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by

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INTRODUCTION TO A LIBRARY OF CREEP AND STRAIN RECOVERY DATA FOR DTD 5070A ALUMINIUM ALLOY

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SUMMARY

This paper introduces the library of tensile creep data from a research programme carried out by Structures Department during the period January 1969 to March 1976. Specimens were cut from a single sheet of high strength aluminium alloy to DTD 5070A and were creep tested at 150, 165, 180, and 195°C over a range of stress levels to strains near rupture. Subsequent unloading, where possible, provided strain recovery data. Additional tests investigating the interaction of creep and strain recovery periods were extended in some cases to provide cyclic creep data useful in the exploration of history effects. Further work, mainly at 180°C investigated the effects of periods of prior heating and of step changes in load level.

The data were obtained under conditions of temperature, load and load axiality controlled more closely than is usual in conventional creep testing and can be compared with some confidence. In addition each test phase was fitted with a seven degree polynomial to high accuracy and processed data was produced listing time, measured and fitted strain, strain rate and second derivative of strain with respect to time together with the appropriate polynomial coefficients.

This Report details the techniques used, describes the results in a qualitative manner and serves as an index to the library of processed data which is available in microfiche form in a companion report.

Departmental Reference: Structures YSE/B/0639

LIST OF CONTENTS

1 INTRODUCTION

The creep data library described in this Report is a result of the interest generated in material behaviour at elevated temperatures by the development of the supersonic transport aircraft. Although overall creep strain was used as a design criterion based on consideration of structural deformation it was recognized that local creep strains in areas of stress concentration could be an order of magnitude larger and might affect the accumulation of fatigue damage and the residual static strength. Thus a knowledge of local creep behaviour was needed for the better appreciation of possible interactions between creep, fatigue and static strength.

The approach adopted was to investigate the basic responses to stress and temperature levels and to variations in prior history with the intention of developing relationships which could subsequently be used to predict the growth of both overall and local creep strains. Early work was started on the effects of time at temperature on the creep of notched and plain specimens and on the effect of load changes during creep testing[2-5].

It had been realized that the repeatability achieved in conventional creep testing was not adequate and much effort was expended to improve the control and measurement of temperature, load accuracy and axiality, and strain measurement. The testing techniques adopted are described in section 3. Another problem was that of data handling as the manipulation and comparison of test data to the extent required could not be undertaken by the manual plotting of individual data points. It was considered essential that the mass of strain/time data points generated in any test phase should be condensed in some way and consequently a routine system was developed for the accurate fitting of the data with a seven degree polynomial as described in section 4.

With testing and processing techniques established, an extensive creep library was progressively accumulated using plain specimens cut from aluminium alloy DTD 5070A. Details of these specimens and the material are given in section 2. This programme of work which is detailed in section 6 included continuous tensile creep tests at a range of stresses (80-250 MN m^{-2}) and temperatures (150-195°C) together with further tests, mainly at 180°C, involving various amounts of prior heating. Cyclic loadings and step changes in temperature, also mainly at 180°C, were included to provide information on transient response and the effect of strain recovery periods.

Initial analysis was largely negative and only emphasized the unsatisfactory nature of current creep theories. Attempts to develop a continuous function also met with only limited success and attention was therefore directed towards relationships representing the individual phases of the classic creep curve based on the concept of a transient approach to a 'steady-state' condition. A report[6] was subsequently published describing a strain modified 'steady-state' relationship.

Publication of this creep data library has been undertaken so that it can be made available to other workers in the field as a body of accurate processed material suitable for further analysis work. In order that some assessment of its potential usefulness can be made a broad qualitative description of trends and features has been attempted in section 8.

The data itself is in the form of a computer print-out listing time, measured strain, fitted strain and first and second derivatives together with the appropriate polynomial coefficients. Some 4000 pages are involved and these have been condensed by reproduction, in full, on 50 microfiche which form the main body of a supplementary report[1].

The purpose of this current Report is therefore to serve as an introduction to the data available and to provide potential users with the information necessary for them to assess its value.

2 MATERIAL AND SPECIMENS

RR58 was considered to be a suitable aluminium alloy for the structure of a supersonic transport and a clad sheet form of this material to specification DTD 5070A (see Appendix) was selected for the creep programme. This material was eventually superseded by improved versions of similar chemical composition but since it was expected that the overall pattern of behaviour would be similar work was continued on the earlier material.

Specimens were cut in the direction of rolling from a single sheet 1.63mm (16 SWG) thick and conformed to the British Non-Ferrous Metals Research Association (BNF) design shown in Fig 1 which provides a gauge length of 114.3 mm (4.5 in). Both specimen edges were ground flat to ±0.0038 mm (0.00015 in) to eliminate the small curvature found after milling, thus minimizing the bending stress resulting from this curvature and also to provide suitable surfaces for the measurement of load axiality. In addition a small number of specimens were cut from the same sheet of DTD 5070A at 90° to the direction of rolling to assess the effect of anisotropy.

3 TESTING TECHNIQUES

Tests were conducted in fourteen 20kN (2 ton) capacity high sensitivity creep testing machines located in a laboratory with a controlled ambient temperature of 21 $\pm 1^{\circ}$C. Load was applied by deadweight acting through a 10:1 overhead lever beam to an accuracy of ±0.25% with the load axis being as near vertical as possible. The testing machines were fitted with ovens having an internal diameter of 0.13 m (5 in) and a length of 0.61 m (24 in) and heated by three separate windings supplied from a solid state temperature controller through additional controls for temperature gradient correction. Effects from fluctuations in mains electricity were minimized by the use of a voltage regulator.

A completely unloaded condition was not possible as the weight of test components produced a small stress varying from specimen to specimen. In order to standardize this minimum stress condition, and to provide a small tensile load to maintain alignment, a lever beam balance technique was devised to produce a stress of 2.76 MN m^{-2} (400 lb in^{-2}) in all cases.

Specimens were attached to the pull rods of the machine via universal joints which formed part of a specimen alignment system[7] and were used in conjunction with measuring bars to align the specimen in both significant planes to within ±0.008 mm (0.0003 in). Specimen extension was measured using optical lever type extensometers of Structures Department design[8]. Geometrical effects were avoided by connecting each pair of legs together with two leaf springs to form a parallel motion system free only in the direction of measurement and magnetic loading of the measuring rollers in the optical sensing unit reduced frictional effects to a minimum. Two extensometers were attached to each test specimen by conical pointed pinch screws using a simple jig to position them and set the gauge length. It was recognized that this form of attachment would prejudice the rupture life but the accurate measurement of bulk creep strain was considered to be more important and the system was optimized to this end. Young's modulus was determined at laboratory temperature (21°C) to verify the quality of each test assembly by an incremental loading to a stress level restricted to 55 MN m^{-2} (3.56 ton in^{-2}) to avoid prior cold work. The difference between the two extensometer readings expressed as a percentage of their mean was in all cases less than 2½%, a reflection of the special measures taken to ensure good axial alignment.

The test temperature was measured by three miniature platinum resistance thermometers (PRT) equally spaced along the gauge length and these were calibrated at the test temperature required by comparison with laboratory standards in a comparator block. Specimens were heated to within $+1^{\circ}C$ to $-5^{\circ}C$ of the test value during the first hour. The remainder of the first day was required to achieve the required accuracy of $\pm 0.2^{\circ}C$ at the three measuring stations and a maximum temperature gradient of $0.3^{\circ}C$.

The load required was calculated from the specimen area measured at ambient temperature making due allowance for the minimum stress level of 2.76 MN m^{-2}. This was generally applied, with the exception of the tests involving periods of prior heating, 24 hours after the start of heating in one smooth increment, taking approximately 0.005 h (18 s) at the 170 MN m^{-2} stress level. Loading times at other stress levels were approximately proportional. Extensometer and temperature readings were taken just prior to loading, at the time of full load application and thereafter at 0.005 h intervals decreasing progressively to 0.5 h intervals at the end of the first day. All tests were conducted at constant load apart from the cyclic load tests, where several loadings on the same specimen were required and loads were modified for second and subsequent loadings to allow for the reduction in cross-sectional area using the constant volume assumption.

The tolerances used for temperature, stress and load axiality were aimed at restricting the effects of test to test variability to ±5% on the time to a given creep strain. It should be noted that the tolerances were derived from the temperature and stress sensitivities of the test material DTD 5070A and would not therefore necessarily apply to other materials with different characteristics.

4 DATA PROCESSING

As each test phase involved a large number of individual strain/time readings, the use of manual plotting for subsequent analysis would have been laborious and time consuming and therefore some method was required for condensing the data, with minimum loss of accuracy, into a form suitable for subsequent graphical analysis. The basis of the method adopted was to express the data from each test phase in terms of a polynomial; for tests which did not extend much beyond the point of minimum creep rate and also for tests involving strain recovery it was found that a seven degree polynomial in time raised to a positive fractional power fitted the data satisfactorily

$$\varepsilon = \sum_{i=0}^{i=7} E_i t^{im}$$

where ε = total strain (elastic + plastic)

t = time in hours

$m = 1/6$.

No form of single polynomial was found which would fit tests extending well into the tertiary region of creep to an accuracy comparable to that of the measured strain and in these cases the data was divided into two parts with a substantial overlap covering the region of minimum creep rate. Two polynomials were then fitted using $m = 1/6$ and $m = 1/2$ for the first and second sections respectively.

A digital computer was used to perform the numerical evaluation of the coefficients using the method of least squares. The differences between the test data and values calculated from the fitted polynomial, termed the residuals, were generally randomly distributed with a standard deviation less than 0.0002% strain. Residuals greater than 0.0010% were regarded as erroneous and these data points were normally discarded unless they occurred in known areas of uncertainty or within the second part of a high strain test where a limit of 0.0020% was considered acceptable. A computer print-out of the edited data was then obtained which listed time, measured total strain (elastic plus plastic), residual, fitted total strain, strain rate and second derivative together with the appropriate set of polynomial coefficients.

The reader is referred to the supplementary report[1] which presents the processed data and which also includes further information on its production and usage.

5 DATA ANALYSIS SYSTEM

The data processing described in the previous section made possible the manual plotting of strain and its derivatives but it was considered that its full potential could not be realized without an analysis system capable of regenerating the data, or any function of it, from the appropriate set of polynomial coefficients together with a visual display for presentation and comparison. This was achieved by using a programmable calculator and plotter which allowed speedy graphical analysis as required. Data, in the form of polynomial coefficients was stored on magnetic cards or tape and could be used with a programme written to complete the task required.

6 TEST PROGRAMME

The creep research programme was intended to provide comprehensive tensile creep data over a range of test parameters and prior history. Temperature and stress sensitivity were investigated by constant load tensile creep tests at temperatures of 150, 165, 180 and 195°C and stresses of 80, 108, 140, 170, 200, 230, 250 MN m^{-2} generally to strain levels in the region of 2% although longer term tests did not achieve this level. Tests were normally concluded by unloading and recording the subsequent strain recovery. Table 1 is a catalogue of the tests showing the location of the data.

In addition to the longitudinal specimens used throughout this work a small number of test specimens cut at right angles to the direction of rolling were tested over a more limited range of stresses at the above temperatures. These transverse tests are listed in Table 2.

Time at temperature was known to be significant for precipitation hardened material and this factor was investigated by further continuous tensile creep tests, mainly at 180°C, involving prior heating periods at 195°C, as listed in Table 3.

The effect of load changes was the major area of interest and the response throughout a sequence of load changes was therefore investigated. The simplest test possible was one involving alternate periods with the load applied and removed. This led to a consideration of the effect of time under load on subsequent strain recovery and the effect of strain recovery on subsequent loading. Tests designed to investigate these effects at 165°C and 180°C are listed in Tables 4 and 5 respectively.

It should be noted that tests included in Table 1 contain data which may be useful to extend an analysis of these factors. A number of miscellaneous tests, whether abandoned prematurely or unusual in some way are also included.

The investigation of load change effects also included tests at 165°C and 180°C involving alternative periods with the load applied and removed, the sequence being repeated to form the regular cyclic loading and strain recovery tests listed in Table 6. Some of these tests at 180°C involved prior heating for 1056 h at 195°C and are also included in Table 6.

The final section of the test programme consisted of step changes in load level at 180°C as listed in Table 7. Three tests investigated the response on unloading to 140, 108 and 80 MN m^{-2} after an initial period of 96 h at 170 MN m^{-2}. Two further tests with initial periods of 24 h and 336 h respectively extended the data available on unloading to the 140 MN m^{-2} stress level. Two more tests involved alternative periods at 170 and 140 MN m^{-2} the sequence being repeated to provide cyclic data. Both tests were identical with the exception that the order was reversed; thus one started at 140 MN m^{-2} while the other started at the 170 MN m^{-2} stress level.

7 DATA PRESENTATION

The data available is mainly in the form of computer print-outs whose format has already been discussed in section 4. It was considered that it should be published in full as this allowed several methods of use. The data could be used directly since total strain, strain rate and second derivative were listed at each test time. Alternatively data could be regenerated from the appropriate set of polynomial coefficients, in the form required, by the use of a programmable calculator or computer and displayed automatically by an associated plotter. Additionally since the basic coordinates of time and strain were included reprocessing was possible thus allowing the fitting of alternative relationships. The data has therefore been reproduced on microfiche, a form adopted to avoid the unacceptable bulk of the original computer print-outs while preserving the advantages of this format. Even so 50 microfiche are involved and it was considered inappropriate to include this bulk of data in an introductory report of this type. They are therefore being made available in a supplementary report[1] which also describes the processing and format of the data and discusses certain constraints on the regeneration and use of the data. Also included are the collected values of Young's modulus at ambient temperature for each test prior to loading and a table of the strains obtained on the initial loading of each specimen to the test conditions applied.

To allow potential users to form some assessment of the usefulness of the data a qualitative description of the response of the material to the various testing conditions and sequences has been attempted by the graphical presentation of the data in Figs 2-74 which will be discussed in more detail in the following section. In all cases the curves have been regenerated from the appropriate set of polynomial coefficients using a programmable calculator and plotter.

8 DISCUSSION

Before discussing the graphical presentation of the results it may be useful to define the terms to be used in describing the form of the curves. The rather general term 'transient response' is used not only to describe conventional primary creep but also the response after any change in applied loading including strain recovery. This then implies that a 'steady-state' strain rate, appropriate to the stress applied, exists after the decay of this transient response. In fact accelerating tertiary creep occurs and it is assumed that structural changes resulting from time at temperature and accumulating damage continuously modify the 'steady-state' to produce this effect.

Tests are presented in the order previously discussed in section 6, 'Test programme' and listed in Tables 1 to 7. In addition the attention of readers is drawn to an alternative presentation of some aspects of the available data in an earlier report[6] which derives a strain modified 'steady-state' relationship by plotting log strain rate against linear strain.

8.1 Continuous creep

The basic tensile creep data is probably best represented in a limited space by a logarithmic plot of strain against time and Figs 2-5 present this data for the temperature levels of 150, 165, 180, and 195°C respectively. Data below 0.1 h has been omitted as errors in time and strain become dominant in log plotting at small values. It should also be noted that plastic strain accumulated during the loading process has not been included and its addition can significantly modify the early part of these curves.

The more limited data available from transverse specimens at the same temperature levels are plotted in the same manner on Figs 6-9. In each case the equivalent longitudinal test has been included for comparison. Generally the picture is confused with the largest differences being apparent at 165°C, Fig 7, where considerably more strain is accumulated from the transverse specimens at 230 and 200 MN m^{-2} and considerably less at 170 MN m^{-2}. However there is probably less strain accumulated during the transient phase and more during the modified 'steady-state' in the majority of cases.

8.2 Continuous creep after prior heating

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 h then produces the optimum conditions for maximum tensile strength. Additional time at temperature may therefore be expected to further modify mechanical behaviour and this factor was investigated by the additional heating of test specimens prior to continuous creep testing. The selection of times and temperatures was governed by the desire to obtain a significant change in properties in a reasonable time and accordingly an exposure of 1056 h at 195°C was chosen. It is generally accepted that the

Dorn parameter may be used to relate time and temperature combinations and its use in this case together with a previously derived value[6] for the activation energy (Q) of 37060 cal/mol allows the calculation of equivalent times at other temperature levels. These are listed in Table 8 for the conditions of interest.

Creep tests were conducted at 180°C after the prior heating specified, at stresses of 80, 108, 140, 170 and 200 MN m^{-2}. In each case the temperature was reduced from 195°C to 180°C, 24 h before loading. Fig 10 illustrates the response obtained by plotting creep strain against time on logarithmic axes and makes a comparison with the 'as received' material under the same conditions of temperature and stress. It is immediately apparent that the effect of prior heating is dependent on stress level since at the higher stresses an increase in creep strain results while at lower levels a decrease relative to the 'as received' material becomes apparent. The drop in creep strength at the higher stresses is consistent with the fall in tensile properties known to result from increasing prior time at temperature. The reversal in this trend as lower stresses are approached is interesting and it has been tentatively suggested[6] that it may be linked to a progressive change from ductile transgranular to brittle intergranular modes of failure.

Further tests were carried out at 180°C under applied stresses of 140 and 170 MN m^{-2} to investigate the effect of varying prior heating times. Two additional tests were conducted at each stress level after prior heating times of 288 and 3192 h at 195°C respectively. Creep curves are therefore available after 0 (as received), 288, 1056 and 3192 h of prior heating under stress levels of 140 and 170 MN m^{-2} and are shown on Figs 11 and 12 respectively as linear plots of creep strain against time. Inspection of the curves at 140 MN m^{-2} reveals the strengthening effect of prior heating already noted at this stress level. However there is a reversal in trend at a prior heating time greater than 1056 h and the result after 3192 h is again approaching the 'as received' response. It should be noted that the change from a strengthening to a weakening response after 1056 h of prior heating takes place between 140 and 170 MN m^{-2} as seen in Fig 10. A test carried out just below the critical stress might therefore be expected to exhibit a small strengthening response after low prior heating times changing to a weakening mode at longer exposures consistent with the behaviour observed at 140 MN m^{-2}.

At the higher stress level of 170 MN m^{-2} Fig 12 shows that the response with increasing prior heating is a progressive increase in creep strain as expected. The change is small after 288 h, moderate after 1056 h and very large after 3192 h of exposure.

8.3 Strain recovery after continuous creep

The continuous creep data discussed in the previous sections was generally terminated, if rupture had not occurred, by a strain recovery period at 2.76 MN m^{-2}, the lowest stress possible. Figs 13-16 illustrate this recovery data obtained after creep testing the 'as received' material at the four temperature levels involved by plotting linear strain against log time. Comparison is difficult as tests were unloaded at various values of accumulated creep strains as noted on the individual curves, but some general points may be made.

In the first place it is apparent that strain recovery is nowhere completed even after recovery periods extending to 16000 h. Secondly the rate of recovery is dependent on the stress level imposed in the prior creep test. If the original creep strain was accumulated slowly then subsequent strain recovery was also slow. Finally although the ultimate magnitude of strain recovery is not available some evidence exists to show that it may be dependent on stress level. For instance Fig 14 shows the strain recovery curves at 170, 200 and 230 MN m^{-2} converging and crossing towards the end of the data thus indicating that a progressively larger ultimate strain recovery is associated with a progressively lower stress level during the prior creep test. Some convergence is also present at 180°C, Fig 15, where recovery after 140 MN m^{-2} is approaching that achieved after 170 MN m^{-2}. In addition the association of decreasing ultimate values of transient strain with increasing stress levels has been noted during forwards creep where values have been derived using a strain modified 'steady-state' relationship[6].

The small amount of recovery data available from the transverse specimens is not shown graphically in this Report as the problems of comparison preclude any definite conclusions. However as far as can be determined there is little difference between the longitudinal and transverse material in this respect.

The more extensive data showing the effects of prior heating is presented on Figs 17-19. The strain recovery curves available after creep testing at 80, 108, 140 and 170 MN m^{-2} following a heating period of 1056 h at 195°C are illustrated on Fig 17. All prior heading tests show lower recovery strains than the 'as received' tests included for comparison but their accumulated creep strains are also smaller in all cases and no conclusion is possible. However the additional tests with prior heating times of 288 and 3192 h are available at 140 and 170 MN m^{-2} and Figs 18 and 19 show the response obtained. At 140 MN m^{-2} only one of these tests is available, as the other was terminated by creep rupture. The accumulated creep strain after 3192 h prior heating is about 2%

and the response is very similar to that after 1056 h prior heating with 1.4% accumulated creep strain. Both show less creep recovery than the 'as received' test with 1.8% strain. A similar picture emerges at the higher stress level, see Fig 19 with the 3192 and 1056 h prior heated tests showing similar responses after 2.3 and 1.2% accumulated creep strain and less creep recovery than the 'as received' test with 1.5% creep strain. The additional curve after 288 h prior heating is also available in this case with an accumulated creep strain of 1.8% and it also exhibits less creep recovery than the 'as received' curve though the effect is less marked. On the basis of this evidence therefore it would appear that prior heating either reduces the amount of strain recovery possible or alternatively leads to a slower rate of recovery.

8.4 Strain recovery after varying times at load

The creep and recovery behaviour associated with continuous testing to high strain levels and the effect of prior heating on this type of test was discussed in the previous sections. Consideration will now be given to the effect of varying the times of loading and strain recovery on the subsequent behaviour.

The first step is to examine the strain recovery curves after different times of prior loading which are shown on Figs 20 and 21 for the conditions of 140 and 170 MN m^{-2} at 180^{o}C respectively. The magnitude of strain recovery is clearly linked to the duration of the prior loading period in both cases. It is unfortunate that more data is not available for longer times of loading and larger accumulated creep strains following which a limiting value of strain recovery would be anticipated.

The effect of additional prior history on strain recovery after varying times on load was also obtained by determining the response after second loadings. Two histories were used. In each case an initial loading of 96 h at 170 MN m^{-2} and 180^{o}C was applied. This was followed by a strain recovery period of 912 h in the first history and 72 h in the second. Second loadings of varying duration at 170 MN m^{-2} were then imposed followed by the strain recovery periods of interest. The resulting curves are presented on Figs 22 and 23 respectively. Fig 22 also includes the strain recovery behaviour after varying the duration of the first loading periods previously shown on Fig 21, while Fig 23 makes a direct comparison between second strain recovery periods after the two types of prior history. Examination shows little significant difference between first and second recovery curves where the prior history included the long first recovery period of 912 h. Possible exceptions are those recovery curves obtained after the shortest loadings of 0.2 and 1.0 h where second recoveries were somewhat larger, see Fig 22. A comparison of the second recoveries resulting from these two types of prior history however reveals that significantly larger values of strain recovery were obtained in the test series containing the short first recovery period, see Fig 23. It is interesting to note that this occurs despite the smaller value of accumulated strain existing at the time of unloading.

8.5 The effect of strain recovery on subsequent creep

Tests were conducted at 170 MN m^{-2} and 180^{o}C to determine the effect of recovery time on subsequent behaviour. An initial loading of 96 h at the above conditions was followed by recovery periods ranging from 72 to 4513 h. A second loading at 170 MN m^{-2} then followed and plots of accumulated strain against total time on load are shown on Fig 24 which includes the appropriate continuous test for comparison.

It is seen that, in general, the recovery period led to larger accumulated creep strains than in the continuously loaded case, the effect becoming progressively greater with increasing recovery time. The exception is the lowest recovery time of 72 h where the subsequent loading curve falls slightly below the continuous one. This however is considered to be a low result as a comparison of its first loading period with the continuous test also shows lower creep strain.

It is considered that two effects are involved in this generally larger creep strain. Additional time at temperature must be considered as a factor as it is known to result in larger creep rates at this stress level. Nevertheless it has been demonstrated, see Fig 19, that a prior heating equivalent to 1078 h at 180^{o}C has only a small effect and therefore it is unlikely that tests involving recovery times of less than this value will be greatly affected. The main effect is in fact considered to be a transient response dependent on the time allowed for recovery prior to reloading. For example, an instantaneous unloading and reloading would result in no strain recovery and no subsequent transient on reloading (the continuously loaded case) whereas complete recovery might be expected to lead to the transient response associated with the 'as received' material on its first loading. It might be argued that the transient strain recovered during the period off load should be equal and opposite to the transient resulting from the subsequent loading with therefore a zero nett effect on accumulated creep strain. In practice this does not appear to be so and in all cases the transient response associated with loading would seem to be much larger than the prior transient strain recovery.

The response obtained from the second loadings is compared with the original response of the 'as received' material by an additional linear plot of creep strain against time on Fig 25. It is evident that the magnitude of the transient response although increasing with recovery time is generally smaller than the transient shown by the 'as received' material. The exception is the result after 4512 h recovery where the additional time at temperature is expected to produce a significant increase in creep strain. The interpretation is also complicated by the difference in accumulated creep strain level of about 0.3% which would be expected to increase the 'steady-state' rate for the second loadings. This does indeed seem to be the case as, with the exception of the loading curve after 72 h recovery (a low test), the curves cross or approach the 'as received' data. The additive effect of these factors should be considered in assessing transient response particularly in the case of the 4512 h recovery period.

A similar exercise has been completed to determine the effect of recovery time on third loadings at the same stress and temperature. The prior history consisted of an initial loading of 96 h followed by 912 h strain recovery. A second loading also of 96 h was then followed by recovery periods ranging from 72 h to 912 h. The subsequent third loading is illustrated as before by plotting creep strain against time on load and also creep strain against time in Figs 26 and 27 respectively. Comparison against the continuous test is again provided and is supplemented by the inclusion of a test having a common history followed by a continuous second loading. The response is seen to be very similar to that noted for second loadings and within the limitations already discussed the same conclusions also apply.

8.6 Regular cyclic loading and strain recovery at 165°C

Cyclic tests were conducted in which a period on load was followed by a period with the load removed. This sequence was repeated until the testing time became excessive or rupture intervened. The body of this work was carried out at 180°C and is discussed in section 8.7 but in addition two tests were made at 165°C and these will now be discussed in some detail. In the first of these a stress level of 140 MN m^{-2} was imposed for 384 h and was followed by a strain recovery period of 3648 h. Six of these cycles were completed followed by a continuous loading to rupture. The strain accumulation during each successive loading is plotted on Fig 28. The creep strain per cycle is seen to decrease until the fifth loading where the trend reversed to show a progressive increase for cycles 6 and 7. The major point of interest is the large decrease in creep strain between cycles 1 and 2 and this is considered to result from incomplete strain recovery. The subsequent behaviour where similar states would be expected at the start of each loading, show little change in the size of the transient response. An additional factor in the comparison of successive loadings is the effect of time at temperature resulting mainly from the recovery periods and which is known to reduce creep response at this particular stress level. Creep damage is also accumulating and the increasing creep response noted in cycles 6 and 7 is taken to be a reflection of this factor. The strain recovery during each unloaded period is shown on Fig 29. Successive curves are very similar with a small progressive increase throughout the sequence, a reflection of similar transient responses.

The accumulation of strain and its effect on strain rate is illustrated on Fig 30 as plots of log strain rate against linear accumulated strain. The results of successive loadings are plotted with a strain datum correction equal to the sum of the strains accumulated during prior periods on load less the sum of the strains recovered resulting from the prior periods off load. A continuously loaded test carried out under the same conditions of temperature and stress is included for comparison. This type of plotting has been used to derive a strain modified 'steady-state' relationship which defines the response at larger strain levels.

$$\dot{\varepsilon} = K \exp k\varepsilon$$

where $\dot{\varepsilon}$ = strain rate

ε = accumulated strain

K = true minimum strain rate

$1/k$ = true creep elongation

The non-linear response at lower strain levels is assumed to be the result of a transient approach to this relationship. The long seventh loading concluding this cyclic test provides an opportunity to compare behaviour after the decay of the transient response. It is seen to fall below the continuously loaded case, possibly due to the large difference in time at temperature. The test also exhibits a lower response than the continuously loaded case where a direct comparison can be made during the first loading and this may be a contributory factor.

The second of the tests at 165°C was identical except that the stress level was 170 MN m^{-2}. Rupture ended the test on the sixth loading. A similar presentation has been adopted and Figs 31, 32 and 33 show loading and recovery behaviour and the effect of accumulating strain on the strain rate throughout this test. The creep strain per loading is seen to decrease initially on the second loading. The effect is concentrated on the early or transient response and it is apparent that the end of the loading curve is approaching that of the first loading. This acceleration is more marked in the third loading although it is still coupled with a reduced transient. The fourth loading is not shown as an error resulted in only partial loading for the first 0.14 h of this phase. Fifth and sixth loadings however continue the accelerating behaviour and at this stage even the early response exceeds that of the first loading. The significant factors have already been discussed for the first of these cyclic tests and the effect of incomplete recovery is still evident in this case. Time at temperature at this higher stress level is expected to result in greater creep strain and is considered to be a major factor in the strongly accelerating behaviour. Additionally the creep strain accumulated per cycle is much larger in this test and the resulting creep damage would also be expected to lead to a significant increase in strain rate. Strain recovery behaviour is again very similar and exhibits a small increase throughout the sequence. Considering the large changes occurring in the amount of creep strain per loading throughout the test this is a notable result.

The effect of accumulated strain on strain rate is compared with the appropriate continuous test on Fig 33. The first loading demonstrates that it falls below the continuous curve but nevertheless greater rates are soon apparent,a reflection of the time at temperature effect at this stress level.

8.7 Regular cyclic loading and strain recovery at 180°C

The main data on cyclic loading was obtained at 180°C for stress levels of 108, 140 and 170 MN m^{-2}. Two tests were made at the lowest stress level with periods under load of 96 and 936 h respectively but with the same recovery time of 912 h. Little strain was accumulated in the succession of 96 h loadings and the test was ended after 11 cycles. For this reason a plot of log creep strain rate against accumulated strain has been omitted although loading and recovery responses are presented on Figs 34 and 35 respectively. The second test at 108 MN m^{-2} was terminated by rupture during the ninth loading and the corresponding curves are presented on Figs 36 and 37 and an additional curve of log strain rate plotted against accumulated strain on Fig 38. Both tests exhibit a similar response during the periods under load to that noted at the lower temperature level. The large reduction in transient response is again evident and although the subsequent increasing creep response is not present in the first of these tests it is apparent in the second where creep strains are much larger. Time at temperature at low stresses is known to decrease the creep rate and the acceleration in creep response must therefore be attributed to accumulating creep damage alone. Strain recovery behaviour is also similar although the progressive increase previously noted is more significant in the second of these tests at 108 MN m^{-2} see Fig 37. The correlation of the cyclic loadings with a continuously loaded test is demonstrated on Fig 38. In this case the continuously loaded comparison included a second loading terminated by rupture after a recovery period of 4752 h and this is also included.

Four tests were conducted at 140 MN m^{-2} having periods under load of 96, 192, 432 and 168 h and strain recovery periods of 912, 984, 912 and 4704 h respectively. The data is presented on Figs 39 to 50 using the format previously established. Behaviour under load follows the familiar pattern, a large reduction in the response on the second loading being followed by a progressive reduction to a minimum which is succeeded by progressive acceleration although still exhibiting a small transient response, see Figs 39, 42, 45 and 48.

Strain recovery behaviour is illustrated on Figs 40, 43, 46 and 49 and also follows the pattern established in previous results although the slow increase in strain recovery is not progressive in all instances and this is attributed to small datum errors affecting the ranking of individual recovery periods.

The remaining Figs.41, 44, 47 and 50 show the correlation obtained between cyclic loadings and the corresponding continuously loaded test by plotting log strain rate against accumulated creep strain. Agreement is best in the case of RF 60 see Fig 47 and it is perhaps significant that this test contains the smallest number of cycles to rupture; the agreement becomes progressively worse as the number of cycles increases. The number of loadings may therefore be a factor or alternatively the longer time at temperature resulting from the larger number of recovery periods may be significant. The fourth test in this series, RF 32 contains longer strain recovery periods of 4707 h with a time on load of 168 h resulting in relatively few cycles to rupture coupled with a greatly increased time at temperature. Fig 50 shows the response diverging from the continuous test very rapidly indicating that time at temperature is possibly the significant factor.

The effect of prior heating at the stress level of 140 MN m^{-2} has been discussed previously in section 8.2 and the response noted in these cyclic tests is not inconsistent with the previous observation that initial strengthening changes to weakening at longer exposures under these circumstances.

The only regular cyclic test conducted at 170 MN m^{-2} had periods of 96 h on load coupled with 912 h strain recovery and ruptured on the sixth loading. Figs 51, 52 and 53 illustrate the behaviour and reinforce the evidence obtained at the other stress levels. It should be noted that time at temperature increases creep response at this higher stress level after all exposures and therefore accelerating effects are dominant even though the smaller transient response is still evident.

8.8 Regular cyclic tests after prior heating

Regular cyclic tests were carried out at 108, 140 and 170 MN m^{-2} and 180^{o}C after a prior heating period of 1056 h at 195^{o}C. The subsequent histories of these four tests were matched to those carried out in the previous section and direct comparison is possible. Patterns of behaviour, shown on Figs 54 to 65 are similar to those previously experienced but magnitudes are influenced by the additional time at temperature. Responses are depressed at 108 and 140 MN m^{-2} and accelerated at 170 MN m^{-2} while strain recovery magnitudes are reduced; these effects were all observed previously and were described in sections 8.2 and 8.3.

8.9 Step changes in load level at 180^{o}C

A limited number of tests were carried out involving step changes between load levels and these comprise the final section of the data to be discussed. Three tests involved a step change between 170 MN m^{-2} and 140 MN m^{-2} after times of 24, 96 and 336 h at the higher level. Fig 66 shows the responses obtained after unloading to the lower stress level as a linear plot of creep strain against time. In all cases a negative transient response or strain recovery was experienced and as this decayed the strain rate increased progressively, through zero, to a value appropriate to the new stress level. An additional plot of log strain rate against accumulated creep strain is included as Fig 67 and demonstrates the correlation achieved with the equivalent continuously loaded test.

Two further tests were conducted involving step reductions to 108 and 80 MN m^{-2}, after an initial period of 96 h at 170 MN m^{-2}. Fig 68 illustrates the behaviour at the lower stress levels as creep strain against time and includes the response at 140 MN m^{-2} which has just been discussed. The alternative presentation of log creep strain rate against accumulated creep strain is shown on Fig 69. Correlation with the appropriate continuous test is good at the two higher stress levels but the result at 80 MN m^{-2} is exceptional in crossing the corresponding continuously loaded test rising to a significantly higher value before starting to fall. Its premature ending prevents further comparison but this would seem to be an interesting condition for further study.

The final two tests were cyclic step changes between 170 and 140 MN m^{-2} with loading periods of 96 and 576 h respectively chosen to give approximately equal creep strains during each period. The initial loading was at the higher stress level in the first test and rupture resulted during the third loading at this level. The second test was started at the lower stress level of 140 MN m^{-2} and was terminated by rupture during the third loading at this level.

The behaviour during successive loadings at 170 MN m^{-2} is illustrated on Fig 70 for both tests as creep strain against time and the corresponding behaviour at 140 MN m^{-2} is shown on Fig 71. Initial loadings at both stress levels show the respective transient responses. Subsequent loadings at 170 MN m^{-2} involve a stress change of only +30 MN m^{-2} and the transient response is positive but greatly reduced whereas for subsequent loadings at 140 MN m^{-2} the stress change is -30 MN m^{-2} leading to the negative transient response clearly seen in these cases. At both stress levels successive loadings show the accelerating behaviour experienced in previous cyclic testing and attributed to the summation of effects resulting from creep damage and time at temperature. The negative transient response is examined more closely on Fig 72 where the creep strain resulting from the periods at 140 MN m^{-2} is plotted against log time. The largest negative effect, on the fourth load stage of RF 89 is progressively approached and the fifth (final) load stage of RF 92 shows the reversal of trend attributed to accumulated creep damage modified by time at temperature effects.

Plots of log creep strain rate against accumulated creep strain are again included as Figs 73 and 74 where these cyclic tests may be compared with the continuously loaded cases. Effects consistent with time at temperature are clearly demonstrated accelerating the response at 170 MN m^{-2} but producing the opposite effect at the lower stress level.

9 CONCLUDING REMARKS

High quality creep data has been produced from a test programme carried out on a version of RR 58 aluminium alloy. A particular aspect of this work was the investigation of transient response and, in addition to providing continuous tensile creep data at 150, 165, 180 and 195°C, the programme investigated strain recovery and its effect on subsequent loadings. Regular cyclic loading and step changes in load level were also included and the effects of time at temperature were assessed by tests involving periods of prior heating.

Analysis work has been restricted to an examination of 'steady-state' behaviour and a strain modified 'steady-state' relationship has been proposed elsewhere[6]. No effort is available for further analysis but it is hoped that this introductory Report will stimulate interest in the transient behaviour by other workers. To this end the data is presented graphically and discussed qualitatively. Generally the behaviour is consistent with the concept of a transient approach to a 'steady-state' modified by accumulating strain. In addition prior heating has been shown to further modify the behaviour leading to a reduction in creep strength at high stresses. The effect is reversed at low stresses where increasing the time of prior heating leads to an increase in creep resistance.

More testing is of course desirable to amplify areas of doubt and to extend the range of the data. In particular the effect of cyclic changes in temperature has not been attempted and the effect of compressive loading on transient response has not been considered. However it is hoped that the present data is sufficiently extensive to allow some useful analysis work to be undertaken. Any interested workers are referred to the supplementary RAE Technical Report 76067 [1] which makes the data available in full on 50 microfiche.

Acknowledgments

The data described in this Report rests on the work of many careful and conscientious people but above all reference must be made to the role of the late Mr D A Berry who was responsible for the programme until his death in 1973 and who saw the need for the improvements in testing technique and data handling detailed in this Report.

Appendix

Extract from specification DTD 5070A for clad aluminium alloy sheet.

(a) Chemical composition of core material:-

Element	Per cent Minimum	Per cent Maximum
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	Per cent Minimum	Per cent Maximum
Zinc	0.8	1.2
Aluminium	-	the remainder

(c) Minimum mechanical properties:-

0.1% proof stress	not less than	309 MN m^{-2}
Tensile strength	not less than	386 MN 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 h.

