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LARSON-MILLER AND MANSON-HAFERD PARAMETRIC EXTRAPOLATION OF RUPTURE DATA FOR TYPE 304(18Cr-8Ni), GRADE 22(2-1/4Cr - 1Mo) AND GRADE 11 (1-1/4Cr - 1/2Mo - 3/4Si) STEELS

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The "100,000-hour rupture strength" of alloys is a major factor in the establishment of design stresses in the temperature range where creep governs strengths of alloys. The Boiler and Pressure Vessel Committee of the American Society for Mechanical Engineers considers the average and minimum rupture strengths in determining design stresses. The 100,000-hour rupture strengths are obtained by extrapolation from tests of shorter duration. This is done by conducting sufficient tests to enable one to draw curves of log stress versus log rupture time which are adequate for extrapolation as straight lines to 100,000 hours. In many cases, the longest tests may be of the order of 1000 hours, although tests of the order of 10,000 hours are preferred.

For a number of years, mathematical methods of extrapolation have been in the process of development. These are based on "parameters" which depend upon the equivalence at a given stress of temperature and rupture time. The first and most widely used method was proposed by Larson and Miller.(1) A number of other parametric methods have been proposed which are intended to improve accuracy. The development of these are thoroughly described in several papers.(2, 3, 4)

This report deals with the application of two parameters to the available rupture data for three steels in the Codes of the Boiler and Pressure Vessel Committee. The two parameters, the Larson-Miller and the Manson-Haferd (often called "Linear") Parameters, were used with the Mendelson, Roberts and Manson computer program(5) to optimize the constants. The Larson-Miller parameter was also included with the commonly used constant C of 20.

The object of the program was to compare 100,000-hour strength levels as determined by the parametization of rupture data with the values established by graphical extrapolation of stress-rupture time curves. Initially, rupture data for Type 304 (18Cr-8Ni) austenitic stainless steel and for Grade 22 (2-1/4Cr - 1Mo) steel were evaluated. Both of these are widely used under conditions where the 100,000-hour strengths govern design stresses. Moreover, the strength values determined by extrapolating their log-stress log-rupture time curves have not been extensively questioned. For these reasons, they appeared to offer a basis for judging extrapolation utilizing parameter methods. Subsequently, Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) steel was added as a contrasting case where there was considerable question as to the reliability of the strength levels derived by extrapolation of the rupture curves.

Only data for wrought materials (in most cases, in the form of tube, pipe or bar) were evaluated. In general, the data considered were limited to those obtained from materials which met current ASTM specifications. In a few cases, comparative 100,000-hour strengths were obtained for non-specification materials. In addition, parametization of the data enabled strength levels to be established from the limited tests characteristic of "parameter data" for which no comparative strengths could be obtained by rupture curve extrapolation.

PROCEDURES

Selection of Parameters

With the advice of a Steering Committee of Subcommittee I on Engineering Properties of Boiler and Pressure Vessel Steels of the Metal Properties Council, the Larson-Miller and Manson-Haferd (Linear) Parameters with optimized constants were selected for the investigation. This selection was arbitrary in the sense that it was based on the experience of the individuals as a best way to proceed for the amount of effort to be expended. It is not to be construed, therefore, as a criticism of other parameters which have been proposed. There was simply not time to do justice to any more parameters.

Manson[5] has shown that a number of parameters evolve from the following general equation:

$$P = \frac{\frac{\log t}{\sigma^{Q}} - \log t_A}{(T - T_A)^R}$$

where t is the rupture time in hours, σ is the stress in psi, and T is the test temperature in °F; T_A, $\log t_A$, Q, and R are constants determined from the experimental stress-rupture time data. The parameter P is plotted versus the log of the stress to establish a master curve for interpolation and extrapolation of data. If Q = 0, R = -1, and T_A = -460°F, the Larson-Miller parameter results:

$$P = (T + 460)(C + \log t)$$

This is commonly written, $P = T(C + \text{Log } t)$, where T is the absolute temperature. If Q = 0, and R = 1, the Manson-Haferd (Linear) parameter results:

$$P = \frac{\log t - \text{Log } t_A}{T - T_A}$$

Values of Parameter Constants

The data were used to determine optimized constants for the two parameter equations. The computer program developed by Mendelson, Roberts, and Manson[6] for determining constants was used for two reasons:

1. The Code Committee data were generally not adequate to establish constants by the graphical methods that have been proposed.

