AD NUMBER

AD468683

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies and their contractors; Critical Technology; MAY 1965. Other requests shall be referred to Air Force Materials Lab., AFSC, Wright-Patterson AFB, OH 45433.

AUTHORITY

AFML ltr, 12 Jan 1972

AFML-TR-65-181
Part I

MECHANISMS ASSOCIATED WITH LONG TIME CREEP PHENOMENA

Part I: Presentation of Creep Data and Structural Analysis

R. Widmer, J. M. Dhosi, A. Mullendore, and
N. J. Grant

New England Materials Laboratory, Inc.

TECHNICAL REPORT AFML-TR-65-181, PART I

June, 1965

Air Force Materials Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

NOTICES

MECHANISMS ASSOCIATED WITH LONG TIME CREEP PHENOMENA

PART I: Presentation of Creep Data and Structural Analysis

R. Widmer, J.M. Dhosi, A. Mullendore, and
N. J. Grant

New England Materials Laboratory, Inc.

FOREWORD

This report was prepared by New England Materials Laboratory, Inc., Medford, Massachusetts, under USAF Contract No. AF 33 (616)-8225 and No. AF 33 (657)-11237. The contract was initiated under Project No. 7351, "Metallic Materials", Task No. 735106, "Behavior of Metals". The work was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division, with Mr. K. D. Shimmin acting as project engineer.

This report covers work conducted from March 1961 to July 1964.

Manuscript released by the authors May 1965 for publication as an RTD Technical Report.

This technical report has been reviewed and is approved.

W. J. Trapp

W. J. TRAPP
Chief, Strength and Dynamics Branch
Metals and Ceramics Division

ABSTRACT

A creep-rupture investigation was conducted on two high temperature alloys: a nickel-base age hardened alloy, Udimet 500, and a cobalt-base alloy, L-605. Creep-rupture tests were conducted over a range of rupture lives from 1 to 20,000 hours at 1200°, 1350°, 1500°, 1650°, and 1800° F. Additional long time tests with expected lives up to 50,000 hours were initiated and are still in progress.

The test data were supplemented by extensive examination of structural changes during testing as well as the nature of crack initiation and propagation as a function of stress, temperature, and time. Additional groups of tests at particular stresses and temperatures were run to establish the reproducibility of data. The intent was to characterize thoroughly the materials, their structures, and the nature of deformation and fracture processes in order to evaluate the applicability of extrapolation procedures.

TABLE OF CONTENTS

ILLUSTRATIONS

APPENDIX IV - ILLUSTRATIONS

I INTRODUCTION

The extrapolation of short-time creep-rupture data of complex high temperature alloys to obtain the very long-time properties is fraught with uncertainties. In addition to questions regarding the soundness and general applicability of existing extrapolation techniques, one is also concerned with the reliability and reproducibility of the short-time data due both to non-uniformity in the composition or structure of the materials tested and to variability of procedures used in testing.

It was the purpose of this study to examine in detail two high temperature superalloys, L-605 (Haynes 25) and Udimet 500, using uniformly heat treated material from a single heat in each case and utilizing the most exacting creep-rupture testing procedures. These materials were chosen as representative wrought cobalt and nickel-base superalloys. The L-605 is representative of alloys which always show instantaneous plastic flow on loading; the U-500 is representative of alloys without significant plastic deformation on loading, and which do not show a true minimum creep rate. Both are expected to behave differently in terms of response to temperature and strain rate, and will therefore present different problems in extrapolation studies.

These data, covering the rupture time range of 1 to 10,000 hours at temperatures from 1200° to 1800° F, were supplemented by extensive examination of structural changes occurring during testing and the nature of crack initiation and propagation as a function of stress, temperature, and time. Additional groups of tests at particular stresses and temperatures were run to establish the reproducibility of the data. Thus, the intent was to characterize thoroughly the materials, their structures, and the nature of deformation and fracture processes in order to evaluate the applicability and reliability of extrapolation procedures.

Long-time creep-rupture tests with rupture lives from 10,000 to 50,000 hours were also initiated at 1200° and 1500° F to provide the ultimate check on the extrapolation techniques. Some of these tests are still in progress (see Appendix IV).

This report presents the data collected to the present time, and identifies structural or surface instabilities and their effects on deformation and fracture behavior in order to define the statistical variation of the creep-rupture data. It is intended in a future report to apply extrapolation techniques to the data.

II MATERIALS AND TESTING PROCEDURE

A. Materials

The chemical compositions of Udimet 500, an age-hardenable nickel-base alloy, and L-605 (Haynes 25) a cobalt-base alloy, are given in Table 1. The structure of Udimet 500, aged at 1500° F for 24 hours, then at 1400° F for 16 hours is shown in Figure 1. This material has a duplex grain structure with longitudinal bands of two different grain sizes (0.002 and 0.006 cm in diameter) and contains a fine uniform precipitate along grain and twin boundaries which, based on prior investigations of the alloy, is chromium carbide. The larger globular precipitate which appears gray in the photomicrograph and occurs preferentially in the fine grain size bands is a carbonitride of titanium. The fine structure which is seen in the small grains in Figure 1 is due to etch pits associated with ultrafine Ni_3 (Al, Ti) or gamma prime (γ') precipitate.

Figure 2 shows the "as received" microstructure of L-605 (annealed at 2250° F and water quenched). The structure is composed of a uniform grain size (0.015 cm diameter); in the tested condition the structure shows precipitate particles of Co_2W and a carbide of the M_6C type.

All materials were ultrasonically inspected for uniformity and flaws using the pulse-echo technique in both the longitudinal and transverse directions. Any of the rods so examined which were found to contain irregularities of any kind were rejected prior to machining.

B. Test Procedures

Test frames used were of the simple beam loading type having a maximum lever arm ratio of 20 to 1. Depending on the load required, a 10 to 1 ratio or direct loading was used. Weights used have been calibrated against a reference weight certified by the Commonwealth of Massachusetts Bureau of Weights and Measures. The accuracy of applied load was within 0.75 percent.

The furnaces used for the testing were of Nemlab design. The core of the creep testing furnace is an 18-inch alundum tube (1 1/4" I.D.) with a Nichrome resistance winding. Creep measurements are made through a viewing window covered with pyrex glass and opaque covers to minimize heat losses. The tube winding is composed of four sections each of which can be switched in or out of the series circuit or varied by external resistances. In addition there is rheostat control of the upper and lower halves of the main winding. This design permits exceptionally fast temperature adjustments to be made. Figure 3 is a schematic drawing of the furnaces used. Indicated temperature deviations from nominal were maintained at a maximum of ±2° F throughout the duration of the tests. Maximum gradient along the gauge length of the specimen was 3° F. Three chromel-alumel thermocouples were affixed to the specimen gauge sections and test temperature was maintained by Minneapolis-Honeywell "Electronik" on/off controllers. Furnace control was effected through the centrally located thermocouple, and the temperature at this location was recorded continuously. The two thermocouples near the extremities of the gauge length were checked and the temperature simultaneously printed on the same recorder chart twice daily. Figure 4 shows a specimen which has been prepared for testing, and Figure 5 is a drawing of the specimen type used in this investigation.

The standard loading practice employed was as follows:

(1) Prior to insertion of the test specimen, with its linkages, the furnace was brought to test temperature and any gradients which existed in the specimen zone of the furnace were eliminated by the continuously adjustable rheostats.

(2) The specimen was inserted into the furnace and connected firmly into the loading column. Any residual gradient, as determined at this point by the thermocouples on the specimen itself were eliminated.

(3) A thirty minute period of soaking was then allowed.

(4) The initial loading was done in small increments well within the elastic range which had been determined previously. With the addition of each load increment, a reading of elongation was made. The remainder of the load then was applied in a total time of less than thirty seconds, the required weights being loaded manually.

(5) The first reading was completed within thirty seconds after application of the full load. This procedure allowed the determination of the plastic deformation on loading with a delay time of one minute.

Subsequently a minimum of three creep deformation readings were made daily during the first fifty hours of testing. More frequent readings (as many as ten per hour) were made when the nature of the creep curve so warranted. Creep data were always recorded and plotted immediately.

In making the plots of time versus creep deformation, the elastic contribution was determined and subtracted from the readings of total elongation.

Creep extension measurements were made optically using notched platinum wire-in-tube extensometers mounted on the shoulders of the specimens (between the thread and the gauge section). Two platinum wire-in-tube sets were spot-welded on each specimen 180 degrees apart so that corresponding readings on two sides of the specimen could be averaged to compensate for any unavoidable lack of uniaxiality in deformation (see Figure 4). The filar eyepiece microscope used reads directly to 0.00004 inch.

Upon fracture of a specimen the timing device, which was started at the inception of the test (application of full load) stops automatically, and the power to the furnace decreases simultaneously.

III RESULTS

Creep-rupture testing was performed primarily at 1200°, 1350°, 1500°, 1650°, and 1800° F, and a few tests were made at the intermediate temperatures of 1275°, 1425°, and 1575° F.

The data obtained for all creep-rupture tests for both alloys are given in tabular form in Appendix I. The table contains short and long time tests, including those still in progress; scatterband tests for determining the statistical spread in rupture life; and tests which were interrupted at various fractions of the rupture time for structural observations. These data are also presented graphically in Figures IV-1 through 4 and Figures IV-9 through 12. Since the two alloys are not similar in their properties, they will be discussed separately.

A. Udimet 500

1. Creep-Rupture Data

The log stress versus log rupture time and log stress versus log minimum creep rate plots for Udimet 500 are shown in Figures 6 and 7. In both cases, the data can be represented by straight line segments using the log-log plotting convention and the junctions of these segments can be associated with changes in structure and in deformation and fracture characteristics. The corresponding line segments at the various testing temperatures are labelled A_1, A_2, A_3, and B_1, B_2, B_3, etc., in order of ascending temperature. The identification of the instabilities Ab, Bc, etc., will be discussed later.

The straight line segments drawn in Figures 6 and 7 were determined by a least squares analysis of the data as described in Appendix III. The intersections of these straight lines determine the positions of the instability points. Since the differences in slopes of two intersecting line segments are often small, the position of the intersection can vary considerably.

The equation of the line segments will be of the form:

$$\log \sigma = K + m \log x \qquad 1)$$

where x represents either minimum creep rate, $\dot{\varepsilon}_{min}$, or rupture time, t_r. The constant m is the slope of the line segment and K equals log σ when x equals 1. Values of m and K determined by the least squares method are listed in Table 2.

The deviations of the experimental values of rupture time and minimum creep rate from the calculated least squares line were determined and are summarized in Table 2 as the root mean squares value of the log t_r and log $\dot{\varepsilon}_{min}$ deviations for each line segment. These values (which are approximately equal to the standard deviation) vary from 0.004 to 0.0452 log cycles. The corresponding root mean squares deviations in terms of log stress are obtained simply by multiplying the $D_{\log t_r}$ or $D_{\log \varrho}$ by the corresponding value of the slope, m, and these are also given in Table 2. It is interesting to note that a typical value of $D_{\log \sigma}$ of 0.01 corresponds to about a 2 percent deviation of stress; fairly small, considering that the ASTM Specification on the accuracy of the load in a creep test is 1 percent.

Examination of the D values as a function of temperature (Figure 8) shows that maximum scatter of data occurs at the highest temperature of testing, and minimum scatter occurs at 1350° F. This behavior is unfortunate from the standpoint that one ordinarily utilizes short time high temperature data to extrapolate to long times at lower temperatures.

An additional measure of the variation of rupture life was obtained by running groups of seven or eight tests at each of two stresses at 1200° and 1500° F. These data are summarized in Table 3, which includes the log rupture time values, log t_r obtained from the best least squares line previously calculated, rupture time, and the RMS (root mean squares) deviation of the scatter tests from this value. These deviations are about the same at 1200° F as those shown in Table 2 and Figure 8; however, at 1500° F (particularly at 30,000 psi) the RMS deviation is higher. The RMS deviation of the log rupture time values about their mean value is also higher (0.2255) than that in Figure 8.

In terms of actual values, one observes from Table 3 and Figure 6 that the spread of rupture lives is at least 3 to 1 except at 1500° F and 30,000 psi where the spread is 5 to 1. The listed ductility values in Table 3 show a maximum spread of 3 to 1. Based on testing procedures and use of minimum test values this represents a great penalty in the use of alloys for high temperature applications. Efforts to decrease this spread through structure control would appear warranted, because the testing procedures appear not to be at fault (1).

Figures 9, 10, and 11 present curves of log-stress versus log-time to 0.1, 0.5, and 1.0 percent plastic strain. For convenience, the data are represented by straight line segments to see if there is some possibility that such a procedure might permit extrapolation. This will not be known adequately well until considerably longer time points are obtained.

Ductility data for Udimet 500 are presented in Figures 12 and 13 as total elongation and reduction of area versus log rupture time. Of significance is the low ductility observed in tests at 1200° F for rupture times from about 50 to 1,000 hours. Total elongation, except at 1200° F, shows wide scatter of data without any particular relationship to rupture life. The only observation to be made is that at each temperature from 1350° to 1800° F there are numerous values near 5 percent as a minimum with random scatter between 5 and about 20 percent elongation. This lack of directionality in total elongation versus rupture time has been reported previously (2).

Reduction of area values show more of a trend than do elongation values, decreasing with increasing rupture time. The decreases in reduction of area tend to occur near observed instability areas (Figure 6) and are often associated with increasing tendency for increasing intercrystalline cracking (2). On the average, reduction of area values are less affected than elongation by the opening and lateral spreading of intercrystalline cracks (3).

2. Microstructures of Creep Specimens

In interpreting creep data, it is important to have information on structural changes taking place in the material during testing. Representative photomicrographs of ruptured creep specimens of Udimet 500 are shown in Figure 14. All of these are from longitudinal sections with the tension axis horizontal. The Udimet 500 specimens were, in all cases, etched with modified Aqua Regia.

Several general features are to be noted in the microstructures. The γ' precipitate in the grains begins to show evidence of coarsening only at 1500° F in long time tests. This agglomeration is sharply evident at 1650° F and higher. Electron microscopy will be further utilized to study the coarsening between 1350° and 1500° F because of the slow growth of the particles. The chromium carbide grain boundary precipitate which is present in the "as received" condition is relatively unchanged during creep at temperatures below 1650° F. At this temperature, in the long time tests, growth and agglomeration in the grain boundaries are noted. The presence of this precipitate has bearing on the nature of fracture since intercrystalline cracks start between these particles in the grain boundary.

In long time tests at 1800° F, the chromium carbide dissolves completely but is clearly present in short time tests. The scatter of test data at 1800° F (Figures 6 and 7) is obviously related to the extreme structural instability of the alloy.

B. L-605

1. Creep-Rupture Data

The log stress versus log rupture time and log stress versus log minimum creep rate plots for L-605 are shown in Figures 15 and 16. Again, the straight line segments have been determined by the least squares technique and instabilities are defined at BC_3, BC_4, and BC_5 for the temperatures 1500°, 1650°, and 1800° F. This instability probably also occurs at 1350° F at the long time limit of the data. There are indications of other structural instabilities as shown by metallography and ductility values, but these appear not to affect noticeably the rupture life and minimum creep rate data. The "BC" breaks are associated with marked increases in intercrystalline cracking as will subsequently be revealed.

It is interesting to observe the greater relative stability of L-605 compared to Udimet 500 at the higher temperatures in terms of the scatter of test values (Figures 6 and 15), and the smaller difference in rupture strength as 1800° F is reached.

Figures 17, 18, and 19 are log-stress versus log-time to 0.1, 0.5, and 1.0 percent plastic strain. In all instances, the data can be reasonably well represented by straight lines.

Because of the significantly large difference in plastic deformation on loading of L-605 compared to Udimet 500, the time to reach 0.1 percent strain is markedly in favor of Udimet 500, an alloy with no primary creep. Only when 0.5 percent strain is reached is it possible to obtain relatively complete curves for L-605 (see Figures 17 and 18).

In Figures 20 and 21, the total elongation and the reduction in area values are plotted respectively, versus the log of the rupture life. In general, a decrease in ductility can be observed with increasing life; this is observable both in terms of total elongation and reduction of area.

Evaluation of scatter of test data is summarized in Table 4 for repeat tests at 1200° and 1500° F. Results are considerably better than for Udimet 500. The worst scatter of data represents only a variation of 3 to 1 in rupture time and 2.5 to 1 in ductility. This alloy is obviously much more stable (and considerably weaker) than Udimet 500.

2. Microstructures in Creep Specimens

The aging response of L-605 is quite interesting. At 1200° F and in short time tests at 1350° F there is evidence of limited precipitation of pre-precipitations which leads to etching response that suggests actual aging. Electron microscopy failed to show actual precipitate particles. Then, in long time tests at 1350° F and in all tests at 1500° F and above, the precipitation of Co_2W takes place at an increasing rate. Structures are quite coarse even at 1500° F but growth takes place slowly even at 1800° F in long time tests (see Figure 22).

C. Fracture Analysis

The description of the nature of the progress of fracture is important to a thorough study of the stress-rupture behavior of metals for at least two reasons. First, it is possible that random variations in rupture life, creep rate and ductility may be the result of chance variations in the initiation and propagation of fracture. Secondly, it may be possible, through the time, stress and temperature variation of fracture behavior to establish more exact inter-relationships between ductility, creep rate and rupture life.

Fracture behavior has been measured both by the determination of the density of stress-rupture specimens, by weighing in water, and by lineal analysis of crack volume in sectioned specimens. This work was done mainly on fractured specimens and was supplemented by measurements on several series of specimens carried to various degrees of elongation short of fracture.

In the course of the above work, it was noted that under certain conditions of temperature and stress, fractured specimens displayed a net increase in density despite the opposing contribution of the crack volume. Because of this and because of apparently negative creep rates observed in the early stage of some tests, additional measurements were made of density changes in specimens under no-load conditions at 1200° and 1500° F. These densities were obtained by measurements of length contraction at temperature as a function of time and by weighing in water at the conclusion of the tests. Since these results affect the interpretation of the crack volume measurements, their discussion is included in this section.

1. Determination of Densities by Weighing in Water

Densities of fractured specimens were determined on a 3/4 inch length of the rupture specimen which included the fracture. In general, this part of the stress-rupture specimen is the one subsequently mounted for metallography and lineal analysis to determine crack volume. Early in this investigation, densities by weighing were not determined and consequently these data are not available. The density values attained are included in Appendix II.

2. Determination of Crack Volume by Lineal Analysis

Crack volume by lineal analysis was determined for specimens tested at 1200°, 1500°, and 1800° F with only a few spot checks at intermediate temperatures. Determinations were made on longitudinal sections through the centers of the stress-rupture specimens. Each determination of the total crack volume fraction, F_v, represents the average lineal intercept on about nine lines parallel to the specimen axis at various distances from the center. In computing F_v, the lineal fraction of cracks for each line was weighted according to the specimen volume it represented. The details of this analysis are given in Appendix II.

In addition to F_v, the crack volume fraction near the surface of the specimen F_s (0.3 mm from the surface) was measured as well as F_c the crack volume fraction in the remainder of the specimen.

Whenever a significant variation in crack volume existed with respect to distance from the fracture surface, additional traverses perpendicular to the specimen axis were made at various distances from the fracture.

All of the lineal analysis results are presented in Appendix II including the F_v, F_s, and F_c values.

At 1200° F only wedge type surface cracks were observed in the ruptured specimens. Their number was greatest at intermediate stresses (or rupture times) and no intercrystalline cracks were observed in the lowest stress (28,000 psi) test.

At 1500° F, one again observes surface cracks only in the high stress, low rupture time specimens but they are more numerous and longer than at 1200° F. At rupture lives of 25 hours and longer, internal intercrystalline cracking is also observed which increases with rupture life. Many of the cracks are of more or less equiaxed shape occurring at triple points and adjacent to precipitates in the grain boundary. Often the continuous cracks that are present appear to be formed by the linking of a number of small voids.

At 1800° F, one encounters surface cracks alone only at very low rupture time values around one hour. At somewhat longer times (28 hours), wedge type internal cracks are present, and with further decreases in stress (increased rupture time) there are increasing numbers of voids and linked void cracks and fewer wedge type cracks. Also, the region of high crack volume extends further and further from the fracture. Surface cracking decreases away from the fracture with decreasing stress as at 1500° F.

3. Density Values of Rupture Specimens

The density values of ruptured specimens obtained by weighing in water are plotted in Figure 23 as a function of rupture time. The density of the as received condition for L-605 (annealed at 2250° F and water quenched) is indicated by the dashed line. A number of trends are immediately obvious from this plot. First, a marked drop in density, presumably due to intercrystalline cracking, occurs with increasing rupture time at each temperature of testing above 1350° F; the rupture time at which this drop occurs is longer the lower the temperature. At 1350° and 1200° F, this drop is not discernible. The drop of density at 1500° F and above corresponds to a relative crack volume of approximately one percent. It may be seen by comparison of the elongation data in Figure 24 that the drop of density is associated with a decrease of ductility.

The results of the lineal analysis of crack volume of L-605 at 1200°, 1500°, and 1800° F are shown in Figures 25 and 26. Since the surface cracking and the internal cracking were observed to change in opposite directions with stress or rupture time, it was decided to treat the two contributions separately. A surface shell of 0.3 mm thickness was arbitrarily chosen as the volume on which to base the fractional surface crack volume, F_S, and these data are shown in Figure 25.

At 1200° F the surface crack volume decreases with increasing rupture time, but the amount is extremely small in all tests. At 1500° and 1800° F the amount of surface volume cracking decreases significantly with increasing rupture time, with little difference observable between the two test temperatures (see Figure 25).

By comparison, the internal cracking appears to be opposite to that observed near the surface. Cracking at 1200° F is virtually zero, but at 1500° and 1800° F, there is a sharp rise in intercrystalline cracking internally with increasing rupture time. The net effect is to show a significant increase in total crack volume with increasing rupture time at 1500° and 1800° F.

IV SUMMARY AND CONCLUSIONS

1. A study has been made on the long time creep behavior of two practical and widely used superalloys. The results are presented in terms of creep and rupture data as well as observed structural changes.

2. The data are still preliminary in nature, as long time tests with an expected duration of up to 50,000 hours are still being continued and structural analyses are extended; but the results presented here show very clearly the important influence of structural instabilities on creep and rupture data. The exact interrelations will be reported in greater detail at a later date, at which point information on longer time tests will be available.

3. A preliminary study of parameter techniques for the extrapolation of creep-rupture properties has been reported previously (4). Again, a complete evaluation of all methods of extrapolation applied to the alloys investigated here will be made on the basis of additional information on long time tests.

REFERENCES

(1) Monkman, F.C. and Grant, N.J., "An Empirical Relationship Between Rupture Life and Minimum Creep Rate in Creep-Rupture Tests", Trans. ASTM, 1956.

(2) Grant, N.J. and Bucklin, A.G., "On the Extrapolation of Short Time Stress-Rupture Data", Trans. ASM, vol. 42, 1950, p. 720.

(3) Widmer, R. and Grant, N.J., "The Role of Atmosphere on the Creep-Rupture Behavior of 80 Ni-20 Cr Alloys", Trans. ASME, J. Basic Eng., December 1960.

(4) Mullendore, A.W., Dhosi, J.M., Widmer, R., and Grant, N.J., "Study of Parameter Techniques for the Extrapolation of Creep-Rupture Properties". Joint International Conference on Creep, August 1963. Published by Institution of Mechanical Engineers, London.

TABLE 1

Composition of Alloys - Weight Percent

Element	Udimet 500	L-605
Ni	51.7	9.65
Co	19.2	51.8
Cr	19.4	20.02
W	-	14.84
Mo	4.30	-
Fe	0.18	1.49
Al	2.95	-
Ti	2.88	-
C	0.07	0.09
Si	0.12	0.51
Mn	0.10	1.49
P	-	0.007
S	0.005	0.012

TABLE 2

Values of Constants in Equation 1) for Udimet 500 and RMS Deviations of Data

		t_r				ϵ_{min}			
T (° F)	Segment	m	K	$D_{\log t_r}$	$D_{\log \sigma}$	m	K	$D_{\log t_r}$	$D_{\log \sigma}$
1200	A_1	-0.0726	5.1973	0.196	0.0142	0.0444	5.2191	0.190	0.00845
1350	A_2	-0.0929	5.0823	0.070	0.00650	0.0621	5.1448	0.004	0.0002
1200	B_1	-0.0872	5.2473	0.147	0.0128	0.0905	5.4334	0.149	0.0135
1350	B_2	-0.1266	5.1406	0.035	0.0044	0.1002	5.2455	0.023	0.0023
1500	B_3	-0.1274	4.9249	0.100	0.0127	0.0887	5.0028	0.180	0.0159
1500	C_3	-0.1913	5.0664	0.097	0.0186	0.1819	5.4068	0.189	0.0344
1650	C_4	-0.1667	4.668	0.135	0.0225	0.1548	4.943	0.143	0.0222
1800	C_5	-0.2226	4.417	0.248	0.0552	0.1386	4.5912	0.326	0.0452

TABLE 3

Summary of Data from Scatterband Tests of Udimet 500

Stress	Least Square Previously Determined	R.L.	$\sqrt{\frac{\Sigma\ (Dev)^2}{N}}$	% El.	% R.A.
		1200° F			
140,000	$\log t_r = 0.820$	3.2	.1645	15.8	32.2
		5.6		23.1	25.3
	$t_r = 6.6$	7.2		19.8	20.2
		8.4		20.3	22.3
		9.3		20.0	20.3
		10.7		15.5	10.1
100,000	$\log t_r = 2.800$	541.4	.2154	2.5	8.5
		807.5		1.9	5.2
	$t_r = 631$	887.7		1.9	6.1
		952.6		1.5	5.8
		1240.0		1.6	4.5
		1497.0		4.6	6.5

TABLE 3 (continued)

Stress	Least Square Previously Determined	R.L.	$\sqrt{\frac{\Sigma\ (Dev)^2}{N}}$	% El.	% R.A.
		1500° F			
60,000	$\log t_r = 1.153$	11.9	.1560	13.3	30.1
		16.2		13.2	30.0
	$t_r = 14.2$	16.7		16.7	26.9
		17.1		10.0	28.6
		20.8		22.2	23.1
		24.2		17.0	31.2
		26.9		16.9	29.8
		10.5		12.2	28.0
30,000	$\log t_r = 3.079$	337.1	.2681	6.6	34.2
		466.6		4.4	25.9
	$t_r = 1200$	1189.3		8.8	12.7
		1333.8		9.8	23.2
		1426.4		10.1	27.0
		1691.4		16.8	25.1
		1255.4		6.8	7.2

TABLE 4

Summary of Data from Scatterband Tests of L-605

Stress	Least Square Previously Determined	R.L.	$\sqrt{\frac{\Sigma\ (Dev)^2}{N}}$	% El.	% R.A.
		1200° F			
40,000	$\log t_r = 2.717$	686.3	.3425	3.7	6.0
		797.6		5.05	9.3
	$t_r = 521$	1160.0		2.0	4.0
		1199.9		4.0	4.4
		1295.2		4.0	7.5
		1636.1		3.8	5.3
60,000	$\log t_r = 1.015$	3.9	.2135	24.8	25.0
		5.4		13.5	18.8
	$t_r = 10.4$	5.6		16.0	21.4
		6.2		16.4	19.5
		8.0		13.8	18.2
		8.6		16.5	14.7
		10.1		16.7	20.2
		11.8*		13.4	13.8
		12.7		14.3	16.0

*Specimen at temperature without load 24.7 h.

