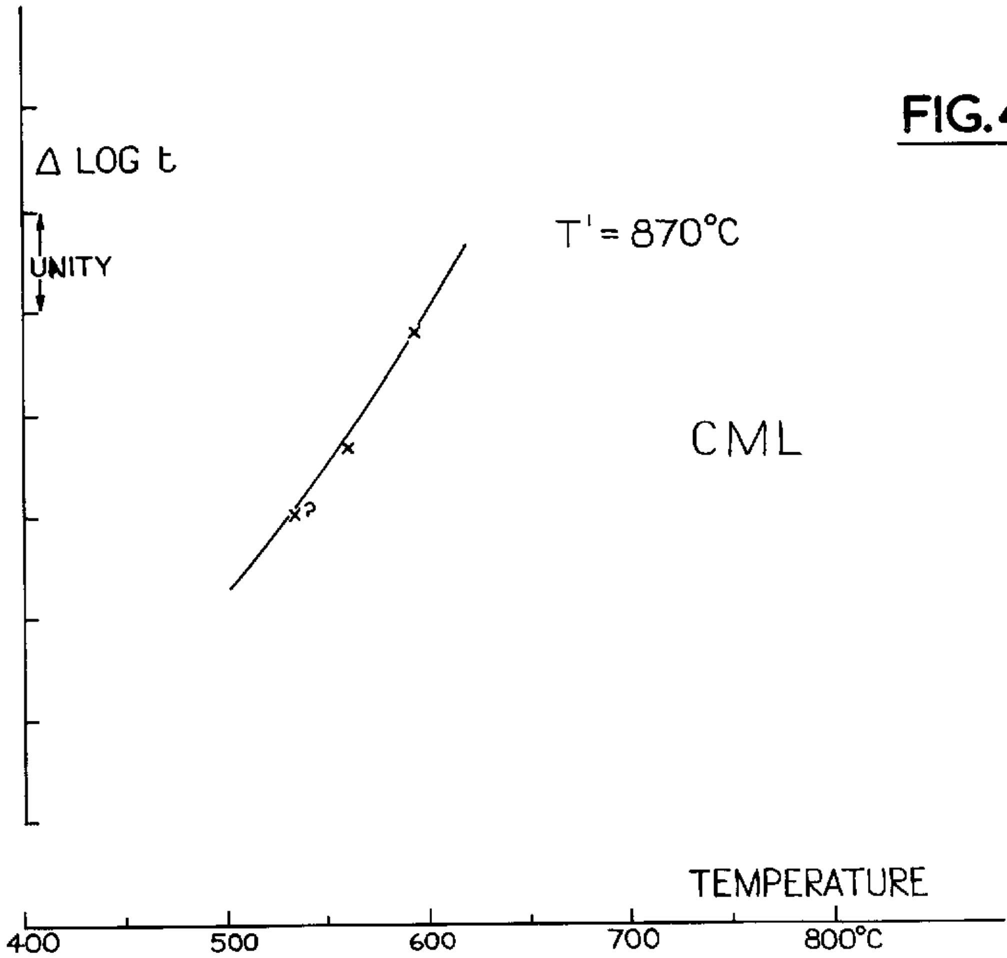
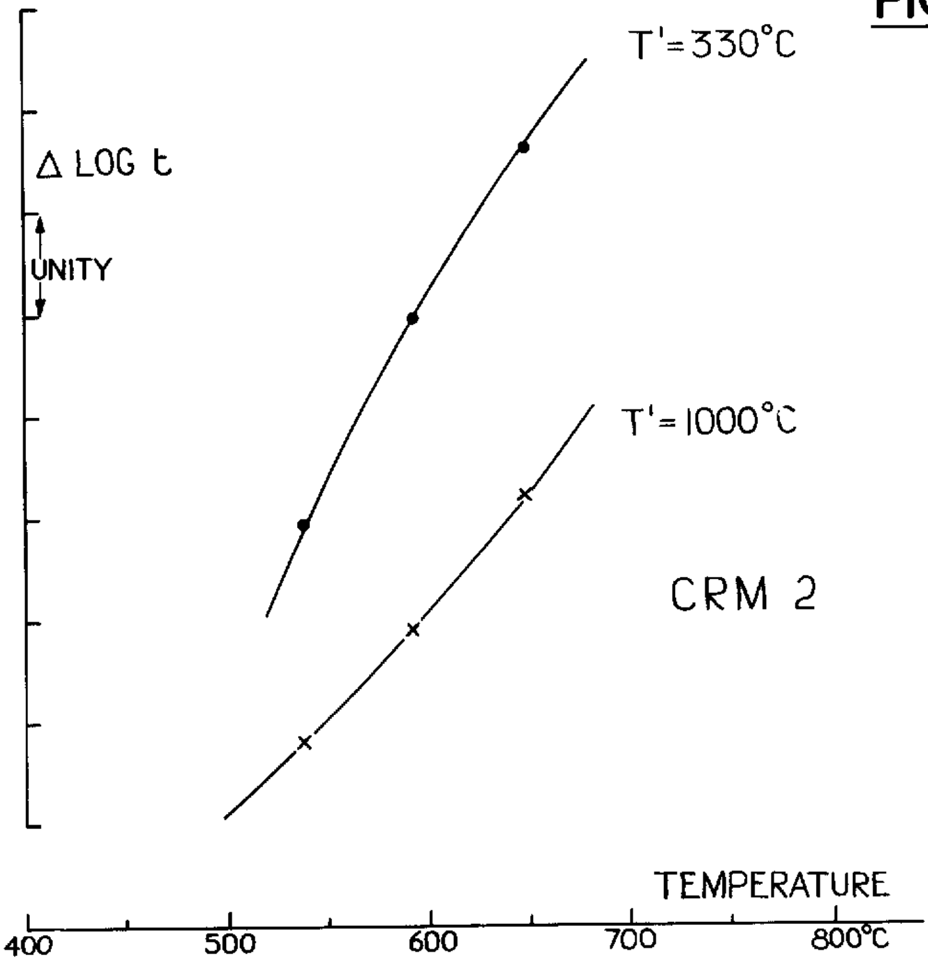
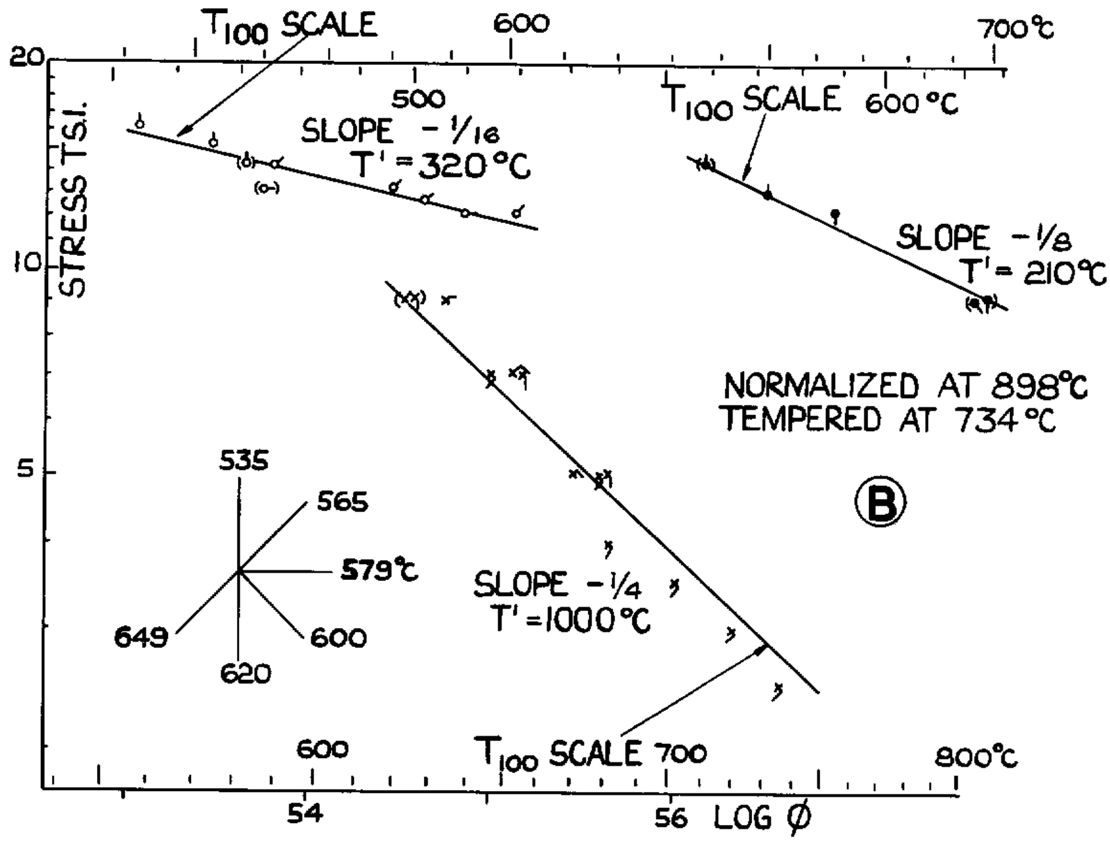


FIG. 42a



Δ LOG t/T PLOTS ESSHETE CML AND CRM2

FIG. 43



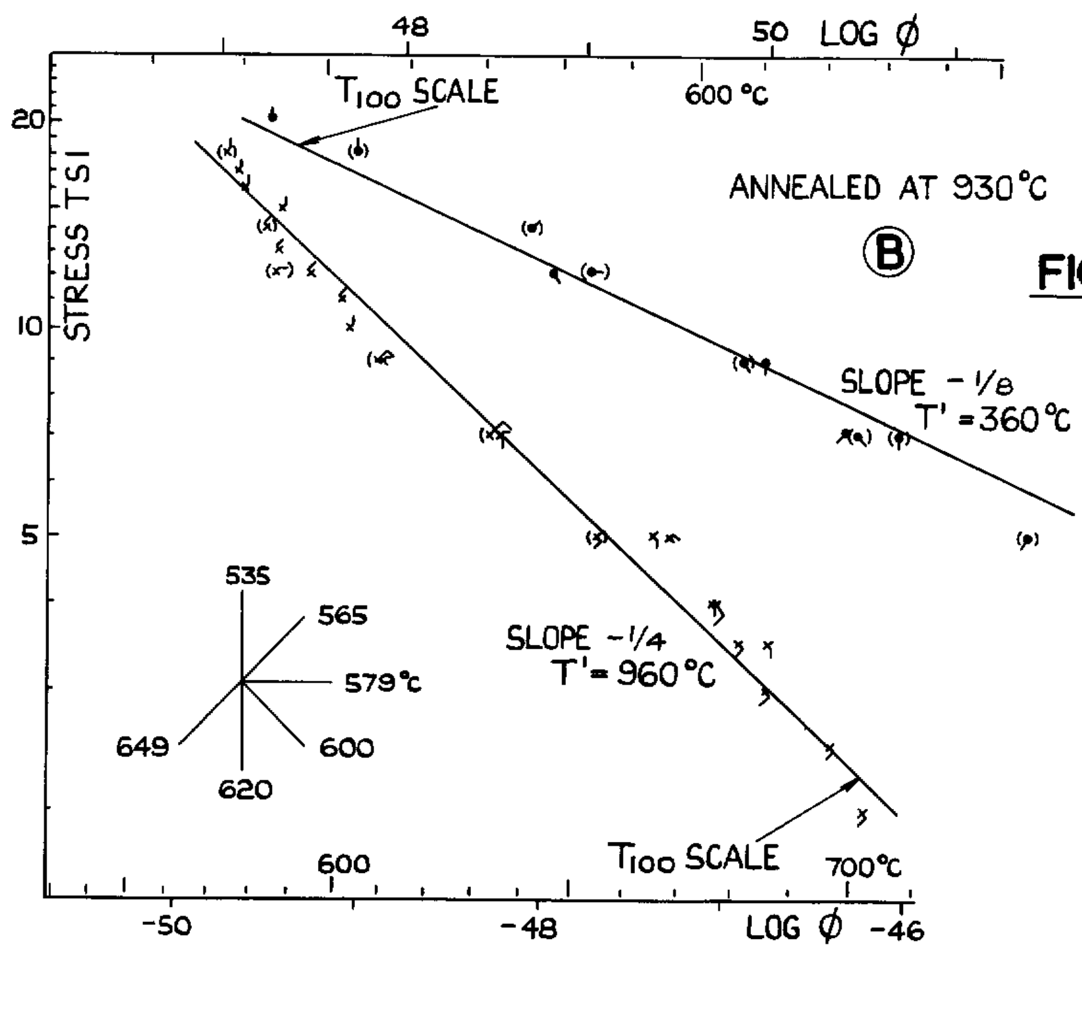


FIG. 44

CREEP RUPTURE ESSHETE CRM 2

FIG. 43a

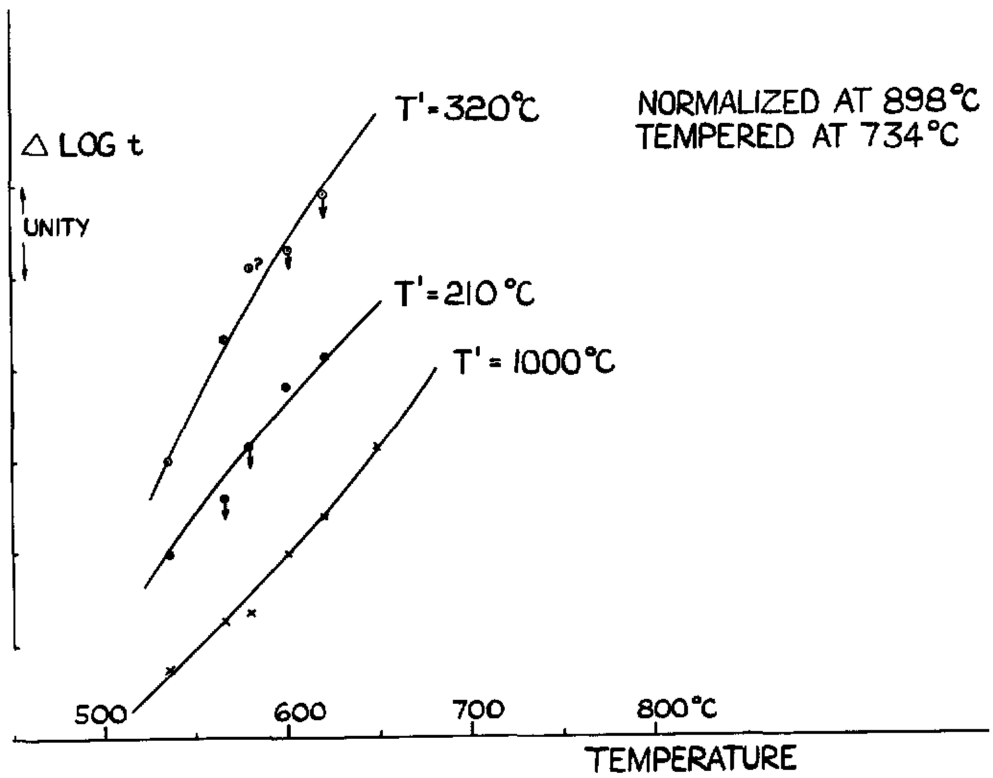
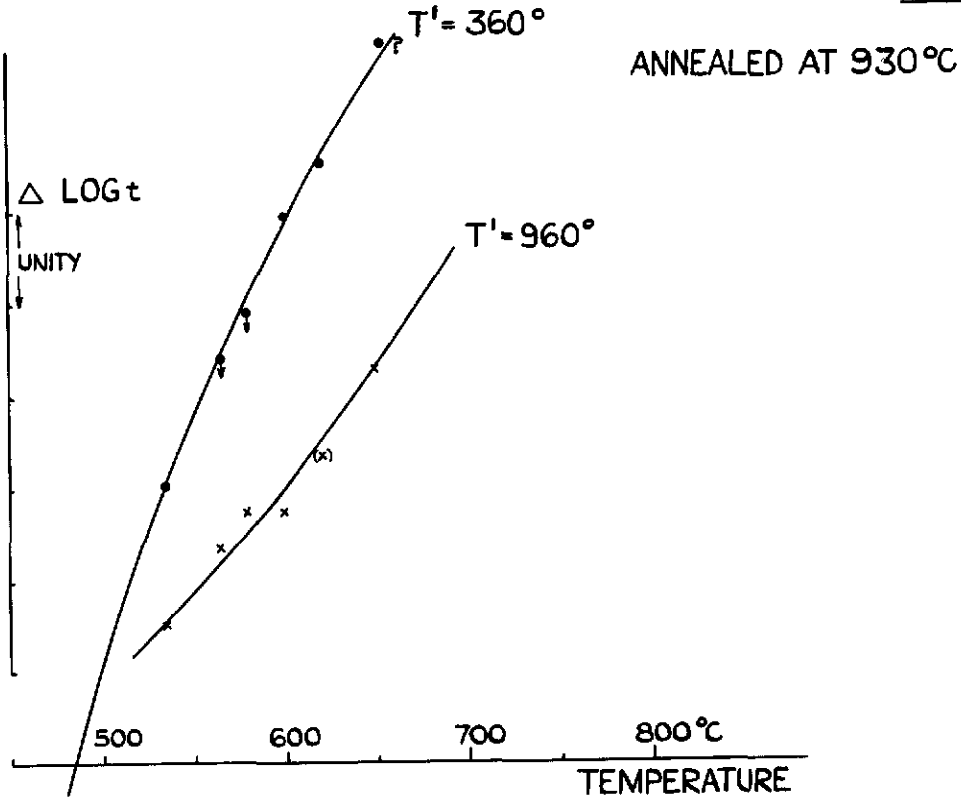


FIG. 44a



△ LOG t/T PLOTS ESSHETE CRM 2

FIG. 45

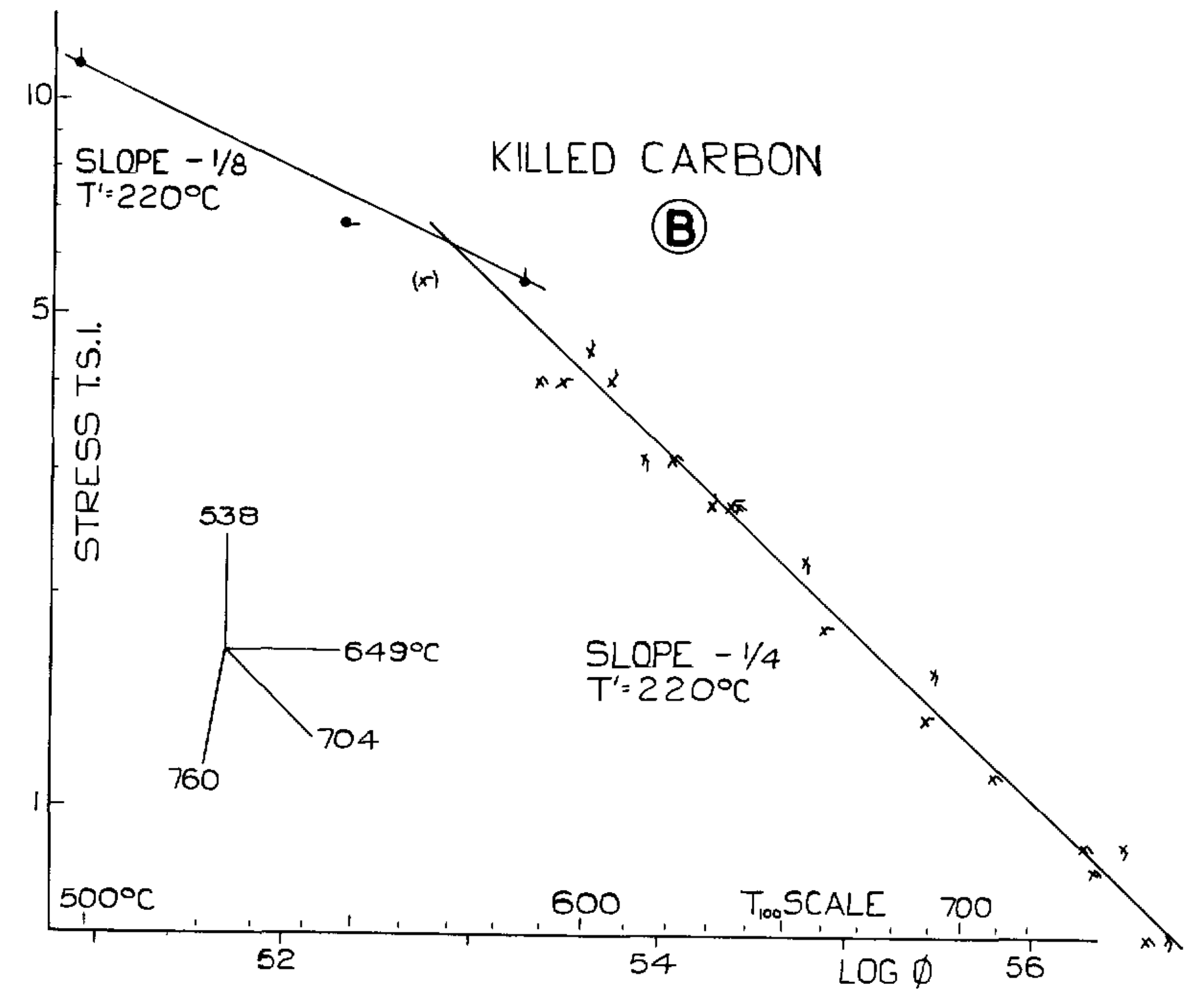
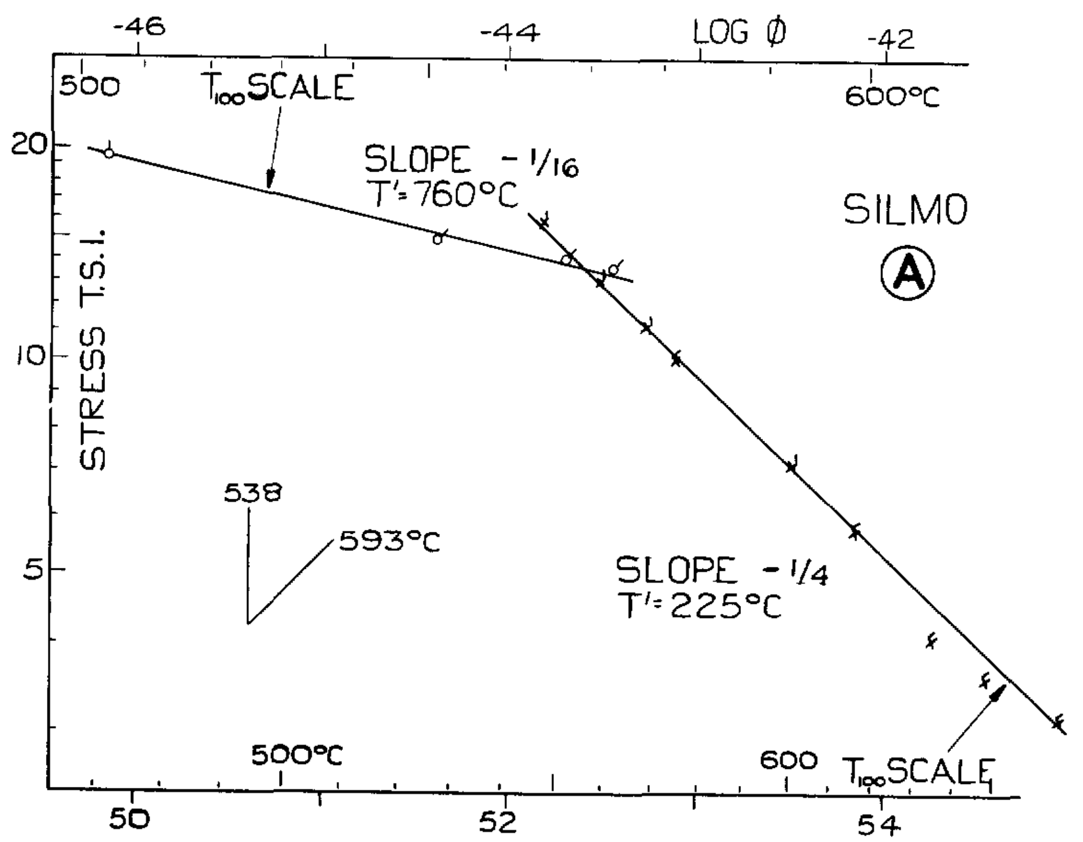


FIG. 46



CREEP RUPTURE

KILLED CARBON AND SILMO STEELS

FIG. 45a

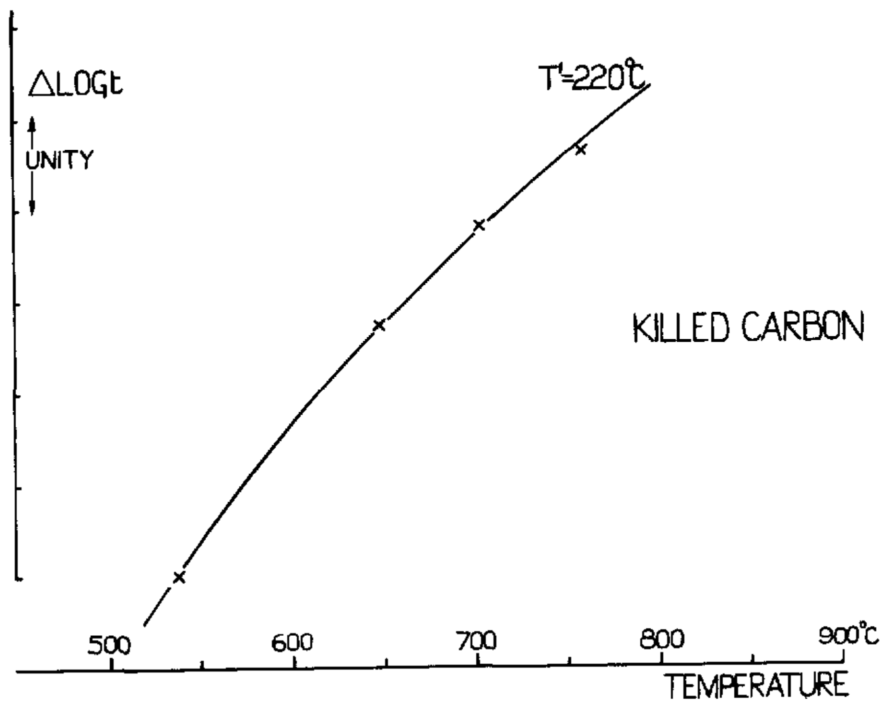
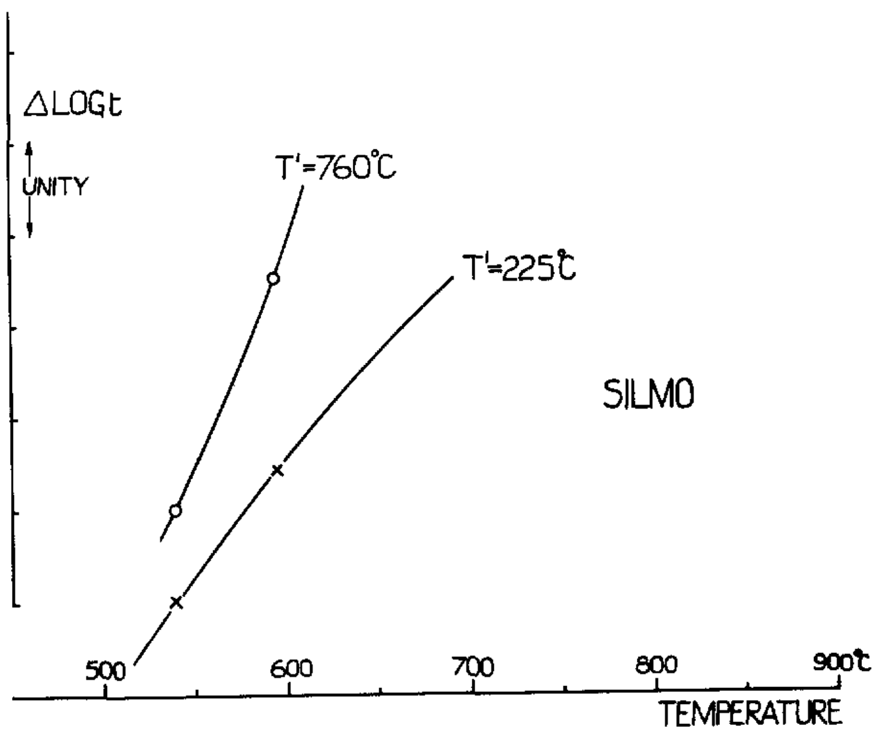
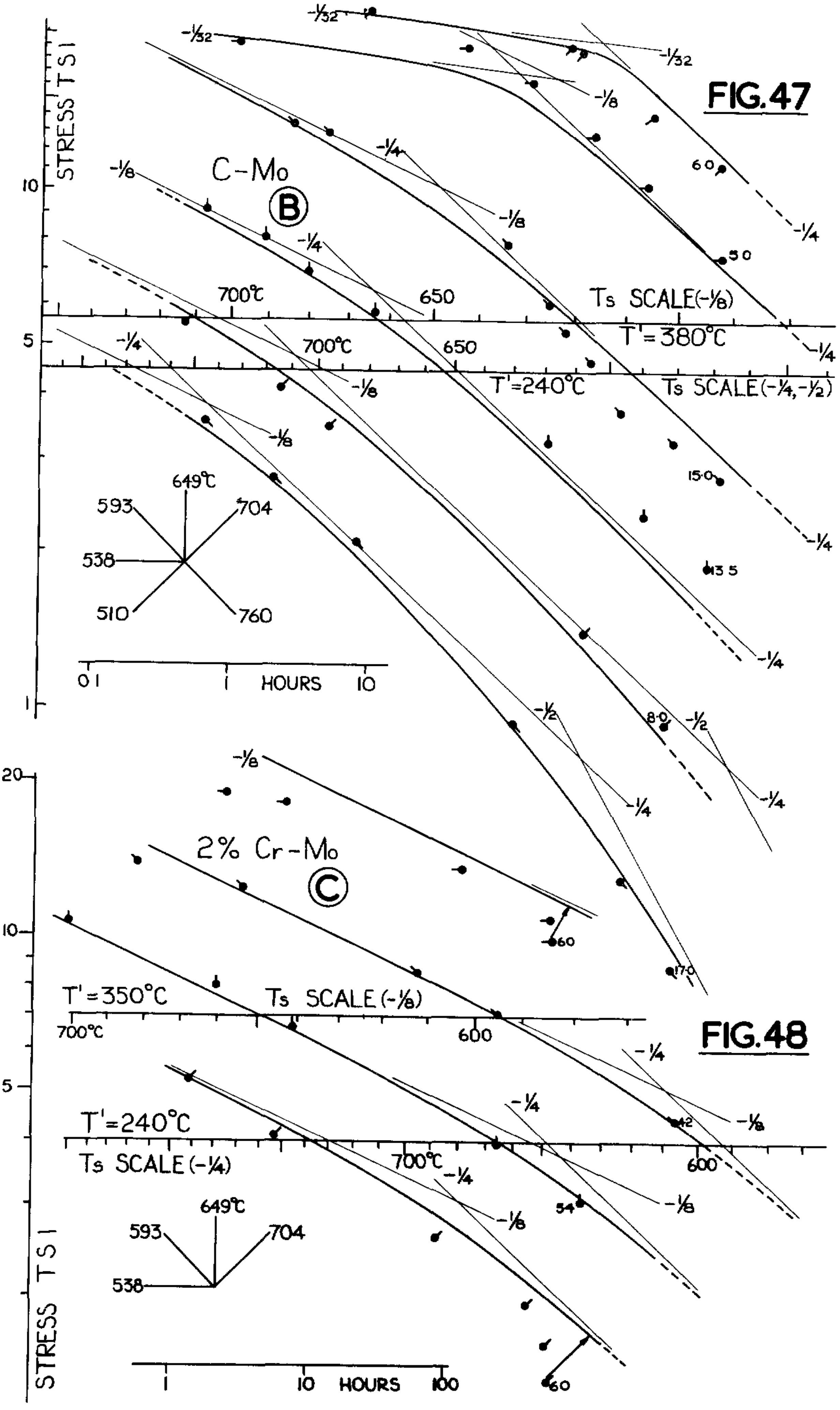


FIG. 46a



ΔLOGt /T PLOTS KILLED CARBON AND SILMO STEELS



SEE FIG 8c FOR LEGENDS

CREEP RUPTURE C-Mo AND 2% Cr-Mo

FIG. 47a

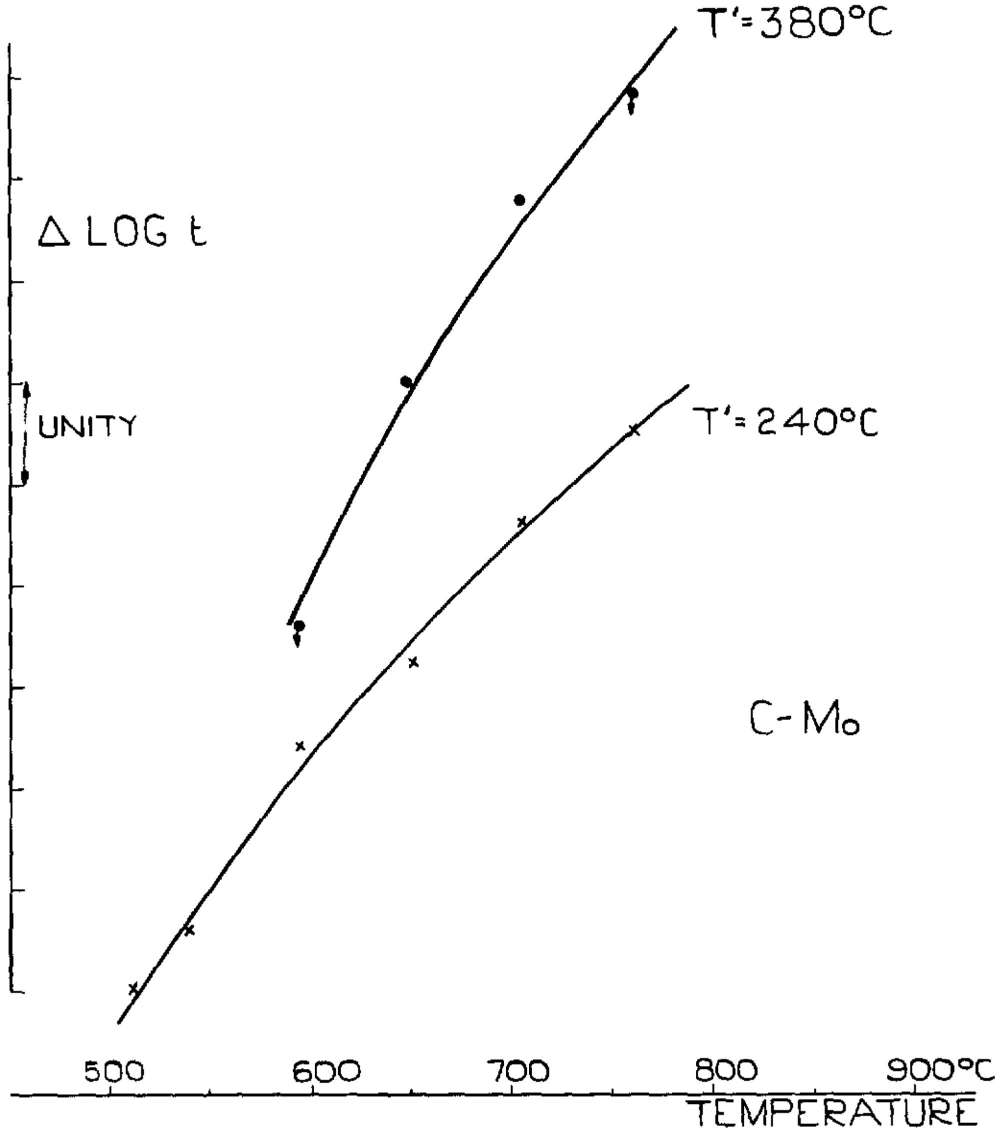
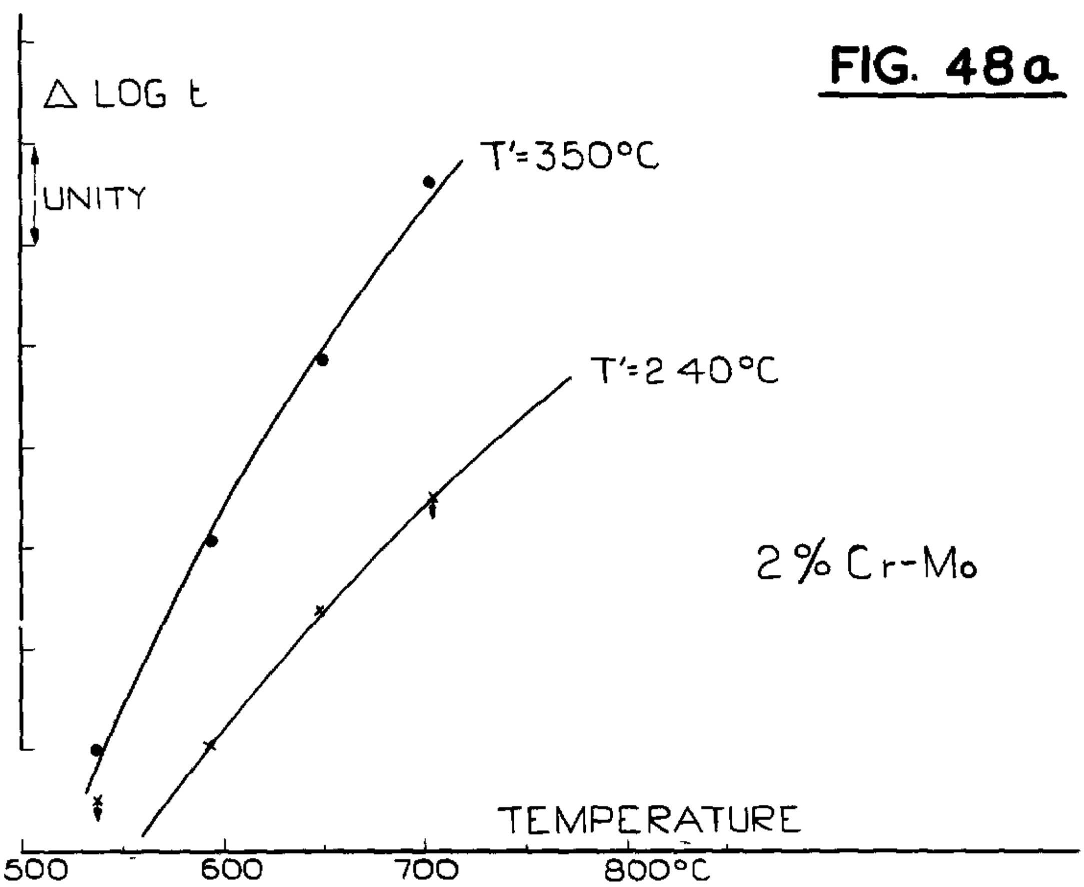