Furthermore, universal or average constants are not available for the Manson-Haferd parameter and the computer program was designed to establish constants for data where the iso-stress data required for graphical determination of constants are not available.

2. The Larson-Miller parameter is widely used with a constant C of 20. However, this is an "average" value. Those who have worked with this parameter have recognized that a considerably better representation of any one set of data might be obtained by determining the values of C which each set of data indicates as optimum. The computer program was designed to do this without special iso-stress tests.

From the Code Committee work on Grade 11 and Grade 22 steels, values of the Larson-Miller parameter were available for a constant C of 20, and 100,000-hour strengths had been estimated from graphs of log stress versus P. In this investigation, parameters based on a constant C of 20 were calculated for the data for Type 304 steel.

Important Features of the Parameters

In using the parameters, it is important to recognize certain characteristics which are related to the nature of parameters.

1. Data at only one temperature cannot be used for establishing constants. Consequently, the data where tests were limited to one temperature were not used in this investigation.

2. It is generally agreed that parameter curves cannot be extrapolated beyond the range of the test data. In other words, the parameters can only be used to derive rupture strengths which lie within the range of test stresses.

3. The parametric treatment of data give extrapolated rupture strengths for 100,000 hours at lower temperatures than those of the tests due to the time-temperature equivalence "trade-off" of the parametric

method. For this reason, there are no comparable 100,000-hour strengths for the highest temperature tests for which the stress-rupture time curves were extrapolated.

Computer Programs

The computer program for optimizing parameter constants[6] was adapted to the Michigan Terminal System (MTS). The optimized or "best" values of the constants are those which result in a parameter curve that best fits the data. To find these values, the program uses the 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. (Examples of computer outputs are presented in Fig. 1.)

The usual next step is to plot the log stress versus parameter curves for each set of data and handfit a curve through the points. The values of the parameter for rupture in 100,000 hours (within the range of the test parameter values) can then be calculated and the stresses read off for the temperatures of interest. However, curve plotting for the large number of data sets being investigated would be rather time consuming, and drawing the curves by eye introduces the possibility of human bias. Furthermore, calculation of the parameter values for the rupture strengths of interest is tedious and exacting. For these reasons, the possibility of using a computer program to calculate rupture strengths was investigated.

A program was developed which, 1) utilized the parameter values and their corresponding stresses to fit a stress-parameter curve by minimizing the standard deviation; 2) calculated the parameter values for the desired rupture strengths; 3) determined and printed out the rupture strengths at 50°F intervals; and, 4) restricted the calculated strength values to the range of stresses for which test points were available. In addition to the stresses for rupture in 100,000 hours, stresses for rupture in 100, 1000, and 10,000 hours were also produced by the program. Thus, besides the possible interest in these shorter-time strengths themselves, they could be used to check how well the strength values within the actual testing time range were being computed. (Examples of the computer outputs are presented in Fig. 2).

All data points, no matter how short in duration, were used since one of the presumed advantages of parameters is their ability to predict long time strengths at lower temperatures from short time tests at higher temperatures. Also, there was not adequate background for eliminating data points. The assumption was made that if the data were included in the compilation, it was valid.

Data Point Requirements for the Computer Program

Inherent in the parametization of rupture behavior by optimization of the constants with the computer program are certain minimum requirements for the test data. These requirements can be summarized as follows:

a. A minimum of two test temperatures.

b. A minimum in the total number of test points, which is dependent upon the parametric method and the degree of the fitted stress-parameter polynomial -

    i. Larson-Miller, $n = 3 + m$
    ii. Manson-Haferd, $n = 4 + m$

    where, n = number of data points
    m = degree of polynomial

Thus, when only a limited number of test points are available, the maximum degree of the polynomial that can be used to fit the stress-parameter data is limited.

The maximum degree of the polynomial was arbitrarily set at 7. In the cases where the maximum degree possible was limited because of the limits in the number of data points, the minimum degree studied was reduced accordingly. The degree polynomials used are summarized below:

Number of Data Points (n)	Degree of the Polynomial Larson-Miller	Manson-Haferd
n ≤ 7	1 to n-3	1 to n-4
8	2 to 5	1 to 4
9	2 to 6	2 to 5
10	2 to 7	2 to 6
n ≥ 11	2 to 7	2* or 3 to 7

* The program was changed to include 2 after a few initial calculations.

