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CURRENT PAPERS

A Parameter to Represent the Mechanical Properties of Aluminium Alloys after Soaking at Elevated Temperatures

by

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Addendum to
Technical Note No. Structures 270

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ROYAL AIRCRAFT ESTABLISHMENT

CALCULATION OF CUMULATIVE EFFECTS FROM SOAKING AT TWO OR MORE TEMPERATURES

SUMMARY

It is shown that, if the hypothesis of over-ageing as a combined time-temperature effect is correct, a simple cumulative rule follows for the total combined over-ageing effect after heating at a number of different temperatures.

A recently published I.A.S. paper, by Cord & Burns, provides experimental verification of this rule for the alloy 2024 - T81.

TWO SOAK TEMPERATURES T_1 AND T_2

(1) The hypothesis assumes that, if the material is heated at T_1 for a time t_1 hours and then at temperature T_2 for t_2 hours, the same final state (and hence the same room temperature 0·1% proof strength and ultimate strength) is obtained irrespective of the order of heating; further, that the heating times can be 'programmed' in fractions of t_1 and t_2, and the result will still be the same when the total times amount to t_1 and t_2 respectively.

(2) By plotting against $\log_{10} t$ instead of $\frac{8600}{T} - \log_{10} t$, the parametric plot of Fig.4 can be split into two exactly similar over-ageing curves, one for T_1 and the other for T_2, displaced horizontally by a distance $8600\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$ - see Fig.A1.

(3) Three conditions or 'states' of the material, as defined by the room temperature 0·1% proof stress f, will be considered:

Condition 'o' before heating, defined by P.S. fo
Condition 'B', after heating, defined by P.S.fB
Condition 'A', any intermediate condition, P.S. fA

(4) The diagram, Fig.A1, shows that, starting with the condition fo, the ratio of the soaking time to reach condition fA to the time taken at the same temperature to reach condition B is independent of the soak temperature.

(5) Let the time t_1A to reach condition A by heating at T_1 be xt_1B where t_1B is the time to reach condition B.

Then the time t'_2B to transform from condition A to condition B at T_2 will be $(1 - x)\ T_{2B}$.

(Changes in temperature are assumed to be virtually instantaneous).

Thus the sum of the time ratios $\frac{t_1A}{t_1B} + \frac{t'_2B}{t_2B}$

$= x + 1 - x = 1.$

MULTI-STAGE HEATING

The above simple rule can be readily extended to cases of 3, 4 or more heating temperatures, giving

$$\Sigma_i \frac{ti}{tiB} = 1$$ [*]

for the transformation from condition 0 to condition B where each $\frac{t}{tB}$ is the ratio of actual heating time at a given temperature to the heating time at that temperature to transform from 0 to B.

If $\Sigma\ {}^{t}/t_B > 1$ the strength will be lower than at condition B,

if $\Sigma\ {}^{t}/t_B < 1$ the strength will be greater than at condition B.

The same rule must also apply for a specified reduction in ultimate strength at room temperature.

SUPPORTING EXPERIMENTAL EVIDENCE

The above rule for cumulative deterioration has been deduced on the hypothesis of equivalent time-temperature effects, suggested by the results on DTD364 and RR58 clad sheet.

In a recent paper,[**] J.M. Cord and A. Bruce Burns have suggested the same rule on empirical grounds, and have done heating tests on an American alloy, 2024 - T81, at three successive temperatures. The results of these tests verify that, within the limits of experimental error, the rule does indeed apply to that alloy. They thus provide a convincing verification of the over-ageing hypothesis suggested here.

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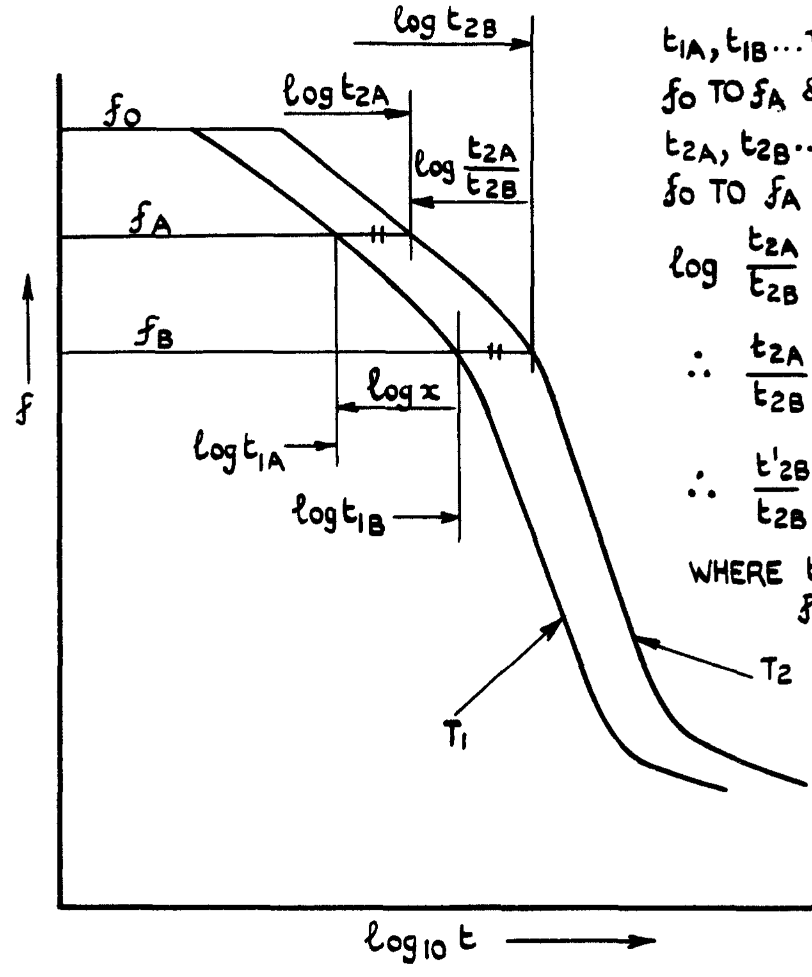
[*] Cf. the Palmgren-Miner Cumulative Rule for fatigue damage.

$$\Sigma\ {}^{n}/_{N} = 1$$

[**] 'Some Aspects of Designing Aluminium Structures for Thermal Environments' by J.M. Cord and A. Bruce Burns. Inst. of the Aeronautical Sciences, I.A.S. Paper No. 60 - 7 (I.A.S. 28th Ann. Meeting, New York, January, 1960).



t_{1A}, t_{1B} ... TIMES TO OVER-AGE FROM f_0 TO f_A & f_B AT T_1

t_{2A}, t_{2B} ... TIMES TO OVER-AGE FROM f_0 TO f_A & f_B AT T_2

$$\log \frac{t_{2A}}{t_{2B}} = \log \frac{t_{1A}}{t_{1B}} = \log x$$

$$\therefore \frac{t_{2A}}{t_{2B}} = \frac{t_{1A}}{t_{1B}} = x$$

$$\therefore \frac{t'_{2B}}{t_{2B}} = \frac{t_{2B} - t_{2A}}{t_{2B}} = 1 - x$$

WHERE t'_{2B} = TIME TO OVER-AGE FROM f_A TO f_B AT TEMP. T_2

FIG. A 1. COMBINED OVER-AGEING AT TWO DIFFERENT TEMPERATURES.

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ROYAL AIRCRAFT ESTABLISHMENT

A PARAMETER TO REPRESENT THE MECHANICAL PROPERTIES OF ALUMINIUM ALLOYS AFTER SOAKING AT ELEVATED TEMPERATURES

by

W. A. P. Fisher, B.A., A.F.R.Ae.S.

SUMMARY

Test data on the tensile mechanical properties of two structural aluminium alloys after heating for long periods at fixed temperatures are correlated on the assumption that the degree of over-ageing can be expressed by the value of the 0.1 per cent proof stress at room temperature after heating.

Rate process theory is applied to show that the time t (hours) and the absolute temperature T (°K) are related by the formula $T (C + \log_{10} t) = B$, where B has the same value for various conditions of over-ageing, but the term C is a single-valued function of the condition.

Curves are plotted for RR.58 clad sheet showing the change in proof stress, at room temperature and at the soak temperature, for fixed times at various 'soak' temperatures.

By using the above formula, extrapolated curves for 10^4 hours or longer can be obtained. This affords a basis for advance project study for the employment of this or other aluminium alloys for supersonic aircraft.

