CREEP-RUPTURE TESTING OF ALUMINUM ALLOYS TO 100,000 HOURS

Part I - Rupture Data for 1100-O and 5454-O Plate and A Modified Extrapolation Technique Used To Establish Stresses for the Initiation of 15,000 and 100,000 Hour Tests.

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SUMMARY

An investigation is in progress which is designed to provide creep-rupture data for five aluminum plate materials to 100,000 hours. In the presently reported Part I, the shorter time data obtained and the special extrapolative procedure used to determine stresses for tests to be initiated on 1100-O and 5454-O alloys at 200° to 500°F with aim rupture times of 15,000 and 100,000 hours are presented. The testing in a similar investigation is well under way for 1100-H14, 5454-H34 and 6061-T651 materials and will be reported later. The results of the prolonged tests will also be reported as they become available.

The major objective of the long time tests is to provide actual test data to evaluate methods of extrapolating rupture data and to characterize the long-time creep-rupture properties of the alloys. The tests being reported now are those deemed necessary to determine suitable test stresses for the prolonged tests and to satisfy the requirements of extrapolation procedures. Testing times up to about 3000 hours for temperatures from 200° to 600°F were used. The stress-rupture time curves at each temperature for the time periods of the tests were established with extensive and replicate data from two laboratories.

The determination of stresses for tests to actually rupture in approximately 15,000 and 100,000 hours presented a unique problem in extrapolation. Rupture time is exceedingly sensitive to stress for the prolonged tests. Extrapolations by usual methods which would be considered an excellent determination of rupture strengths were found to

involve differences and uncertainties of rupture time which would be unacceptable for the tests. To circumvent the constraints inherent to the conventional methods of extrapolation, the technique finally adopted utilized graphical extrapolation of iso-stress curves of rupture times as functions of temperature as a family-of-curves. This avoided the assumption of definite iso-stress time versus temperature relationships forced by the mathematics of specific parameter methods. While cumbersome, this procedure gave results which should be more responsive to the actual stress-rupture time characteristics at any one temperature and time and, therefore, provide a more sensitive measure of the long time strengths. These rupture strengths were then adjusted upward to provide reasonable certainty that data scatter could not result in the actual tests exceeding 100,000 hours.

The five materials in the entire program cover a range of types of alloys ranging from the 1100-O material free from phase changes through the non-heat treatable 5454-O alloy to the heat treatable 6061-T651 alloy. The effects of cold work are covered by the 1100-H14 and 5454-H34 conditions of those two materials. This, then, offers a range of structural effects which may influence creep-rupture characteristics and introduce instabilities complicating extrapolation procedures.

In addition to the stress-rupture time data for the two materials covered by this report, creep data from the tests are summarized. Tests on notched specimens showed marked notched strengthening for time periods of about 1000 hours.

INTRODUCTION

The results are presented for a creep-rupture testing program conducted to enable the determination of stresses for tests of 15,000 and 100,000 hours duration on 1100-O and 5454-O aluminum alloy plate materials. The ultimate objective of the program is to characterize long-time creep-rupture properties of these types of aluminum alloys and the validity of methods of extrapolation of the usual shorter-time tests. Because of the difficulty of defining the stresses for rupture in a given time, the testing has been extensive for time periods up to 2000 to 3000 hours over the temperature range of 200° to 600°F. A study was made of the methods of extrapolation of the stress-rupture time data in order to predict as accurately as possible the 15,000 and 100,000 hour strengths.

The 1100-O and 5454-O plates were the first tested of the five materials in the complete program. Similar tests and data extrapolation procedures are now in progress on 6061-T651, 1100-H14 and 5454-H34 plates, and will be reported at a later date.

The 1100-O material was included as representative of a commercially "pure" metal, presumably free from the structural changes considered to complicate extrapolations to long rupture times. The 5454-O material is a representative annealed, non-heat treatable alloy.

The testing program being reported was based on the following objectives:

(1) Define the stresses for the planned tests of approximately 15,000 and 100,000 hours duration. The reader is reminded

that rupture time is exceedingly sensitive to test conditions. Accordingly, extensive testing and study of methods of extrapolation have been carried out to refine the extrapolation of the data for the determination of the stresses.

(2) Provide the test data up to 2000 to 3000 hours over the necessary range of temperatures required for foreseeable extrapolation methods which can eventually be checked by the prolonged tests.

Creep data were obtained for the rupture tests. The program included sufficient tests on notched specimens to establish the relative strengths of sharp-notched and smooth specimens for the test times of 1000 to 3000 hours.

Extensive analysis of extrapolation procedures using the test data was carried out, especially in connection with concepts derived from a current study of parameter methods being carried out for The Metal Properties Council by two of the authors. The analysis showed that, in arriving at the recommended test stresses, it was better to utilize basic principals of parameters rather than specific parameters with definite constants. However, results obtained from the application of two commonly utilized parameter methods are also presented.

The program is sponsored by The Metal Properties Council and administered by a Task Force of its Subcommittee I. Tests up to and including 300°F are being conducted by Materials Technology Corporation; and tests at 350°F to 600°F by the Department of Chemical and Metallurgical Engineering of The University of Michigan. This use of two technical groups improves technical reliability and continuity. Data obtained by the ALCOA Research Laboratories, Aluminum Company of America, from specimens cut from other lengths of the same plates were also used in the extrapolations to long time periods. This data agreed with the data from the authors' laboratories; and its inclusion increased confidence in the stress-rupture time curves established.

The tests designed to accumulate data for parameter extrapolation followed a program recommended by Messrs. R. Goldhoff and S. Manson. Their advice, as well as that of the Task Force administering the program, was utilized in conducting the program. Particular thanks are due to ALCOA for the replicate testing in their laboratory.

The two laboratories conducting the prolonged tests have the unique difficult problem of determining the stresses for rupture in specific prolonged time periods. These rupture times are extremely sensitive to stress. In some cases, if the stress should be as little as a few per cent too low, the rupture times would be extended far longer than the specified 15,000 or 100,000 hours. This situation is in marked contrast to the usual case where the object is to determine the rupture strength; then, uncertainties of stress which would be intolerable for this investigation are considered very good determinations of strength. Since this investigation does not anticipate running tests lasting in excess of 100,000 hours, and because an essential requirement is for the tests to reach rupture, rupture in 60,000 hours would be far better than to have a rupture time turn out to be 150,000 hours or longer. In view of this, the procedure adopted was:

(1) Establish the stresses for rupture in 15,000 and 100,000 hours as precisely as possible.

(2) Recommend the stresses for the prolonged check tests on the following basis:

   (a) The stresses as established under (1) for rupture in 15,000 hours are recommended for the tests with only slight rounding off to even values.

   (b) Recommend stresses for the longer time tests that are the stresses as established under (1) for 100,000 hours, but increased somewhat in view of the uncertainties involved to insure rupture in time periods no longer than 100,000 hours.

EXPERIMENTAL DESIGN

Rupture tests were conducted to enable determination of stresses for the following long time tests:

	Proposed Prolonged Tests, Hours, at Indicated Temperatures				
Alloy	200°F	300°F	350°F	400°F	500°F
1100-O	15,000	--	15,000	15,000	--
	100,000	--	100,000	100,000	--
5454-O	15,000	15,000	15,000	15,000	15,000
	100,000	100,000	100,000	100,000	--

The rupture test times used to determine the stresses for these prolonged tests were limited to a maximum of about 3000 hours. The program was designed to enable establishing of the stresses by known methods of extrapolation.

The testing program was structured to include the following:

(1) Initially, replicate tests were conducted to determine whether properties of plate materials would be sufficiently uniform for this type of study.

(2) Besides the tests at each of the above temperatures used to establish the stress-rupture time curves, additional tests were conducted at intermediate and higher temperatures for the following purposes:

  (a) Provide a "family-of-curves" to aid in deciding the nature of the stress-rupture time curves within the time periods of the tests; and to serve as an indicator of the reliability of the extrapolations.

  (b) Provide test results for application of parameter methods over the stress range expected for the prolonged tests. These were reinforced with tests concentrated at a number of iso-stress levels, to aid in establishing the optimum constants in parameter equations. An effort was made to have the iso-stress data close to the expected long time strengths, a procedure which maximized the value of the data for parametric treatment. As previously stated, this part of selection of test conditions was done with the advice of well-known experts on parameters.

EXPERIMENTAL MATERIALS

The test materials used in the investigation were commercially pure annealed aluminum (1100-O)and annealed 5454-O alloy. The Aluminum Association arranged for the ALCAN Aluminum Corporation to furnish mill finished annealed (O-condition) plates, 1-inch thick, with the following reported compositions (weight per cent):

	Al	Si	Cu	Ti	Ga	Mn	Mg	Cr
1100-O	Bal	.15	.46	.11	.01	.02	--	--
5454-O	Bal	.08	.22	.03	.01	--	2.65	.08

The Certificate of Confirmation submitted by the ALCAN Aluminum Corporation included the following reported tensile properties at room temperature:

Alloy	Ultimate Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation in 2-Inches (%)
1100-O	12,800	5,000	43.0
	12,900	5,200	42.0
5454-O	36,100	16,900	23.0
	36,200	16,900	23.0

EXPERIMENTAL PROCEDURES

Coupons, 1-inch square by about 5-3/4 inches long, were cut in the direction of rolling from the 1-inch thick plate. Figure 1 shows the location of the coupon for each test. Locations of the specimens for each test temperature were randomized. All the specimens tested were machined from the coupons by an instrument maker experienced in making specimens. The machining procedure minimized surface cold work and surface roughness.

For the creep-rupture tests on smooth specimens, standard 0.505-inch diameter specimens were used. For the tests on notched specimens, the major diameter was 0.750-inch, with a diameter at the base of the notch of 0.505-inch. A 60° V-notch was used with a root radius <0.0006-inch.

The creep-rupture tests were conducted in accordance with ASTM Recommended Practice E139-58T, using four to six hours for heating and temperature adjustment before loading. Creep data were obtained for the tests by means of an optical extensometer system. Initially, in the tests at The University of Michigan, the creep deformation was determined to approximately 5 per cent with a high-sensitivity system. Subsequently, the sensitivity was reduced and the deformation was measured throughout the tests. The creep deformation was determined throughout the tests carried out at Materials Technology Corporation.

EXPERIMENTAL DATA

The test data obtained at The University of Michigan and at Materials Technology Corporation are presented in Tables 1, 2, 5 and 6 for the smooth specimens, and Tables 4 and 8 for the notch specimens. The data from the tests conducted by the ALCOA Research Laboratories, Aluminum Company of America, are included as Tables 3 and 7.

The stress-rupture time curves for the smooth specimens, Figures 2a and 2b, were drawn to form a "family", based on consistent slopes between temperatures. The extrapolations to prolonged time periods are based on an extrapolation procedure described later. There were distinct changes in slope with both time and temperature. It will be noted that the data from the three laboratories are consistent with the curves and, therefore, increase the confidence in the way the curves are drawn.

The ranges in rupture times obtained for the replicate tests were narrow, expecially in view of the fact that the specimens were machined from 1-inch plate. Moreover, the agreement among the three laboratories indicated that the data obtained at all the testing facilities could be treated as equal and the use of the combined data would materially improve the determination of the stresses for the long time tests.

The test results show that the materials tested had extremely high ductilities, the rupture elongations and reductions of area in some cases being in the order of 100 per cent.

The minimum creep rates reported in Tables 1, 2, 5 and 6 were obtained from a plot of deformation versus time for each individual test.*

The initial program specified tests on notched specimens at the same nominal stress at the base of the notch as for smooth specimen tests of 1000 hours or longer duration. Initial testing indicated that the rupture times of the notched specimens would be more than a factor of ten times longer than the smooth specimens. These tests would not rupture in reasonable time periods and would only demonstrate unknown higher strengths than smooth specimens. Consequently, the program was

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* The creep curves are included as Appendix I.

changed to provide tests at higher stress levels to evaluate actual notch strengths at about 1000 hours. These tests (Tables 3 and 7) gave rupture strengths all so near to 1.5 times those of the smooth specimens that the test results were highly predictable at the temperatures and time periods covered by this report. The much higher rupture strength of the notched specimens is shown graphically by Figure 3. The solid curves of Figure 3 for the smooth specimens are the same as those established by Figure 2.

EXTRAPOLATION TO 15,000 AND 100,000 HOURS

The data were extensively treated to arrive at the stresses for rupture in 15,000 and 100,000 hours. The most probable values are given by the curves of Figure 2 and Tables 9 and 10. Some changes from the indicated 100,000-hour strengths were made to arrive at the stresses recommended in Table 11 for the prolonged tests to insure rupture in time periods no longer than 100,000 hours. The long-time strengths were derived from extrapolation of iso-stress lines as consistent family-of-curves, as described later.

Initially, the data were extrapolated using straight line extension of log-log curves, and using standard parameter methods. Inadequacies in these methods led to the procedure finally used. The extrapolation of iso-stress lines as a consistent family-of-curves was, in fact, a "parametric method" in that the nature of the high-temperature short-time curves were utilized to predict the long-time characteristics at lower temperatures. However, it avoided assumptions regarding iso-stress curves inherent in most parameter methods.

It must be emphasized that the objective of the test program was to determine the stresses for tests to be conducted that will rupture in definite prolonged time periods. Since very small variations in stress have a very marked effect on the rupture time, it was necessary to utilize the data in extreme detail, with modifications and extensions of the usual methods of extrapolation. Some of the numerous "standard" methods of extrapolation which have been proposed for rupture data were carried out. They serve, however, mainly as interesting demonstration of the difference in strength that can result from the application of various parameter methods. In fact, the problems which were encountered in using common methods of extrapolation as applied to the data in this report and in other work for The Metal Properties Council led to the procedure of extrapolating iso-stress lines.

To evaluate relative reliability of the published parameter extrapolation methods seems premature until the long-time tests are completed. In addition, no consideration has been given to the ways that the number of tests could have been reduced and still provide acceptable extrapolated strengths. It is, however, recognized that useful information certainly could be obtained by consideration of limited data for the purpose of estimating long-time rupture strengths.

The analyses were carried out using the data from ALCOA as well as from the testing programs at The University of Michigan and Materials

Technology Corporation. For comparative purposes, limited analyses by computerized parameter methods were also made using only the data obtained at The University of Michigan and Materials Technology Corporation.

Graphical Determination of the Stress-Rupture Time Curves

The test data were plotted to co-ordinates of log stress versus log rupture time (Figure 2). Within the limits of the rupture times of the tests, the curves were drawn by eye with the requirement that the slopes made consistent "families-of-curves." It will be noted that the 5454-O data apparently fell into three "regimes" of differing slopes (Figure 5, Tables 5, 6 and 7) while there was some limited evidence that two such "regimes" occurred for the 1100-O alloy.

The extrapolated rupture curves of Figure 2 were derived from iso-stress curves, as is described subsequently. The rupture curves could not be drawn as a consistent family by eye alone without recourse to other methods because it is not possible to predict the spacing of the curves when changes in slope were probably beyond the testing-time periods. The iso-stress curves greatly reduced this uncertainty since they provided an indication of the spacing of rupture curves at constant stress levels.

It could be argued that the instabilities in the curves as drawn are merely fortuitous effects of data scatter. In view of metallurgical characteristics, the 1100-O material would be least likely, in theory, to show instabilities. Consequently, in Figure 4, one set of rupture curves with consistent slopes were drawn without instabilities, with the variations treated as data scatter. However, the curves drawn with instabilities (Figure 2a) resulted in consistent "families-of-curves" and are, therefore, considered to be more correct. Long experience of the authors has demonstrated that such instabilities are invariably real and drawing the curves to fit the family concept results in highly predictable rupture times. Although it has not been done in this case, the occurrence of such instabilities usually can be related to metallurgical changes or changes in the creep-rupture mechanism. It will be noted that the data fit the curves as drawn better than the agreement among repetitive tests would seem to predict. This has been the general experience of the authors and may be related to the probability of any one test being near the average.

Extrapolation of the Rupture Curves Utilizing Computerized Parameter Methods

Two parameters, the Larson-Miller (ref. 1) and the Manson-Haferd ("Linear") parameter (ref. 2), were used with the Mendelson, Roberts and Manson computer program to optimize the constants (ref. 3). This program uses a method of least squares whereby the parameter curve is represented by a polynomial in the logarithm of the stress, and a best fit is obtained by minimizing the sums of the squares of the deviations (the residuals) of the data from the curves (i.e., optimizes the parameter and polynomial constants). A program, developed at The University of Michigan, was used to calculate the rupture strengths of interest. The latter program fits a stress-parameter curve (by minimizing the standard deviation) through the data parameterized using the optimum constants, and prints out the desired rupture strengths.

When the bulk of the data became available, 15,000 and 100,000 hour rupture strengths were determined by using data derived at The University of Michigan and Materials Technology Corporation. Subsequently, the analyses were repeated including the ALCOA data (Tables 3 and 7). The following factors were evident from the results:

(1) Very little difference in rupture strengths were obtained with and without the inclusion of the ALCOA data (Tables 9 and 10) for each individual parameter method.

(2) Very considerable differences existed between the values determined by the two individual parameter methods used. As is usually the case, the Larson-Miller parameter gave higher rupture strengths than the Manson-Haferd parameter.

(3) The maximum degree of the polynomial used to fit the stress-parameter data was arbitrarily set at 7. The complex nature of the parameter curves was evident as the standard deviation decreased appreciably as the degree of the polynomial was increased to 4 for the 5454-O and to 3 for the 1100-O material. At higher polynomial degrees, very little variation in the standard deviation occurred.

(4) For confidence in the strength levels determined by parameter methods, it is essential that the data be consistent with the mathematical relationships present in the parameter equation. The standard deviation of the data from the computer-fitted

parameter curves (Tables 9 and 10) does to some extent reflect the degree to which the data conforms to the parameter method. However, factors such as data scatter resulting from testing variations and the degree of the polynomial also influence the standard deviation. Consequently, a value judgment as to the extent to which the parameter methods were mathematically consistent with the data sets analysis was not made from the computer outputs. Instead, the applicability of the parameter methods was evaluated by graphical techniques as is described in a subsequent section.

Current research being conducted at The University of Michigan by Wilson and Freeman for The Metal Properties Council has determined that in many instances the extrapolation of rupture data by parameter methods can be considerably improved by dividing the data into self-consistent sub-sets, each of which is parameterized individually. It was evident that this would be the case for the 5454-O data evaluated in the present program, for which the rupture curves exhibited distinct "regimes" of slope. The occurrence of "regimes" of differing slopes indicates that a single simple parameter with one set of optimized constants probably would not be precisely consistent with the entire data set. It is more likely that each individual "regime", however, may be correlated using an appropriate parameter together with its optimized constants. Consequently, the data for the 5454-O material was sub-divided according to the three "regimes" present (designated A, B and C in Tables 5 to 7, and

Figure 5). Rupture strengths were determined for each of the regimes using the computer programs (Table 10).

It is generally agreed that the parameter curves should not be extrapolated beyond the range of test data. In other words, the parameters can only be used to derive rupture strengths which lie within the range of test stresses. As the testing program was designed so that the results would encompass the range of rupture strengths expected for the long time tests, no extrapolation of parameter curves was necessary when all the test data was parameterized. However, because instabilities in rupture curves frequently do not occur at constant stress levels for different test temperatures, it is frequently necessary to extrapolate the stress-parameter curves outside the range of test stresses considered when strength values are determined from a sub-set of data.

The parameter curves derived from data sub-sets are usually polynomials of low degree and, consequently, can be extrapolated without introducing the uncertainties associated with higher degree polynomials. From the computer outputs (Table 10), it is evident that the parameter curves for each of the "regimes" of 5454-O were as adequately described by straight lines (degree one) as by higher-degree polynomials. Where a higher degree polynomial was chosen, the associated standard deviation was only slightly less. Consequently, the strength values were evaluated for the optimum polynomial degree and also for degree one.

For a given data set, a rupture strength of interest must be selected from the result given by the appropriate "regime". For two adjacent regimes where the slopes of the rupture curve are greater in the lower stress than the higher stress regime, i.e., downward breaks, then the appropriate strength level is derived from the regime which resulted in the lower value. Naturally, for an upward break, as existed at low stress levels for the 5454-O material, the converse is true.

As expected, the results for the 5454-O alloy demonstrate that different optimized constants are applicable to each individual regime. The trends are most readily appreciated for the Larson-Miller parameter for which optimum constants for the regimes A, B and C were 16.7, 13.0, and 13.3 respectively. (These values were obtained for stress-parameter polynomials of degree one.) The treatment using all of the data resulted in a constant of 13.9 which can be considered as an "average value" of the constants applicable to each of the individual regimes. Corresponding to the relative differences in the values of the constants, the strength levels obtained from regime A were higher, and those from regimes B and C lower, than the strengths determined by using the constant derived from all of the data (Table 10) treated as a single set. Corresponding relative differences in values of the constants and in strength levels were obtained when the Manson-Haferd parameter was applied to the data sets (Table 10).

Parameter - Iso-Stress Line Relationships

From the computer outputs, it was impossible to determine to what extent either of the parameter methods used was applicable to the data sets evaluated, i.e., to what extent the data was consistent with the mathematics of each of the parameter methods. Such evaluations can be made by graphical techniques (ref. 4). The mathematical formulation of the Larson-Miller parameter requires that iso-stress curves on a plot of Log t (t = rupture time) versus 1/T (T = temperature on the absolute scale) are straight lines which converge to a single point on the line 1/T = 0. The Manson-Haferd parameter dictates that iso-stress lines are straight lines and converge to a point on a plot of Log t versus T. In a similar manner, the mathematics of other parameter methods that have been proposed require certain characteristic distribution of iso-stress lines.

Constant-stress lines were constructed for each material. Initially, "cross plots" of iso-time curves were plotted for log-stress versus temperature, using values taken from the stress-rupture time curves within the range of experimental data (Figures 6 and 7). Values from these figures were used to plot the iso-stress curves, log t versus T and log t versus 1/T (Figures 8 - 11). Several features were noted:

(1) Some of the iso-stress curves for both alloys exhibited pronounced curvature. It is, therefore, apparent that the data sets do not meet the requirements for straight line iso-stress curves required by the mathematics of commonly-used parameter methods. In fact, no inherent reason exists why the iso-stress curves should be straight lines.

(2) The stress-rupture time curves, particularly for the 5454-O material, exhibit regimes of different slopes. It would be expected that these different slopes would be reflected in the iso-stress curves. Consider, for example, the iso-stress curves for log t versus T for the 5454-O material. At stresses above about 15 ksi, the iso-stress curves are very nearly straight and parallel (Figure 11). The curves are derived from the data of regime A of Figure 2b. At lower stress levels, regimes B and C, the rupture curves had more slope. This resulted in iso-stress curves which had larger gradients, distinct curvature and convergence with increasing time.

(3) When the iso-stress curves were plotted as a function of 1/T (Figure 10), the curves were approximately straight lines below about 12.5 ksi (regimes B and C) and diverged with increasing time. These results conform to a great extent with the requirements of the Larson-Miller parameter. Consequently, some degree of confidence can be placed in the strength levels derived from the parameterization of the sub-sets, B and C, using the Larson-Miller parameter by computer program (described previously). The values are almost identical with those established using extrapolation of iso-stress lines described in the subsequent section.

Parameter extrapolation of rupture curves by standard graphical techniques is carried out by the determination of parameter constants from the iso-stress lines and construction of a master curve of log-stress versus the parameter values. The desired long time strengths are read from the master curves at the appropriate parameter values. This method, as was the case for the computer methods used, forces the mathematical behavior of a preconceived parameter onto the data. The use of a particular parameter is perfectly justified when the data is consistent with the mathematics of the parameter method chosen. However, there is no doubt but that for most data sets, as in the case of the present study, the data deviate from the mathematical assumptions for iso-stress lines in the commonly used parameters with varying effects on the predicted rupture strengths.