Rating the Adaptability of the Data Sets to the Extrapolation Method

Without actual tests to 100,000 hours, it is impossible to establish unequivocably the strengths for this time period. This limits the degree to which the accuracy of the extrapolation methods can be known. However, for any confidence to be placed in the derived strength levels (either by extrapolation of stress-rupture time curves or by parametric methods) it is essential that the data can be described adequately by the mathematical method (i.e., extrapolation method) employed. The "adaptability" or "response" of each data set to the mathematics of each method were therefore evaluated qualitatively as "Good", "Fair", "Poor", or "Omit." (Tables 1, 2, 3).

The reader should therefore be cautioned that

a. the derived strengths were not considered part of the evaluation of the adaptability;

b. even if the data apparently adapted mathematically to the method, this did not assure accuracy of the derived strengths; and

c. in some cases, the indicated strengths seemed quite reasonable, even though the data sets apparently were not consistent with the mathematical treatment used.

In order to help clarify the reasoning behind the ratings, a description of them follows.

Log Stress-Log Rupture Time Curves

The 100,000-hour rupture stregnths were obtained from the stress rupture time curves by straight-line extrapolation. In some cases, "breaks" or increases in slope were incorporated into the rupture curves in order to fit the data adequately. Thus, the mathematical concept used involved fitting straight line(s) through iso-temperature data. The response of a data set to this mathematical formulation was therefore rated as "Poor" when 1) the data scatter was excessive; or when, 2) the data was insufficient to define the rupture curve at relatively long time periods with confidence. A rating of "Good" was used when there were a number of tests with little scatter out to several thousand hours at any one temperature. "Fair" was used when the rupture curves fitted limited data well, when the test times were not longer than about 1000 hours, or when there was some, but not excessive, data scatter.

In a number of cases, the stress-rupture time curves at some temperatures appeared well defined and were therefore rated as "Good." However, their slopes were apparently inconsistent with those at adjacent temperatures. These rupture strength sets were noted by a "Good*". Behavior of this type was most prevalent for Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) steel; and an example is shown in Figure 3, where a steeper rupture curve occurred at 1000°F than at 1100°F.

This type of behavior suggests the possibility of changes in the slopes of the rupture curves outside the range of available test data. For the example shown, either the curve at 1000°F must change to a lower slope at a longer time, or the curve at 1100°F must break down, if cross over of stress rupture time curves is to be prevented. The parameter analyses indicated that the 1000°F curve should flatten out.

It should be clearly understood that the log-stress log-rupture time curve at each temperature was judged on its own merits and without consideration of the curves at lower or higher temperatures for the same material. For this reason, there are cases where the rating given does not apply to all the temperatures for which 100,000-hour rupture strengths are given.

Parameter Extrapolation

The computer program for the parametization of the data resulted in an optimized set of constants for each data set. Based on these constants, the parameter values for each data point in the set, together with the standard deviation and the degree of the fitted stress-parameter polynomial, were obtained (Fig. 1). Evaluation of these output values, along with the characteristics of the log-stress versus log-parameter curve, were used as the basis for determining the adaptability of the data to the parameter method. The rating was noted "Good" when:

a. the data defined a log-stress versus log-parameter curve which exhibited no inconsistencies (such as mismatch, or drastic changes in slope between data from different test temperatures);

b. the number of data points were somewhat greater than the minimum required to satisfy the mathematics of the optimizing process;

c. the standard deviation of the data for the fitted stress-parameter curve was low;

d. the degree of the stress-parameter polynomial was low; or, if the degree was high, then when the associated standard deviation would not be markedly increased by using a lower degree polynomial.

A rating of "Fair" was used where the criteria for "Good" were not as well satisfied.