FIG. 48a



Δ LOG t/T PLOTS C-Mo AND 2% Cr Mo STEELS

FIG. 49

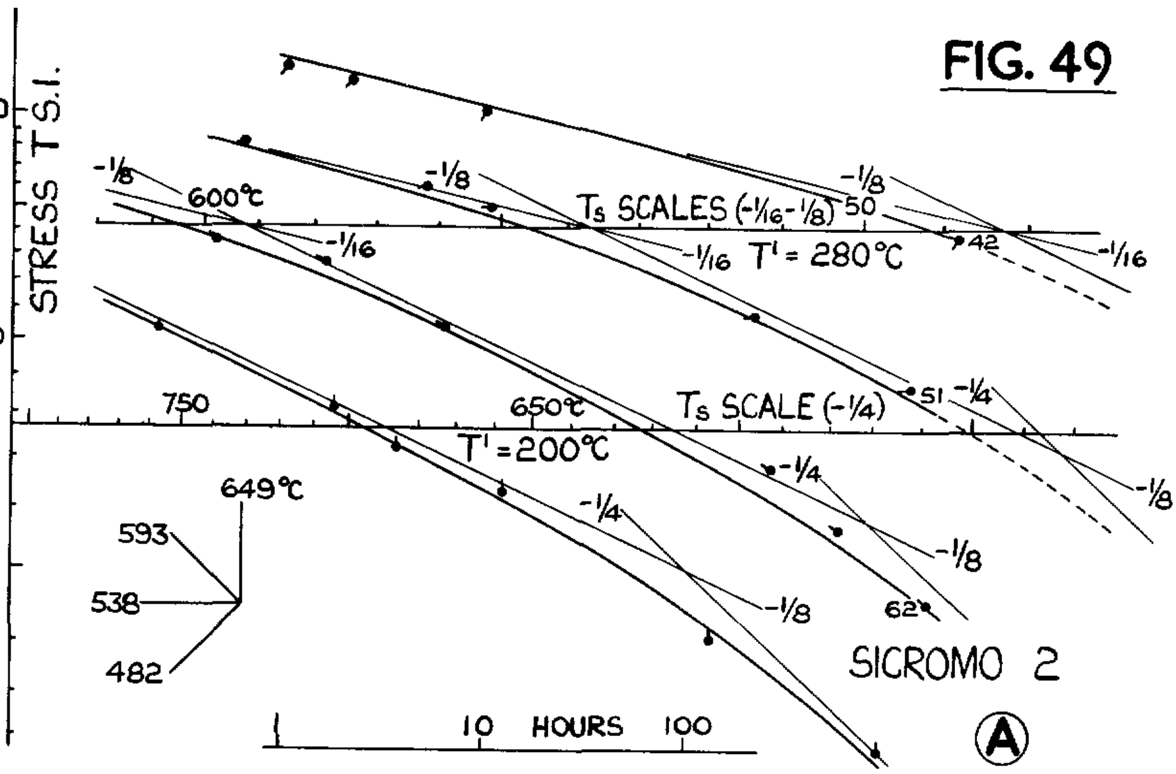
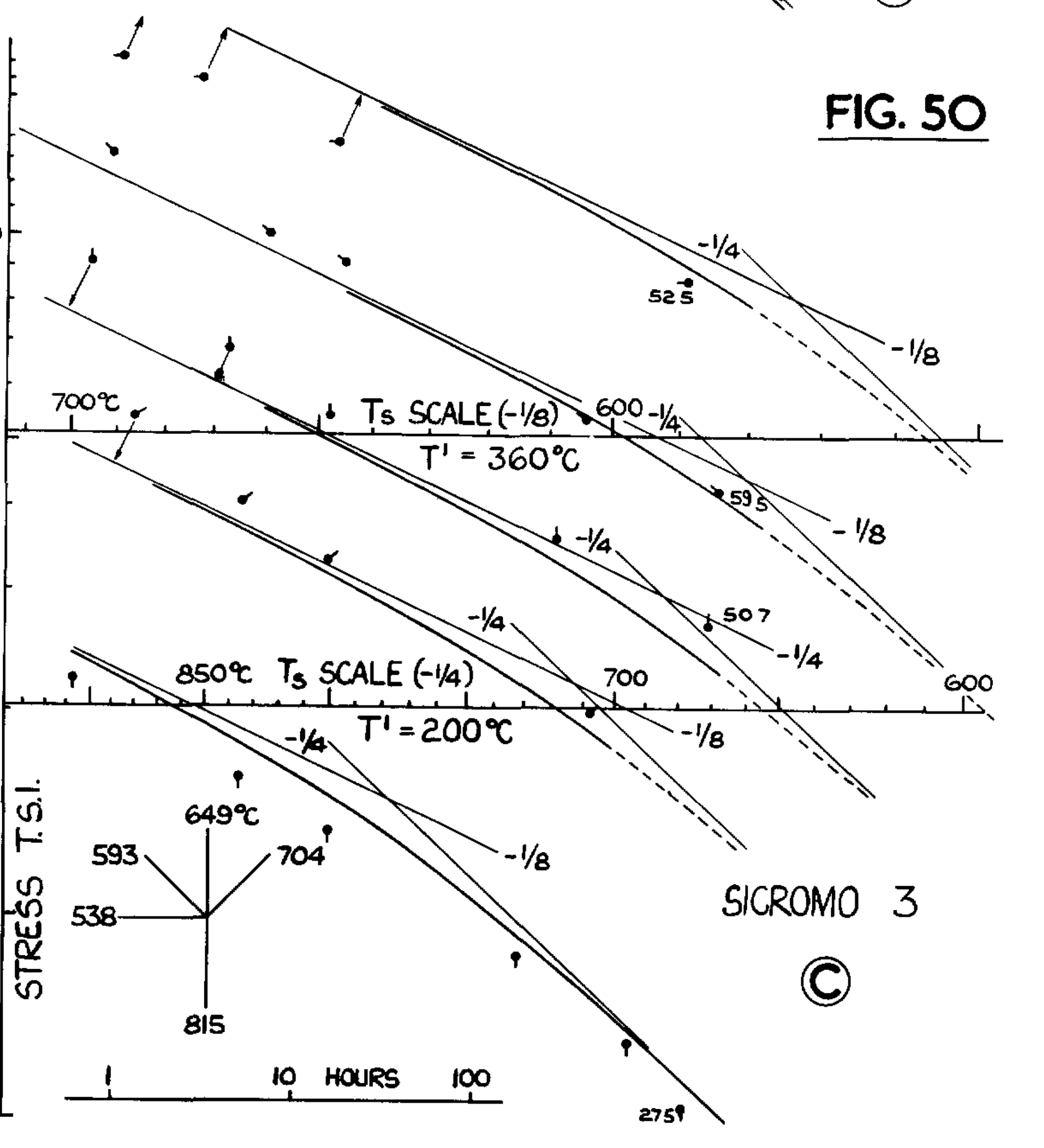


FIG. 50



CREEP RUPTURE SICROMO 2 AND SICROMO 3

FIG. 49a

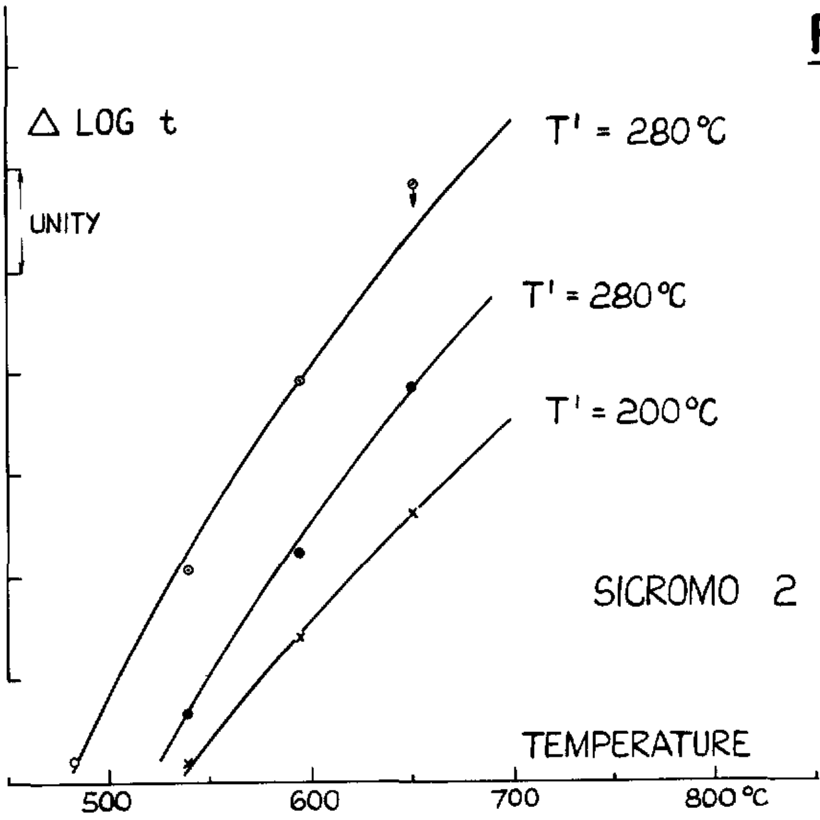
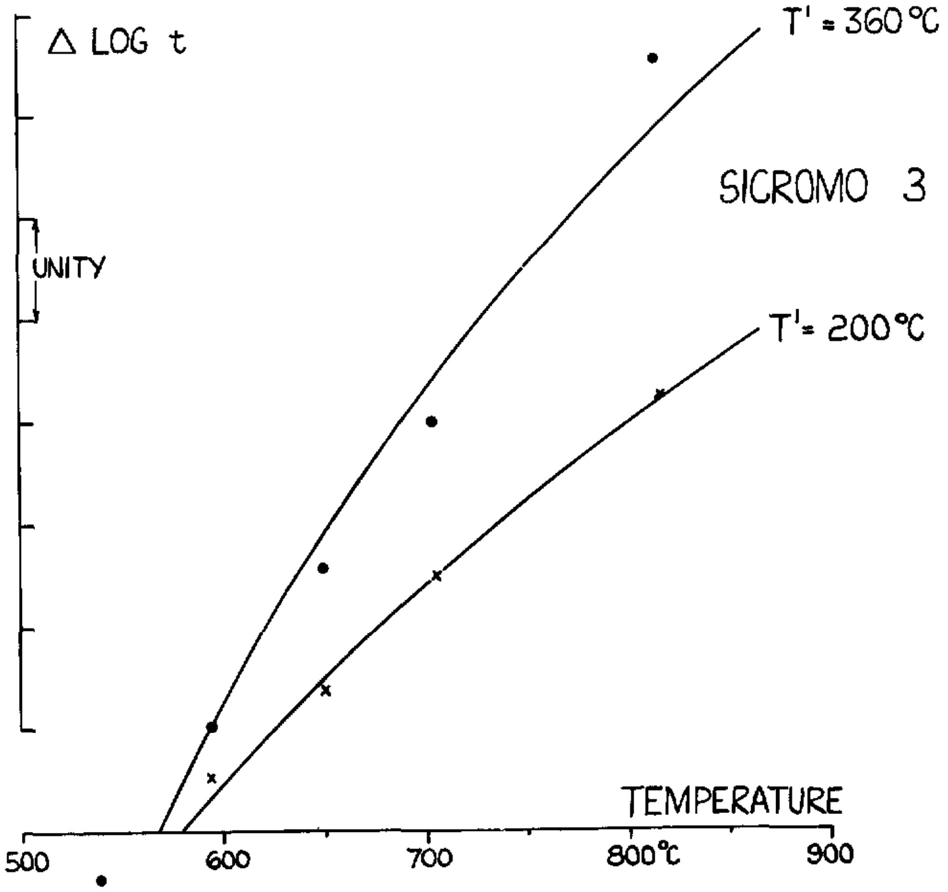


FIG. 50a



LOG t/T PLOTS SICROMO 2 & SICROMO 3

FIG. 51

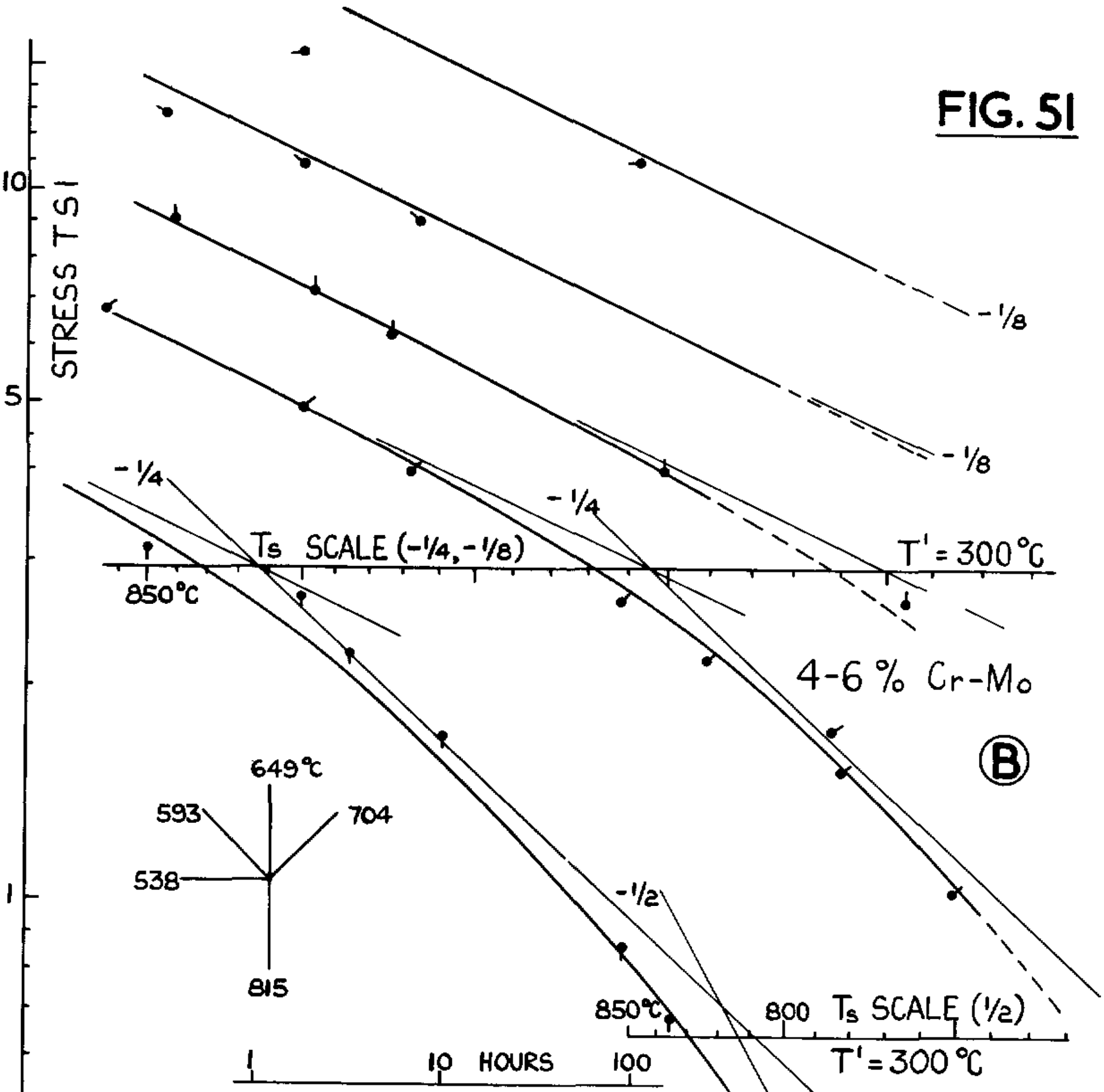
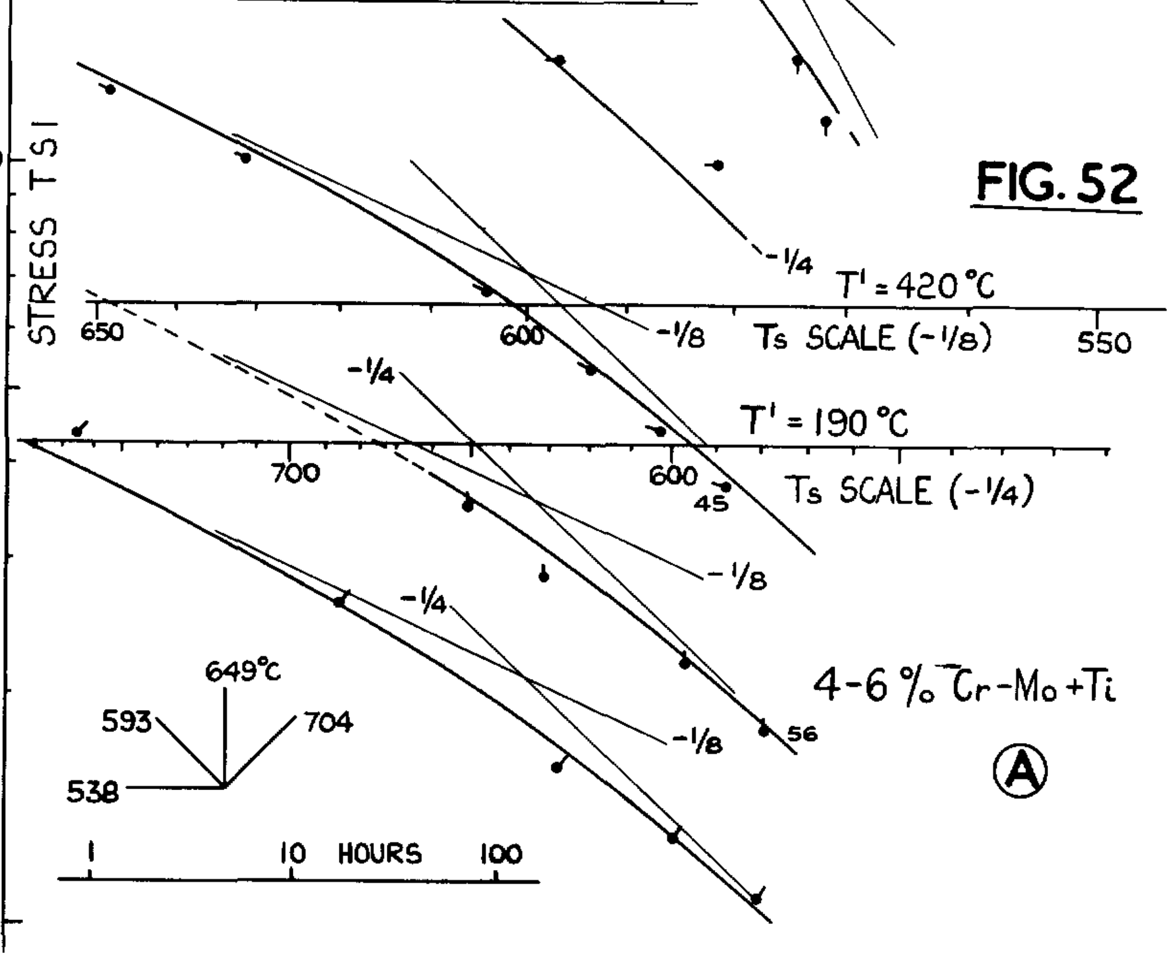


FIG. 52



CREEP RUPTURE 4-6% Cr-Mo & 4-6% Cr-Mo+Ti

FIG. 51a

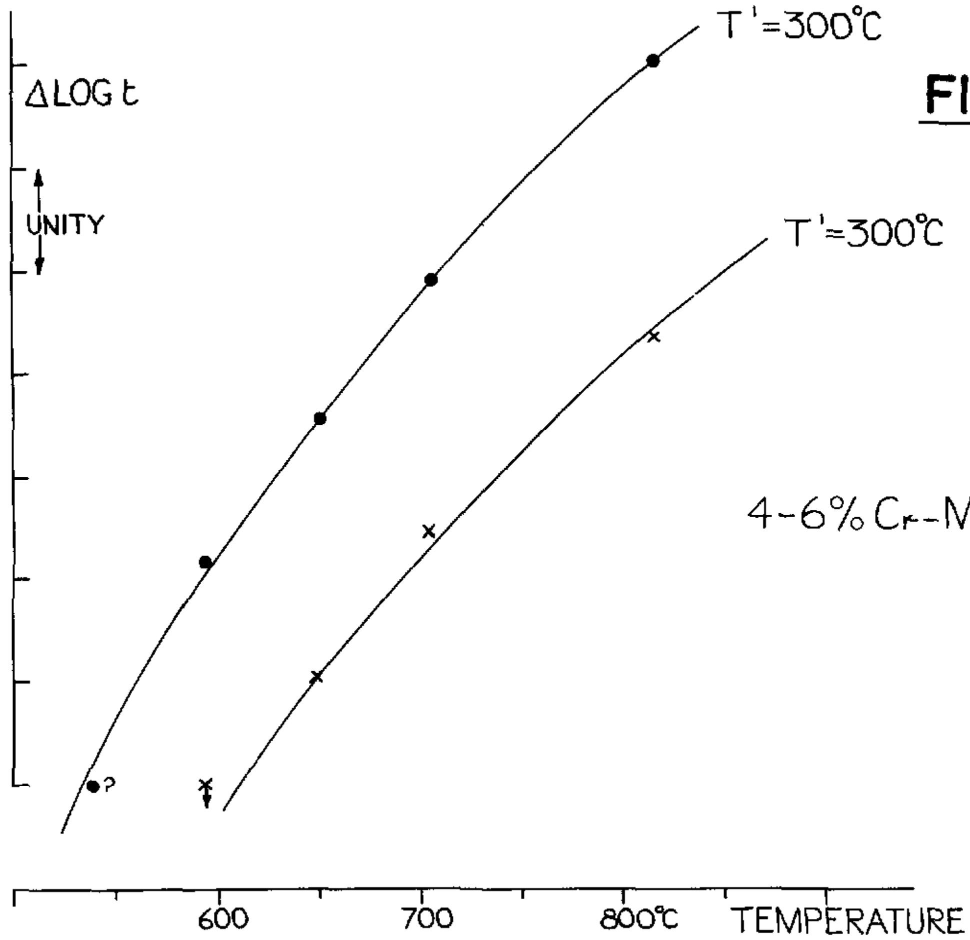
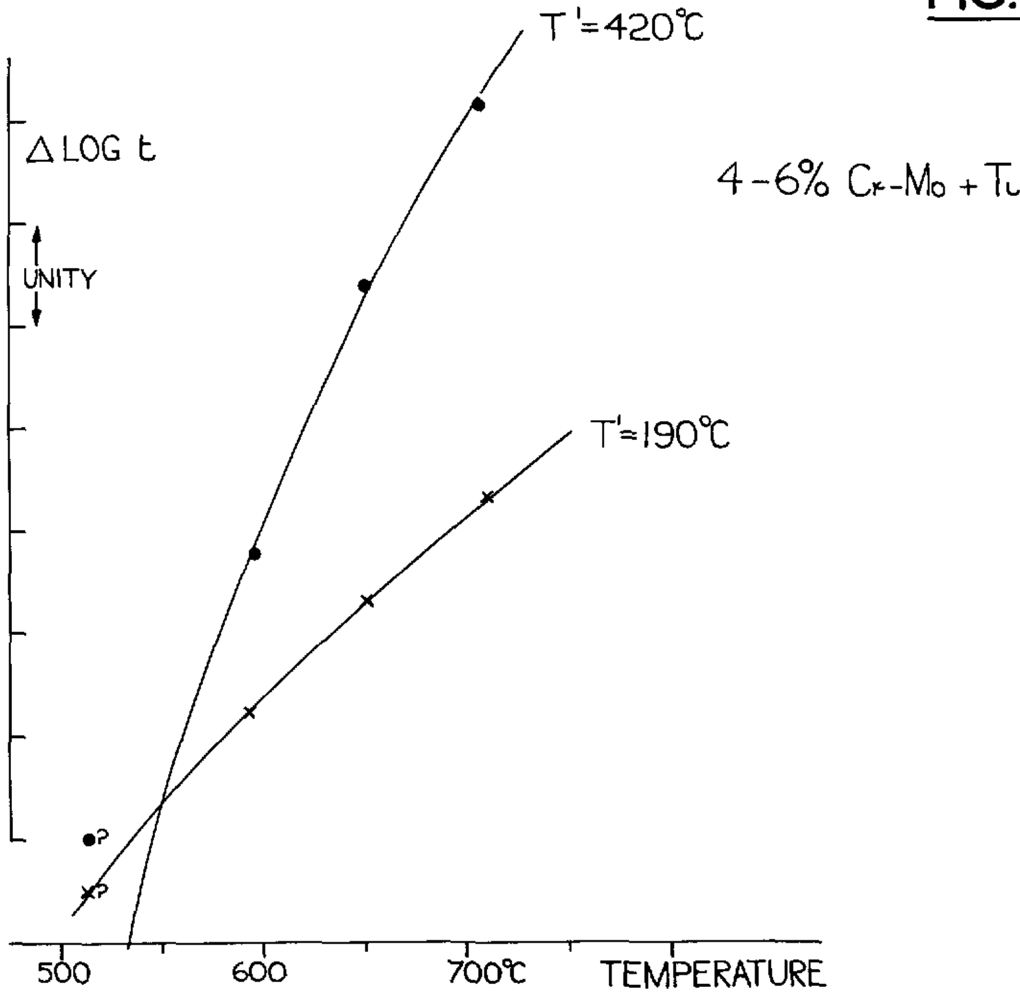
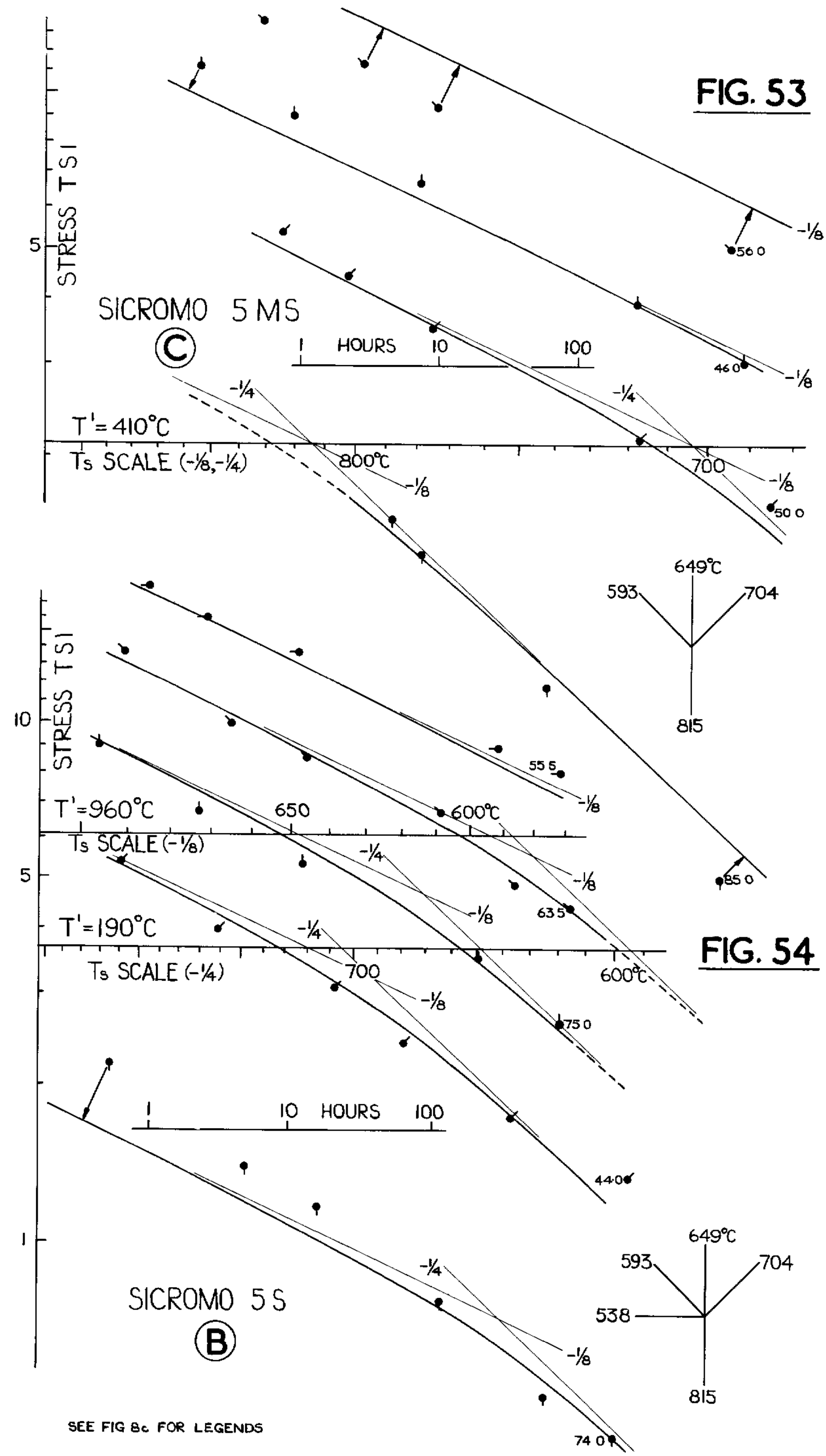


FIG. 52a



ΔLOG t/T PLOTS 4-6%Cr-Mo AND 4-6%Cr-Mo+Ti



CREEP RUPTURE SICROMO 5 MS AND SICROMO 5 S

FIG. 53a

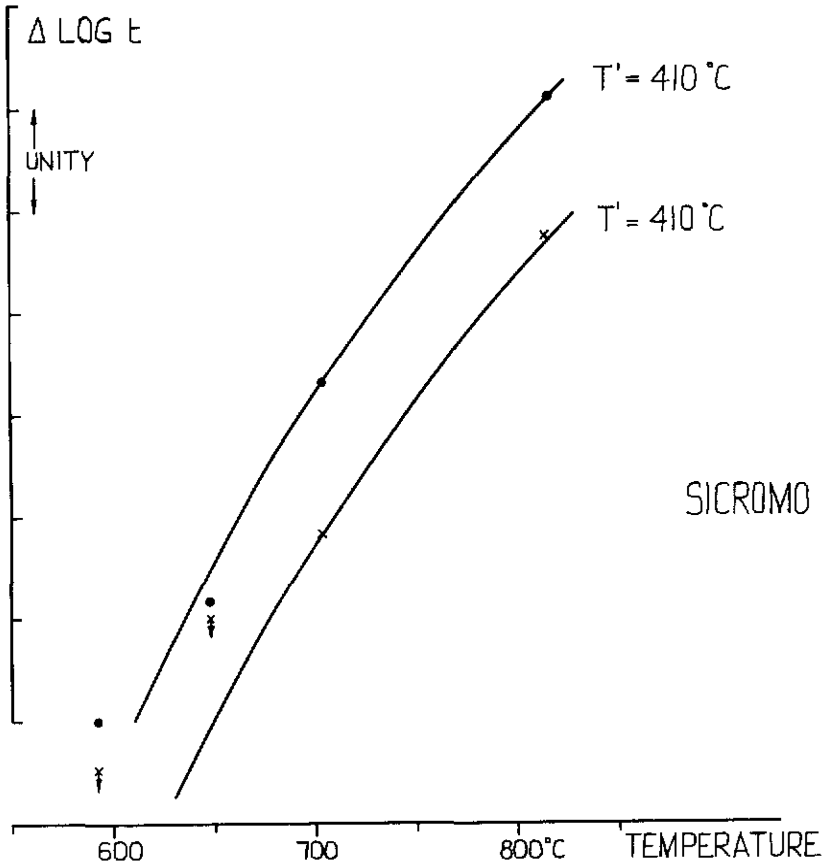
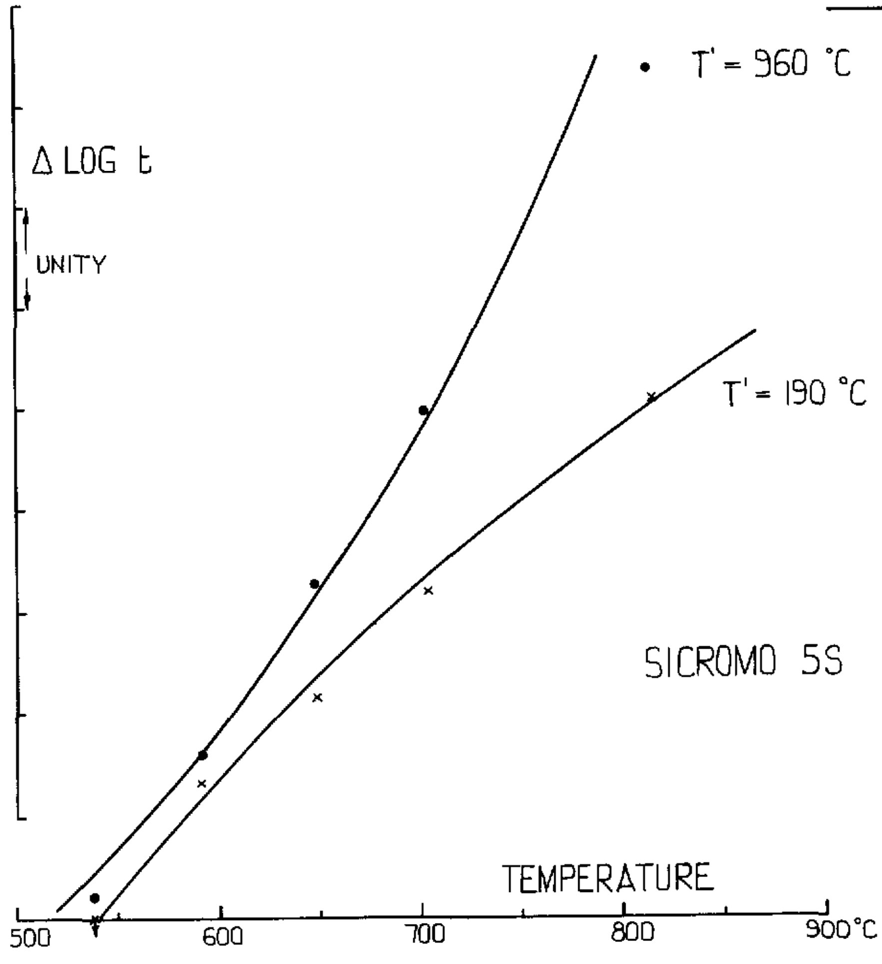