TABLE 4 (continued)

Stress	Least Square Previously Determined	R.L.	$\sqrt{\frac{\Sigma\ (Dev)^2}{N}}$	% El.	% R.A.
		1500° F			
30,000	$\log t_r = 1.105$	10.2	.1107	22.7	21.5
		10.4		12.8	17.5
	$t_r = 12.7$	11.9		14.9	20.9
		13.4		14.1	18.7
		15.2		15.0	20.2
		23.4		12.4	15.3
		11.3		11.7	12.8
17,000	$\log t_r = 3.075$	1203.2	.1487	11.1	16.3
		1661.8		15.3	19.1
	$t_r = 1189$	1764.7		10.3	16.7
		1802.8		14.5	14.7
		1729.4		8.15	11.7
		2010.3		11.7	12.2

Figure 1. Udimet 500. As received, aged condition. Longitudinal section; etched with modified aqua regia; 1000X.

Figure 2. L-605. As received condition. Longitudinal section; electrolytically etched with 5% chromic acid; 1000X.

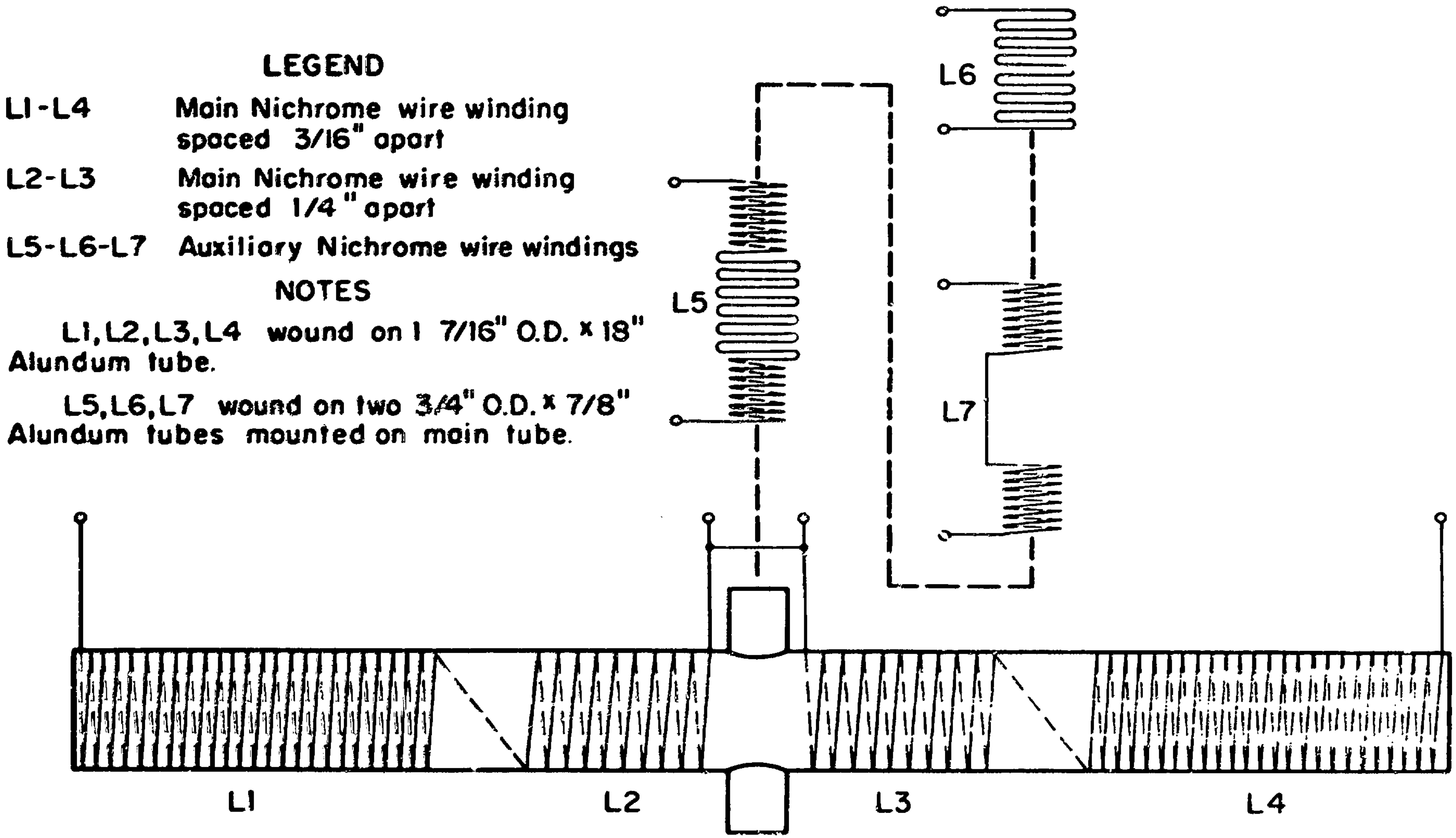


Figure 3: Schematic drawing of furnace.

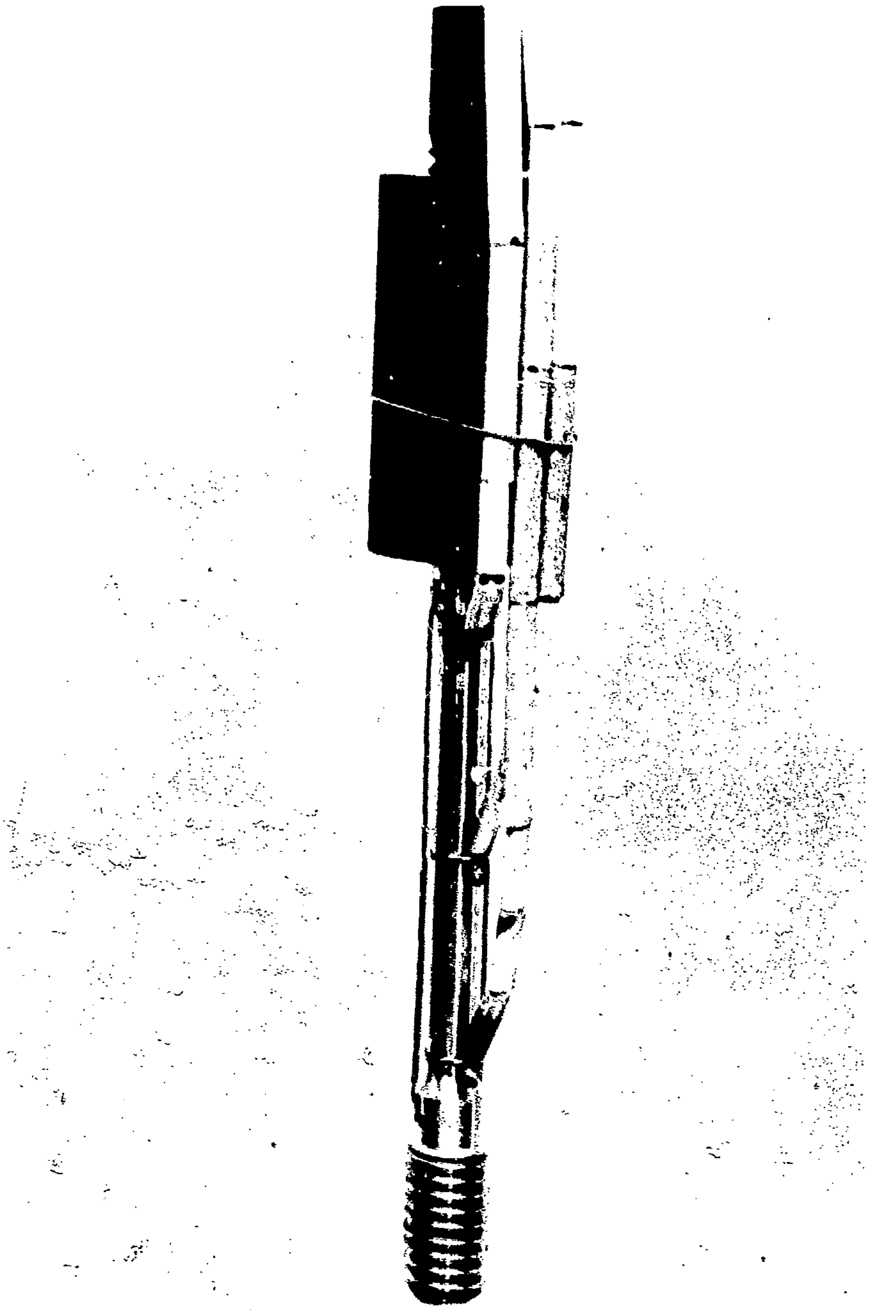


Figure 4. Specimen prepared for testing.

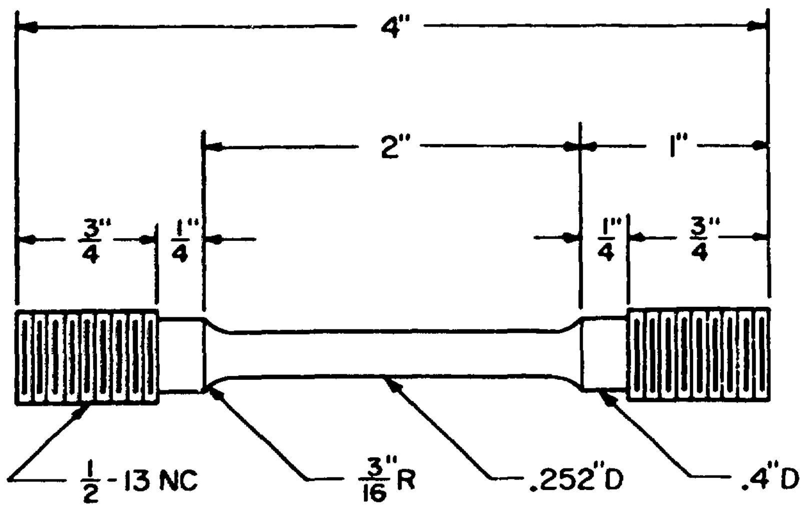


Figure 5: Drawing of Creep Rupture Specimen.

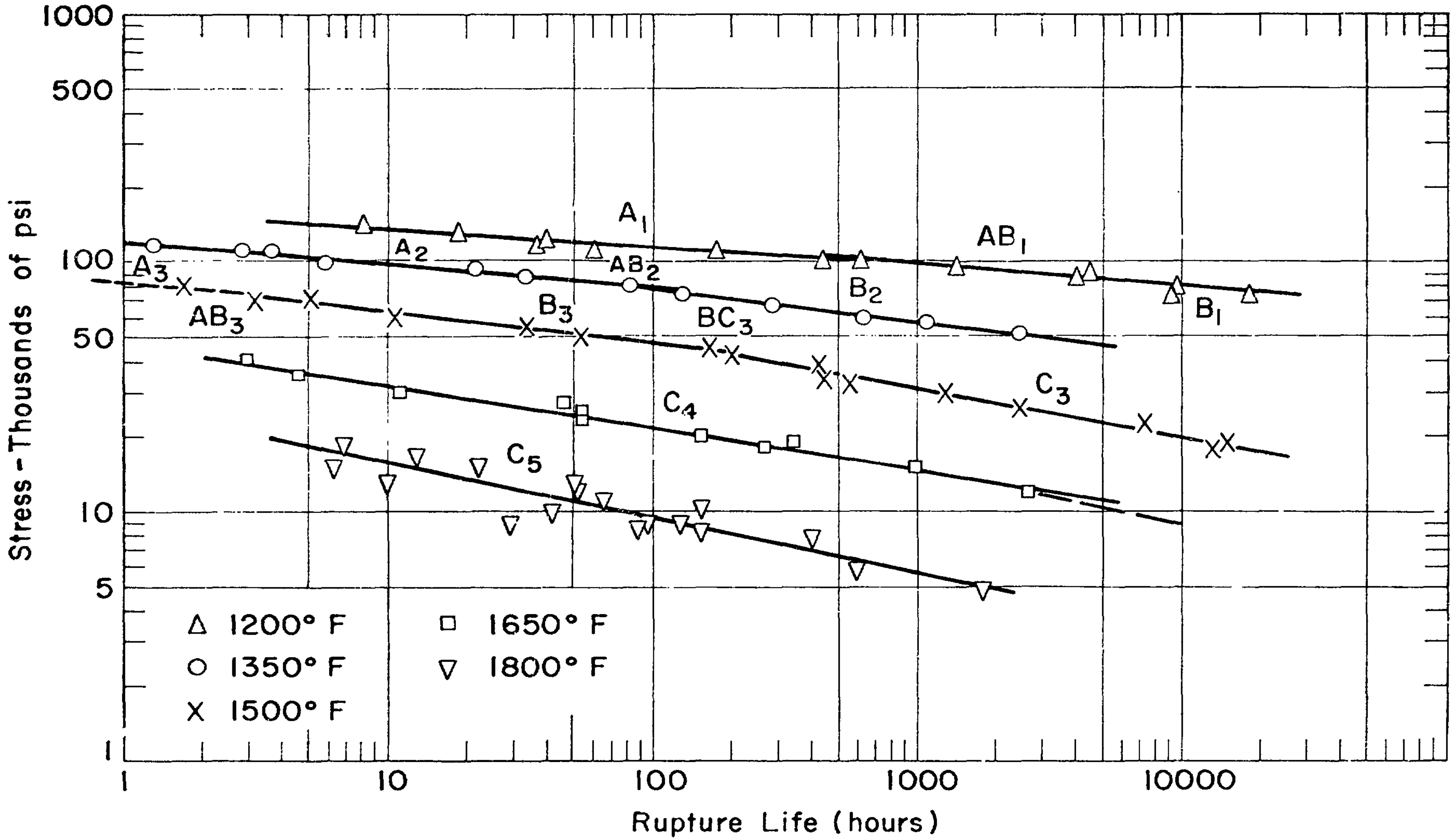


Figure 6: Log stress versus log time to rupture for Udimet 500.

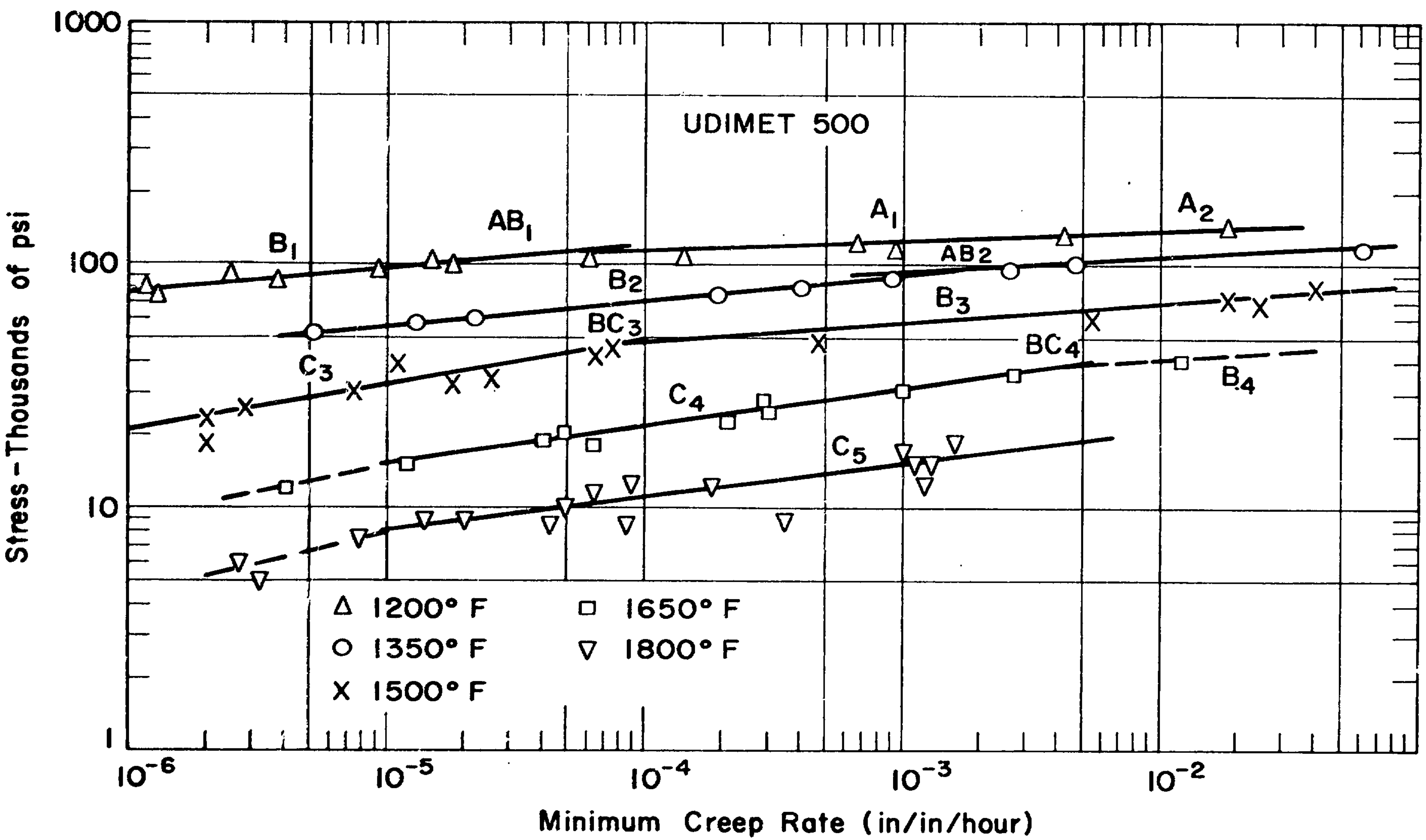


Figure 7: Log stress versus log minimum creep rate for Udimet 500.

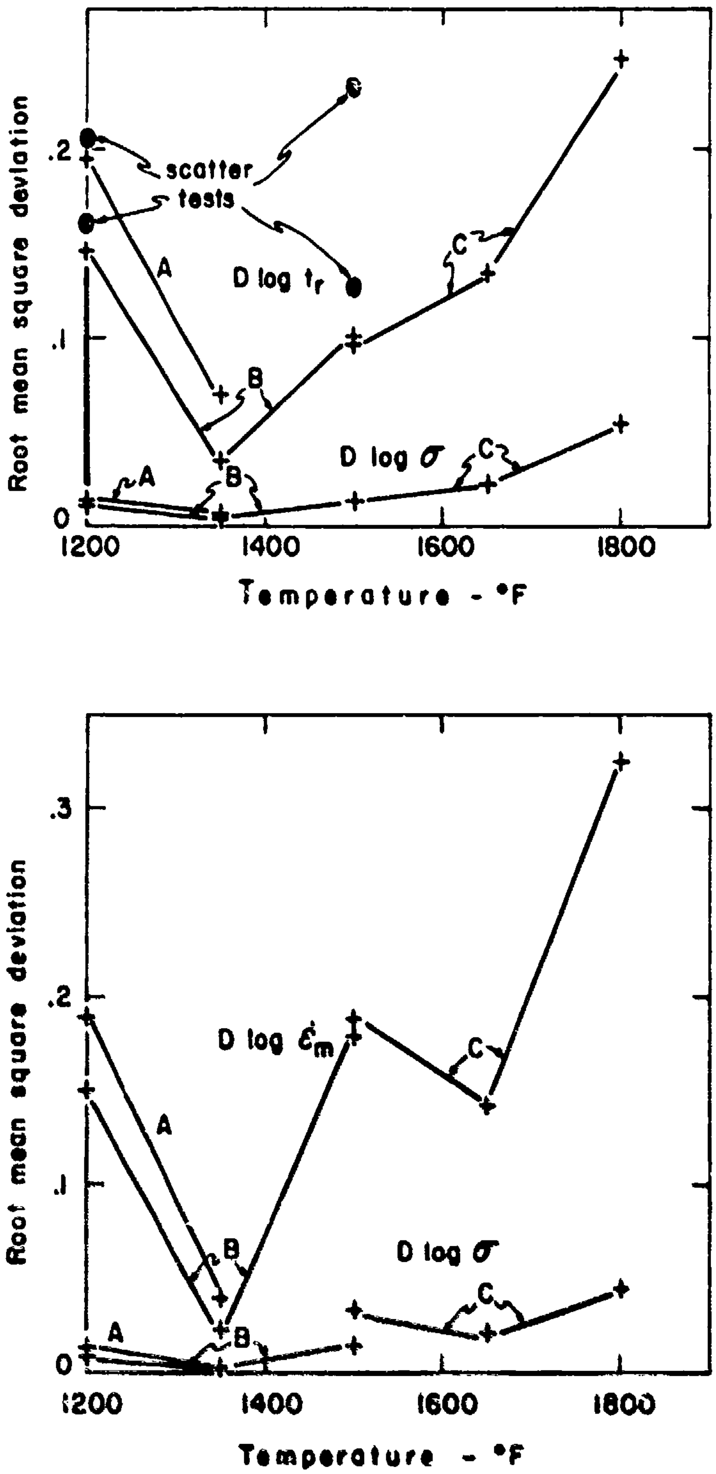


Figure 8: Root mean square deviations of creep-rupture data versus temperature. (Udimet 500).

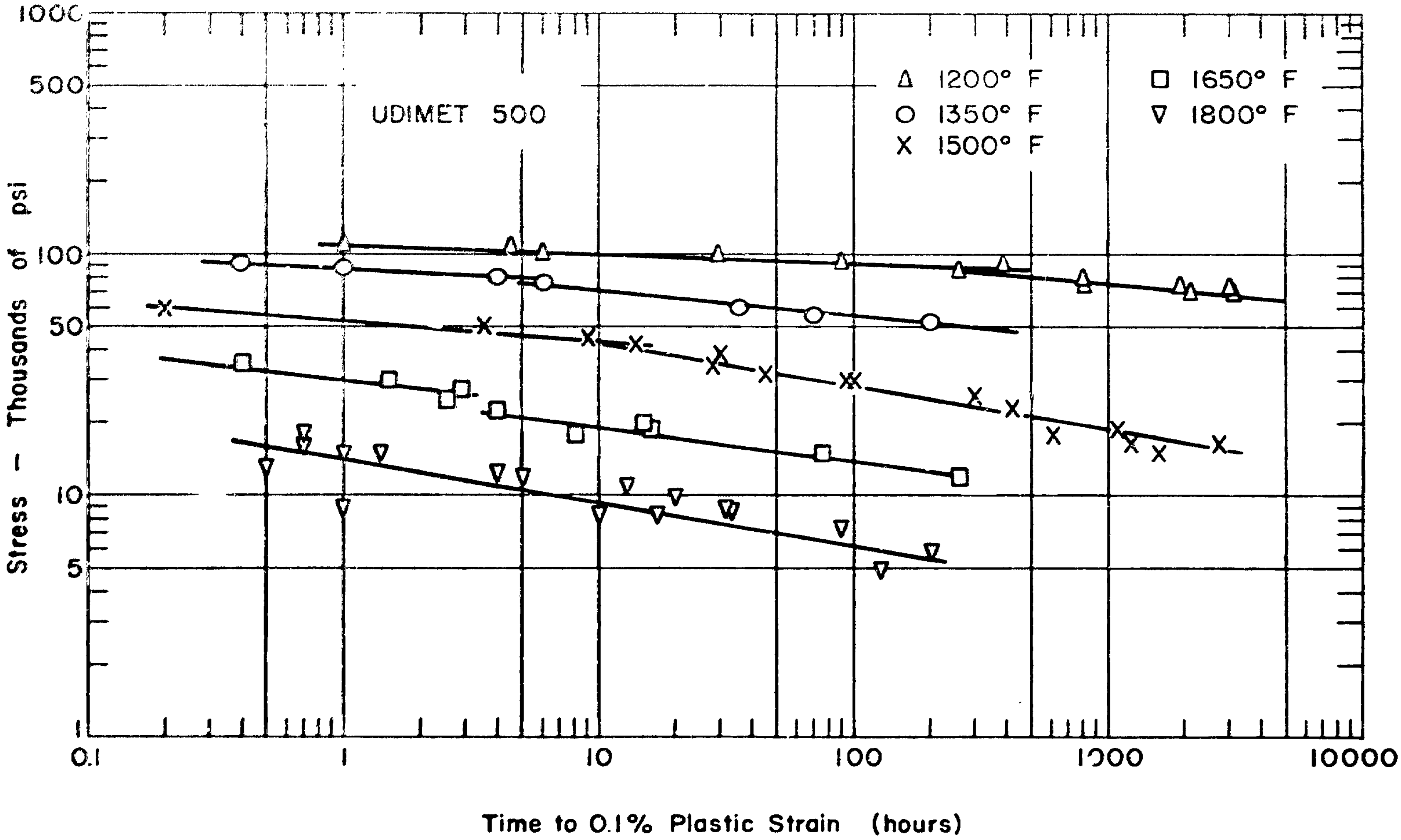


Figure 9: Log stress versus log time to 0.1% plastic strain for Udimet 500.