The "Poor" rating was used when little confidence could be placed in the way the data set adapted to the method because it lacked one or more of the reasons described for a "Good" rating. This was done even though, in many cases, the derived 100,000-hour strengths agreed remarkably well with those derived by other methods. In a few cases, the parametized data was so completely unreasonable that it should not have been used and was therefore designated "Omit" in the Tables. An example of this for the Larson-Miller parameter is presented in Fig. 4A, where the optimized constant was 2.3 and the data set was rated "Omit". This should be compared with the result when a constant of 20 was used and the data set rated "Fair" as in Figure 4B.

Stress-Parameter Curves. The parameter constants can be derived graphically(3) from iso-stress lines on plots of 1/T+460 versus Log t for the Larson-Miller parameter, and T versus Log t for the Manson Haferd parameter. The computer program offers a method for establishing constants when the iso-stress data at a number of temperatures required for graphical methods are not available. Depending on the extent of the test data, the program resulted in the following important features.

1. When the data are sufficiently extensive, there can be considerable overlap in the parameter curves for tests at different temperatures. The derived constants may result in placing the test points at different temperatures on a single parameter curve (see Fig. 5), which is one of the requirements for a "Good" rating. On the other hand, even for a parameter curve of "best fit", i.e., the lowest standard deviation, separate curves for each temperature often result (see Fig. 6 for an example). This mismatch of the separate parameter curves for each test temperature was often typified by an "eyebrow" appearance (see Fig. 7). This lack of agreement or mismatch between temperatures must be a basis for suspecting or excluding the 100,000-hour strengths derived from the parametric analysis. Thus, where mismatch was severe, the adaptability of the data was rated "Poor." A rating of "Fair" indicated that the matching was average, or reasonably good.

2. In many cases, there was no overlap in the parameter curves of tests from different temperatures. It became more difficult to rate the adaptability of the data in these cases since to a great extent the criteria

upon which to base the evaluation were not as evident as when overlap occurred. Thus, in many cases when gaps between parameter curves for different temperatures occurred, it was impossible to place much confidence in the derived strength levels. Only if the matching of parameter curves (from different temperatures) appeared acceptable and if there was some degree of continuity or similarity of slopes throughout the parameter curve, was the adaptability of the data rated "Good" or "Fair." In all other cases, the rating was "Poor." For example, in Figure 8 the overall rating of the data was "Poor." However, if the 1000°F data were considered in conjunction with the 1100°F data, the rating would be at least "Fair."

The reasons for the mismatch in the log stress parameter curves for different temperatures is apparently complex and would require effort beyond the scope of this report to be adequately covered. Certainly optimization of the constants did not in many cases serve to eliminate this problem.

Standard Deviation, Number of Data Points, and Degree of the Polynomial. In rating the data, the standard deviation, number of data points and the degree of the polynomial were useful (see Tables 4, 5, 6). These factors are not independent. For a given data set, the degree of the polynomial, i.e., the complexity of the log stress-parameter curve, was varied and the curve with the minimum standard deviation was selected. The data sets gave a range of values of standard deviation and degree of polynomials. A limited study of these indicated the following:

1. For some data sets, the number of data points was so limited that the degree of the polynomials studied was restricted to the low orders (1 or 2). These sets were rated "Poor" or "Fair", depending upon the other criteria such as the standard deviation.

2. There were data sets which fitted the parameter well, i.e., had a low standard deviation. The degree of the polynomial, however, could be high. In many of these cases, the improvement in the standard

was very small due to increasing the degree of the polynomial above about m = 3. Thus, the inflections were small and of no real significance. In such cases, the data set was rated "Good," (see Table 7).

3. In every case where the standard deviation was considered high, the data sets were questionable and rated no better than "Fair," and, usually "Poor." Data scatter was a common cause of this problem. It also occurred when there was severe mismatch in parameters among temperatures (as discussed in the preceding section), that is, when the mathematical requirements of the parameter were not being met by the data.

4. It was especially difficult to rate the data from testing programs which were designed only to provide parameter data. If the standard deviation was high, the sets could be rated as "Poor." However, in many cases the standard deviation was low or at intermediate levels. If the standard deviation was low and other criteria, such as a low degree polynomial, reasonable constant values, etc., were met, the set was rated "Fair." In other cases, the data set was rated "Poor." The major reason for doing this was the absence of sufficient data to judge the set appropriately (such as whether or not "eyebrow" effects were severe).