The value of the activation energy for the over-ageing process is deduced.

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1 INTRODUCTION

Both ferrous and non-ferrous alloys may require heat treatment so as to give them the mechanical properties suitable for any particular application. Alloy steels, for example, are quenched from a high temperature, resulting in a very high-strength product but with low ductility and toughness. A second heat treatment at a lower temperature, known as 'tempering' is usually required to give a product with sufficient toughness.

The class of aluminium alloys known as 'double heat treatment alloys' behave quite differently. The 'solution' treatment (soaking at a high temperature and then quenching) produces a low-strength, highly ductile condition. To obtain maximum strength properties (particularly necessary for aircraft structures) the material is subjected to a 'precipitation' treatment (i.e. artificial ageing) by soaking at a temperature in the 150-200°C range for a period of up to 20 hours as specified. The precipitation of crystals formed by combination of solute atoms with the principal constituent metal - e.g., $Cu\,Al_2$ - forms internal barriers against slip. If the soaking is continued too long, however, these precipitates will start to redissolve and the atoms will be redistributed by diffusion. The physical effect is a progressive deterioration in strength, known as over-ageing. Similarly, the tempering of steel, if done at too high a temperature or too long a time, can result in a serious loss of strength with no compensating advantages.

For structural aluminium alloys, when over-aged, the degree of over-ageing is shown by the alteration of the stress-strain curve at room temperature. Thus the 'recovery' 0.1% proof stress (i.e., the value determined at room temperature after prolonged soaking at high temperature) may be used to define the degree of over-ageing.

Despite the great complexity of the metallurgical processes involved, test results show that the time-temperature relationship conforms with a simple pattern.

By the application of 'rate process' theory, a method for extrapolating test data has been developed and applied to data for RR.58 clad sheet.

2 RATE-PROCESS THEORY APPLIED TO OVER-AGEING

Tempering and over-ageing are both examples of the same type of process, a chemical process governed by rate of diffusion. The diffusion rate of atoms in solid solution is an exponential function of T the absolute temperature and of a quantity known as the 'activation energy' Q, which has a fixed value for a given element.

Thus, if r denotes the reaction rate, the following relationship holds

$$r = A.\exp\left(-\frac{Q}{RT}\right) \qquad (1)$$

where A is a constant and R is the universal gas constant. Equation (1) is derived from the Boltzmann equation, the derivation of which is given in standard works on statistical mechanics.

Let f_1 be the 0.1% proof stress at room temperature (22°C) after soaking for t hours at a temperature T (°K). For a fixed straining rate, the value of f_1 defines the metallurgical condition, and because of (1) it follows that f_1 is a function of the parameter $t.e^{-Q/RT}$, analogous to the Dorn parameter for creep.

It is shown in Appendix 1 that, in consequence, the time t and the temperature T required for producing the condition defined by f_1 are related by the equation

$$T\left[\phi(f_1) + \log_{10} t\right] = \frac{Q}{R}\log_{10} e \tag{2}$$

where $\phi(f_1)$ is a function which has a fixed value for a given degree of over-ageing.

Hence, for a fixed value of f_1 we can write

$$T\,(C + \log_{10} t) = B \tag{3}$$

where $B = \frac{Q}{R}\log_{10} e$, which is independent of time and temperature*, and C has a fixed value.

Therefore, if soaking for t_1 hours at a temperature T_1 produces the same over-ageing as soaking for t_2 hours at temperature T_2, then

$$T_1\,(C + \log_{10} t_1) = T_2\,(C + \log_{10} t_2) \tag{4}$$

Equation (2) shows that if f_1 for various times and temperatures is plotted against $\frac{B}{T} - \log_{10} t$, the points should all fall on a single curve.

3 APPLICATION OF THEORY TO ALUMINIUM ALLOY TO D.T.D.364.B

Fig. 1 shows room temperature (or 'recovery') stress strain curves[1] after various soaking times at (1) 170°C and (2) 252°C. It will be seen that the resemblance between the curves for 1,000 hours soak at 170°C and for 1 hour soak at 252°C is remarkable, suggesting that the two sets of soaking conditions did in fact produce the same metallurgical state.

Let this condition be identified as 'condition (a)'. In terms of the room temperature mechanical properties, it represents a drop of $22\frac{1}{2}\%$ in the 0.1% proof stress. Assuming that, when soak time and temperature are varied, if the same metallurgical condition of over-ageing is produced, the value of $T\,(C + \log_{10} t)$ is the same, it is possible to calculate the constant C.

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* Unless the temperature is so high that the mechanism of over-ageing is radically changed.

Thus

$$T_1 = 170 + 273 = 443 \ ^\circ K$$

$$T_2 = 252 + 273 = 525 \ ^\circ K$$

$$t_1 = 1{,}000 \qquad \log t_1 = 3$$

$$t_2 = 1 \qquad \log t_2 = 0$$

If

$$T_1 (C + \log_{10} t_1) = T_2 (C + \log_{10} t_2)$$

$$443 (3 + C) = 525 (0 + C)$$

giving

$$\underline{C = 16{\cdot}2}$$

whence

$$B = T (C + \log_{10} t) = 8{,}500$$

As the tests were made at two temperatures only, the results cannot be generalised by curve plotting. However, assuming $T (16{\cdot}2 + \log_{10} t)$ to be constant for condition (a) log t can be plotted against T.

Then, for a temperature T °K

$$T (16{\cdot}2 + \log t) = 8{,}500$$

e.g. when $T = (130 + 273)$, $\log t = 4{\cdot}85$ or $t = 71{,}000$ hours (point X, Fig. 2).

A similar extrapolation can be made for the condition shown by the stress-strain curve (Fig. 1) obtained after 100 hours' soak at 170°C. This shows a reduction in proof stress as compared with the unheated material of about 1 ton/in^2 or $3\frac{1}{3}$%. Call this condition (d) and let the corresponding value of C be C_d.

Now, $T = 273 + 170 = 443$, $\log_{10} t = 2$ and $B = 8{,}500$,

giving

$$\underline{C_d = 17{\cdot}2}$$

To determine the soak time t_d for any temperature in the range 100-190°C which would give the condition (d) we have

$$\log_{10} t_d = \frac{8{,}500}{T} - 17{\cdot}2$$

where T = temperature °K, which gives the values below:-

T°C	100	130	150	170	190
T°K	373	393	423	443	463
log t_d	5·6	3·8	2·8	2	1·15
t_d (hrs)	398,000	6,300	632	100	14·1

These values are plotted as curve (d) in Fig. 2.

It was felt that tests to confirm predicted times for conditions (a) and (d) were necessary to substantiate these predictions. Unfortunately, however, no spare material of this batch was to be had. Interest was therefore turned to a series of tests by Metallurgy Department, R.A.E., on clad sheet to Specification RR.58 (now covered by D.T.D.5070). These tests, being more comprehensive, showed better possibilities of correlation and of testing the theory outlined above.

4 APPLICATION OF THE THEORY TO CO-ORDINATION OF TEST RESULTS FOR RR.58 CLAD SHEET

Test results

Ref. 2 gives the variation with soaking time and temperature of the principal mechanical properties - 0·1%, 0·2% and 0·5% proof stresses, U.T.S., etc. As a convenient measure of the degree of over-ageing, the 0·1% proof stress in tension is chosen.

4.1 Plotting of room temperature values

The recovery values of 0·1% proof stress in tension after 1, 200 and 1,000 hours soak times at 100°, 150°, 200°, 250° and 300°C are shown in Table 1. They are plotted in Fig. 3 as large circles.

With such wide intervals of temperature, it would seem at first sight that the exact form of the curves for 1, 200 and 1,000 hours respectively would be indeterminate. But if it be assumed that for any given material condition (defined by a fixed value of the 0·1% proof stress at room temperature) $T(C + \log_{10} t)$ has a fixed value, the fitting of the curves to the test data is facilitated, though it is still necessary to use a 'trial and error' procedure.

In Fig. 4, these same results are used for plotting f_1 against the parameter

$$\frac{8600}{T} - \log_{10} t$$

(Reasons for taking B = 8600 are given later).

It will be seen that the results for 150°, 200° and 250° fall on a single curve, as predicted by theory (see end of para.2). Results for 100°C are omitted as over-ageing had not occurred. For 300°C, the results do not quite conform, though the value for 1 hour might do so having regard to the fact that some part of the heating-up time should be added to the short soak time. This temperature region, however, is of little practical importance in view of the very low strengths reached.