Table 1

CONTINUOUS CREEP AND STRAIN RECOVERY

Temperature °C	Stress MN m^{-2}	Test No.	History	Microfiche No.
150	140	75	15985 h on load, 102 h recovery	1
	170	76	9620 h on load, ruptured	1, 2
	200	74	2916 h on load, ruptured	2
	230	77	849 h on load, ruptured	2
	250	88	216 h on load, 1350 h recovery	2
165	108	65	26392 h on load, 1134 h recovery	3
	140	44	7156 h on load, ruptured	3, 4
	170	45	2065 h on load, 1589 h recovery	4
	200	48	672 h on load, 2744 h recovery	4
	230	73	192 h on load, 2381 h recovery	4
180	80	24	14928 h on load, 16222 h recovery	5, 6
	108	12	4565 h on load, 4752 h recovery	6
	108	12	3510 h 2nd load, ruptured	6
	108	66	6360 h on load, ruptured	6, 7
	140	18	1920 h on load, 1902 h recovery	7
	170	10	504 h on load, 3964 h recovery	7
	200	63	199 h on load, ruptured	7
195	80	80	7954 h on load, ruptured	8
	108	79	1897 h on load, 1518 h recovery	8
	140	83	623 h on load, 1110 h recovery	8
	170	78	178 h on load, ruptured	8

Table 2

CONTINUOUS CREEP AND STRAIN RECOVERY OF TRANSVERSE SPECIMENS

Temperature °C	Stress MN m^{-2}	Test No.	History	Microfiche No.
150	200	94	2675 h on load, ruptured	9
	250	99	216 h on load, 1110 h recovery	9
165	170	93	2575 h on load, ruptured	9
	200	100	671 h on load, ruptured	9
	230	98	167 h on load, ruptured	9
180	108	81	7200 h on load, 1158 h recovery	10
	170	72	336 h on load, 1469 h recovery	10
	170	70	504 h on load, 918 h recovery	10
	200	97	168 h on load, 1110 h recovery	11
195	108	90	2137 h on load, 990 h recovery	11
	140	95	222 h on load, test abandoned	11
	170	96	168 h on load, 1326 h recovery	11

Table 3

CONTINUOUS CREEP AND STRAIN RECOVERY AFTER PRIOR HEATING

Stress MN m^{-2}	Prior time at 195°C h	Test No.	History	Microfiche No.
		(a)	Test temperature 165°C	
170	1056	47	1512 h on load, 4781 h recovery	12
		(b)	Test temperature 180°C	
80	1056	41	14904 h on load, 7197 h recovery	12
108	1056	13	4656 h on load, 4752 h recovery	13
		13	4942 h 2nd loading, ruptured	13
140	288	86	2615 h on load, ruptured	14
140	1056	42	1945 h on load, 1157 h recovery	14
140	3192	82	2233 h on load, 702 h recovery	14
170	288	91	576 h on load, 1014 h recovery	15
170	1056	14	336 h on load, 222 h recovery	15
170	3192	84	267 h on load, 791 h recovery	15
200	1056	53	70.4 h on load, ruptured	15
200	1056	85	48.1 h on load, ruptured	15
		(c)	Transverse specimens at 180°C	
170	1056	71	337 h on load, 1085 h recovery	15

Table 4

MISCELLANEOUS LOADING AND STRAIN RECOVERY PERIODS AT 165°C

Stress MN m^{-2}	Test No.	Load and recovery times				Remarks	Microfiche No.
		1L	1R	2L	2R		
200	58	408	4081	151.6	-	ruptured	16
200	51	673	1973	-	-	test stopped	16

Table 5

VARIATION OF LOADING AND STRAIN RECOVERY PERIODS AT 180°C

Stress MN m^{-2}	Test No.	Load and strain recovery times h						Remarks	Microfiche No.
		1L	1R	2L	2R	3L	3R		
108	15	96	72	4632	4326	-	-	Test stopped	17
140	35	1.0	1008	167	1008	1008	562	" "	18
140	16	24	1032	144	1008	1008	414	" "	18
140	17	144	1008	24	1008	1008	414	" "	19
140	19	168	1008	960	462	-	-	" "	19
170	68	0.2	2470	-	-	-	-	" "	20
170	69	1.0	1966	-	-	-	-	" "	20
170	33	96	30	-	-	-	-	Test abandoned	20
170	34	96	72	0.2	1566	-	-	Test stopped	20
170	27	96	72	1.0	893	-	-	" "	20, 21
170	31	96	72	24	912	-	-	" "	21
170	52	96	72	96	912	336	1061	" "	21
170	5	96	72	432	150	-	-	" "	21
170	30	96	192	-	-	-	-	" "	22
170	9	96	312	336	336	-	-	" "	22
170	4	96	436	-	-	-	-	Test abandoned	22
170	1	96	600	418	-	-	-	Ruptured	22
170	29	96	912	0.2	912	-	-	Test stopped	22
170	28	96	912	1.0	912	-	-	" "	23
170	26	96	912	24	912	-	-	" "	23
170	3	96	912	96	72	336	222	" "	23
170	8	96	912	96	312	336	318	" "	24
170	7	96	912	96	600	327	-	Ruptured	24
170	6	96	912	96	912	336	246	Test stopped	25
170	2	96	912	336	246	-	-	" "	25
170	49	96	4513	336	653	-	-	" "	25, 26
170	11	336[1]	967	-	-	-	-	" "	26
170	20	-[2]	1560	336	222	-	-	" "	26
200	23	96	912	35	-	-	-	Ruptured	26

1. Fast loading
2. Incremental loading to 282 MN m^{-2} followed by strain recovery.

Table 6

REGULAR CYCLIC LOADING AND STRAIN RECOVERY

Stress MN m^{-2}	Test No.	Loading time h	Strain recovery time h	Remarks	Microfiche No.
(a) Test temperature 165°C					
140	56	384	3648	6 cycles, 7th loading 6487 h ruptured	27, 28
170	64	384	3648	Ruptured 174 h into 6th loading	29, 30
(b) Test temperature 180°C					
108	25	96	912	Stopped after 11 cycles	31, 32
108	61	936	912	Ruptured 391 h into 9th loading	32, 33
140	22	96	912	Stopped after 16 cycles	34, 35, 36
140	32	168	4704	Ruptured 12 h into 9th loading	36, 37, 38
140	43	192	984	Ruptured 78 h into 10th loading	39, 40
140	60	432	912	Ruptured 175 h into 5th loading	40, 41
170	55	96	912	Ruptured 1.5 h into 6th loading	41
(c) At 180°C after prior heating of 1056 h at 195°C					
108	59	936	912	Ruptured 702 h into 9th loading	42, 43
140	21	96	912	Stopped after 16 cycles	43, 44, 45
140	62	432	912	Ruptured 12 h into 6th loading	46
170	57	96	912	Ruptured 1.6 h into 5th loading	47

Table 7

STEP CHANGES IN LOAD LEVEL AT 180°C

Stress 1 MN m^{-2}	Time on load h	Stress 2 MN m^{-2}	Time on load h	Remarks	Test No.	Microfiche No.
170	96	80	912	Test stopped	37	48
170	96	108	4776	Followed by 1566 h recovery	36	48
170	96	140	1488	Followed by 990 h recovery	38	49
170	24	140	1512	Followed by 1902 h recovery	46	49
170	336	140	1129	Followed by 989 h recovery	39	50
170	96	140	576	Cyclic. Ruptured after 65 h at 170 MN m^{-2} 3rd cycle	89	50
140	576	170	96	Cyclic. Ruptured after 118 h at 140 MN m^{-2} 3rd cycle	92	50

Note: 1% has been added to the total creep strains to allow routine processing of the following test phases:

RF 36 2nd loading at 108 MN m^{-2} Part 1
RF 38 2nd loading at 140 MN m^{-2} Part 1
RF 46 2nd loading at 140 MN m^{-2} Part 1
RF 39 2nd loading at 140 MN m^{-2} Part 1
RF 89 2nd, 4th loadings at 140 MN m^{-2}
RF 92 3rd, 5th loadings at 140 MN m^{-2}

The data listed on the appropriate microfiche is therefore affected accordingly and 1% should be subtracted from all total strains and from the coefficient, E_0 , to recover the original data in these cases.

Table 8

PRIOR HEATING AT 195°C AND EQUIVALENT TIMES AT 180, 165 AND 150°C

Temperature °C	t_2/t_1	Time h		
195	1	288	1056	3192
180	3.74	1078	3953	11948
165	15.32	4412	16178	48901
150	69.38	19981	73265	221460

$$t_1 \exp - \frac{Q}{RT_1} = \phi = t_2 \exp - \frac{Q}{RT_2}$$

then

$$\log \left(\frac{t_2}{t_1}\right) = \frac{Q \log e}{R} \left[\frac{1}{T_2} - \frac{1}{T_1}\right]$$

where activation energy (Q) = 37060 cal/mol

Boltzmann's constant (R) = 1.987 cal/mol

t_1, t_2, times in h at temperatures T_1, T_2 deg K

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No.	Author	Title, etc.
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2	W.A.P. Fisher	A parameter to represent the mechanical properties of aluminium alloys after soaking at elevated temperatures. RAE Technical Note Structures 270 (1959)
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6	J.N. Webb	A strain modified 'steady-state' creep relationship for high strength aluminium alloy. RAE Technical Report 76085 (1976)
7	J.N. Webb	A system for the axial loading of creep specimens. RAE Technical Report 76043 (1976)
8	J.N. Webb	A parallel motion creep extensometer. Aeronautical Research Council, CP No.1173 (1971)

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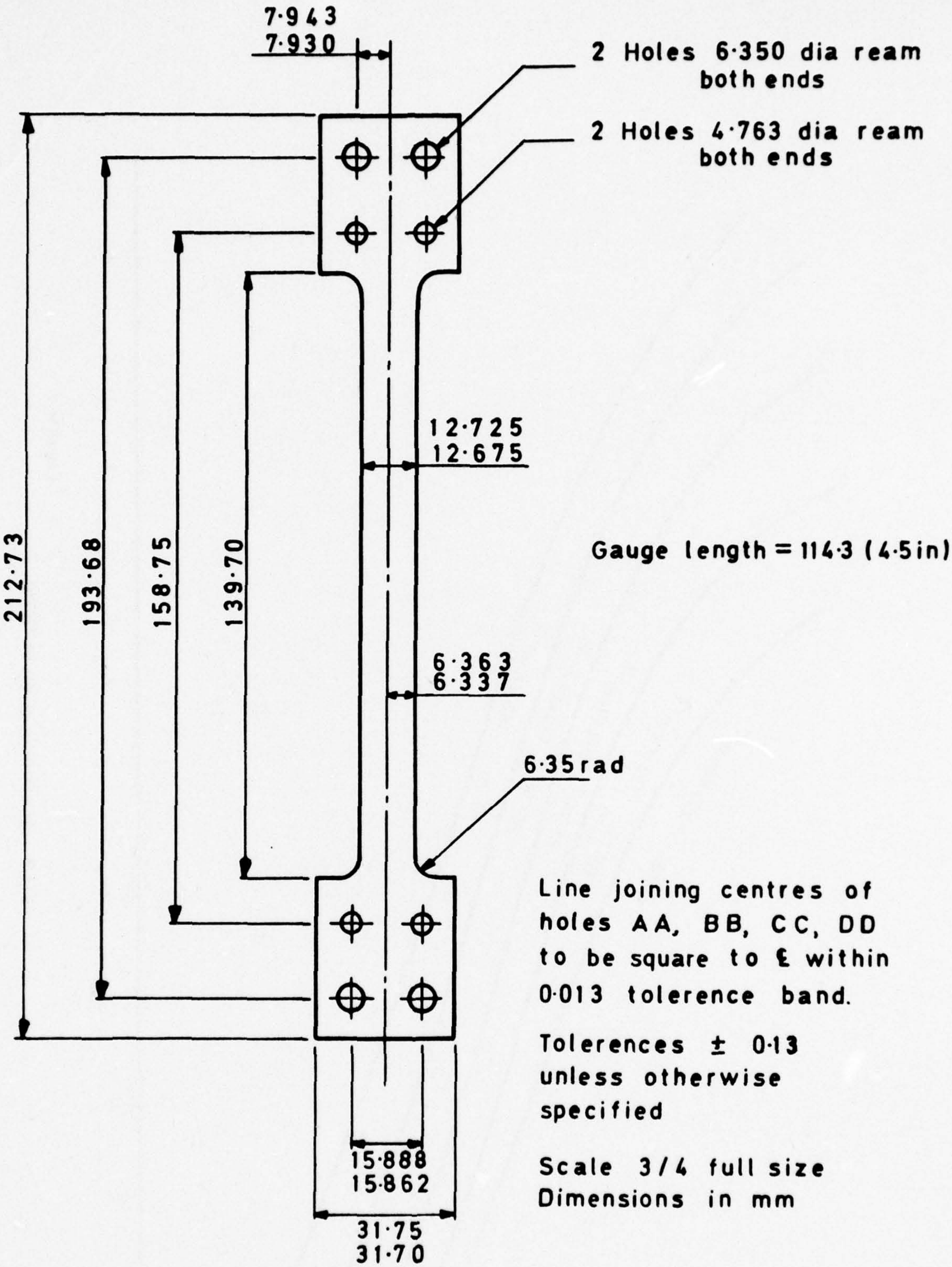

