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TECHNICAL NOTE 2890

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A LINEAR TIME-TEMPERATURE RELATION FOR EXTRAPOLATION  
OF CREEP AND STRESS-RUPTURE DATA

By S. S. Manson and A. M. Haferd

Lewis Flight Propulsion Laboratory  
Cleveland, Ohio



Washington  
March 1953





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The words "determined in figure 7" should be omitted from the legend of figure 7.

The legends of figure 8 should reference figure 7.

The legends of figure 10 should reference figure 9.

The legends of figure 13 should reference figure 12.

The legends of figure 14 should reference figure 13.

## TECHNICAL NOTE 2890

A LINEAR TIME-TEMPERATURE RELATION FOR EXTRAPOLATION  
OF CREEP AND STRESS-RUPTURE DATA

By S. S. Manson and A. M. Haford

## SUMMARY

A time-temperature parameter based on examination of the published stress-rupture data for a variety of materials, rather than on physical theory, is proposed in the form  $(T - T_a)/(\log t - \log t_a)$ , where  $T$  is temperature in degrees Fahrenheit,  $t$  is rupture time in hours, and  $T_a$  and  $\log t_a$  are material constants which appear to be determinable from rupture data in the time range between 30 and 300 hours. This parameter expresses the observed approximate linearity of the function  $\log t$  against  $T$  for constant nominal stress in the rupture-time range above 10 hours and the tendency for lines of constant stress to converge to a single point  $(T_a, \log t_a)$ . A plot of this parameter against stress for a given material results in a single curve with relatively little scatter for various combinations of time, temperature, and stress in the rupture-time range above approximately 10 hours. For 40 materials investigated, the use of data in the time range below 300 hours resulted in very good extrapolation to longer times (up to 10,000 hr when data were available) compared with corresponding predictions obtainable from a parameter recently proposed in the form  $(T + 460)(20 + \log t)$ , where  $(T + 460)$  is the absolute temperature in degrees Rankine. The parameter  $(T - T_a)/(\log t - \log t_a)$  also appears to be applicable in the correlation of total creep elongation data. In order to correlate minimum creep rate data, however, the parameter used is in the form  $(T - T_a)/(\log r + \log r_a)$ , where  $\log r$  is the minimum creep rate and  $\log r_a$  is a material constant.

## INTRODUCTION

The subject of extrapolation of creep and stress-rupture data on materials at high temperature is of considerable current interest. This interest arises in part from the large number of materials under consideration for application in steam- and gas-turbine blading. Because extensive testing cannot be conducted on all these materials, an extrapolation procedure materially assists in the identification of the more

promising materials, which can then be subjected to more intensive development and testing. In some cases, the intended life of the apparatus is well in excess of 10,000 hours, and since rupture tests extending to such a long expected service life are expensive and introduce considerable delay in material selection, an approximation of material behavior in the high time range is of considerable value.

Two interesting contributions have recently been made to the subject of creep and stress-rupture data extrapolation. In reference 1, a new method has been applied to the analysis of high-temperature cobalt-base alloys, S-816 and S-590. The method makes use of the locations of discontinuities in the conventional logarithmic stress-rupture plots of nominal stress against time at constant temperatures. The authors attribute the discontinuities to changes in metallurgical behavior and in the mode of rupture, and make use of metallurgical examination to assist in the determination of the exact location of these discontinuities. They point out that the discontinuities may be gradual rather than sharp, but that treating them as sharp is helpful in the analysis. Use is also made of very short-time data to obtain additional points of discontinuity for purposes of analysis.

Another method of creep and stress-rupture extrapolation which has the great advantage of simplicity is presented in reference 2. This method is based on the rate-process equation, from which a deduction was made that at a given nominal stress, the parameter  $(T + 460)(C + \log t)$  is a constant, where  $T$  is temperature in degrees Fahrenheit ( $T + 460$  is the absolute temperature in degrees Rankine),  $t$  is the rupture time in hours, and  $C$  is a constant which depends upon the material and possibly the stress. For a number of materials examined,  $C$  was found to range between 14 and 22 when considered as a material constant. Since the usefulness of the method is greatly enhanced by considering  $C$  as a universal constant,  $C$  was selected equal to 20 as an approximation for all materials at all stress levels. Thus a plot of  $(T + 460)(20 + \log t)$  against stress should yield a single curve for each material irrespective of the individual values of time, temperature, and stress. If this curve is established by use of data at shorter rupture times (and correspondingly higher temperatures), then it should be usable to determine rupture behavior at longer times and lower temperatures. The selection of  $C$  equal to 20 greatly reduces the amount of testing required for the prediction of the behavior of a given material, and for many applications the results obtainable by this approximation are very useful. For example, this approximation has found considerable use in the evaluation of the relative merits of alloys under development. Accompanying the simplicity of the universal relation there is, however, a sacrifice in accuracy for certain applications. For example, if the stress and temperature are specified, a very considerable error, in some cases by a factor of 10, may result in the prediction of rupture time in the very long-time range when only short-time data are available for the extrapolation.

The object of this report is to present the results of a critical analysis conducted at the NACA Lewis laboratory to determine the sources of discrepancy arising from the use of the  $(T + 460)(20 + \log t)$  parameter, and to propose a different time-temperature parameter involving two material constants derived as a consequence of the analysis that has been found to yield considerably improved accuracy when used for long-time extrapolation.

#### EXAMINATION OF PARAMETER $(T + 460)(20 + \log t)$

Plots of the parameter  $(T + 460)(20 + \log t)$  against stress for several materials, as shown in figure 1 for 18-8 stainless steel, are presented in reference 2. Although, in general, there is a tendency for the various experimental data points to establish a single curve for a given material, the deviations are too systematic to be attributed to experimental scatter. Consideration of all the data shows that the points range about a mean curve; but at various constant temperatures, they fall on different individual smooth curves considerably removed from the mean curve. Likewise, data obtained only at low rupture times establish a different curve from that obtained using data covering a wide range of rupture times. For example, if a curve is drawn using data at rupture times less than 100 hours, it is considerably different from the mean curve.

In a plot of this nature, minor displacements of the data points from the mean curve can result in rather large errors in predicted rupture time at a given stress and temperature. Figure 2(a) shows a conventional stress-rupture plot for 18-8 stainless steel, together with the curves predicted from figure 1 using data for less than 100 hours for comparison. Figure 2(b) shows a similar plot for DM steel, and in each case there is a considerable discrepancy between the predicted curves and the experimental points. For a specified rupture time and temperature, the error in stress in the medium-time range is rarely greater than 10 to 20 percent, as indicated in reference 1. At the higher times, however, considerably greater error in stress may be observed, and for a specified temperature and stress, the error in rupture time frequently exceeds a factor of 5, the predicted rupture time being, in general, too high for 18-8 stainless steel and too low for DM steel.

An attempt was made to find the possible source of errors arising in the use of the  $(T + 460)(20 + \log t)$  parameter by investigating the assumed linearity of plots of  $-\log t$  against  $\frac{1}{T + 460}$  at constant nominal stress and the hypothesized convergence of the constant-stress

lines at  $\frac{1}{T + 460} = 0$ . Since very few points at a given stress were directly obtainable from conventional curves, cross plots were made to obtain a better delineation of the curves at constant stress. In the preparation of these plots, the variation of the logarithm of stress with temperature was first cross-plotted with time as a parameter. Figure 3 shows schematically the nature of such plots obtained by fairing the data to be consistent with the family relation among various materials.

When plots of  $\log t$  against  $\frac{1}{T + 460}$  based on the cross-plotted constant nominal stress curves were examined for a number of materials, deviations from the assumed relation were observed, as shown schematically in figure 4. The nonlinearity trends were too general and systematic to be attributable either to cross-plotting or to experimental scatter. (The appendix shows a detailed analysis of 16-13-3 steel for illustration purposes.) These deviations from linearity have been emphasized by extension of the constant-stress curves as indicated by the dotted lines, but the trends shown by the curves in this figure are characteristic of the data for the materials examined. It is seen that curvature occurs at very short and very long rupture times; thus the use of short- and moderate-time data can be expected to lead to error in the prediction of long-time data due to the nonlinearity in the range of extrapolation.

The assumption of  $(T + 460)(20 + \log t)$  as the correlating parameter is represented by the straight lines converging at the point  $\log t = -20$  on the vertical axis. Further error is therefore introduced when the experimental curves do not converge to a point on the  $\log t$  axis, and in particular, when they do not tend to converge to the point  $\log t = -20$ . Considerable improvement in correlation for times between 1 and 1000 hours would be obtained if a value of  $C$  other than 20 were used for a particular material (in the illustrative case a better average value might be  $C = 30$ ); however, some error results in any case from nonlinearity of the experimental curves and the lack of true tendency for these curves to converge to a single point on the  $\log t$  axis.

#### NEW TIME-TEMPERATURE PARAMETER

##### Assumed Relation and Material Constants

Reference to the schematic cross plot in figure 3 shows that at a given stress, equal increases in  $\log t$  result in approximately equal increases in  $T$  in the range of  $\log t$  greater than unity, suggesting that a plot of  $\log t$  versus  $T$  at constant stress should be approximately linear for times over 10 hours. Figure 5 shows the typical sche-

matic results obtained when plots are made of this function. At the very short rupture times there is considerable curvature in the constant-nominal-stress lines (increased by the use of the direct scale for temperature rather than the reciprocal scale), but in the practical range, for most applications between 10 and 10,000 hours the lines are quite straight and tend to converge to a common point. Therefore, over the time range in which the relation is approximately linear, a new time-temperature parameter can be derived based on the assumption of the convergence of all stress lines to a common point  $(T_a, \log t_a)$ , where  $T_a$  and  $\log t_a$  are material constants. The equation of each line is

$$\frac{T - T_a}{\log t - \log t_a} = S \quad (1)$$

where  $T$  and  $\log t$  are corresponding temperature and rupture time and  $S$  is the slope. In equation (1) the only term dependent upon the stress is  $S$ ; hence, a plot of  $\frac{T - T_a}{\log t - \log t_a}$  against stress should result in a single curve which, if once determined from data at moderate rupture times, should be useful for extrapolation to longer rupture times.

Because the relation  $\frac{T - T_a}{\log t - \log t_a}$  arises from the assumption that constant-stress lines are linear on the  $\log t$  against  $T$  coordinates, it will hereinafter be called the linear time-temperature parameter.

The assumption of convergence of all constant-stress lines to a common point  $(T_a, \log t_a)$  is consistent with the observed trend of the experimental data; it also simplifies the form of the time-temperature relation and reduces greatly the amount of experimental data required for a complete characterization of a material. Use of the linear approximation results in predicted trends of constant-temperature curves (in conventional stress-rupture plots) that have a very reasonable appearance in the time range immediately beyond the experimental range. However, the extent to which extrapolation may be performed in the time range considerably above 10,000 hours cannot be predicted in the absence of suitable experimental data. The point  $(T_a, \log t_a)$  is not considered to have physical significance; it is considered only to be the point of convergence of the tangents to the curves of  $\log t$  against  $T$  in the time range from approximately 10 to 10,000 hours. Since there is relatively little curvature in this time range, the tangents represent a good approximation to the experimental curves, but no conclusions can be drawn about the linearity in longer time ranges.

It is probably also true that application of the linear relation will be invalidated in any temperature range where major metallurgical transformations take place. Hence, caution must be exercised in the prediction of properties at temperatures beyond the range of experience.

### Illustrative Examples

The method of determining the optimum values of  $T_a$  and  $\log t_a$  for a given material requires a certain amount of data analysis which depends on the amount and type of rupture data available. The method used in the investigation will be discussed in a later section. The present intention is to demonstrate that for the materials considered all the available data at rupture times above approximately 10 hours can be well correlated once  $T_a$  and  $\log t_a$  have been determined.

Analyses of the type presented have been made on 40 different materials. These materials represent ferritic and austenitic steels (ref. 2), high-temperature alloys of the nickel-base type (refs. 3 and 5), high-temperature alloys of the cobalt-base type (ref. 4), and aluminum (ref. 6), as well as various experimental high-temperature alloys for which data are not published. The materials used for illustrative purposes are not necessarily those best correlated by the linear time-temperature relation, but rather they are representative of the various types encountered. DM steel and 18-8 stainless steel, respectively, represent ferritic and austenitic steels which correlate well with the linear time-temperature relation but poorly with the  $(T + 460)(20 + \log t)$  relation. The alloy S-590 represents a cobalt-base alloy for which a large amount of very short-time data was available and which shows relatively good correlation with the  $(T + 460)(20 + \log t)$  parameter. The 25-20 stainless steel is a relatively unstable material compared with other steels, such as DM steel. Inconel X is included to illustrate a typical nickel-base high-temperature alloy for which data are available over a large range of stress values.

Figure 6 shows the basic data for the five illustrative materials taken from references 1 to 4. Cross-plotting and fairing the data give the constant-time curves for these materials such as shown in figure 3. From the intersections of these curves with horizontal constant-stress lines, a sufficient number of points became available to construct  $\log t$  against  $T$  plots such as those shown in figure 5. Rupture data above approximately 30 hours were used to determine the point of convergence of the constant-stress lines ( $T_a, \log t_a$ ). (It has been found that the best results are obtained if data involving rupture times between 30 and 300 (or more) hours are used in determining the constants. After the constants have been determined, however, all rupture data above 10 hours can be used to construct the master curve.) Although the values of  $T_a$  determined for most of the



materials examined ranged from 0° to 200° F, values as high as 700° F were found in several cases. However, since the results in extrapolation depend largely upon the use of the proper combination of  $T_a$  and  $\log t_a$ , rather than on the individual values of these constants, it is possible that a single value of  $T_a$  can be used for all materials to reduce the amount of testing. A low value of  $T_a$ , such as 0° F, will in general result in relatively little error in the usual time range of interest.

Master plots of logarithm of stress against  $\frac{T - T_a}{\log t - \log t_a}$  utilizing constants so determined are shown in figure 7 for each of the illustrative materials. Only the actual experimental data points from figure 6 are used in the construction of the master plots. For each material the experimental points satisfy a fairly universal relation which is shown by the solid curves in figure 7. Figure 8 shows the computed constant-temperature curves on conventional stress-rupture plots of stress against time on logarithmic coordinates. These curves could be obtained either by computation from the master plots in figure 7 or directly from constant-stress plots.

In figures 9 and 10 a corresponding analysis of the same materials based on the  $(T + 460)(20 + \log t)$  parameter is shown. Figure 9 shows the master plots based on this parameter for all data points in figure 6. Two curves are drawn through these points, the mean curve for all the data and a curve representing rupture times below 100 hours. Conventional stress-rupture plots derived from these curves are shown in figure 10. Since the master curve obtained from using all the data covers a wider range of rupture times, the resulting derived constant-temperature curves average all the data but do not properly represent the basic shape of corresponding experimental curves. Usually the experimental data fall above the predicted curve in some ranges, below in others. Thus, if data are available over a wide range of rupture times, the parameter  $(T + 460)(20 + \log t)$  can be successfully applied for approximate interpolation purposes. Extrapolation, however, results in greater error; considerable deviations occur between the experimental data points and the predicted curves in figure 10. This is true for all the materials examined. The best agreement among the 40 materials was the S-590 alloy. In this case, the parameter  $(T + 460)(20 + \log t)$  gives better results than the linear parameter in the range of low rupture times and relatively good long-time predictions.

#### Determination of Constants

The analytical approach depends upon the amount and type of experimental data available. For the analysis of data obtained in a series of conventional tests at several constant temperatures, the approach used

must be different from that employed when constant nominal stress tests have been conducted to fit the needs of the analysis. Each of these cases will therefore be considered separately.

Constant rupture-time curves, such as shown in figure 3, are used in analyzing conventional data. For the construction of such curves when the available data are limited, use can be made of the general features of such families of curves. Generally, the rupture-time curves have a convex curvature, converging at a stress level near the room-temperature ultimate tensile strength of the material. (In some cases, the curvature tends to reverse at very low stress levels.) Elevated-temperature tensile data may be used as a guide in fairing the rupture data. Thus, if a plot is made of tensile strength against temperature over the range of temperatures covered by the rupture tests, it will be found that the curve so obtained agrees approximately in shape with that for 0.1-hour rupture data. Further, since such curves are to be used in establishing the best constants for a linear time-temperature parameter, curves of equal increments of  $\log t$  should be equally spaced, at least in the time region above 30 hours. When the constant-stress curves are to be constructed from the cross plots, as many stress levels as desired can be used in the analysis, provided they are in the range where sufficient data are available for interpolation. On the bases of the analyses made, the most satisfactory stress range for determining the point of intersection is between approximately 10 and 40 percent of the room-temperature ultimate tensile strength of the material.

If the experimental data are to be obtained from a minimum number of tests expressly for such an analysis, a series of constant-nominal-stress tests best serve for the determination of  $T_a$  and  $\log t_a$ . It is desirable to obtain data in the range of approximately 30 through 300 hours for at least two stress levels, at about 10 percent and 40 percent of the ultimate tensile strength. Once these constants have been determined, the master plot of the logarithm of stress against  $(T - T_a)/(\log t - \log t_a)$  can be constructed using any data above approximately 10 hours at other stress levels as necessary.

#### Extrapolation of Short-Time Data

Experience with analysis of a number of materials has suggested that the differences which can be introduced in the determination of these constants by use of data in the range between 30 and 300 hours, as compared with the use of data for longer times, have relatively little effect on the results of extrapolation up to at least 10,000 hours. However, the question of precisely how many tests in the 30- to 300-hour rupture-time range might be required in any specific case is left to experimental investigation.

In figure 7 the solid points represent the data below 100-hour rupture time. If the same values of  $T_a$  and  $\log t_a$  are used for each material as were determined using longer rupture times, it can be seen that the master curves will be almost exactly the same when data are limited to the 100-hour time range as when all the data are used. Hence the plots in figure 10, including the extrapolated data to 10,000 hours, would be exactly the same, although only the data below 100 hours are used to obtain the master curve. However, it should be emphasized that data below approximately 10-hour rupture time often deviate sufficiently from the linear portion of the constant nominal stress curves to introduce error in the master plot. For example, in the case of S-590 alloy, the low-time data are not included in the master plot, and correspondingly, the conventional plot in figure 8(e) based on the master curve of figure 7(e) does not fit the low-time data.

#### APPLICATION TO CREEP

Only limited creep data are available in the literature suitable for a critical analysis of the applicability of a given time-temperature relation. Analysis of suitable available data indicated, however, that the use of the parameter  $(T + 460)(20 + \log t)$  to correlate creep data at a given stress, where  $t$  is the time to produce a given total elongation, leads to the same type of discrepancies as its use to correlate stress-rupture data. On the other hand, the linear time-temperature relation was found to yield an improved correlation. Figure 11 shows a master plot for Nimonic 80 based on the linear parameter. These data are presented in reference 5 in the form of average curves rather than experimental data points, and the data points used for figures 11 represent values from these curves. The three curves shown are for rupture, for 0.2-percent plastic creep strain, and for 0.1-percent plastic creep strain. For each of these conditions, stress is plotted against  $\frac{T - 100}{\log t - 17}$ , where  $T$  is the temperature in degrees Fahrenheit and  $t$  is the time in hours. It is seen that the data points at all temperatures correlate very well with the master curves drawn through them. In this case,  $T_a$  and  $\log t_a$  for rupture and for each of the two conditions of plastic creep strain are the same, although it is possible that for other materials different values of  $T_a$  and  $\log t_a$  will apply to fracture and to creep.

Reference 2 recommends the use of the parameter  $(T + 460)(20 - \log r)$  to correlate minimum creep data, where  $r$  is the minimum creep rate. Data covering a sufficiently wide range of the creep variables to permit an adequate critical analysis of this parameter are not generally available. However, the linear parameter in the form  $(T - T_a)/(\log r + \log r_a)$  where  $r$  is the minimum creep rate and  $r_a$  is a material constant, has

been applied with good results in several cases where extensive data are available - principally for S-590 alloy (ref. 1) and Monel (ref. 7). The value of  $T_a$  was found to be about the same as that for correlating the stress-rupture data for these materials; the value of  $\log r_a$  was found to be approximately 2 to 4 units lower than  $\log t_a$  (the correlating constant for stress-rupture data) when  $r$  and  $r_a$  are expressed in percent per hour and  $t$  and  $t_a$  in hours.

### CONCLUSIONS

The examination of published data on 40 materials representing ferritic and austenitic steels, high-temperature alloys, and aluminum alloys has led to the following conclusions, which have been found to apply in the range of rupture times between 10 and 10,000 hours:

1. The experimental data justify the assumption that when the logarithm of the rupture time is plotted directly against temperature with nominal stress as a parameter, reasonably straight lines result and these lines tend to converge to a single point ( $T_a, \log t_a$ ). Based on this assumption of linearity and convergence, a time-temperature parameter in the form  $(T - T_a)/(\log t - \log t_a)$  is proposed for the correlation of rupture data and the prediction of long-time behavior from data in the moderate-rupture-time range. It is believed that data in the rupture-time range below 300 hours should suffice to determine the constants  $T_a$  and  $\log t_a$ , and the greater portion of the data used to determine the master plot can be in the 10- to 100-hour time range. In all cases examined, the use of data at rupture times below 300 hours resulted in accurate predictions of rupture times in the 10,000-hour range.