Values of C and the fixed value of B depend, of course, on how the curves in Fig. 3 are drawn. To conform with Fig. 4, these curves would seem to have three sharp breaks. The first corresponds to the threshold of over-ageing. It seems likely that each of the other two breaks indicates some important change in the mechanism of deterioration*.

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* For temperatures above the prior ageing temperature the same value of f_1 may not necessarily indicate quite the same metallurgical condition.

A calculation of the constant B for the tests on RR.58 clad sheet is given in Appendix 1. Also, values of C corresponding to the levels of f_1 indicated in Fig.3 are computed and tabulated.

For the 'threshold of over-ageing', C = 18 and a value B = 8600 is computed (equation 6, Appendix 1).

4.2 Extrapolation of room temperature values

The extrapolated curves for 1, 50 and 10,000 hours have been plotted using the relation $T_1 (C + \log_{10} t_1) = T_2 (C + \log_{10} t_2)$ and the tabulated values of C.

Example: To determine the soak temperature at which over-ageing commences after 10,000 hours. Let this temperature be T°K.

Point E in Fig.3 gives

$$\log_{10} t = \log_{10} 200 = 2{\cdot}301 \text{ when}$$

$$T = 273+150 = 423°K = T_1 (\text{say}) .$$

We wish to find the temperature T_2 such that

$$T_2 (18 + \log_{10} t_2) = T_1 (18 + 2{\cdot}301)$$

when $$t_2 = 10^4 .$$

Thus

$$T_2 = T_1 \times \frac{20{\cdot}301}{22} = 390°K = \underline{117°C} .$$

This gives point G in Fig.3 for 10,000 hours.

Further points (e.g. W and O) each for a specified drop in proof stress are obtained by a similar process, using the appropriate value of C (see Appendix 1 or Fig.4).

The same equation serves to extrapolate back to shorter times (points D, R and L for 50 hours soak), though in practice it saves much testing time to determine these values experimentally and use the extrapolation for predicting the effect of very long times.

4.3 Plotting of proof stress at soak temperature

The test data are given in Table 2. They are plotted on Fig.5 as large triangles, to the same stress and temperature scales as the room temperature values in Fig.3.

It is to be supposed that the onset of over-ageing will produce an 'elbow' in the lower curves at the same temperatures and soak times as those shown by the room temperature values. Thus the points E and F (taken from Fig.3) which show the temperatures for the threshold of over-ageing after 200 hours and 1,000 hours respectively, are key points for the proper delineation of the curves for soak temperatures, because they indicate the 'threshold of over-ageing' after these soak times. The point E' in the lower diagram corresponds to E, likewise F' to F. The line A F' E' gives the properties before over-ageing, and the steeply dipping lines correspond to over-ageing.

4.4 Extrapolation of 'soak temperature' results

If the room temperature curves and the 'soak temperature' curves are plotted on one and the same diagram, as in Fig.6, it is easily seen that a point on a 'soak temperature' curve represents the same material condition as the point vertically above it for the same soak time in the room temperature diagram. Thus points on the extrapolated curves of the latter give corresponding points in the soak temperature diagram.

If A F' E' be extended to C' (corresponding to C in the upper diagram, i.e., 1 hour soak) points C' D' E' F' and G' show the positions of the 'elbow' in the lower diagram, i.e. the 'threshold of over-ageing', after 1, 50, 200, 1,000 and 10,000 hours respectively. A F' E' is assumed to be straight in the absence of evidence to the contrary.

Now that the starting-points of the over-ageing curves in the 'soak temperature' diagram have been determined, it remains to determine the over-ageing curves themselves. On Fig.6 a stress level is chosen such as $f_1 = 24{\cdot}3$ tons/in^2, representing, by hypothesis, a definite condition of over-ageing. The line $f_1 = 24{\cdot}3$ cuts the experimental room temperature curves for 200 hours and 1,000 hours at P and Q respectively. Thus P and Q are 'corresponding' points.* A perpendicular is dropped from P intersecting the 200 hour 'soak temperature' curve at P', and another from Q intersecting the 1,000 hour 'soak temperature' curve at Q'. Then P and P' are corresponding points, and so are Q and Q'. Thus the material condition is the same for P' and Q'. The line P' Q' is extended in both directions, giving a curve of 0·1% proof stress against temperature for the condition of over-ageing defined by $f_1 = 24{\cdot}3$. The horizontal line PQ in the upper diagram is also extended, crossing the extrapolated curves at points W and R marked by a square. Projecting vertically from these points, the intersections with P' Q' extended are also marked by a square, all being corresponding points. Thus a point on the 50 hour soak curve and one on the 10,000 hour soak curve are obtained. The process is repeated for a lower value, defined by points M and N ($f_1 = 21{\cdot}7$) and the inverted triangles. The curve M' N' is a further curve of constant over-ageing, as defined by $f_1 = 21{\cdot}7$. The intersections O' L' of the ordinates from O and L with the extrapolated curve M' N' give the points corresponding to O and L, i.e. for 10^4 hours and 50 hours soak tested at the respective soak temperatures. The curves for 50 hours (L' R' D') and for 10,000 hours (O' W' G') can now be drawn.

5 MODE OF PRESENTATION

(a) Properties at soak temperature

Fig.7 (obtained by cross-plotting from Fig.6) is a plot of proof stress (at soak temperature) against log t for various temperatures. For any particular temperature, the curve consists of two portions, one virtually straight and horizontal, the other sloping. The intersection of these gives the threshold of over-ageing. The test conditions, shown plotted as triangles

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* i.e. by hypothesis the time-and-temperature combination for P produces the same state as the time-and-temperature combination for Q.

(as in Fig.5) indicate the extent of extrapolation, to longer and to shorter times. Extrapolation back to 1 hour (i.e., log t = 0) is somewhat extreme on the basis of so restricted data, and might well be in error by several hours at 200°C.

It seems probable that at temperatures just above 200°C there is a change in the mechanism of the over-ageing process, coupled probably with a change in the activation energy and of the constant B in the extrapolation formula. This is of theoretical, rather than practical interest, except for lives of comparatively short duration.

(b) Properties at any other temperature

Fig.7 shows the proof strengths at the soak temperature only. If the proof strength at some other temperature is required, the family of curves typified by P' Q' and M' N' in Fig.6 must be used. Each such curve shows the variation of proof stress with temperature for a fixed degree of over-ageing. From Fig.6 the cumulative 'soak damage' can be determined for soaking at more than one temperature, e.g., 50 hours' soak at 180°C has the same damaging effect as 1,000 hours' soak at 150°C. Furthermore, the points C' D' E' F' and G' are related by the same formula as C, D, E, F, and G, namely $T\ (18 + \log_{10} t) = 8600$.

6 EFFECT OF PRIOR PRECIPITATION TREATMENT

The quoted precipitation treatment for this batch of material is 10 hours' soak at 200°C. The 10 hours is the total heating time, not time actually at temperature. The latter could be only 2-4 hours for a full furnace load, or as long as 8 hours with light loading, and the tensile properties "as received" could vary on this account. The control specimens for this batch gave a 0·1% proof stress "as received" of 25·3 tons/in^2 compared with a minimum specification value of 20 tons/in^2, indicating that the heat treatment must have been such as to produce optimum strength.

Had the material been "under-aged" a considerable rise in strength would have been expected before the onset of over-ageing. As seen from Fig.3, a rise of only 0·2 tons/in^2 was observed.

As already indicated, the changes in substructure which cause these changes in strength are governed by an integrated time-temperature function, the integration being from the solutionised condition. For this material, any "natural" ageing at room temperature can be neglected. So the full soaking effect is really that sustained in the test plus that given in the production heat treatment. The pattern of curves could, in fact, be fitted equally well to the total soaking time by a small change in the value of the constant C (e.g., from C = 17 to C = 16·7). The change would scarcely affect the agreement with the experimental points, and the correction to the extrapolation for long soak times would be negligible, because the effect of small errors in C becomes less and less as log t increases.

7 THE ACTIVATION ENERGY Q

The quantity $\frac{Q \log_{10} e}{R}$ determined from the test data is the same for the two materials within the accuracy of the tests (8,500 for D.T.D. 364B and 8,600 for RR.58 clad sheet).

R, the gas constant, is 1·987 calories per degree Centigrade per mole.

