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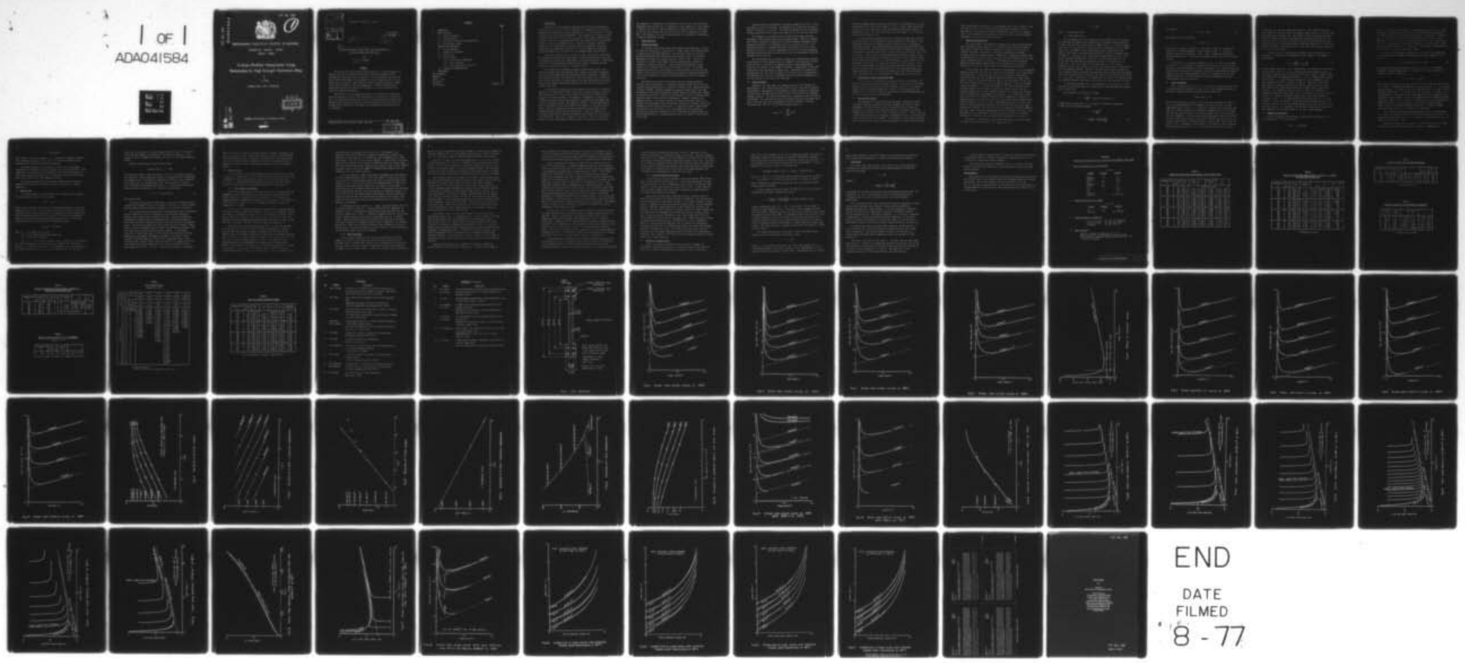

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A Strain Modified 'Steady-State' Creep Relationship for High Strength Aluminium Alloy

by

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A STRAIN MODIFIED 'STEADY-STATE' CREEP RELATIONSHIP FOR HIGH STRENGTH ALUMINIUM ALLOY

by

(10) J. N. Webb

SUMMARY

The concept that creep response is the result of a transient approach to a minimum strain rate continuously modified by accumulating damage has been investigated using high precision creep data. It was considered that the accumulated creep strain might be some measure of internal damage and curves of log creep strain rate against creep strain are shown to exhibit linearity at higher strain levels consistent with these assumptions. A modified 'steady-state' relationship has been derived and the variation of its two coefficients with stress and temperature explored.

The effect of load and temperature history is illustrated by varying the prior heating time, by cyclic load testing and by step reductions in load level, and it is tentatively concluded that tests of these types may be correlated with the appropriate continuous creep test by using the modified 'steady-state' relationship with corrections for differences in accumulated creep strain and time at temperature.

* Replaces RAE Technical Report 76085 - ARC 36951.

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1 INTRODUCTION

Interest in creep testing was generated within Structures Department in the late 1950s in the context of the behaviour of aluminium alloy at elevated temperatures in supersonic transport applications. It was then decided to study creep behaviour with particular emphasis on the extrapolation of short term data to service conditions. The material chosen was a high strength aluminium alloy, a version of RR 58 to specification DTD 5070A (see Appendix), which was thought likely to be used in the manufacture of a supersonic transport. Work was started on the determination of mechanical and creep properties after prior ageing with and without applied stress, on the creep response of plain and notched specimens and on the effect of load changes during creep testing[1-4].

It was soon realized that two aspects of creep testing needed improvement. The first was the problem of repeatability in creep testing and the second that of handling and analysing the large number of data points generated. Considerable effort was therefore expended on improving both testing techniques and data handling as described in section 2, 'Creep test data'.

The introduction of improved techniques allowed high precision creep testing to proceed with more confidence and a library of accurate continuous, cyclic, and load change creep data was progressively accumulated. Attempts to fit continuous functions to this data met with only limited success since they could only be optimised to certain ranges of the data, and attention was therefore directed towards relationships representing the individual phases of the classic creep curve.

It is generally accepted that creep response is the result of a transient approach to a 'steady-state' condition, and this certainly provides a qualitative description for the form of the creep curve and for the response after changes in the applied loading. Unfortunately a 'steady-state' condition of constant strain rate does not seem possible as accumulating creep damage leads to an accelerating creep rate and ultimately, rupture. It was thought however that the accumulated creep strain might be some measure of these accelerating effects and it was considered that strain rate/strain curves might be more illuminating than conventional strain/time plots. Section 3 'Analysis and discussion' presents this approach and derives a relationship for the variation of 'steady-state' creep rate in terms of creep strain. The two coefficients required in this relationship are shown to vary in a rational way with stress and temperature. Appropriate relationships are discussed for these stress and temperature sensitivities and are compared with those suggested by other workers. In addition the effect of time at temperature is explored and it is shown that cyclic and stress change tests may be correlated with the appropriate 'steady-state' relationship at the same accumulated strain if allowance for differences in time at temperature be made.

2 CREEP TEST DATA

2.1 Testing techniques

All the data used in this Report were obtained using specimens cut in the direction of rolling from a single sheet of 1.63mm (16swg) clad aluminium alloy to specification DTD 5070A (Appendix). The specimens conform to a British Non-Ferrous Metals Research Association design shown in Fig.1 and allow the measurement of strain over a gauge length of 114.3mm (4.5in). Tests were conducted in 14 20kN (2 ton) capacity creep testing machines located in a temperature controlled laboratory. Load was applied by deadweight acting through a 10:1 overhead lever beam to an accuracy of ±0.25%. The testing machines were fitted with ovens having an internal diameter of 0.13m (5in) and length of 0.61m (24in) and were heated by three separate windings supplied from a solid state temperature controller through additional controls for gradient correction.

Specimens were attached to the machine pull rods through adjustable universal joints forming part of a specimen alignment system[5] and were used in conjunction with measuring bars to align the specimen in both significant planes to within ±0.008mm. Specimen extension was measured using optical lever type extensometers to Structures Department design[6]; geometrical effects were avoided by connecting each pair of legs by two leaf springs to provide a parallel motion system free only in the direction of measurement. Magnetic loading of the measuring rollers in the optical sensing unit reduced frictional effects to a minimum. Two extensometers were used and were attached to the edges of the test specimen by conical pointed pinch screws. A completely unloaded condition was not possible due to the weight of the test assembly and it was decided to increase this slightly by adjustment of the testing machine balance weight to allow standardisation at a minimum specimen stress of 2.758MN m^{-2} (400 lb in^{-2}) in all cases.

Young's modulus was determined at laboratory temperature (21°C) to verify the quality of each test assembly. The maximum stress level was restricted to 55MN m^{-2} to avoid prior cold work. The difference between the two extensometer readings expressed as a percentage of the mean was in all cases less than 2½%.

Test temperature was measured by three miniature platinum resistance thermometers (PRT) equally spaced along the gauge length. These were compared with transfer standards calibrated by the National Physical Laboratory at the temperature required in the subsequent test to an accuracy of ±0.1°C. The specimen was heated to a temperature within +1°C and −5°C of the test value during the first hour. The test requirement of ±0.2°C at all three measuring positions was then achieved by controller and oven zone adjustments during the remainder of the first day.

The load required was calculated on initial, cold specimen area, making due allowance for the standing stress of 2.758MN m^{-2}, and was applied 24 hours after the start of heating in one smooth increment, taking approximately 0.005 hour (18 seconds) at the 170MN m^{-2} condition. Loading times at the other stress levels were approximately proportional. Extensometer and temperature readings were taken just before loading, at the time of full load application and thereafter at 0.005 hour (18 seconds) intervals decreasing progressively to 0.5 hour intervals at the end of the first day.

2.2 Data processing

Because of the large number of readings involved, it was thought to be impracticable to use discrete data points, directly, for the study of empirical relationships. Consequently it was necessary to evolve a method of condensing the data, with a minimum loss of accuracy, into a form suitable for subsequent graphical analysis. The basis of the method was to express the data in terms of a polynomial. For tests which do not go much beyond the point of minimum creep rate it has been found that a polynomial in time (t) raised to a positive fractional power (m), will fit the data satisfactorily, i.e.

$$\text{strain } (\varepsilon) = \sum_{i=0}^{i=7} E_i t^{im} \quad .$$

No form of single polynomial has been found which will satisfactorily fit tests extending well into the tertiary region of creep. In these cases the data was divided into two sections with a substantial overlap covering the region of minimum creep rate. The first section was dealt with using $m = 1/6$ and the second section using $m = 1/2$.

An ICL 1904 digital computer was used to perform the numerical evaluation of the coefficients of the polynomial using the method of least squares. The difference between the test data and values calculated from the polynomial, termed the residuals, were randomly distributed with a standard deviation less than 0.0002% strain. Residuals greater than 0.0010% were regarded as erroneous and were normally erased unless they occurred in areas of uncertainty, i.e. close to rupture. A print out of the edited data was then obtained including time, actual total strain (elastic plus creep), fitted total strain, residual, strain rate and the second derivative of strain with respect to time together with the polynomial coefficients. In general the accuracy of strain rates calculated from the polynomial appears to be good with the exception of the ends of the fitted data where local fluctuations can lead to the calculated strain rates being less well defined. The data from any test were thus characterised by eight coefficients and could be regenerated to high accuracy when required.

2.3 Publication of basic and processed data

It has not been found possible to include the basic and processed creep data in this particular paper for reasons of bulk. For instance the continuous tensile creep tests alone involve almost 500 pages of data. It is recognised however that this information may be of interest to other workers and the publication of a library of creep data accumulated in Structures Department over the last six years is now being undertaken.

2.4 Data analysis system

The regeneration of the data from the polynomial coefficients using a centralised computer was possible but time consuming. The advent of desk programmable calculators together with an associated plotter changed the situation and permitted speedy graphical analysis. A generalised plotting programme was developed to plot curves in terms of function X against function Y where these functions were changeable sub-programmes written to calculate the values for the specific plot required. For instance, in this paper, log strain rate is plotted against strain, and sub-programmes to calculate these functions from the polynomial were prepared. All programmes were stored on magnetic card and could be entered into the calculator when required together with the appropriate set of polynomial coefficients which were also stored on magnetic card. A more powerful second generation machine is now in use with storage of programmes and coefficients on magnetic tape.

3 ANALYSIS AND DISCUSSION

The creep response resulting from a change in the applied conditions has been attributed by some workers[7-9] to a redistribution of internal stresses. This concept results in a transient approach to a steady state condition of constant strain rate and provides an attractive explanation of primary, secondary and strain recovery effects. However it is immediately apparent that a steady-state does not take place in practice since accelerating tertiary creep occurs leading ultimately to rupture. It is known that internal voids are generated in many metals during tensile creep testing and it is generally considered that they are a major factor in accelerating tertiary creep.

It was thought that creep strain might be some measure of this accumulating damage and therefore that plots of creep strain rate against creep strain might be illuminating. It was found that plots of log creep strain rate against creep strain supported this assumption exhibiting linearity at higher strain levels. Figs.2 to 5 show plots of this type at test temperatures of 150, 165, 180, 195°C respectively over a range of applied stresses. Each curve exhibits a transient approach to a linear relationship. The size and duration of the transient appears to be related to stress level; high stresses result in a relatively rapid decay and early linearity while at low stresses the transient is still significant at much higher strain levels. It is interesting to note that in all cases the transient response is still significant at the point of minimum strain rate and the use of this rate as a basic material property would therefore appear to be open to error. Unfortunately some of the tests at low stresses had previously been terminated at about this level due to the large testing times involved. The curve for the test conditions of 195°C and 80MN m^{-2}, see Fig.5, shows a sharply increasing strain rate at the end of the data. This particular test specimen ruptured at this point and the effect is therefore attributed to the additional contribution from the growth of a creep crack.

The modified 'steady-state' relationship indicated by the linear portion of these strain rate/strain plots is of exponential form

$$\overset{\circ}{\varepsilon} = Ke^{k\varepsilon} \tag{1}$$

where ε = creep strain, and

$\overset{\circ}{\varepsilon}$ = creep strain rate.

At each temperature, with the exception of the 150°C level, the slope of the linear portion appears to be constant for all available stress levels and a common slope has been fitted giving a constant value of k for each temperature level. In the case of the curves at 150°C it is possible to fit a common slope at 170 and 200MN m^{-2} but a significantly lower slope exists at the 230MN m^{-2} level and an even more marked reduction occurs at the highest stress of 250MN m^{-2}. Individual slopes have therefore been fitted to all the curves at this particular temperature. Values of k together with those for K derived from the intercepts are presented in Table 1. This derivation of values for k and K to describe the linear behaviour is not entirely satisfactory as the creep strain used to plot the curves includes a contribution from the transient response. However as the additional strain resulting from this transient attains a limiting value when the curve of log strain rate against creep strain becomes linear the slope of the lines is not affected and the values of k are valid. The values of K however are too low since the subtraction of the limiting transient strain would alter the value of the intercept, see Fig.6.

In considering possible ways of estimating the true values of K it was found that a strain rate/time relationship could be developed which was independent of strain level.

The integration of equation (1) yields:

$$t = -\frac{e^{-k\varepsilon}}{Kk} + \text{constant of integration} \quad .$$

At time $(t) = 0$, creep strain $(\varepsilon) = 0$, hence the constant of integration $= 1/Kk$ and the relationship becomes:

$$t = \frac{1 - e^{-k\varepsilon}}{Kk}$$

or

$$\varepsilon = \frac{1}{k \log e} \log \left[\frac{1}{1 - Kkt}\right] \tag{2}$$

and from (2)

$$\overset{\circ}{\varepsilon} = K/(1 - Kkt) \quad . \tag{3}$$

Rearranging this gives the form:

$$\overset{\circ}{\varepsilon} = K(k\overset{\circ}{\varepsilon}t + 1) \quad .$$

Plots of $\log \overset{\circ}{\varepsilon}$ against $\log(k\overset{\circ}{\varepsilon}t + 1)$ are shown on Figs.7 to 10 using the values of k already determined. Fitting lines of slope $= 1$ gives the required values of the intercept, $\log K$. Table 2 summarises these values together with those of k previously determined from the log strain rate/strain plotting.

The constant K in these relationships is seen to be the 'true minimum strain rate'. It is unlikely to be measured directly since it occurs at time zero when a transient response is usually superimposed. The conventional minimum creep rate will be larger, the difference between them varying with the applied stress level and the current transient state. It is apparent that the 'true minimum strain rate' (K) varies with both stress and temperature and these relationships will now be discussed.

3.1 Stress dependence

Power, exponential and hyperbolic relationships have previously been used to represent stress dependence but none of them is particularly convincing in predicting limiting conditions, although Norton's power law[10]:

$$\text{strain rate} = C\sigma^n$$

has found wide acceptance at lower stress levels and encouraged the author to plot 'true minimum strain rate' (K) against the applied stress (σ), using logarithmic scales on Fig.11. It is generally considered that the stress exponent (n) in Norton's power law is temperature dependent and it is unfortunate that the data available from our own test programme is not extensive enough to test this assumption. The linear relationship expected at lower stress levels is seen to apply below a stress level of about 140MN m^{-2} but values of K are limited in this region, two being available at 195 and 180°C, one at 165°C and none at 150°C. Accordingly for the purposes of this Report a common slope has been fitted giving a value for n of 5.25 and intercepts ($\log C$) for each temperature level are then summarised in Table 3. Above 140MN m^{-2} the data curves away from linearity to give increasingly larger values of strain rate than those predicted by the power law. This change in stress sensitivity has been found by a number of workers in many materials and has been associated[11] with a transition from brittle intercrystalline to ductile transcrystalline fracture. The usual practice of fitting two slopes did not seem appropriate in view of the progressive departure from linearity of our own results and a better representation of the data was sought.

It seems sensible to assume that a limiting stress exists and that the behaviour is a reflection of the approach to this condition. The empirical relationship,

$$K = C\sigma^n \Big/ \left[1 - (\sigma/\sigma_0)^n\right] \tag{4}$$

has the required properties since it approximates to a power law at low stresses but incorporates the term σ/σ_0 to represent high stress behaviour where σ_0 represents a limiting stress. Curves have been drawn on Fig.11 using the above relationship with the appropriate values of C and n already derived together with values of σ_0 found to produce the best fit to the experimental data. These values are listed for reference in Table 3. Early work on DTD 5070A established the mechanical properties at elevated temperature after various prior times at test temperature and values of ultimate tensile stress after 24 hours at test temperature are also listed in Table 3 for comparison. A considerable difference exists which is not fully understood but it is shown in section 3.4.1 that prior heating is significant for this alloy leading to increasing values of K at high stresses and decreasing values of K at low stresses. It seems reasonable to assume that the same ageing processes occur during the time on load with the same modifying effect on the values of K and hence the values of σ_0 required to fit the data. Correction for this effect would therefore lead to higher values of σ_0 and a better agreement.

3.2 Temperature dependence

Dorn[12] has suggested that temperature dependence should appear in the form fundamental to all rate processes.

$$\text{rate} = P \exp(-Q/RT)$$

where Q is the activation energy, R is Boltzmann's constant and T is the temperature in degrees absolute. A plot of log minimum strain rate against 1/T should therefore be linear with a slope equal to $-Q \log e/R$. This has been done on Fig.12 for each of the stress levels involved using the data previously collected in Table 2. As expected linearity is seen at each stress level and a common slope can be fitted. Taking R = 1.987cal/g mol/K a value of 37060 has been found for Q. Values of P derived from the intercepts are given in Table 4 for each of the stress levels.

The stress and temperature dependence of the true minimum strain rate (K) for DTD 5070A can therefore be represented by extending equation (4) as follows:

$$K = L \exp(-Q/RT)\sigma^n/[1 - (\sigma/\sigma_0)^n] \quad . \tag{5}$$

The analysis of temperature dependence above assumes that P is constant throughout a range of temperatures at any given value of applied stress. It can be seen from (5) above that

$$P = L\sigma^n/[1 - (\sigma/\sigma_0)^n]$$

and it should be noted that the form of stress function chosen includes the term $[1 - (\sigma/\sigma_0)^n]$ to represent the approach to a limiting stress σ_0. It was found that the value of σ_0 decreases with increasing temperature, see Table 3, and it therefore follows that P is a weak function of temperature. The effect of σ_0 is negligible at low stresses but one would expect to see some evidence of its presence at higher stresses. In fact a re-examination of the temperature sensitivity plot, Fig.12, is inconclusive as insufficient points are available at the higher stress levels and any deviations do not exceed the general scatter. However it should be recognized that the values of P obtained at higher stresses are mean values over the range of σ_0 applicable.

Log P has been plotted against log-stress, see Fig.13, and the values of n and L determined from the low stress linear portion of the curve. The value of 5.25 previously found for n, see Table 3 is confirmed and log L is found to have a value of 3.285.

Similarly the values of the constant C obtained from the stress sensitivity plot and listed in Table 3 should be related to temperature by

$$C = L \exp(-Q/RT) \quad .$$

Fig.14 shows log C plotted against 1/T to produce the expected linearity, and confirmatory values for log L and Q of 3.072 and 36600 have been obtained from the intercept and slope respectively.

The second constant k , in equation (1) was found to be generally independent of the applied stress at temperatures of 165, 180 and 195°C. Some significant stress sensitivity has however been noted with high stresses at 150°C and the possibility exists that a similar effect may occur at stresses above those covered at the other temperature levels.

A reduction in magnitude with increasing temperature exists and this temperature sensitivity is illustrated on Fig.15 by plotting k against temperature.

3.3 Rupture life

It is interesting to note that rupture life is implicit in the strain, time relationship, equation (2) since, when

$$t = 1/Kk \qquad \text{then} \qquad \varepsilon = \infty \quad .$$

Rupture life is therefore predicted to be inversely proportional to the 'true minimum strain rate' (K). Little rupture data has been obtained from our own programme as the accurate measurement of creep strain and strain recovery have been the primary objectives but other workers[13,14] have noted a correlation between conventional minimum strain rate and rupture life of this type for many materials, and have proposed the following relationship

$$\mathring{\varepsilon}_{min} \, . \, t_r^m = \text{constant}$$

where m is a number near to unity

$\mathring{\varepsilon}_{min}$ is the conventional minimum creep rate

t_r is the time to rupture.