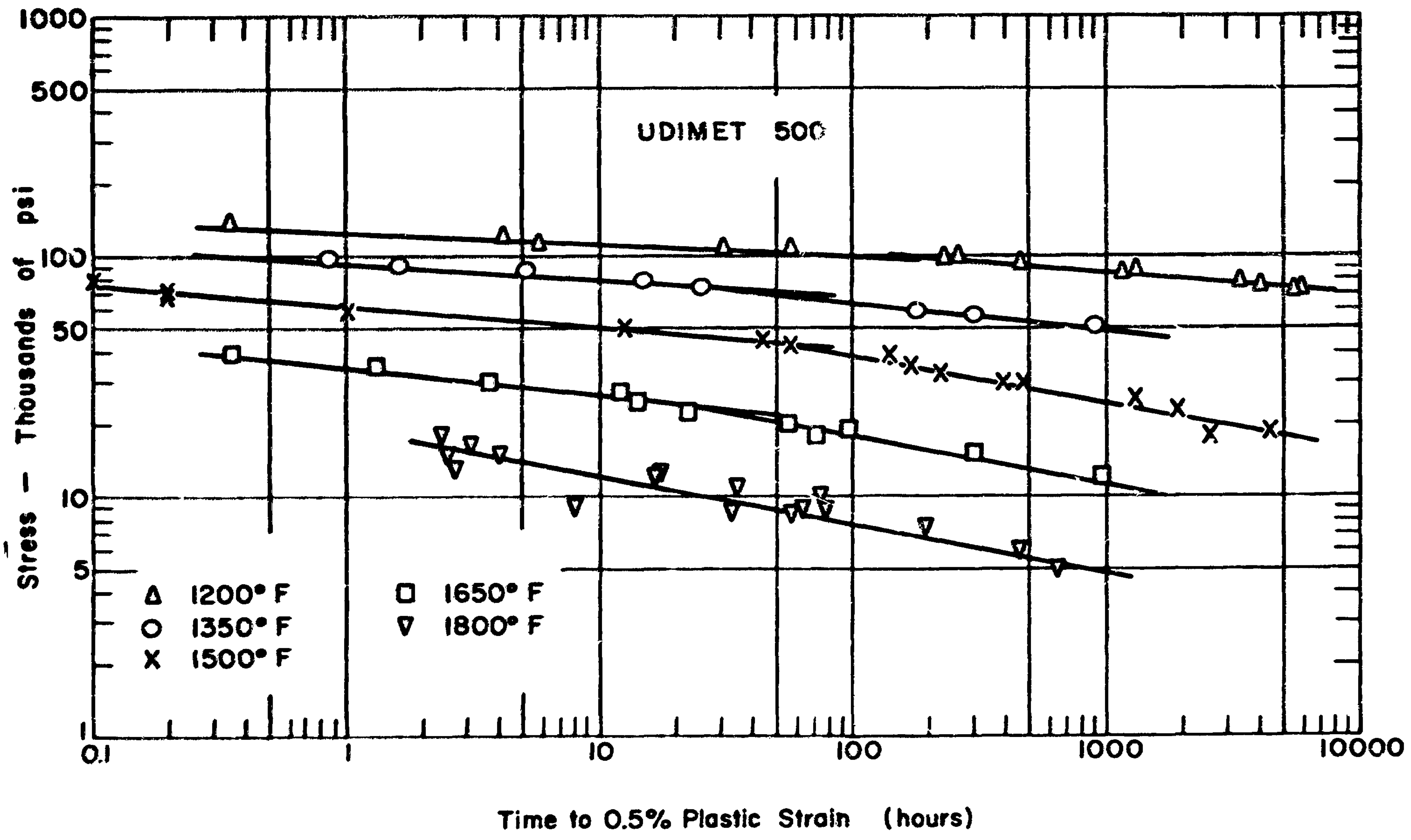


Figure 10: Log stress versus log time to 0.5% plastic strain for Udimet 500.

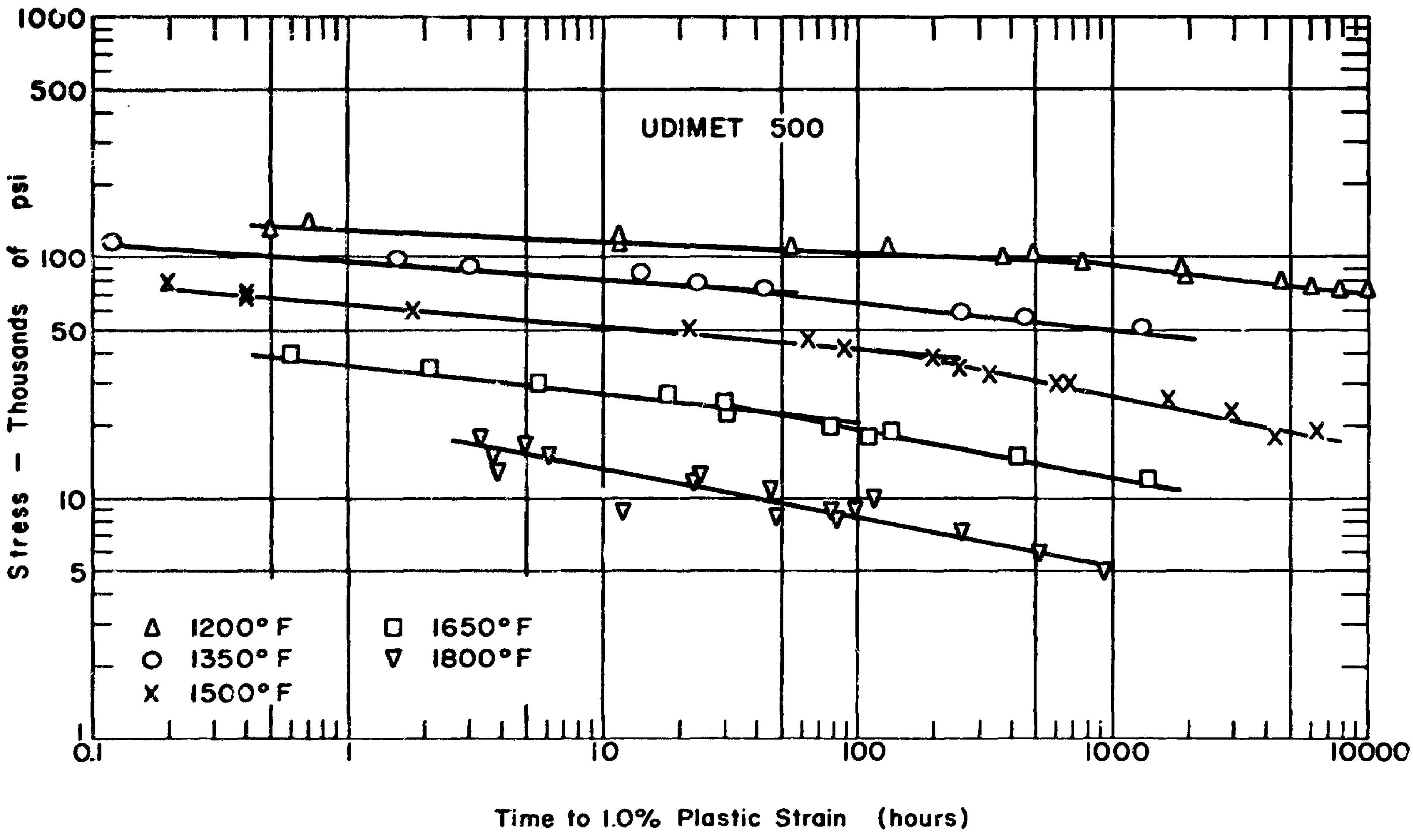


Figure II: Log stress versus log time to 1.0% plastic strain for Udimet 500.

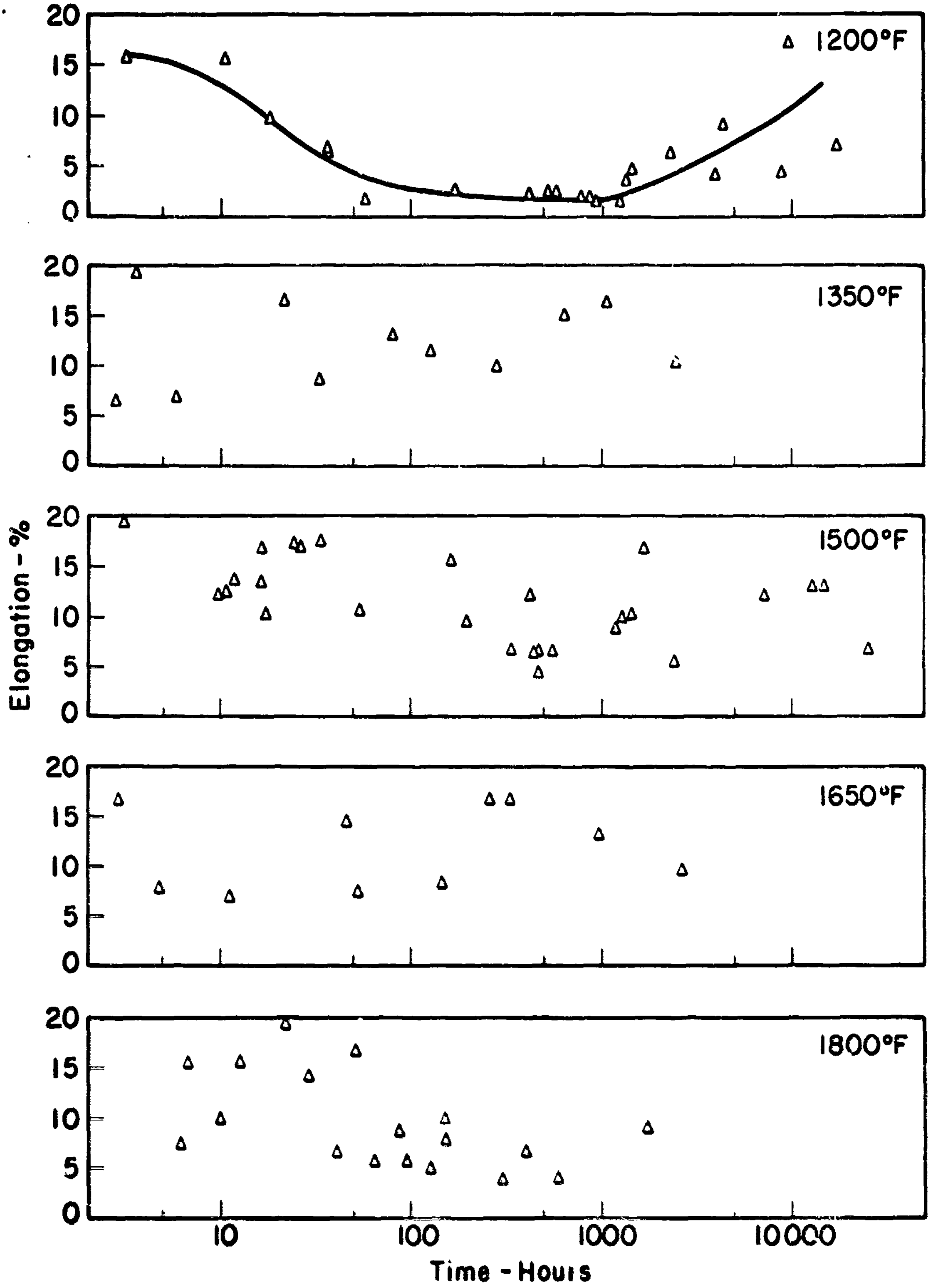


Figure 12 : Total elongation versus log time to rupture for Udimet 500.

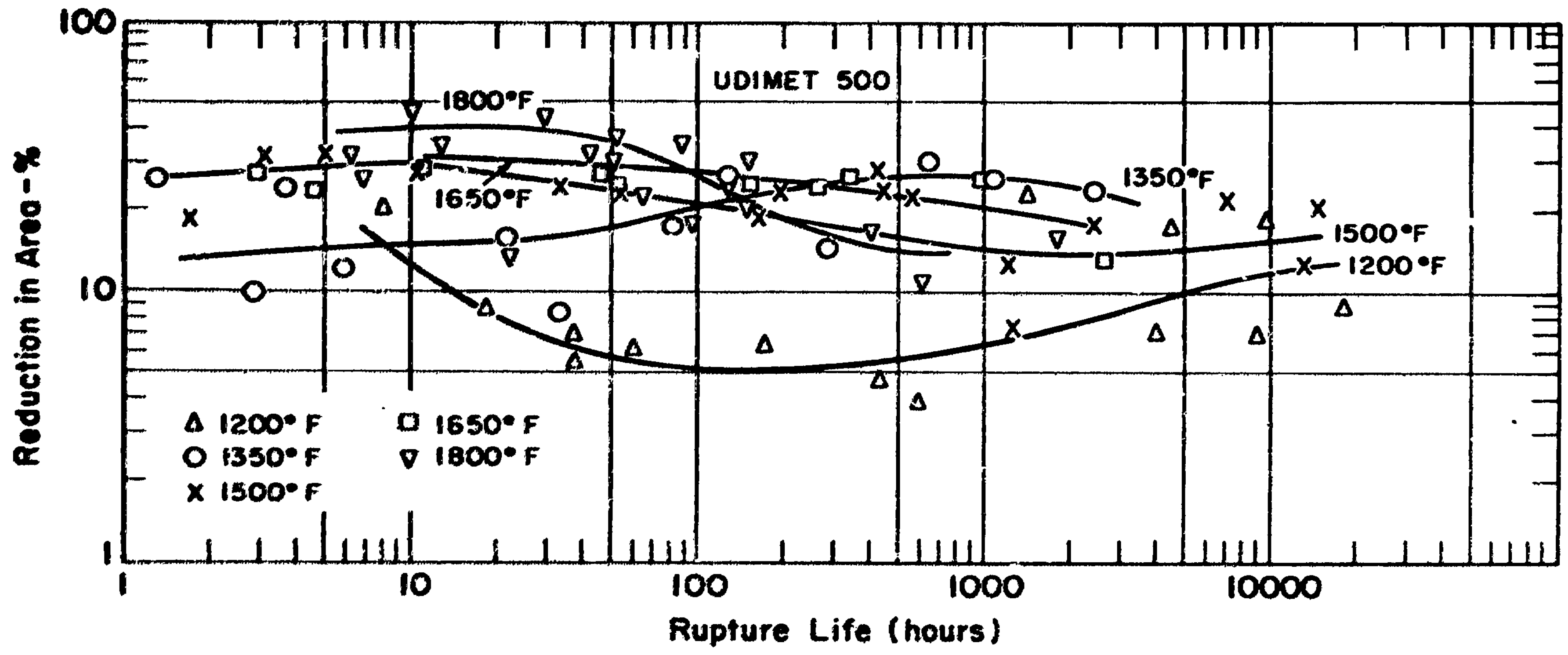
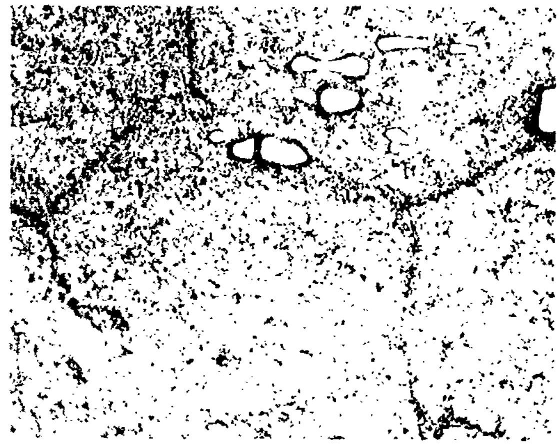


Figure 13: Reduction in area versus log time to rupture for Udimet 500.

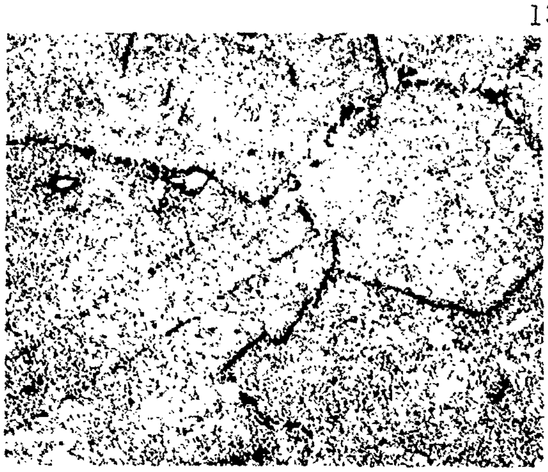
1200° F

a. Tested at 117,000 psi.
Rupture life 37.0 hours.



b. Tested at 90,000 psi.
Rupture life 4428.9 hours.

1350° F



c. Tested at 100,000 psi.
Rupture life 5.8 hours.

d. Tested at 52,000 psi.
Rupture life 2410.7 hours.

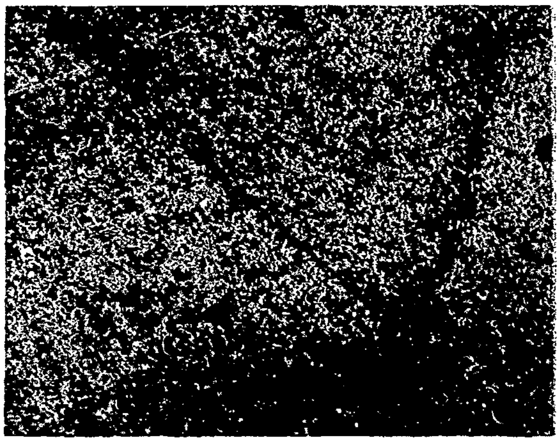
1500° F

e. Tested at 72,000 psi.
Rupture life 5.0 hours.

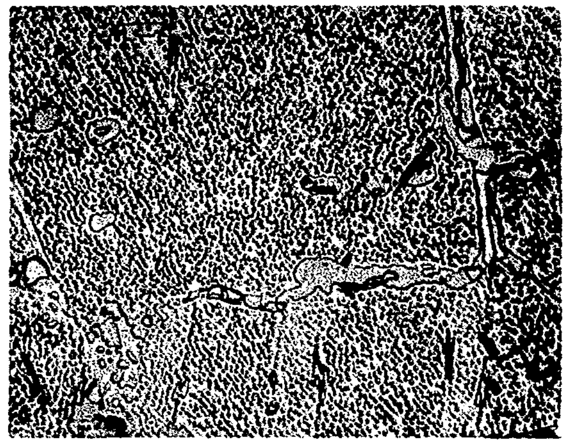
f. Tested at 26,000 psi.
Rupture life 2401.1 hours.

Figure 14. Microstructures of Udimet 500 stress-rupture bars tested at various temperatures. Longitudinal sections, 1000X, etched with modified Aqua Regia.

1650° F

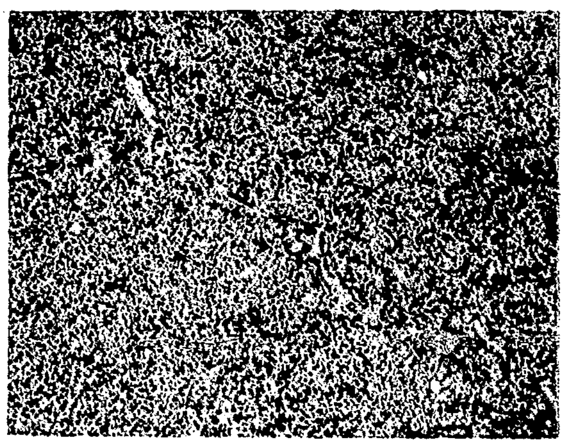


g. Tested at 35,000 psi.
Rupture life 4.6 hours.

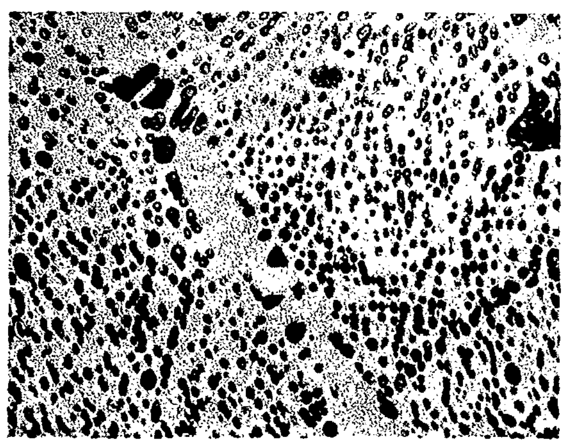


h. Tested at 12,000 psi.
Rupture life 2639.7 hours.

1800° F



i. Tested at 18,000 psi.
Rupture life 6.7 hours.



j. Tested at 5,000 psi.
Rupture life 1772.4 hours.

Figure 14. Microstructures of Udimet 500, continued.

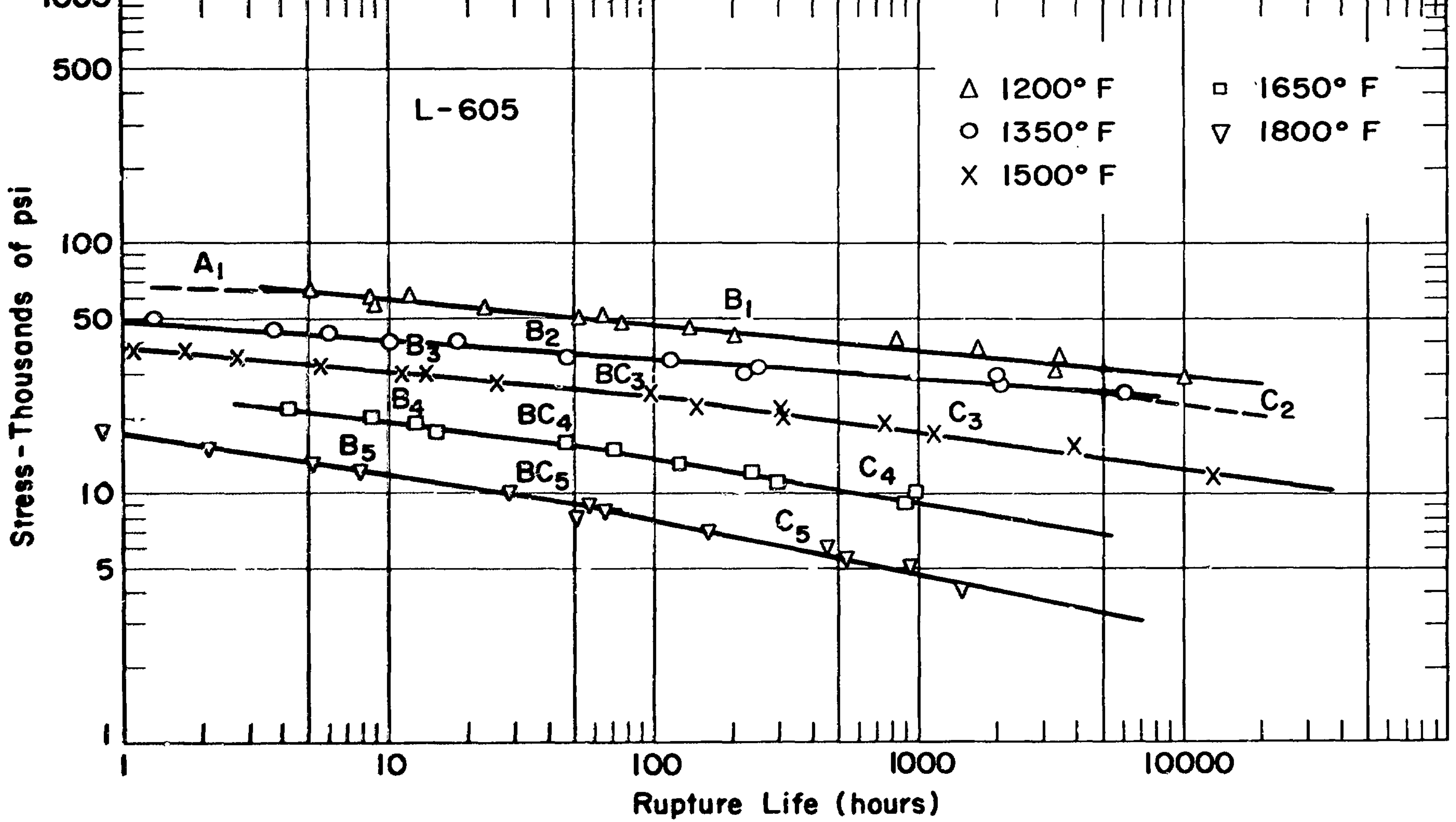


Figure 15: Log stress versus log time to rupture for L-605.