<u>Magnitude of Constants.</u> It was quite evident with the Larson-Miller Parameter that poorly adapted data could give abnormal constants. In those cases where the constants were clearly questionable (i.e., <15 or, >25), it was due to the data and not characteristics of the material. Even when values were only slightly higher than 15 or slightly lower than 25, there were clearly questions as to the adaptability of the data to the method.

There seemed to be good evidence that the "optimized" constants for the Larson-Miller parameter varied with test temperature (and, in some cases, with testing time). It was clear that some additional effort could establish guides for the selection of test conditions which could control this problem. There was an inter-relationship between the slopes and breaks in the curves which could be controlled. A major problem with the computer program was its inability to take such factors into account. This seemed to be the reason for "Poor" ratings (from mismatch of parameters between temperatures) seeming to occur when the test data covered a wide range of temperatures and times.

It also became clear that force-fitting a constant of 20 to the Larson Miller parameter was more than an "average" resulting from variation among sets of data. Such force-fitting of an approximately correct constant caused the available data to produce an approximately correct result, even though its adaptability was "Poor."

A basis for judging the constants for the Manson-Haferd parameter was not as clear. Enough study was carried out, however, to be sure that a correlation can be made which would serve as a basis for determining if the constants were reasonable.

RESULTS

For the most part, the 100,000-hour strengths indicated by the parameters differ to some degree from those derived from extrapolation of stress-rupture time curves. There were also differences among the values from the different parameters. Although with available information it is not possible to determine which values were most nearly correct, it is very difficult to present the results without considering accuracy. Analysis of the results, on the other hand, certainly emphasized the need to review carefully the inter-relationships between the actual data and the adaptability to mathematical treatment, with the consequent influence on the parametric extrapolations. This is not complete. Therefore, there is no alternative to presenting as a first result the recommendation that this should be undertaken by continuing the investigation. The present report, then should be considered a progress report.

The 100,000-hour rupture strengths for all three alloys, which were derived from the Larson-Miller and Manson-Haferd parameters based on optimized constants, are given in Tables 1, 2 and 3. The strengths obtained by straightline extrapolation of log stress-log rupture time curves, together with comparative values for the commonly-used Larson-Miller parameter based on a constant C of 20, are also presented in these Tables.

Although tabulations are the most exact way to compare the values developed by the four procedures, the overall differences are easier to appreciate if they are presented as graphical comparisons.

Direct comparison of 100,000-hour strengths obtained by the parameter method with those determined by extrapolation of log stress-log rupture time curves was limited to a relatively small number of data points. There were two reasons for this.

1. The optimized parameter method cannot be used to extrapolate data limited to one temperature, and a large proportion of the data was iso-temperature, e.g., a great number of strengths from stress-rupture

time curves for Type 304 were for tests limited to 1200°F, and comparative values from parameters could not be calculated. Thus, since iso-temperature data could not be treated by parametric methods, those data sets were completely excluded from the tabulations of the results.

2. The parameters gave 100,000-hour strengths at lower temperatures than the highest test temperature. Thus, where test data were available at more than one temperature, the direct comparison between parameter and log-log extrapolation was limited to the lower temperatures, where the parameter values for 100,000 hours were available from tests at higher temperatures.

An individual analysis of the strengths obtained for each of the three steels considered in this investigation follows.

Type 304 (18Cr - 8Ni) Austenitic Stainless Steel

The more significant features of the 100,000-hour rupture strengths derived by the various extrapolation methods are summarized in the following sections.

Log-Log Extrapolation of Rupture-Time Curves versus Parametric Extrapolation.

The following features are evident from cross plotting the strengths obtained by rupture curve extrapolation versus the strength derived by each parametric method (Fig. 9A, B, C).

1. There was a slight tendency for the Larson-Miller parameter (both optimized and with a C of 20) to give higher strengths at the higher temperatures (low strengths), and to give lower strengths at the lower temperatures (high strengths). (Fig. 9A and B).

2. In general, the Manson-Haferd parameter tended to give lower values. (Fig. 9C).

3. For some data points, the differences in strengths were greater for the Manson-Haferd parameter than for the Larson-Miller parameter.

4. It is important to understand the magnitude of the differences in strength. From casual inspection, the differences seemed smaller than was actually the case. (See Table 1.)