Taking $m = 1$ the constant proposed is seen to correspond to the value of 1/k with the dimensions of strain and has been termed[11] the 'true creep elongation'. It has been seen that k is proportional to the slope (k log e) of the log strain rate/strain plot and, if the assumption that the increase in strain rate is the result of internal damage is correct, then it is a measure of the rate that damage is accumulating. The higher the value of k the greater the rate of damage and the smaller the value of 'true creep elongation' becomes.

Rupture lives calculated from the relationship:

$$\text{rupture life } (t_r) = 1/(Kk) \tag{5}$$

are presented in Table 2 using the values of K and k previously listed in this same Table. Fig.16 shows these rupture lives graphically by a logarithmic plot against stress. The pattern is obviously the inverse of that previously found between the 'true minimum strain rate' (K) and stress (σ), shown on Fig.11, modified by the multiplying constant k . Curves have therefore been drawn using the relationship for K , equation (4) by plotting

$$t_r = [1 - (\sigma/\sigma_0)^n]/(kC\sigma^n) \tag{6}$$

with equal success.

In the case of the curve at 150°C where k was seen to become a function of stress above 230MN m^{-2} the low stress value of 0.967 for k has been used in the above relationship providing an acceptable fit to the points on Fig.16.

Little rupture data was accumulated in our programme to test this relationship for rupture life since it was generally considered more important to measure strain recovery than to proceed to failure. Secondly the method of extensometer attachment had been optimized for the accurate measurement of bulk strain and rupture invariably occurred across the top pair of extensometer points. This data has therefore not been included in detail although it may be useful to record the general trend of rupture lives decreasing from 86% to 50% of the predicted values as stress levels were reduced. It is probably unrealistic to expect more than an 'ideal' rupture life prediction from this approach even with perfect extensometer attachment since surface defects, inclusions, specimen shape and eccentricity of loading may produce stress variations even in simple tensile creep testing and it is suggested that these local effects may be more significant in the low stress region of brittle intercrystalline fracture. It is als possible that transitions in behaviour may occur outside the range of variables covered in testing. Certainly in the case of some steels a most complex shape of stress rupture curve exists[15] and the metallurgical processes of oxidation, decarbonization, recrystallization, grain growth, spheroidization, graphitization and phase changes have been suggested as possible causes. Extrapolation should be therefore treated with caution.

3.4 History effects

Creep is known to be history dependent and any relationship must hold for a range of prior experience. Factors thought to be significant were prior time at temperature, prior accumulated strain and the current transient state; accordingly a limited number of prior heated, cyclic load and load reduction tests were conducted to form a preliminary assessment of these effects.

3.4.1 Prior time at temperature

DTD 5070A is a precipitation hardened material with mechanical properties dependent on the size and distribution of precipitate particles within the metallic structure. An initial solution treatment at 530°C and subsequent quenching produces a highly ductile material of low strength. Precipitation at 190°C for between 10 and 30 hours then produces the optimum conditions for maximum tensile strength.

The selection of a time and temperature for prior heating was governed by the desire to obtain a significant change in properties in a reasonable time and accordingly the maximum test temperature of 195°C was selected together with a time of 1056 hours. Using the Dorn parameter and the value of Q previously derived the equivalent times at the remaining test temperatures of 180, 165 and 150°C were calculated to be 3950, 16200 and 73300 hours respectively.

Creep tests were therefore conducted after first heating test specimens for 1056 hours at 195°C, in each case reducing the temperature to the test value of 180°C one day before loading. Stresses of 80, 108, 140, 170 and 200MN m^{-2} were used and Fig.17 shows plots of log strain rate against strain for these conditions. The general pattern of behaviour is seen to be similar to the 'as received' material already presented in Fig.4. This again indicates a transient approach to an exponential relationship and lines defining this modified 'steady-state' relationship for the 'as received' material are included for comparison. The response at the highest stress of 200MN m^{-2} has been considerably modified with greatly increased strain rates and linearity has not been achieved at the maximum strain level of 2%. The response at the remaining lower stress conditions although not extending far enough to be definitive in most cases are not inconsistent with an assumption of a common slope equal to that for the 'as received' material. A particularly interesting aspect of these results is the reversal of behaviour within the stress range, prior heating producing smaller strain rates at stresses of 80, 108 and 140MN m^{-2} and larger rates at the 170 and 200MN m^{-2} conditions when compared with the response of the 'as received' material.

It is interesting to compare this pattern of behaviour with the shape of the stress sensitivity plot, Fig.11, where the 140MN m^{-2} stress level is seen to be close to the change between linear low stress to non-linear high stress behaviour. One is led to the belief that this response might be linked to the change in failure mode associated with these two regions. The increase in creep strain rate at the higher stresses is seen to be consistent with the known fall in mechanical properties with increasing time at temperature while it is conceivable that the continuing change in precipitation size and distribution within the material under the same circumstances may have the reverse effect within the low stress region where the intercrystalline mode of fracture is expected to predominate.

To determine the true values of K , log $\mathring{\varepsilon}$ is plotted against ($k\mathring{\varepsilon}t$ + 1), see Fig.18, using the values of k found previously for the equivalent 'as received' tests. K is derived as before from the intercepts and collected values are summarised in Table 5. A graphical comparison with the 'as received' values is shown on Fig.19 in the form of a logarithmic plot of K against stress. This stress sensitivity plot indicates that the slope of the linear low stress region has not changed with prior time at temperature, the intercept however has a lower value reflecting increased creep resistance, see Table 6. The transition to non-linear behaviour is seen to occur at a lower stress level, but the overall shape of the curve is similar.

3.4.2 Cyclic behaviour

If the original assumption, that strain is some measure of internal damage, is valid, one would expect that the strain rate during any one of successive cyclic loadings would conform to the 'steady-state relationship for the same stress level with a change in datum equal to the strain accumulated throughout its prior cyclic history. A cyclic test however contains alternative periods with the load applied and removed leading to a longer time at temperature than that experienced by the corresponding continuous test. Effects consistent with this difference in time at temperature might therefore be anticipated.

Figs.20 to 25 show log strain rate/strain plots for cyclic tests at 180°C in which stress levels of 108, 140, or 170MN m^{-2} were periodically applied and removed. For each test the results of successive loadings are plotted with a strain datum correction equal to the prior accumulated strain. The correction involved is the sum of the strains accumulated during prior periods of loading less the sum of the recovery strains resulting from prior periods of unloading.

This definition should be examined in more detail. During forward creep the strain accumulating is the sum of that due to the transient and the modified 'steady-state' responses while during an unloaded period only a transient response exists. In a cyclic load test of this type one might expect that a state of equilibrium would ultimately be achieved with the transient responses from successive loading and unloaded phases being equal and opposite with a magnitude dependent on the amount of strain recovery possible in the time off load. However this does not seem to be the case and in practice the loading transient appears to be considerably larger than the recovery transient in each cycle throughout a cyclic test of this type. The above calculation of prior accumulated strain includes this transient contribution automatically as part of the strain history. Table 7 gives the strain in individual loading and recovery periods for all the tests involved.

Some aspects of the interpretation of these cyclic plots also need emphasising at this stage. The requirement for a reasonable number of loadings before creep rupture involves individual cyclic loadings which are not sufficiently long for the complete decay of transient response and we cannot therefore fit the expected exponential relationship to them. We can however compare these loadings with the continuous test and form some assessment of any weakening or strengthening effect. It should be noted that the first cycle is directly comparable with the continuous test as the applied conditions are nominally identical. Any difference is therefore a reflection of the degree of repeatability being achieved and should be considered when examining subsequent loadings.

Fig.20 shows the behaviour at 108MN m^{-2} for individual loading and recovery times of 936 and 912 hours respectively. The first few loadings are seen to approach the continuous response very closely but a progressive drift to values of strain rate below the modified steady-state line becomes apparent. This test falls in the low stress region and the increasing creep resistance is consistent with the previously noted effect of increasing time at temperature.

Fig.21 illustrates the response at 140MN m^{-2} for loading and recovery times of 432 and 912 hours. A slight strengthening effect is seen through the first four cycles but the final cycle indicates reduced resistance, possibly due to the imminence of rupture with its associated local effects. Fig.22 shows another test at 140MN m^{-2} but with a shorter loading time, more cycles to rupture and consequently with time at temperature increasing more rapidly with respect to the continuous test. The behaviour is seen to be consistent with the noted effect of prior time at temperature for this particular stress level, involving a transition from a strengthening to a weakening response. Fig.23 reinforces this conclusion with an even smaller time on load and a faster drift away from the continuous test. Cycles to rupture and time at temperature were both increasing during these three tests and the test shown in Fig.24 was designed to discriminate between these two possible factors. The recovery time was increased to 4707 hours with a time on load of 168 hours to give relatively few cycles to rupture with a greatly increased time at temperature. The response is seen to depart from the continuous very rapidly, indicating that time at temperature is the significant factor.

The plot of a test at the higher stress of 170MN m^{-2} in Fig.25, falls into the region of high stress response and shows a decreasing creep resistance as expected. Modified 'steady-state' lines obtained from the prior time at temperature tests have been drawn on the above cyclic plots. It would be interesting to compare the cyclic response with the continuous response after an equivalent time at temperature and the appropriate loading cycle nearest to this condition has been indicated on all plots. For reasons already discussed a direct comparison is not possible but the behaviour is not inconsistent with the assumption that cyclic 'steady-state' response can be related to the continuous behaviour by the use of accumulated strain and time at temperature.

In this paper we are primarily concerned with the modified 'steady-state' relationship but it must be emphasised that transient effects are additive and can be significant where a difference exists between forward and reverse transient responses. Fig.20 has already been introduced to illustrate increasing creep resistance resulting from the effect of time at temperature on the modified 'steady-state' relationship during a cyclic test. Fig.26 now compares this cyclic test at 108MN m^{-2} with the appropriate continuous test in the conventional way by plotting accumulated creep strain against time on load. The cyclic test is shown to accumulate creep strain faster during the first few cycles due to the transient difference but eventually the decreasing modified 'steady-state' rate becomes the dominant effect and the cyclic curve again approaches the continuous curve (extrapolated) at about 2% creep strain.

3.4.3 Step reductions in load level

A limited number of tests involving a step change between 170MN m^{-2} and a lower stress level have been carried out. A recovery period was not included and the differences in time at temperature are due only to the different times required to reach a given strain at the two stress levels. In most cases the effect is small compared with cyclic tests including an extended period off load and has been ignored in this paper.

Fig.27 shows the log strain rate/strain plot for a drop in stress to 140MN m^{-2} after times of 24, 96 and 336 hours at 170MN m^{-2}. The correction for prior accumulated strain has again been made. The transient response in these cases is a summation of strain recovery and forwards creep. The plots therefore show the creep rate accelerating from zero rate towards the continuous test response. The test with 24 hours at the higher stress level shows a higher rate than expected but the agreement of the other two with the continuous test is good. Fig.28 illustrates the behaviour after step changes from 170 to 140, 108 and 80MN m^{-2} after 96 hours at the higher level. Again creep rate is shown to be accelerating from zero rate. The behaviour of the test unloaded to 80MN m^{-2} is particularly interesting in that it crosses the corresponding continuous test and rises to a significantly higher level before falling again towards the 'steady-state' line. It is particularly unfortunate that this particular test was stopped prematurely before the decay of the transient was completed. The agreement of the other two with the appropriate modified steady-state lines is again very good.

3.5 Accuracy of representation

Before concluding the analysis it would be useful to compare the experimental strain/time data points for continuous creep with the curve predicted by the modified 'steady-state' relationship derived in this paper.

Before this can be attempted the size of the limiting transient strain must be determined in each case and added to the modified 'steady-state' response. These strains may be calculated from the difference between the two values of K as determined by the log rate/creep strain and the log rate/$(k\mathring{\varepsilon}t + 1)$ curves together with the slope k log e , see Fig.6, since

$$\text{limiting transient strain} = (\log K_2 - \log K_1)/k \log e$$

where K_1 = value of K derived from log rate/creep strain plots, see Table 1
K_2 = value of K derived from log rate/$(k\mathring{\varepsilon}t + 1)$ plots, see Table 2.

Table 8 summarises the appropriate values and lists the limiting transient strains derived from them.

A direct comparison may now be made and Figs.29, 30, 31 and 32 show the experimental creep curves compared with plots of

$$\varepsilon = \frac{1}{k \log e} \log \left[\frac{1}{1 - kKt}\right] + \text{limiting transient strain}$$

using the appropriate values of k and K from Table 2 for the range of stresses at each temperature level. To provide a better comparison between tests proceeding at varying rates the time base has been divided in each case by the predicted rupture life (1/Kk). The agreement between test and fitted curves is generally good in the area of validity at greater than 30% rupture life. Some small offsets in strain exist as might be expected since the calculated value of limiting transient strain depends on a small difference between large numbers. The curvature is well represented with perhaps the exception of 230MN at 165°C, Fig.30.

No attempt has been made in this paper to model the complete creep behaviour but the usual function for transient creep

$$\varepsilon = At^m$$

where m is a fractional power near to one third, when combined with the relationship proposed in this paper, produces a close approximation to creep response which may be adequate in simple cases. Alternatively the two or multi element models referred to earlier[7-9] remain to be investigated and may provide a more satisfying representation of transient and strain recovery effects.

4 CONCLUSIONS

The concept that creep response is the result of a transient approach to a 'steady-state' continuously modified by increasing damage has produced the empirical relationship

$$\mathring{\varepsilon} = Ke^{k\varepsilon}$$

leading to

$$\varepsilon = \frac{1}{k \log e} \log \left[\frac{1}{1 - Kkt}\right]$$

to represent the secondary and tertiary creep of aluminium alloy DTD 5070A. The coefficients K and k are identified as the 'true minimum strain rate', occurring at time zero, and the inverse of the 'true creep elongation' respectively.

The 'true minimum strain rate' (K) has been found to be dependent on stress and the widely used power law attributed to Norton has been modified to represent the behaviour at high stresses. K is also dependent on temperature and the variation over the range tested is shown to be consistent with the function proposed by Dorn. The second coefficient, k, is found to be dependent on temperature, its value falling with increasing temperature. It has been found to be generally independent of stress level except for high stresses at $150^{\circ}C$ where increases in stress level produce large reductions in the value of k.

Prior heating is shown to decrease creep resistance at high stresses, a result consistent with the fall in mechanical properties known to occur under these circumstances. The situation however is shown to be reversed at low stresses where increasing time at temperature leads to an increase in creep resistance.

Some cyclic creep tests of the 'load on', 'load off' type have been shown qualitatively to conform to the appropriate modified 'steady-state' line for the test conditions if corrections for the prior accumulated strain and differences in the total time at temperature are applied. The significance of the unrecovered transient in the accumulated strain has been indicated.

A limited number of step reductions in load level have been investigated and these also appear to conform to the modified steady-state line if the correction for accumulated strain is applied.

The relationship proposed is therefore seen to be consistent with many aspects of current creep theory and to show some promise of being valid under cyclic conditions.

Acknowledgments

This paper rests on the library of accurate creep test results accumulated over several years by the laboratory staff involving many careful and conscientious people. Most of all, however, it rests on the work of the late Mr. D.A. Berry who as section leader saw the necessity for the improvements in testing technique, data handling and data analysis required for effective work in this field.

Appendix

EXTRACT FROM SPECIFICATION DTD 5070A FOR CLAD ALUMINIUM ALLOY SHEET

(a) Chemical composition of core material:

Element	Minimum (per cent)	Maximum (per cent)
Copper	1.8	2.7
Magnesium	1.2	1.8
Silicon	-	0.25
Iron	0.9	1.4
Manganese	-	0.2
Nickel	0.8	1.4
Zinc	-	0.1
Lead	-	0.05
Tin	-	0.05
Titanium	-	0.2
Aluminium	-	the remainder

(b) Chemical composition of coating:

Element	Minimum (per cent)	Maximum (per cent)
Zinc	0.8	1.2
Aluminium	-	the remainder

(c) Minimum mechanical properties:

0.1% proof stress	not less than 309MN m^{-2}
tensile strength	not less than 386MN m^{-2}
elongation	not less than 6% .

(d) Heat treatment:

Solution treatment by heating at 530 ± 5°C
Quench in water at a temperature not exceeding 40°C
Precipitation treatment by heating uniformly at 190 ± 5°C for 10 to 30 hours.

Table 1

VALUES OF COEFFICIENTS FROM LOG-RATE, CREEP STRAIN CURVES

Temperature ^oC	Stress $MN\ m^{-2}$	Test No.	Slope k log e	k	Intercept log K	K $\%\ h^{-1}$
150	140	RF 75	insufficient data			
150	170	RF 76	0.420	0.967	-4.202	6.28×10^{-5}
150	200	RF 74	0.417	0.960	-3.612	2.44×10^{-4}
150	230	RF 77	0.366	0.843	-2.978	1.05×10^{-3}
150	250	RF 88	0.288	0.663	-2.373	4.24×10^{-3}
165	108	RF 65	0.368	0.847	-4.660	2.19×10^{-5}
165	140	RF 44	0.368	0.847	-4.019	9.59×10^{-5}
165	170	RF 45	0.368	0.847	-3.482	3.30×10^{-4}
165	200	RF 48	0.368	0.847	-2.968	1.08×10^{-3}
165	230	RF 73	0.368	0.847	-2.308	4.92×10^{-3}
180	80	RF 24	0.330	0.760	-4.648	2.25×10^{-5}
180	108	RF 12	0.330	0.760	-4.000	1.00×10^{-4}
180	140	RF 18	0.330	0.760	-3.422	3.78×10^{-4}
180	170	RF 10	0.330	0.760	-2.861	1.38×10^{-3}
180	200	RF 63	0.330	0.760	-2.278	5.27×10^{-3}
195	80	RF 80	0.300	0.691	-4.073	8.45×10^{-5}
195	108	RF 79	0.300	0.691	-3.446	3.58×10^{-4}
195	140	RF 83	0.300	0.691	-2.839	1.45×10^{-3}
195	170	RF 78	0.300	0.691	-2.256	5.55×10^{-3}

Table 2

VALUES OF COEFFICIENTS FROM LOG RATE, $\log(k\dot{\varepsilon}^{o}t + 1)$ CURVES AND PREDICTED RUPTURE LIFE

Temperature ^{o}C	Stress $MN\ m^{-2}$	Test No.	Intercept log K	K $\%\ h^{-1}$	k	$t_r = 1/Kk$ h
150	140	RF 75	-	2.72×10^{-5}*	0.967*	38019*
150	170	RF 76	-4.103	7.89×10^{-5}	0.967	13109
150	200	RF 74	-3.532	2.94×10^{-4}	0.960	3546
150	230	RF 77	-2.921	1.20×10^{-3}	0.843	989
150	250	RF 88	-2.327	4.71×10^{-3}	0.663	320
165	108	RF 65	-4.534	2.92×10^{-5}	0.847	40433
165	140	RF 44	-3.928	1.18×10^{-4}	0.847	10003
165	170	RF 45	-3.412	3.87×10^{-4}	0.847	3049
165	200	RF 48	-2.925	1.19×10^{-3}	0.847	993
165	230	RF 73	-2.249	5.64×10^{-3}	0.847	210
180	80	RF 24	-4.567	2.71×10^{-5}	0.760	48550
180	108	RF 12	-3.909	1.23×10^{-4}	0.760	10671
180	140	RF 18	-3.333	4.65×10^{-4}	0.760	2833
180	170	RF 10	-2.795	1.60×10^{-3}	0.760	821
180	200	RF 63	-2.240	5.75×10^{-3}	0.760	229
195	80	RF 80	-4.004	9.91×10^{-5}	0.691	14603
195	108	RF 79	-3.350	4.47×10^{-4}	0.691	3240
195	140	RF 83	-2.770	1.70×10^{-3}	0.691	852
195	170	RF 78	-2.210	6.17×10^{-3}	0.691	235

* Extrapolated values

Table 3

CONSTANTS ASSOCIATED WITH STRESS DEPENDENCE

Temperature °C	Slope n	Intercept log C	C	σ_0 MN m^{-2}	UTS MN m^{-2}
150	5.25*	-15.832*	1.472×10^{-16}*	255	377
165	5.25	-15.198	6.339×10^{-16}	246	363
180	5.25	-14.589	2.576×10^{-15}	235	340
195	5.25	-14.038	9.162×10^{-15}	227	315

* Extrapolated values

Table 4

CONSTANTS ASSOCIATED WITH TEMPERATURE DEPENDENCE

Stress MN m^{-2}	Slope -Q log e/R	Q	Intercept log P	P
80	8100	37060	13.311	2.046×10^{13}
108	8100	37060	13.973	9.397×10^{13}
140	8100	37060	14.553	3.573×10^{14}
170	8100	37060	15.091	1.233×10^{15}
200	8100	37060	15.609	4.064×10^{15}
230	8100	37060	16.229	1.694×10^{16}
250	insufficient data		16.827*	6.714×10^{16}

* Assuming slope of 8100

Table 5

VALUES OF COEFFICIENTS FROM LOG RATE, $\log(k\dot{\varepsilon}t + 1)$ CURVES FOR PRIOR HEATED TESTS

Temperature ^{o}C	Stress $MN\ m^{-2}$	Prior time at $195^{o}C$ h	Test No.	Intercept log K	K $\%\ h^{-1}$	k $\%^{-1}$
180	80	1056	41	insufficient data		
180	108	1056	13	-3.970	1.072×10^{-4}	0.760
180	140	1056	42	-3.400	3.981×10^{-4}	0.760
180	170	1056	14	-2.703	1.982×10^{-3}	0.760
180	200	1056	53	non linear response		
180	200	1056	85			