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Fig. 1 Test specimen

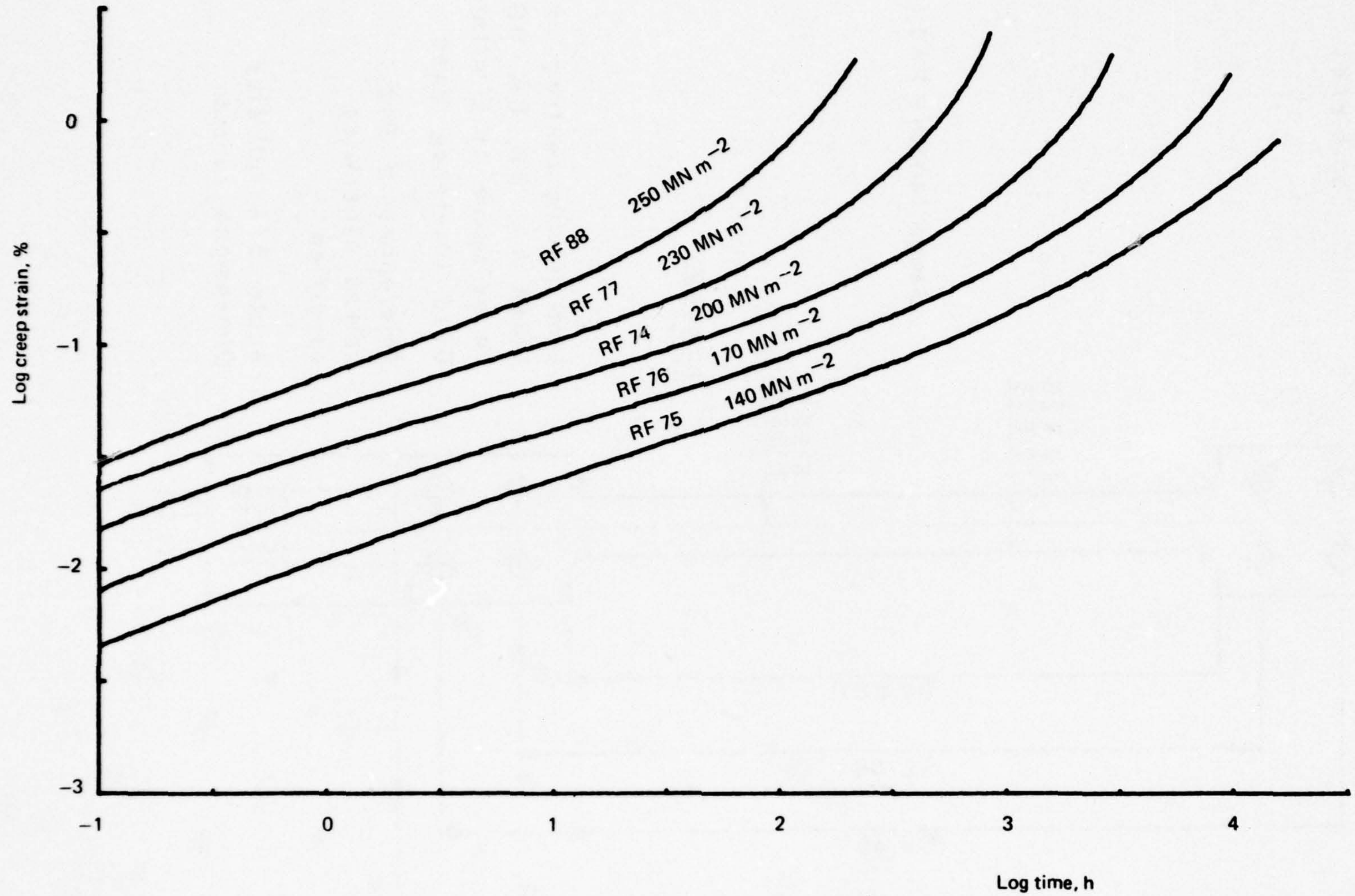


Fig 2 Continuous creep at 150°C

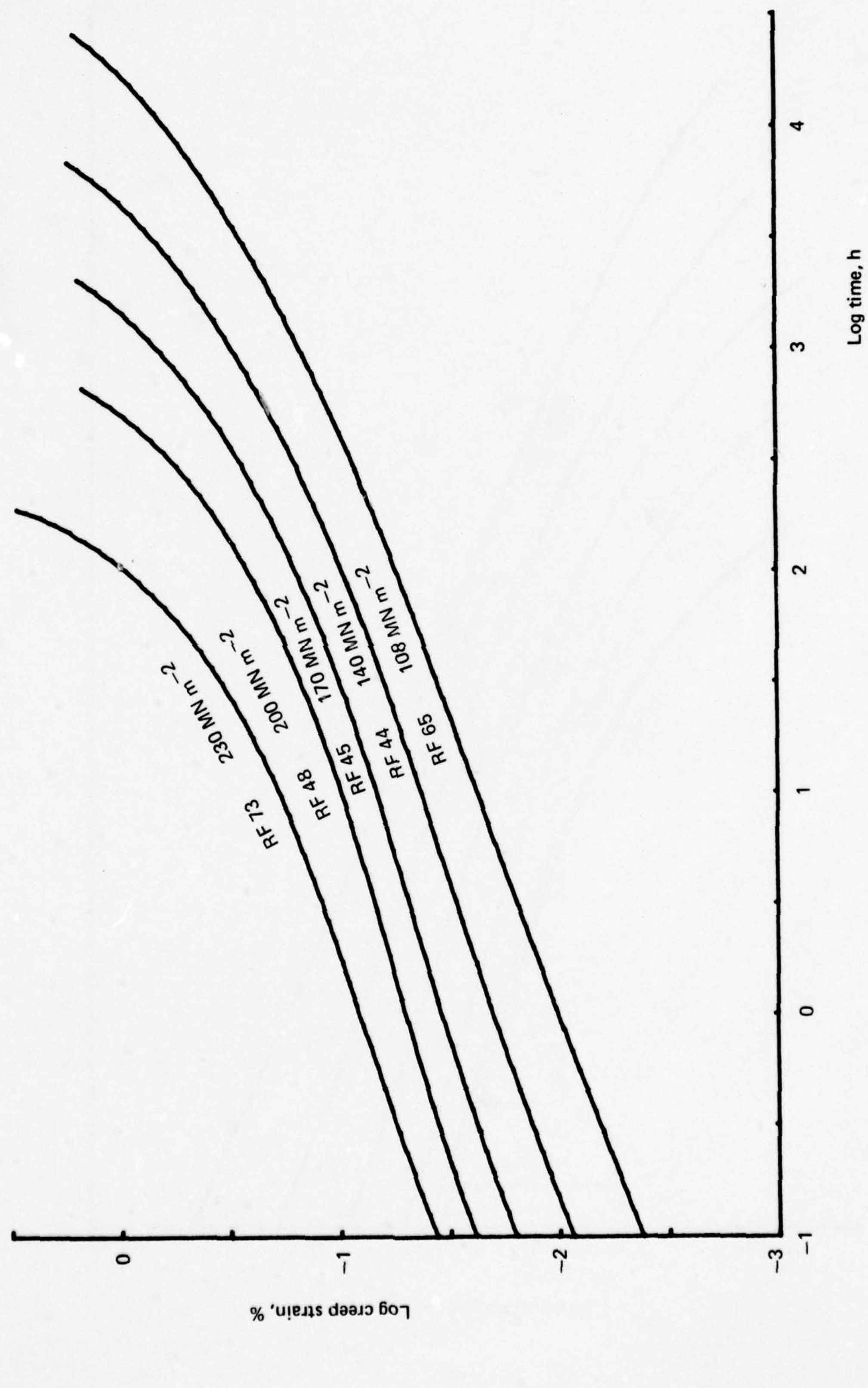


Fig 3 Continuous creep at 165°C

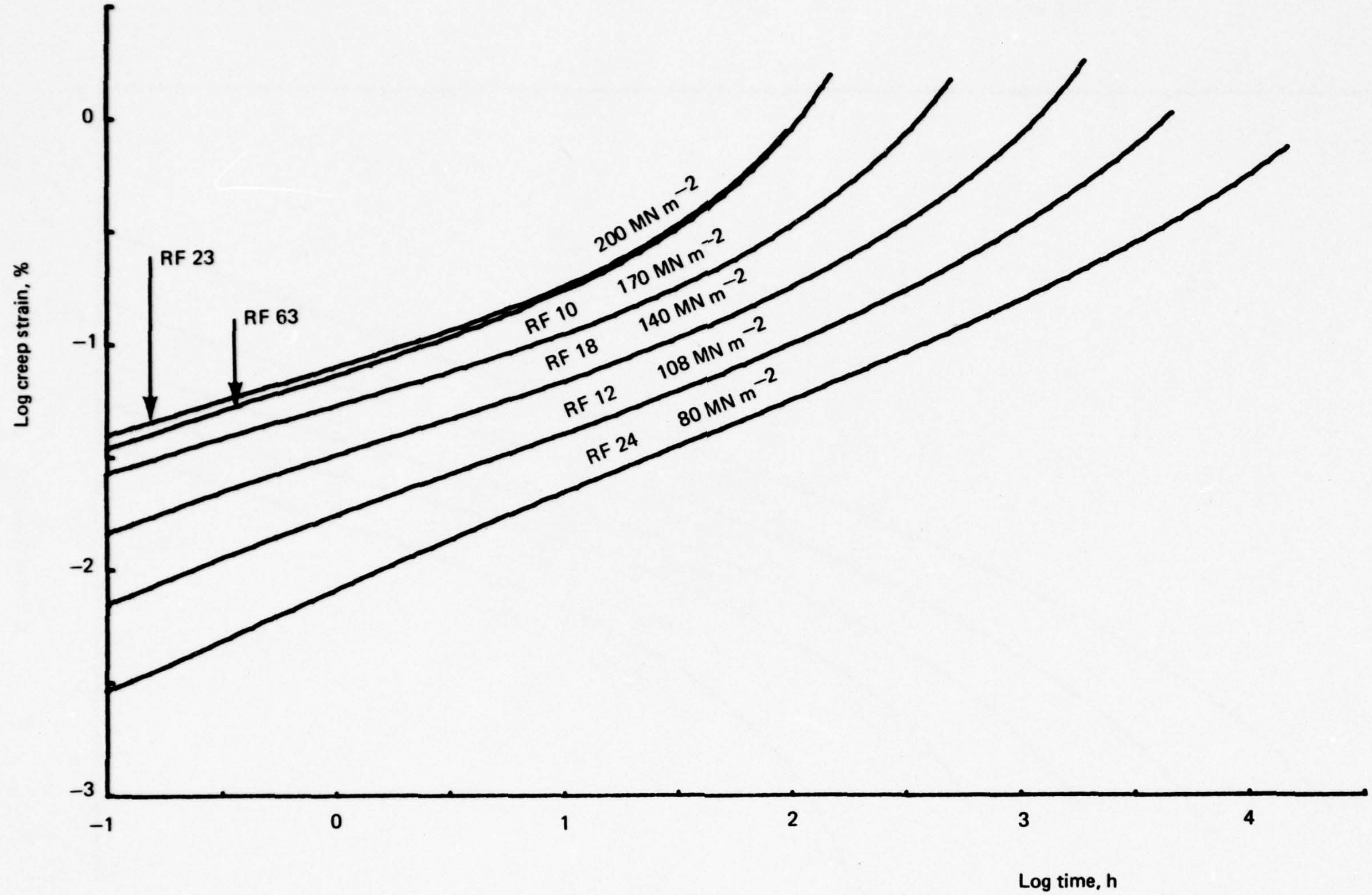


Fig 4 Continuous creep at 180°C

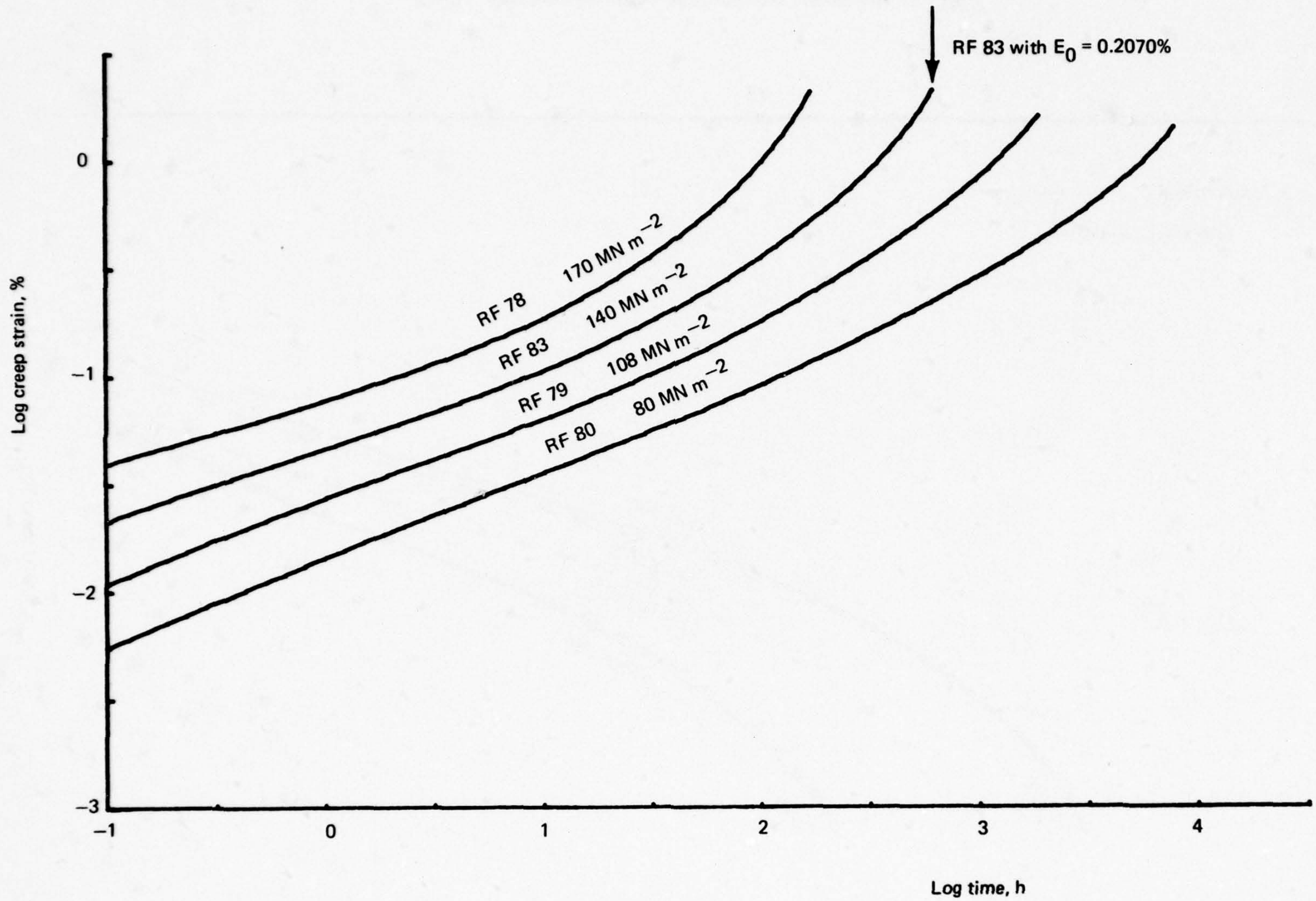


Fig 5 Continuous creep at 195°C

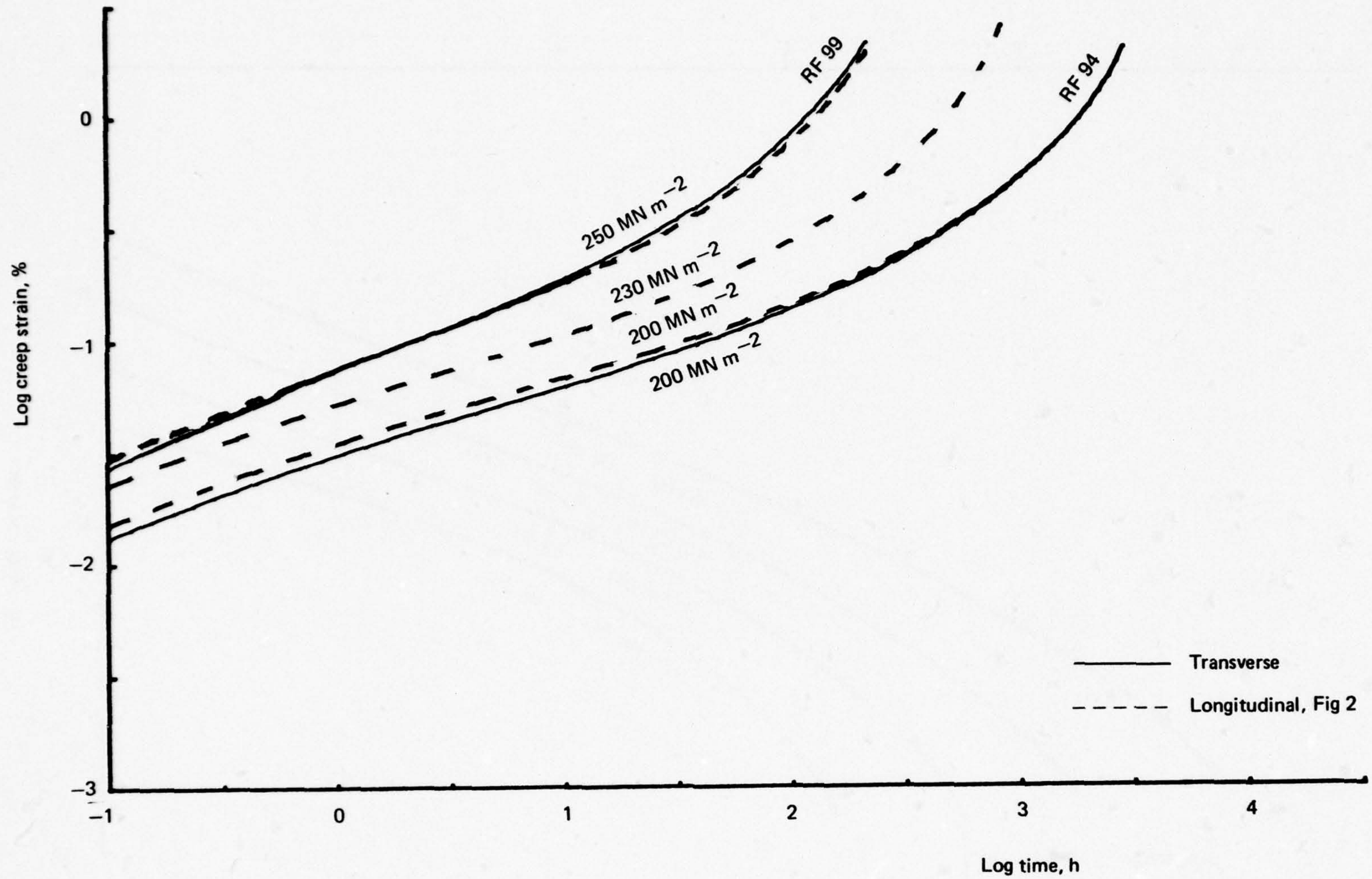


Fig 6 Continuous creep of transverse specimens at 150°C

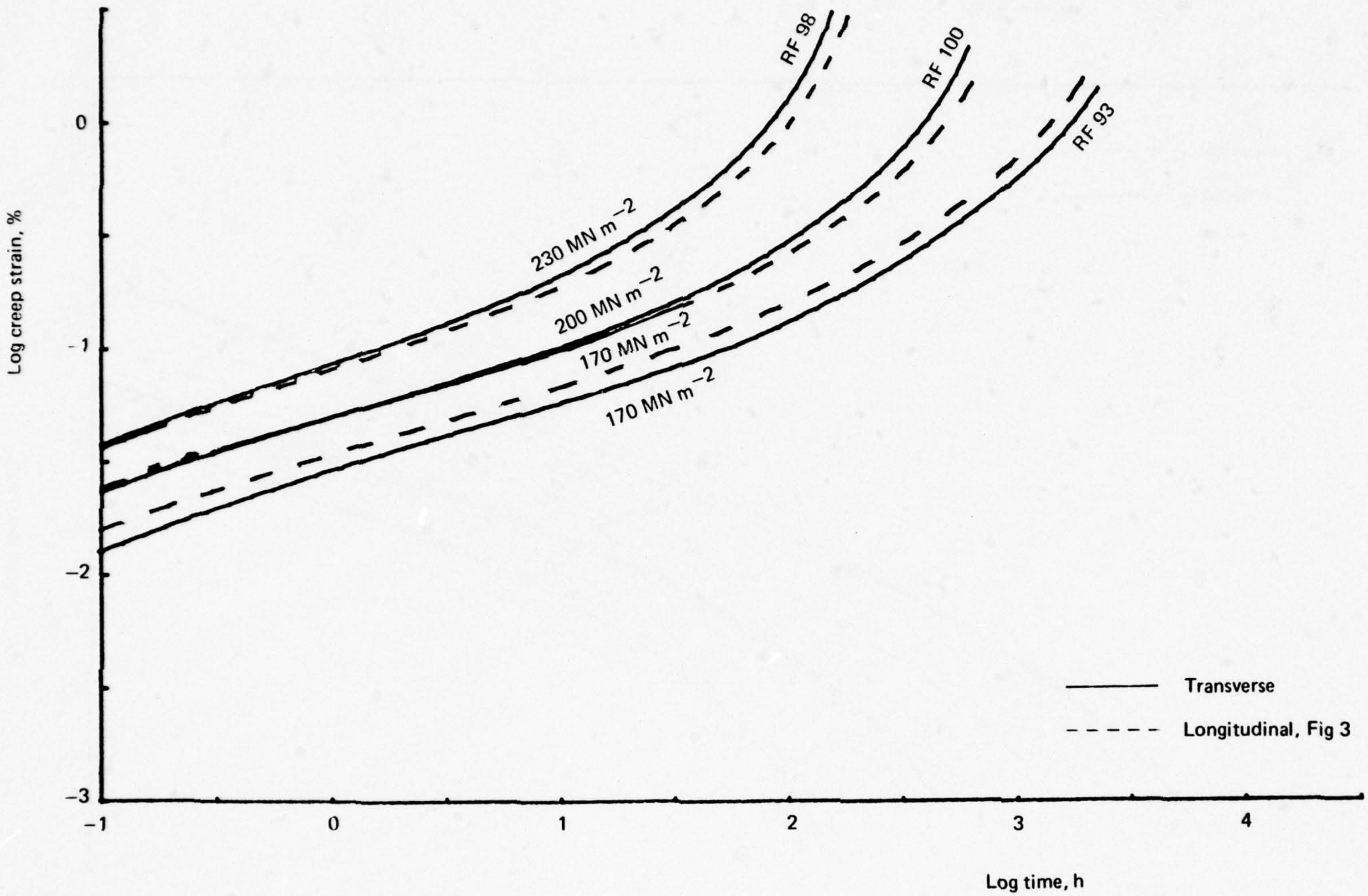


Fig 7 Continuous creep of transverse specimens at 165°C

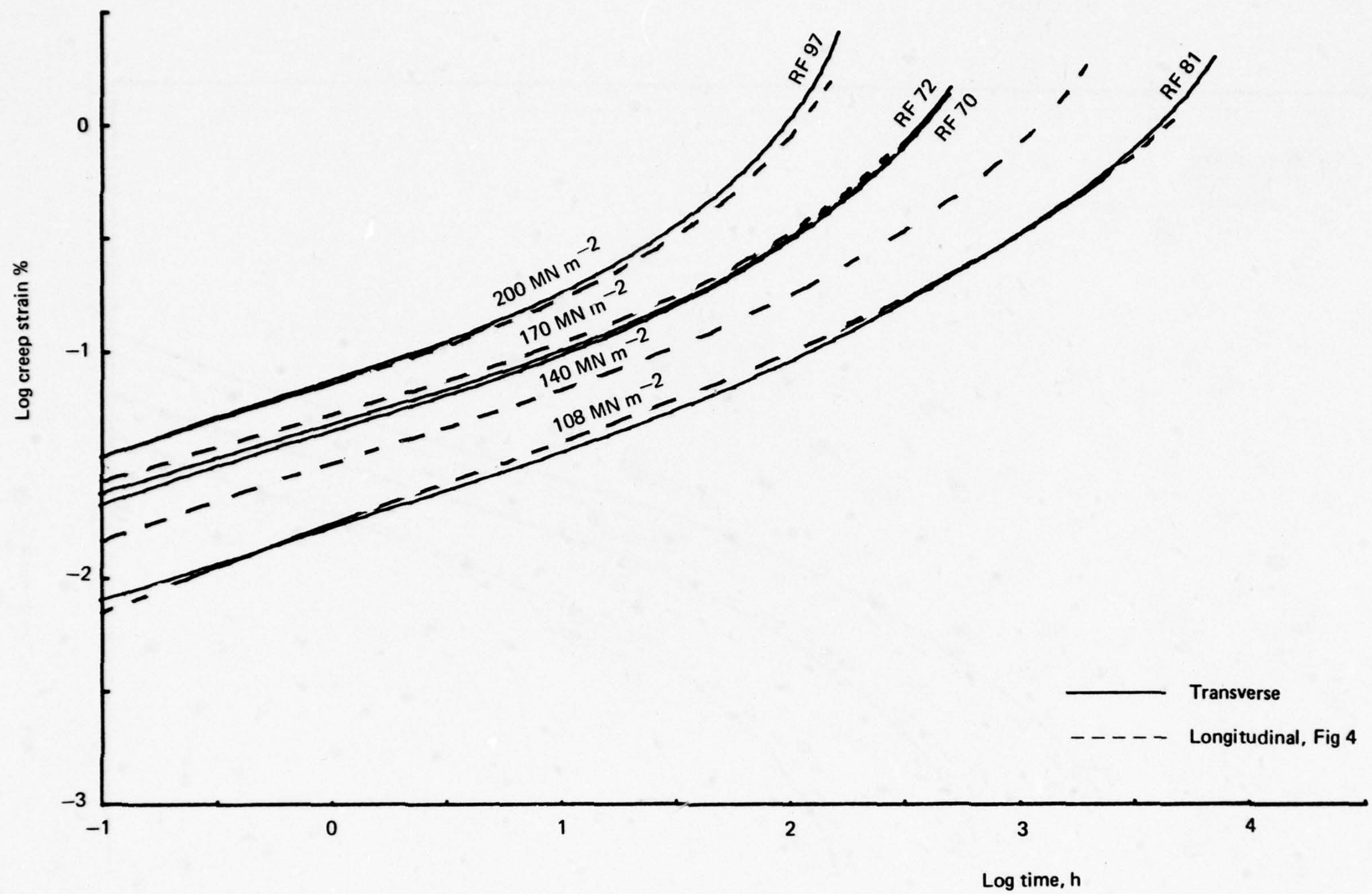


Fig 8 Continuous creep of transverse specimens at 180°C

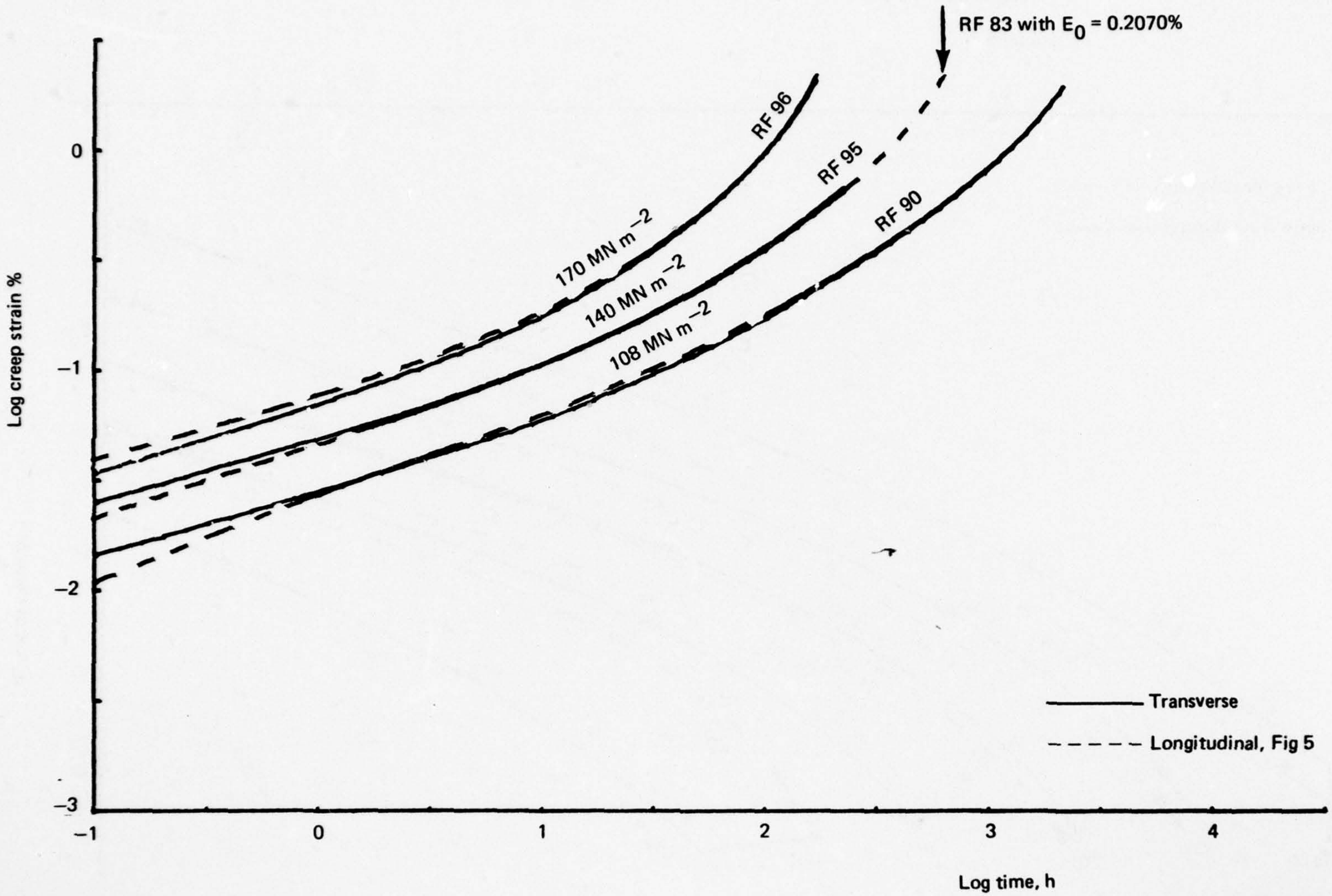


Fig 9 Continuous creep of transverse specimens at 195°C

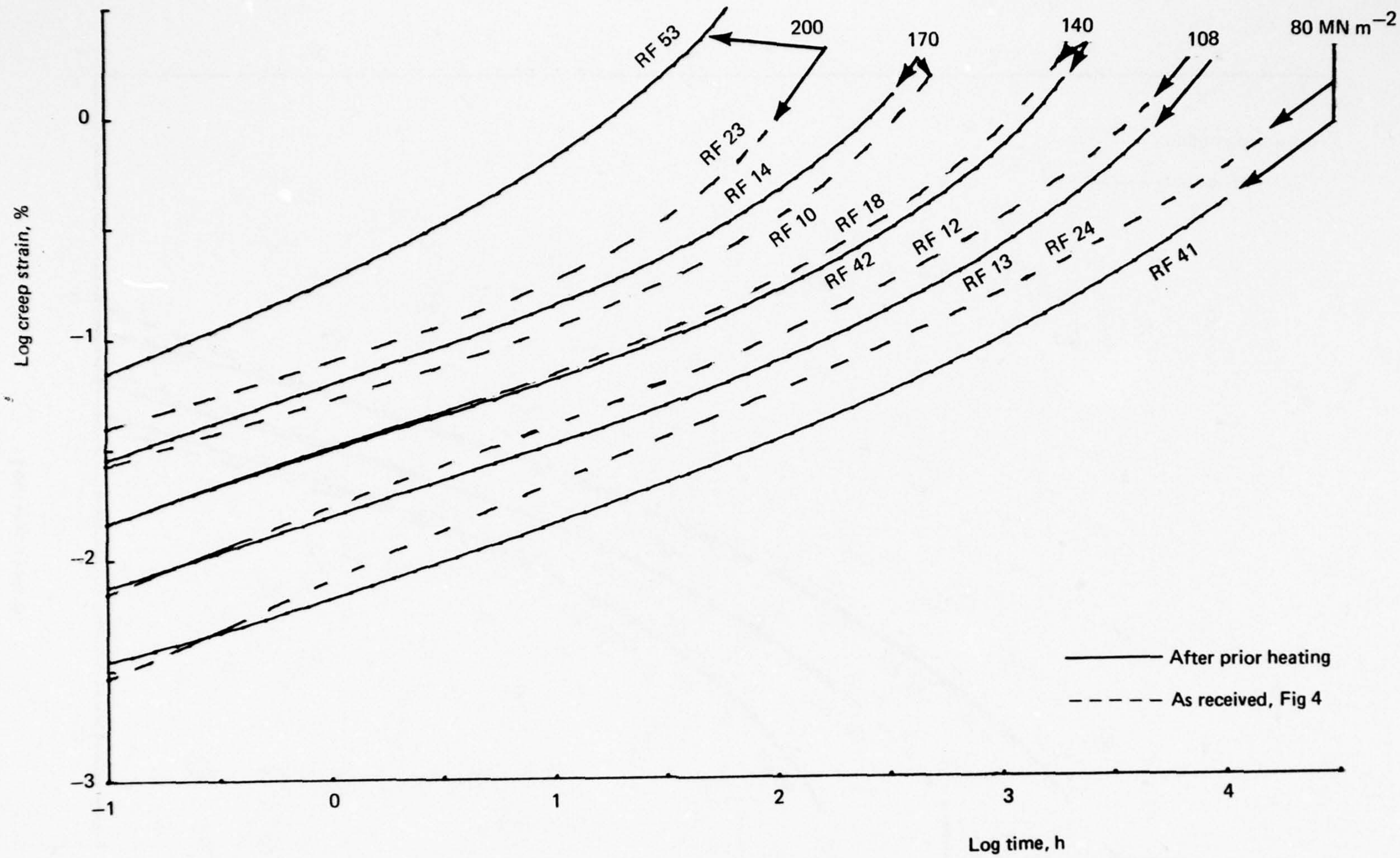


Fig 10 Creep at 180°C after prior heating for 1056 h at 195°C

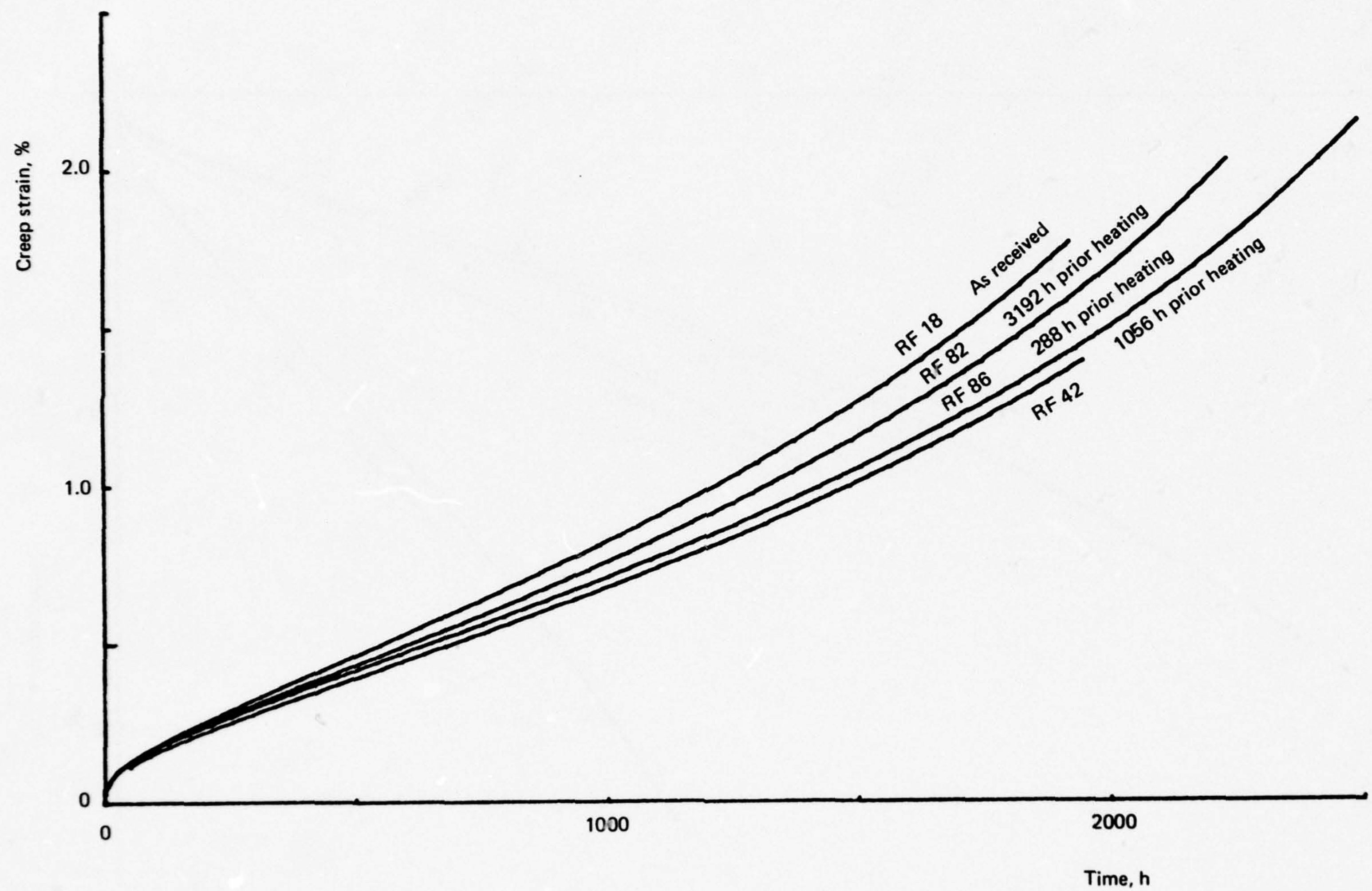


Fig 11 Creep at 140 MN m^{-2} and 180°C after prior heating at 195°C

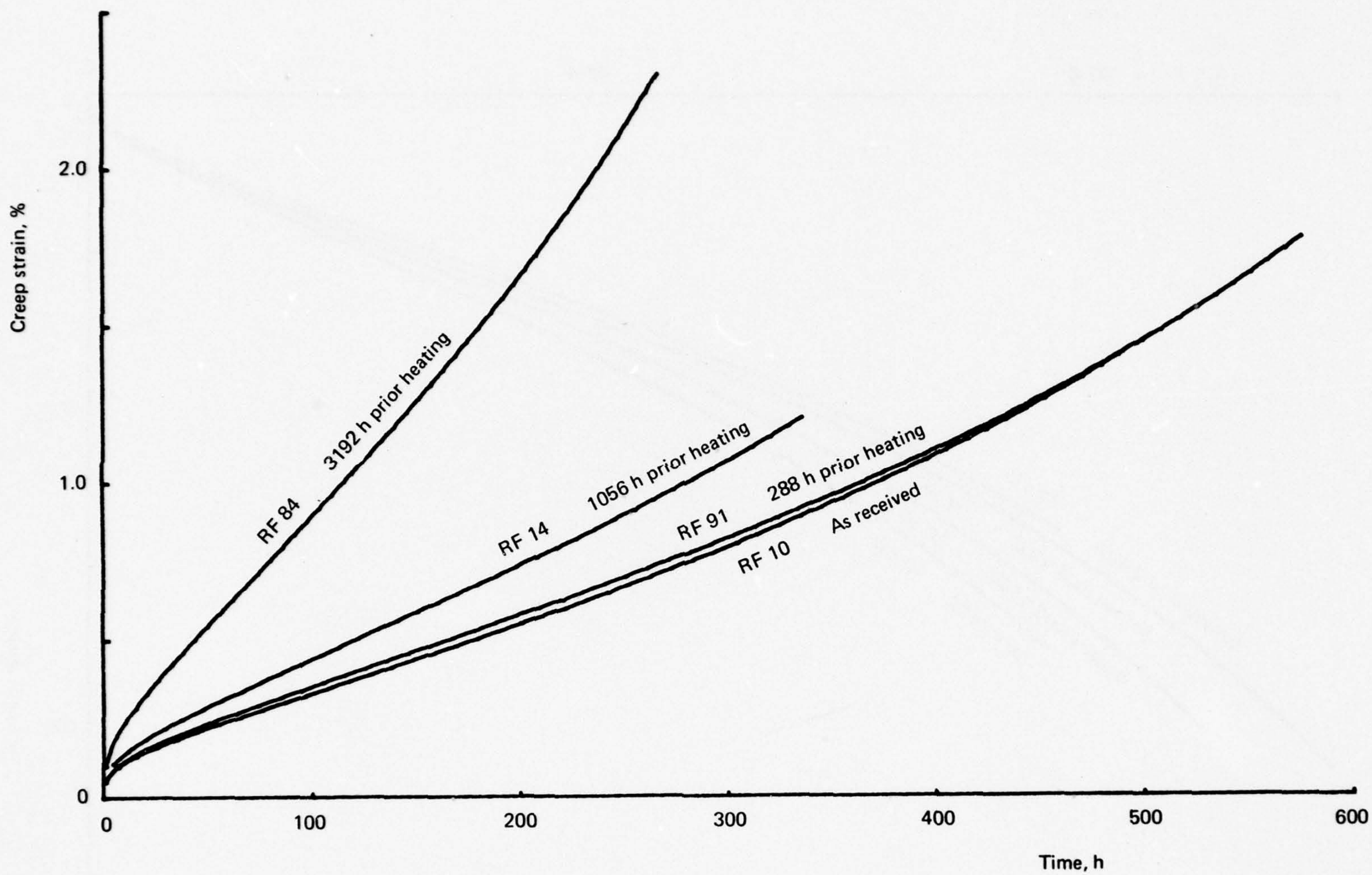


Fig 12 Creep at 170 MN m^{-2} and 180°C after prior heating at 195°C

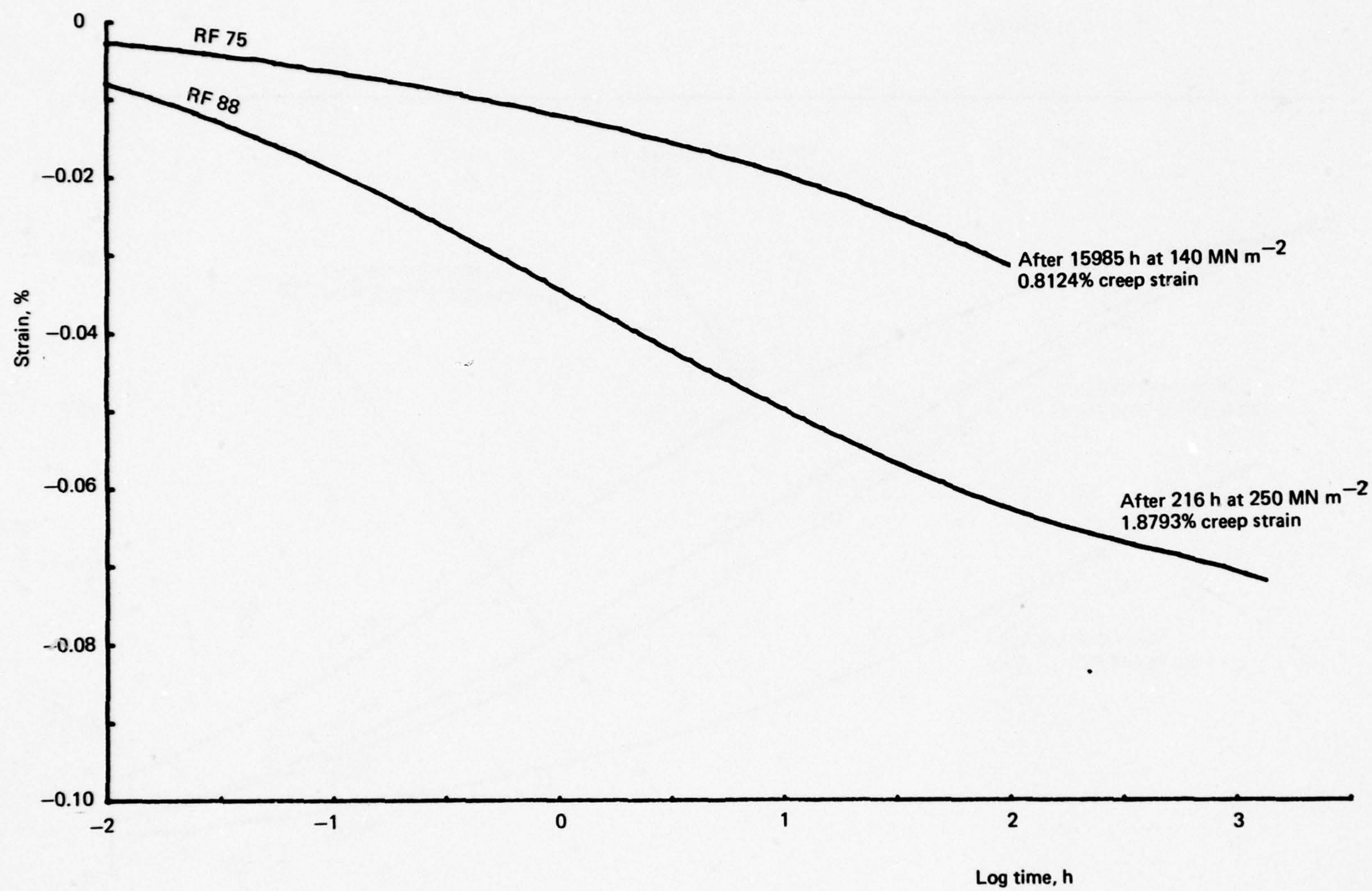


Fig 13 Strain recovery at 150°C

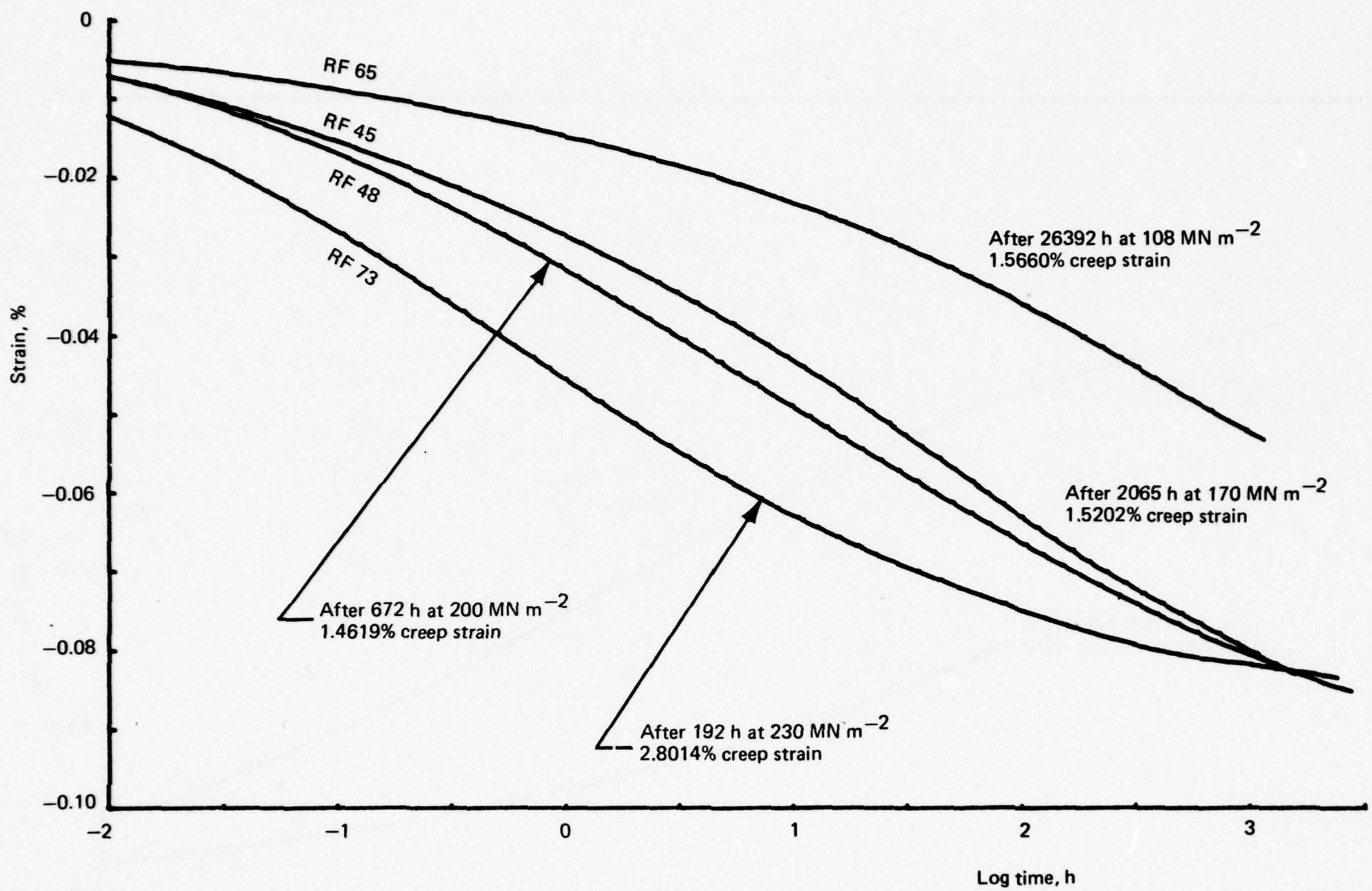


Fig 14 Strain recovery at 165°C

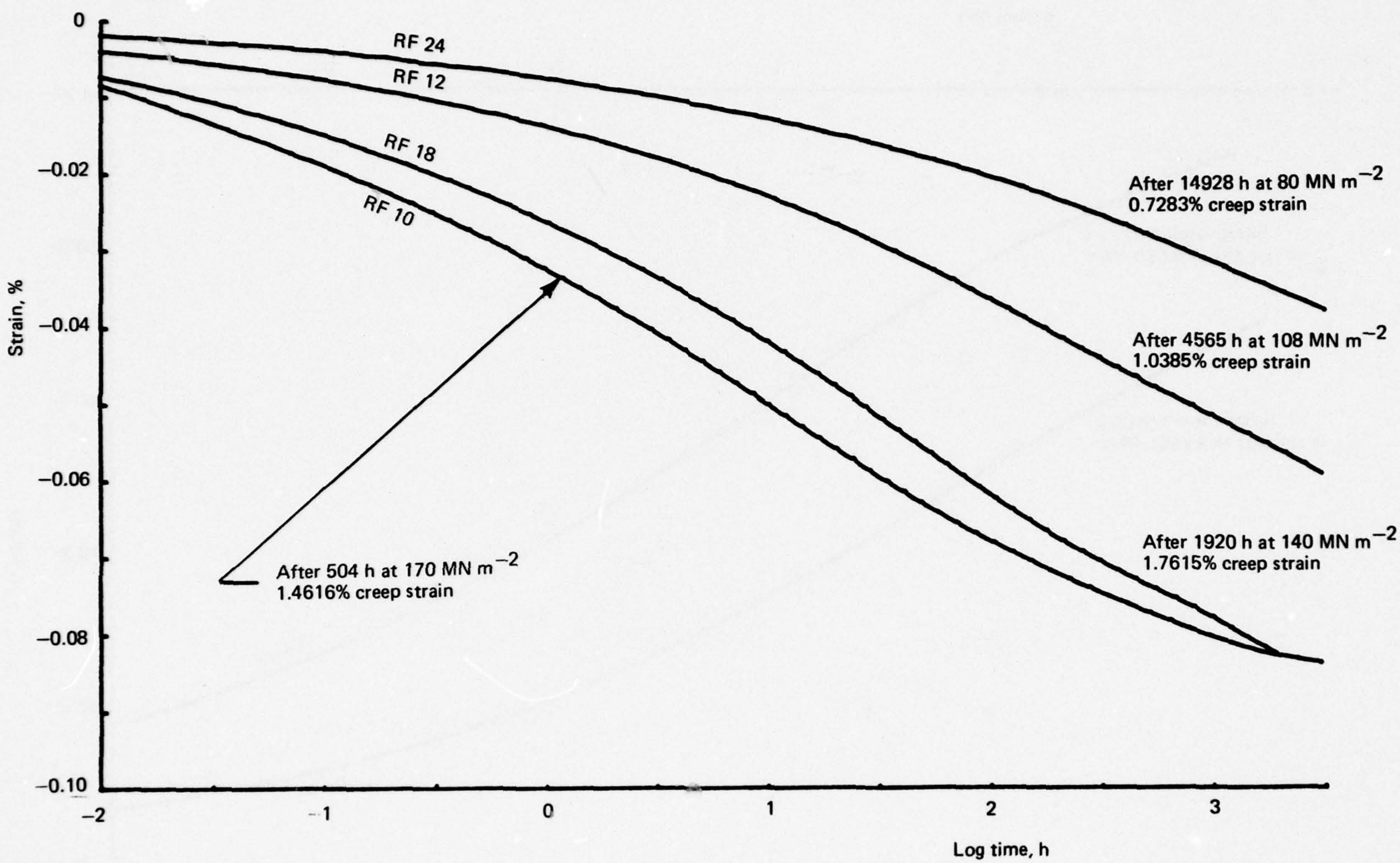


Fig 15 Strain recovery at 180°C

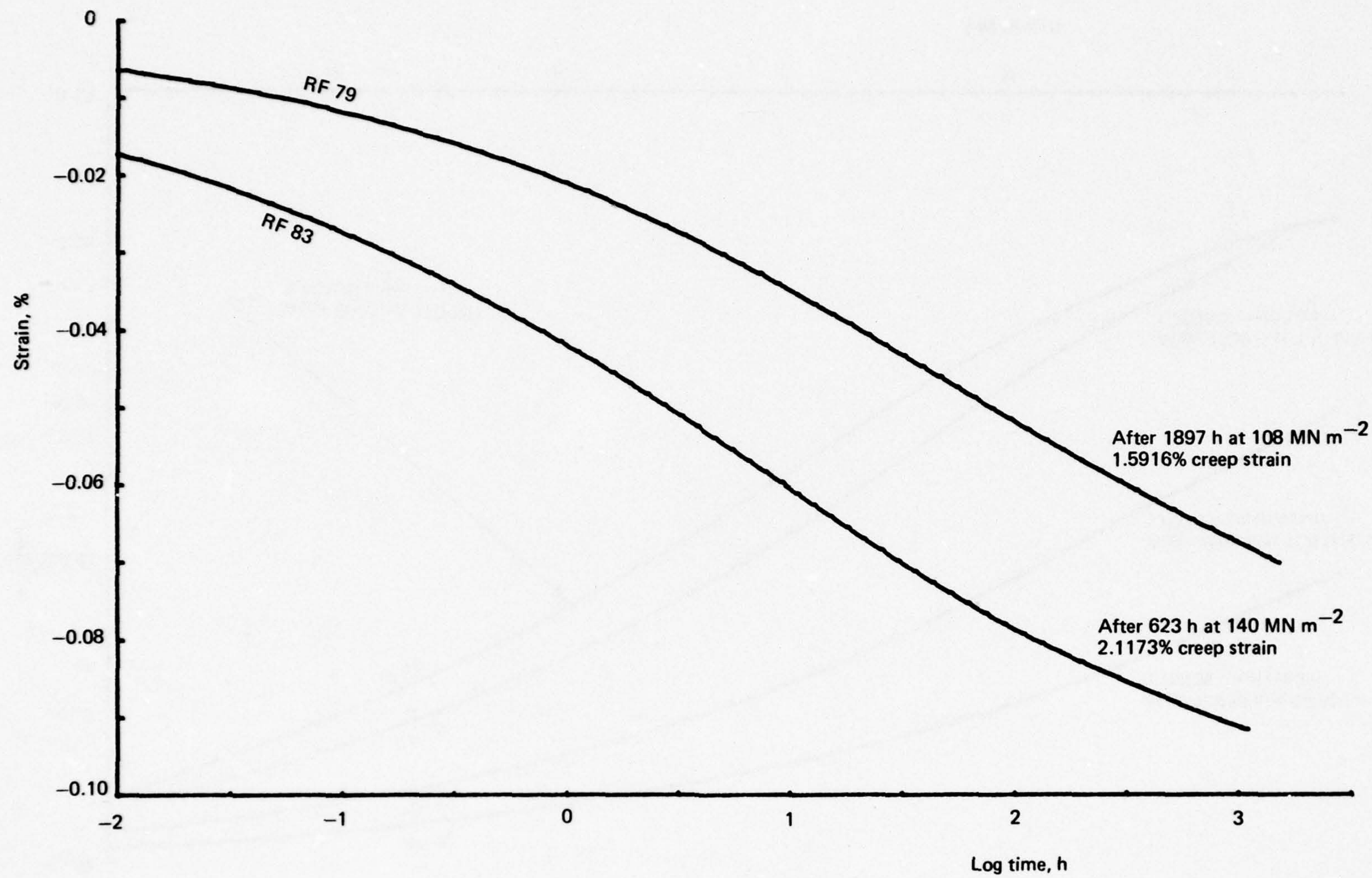


Fig 16 Strain recovery at 195°C

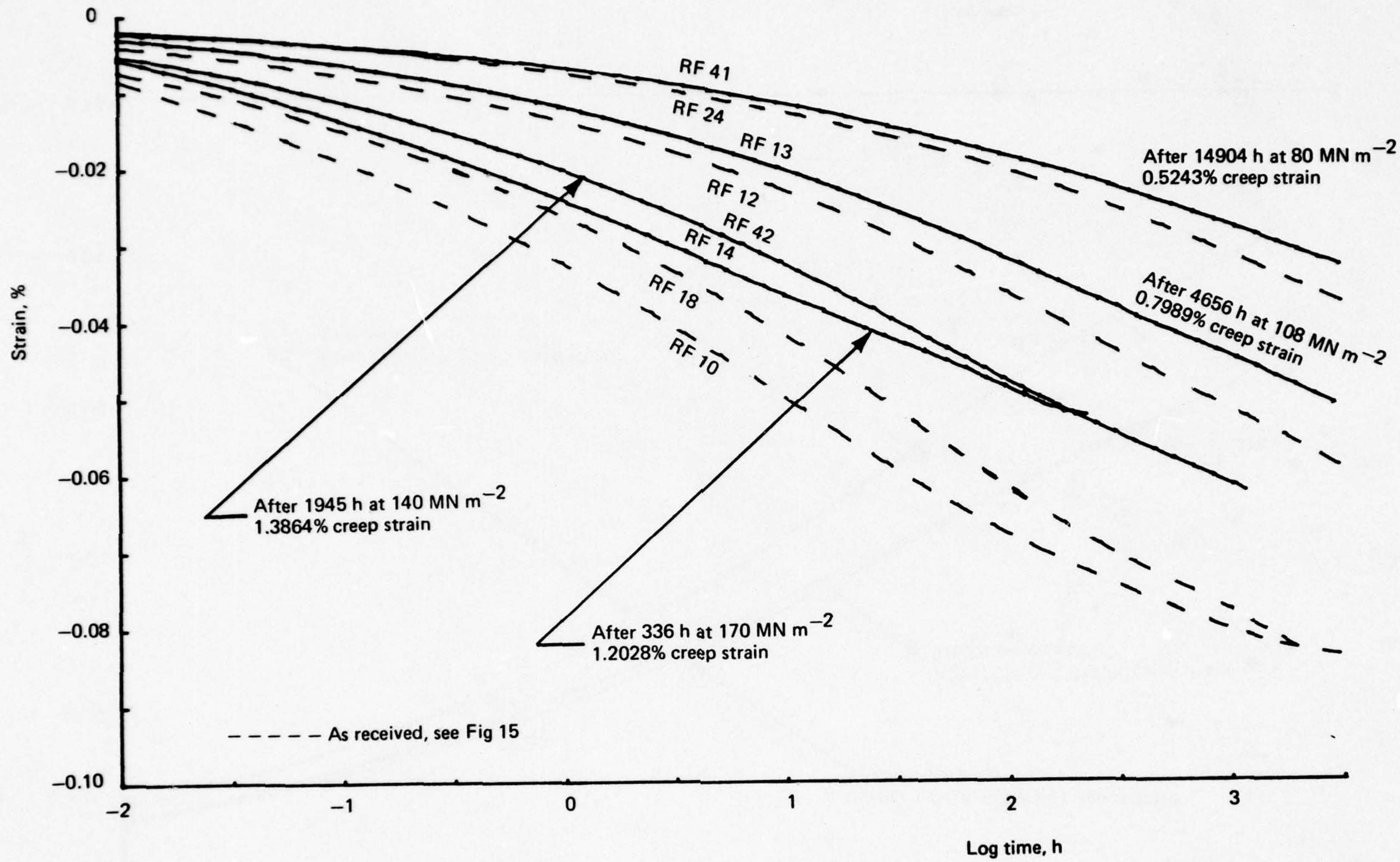


Fig 17 Effect of prior heating on strain recovery at 180°C