2. Examination of limited available creep data indicates that a parameter in the form  $(T - T_a)/(\log t - \log t_a)$  is suitable for correlation and prediction of time to produce a given total creep elongation; and a parameter in the form  $(T - T_a)/(\log r + \log r_a)$  is suitable for correlation and prediction of minimum creep rate.

3. The parameter  $(T + 460)(20 + \log t)$  was found in some cases to yield rupture times in error by a factor of 10 when 10,000-hour data are predicted from 100-hour data. These discrepancies arise from the use of a universal constant equal to 20 and also from the nonlinearity of the relation between the logarithm of the rupture time and the reciprocal of the absolute temperature (at a given stress).

Lewis Flight Propulsion Laboratory  
National Advisory Committee for Aeronautics  
Cleveland, Ohio, December 11, 1952.

## APPENDIX - CRITICAL EXAMINATION OF LINEARITY OF PLOT OF

$$\text{LOG } t \text{ AGAINST } \frac{1}{T + 460}$$

The following analysis of 16-13-3 steel is presented in order to demonstrate by numerical example the basis for showing in figure 3 the

typical shapes of plots of  $\log t$  versus  $\frac{1}{T + 460}$ .

Figure 12 shows the conventional stress-rupture data for 16-13-3 steel as taken from reference 2. The solid lines are drawn for reasonable fit with the data in the experimental range. Extrapolations of one-half a time cycle for the 1200° F and 1400° F curves are shown by the dotted lines. Figure 13 shows constant rupture-time curves derived by cross-plotting the values from the curves in figure 12. The constant rupture-time lines from  $\log t = -1.0$  to  $\log t = 3.5$  are shown as solid lines; the dotted lines for  $\log t = 4.0$  and  $\log t = 4.5$  are based on the points A, B, C, and D and on the general family relation among such curves as established in the range of actual experimental data.

Figure 14 shows cross plots from figure 13 of  $\log t$  against  $\frac{1}{T + 460}$ .

The stress range of primary interest for analysis is between 5000 and 20,000 pounds per square inch, where the high-rupture-time data are established with the most certainty; the curve for 30,000 pounds per square inch, which involves only low rupture times, is also included for later use. For various constant stress values, curvature is observed at the high rupture times. To ascertain the significance of this curvature in relation to extrapolation of short-time stress-rupture data, straight lines are drawn to best fit the experimental data in the rupture time range up to about 300 hours. If only the rupture data below 300 hours were available, the best extrapolation based on the linearity of plots

of  $\log t$  against  $\frac{1}{T + 460}$  would be therefore by extension of these

lines. (This case represents the assumption that  $C$  in the relation of ref. 2 varies with both material and stress, and should therefore give the best over-all results available from the rate-process equation.) If the 1200° F curve in figure 12 is to be determined by extrapolation from data below the 300-hour rupture-time range, points on this curve are determined from figure 14 by the intersection of the vertical line at 1200° F with the extensions of the straight lines representing the data in the rupture-time range below 300 hours. These points establish the curve EF in figure 12, where it differs appreciably from the experimental curve even in the range where data are available.

Figure 15 shows constant stress cross plots of  $\log t$  against temperature using the same data as those used for the construction of figure 13, and the linearity is considerably improved. Establishment of the  $1200^{\circ}$  F curve in figure 12 by linear extension in figure 15 of the rupture data below 300 hours to the points of intersection with the  $1200^{\circ}$  F line is seen to be in better agreement with the experimental  $1200^{\circ}$  F curve.

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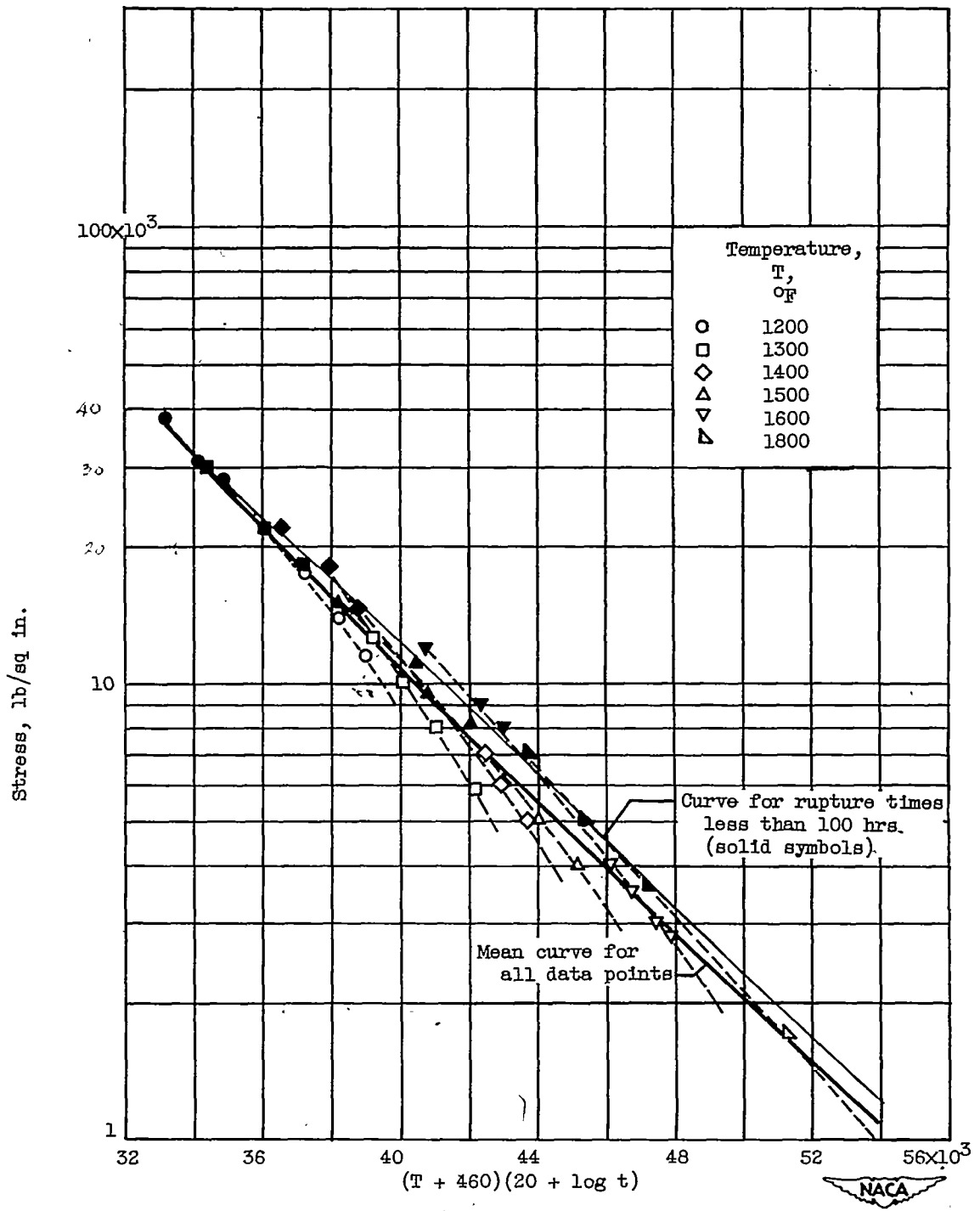
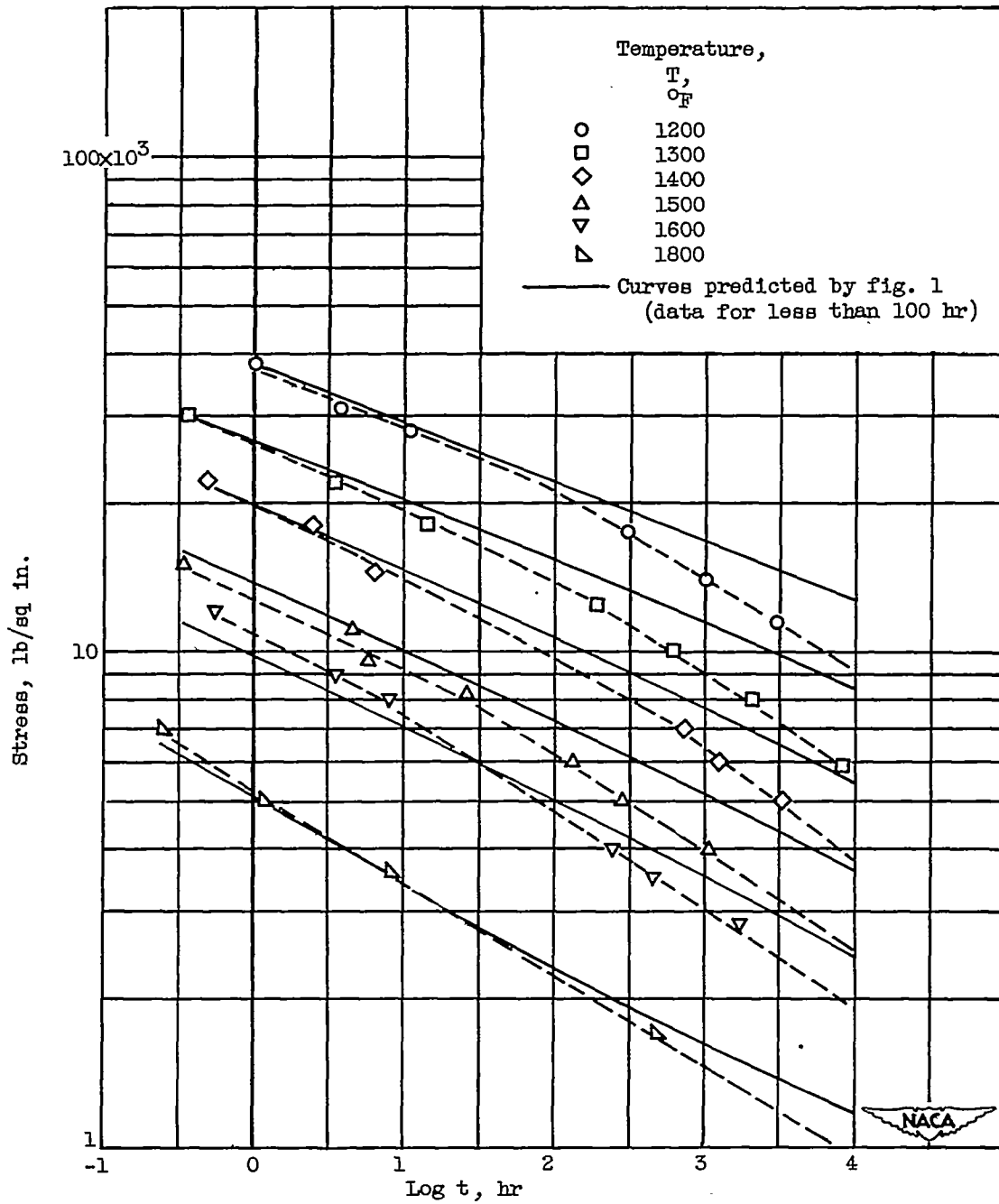


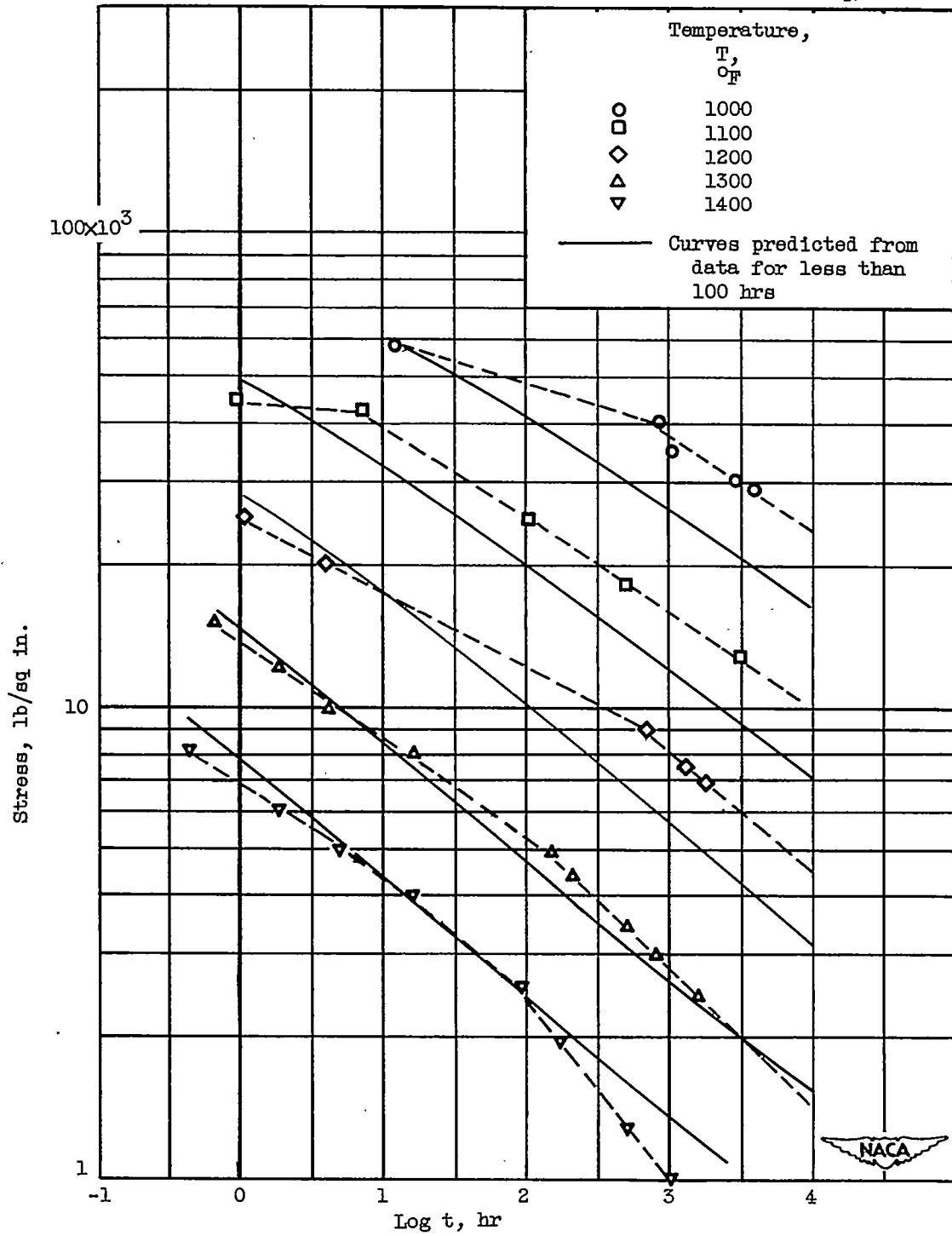
Figure 1. - Master rupture curves for 18-8 steel using parameter  $(T + 460)(20 + \log t)$ .



(a) 18-8 stainless steel.

Figure 2. - Conventional stress-rupture plots derived from  $(T + 460)(20 + \log t)$  parameter using data for less than 100 hours.





(b) DM steel.

Figure 2. - Concluded. Conventional stress-rupture plots derived from  $(T + 460)(20 + \log t)$  parameter using data for less than 100 hours.

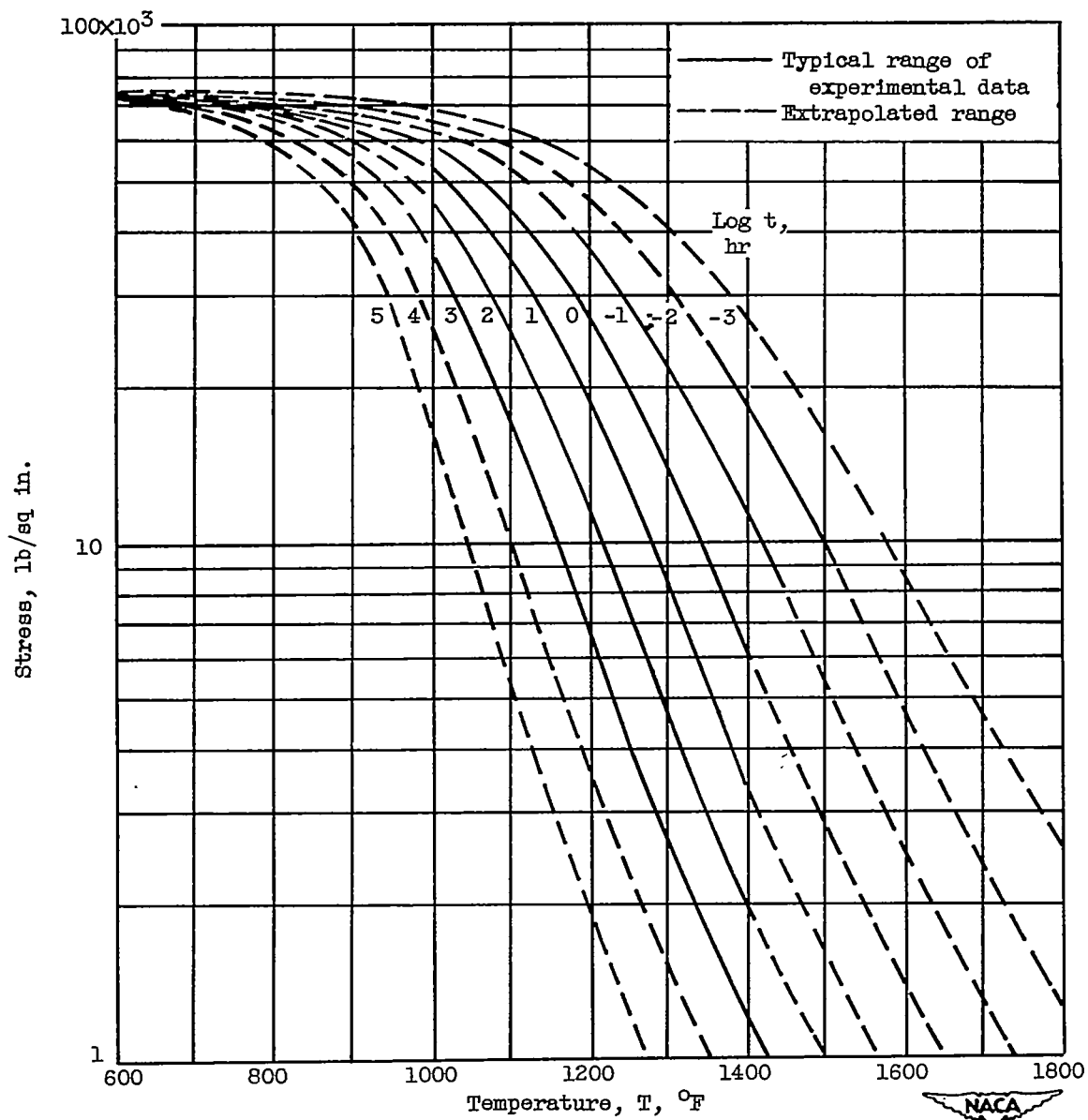


Figure 3. - Schematic diagram showing typical constant-time cross plot used in analysis of data.