Table 6

EFFECT OF PRIOR HEATING ON STRESS DEPENDENCE

slope n = 5.25

Temperature ^{o}C	Time at $195^{o}C$ h	Intercept log C	C
180	1056	-14.652	2.228×10^{-15}

Table 7

CYCLIC STRAIN VALUES

temperature = 180^{o}C

Stress ($MN\ m^{-2}$)			108	140	140	140	140	170
Test No.			RF 61	RF 60	RF 43	RF 22	RF 32	RF 55
Time on load (h)			936	432	192	96	168	96
Time off load (h)			912	912	984	912	4704	912
% creep strain	1st	Loading	0.3277	0.4470	0.2575	0.1754	0.2441	0.3117
	1st	Recovery	-0.0371	-0.0546	-0.0483	-0.0432	-0.0539	-0.0614
	2	L	0.2242	0.3886	0.1957	0.1264	0.1957	0.3396
	2	R	-0.0404	-0.0579	-0.0490	-0.0409	-0.0484	-0.0600
	3	L	0.2212	0.4409	0.1902	0.1155	0.1980	0.4103
	3	R	-0.0432	-0.0612**	-0.0498	-0.0420	-0.0483	-0.0622
	4	L	0.2313	0.5663	0.1964	0.1111	0.2223	0.5674
	4	R	-0.0446	-0.0653	-0.0511	-0.0425**	-0.0483	-0.0620
	5	L	0.2489	0.3569*	0.2097	0.1112	-0.2736	0.9052
	5	R	-0.0478		-0.0525	-0.0421**	-0.0473	-0.0626
	6	L	0.2754		0.2316	0.1121	0.3658	0.0984*
	6	R	-0.0495		-0.0539	-0.0428	-0.0498	
	7	L	0.3109		0.2628	0.1123	0.5403	
	7	R	-0.0487**		-0.0553	-0.0420	-0.0537**	
	8	L	0.3615		0.3073	0.1160		
	8	R	-0.0540		-0.0565	-0.0434		
	9	L	0.1974*		0.3753	0.1220		
	9	R			-0.0577	-0.0446		
	10	L			0.2269*	0.1277		
	10	R				-0.0448		
	11	L				0.1344		
	11	R				-0.0453		
	12	L				0.1452		
	12	R				-0.0475		
	13	L				0.1552		
	13	R				-0.0473		
	14	L				0.1688		
	14	R				-0.0471		
	15	L				0.1854		
	15	R				-0.0489**		
	16	L				0.2081		

* Denotes rupture

** Denotes variation from specified cyclic time

Table 8

VALUES OF LIMITING TRANSIENT STRAIN

Temperature °C	Stress $MN\ m^{-2}$	Test No.	k log e	log K_1	log K_2	Limiting transient
150	140	RF 75	insufficient data			
150	170	RF 76	0.420	-4.202	-4.103	0.236
150	200	RF 74	0.417	-3.612	-3.532	0.192
150	230	RF 77	0.366	-2.978	-2.921	0.156
150	250	RF 88	0.288	-2.373	-2.327	0.160
165	108	RF 65	0.368	-4.660	-4.534	0.342
165	140	RF 44	0.368	-4.019	-3.928	0.247
165	170	RF 45	0.368	-3.482	-3.412	0.190
165	200	RF 48	0.368	-2.968	-2.925	0.117
165	230	RF 73	0.368	-2.308	-2.249	0.160
180	80	RF 24	0.330	-4.648	-4.567	0.246
180	108	RF 12	0.330	-4.000	-3.909	0.276
180	140	RF 18	0.330	-3.422	-3.333	0.270
180	170	RF 10	0.330	-2.861	-2.795	0.200
180	200	RF 63	0.330	-2.278	-2.240	0.115
195	80	RF 80	0.300	-4.073	-4.004	0.230
195	108	RF 79	0.300	-3.446	-3.350	0.320
195	140	RF 83	0.300	-2.839	-2.770	0.230
195	170	RF 78	0.300	-2.256	-2.210	0.153

Limiting transient = $(\log K_2 - \log K_1)/k \log e$

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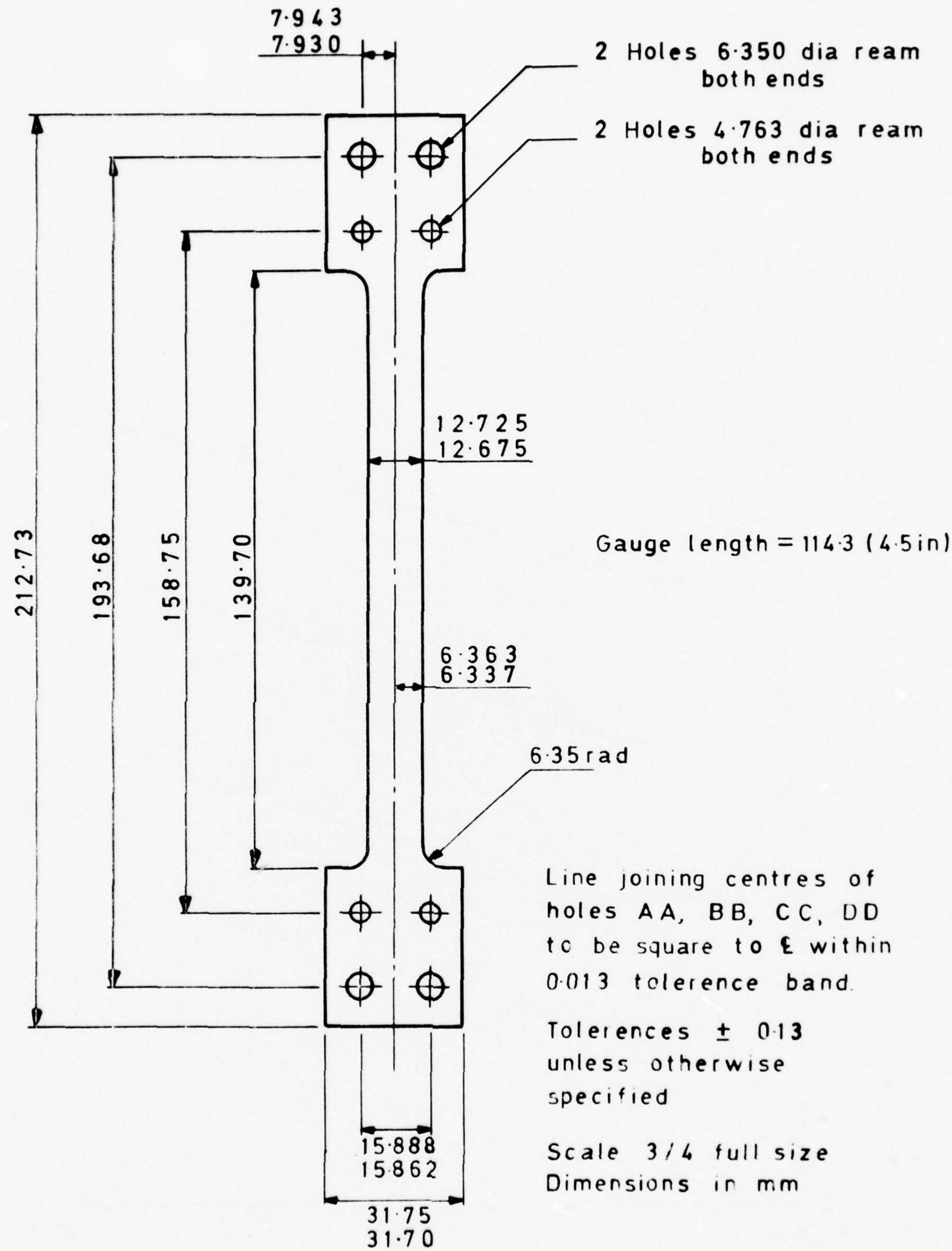