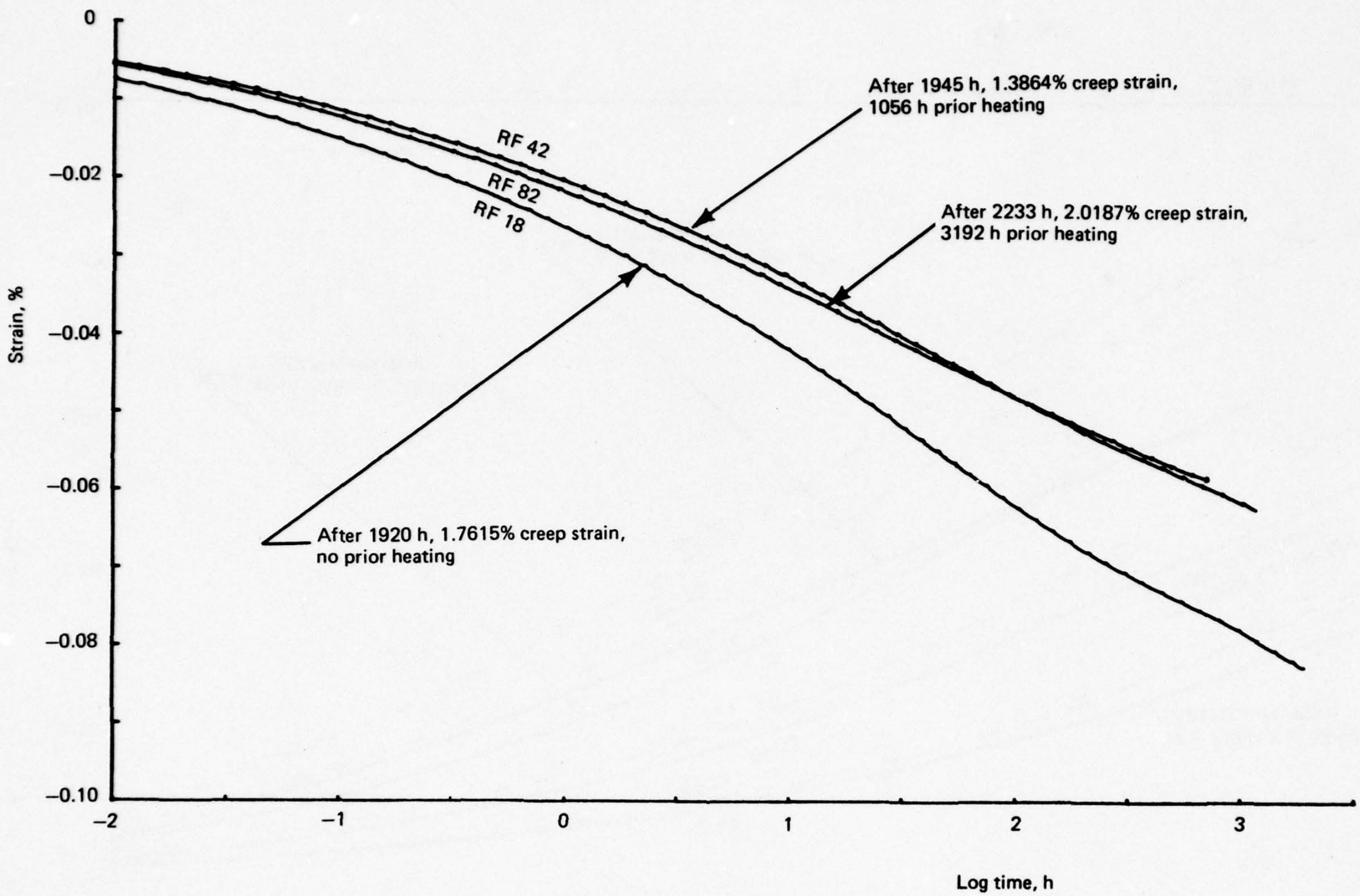


Fig 18 Effect of prior heating on strain recovery after 140 MN m^{-2} at 180°C

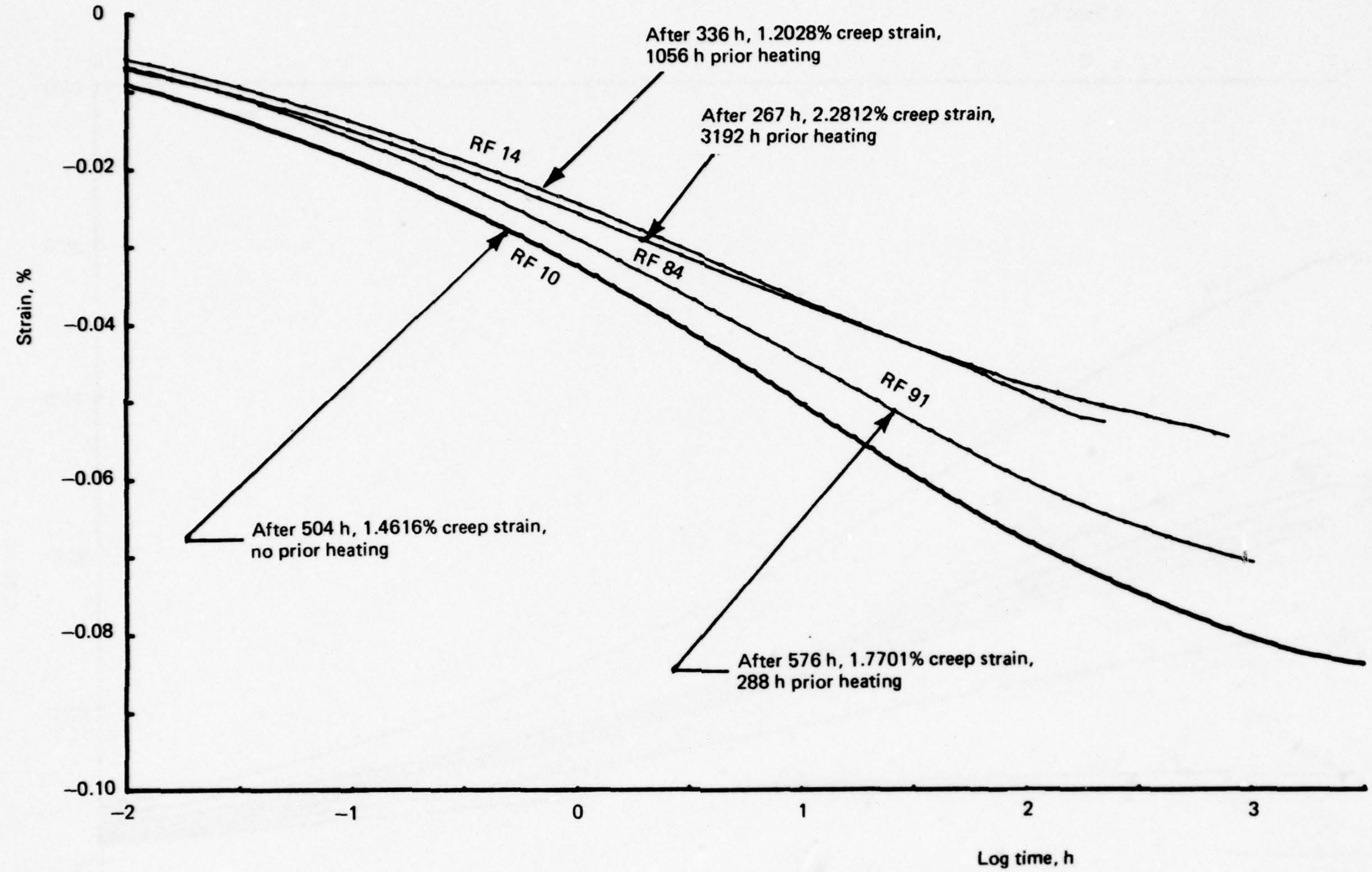


Fig 19 Effect of prior heating on strain recovery after 170 MN m^{-2} at 180°C

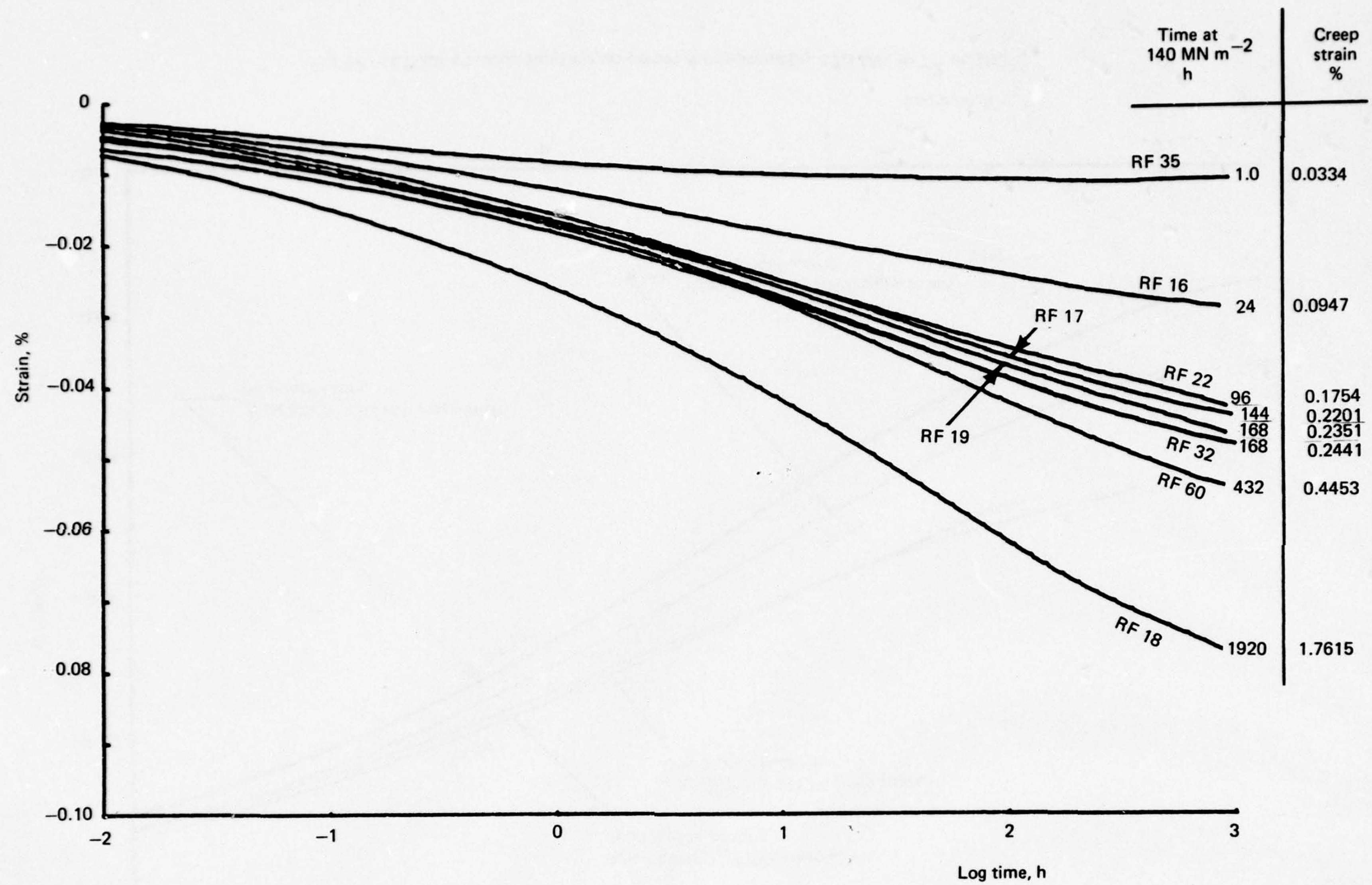


Fig 20 Strain recovery at 180°C after various times at 140 MN m^{-2}

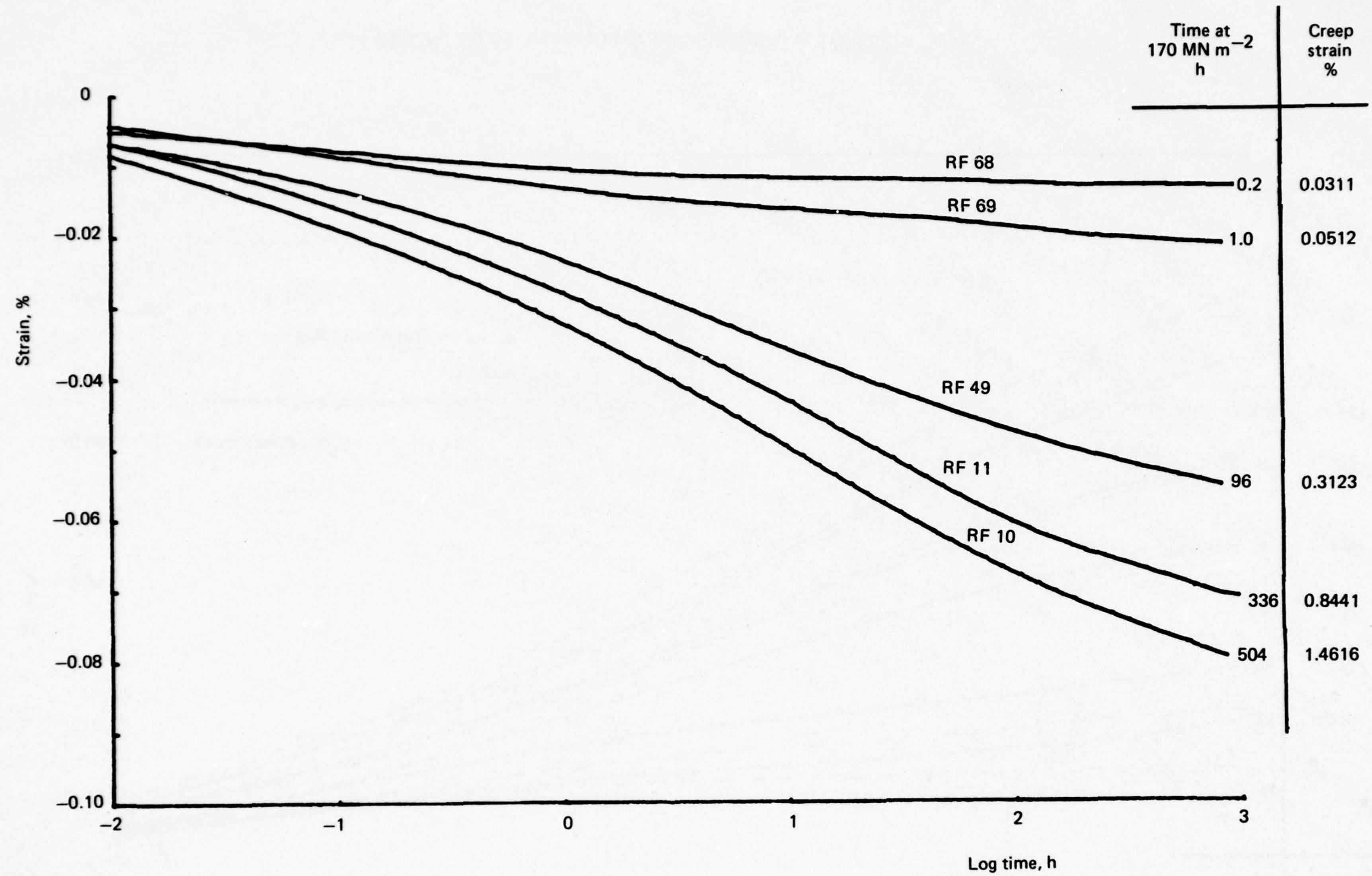


Fig 21 Strain recovery at 180°C after various times at 170 MN m^{-2}

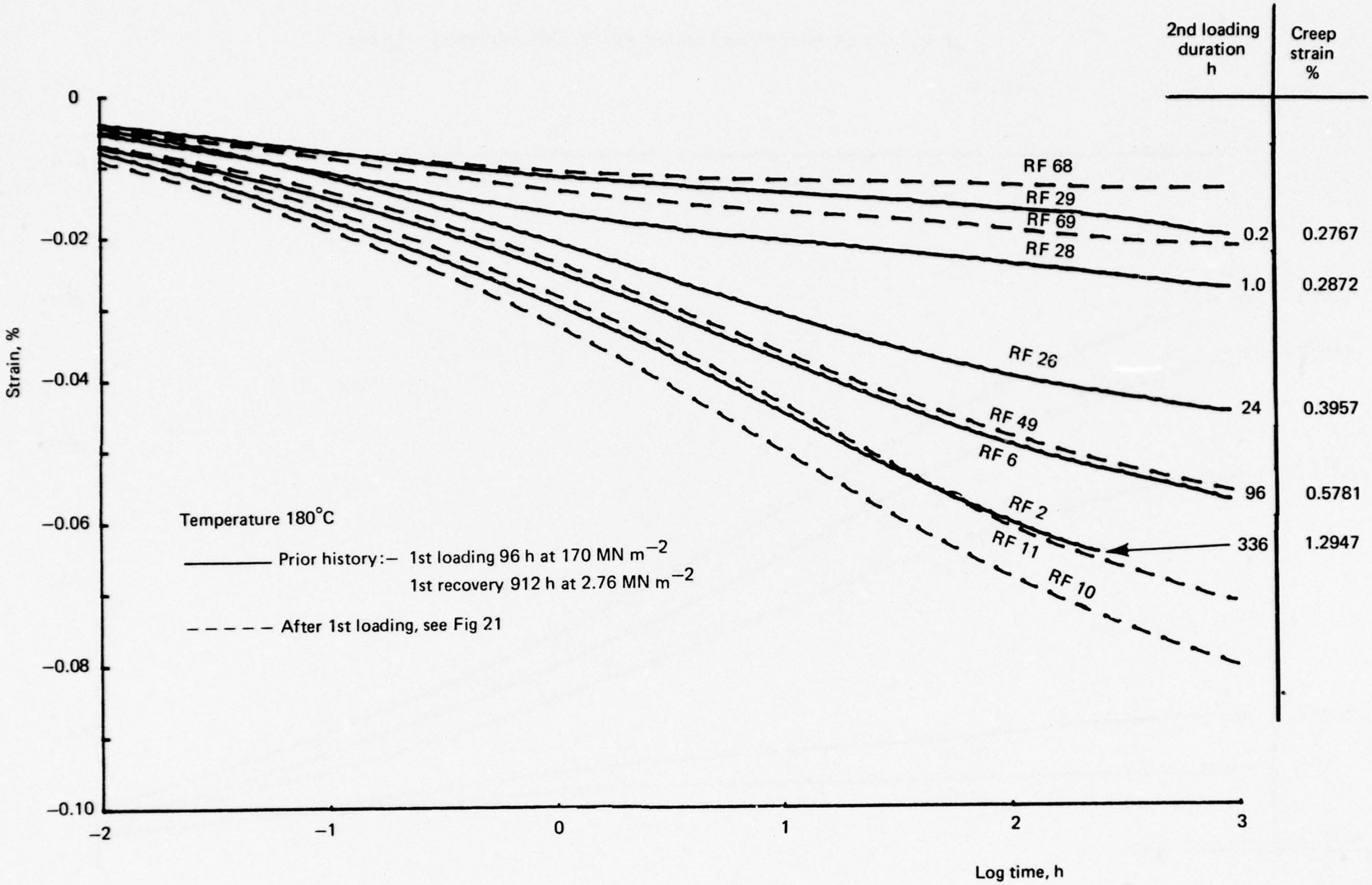


Fig 22 Strain recovery after second loading at 170 MN m^{-2}

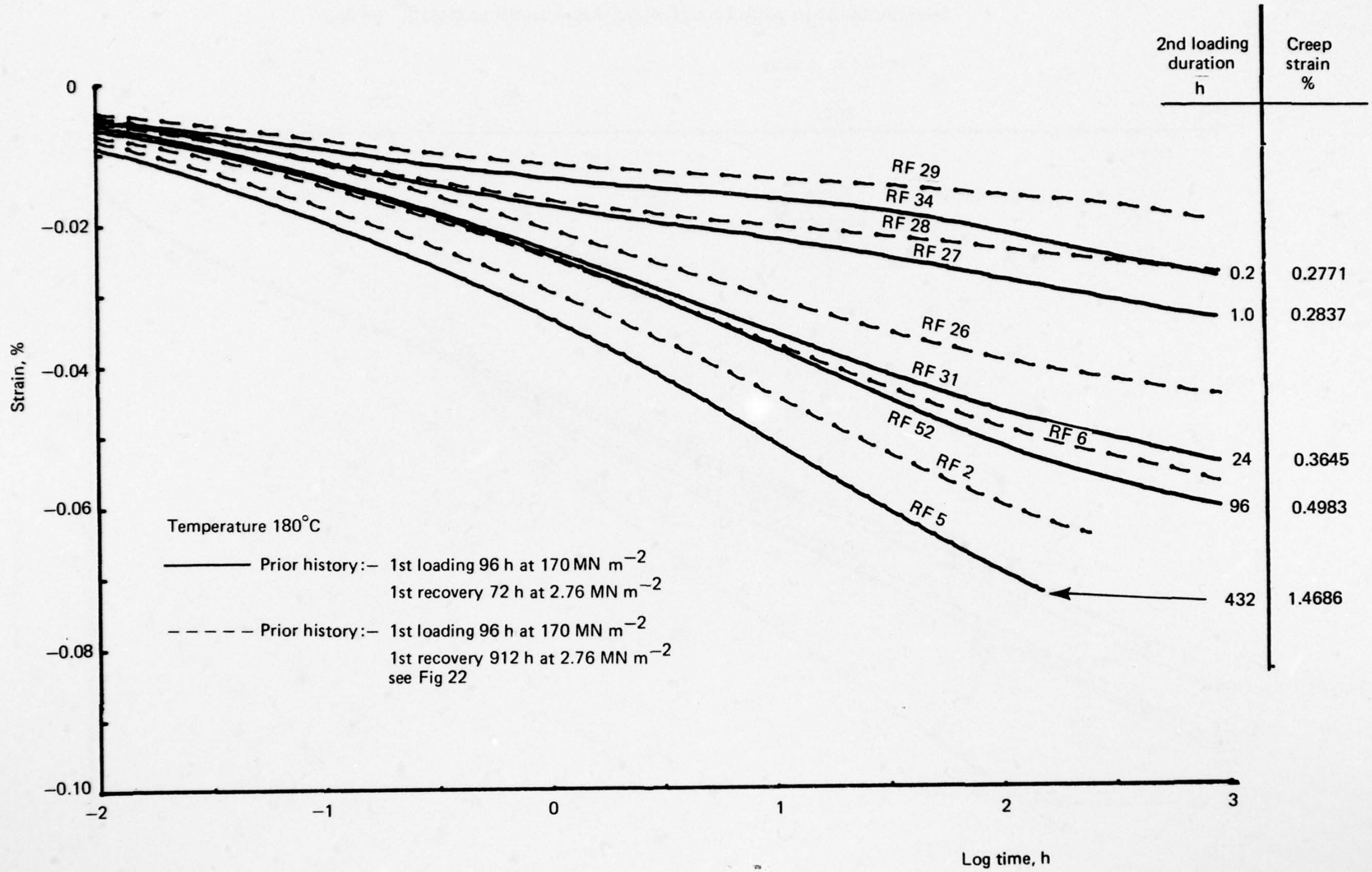


Fig 23 **Strain recovery after second loading at 170 MN m^{-2}**

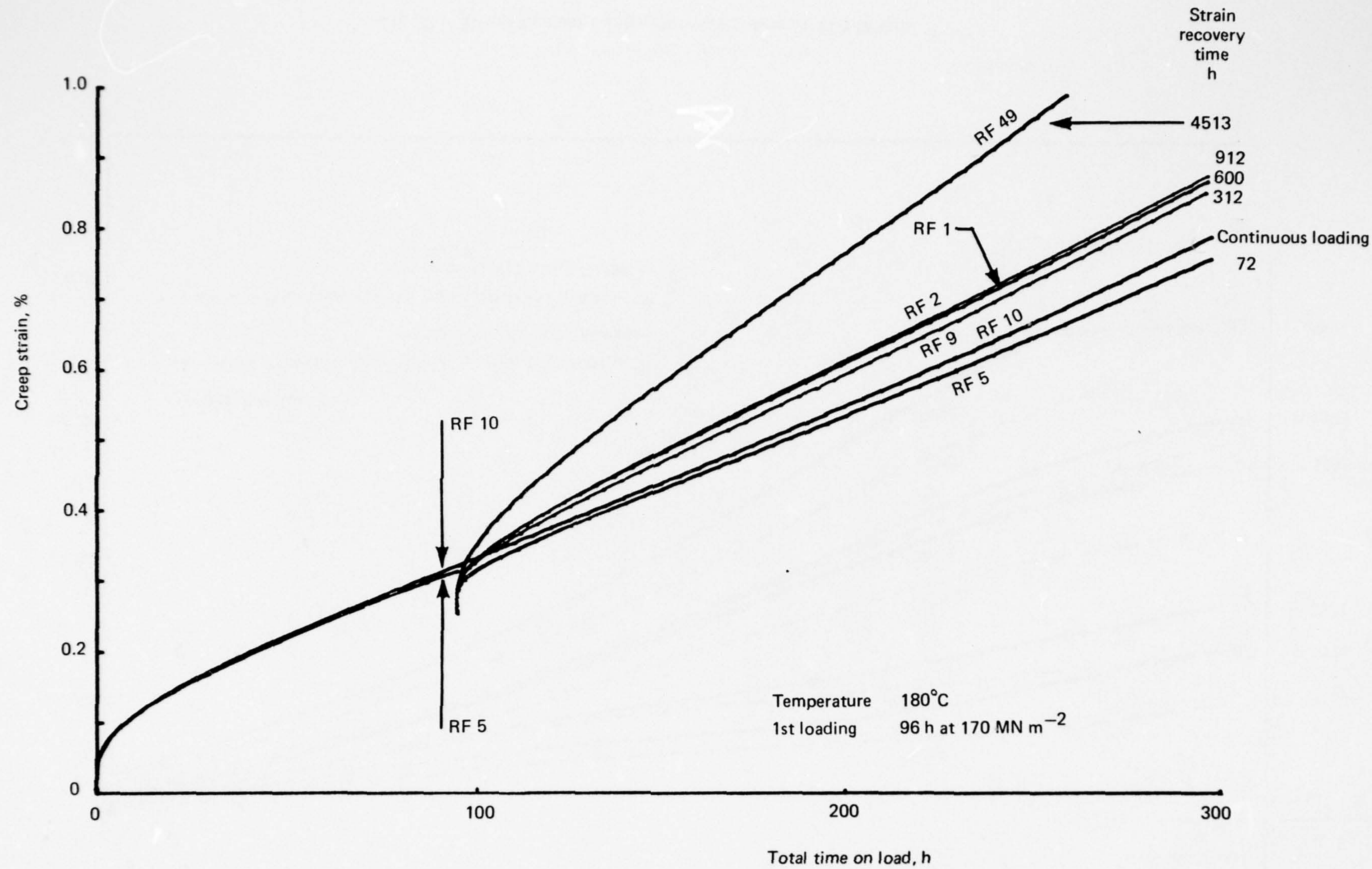


Fig 24 Effect of interrupting loading by a period of strain recovery

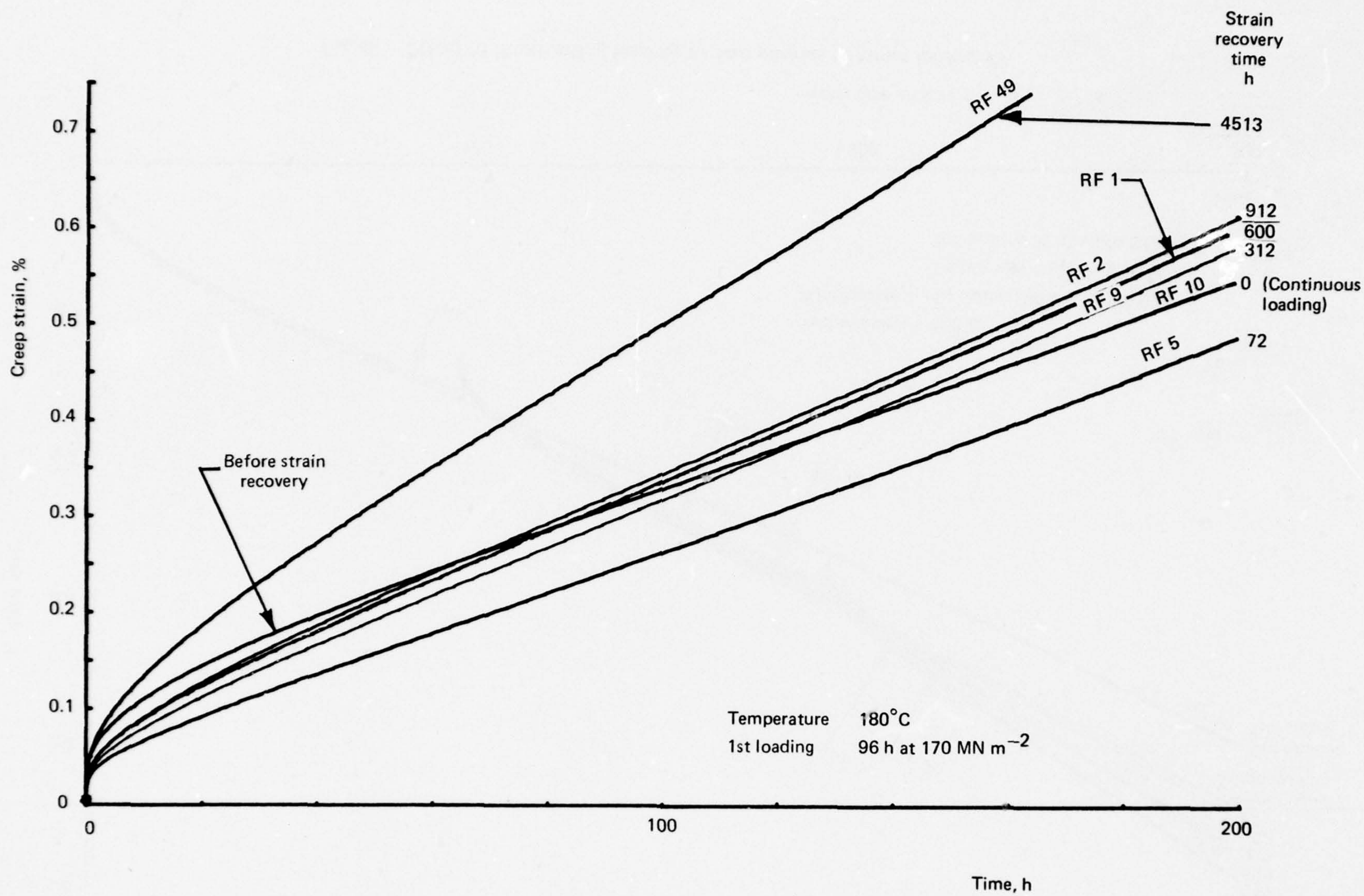


Fig 25 Response after strain recovery

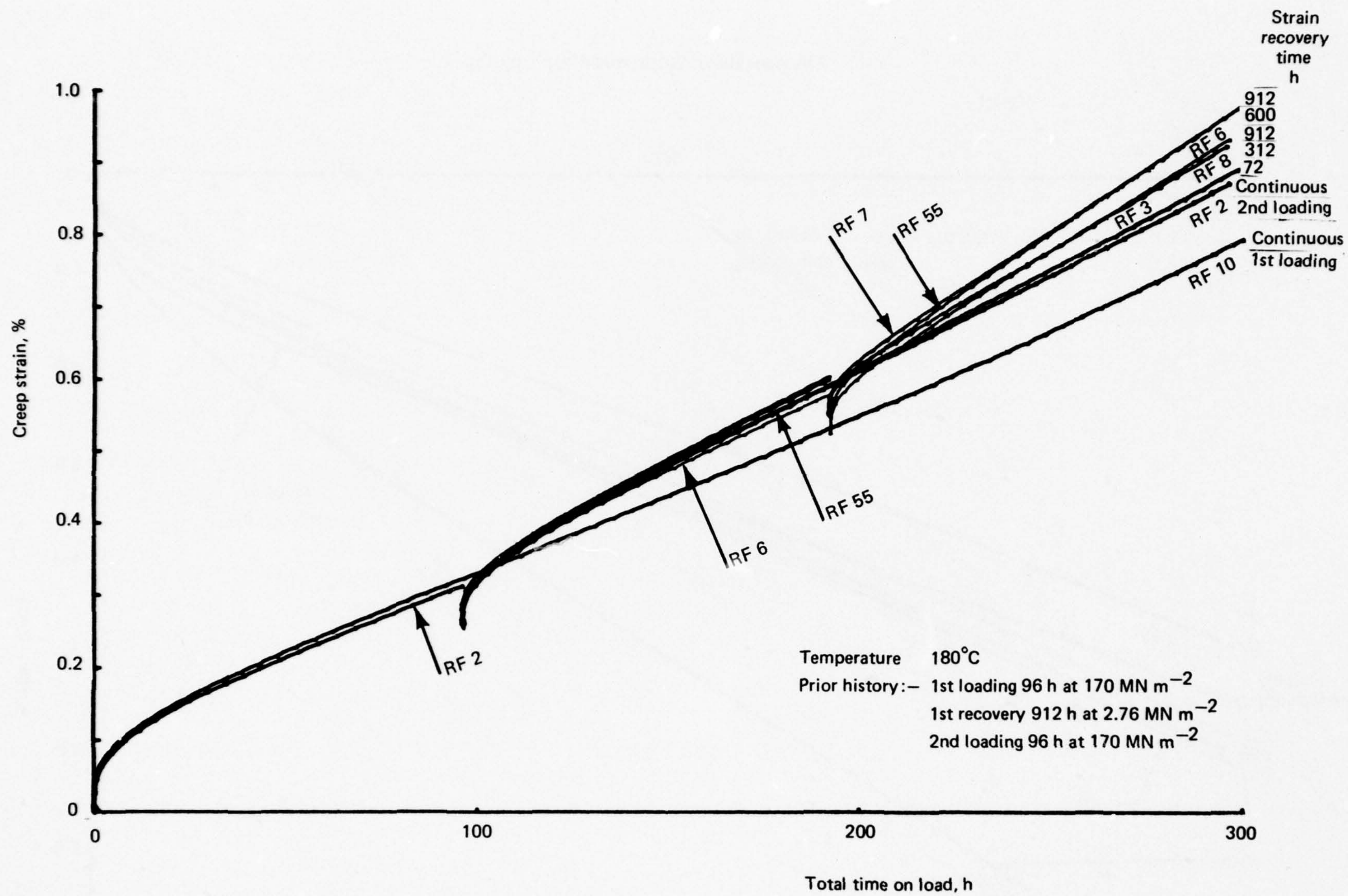


Fig 26 Effect of interrupting loading by two periods of strain recovery

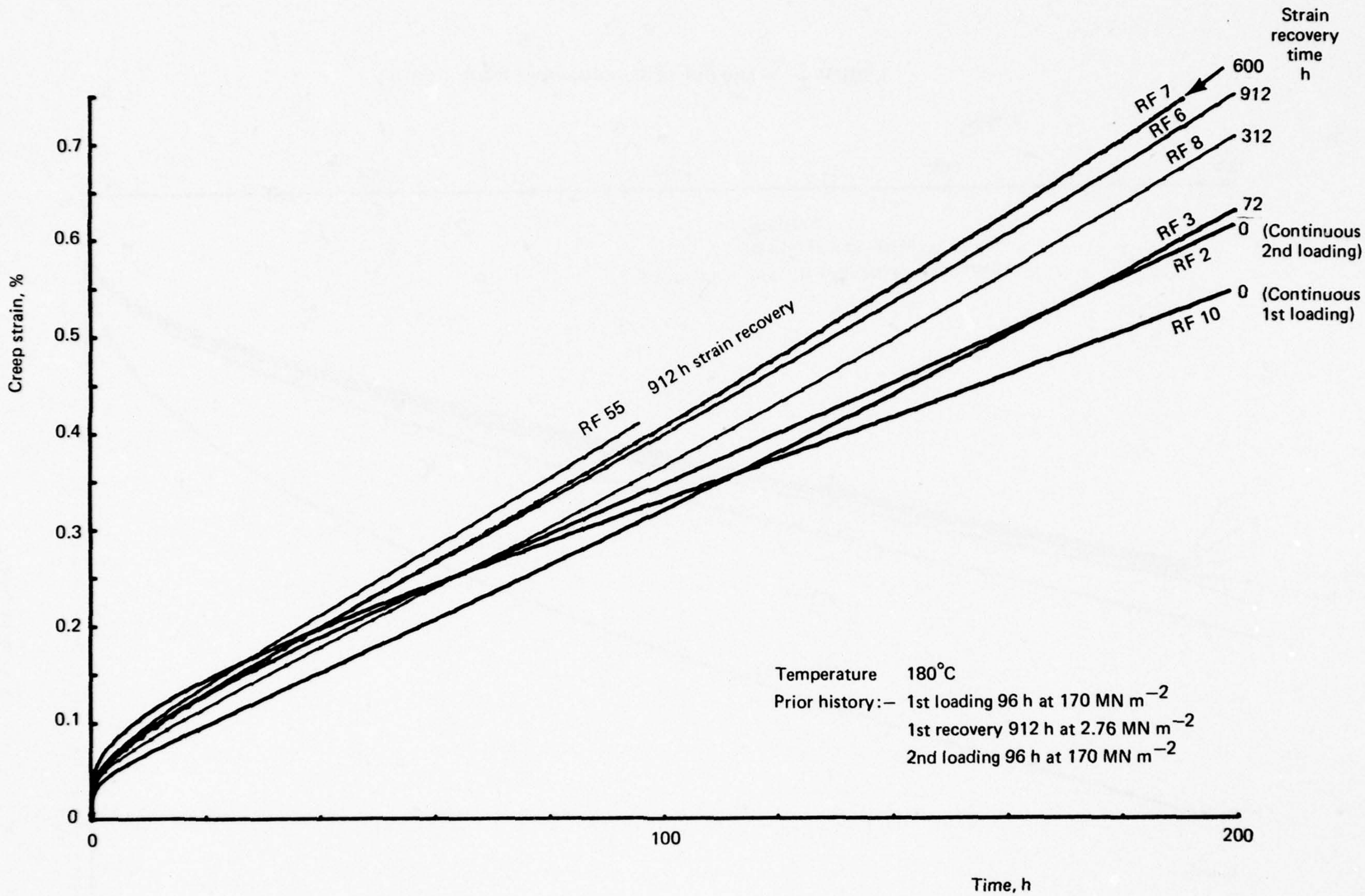


Fig 27 Response after two periods of strain recovery

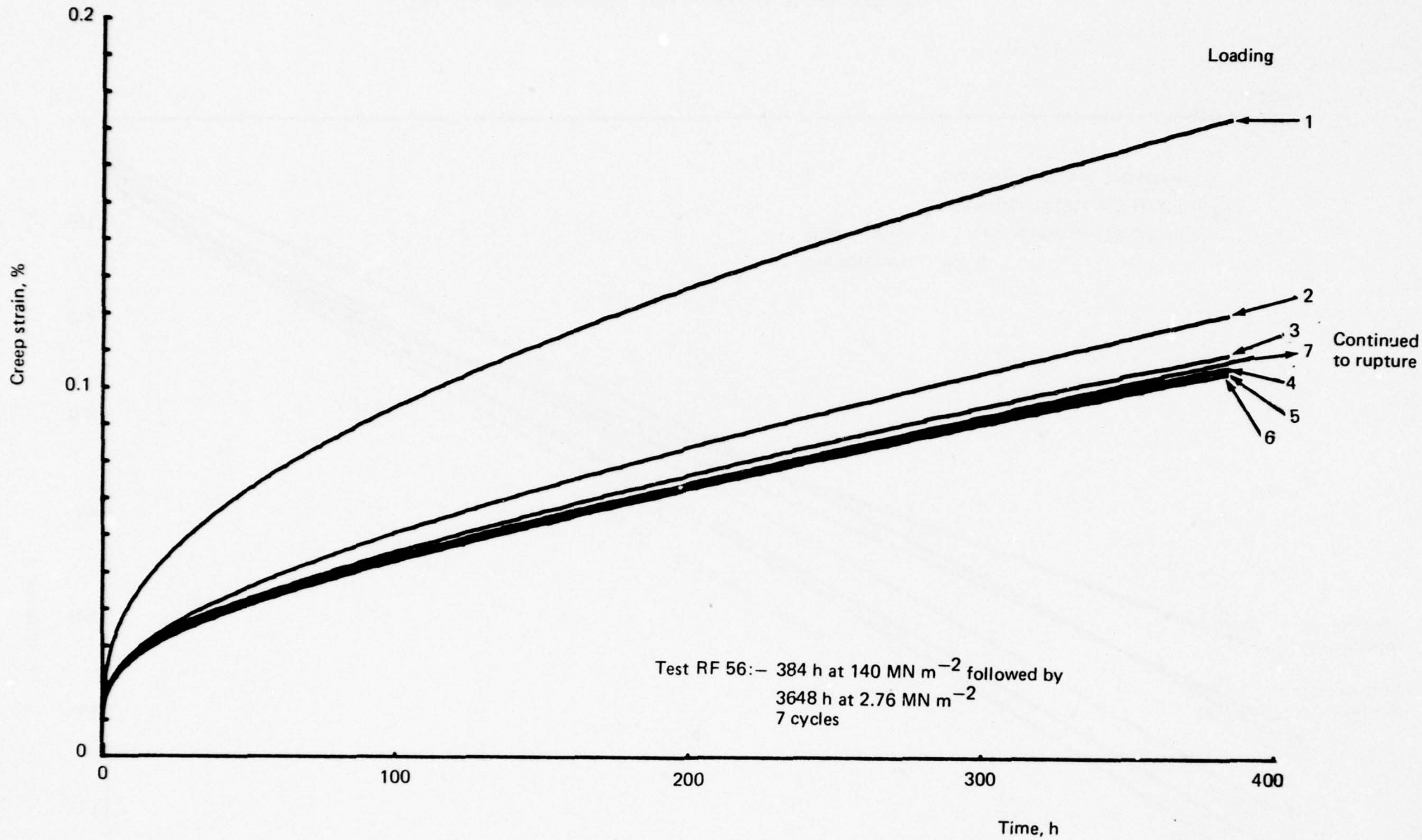


Fig 28 Successive responses to 140 MN m^{-2} at 165°C

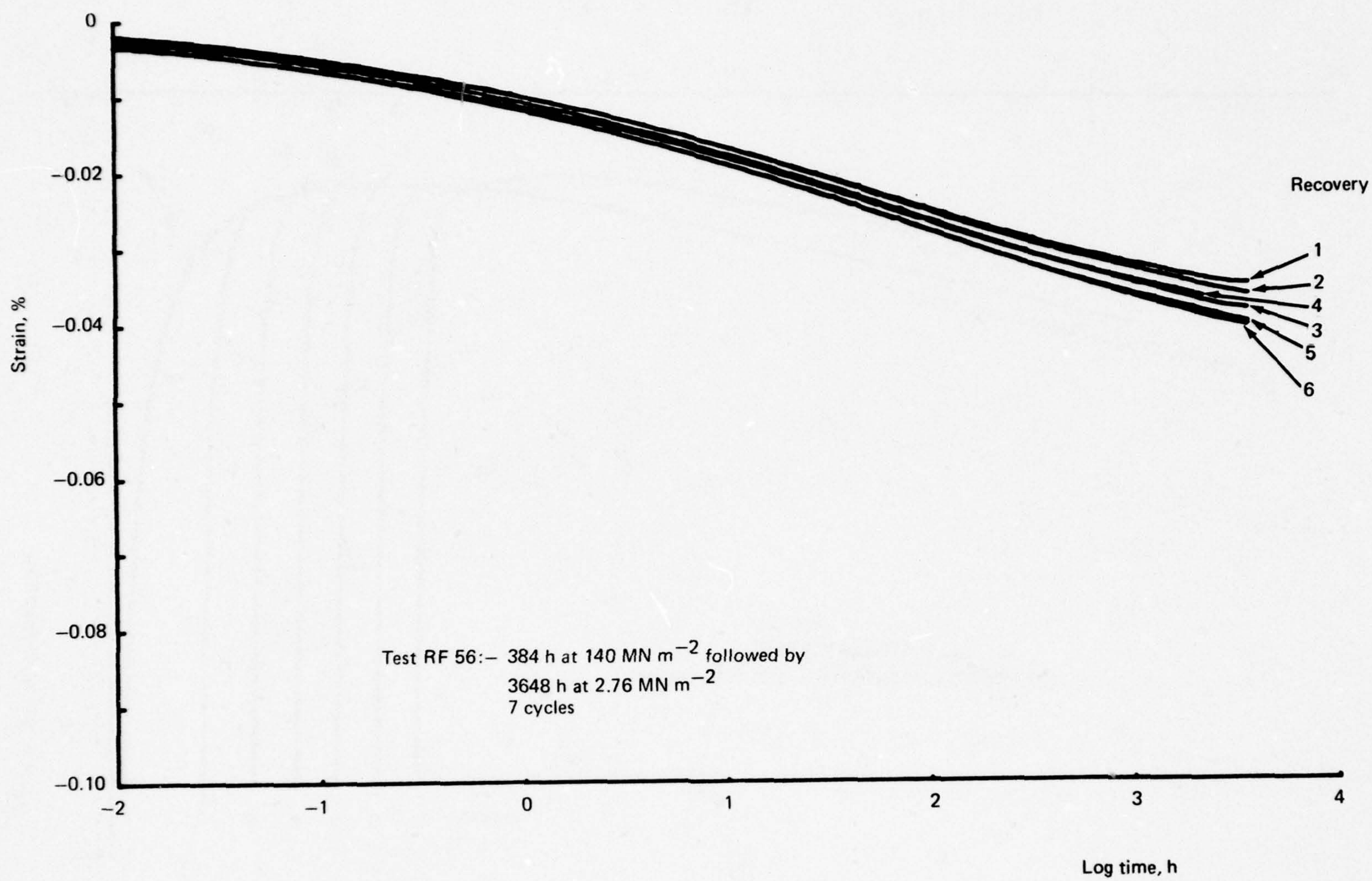


Fig 29 Successive recoveries after 140 MN m^{-2} at 165°C

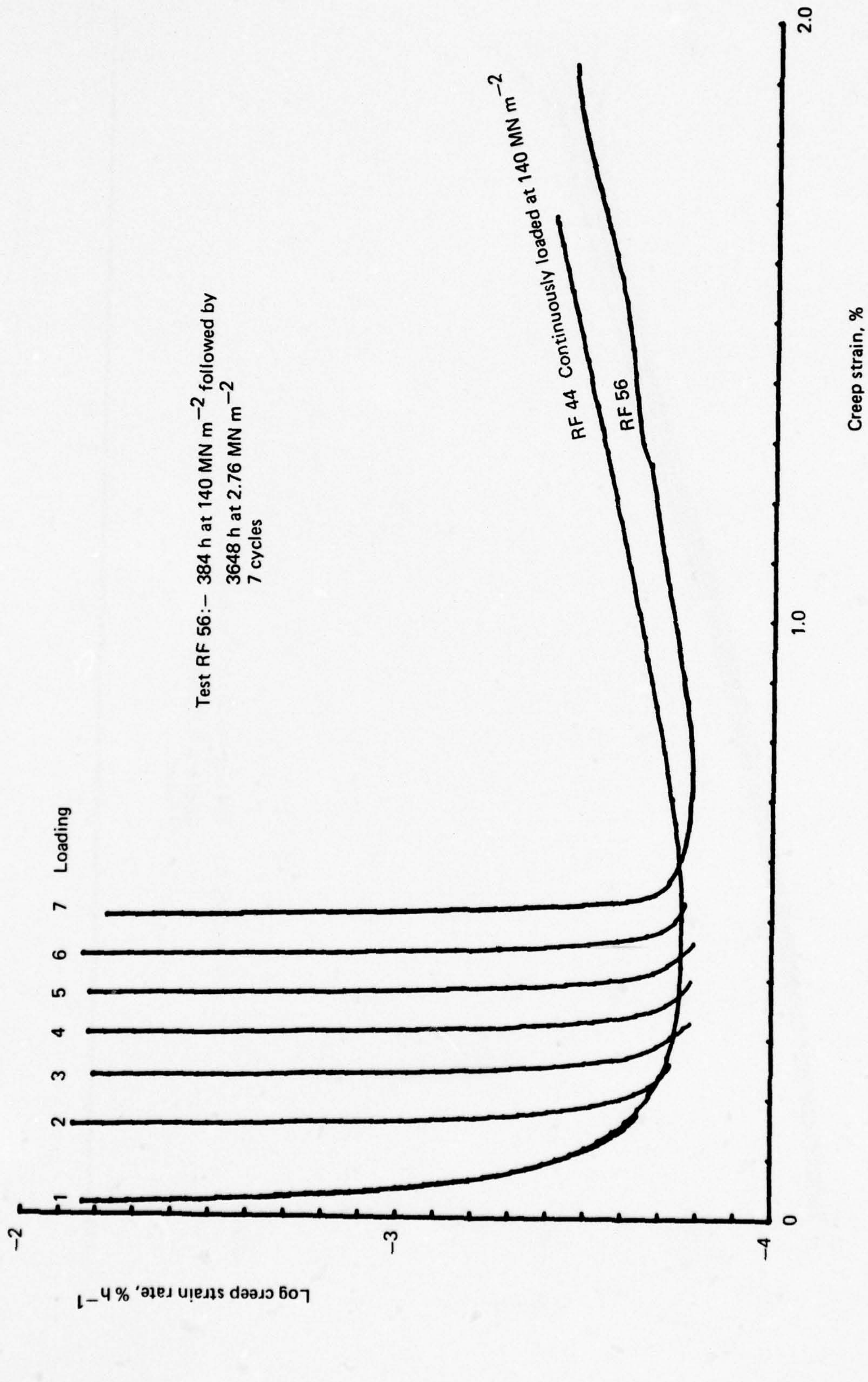


Fig 30 Successive strain rates for 140 MN m^{-2} at 165°C

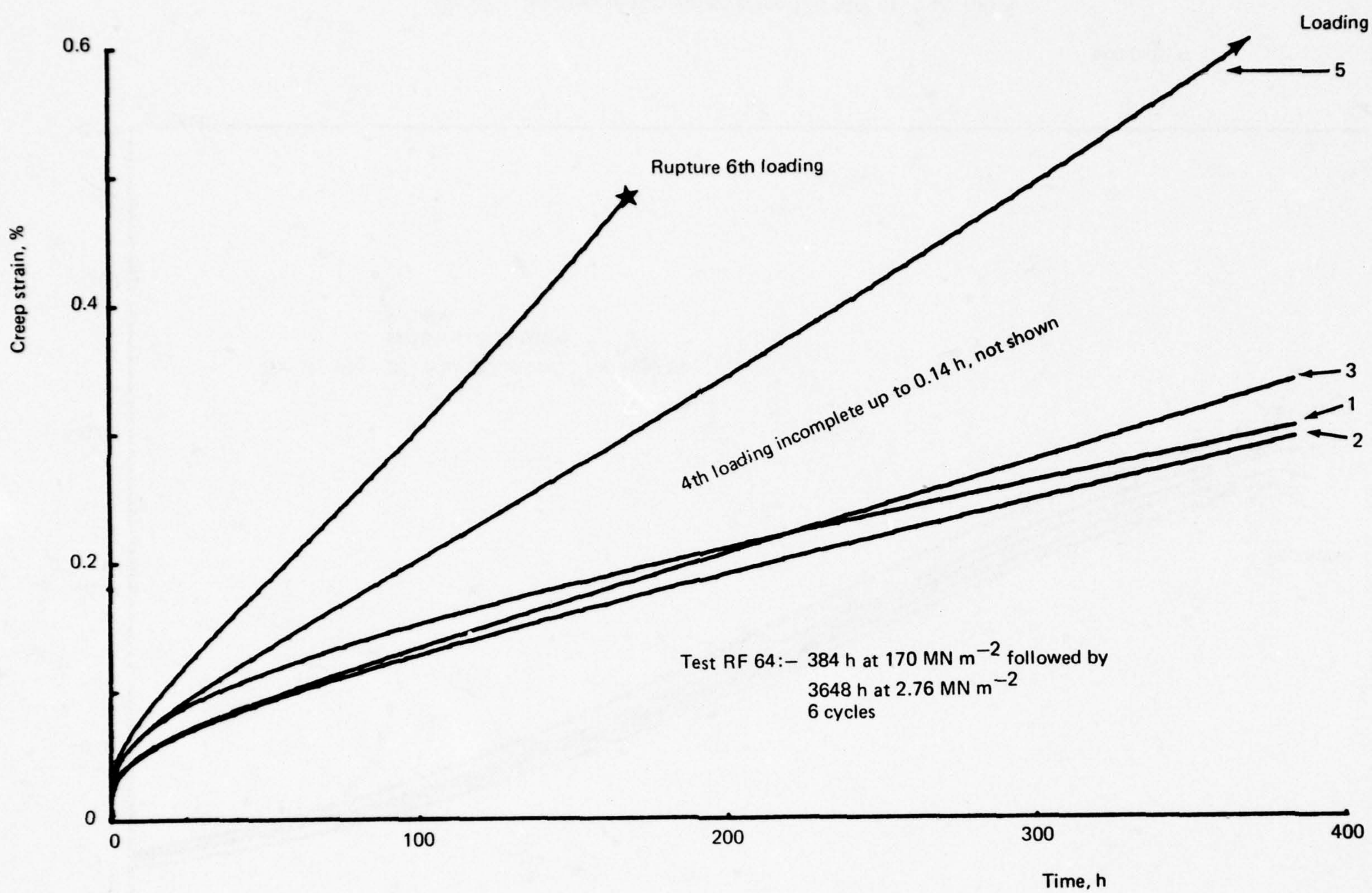
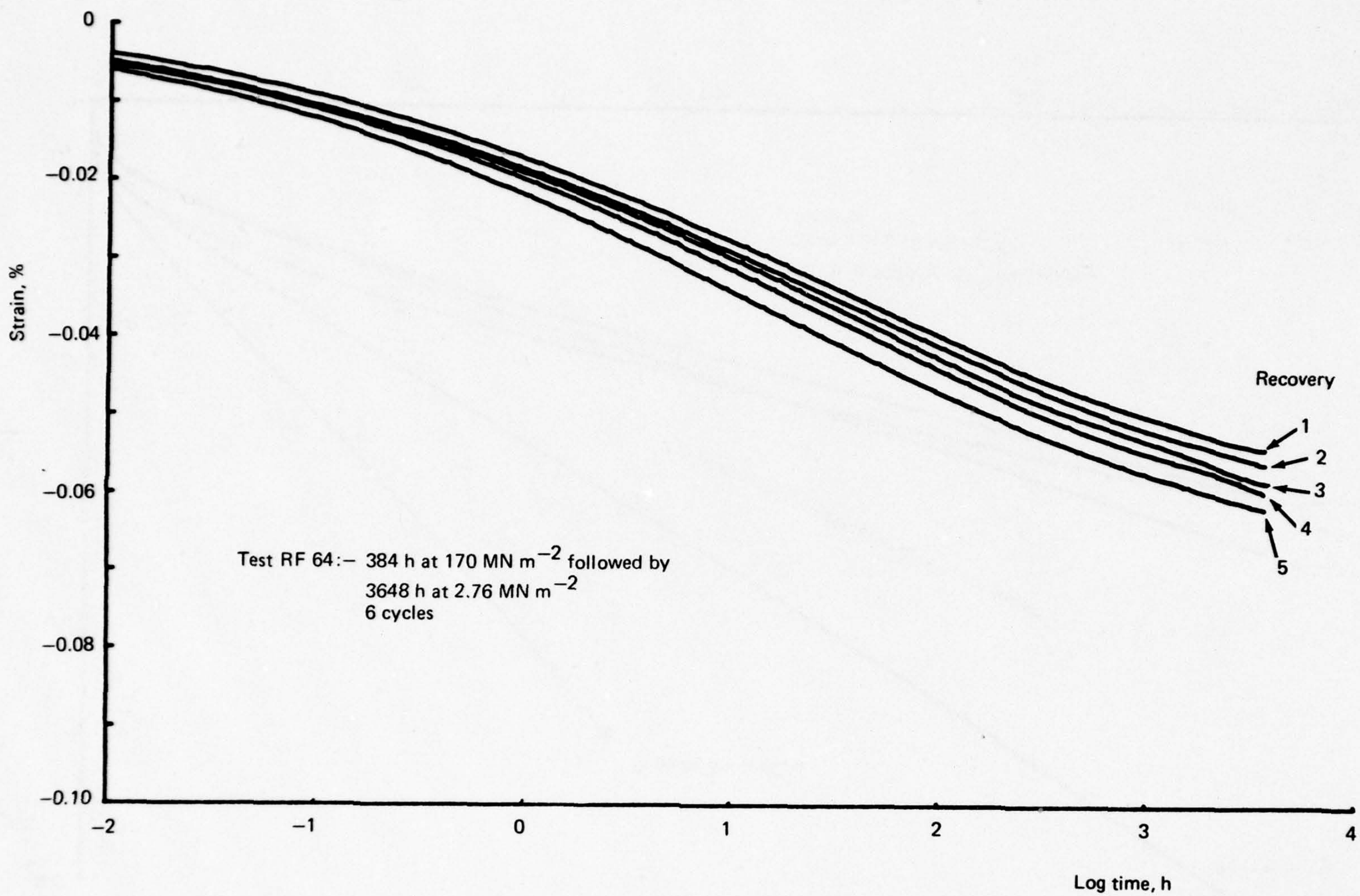