Graphical Method Used to Determine the Long-Time Strengths

Consideration of the results obtained with the parameter methods used indicated that the assumption of the specific characteristics of iso-stress curves biased the extrapolations to an extent greater than acceptable for choosing a test to rupture in a specific time. Extrapolation of log-log stress-rupture time curves, even as a family-of-curves, was also inadequate. In the latter case, the main problem was the uncertainty of the time at which breaks in curves should occur beyond the testing times. These problems could be circumvented if some way could be found to extrapolate the iso-stress curves in time. This would avoid the problem of assuming fixed iso-stress curve characteristics. This unusual and perhaps clumsy procedure seemed justified in this case because the testing times of the proposed long time tests were so sensitive to stress. Also, there was no need for a master parameter curve.

The best way of extrapolating the iso-stress curves was to develop a family-of-curves graphically. Consequently, in Figures 8 - 11, the iso-stress curves were extrapolated by eye, taking into account the spacing relationships between the adjacent curves and the degree of curvature exhibited by the curves. Stress values were then taken from the iso-stress curves at suitable long time periods and plotted on the original stress-rupture time graphs. From these data points the rupture curves to 100,000 hours were derived (Figure 2). It is inherent in this method that if the iso-stress curves are extrapolated in the correct manner, then the same long-time strengths will result, independent of the time and temperature functions used to plot the iso-stress data. The more nearly linear the iso-stress lines, the easier it is to extrapolate them with confidence. Consequently, the greatest weight was placed on the strength levels derived from iso-stress lines on the plots of Log t versus T or 1/T depending on which function of temperature resulted in the more nearly linear curves.

It should be noted that S. S. Manson has recently reported the development of a computer method for parameterization which achieves nearly the same result the graphical method used for this report. The technique differs, however, in that iso-stress curves are not extrapolated individually, but are mathematically combined prior to the necessary extrapolation to long-time periods. It is expected that Mr. Manson will present the long-time strengths computed by this method as a discussion to a paper planned to be prepared from the present report.

STRESSES FOR THE 15,000 AND 100,000 HOUR TESTS

The following tabulation shows the stresses to be used for the 15,000 and 100,000 hour tests which will provide long time creep and rupture data for the 1100-O and 5454-O materials (Table 11):

Temperature (°F)	Aim Testing Time (Hours)	Test Stress (psi)	"Iso-Stress" Extrapolated Rupture Strength (psi)
	1100-O Aluminum		
200	15,000	5,750	5,750
	100,000	5,400	5,150
350	15,000	2,500*	2,420
	100,000	2,200	2,050
400	15,000	1,750	1,770
	100,000	1,500	1,460
	5454-O Aluminum		
200	15,000	20,000*	19,200
	100,000	17,000	15,900
300	15,000	9,000	9,200
	100,000	7,250	7,000
350	15,000	6,500	6,350
	100,000	5,000	4,850
400	15,000	4,500	4,450
	100,000	3,600	3,500
500	15,000	2,500	2,450

*Tests in progress that were initiated prior to the analysis.

The following comments explain why the stresses chosen for the tests differ from those determined by extrapolation of the iso-stress curves as is shown by the tabulation:

(1) Ideally, the test stresses and the extrapolated strengths should be the same. However, data scatter introduces the possibility that the 100,000-hour tests could be abnormally prolonged. Since it is considered essential that the tests actually rupture, it would be better to have a test rupture short of the aim rupture time rather than to be so long that it would have to be discontinued.

(2) The stresses of the tests with aim rupture times of 15,000-hours are the same as the extrapolated 15,000-hour strengths with only slight rounding off. Even considering the possible effects of data scatter, these tests should rupture in reasonable time periods.

(3) The stresses for the tests with aim rupture time of 100,000-hours were increased from the extrapolated strengths with the view to insure rupture by 100,000 hours, in spite of data scatter. The increase was greater for the lower temperature tests where the stress-rupture time curves had less slope than at the higher temperatures. It is known that the rupture time is more variable for a given stress the less the slope of the curve, and, therefore, the chance of excessively prolonged tests increase as the slope of the curves decreases.

In the mental process of adjusting the stress to insure that the tests rupture in 100,000 hours, other factors were considered along with the possible effects of data scatter. In determining whether the stresses chosen would result in acceptable rupture time, straight-line extrapolation of the rupture curves were considered as indicating limiting values.

(4) It is admitted that tests could rupture in times significantly shorter than the aim. It is evident from the available data that if this should occur, the test result would still fulfill the objectives of the program. However, the creep curves will be checked and, if an abnormally short test is recognized, then an additional specimen may be started.

(5) There are two other features of the list of stresses which need to be recognized:

(a) Two tests, started early in the program (1100-O at 350°F under 2500 psi and 5454-O at 200°F under 20,000 psi) before the slope of the curves were established, proved to be at stresses so low that the rupture time would be far longer than the intended 3000 hours needed for the initial evaluation. They were continued, however, when data analysis indicated that they should meet the rupture time requirements for the indicated long time tests.

(b) A few tests now in progress may rupture before the long time tests are started and indicate that some stresses should be changed slightly.

In order to demonstrate whether or not notch sensitivity develops during the prolonged tests, notch specimens will be run at the same nominal stresses considered earlier for smooth specimens. On the basis of the data in this report, the rupture time of these specimens should be at least an order of magnitude longer than the smooth specimens. Consequently, it appears that the rupture times of the notched specimens would be so long as to make it impractical to continue the notched specimens after the smooth specimen ruptures.

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3. Alexander Mendelson, Ernest Roberts, Jr., and S. S. Manson, "Optimization of Time-Temperature Parameters for Creep and Stress-Rupture, with Application to Data from German Cooperative Long-Time Creep Program," NASA Technical Note No. TN D-2975 (1965).

4. E. C. Larke and N. P. Inglis, "A Critical Examination of Some Methods of Analysing and Extrapolating Stress-Rupture Data," Joint International Conference On Creep, The Institution of Mechanical Engineers, London, pp. 6-33 - 6-47 (1963).

TABLE I

Creep-Rupture Data for Smooth Specimens of 1100-O Aluminum (Materials Technology Corp.)

Specimen	Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elong. (%)	RA (%)	Minimum Creep Rate (%/hr.)
1100-O-178	200	8000	50	75	90	0.58
55		7000	399	67	87	0.069
48*		6500	1748	68	90	0.012
18*		5000	Discontinued at 3650 hr.			(0.00007)
1100-O-123	250	7000	15	90	89	2.0
8*		6000	338	57	90	0.058
43*		5500	642	67	91	0.035
1100-O-168	275	5500	144	56	89	0.15
1100-O- 33	300	7000	0.9	81	90	34.
128		5000	66	90	91	0.42
164		4500	211	84	93	0.12
54*		4000	2346	47	92	0.0080
14*		3500	In progress			0.0016
1100-O-152	350	4000	46	73	61	0.56
11		3500	240	63	93	0.095
165		3500	176	86	94	0.13
1100-O- 4	400	3000	48	72	96	0.49
38		3000	63	77	93	0.51

* Test data not parameterized utilizing the computer method (in progress or ruptured subsequent to completion of the analysis).

TABLE 2

Creep-Rupture Data for Smooth Specimens of 1100-O Aluminum (University of Michigan)

Specimen	Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elong. (%)	RA (%)	Minimum Creep Rate (%/hr.)
1100-O-160	350	4000	53	85	94	--
132		3500	214	67	94	0.0964
9		3000	1229	65	95	0.0157
166*		2500	In progress			0.0064
1100-O- 5	375	3000	295	84	95	0.0813
1100-O-125	400	3500	23	92	95	--
12		3000	60	76	89	--
31		3000	61	79	95	--
122		3000	74	87	95	--
179		3000	77	88	98	--
13		2500	504	46	96	0.0417
10		2250	1172	68	96	0.0132
1100-O- 47	450	3000	6.8	54	80	--
124		2000	194	80	96	--
6		1500	2041	66	97	0.00668
1100-O-167	500	2000	18	100	97	--
56		1500	238	80	97	--
17*		1200	1795	81	96	0.00718
1100-O-176	550	1500	30	78	97	--
161		1200	275	70	96	0.0655
1100-O-169	600	1200	55	80	96	0.465

* Test data not parameterized utilizing the computer method (in progress or ruptured subsequent to completion of the analysis).

TABLE 3

Rupture Data for Smooth Specimens of 1100-O Aluminum (Aluminum Company of America)

Specimen	Temperature (°F)	Stress (psi)	Rupture Time (hours)
1100-O	212	7000	233
1100-O	250	7000	15
		6500	40
		6000*	157
		6000*	419
		5500	1082
		5500*	In progress
1100-O	300	5500	23.5
		4500	254
		4000*	In progress
1100-O	350	4500	12
		4000	49
		3500	185
1100-O	400	3500	9.5
		3500	11
		3500	11
		3500	11.5
		3500	12.5
		3000	56
		2500	357
1100-O	450	2500	28
		2000*	200
		2000*	240
1100-O	500	2000	23.5
		1500*	166
		1500*	289
1100-O	550	1500	35
1100-O	600	1500	7

* Test data not parameterized utilizing the computer method (in progress or ruptured subsequent to completion of the analysis).

TABLE 4

Rupture Data for Notched Specimens of 1100-O Aluminum

Specimen	Temperature (°F)	Stress (psi)	Rupture Time (hours)	$\frac{N}{S}$ Ratio
* 1100-O-150	200	10,000	In progress 1035	> 1.49
* 1100-O-175	250	8,500	868	1.56
* 1100-O-129	300	6,000	In progress 1127	> 1.46
1100-O- 58	350	4,500	3142	1.69
151		4,000	In progress 7247	> 1.55
1100-O- 49	400	4,000	267	1.54
149		3,000	7202	1.58
1100-O- 57	450	3,000	346	1.62
1100-O-172	500	2,000	2363	1.71
1100-O-148	550	1,500	4289	

* Specimens tested at Materials Technology Corporation. All others tested at the University of Michigan.

TABLE 5

Creep-Rupture Data for Smooth Specimens of 5454-O Aluminum
(Materials Technology Corp.)

Specimen	Temp. (°F)	Stress (psi)	Rupture Time (hours)	Regime	Elong. (%)	RA (%)	Minimum Creep Rate (%/hr.)
5454-O- 32	200	27,500	166	A	56	50	0.11
146		25,000	432	A	49	58	0.050
179		25,000	441	A	63	60	0.045
6*		22,500	1516	A	60	57	0.015
160*		20,000	In progress				0.0015
5454-O- 34	250	25,000	21	A	59	55	1.0
173		22,500	98	A	58	58	0.21
18*		17,000	In progress				0.0036
5454-O-185	300	25,000	1.25	A	54	61	18.
14		20,000	25	A	47	65	0.72
45		17,000	159		52	68	0.083
21		14,000	1021	B	55	78	0.0050
147*		11,000	In progress				0.00095
5454-O- 28	350	14,000	75		53	77	0.19
181		11,000	435	B	68	75	0.036

* Test data not parameterized utilizing the computer method (in progress or ruptured subsequent to completion of the analysis).

TABLE 6

Creep-Rupture Data for Smooth Specimens of 5454-O Aluminum (University of Michigan)

Specimen	Temp. (°F)	Stress (psi)	Rupture Time (hours)	Regime	Elong. (%)	RA (%)	Minimum Creep Rate (%/hr.)
5454-O- 7	350	17,000	12.2	A	66	69	0.816
42		16,000	28.1	A	76	82	0.433
9		14,000	106	-	75	77	0.169
182		11,000	484	B	77	80	0.0223
25		11,000	510	B	83	80	0.0237
149		9,000	1580	B	69	84	0.00834
5454-O-184	375	9,000	476	B	83	85	0.0413
5454-O-148	400	11,000	47	B	94	80	0.458
10		10,200	95	B	85	82	0.112
2		9,000	158	B	97	89	0.1614
22		9,000	188	B	82	84	0.0956
47		9,000	170	B	85	83	--
192		9,000	198	B	72	85	0.1074
15		7,000	711	B	88	87	0.0321
39		6,000	1911	B	119	88	0.0127
5454-O- 29	450	9,000	37	B	117	86	--
17		7,000	101	B	101	88	0.302
191		4,000	3587	C	109	92	0.00532
5454-O-187	500	7,000	19	B	123	90	--
3		5,000	114	B	102	90	--
41		4,500	217	B	156	94	--
30		4,000	381	-	121	92	0.0640
16		3,750	626	C	99	92	0.0324
19		3,500	1155	C	119	93	0.0186
33		3,000	3020	C	113	94	0.00552
5454-O-183	550	4,000	68	-	148	79	--
5454-O- 8	600	4,000	13	-	74	80	--
178		3,000	74	C	85	94	--
40		2,500	213	C	106	79	--
190		2,000	754	C	69	85	0.0242
31		2,000	841	C	97	87	0.0282

TABLE 7

Rupture Data for Smooth Specimens of 5454-O Aluminum (Aluminum Company of America)

Specimen	Temperature (°F)	Stress (psi)	Rupture Time (hours)	Regime
5454-O	212	30,000	15.5	A
		25,000	222.5	A
5454-O	250	25,000	22	A
		20,000	461	A
5454-O	300	20,000	32.5	A
		17,000	179	-
		14,000	955	B
5454-O	350	17,000	13	A
		16,000	27	A
		14,000	64	-
		11,000	360	B
		11,000	391	B
5454-O	400	11,000	53	B
		9,000	132	B
		9,000	150	B
		9,000	164	B
5454-O	450	9,000	22.5	B
		7,000	87	B
		7,000	91	B
		7,000	107	B
5454-O	500	7,000	19.5	B
		5,000	97	B
		5,000	128	B
		4,000*	351	-
5454-O	550	4,000	70	-
5454-O	600	5,000	4.2	B
		4,000	11.5	-
		3,000	80	C
5454-O	700	2,000	32.5	C

* Test data not parameterized utilizing the computer method (in progress or ruptured subsequent to completion of the analysis).

TABLE 8

Rupture Data for Sharp-Notched Specimens of 5454-O Aluminum

Specimen	Temperature (°F)	Stress (psi)	Rupture Time (hours)	$\frac{N}{S}$ Ratio
* 5454-O- 49	200	35,000	1666	1.56
* 5454-O-176	250	30,000	777	1.58
* 5454-O-141	300	25,000	283	1.56
* 177		20,000	1396	1.50
5454-O- 44	350	17,000	394	1.51
144		14,000	1129	1.46
5454-O- 51	400	14,000	134[a]	> 1.49
50		11,000	512	1.48
162		9,000	2075	1.54
5454-O-143	450	9,000	179	1.42
175		7,000	995	1.46
5454-O-188	500	7,000	104	1.37
164		5,000	1345	1.47
5454-O-189	600	4,000	83	1.35
163		2,500	1144	1.40

[a] Stripped out of threads.

* Specimens tested at Materials Technology Corporation. All others tested at The University of Michigan.

TABLE 9

Extrapolated 15,000 and 100,000 Hour Strength Levels for 1100-O Aluminum

Extrapolation Methods - L-L = Straight-Line Extrapolation of Log Stress-Log Rupture Time Curves.

L-M = Larson-Miller Parameter with an Optimized Constant

M-H = Manson-Haferd (Linear) Parameter with Optimized Constants

I-S = Extrapolation of Iso-Stress Lines as a "Family-of-Curves".

Sources of Data Analyzed - Materials Technology Corporation (MTC), Aluminum Company of America (ALCOA), and University of Michigan (UM)

Data Analyzed -	All Data	MTC and UM		All Data		All Data
Extrapolation Method -	L-L	L-M	M-H	L-M	M-H	I-S
Temperature, °F						
		15,000 Hour Strengths, 1000 psi				
200	5.75	5.6	5.4	5.65	5.4	5.75
350	2.42	2.35	2.25	2.35	2.25	2.42
400	1.77	1.75	1.65	1.8	1.7	1.77
		100,000 Hour Strengths, 1000 psi				
200	5.15	4.7	4.3	4.8	4.25	5.15
350	2.05	1.85	1.65	1.9	1.7	2.05
400	1.48	1.35	1.25	1.45	1.3	1.46
Optimized Parameter Data						
Polynomial Degree		7	5	7	7	
L-M Constant		16.84		17.15		
M-H Temperature Intercept °F			-500		-500	
M-H Log time Intercept			21.53		21.66	
Standard Deviation		.093	.098	.109	.116	

TABLE 10

Extrapolated 15,000 and 100,000 Hour Strength Levels for 5454-O Aluminum

Extrapolation Methods - L-L = Straight-Line Extrapolation of Log Stress-Log Rupture Time Curves; L-M = Larson-Miller Parameter with an Optimized Constant; M-H = Manson-Haferd (Linear) Parameter with Optimized Constants; I-S = Extrapolation of Iso-Stress Lines as a "Family-of-Curves".

Sources of Data Analyzed - Materials Technology Corporation (MTC); Aluminum Company of America (ALCOA); and University of Michigan (UM).

Data Analyzed -		All Data	MTC and UM		All Data		All Data - Regime A*				All Data - Regime B*				All Data - Regime C*				All Data
Extrapolation Method -		L-L	L-M	M-H	L-M	M-H	L-M		M-H		L-M		M-H		L-M		M-H		I-S
Temp., °F																			
15,000 Hour Strengths	200	19.3	18.7	17.8	18.7	17.5	19.8	20.0	19.2	18.6	19.6	21.0	18.9	18.9	15.5	15.5	30.5	--	19.2
	300	10.4	9.7	8.9	9.6	8.6	12.2	11.3	12.5	11.2	9.2	9.10	7.4	8.0	8.1	8.1	10.0	--	9.2
	350	6.35	6.7	6.1	6.6	6.0	9.5	--	10.2	8.7	6.3	6.2	5.5	4.9	6.2	6.2	6.5	5.4	6.35
	400	4.15	4.6	4.4	4.6	4.2	7.4	--	8.3	6.9	4.3	4.4	4.0	3.3	4.5	4.5	4.3	4.3	4.45
	500	2.45	2.4	2.3	2.4	2.2	4.5	--	5.7	4.4	2.0	2.3	2.3	1.8	2.3	2.3	2.2	2.1	2.45
100,000 Hour Strengths	200	17.0	15.9	13.7	15.7	13.3	17.5	17.5	16.6	15.3	15.5	15.9	12.6	14.4	13.5	13.5	18.5	--	15.9
	300	8.8	7.5	6.3	7.4	6.1	10.5	--	10.9	9.0	7.0	6.9	5.5	4.8	6.8	6.8	6.6	5.5	7.0
	350	4.7	5.0	4.3	5.0	4.2	8.1	--	8.9	7.1	4.7	4.7	3.9	3.0	4.8	4.8	4.3	4.4	4.85
	400	3.5	3.5	3.0	3.5	2.9	6.3	--	7.3	5.6	3.1	3.3	2.9	2.0	3.4	3.4	2.9	3.1	3.50
Optimized Parameter Data																			
Polynomial Degree			7	7	6	6	1	6	1	6	1	2	1	6	1	1	1	5	
L-M Constant			14.18		13.94		16.71	16.44			12.99	12.91			13.34	13.34			
M-H Temperature Intercept, °F				-500		-500			-3000	-500			-500	0			-500	0	
M-H Log time Intercept				19.18		18.85			84.75	20.59			17.55	9.206			18.75	11.35	
Standard Deviation			.075	.064	.079	.078	.061	.043	.060	.036	.055	.050	.063	.057	.030	.030	.054	.033	

* Parameterized using an optimum polynomial degree and also by force fitting a degree 1 polynomial on the data.

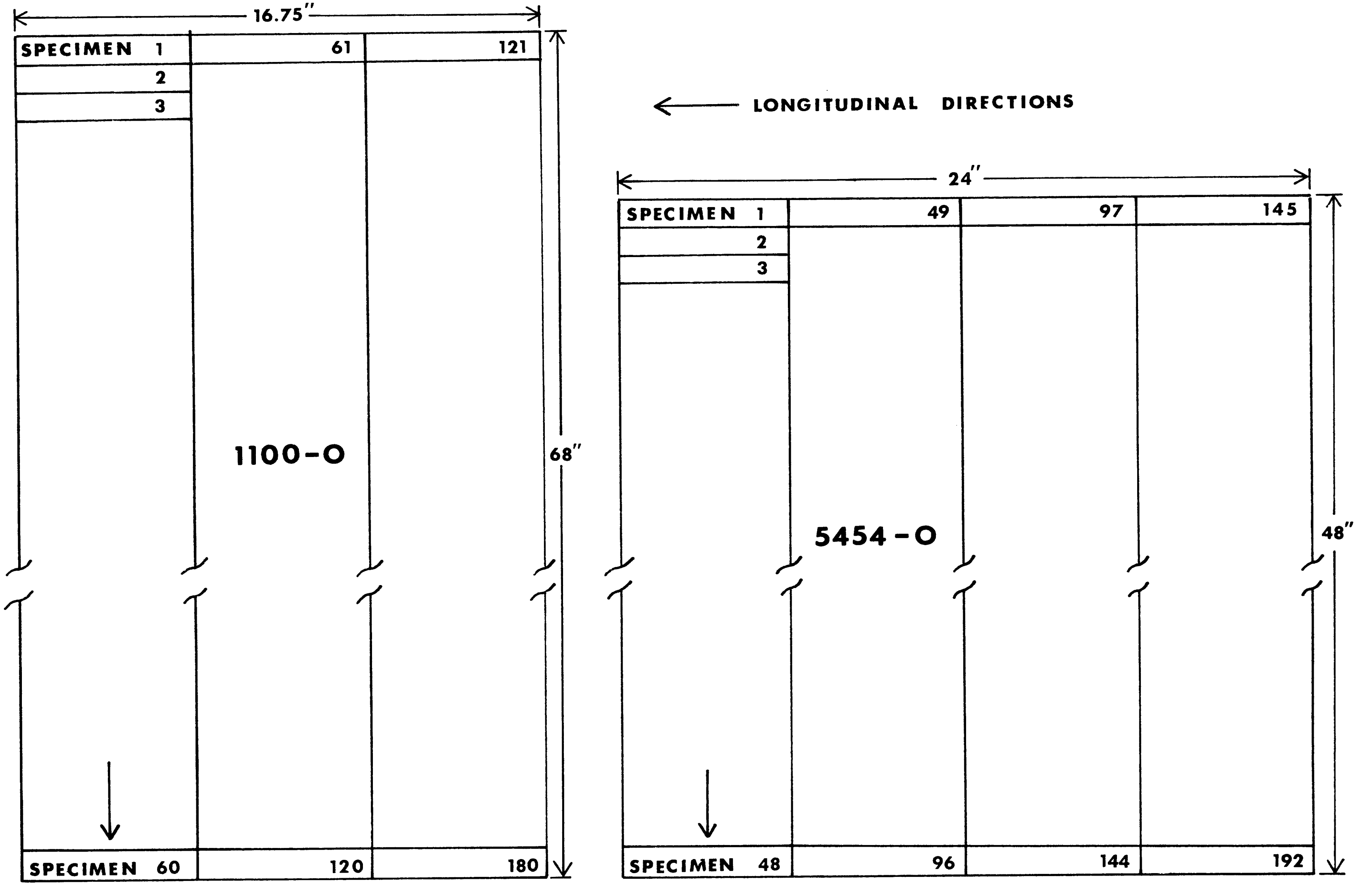


Figure 1. Locations of 1100-O and 5454-O specimens cut from 1-inch thick mill annealed plates.

(Note: Coupons were numbered consecutively from top to bottom as indicated.)