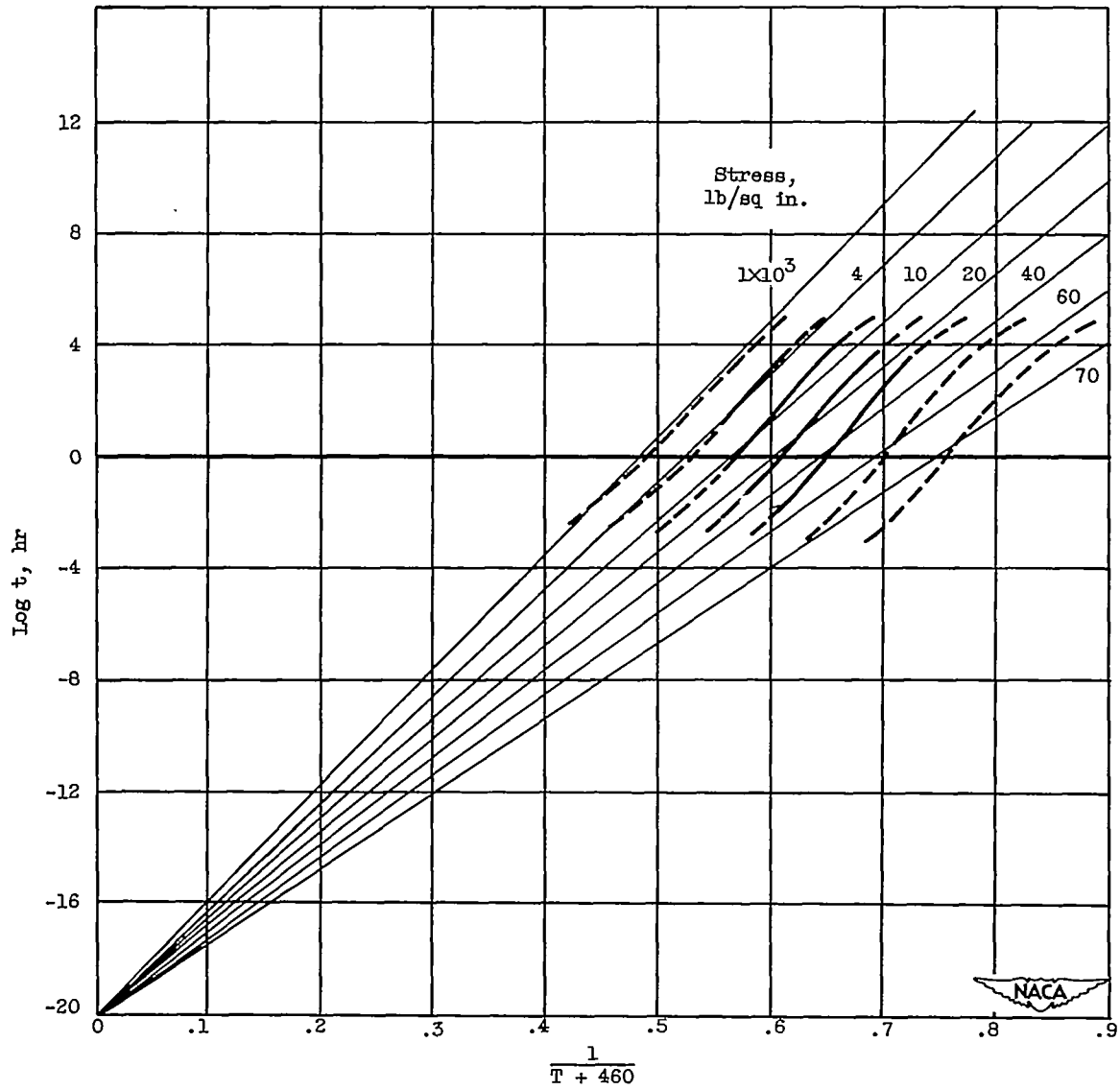


Figure 4. - Schematic representation corresponding to figure 3 showing constant nominal stress curves for logarithm of rupture time against reciprocal of absolute temperature.

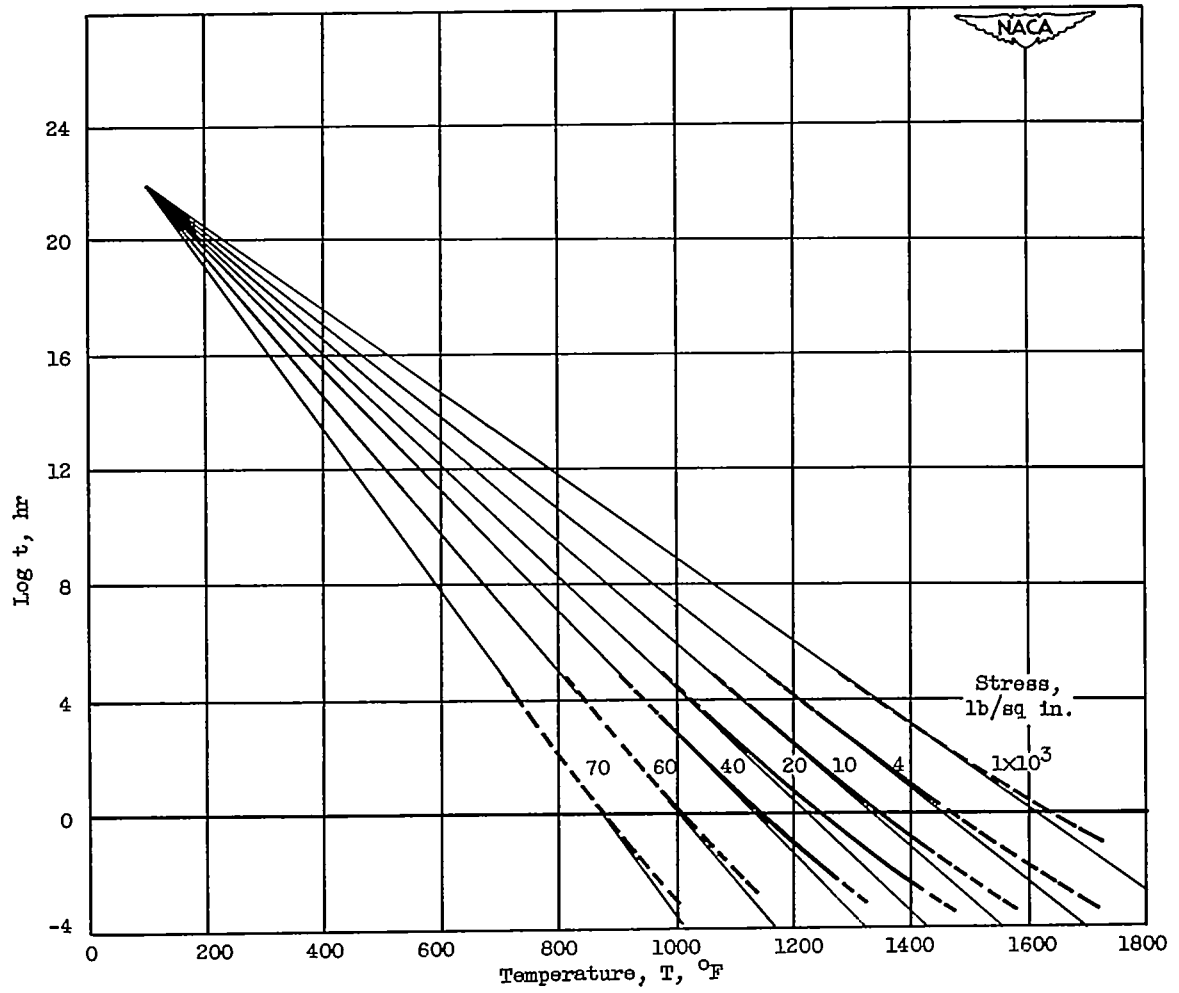
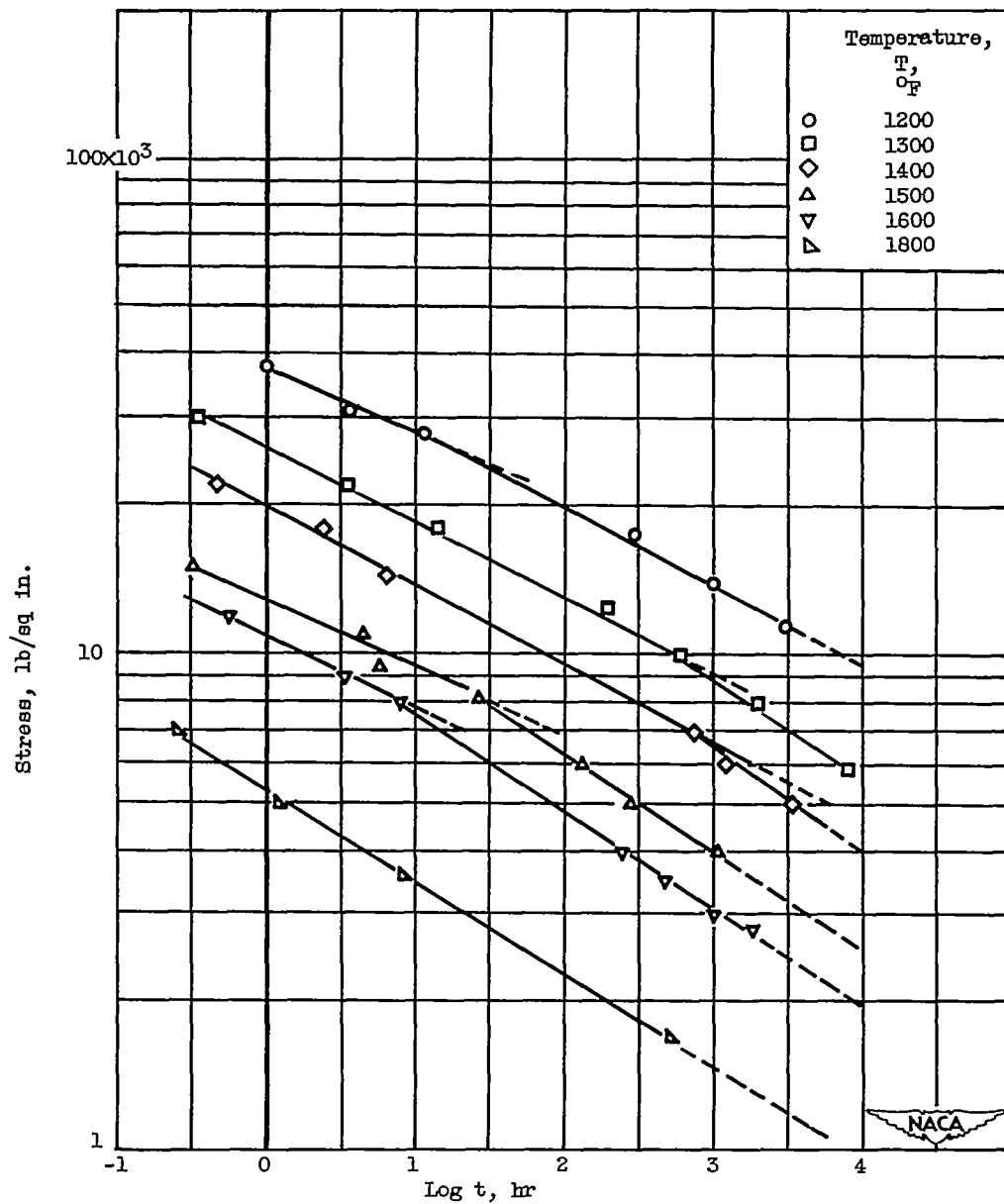
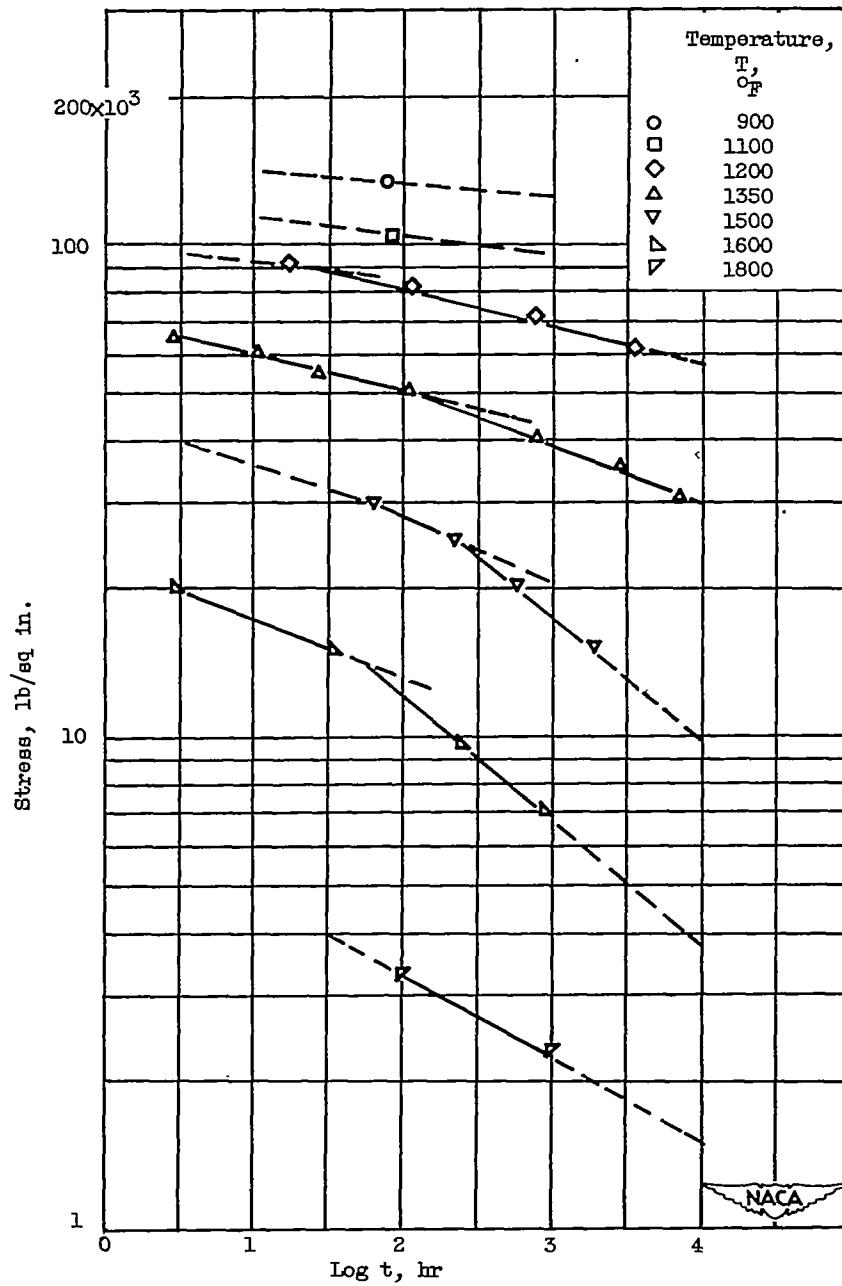


Figure 5. - Schematic diagram corresponding to figure 3 of constant-nominal stress curves for logarithm of rupture time against temperature.



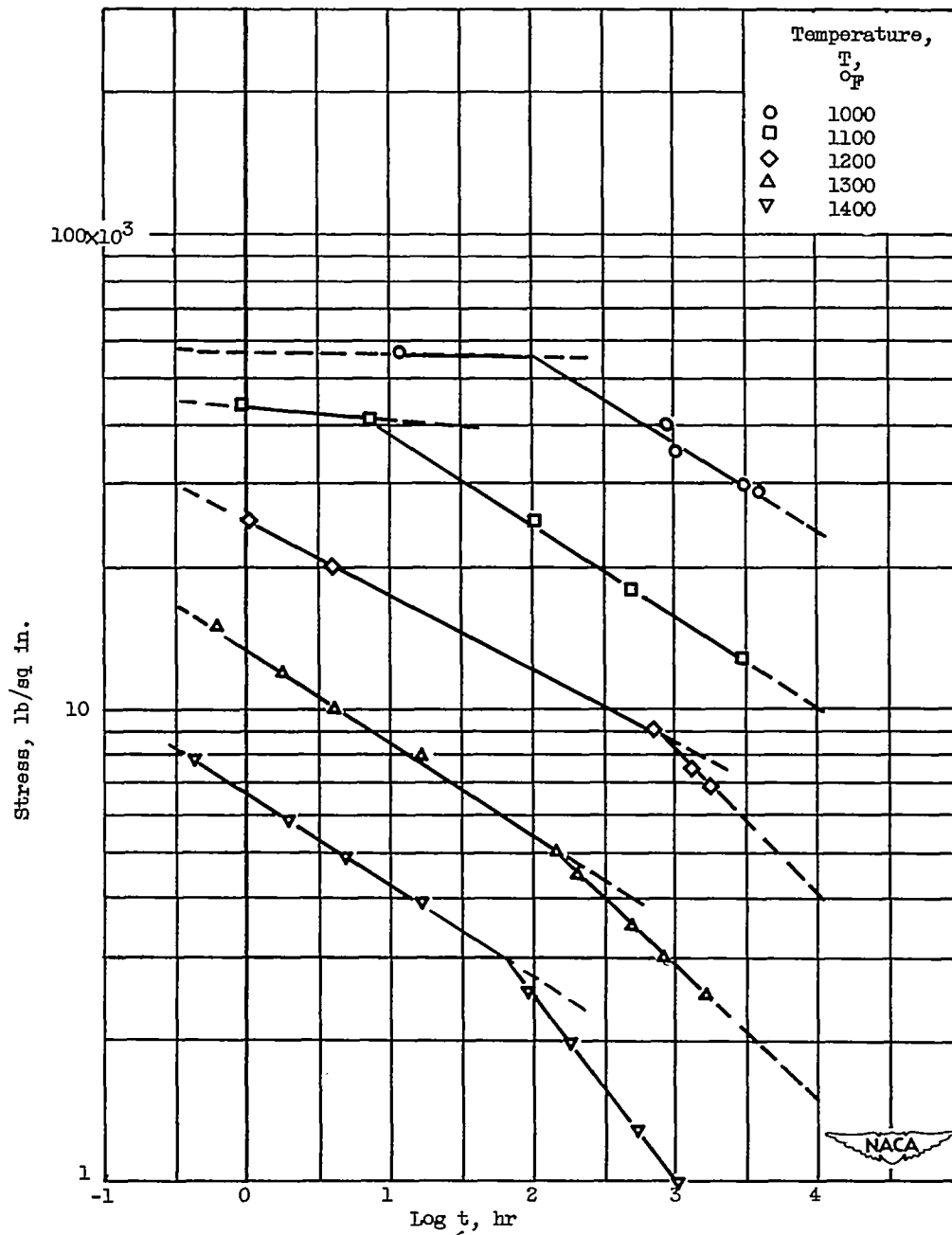
(a) 18-8 stainless steel (ref. 3).

Figure 6. - Basic stress-rupture data taken from published sources.



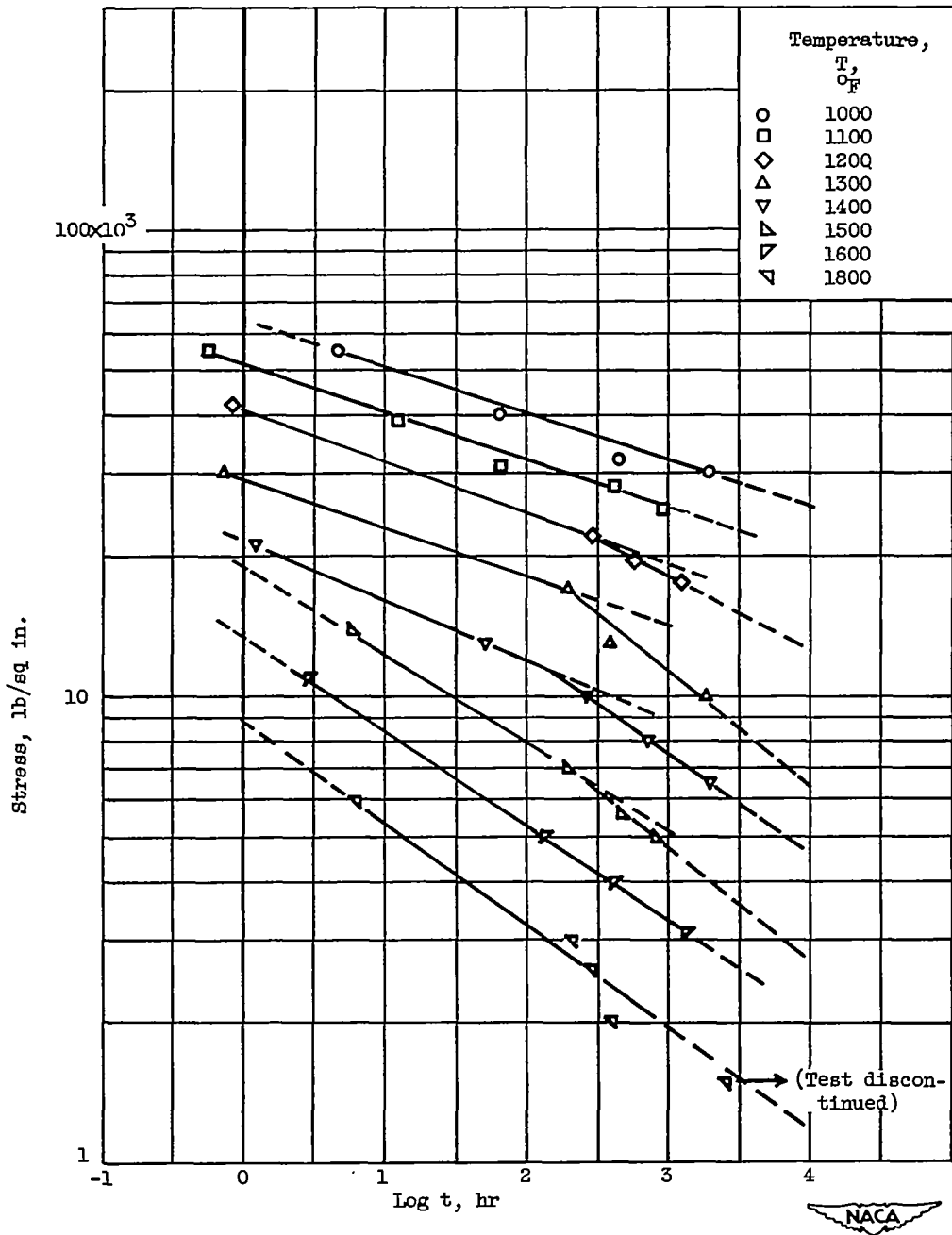
(b) Inconel X (ref. 4).

Figure 6. - Continued. Basic stress-rupture data taken from published sources.



(c) DM steel (ref. 3).