Fig 31 Successive responses to 170 MN m^{-2} at 165°C



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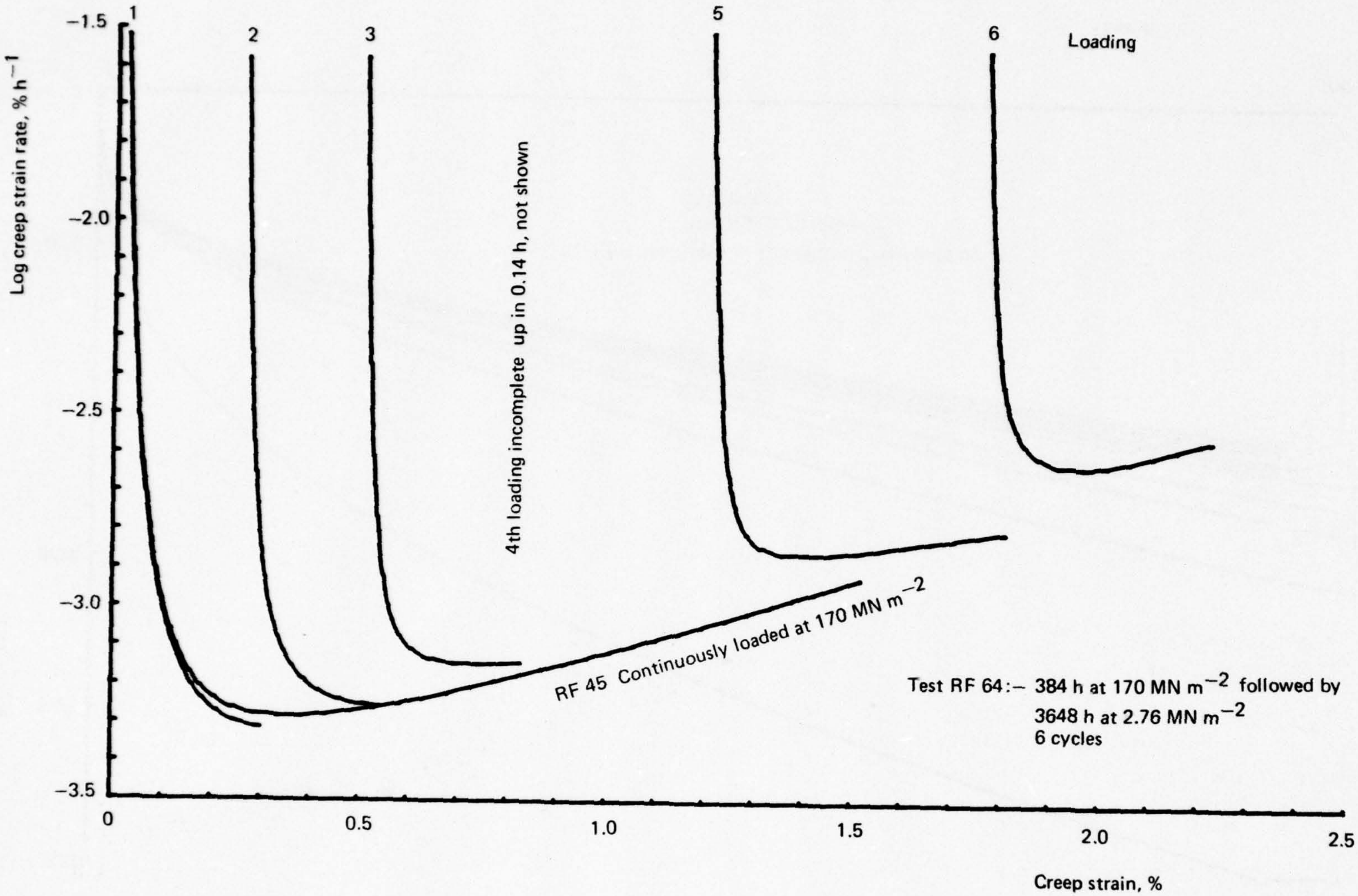


Fig 33 Successive strain rates for 170 MN m^{-2} at 165°C

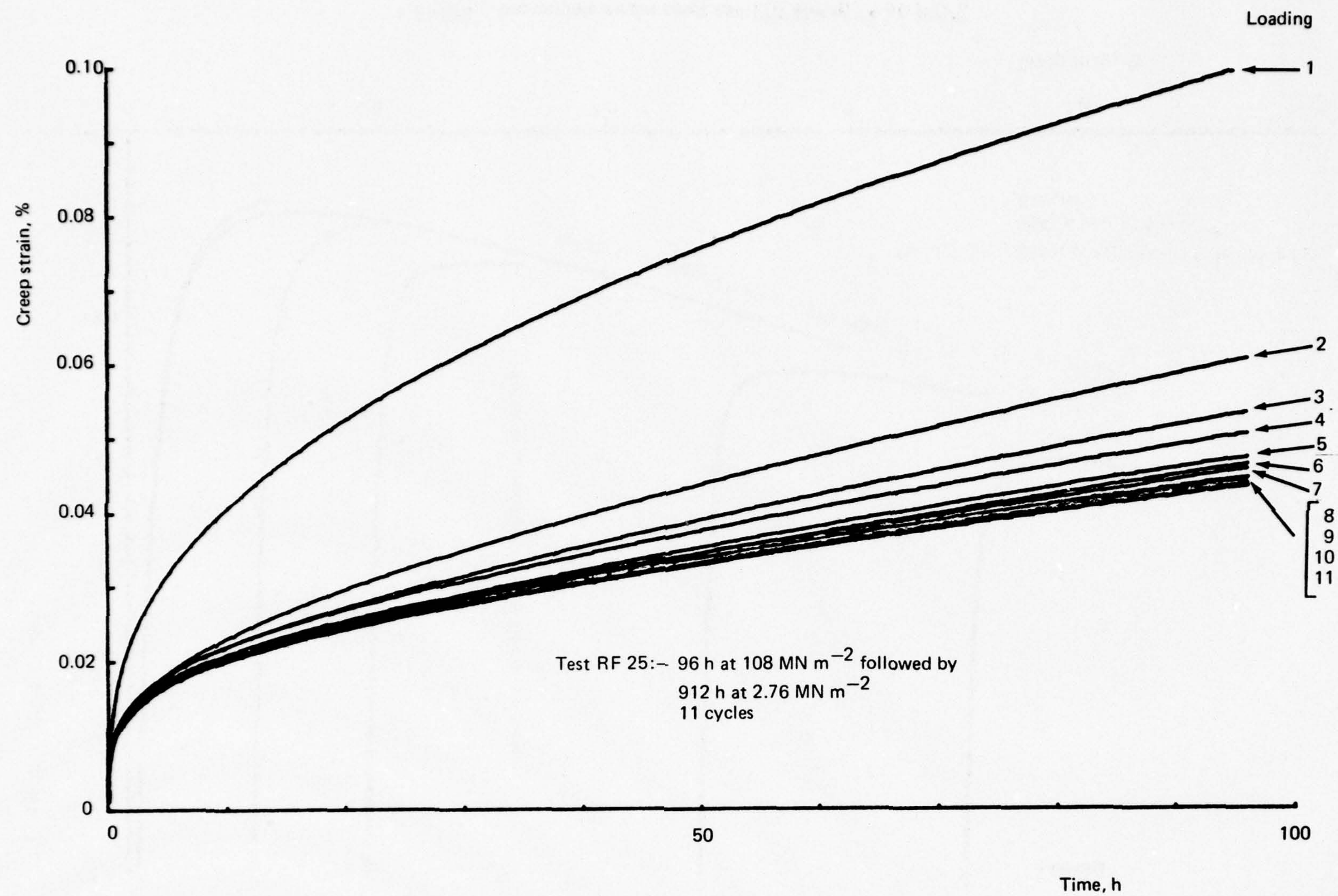


Fig 34 Successive responses to 108 MN m^{-2} at 180°C

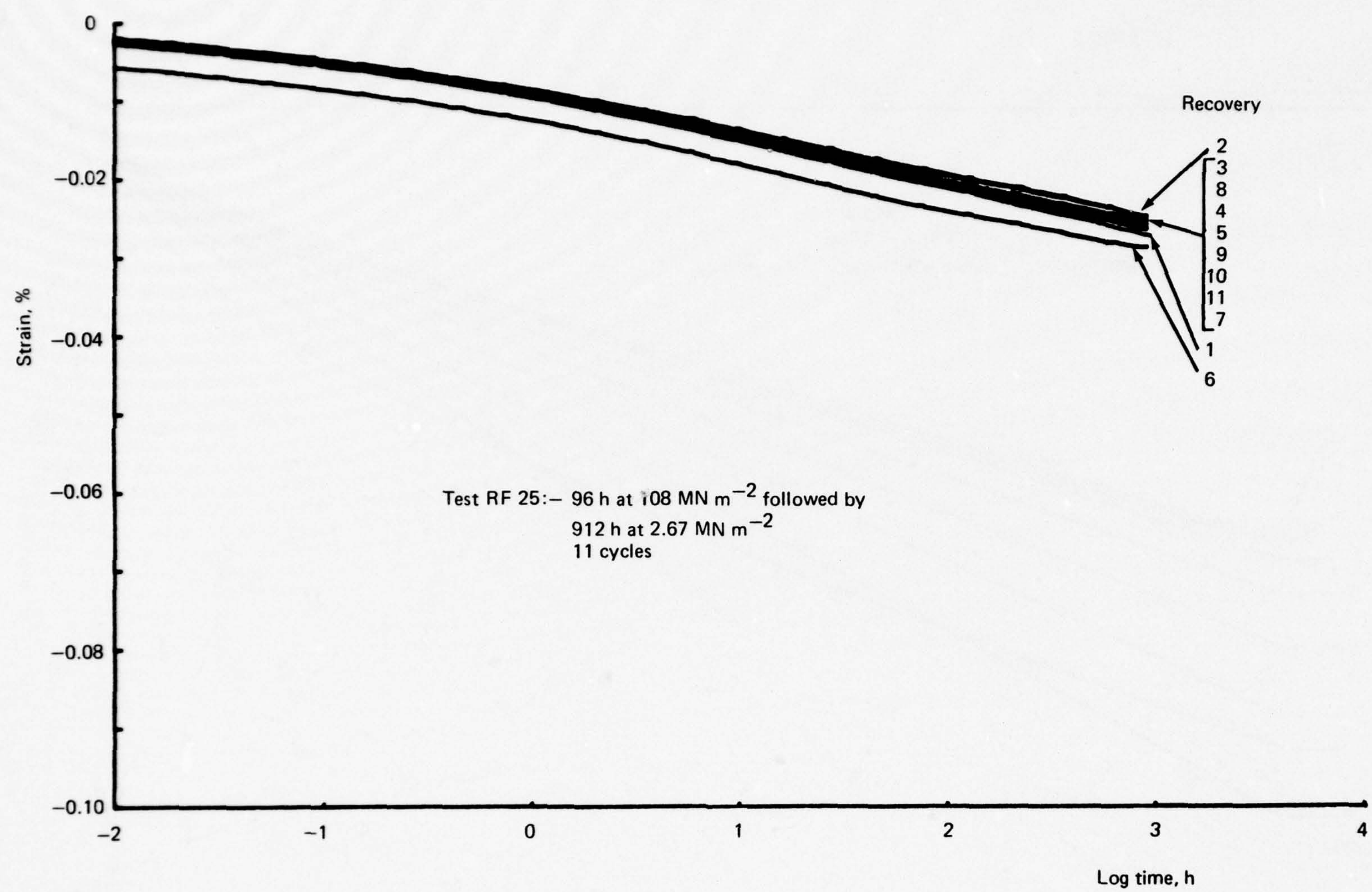
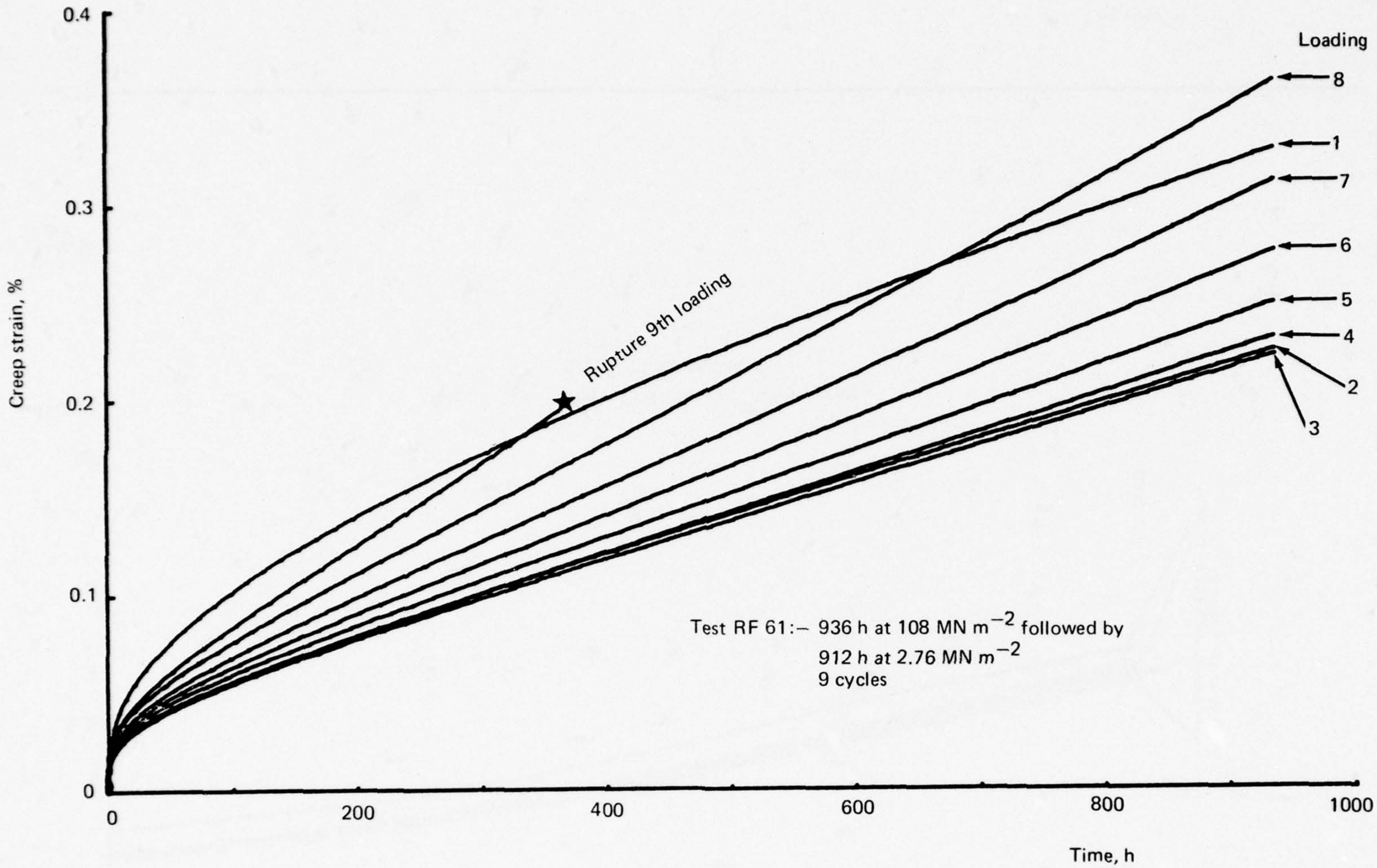


Fig 35 Successive recoveries after 108 MN m^{-2} at 180°C



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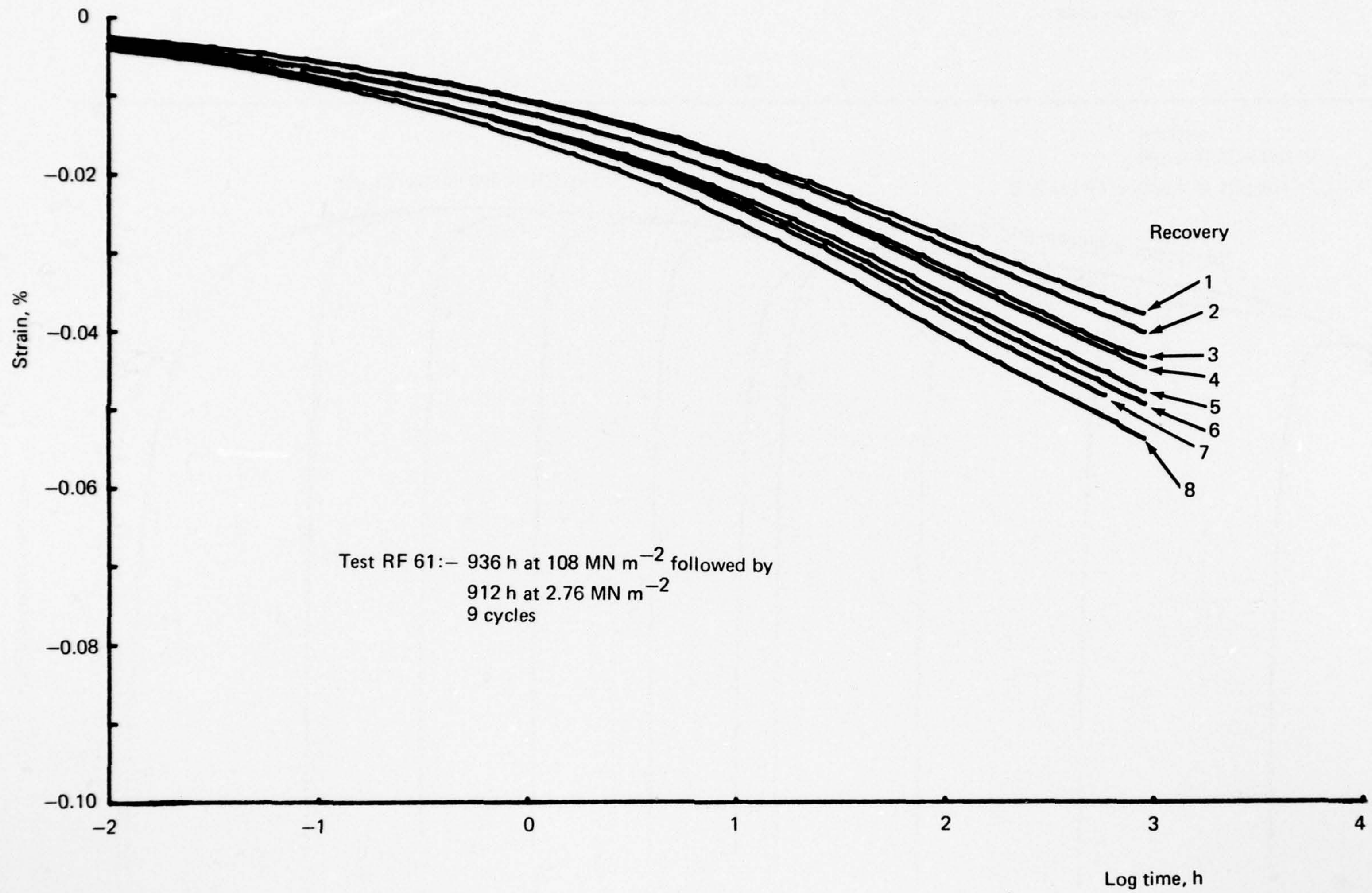

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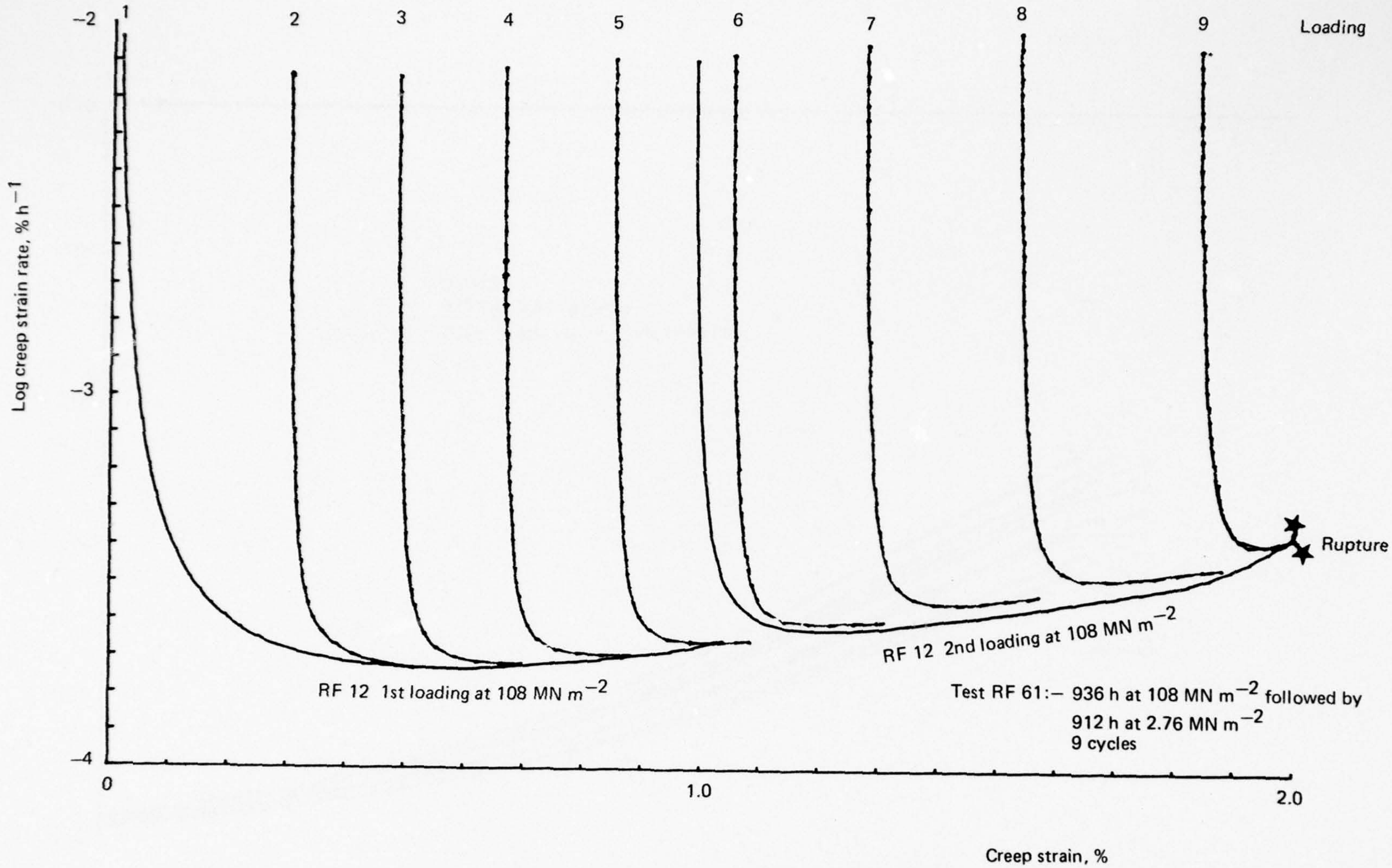


Fig 38 Successive strain rates for 108 MN m^{-2} at 180°C

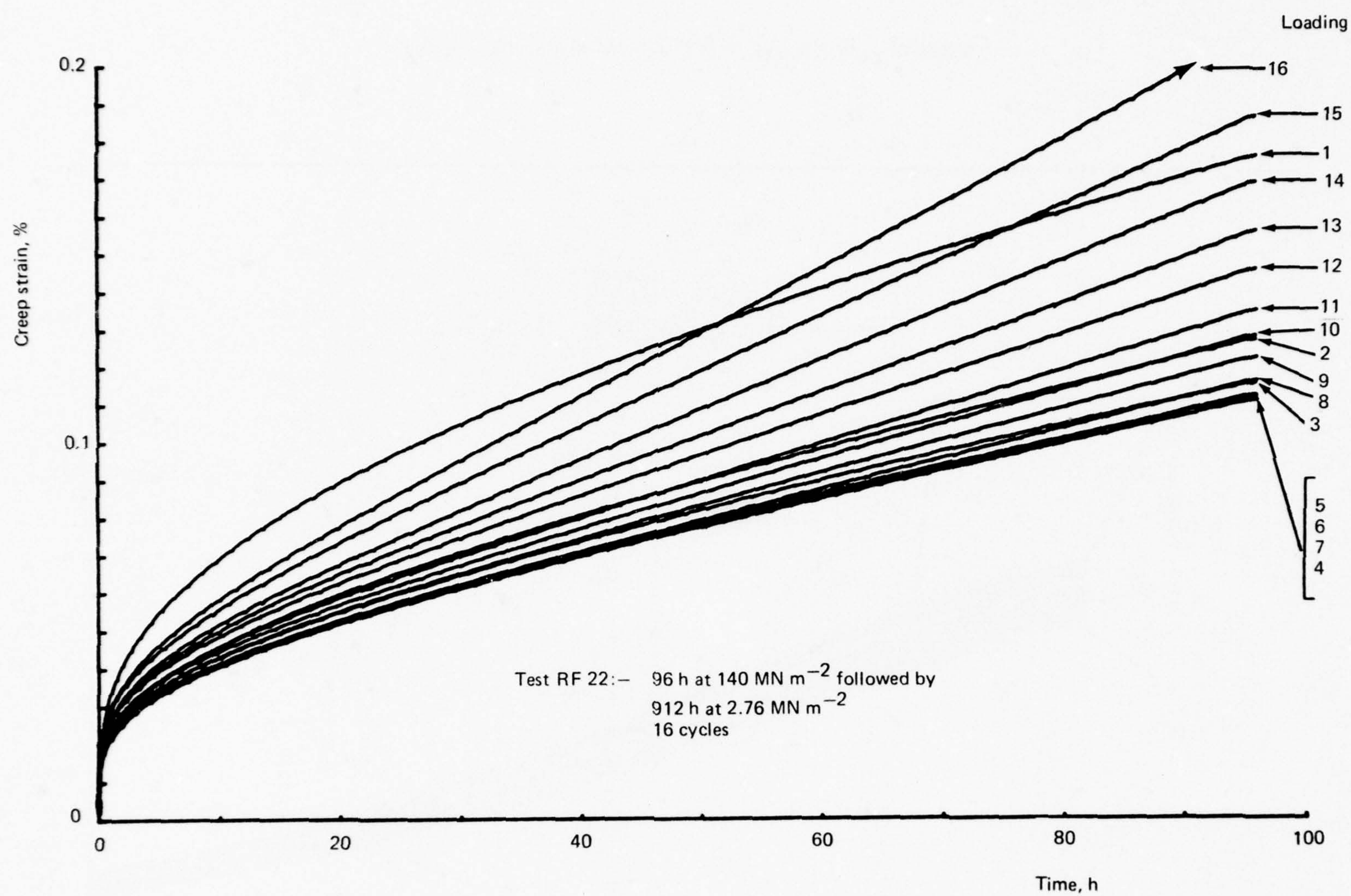
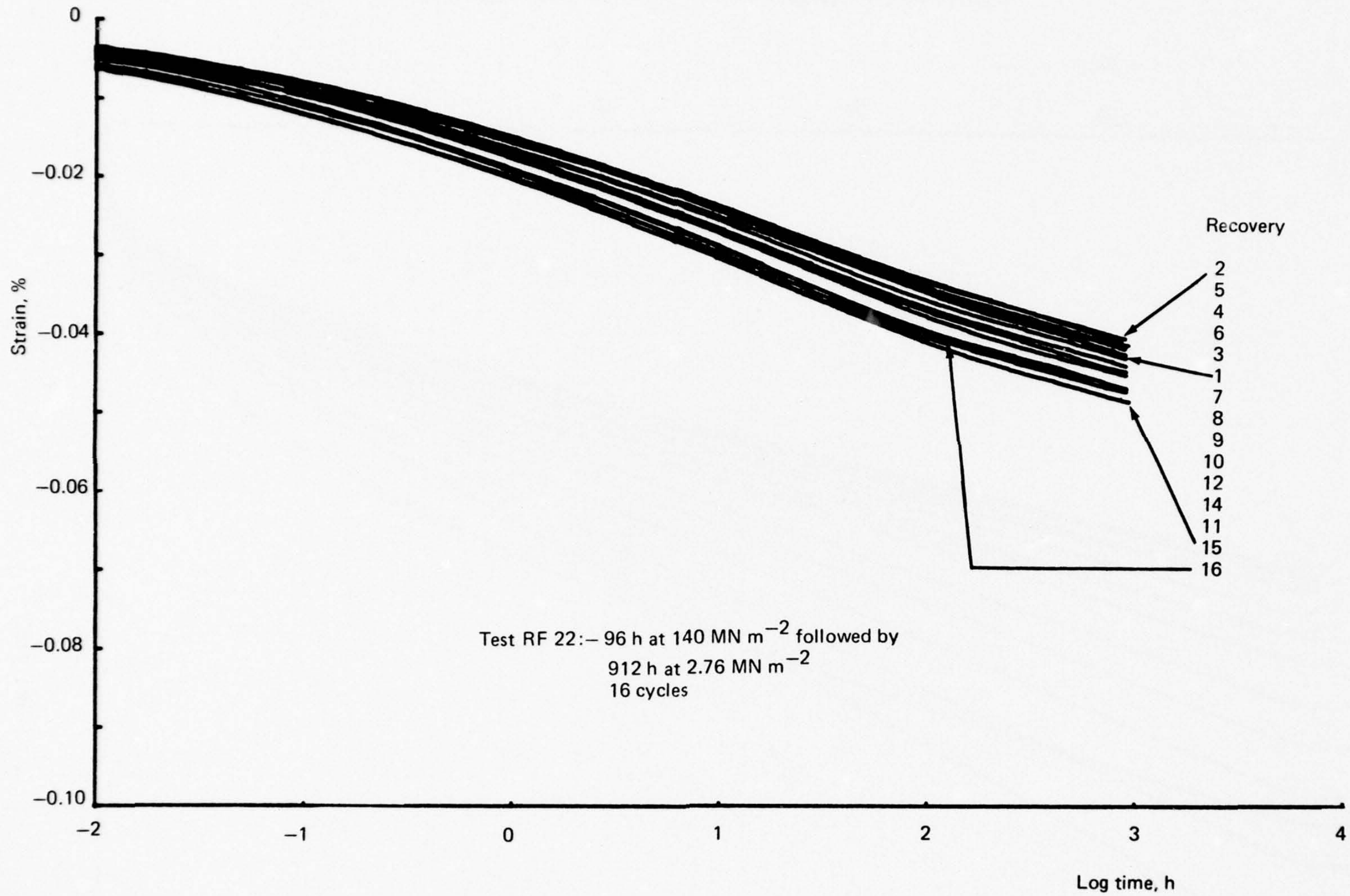


Fig 39 Successive responses to 140 MN m^{-2} at 180°C



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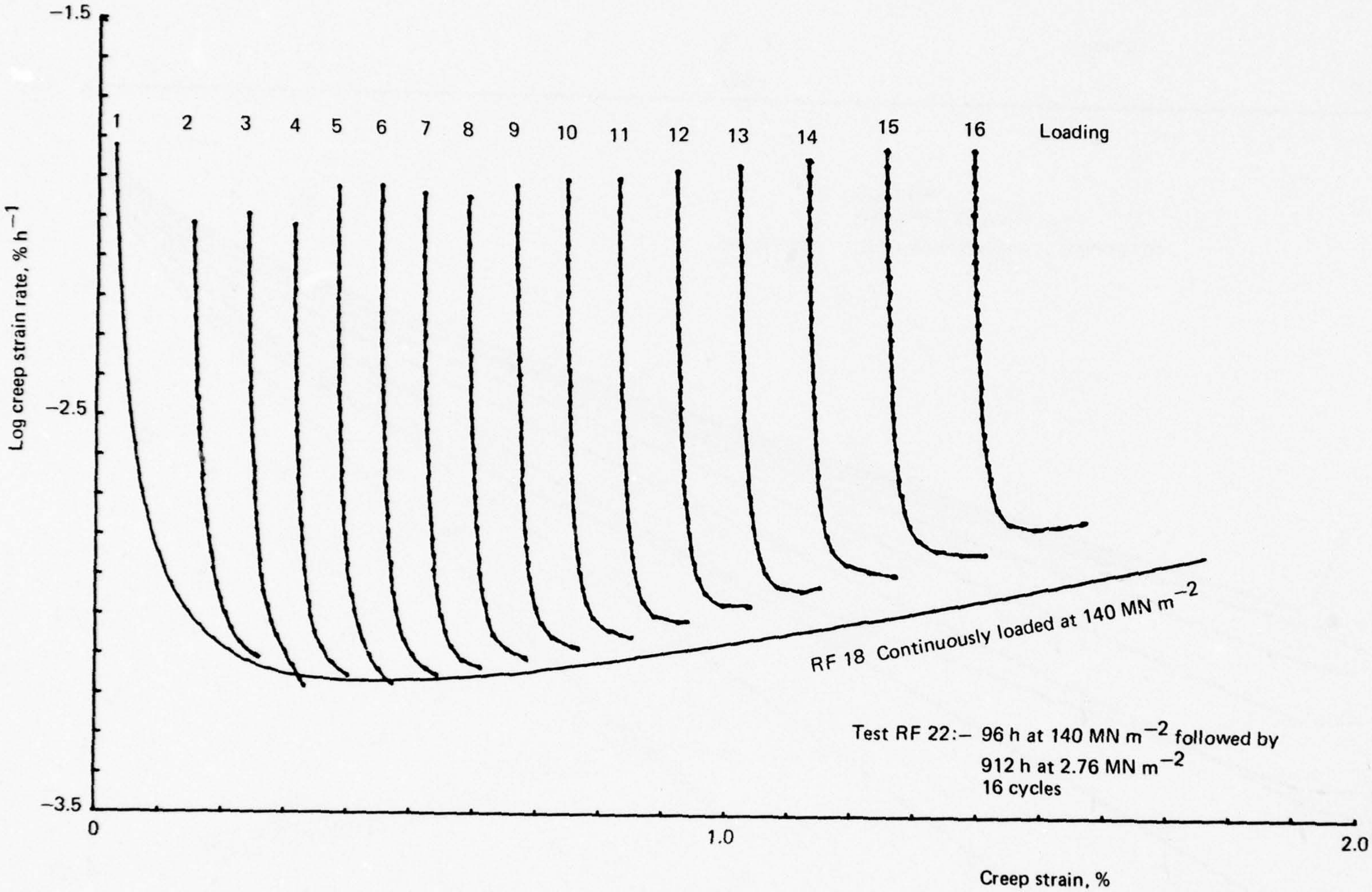


Fig 41 Successive strain rates for 140 MN m^{-2} at 180°C

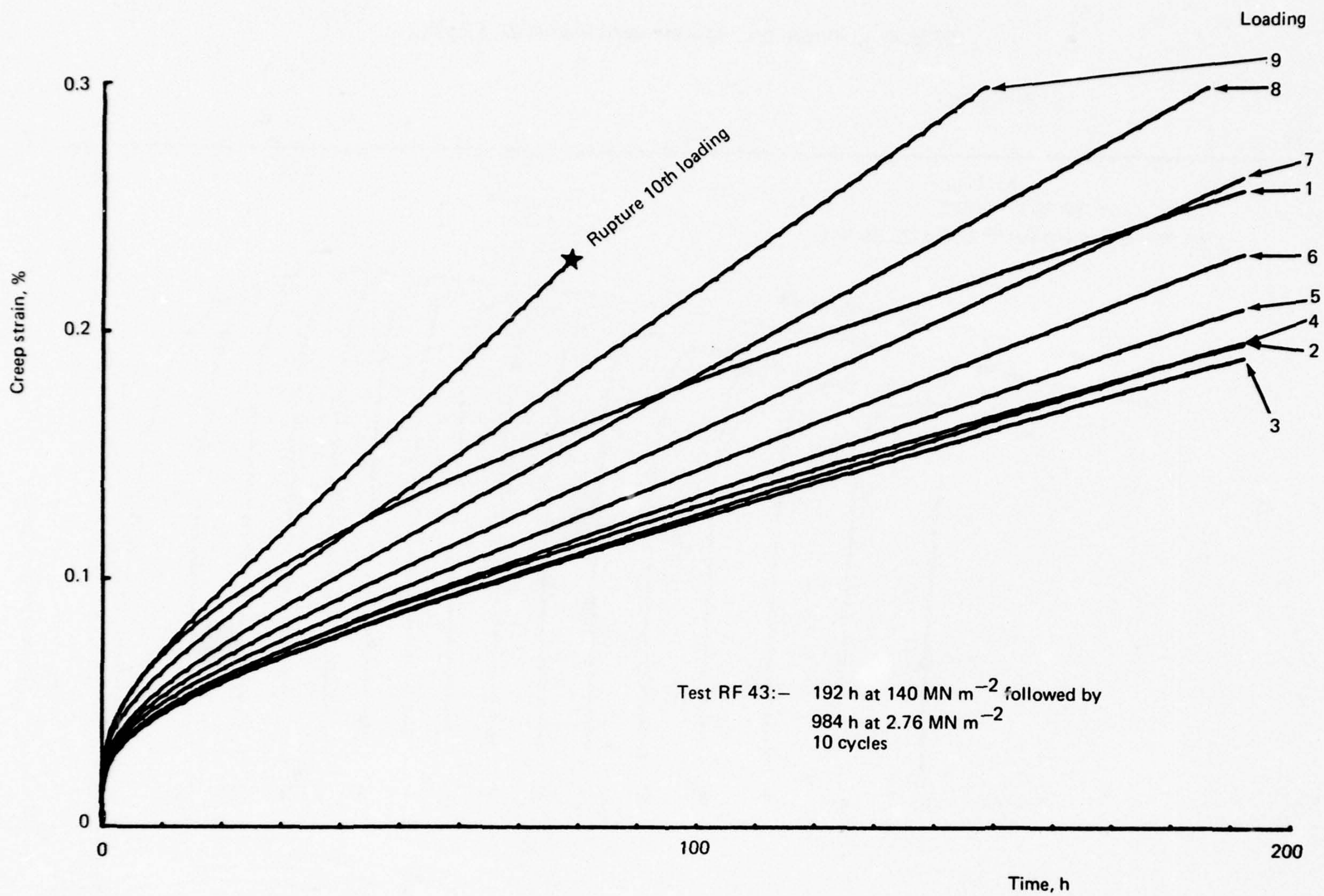
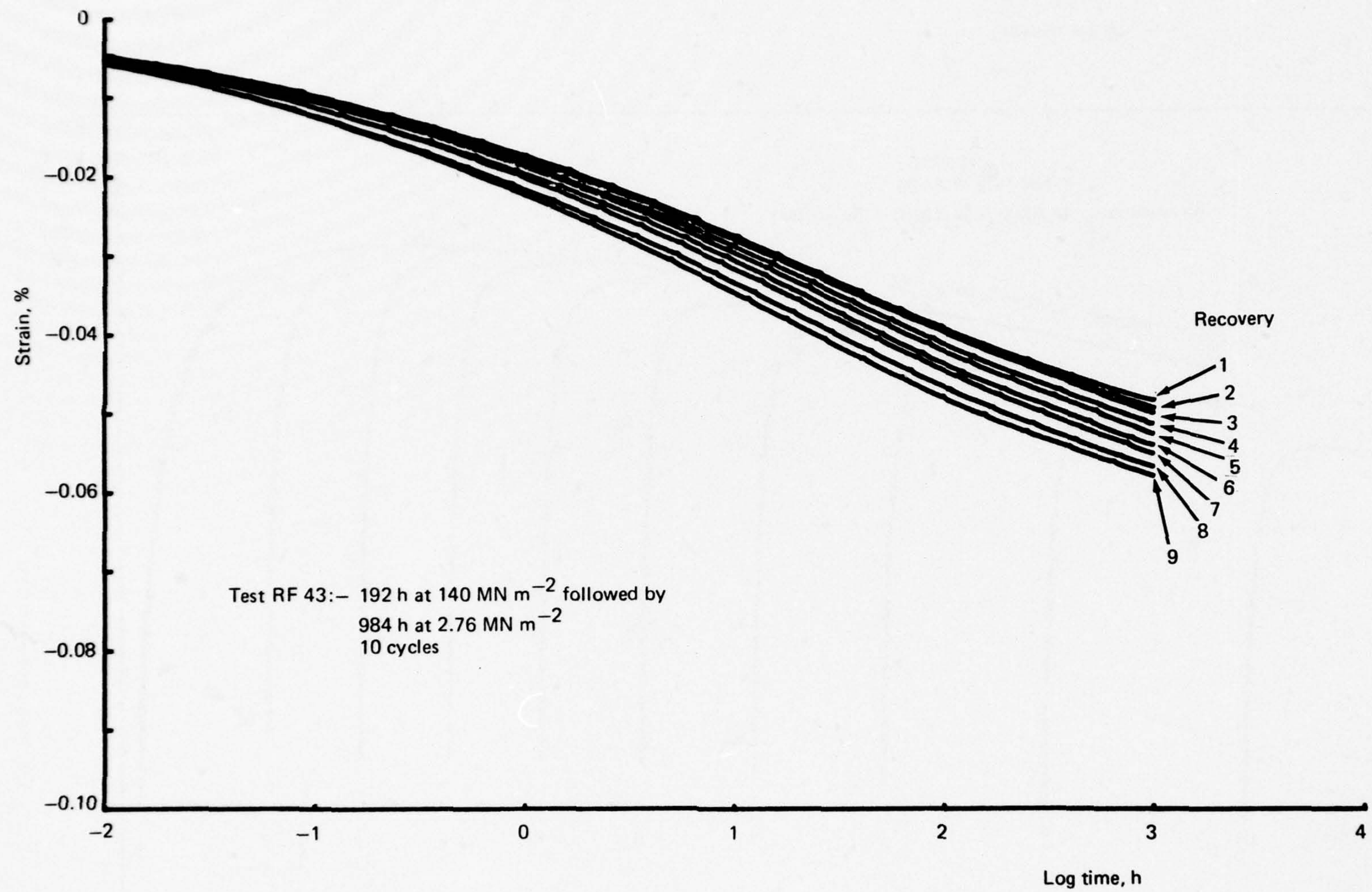