FIG. 54a



Δ LOG t/T PLOTS SICROMO 5MS AND SICROMO 5S

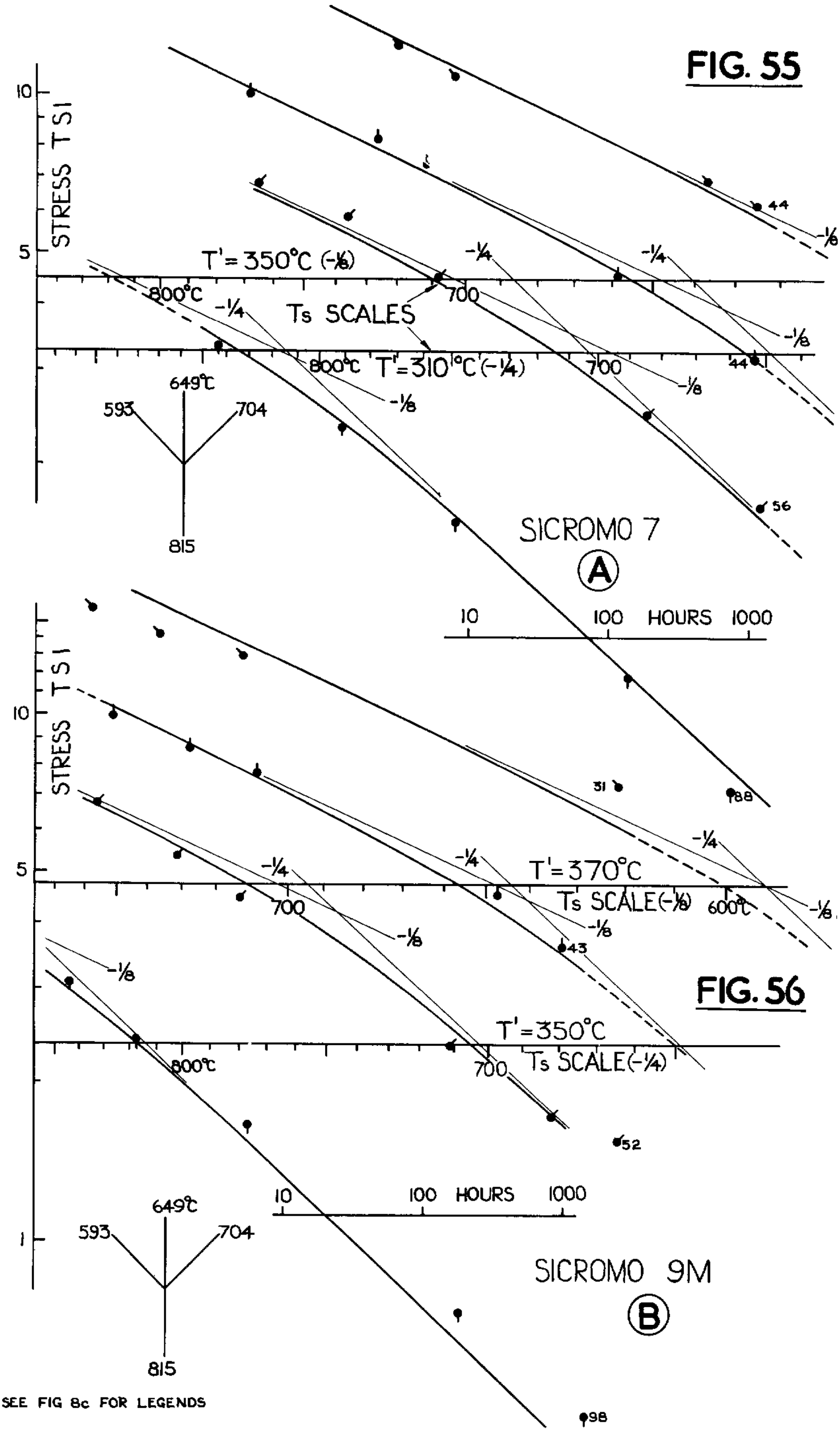


FIG. 55

FIG. 56

SEE FIG 8c FOR LEGENDS

CREEP RUPTURE SICROMO 7 AND SICROMO 9M

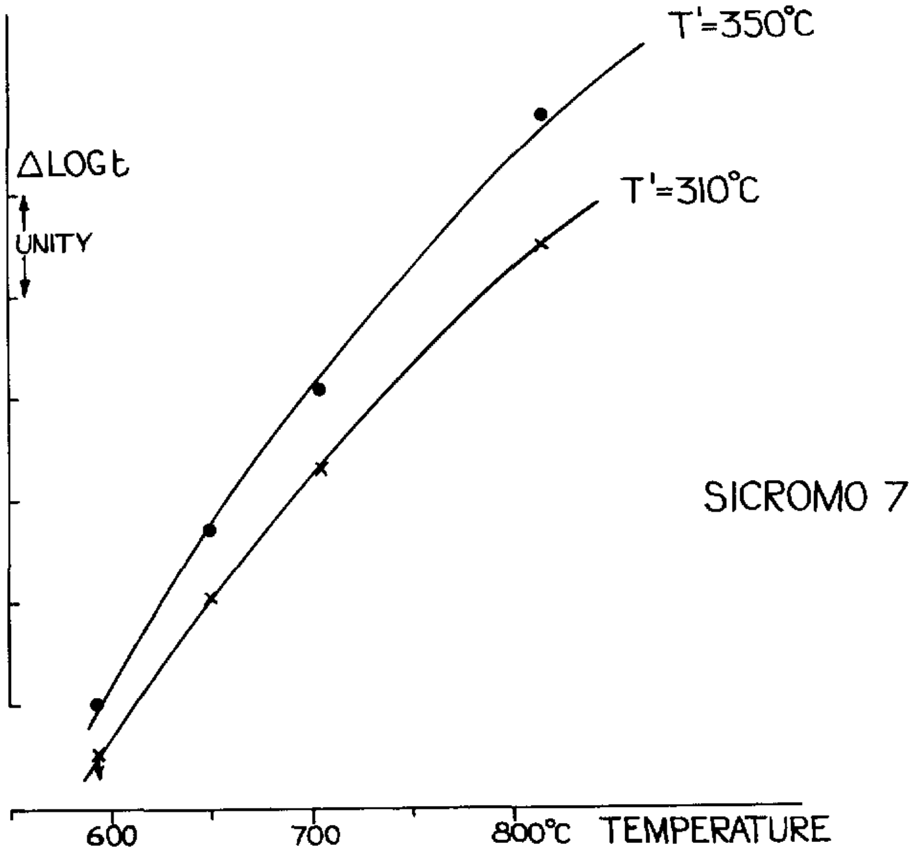
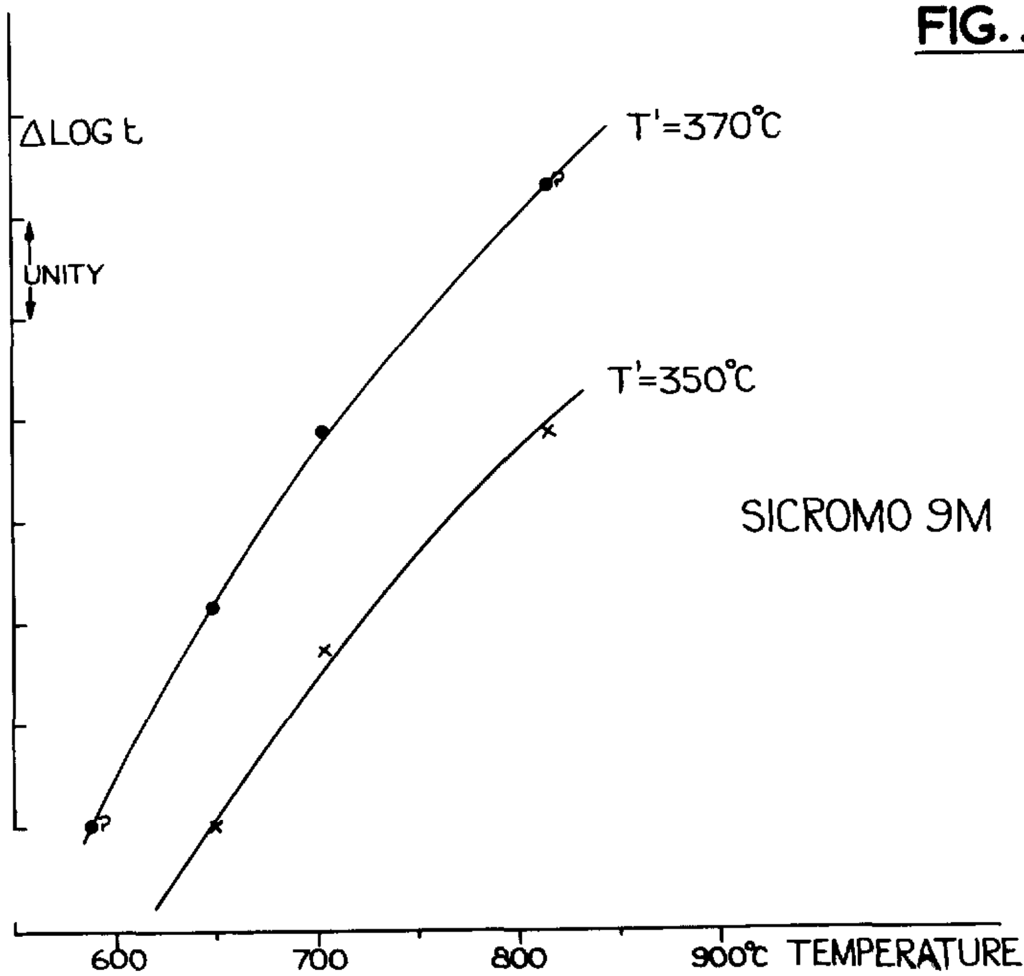


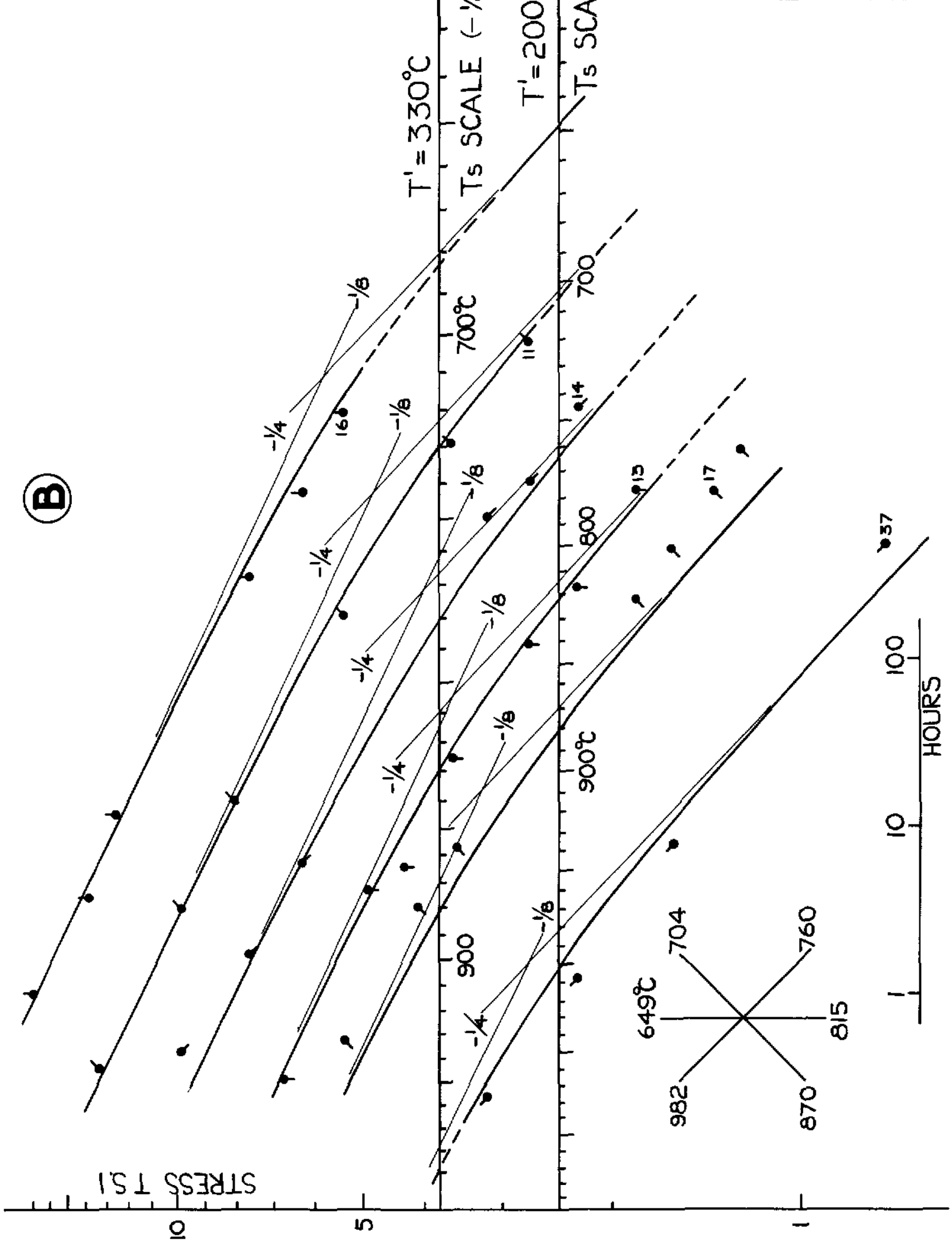
FIG. 55a

FIG. 56a



Δ LOG t/T PLOTS SICROMO 7 AND SICROMO 9 M

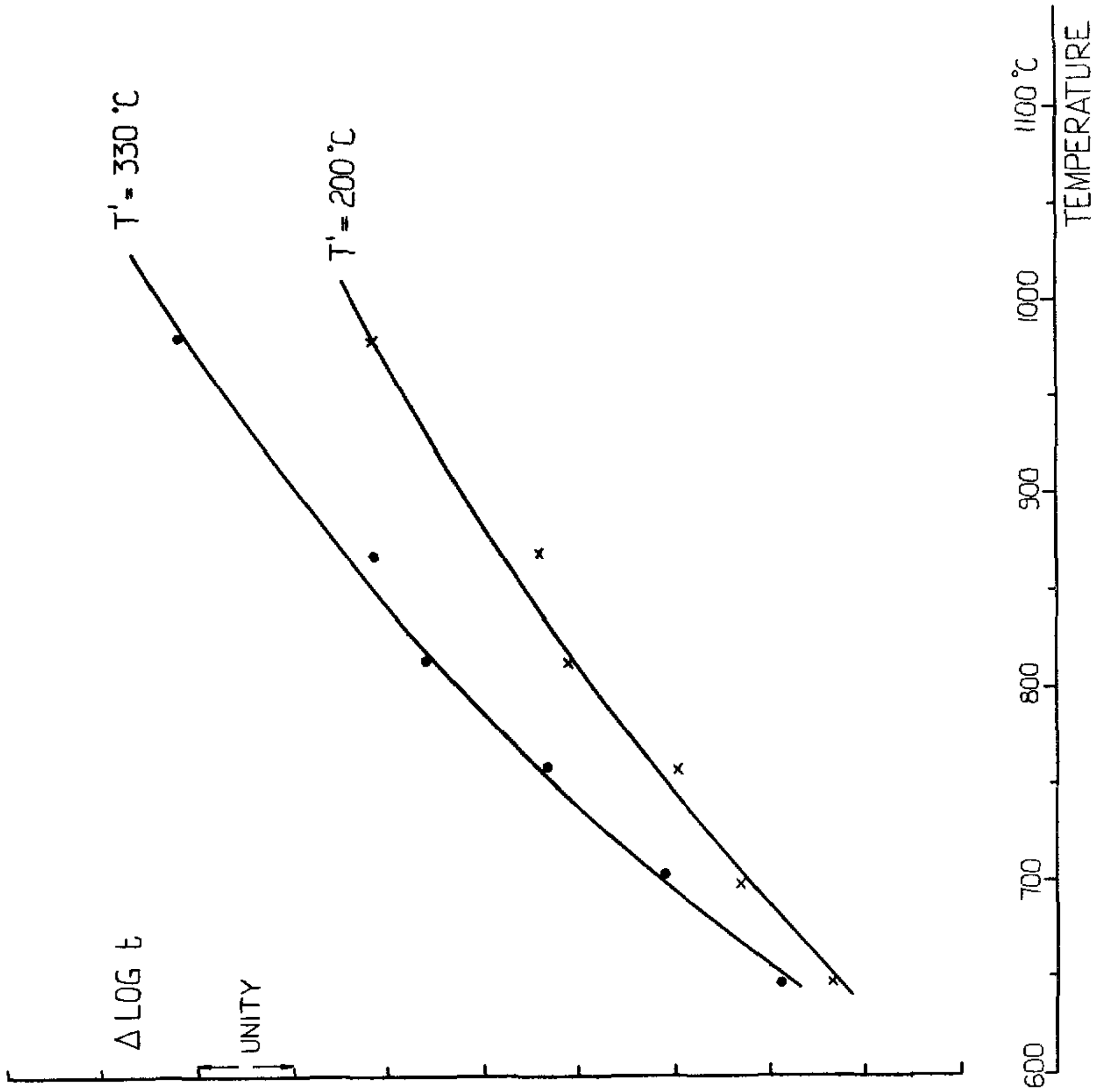
FIG. 57



SEE FIG 8c FOR LEGENDS

CREEP RUPTURE 18–8

FIG. 57a



Δ LOG t/T PLOT 18-8

CREEP RUPTURE S 816

SEE FIG 8c FOR LEGENDS

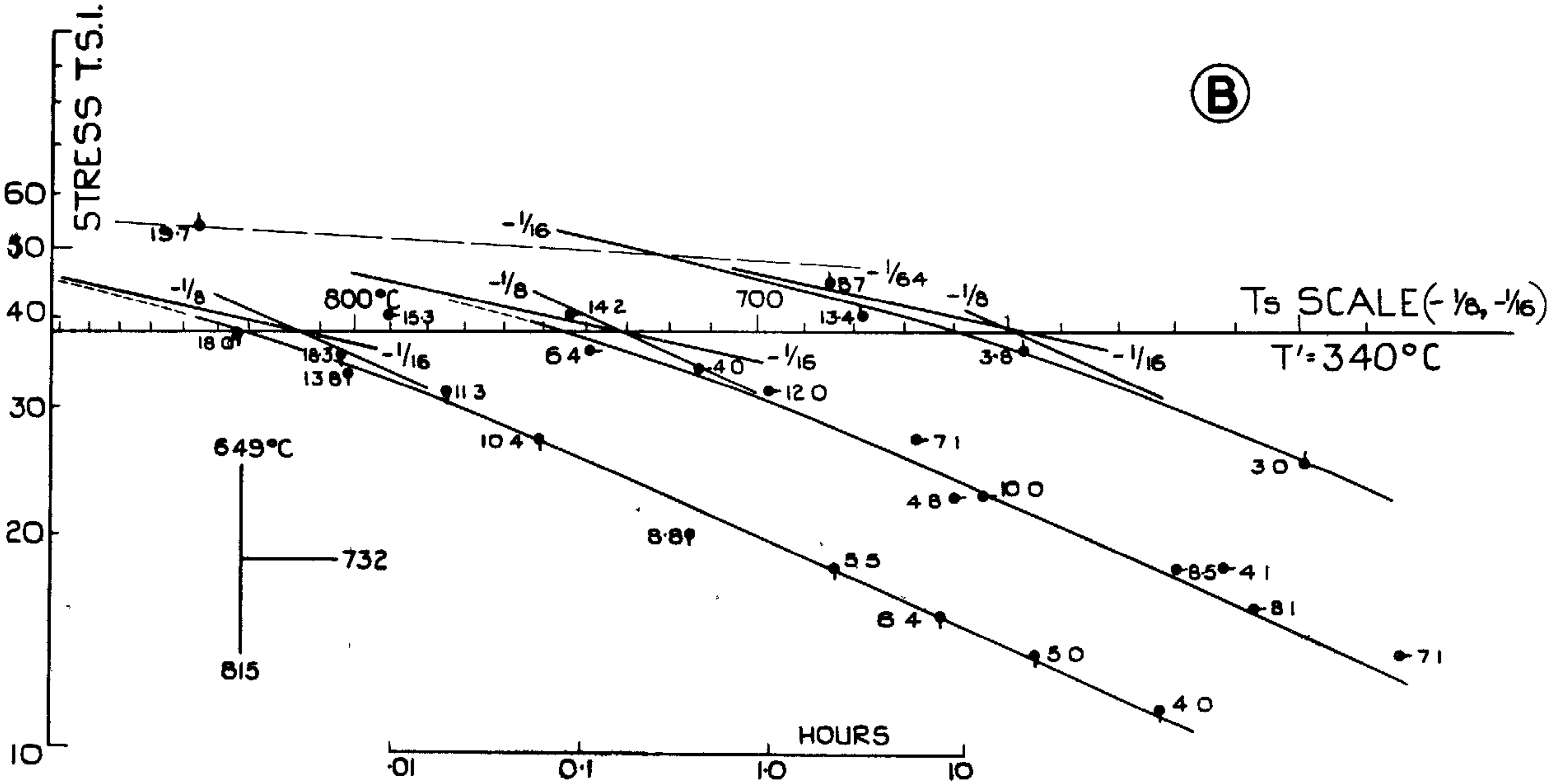
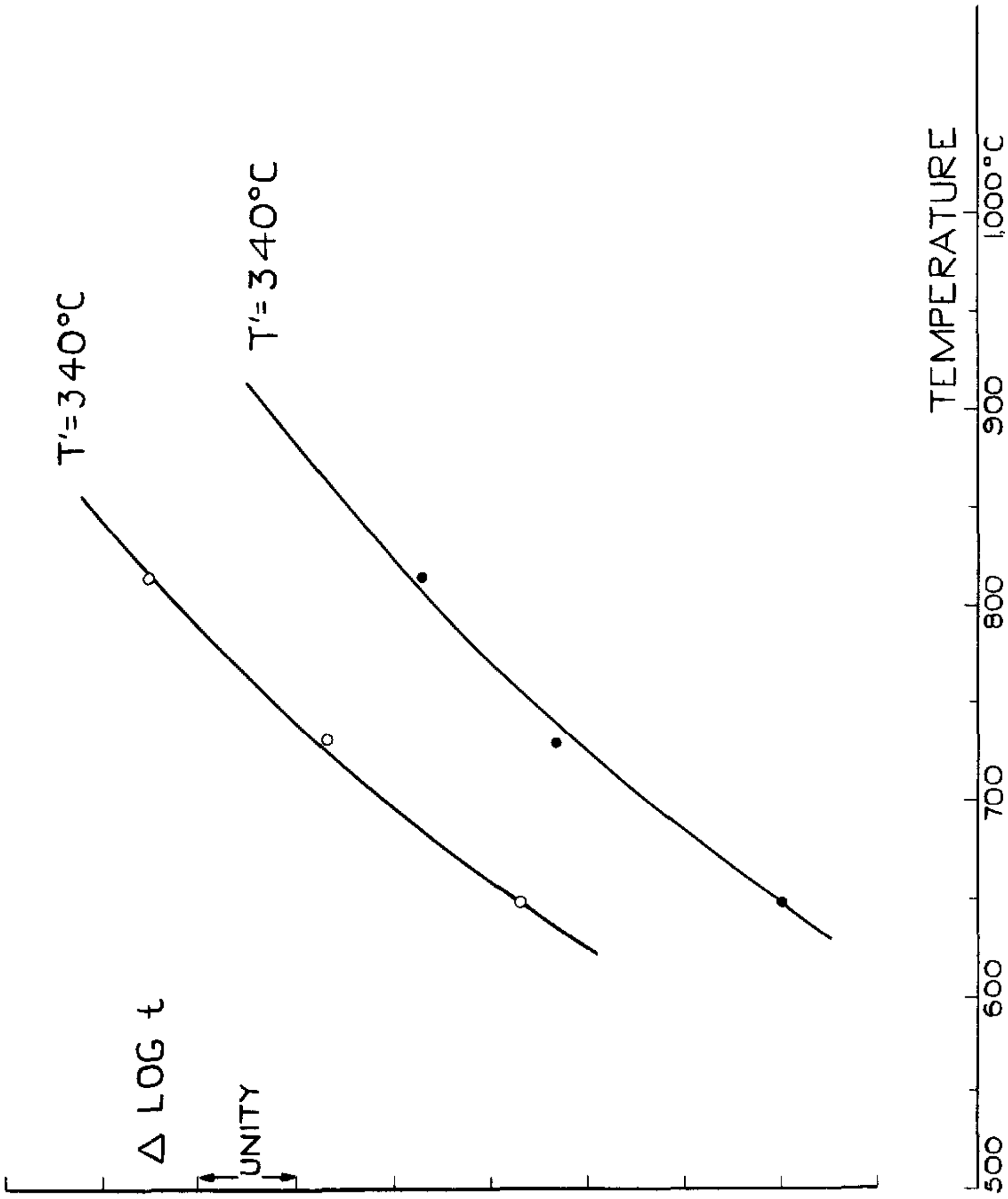


FIG. 58

FIG. 58a



Δ LOG t/T PLOT S 816

CREEP RUPTURE S 590

FOR LEGENDS SEE REPORT R.190

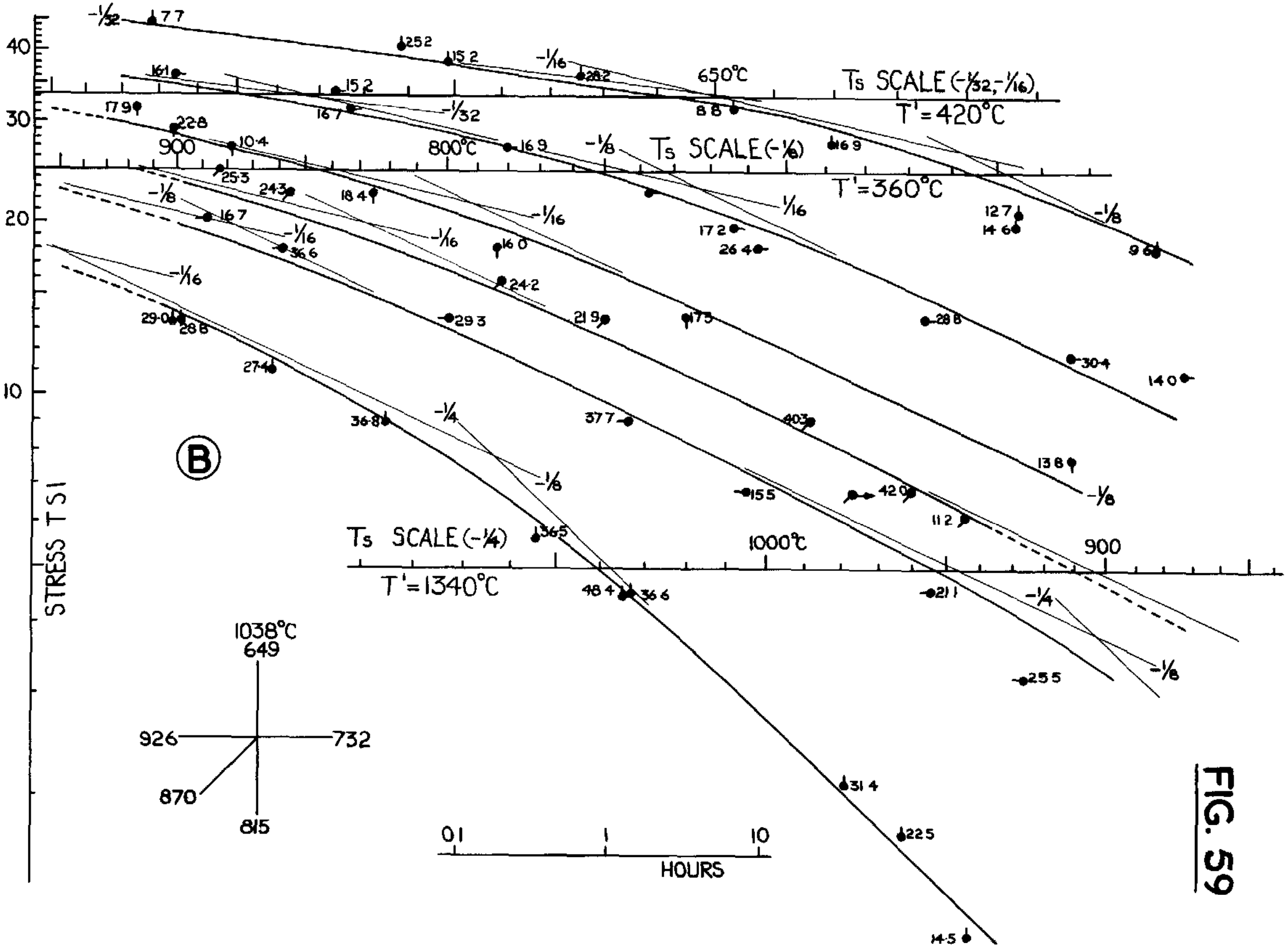
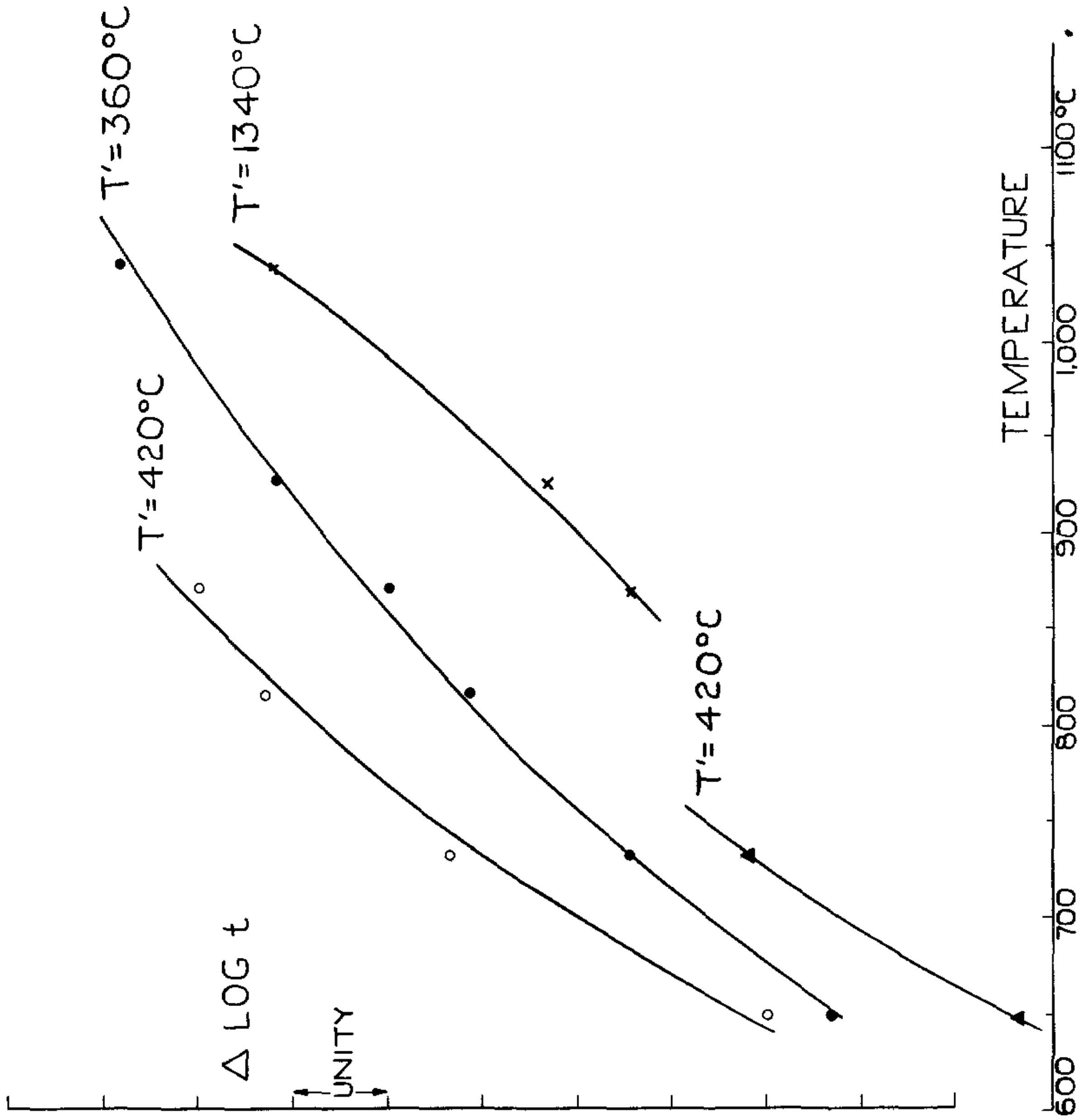