Fig. 1 Test specimen

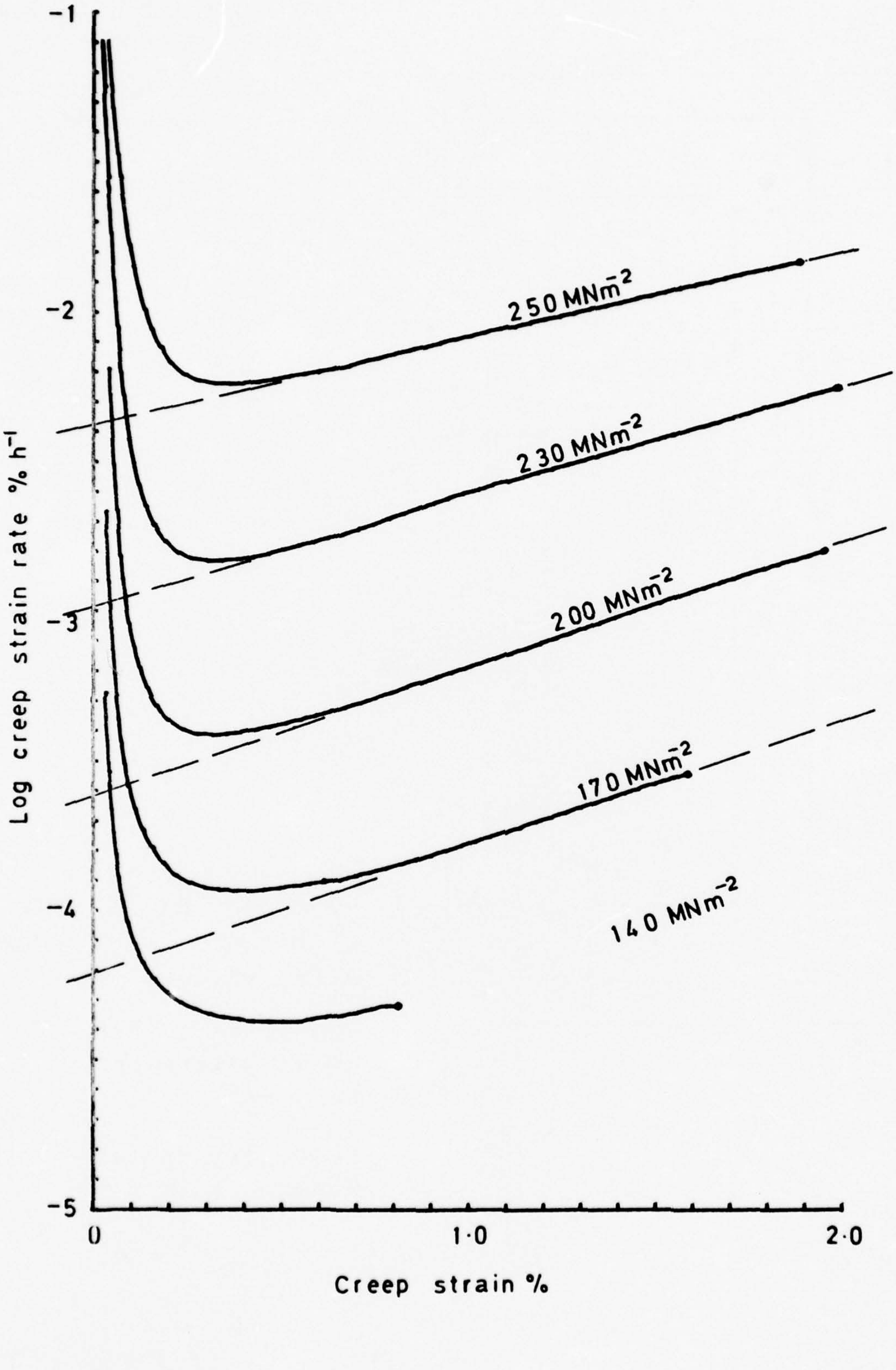

Fig. 2 Strain rate / strain curves at 150°C

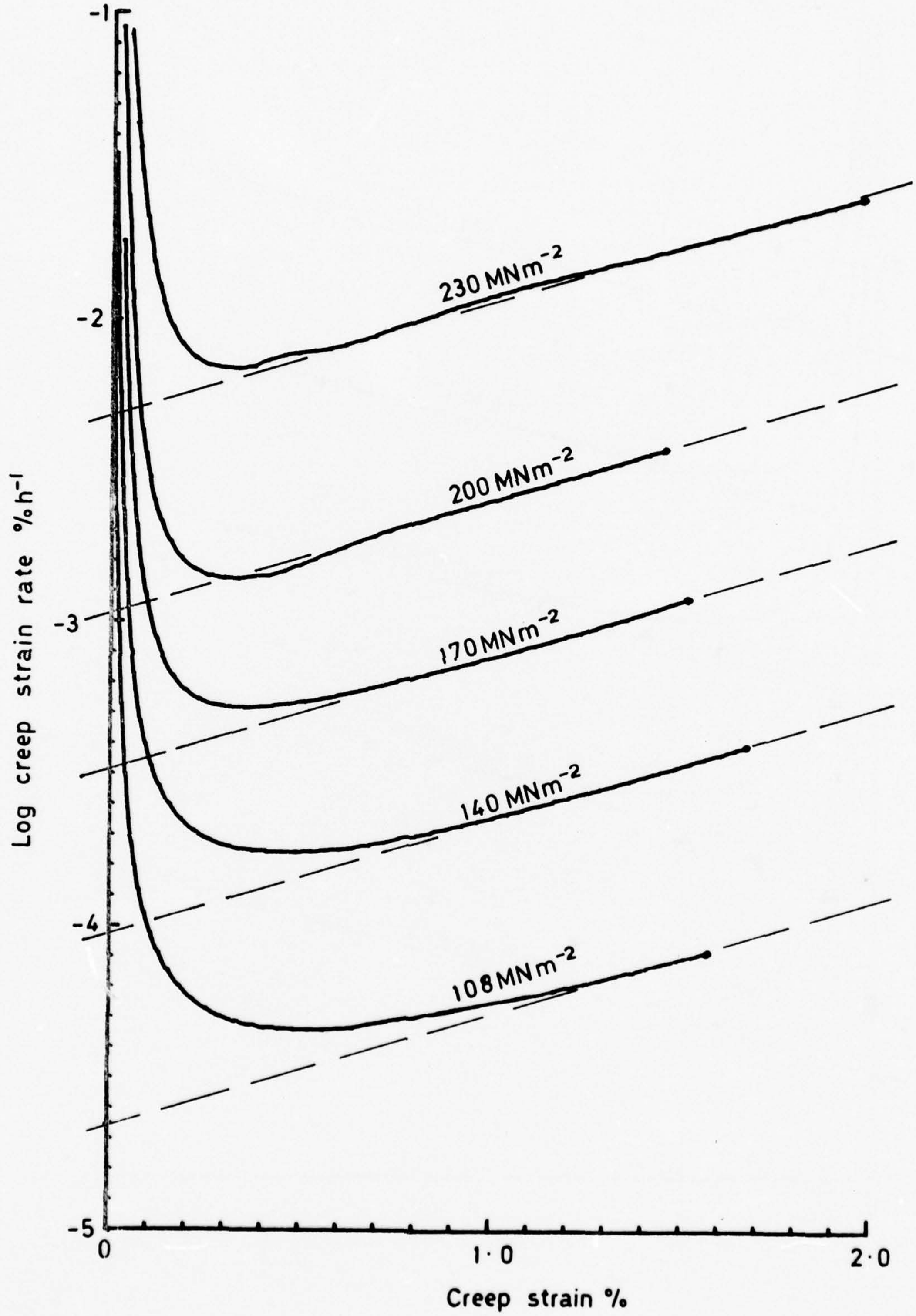

Fig. 3 Strain rate / strain curves at 165°C

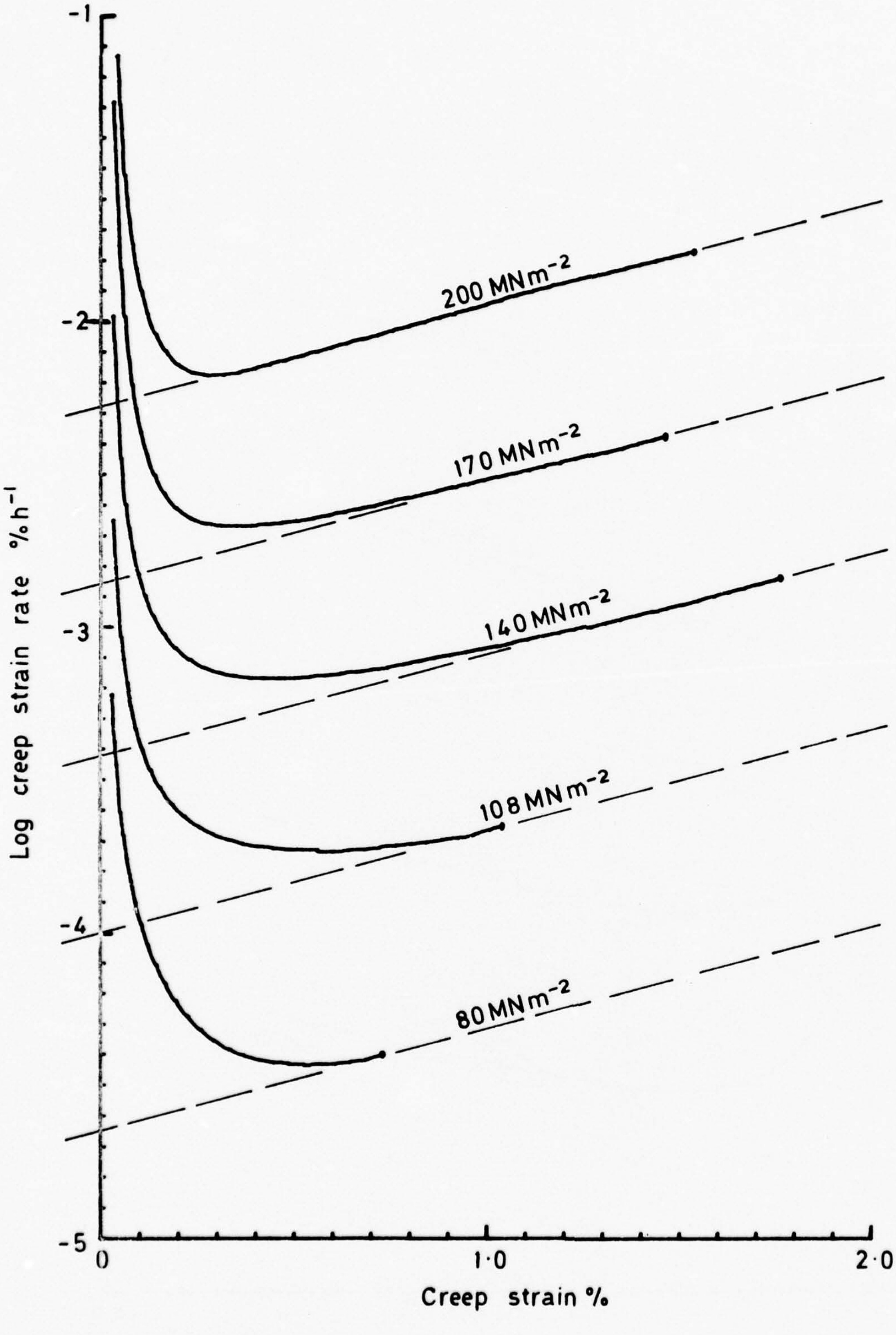

Fig. 4 Strain rate / strain curves at 180°C

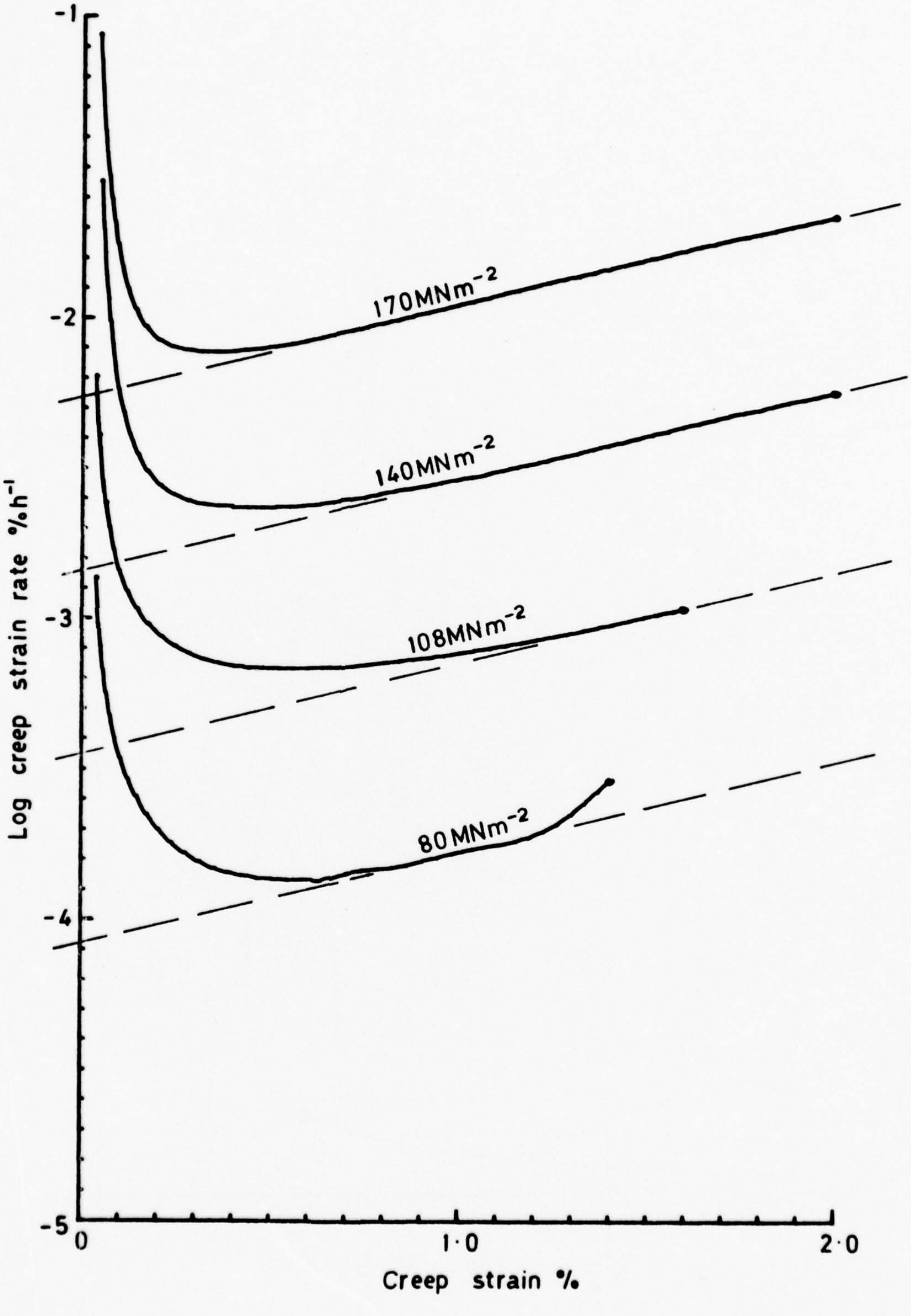

Fig. 5 Strain rate / strain curves at 195°C

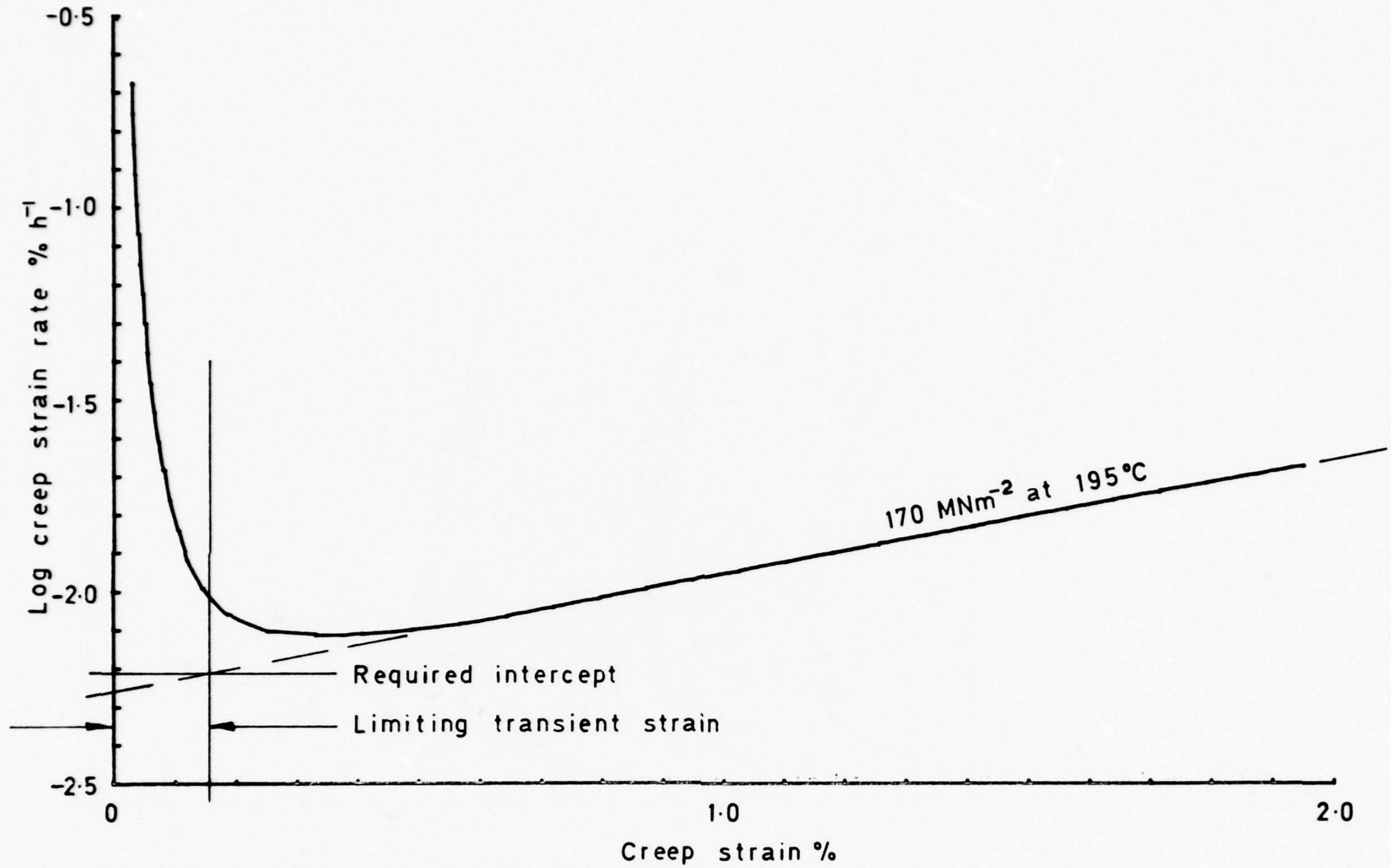

Fig. 6 Effect of transient strain

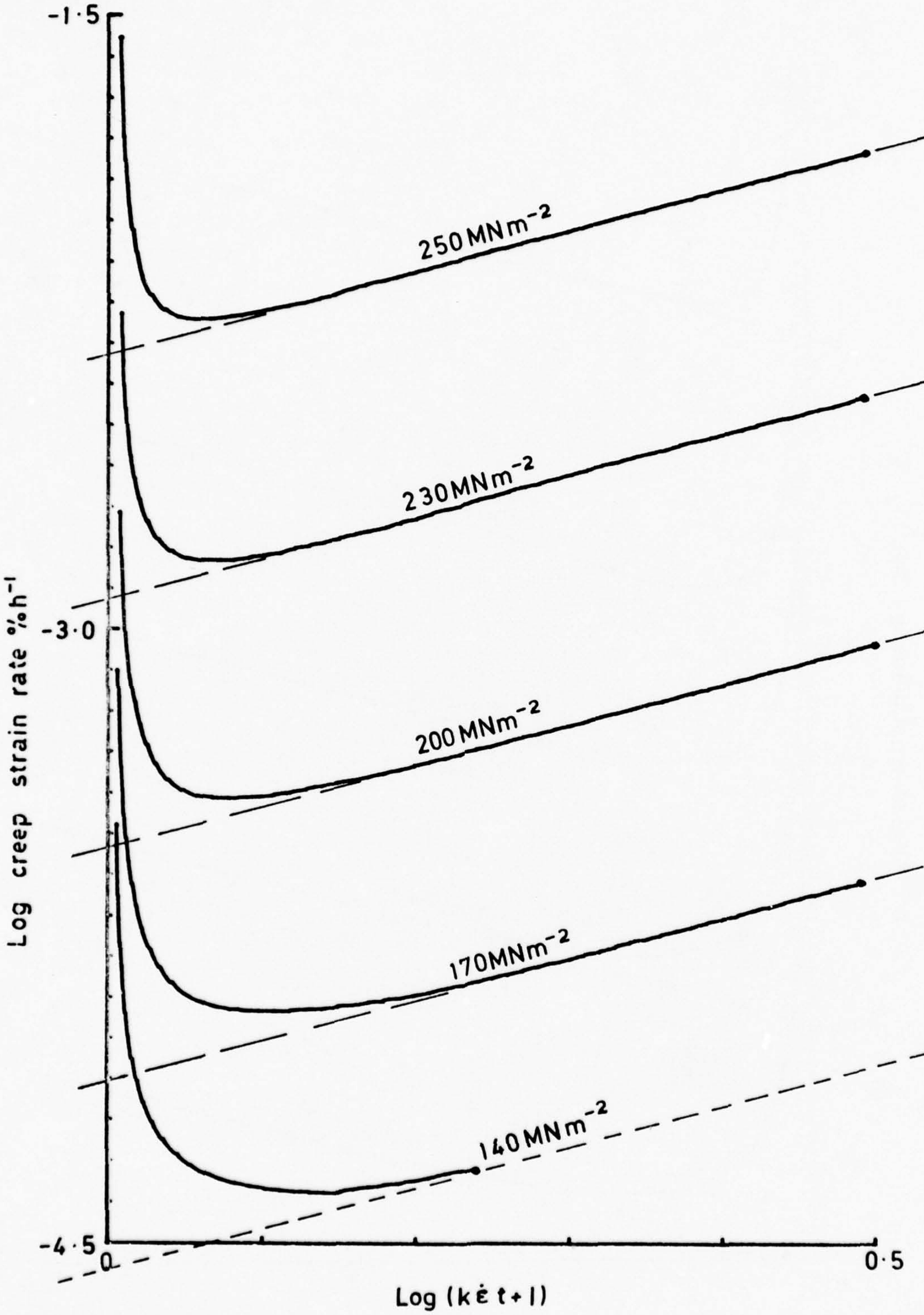

Fig. 7 Strain rate /$(k\dot{\varepsilon}t+1)$ curves at 150°C