Fig 42 Successive responses to 140 MN m^{-2} at 180°C



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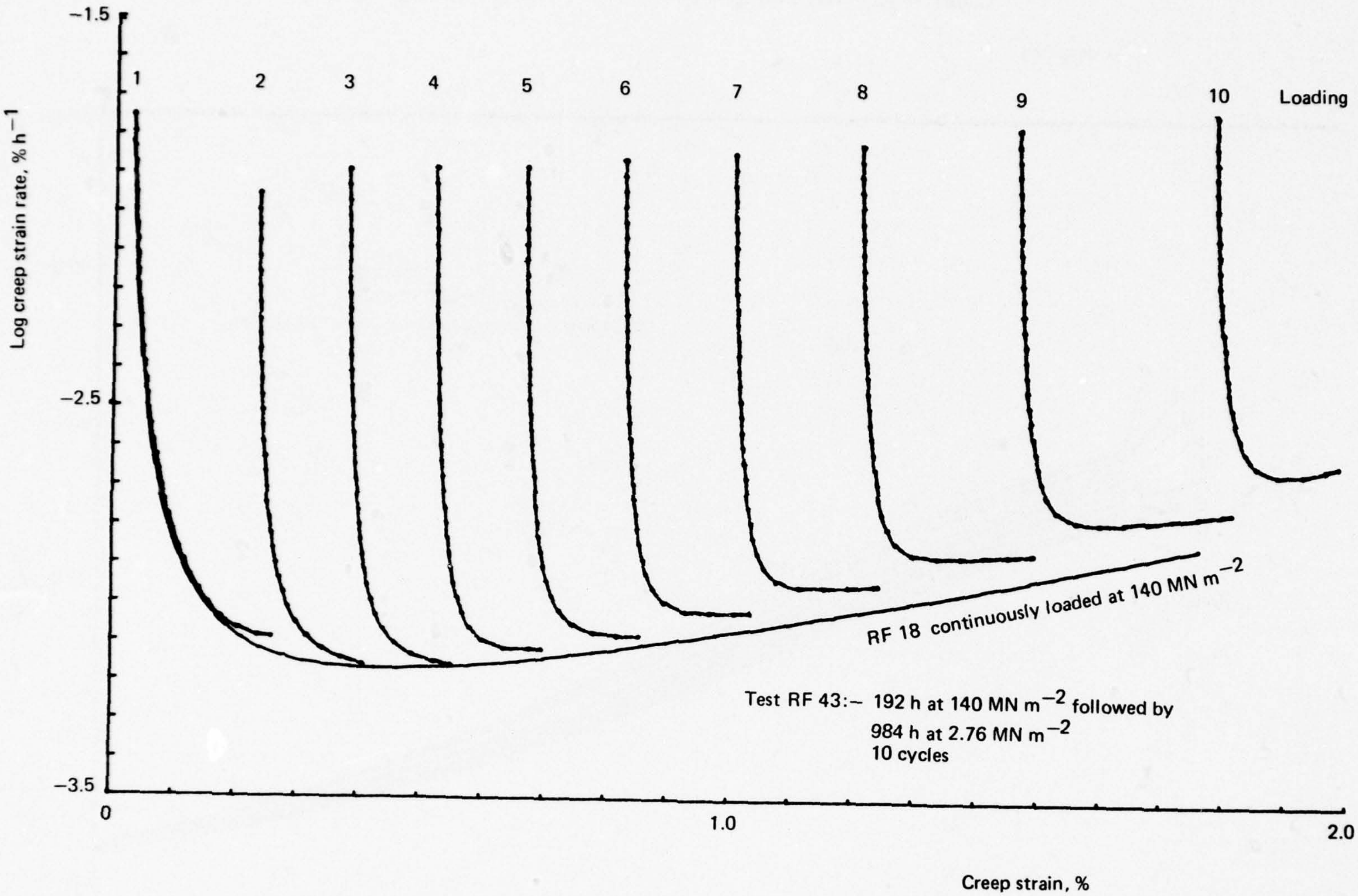
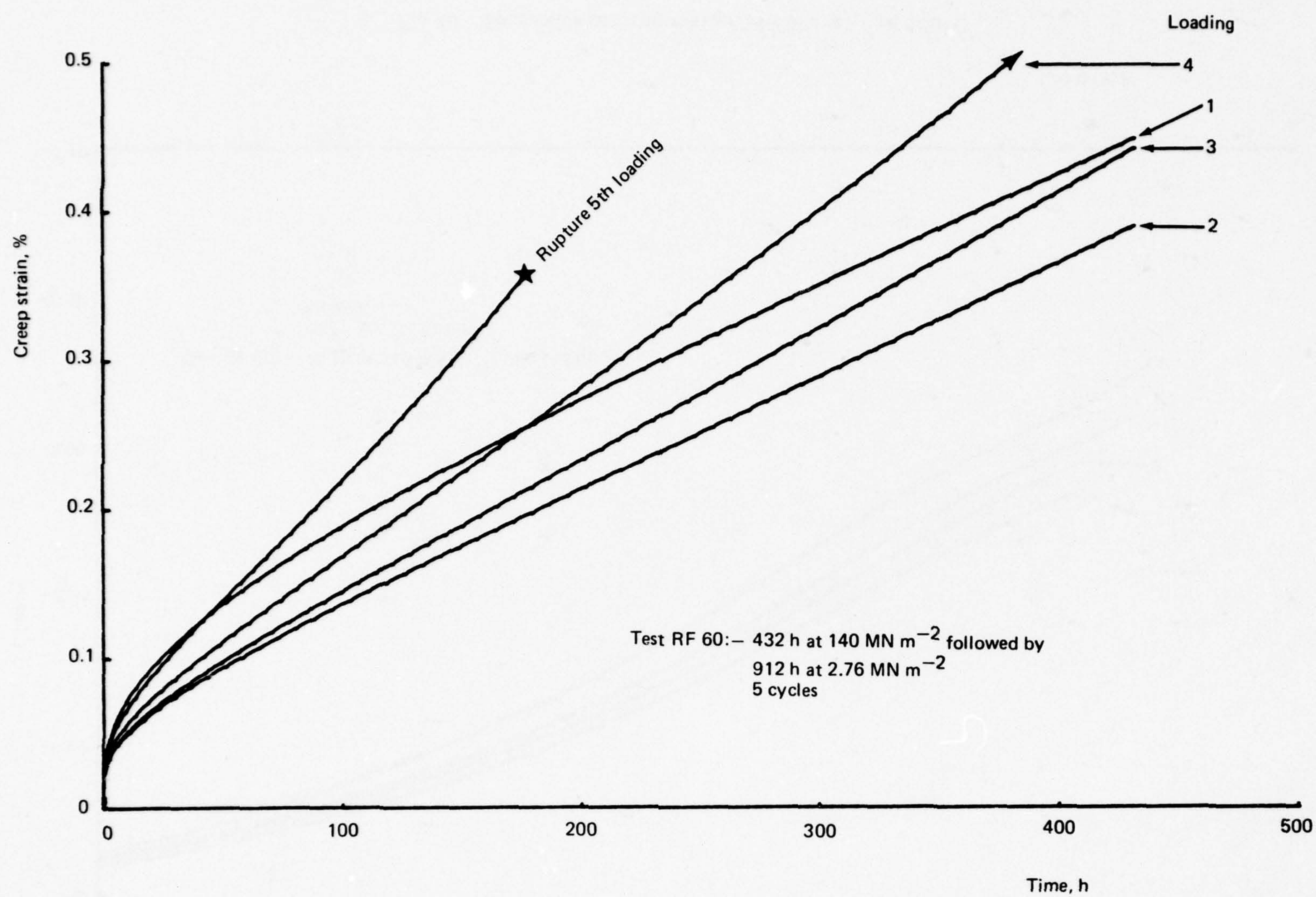


Fig 44 Successive strain rates for 140 MN m^{-2} at 180°C



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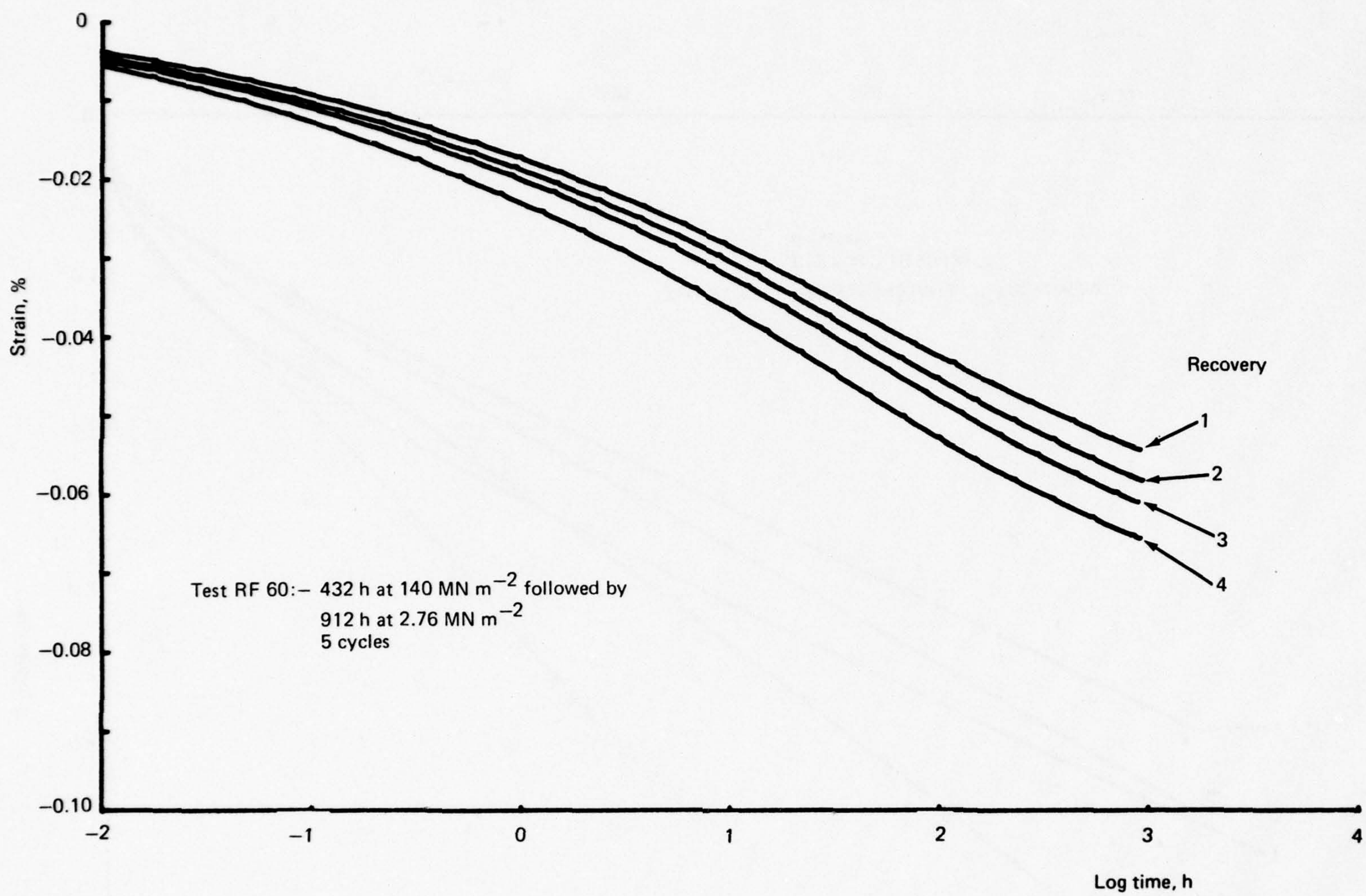