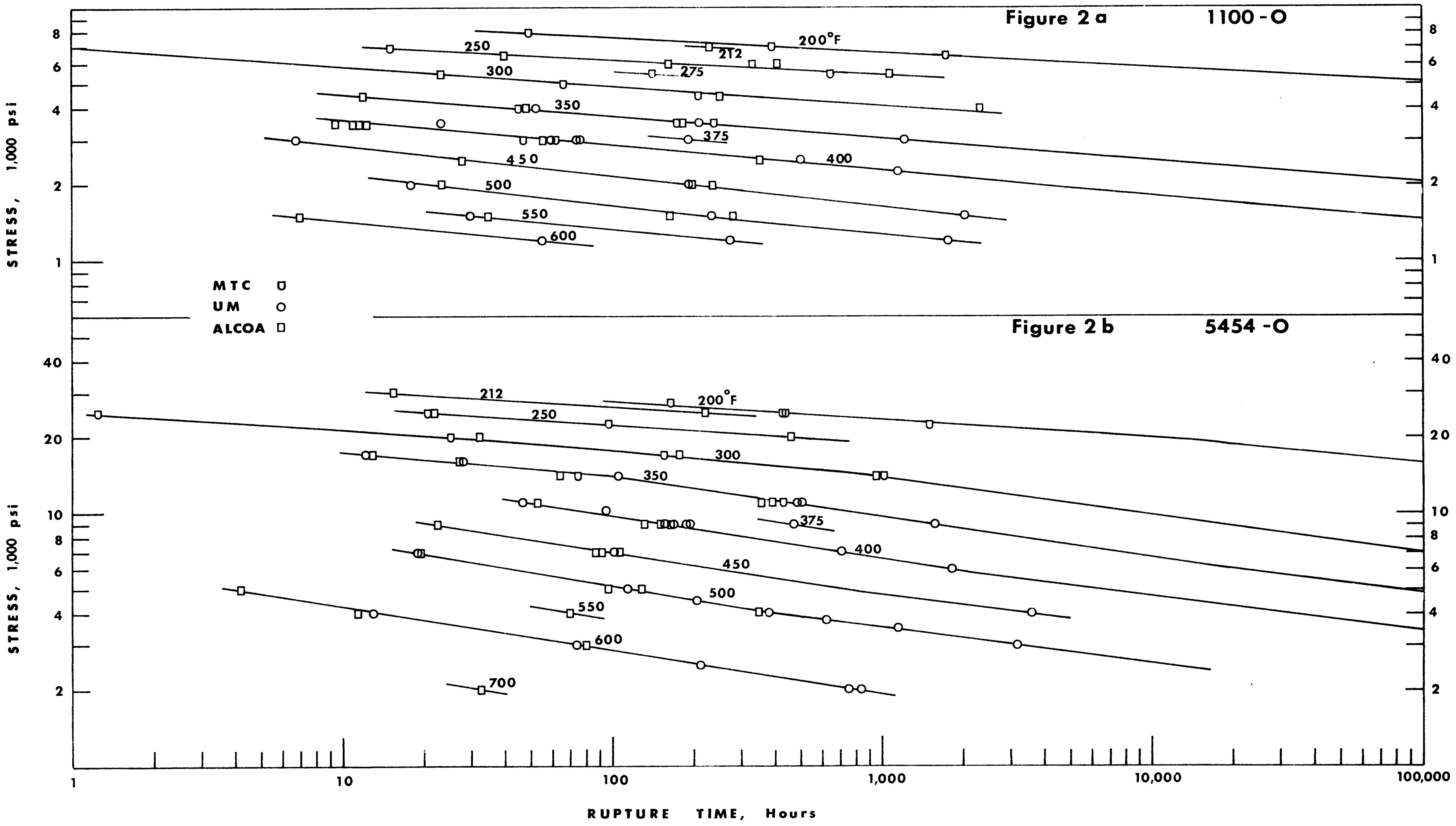


Figure 2. Stress versus rupture time data obtained from smooth specimens of 1100-O and 5454-O aluminum. The rupture curves are drawn as "family-of-curves" within the range of the test data. The extensions of the curves to 100,000 hours were derived from iso-stress line extrapolations.

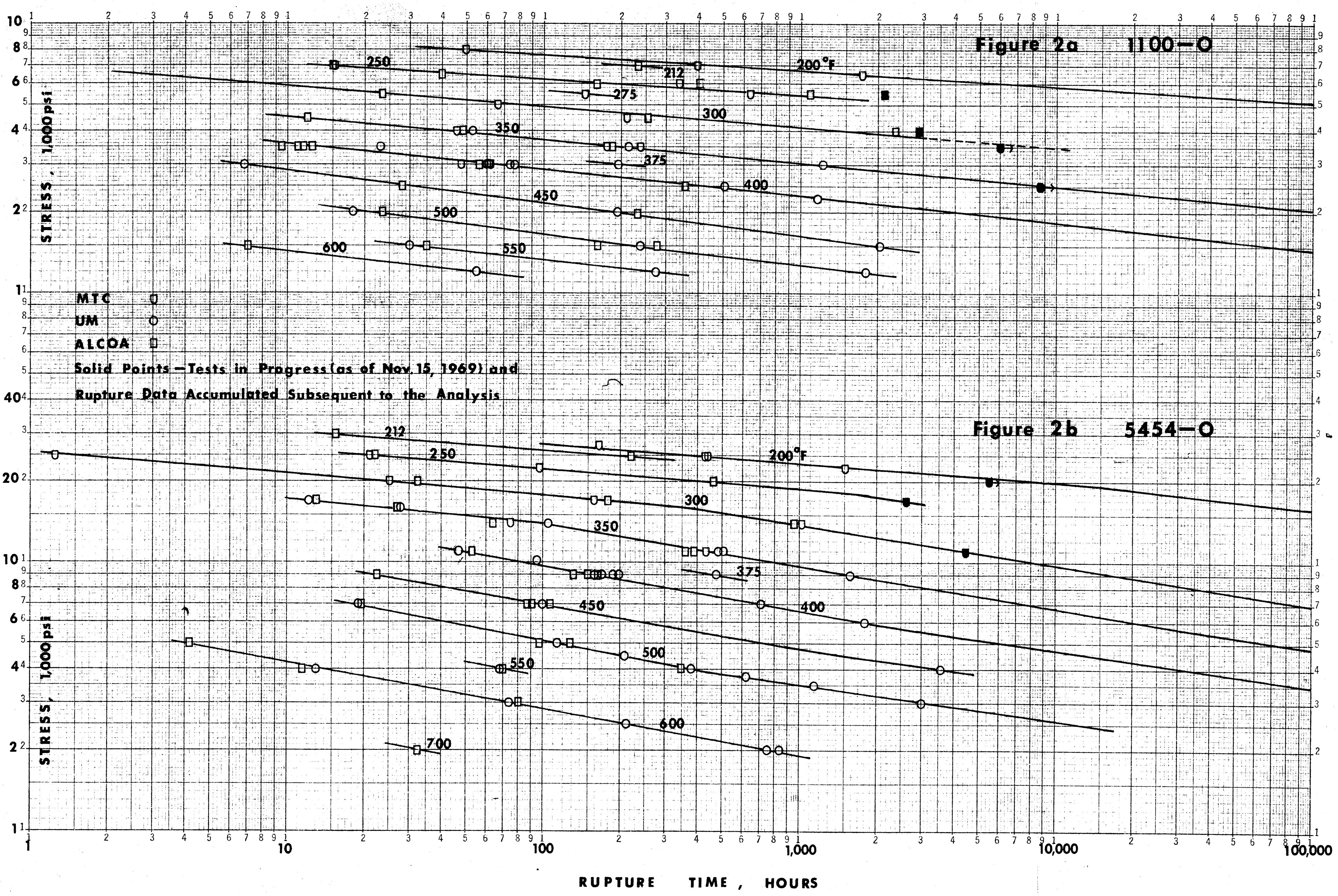


Figure 2a 1100—O

Figure 2b 5454—O

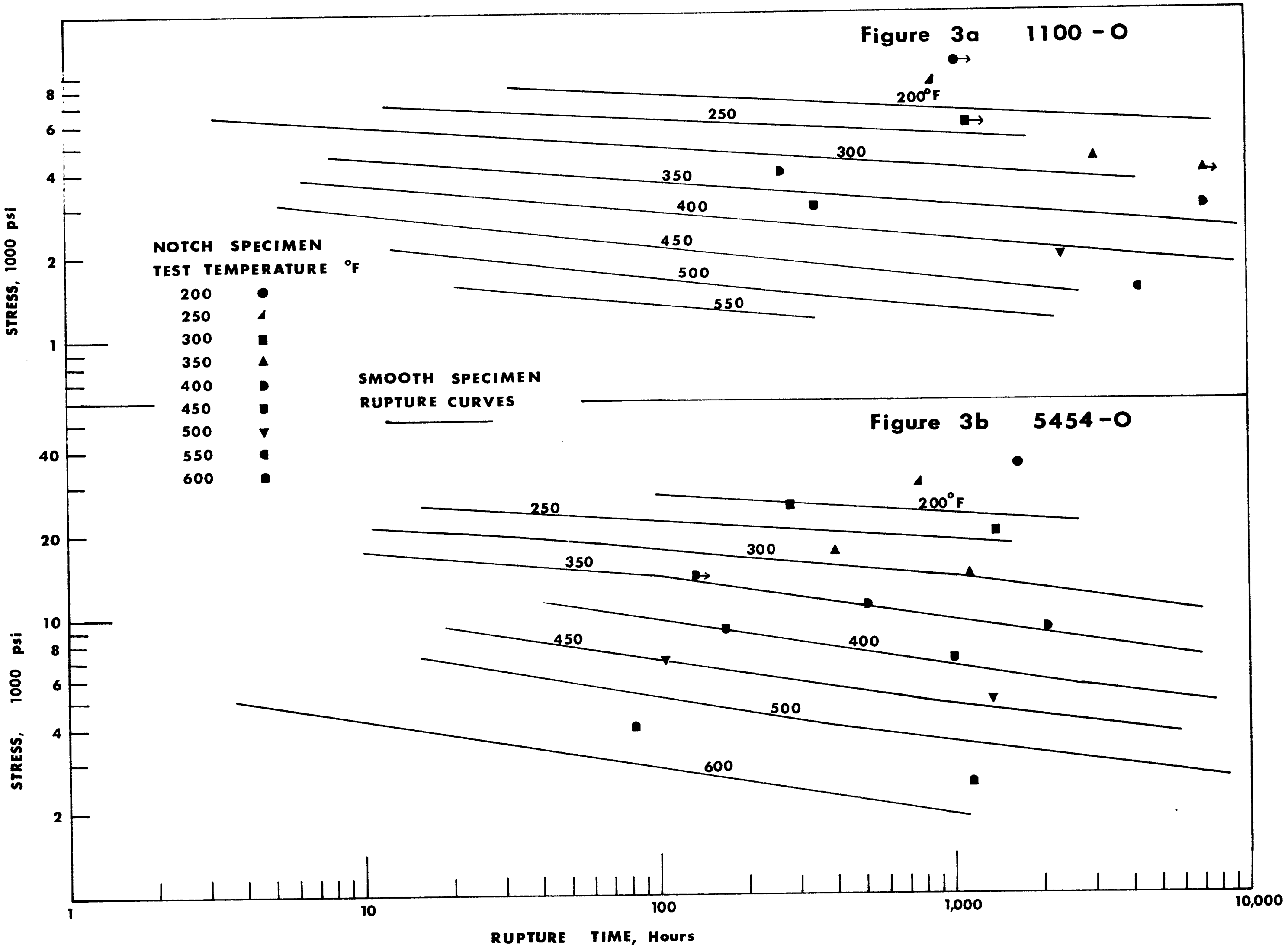


Figure 3. Comparison of Notched-bar Test Points with Rupture Curves for Smooth Specimens of 1100-O and 5454-O Aluminum Alloys.

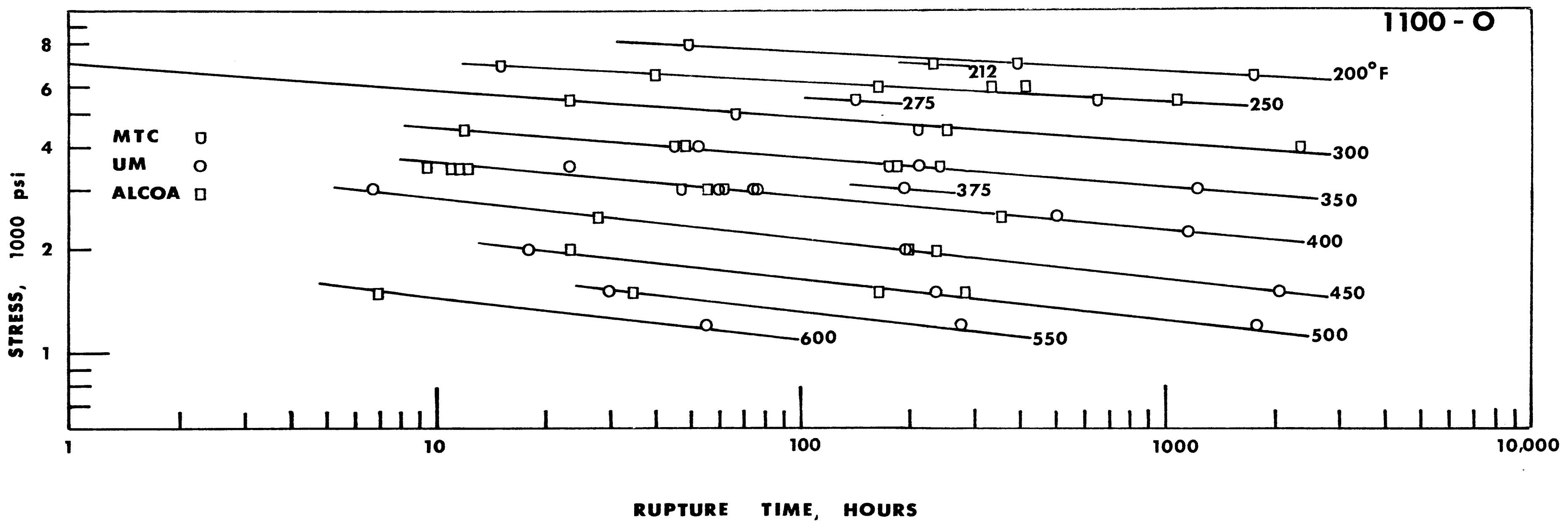


Figure 4. Curves of stress versus rupture time for 1100-O aluminum drawn as straight lines treating apparent instabilities as data scatter.

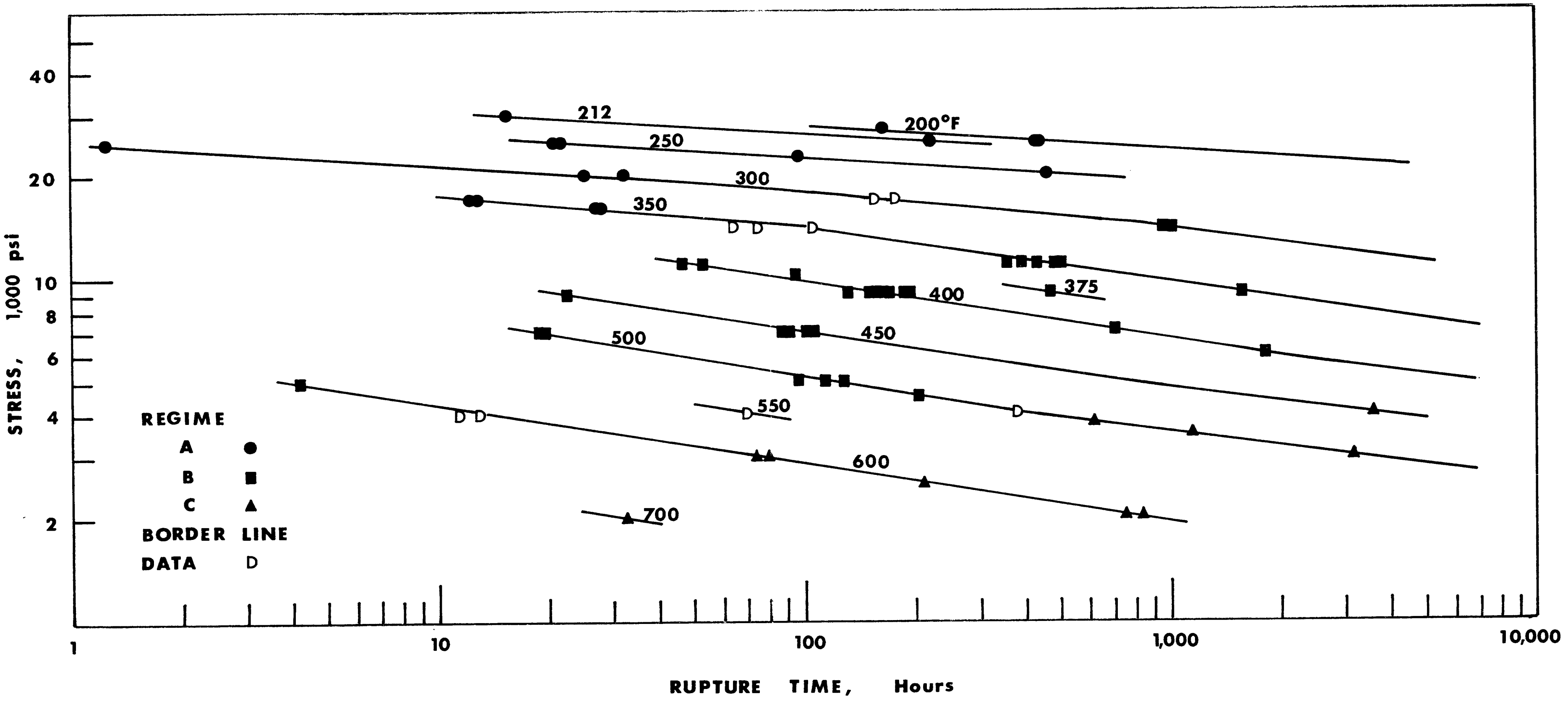


Figure 5. Identification of data points for 5454-O Aluminum by regimes with differing slopes.

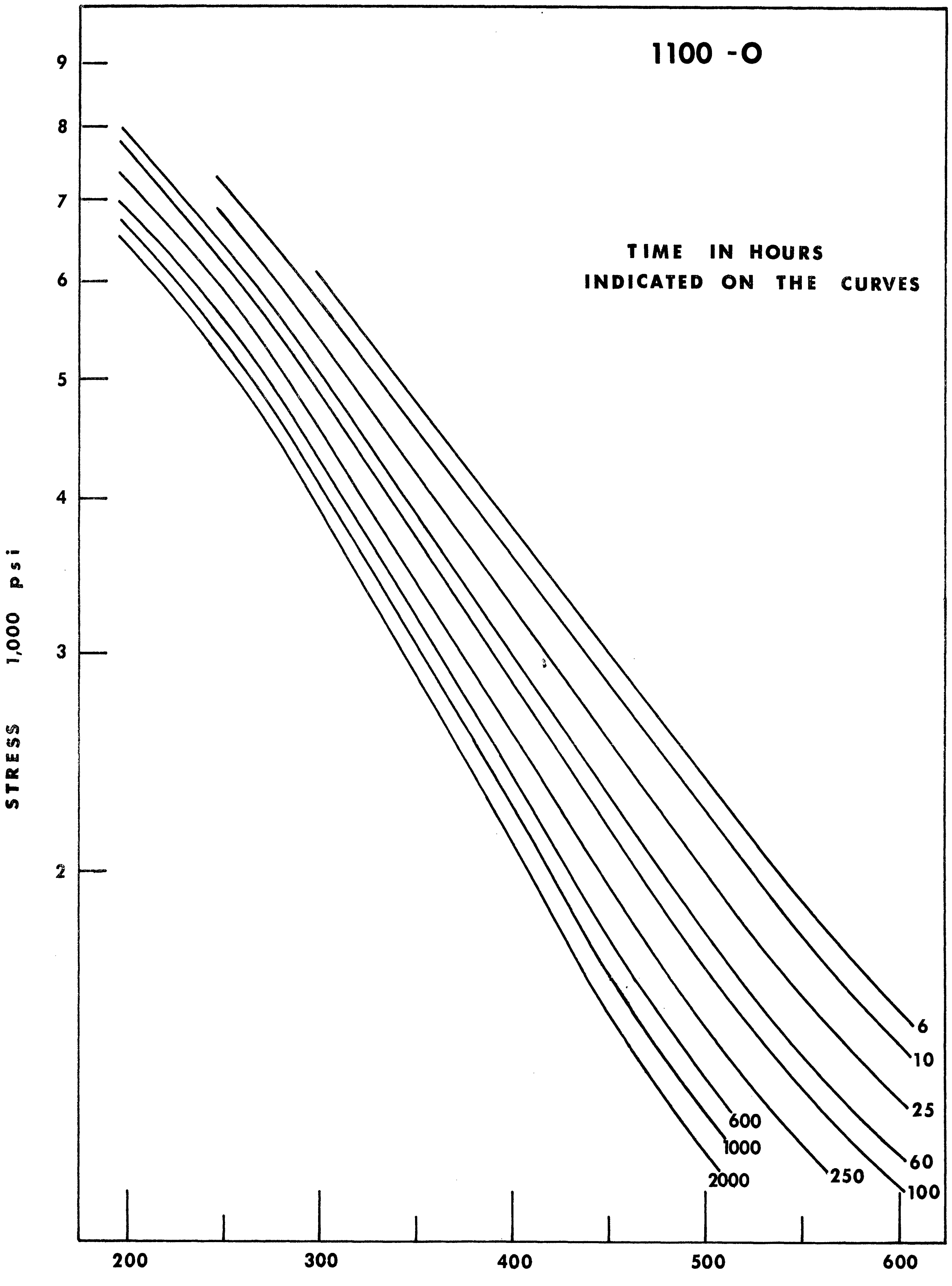


Figure 6. Curves of stress versus temperature for selected rupture times, derived from Figure 2a.

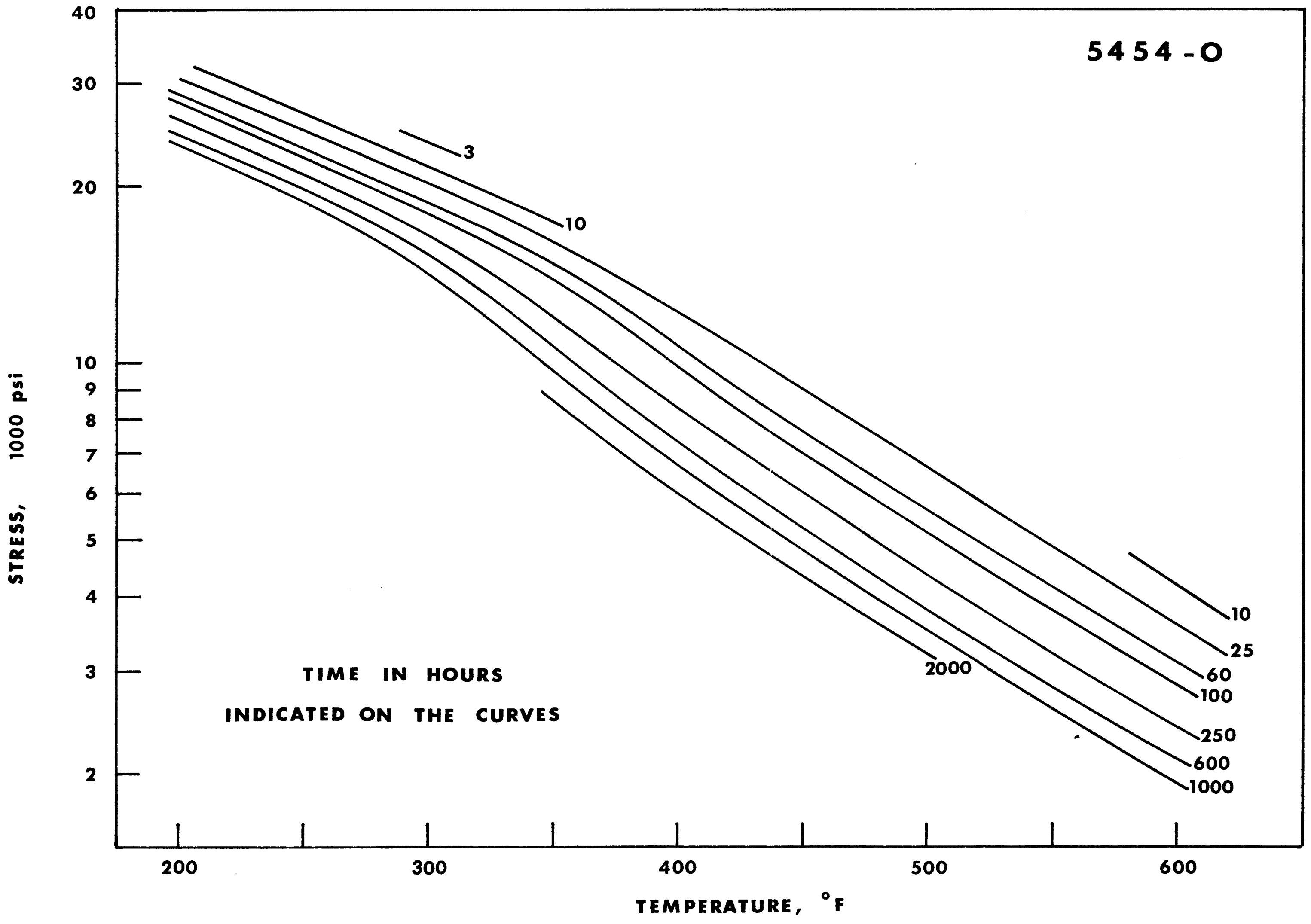


Figure 7. Curves of stress versus temperature for selected rupture times, derived from Figure 2b.