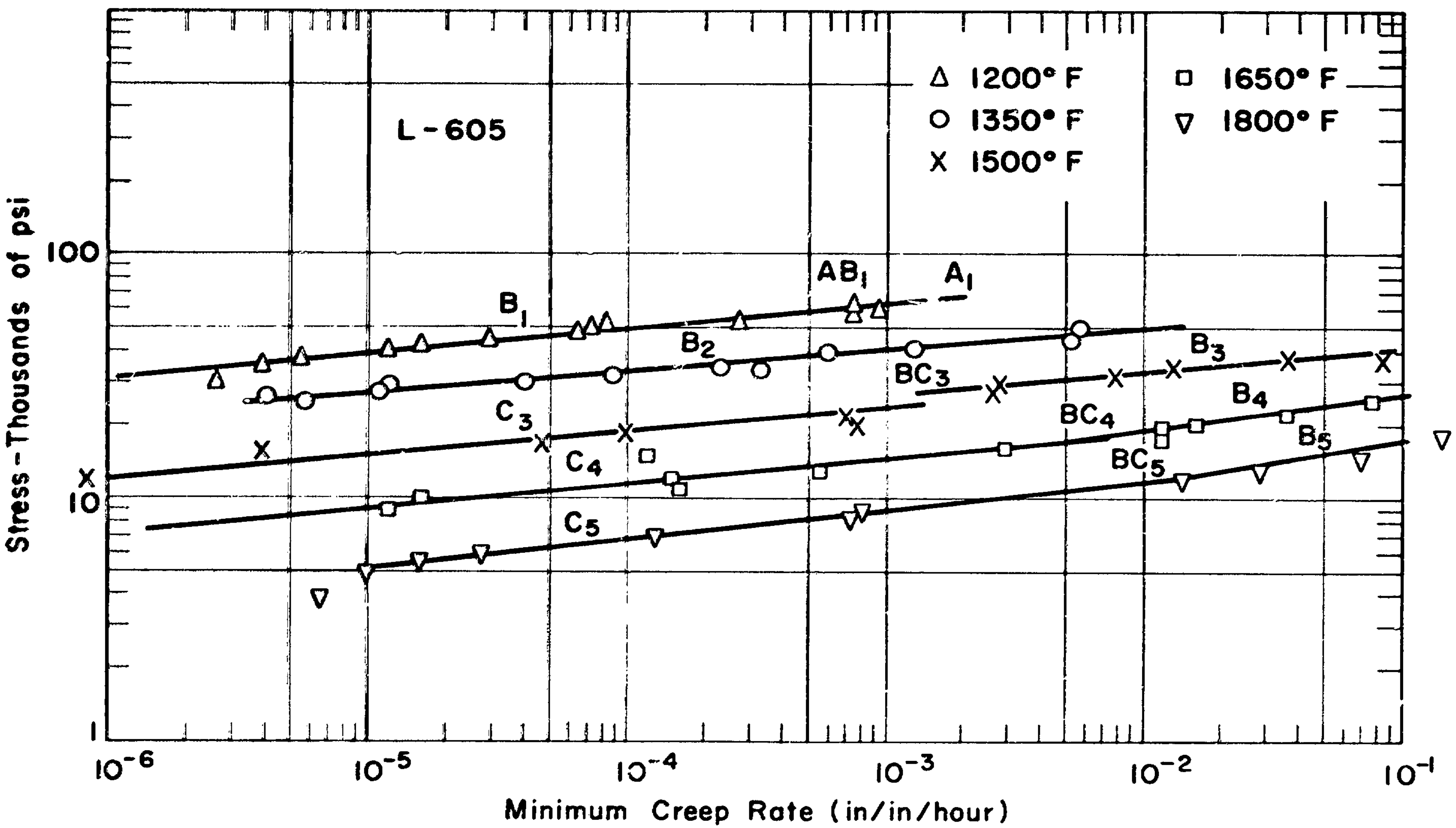


Figure 16: Log stress versus log minimum creep rate for L-605.

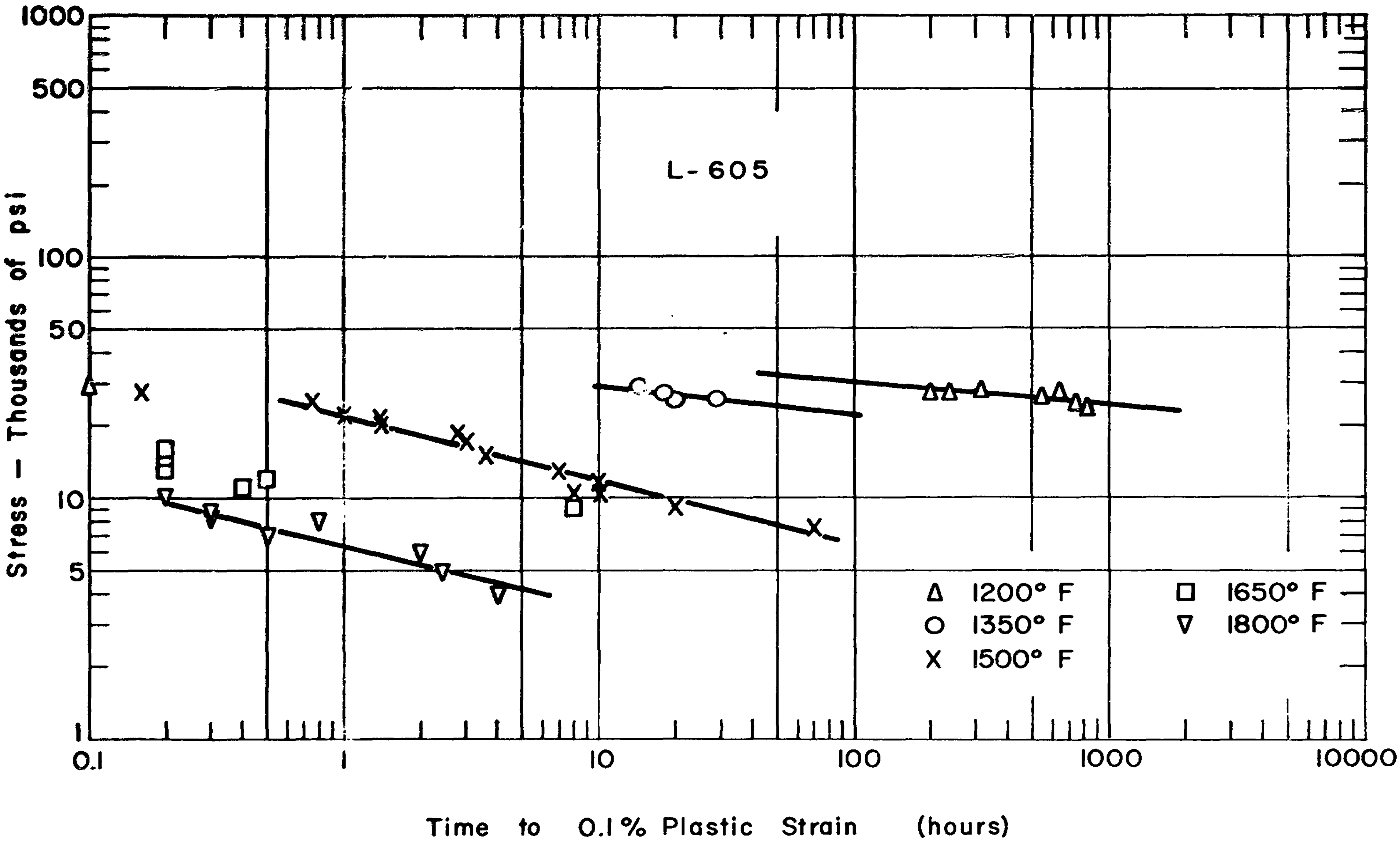


Figure 17: Log stress versus log time to 0.1% plastic strain for L-605.

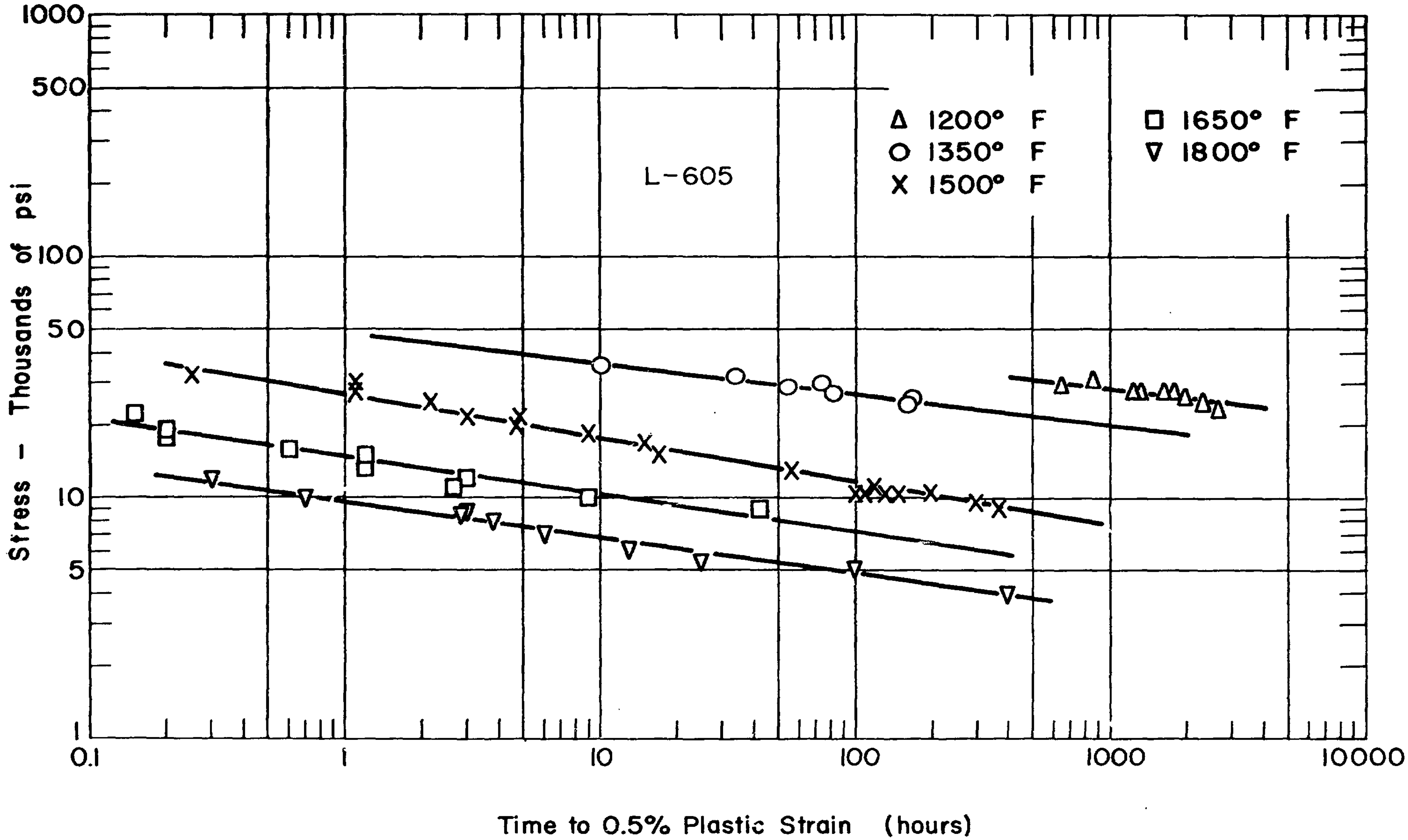


Figure 18: Log stress versus log time to 0.5% plastic strain for L-605.

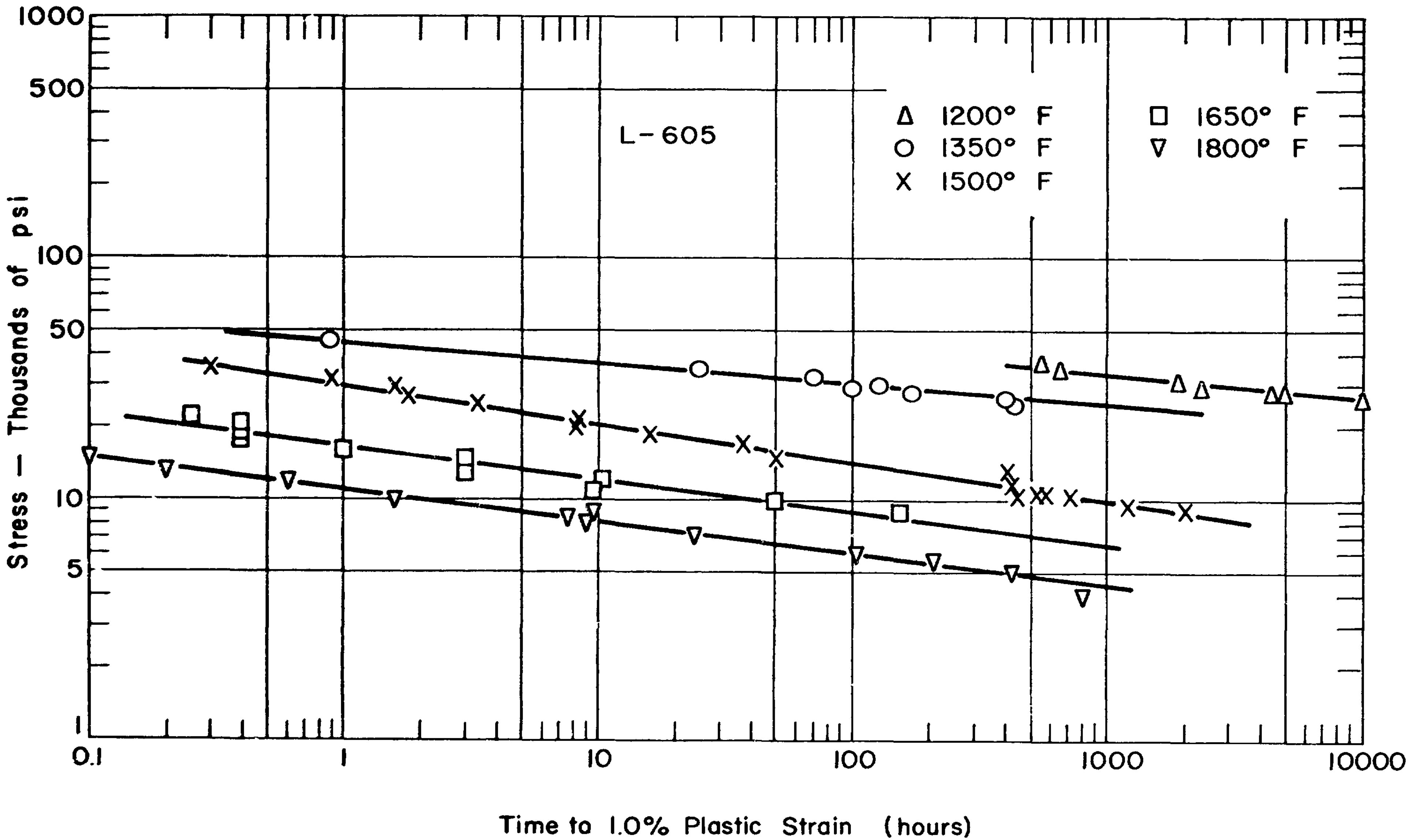


Figure 19: Log stress versus log time to 1.0% plastic strain for L-605.

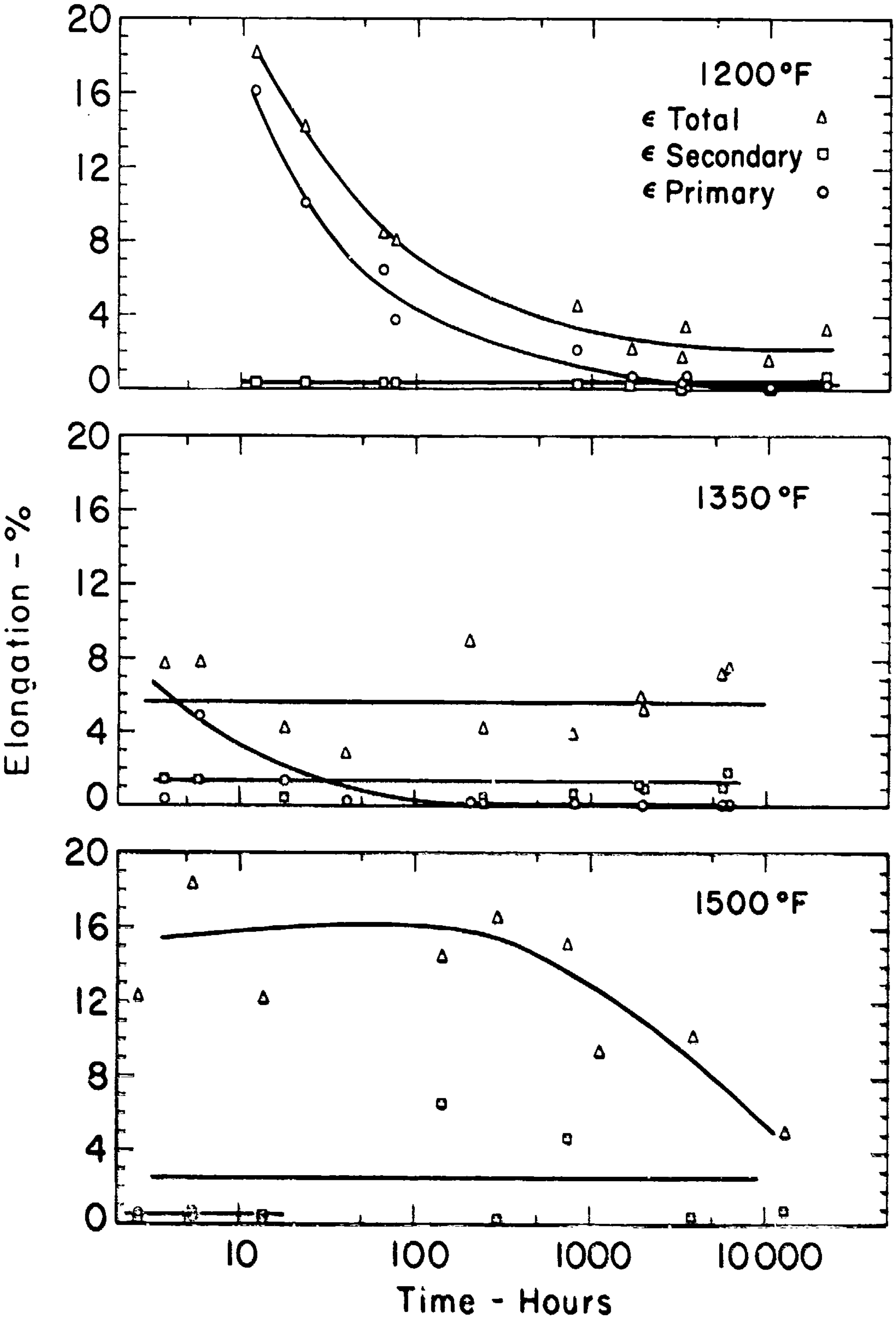


Figure 20a: Elongation versus log time to rupture for L-605.

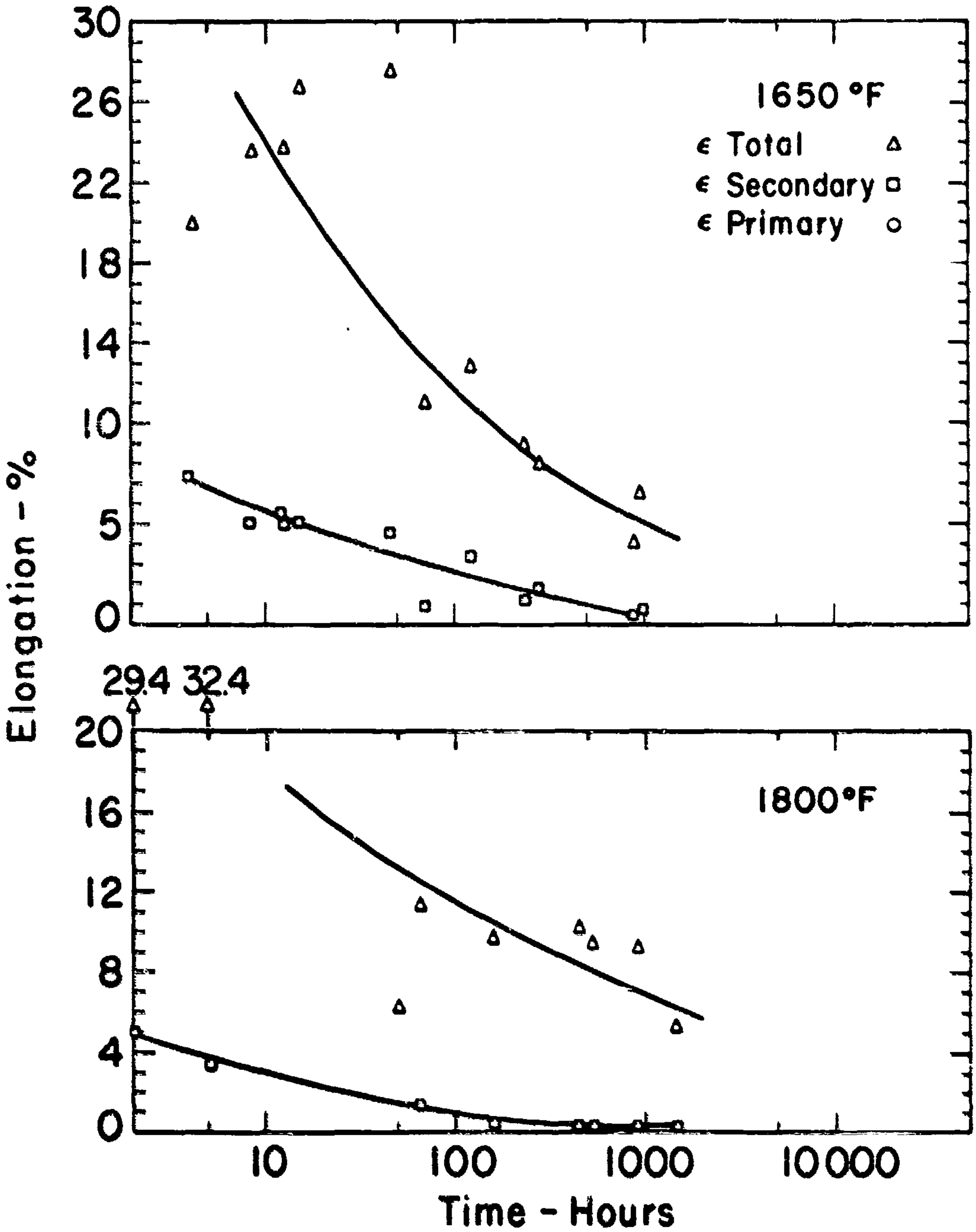


Figure 20b: Elongation versus log time to rupture for L-605.

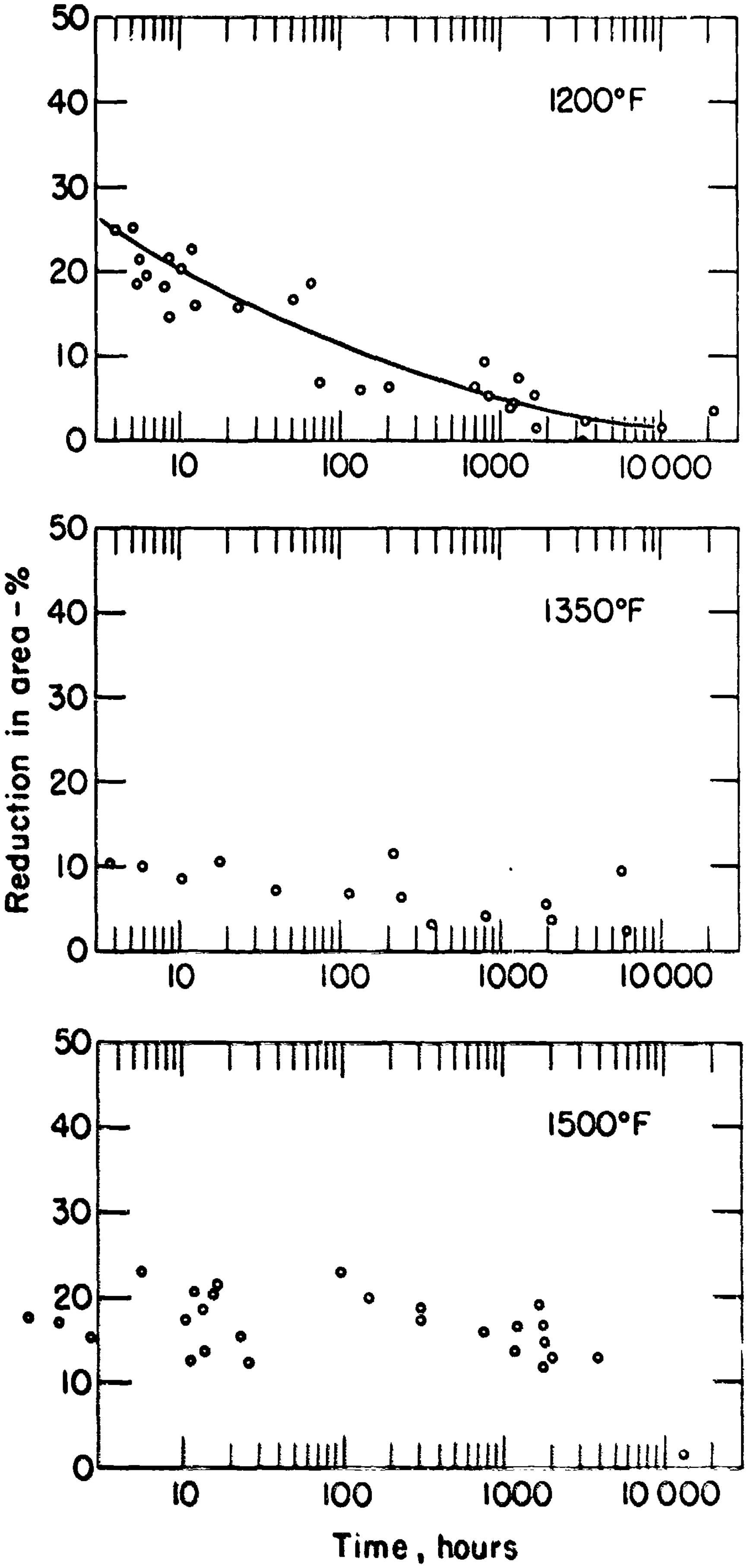


Figure 21a: Reduction in area vs log time to rupture for L-605.