FIG. 59

FIG. 59a



Δ LOG t/T PLOT S 590

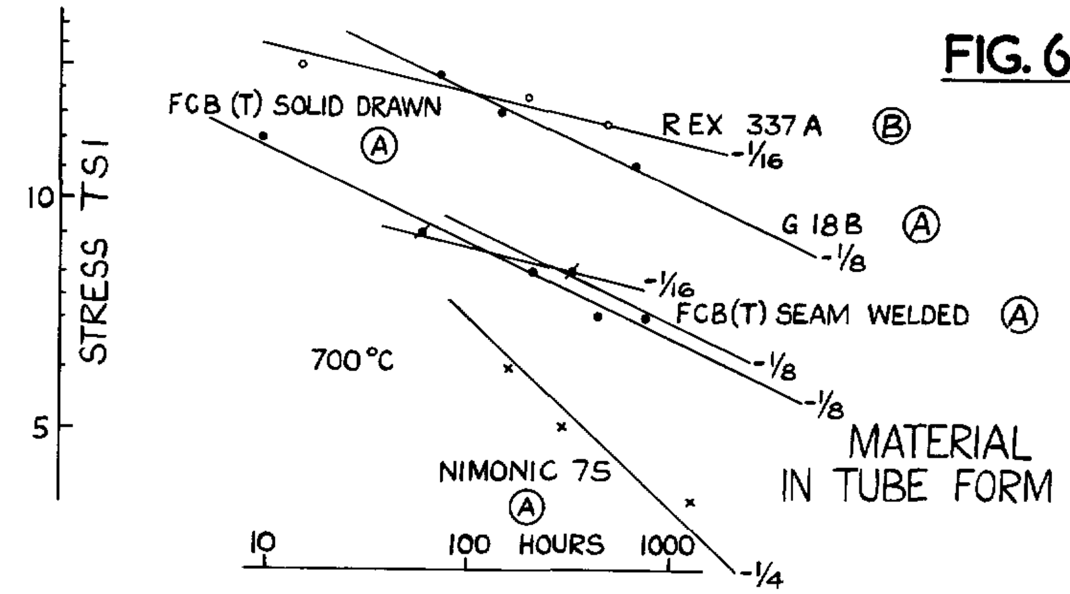


FIG. 60

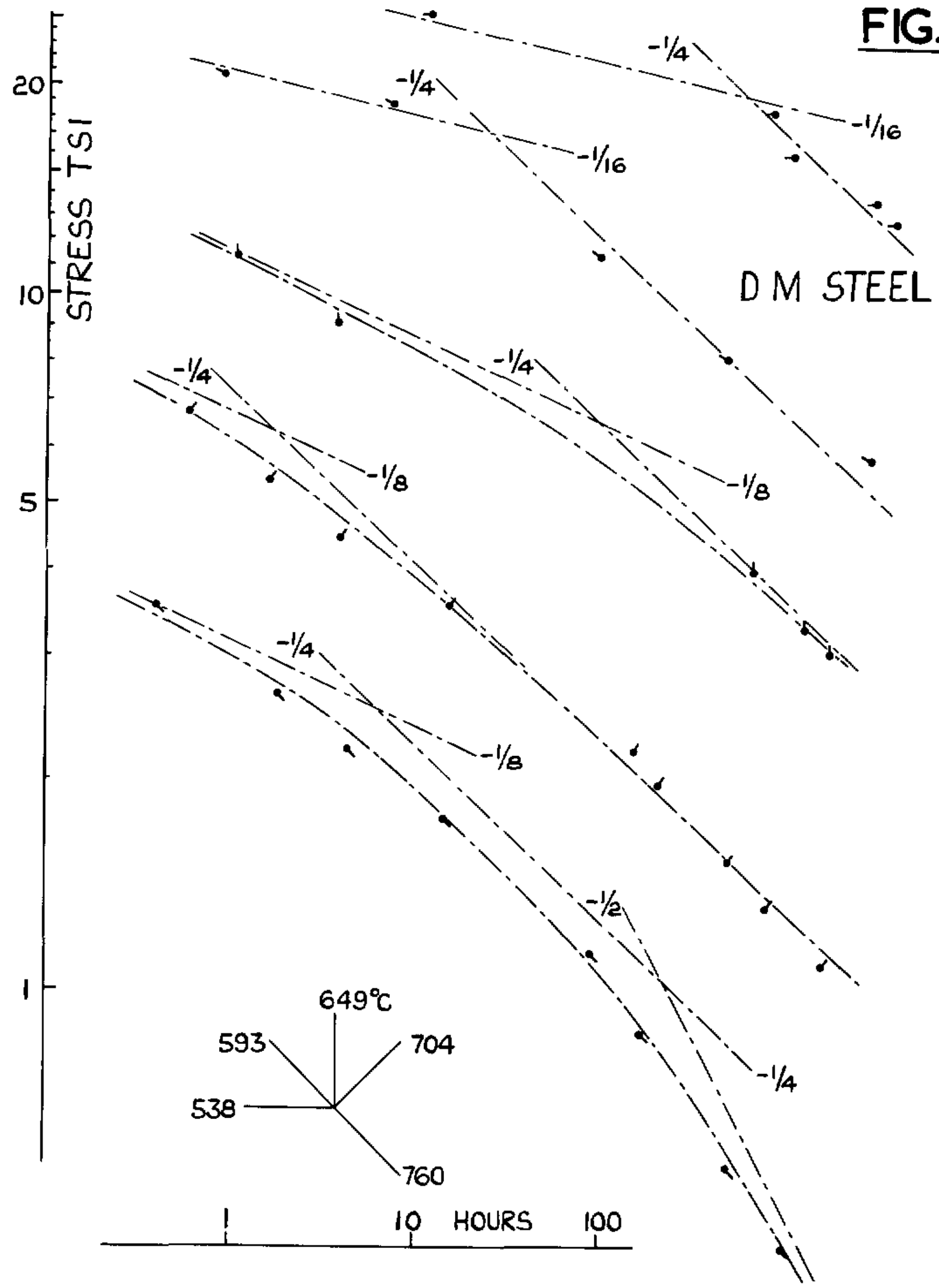


FIG. 61

CREEP RUPTURE DATA, LOG STRESS vs LOG TIME

FIG. 62

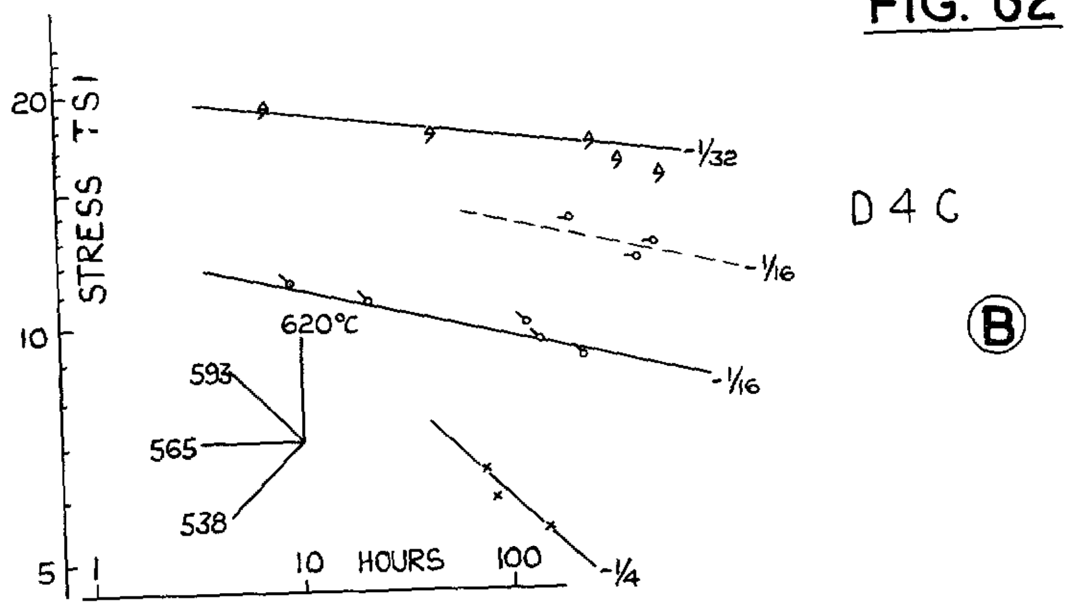


FIG. 63

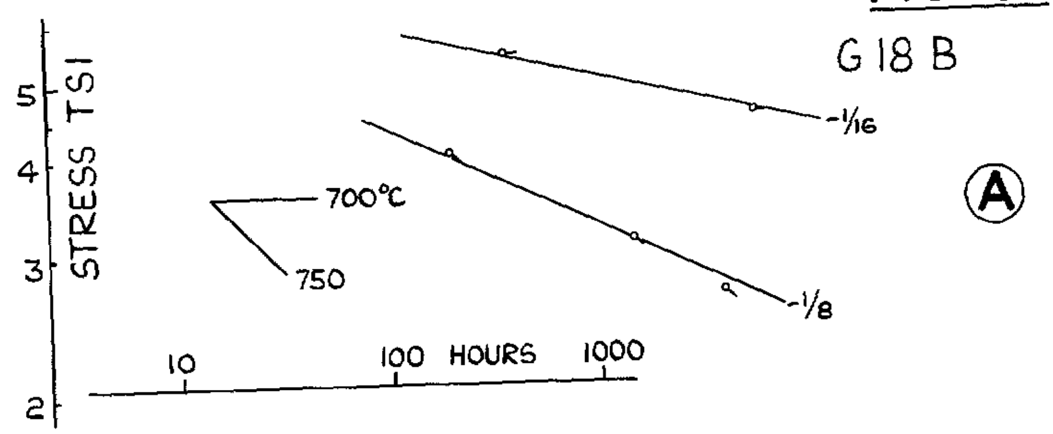
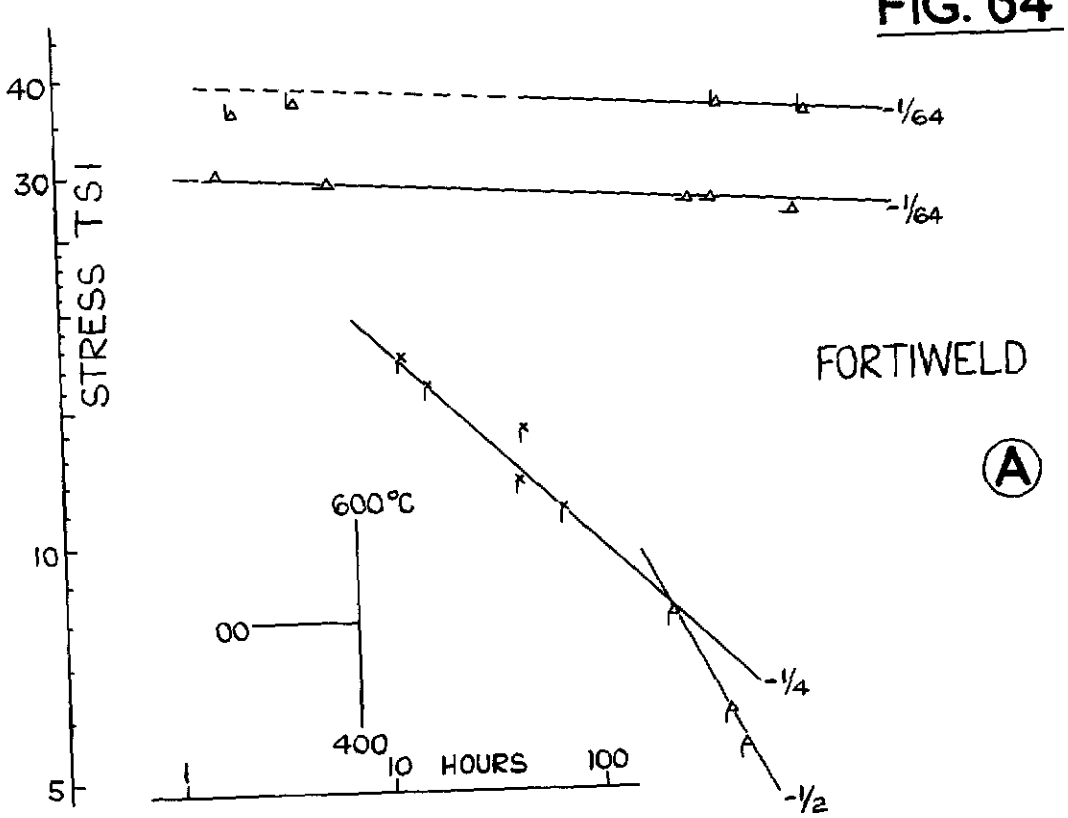
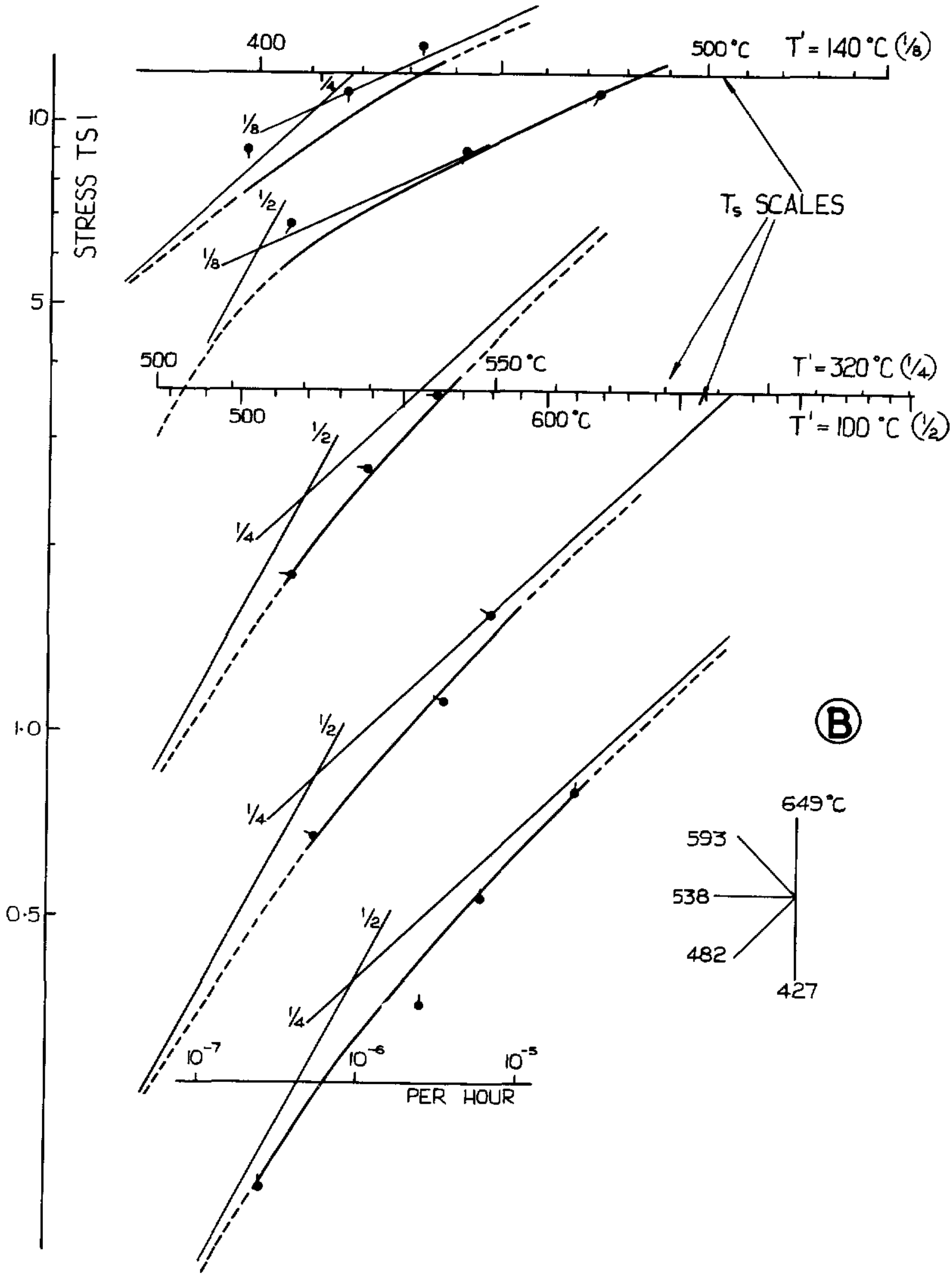


FIG. 64



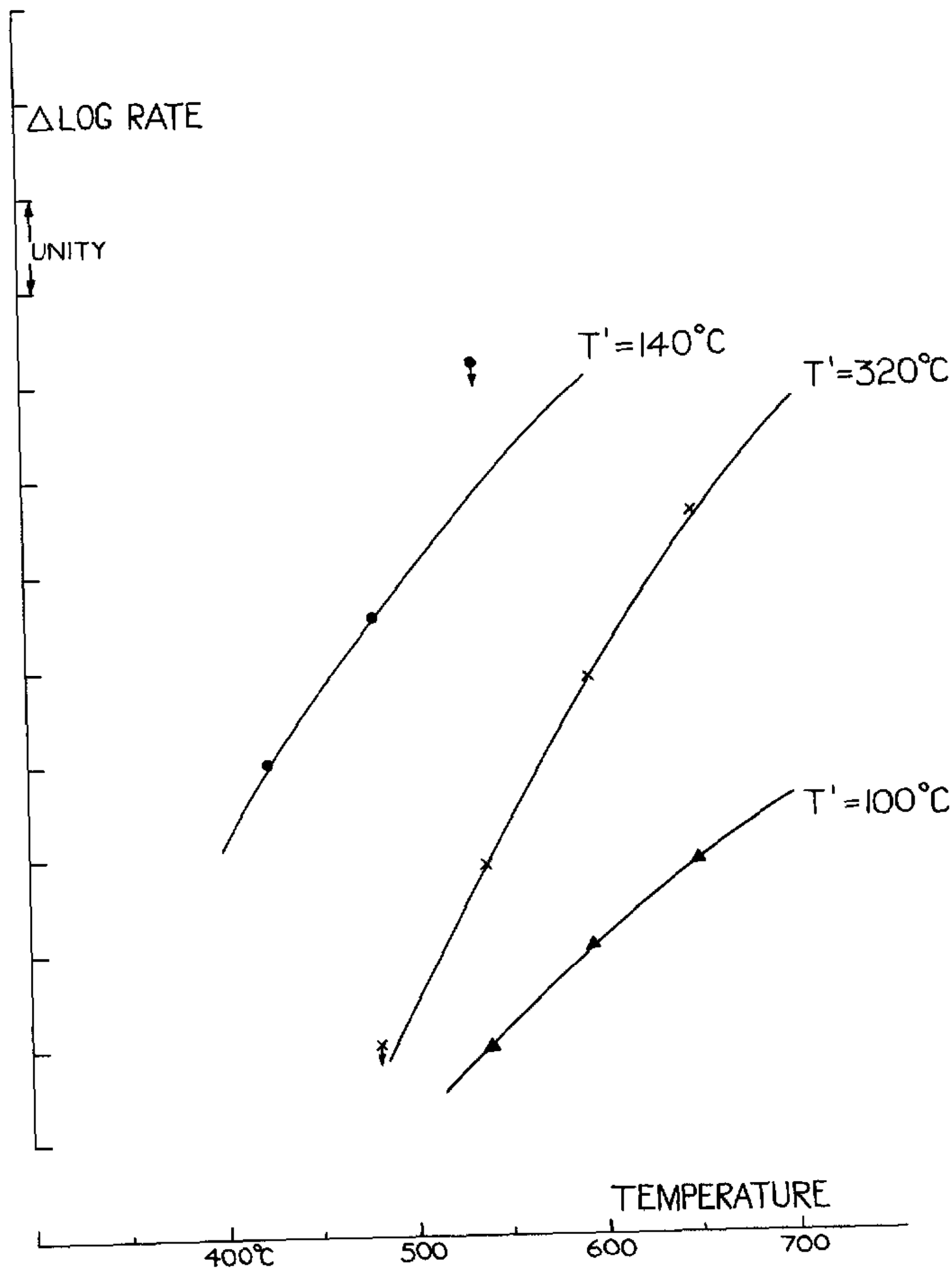
CREEP RUPTURE DATA, LOG STRESS vs LOG TIME

FIG. 65



CREEP RATE KILLED CARBON STEEL

FIG. 65a



ΔLOG RATE PLOT KILLED CARBON STEEL.

FIG. 66

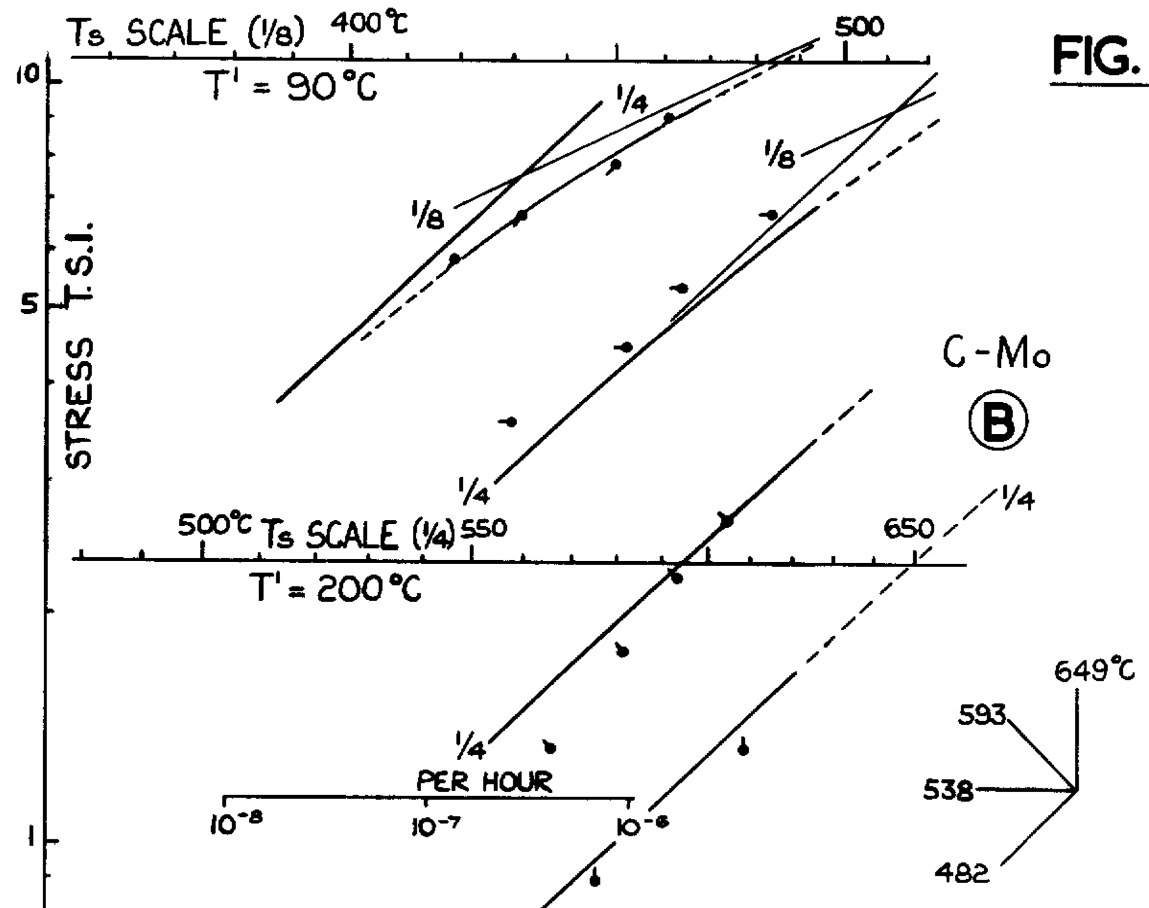
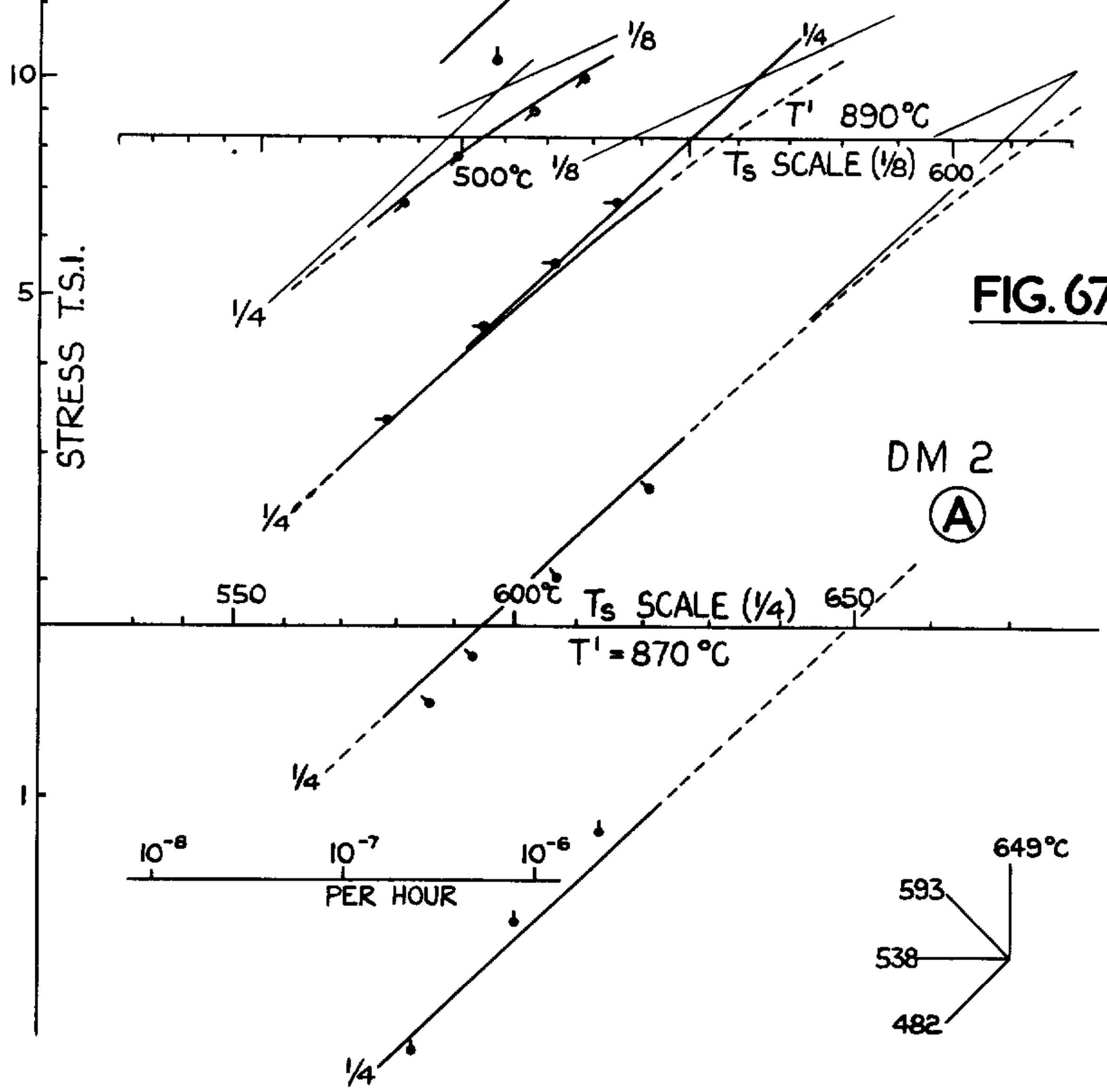


FIG. 67



CREEP RATE C-Mo AND DM 2

FIG. 66a

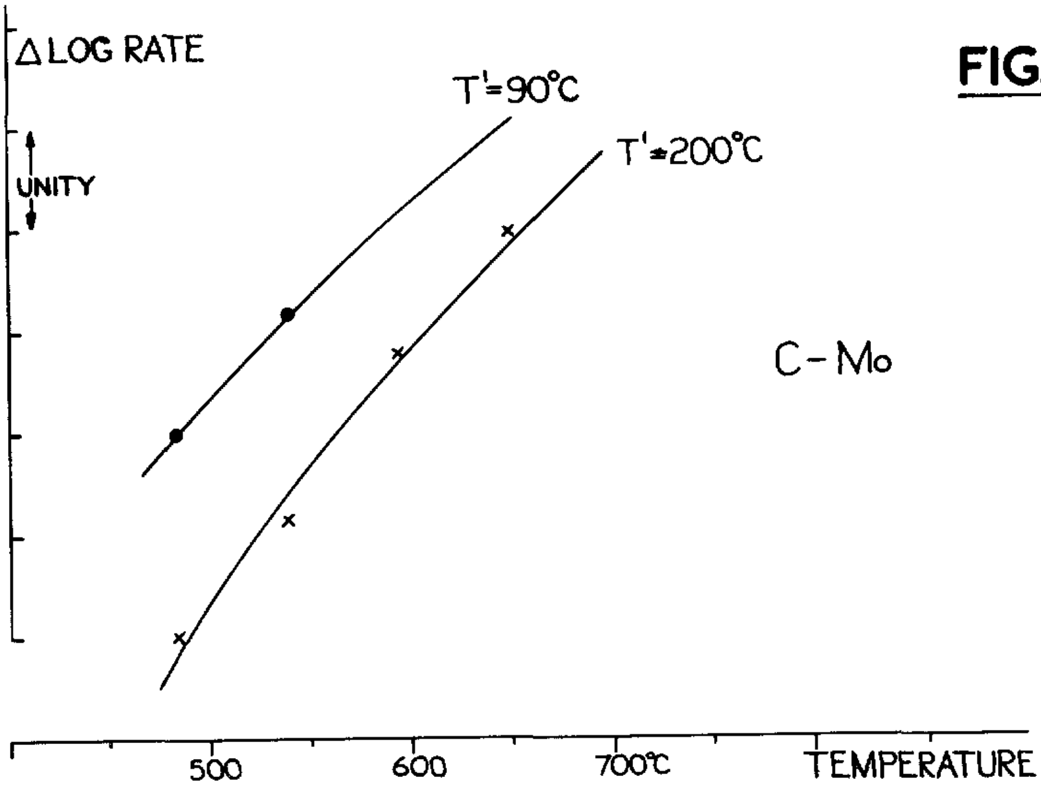
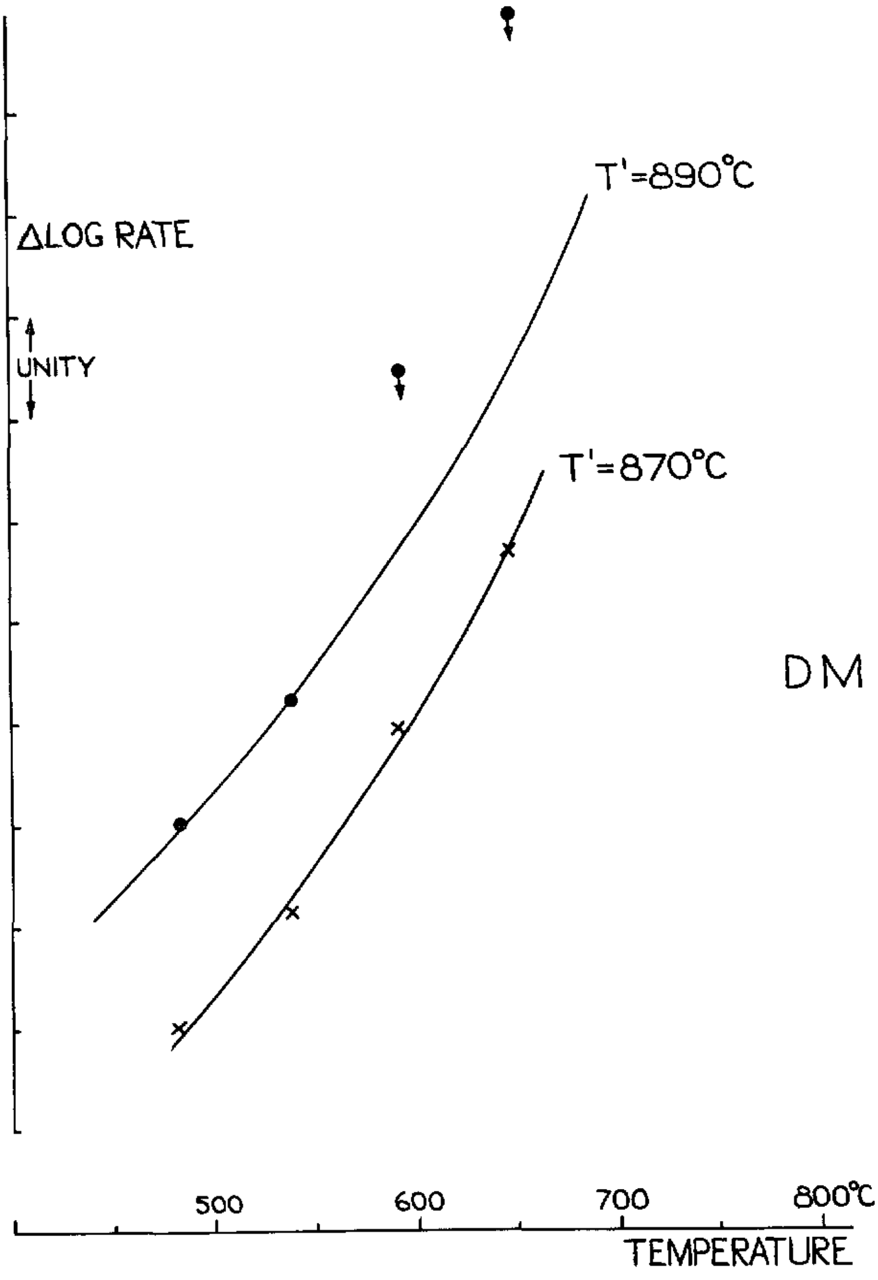