5. Determining reasons for the differences would require additional study of the inter-relationships of data to log-log curves and to the mathematics of the parameters.

Comparison of 100,000-hour Strengths Obtained from Parameters

The prior presentation of strengths from parameters was confined to those cases where there were comparative values from extrapolation of stress-rupture time curves. This placed rather severe limitations on their capabilities. Parameters inherently give strengths at lower temperatures than the tests, and only a relatively few direct comparisons could be made. Accordingly, all strengths derived from parameters were cross plotted for comparison in Figures 9D and E. From these, the following features were evident.

1. The Larson-Miller parameter with a constant C of 20 tended to give very slightly higher strengths than when the constant was optimized. This trend can be attributed to the fact that the values of the optimized constants are generally less than 20.

2. The Larson-Miller parameter (optimized) consistently gave higher strengths than the Manson-Haferd parameter, especially when the strengths from data which adapted poorly were not considered.

3. The scatter in strengths between the Larson-Miller and the Manson-Haferd parameters was fairly large. The range was about 4,000 psi at any given strength level. This was considerably more than the difference between the Larson-Miller parameter with optimized constants versus a fixed constant C of 20. Here, the range was about 2,000 psi (if the "poor" strengths were not considered.

Strengths from Parameters as a Function of Temperature

The curves of rupture strength versus temperature derived from the parameters were plotted in Figures 10, 11, and 12. The minimum and average values derived from the extrapolation of stress-rupture time curves were superimposed for comparison. (Note that the derivation of these curves included consideration of the data sets where only iso-temperature tests were available which were not treated by parametric analysis.) The Larson-Miller parameter C of 20 (Fig. 10) had a higher minimum value while the optimized constants (Fig. 11) gave practically the same minimum curve as the extrapolation of the stress-rupture time curves. Two sets of data from the Manson-Haferd parameter were substantially below the minimum (Fig. 12). No comparison involving averages could be made because the majority of the data which established the average curve for log-log extrapolation were from iso-thermal tests at 1200°F, which could not be used in the parameter program.

The following additional aspects of these results are worth noting:

1. The Larson-Miller parameter gave curves of strength versus temperature which had slopes similar to the minimum and average from the extrapolation of stress rupture time curves.

2. Many of the curves from the Manson-Haferd parameter cross over the minimum and average curves from the stress-rupture time curve extrapolations. There were, however, many curves from the parameter which had shapes similar to those derived from the stress-rupture time curves. There is need for a detailed examination of the inter-relationships to determine why the varying results were obtained.

3. The range in strength values at any one temperature for the data sets evaluated by the parametric method was large. For example, at 1100°F the ranges were--

Larson-Miller, C = 20	7,000 psi
Larson-Miller, optimized	8,000 psi
Manson-Haferd, optimized	9,000 psi

These ranges were greater than the differences in strength levels derived from the various parametric methods (no more than 4,000 psi) for any given data set.

Comparisons Between Methods of Extrapolation as a Function of Test Temperature.

Considerable effort went into finding a way of comparing the strengths from the extrapolation methods as a function of temperature. This was finally done by plotting minimum and "average" curves as log stress versus temperature (Fig. 13). The average curve for extrapolation of log stress-log rupture time curves was omitted because it was based on extensive iso-temperature data at 1200°F which could not be used by the parameters. Only the parameter data rated "Good" or "Fair" was used. It should also be noted that the average and minimum curves at the higher temperatures were derived from relatively few data points.

Figure 13 shows the following.

1. Except for the Manson-Haferd parameter average curve, the curves were nearly straight parallel lines.

Presumably, the deviation of the Manson-Haferd data was due to the crossover of curves discussed earlier.

2. The near linearity and parallelism of the curves indicates that limited data can be extrapolated to adjacent temperatures with fair confidence.

3. These curves show rather graphically the trends previously discussed for the different methods. The type of results obtained for each can be described as--

Larson-Miller, $C = 20$	High strengths
Larson-Miller, optimized	Minimum values similar to log-log curve extrapolation.
Manson-Haferd, optimized	Lower values than the other methods, except possibly at higher temperatures.

Type 304L Data

The data for Type 304L were too limited to draw any definitive conclusions. The data are included in Table 1, and shown graphically in Figures 14, 15, and 16. In general, the trends were the same as those discussed for Type 304 steel.