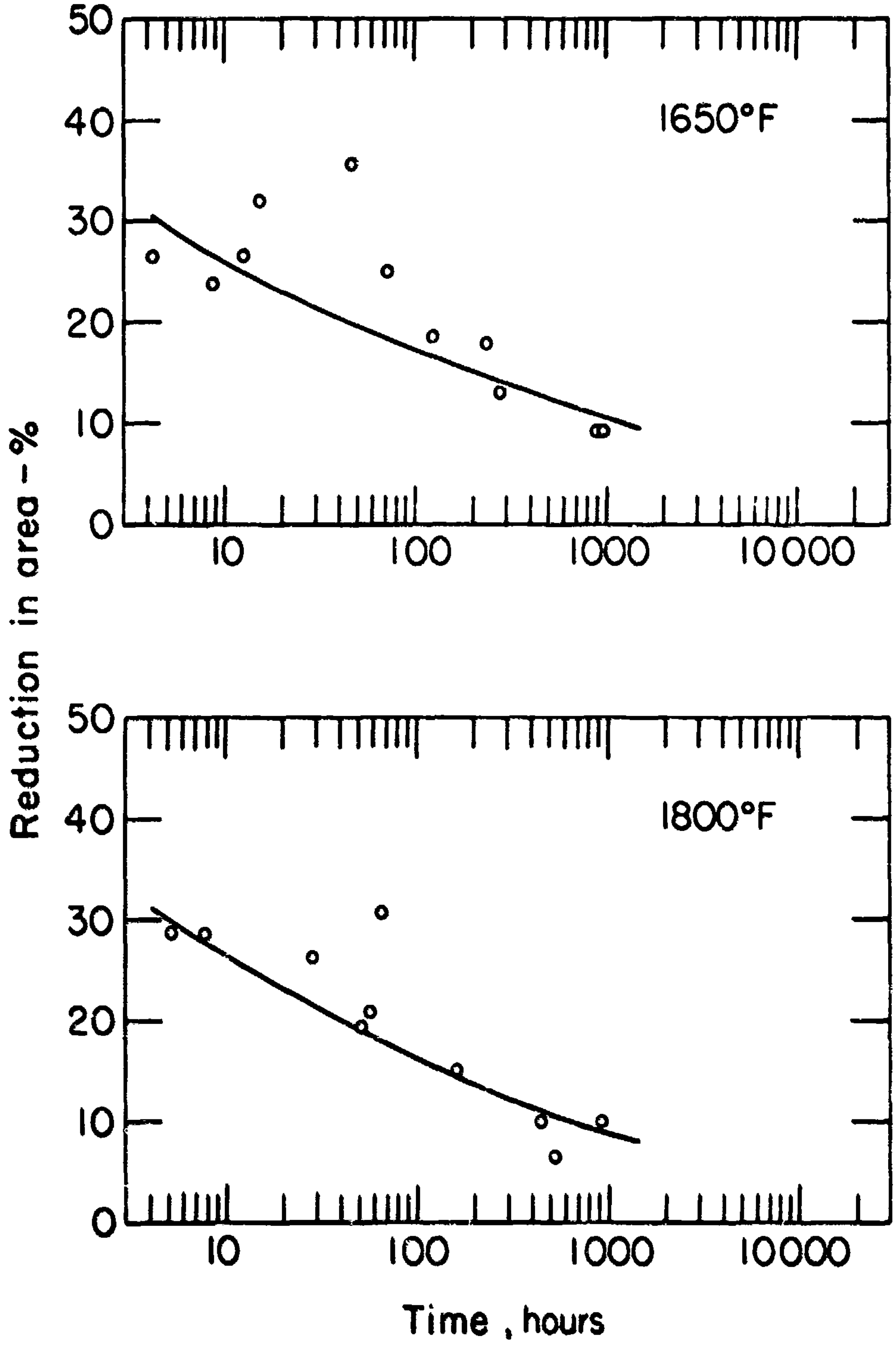
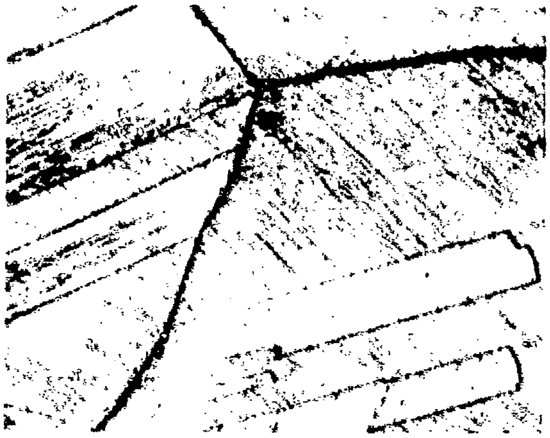


Figure 21 b: Reduction in area vs log time to rupture for L-605.

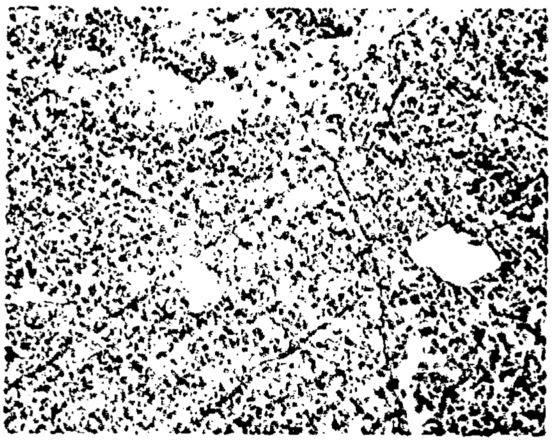
1200° F

a. Tested at 62,500 psi.
Rupture life 12.0 hours.

b. Tested at 37,500 psi.
Rupture life 1693.6 hours.



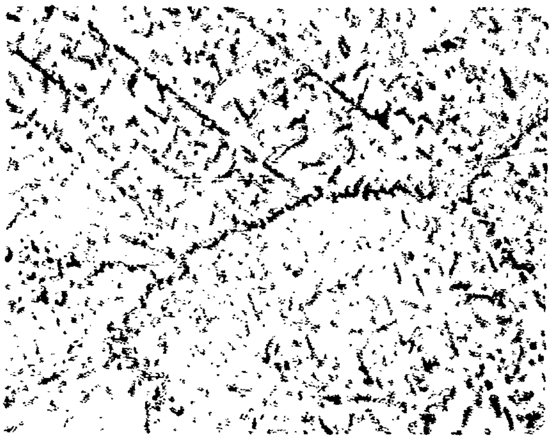
c. Tested at 43,000 psi.
Rupture life 5.9 hours.



d. Tested at 25,000 psi.
Rupture life 6055.2 hours.

1500° F

e. Tested at 32,000 psi.
Rupture life 5.5 hours.

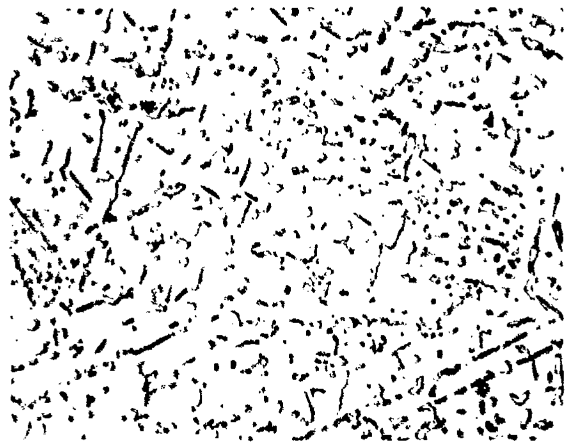


f. Tested at 15,000 psi.
Rupture life 3883.8 hours.

Figure 22. Microstructures of L-605 stress-rupture bars tested at various temperatures. Longitudinal sections, 1000X, etched with modified Vilella's Reagent electrolytically.

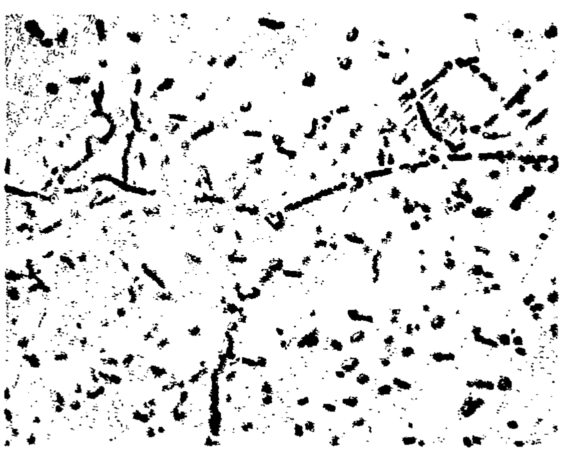
1650° F

g. Tested at 20,000 psi.
Rupture life 8.7 hours.

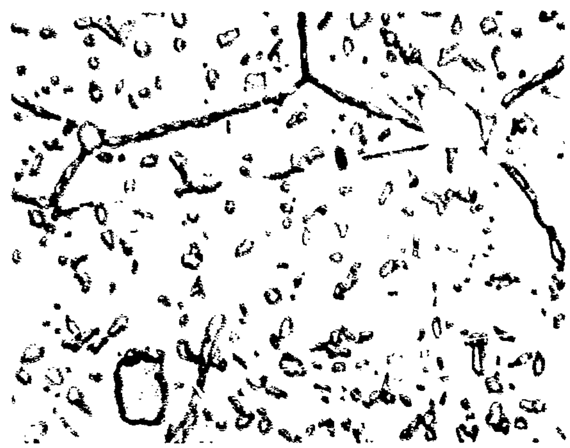


h. Tested at 10,000 psi.
Rupture life 965.9 hours.

1800° F



i. Tested at 13,000 psi.
Rupture life 5.2 hours.



j. Tested at 5,000 psi.
Rupture life 921.9 hours.

Figure 22. Microstructures of L-605, continued.

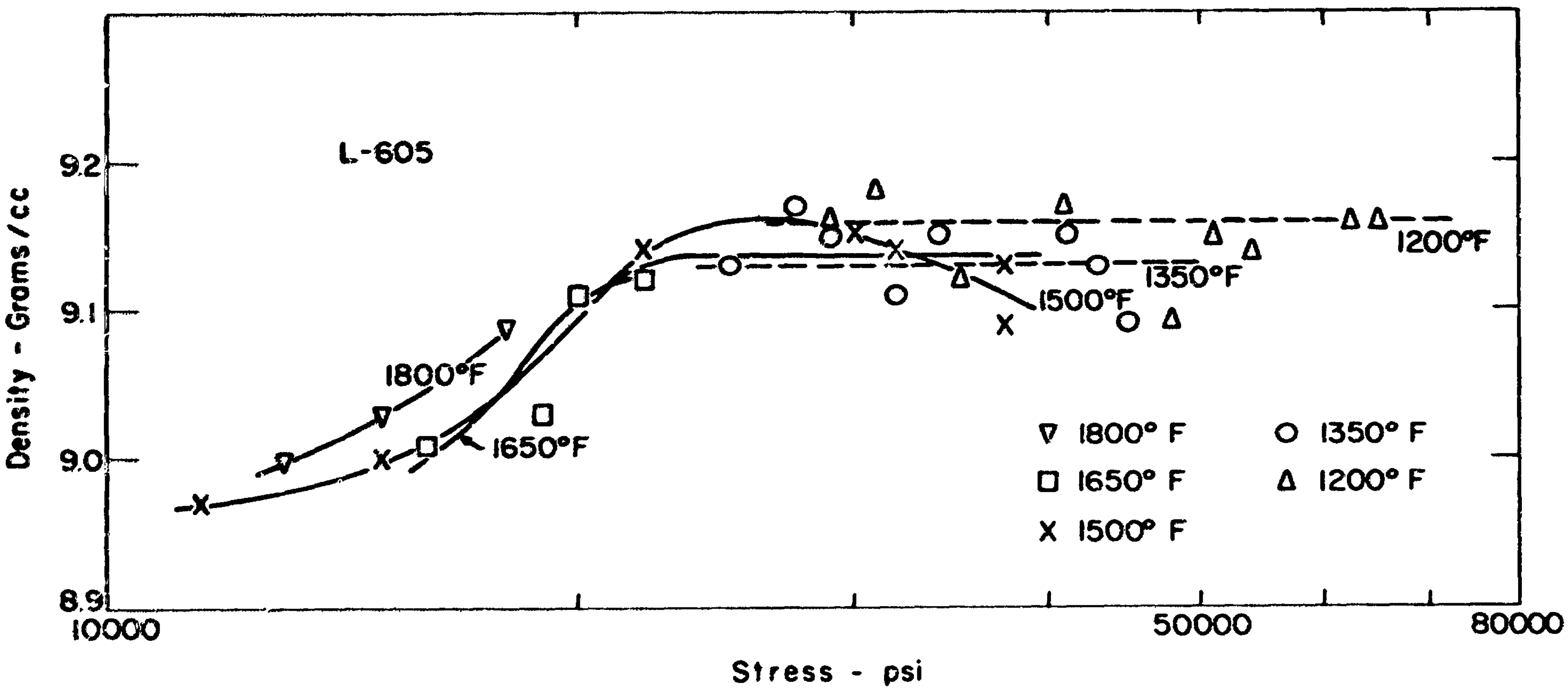


Figure 23: Density of ruptured specimens of L-605 versus stress.

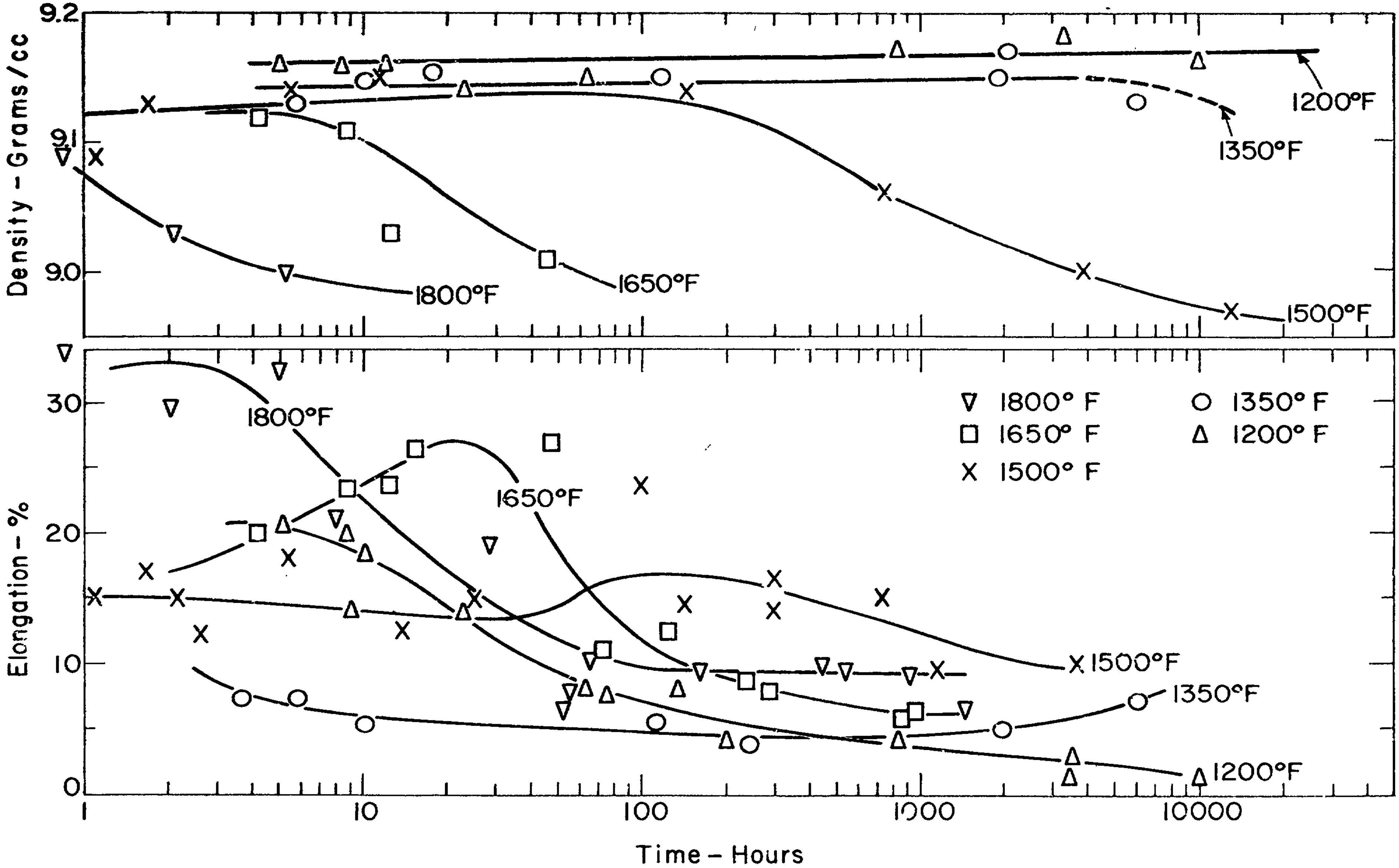


Figure 24: Density of ruptured creep specimens and elongation at rupture for L-605 versus rupture time.

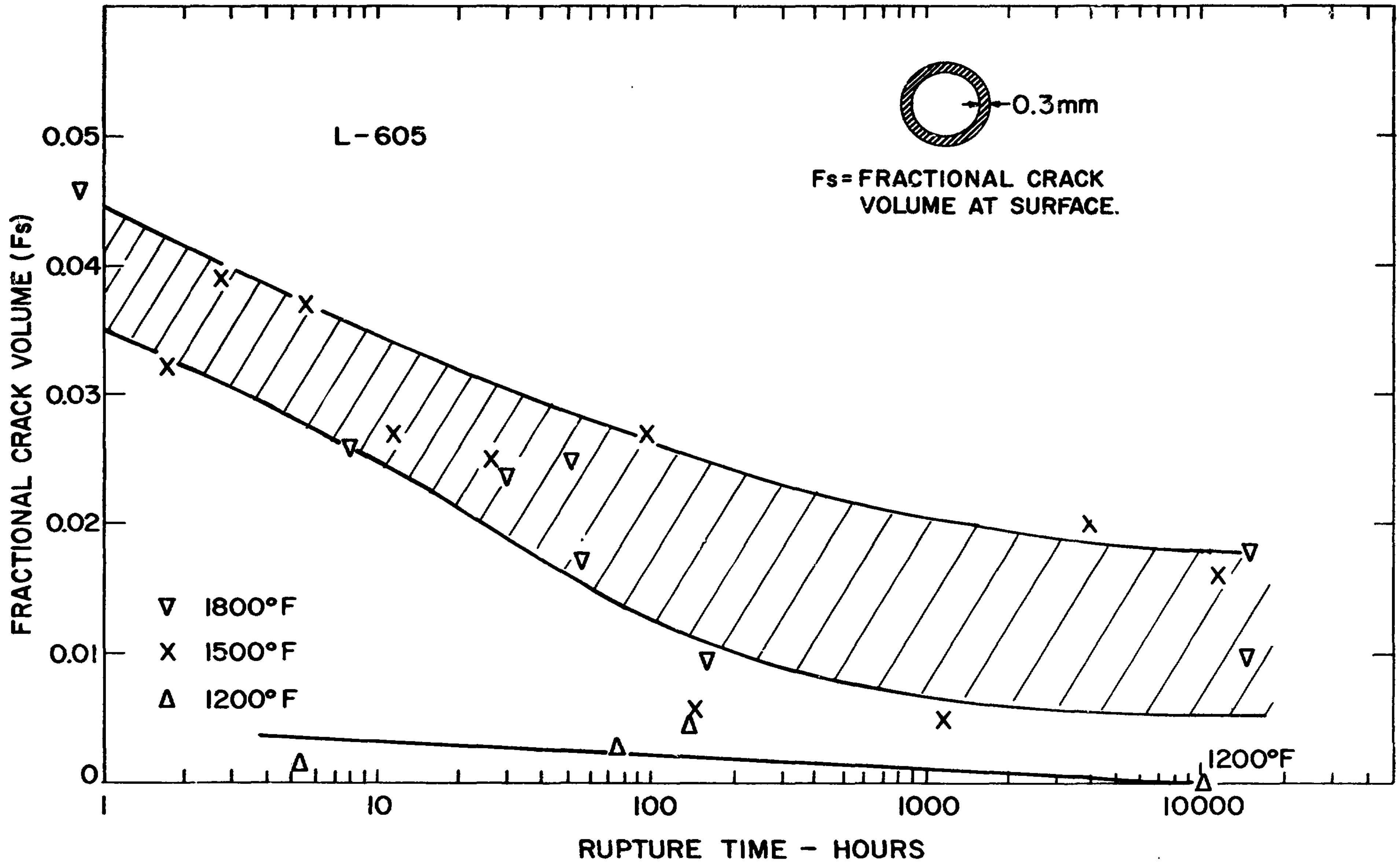


FIGURE 25: Fractional volume of cracks at surface of ruptured specimen in L-605.

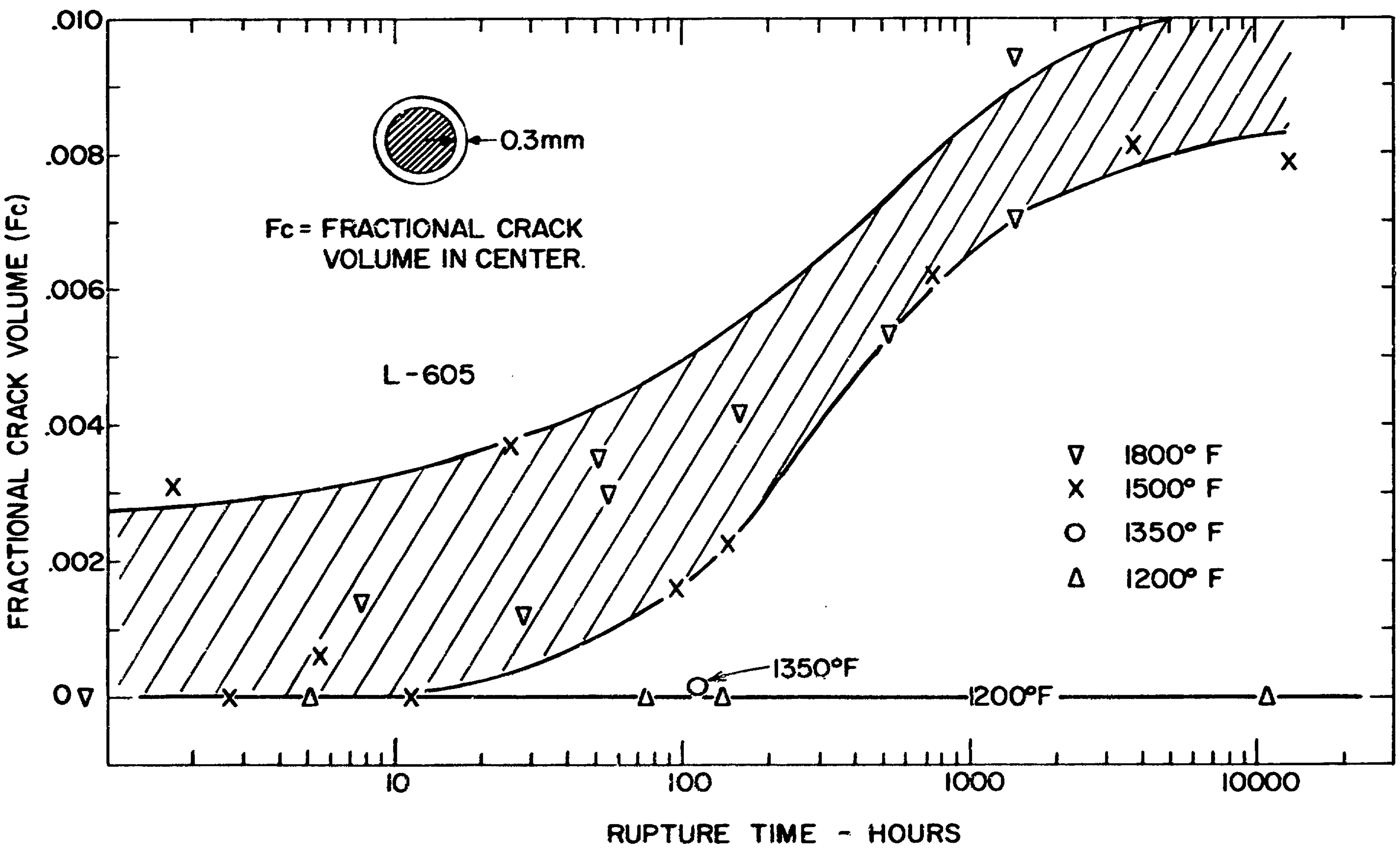


FIGURE 26: Fractional volume of cracks in center of ruptured specimen in L-605.

APPENDIX I

Complete Tables of Creep-Rupture Data for Udimet 500 and L-605

The following tables are a complete compilation of creep-rupture data from all tests. This includes both "short time" tests, up to 10,000 hours and "long time tests" up to 50,000 hours, those still in progress being so indicated. Scatterband tests and tests interrupted after various fractions of the rupture time are also included.