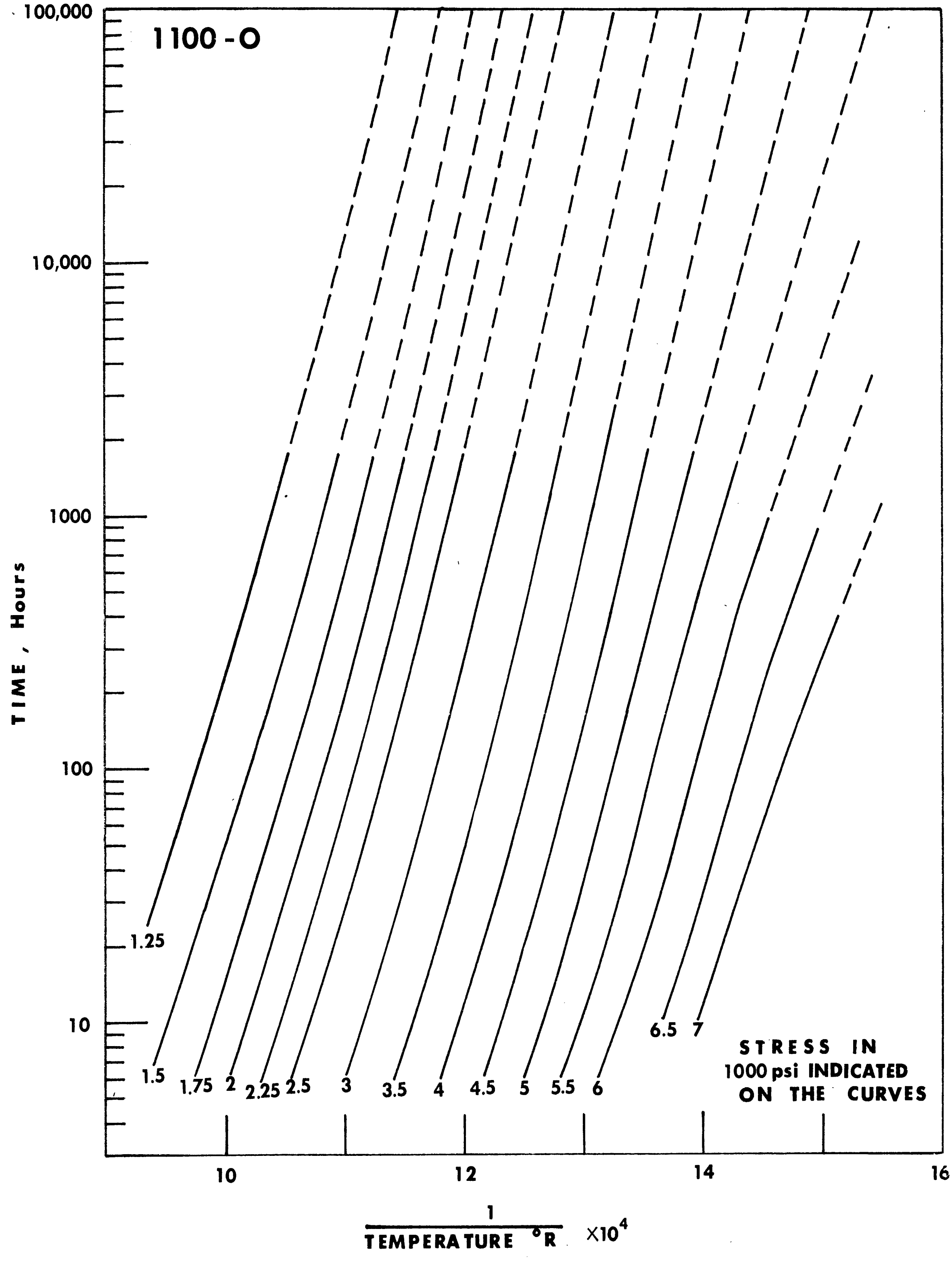


Figure 8. Iso-stress curves of rupture time versus reciprocal absolute temperature, derived from Figure 6 for 1100-O aluminum.

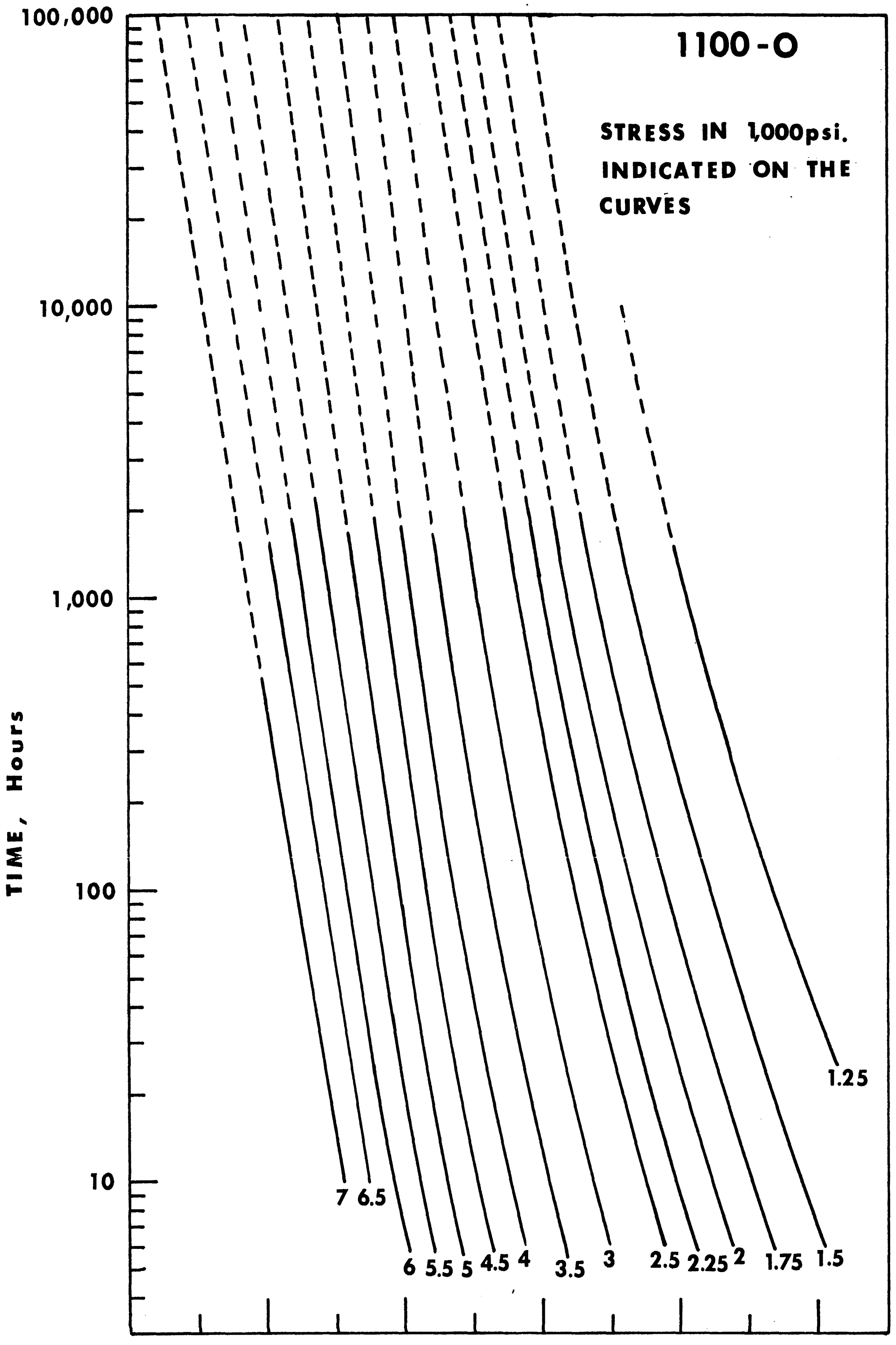


Figure 9. Iso-stress curves of rupture time versus temperature, derived from Figure 6 for 1100-O aluminum.

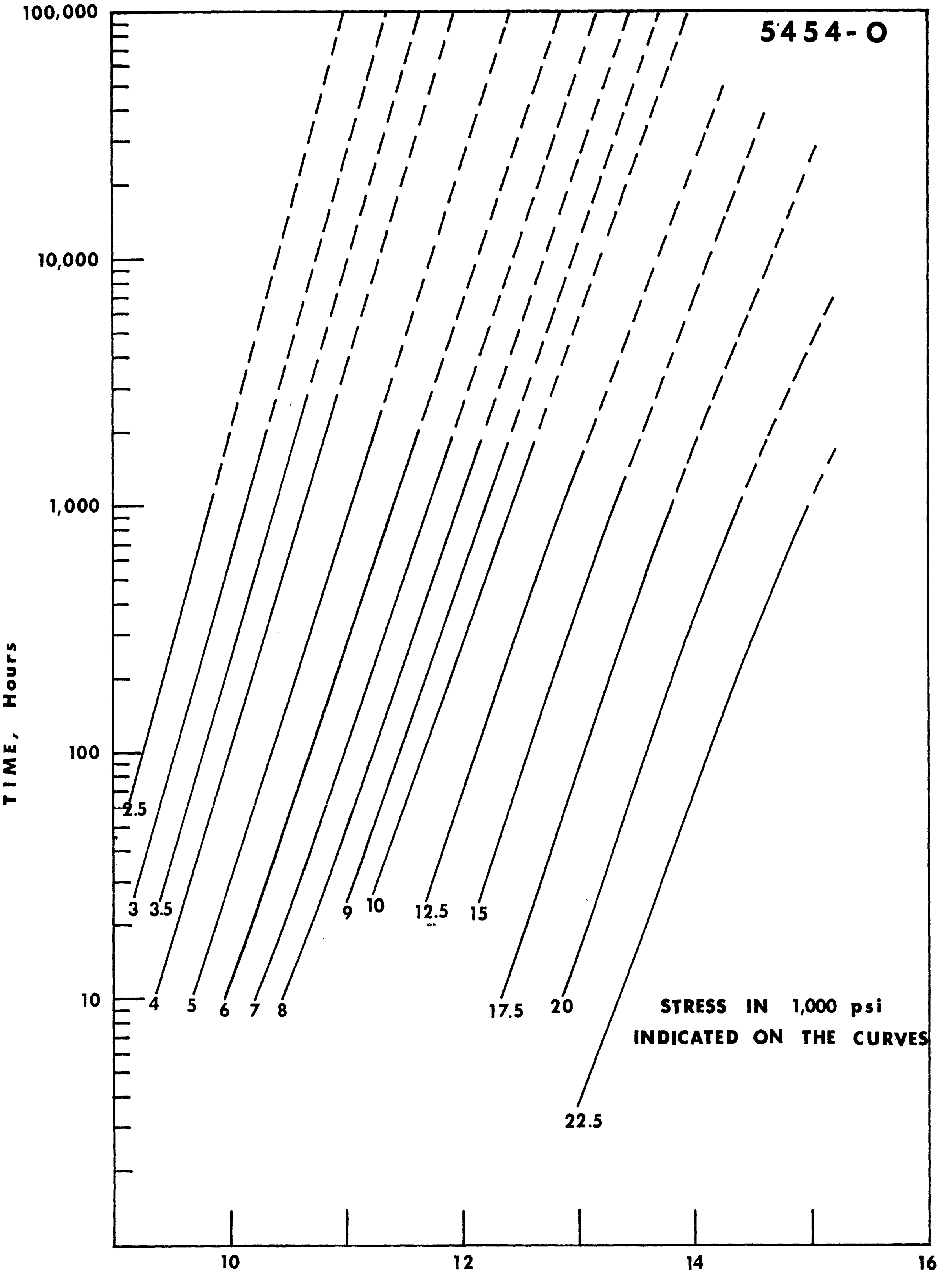


Figure 10 Iso-stress curves of rupture time versus reciprocal absolute temperature, derived from Figure 7 for 5454-O aluminum.

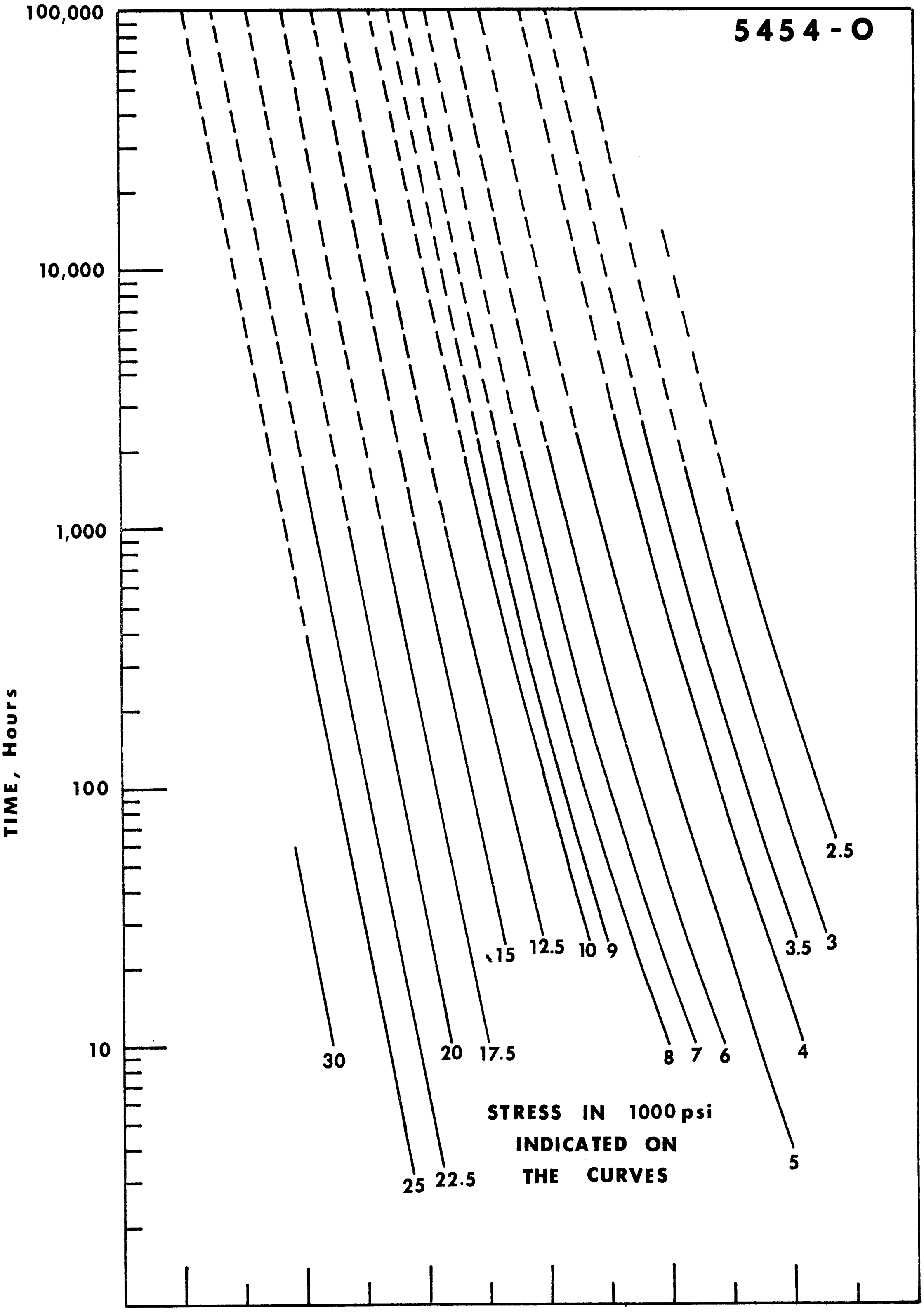
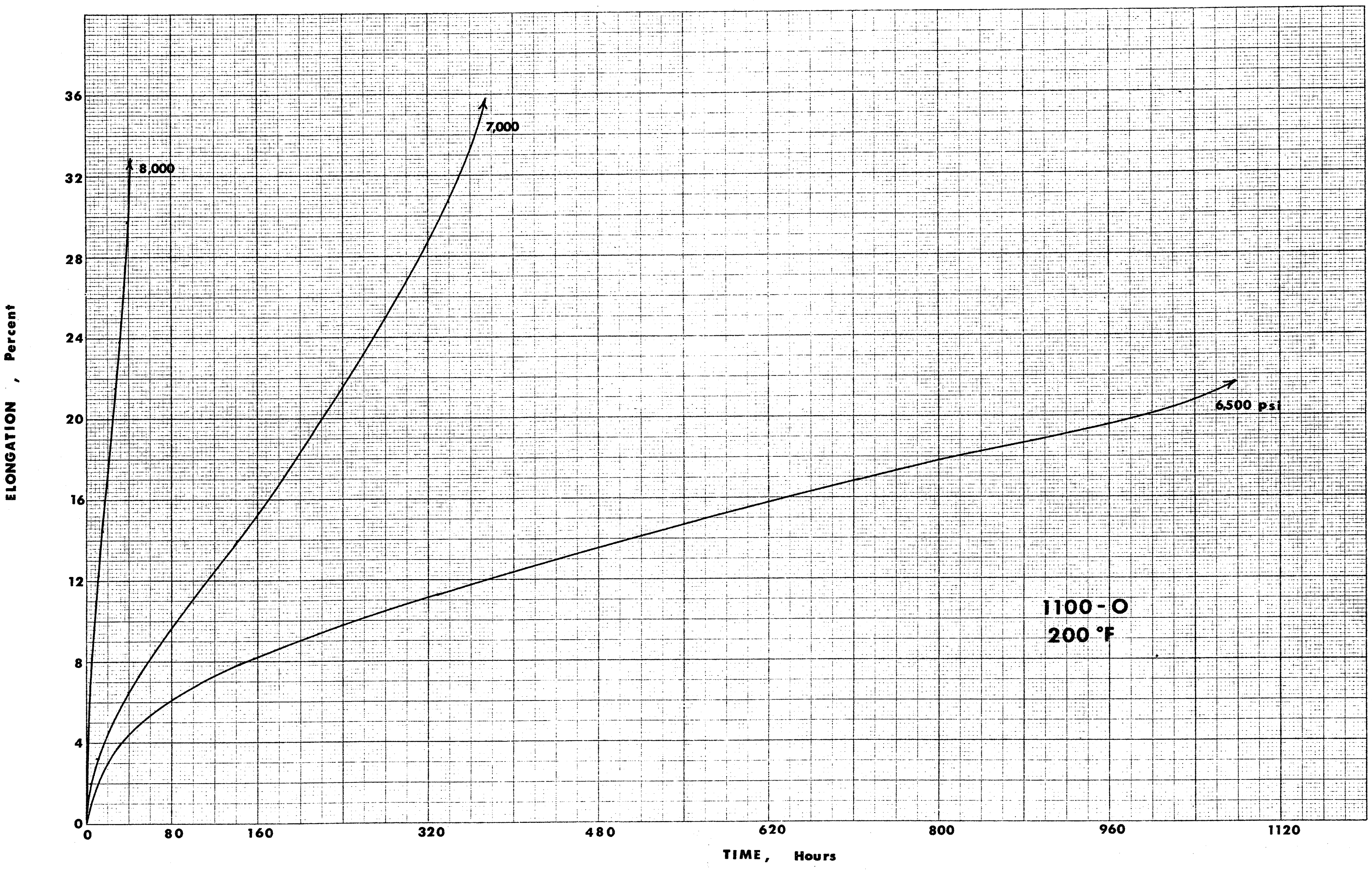