So, if $\frac{Q}{R}\log_{10} e = 8600$, $Q = 39,000$ cal per °C per gram atom. Q could have been determined more accurately if curves for shorter soak time (e.g., 50 hours) had been available.

It is interesting to note that the above value of the activation energy agrees closely with that found directly for the diffusion of copper in aluminium for a 4% copper in aluminium alloy, namely 41,900 calories per gram atom. If allowance were made for the lower percentage (2·2%) of copper in RR58, the agreement should be even better.

8 VERIFICATION OF HYPOTHESIS

The hypothesis on which this correlation depends requires full experimental confirmation before it can be accepted as a theory. Unfortunately, confirmation by the performance of extra tests on the same batch of material was not practicable as there was non left. As a guide to the planning of future tests, a testing scheme is suggested in the table below. From the 'ad hoc' aspect, this scheme would be advantageous in three ways:-

(a) Short-time soak tests would provide a quick check on the condition of the material.

(b) The results of the long-term tests could be predicted long before they have been done.

(c) The results would be applicable not only to the limited test conditions but to all combinations of time and temperature from 100° to 250°C.

	Soak temperature °C					
	100	125	150	175	200	250
Soak times (hour)			10	10	10	10
		100	100	100	100	100
	1000	1000	1000	1000	1000	
	10^4	10^4	10^4	10^4		

Test at (a) Soak temperature.

(b) Room temperature.

(c) Selected temperatures above or below soak temperature.

The 100 hour tests are considered preferable to the 200 hours made in the tests reported here. The extra tests proposed have been marked 'x' in Fig. 7. The tests designated (c) would define the curves for proof stress against test temperature for a given soak condition (see curves P' Q' and M' N' in Fig. 6).

The above testing scheme is recommended for any other alloys of this general type.

9 PRACTICAL SIGNIFICANCE OF THE RESULTS: EXTRAPOLATION

A systematic interpretation of soaking effects such as this can save an enormous amount of testing work. Particularly valuable is the ability to predict the effects of prolonged soaking on the mechanical properties. Although the 0·1% proof stress (σ at soak temperature and f_1 after return to room temperature) is the property of main interest to the designer, it is the ability to predict the complete stress-strain curve that is a really new and advantageous development. It would be easy to design a series of tests to give a family of stress-strain curves such as shown partly in Fig.1, and according to the present evidence, each of these curves would be associated with a particular value of f_1.

Of primary importance is the soak time at a given temperature for the commencement of over-ageing. But also, after over-ageing has begun, cumulative effects of heating at two or more temperatures can be easily computed, because time-temperature effects can be transposed from one temperature to another.

10 REDUCTION OF TEST VALUES TO MATERIAL WITH MINIMUM SPECIFICATION PROPERTIES

Design is always based on the minimum strength allowed by the specification. For design cases where the material is subjected to prolonged soaking at elevated temperature and is loaded at that temperature, the designer needs to know what reductions in strength and in stiffness must be allowed. When the effects of time at temperature have been found for a given batch of material to a particular specification, there still remains the problem of estimating the soak properties for a batch which only just meets the specification. When it is considered that the strength of a sample before heating depends on

(a) variations in composition,

(b) variations in actual heating time, and tolerances on the precipitation temperature, and

(c) cold working (which is not ruled out by the specification), it can be readily appreciated that there is no simple conversion rule. Each of the above variables will produce a different mode of behaviour on soaking. The approach to this problem should be made in two steps: first, the effect of elevated temperature only; second, the further depreciation in properties due to soaking time, which is dependent on over-ageing.

It would seem that the amount of the correction factor could be minimised if extra cold working (which is fundamentally undesirable) were rendered unnecessary by improved heat treatment and if the precipitation temperature were adjusted so that the usual industrial tolerances had the minimum effect. In particular, it is important to ensure that the precipitation treatment can, in no circumstances, pass the 'threshold of over-ageing'.

11 INDICATIONS FOR FURTHER RESEARCH

The agreement of the over-ageing process with a "Dorn" type of parameter confirms the supposition that it is a "rate process", i.e., a reaction involving an activation energy. This opens up a wide field of enquiry directly related to the limitations of these alloys for elevated temperature use.

What is the effect of over-ageing on creep, and conversely, what effect, if any, does creep have on over-ageing? Creep times to rupture, or to a given strain, for similar alloys, at temperatures where over-ageing would be in operation, have been shown to conform with the parameter $T(17 + \log_{10} t)$. Kauzmann[3] has explained this on the theory that secondary creep is itself a "rate process". It is clear that there is a close connection. The effect of applied stress on over-ageing time needs to be investigated on both theoretical and practical grounds.

12 CONCLUSIONS

Test data for aluminium alloy to D.T.D. 364B indicate that the same material condition can be obtained by widely different combinations of soak temperature and time. This is in accordance with chemical-rate theory applied to over-ageing as a "rate" process.

Taking the room temperature 0·1% proof stress after soaking at a given temperature and time as a measure of the material condition, it is shown that for a given change in condition the soak time t(hours) and absolute temperature T are related by the formula $T(C + \log_{10} t) = B$ where B is a constant. C, being a function of the condition only, has a fixed value for a given condition, as defined by the proof stress at room temperature.

By plotting the proof stress at room temperature and at soak temperature for a series of tests on clad sheet to Specification RR58, it is found that the results can be correlated by the above formula and the constant B determined. By applying this formula, a diagram is obtained covering all time and temperature combinations of practical interest. This enables both the room temperature properties and those at soak temperature to be predicted for extended soak times, e.g., for 30,000 hours. In addition, the cumulative effect of soaking at several temperatures can be estimated.

This affords a basis for advance project study for the employment of this or other aluminium alloys for supersonic aircraft.

The activation energy is found to be approximately 39,000 calories per °C per gram atom. This value agrees closely with the activation energy for diffusion of copper in aluminium. It would be advisable to arrange any further testing work so as to eliminate the necessity of producing curves by "eye", to give greater accuracy by using wider time intervals, and to provide numerous cross checks.

The effect of over-ageing on creep and the effect (if any) of creep on over-ageing require investigating.

The proof stresses given here for clad sheet to Specification RR58 must not be regarded as typical of material to D.T.D.5070 in production. They were obtained for material made as an experimental sample under specially controlled conditions, and are likely to be higher than those for material made in regular production.

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Ref. No.	Author(s)	Title, etc.
1	Wright, D. F., Thomas, K.	The strength at room temperature of an aluminium alloy bar material to Specification D.T.D. 364B after heating at two temperatures for various periods of time. R.A.E. Technical Note No. Structures 256, Fig. 16. March, 1959.
2	Hayward, D. C.	The mechanical properties of RR.58 aluminium alloy sheet (clad) in tension and compression at room and elevated temperatures. R.A.E. Technical Note No. Mat. 261 April, 1957.
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APPENDIX 1

DERIVATION OF FORMULA AND METHOD OF EXTRAPOLATION

Let f_1 be the 0.1% proof stress at room temperature (22°C) after soaking for t hours at a temperature T °K.

On the hypothesis that the room temperature mechanical properties, as functions of the degree of over-ageing, are governed by a chemical rate process of atom diffusion,

$$f_1 = F'\left\{ \int_0^t (\text{rate of diffusion})\, dt \right\} \qquad (1)$$

$$= F\left\{ \int_0^t e^{-\frac{Q}{RT}}\, dt \right\} \qquad (2)$$

Q being the activation energy of diffusion

and R the Universal Gas Constant.

If T is constant over the time period t

$$f_1 = F\left(te^{-\frac{Q}{RT}} \right) \qquad (3)$$

The product $te^{-\frac{Q}{RT}}$ is known as the Dorn parameter, which has been applied to creep data,

For soaking at a constant temperature T (°K), to a fixed value of f_1

$$te^{-\frac{Q}{RT}} = \psi(f_1)$$

or

$$\log_{10} t - \frac{Q \log_{10} e}{RT} = \phi(f_1) \qquad \text{(say)}$$

i.e.

$$T[\, \phi(f_1) + \log t\,] = \frac{Q \log_{10} e}{R} \qquad (4)$$

the right hand side of (4), being independent of f_1, has a fixed value, B (say).

For a definite value of f_1, let $\phi(f_1) = C$.

Then

$$T\ (C + \log t) = B \tag{5}$$

Thus for a fixed f_1 T and log t are related in a similar way to that given by parameters of the Larson-Miller type. For different values of f_1, $T\ (C + \log_{10} t)$ keeps the same value B but C changes.