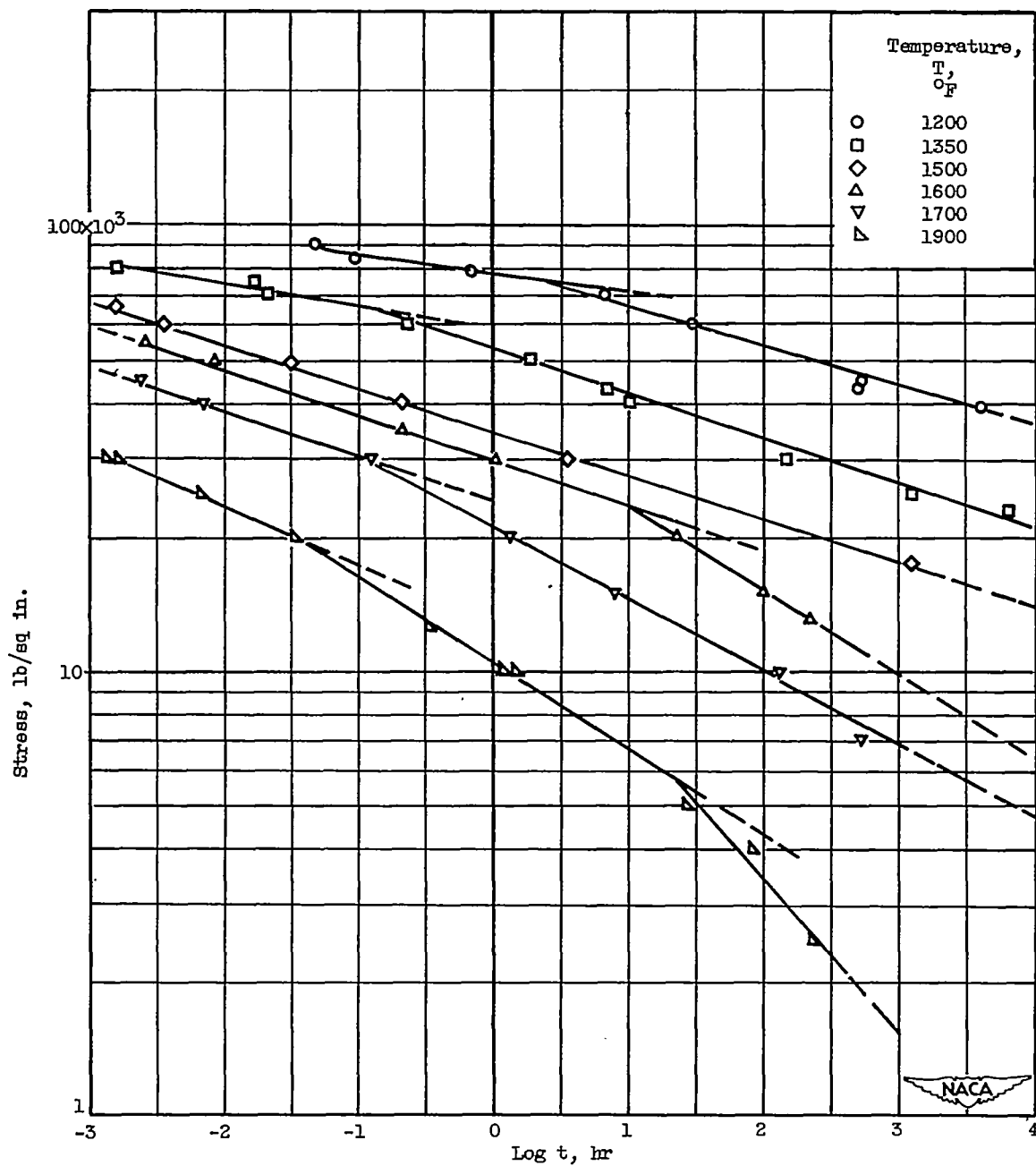
Figure 6. - Continued. Basic stress-rupture data taken from published sources.



(d) 25-20 stainless steel (ref. 3).

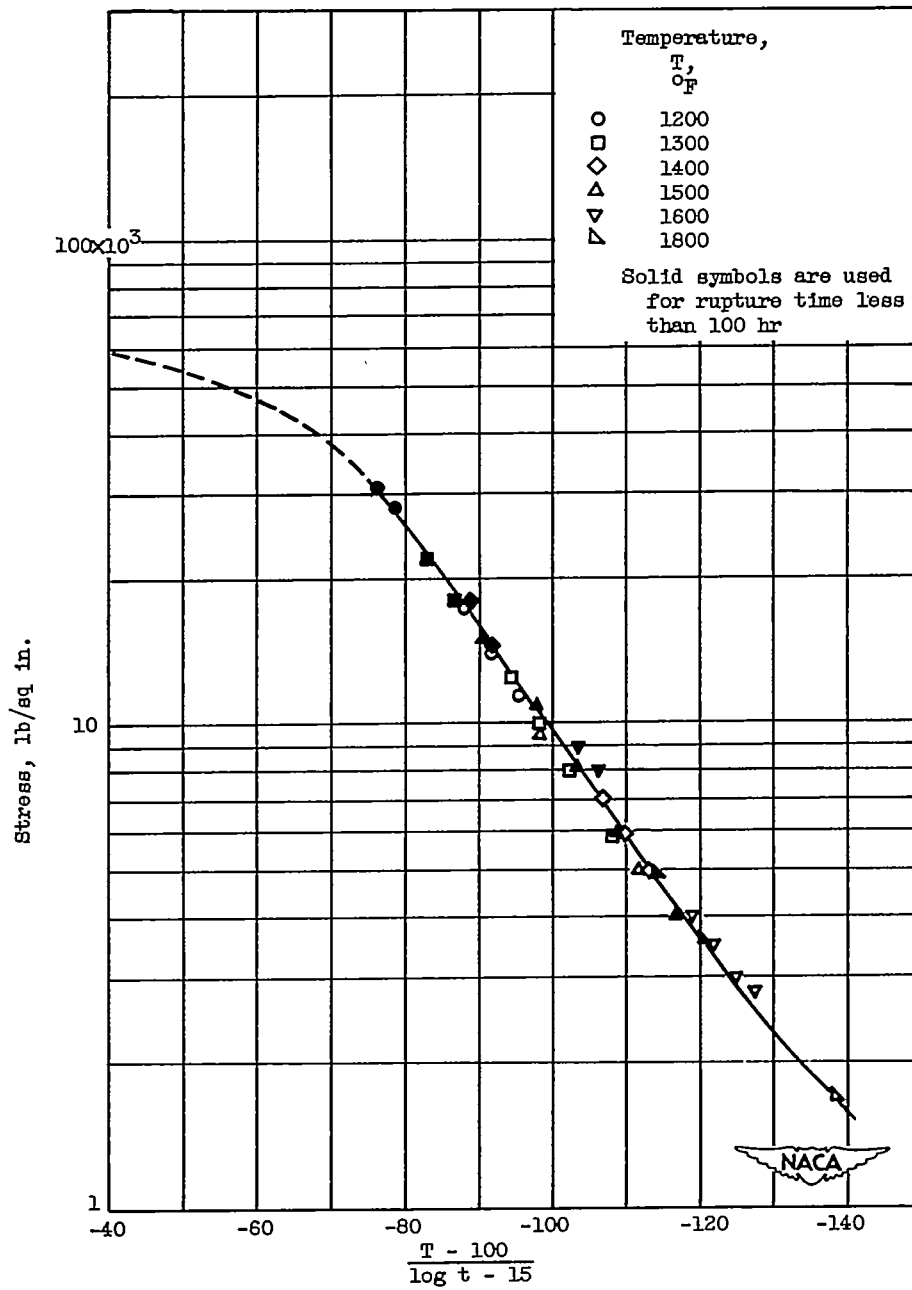
Figure 6. - Continued. Basic stress-rupture data taken from published sources.





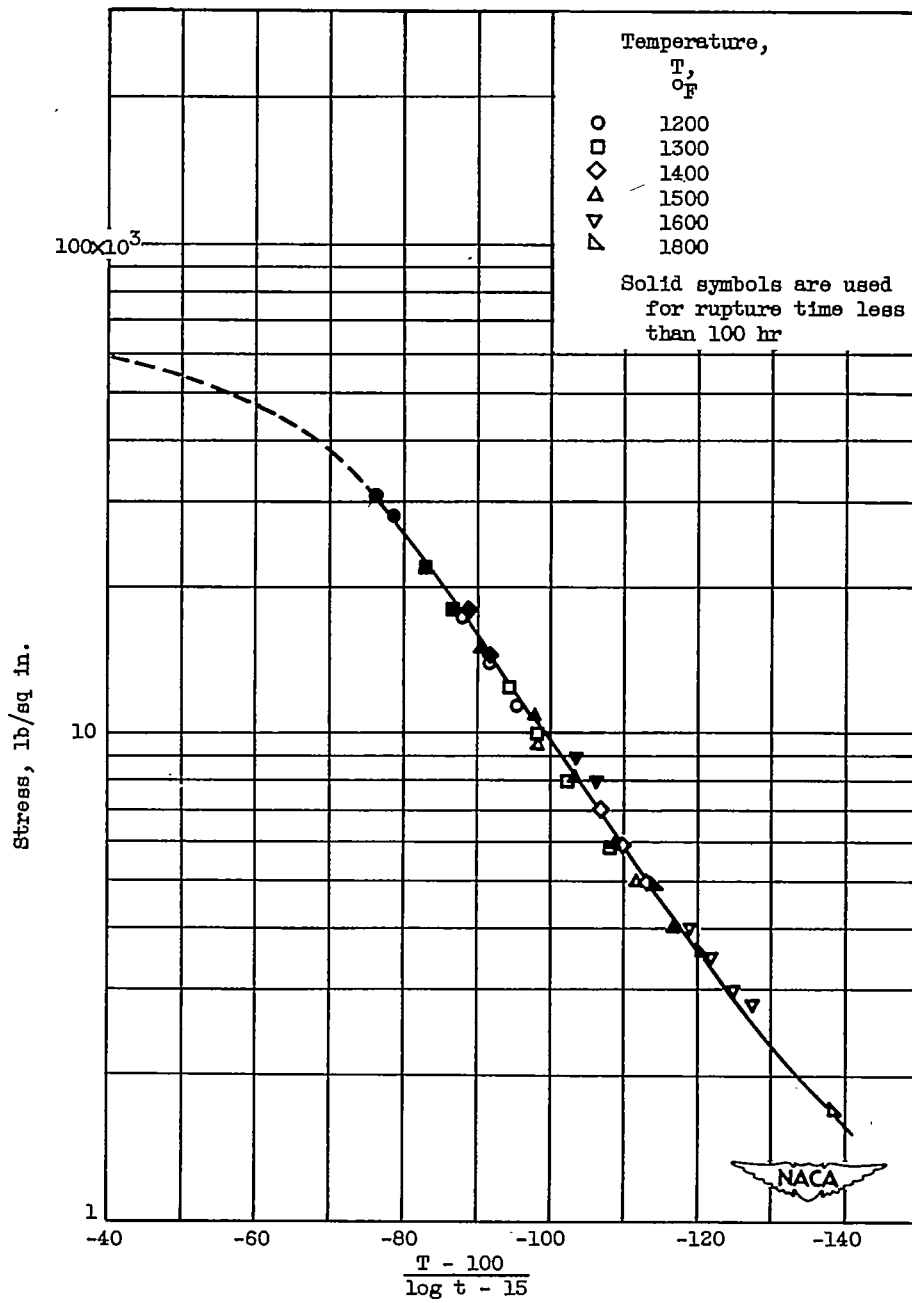
(e) S-590 alloy (ref. 1).

Figure 6. - Concluded. Basic stress-rupture data taken from published sources.



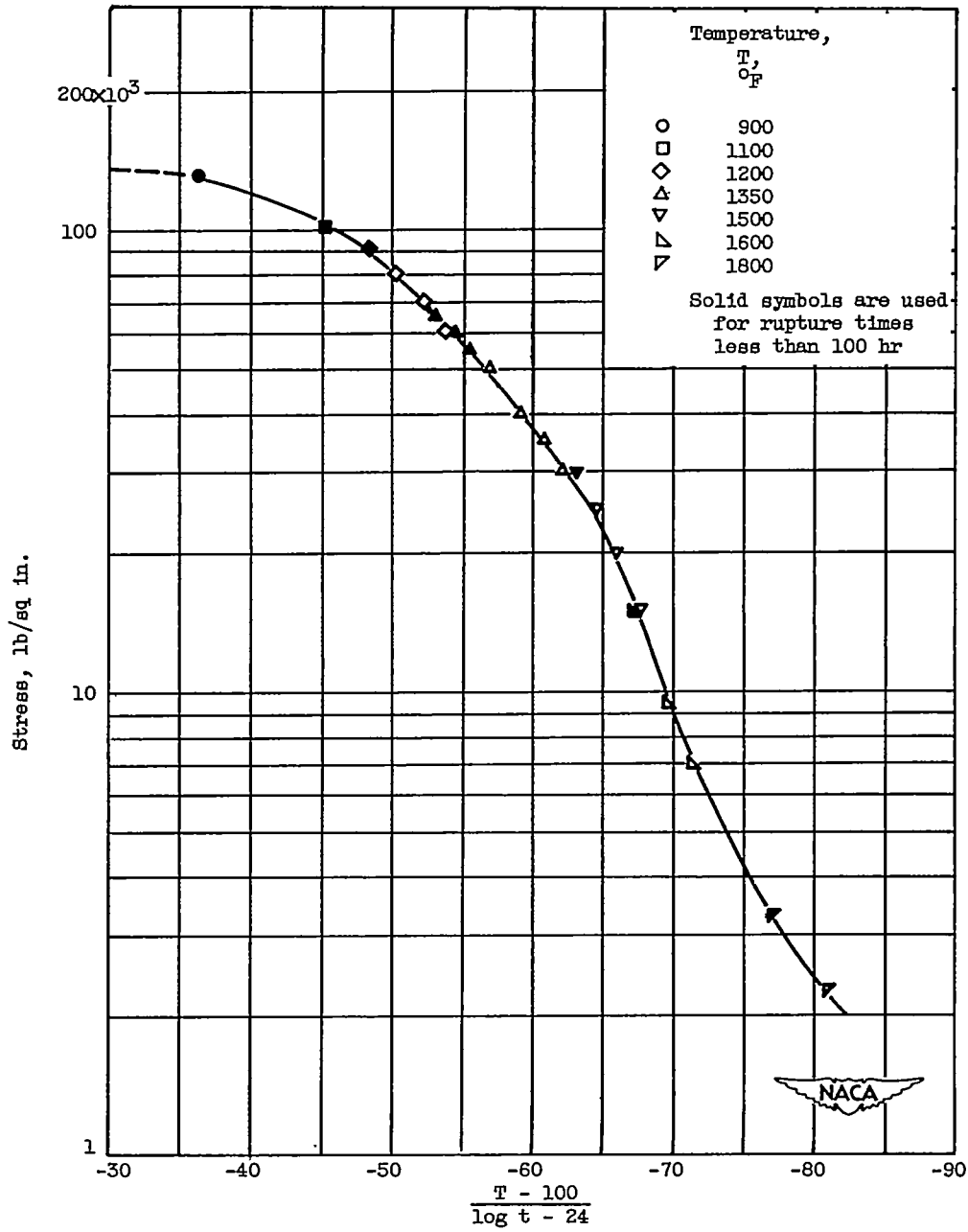
(a) 18-8 stainless steel.

Figure 7. - Master rupture curves for experimental data in time range above 1 hour using values of  $T_a$  and  $\log t_a$  determined in figure 7.



(a) 18-8 stainless steel.

Figure 7. - Master rupture curves for experimental data in time range above 1 hour using values of  $T_a$  and  $\log t_a$  determined in figure 7.



(b) Inconel X.

Figure 7. - Continued. Master rupture curves for experimental data in time range above 1 hour using values of  $T_a$  and  $\log t_a$  determined in figure 7.