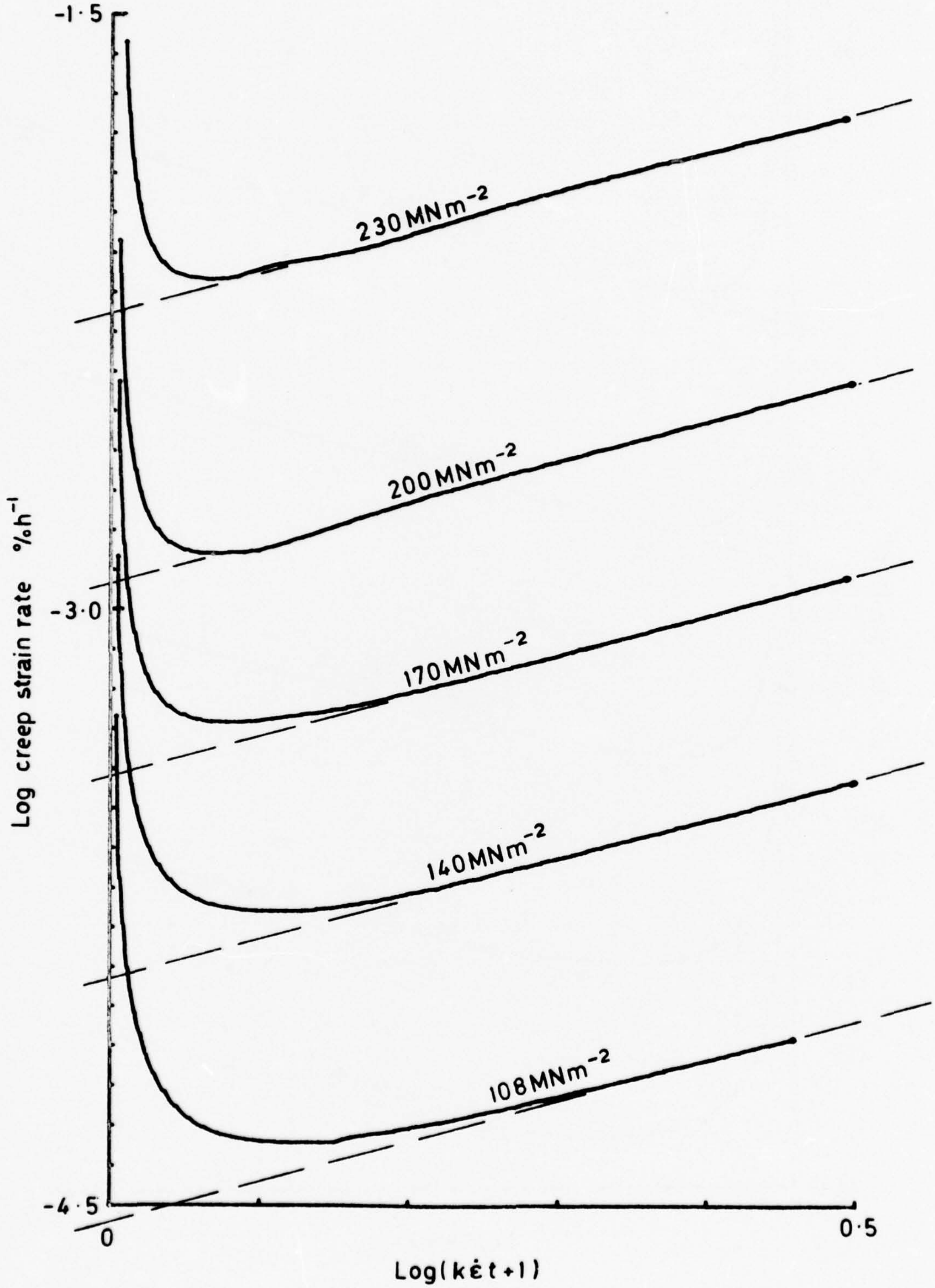

Fig. 8 Strain rate / ($k\dot{\varepsilon}t+1$) curves at 165°C

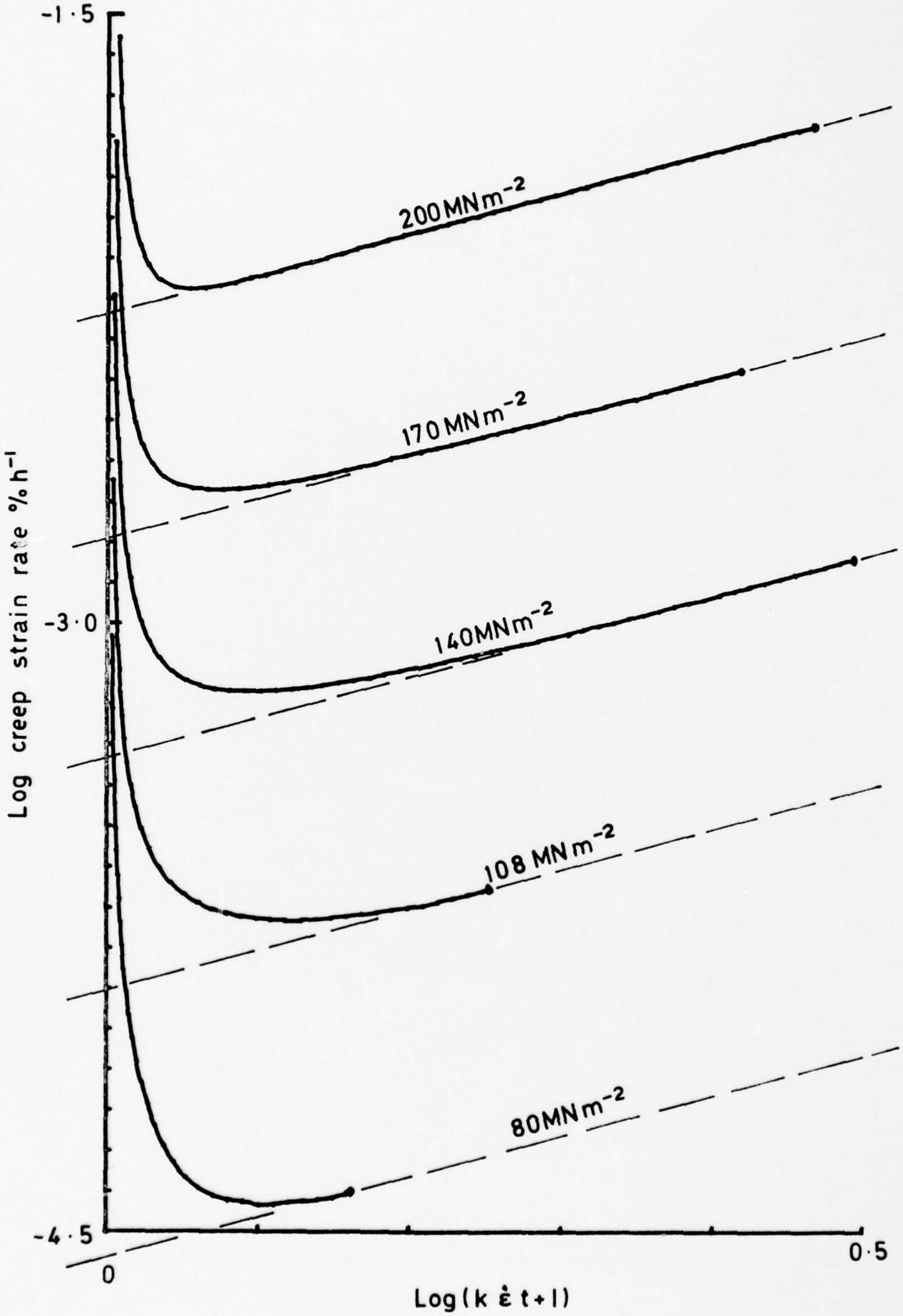

Fig. 9 Strain rate / (k$\dot{\varepsilon}$t+1) curves at 180°C

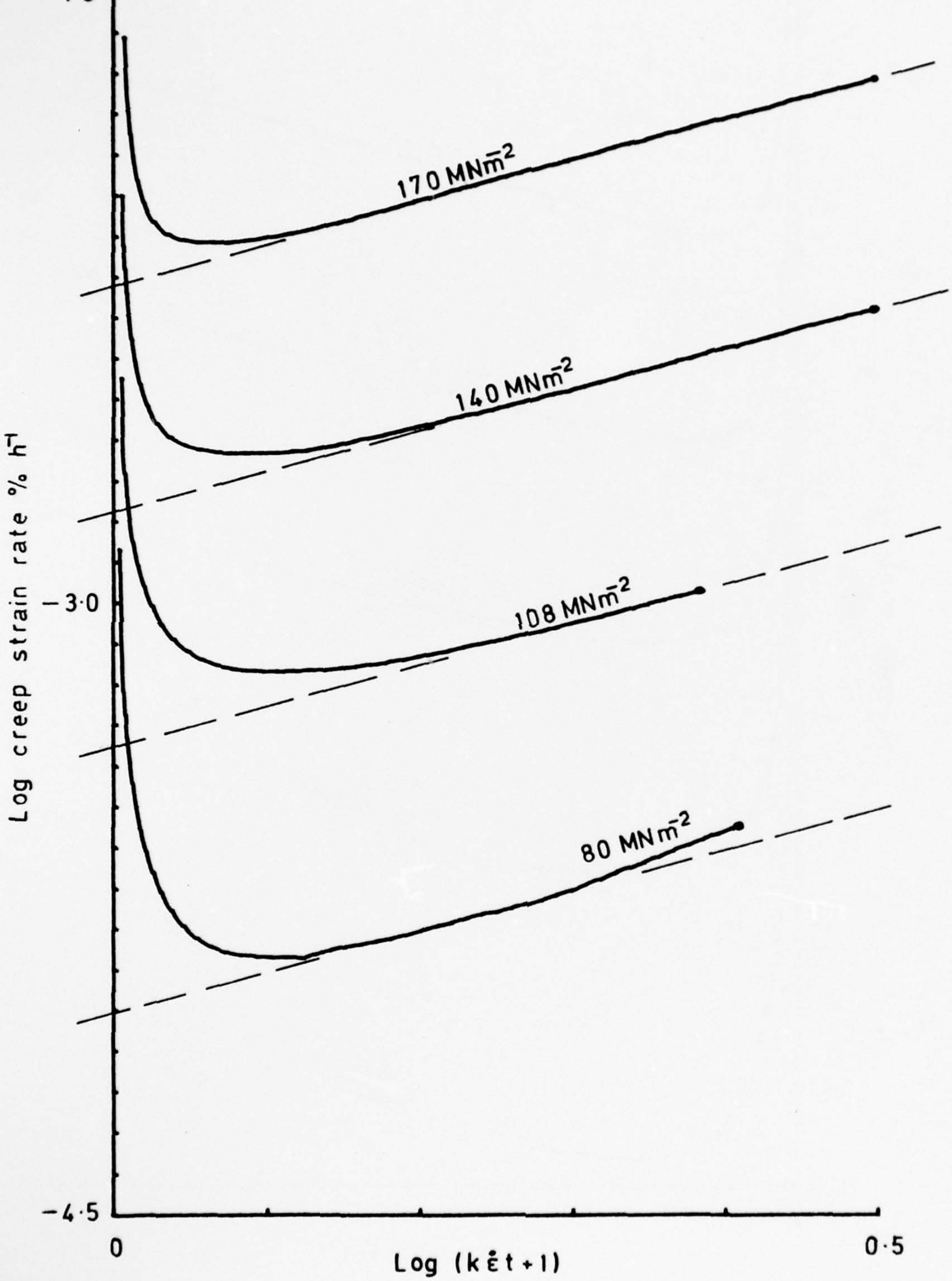

Fig. 10 Strain rate / $(k\dot{\varepsilon}t+1)$ curves at 195°C

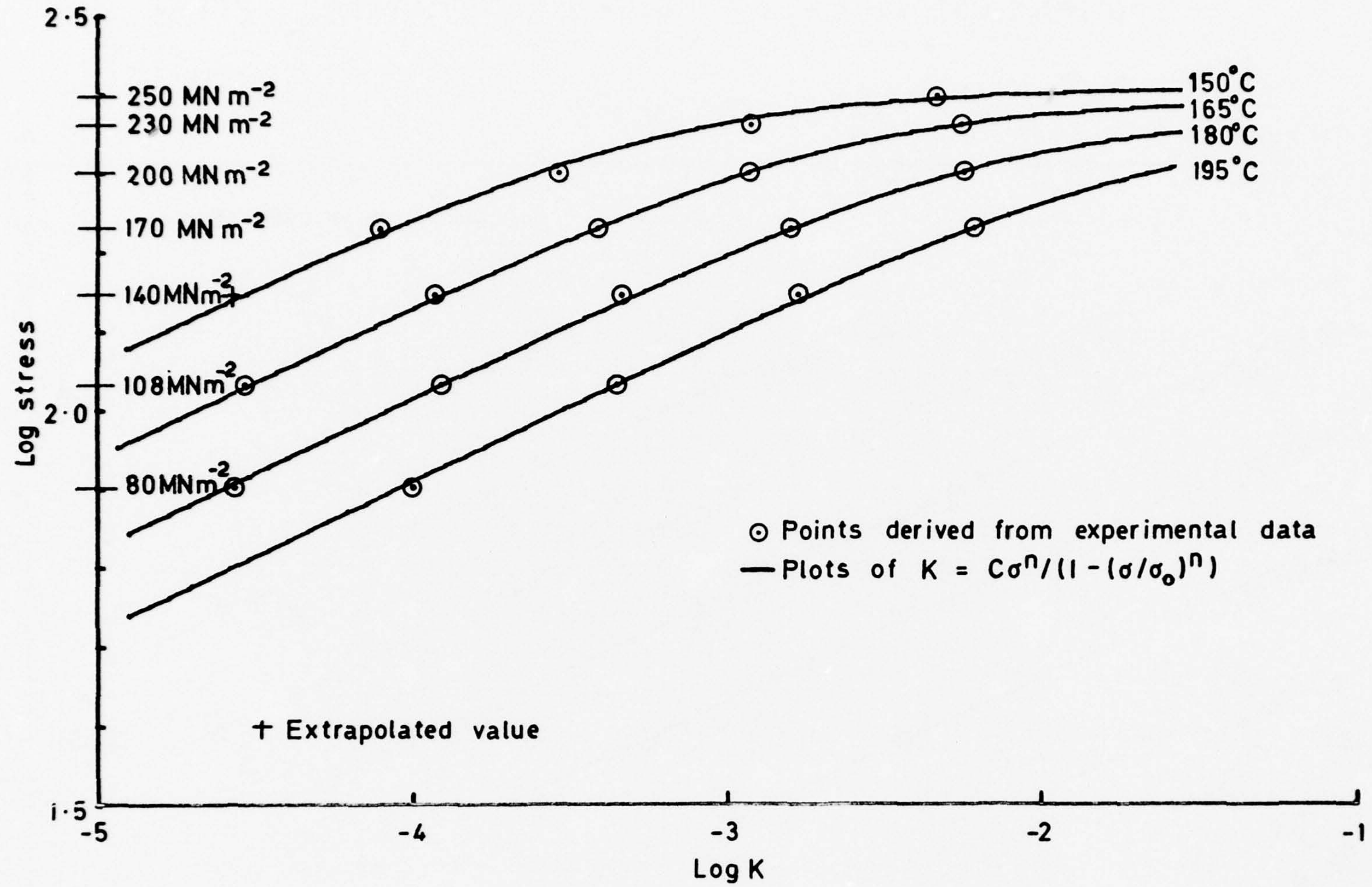

Fig. 11 Variation of K with stress

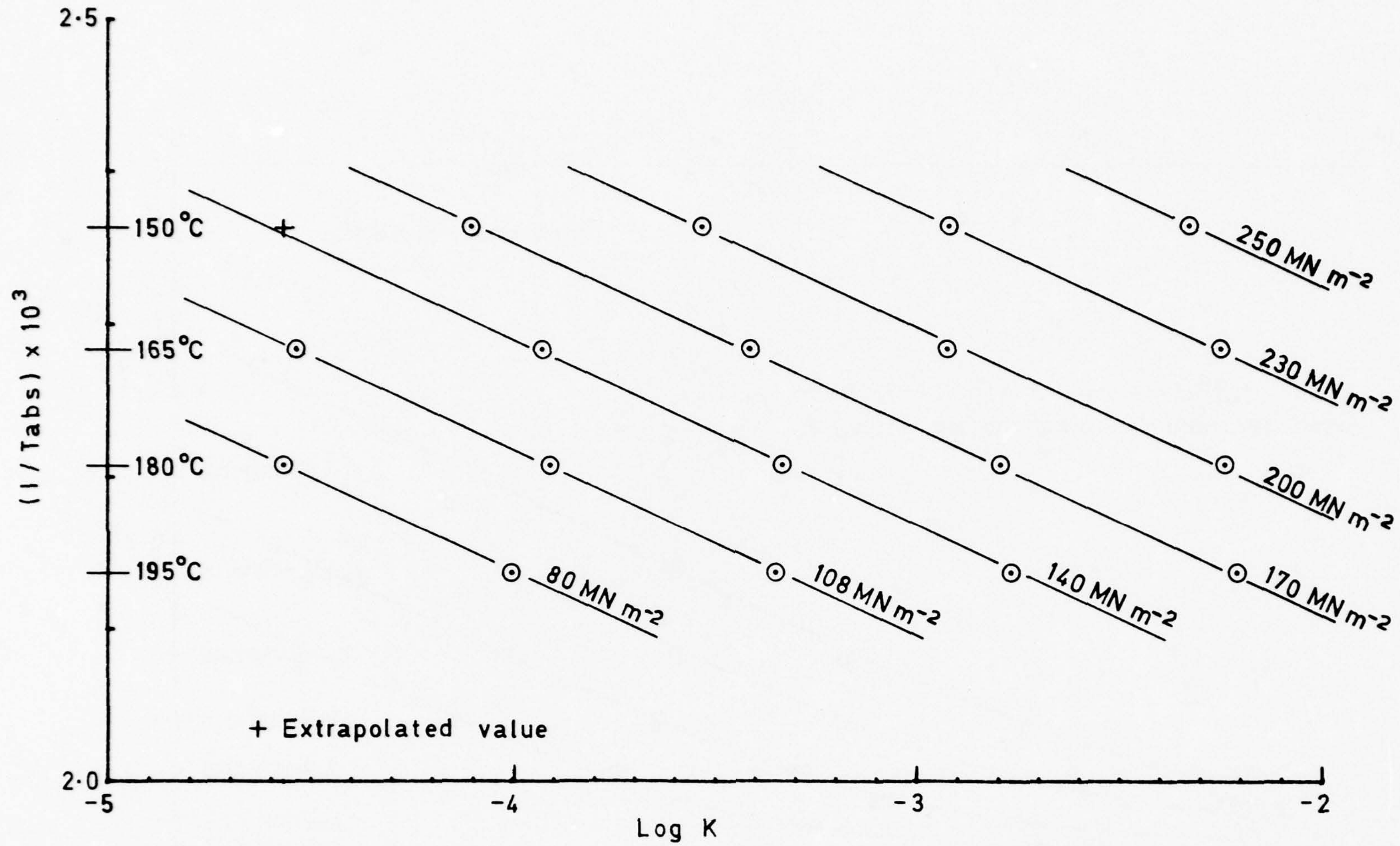

Fig.12 Variation of K with 1 / absolute temperature

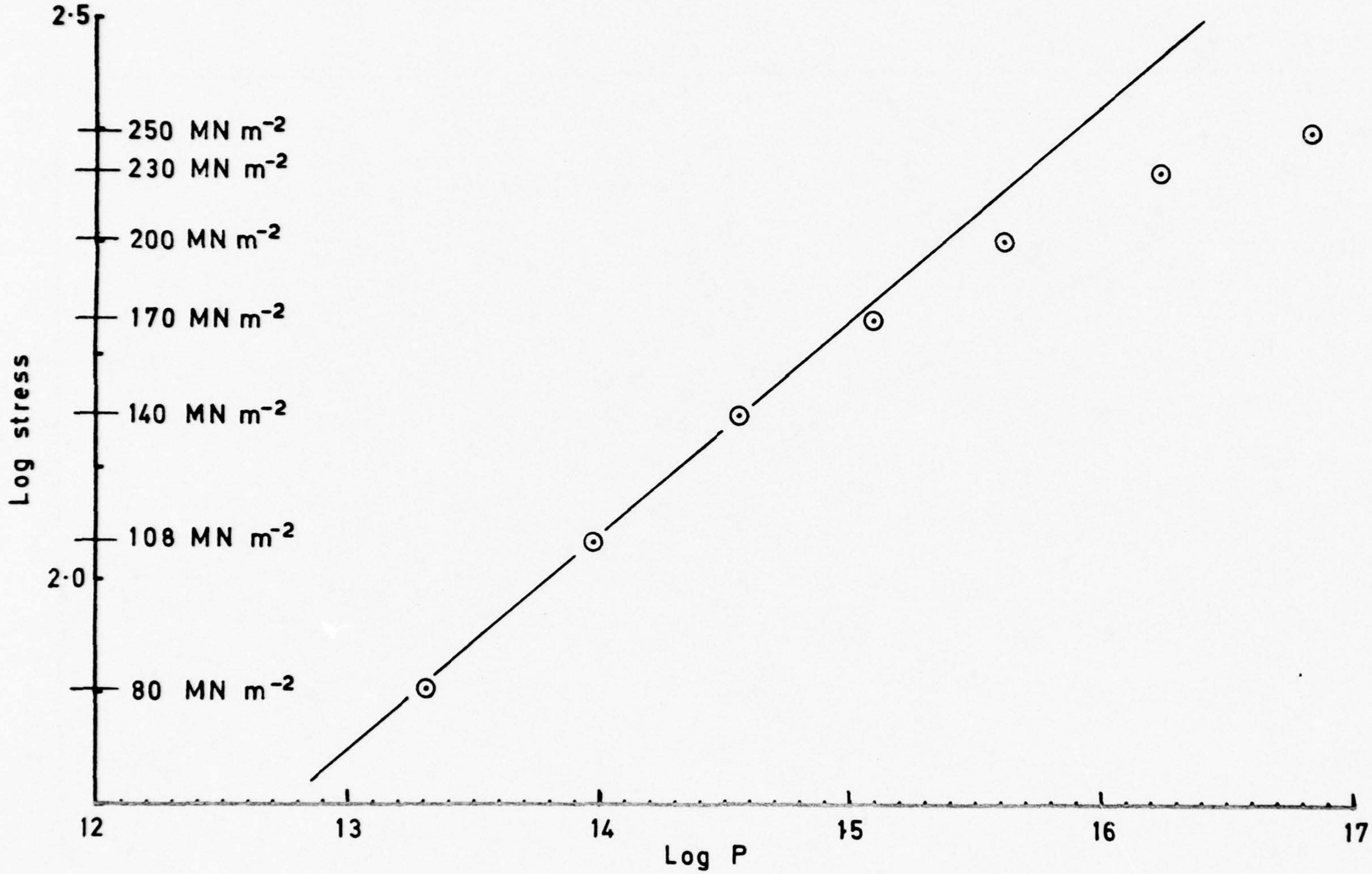