Fig 46 Successive recoveries after 140 MN m^{-2} at 180°C

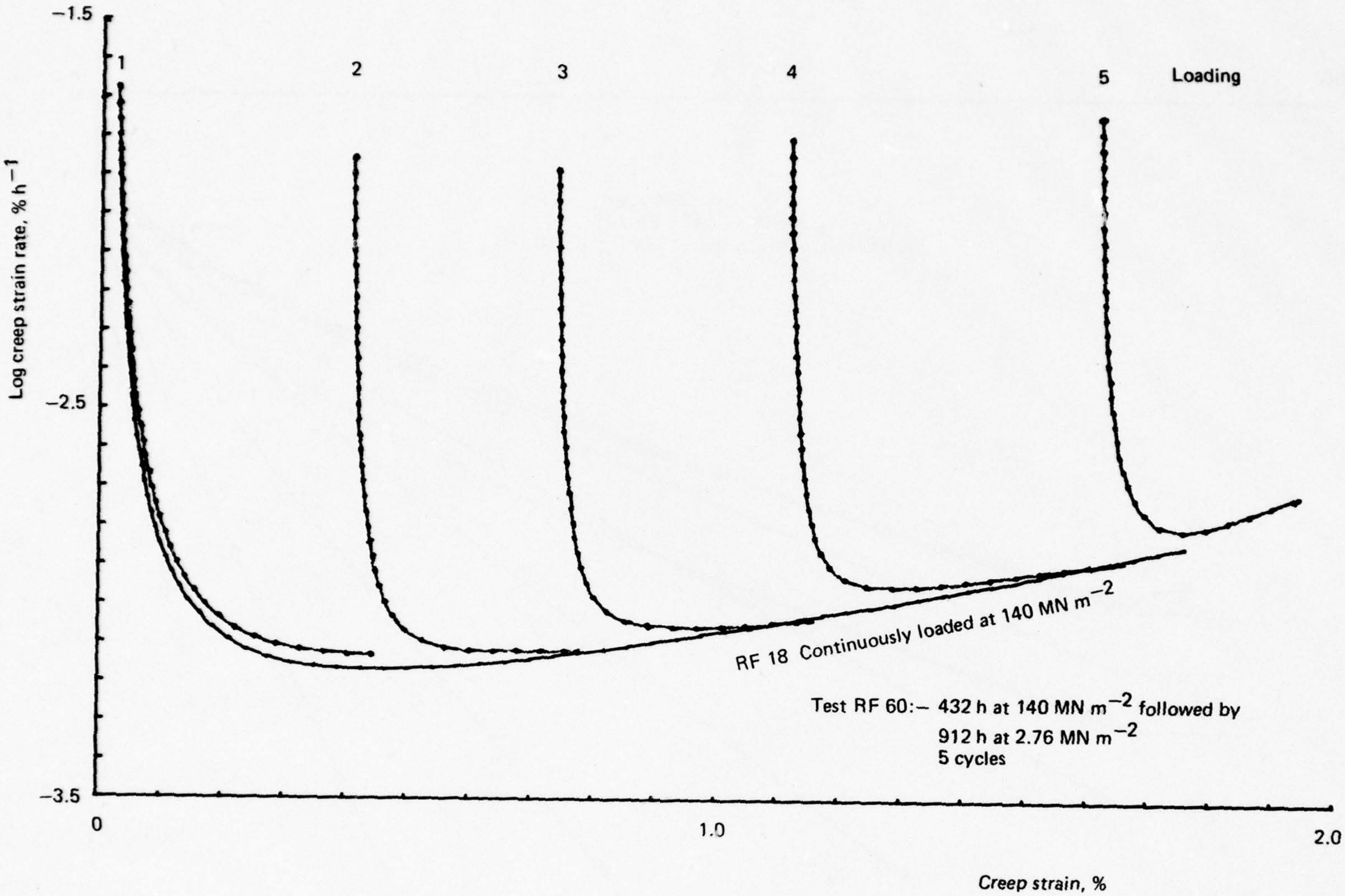

Fig 47 Successive strain rates for 140 MN m^{-2} at 180°C

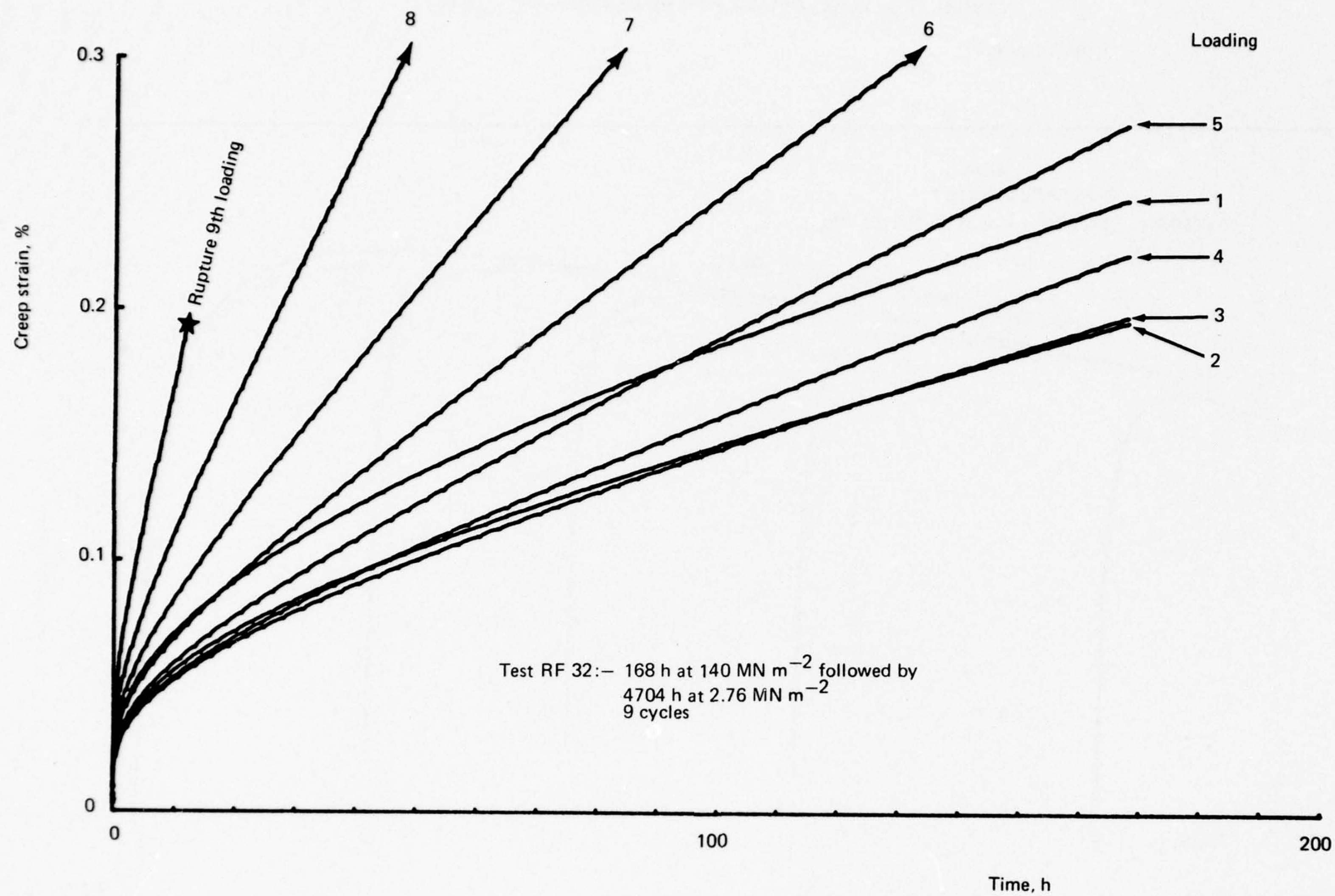

Fig 48 Successive responses to 140 MN m^{-2} at 180°C

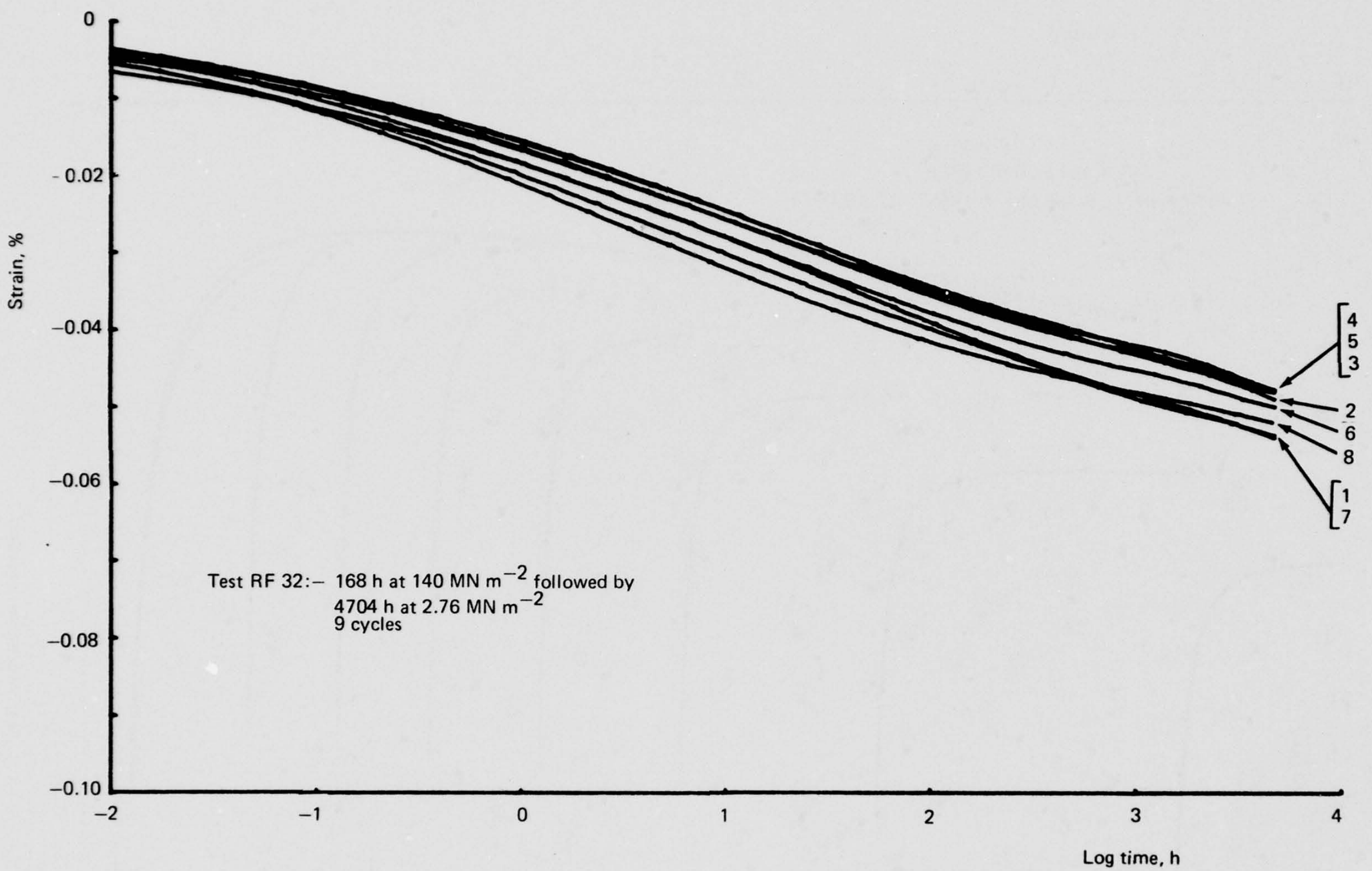

Fig 49 Successive recoveries after 140 MN m^{-2} at 180°C

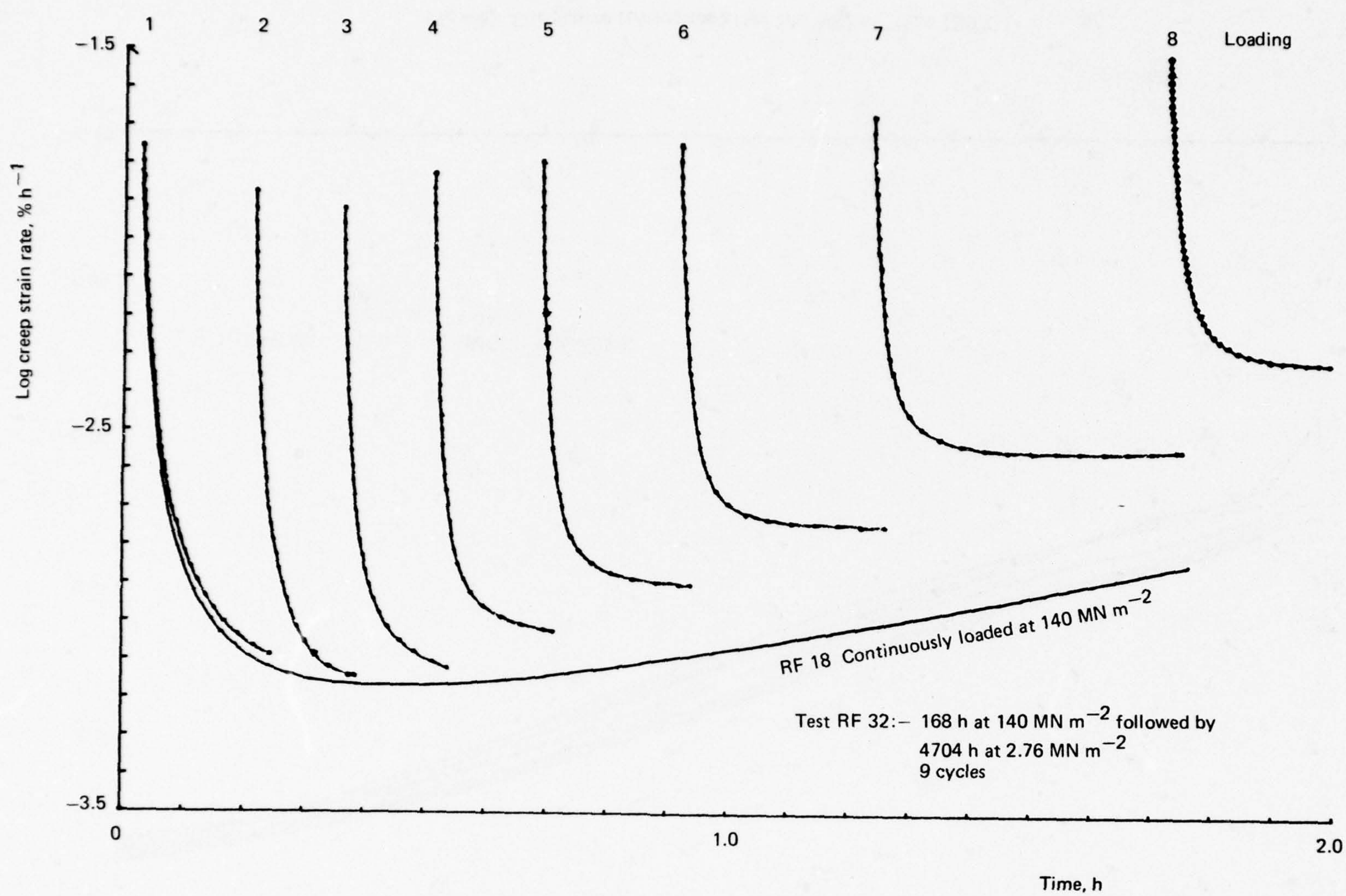

Fig 50 Successive strain rates for 140 MN m^{-2} at 180°C

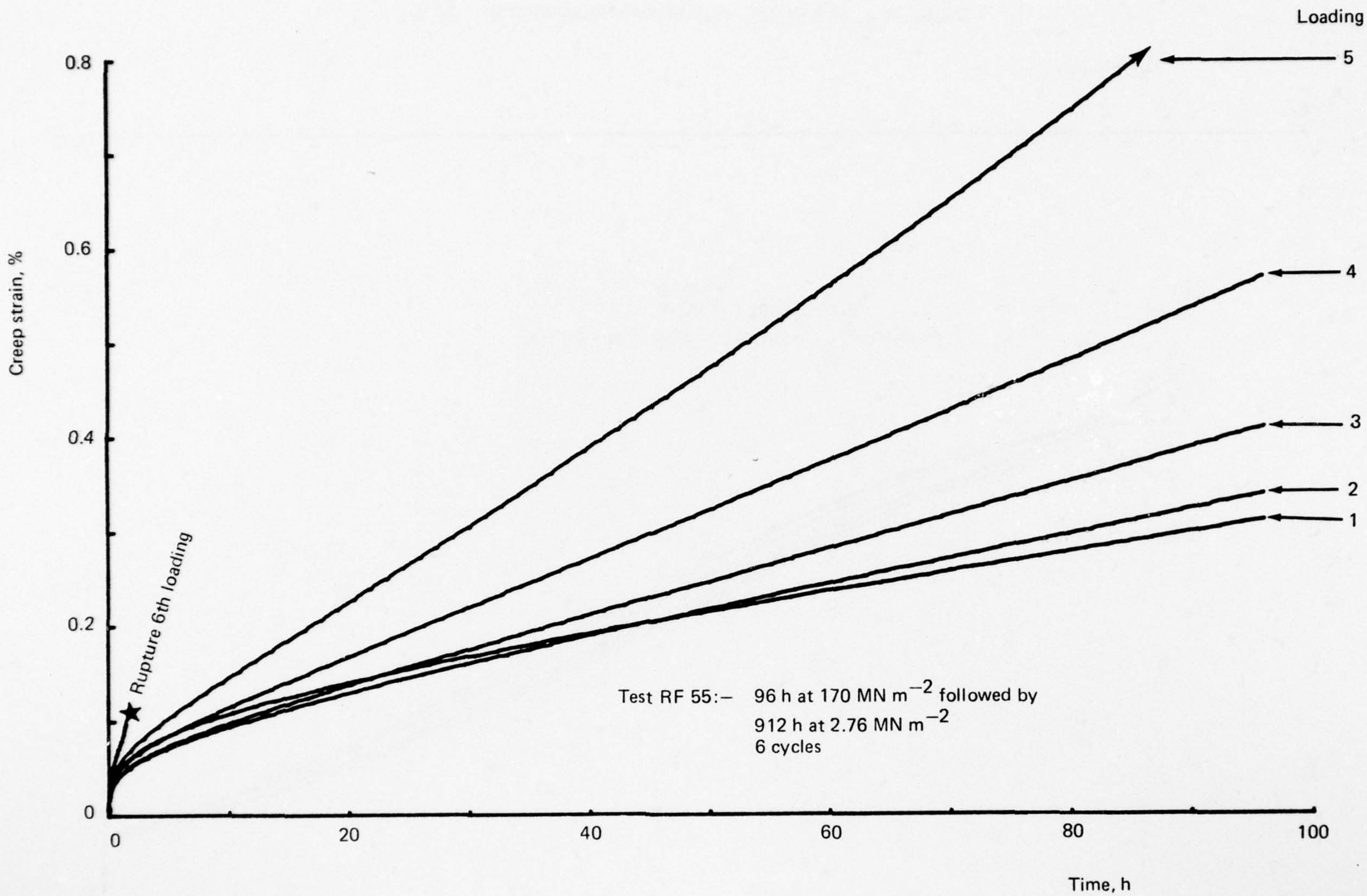

Fig 51 Successive responses to 170 MN m^{-2} at 180°C

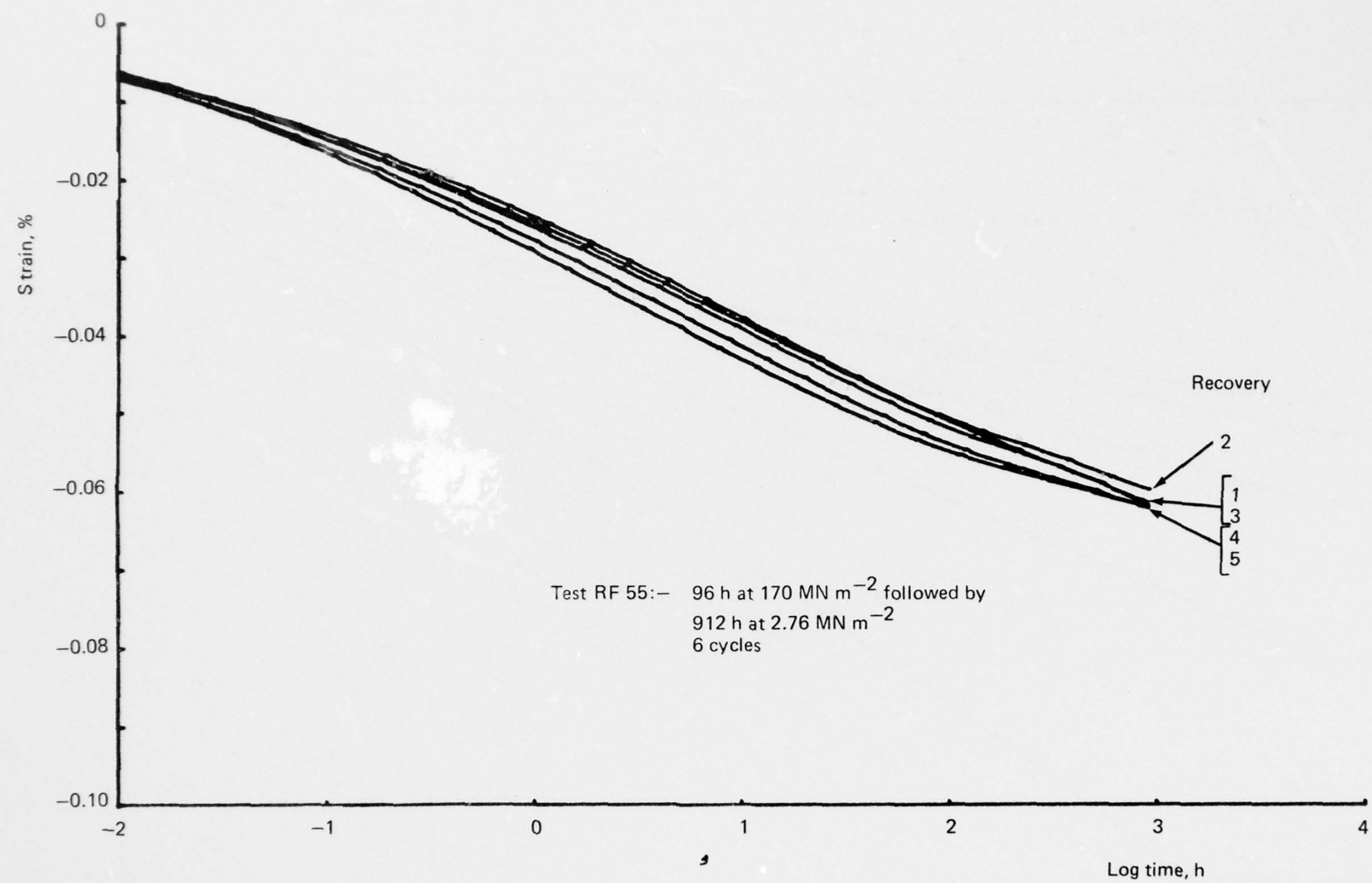

Fig 52 Successive recoveries after 170 MN m^{-2} at 180°C

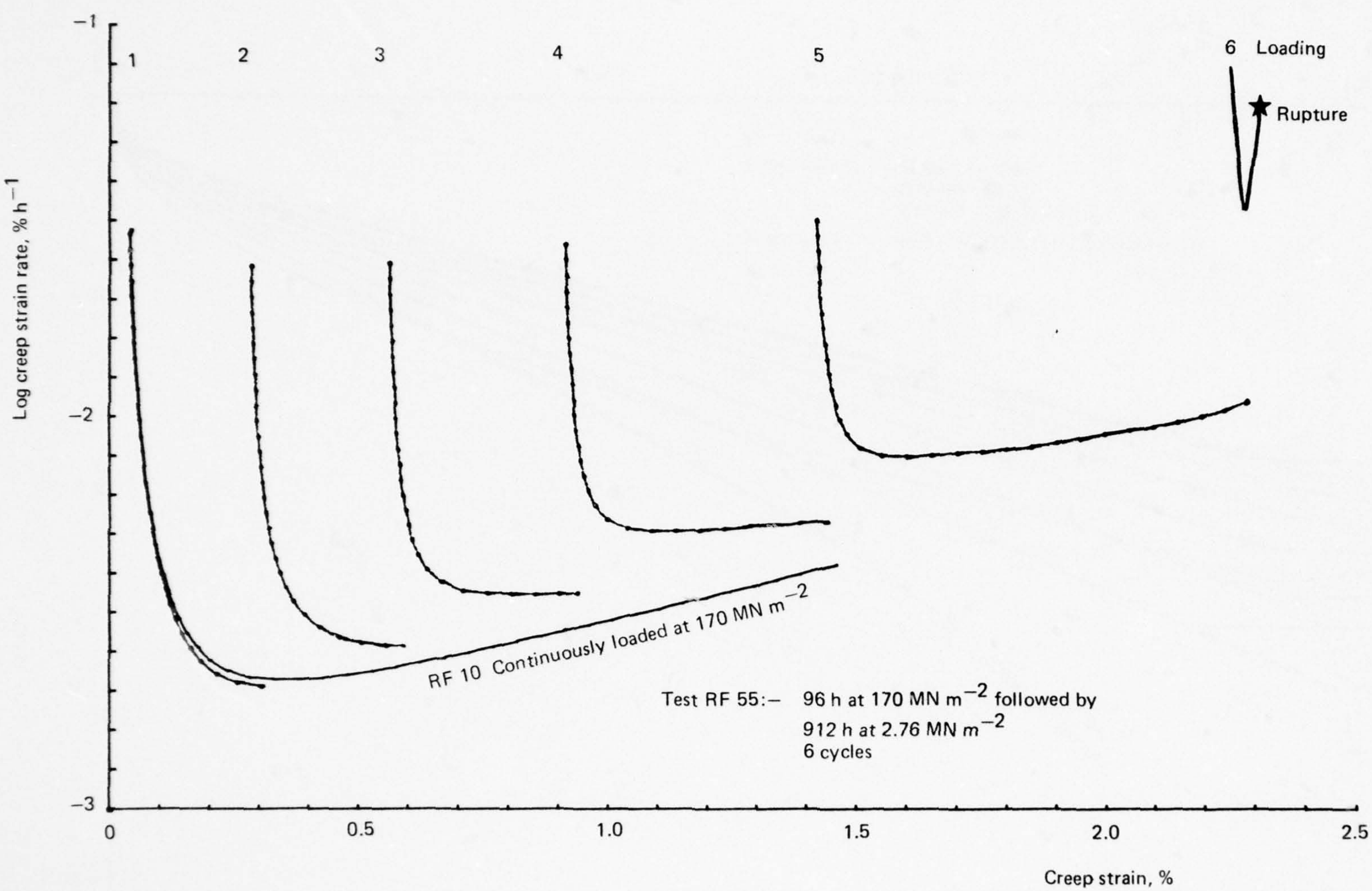

Fig 53 Successive strain rates for 170 MN m^{-2} at 180°C

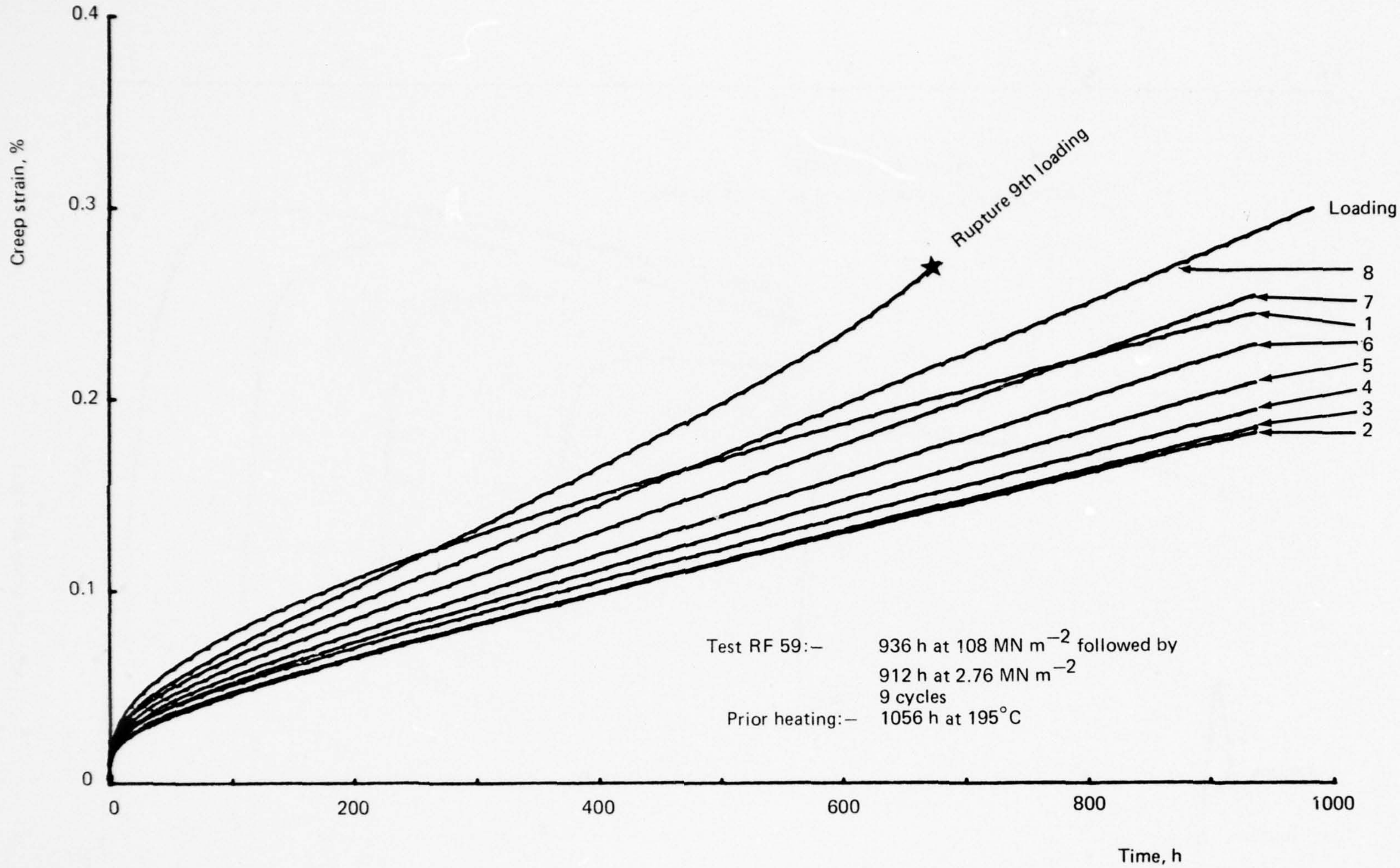

Fig 54 Successive responses to 108 MN m^{-2} at 180°C after prior heating

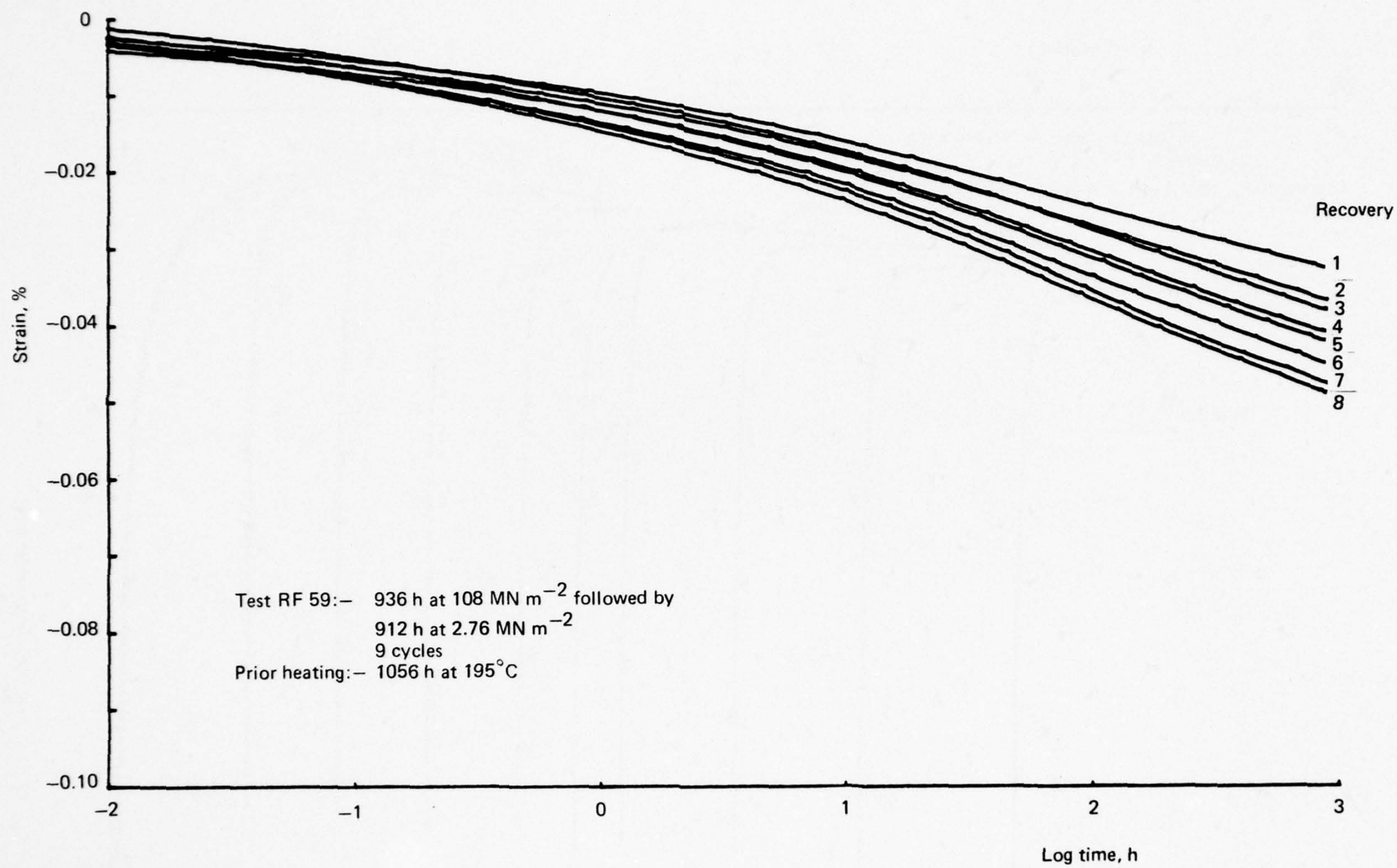

Fig 55 **Successive recoveries after 108 MN m^{-2} at 180°C and prior heating**

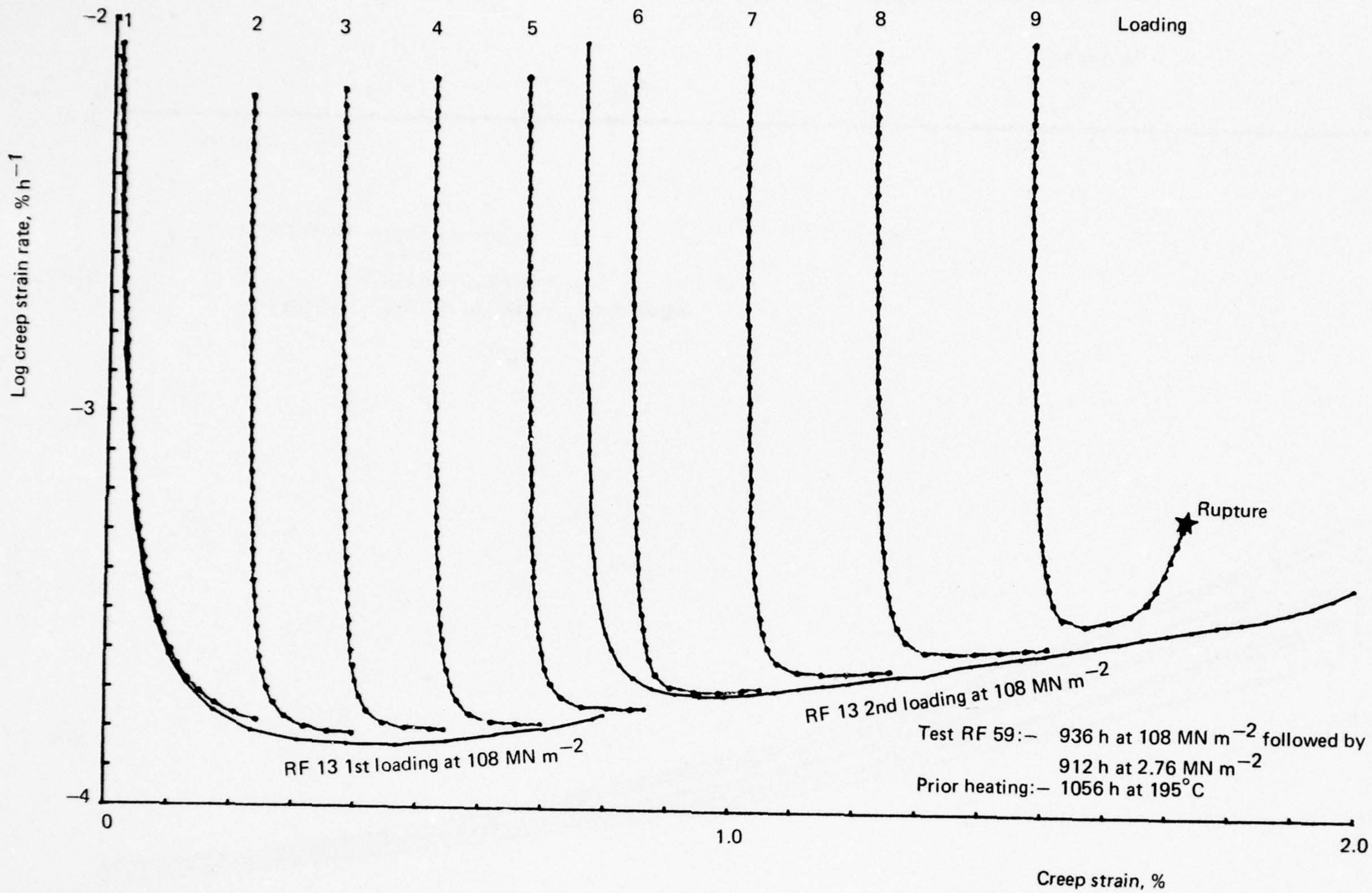

Fig 56 Successive strain rates for 108 MN m^{-2} at 180°C after prior heating

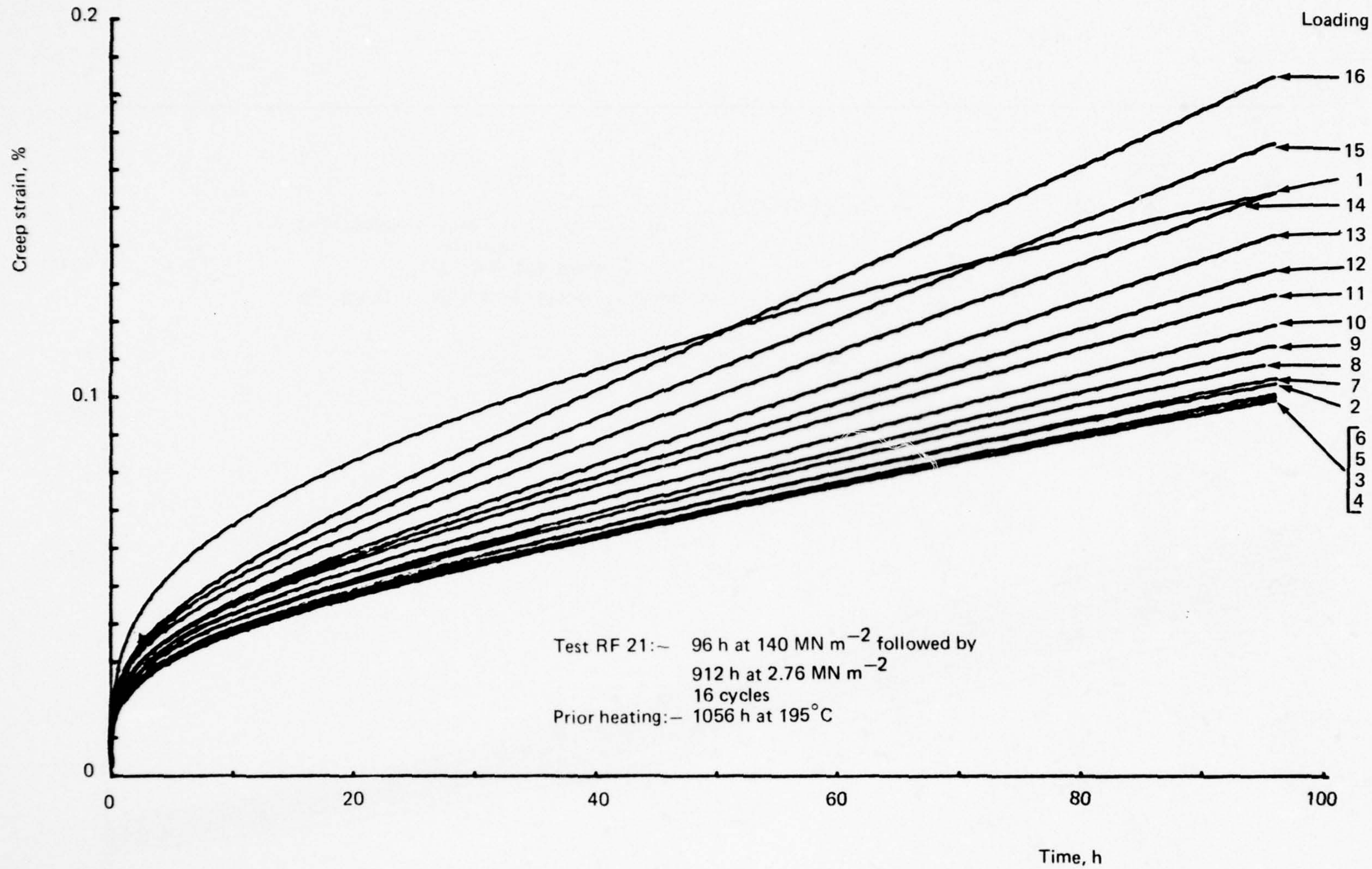

Fig 57 Successive responses to 140 MN m^{-2} at 180°C after prior heating

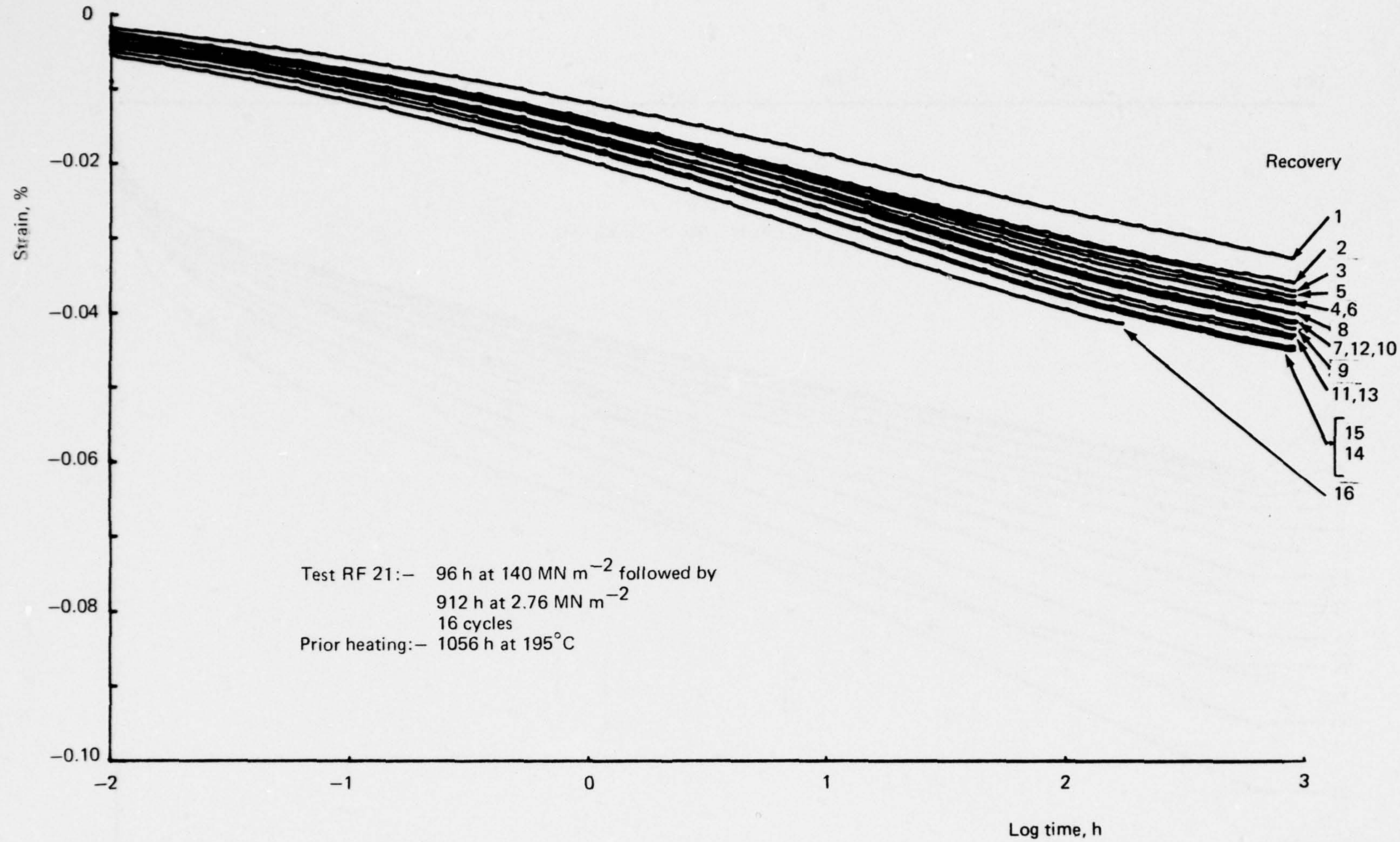

Fig 58 Successive recoveries after 140 MN m^{-2} at 180°C and prior heating

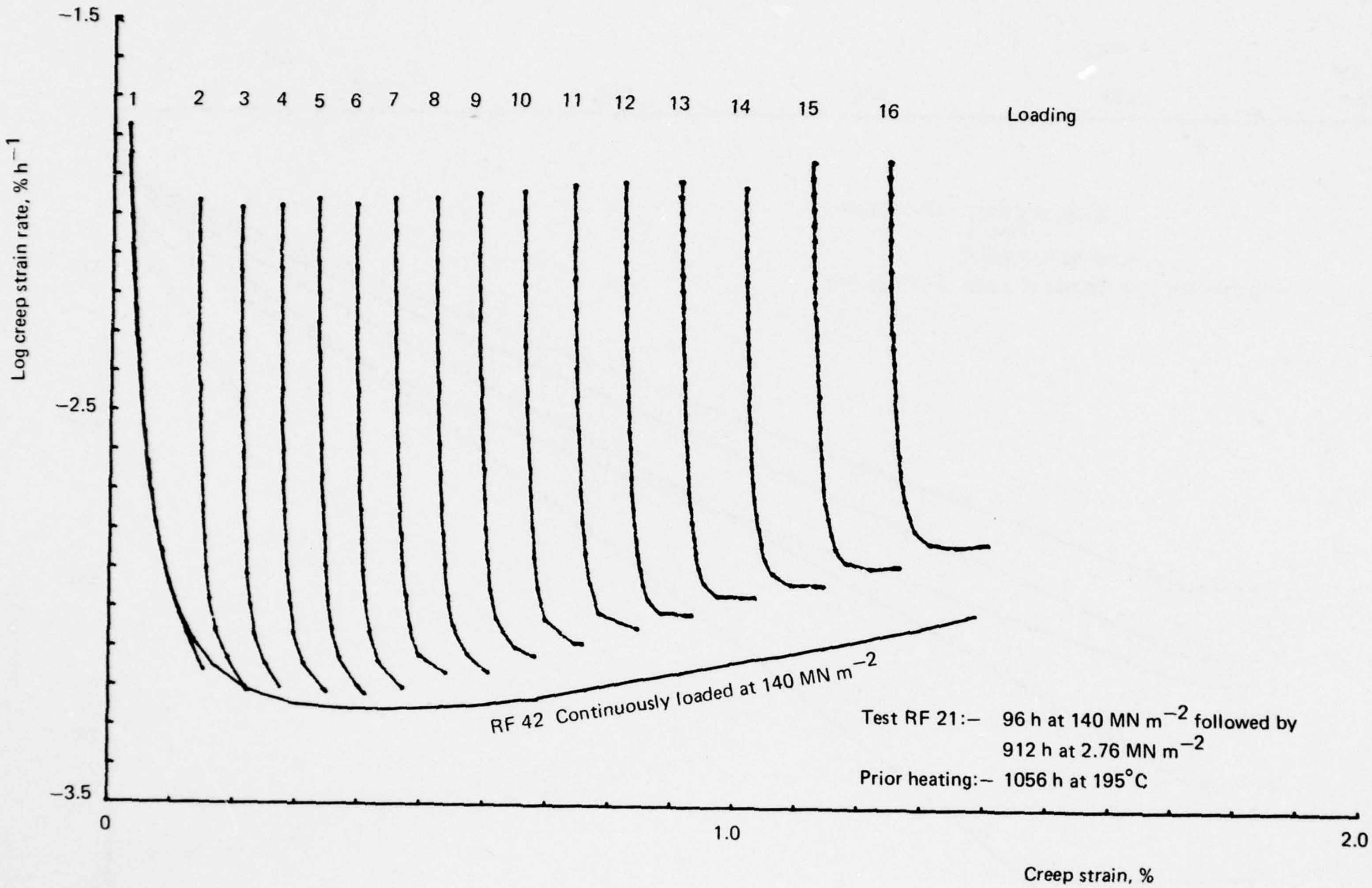

Fig 59 Successive strain rates for 140 MN m^{-2} at 180°C after prior heating

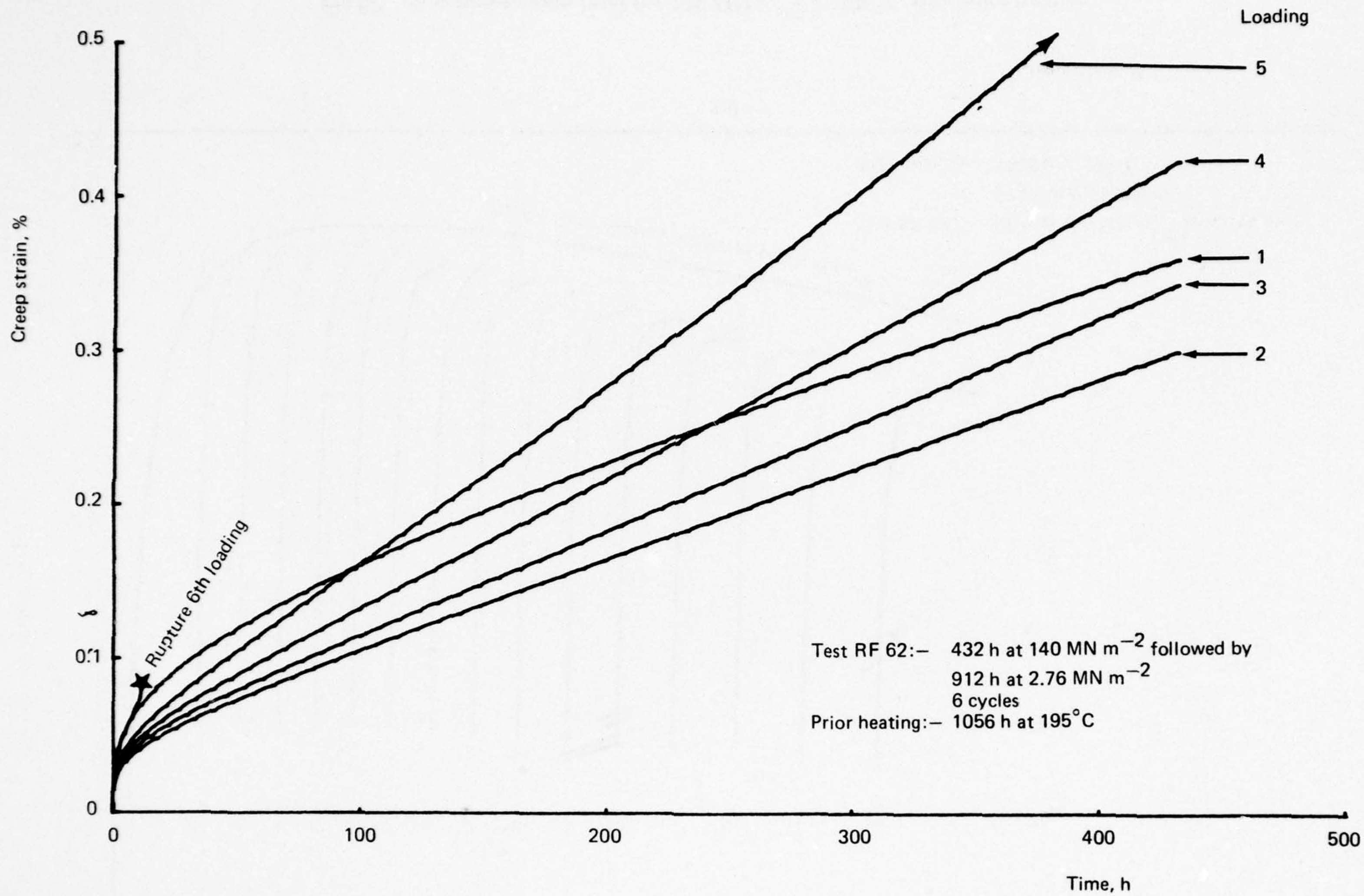

Fig 60 **Successive responses to 40 MN m^{-2} at 180°C after prior heating**

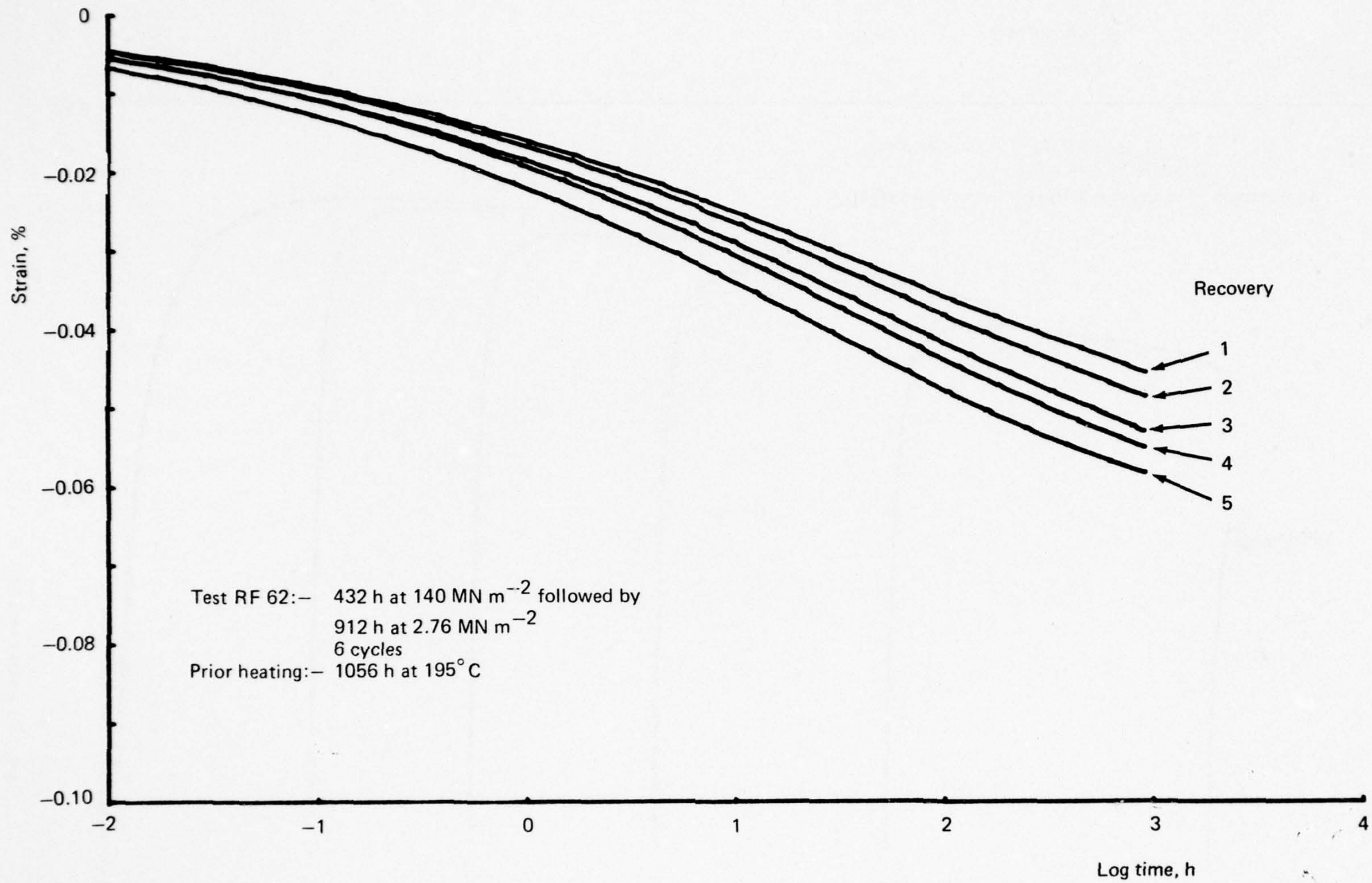

Fig 61 Successive recoveries after 140 MN m^{-2} at 180°C and prior heating

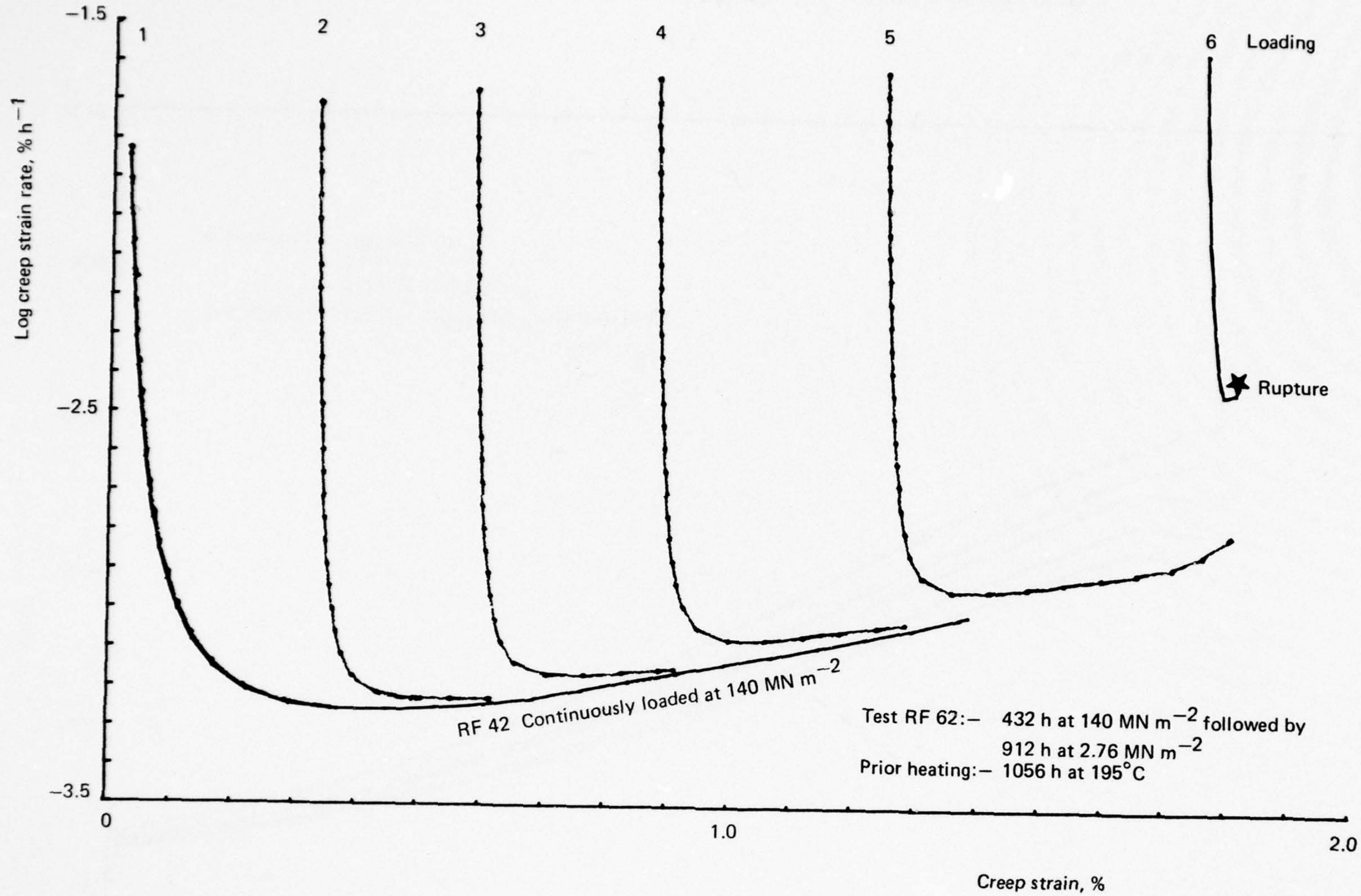

Fig 62 Successive strain rates for 140 MN m^{-2} at 180°C after prior heating

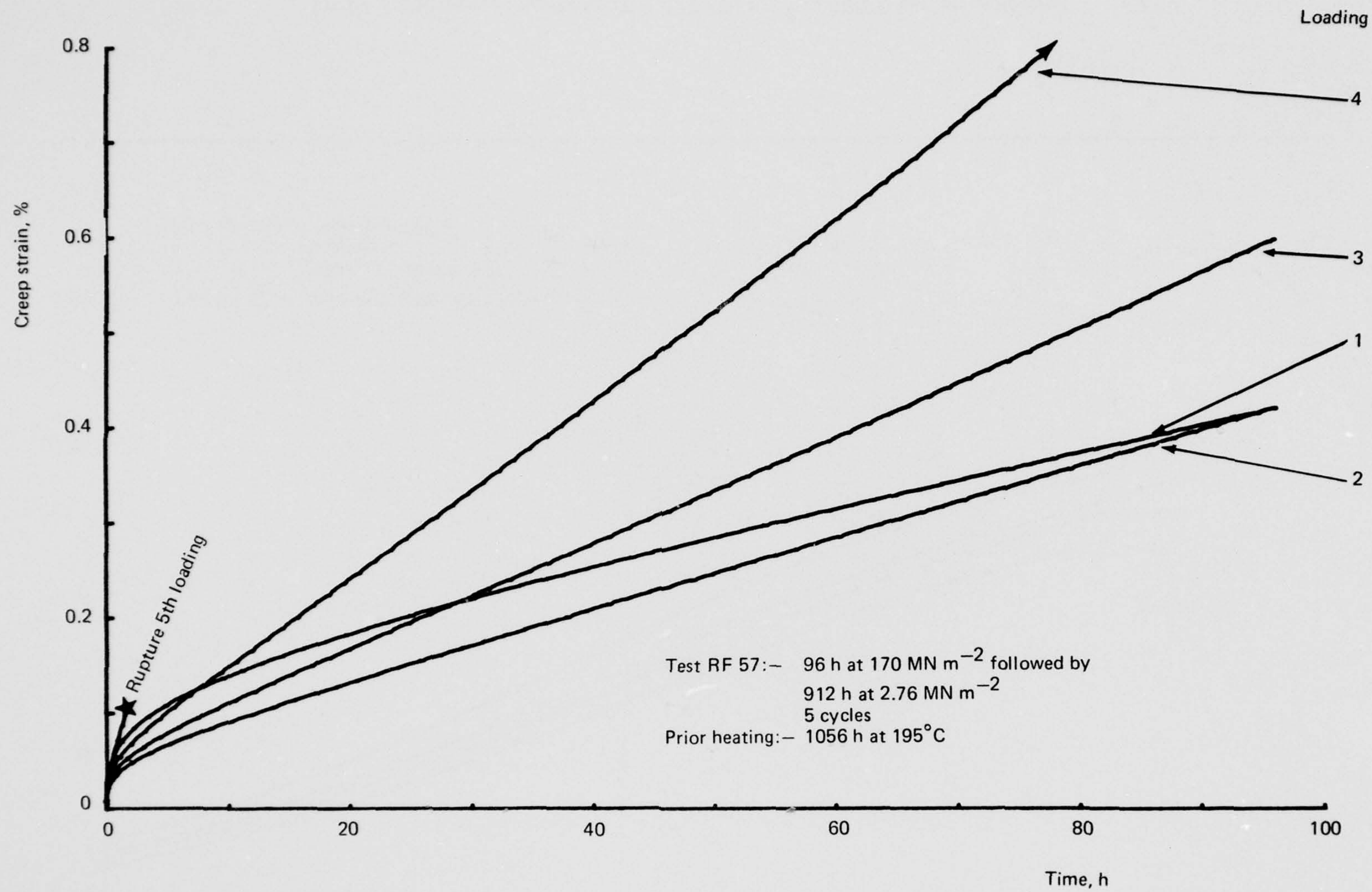

Fig 63 Successive responses to 170 MN m^{-2} at 180°C after prior heating

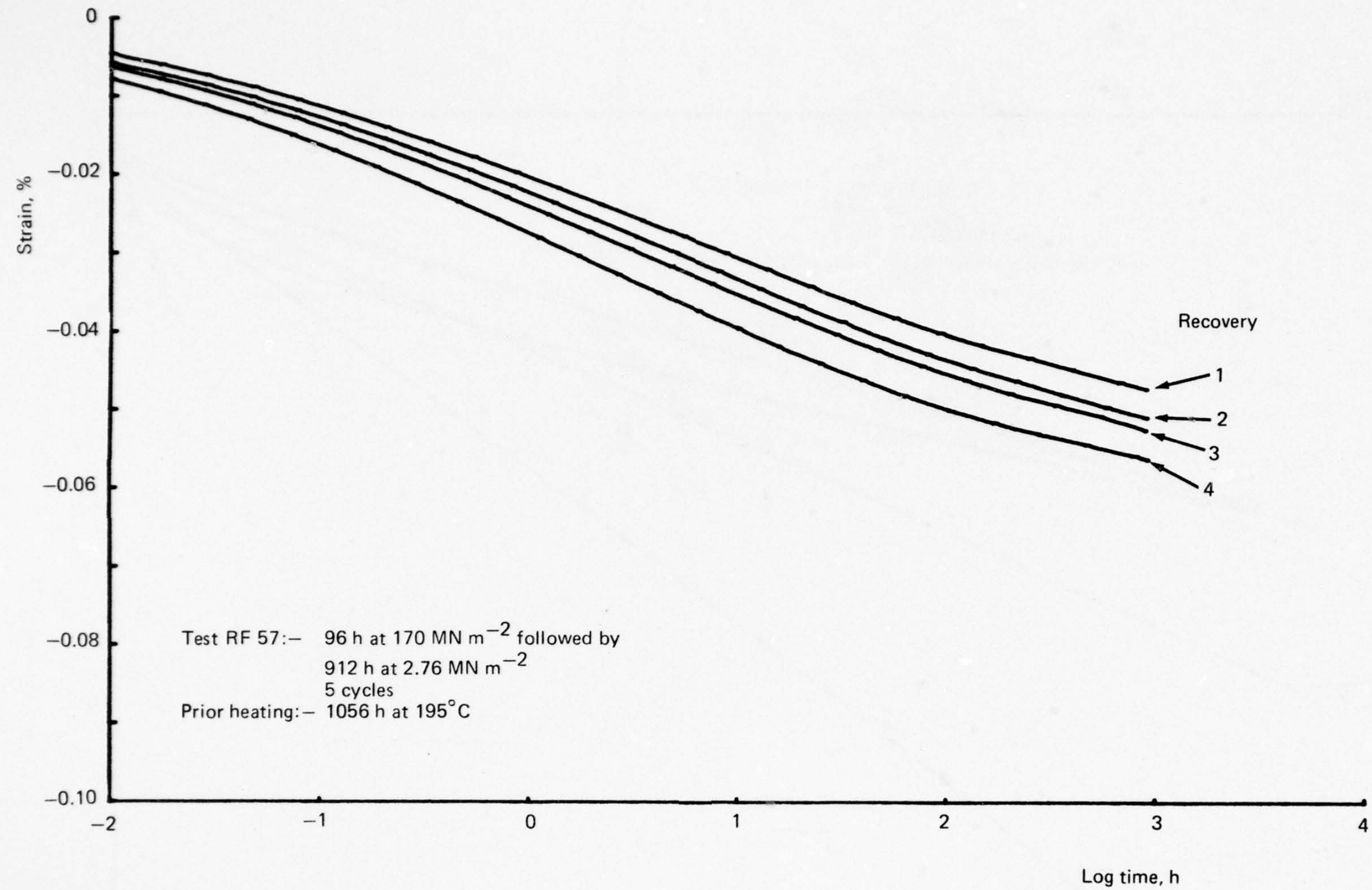

Fig 64 Successive recoveries after 170 MN m^{-2} at 180°C and prior heating

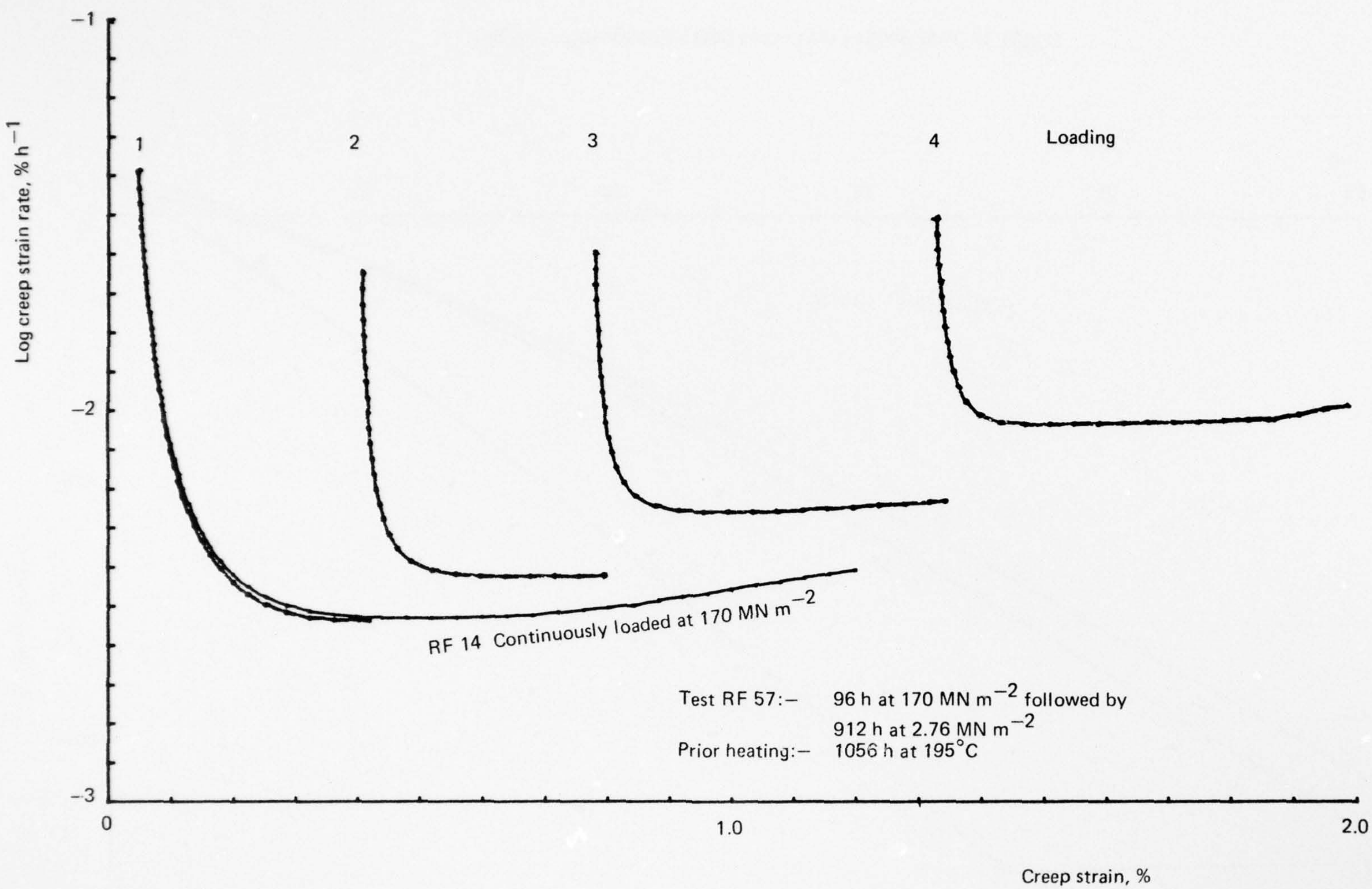

Fig 65 **Successive strain rates for 170 MN m^{-2} at 180°C after prior heating**