FIG. 67a



Δ LOG RATE PLOTS C–Mo AND DM 2

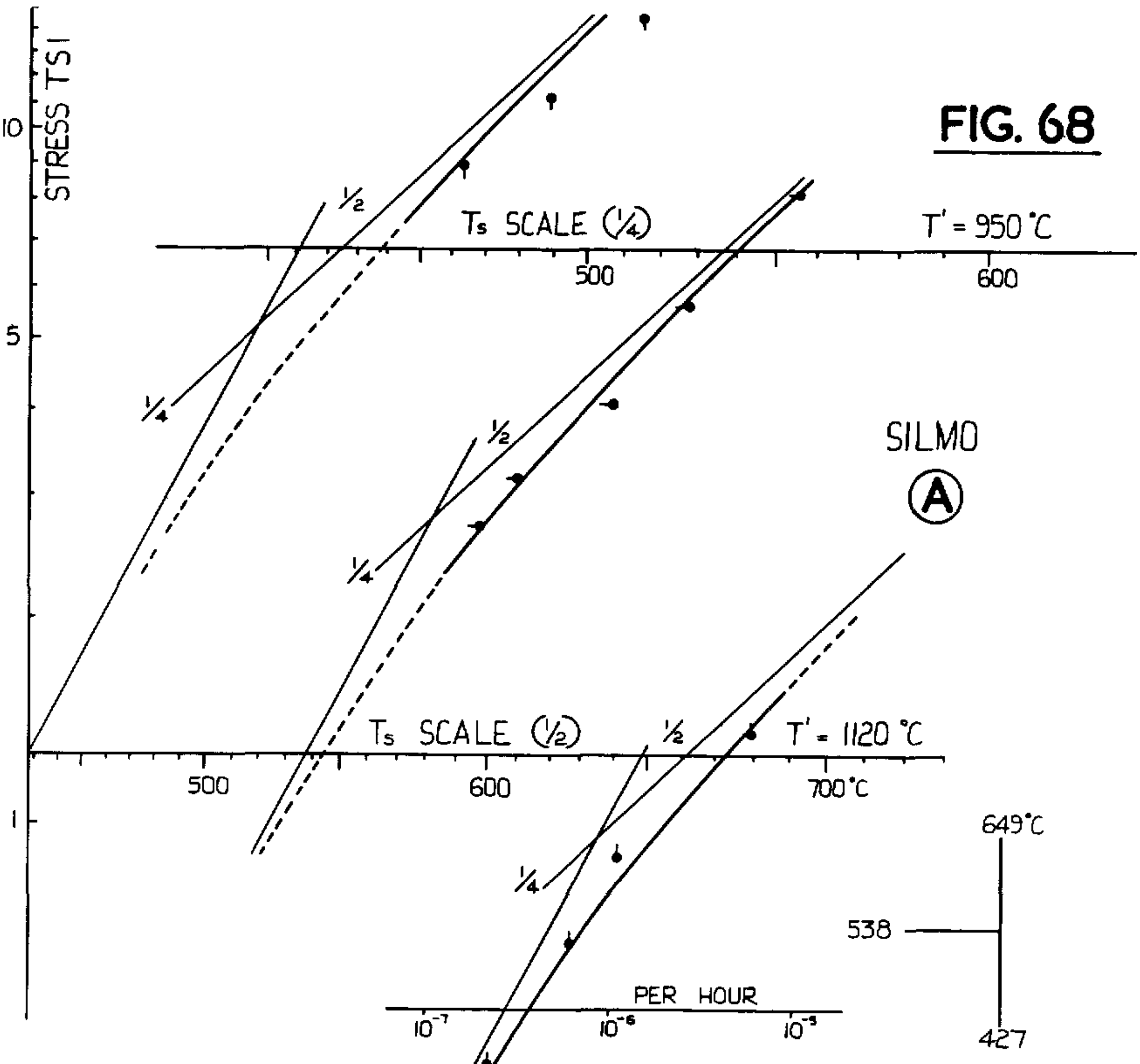


FIG. 68

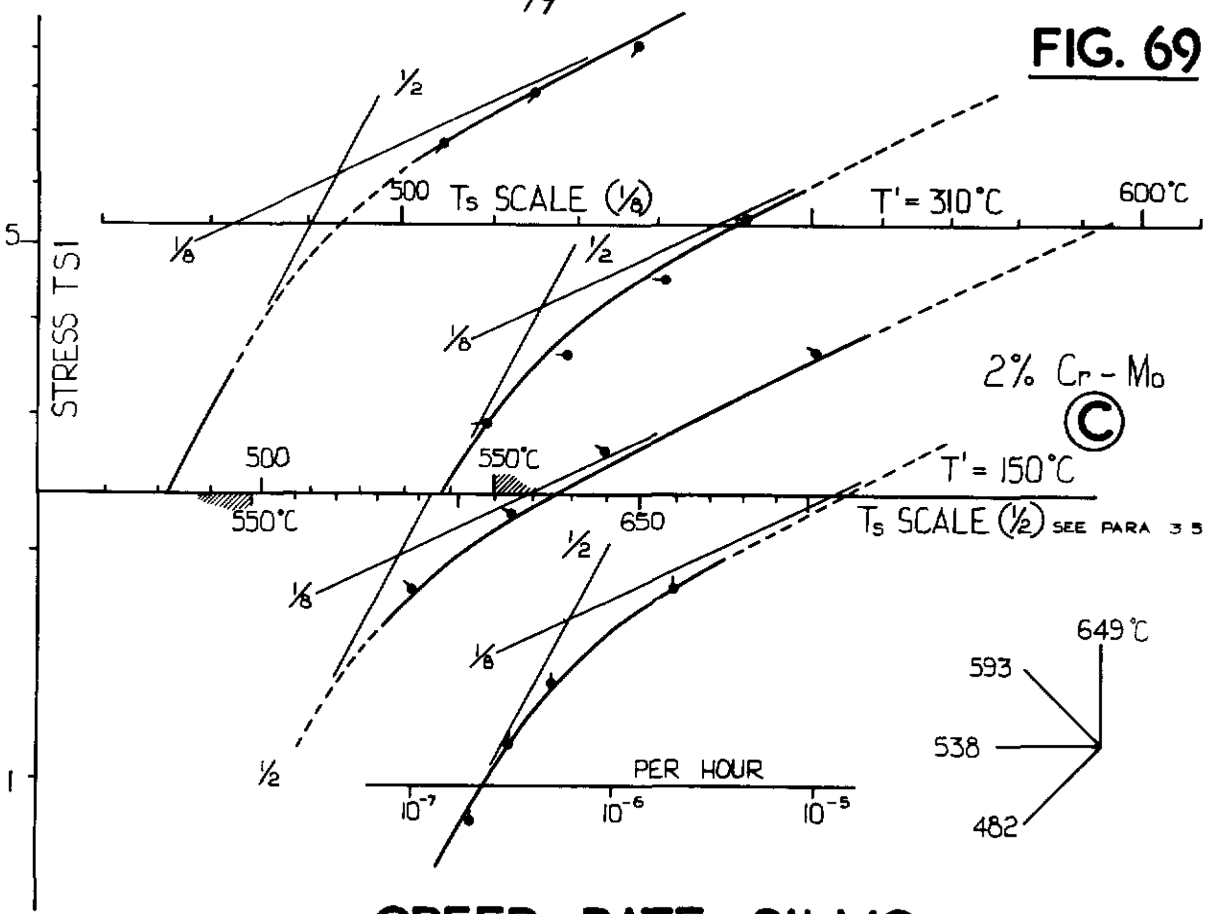
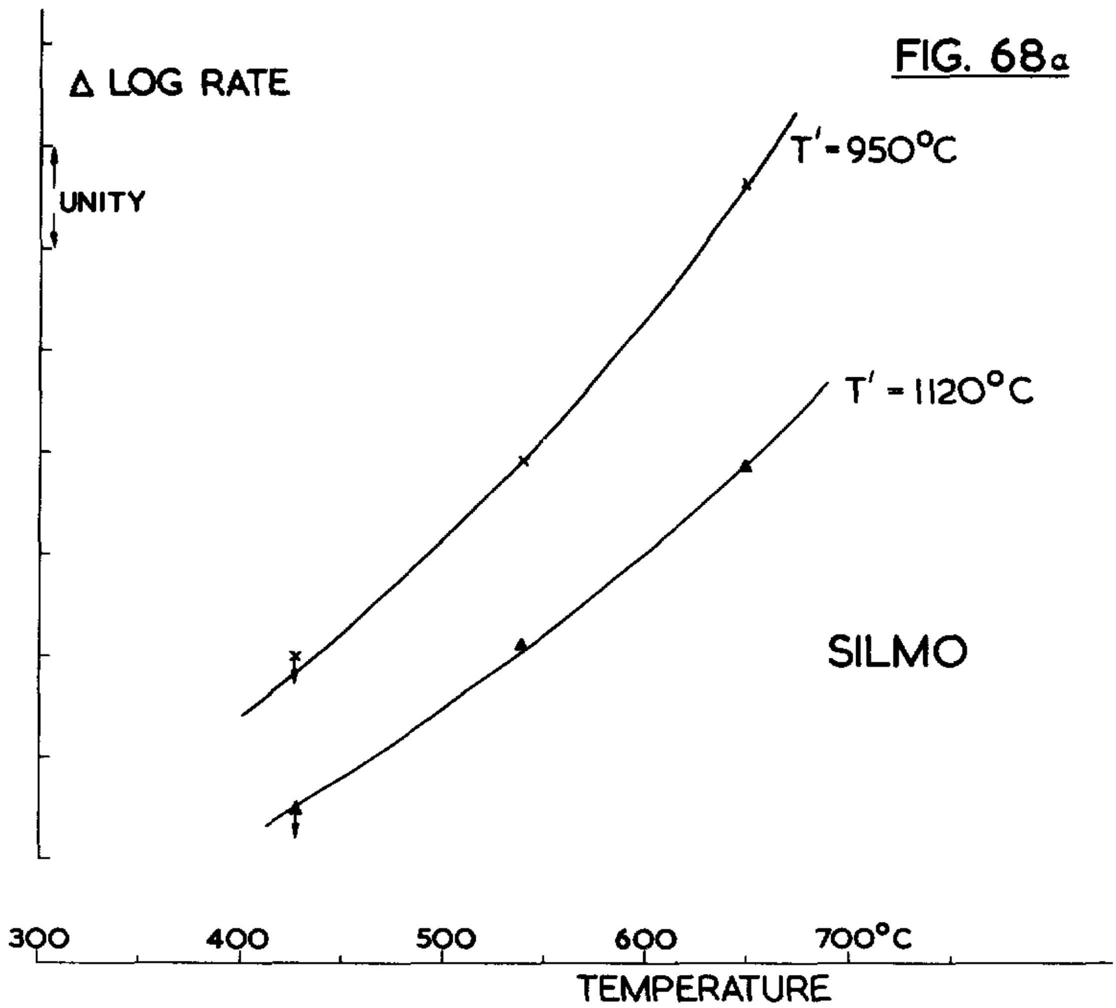
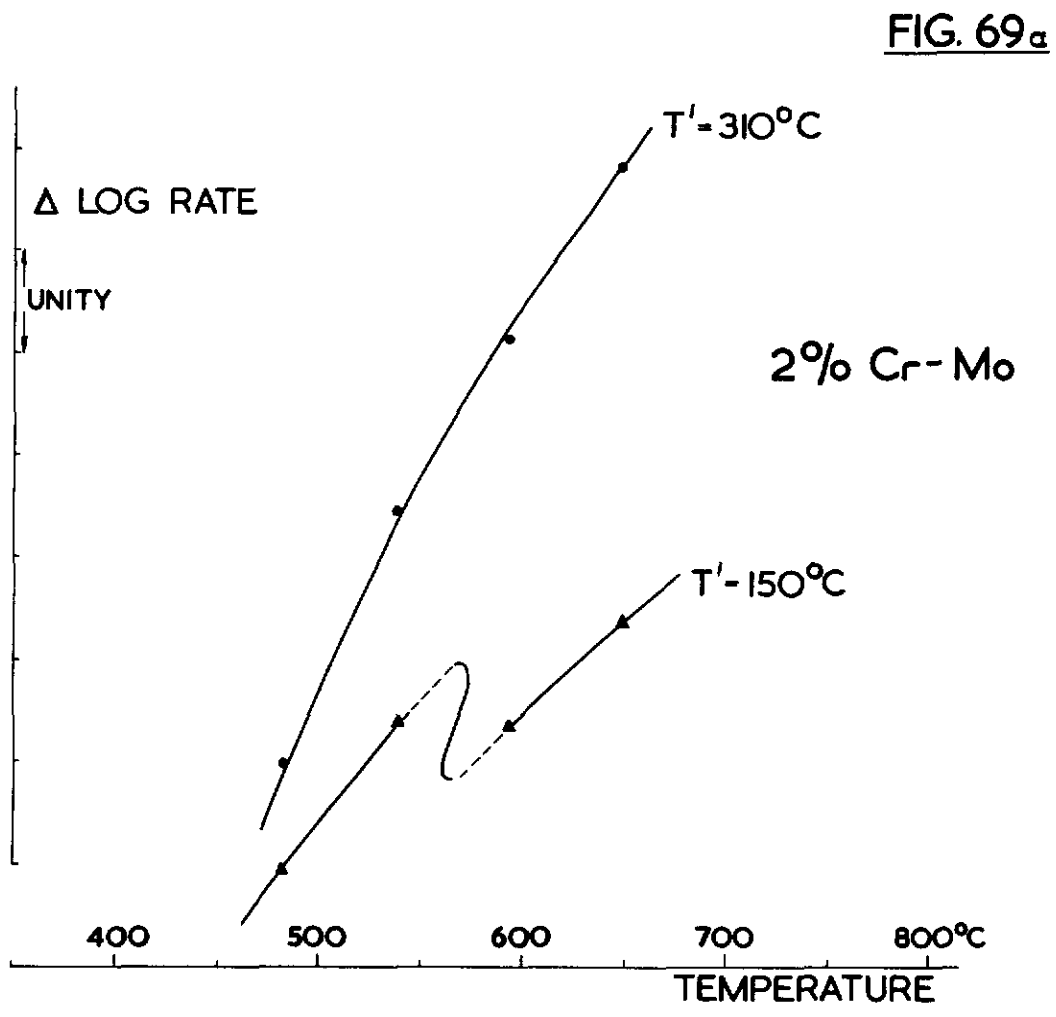


FIG. 69

CREEP RATE SILMO AND 2% Cr-Mo STEELS





Δ LOG RATE PLOTS SILMO AND 2% Cr-Mo STEELS

FIG. 70

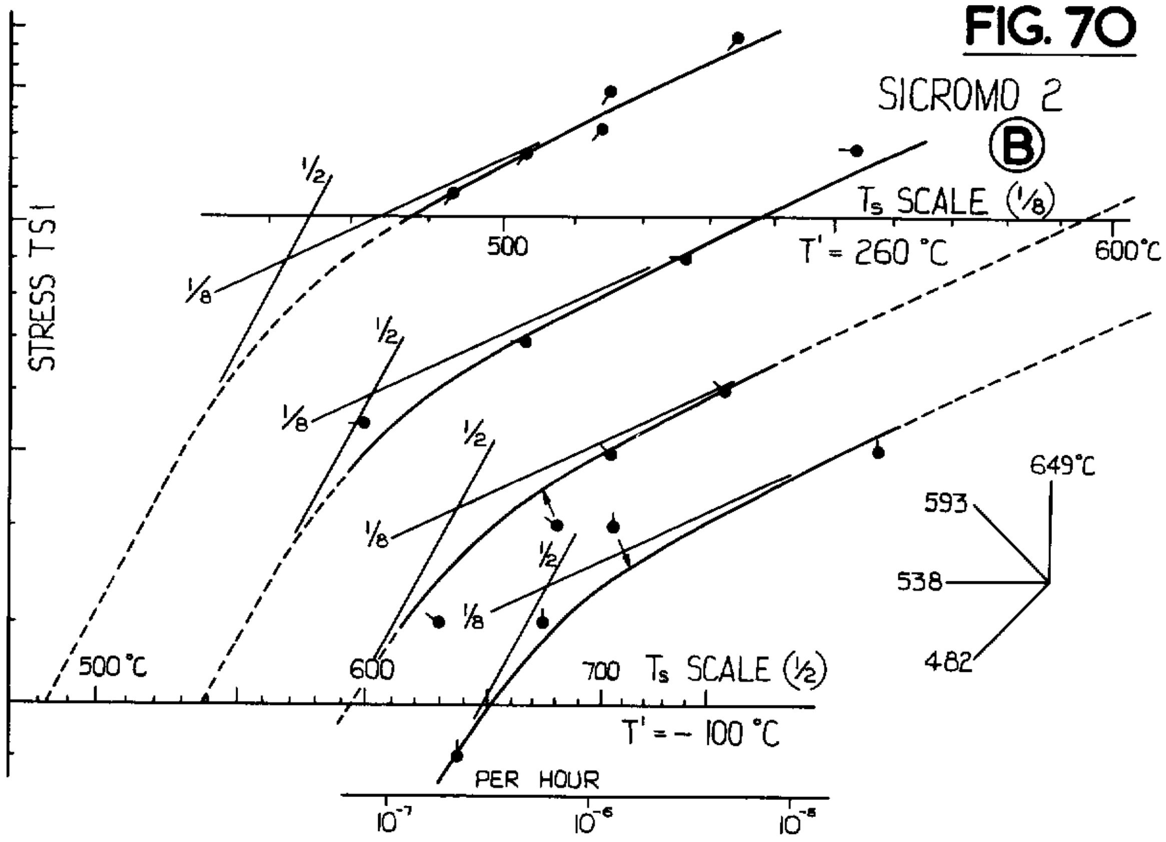
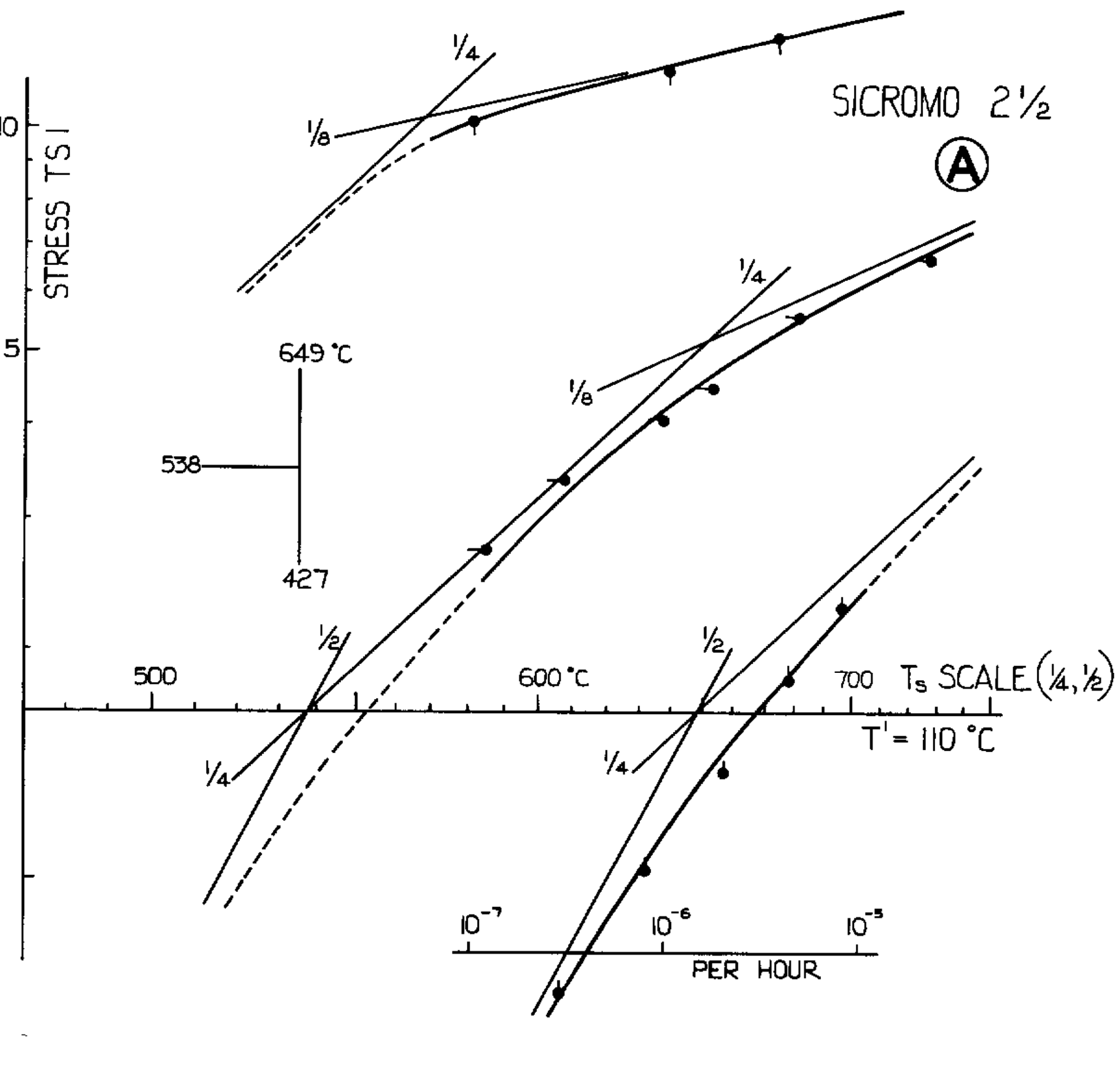


FIG. 71



CREEP RATE SICROMO 2 AND SICROMO 2½

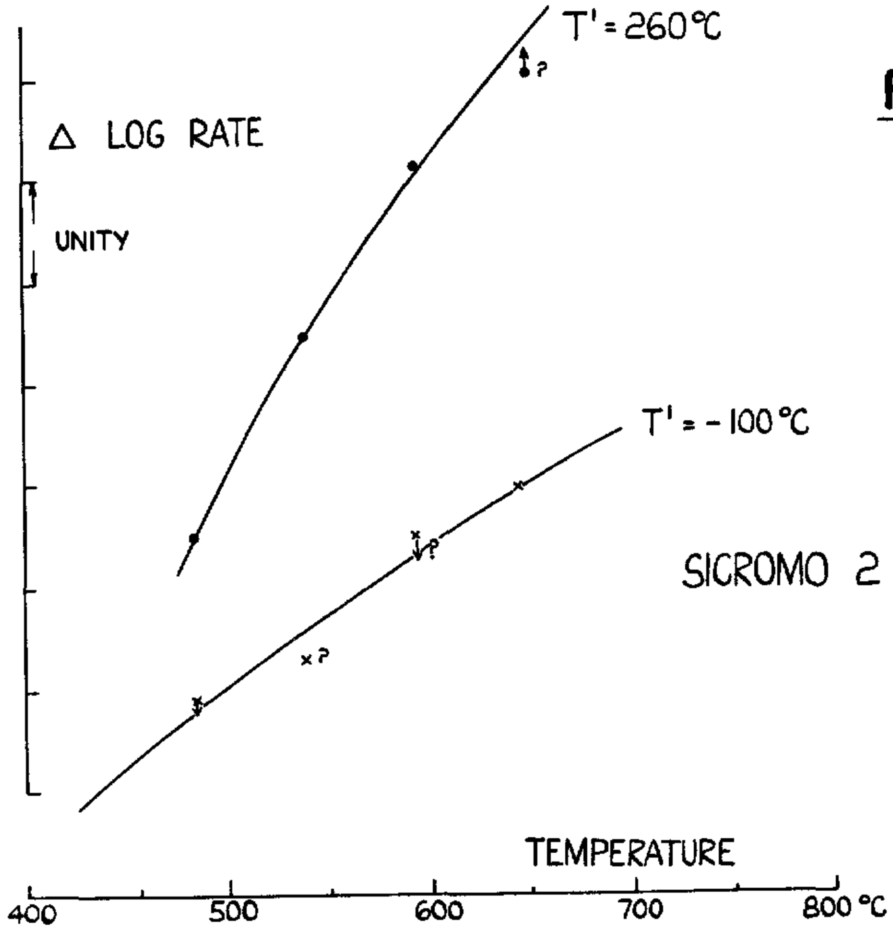


FIG. 70a

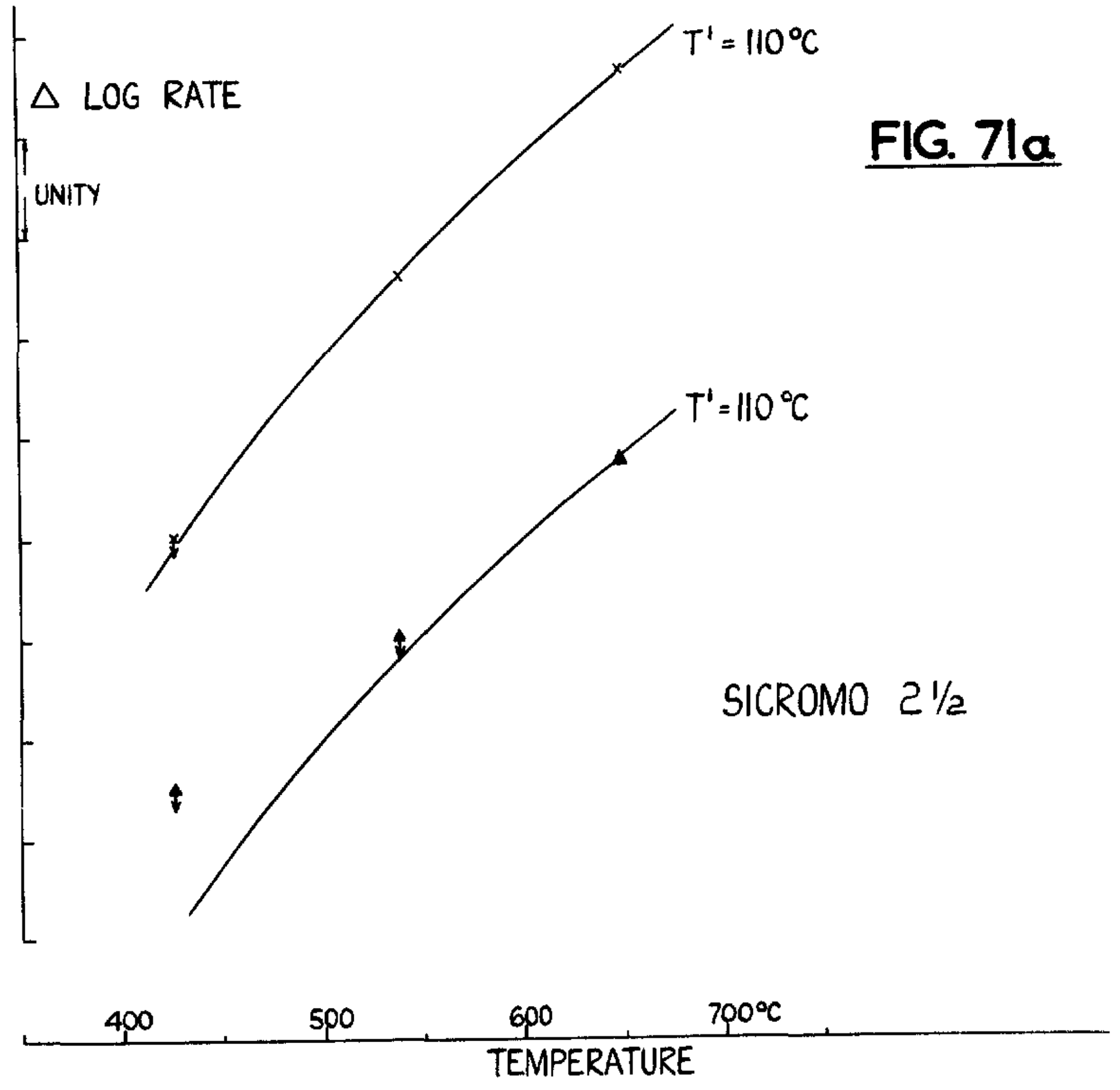


FIG. 71a

Δ LOG RATE PLOTS SICROMO 2 & SICROMO 2½

FIG.72

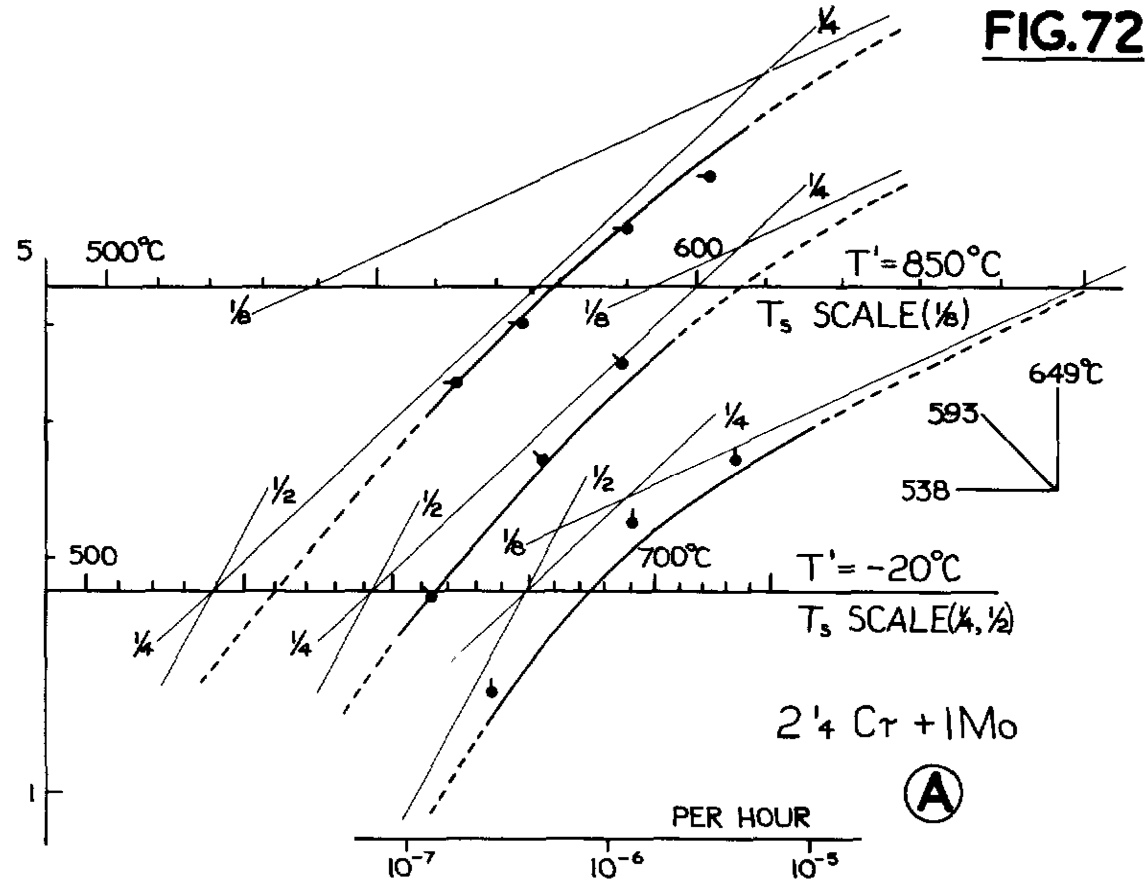
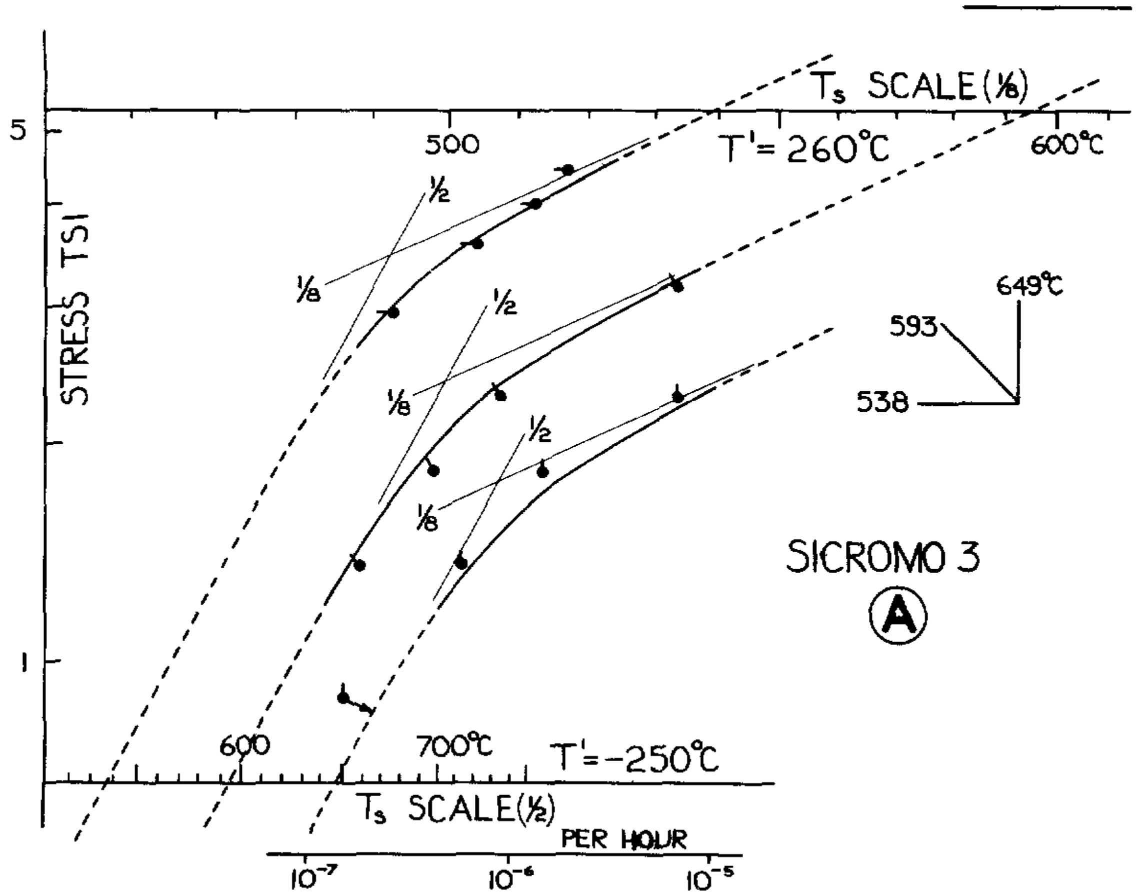


FIG.73



CREEP RATE 2¼ Cr+1Mo AND SICROMO 3

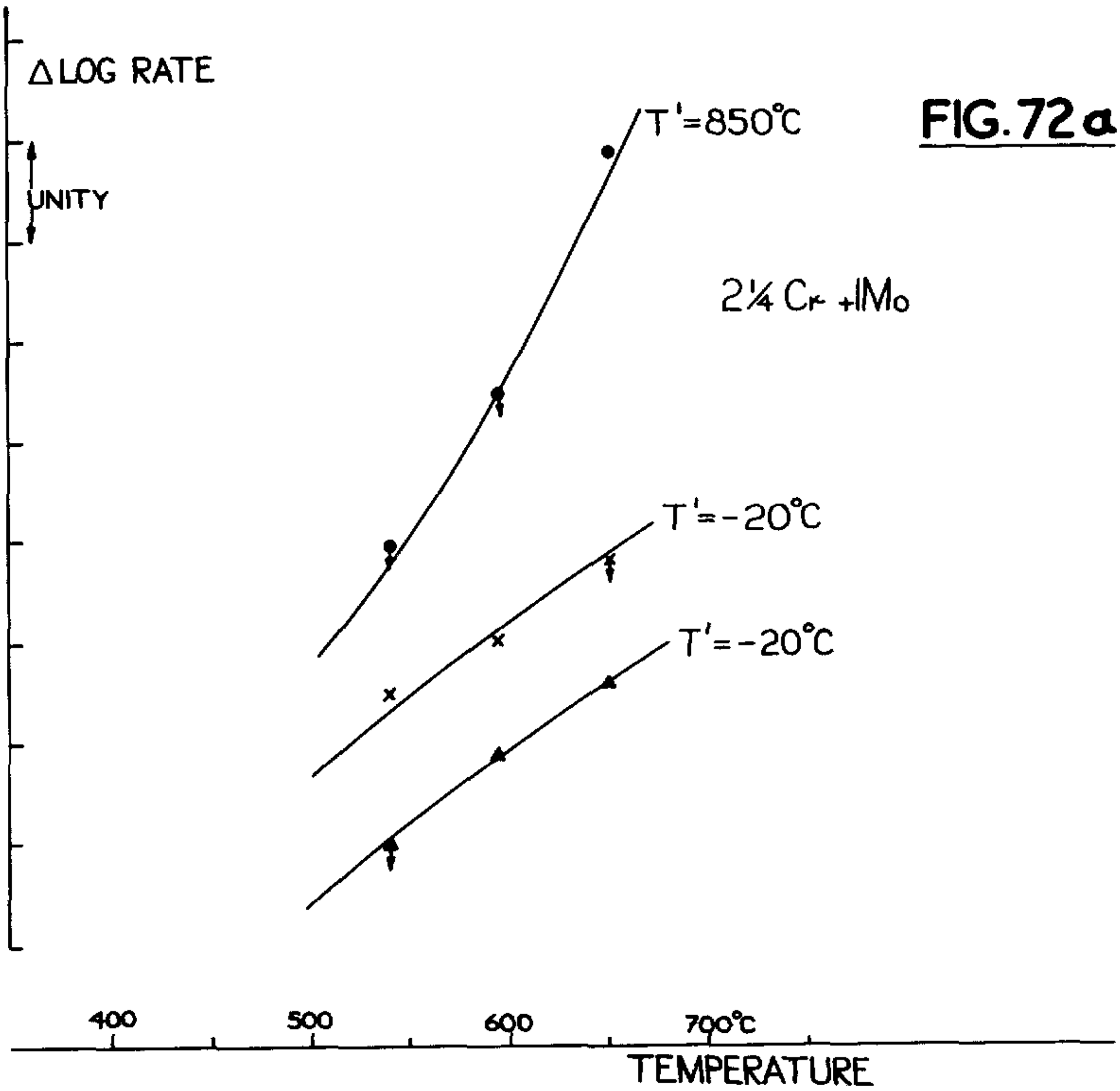
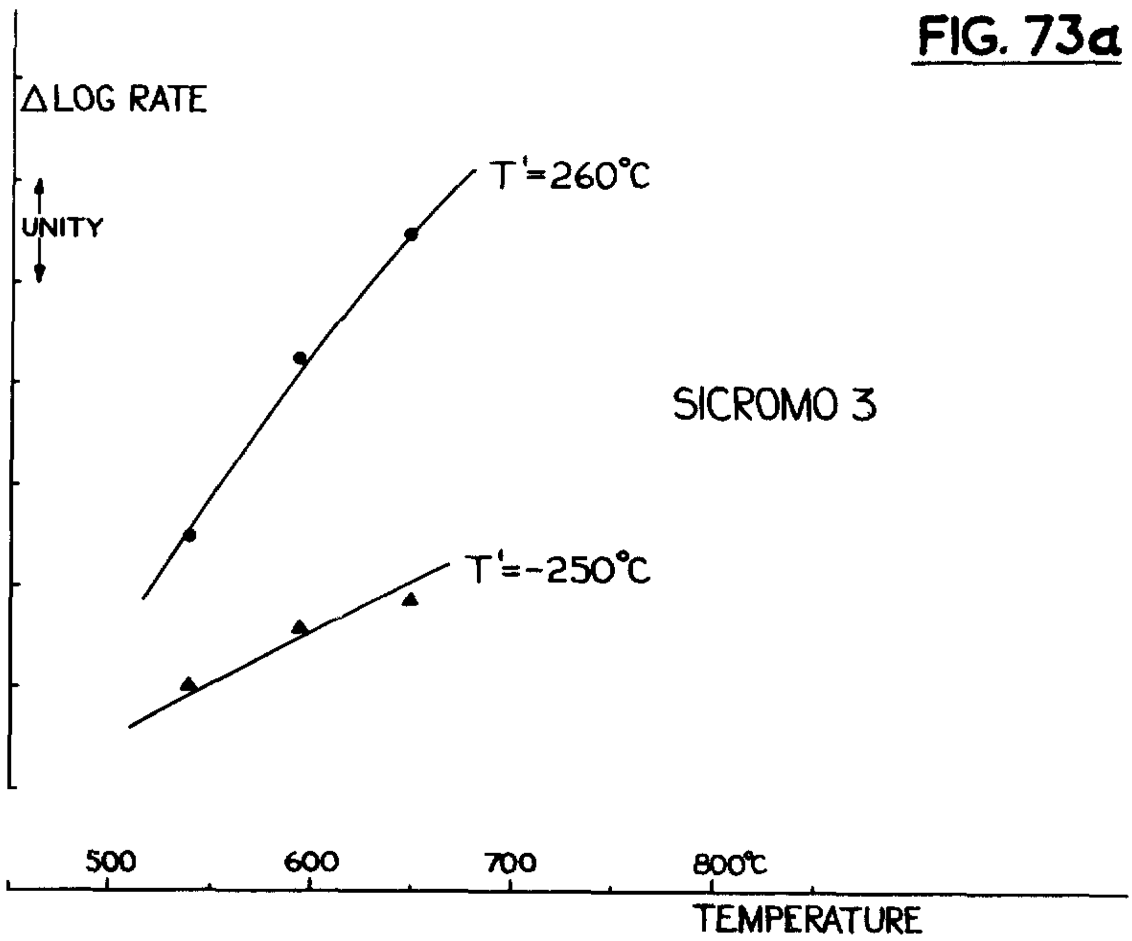