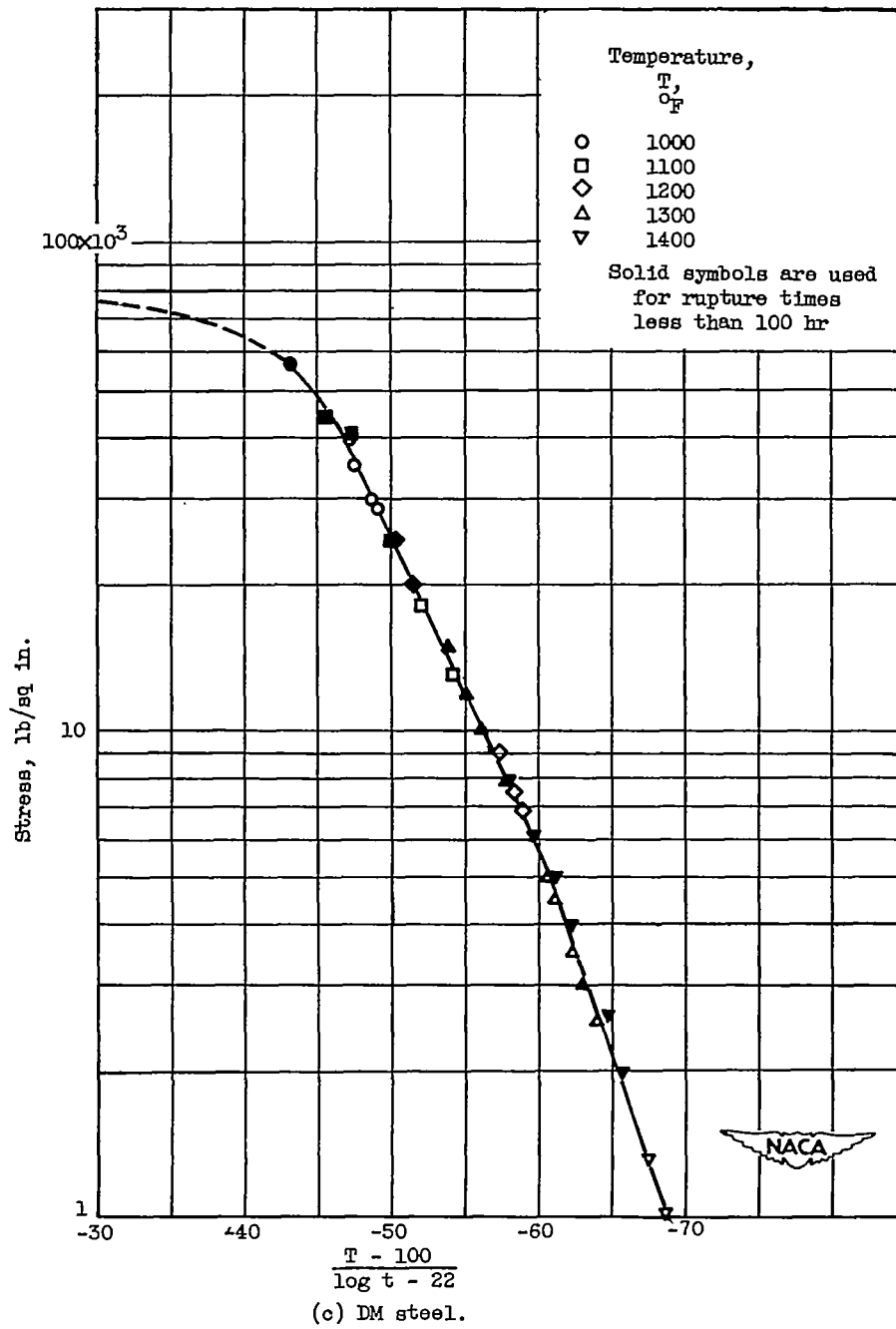
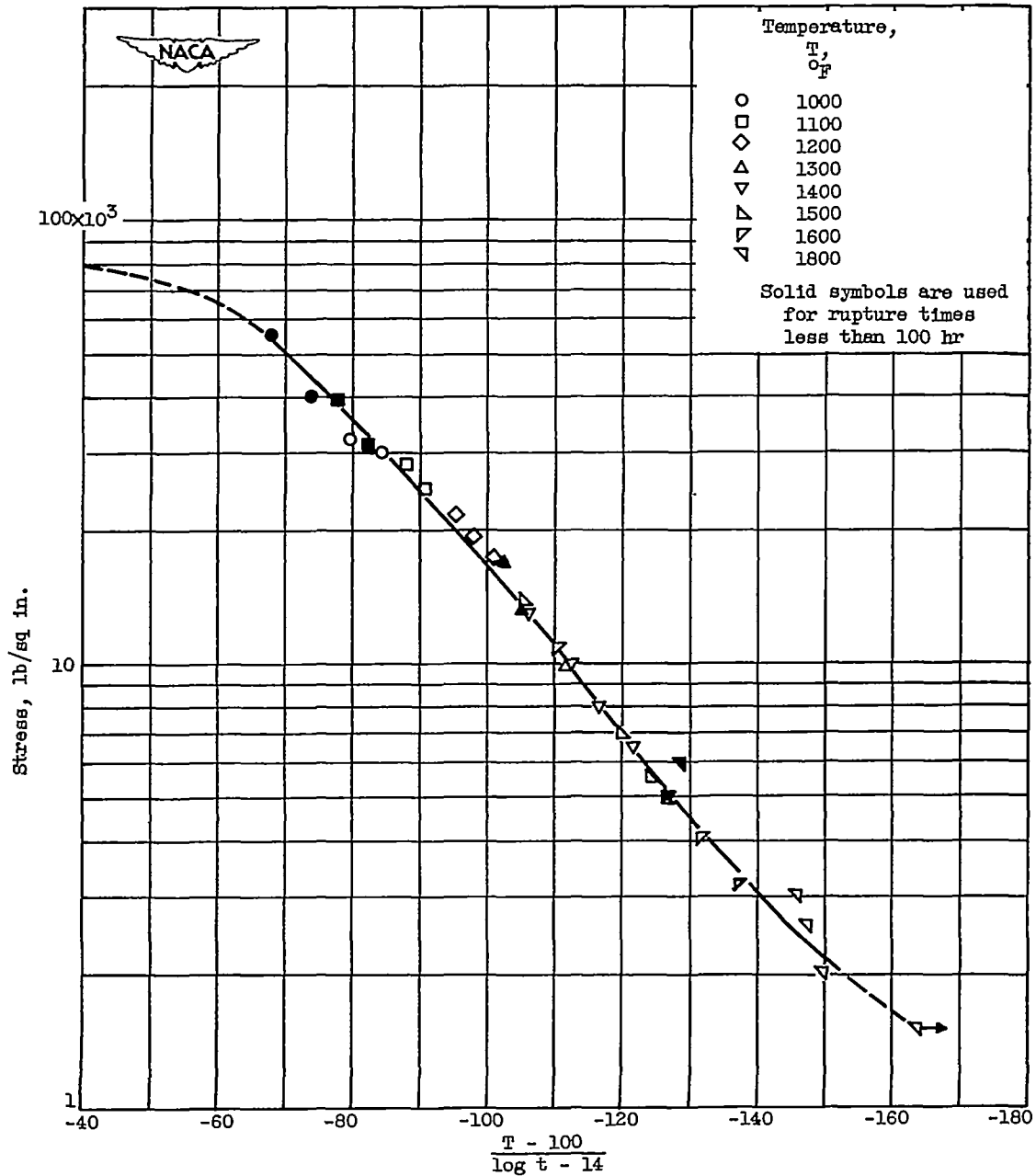
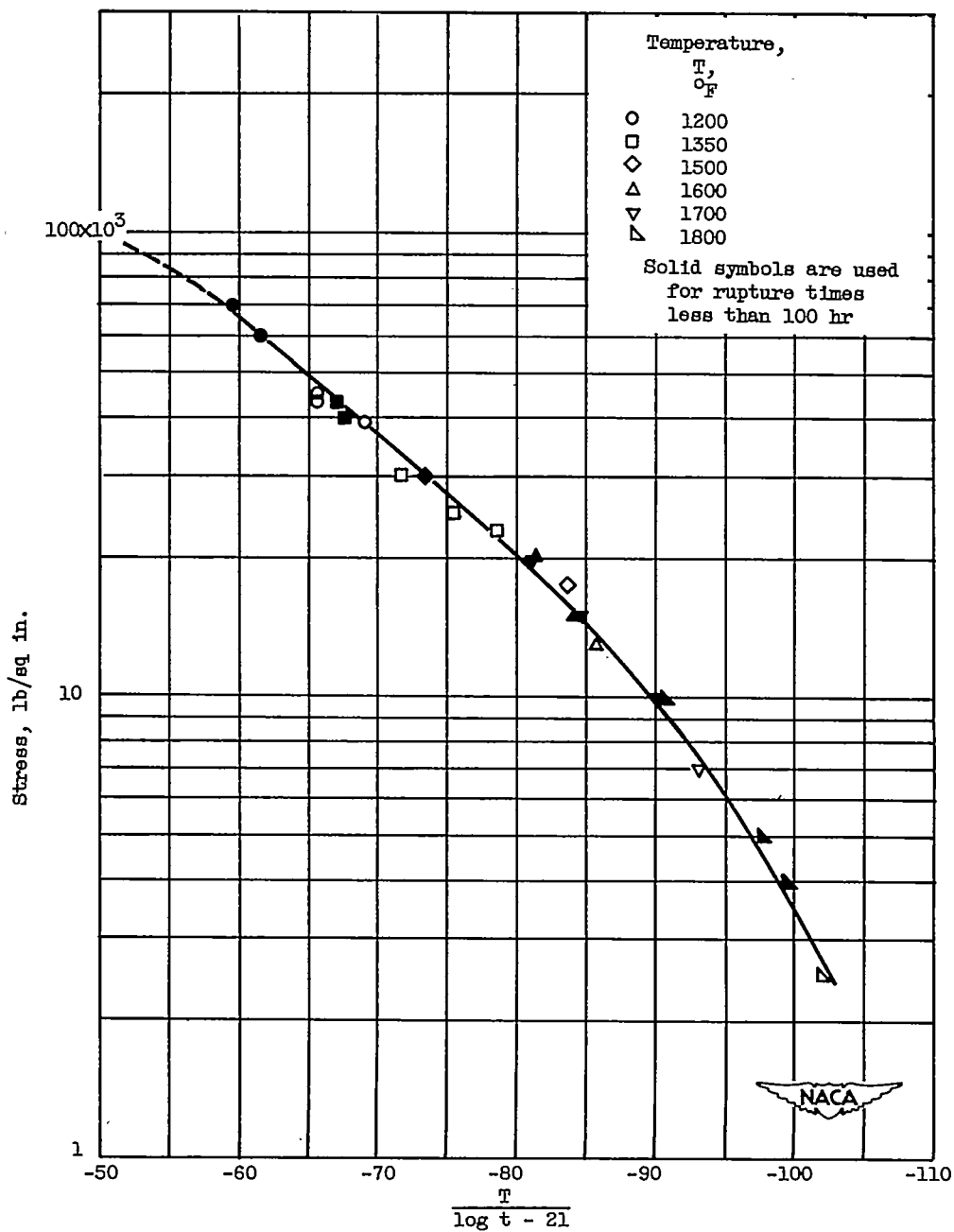


Figure 7. - Continued. Master rupture curves for experimental data in time range above 1 hour using values of  $T_a$  and  $\log t_a$  determined in figure 7.



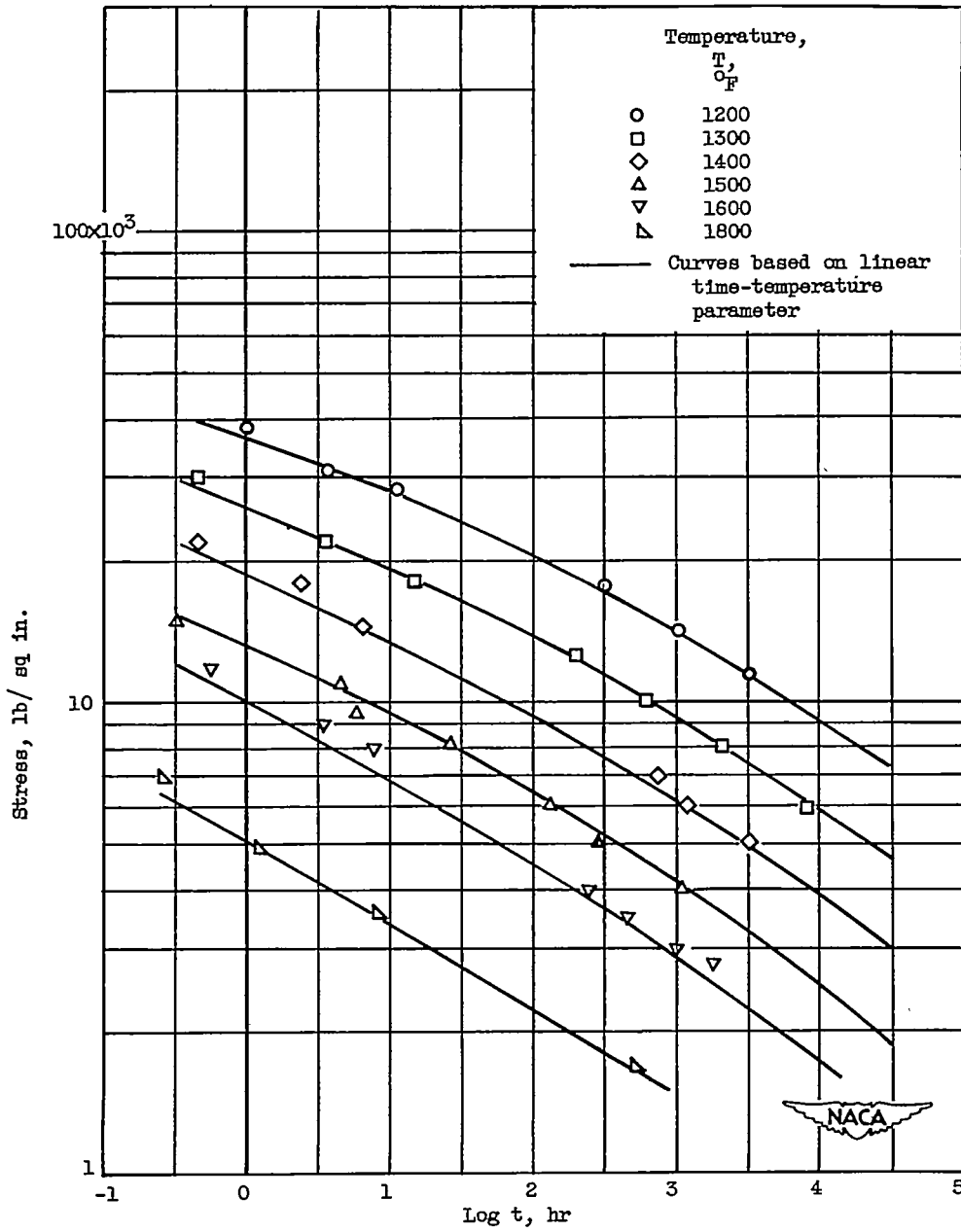
(d) 25-20 stainless steel.

Figure 7. - Continued. Master rupture curves for experimental data in time range above 1 hour using values of  $T_a$  and  $\log t_a$  determined in figure 7.



(e) S-590 alloy.

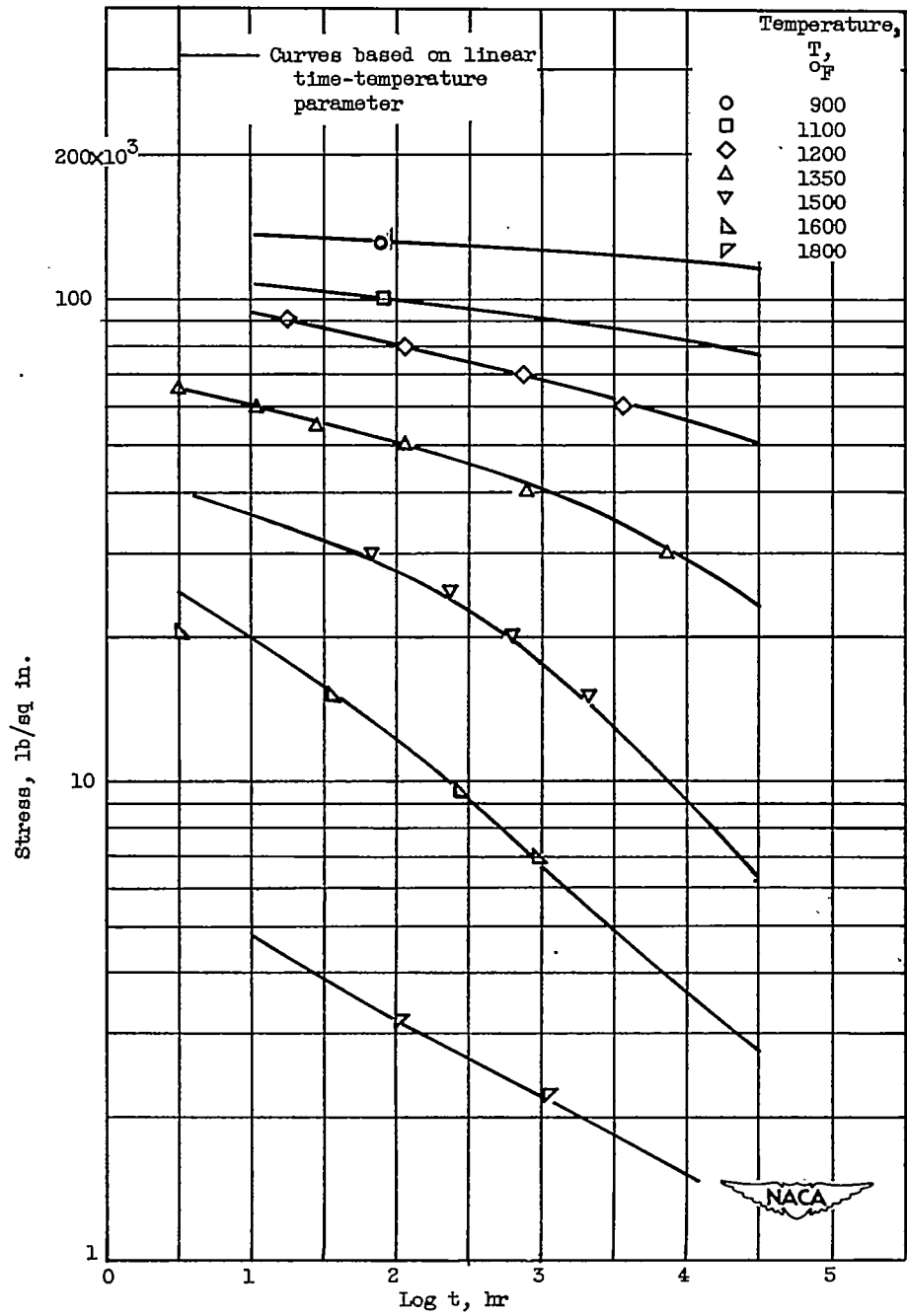
Figure 7. - Concluded. Master rupture curves for experimental data in time range above 1 hour using values of  $T_a$  and  $\log t_a$  determined in figure 7.



(a) 18-8 stainless steel.

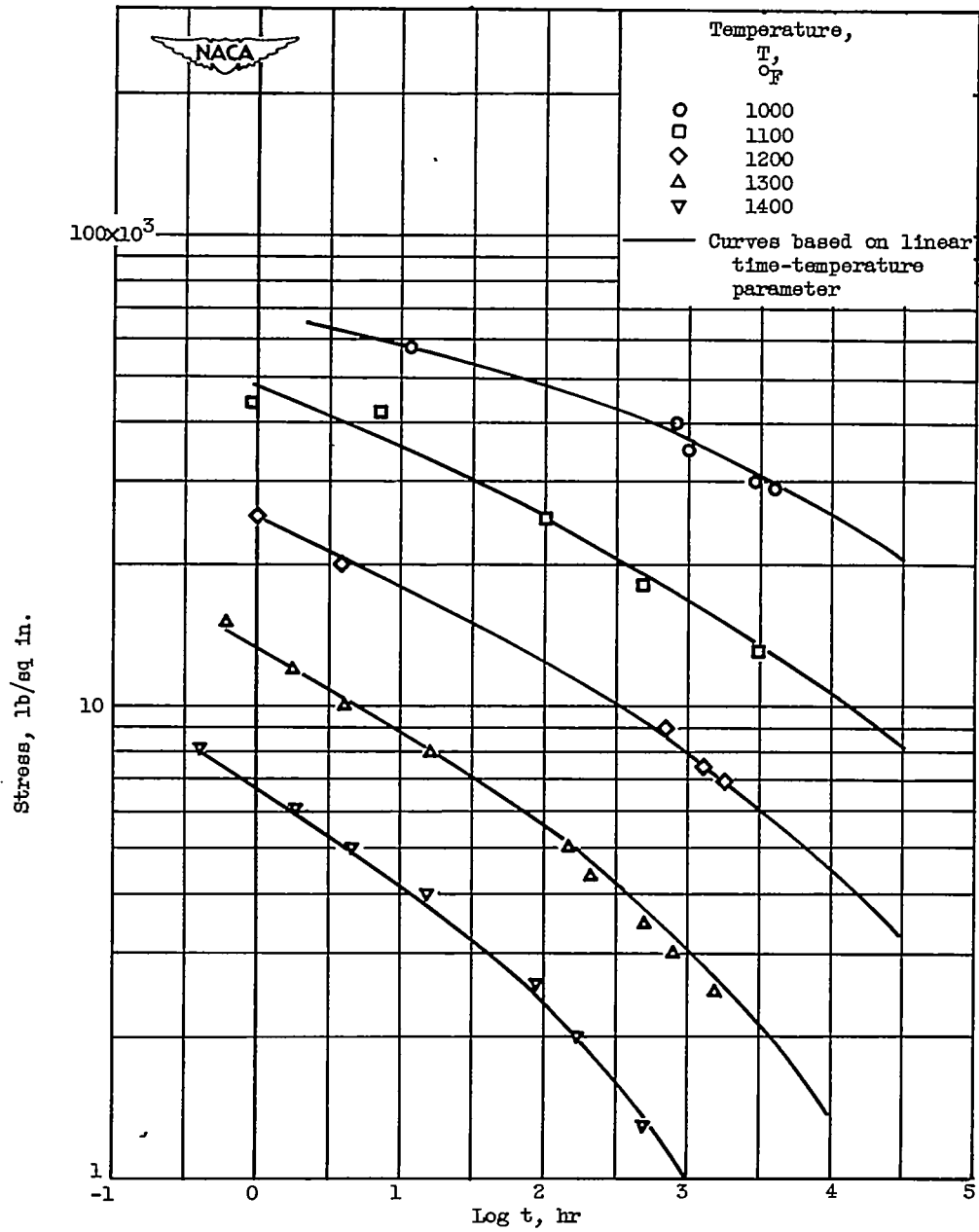
Figure 8. - Conventional stress-rupture curves derived from master curves in figure 9.





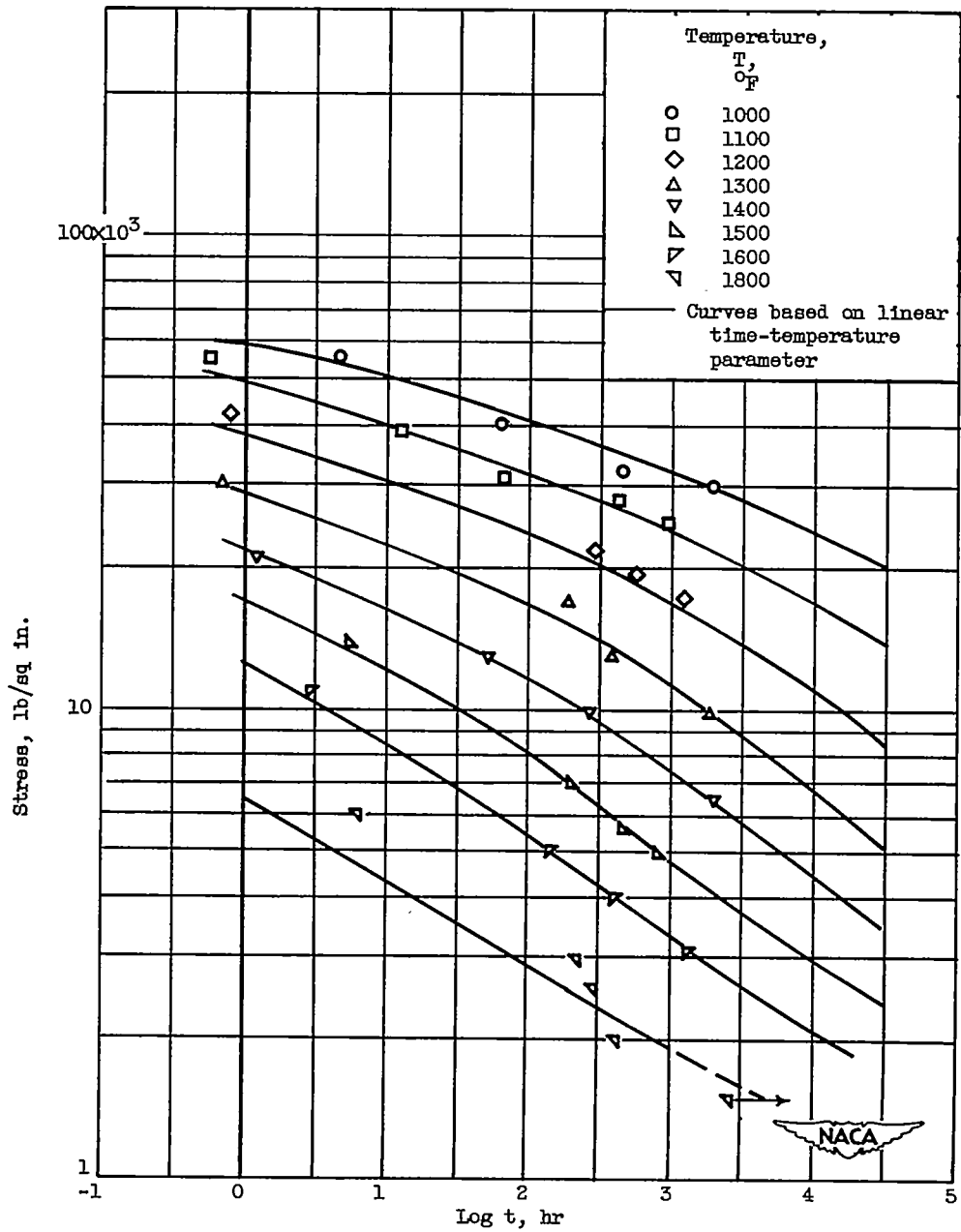
(b) Inconel X.