If test data for different times and temperature define curves for f_1 against T for constant t, the value of C can be found for any given value of f_1 e.g. from Fig. 3 for $f_1 = 25{\cdot}3$ Tons/in^2.

If the material is at the threshold of over-ageing,

when $t = 200$ hours (point E) $T = 423$

when $t = 1000$ hours (point F) $T = 409$

By substituting in (5) it is found that $\underline{C = 18{\cdot}0}$

Denote this value by C_1.

Substituting 18·0 for (f_1) in (4) gives

$$\underline{B = 8600} \tag{6}$$

In Fig. 3 the horizontal line UPQW shows the variation of T with t for $f_1 = 24{\cdot}3$ tons/in^2.

The experimental point Q gives for $t = 100^\circ$

$$T = 273 + 150 = 423.$$

Denoting the new value of C by C_2

$$C_2 + 3 = \frac{8600}{423} \quad \therefore \underline{C_2 = 17{\cdot}3}$$

The next lower line LMNO is for $f_1 = 21{\cdot}7$ tons/in^2.

From the experimental point M we have

$$\text{when } t = 200 \text{ hours} \quad T = 273 = 200 = 473$$

whence

$$\underline{C_3 = 15.9}$$

The experimental point X, for

$t = 200$, $T = 523$ corresponds to $f_1 = 10{\cdot}5$ tons/in^2

Denoting the new value of C by C_4 we get $\underline{C_4 = 14{\cdot}2}$.

Similarly for $f_1 = 4{\cdot}4$, $C_5 = 13{\cdot}4$.

The above values of C are tabulated below:

f_1	25·6	24·3	21·7	10·5	4·4
C	18·0	17·3	15·9	14·1	13·4

For any chosen f_1 the results can now be extrapolated to a time of 10,000 hours or more and also to 50 hours or less, as shown in Fig. 3.

It seems unlikely that the same value of B (i.e. 8,600) will apply to temperatures between 200° and 300°C, which produce severe over-ageing. Hence the values for C_4 and C_5 are questionable. Though the use of these values might lead to considerable errors in extrapolating (say) from 10 hours to 10^4 hours, the error for a factor of 10 in time (i.e. unit change in log t) is small, provided the value of C is determined from well-defined experimental curves.

APPENDIX 2

EXTRACTS FROM MATERIAL SPECIFICATIONS

(a) Extracts from Specification D.T.D. 364B for Extruded Sections 1" in thickness and greater

D.T.D. 364B is an aluminium alloy bar material having the following chemical composition:-

Copper - not less than 3·5% nor more than 4·8%.

Silicon - not more than 1·5%.

Magnesium - not less than 0·3% nor more than 0·6%.

Manganese - not less than 0·4% nor more than 1·2%.

Iron - not more than 1·0%.

Titanium - not more than 0·3%.

D.T.D. 364B shall have the following minimum mechanical properties:-

0·1% proof stress - not less than 28 tons/sq in. (62,720 lb/sq in.).

Ultimate tensile strength - not less than 32 tons/sq in. (71,680 lb/sq in.).

Elongation - not less than 8%.

The heat treatment shall consist of the bars being heated uniformly at a temperature of 510° ±5°C and be quenched in water or oil. Ageing shall be at temperatures between 155°C and 205°C for the requisite period.

(b) Extracts from Specification D.T.D. 5070 (RR.58) for Aluminium Alloy Sheets

D.T.D. 5070 is an aluminium alloy sheet material having the following chemical composition:-

Copper - Not less than 1·8% nor more than 2·7%.

Magnesium - not less than 1·2% nor more than 1·8%.

Silicon - not more than 0·25%.

Iron - not less than 0·9% nor more than 1·4%.

Manganese - not more than 0·2%.

Nickel - not less than 0·8% nore more than 1·4%.

Zinc - not more than 0·1%

Lead - not more than 0·05%.

Tin - not more than 0·05%

Titanium - not more than 0·2%

Aluminium - Remainder

D.T.D. 5070 (RR.58) shall have the following minimum mechanical properties:-

0·1% proof stress - not less than 20 tons/sq in. (44,800 lb/sq in.).

Ultimate tensile stress - not less than 25 tons/sq in. (56,000 lb/sq in.).

Elongation - not less than 6%.

Heat treatment in solution - treat at 530° ±5°C.

Quench in water not exceeding 40°C.

Precipitation treat at 200° ±5°C for 5 to 20 hours.

TABLE 1

f_1 = Tensile 0·1% proof stress of RR.58 sheet aluminium alloy (clad) at room temperature after 1, 200, and 1,000 hours at various temperatures

Temp °C	Soaking Time (hours)	f_1
100	1	25·3
	200	25·3
	1000	25·3
150	1	25·4
	200	25·3
	1000	24·3
200	1	25·3
	200	21·7
	1000	20·4
250	1	23·0
	200	10·5
	1000	4·3
300	1	14·9
	200	4·75
	1000	3·9

TABLE 2

Tensile properties of RR.58 sheet

Aluminium alloy (clad) at elevated temperatures

Temp °C	Soaking Time (hours)	0·1% Proof Stress
100	1	23·5
	200	23·8
	1000	23·8
150	1	20·7
	200	21·1
	1000	20·3
200	1	16·7*
	200	15·4
	1000	14·5
250	1	12·0
	200	7.3
	1000	3·6
300	1	7·5
	200	2·5
	1000	2·0

* Questionable value.

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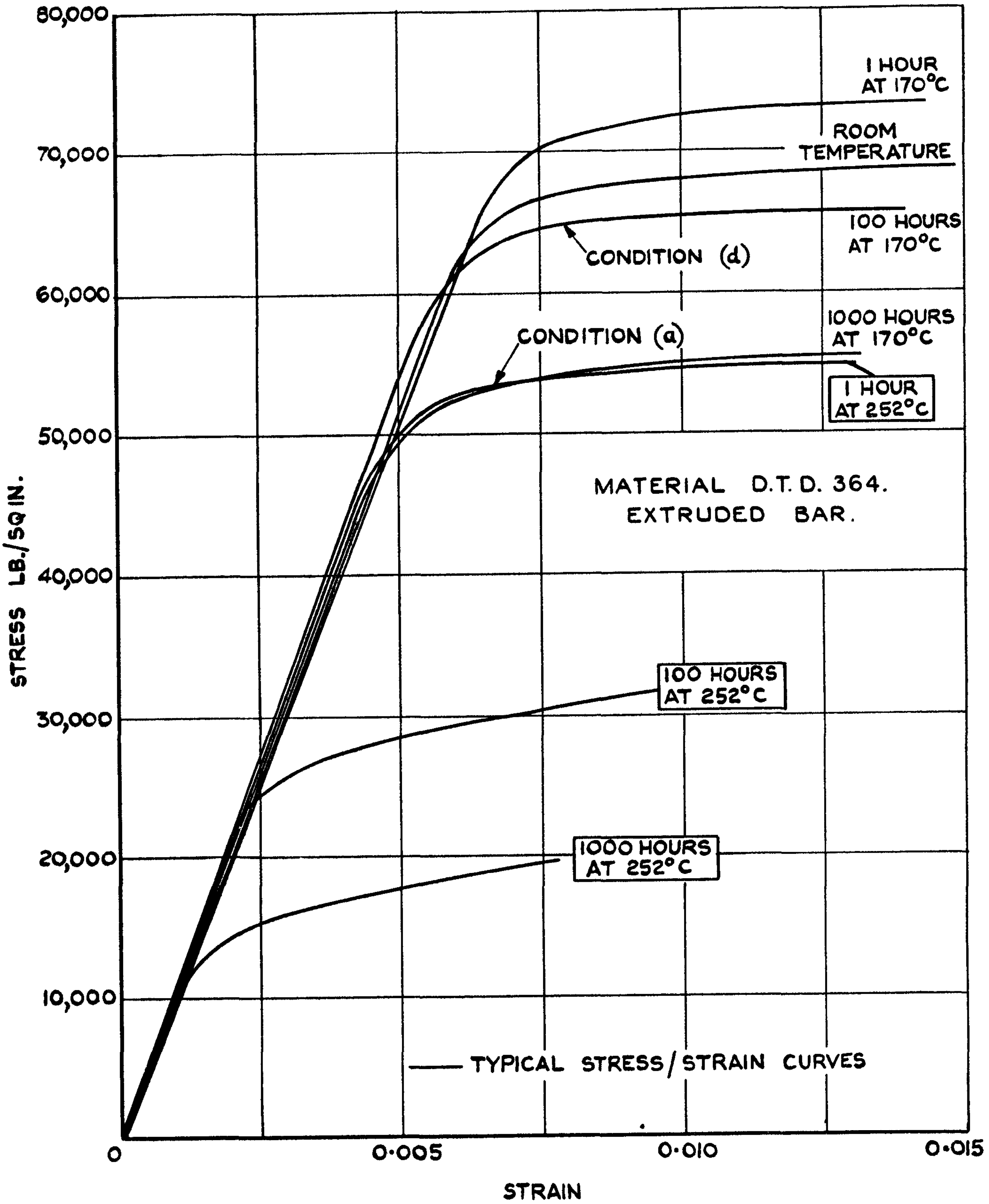


FIG.1 TYPICAL STRESS/STRAIN CURVES FOR SPECIMENS TESTED IN TENSION AT ROOM TEMPERATURE AFTER BEING HEATED AT (i) 170°C (ii) 252°C FOR (i) 1 HOUR (ii) 100 HOURS AND (iii) 1000 HOURS.