Fig.13 Variation of P with stress

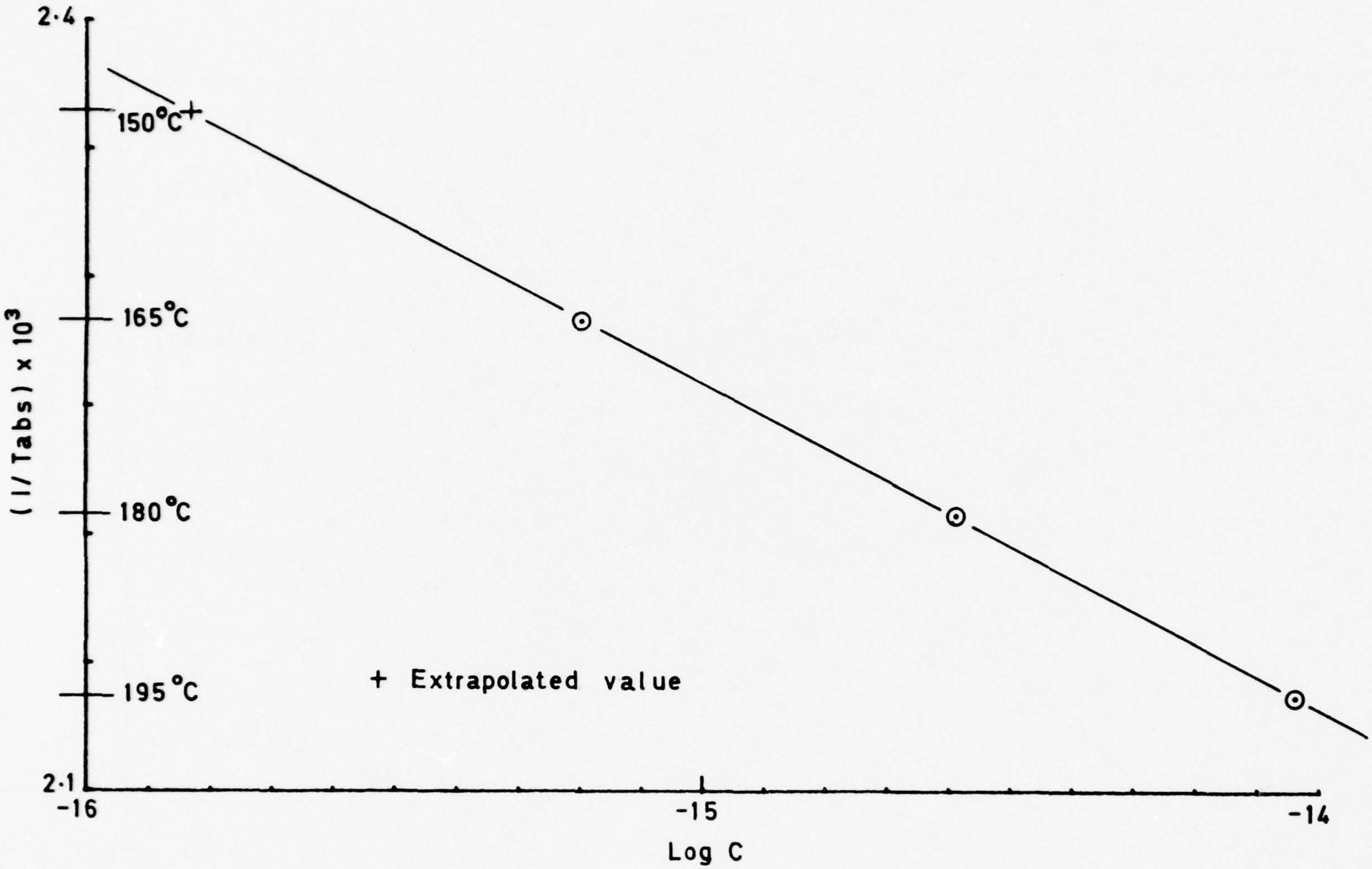

Fig.14 Variation of C with 1 / absolute temperature

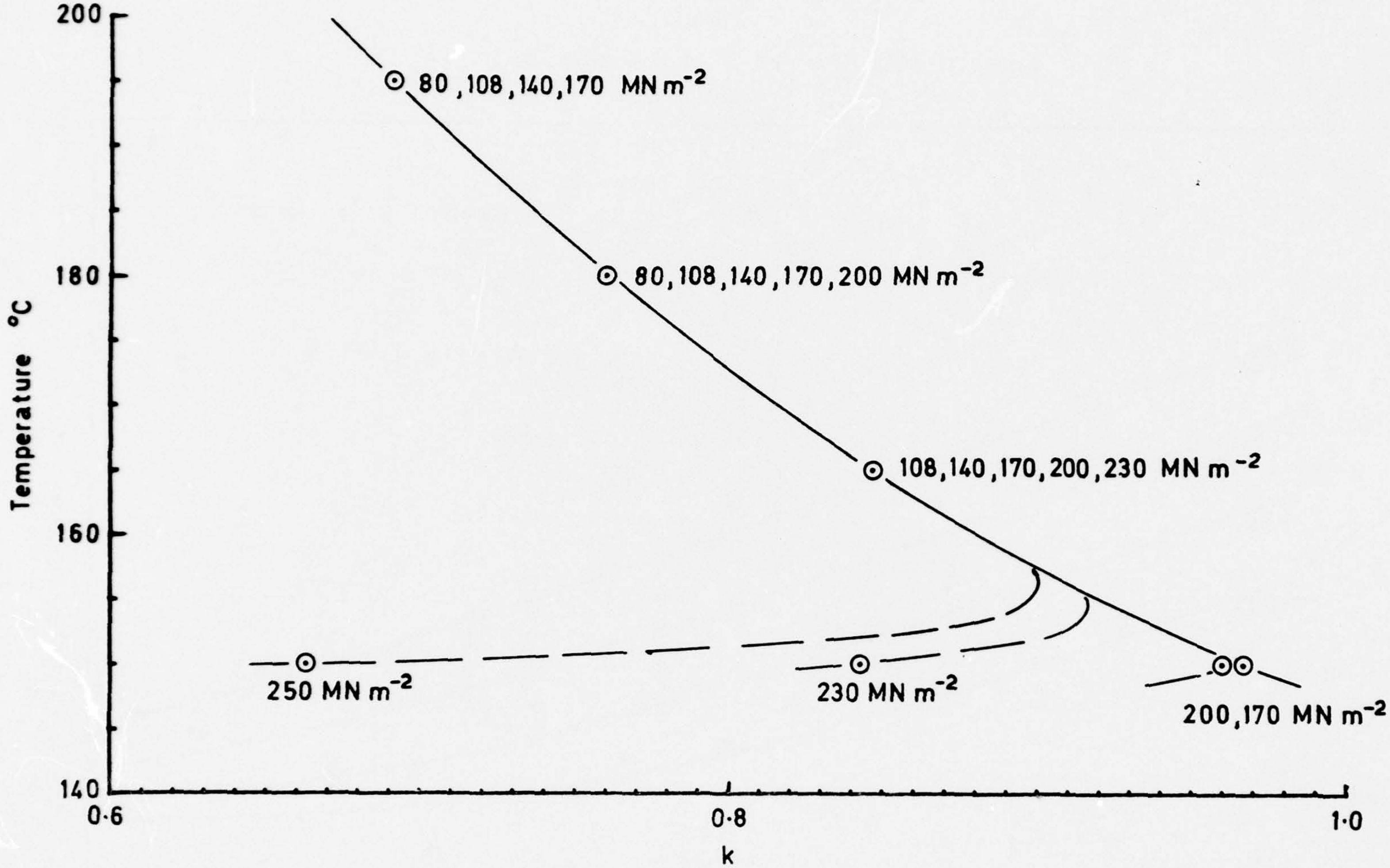

Fig.15 Variation of k with temperature

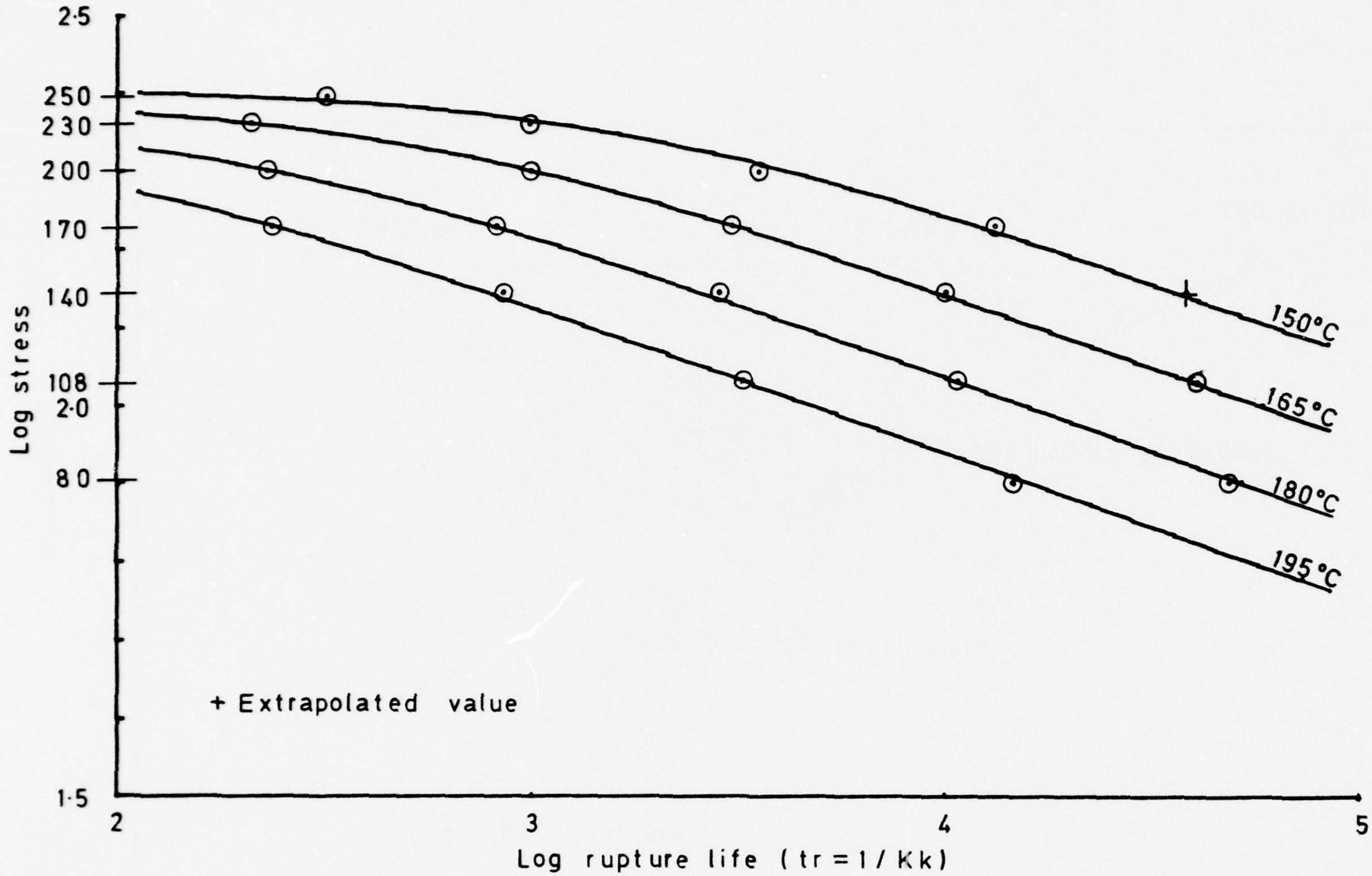

Fig.16 Variation of predicted rupture life with stress

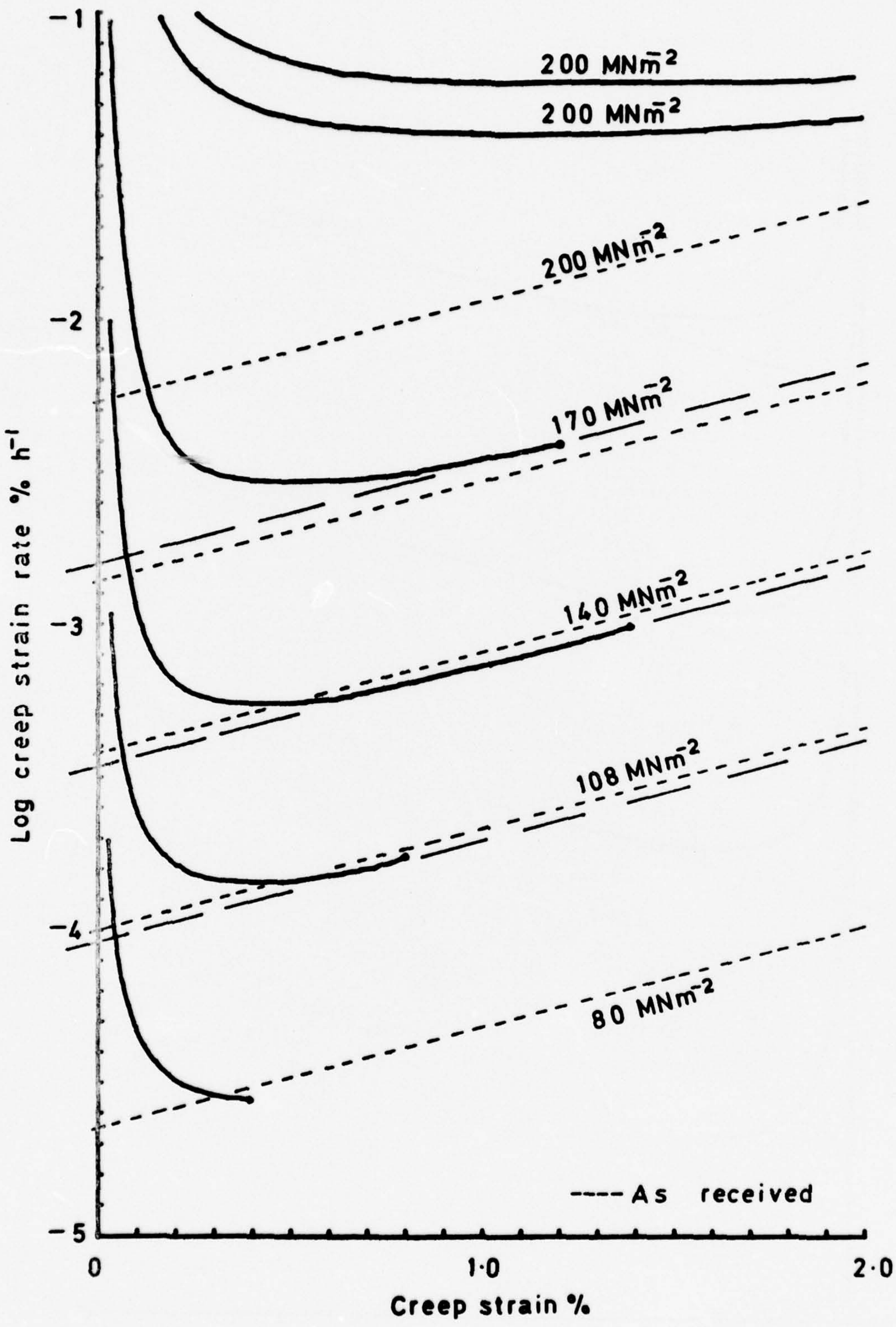

Fig.17 Strain rate, strain, curves at 180°C after 1056 h at 195°C

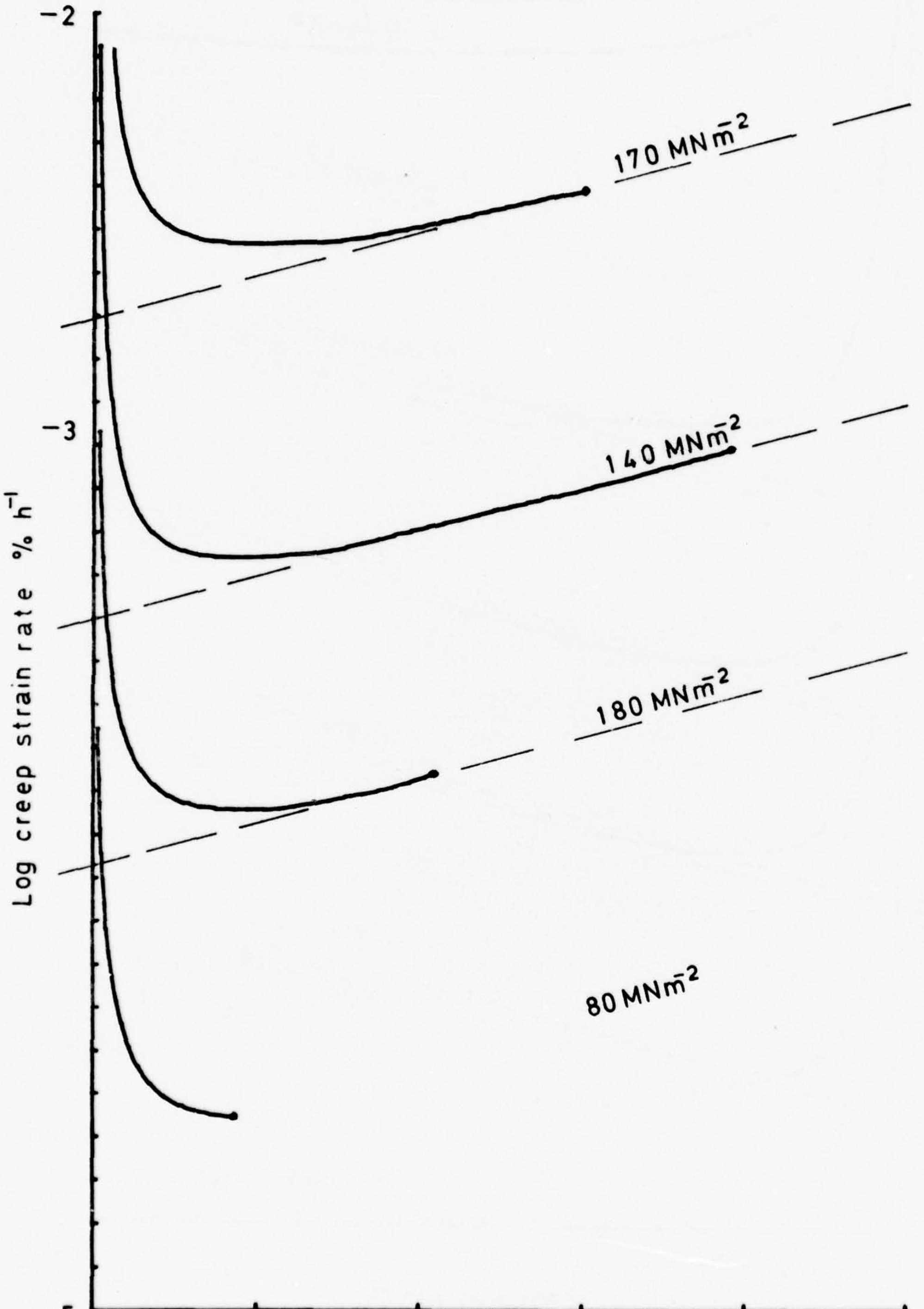

Fig.18 Strain rate, (k$\dot{\varepsilon}$t+1) curves at 180°C after 1056 h at 195°C