FIG. 72a

FIG. 73a



Δ LOG RATE PLOTS 2¼Cr+1Mo AND SICROMO 3

FIG. 74

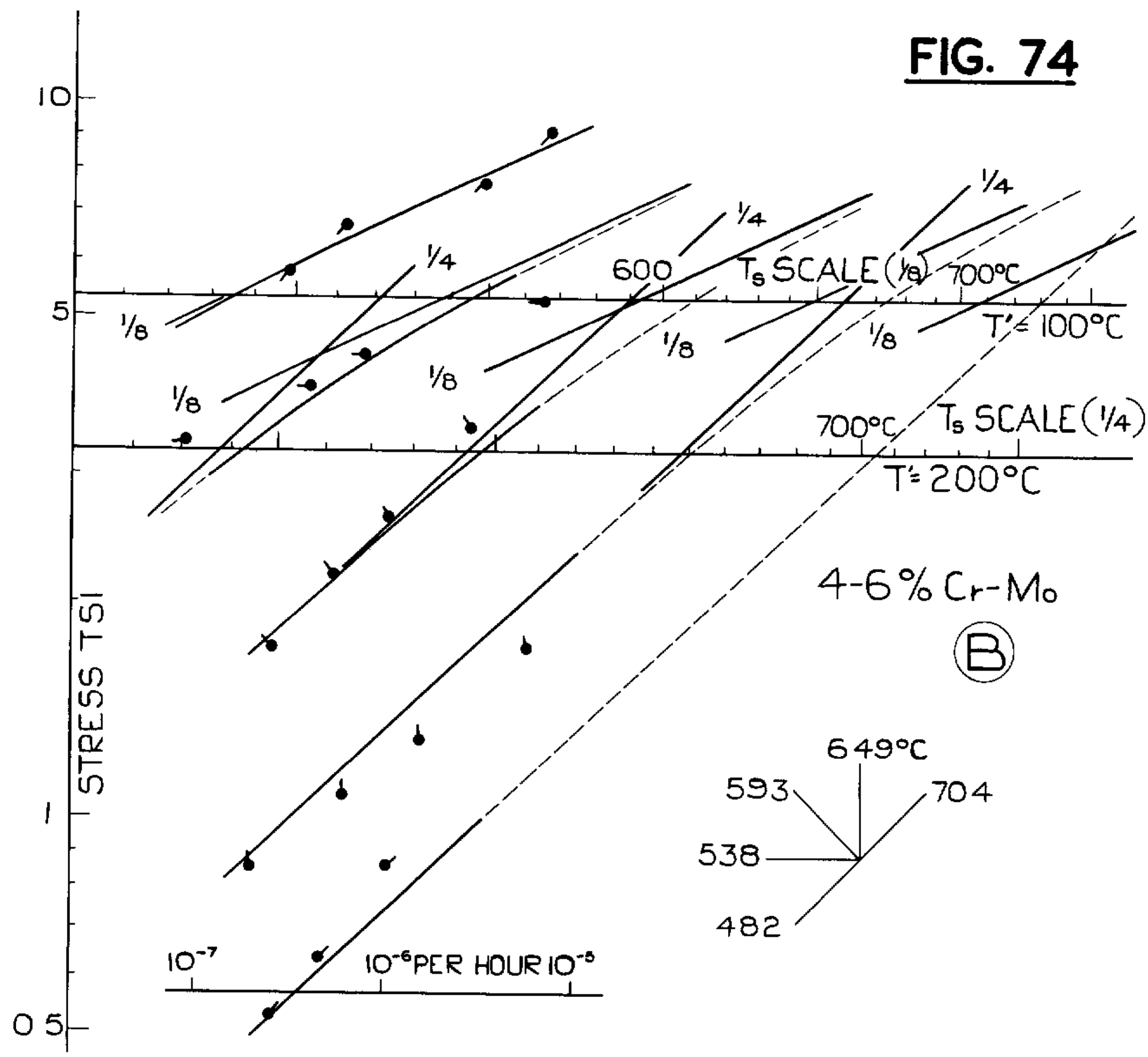
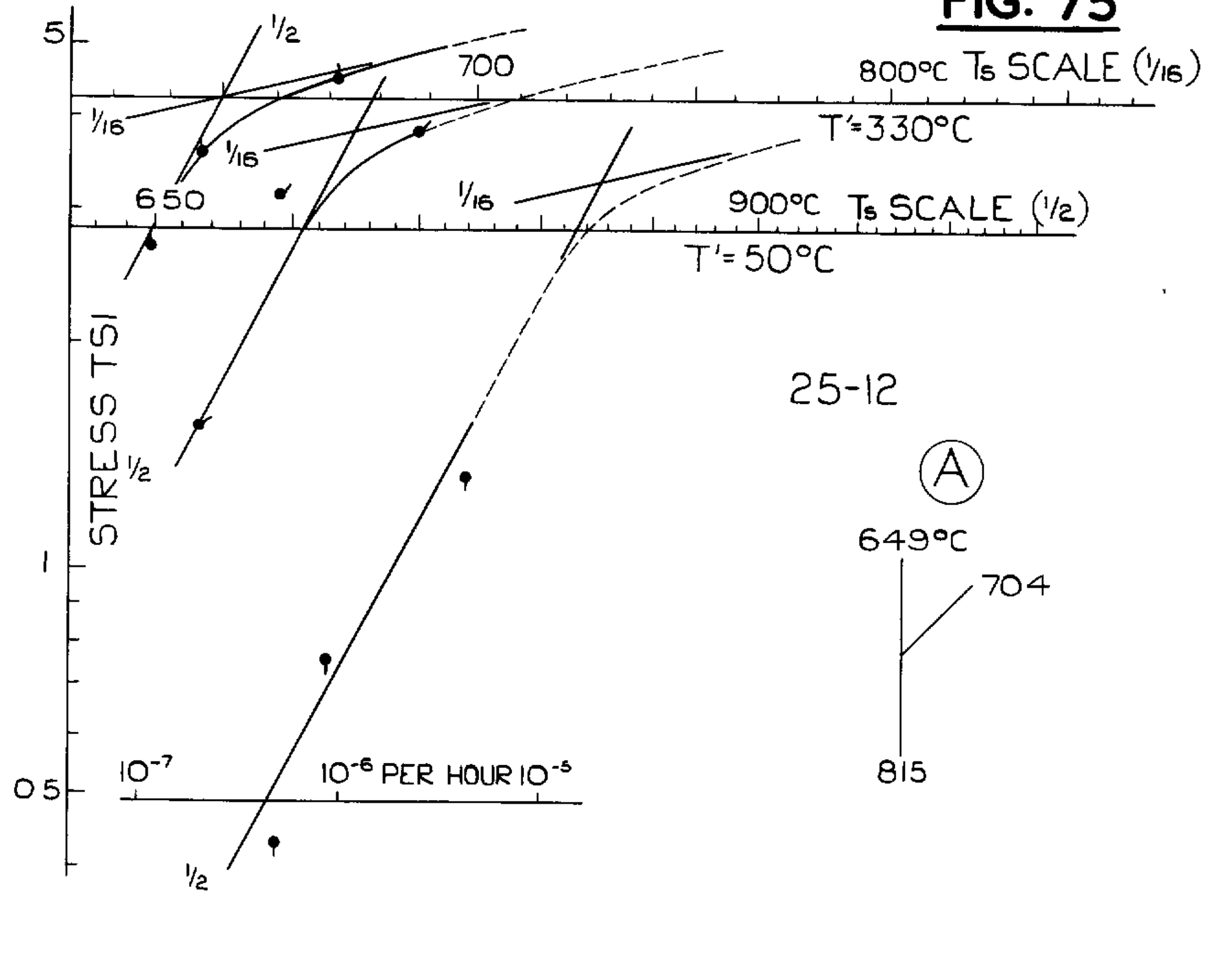


FIG. 75



CREEP RATE 4-6% Cr-Mo AND 25-12

FIG. 74a

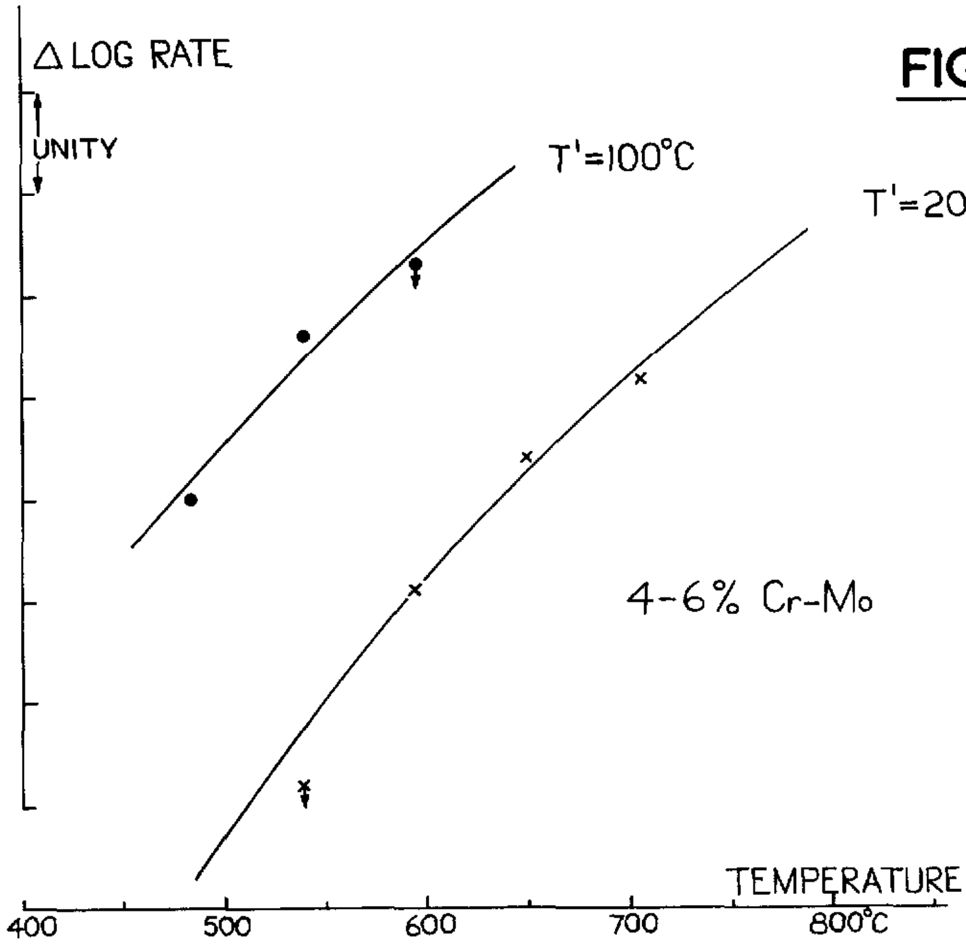
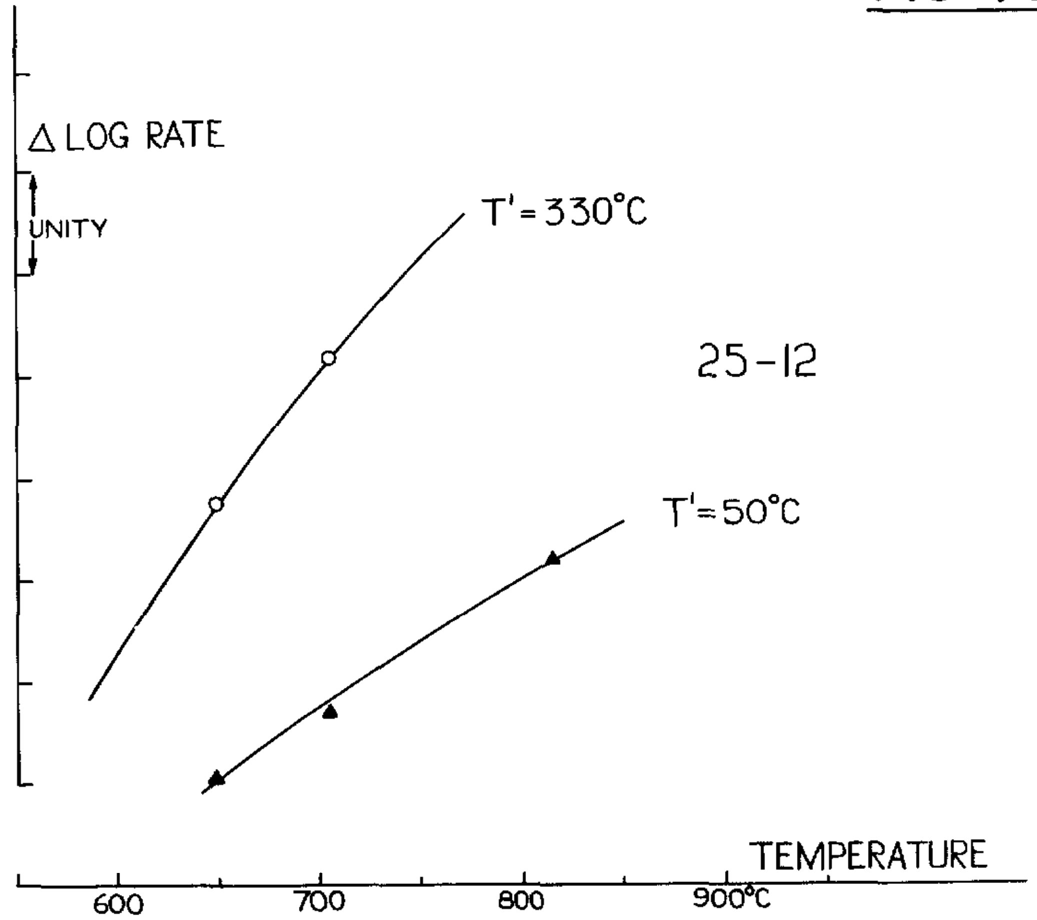


FIG. 75a



Δ LOG RATE PLOTS 4-6% Cr-Mo AND 25-12

FIG. 76

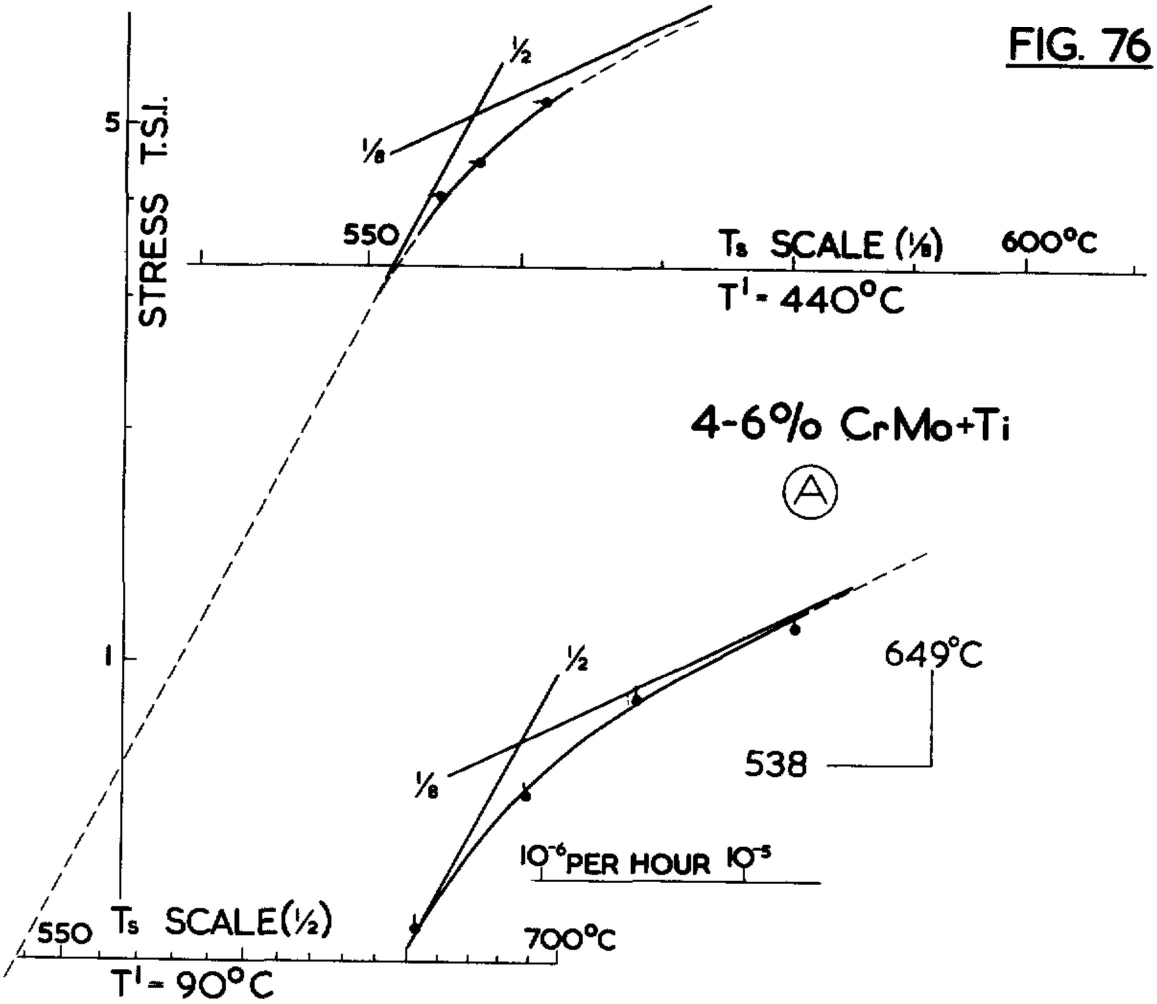
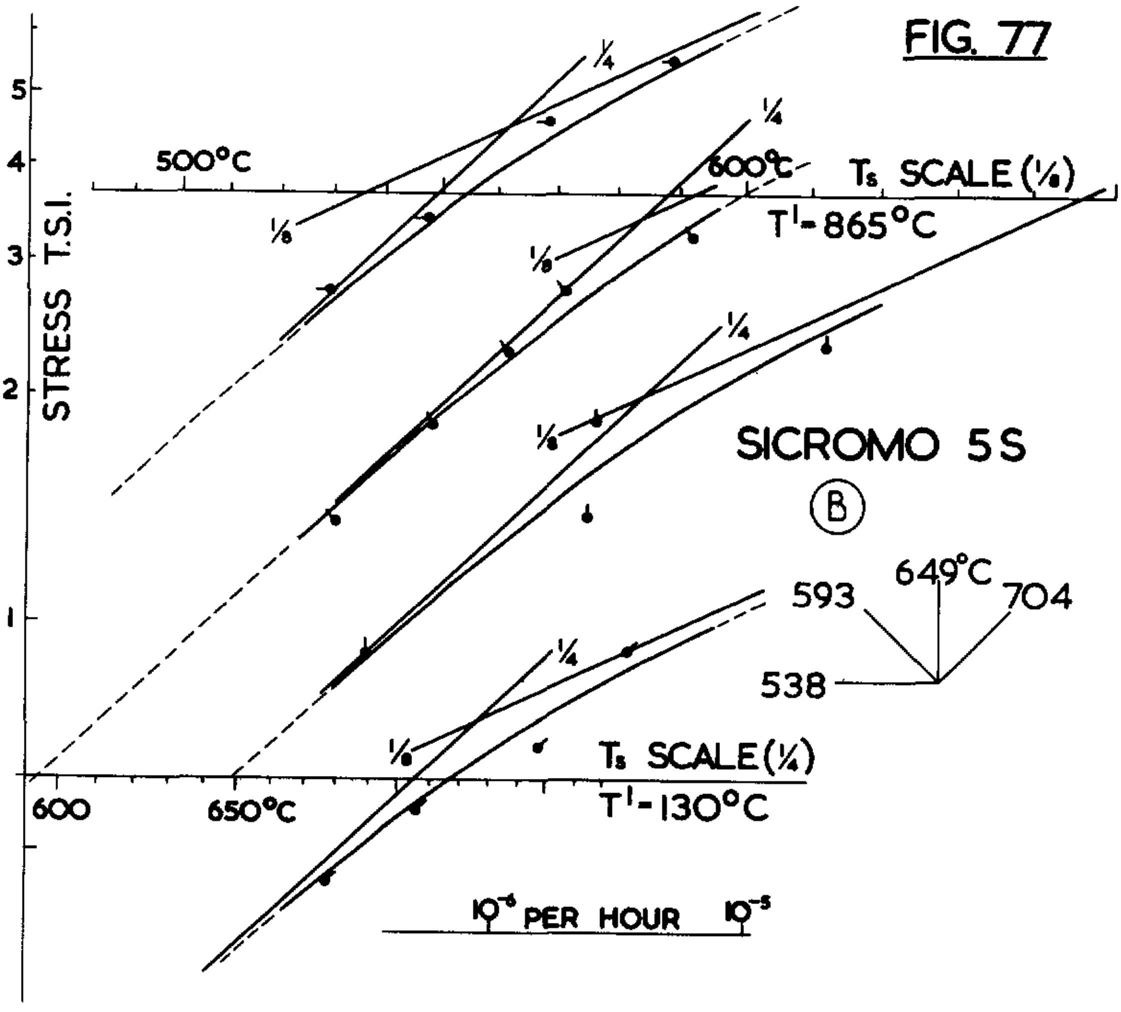


FIG. 77



CREEP RATE 4-6% Cr Mo + Ti AND SICROMO 5 S

FIG. 76a

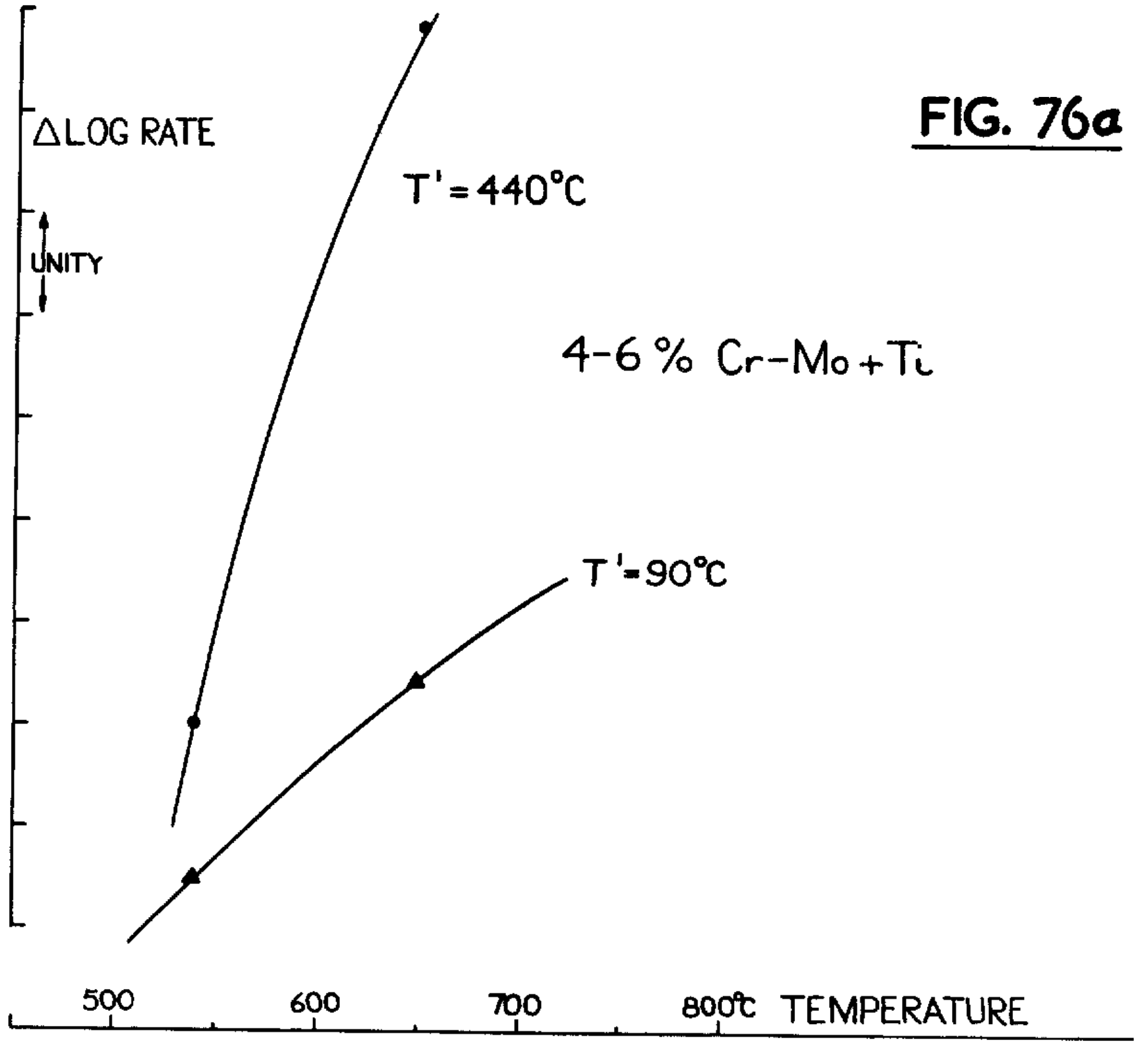
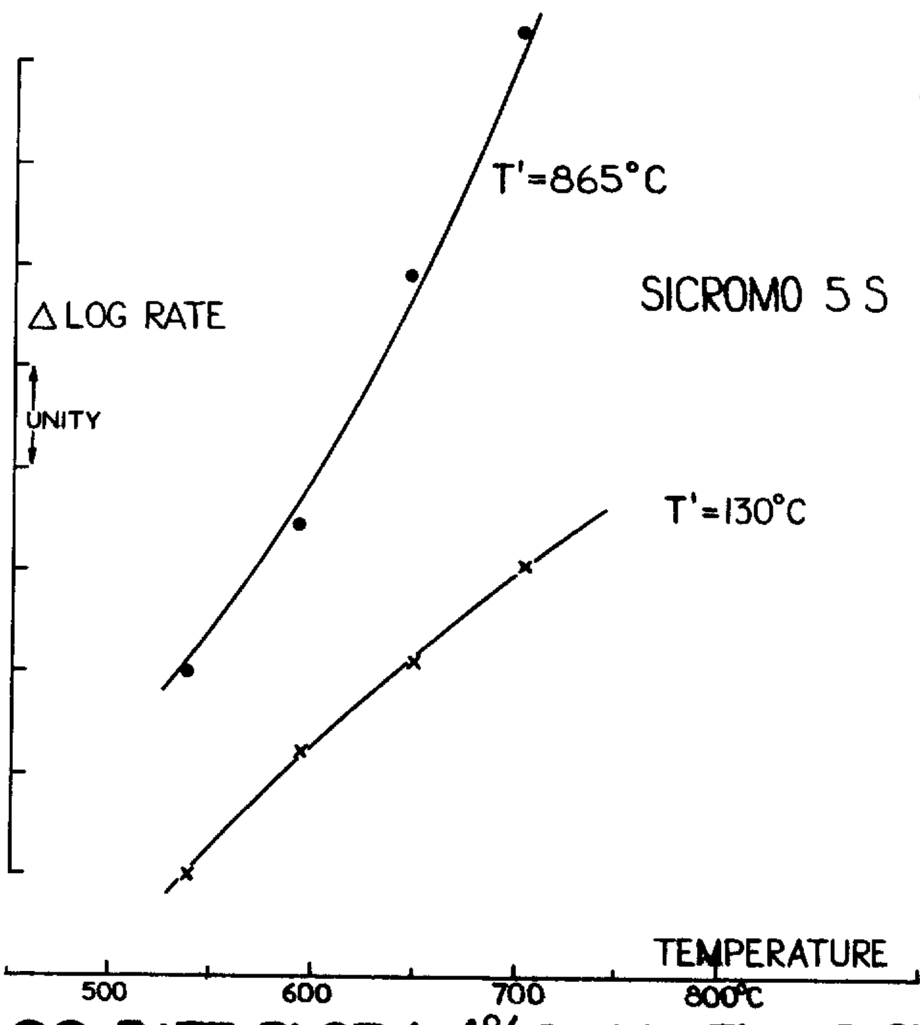


FIG. 77a



Δ LOG RATE PLOT 4-6% Cr-Mo+Ti AND SICROMO 5S

FIG. 78

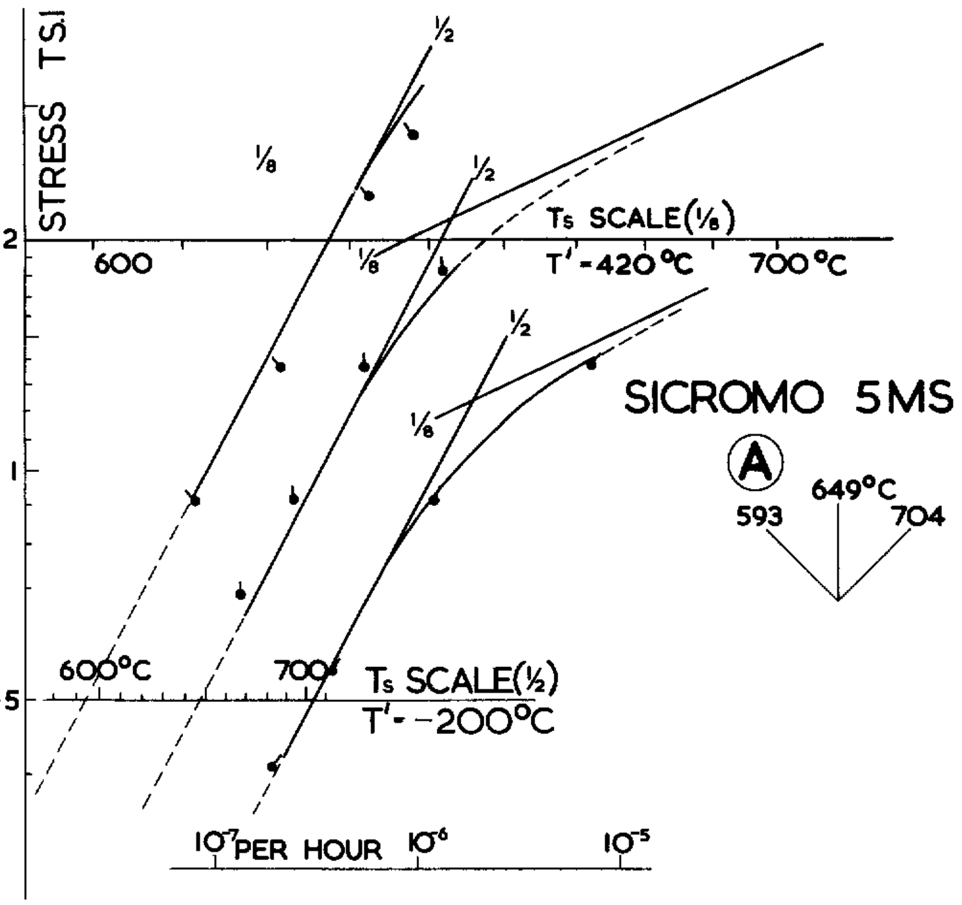
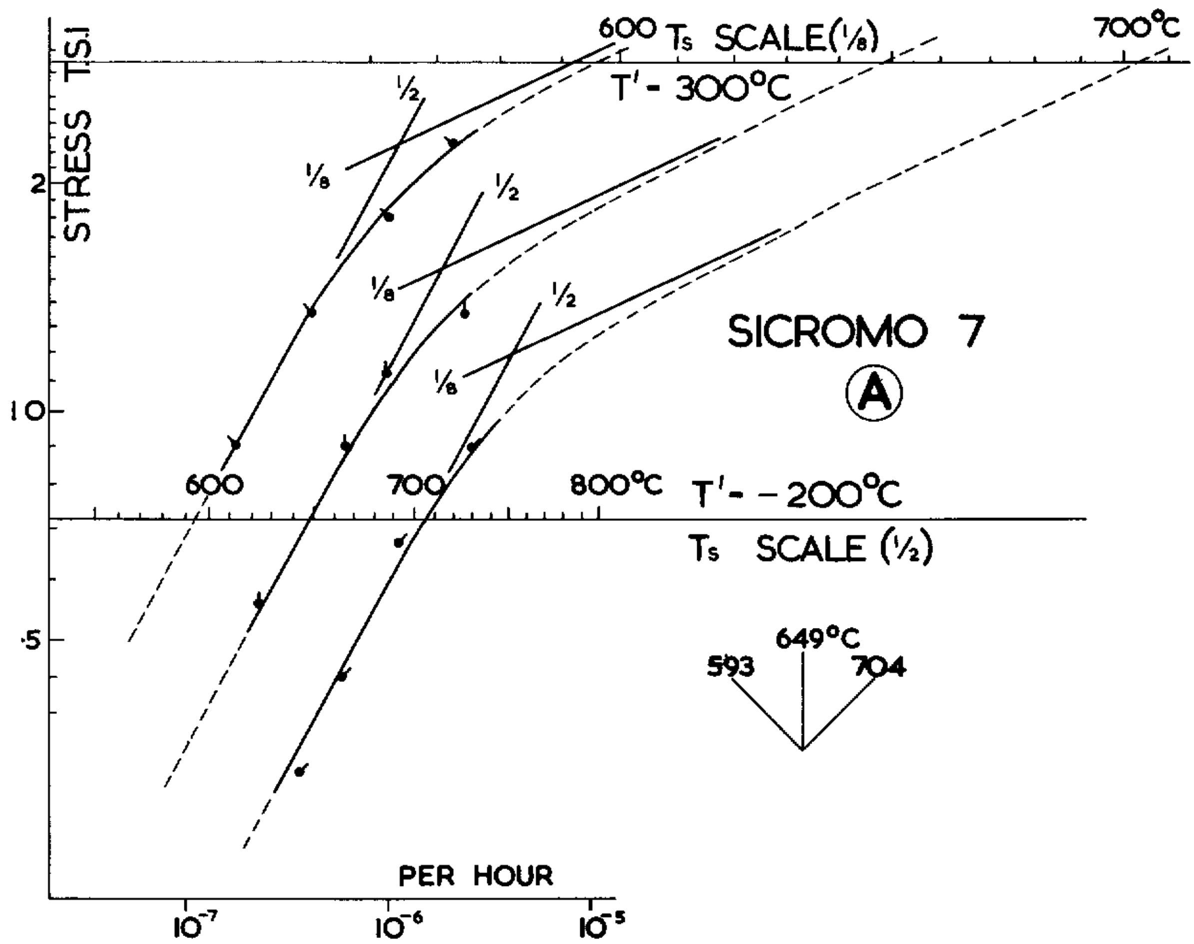