Figure 8. - Continued. Conventional stress-rupture curves derived from master curves in figure 9.



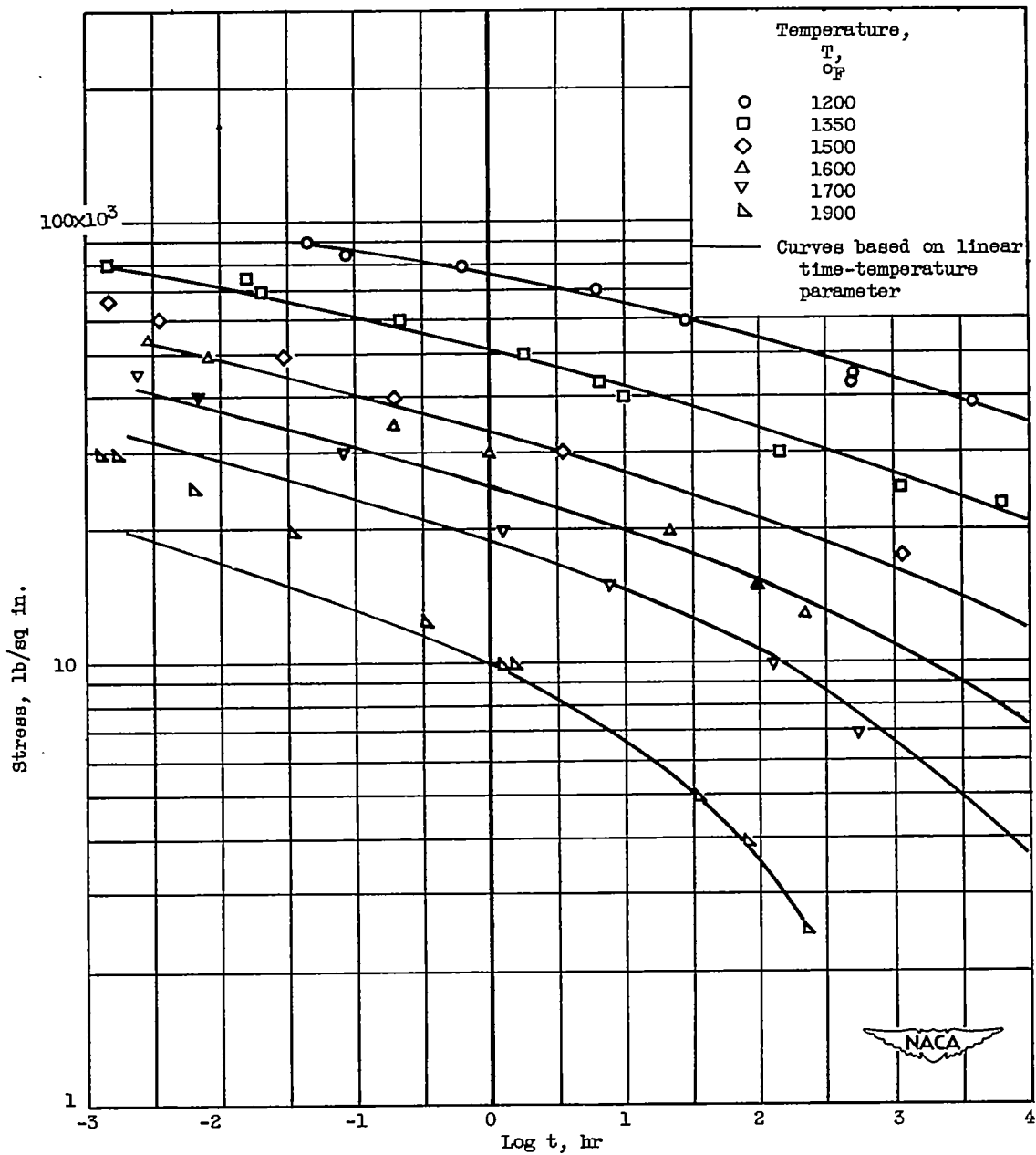
(c) DM steel.

Figure 8. - Continued. Conventional stress-rupture curves derived from master curves in figure 9.



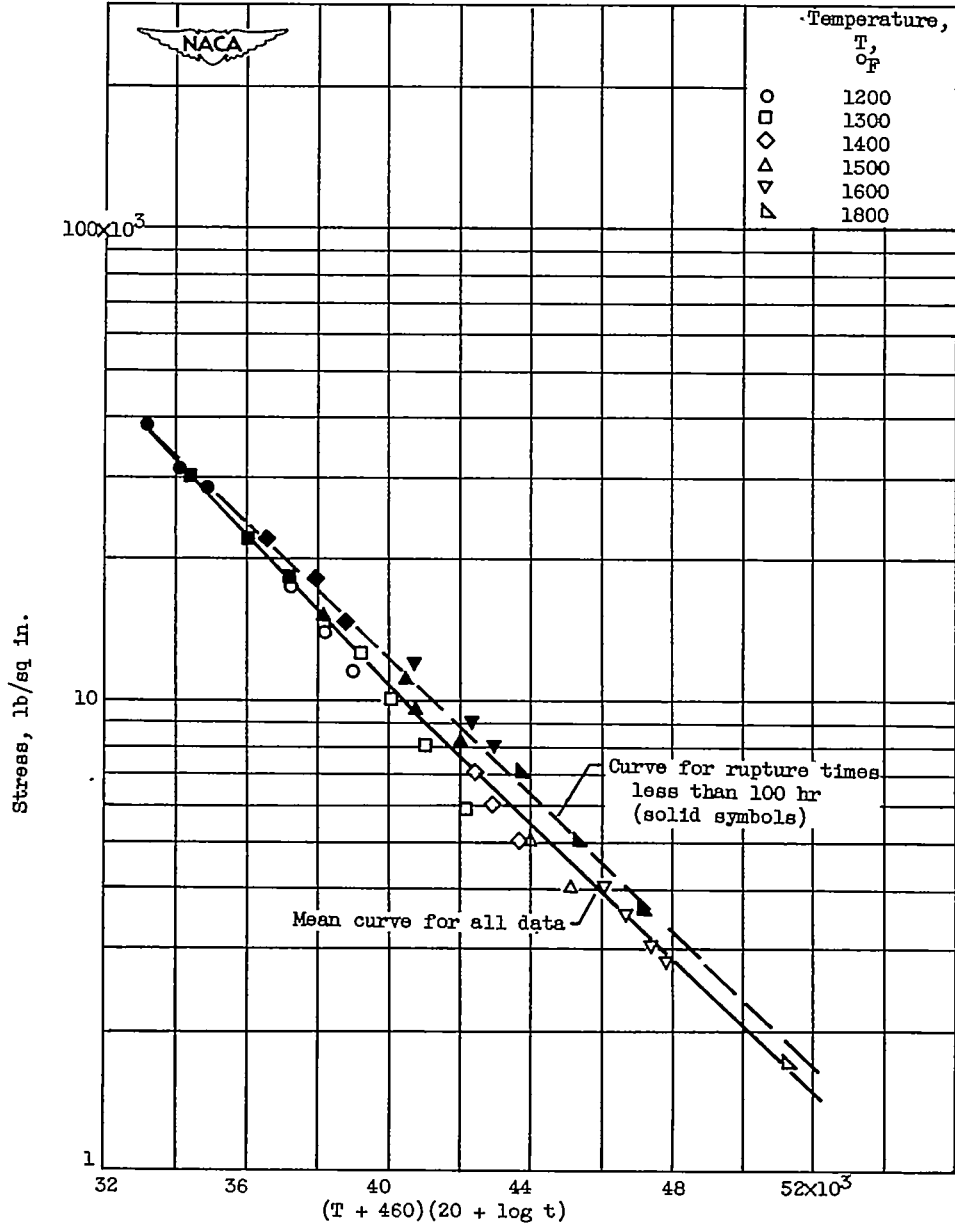
(d) 25-20 stainless steel.

Figure 8. - Continued. Conventional stress-rupture curves derived from master curves in figure 9.



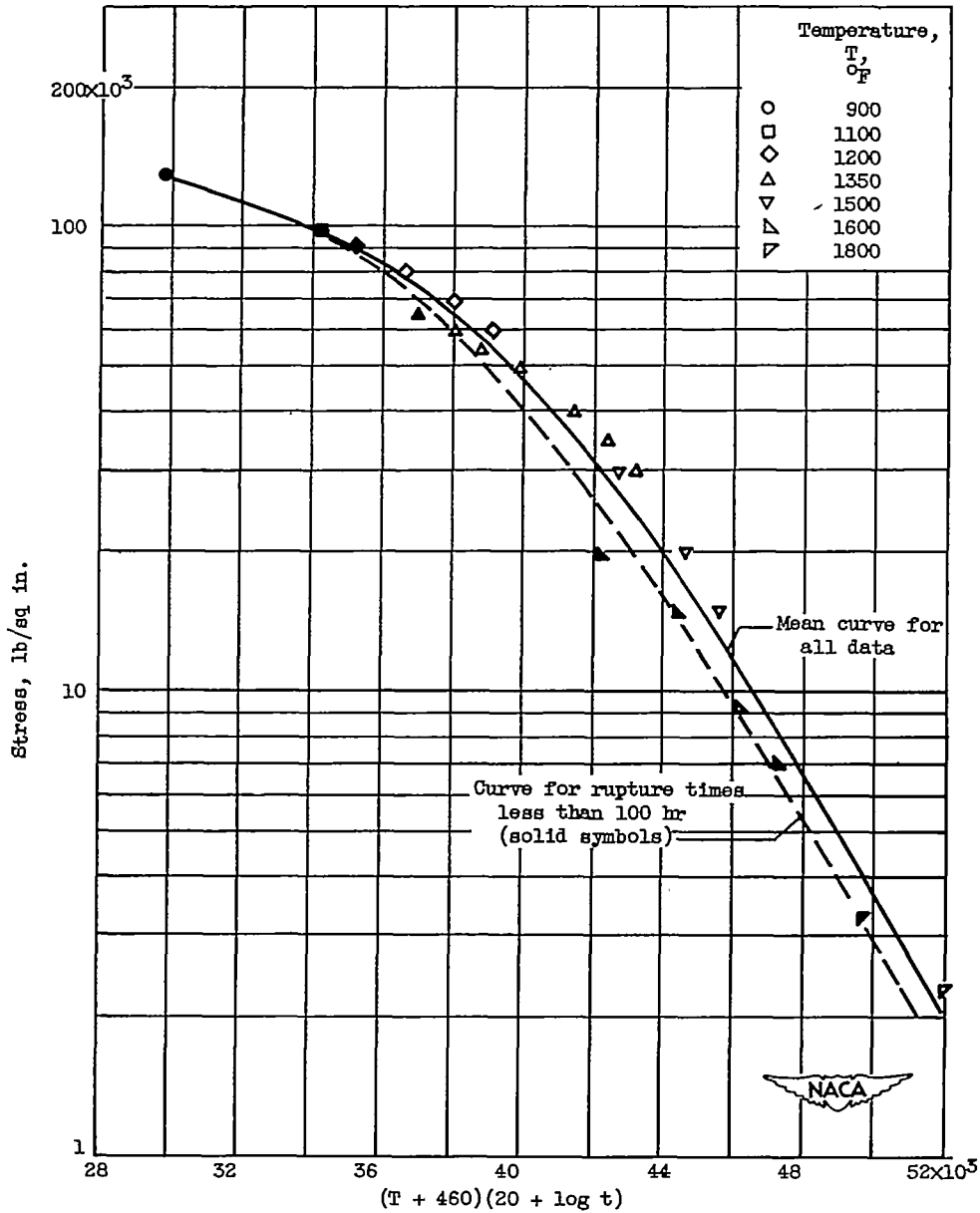
(e) S-590 alloy.

Figure 8. - Concluded. Conventional stress-rupture curves derived from master curves in figure 9.



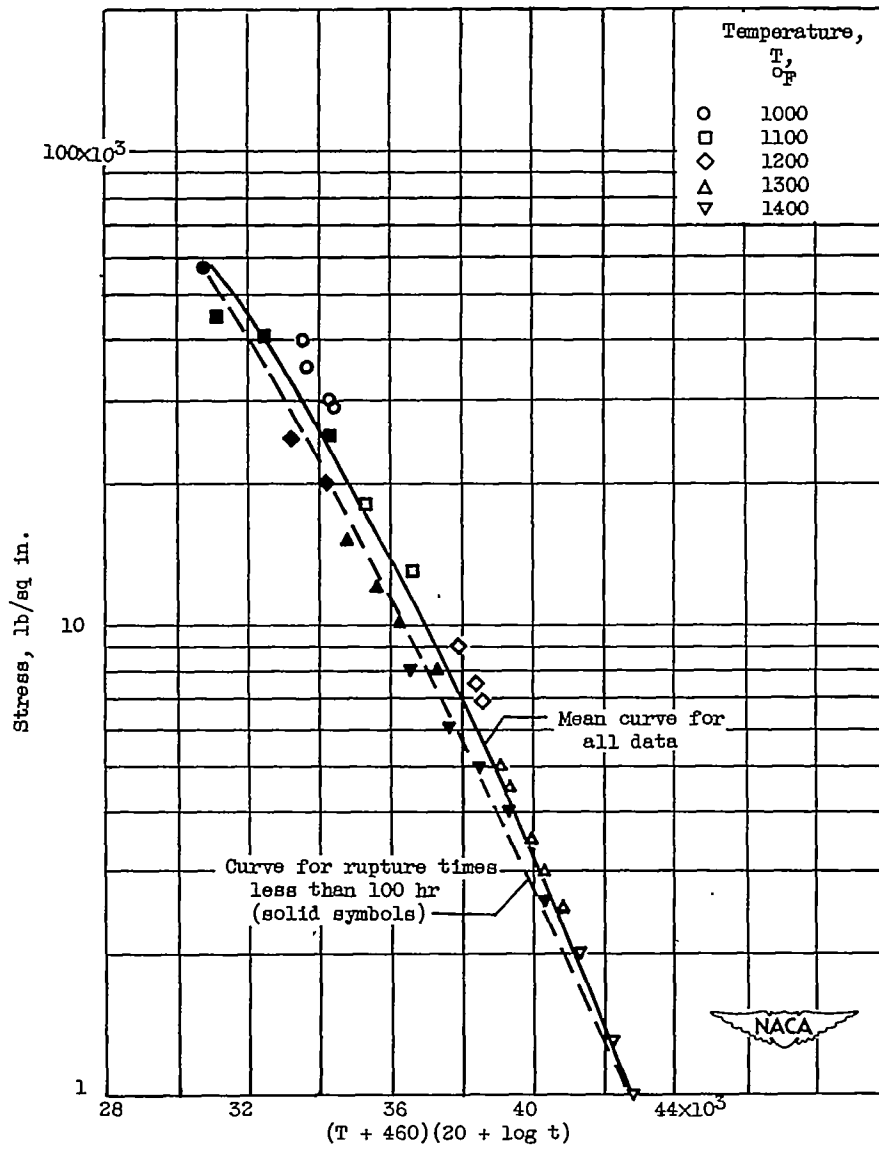
(a) 18-8 stainless steel.

Figure 9. - Master rupture curves using parameter  $(T + 460)(20 + \log t)$ .  
 (Data from fig. 6.)



(b) Inconel X.

Figure 9. - Continued. Master rupture curves using parameter  $(T + 460)(20 + \log t)$ .  
 (Data from fig. 6.)



(c) DM steel.

Figure 9. - Continued. Master rupture curves using parameter  $(T + 460)(20 + \log t)$ .  
(Data from fig. 6.)

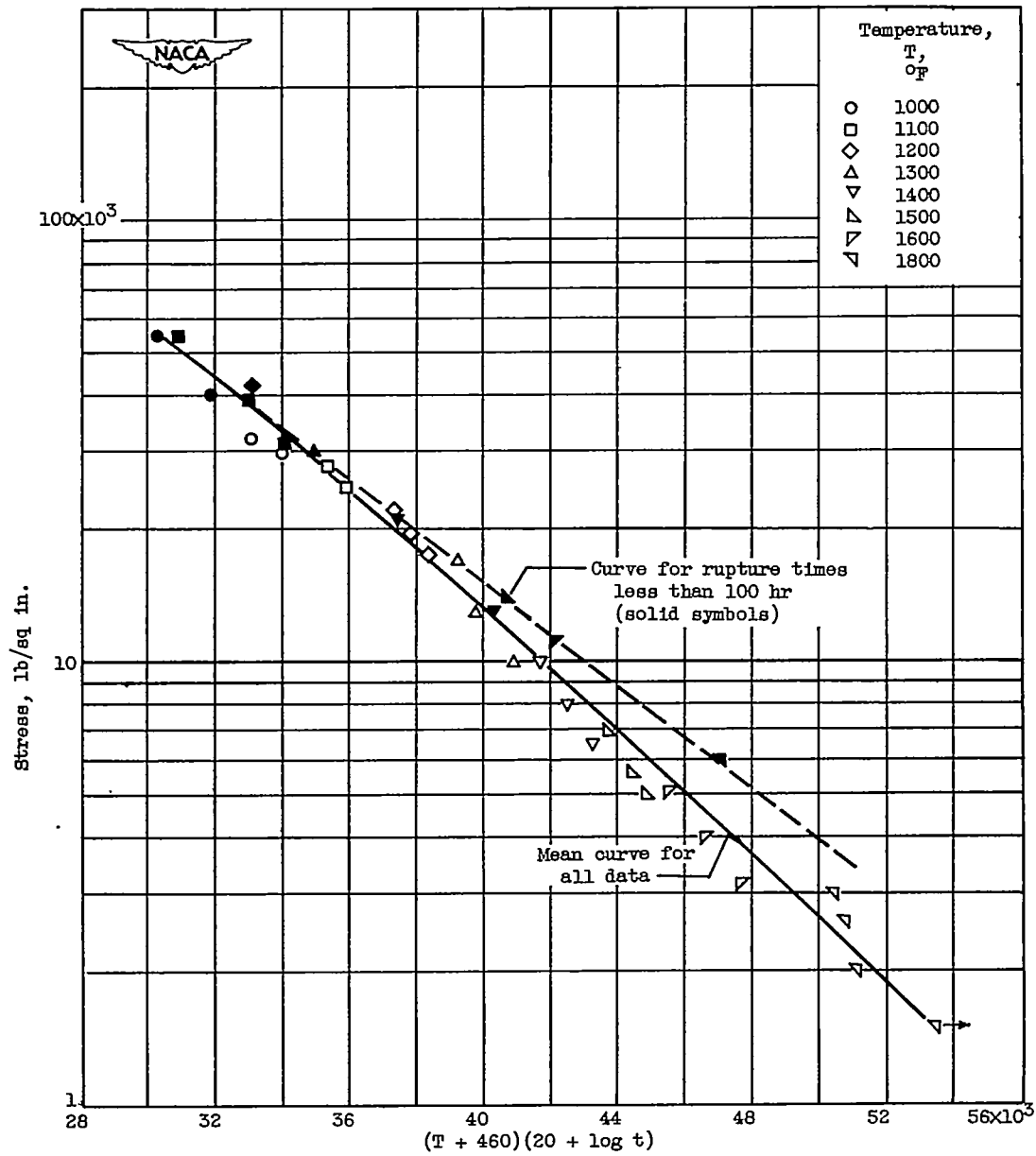
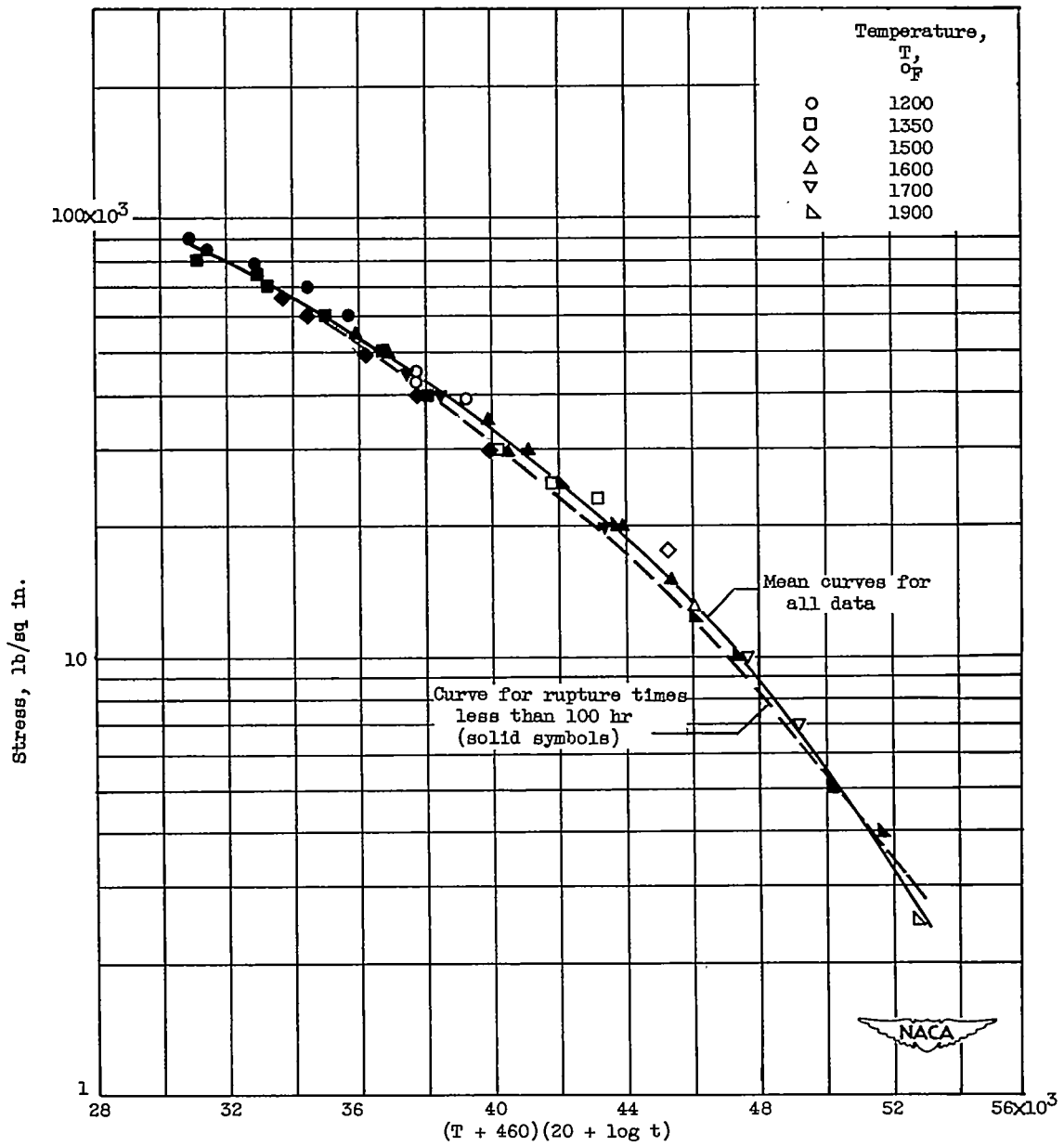