Figure 11. Iso-stress curves of rupture time versus temperature, derived from Figure 7 for 5454-O aluminum.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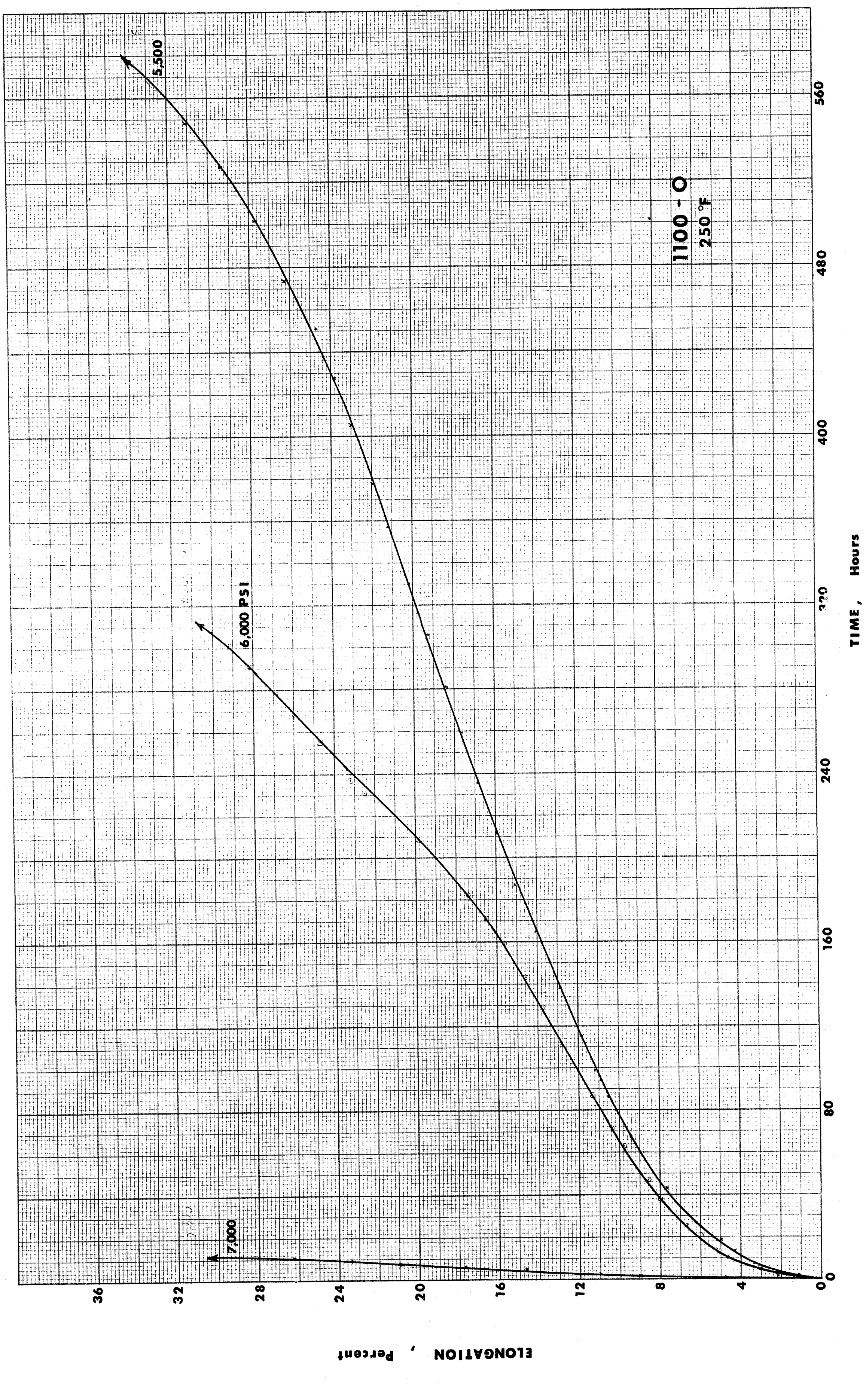
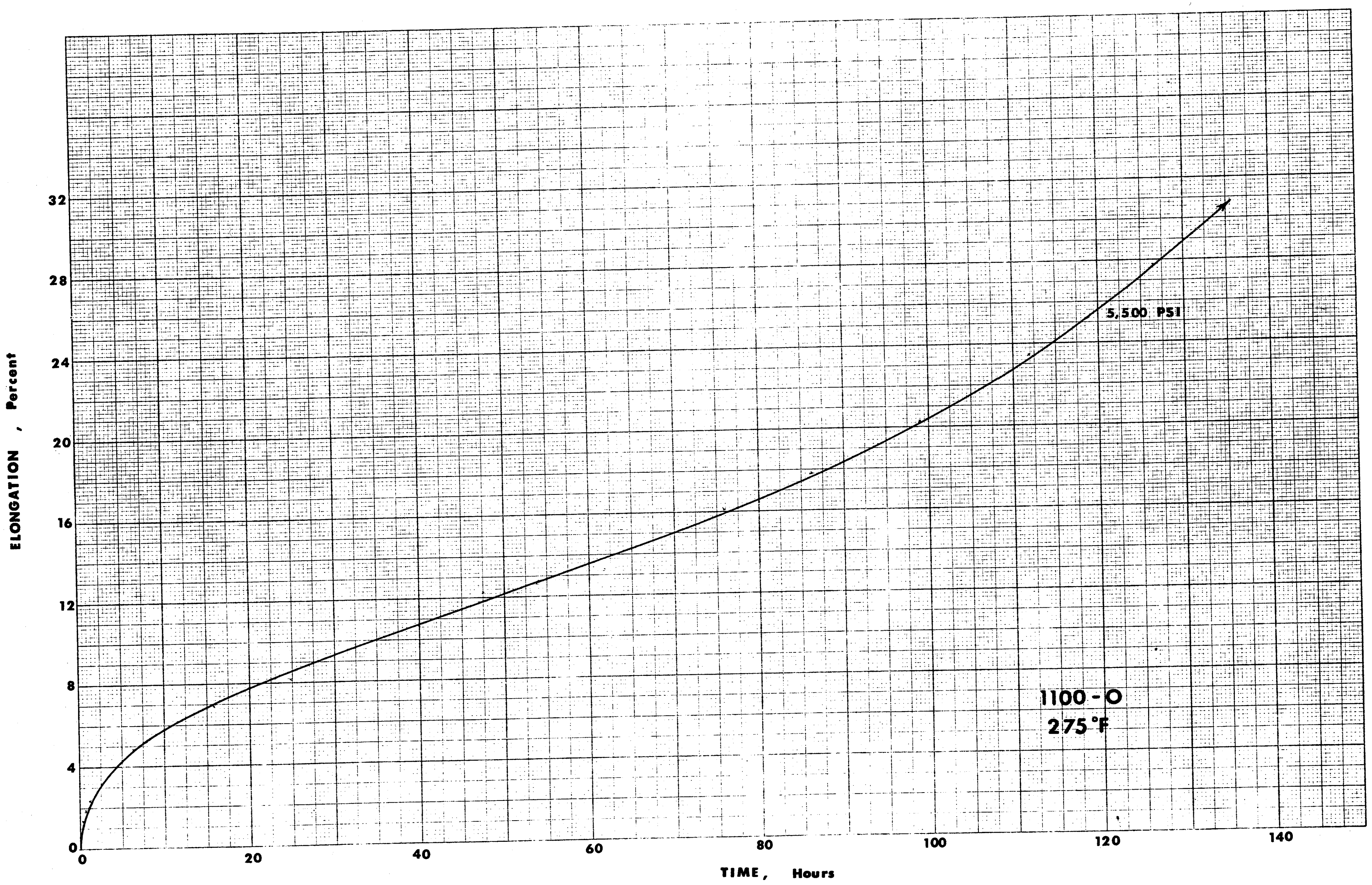
32
28
24
20
16
12
8
4
0
ELONGATION , Percent
0
80
160
320
480
620
800
960
1120
TIME, Hours
8,000
7,000
6,500 psi
1100-O
200 °F


1100 - O
250 °F
7,000
6,000 PSI
5,500
ELONGATION , Percent
0
4
8
12
16
20
24
28
32
36
TIME , Hours
0
80
160
240
320
400
480
560


1100 - O
275 °F
5,500 PSI
ELONGATION , Percent
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4
8
12
16
20
24
28
32
TIME, Hours
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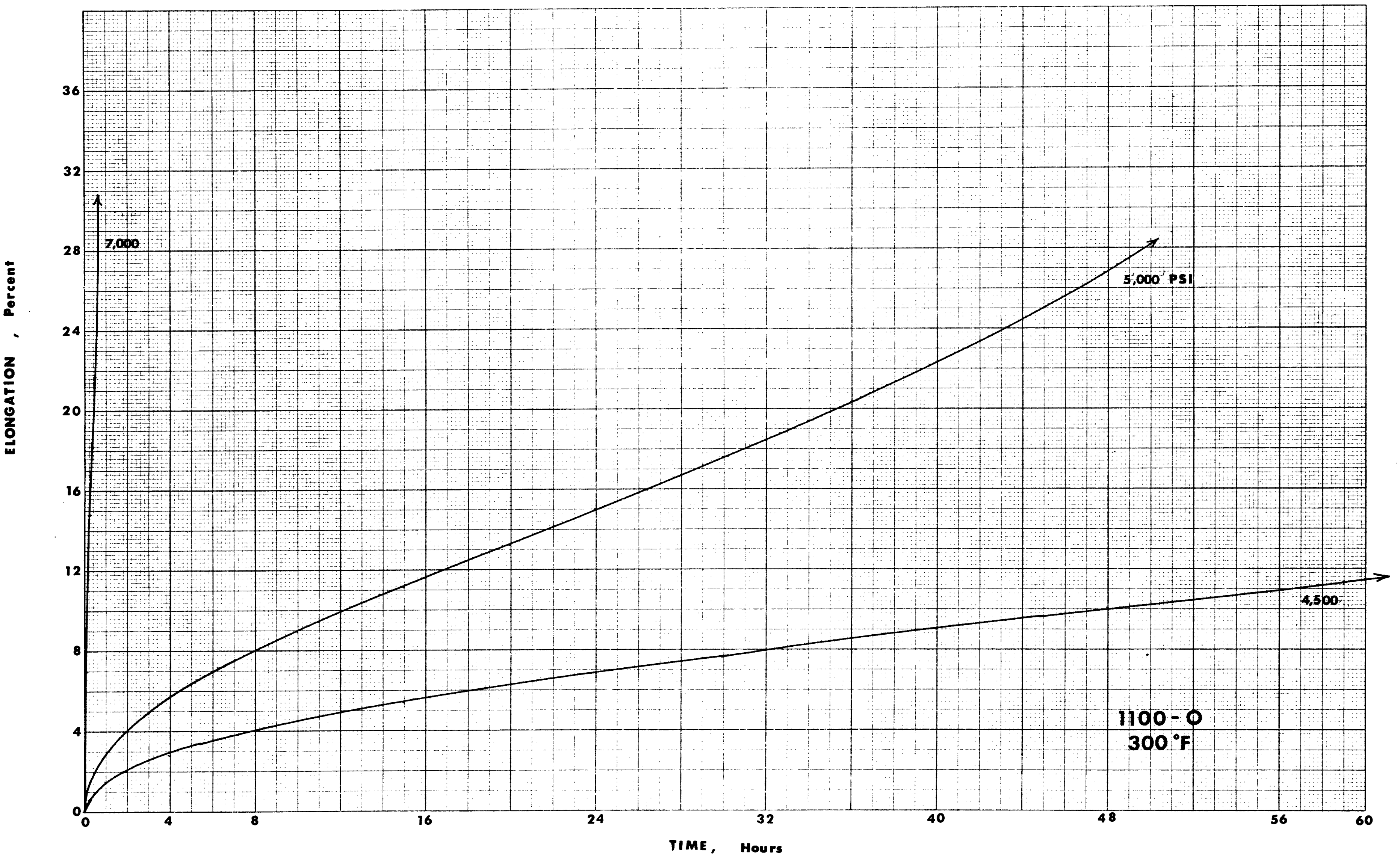
20
40
60
80
100
120
140



ELONGATION , Percent
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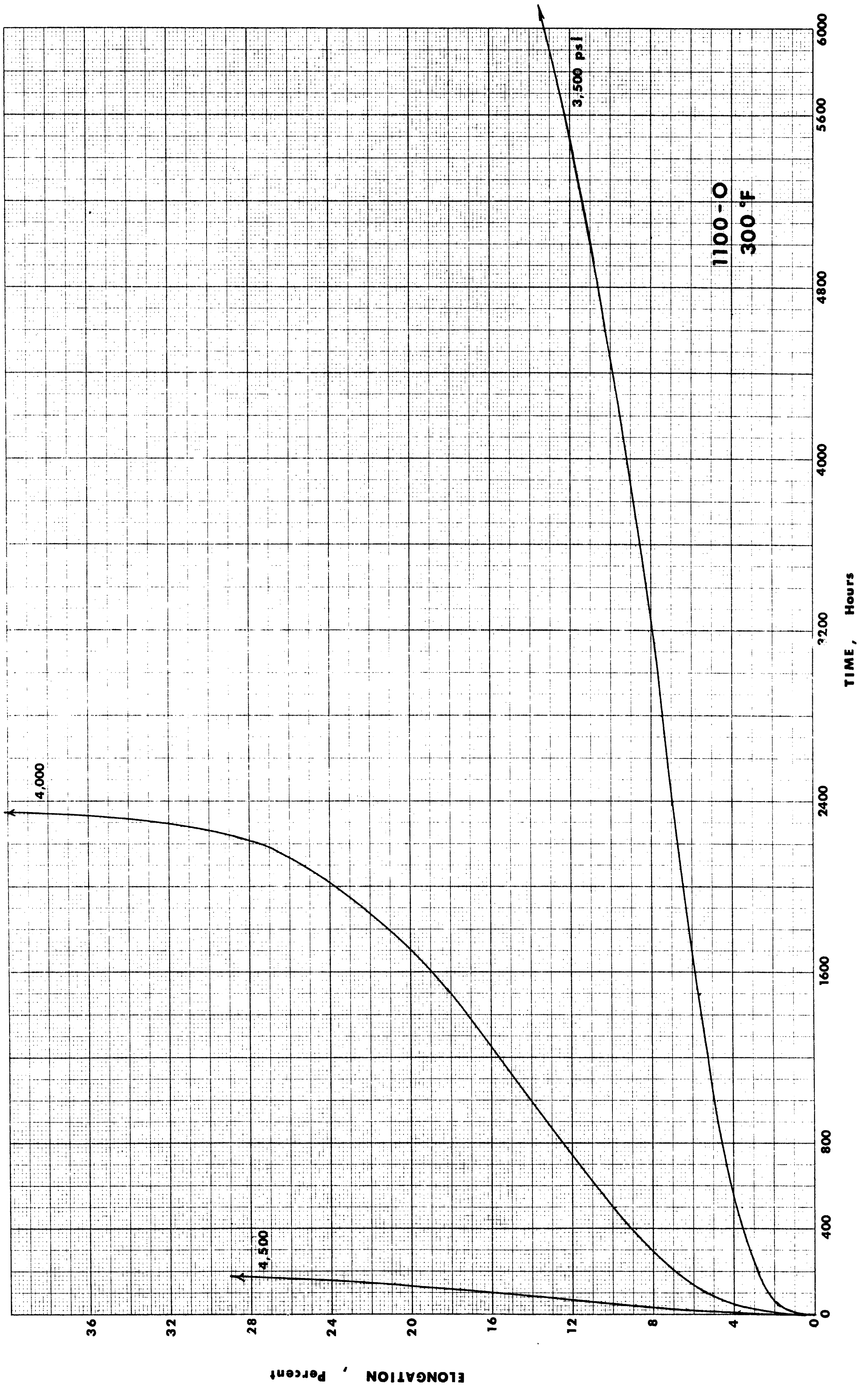
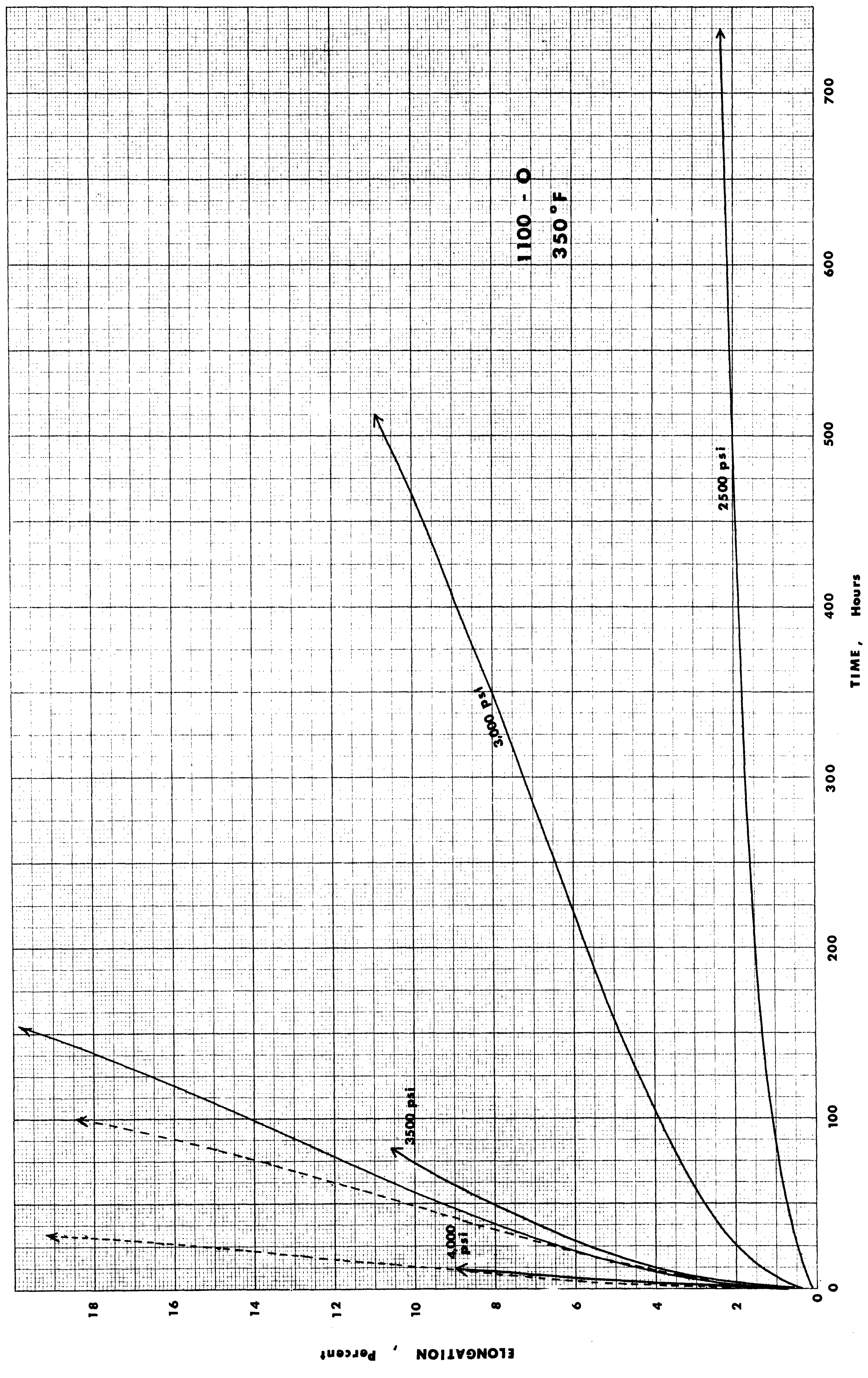
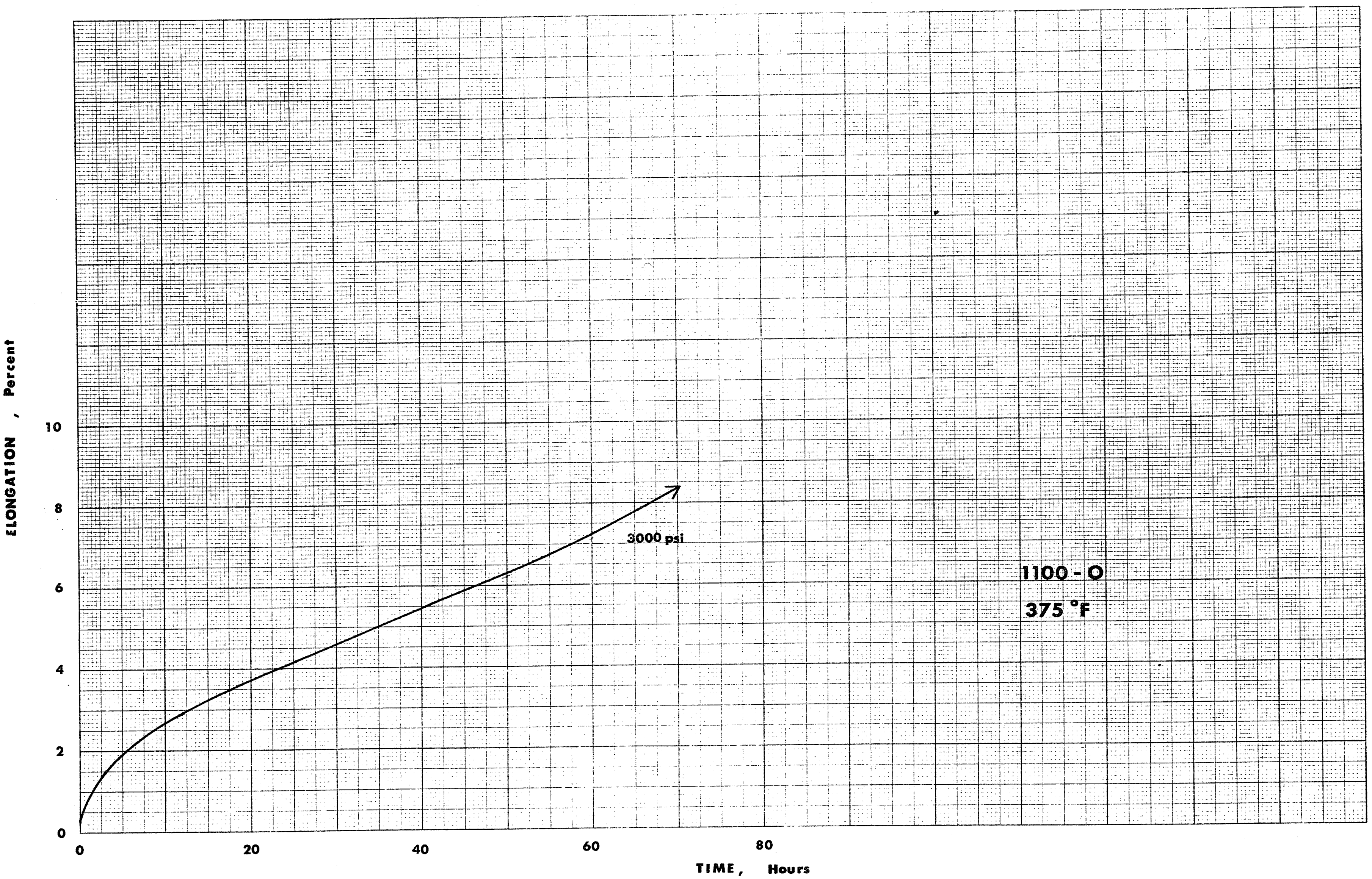
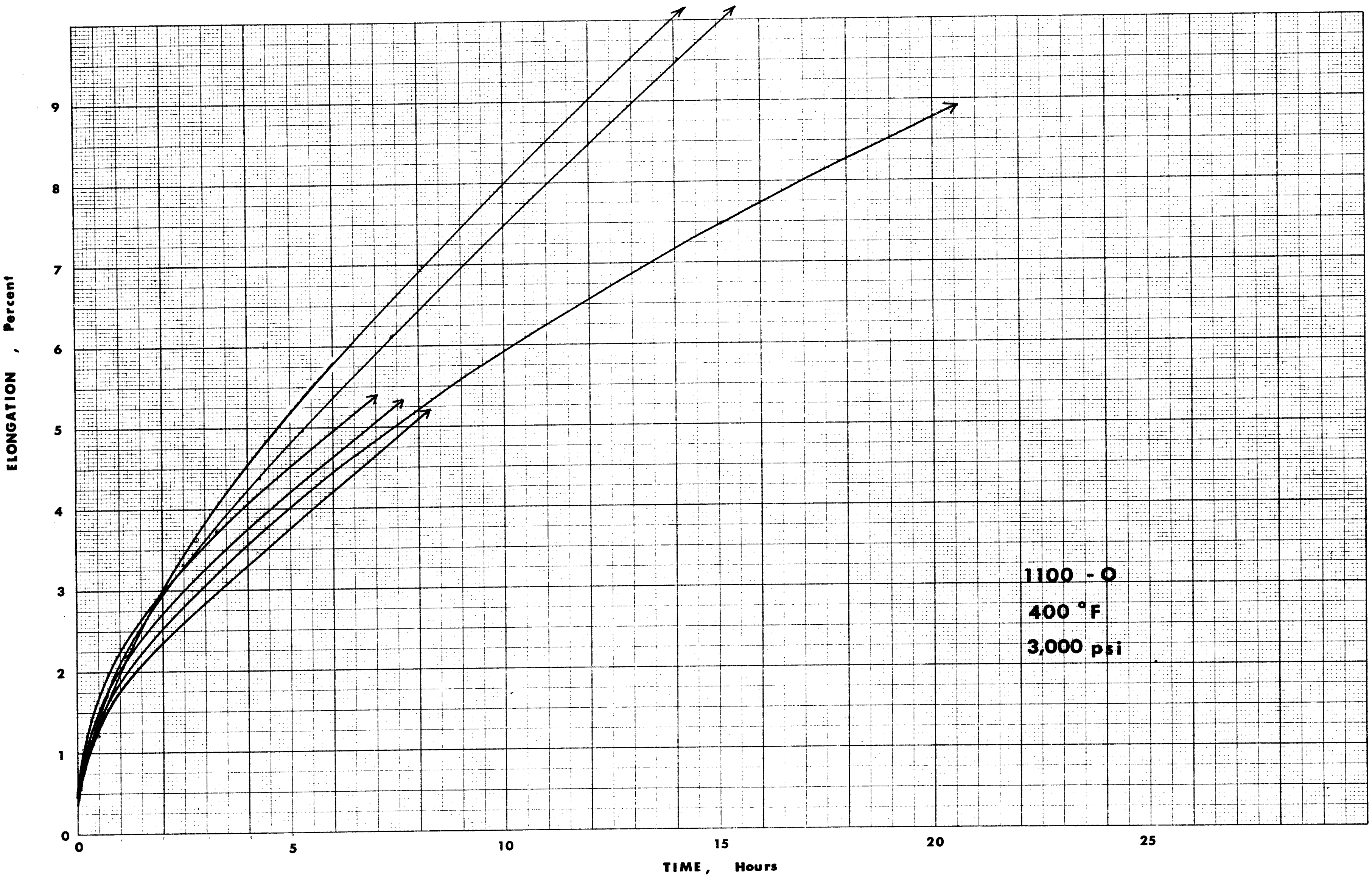
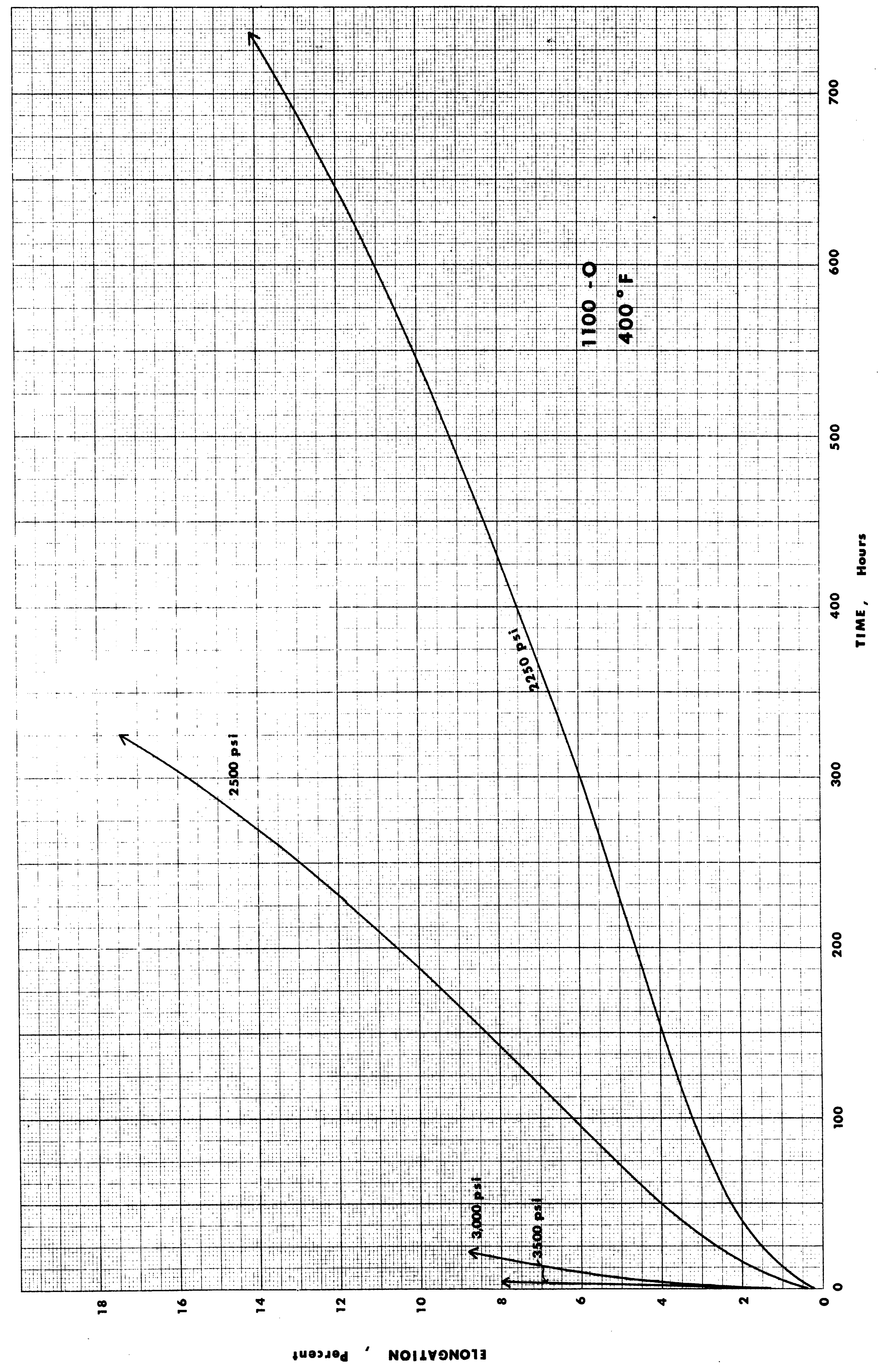
4
8
12
16
20
24
28
32
36
TIME, Hours
0
4
8
16
24
32
40
48
56
60
7,000
5,000 PSI
4,500
1100 - O
300 °F