FIG. 79



CREEP RATE SICROMO 5MS AND SICROMO 7

FIG. 78a

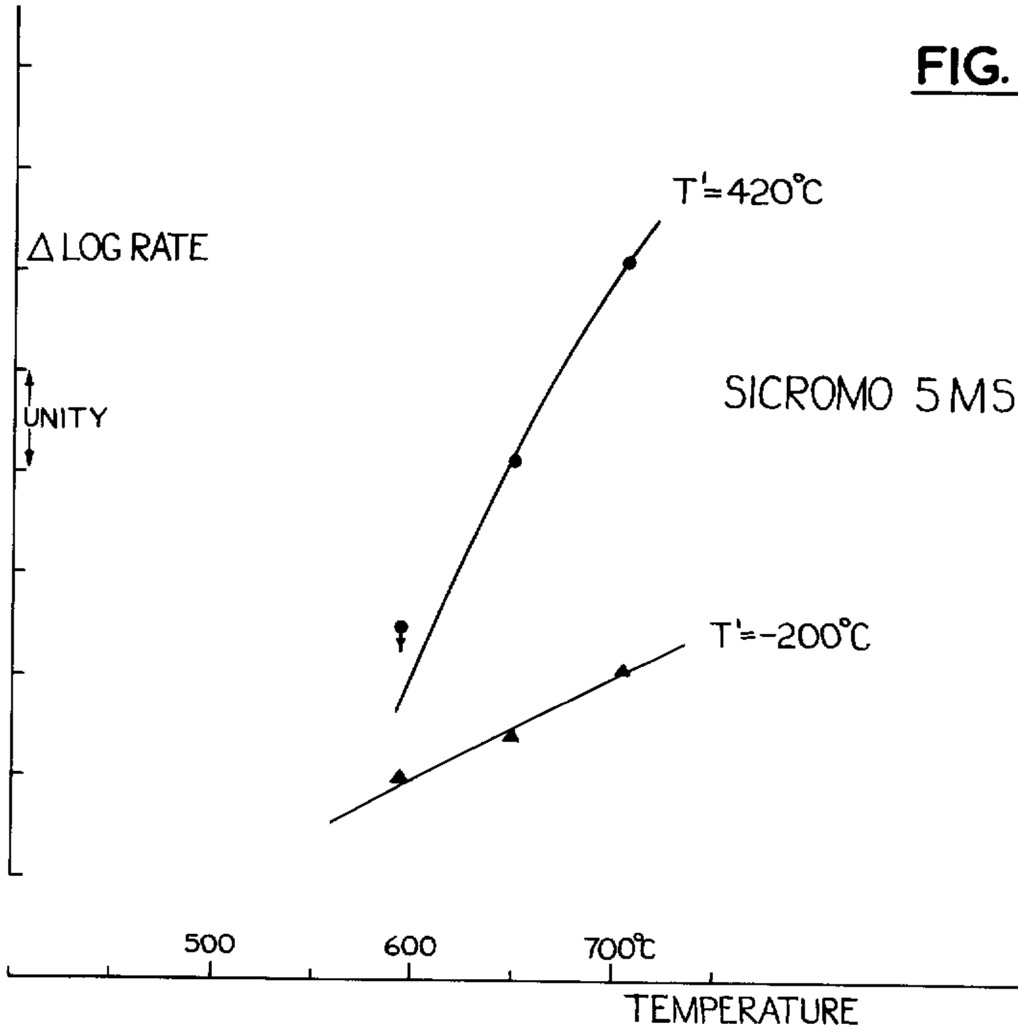
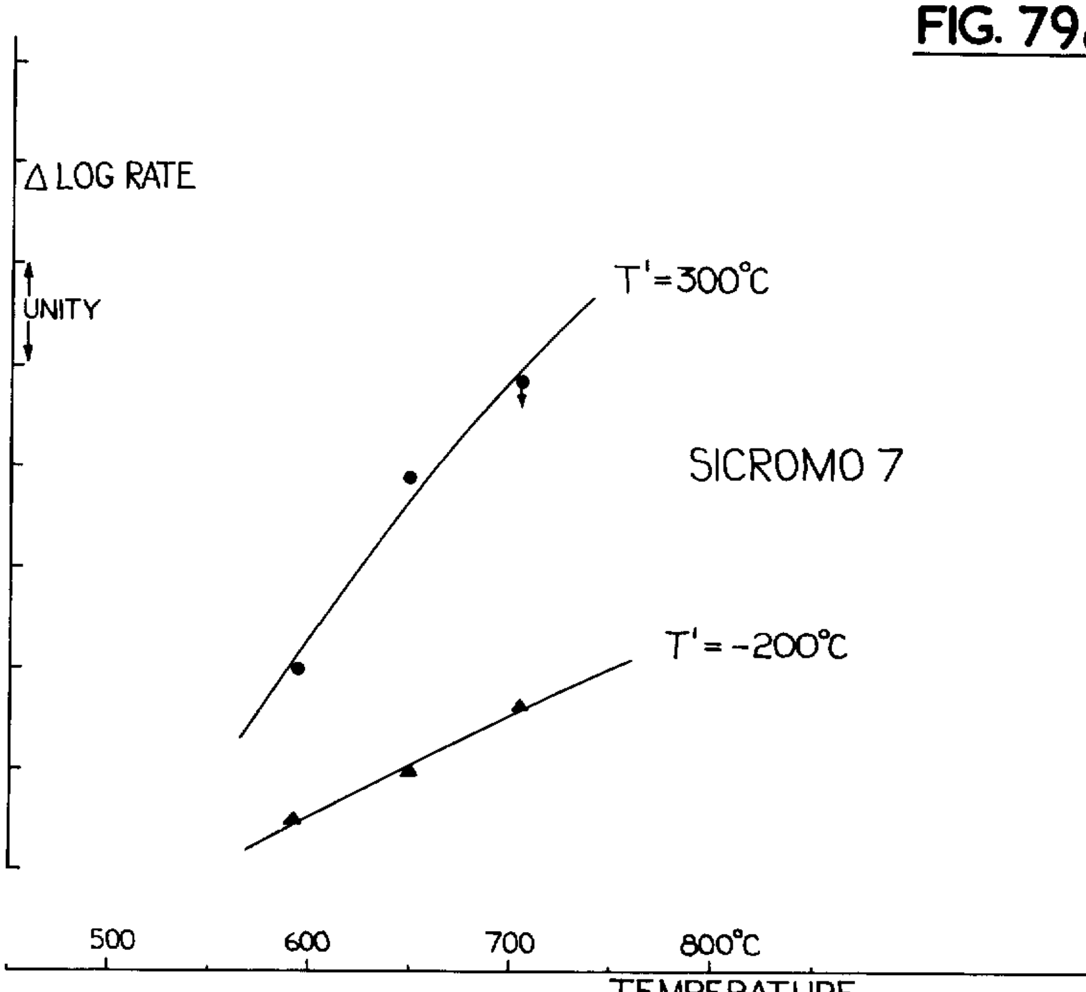


FIG. 79a



Δ LOG RATE PLOTS SICROMO 5MS AND SICROMO7

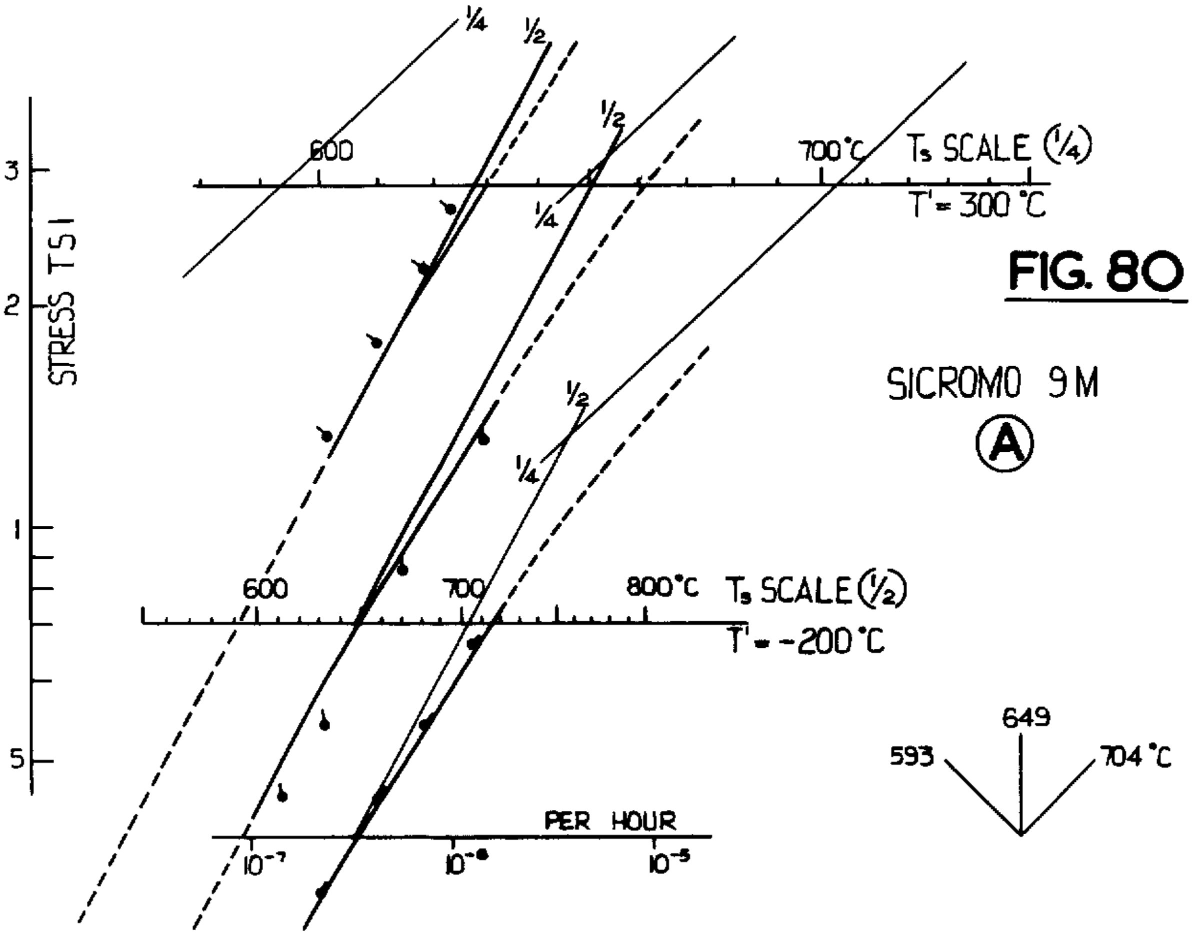


FIG. 80

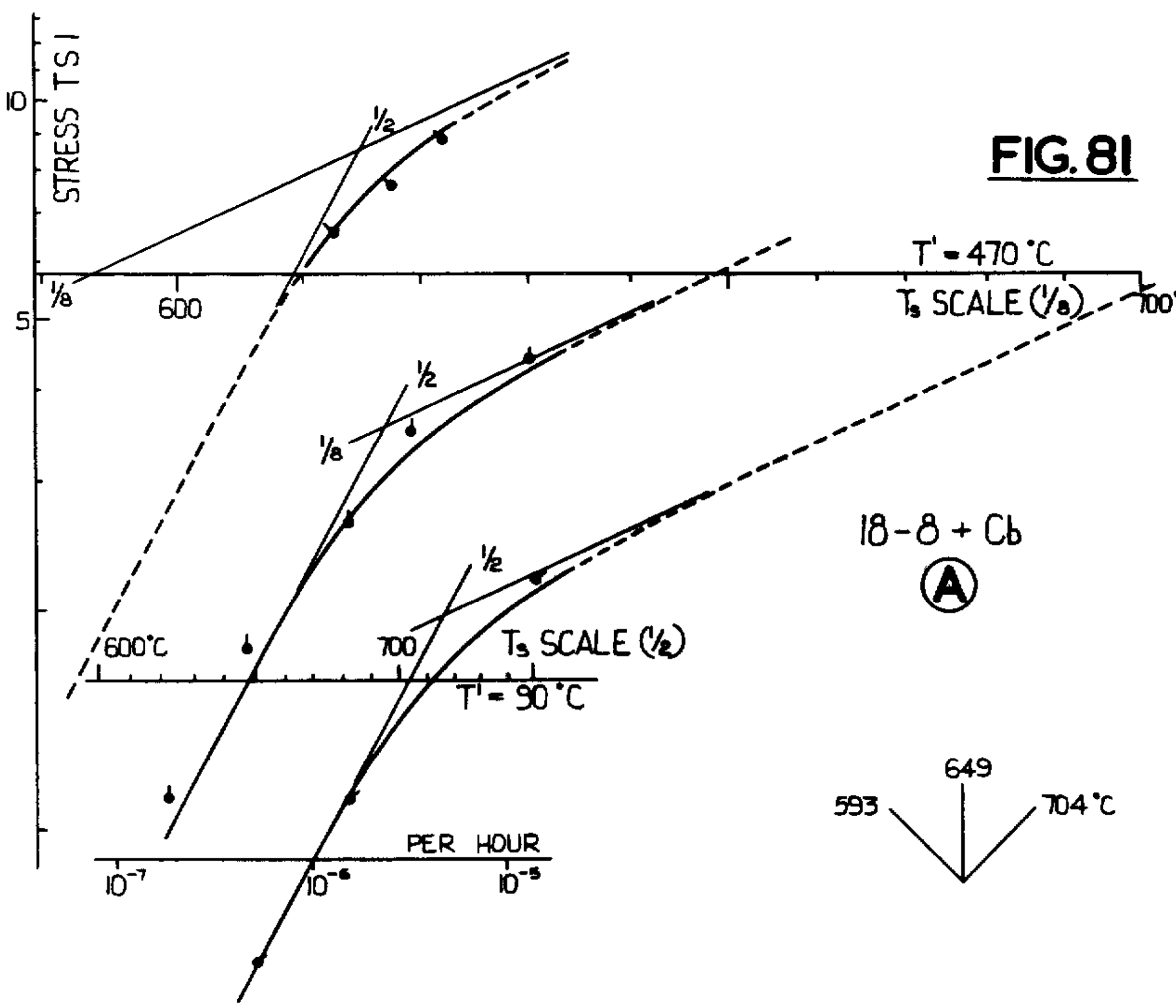


FIG. 81

CREEP RATE SICROMO 9M AND 18-8+Cb

FIG. 80a

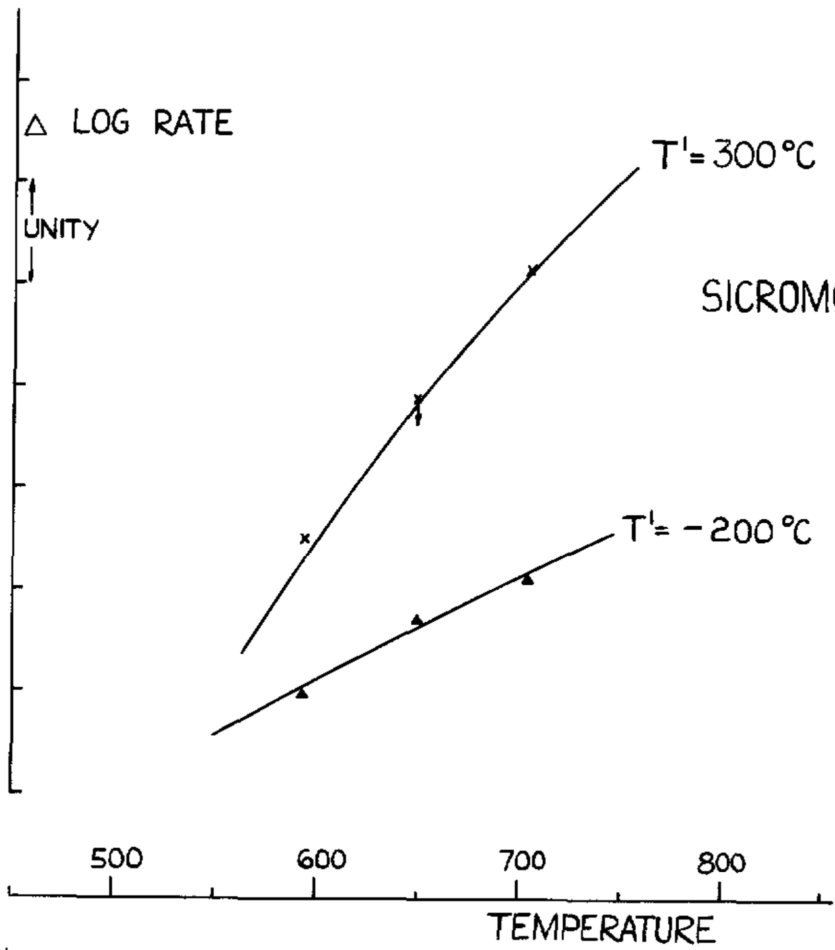
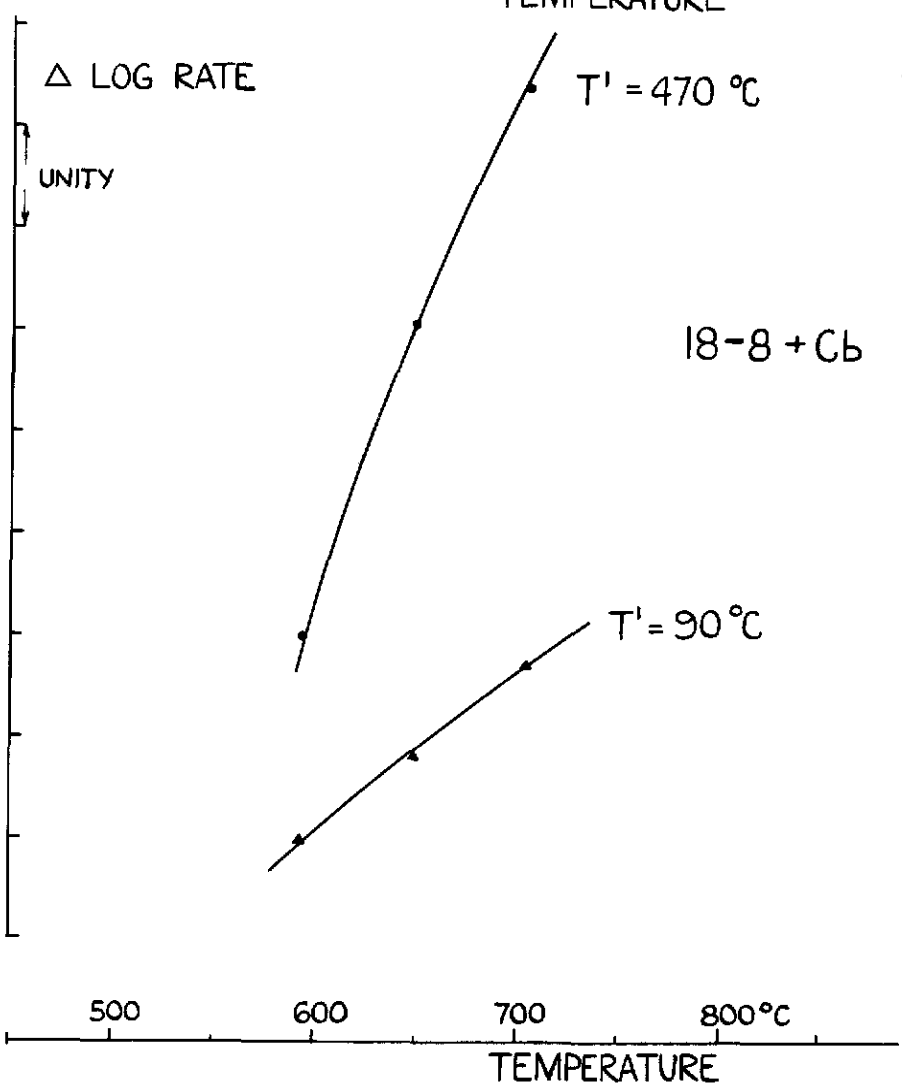


FIG. 81a



△ LOG RATE PLOTS SICROMO 9M & 18-8-Cb

CREEP RATE S 816

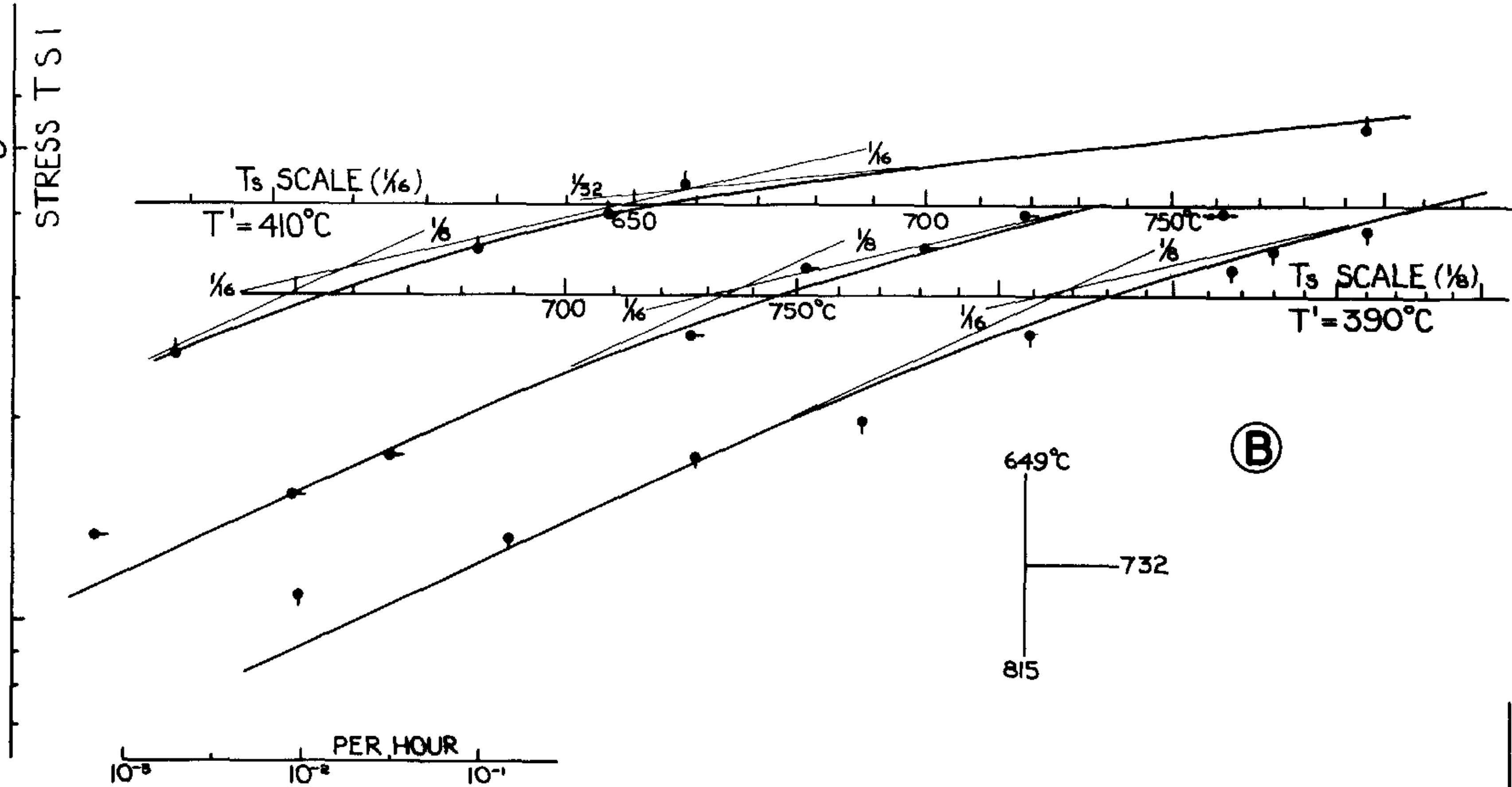
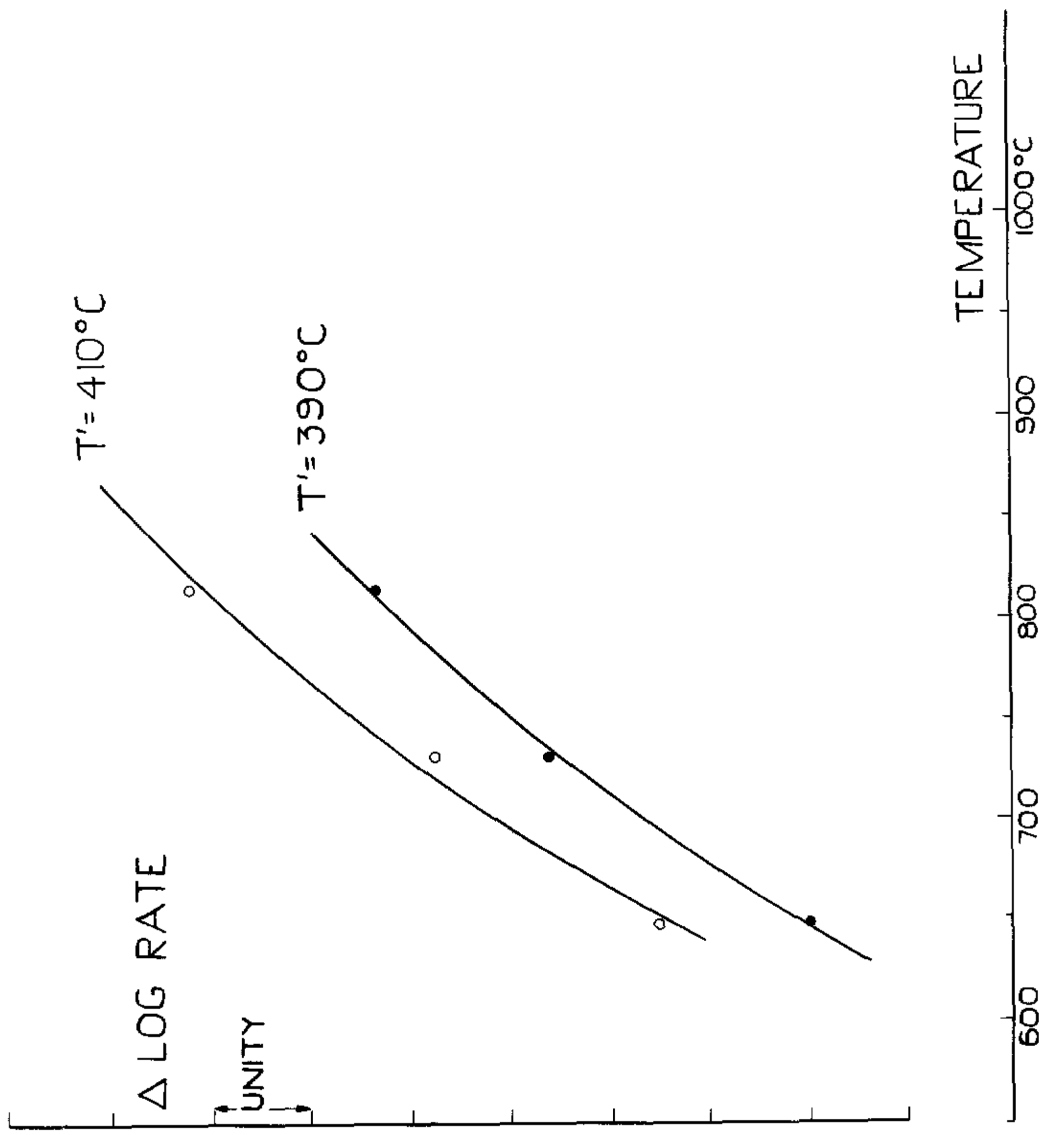


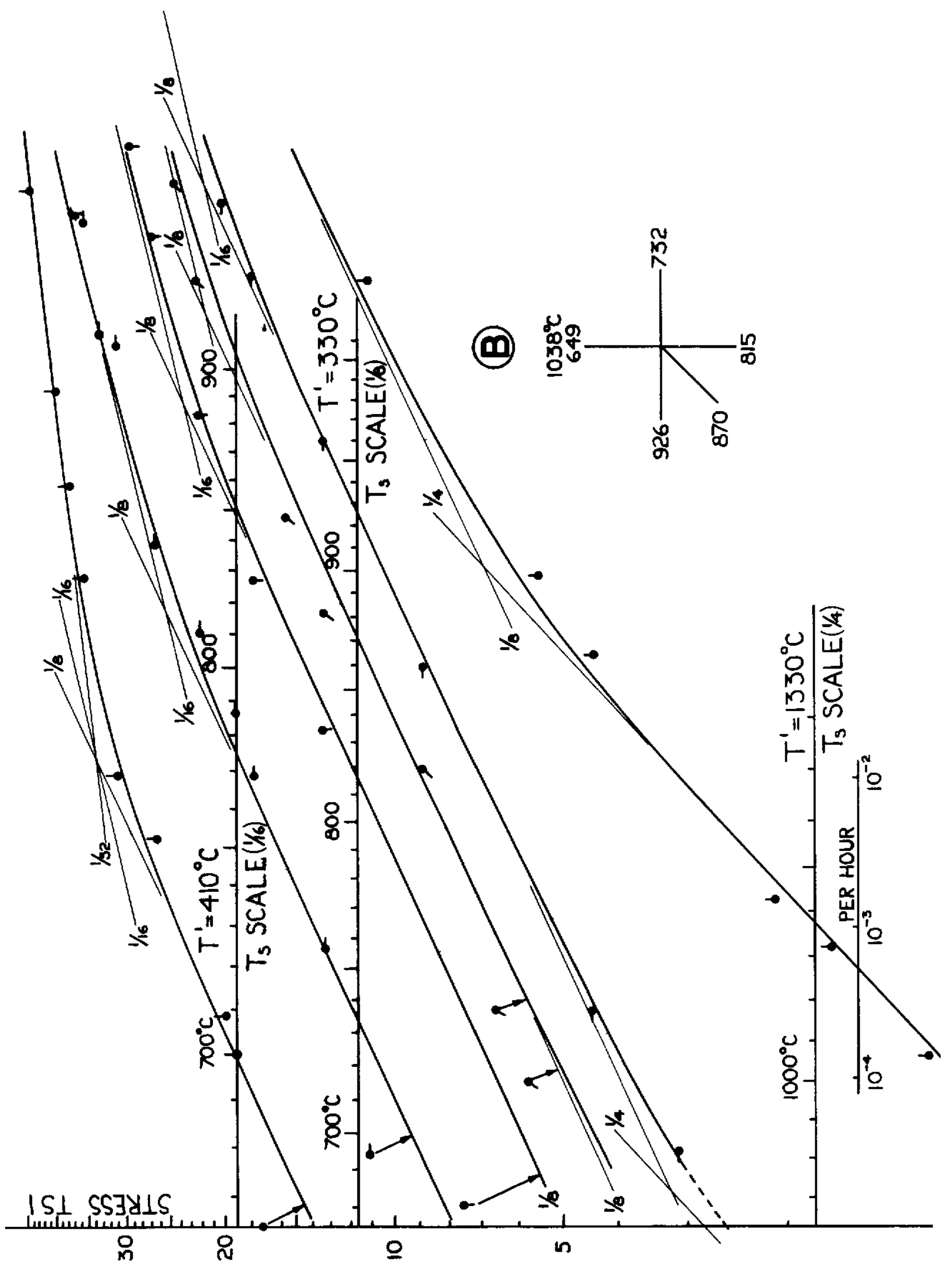
FIG. 82

FIG. 82a



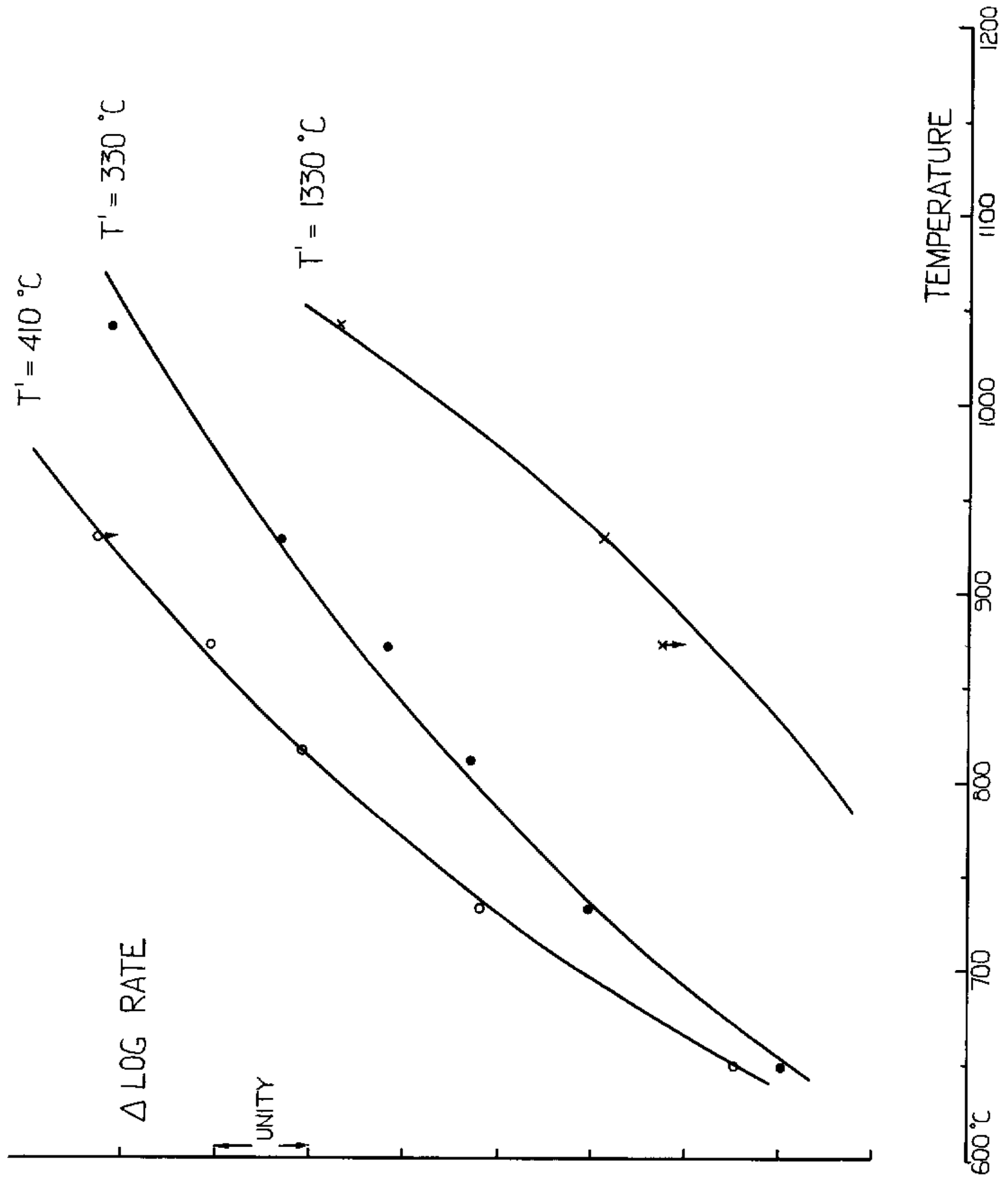
Δ LOG RATE PLOT S 816

FIG. 83



CREEP RATE S590

FIG. 83a



ΔLOG RATE PLOT S590

FIG. 84

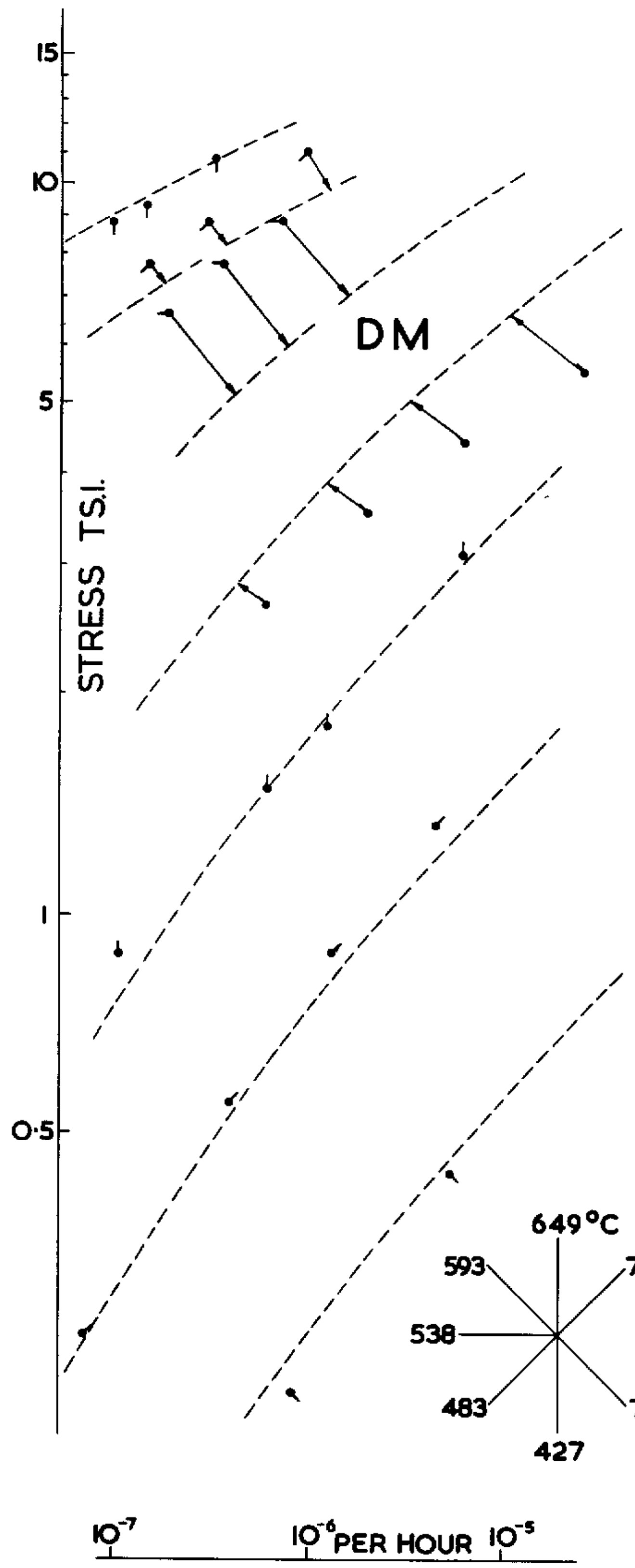
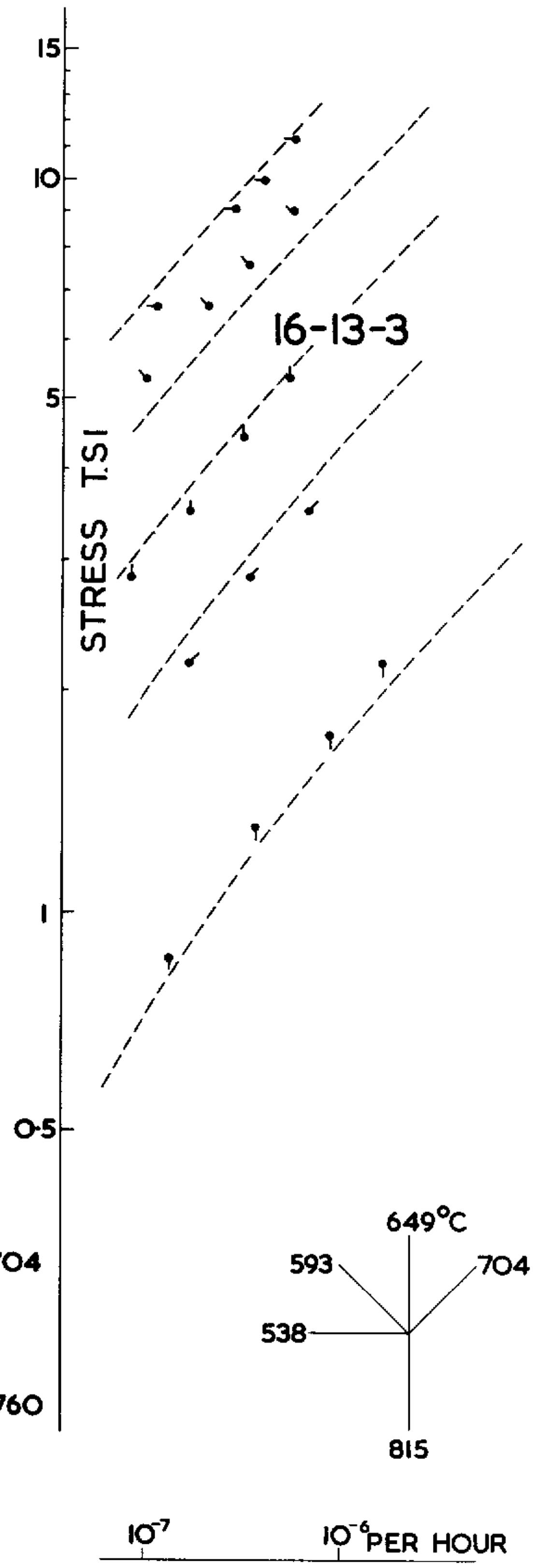