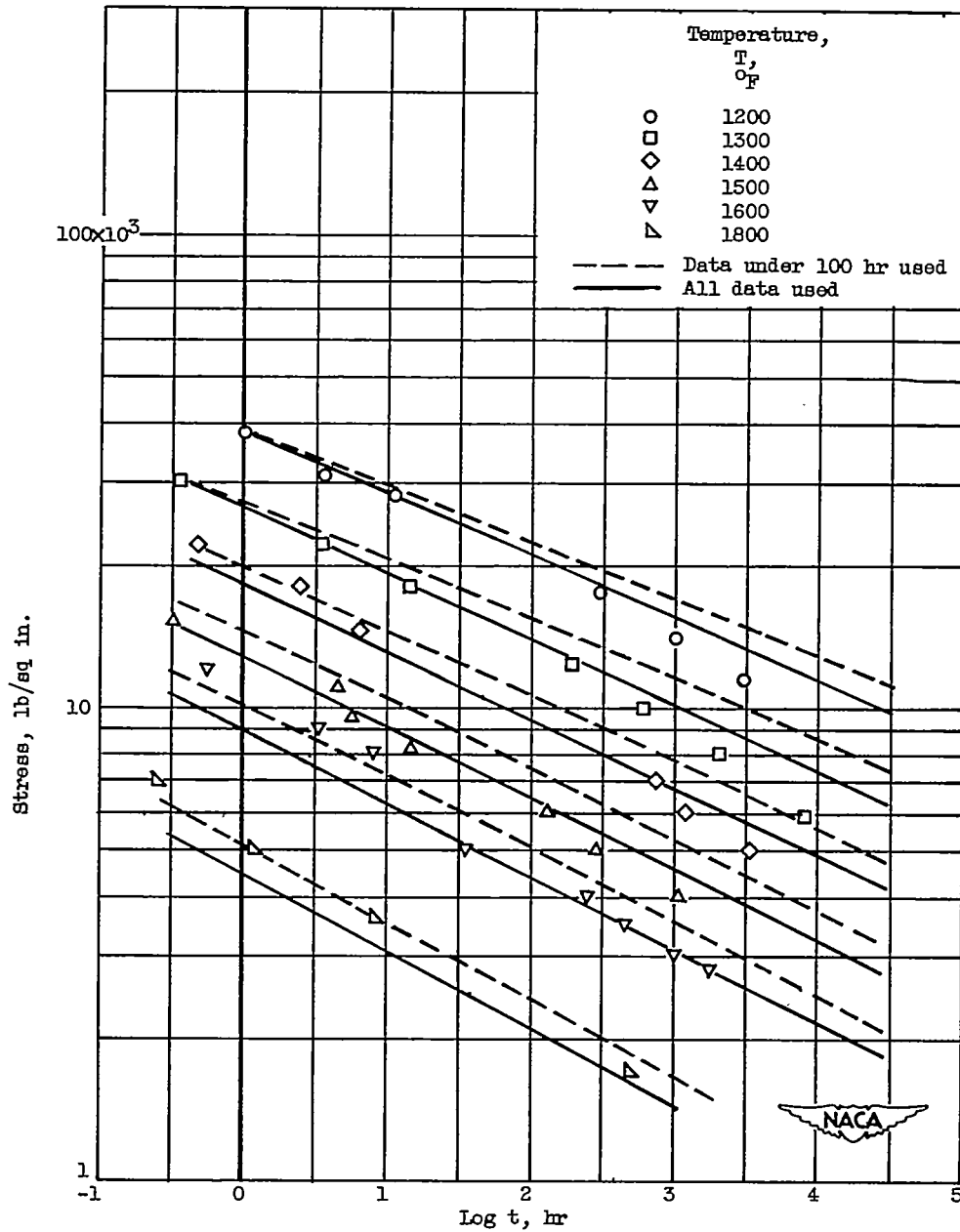
Figure 9. - Continued. Master rupture curves using parameter  $(T + 460)(20 + \log t)$ . (Data from fig. 6.)





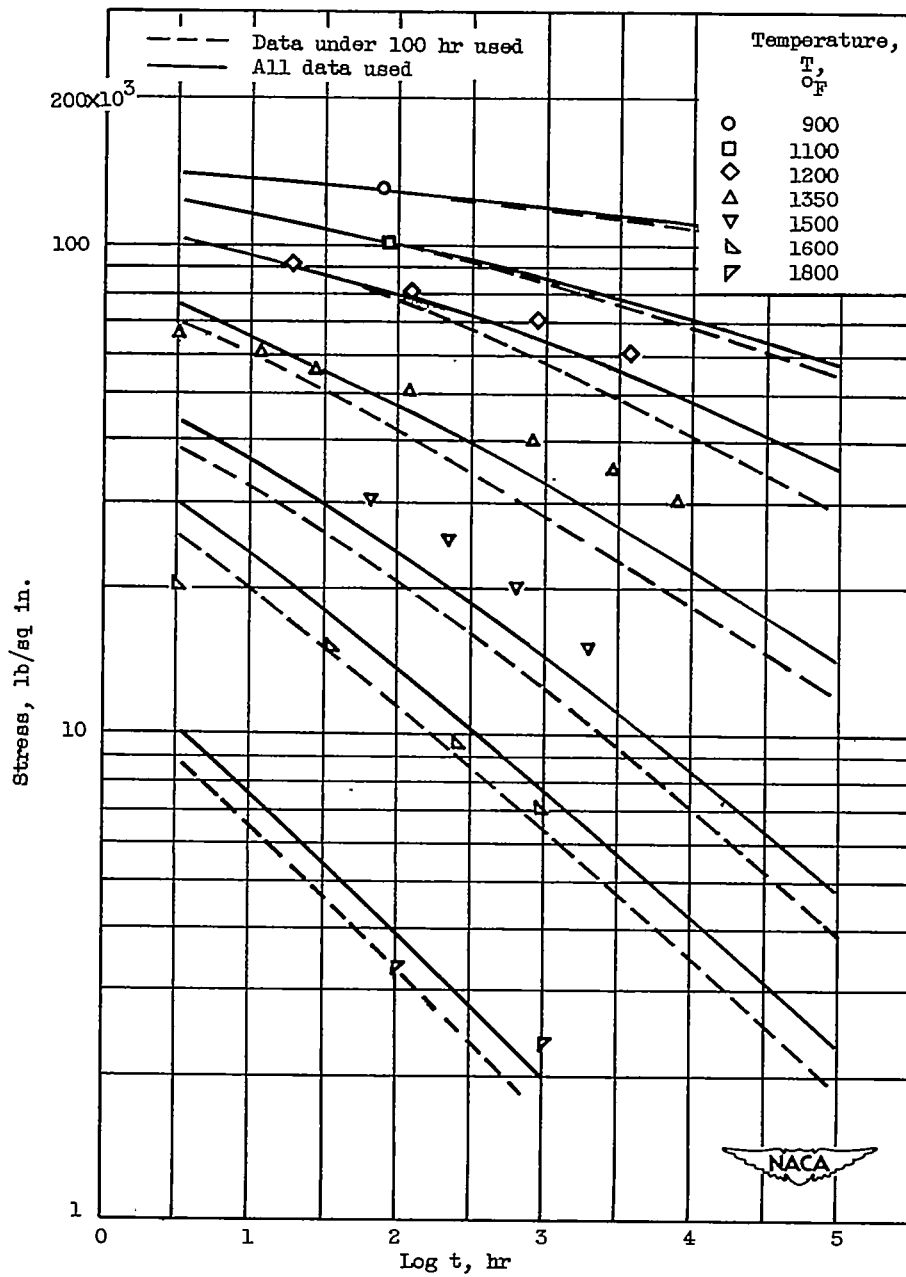
(e) S-590 alloy.

Figure 9. - Concluded. Master rupture curves using parameter  $(T + 460)(20 + \log t)$ .  
(Data from fig. 6.)



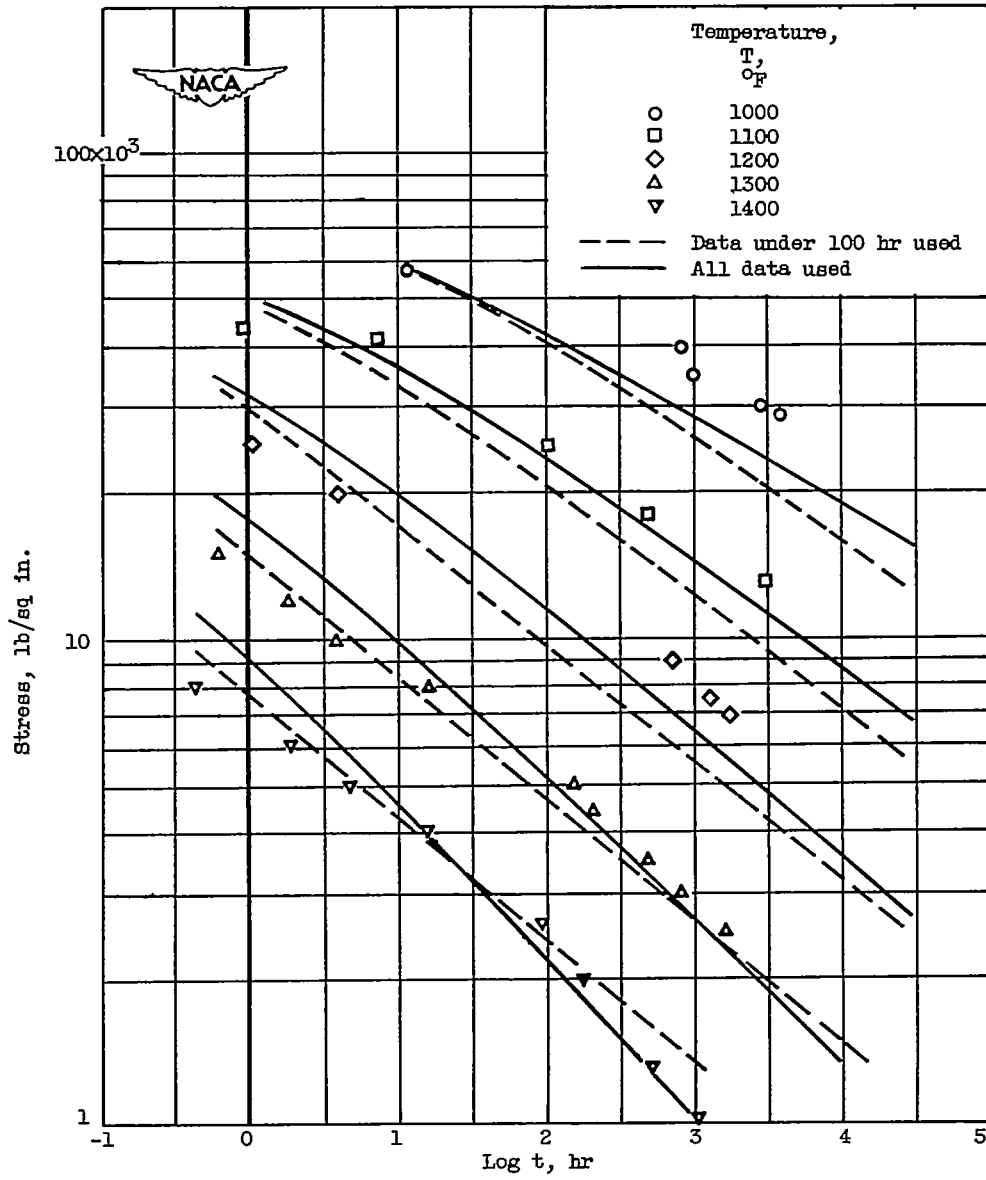
(a) 18-8 stainless steel.

Figure 10. - Conventional stress-rupture curves derived from master plots in figure 11.



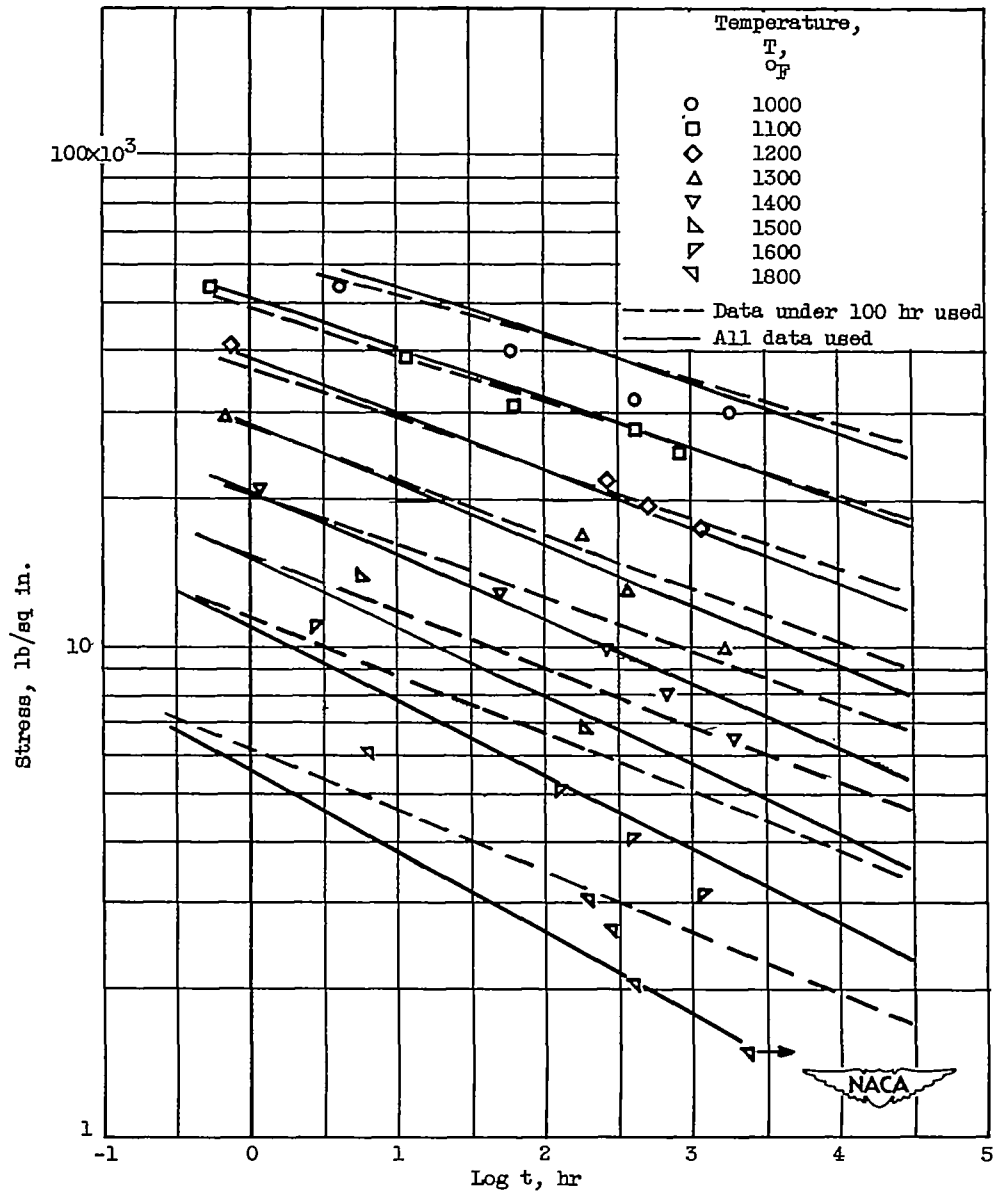
(b) Inconel X.

Figure 10. - Continued. Conventional stress-rupture curves derived from master plots in figure 11.



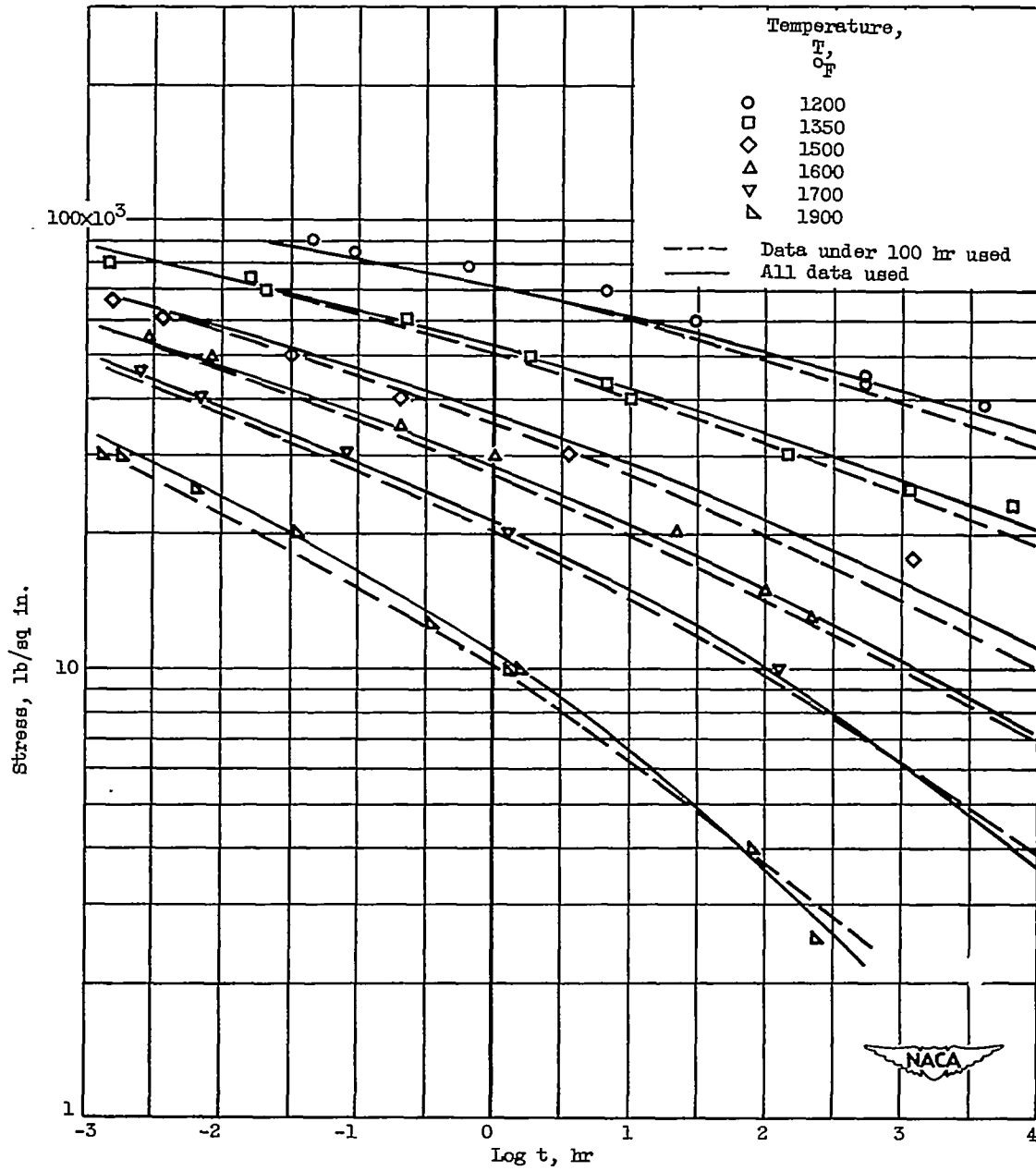
(c) DM steel.