APPENDIX J: Summary of Creep-Rupture Data

Stress, psi	Rupture Life (hrs.)	Hours To Plastic Strain 1.0%	0.5%	0.1%	Minimum Creep Rate in/in/hr	El. %	R. A. %
			L-605 - 1200° F				
65,000	5.1	x	-	-	-	20.8	25.1
62,500	12.0	x	-	-	9.3×10^{-4}	18.4	22.2
62,500	8.5	x	-	-	7.5×10^{-4}	19.9	21.6
60,000	3.9	x	-	-	-	24.8	25.0
60,000	5.4	x	-	-	-	13.5	18.8
60,000	5.6	x	-	-	-	16.0	21.4
60,000	6.2	x	-	-	-	16.4	19.5
60,000	8.0	x	-	-	-	13.8	18.2
60,000	8.6	x	-	-	-	16.5	14.7
60,000	10.1	x	-	-	-	16.7	20.2
60,000	11.8*	x	-	-	-	13.4	13.8
60,000	12.7	x	-	-	-	14.3	16.0
54,000	23.1	x	-	-	2.7×10^{-4}	14.1	15.9
51,000	64.4	x	-	-	8.0×10^{-5}	8.3	18.6
50,000	51.6	x	-	-	7.5×10^{-5}	5.3	16.8
48,000	74.9	x	-	-	6.5×10^{-5}	7.9	6.9
45,000	136.9	x	-	-	2.9×10^{-5}	8.2	6.2
42,500	200.1	x	-	-	1.6×10^{-5}	4.3	6.2
41,000	822.8	x	-	-	1.2×10^{-5}	4.3	5.5
40,000	686.3	x	-	-	-	3.7	6.4
40,000	797.6	x	-	-	-	5.05	9.3
40,000	1160.0	x	-	-	-	2.0	4.0
40,000	1199.9	x	-	-	-	4.0	4.4
40,000	1295.2	x	-	-	-	4.0	7.5
40,000	1636.1	x	-	-	-	3.8	5.3
37,500	1693.6	565.	x	-	5.4×10^{-6}	2.1	1.6
35,000	3445.5	650.	x	-	3.9×10^{-6}	3.2	2.4

Stress, psi	Rupture Life (hrs.)	Hours To 1.0% Plastic Strain	Hours To 0.5% Plastic Strain	Hours To 0.1% Plastic Strain	Minimum Creep Rate in/in/hr	El. %	R. A. %
31,000	3294.	1900.	880.	x	2.6×10^{-6}	1.6	0.1
29,500	17867.6	2350.	650.	0.1	5.2×10^{-7}	2.208	-
28,000	10192.3	5000.	1750.	330.	4.5×10^{-7}	1.4	1.6
28,000	7004.8*	4450.	1800.	650.	-	-	-
28,000	3195.4*	-	1250.	200.	-	-	-
28,000	3023.4*	-	1350.	0.1	-	-	-
28,000	2014.3*	-	1660.	240.	-	-	-
28,000	381.9*	-	-	-	-	-	-
26,500	21789.6	10000.	2000.	550.	9.6×10^{-8}	1.214	-
25,000	9307.3	-	2400.	760.	3.5×10^{-7}	0.87**	-
24,000	9357.9	-	2600.	820.	2.9×10^{-7}	0.85**	-
L-605 - 1275° F							
50,000	5.3	x	-	-	1.1×10^{-3}	10.1	11.8
35,000	539.7	275.0	85.0	x	1.8×10^{-5}	2.0	4.5

Stress, psi	Rupture Life (hrs.)	Hours To 1.0% Plastic Strain	Hours To 0.5% Plastic Strain	Hours To 0.1% Plastic Strain	Minimum Creep Rate in/in/hr	El. %	R. A. %
			L-605 - 1350° F				
50,000	1.3	x	-	-	5.7×10^{-3}	8.7	-
45,000	3.7	0.8	0.06	x	5.3×10^{-3}	7.5	10.4
43,000	5.9	x	-	-	-	7.6	10.0
41,000	10.2	x	-	-	1.3×10^{-3}	5.3	8.5
40,000	18.0	x	-	-	6.0×10^{-4}	4.1	10.8
35,000	40.7	24.7	10.0	x	2.3×10^{-4}	2.7	7.1
34,000	114.2	x	-	-	3.3×10^{-4}	5.7	6.9
32,000	243.7	70.0	34.0	x	8.8×10^{-5}	3.9	6.2
30,000	218.2	128.0	74.0	x	4.0×10^{-5}	8.5	11.5
30,000	815.9	114.0	53.0	x	1.5×10^{-5}	3.7	4.1
29,500	374.6	122.5	55.0	x	3.8×10^{-5}	2.4	3.1
29,000	1969.1	99.0	55.0	14.5	1.2×10^{-5}	5.6	5.5
27,500	2098.8	170.0	83.0	18.0	1.1×10^{-5}	5.0	3.9
26,000	5654.4	390.0	160.0	28.0	4.1×10^{-6}	7.0	9.6
25,000	6055.2	426.3	162.5	20.2	5.7×10^{-6}	7.2	2.5

Stress, psi	Rupture Life (hrs.)	Hours To 1.0% Plastic Strain	Hours To 0.5% Plastic Strain	Hours To 0.1% Plastic Strain	Minimum Creep Rate in/in/hr	El. %	R. A. %
L-605 - 1500° F							
37,500	1.7	x	-	-	3.6×10^{-2}	17.1	17.3
37,500	1.1	x	-	-	8.4×10^{-2}	15.1	17.9
35,000	2.7	0.3	x	-	1.3×10^{-2}	12.3	15.2
32,000	5.5	0.9	0.25	x	7.8×10^{-3}	18.3	22.9
30,000	13.8	1.6	1.1	0.05	2.8×10^{-3}	12.1	13.7
30,000	16.2	x	-	-	-	22.7	21.5
30,000	10.4	x	-	-	-	12.8	17.5
30,000	11.3	x	-	-	-	11.7	12.8
30,000	11.9	x	-	-	-	14.9	20.9
30,000	13.4	x	-	-	-	14.1	18.7
30,000	15.2	x	-	-	-	15.0	20.2
30,000	23.4	x	-	-	-	12.4	15.3
27,500	25.7	1.8	1.1	0.16	2.6×10^{-3}	15.0	12.2
25,000	96.5	3.4	2.3	0.75	9.5×10^{-4}	23.4	22.9
22,000	146.0	5.5	3.0	1.0	7.2×10^{-4}	14.5	20.1
21,500	301.0	8.4	4.8	1.4	7.5×10^{-4}	16.5	18.8
20,000	305.7	8.1	4.7	1.4	7.1×10^{-4}	13.9	17.4
18,500	748.3	16.0	9.0	2.8	9.8×10^{-5}	15.1	15.9
17,000	1157.1	37.0	15.0	3.0	4.7×10^{-5}	9.4	13.6
17,000	1203.2	-	-	-	-	11.1	16.3
17,000	1661.8	-	-	-	-	15.3	19.1
17,000	1729.4	-	-	-	-	8.15	11.7
17,000	1764.7	-	-	-	-	10.3	16.7
17,000	1802.8	-	-	-	-	14.5	14.7
17,000	2010.3	-	-	-	-	11.7	12.2
15,000	3883.8	50.0	17.0	3.6	4.0×10^{-6}	10.0	12.9
13,000	9306.5**	225.0	56.0	7.0	2.0×10^{-5}	3.69**	-
11,500	13018.2	425.	119.3	10.	8.5×10^{-7}	4.9	1.5
10,500	7007.1*	530.	132.	10.	-	-	-

Stress, psi	Rupture Life (hrs.)	Hours To 1.0% Plastic Strain	Hours To 0.5% Plastic Strain	Hours To 0.1% Plastic Strain	Minimum Creep Rate in/in/hr	El. %	R. A. %
10,500	3000.4*	720.	200.	10.	-	-	-
10,500	1199.5*	570.	150.	10.	-	-	-
10,500	501.1*	-	100.	8.	-	-	-
10,500	21472.8**	450.	110.	1.	4.8×10^{-7}	2.63**	-
10,000	6330.1**	1700.0	340.0	18.0	1.2×10^{-6}	1.15**	-
9,500	21765.7**	1200.	300.	1.	3.5×10^{-7}	1.58**	-
9,000	5686.6*	2000.	370.	20.	-	-	-
7,500	766.1*	70.	-	-	6.0×10^{-6}	-	-
			L-605 - 1575° F				
25,000	9.0	0.65	0.4	0.15	1.6×10^{-2}	19.7	18.5
15,000	368.4	30.0	18.3	4.0	1.6×10^{-4}	10.3	18.5
			L-605 - 1650° F				
22,000	4.2	0.25	0.15	x	3.6×10^{-2}	19.9	26.4
20,000	8.7	0.4	0.2	0.1	1.6×10^{-2}	23.5	23.7
19,000	12.7	0.4	0.2	x	1.2×10^{-2}	23.6	26.5
17,500	15.3	0.4	0.2	0.07	1.2×10^{-2}	26.6	31.9
16,000	46.6	1.0	0.6	0.2	2.9×10^{-3}	27.0	35.4
15,000	70.9	3.0	1.2	0.2	1.2×10^{-3}	11.0	25.0
13,000	123.5	3.0	1.2	0.2	5.6×10^{-4}	12.7	18.7
12,000	235.1	10.2	3.0	0.5	1.5×10^{-4}	8.9	18.0
11,000	287.8	9.8	2.7	0.4	1.6×10^{-4}	8.0	13.0
10,000	965.9	50.0	9.0	1.5	1.6×10^{-5}	6.4	9.3
9,000	892.3	157.0	43.0	8.0	1.2×10^{-5}	4.0	9.2

Stress, psi	Rupture Life (hrs.)	Hours To 1.0% Plastic Strain	Hours To 0.5% Plastic Strain	Hours To 0.1% Plastic Strain	Minimum Creep Rate in/in/hr	El. %	R. A. %
L-605 - 1800° F							
18,000	0.8	0.02	x	-	1.4×10^{-1}	32.9	35.1
15,000	2.1	0.1	0.08	0.02	6.9×10^{-2}	29.4	34.9
13,000	5.2	0.2	0.05	x	2.8×10^{-2}	32.4	28.7
12,000	7.8	0.6	0.3	0.04	1.4×10^{-2}	20.8	28.4
10,000	28.6	1.6	0.7	0.2	-	19.1	26.3
8,900	56.6	9.6	3.0	0.3	8.0×10^{-4}	7.8	20.9
8,500	65.8	7.6	2.8	0.3	7.6×10^{-4}	10.7	30.6
8,000	51.0	9.0	3.8	0.8	7.8×10^{-4}	6.3	19.5
7,000	160.0	24.0	6.0	0.5	1.3×10^{-4}	9.6	15.1
6,000	447.2	103.0	13.0	2.0	2.8×10^{-5}	10.0	10.0
5,500	528.4	210.0	25.0	1.0	1.6×10^{-5}	9.3	6.7
5,000	921.9	432.0	100.0	2.4	1.0×10^{-5}	9.1	10.0
4,000	1463.5	810.0	390.0	4.0	6.6×10^{-6}	5.2	4.7

Stress, psi	Rupture Life (hrs.)	Hours To 1.0% Plastic Strain	Hours To 0.5% Plastic Strain	Hours To 0.1% Plastic Strain	Minimum Creep Rate in/in/hr	El. %	R. A. %
Udimet 500 - 1200° F							
140,000	3.2	-	-	-	-	15.8	32.2
140,000	5.6	-	-	-	-	23.1	25.3
140,000	7.2*	-	-	-	-	19.8	20.2
140,000	8.0	0.7	0.35	0.01	1.8×10^{-2}	14.6	20.8
140,000	8.4	-	-	-	-	20.3	22.3
140,000	9.3	-	-	-	-	20.0	20.3
140,000	10.7	-	-	-	-	15.5	10.1
130,000	18.3	0.5	x	-	4.2×10^{-3}	9.7	8.8
122,000	37.6	11.4	4.2	x	6.6×10^{-4}	6.3	5.5
117,500	37.0	11.5	5.8	0.4	9.3×10^{-4}	6.5	6.9
110,000	171.9	129.0	58.0	1.0	6.1×10^{-5}	2.3	6.3
110,000	58.6	54.0	31.0	4.5	1.4×10^{-4}	1.7	6.0
103,000	590.4	490.0	258.0	6.0	1.5×10^{-5}	2.4	3.9
100,000	427.4	372.0	231.0	29.0	1.8×10^{-5}	2.3	4.7
100,000	541.4	340.0	192.1	4.4	-	2.5	8.5
100,000	807.5	700.0	420.0	71.6	-	1.9	5.3
100,000	887.7	883.6	570.7	110.0	-	1.9	6.1
100,000	952.6	907.3	523.6	116.3	-	1.5	5.8
100,000	1240.0	1222.5	790.0	167.1	-	1.6	4.5
100,000	1497.0	833.9	546.2	93.0	-	4.6	6.5
100,000	2387.0	1558.7	1125.4	286.4	-	6.2	10.0
95,000	1396.3	760.0	463.0	90.0	9.3×10^{-6}	3.8	23.6
90,000	4428.9	1848.8	1321.6	385.2	2.5×10^{-6}	9.1	10.7
86,000	4041.5	1910.0	1180.0	260.0	3.8×10^{-6}	4.1	7.0
80,000	9724.3	4500.	3400.	800.	1.15×10^{-6}	17.3	18.7
77,000	9152.8	6000.	4100.	800.	1.3×10^{-6}	4.2	6.8
74,000	17840.3	9800.	6000.	1900.	8.5×10^{-7}	7.0	8.8
74,000	8093.8*	7840.	5630.	1900.	-	-	-

Stress, psi	Rupture Life (hrs.)	Hours To 1.0% Plastic Strain	Hours To 0.5% Plastic Strain	Hours To 0.1% Plastic Strain	Minimum Creep Rate in/in/hr	El. %	R. A. %
74,000	3579.6*	-	-	2990.	-	-	-
74,000	501.8*	-	-	-	-	-	-
74,000	50.0*	-	-	-	-	-	-
71,500	11083.5**	-	7400.0	3000.	2.6×10^{-7}	1.053**	-
70,000	9478.3**	-	-	5700.	2.1×10^{-7}	0.23**	-
70,000	5639.1*	-	-	2130.	-	-	-
Udimet 500 - 1275° F							
100,000	126.9	47.	22.	2.	2.0×10^{-4}	4.1	3.5
70,000	2573.9	1060.	520.	100.	9.0×10^{-3}	9.0	18.8

Stress, psi	Rupture Life (hrs.)	Hours To 1.0% Plastic Strain	Hours To 0.5% Plastic Strain	Hours To 0.1% Plastic Strain	Minimum Creep Rate in/in/hr	El. %	R. A. %
			Udimet 500 - 1350° F				
117,218	1.3	0.12	0.03	x	6.0×10^{-2}	13.8	26.7
110,000	3.6	x	-	-	-	19.45	24.3
110,000	2.8	x	-	-	-	6.4	10.0
100,000	5.8	1.55	0.85	0.05	4.7×10^{-3}	6.8	12.3
92,500	21.2	3.0	1.6	0.4	2.6×10^{-3}	16.5	15.9
87,000	32.7	10.4	5.1	1.0	9.0×10^{-4}	8.7	8.4
80,000	80.9	23.5	15.0	4.0	4.0×10^{-4}	13.0	17.4
75,000	127.0	43.0	25.0	6.0	1.9×10^{-4}	11.2	26.5
67,500	278.7	-	-	-	-	9.8	14.4
60,000	613.6	256.0	180.0	36.0	2.2×10^{-5}	15.0	30.0
57,500	1069.6	464.0	298.0	70.0	1.3×10^{-5}	16.3	25.6
52,000	2410.7	1300.0	900.0	200.0	5.2×10^{-6}	10.3	23.7
			Udimet 500 - 1425° F				
70,000	34.8	6.2	3.4	0.7	1.0×10^{-3}	15.9	14.7
40,000	2661.1	1550.0	1110.0	285.0	3.0×10^{-6}	9.3	25.1

Stress, psi	Rupture Life (hrs.)	Hours To 1.0% Plastic Strain	Hours To 0.5% Plastic Strain	Hours To 0.1% Plastic Strain	Minimum Creep Rate in/in/hr	Ei. %	R. A. %
				Udimet 500 - 1500° F			
80,000	1.7	0.2	0.1	0.001	4.0×10^{-2}	15.0	19.1
72,000	5.0	0.4	0.2	0.005	1.8×10^{-2}	20.5	32.6
70,000	3.1	0.4	0.2	0.02	2.4×10^{-2}	19.5	31.6
60,000	10.5	1.8	1.0	0.2	5.4×10^{-3}	12.2	28.0
60,000	11.9	-	-	-	-	13.3	30.1
60,000	16.2	-	-	-	-	13.2	30.0
60,000	16.3	-	-	-	-	16.7	26.9
60,000	17.1	-	-	-	-	10.0	28.6
60,000	20.8	-	-	-	-	22.0	23.1
60,000	24.2	-	-	-	-	17.0	31.2
60,000	26.9	-	-	-	-	16.9	29.8
55,000	33.0	-	-	-	-	17.4	24.4
50,000	53.2	22.0	12.5	3.5	4.7×10^{-4}	10.5	23.6
45,000	159.6	64.0	44.0	9.0	7.4×10^{-5}	15.5	19.4
42,500	193.0	88.0	57.0	14.0	6.4×10^{-5}	9.2	23.0
39,000	421.2	197.0	138.0	30.0	1.1×10^{-5}	12.0	27.7
35,000	441.6	252.0	167.0	[illegible]	2.5×10^{-5}	6.3	23.5
32,500	548.8	325.0	220.0	[illegible]	1.8×10^{-5}	6.7	22.5
30,000	337.1	188.5	125.0	[illegible]	-	6.6	34.2
30,000	466.6	217.9	150.0	50.0	-	4.4	25.9
30,000	1189.3	620.9	400.0	100.0	-	8.8	12.7
30,000	1255.4	623.8	407.2	90.0	-	9.8	23.2
30,000	1426.1	691.7	455.0	100.0	-	10.1	27.0
30,000	1691.4	694.7	455.2	115.0	-	16.8	25.1
26,000	2401.1	1640.0	1290.0	300.0	2.8×10^{-6}	5.3	17.4
23,000	7146.6	2950.	1900.	425.	2.2×10^{-6}	12.1	21.8
19,000	14773.5	6400.	4400.	1100.	4.0×10^{-5}	12.9	20.4

Stress, psi	Rupture Life (hrs.)	Hours To 1.0% Plastic Strain	Hours To 0.5% Plastic Strain	Hours To 0.1% Plastic Strain	Minimum Creep Rate in/in/hr	El. %	R. A. %
18,000	12879.6	4300.	2600.	600.	2.0×10^{-6}	13.0	12.6
16,500	7006.5*	-	-	2800.	-	-	-
16,500	3238.1*	-	-	1270.0	-	-	-
16,500	2013.8*	-	-	-	-	-	-
16,500	500.0*	-	-	-	-	-	-
16,500	21408.1**	15200.0	10400.0	200.	3.7×10^{-7}	2.68**	-
15,000	7364.9*	-	-	1600.	-	-	-
15,000	3115.4**	-	-	-	-	0.08**	-
13,500	3160.9**	-	-	-	-	0.09**	-

Udimet 500 - 1575° F

Stress, psi	Rupture Life (hrs.)	Hours To 1.0% Plastic Strain	Hours To 0.5% Plastic Strain	Hours To 0.1% Plastic Strain	Minimum Creep Rate in/in/hr	El. %	R. A. %
40,000	39.9	19.0	11.8	2.1	3.4×10^{-4}	6.9	20.6
20,000	3329.3	1700.	1100.	325.	3.3×10^{-6}	19.1	26.9

Stress, psi	Rupture Life (hrs.)	Hours To 1.0%	0.5%	0.1%	Minimum Creep Rate in/in/hr	El. %	R. A. %
		Plastic Strain					
		Udimet 500 - 1650° F					
40,000	2.9	0.6	0.35	0.05	1.2×10^{-2}	16.5	27.6
35,000	4.6	2.1	1.3	0.4	2.7×10^{-3}	7.8	24.0
30,000	11.1	5.6	3.6	1.5	1.0×10^{-3}	5.9	28.4
27,500	46.4	18.0	12.0	2.9	2.9×10^{-4}	14.2	27.2
25,000	52.5	30.0	14.0	2.5	3.0×10^{-4}	7.3	25.0
22,500	53.0	31.0	22.5	4.0	2.1×10^{-4}	6.4	25.6
20,000	148.0	78.0	55.0	15.0	4.8×10^{-5}	8.1	25.0
19,000	334.9	136.0	94.0	16.0	4.0×10^{-5}	16.8	26.6
18,000	263.7	110.0	71.0	8.0	6.3×10^{-5}	16.7	24.4
15,000	970.9	427.0	300.0	75.0	1.2×10^{-5}	13.0	26.0
12,000	2639.7	1380.0	970.0	260.0	4.1×10^{-6}	9.3	13.1

Stress, psi	Rupture Life (hrs.)	Hours To 1.0% Plastic Strain	Hours To 0.5% Plastic Strain	Hours To 0.1% Plastic Strain	Minimum Creep Rate in/in/hr	El. %	R. A. %
Udimet 500 - 1800° F							
18,000	6.7	3.3	2.4	0.7	1.6×10^{-3}	15.2	26.3
16,500	12.7	5.0	3.1	0.7	1.0×10^{-3}	15.3	34.3
15,000	6.2	3.7	2.5	1.0	1.2×10^{-3}	7.2	31.9
15,000	21.8	6.1	4.0	1.4	1.1×10^{-3}	19.2	13.6
13,000	9.9	3.9	2.7	0.5	1.2×10^{-3}	9.8	40.6
12,500	51.0	24.0	17.5	4.0	8.8×10^{-5}	16.6	30.0
12,000	51.9	23.0	16.5	5.0	1.8×10^{-4}	16.5	36.2
11,000	64.1	45.0	34.0	13.0	6.3×10^{-5}	5.6	22.4
10,000	151.8	116.0	75.0	20.0	4.9×10^{-5}	7.8	20.1
10,000	41.0	-	-	-	-	6.4	31.8
9,000	126.5	98.0	78.0	33.0	2.0×10^{-5}	4.9	25.6
9,000	29.3	12.0	8.0	1.0	3.5×10^{-4}	14.0	43.5
9,000	94.9	78.5	64.8	34.0	1.4×10^{-5}	5.4	17.7
8,500	152.5	81.5	57.0	17.0	4.3×10^{-5}	9.6	29.8
8,500	86.9	48.0	37.0	10.0	8.5×10^{-5}	8.5	34.9
7,500	405.6	255.0	192.0	90.0	7.8×10^{-6}	6.8	16.6
6,000	597.8	525.0	423.0	206.0	2.7×10^{-6}	3.9	10.9
5,000	1772.4	920.0	640.0	130.0	3.2×10^{-6}	8.9	15.8

* - Discontinued test   ** - In test

x - Reached more than 1% (0.5%, 0.1% respectively) on loading

APPENDIX II

Lineal Analysis of Crack Volume

Crack volumes were determined by lineal analysis of a longitudinal section of the creep specimen. In the case of rupture specimens, the metallographic specimen consisted of a length of about 25 mm including one of the fracture surfaces sectioned along the central axis of the specimen. A traversing microscope with Hurlbut counter attachment was used for the analysis. A magnification of 200X was employed.

Since crack volume, in general, varies with distance from the fracture surface and with distance from the center of the specimen, several different parameters were determined to describe the distribution. First the average crack volume for the entire specimen and variation of crack volume from center to surface were determined by the fractional length of intercepted line on seven to nine lines parallel to the specimen axis and at various distances from the center. The variation of crack volume with distance from the fracture surface was obtained by measuring the fractional length of intercepted line on 10 to 15 lines perpendicular to the specimen axis across the 6 mm width of the section at various distances from the fracture surface.

In calculating the average crack volume, allowance had to be made for the fact that equal areas of the specimen section at different distances from the center do not represent equal volumes of the specimen.

For the standard 6 mm width section, longitudinal lineal counts were generally made at distances from the two edges of 0, 0.19, 0.58, 1.35, and 2.89 mm. The radial span and the volumes of material which these determinations represent are listed below.

Distance from Edge (mm)	Radius (mm)	Radial Span (mm)	V/V_t
0	± 3.0	± 2.9 - 3.0	0.033
0.19	± 2.81	± 2.7 - 2.9	0.062
0.58	± 2.42	± 2.0 - 2.7	0.183
1.35	± 1.65	± 1.0 - 2.0	0.167
2.89	± 0.1	± 0 - 1.0	0.055
			0.50

Then, to obtain the average volume fraction of cracks, the lineal fraction of cracks for each line is multiplied by its corresponding V/V_t and the products are summed.

The variation of crack volume with distance from surface or from the fracture is expressed by the distance at which the lineal fraction of cracks falls to a value halfway between its peak value and its minimum value.

TABLE II-1: L-605 Lineal Analysis of Cracks

σ	t_r	% El.	% R.A.	ρ	F_v	F_c	F_s
			1200° F				
28,000	2,014*	1.4	1.6	9.176	0	-	-
	3,023.4*	-	-	9.181	0	-	-
	7,004.8*	-	-	9.188	0	-	-
	10,192.3	1.4	1.6	9.16	0	0	0
45,000	136.9	8.2	6.2	-	0.00084	0	0.0044
48,000	74.9	7.9	6.9	9.09	0.00055	0	0.0029
65,000	5.1	20.8	25.1	9.16	0.00027	0	0.0014
			1350° F				
34,000	114.2	5.7	6.9	9.15	0.00015	0.00009	0.0004
			1500° F				
10,500	501.1*	-	-	-	0	-	-
	1,199.5*	-	-	-	0	-	-
	3,000.4*	-	-	-	?	-	-
	7,007.1*	-	-	-	?	-	-
11,500	13,018	4.9	1.5	8.97	0.0095	0.0079	0.016
15,000	3,884	10.0	12.9	9.00	0.0100	0.0081	0.020
17,000	1,157.1	9.4	13.6	-	0.0010	0	0.005
18,500	748.3	15.1	15.9	9.06	0.0130	0.0062	0.043

σ	t_r	% El.	% R.A.	ρ	F_V	F_C	F_S
22,000	146	14.5	20.1	9.14	0.0029	0.0023	0.0057
25,000	96.5	23.4	22.9	-	0.0064	0.0016	0.027
27,500	25.7	15.0	12.2	-	0.0078	0.0037	0.025
30,000	11.3	11.7	-	9.15	0.0052	0	0.027
32,000	5.5	18.3	22.9	9.14	0.0075	0.00065	0.037
35,000	2.7	12.3	15.2	9.14	0.0074	0	0.039
37,500	1.7	17.1	17.3	9.13	0.0085	0.0031	0.032
			1650° F				
13,000	123.5	12.7	18.7	-	0.0052	0.0017	0.020
			1800° F				
5,000	1,463.5	5.2	4.7	-	0.0092	0.0070	0.018
repeat 5,000	1,463.5	5.2	4.7	-	0.0095	0.0094	0.0099
5,500	528.4	9.3	6.7	-	0.0163	0.0053	0.0635
7,000	160.0	9.6	15.1	-	0.0053	0.0042	0.0096
8,000	51.0	6.3	19.5	-	0.0076	0.0035	0.025
8,900	56.6	7.8	20.9	-	0.0056	0.0030	0.017
10,000	28.6	19.1	26.3	-	0.0056	0.0012	0.024
12,000	7.8	-	-	-	0.0060	0.0014	0.026
18,000	0.8	32.9	35.1	9.09	0.0087	0	0.046

*interrupted tests

F_3 = .3mm surface layer F_c = center of spec F_v = average

APPENDIX III

Least Squares Analysis of Rupture Time and Minimum Creep Rate Data

In the log stress versus log rupture time and the log stress versus log minimum creep rate plots, it was concluded that the data could be represented best by straight line segments. Thus, the equation for the lines would be of the form

$$\log \sigma = K + m \log x \qquad 1)$$

where x is either rupture time, t_r, or minimum creep rate, ϵ_{min}, and K and m are constants for the particular line segment. Determination of these constants was done by minimizing squared deviations from the line.