FIG. 85



CREEP RATE DM AND 16-13-3 STEELS

FIG. 84a

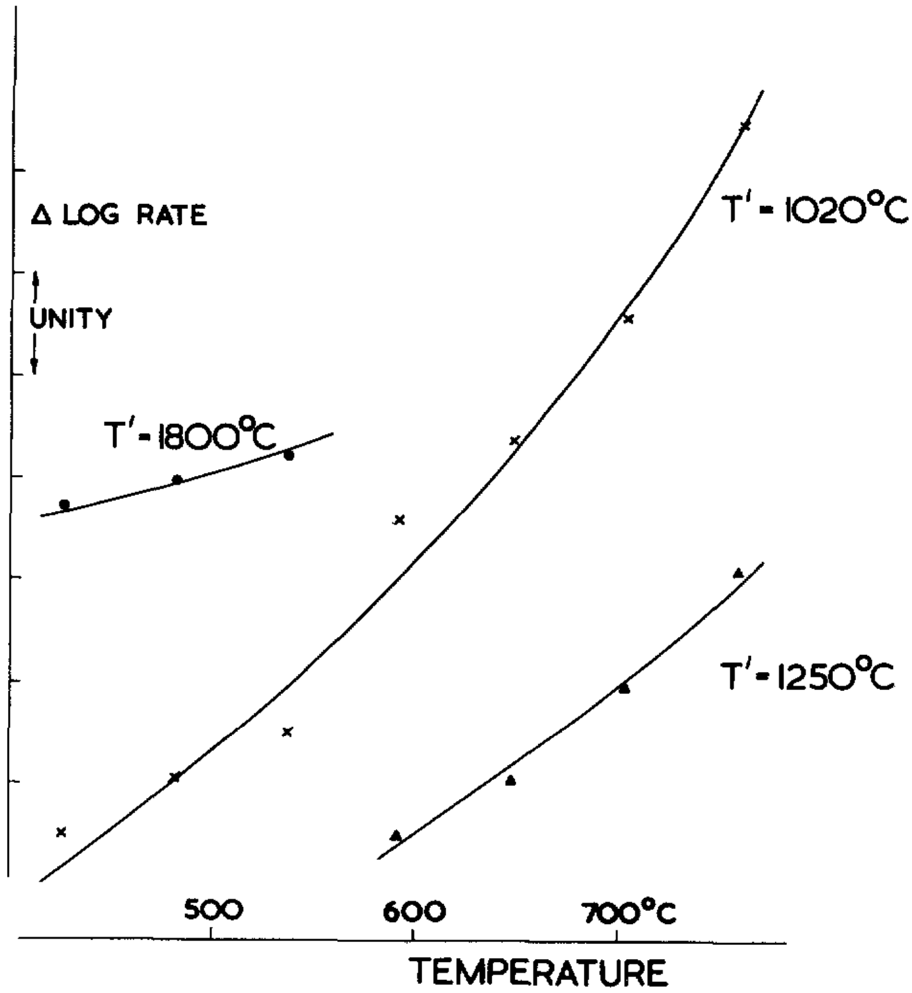
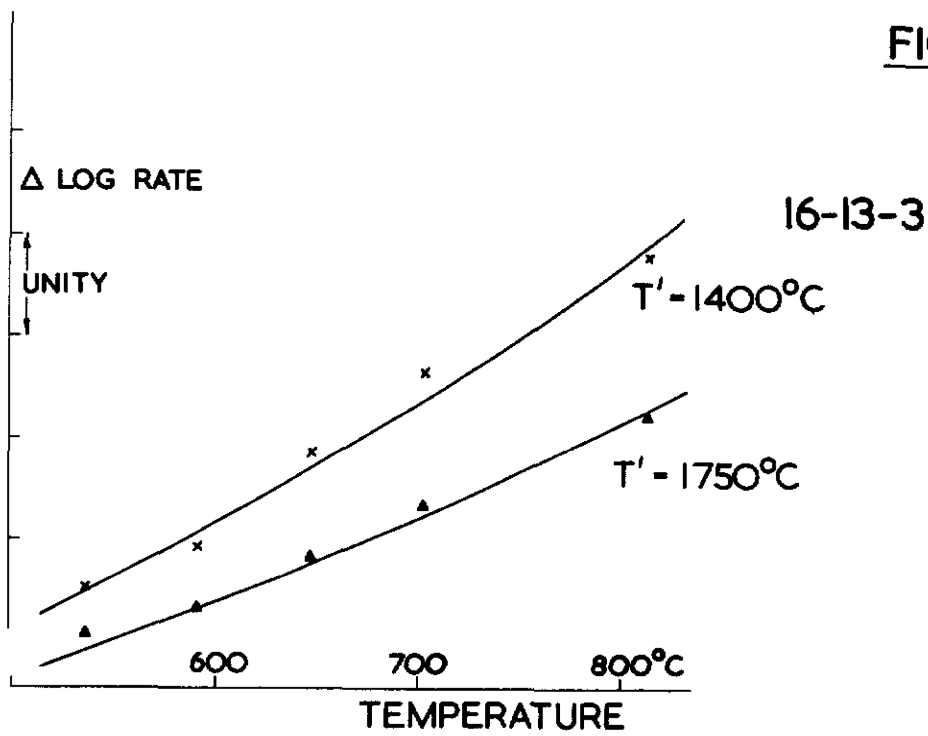


FIG. 85a



Δ LOG RATE PLOTS DM AND 16-13-3 STEELS

FIG. 86

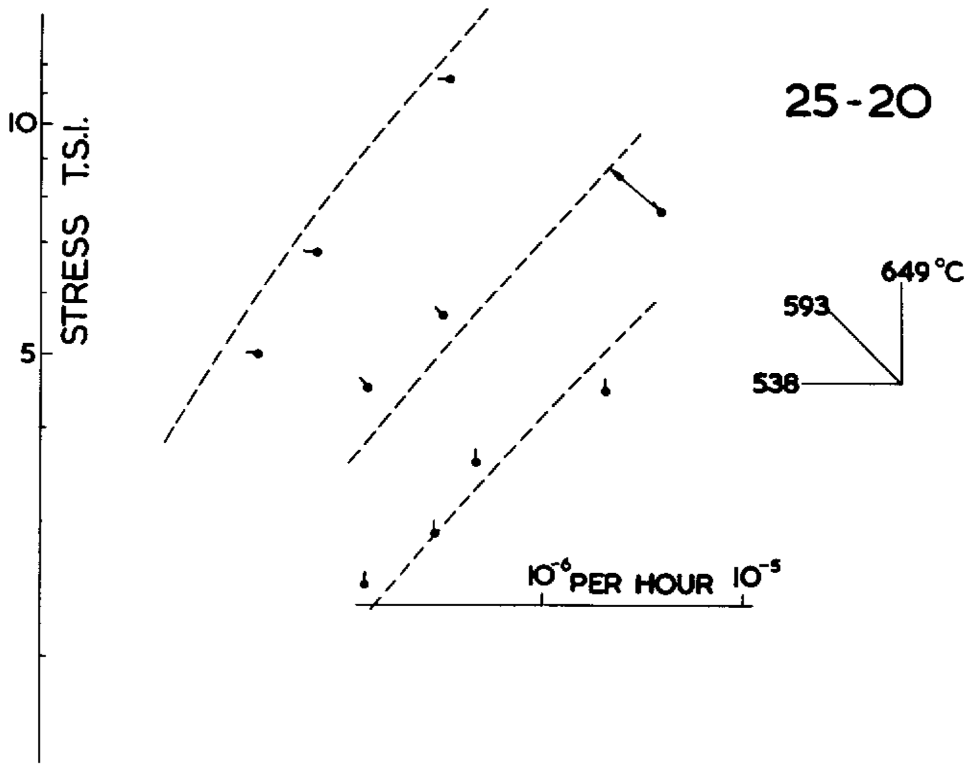
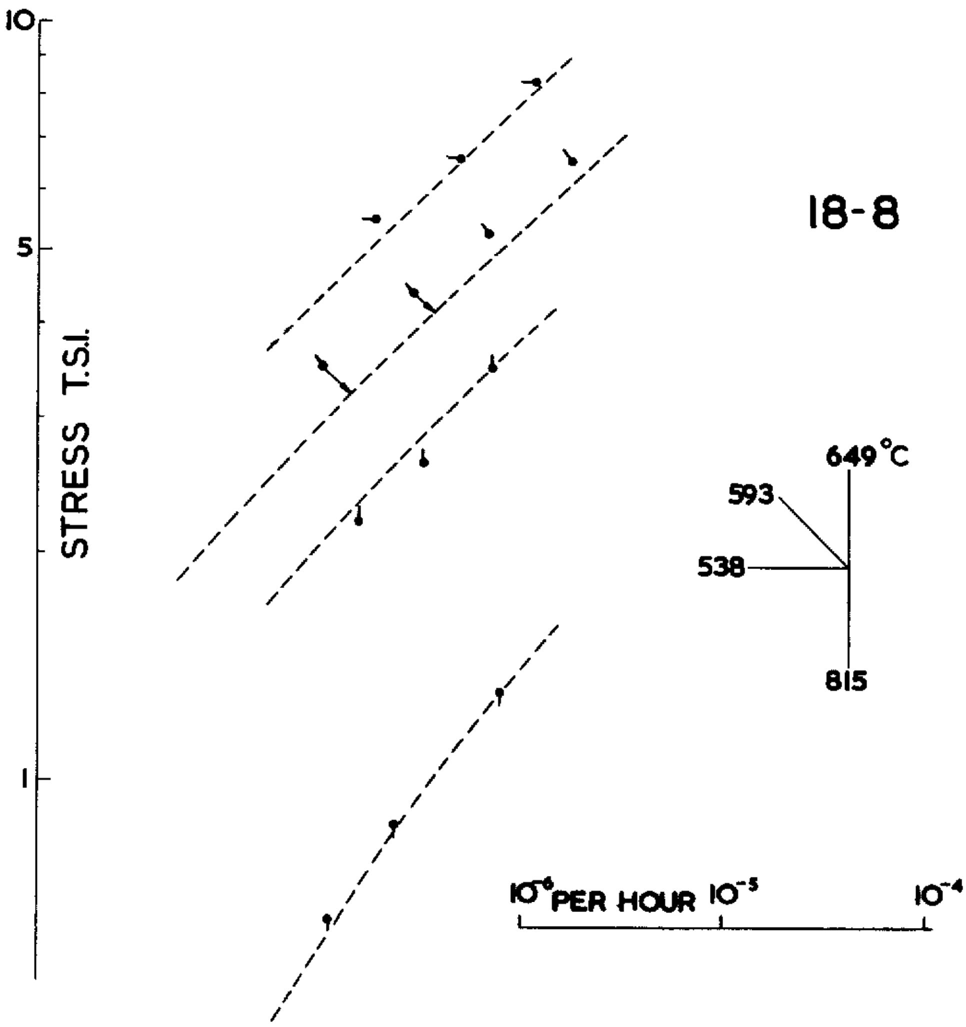


FIG. 87



CREEP RATE 25-20 AND 18-8 STEELS

FIG. 86a

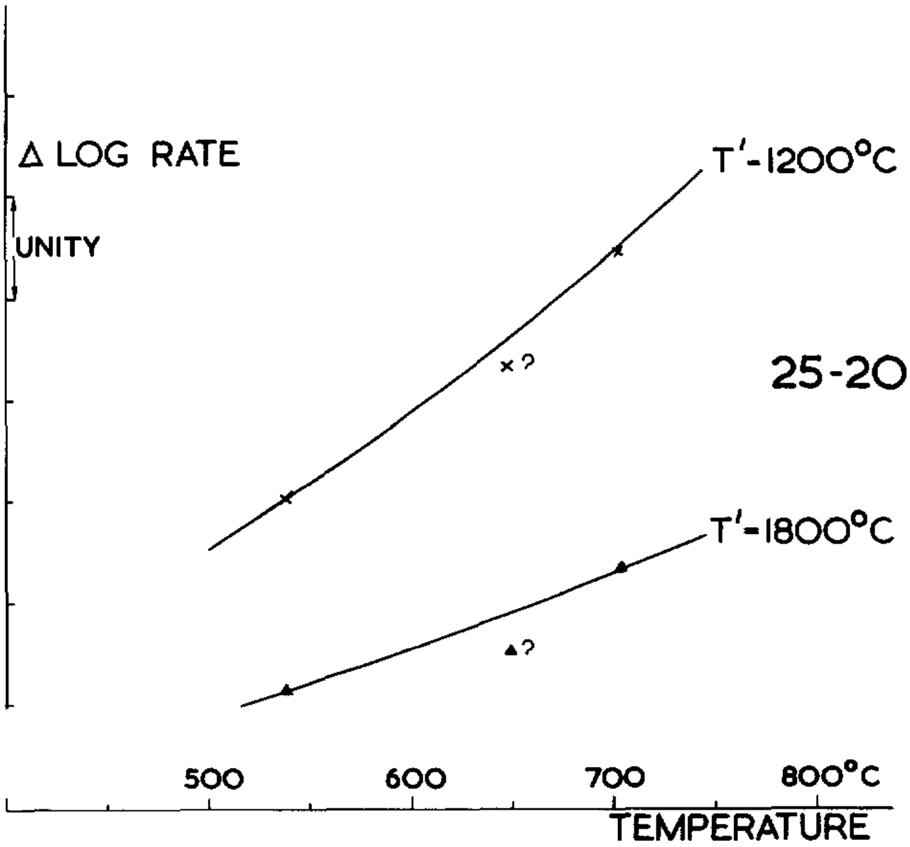
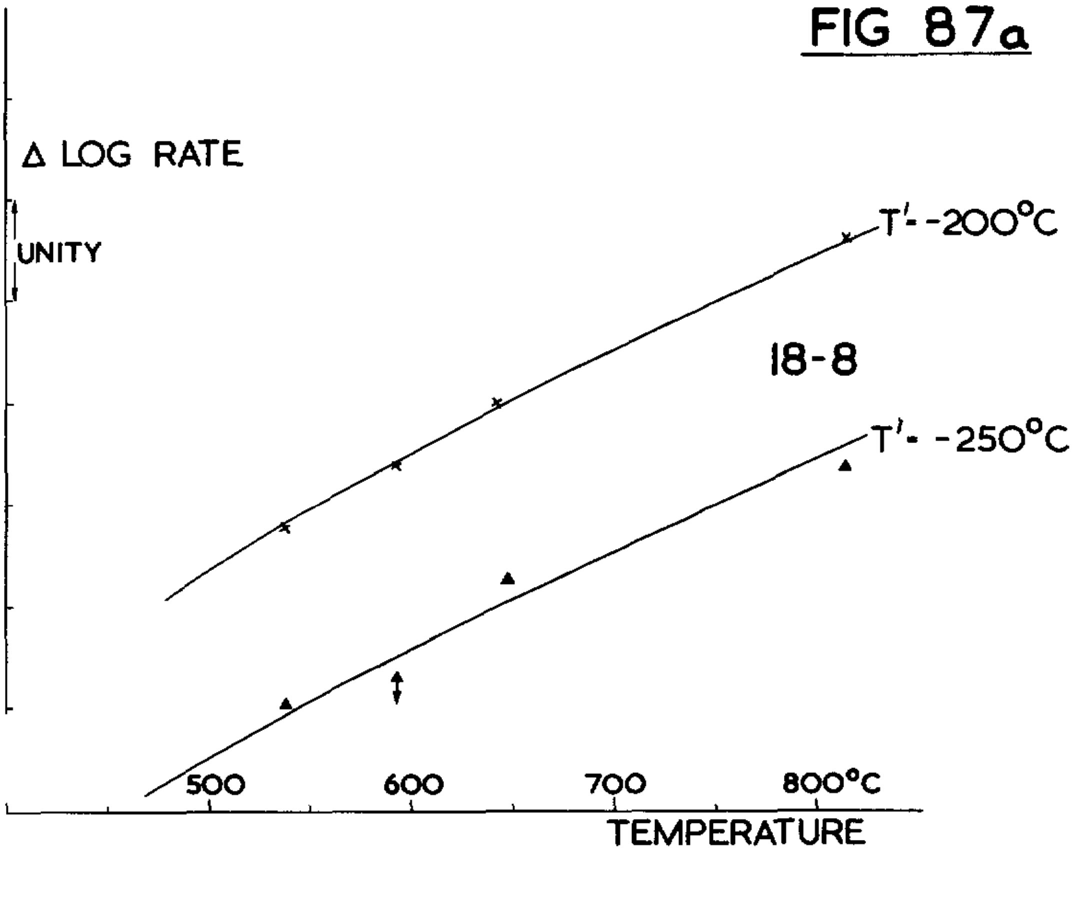


FIG 87a



Δ LOG RATE PLOTS 25-20 AND 18-8 STEELS

FIG. 88

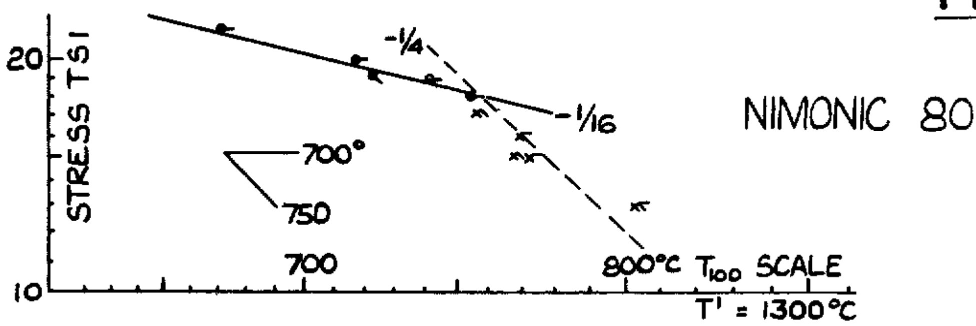
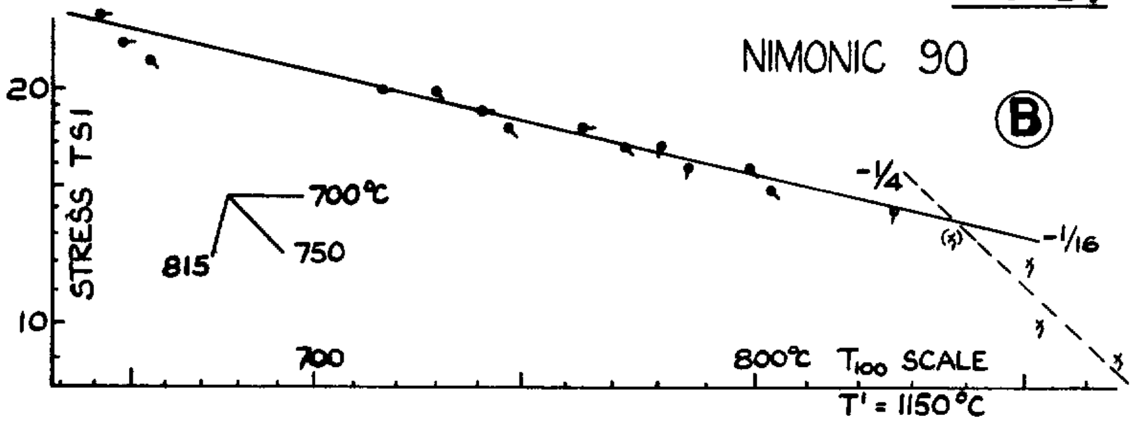


FIG. 89



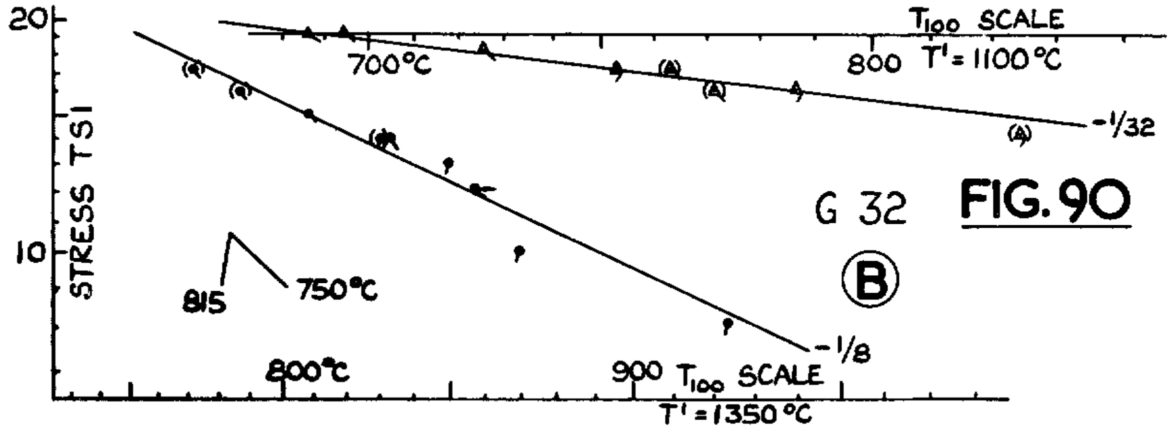


FIG. 90

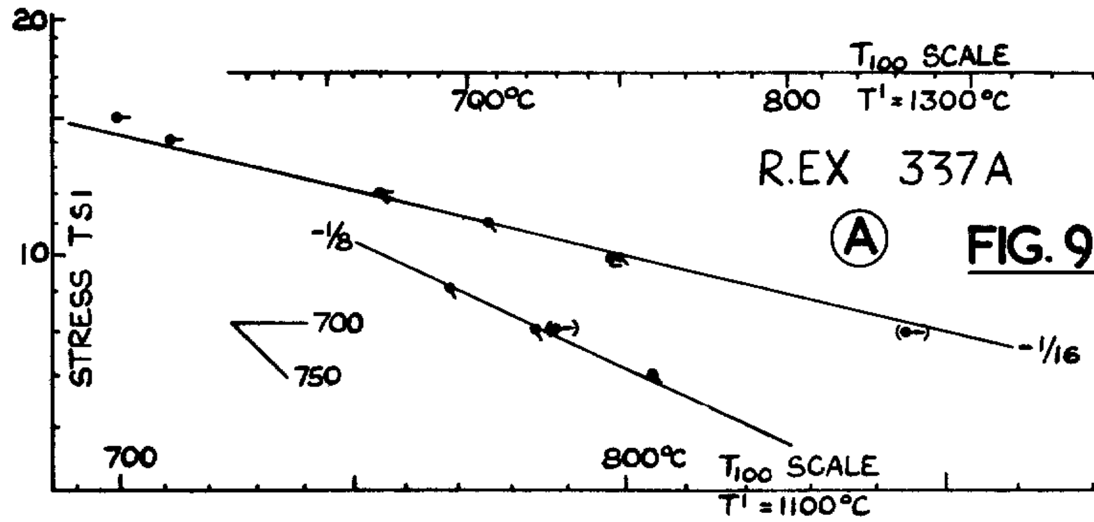


FIG. 91

HOT FATIGUE DATA, PLOTTED BY METHOD (i)

FIG.88a

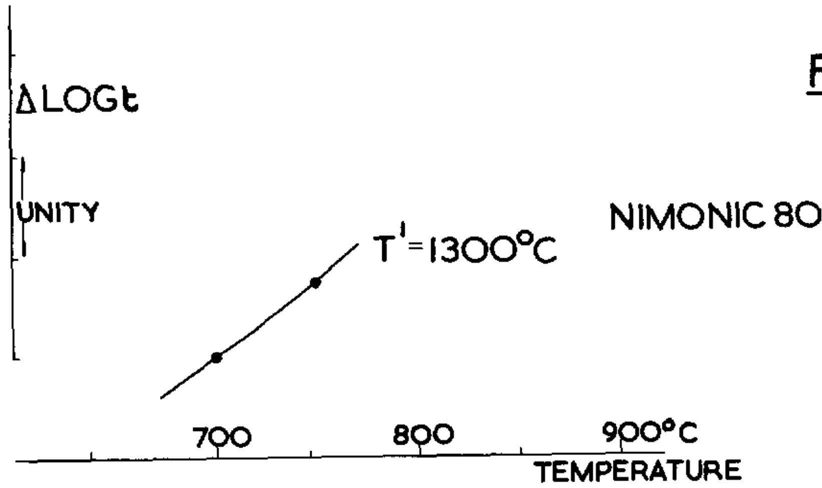


FIG.89a

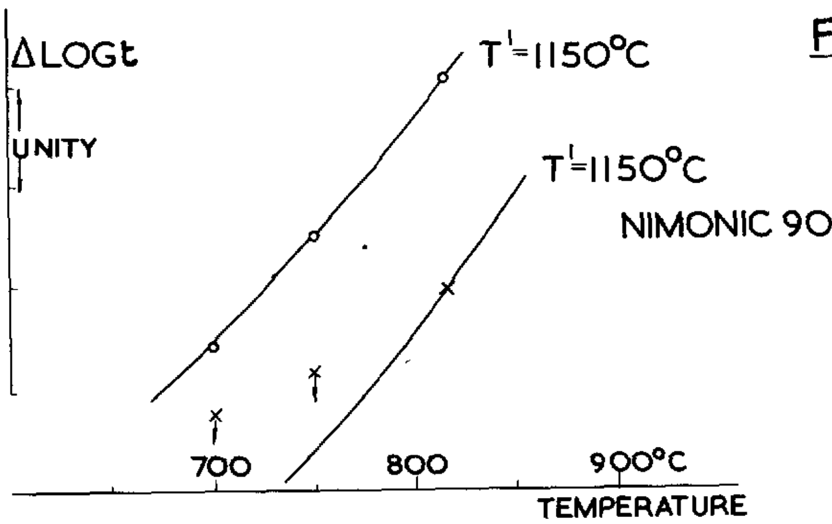


FIG.90a

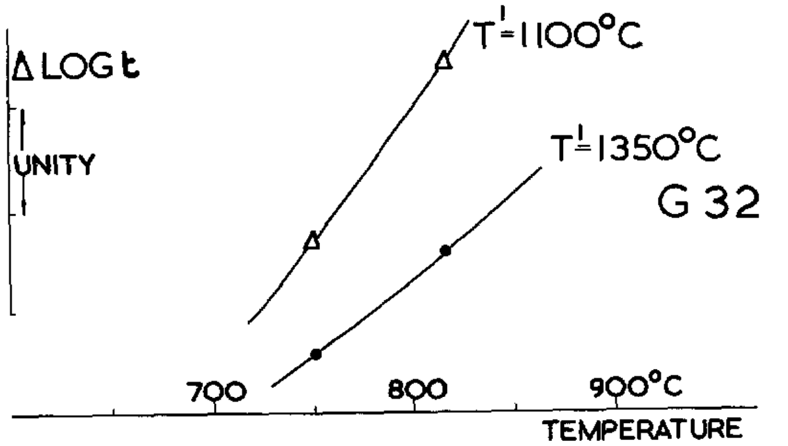
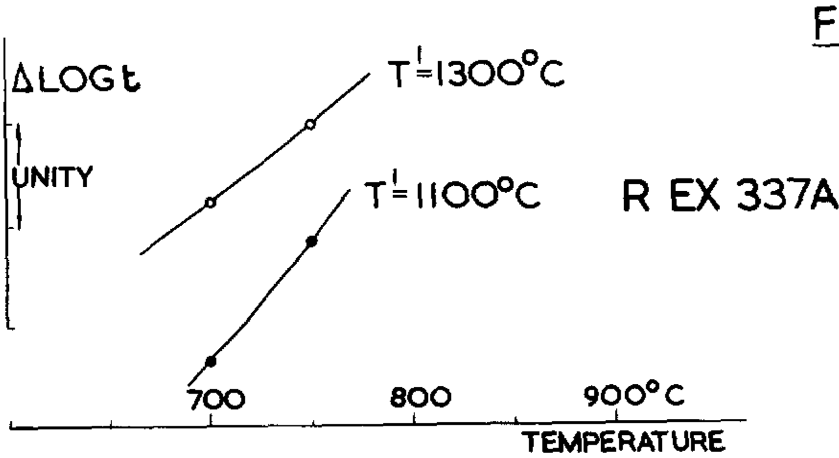


FIG.91a



Δ LOG t/T PLOTS FOR HOT FATIGUE DATA

FIG. 92

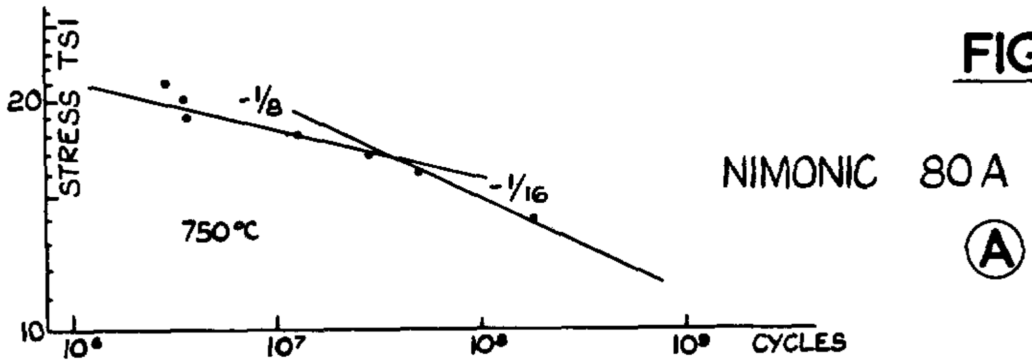


FIG. 93

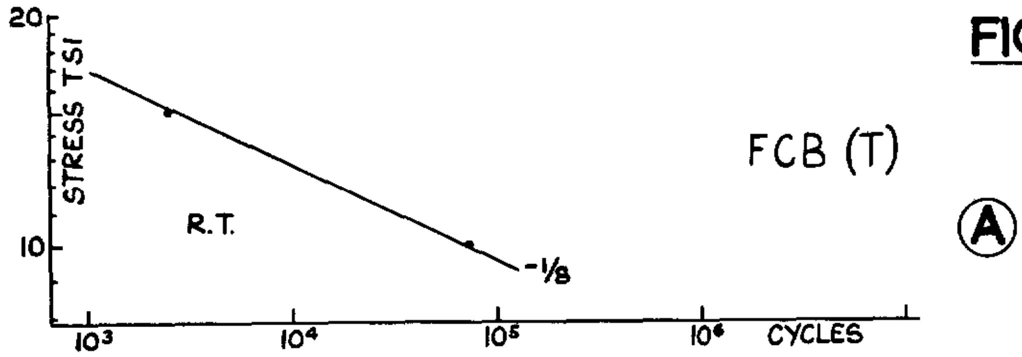


FIG. 94

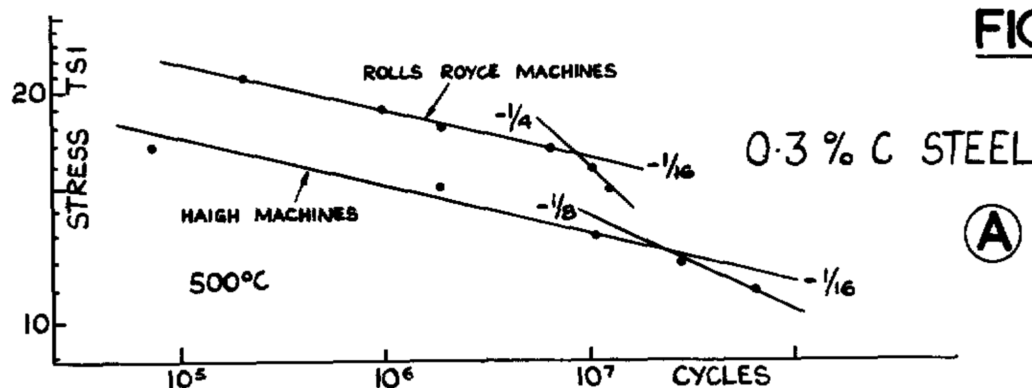


FIG. 95

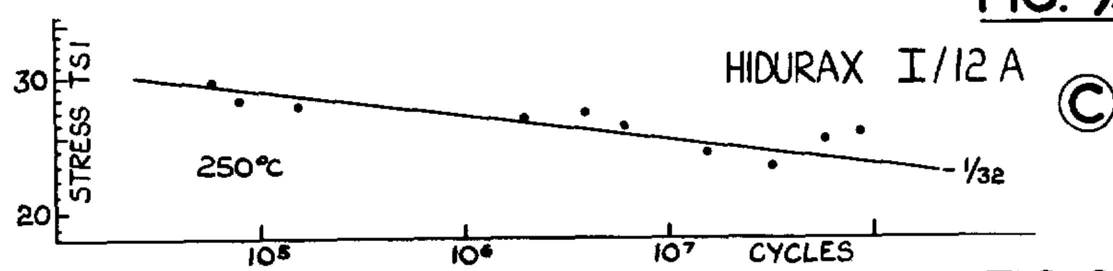


FIG. 96

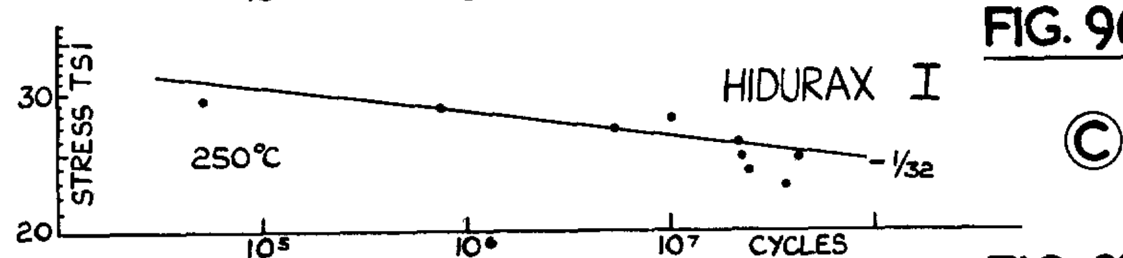
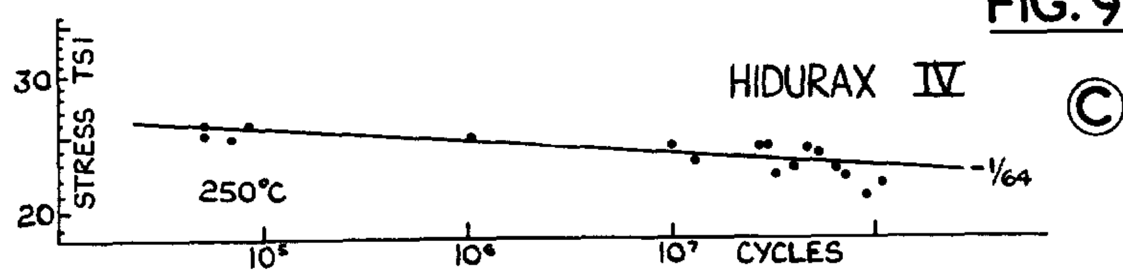


FIG. 97



HOT FATIGUE DATA, LOG STRESS vs LOG CYCLES

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