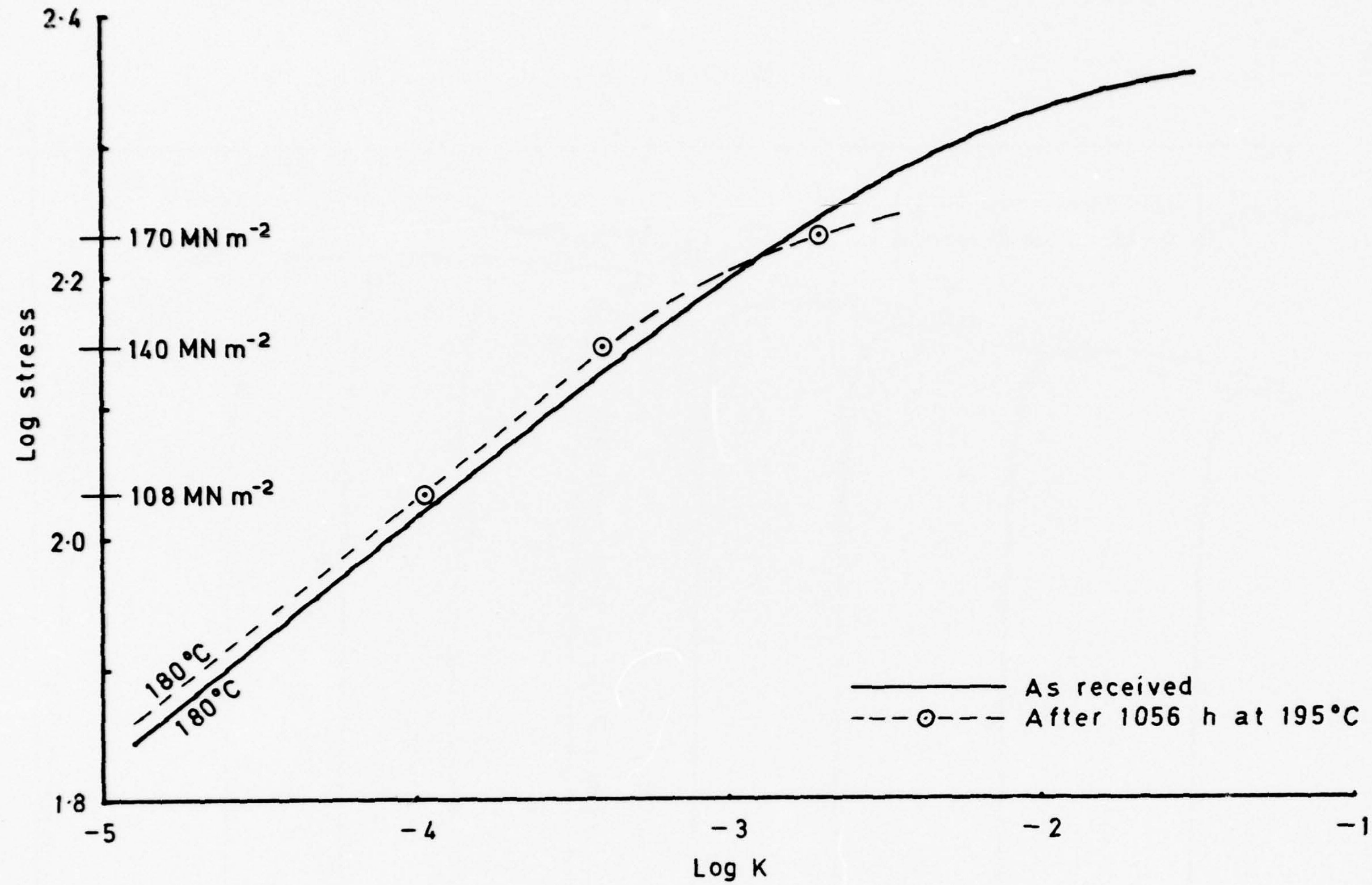

Fig. 19 Variation of K with stress after 1056 h at 195°C

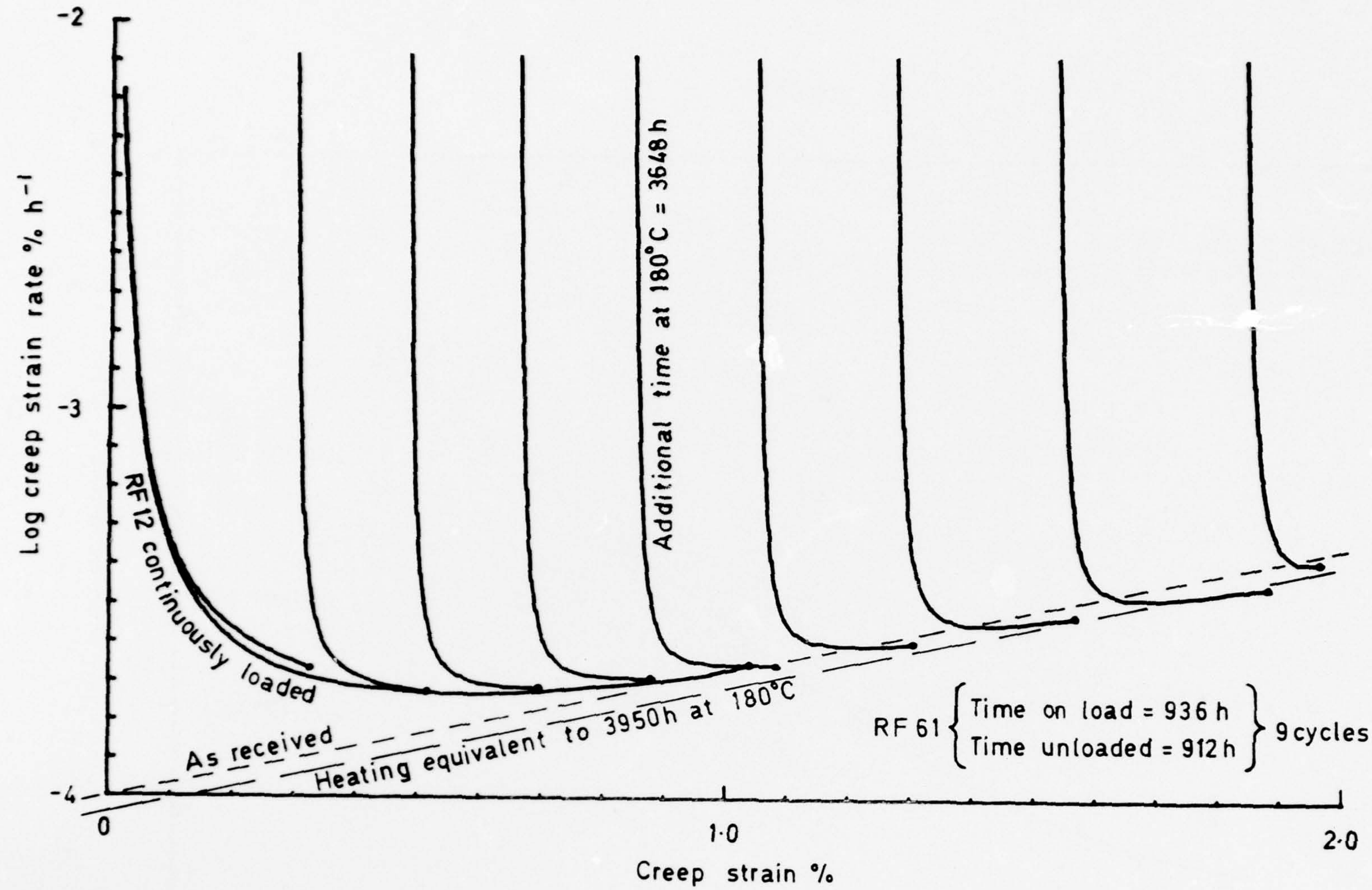

Fig.20 Cyclic creep behaviour, 108 MN m^{-2} at 180°C

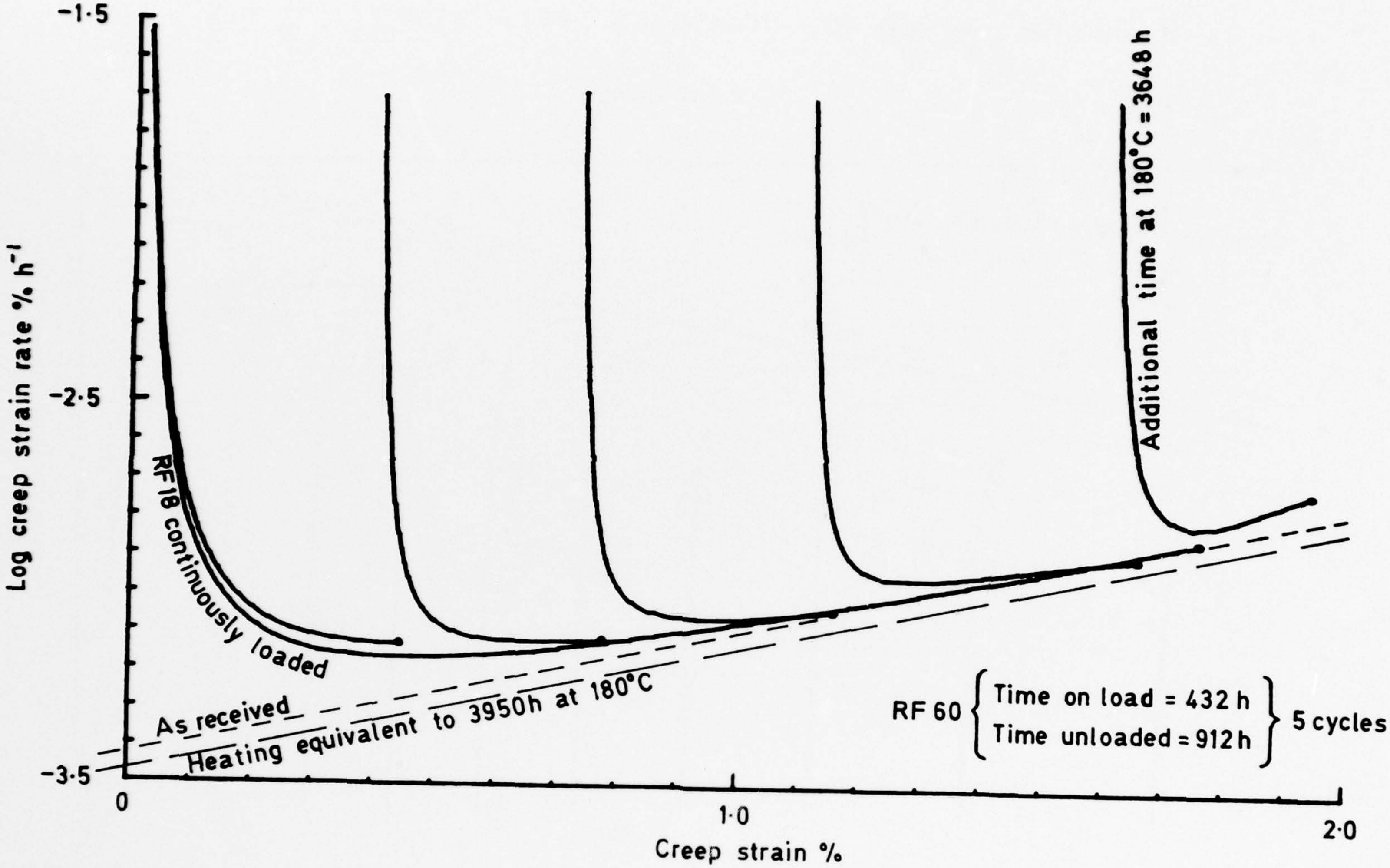

Fig. 21 Cyclic creep behaviour, 140 MN m^{-2} at 180° C

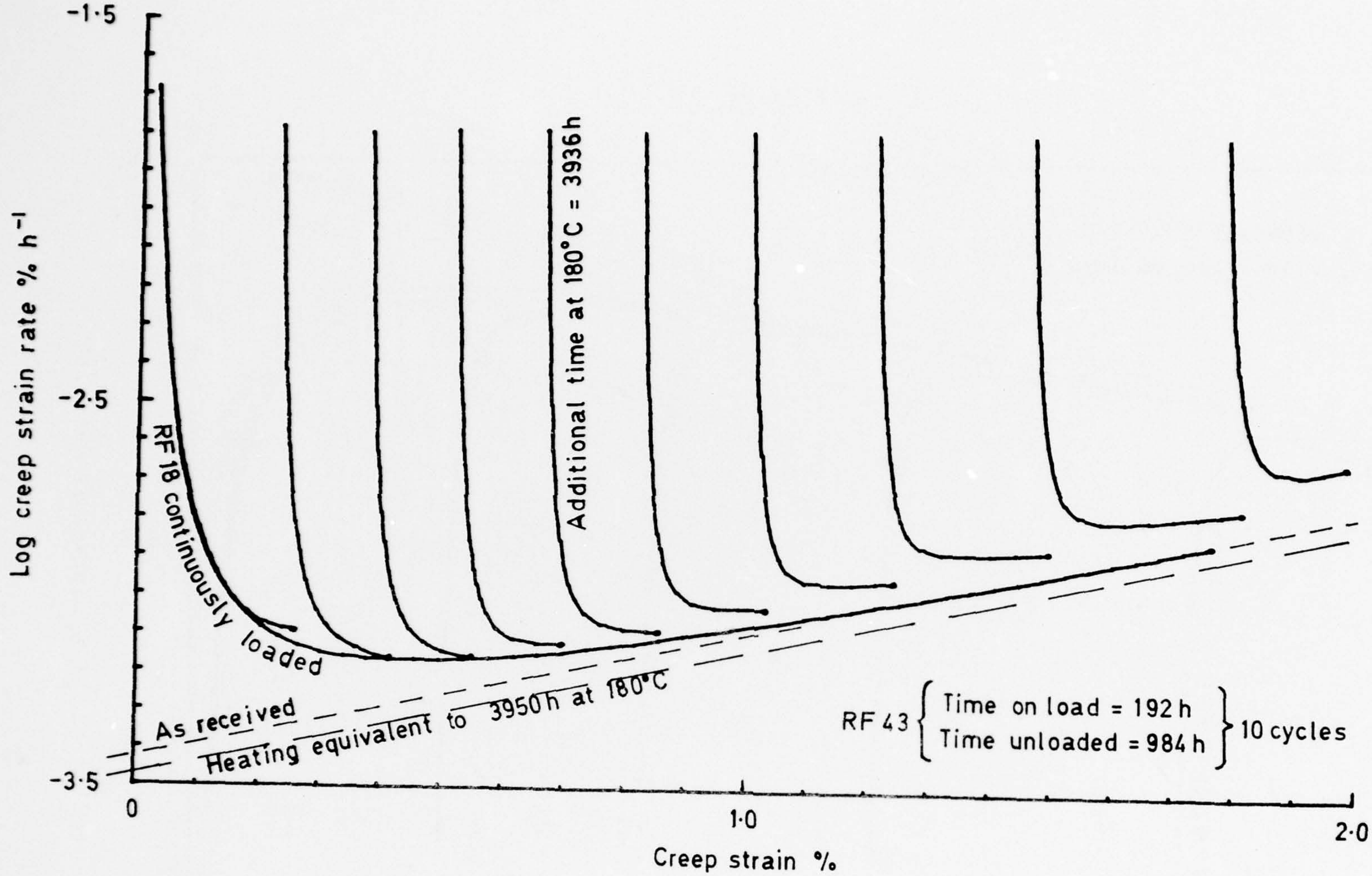

Fig. 22 Cyclic creep behaviour 140 MN m^{-2} at 180°C

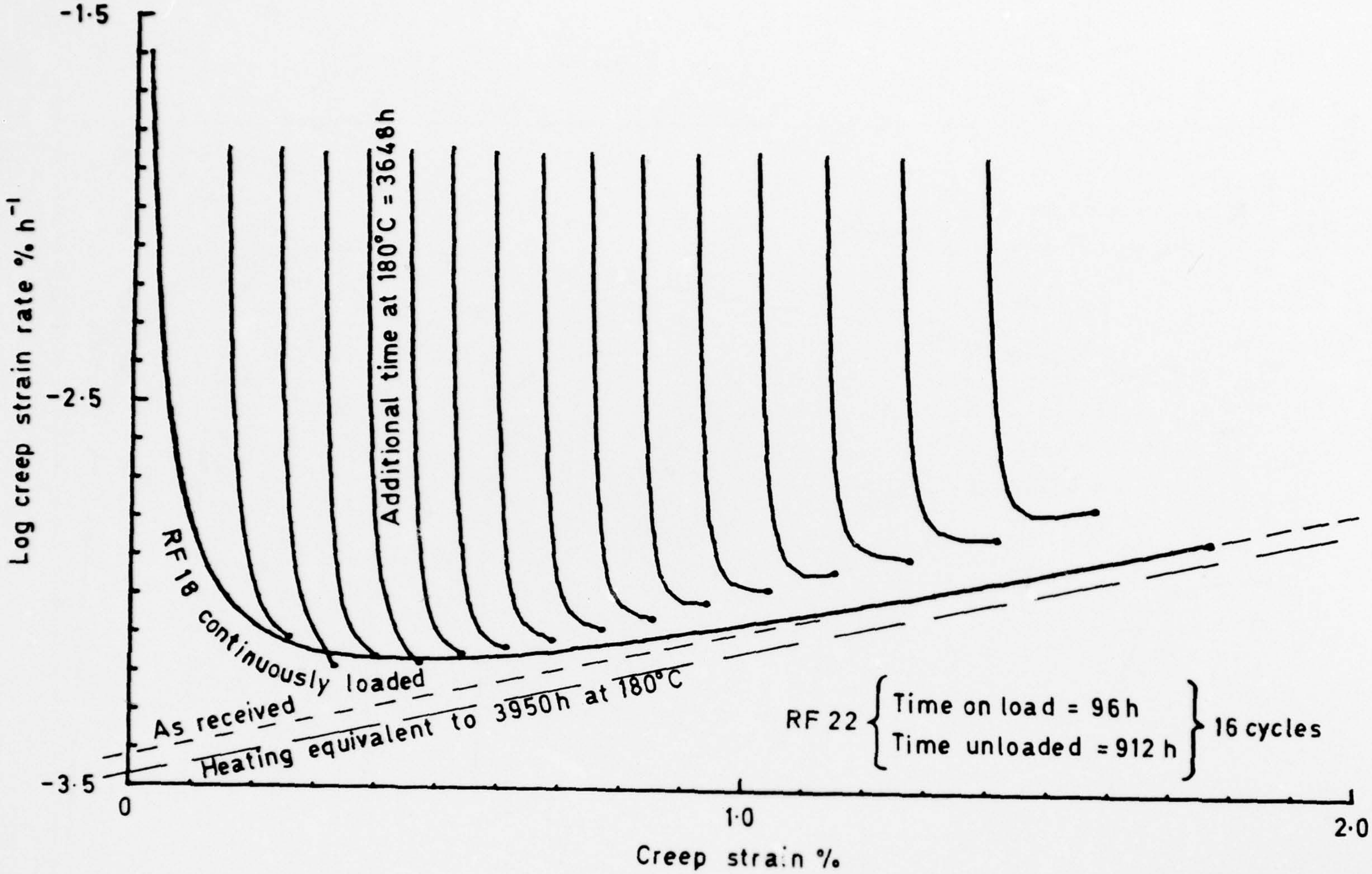

Fig. 23 Cyclic creep behaviour, 140 MN m^{-2} at 180°C

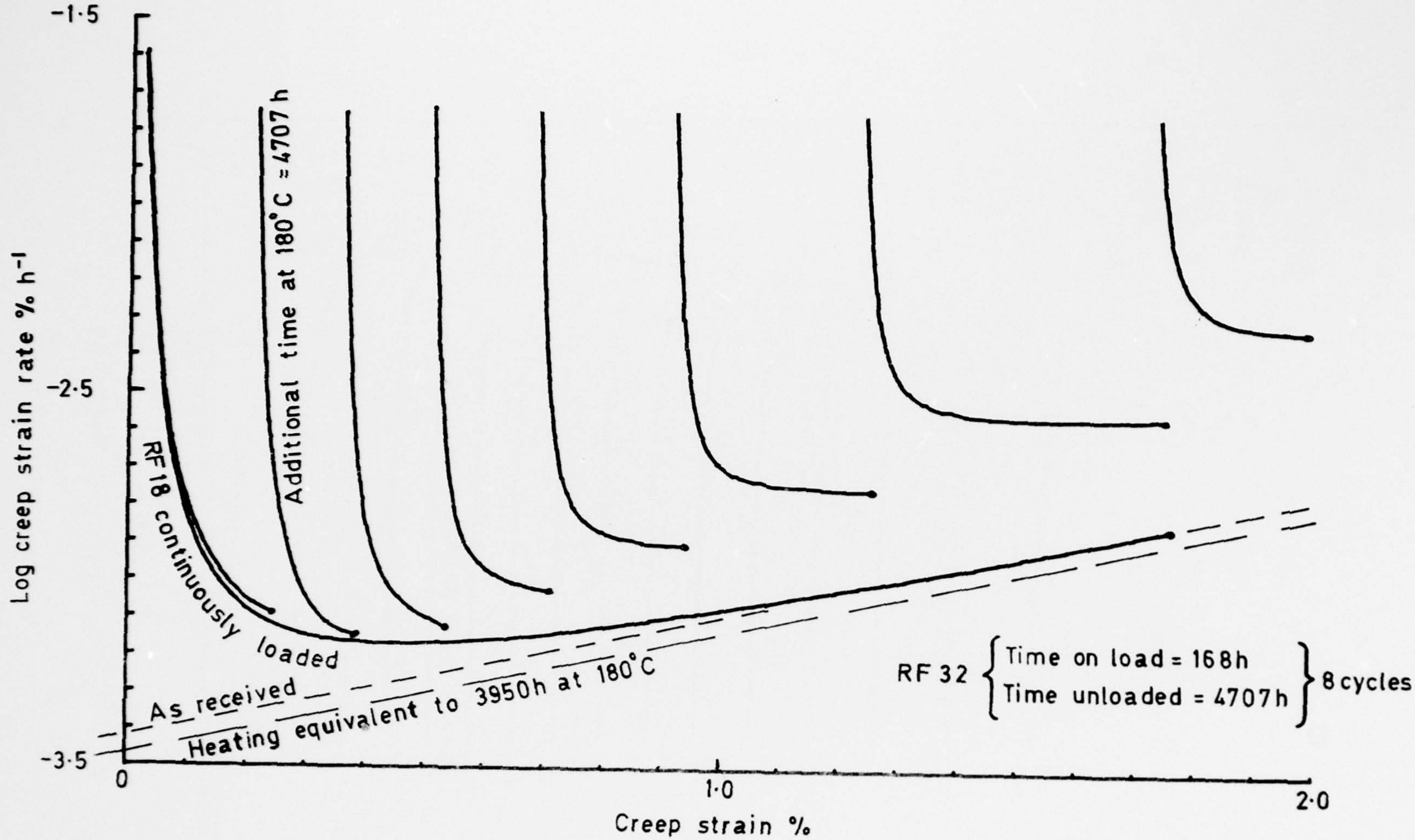

Fig.24 Cyclic creep behaviour, 140 MN m^{-2} at 180° C

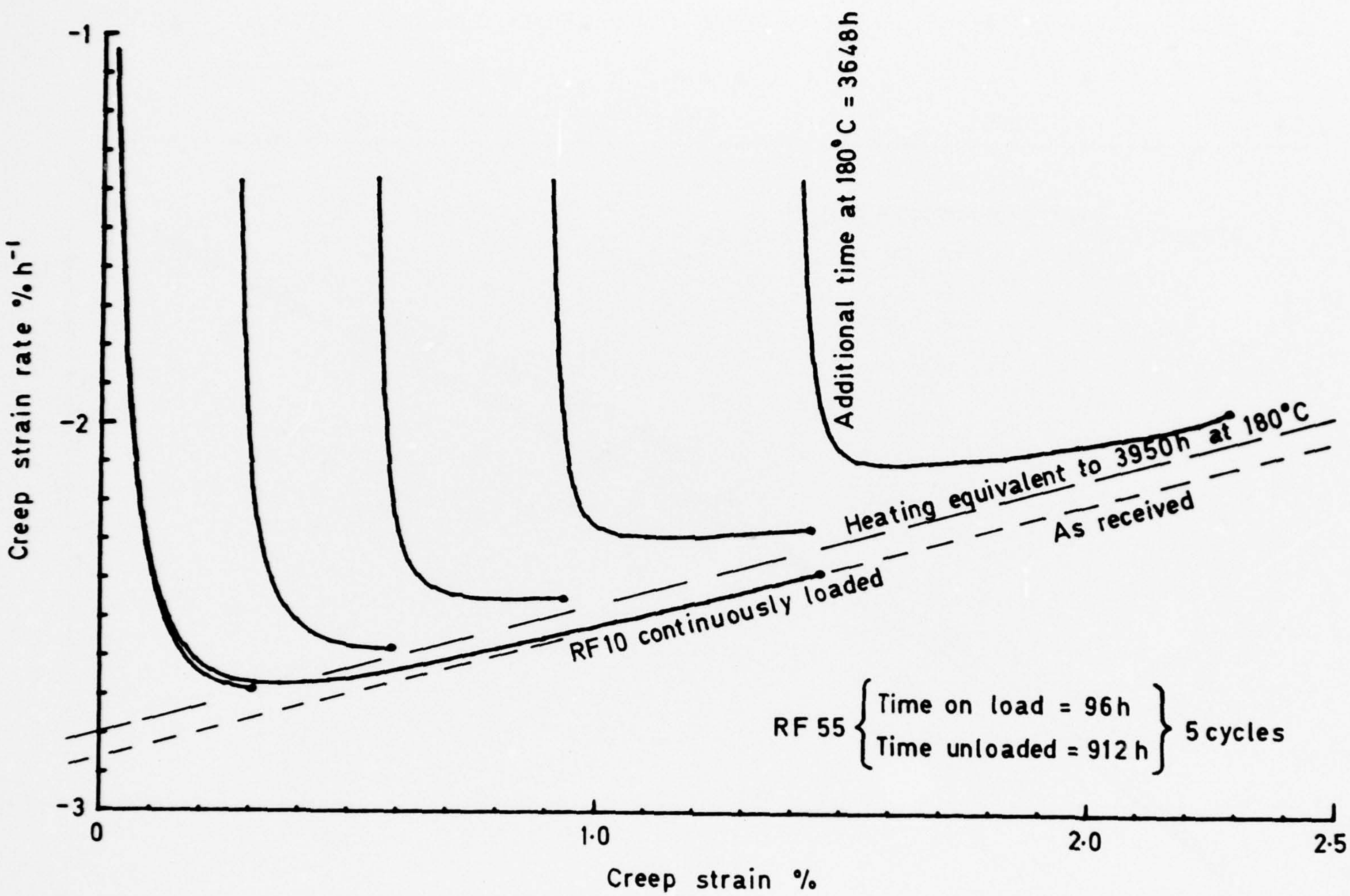

Fig. 25 Cyclic creep behaviour, 170 MN m^{-2} at 180°C

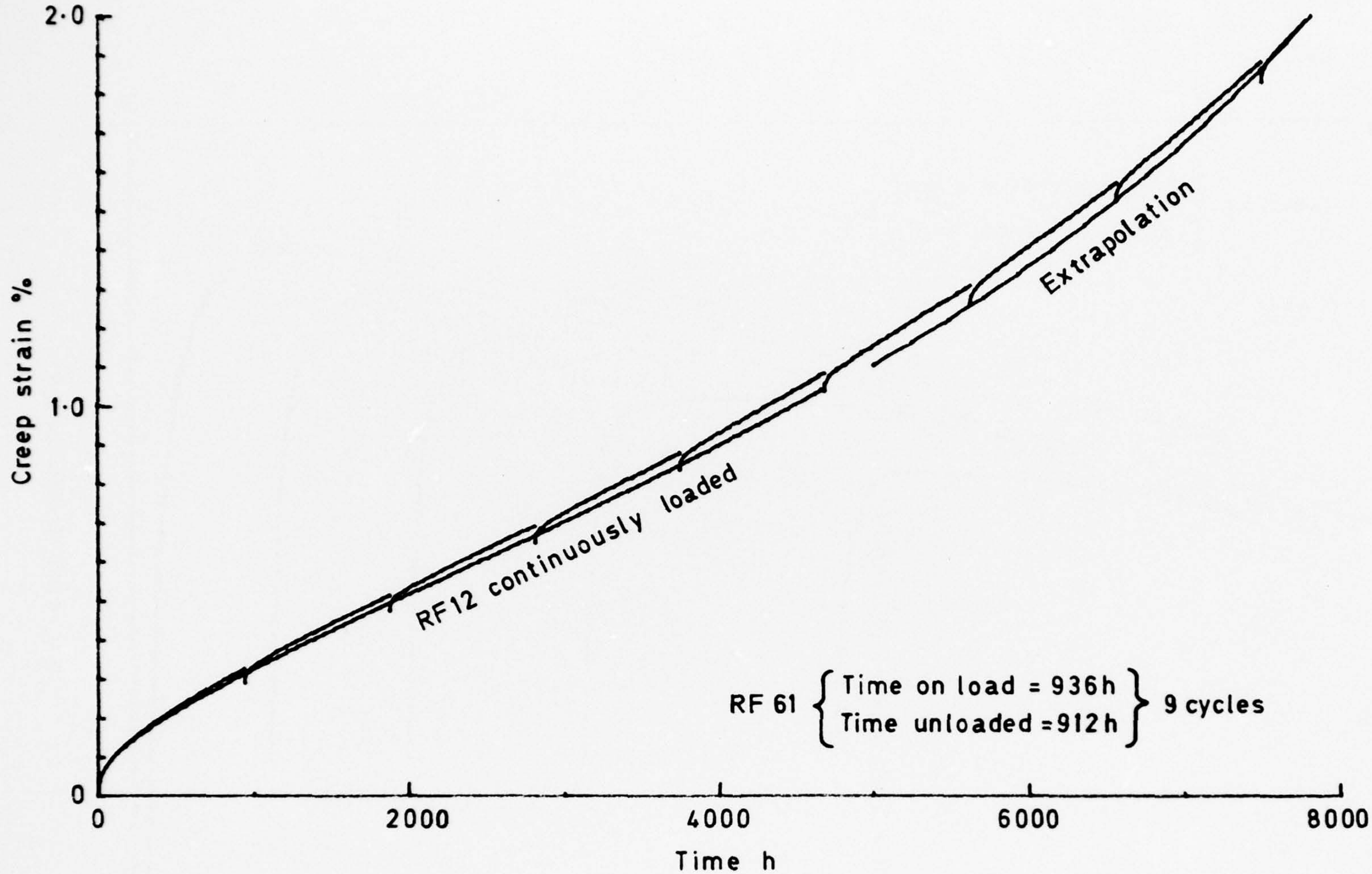

Fig. 26 Cyclic creep behaviour, strain accumulation with time
108 MN m^{-2} at 180°C

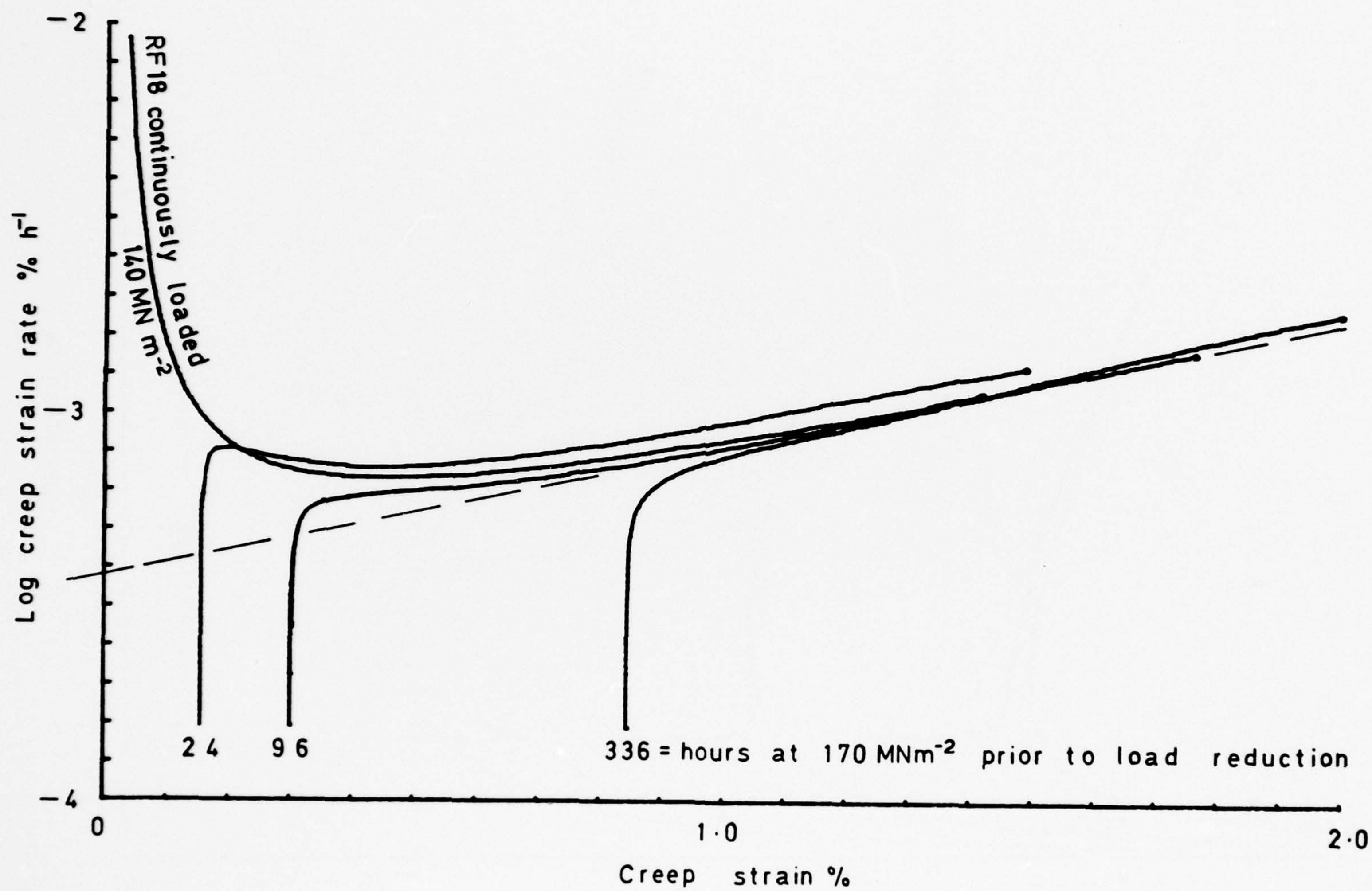

Fig. 27 Strain rate, strain curves after load reduction from 170 to 140 MNm^{-2} at 180 °C