If σ_i and x_i are values from a test, the log σ deviation (D) of this point from equation 1) is

$$D = K - m \log x_i + \log \sigma_i \qquad 2)$$

and the sum of squared deviations (S) for n tests is

$$S = \sum_{i=1}^{n} (-k - m \log x_i + \log \sigma_i)^2$$

Differentiating S, first with respect to K and then with respect to m and equating the derivative to zero to minimize S gives

$$K = \frac{1}{n} \sum_{i=1}^{n} \log \sigma_i - \frac{m}{n} \Sigma \log x_i \qquad 3)$$

and

$$K = \frac{\sum_{i=1}^{n} \log \sigma_i \log x_i - m \sum_{i=1}^{n} \log^2 x_i}{\sum_{i=1}^{n} \log x_i} \qquad 4)$$

Now if we let

$$P = \sum_{i=1}^{n} \log \sigma_i,$$

$$Q = \sum_{i=1}^{n} \log x_i,$$

$$R = \sum_{i=1}^{n} \log^2 x_i, \text{ and}$$

$$V = \sum_{i=1}^{n} \log \sigma_i \log x_i$$

and equate 3) and 4) to solve for m we obtain

$$m = \frac{QP - nV}{Q^2 - nR} \qquad 5)$$

then substitution into equation 3) gives

$$K = \frac{P}{n} - \frac{m}{n} Q \qquad 6)$$

APPENDIX IV

Long Time Creep Tests

Long time creep tests were initiated for both Udimet 500 and L-605 at 1200° and 1500° F. The stresses were chosen on the basis of short time rupture data and an attempt was made to arrive at rupture lives between 10,000 and 50,000 hours.

Table IV-1 includes the data on these tests, Figures IV-1 through IV-4 show the corresponding creep curves. (The creep curves are not completely up to date in all cases.)

It is quite apparent that the two materials show a different type of plastic deformation under creep conditions. The highly age hardened nickel-base alloy shows no primary and hardly any secondary creep, but a continuously increasing creep rate to fracture. On the other hand, the cobalt-base alloy exhibits primary creep under all conditions of loading, indeed in some tests, secondary creep does not start until after 15-20,000 test hours.

In shorter time tests, the general observations on the shape of the creep curves are the same although the amounts of plastic deformation change with the ductility of the material under given conditions of stress and temperature.

For a detailed and meaningful analysis of creep curves, additional data and structural observations are needed. For example, it is important to know what geometric changes a specimen undergoes at a given temperature without a load. Figures IV-5 through IV-8 show that significant length changes can be associated with phase changes only. It would further be of importance to know the influence of stress and strain on the amount of phase change and therefore the contribution of structural instabilities to length changes. It becomes therefore important to distinguish between plastic deformation and changes in specimen length, the latter being partially dependent on density changes.

Another important point in the analysis of creep curves is the aspect of the reproducibility. Figures IV-9 through IV-12 illustrate groups of creep curves; each group represents one condition of stress and temperature for a given material. There is no reason to believe that variable test conditions are responsible for the observed scatter in any major way. One must therefore assume that the observed deviations between the creep curves of a group are due mainly to inhomogeneities in the material. It is therefore quite obvious that a quantitative analysis of creep curves should take into account the range of variability.

Duplicate tests interrupted after different test hours were conducted originally to observe the progress of intercrystalline cracking. It was hoped that the rate of crack progress could be used for extrapolation purposes. Up to this point the study has shown that formation of very small cracks does indeed often start at a very early stage, however, noticeable crack growth usually does not occur until a stage close to fracture is reached. This investigation is being continued and it is anticipated that a clearer picture can be presented with additional available data.

TABLE IV-1: Summary of Long Time Tests

Temperature (° F)	Stress (psi)	Test Time (hours)	% El.	Expected Rupture Life (hours)
		Udimet 500		
1200	70,000	16,534	0.735	50,000
	71,500	18,140	2.760	30,000
	74,000	17,840	7.7	ruptured
1500	13,500	10,217	0.169	50,000+
	15,000	10,171	0.220	50,000
	16,500	24,733	6.7	ruptured
	18,000	12,880	13.0	ruptured
	19,000	14,773	12.9	ruptured
		L-605		
1200	24,000	16,414	0.980	50,000+
	25,000	16,363	0.993	50,000
	26,500	28,846	1.330	40,000
	28,000	10,192	1.4	ruptured
	29,500	21,720	3.1	ruptured
1500	9,500	28,822	1.812	50,000
	10,000	13,386	1.362	40,000
	10,500	28,529	3.532	30,000
	11,500	13,018	4.9	ruptured

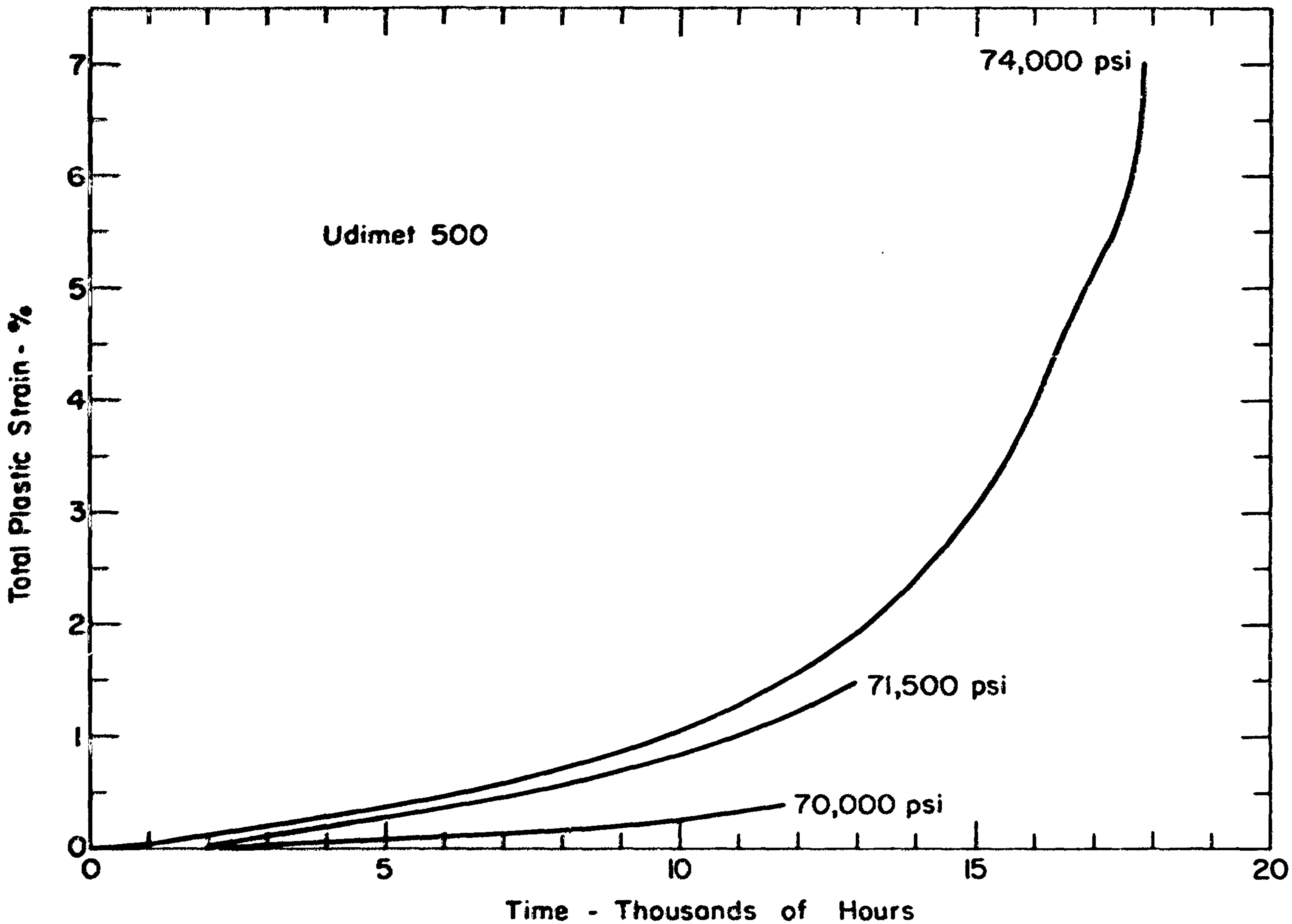


Figure IV-1: Long time creep curves for Udimet 500 at 1200° F.

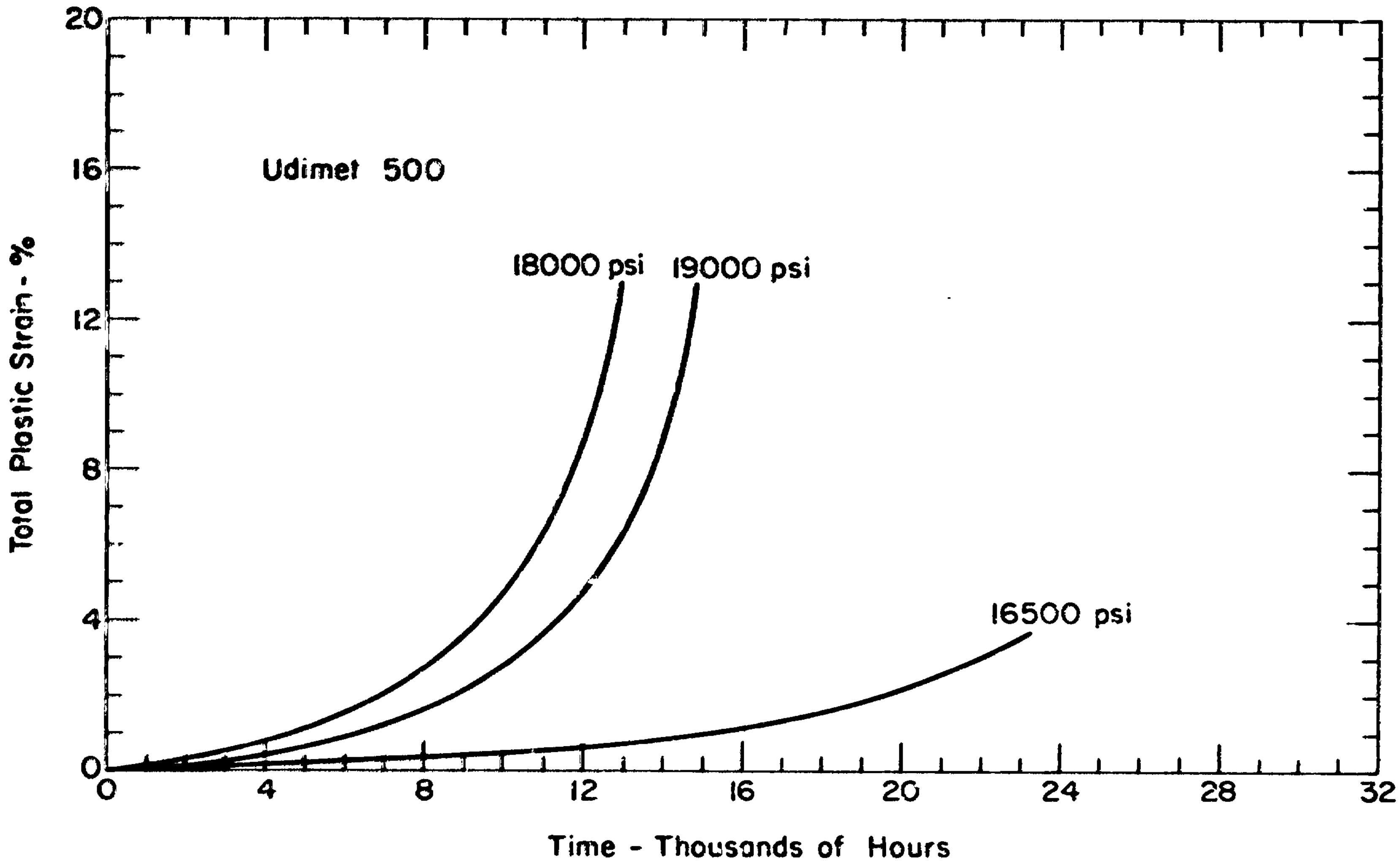


Figure IV-2: Long time creep curves for Udimet 500 at 1500°F.

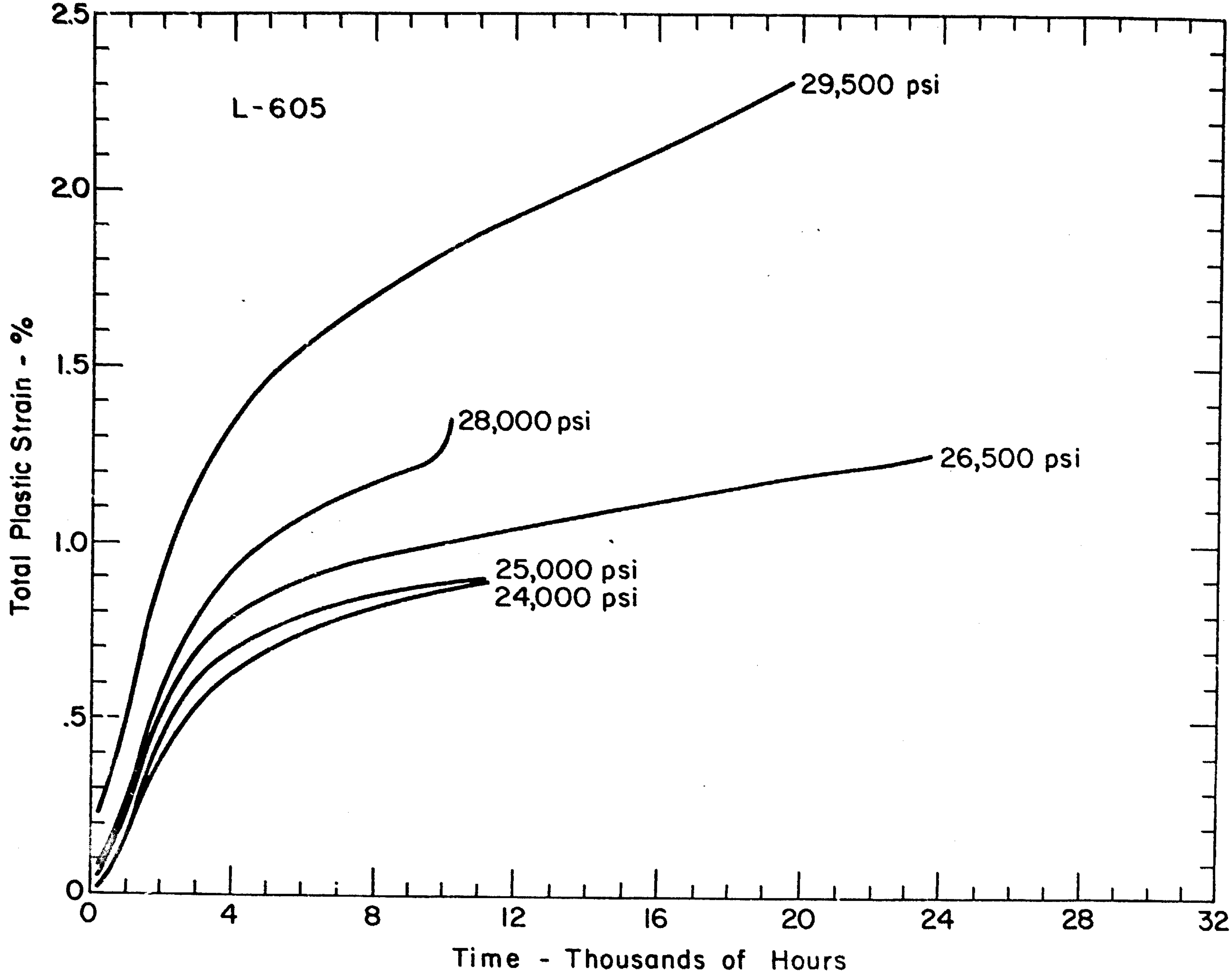


Figure IV-3: Long time creep curves for L-605 at 1200° F.

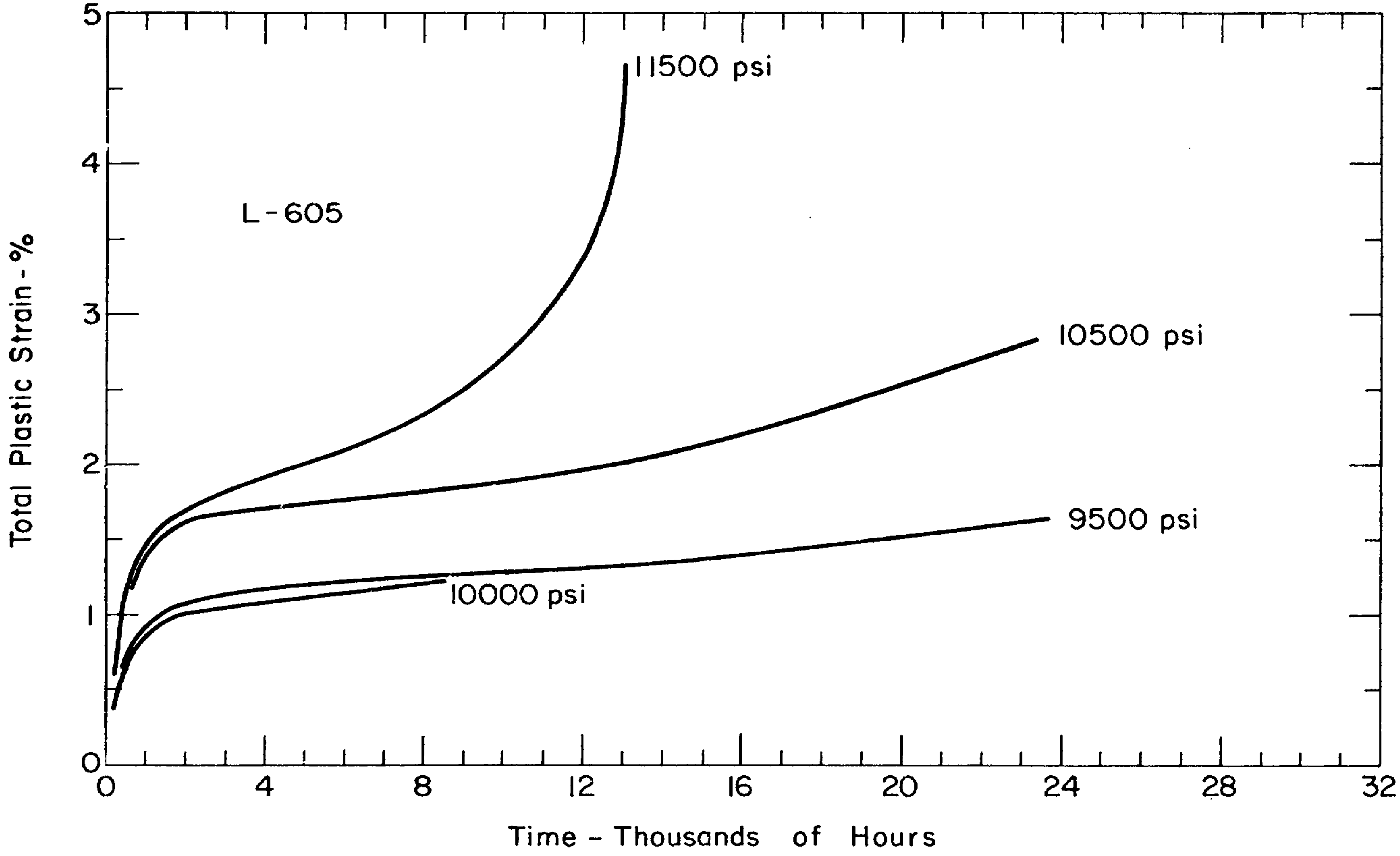


Figure IV-4: Long time creep curves for L-605 at 1500° F.

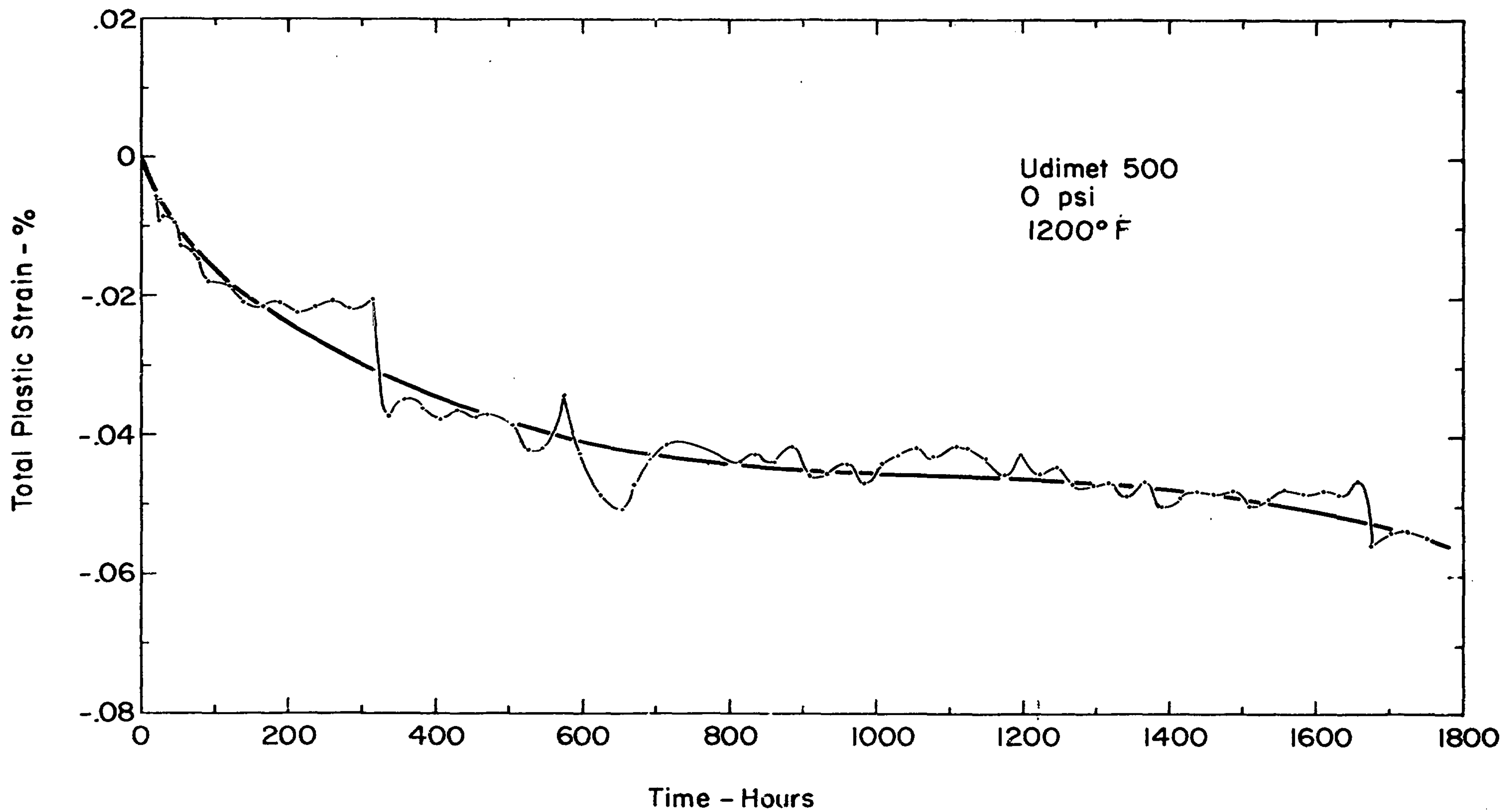


Figure IV-5: No load test, Udimet 500, 1200°F.

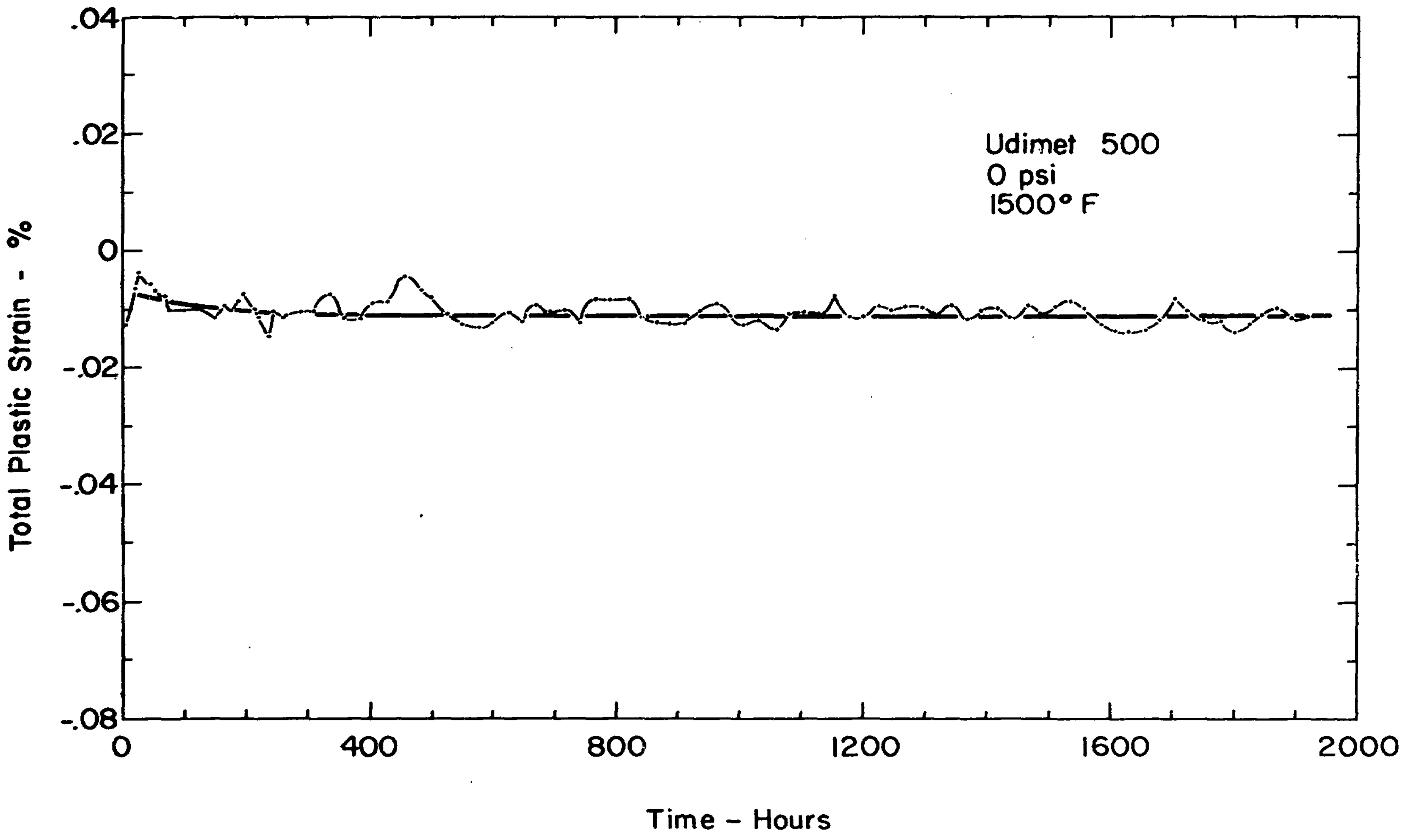


Figure IV-6: No load test, Udimet 500, 1500°F.