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INTRODUCTION TO A LIBRARY OF CREEP AND STRAIN RECOVERY DATA FOR--ETC(U)
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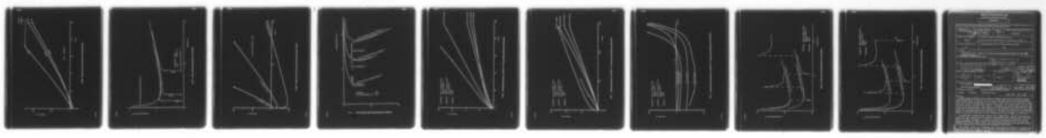

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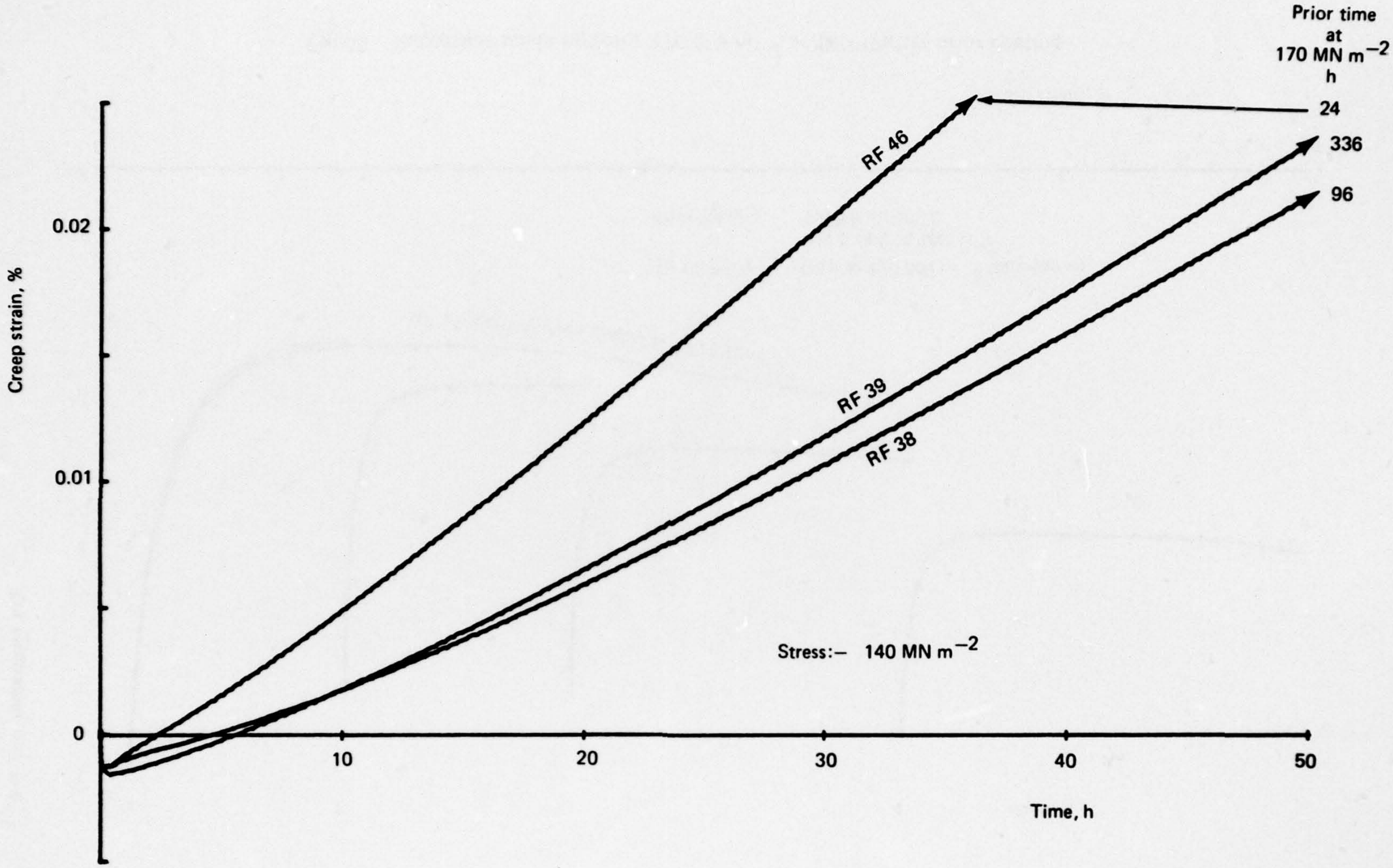


Fig 66 Response to step reduction in load level at 180°C

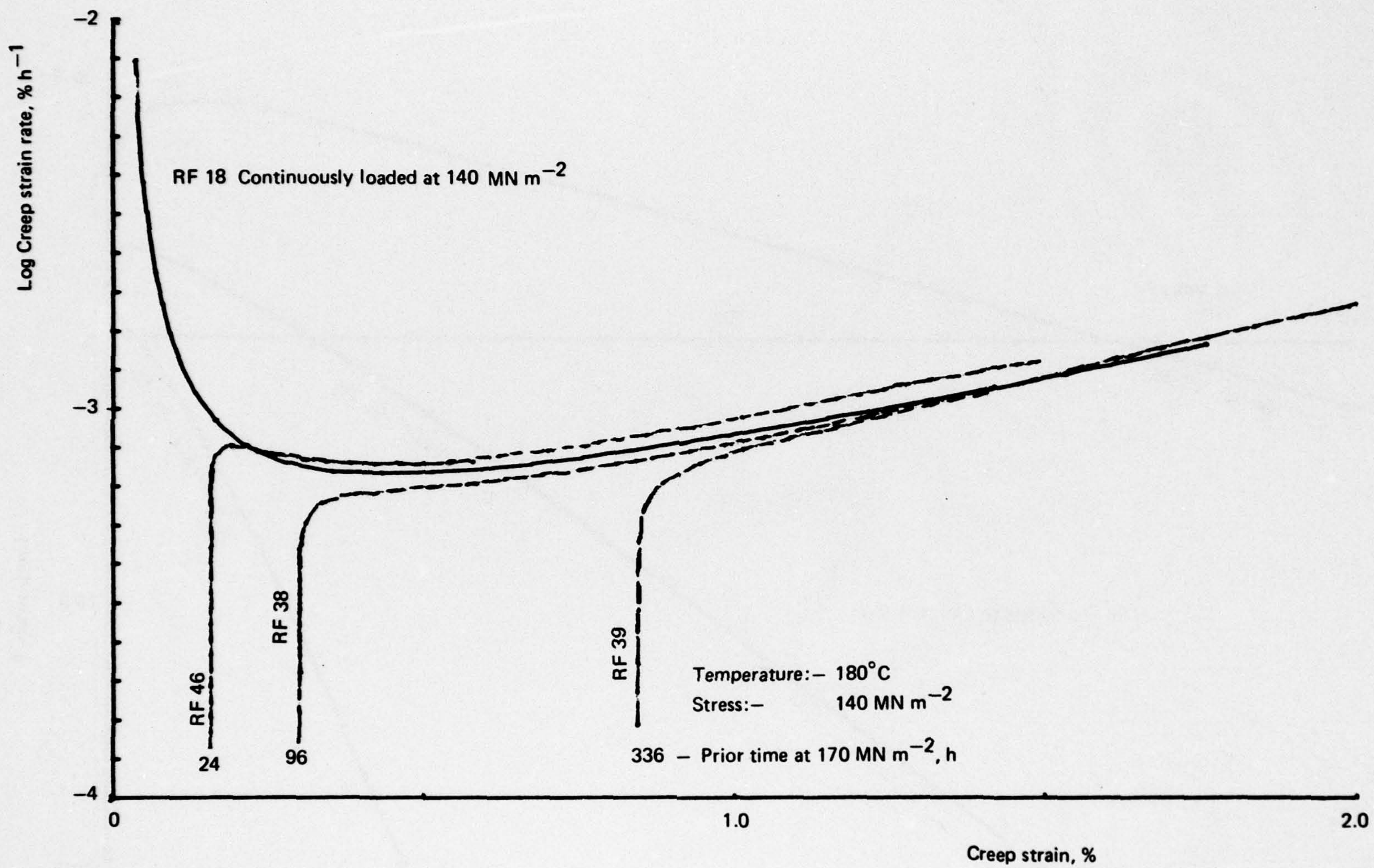


Fig 67 Strain rate after step reduction in load level

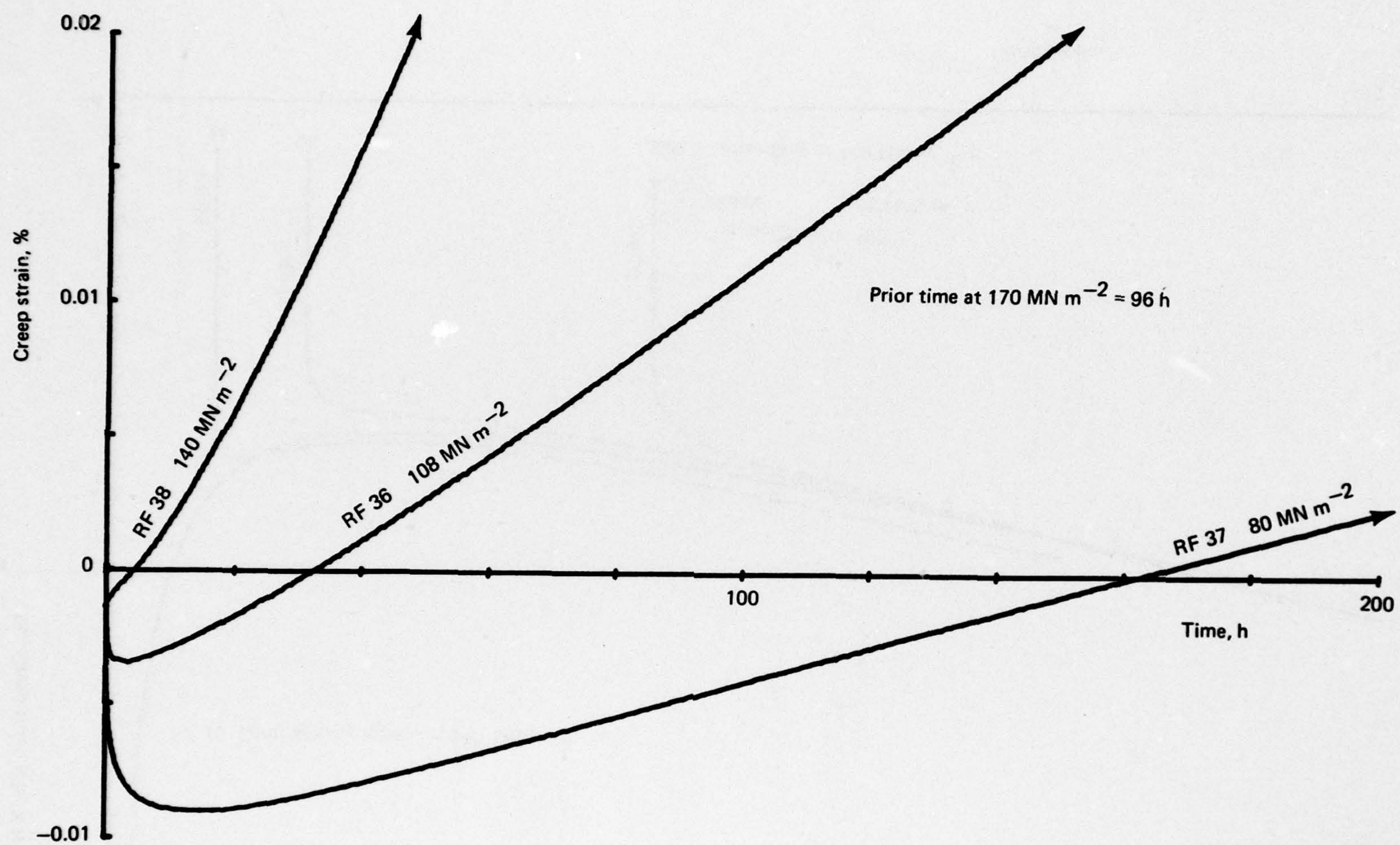
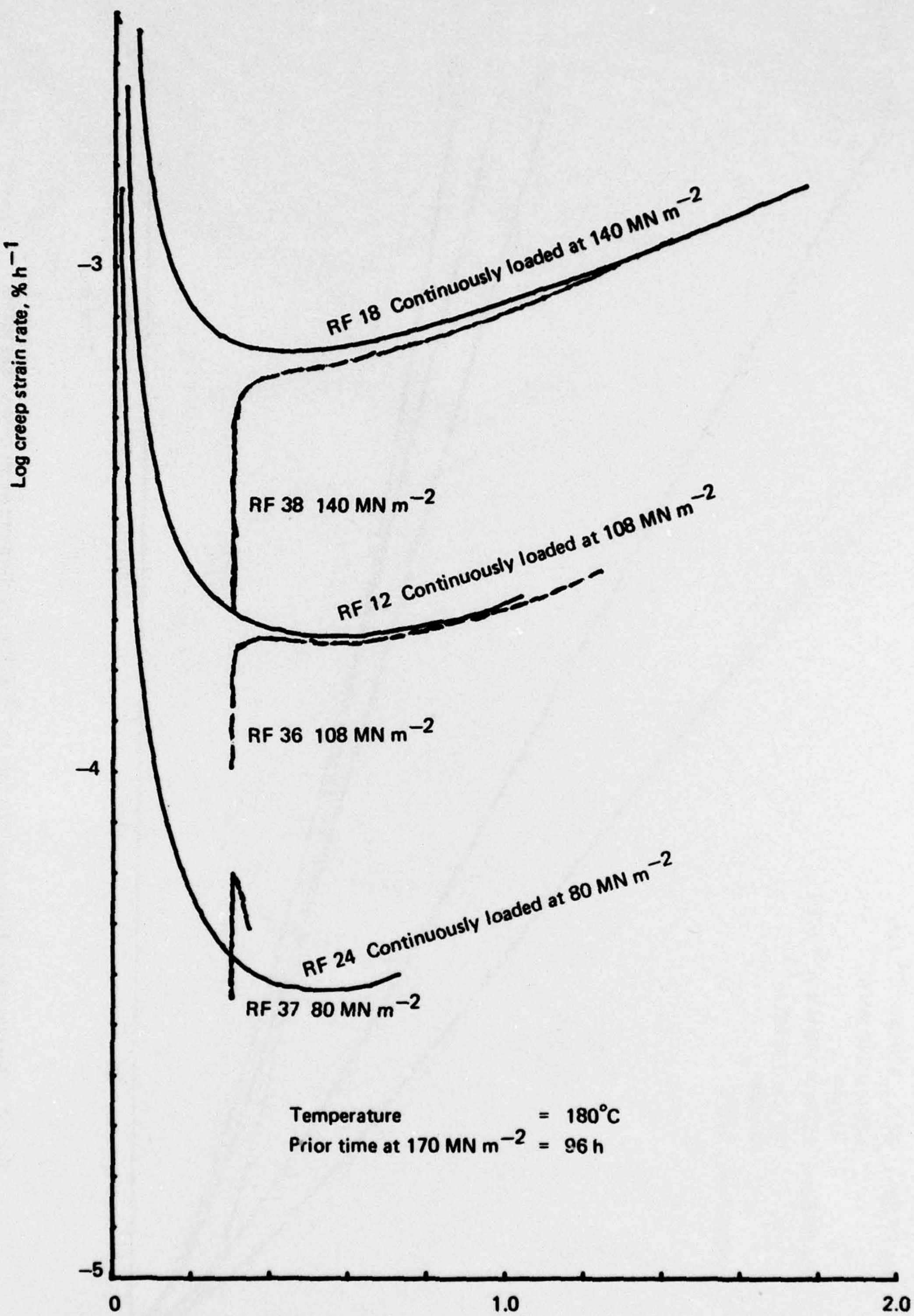


Fig 68 Response to various step reductions in load level at 180°C



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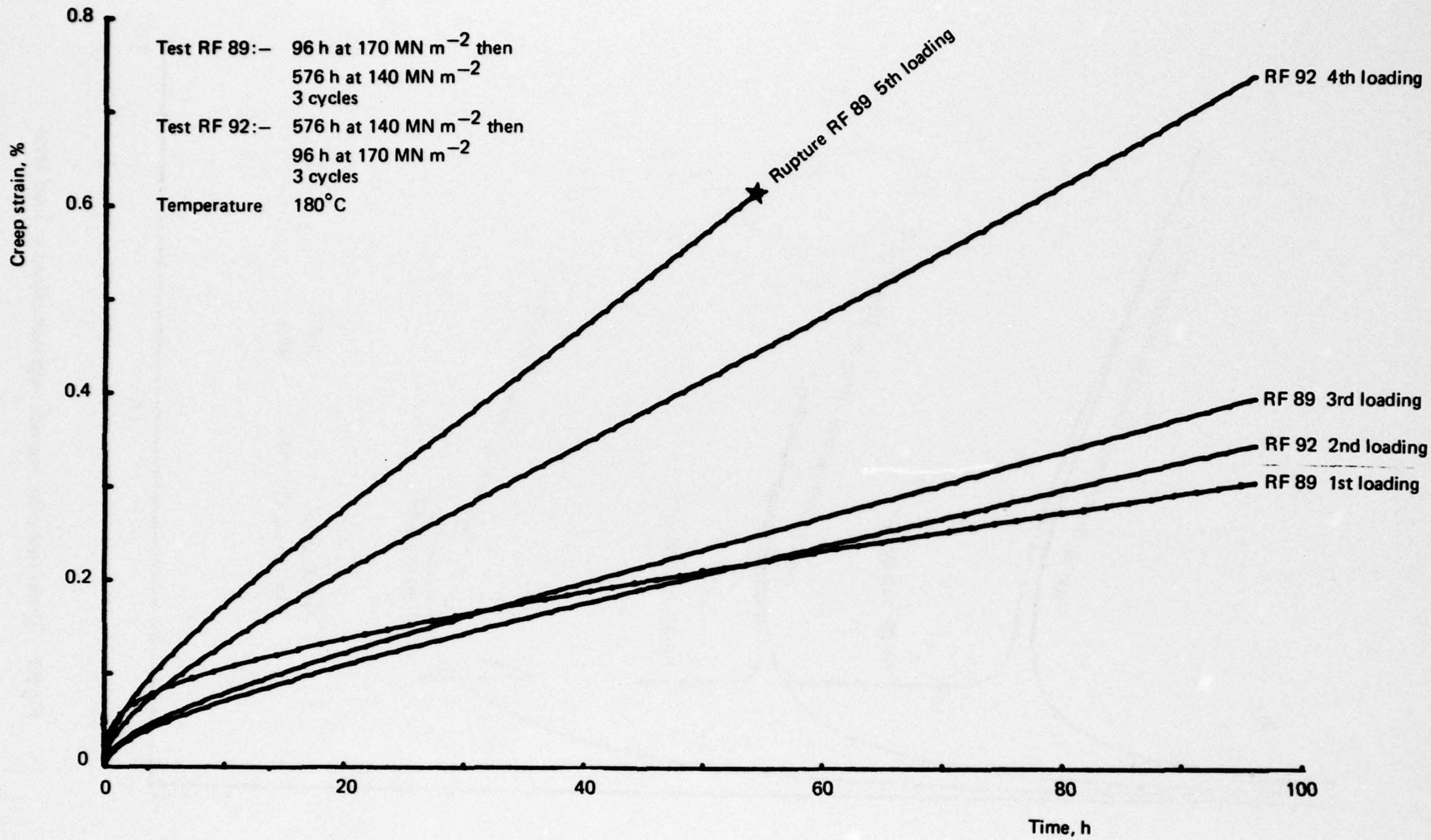

Fig 70 Successive responses to 170 MN m^{-2} during cycling between two stress levels

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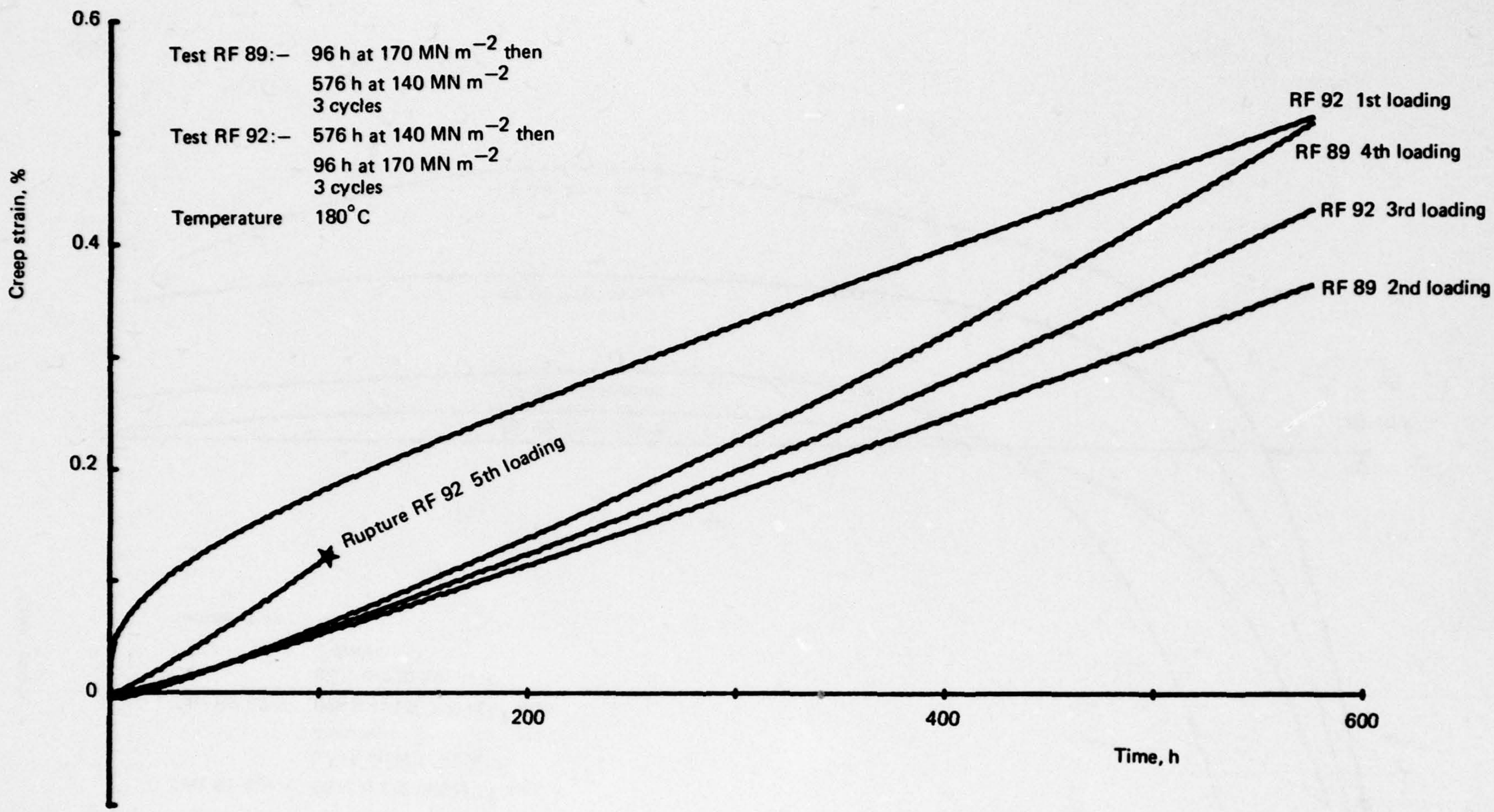

Fig 71 Successive responses to 140 MN m^{-2} during cycling between two stress levels

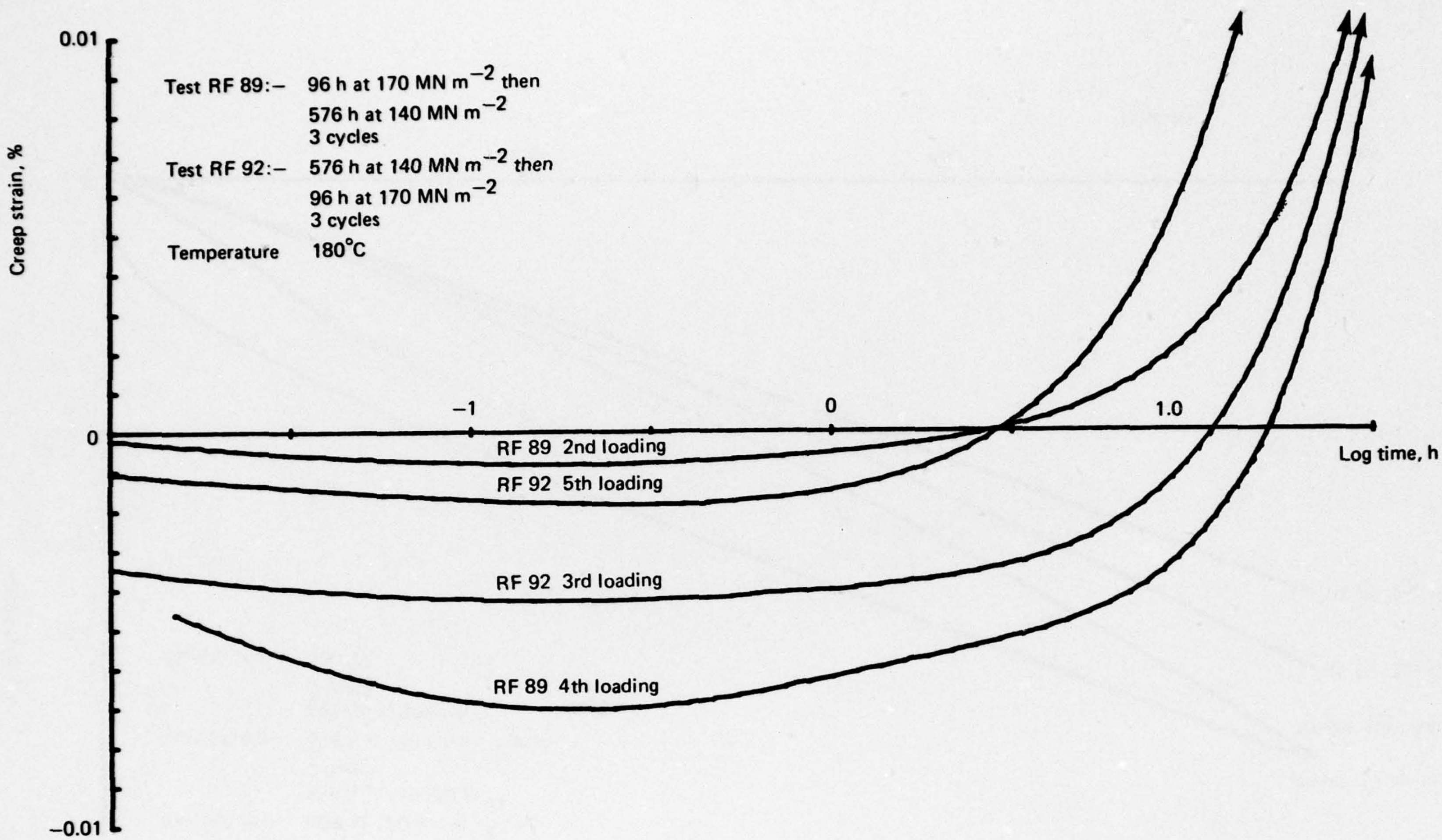

Fig 72 Successive initial responses to 140 MN m^{-2} during cycling between two stress levels

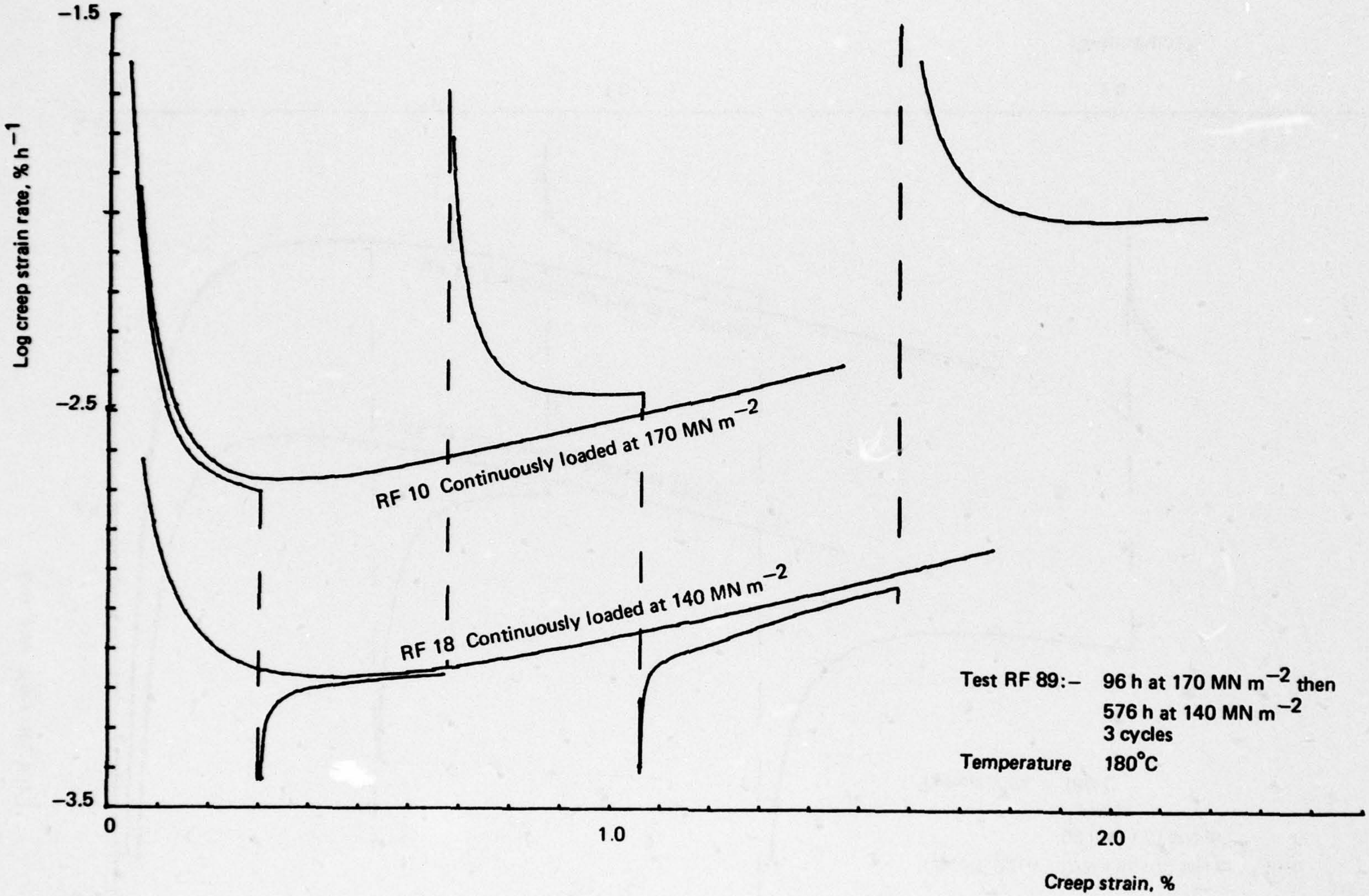

Fig 73 Strain rate for cycling between two stress levels

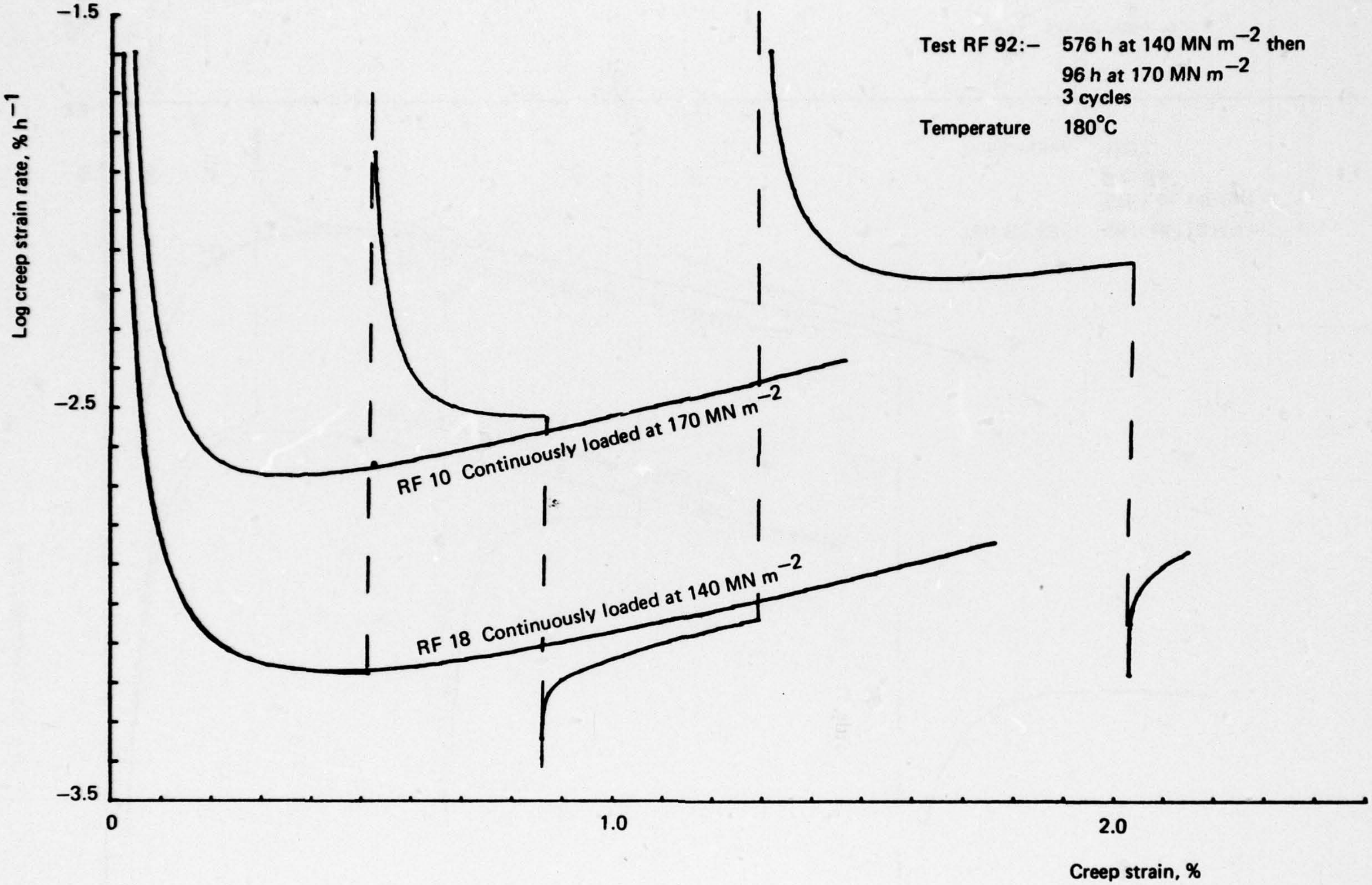

Fig 74 Strain rate for cycling between two stress levels

REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNLIMITED

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7 Title 6

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9 Technical rept.,

7b. (For Conference Papers) Title, Place and Date of Conference

10 J.N./Webb 11 Mar 77 12 106p.

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Webb, J.N.			March 1977		8

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15. Distribution statement

(a) Controlled by [redacted]

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16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Creep. Recovery. Aluminium alloy.

310 450

17. Abstract

This paper introduces the library of tensile creep data accumulated during a research programme carried out by Structures Department during the period January 1969 to March 1976. Specimens were cut from a single sheet of high strength aluminium alloy to DTD 5070A and were creep tested at 150, 165, 180 and 195°C over a range of stress levels to strains near rupture. Subsequent unloading, where possible, provided strain recovery data. Additional tests investigating the interaction of creep and strain recovery periods were extended in some cases to provide cyclic creep data useful in the exploration of history effects. Further work, mainly at 180°C investigated the effects of periods of prior heating and of step changes in load level.

The data were obtained under conditions of temperature, load and load axiality controlled more closely than is usual in conventional creep testing and can be compared with some confidence. In addition each test phase was fitted with a seven degree polynomial to high accuracy and processed data was produced listing time, measured and fitted strain, strain rate and second derivative of strain with respect to time together with the appropriate polynomial coefficients.

This Report details the techniques used, describes the results in a qualitative manner and acts as an index to the library of processed data which is available in microfiche form in a companion report.

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