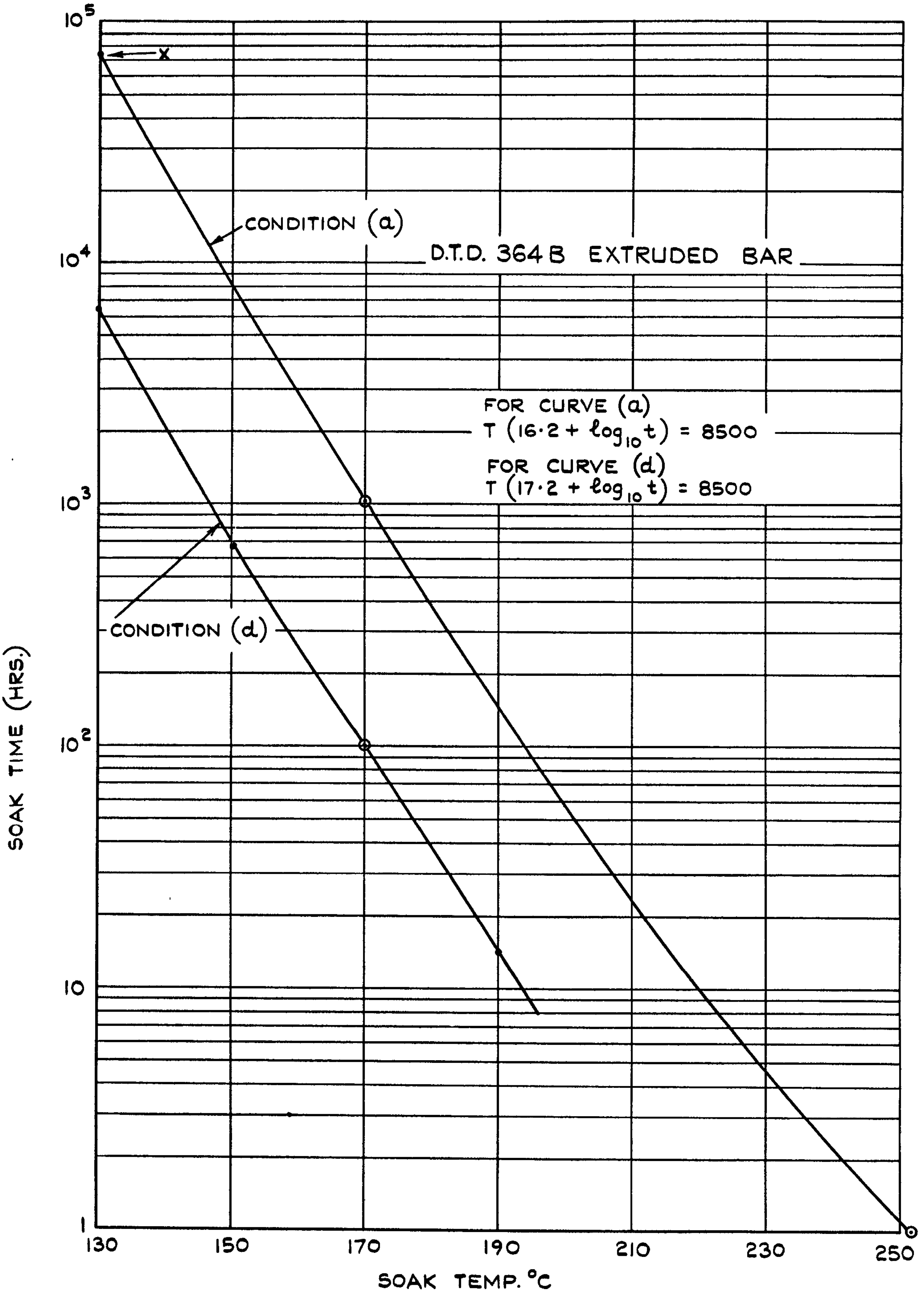
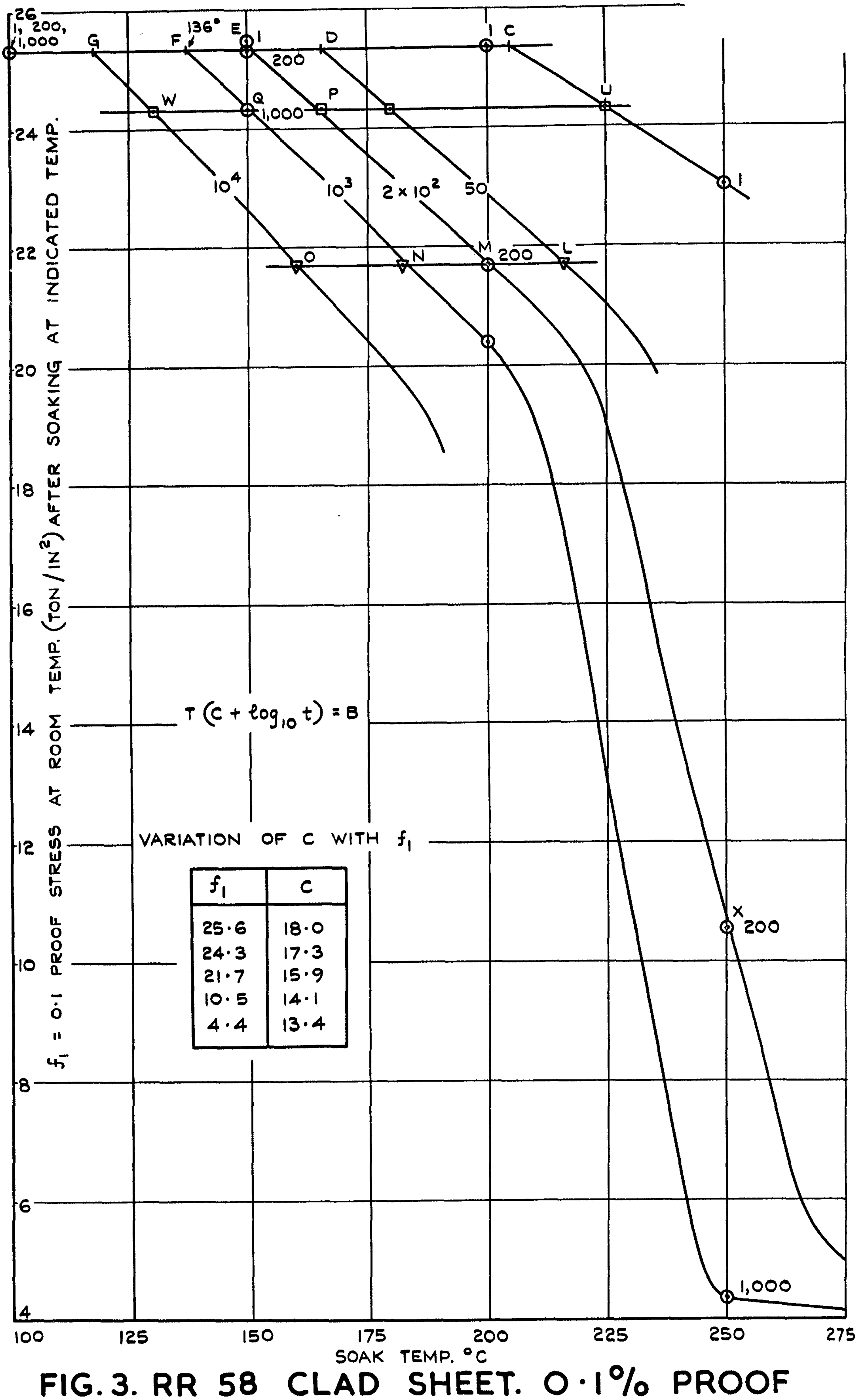


FIG. 2. EXTRAPOLATION CURVES - D.T.D. 364 B.



$$T(C + \log_{10} t) = B$$

VARIATION OF C WITH f_1

f_1	C
25·6	18·0
24·3	17·3
21·7	15·9
10·5	14·1
4·4	13·4

FIG. 3. RR 58 CLAD SHEET. 0·1% PROOF STRESS AT ROOM TEMPERATURE.