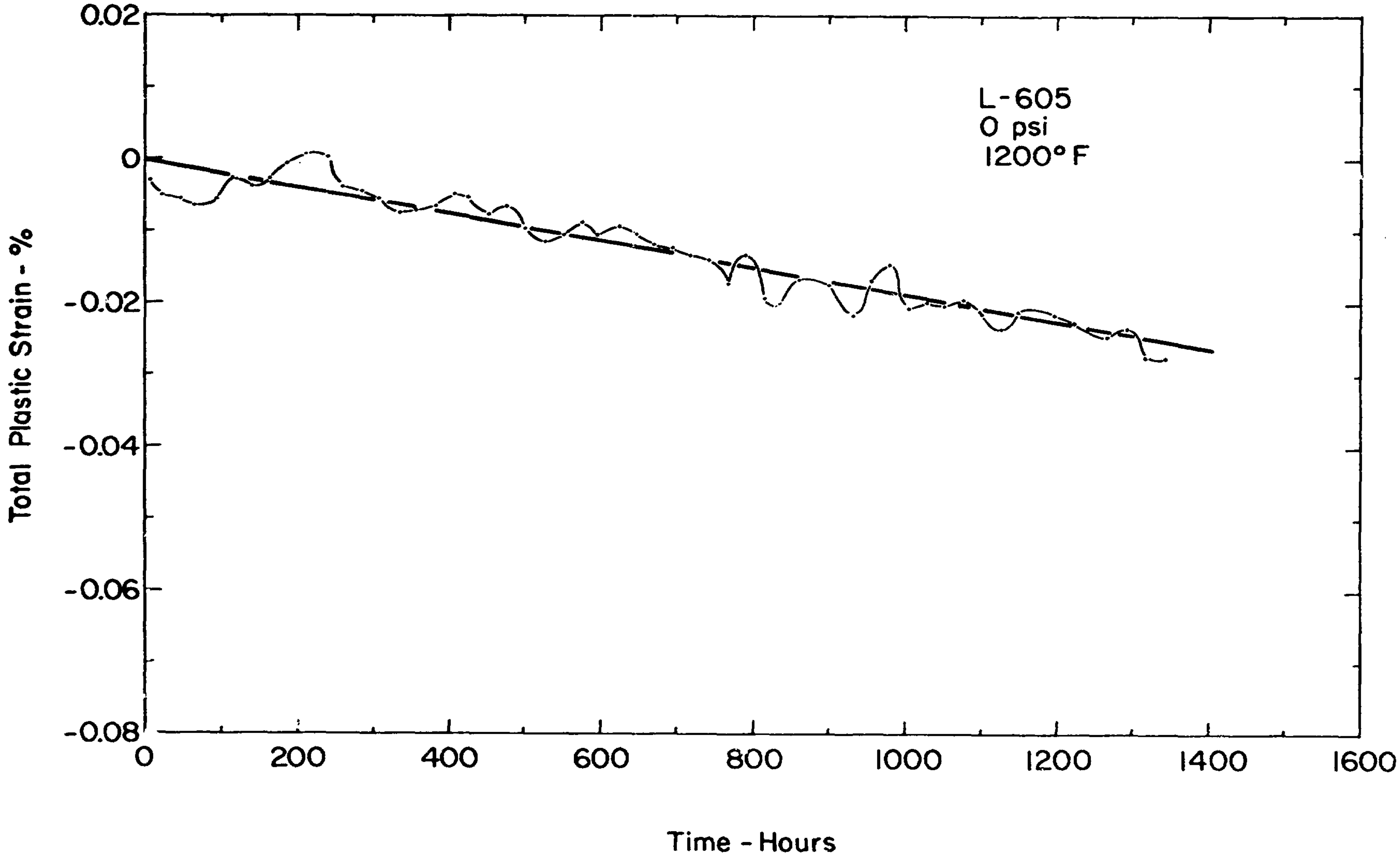


Figure IV-7: No load test, L-605, 1200 °F.

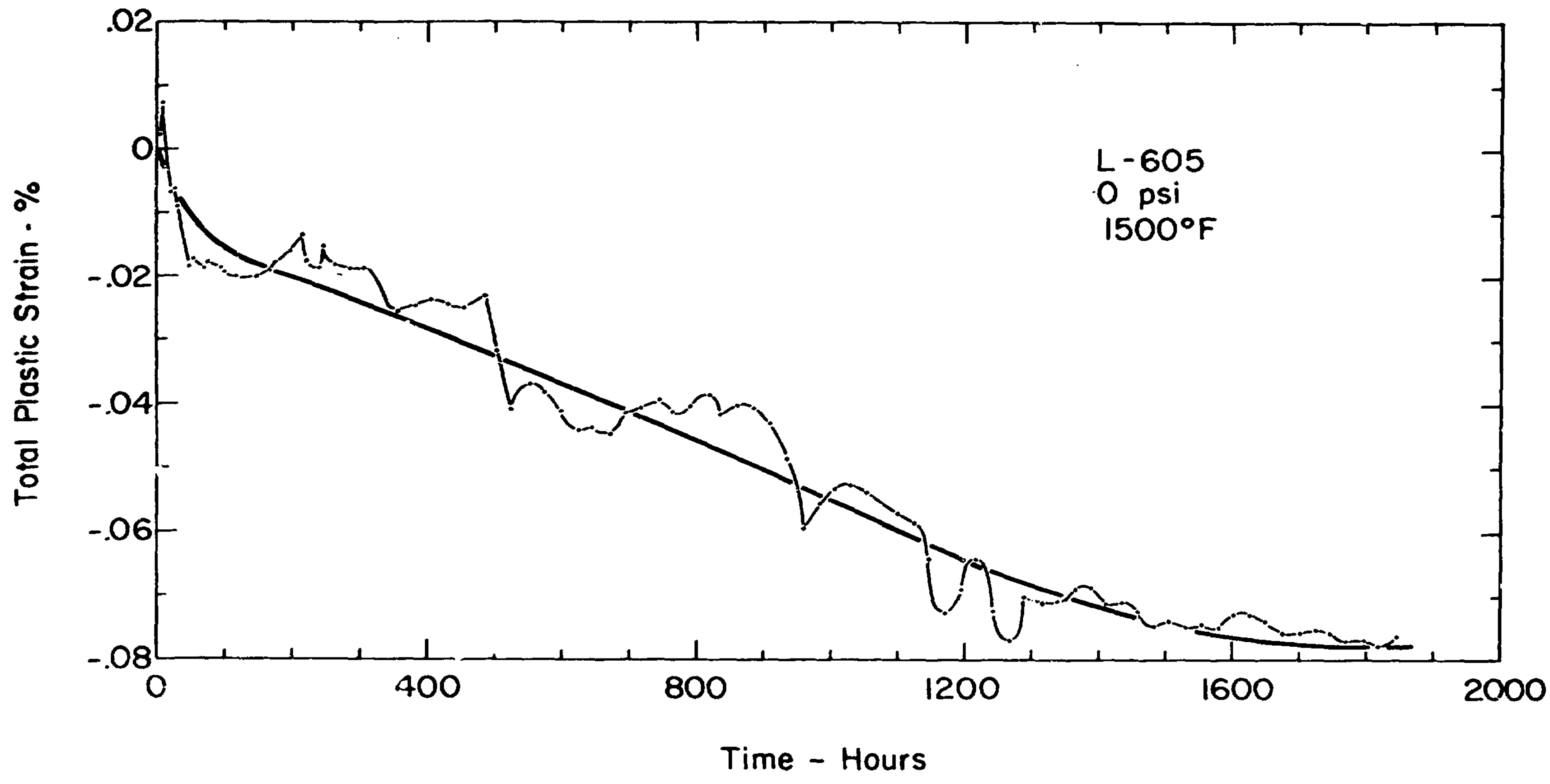


Figure IV-8: No load test, L-605, 1500°F.

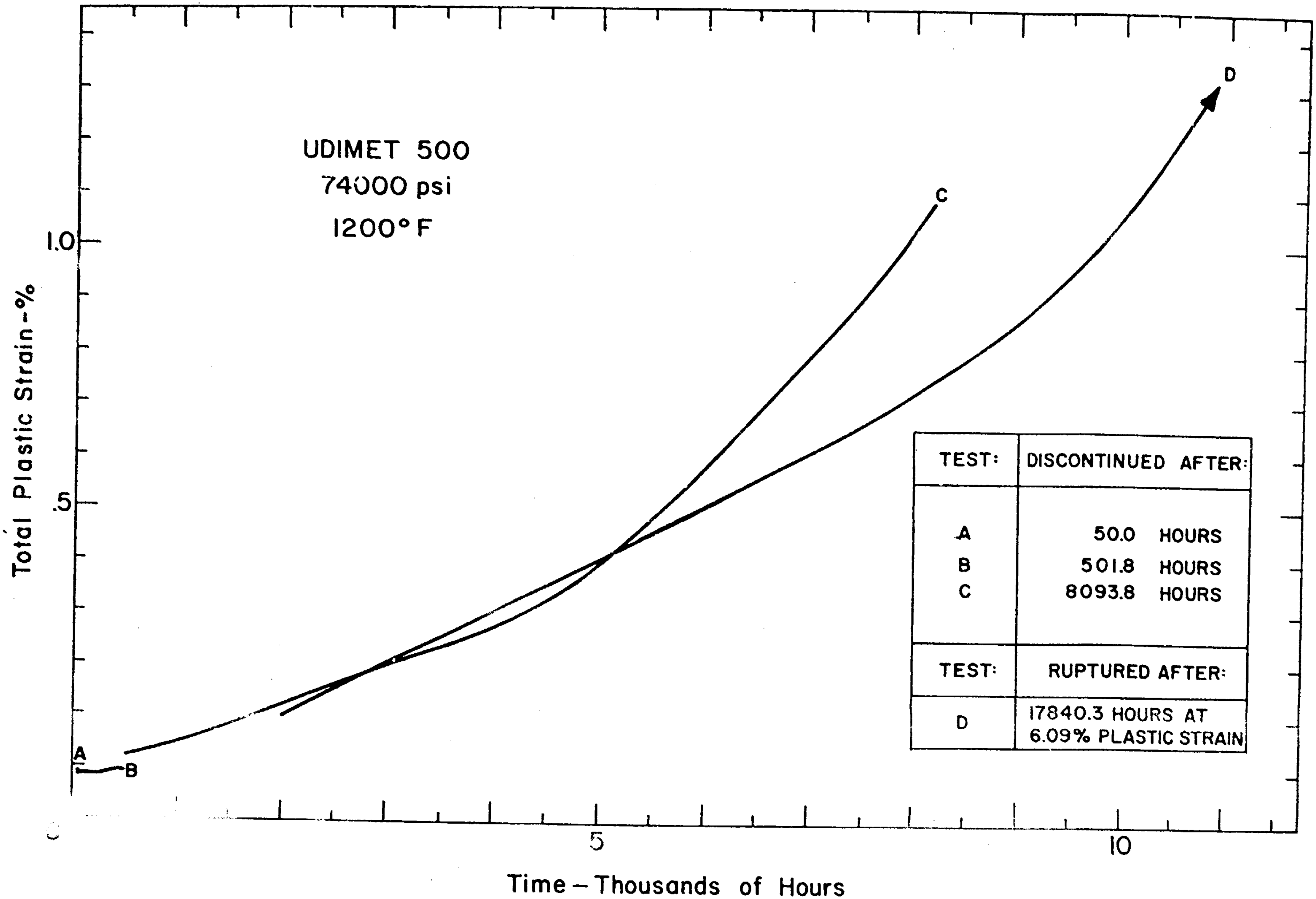


Figure IV-9: Creep curves of tests discontinued after various fractions of the rupture time, Udimet 500, 1200° F.

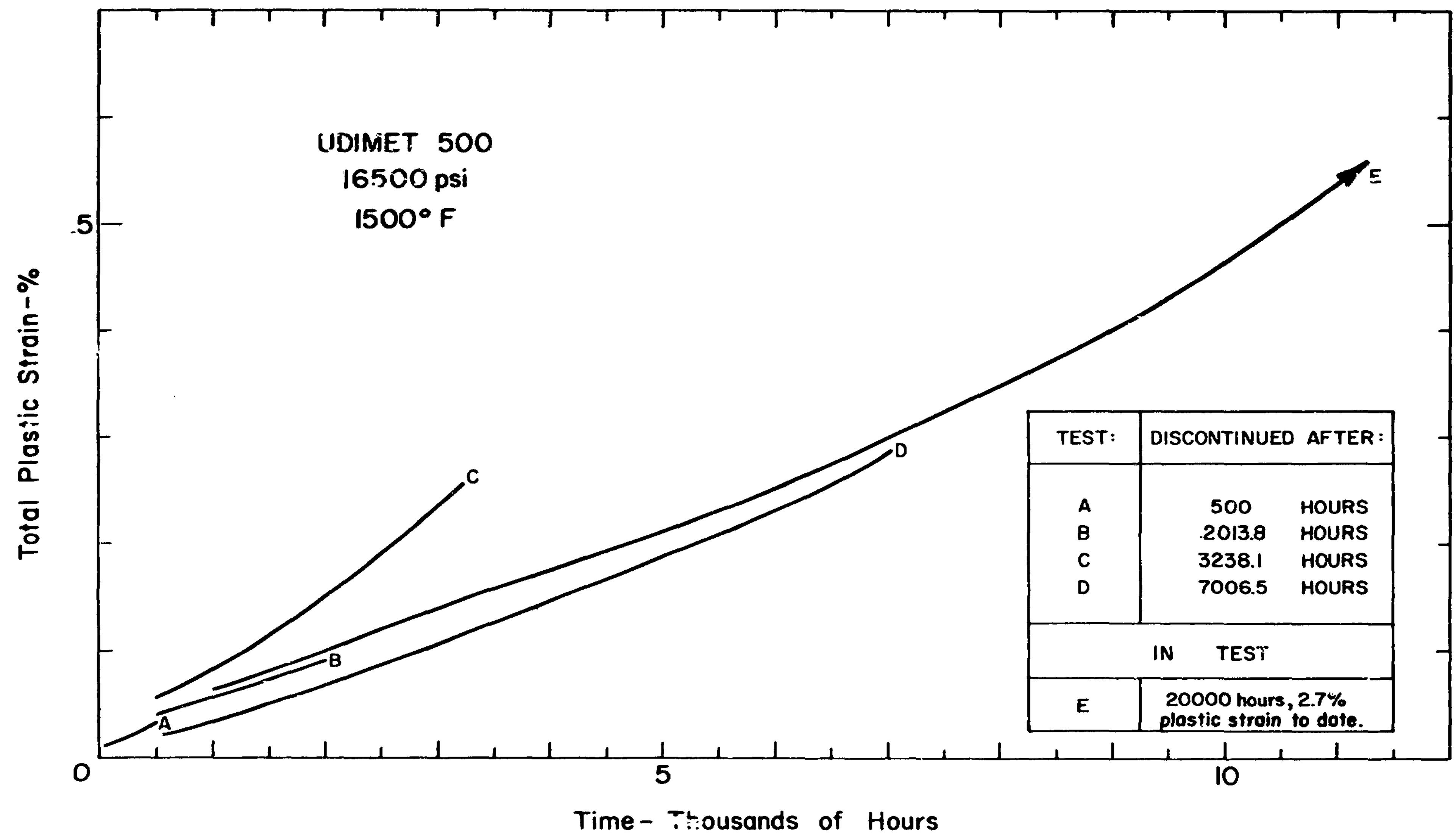


Figure IV-10: Creep curves of tests discontinued after various fractions of the rupture time, Udimet 500, 1500°F.

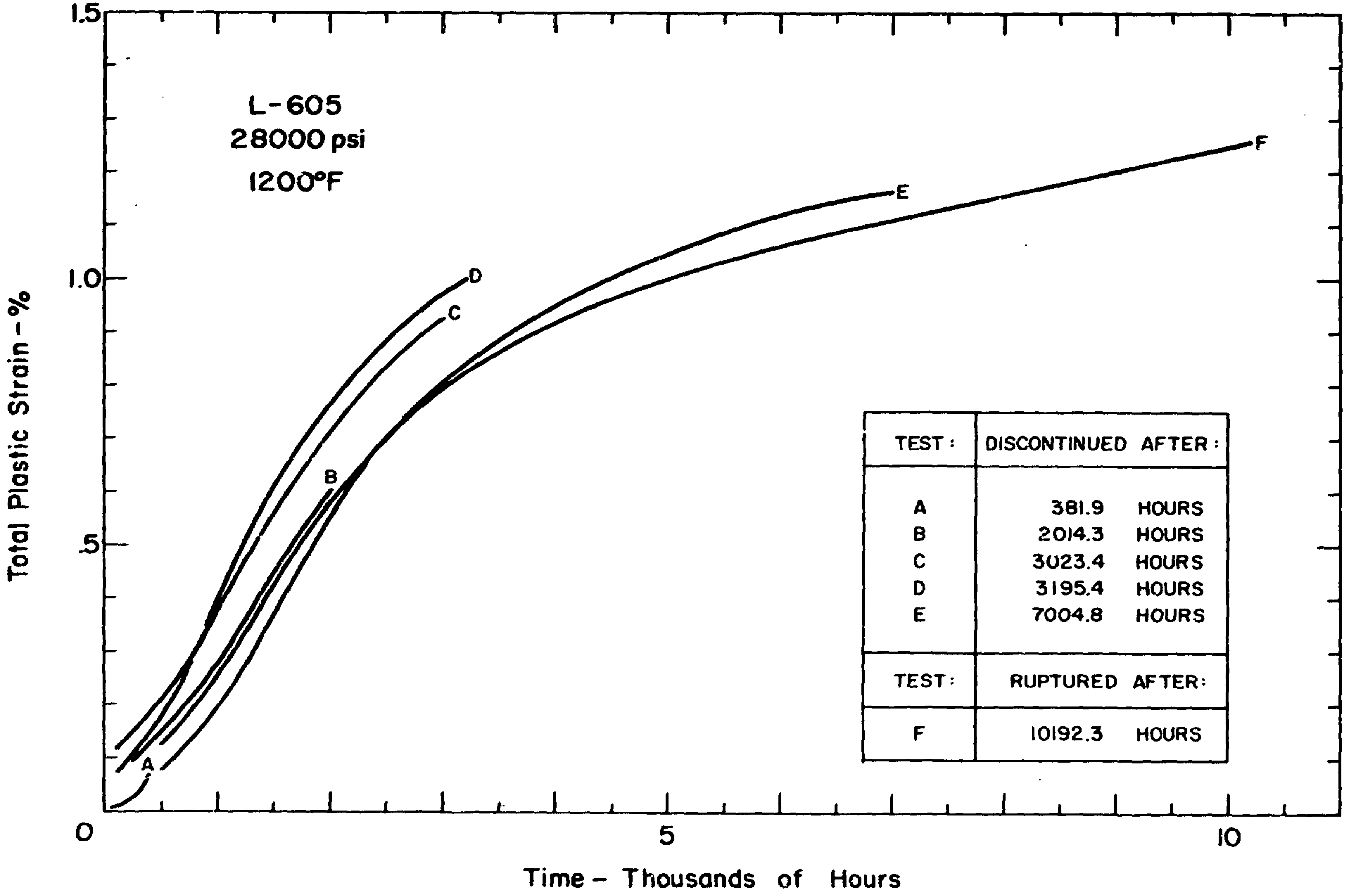


Figure IV-11: Creep curves of tests discontinued after various fractions of the rupture time, L-605, 1200°F.

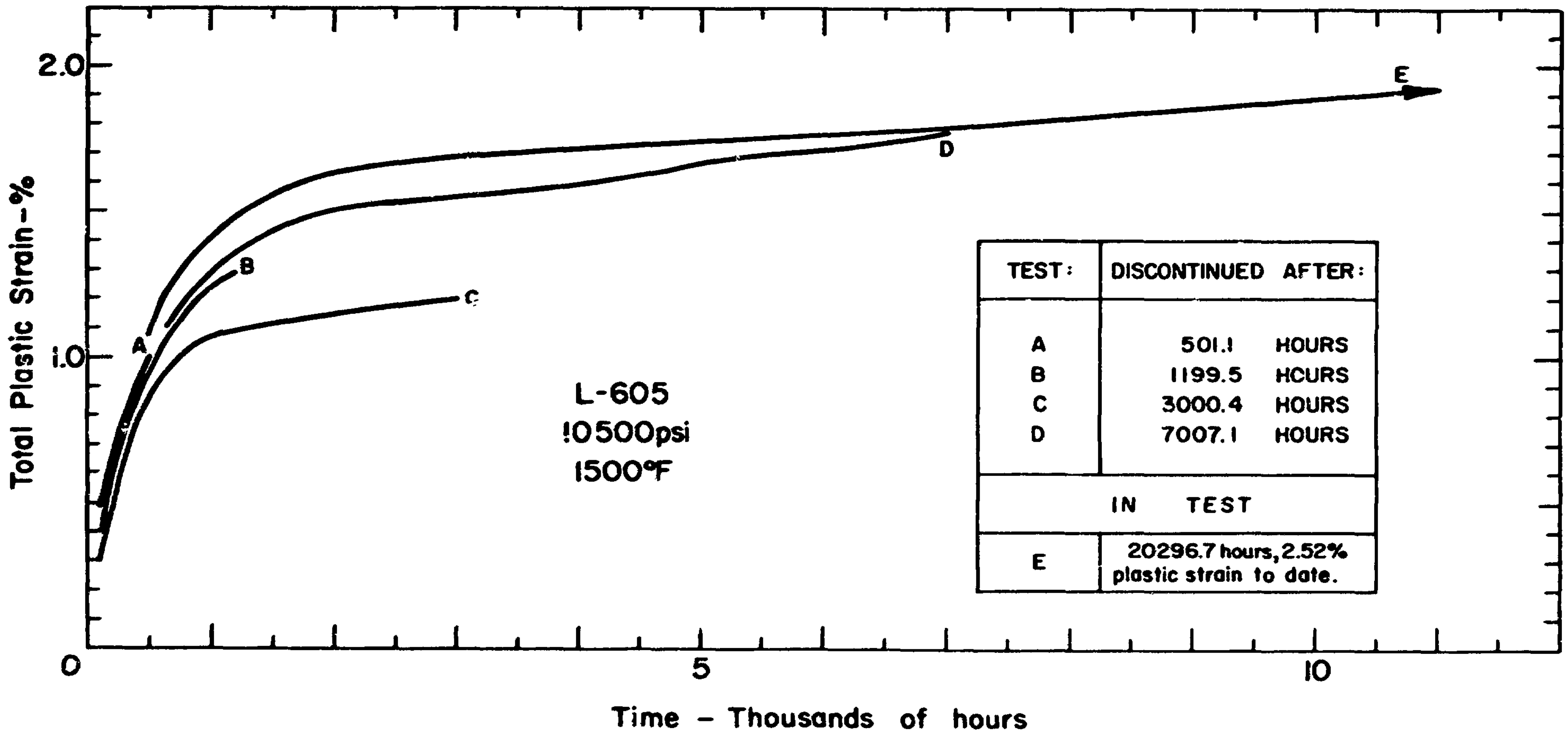


Figure IV-12: Creep curves of tests discontinued after various fractions of the rupture time, L-605, 1500°F.

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) New England Materials Laboratory, Inc. Medford, Massachusetts 02155	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE
MECHANISMS ASSOCIATED WITH LONG TIME CREEP PHENOMENA
PART I: PRESENTATION OF CREEP DATA AND STRUCTURAL ANALYSIS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Report - March 1961 to July 1964

5. AUTHOR(S) (Last name, first name, initial)
Widmer, R., Dhosi, J. M., Mullendore, A., and Grant, N. J.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1965	83	4

8a. CONTRACT OR GRANT NO. AF 33(616)-8225 AF 33(557)-11237 b. PROJECT NO. 7351 c. TASK NO. 735106 d.	9a. ORIGINATOR'S REPORT NUMBER(S) AFML-TR-65-181 Part I 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES
Qualified users may obtain copies of this report from the Defense Documentation Center, Alexandria, Va. Release to CFSTI is not authorized.
(CONTINUED)

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Metals and Ceramics Division (MAMD) Air Force Materials Laboratory Wright-Patterson AFB, Ohio 45433

13. ABSTRACT

A creep-rupture investigation was conducted on two high temperature alloys: a nickel-base age hardened alloy, Udimet 500, and a cobalt-base alloy, L-605. Creep-rupture tests were conducted over a range of rupture lives from 1 to 20,000 hours at 1200°, 1350°, 1500°, 1650°, and 1800° F. Additional long time test with expected lives up to 50,000 hours were initiated and are still in progress.

The test data were supplemented by extensive examination of structural changes during testing as well as the nature of crack initiation and propagation as a function of stress, temperature, and time. Additional groups of tests at particular stresses and temperatures were run to establish the reproducibility of data. The intent was to characterize thoroughly the materials, their structures, and the nature of deformation and fracture processes in order to evaluate the applicability of extrapolation procedures.

DD FORM 1 JAN 64 1473

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.