Figure 10. - Continued. Conventional stress-rupture curves derived from master plots in figure 11.



(d) 25-20 stainless steel.

Figure 10. - Continued. Conventional stress-rupture curves derived from master plots in figure 11.



(e) S-590 alloy.

Figure 10. - Concluded. Conventional stress-rupture curves derived from master plots in figure 11.

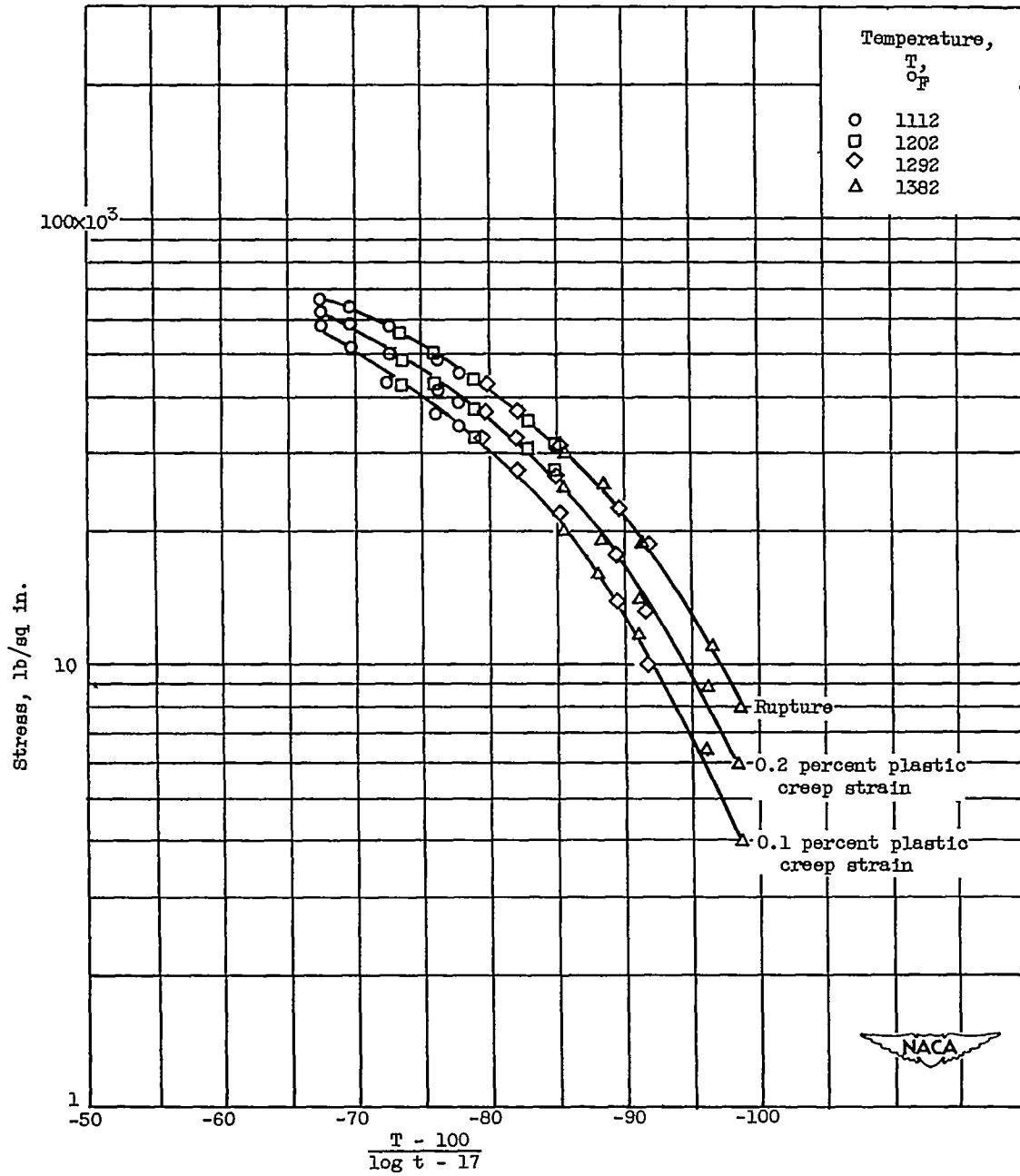


Figure 11. - Master plot for total plastic creep data and rupture data for Nimonic 80. (Data from ref. 5.)

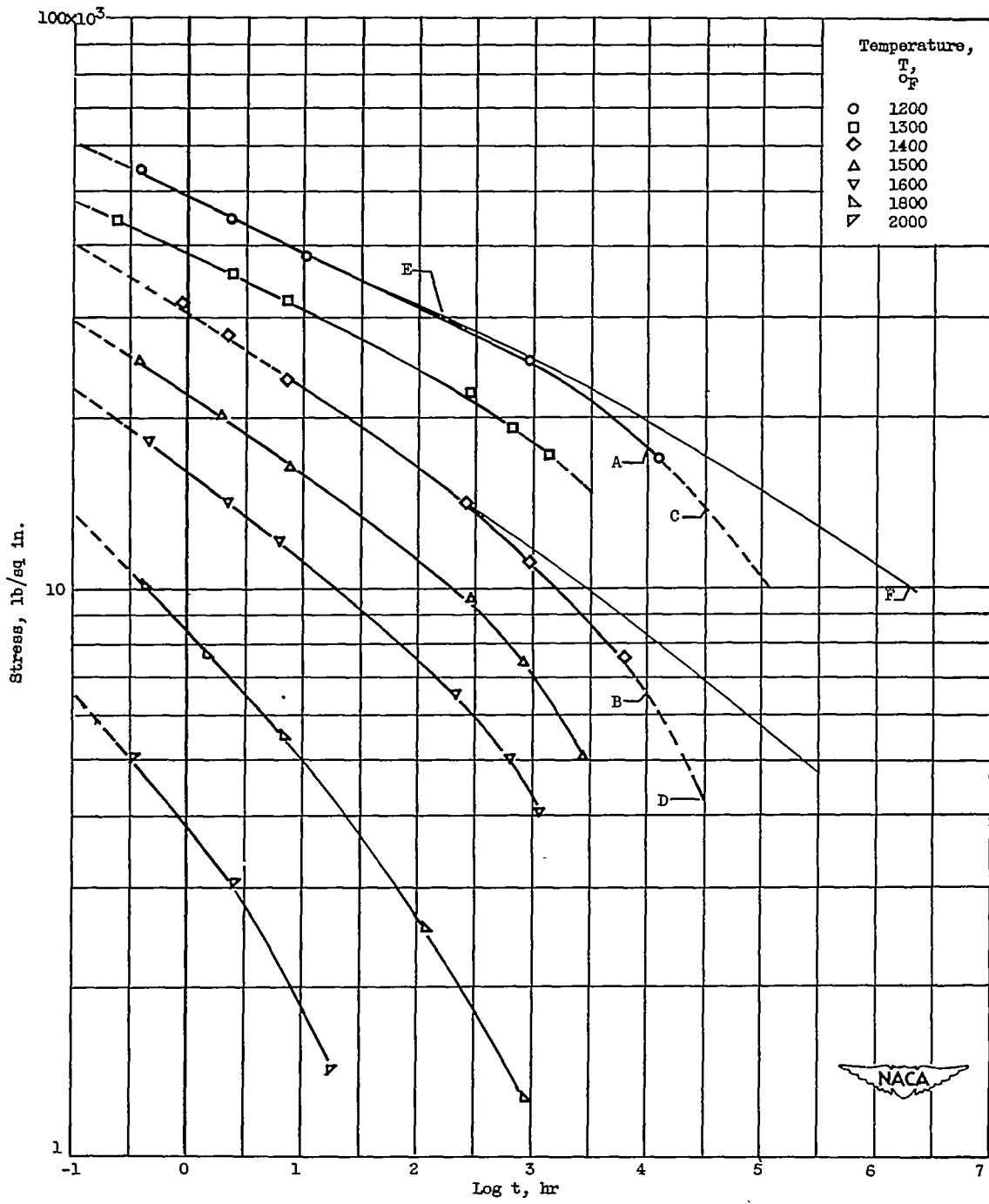


Figure 12. - Conventional stress-rupture plot for 16-13-3 steel. (Data from ref. 2.)



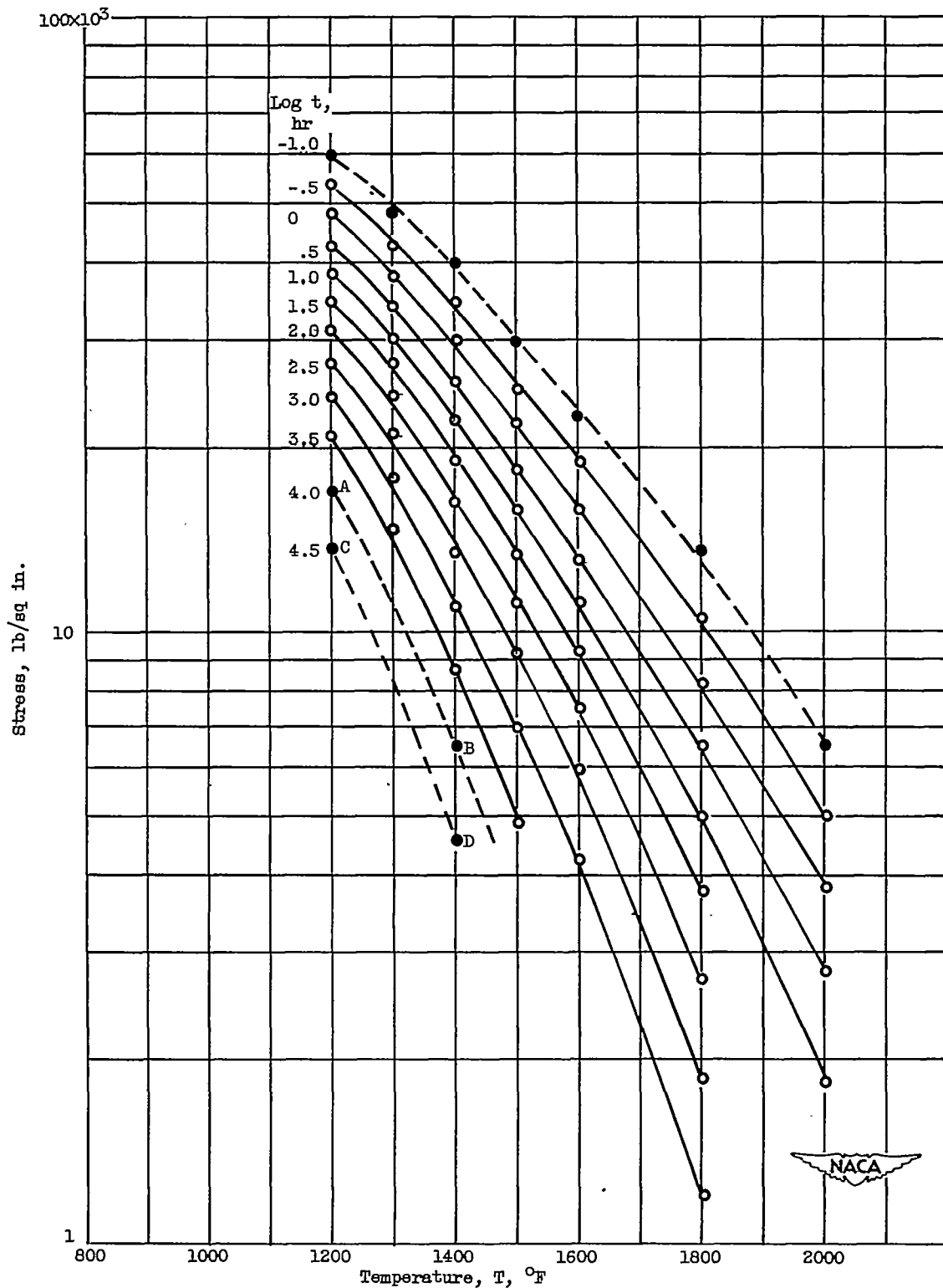


Figure 13. - Constant rupture-time cross plots for 16-13-3 steel derived from figure 14.

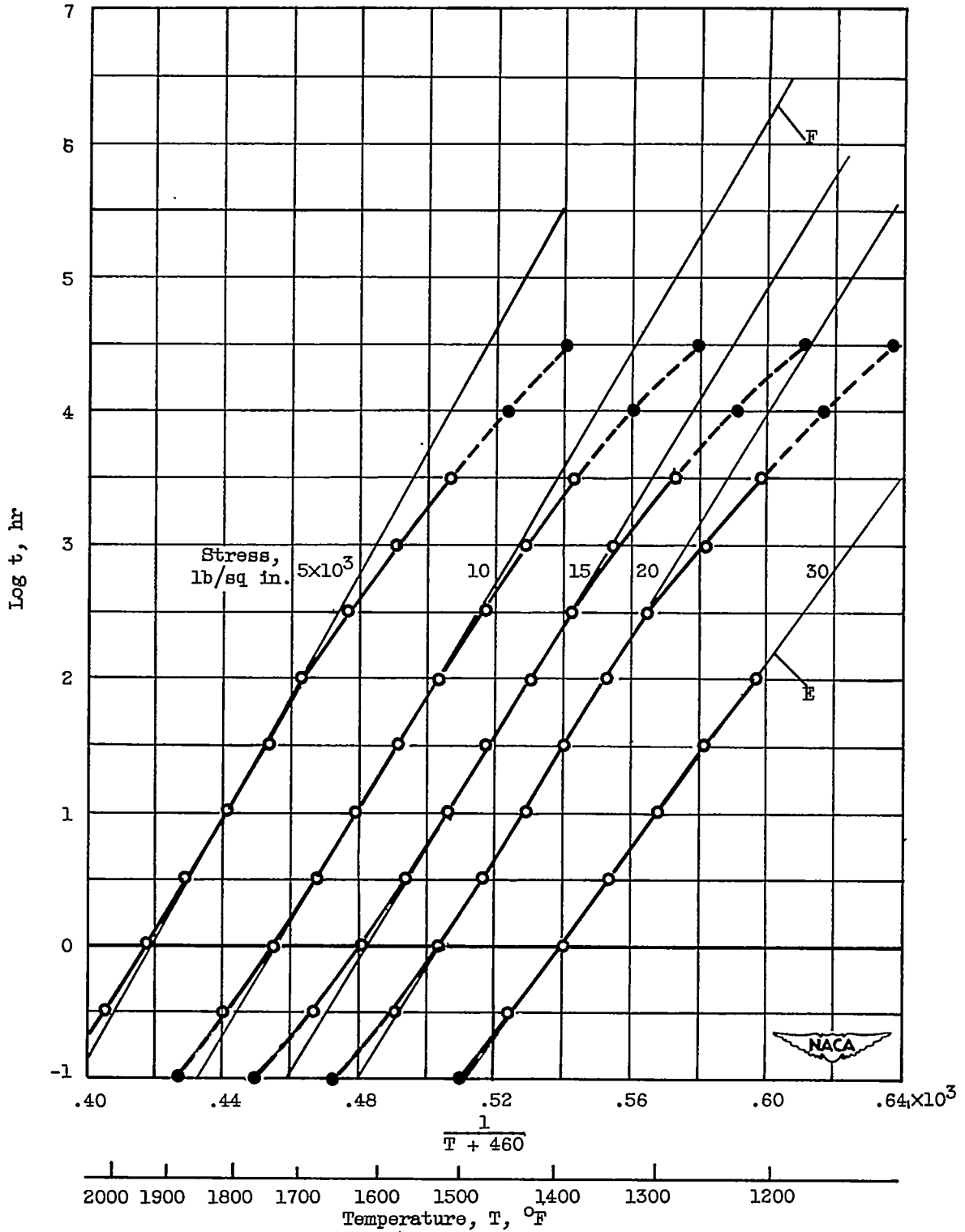


Figure 14. - Plots of logarithm of rupture time against reciprocal of absolute temperature for 16-13-3 steel. (Data from fig. 15.)

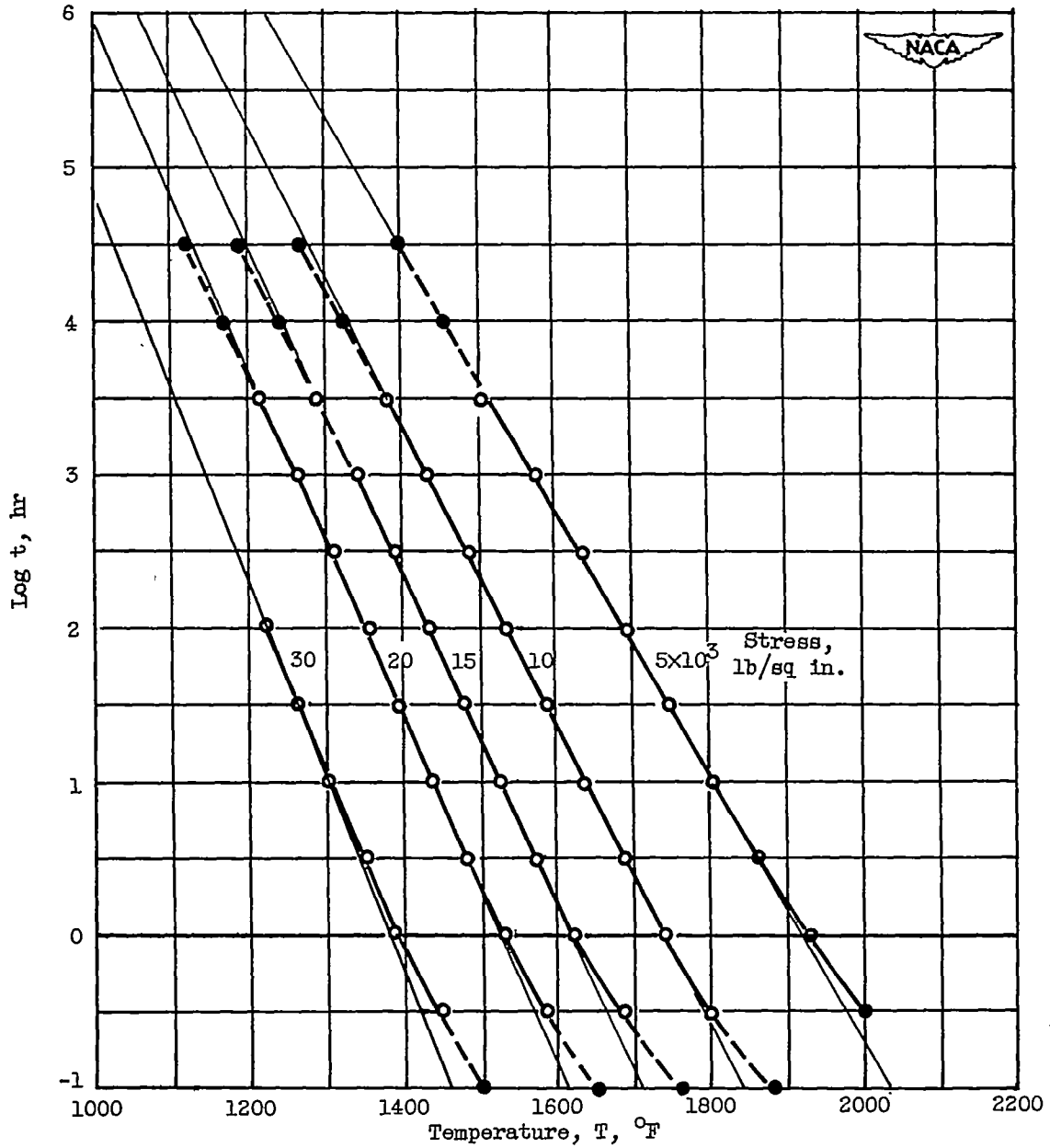


Figure 15. - Logarithm of rupture time against temperature for 16-13-3 steel showing assumed linear relation above approximately 10-hour rupture time. Material constants:  $T_a = 100$ ;  $\log t_a = 17$ .