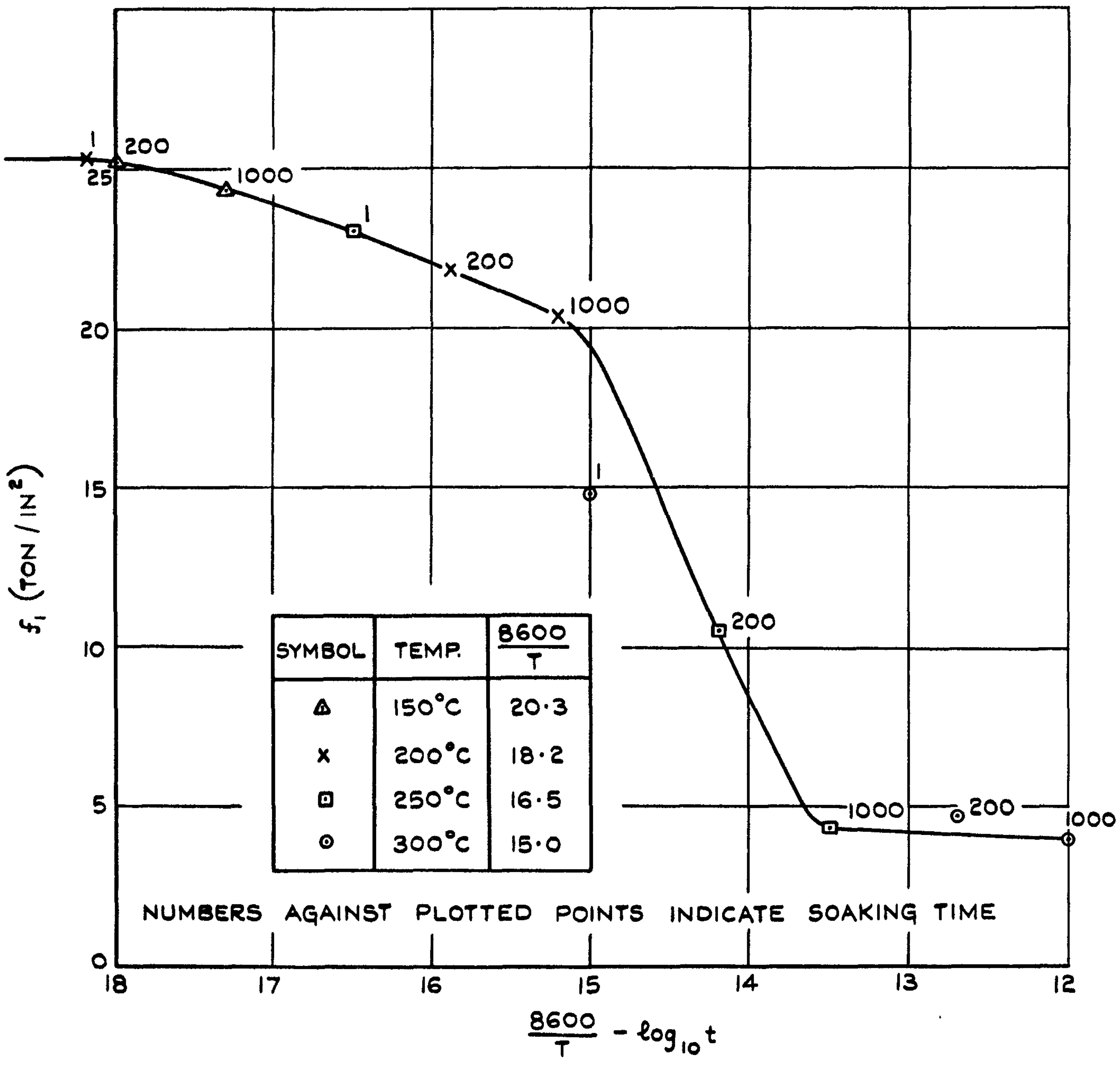


FIG. 4. PARAMETRIC PLOT - f_1 AT ROOM TEMP.

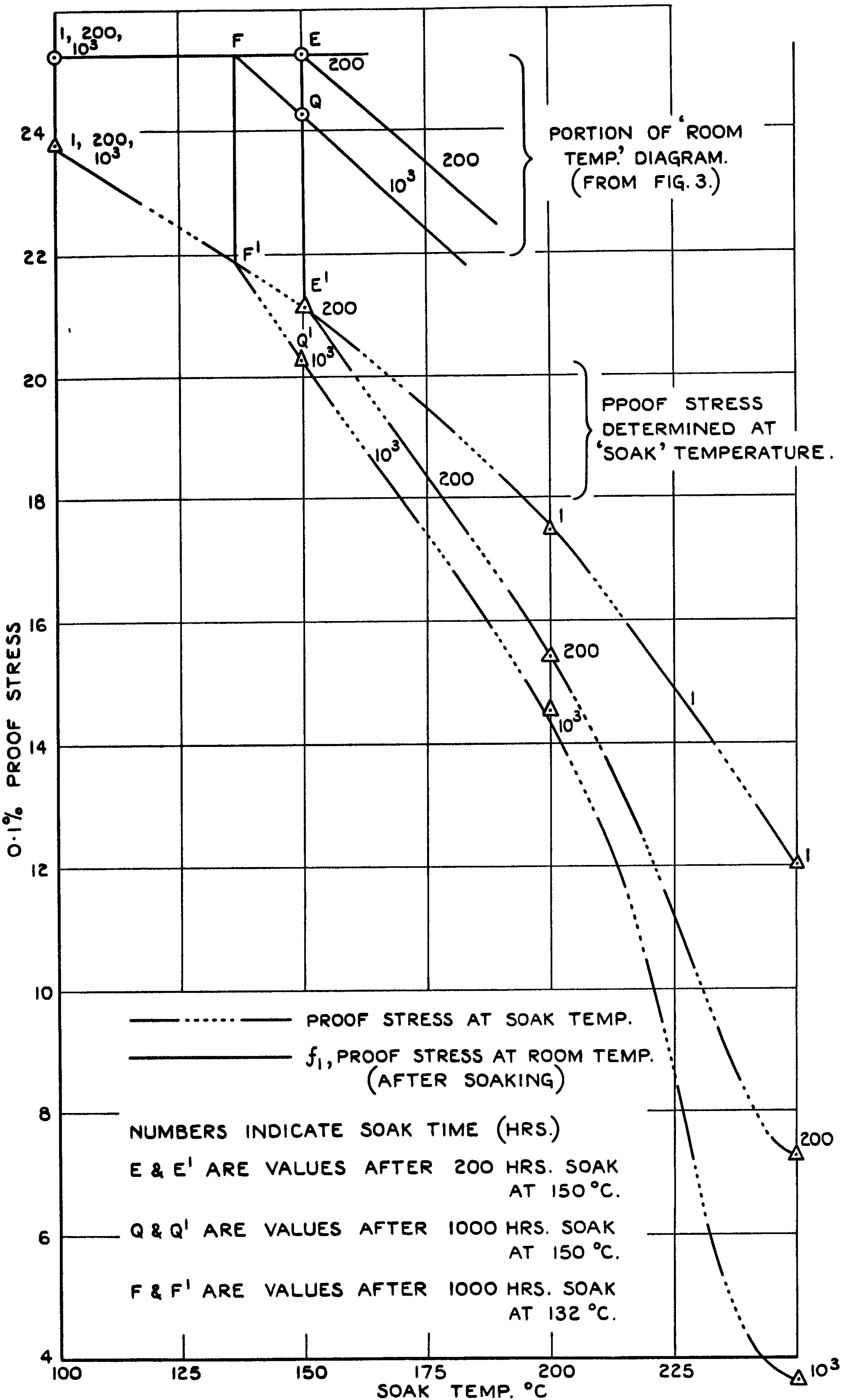


FIG. 5. O·1% PROOF STRESS AT SOAK TEMP. - RR 58 CLAD SHEET.