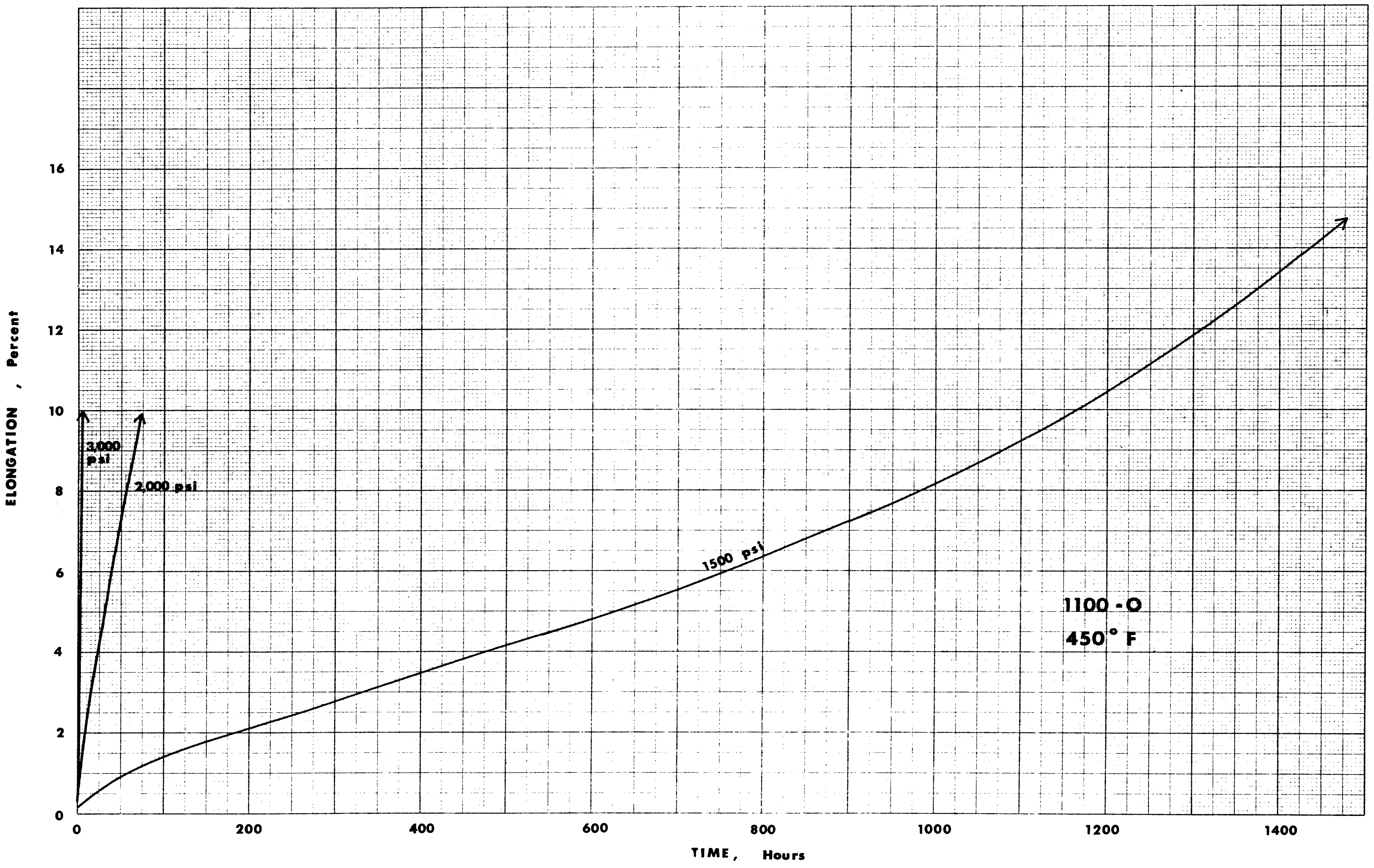

1100-O
300 °F
3,500 psi
4,000
4,500
ELONGATION , Percent
0
4
8
12
16
20
24
28
32
36
TIME , Hours
0
400
800
1600
2400
3200
4000
4800
5600
6000


1100 - O
350 °F
2500 psi
3,000 psi
3500 psi
4,000 psi
TIME , Hours
0
100
200
300
400
500
600
700
ELONGATION , Percent
0
2
4
6
8
10
12
14
16
18

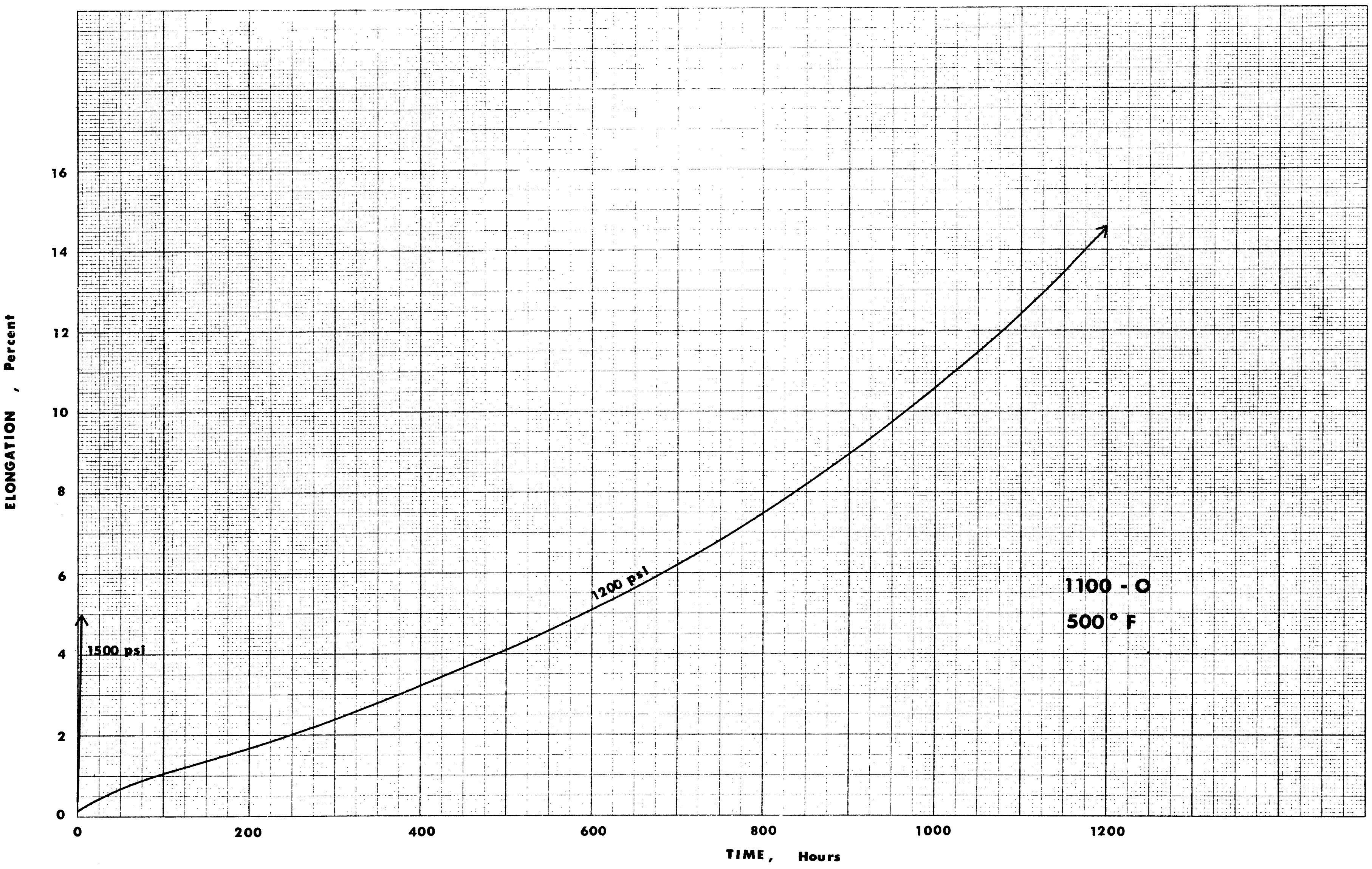

ELONGATION , Percent
0
2
4
6
8
10
0
20
40
60
80
TIME, Hours
3000 psi
1100 - O
375 °F

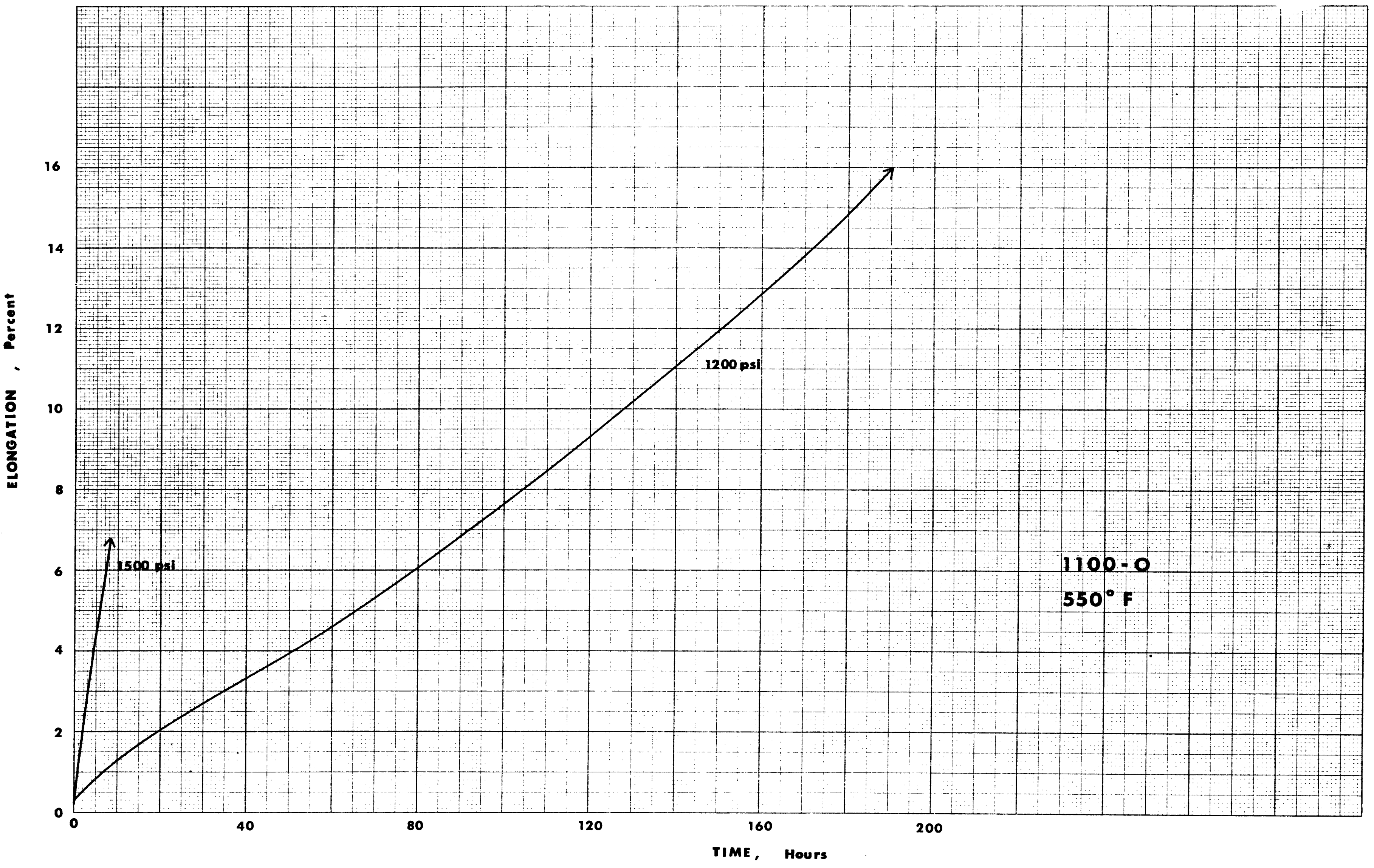

ELONGATION , Percent
0
1
2
3
4
5
6
7
8
9
TIME, Hours
0
5
10
15
20
25
1100 - O
400 °F
3,000 psi

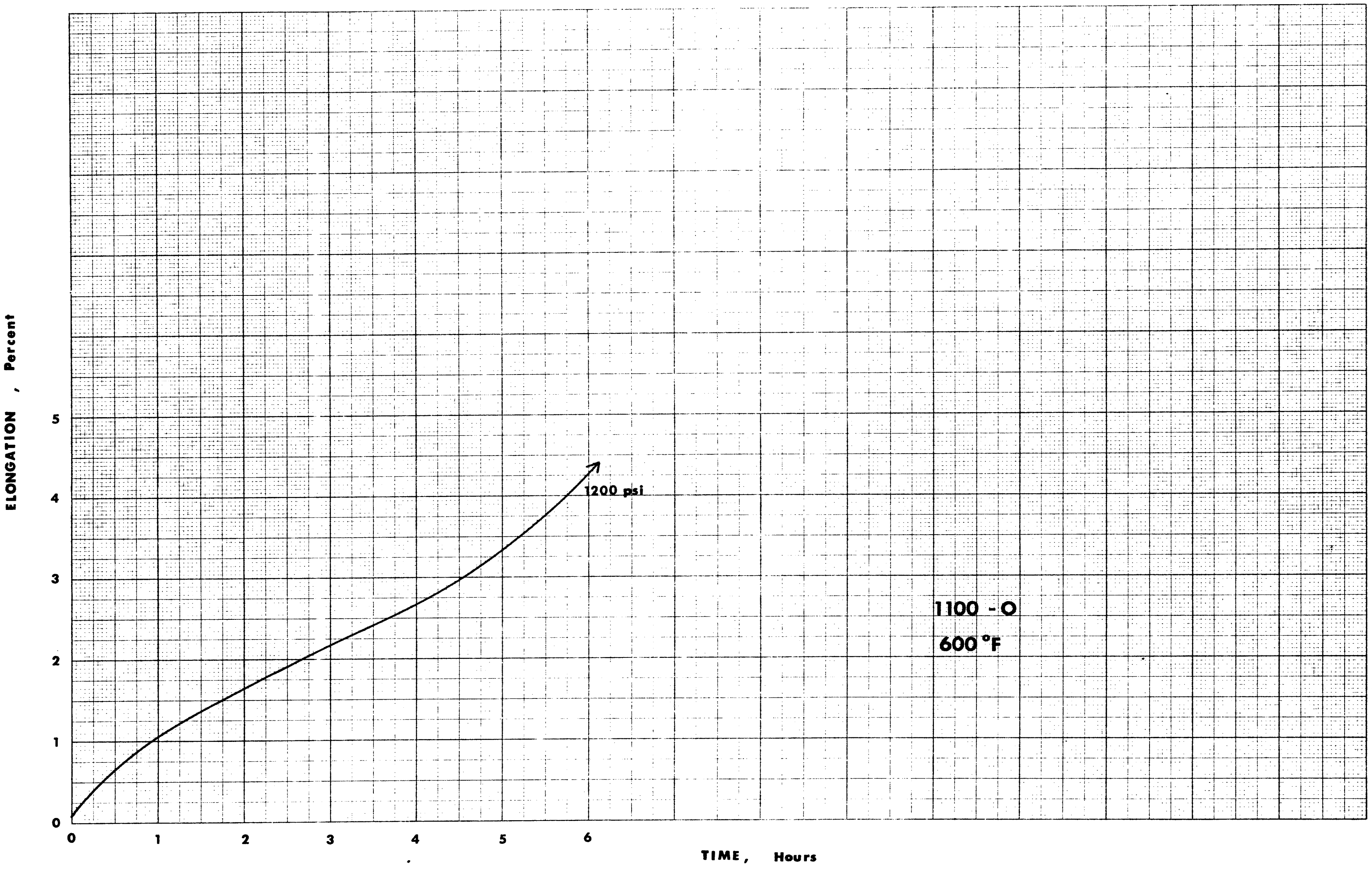

1100 -O
400 °F
2250 psi
2500 psi
3,000 psi
3500 psi
TIME, Hours
0
100
200
300
400
500
600
700
ELONGATION, Percent
0
2
4
6
8
10
12
14
16
18

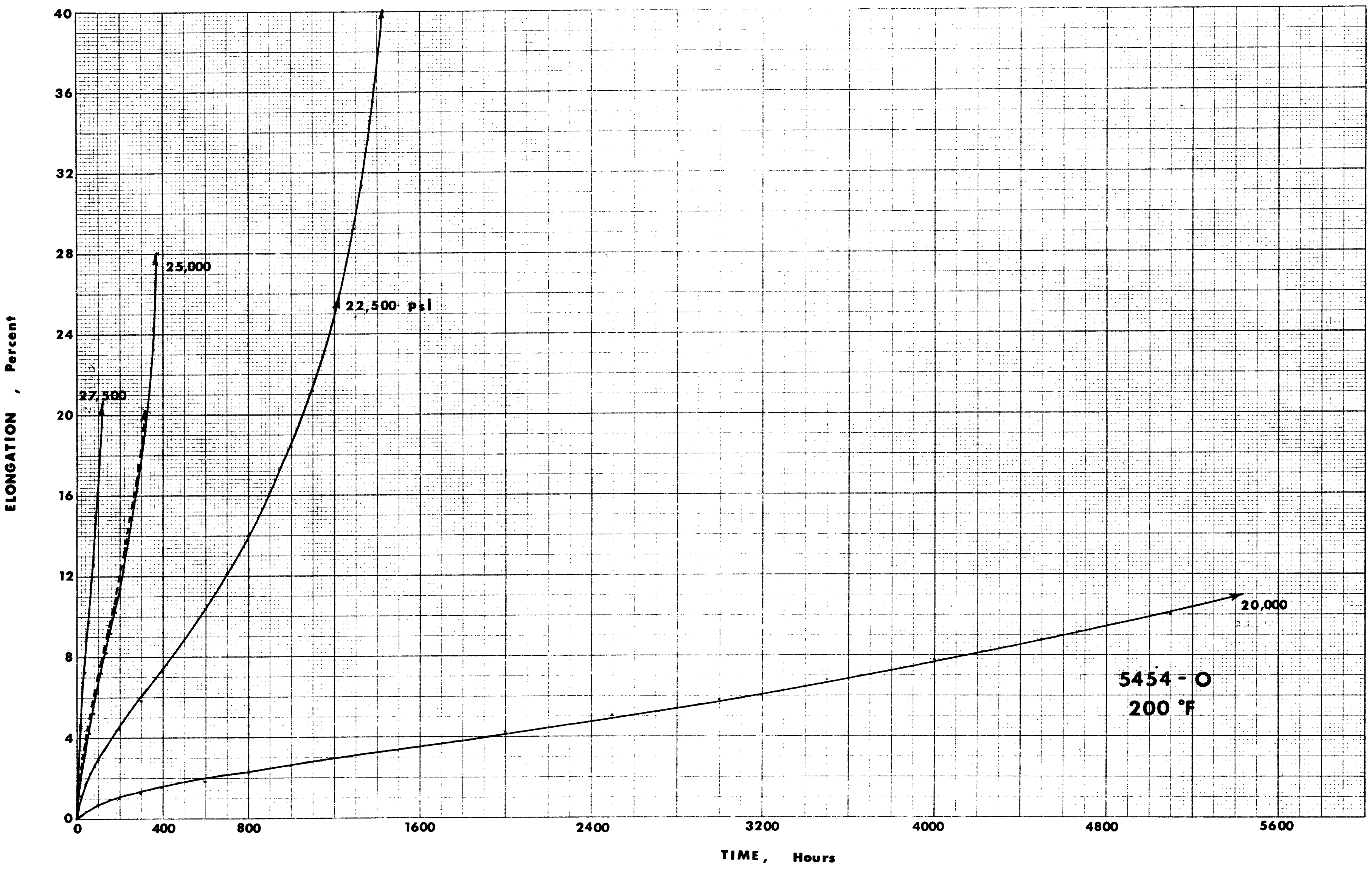


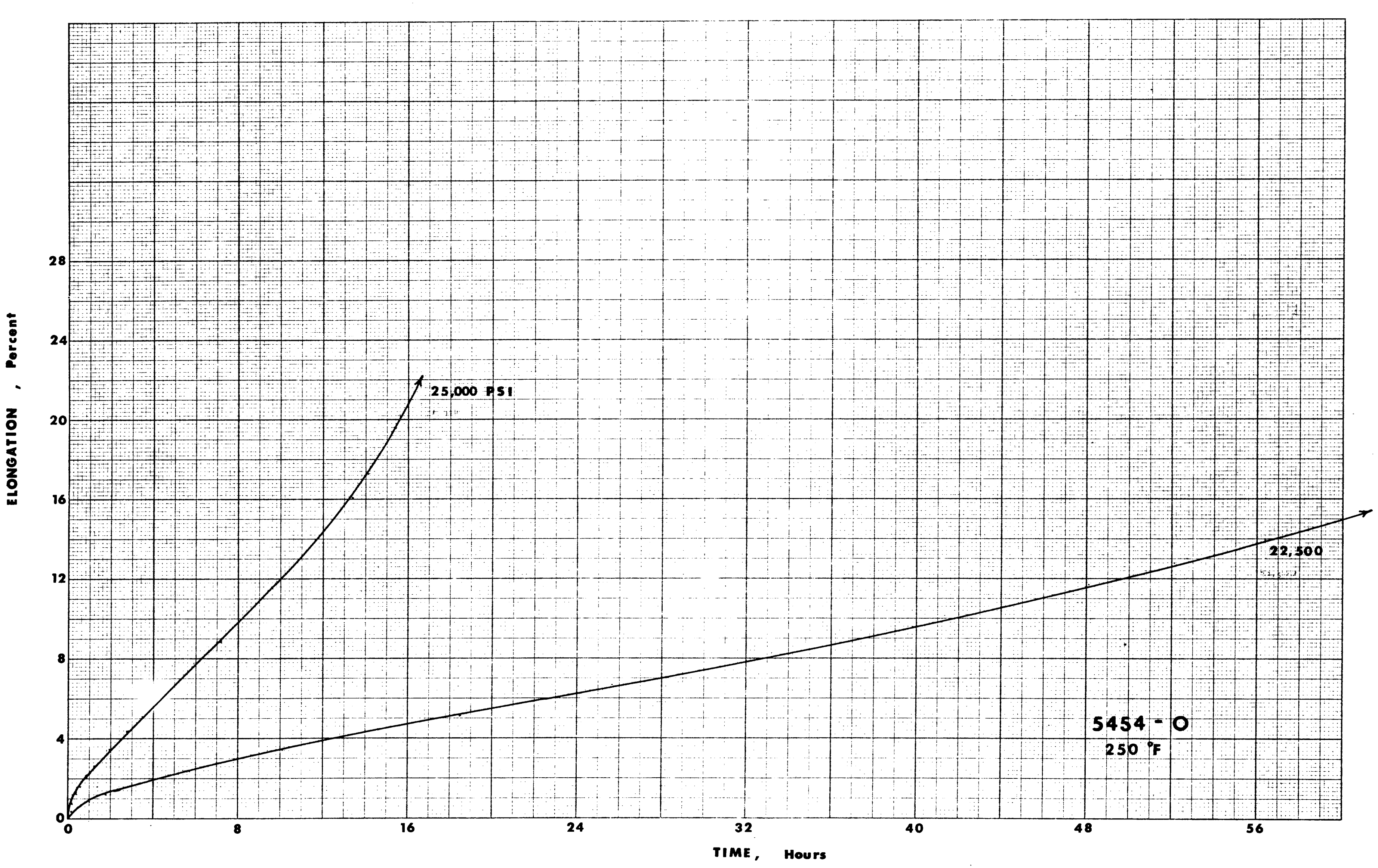
1100 -O
450° F
3,000 psi
2,000 psi
1500 psi
ELONGATION , Percent
0
2
4
6
8
10
12
14
16
TIME, Hours
0
200
400
600
800
1000
1200
1400