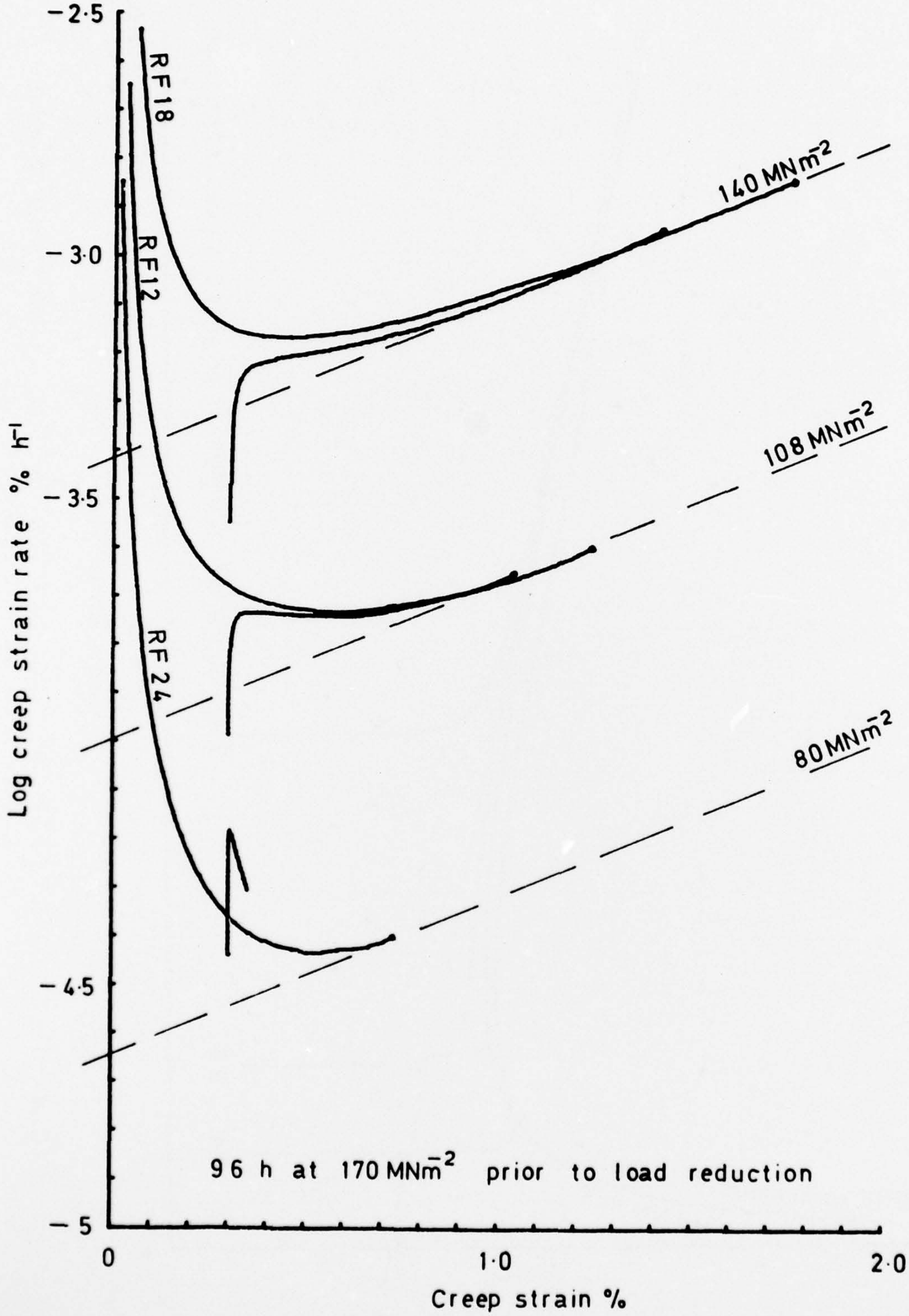

Fig. 28 Strain rate, strain curves after load reduction from 170 to 140, 108, and 80 MNm^{-2} at 180°C

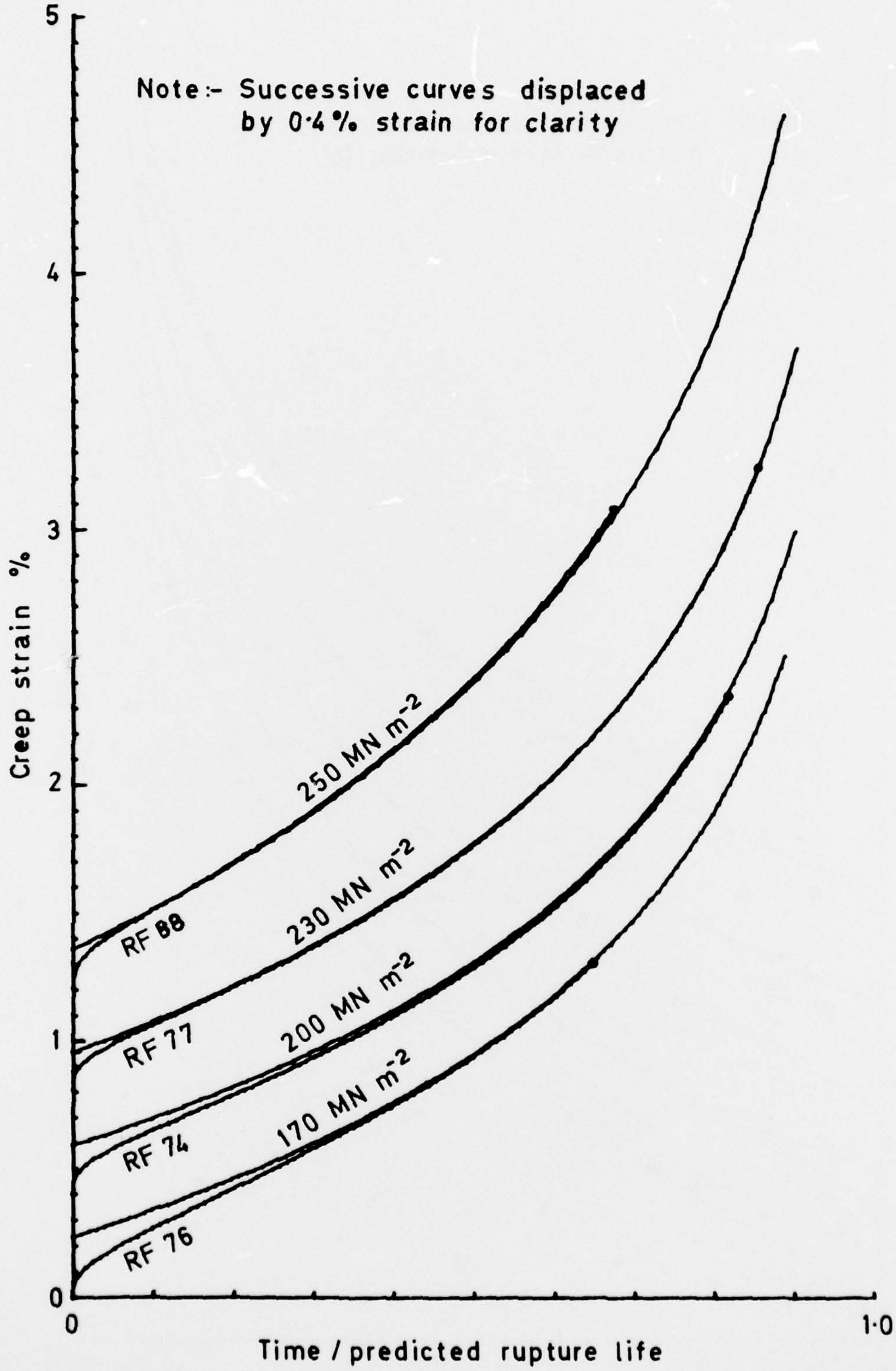

Fig.29 Comparison of creep curves with modified "steady state" relationship at 150°C

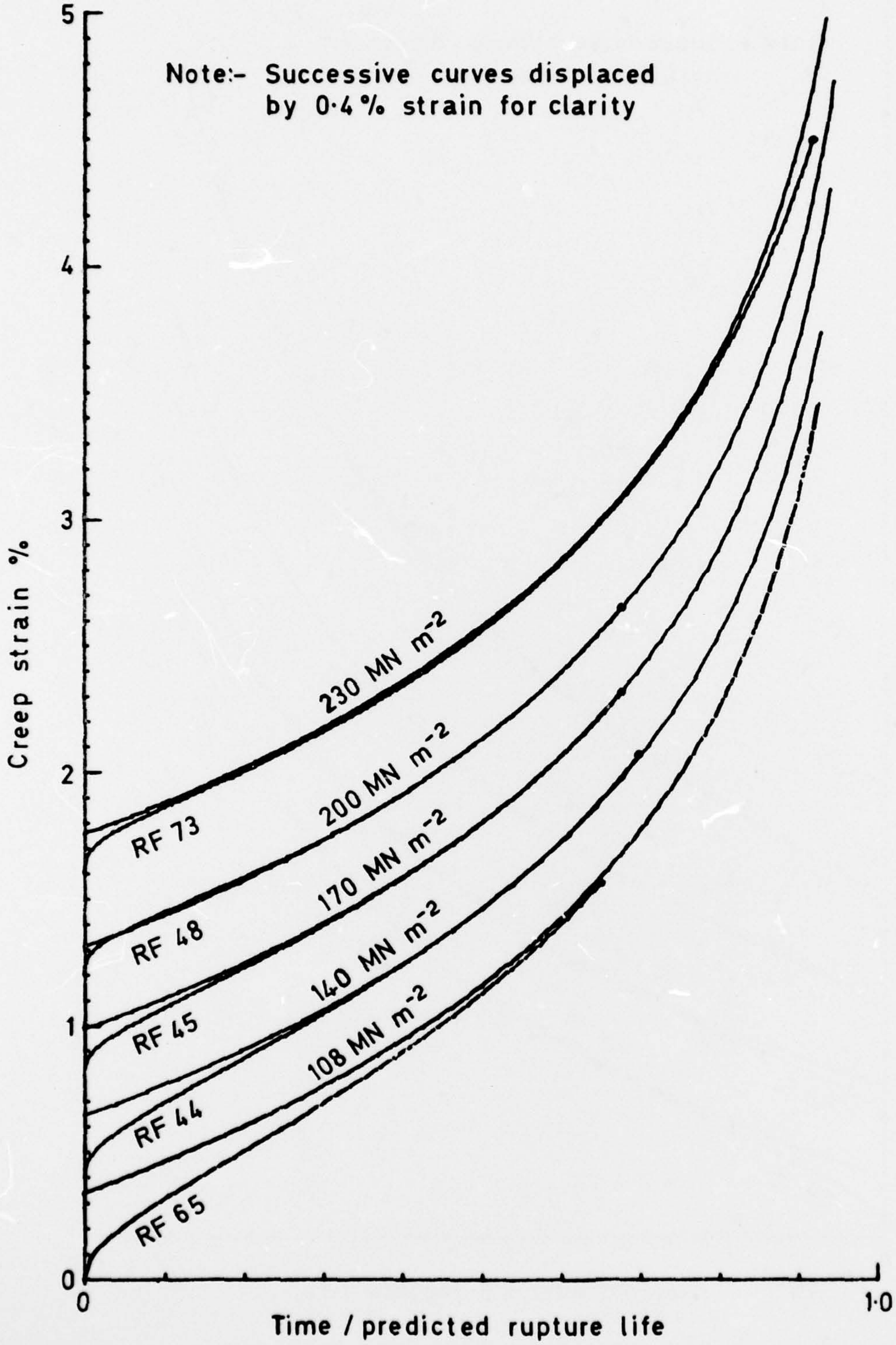

Fig.30 Comparison of creep curves with modified "steady state" relationship at 165°C

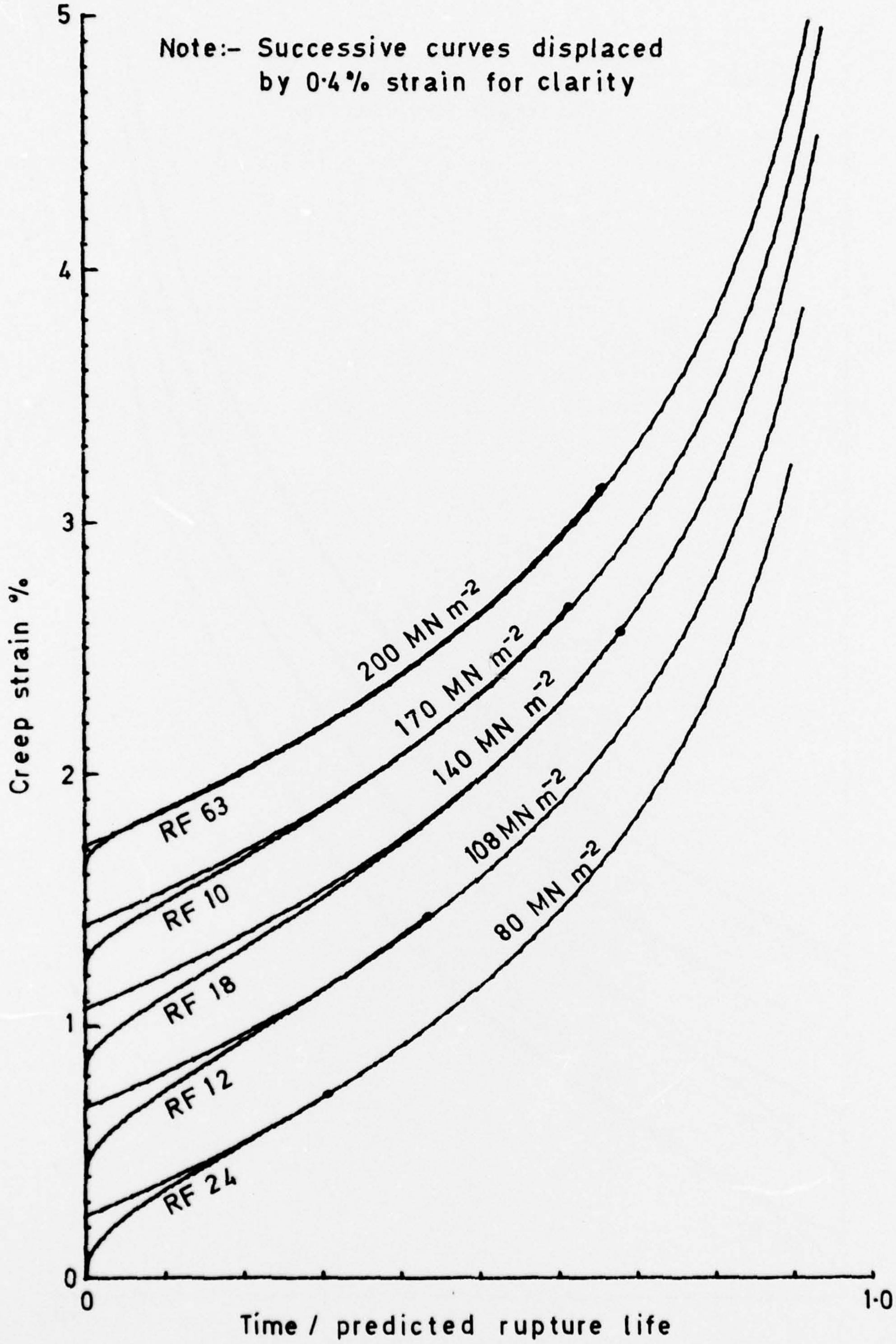

Fig.31 Comparison of creep curves with modified "steady state" relationship at 180° C

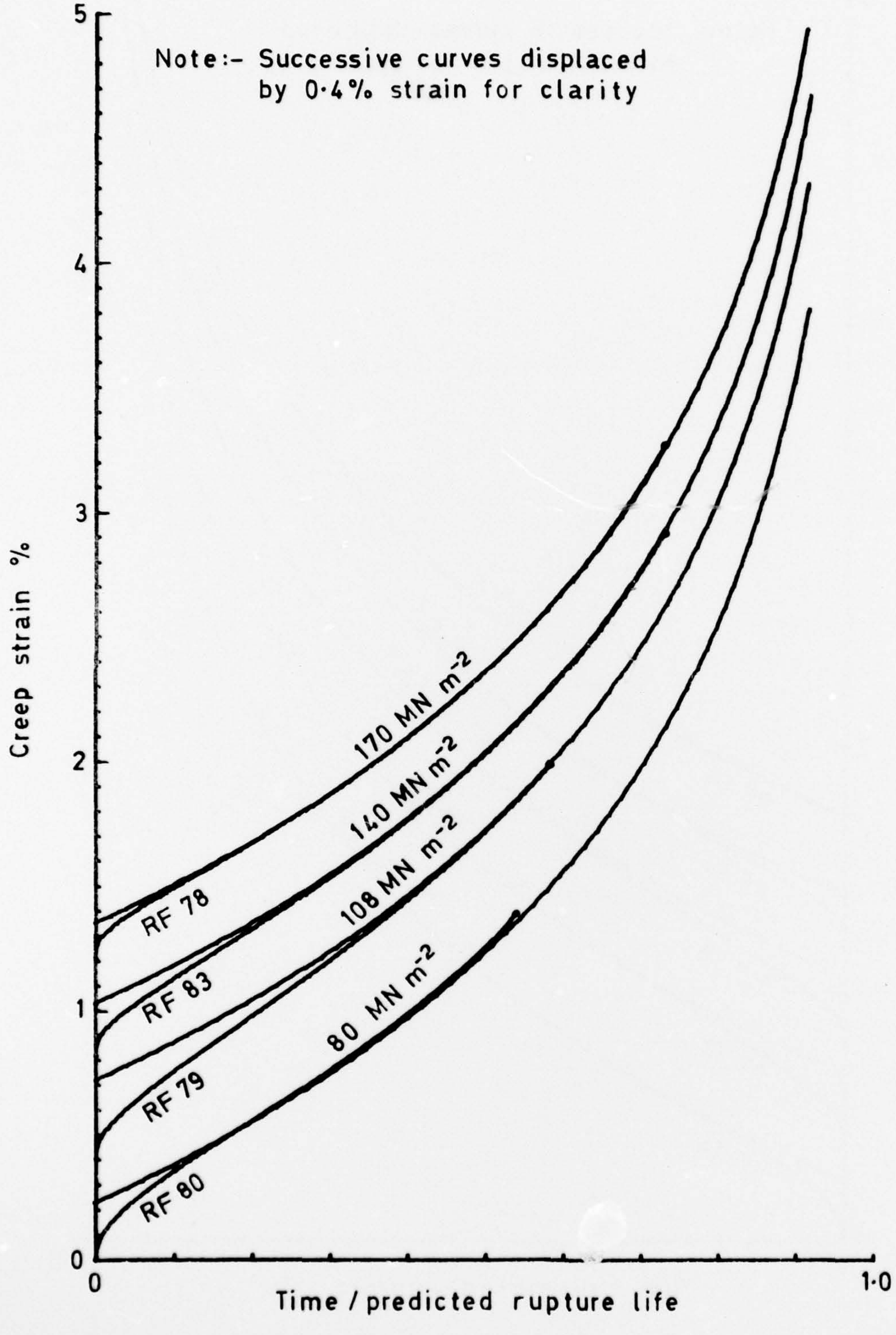

Fig. 32 Comparison of creep curves with modified "steady state" relationship at 195°C

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Webb, J. N.

A STRAIN MODIFIED 'STEADY-STATE' CREEP RELATIONSHIP FOR HIGH STRENGTH ALUMINIUM ALLOY

The concept that creep response is the result of a transient approach to a minimum strain rate continuously modified by accumulating damage has been investigated using high precision creep data. It was considered that the accumulated creep strain might be some measure of internal damage and curves of log creep strain rate against creep strain are shown to exhibit linearity at higher strain levels consistent with these assumptions. A modified 'steady-state' relationship has been derived and the variation of its two coefficients with stress and temperature explored.

The effect of load and temperature history is illustrated by varying the prior heating time, by cyclic load testing and by step reductions in load level, and it is tentatively concluded that tests of these types may be correlated with the appropriate continuous creep test by using the modified 'steady-state' relationship with corrections for differences in accumulated creep strain and time at temperature.

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