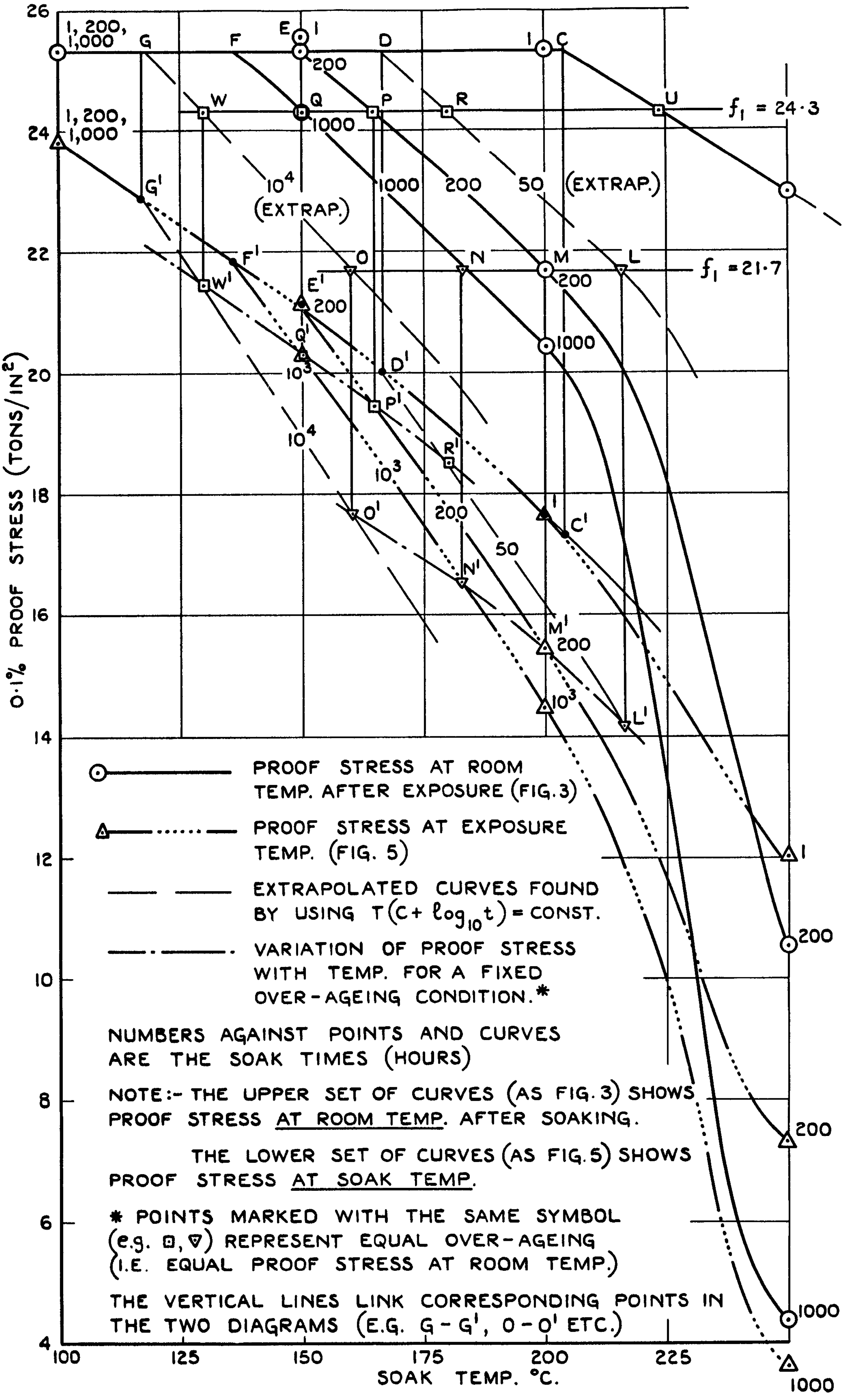


FIG. 6. EXTRAPOLATION GRAPH - RR 58 CLAD SHEET.

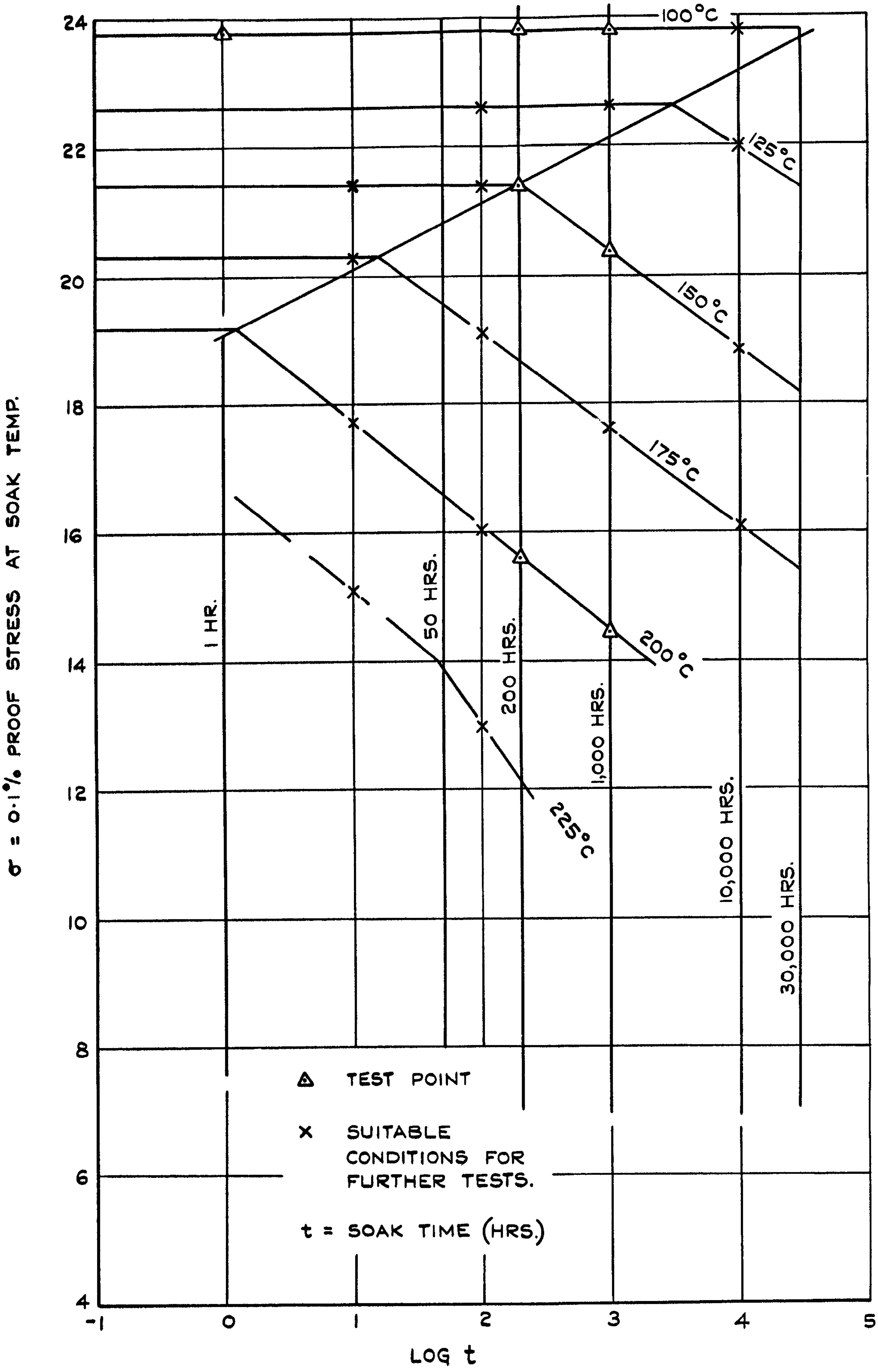


FIG. 7. RR 58 CLAD SHEET. log t DIAGRAM. 0·1% PROOF STRESS AT SOAK TEMP.

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