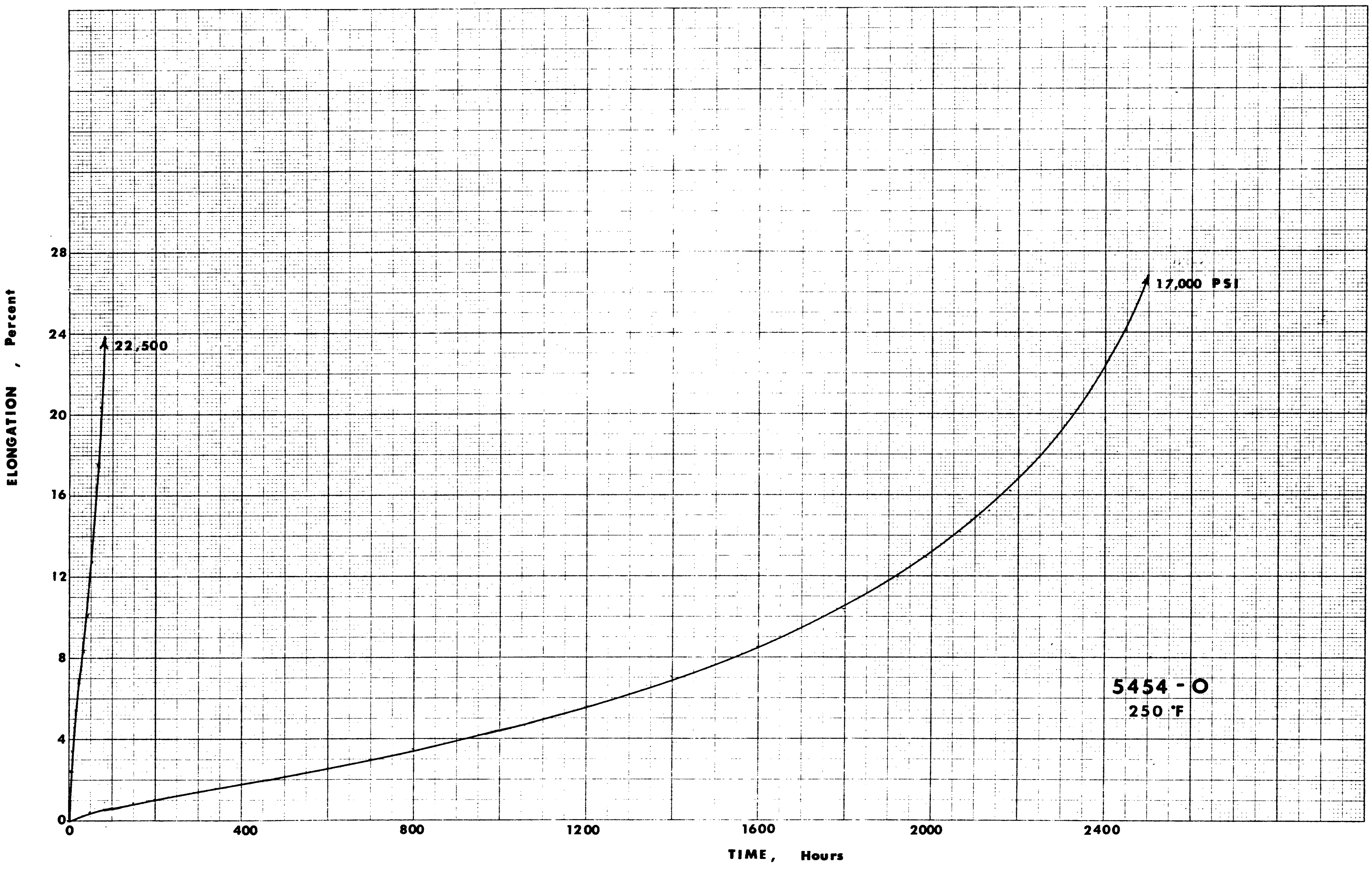

1100 - O
500° F
1500 psi
1200 psi
ELONGATION , Percent
TIME, Hours
0
2
4
6
8
10
12
14
16
0
200
400
600
800
1000
1200

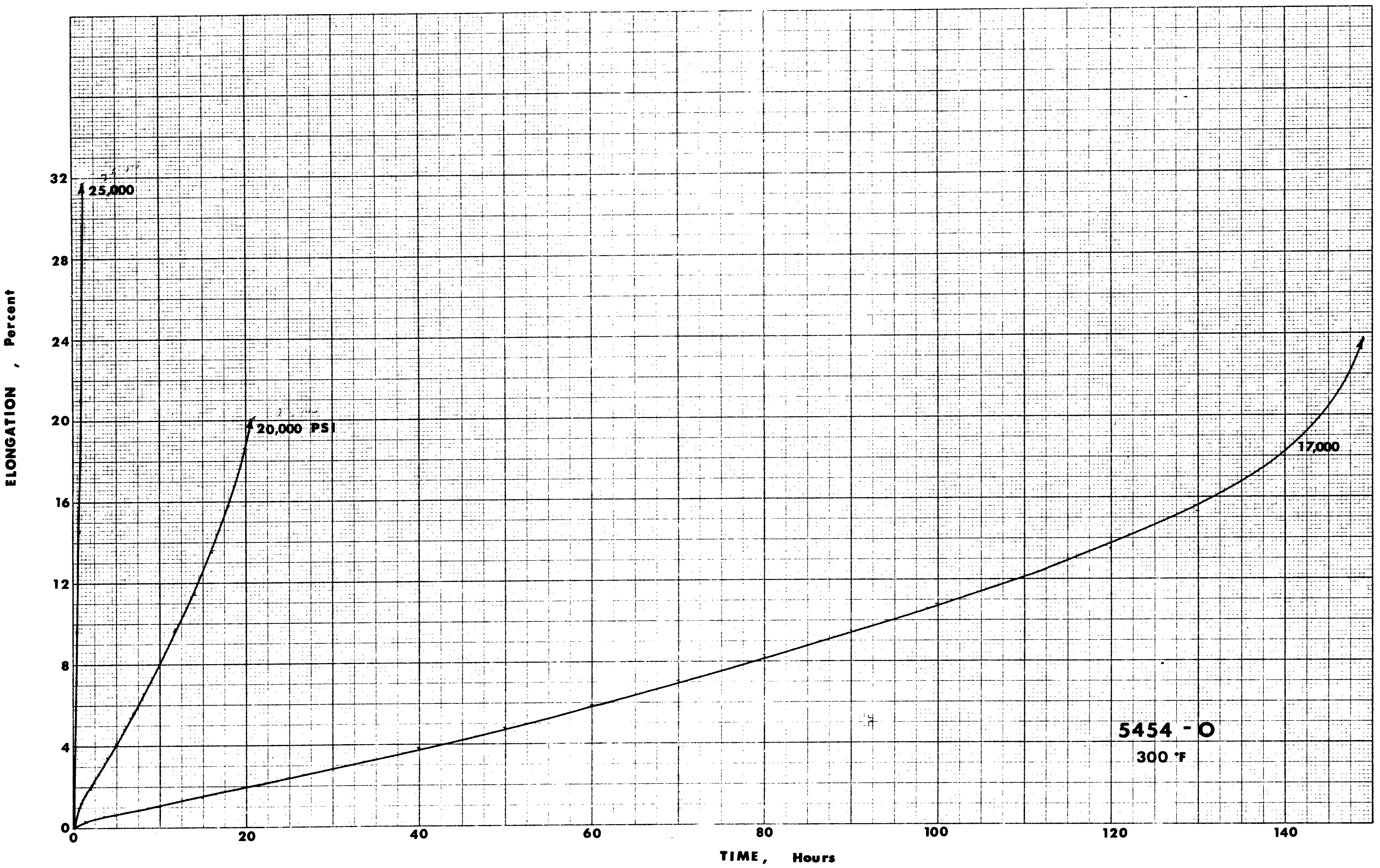

1100-O
550° F
1500 psi
1200 psi
ELONGATION , Percent
0
2
4
6
8
10
12
14
16
TIME, Hours
0
40
80
120
160
200

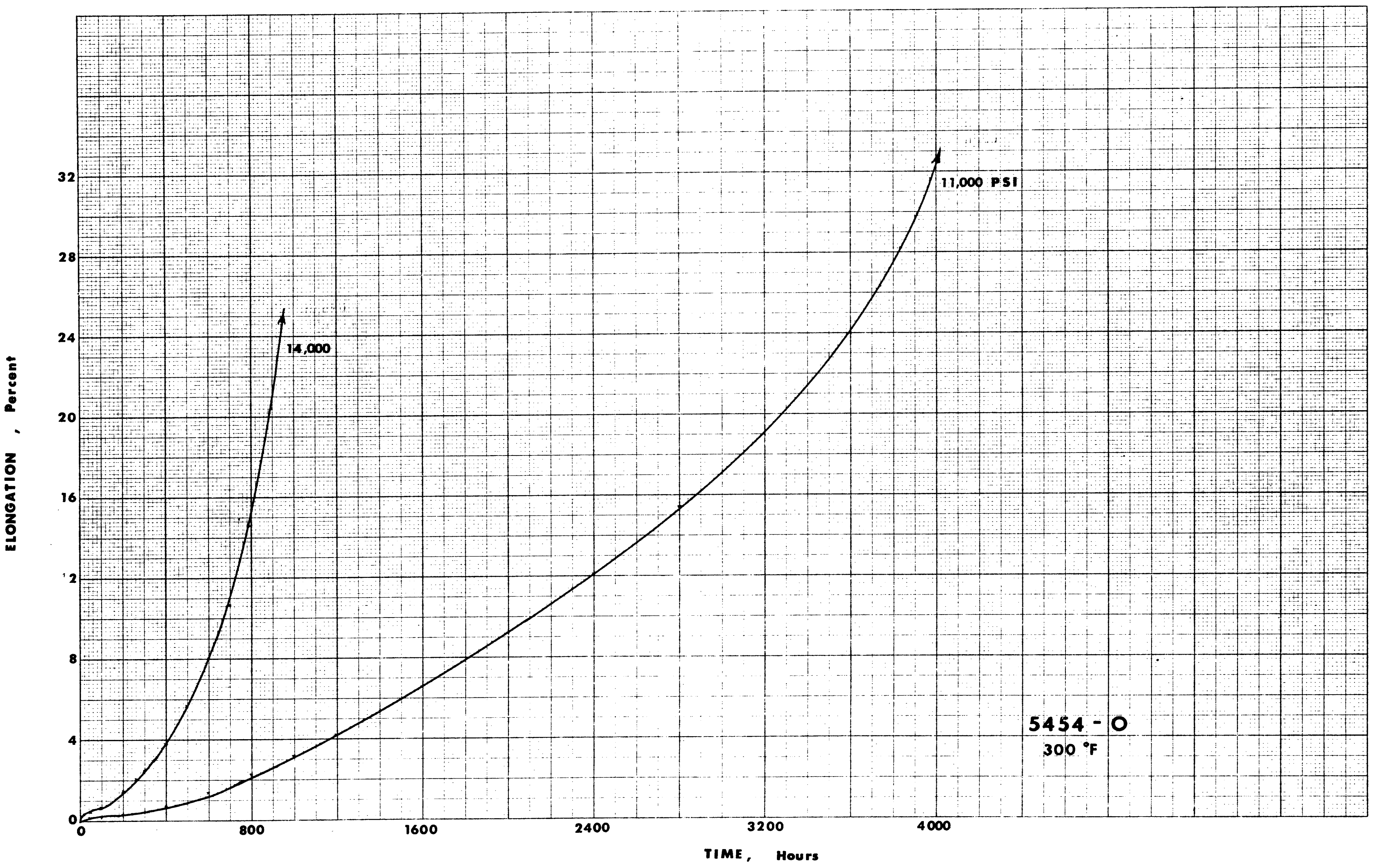

ELONGATION , Percent
0
1
2
3
4
5
0
1
2
3
4
5
6
TIME, Hours
1200 psi
1100 - O
600 °F

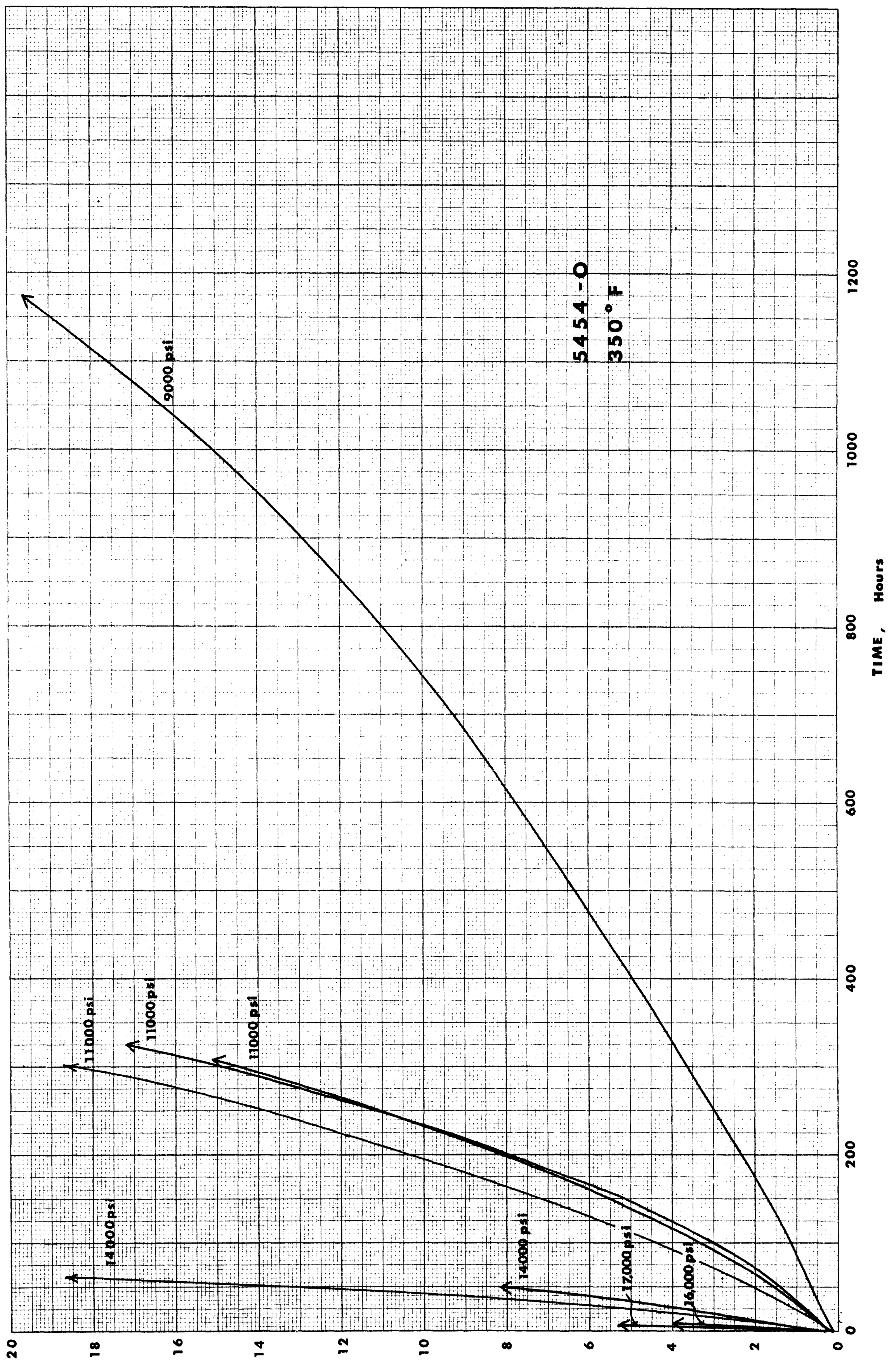

40
36
32
28
24
20
16
12
8
4
0
ELONGATION , Percent
0
400
800
1600
2400
3200
4000
4800
5600
TIME, Hours
27,500
25,000
22,500 psi
20,000
5454 - O
200 °F

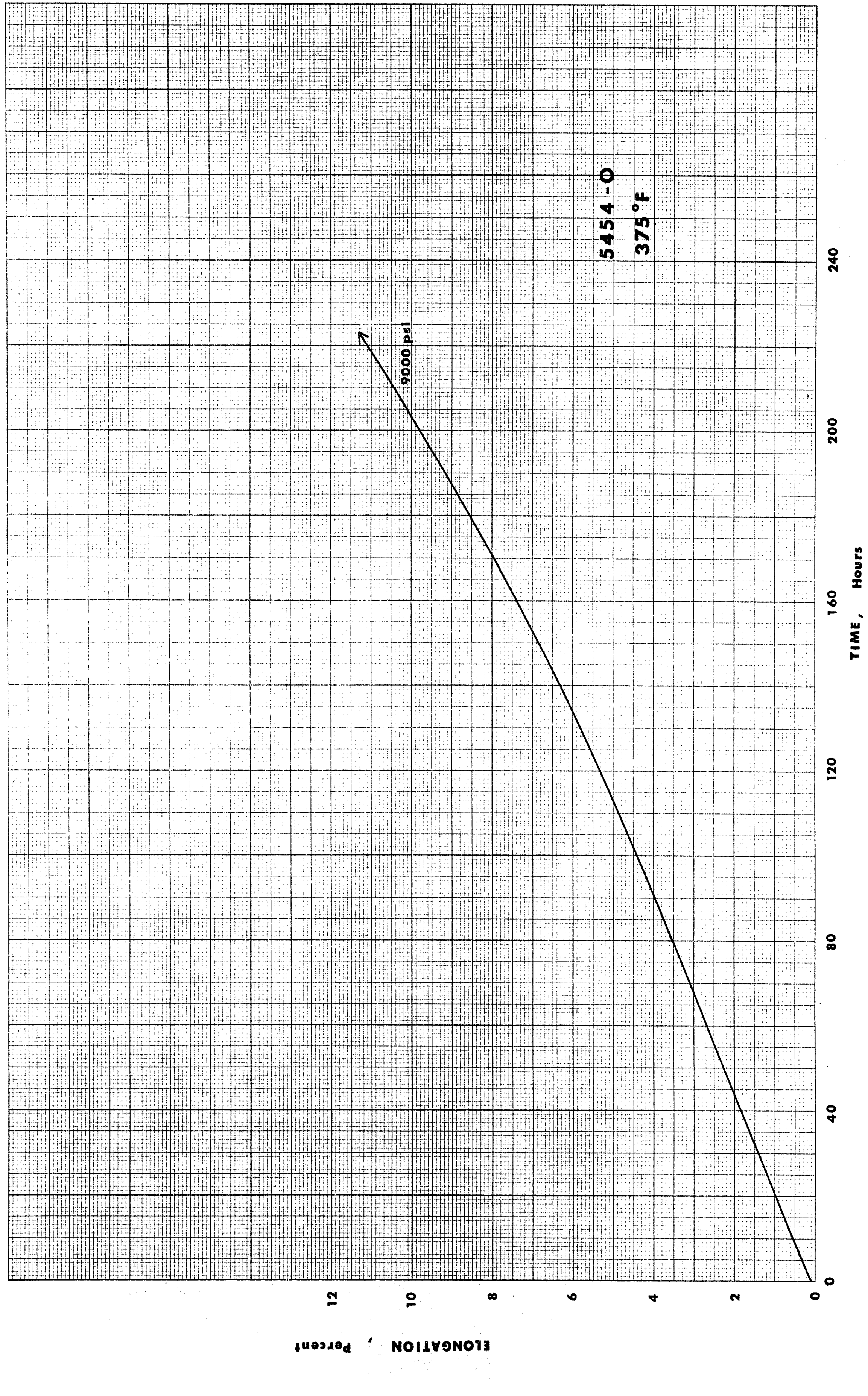

5454 - O
250 °F
25,000 PSI
22,500
ELONGATION , Percent
TIME, Hours
0
4
8
12
16
20
24
28
0
8
16
24
32
40
48
56

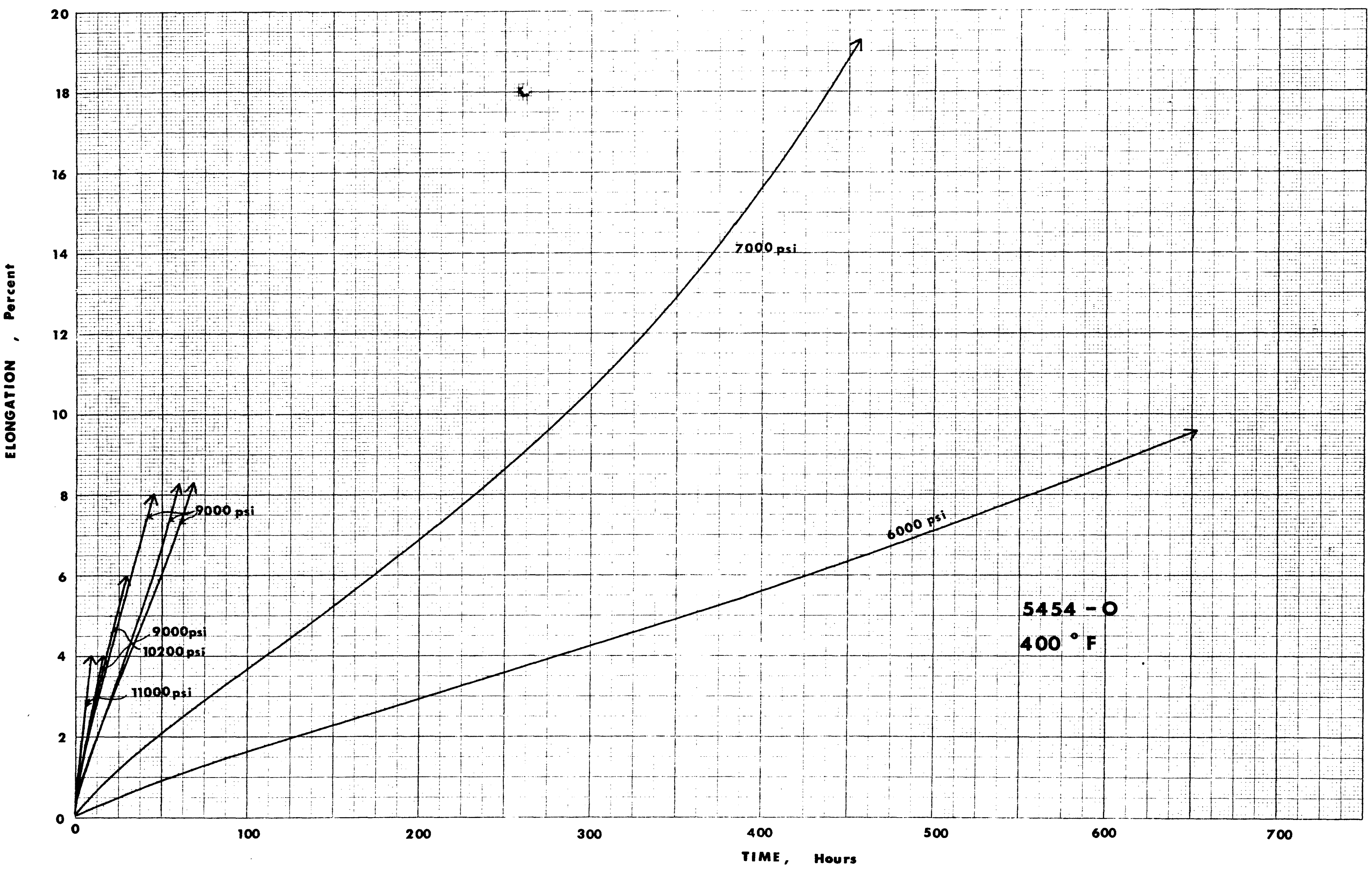

5454 - O
250 °F
17,000 PSI
22,500
ELONGATION , Percent
0
4
8
12
16
20
24
28
TIME, Hours
0
400
800
1200
1600
2000
2400


ELONGATION , Percent
0
4
8
12
16
20
24
28
32
TIME, Hours
0
20
40
60
80
100
120
140
25,000
20,000 PSI
17,000
5454 - O
300 °F

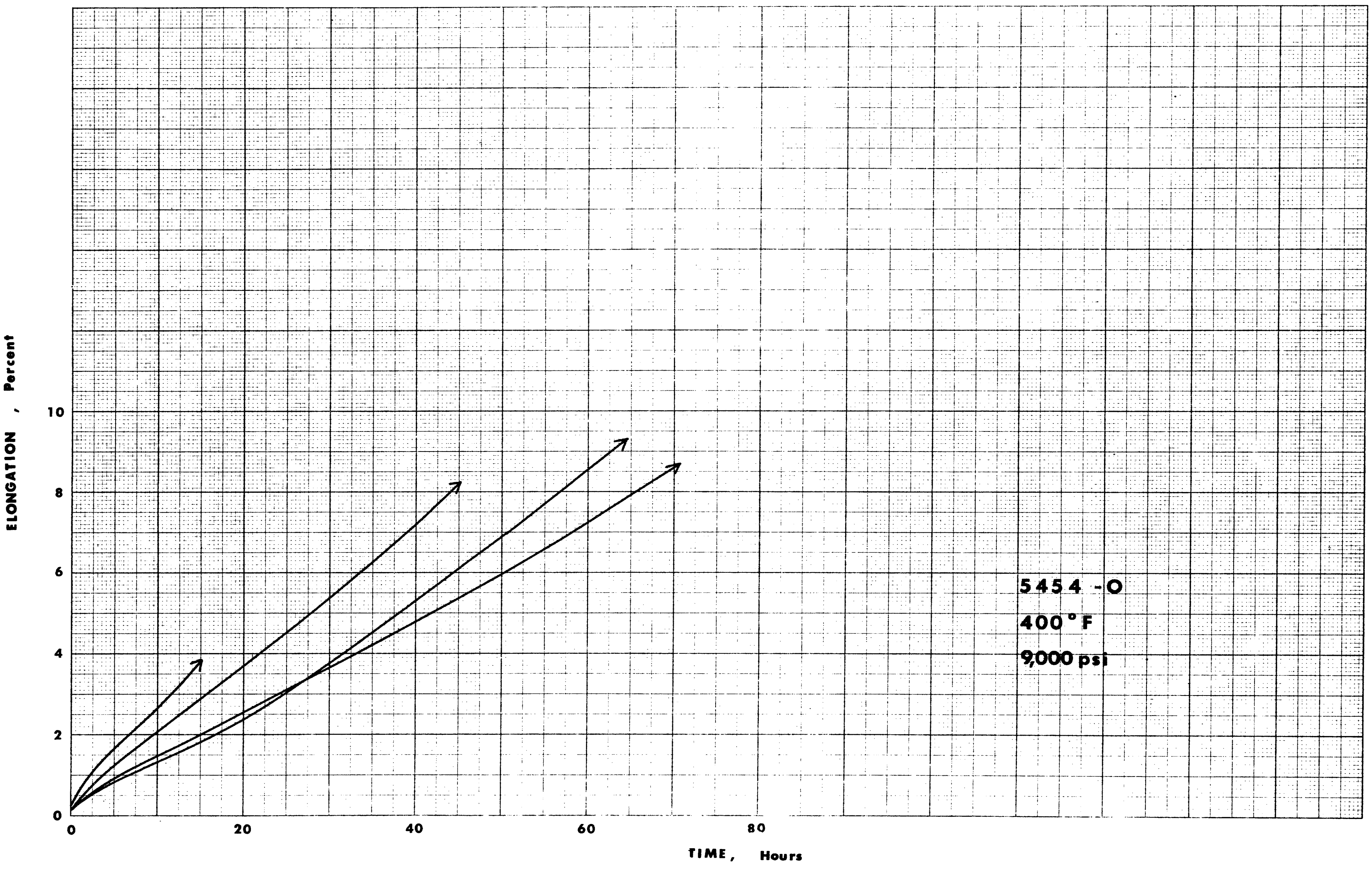

32
28
24
20
16
12
8
4
0
ELONGATION , Percent
0
800
1600
2400
3200
4000
TIME, Hours
14,000
11,000 PSI
5454 - O
300 °F

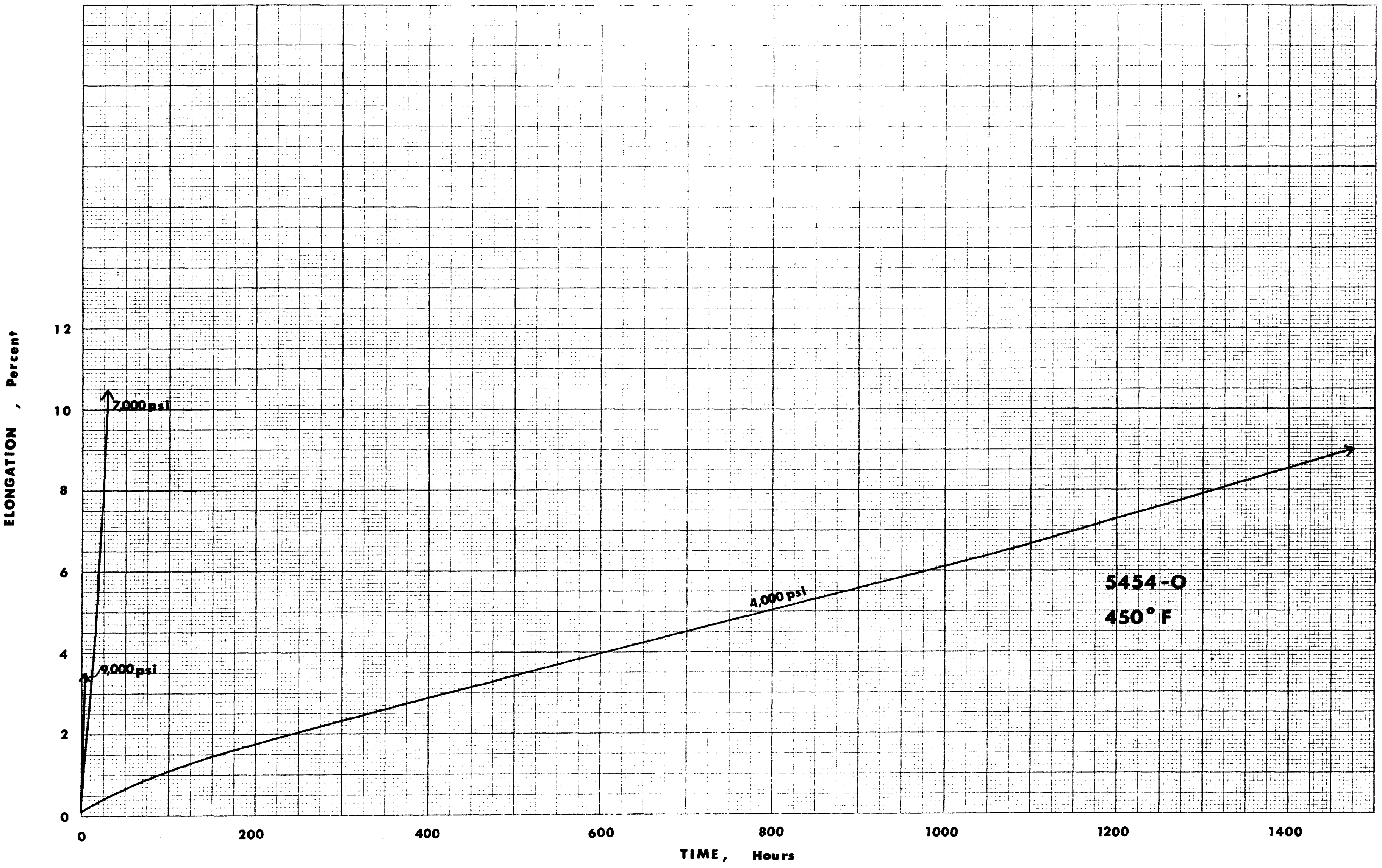

5454-O
350° F
9000 psi
11000 psi
11000 psi
11000 psi
14000 psi
14000 psi
17,000 psi
16,000 psi
TIME, Hours
0
200
400
600
800
1000
1200
ELONGATION, Percent
0
2
4
6
8
10
12
14
16
18
20

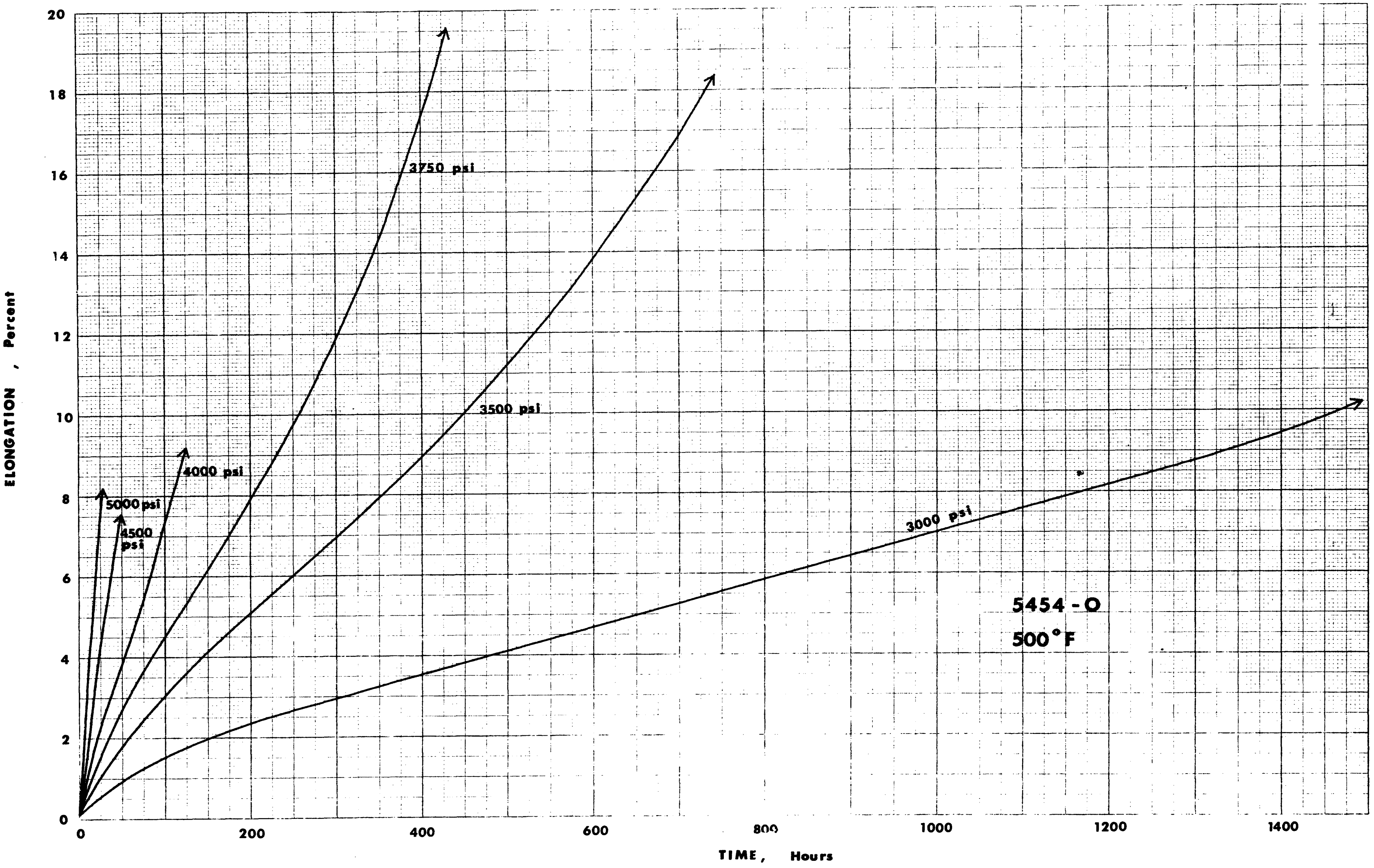

5454-O
375°F
9000 psi
ELONGATION, Percent
0
2
4
6
8
10
12
TIME, Hours
0
40
80
120
160
200
240

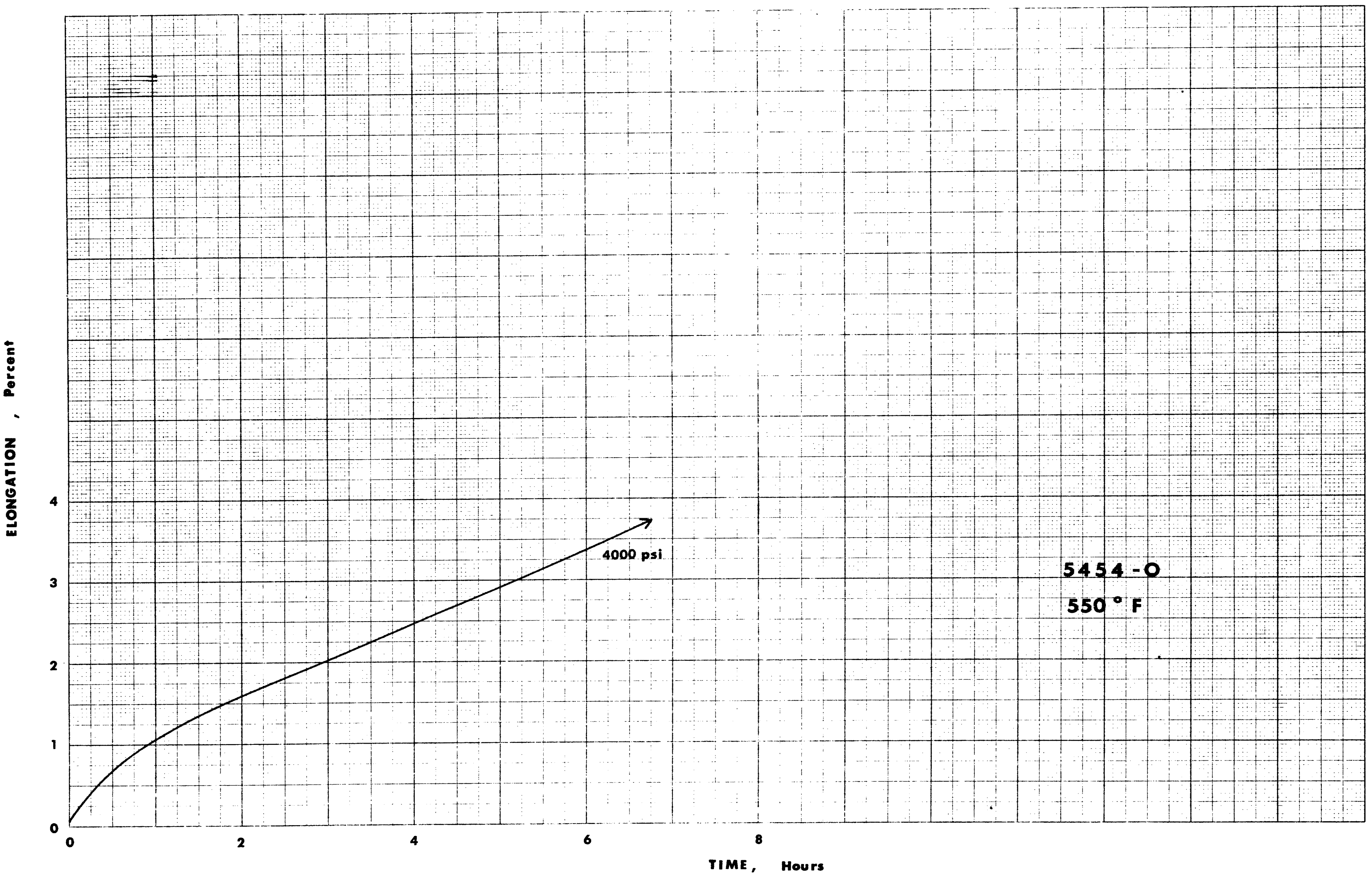


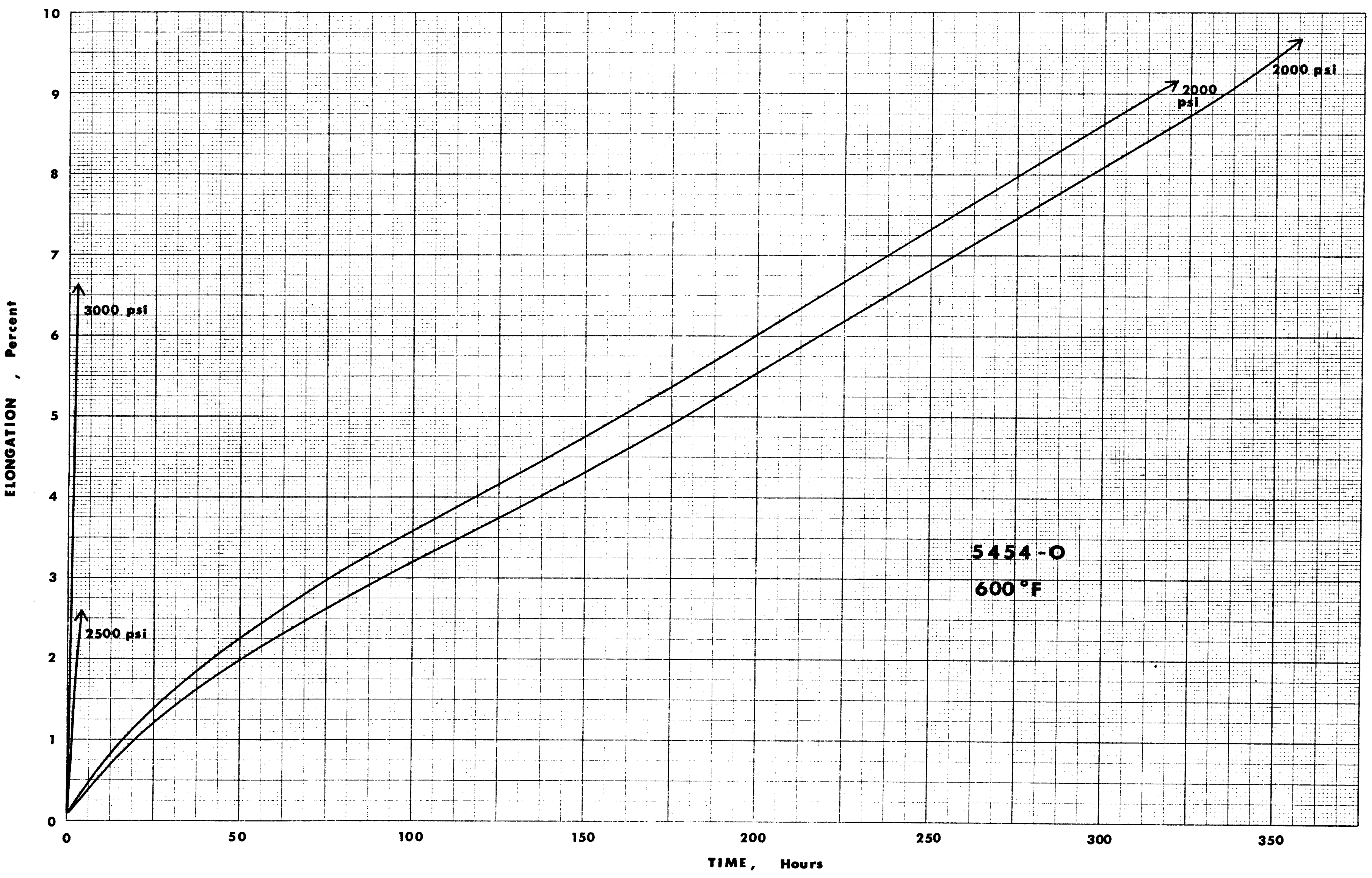
5454 - O
400 °F
7000 psi
6000 psi
9000 psi
9000psi
10200 psi
11000 psi
ELONGATION , Percent
0
2
4
6
8
10
12
14
16
18
20
TIME, Hours
0
100
200
300
400
500
600
700


5454 -O
400 °F
9,000 psi
ELONGATION , Percent
0
2
4
6
8
10
0
20
40
60
80
TIME, Hours


5454-O
450° F
7,000 psi
9,000 psi
4,000 psi
ELONGATION , Percent
0
2
4
6
8
10
12
TIME, Hours
0
200
400
600
800
1000
1200
1400


5454 - O
500°F
ELONGATION , Percent
TIME, Hours
0
2
4
6
8
10
12
14
16
18
20
0
200
400
600
800
1000
1200
1400
5000 psi
4500 psi
4000 psi
3750 psi
3500 psi
3000 psi


5454 -O
550 ° F
4000 psi
ELONGATION , Percent
0
1
2
3
4
TIME, Hours
0
2
4
6
8


5454-O
600 °F
ELONGATION , Percent
TIME, Hours
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
200
250
300
350
3000 psi
2500 psi
2000 psi
2000 psi