Discussion

This investigation was carried out to check extrapolation methods. For this reason, data on Type 304 steel which had been given a stabilizing treatment were included. They were excluded, however, from averages and minimums for log stress-log rupture time curves as non-specification material. The curves for these materials in Figures 10, 11, and 12, were on the high side of the range. This could be more indicative of the strength level of the heats than of any strengthening due to the heat treatments.

Some factors regarding the results are worth noting even though, in most cases, there is a high probability that they may only be characteristic of Type 304 steel and other alloys with similar stress-rupture time characteristics. These factors are as follows.

1. In general, the various methods of extrapolation appeared to give the same relative strength for a given data set even though the strength level might be changed. A possible exception to this was the Manson-Haferd parameter, where there were changes in relative strength with temperature.

2. For the Larson-Miller parameter with a constant C of 20, the strengths indicated for the "Poor" data sets were scattered throughout the strength range (Fig. 10). The use of optimized constants reduced the number of data sets rated "Poor," and, as indicated by Figures 11 and 12, these poor sets were on the high side of the strength range.

Grade 22 (2-1/4Cr - 1Mo) Steel

The observations made on the Type 304 steel data generally apply to the results for Grade 22 steel. Therefore, the following observations are considerably abbreviated.

<u>Comparison of 100,000-hour Strengths from Parameters and Log-Log Extrapolation of Rupture Curves.</u>

There was relatively little difference between the extrapolations by the three parameter methods and the extrapolation of stress-rupture time curves (Fig. 17A, B, C). As was true for Type 304 stainless steel, there was a slight tendency for the Manson-Haferd parameter to give lower strengths.

The Larson-Miller parameter with a constant C of 20 tended to give higher strengths (Fig. 17D) than the optimized constants at low temperatures (high strength values). It will also be noted that the data sets which adapted poorly resulted in far greater differences than those which adapted "Good" or "Fair." The range in strength differences for a given data set and strength level was no more than 3,000 psi, if the "Poor" data are not considered.

It is clear that the Manson-Haferd parameter gave lower strengths than the Larson-Miller parameter with an optimized constant (Fig. 17E). The difference in strength was about 4,000 psi, which is about the same as it was for Type 304 steel.

Strengths from Parameters as a Function of Temperature

The large number of data sets made it difficult to demonstrate strength variations as a function of temperature from parameters. Therefore, the graphical presentation was divided into groups.

1. The strength versus temperature curves were plotted for those sets of data for which there had been extrapolation of stress-rupture time curves for materials within specifications (Figs. 18, 18, 20).

a. For the Larson-Miller parameter with a constant C of 20, (Fig. 18), two sets of data which were rated "Poor" seemed to be out of line and gave very high strength values. The minimum and average curves determined from extrapolation of the stress-rupture time curves suggested that lower strengths occur at lower temperatures than was evident from the parameter. It is expected, however, that if data were available, these curves would also increase in slope at the low temperatures, which would tend to minimize this apparent difference.

b. Optimizing the constant for the Larson-Miller parameter (Fig. 19) resulted in a slightly wider range in strength values for a given temperature than was obtained when the constant was 20. Again, there were curves of poor adaptability on the high side of the strength range which did not agree with the majority of the curves.

c. The Manson-Haferd parameter (Fig. 20) tended to give slightly lower strengths than was the case for the Larson-Miller parameter. And, as was true for the other methods, the curves with high strengths that appeared out of line were from data with poor adaptability.

d. If the curves for the high strength, poorly adapted data sets are excluded, the ranges in strengths for a given temperature are about the same for all the parameter methods. Also, the ranges are of the same order as the differences in strengths for a given data set obtained by the different methods for extrapolation (Fig. 17D, E). This is in contrast to Type 304 steel, where the range at a given temperature was much wider.

2. There were a considerable number of data sets consisting of shorter time tests at comparatively high temperatures, which were conduced for parametric extrapolation only; consequently, there were no stress-rupture time curves. The strengths derived by the parameter methods were added to those previously discussed in Figures 21, 22 and 23. Because the number of data sets was so large, two graphs were used for each parameter. The data for tube and bar stock are on the first graph and the data for pipe material on the second--a division which is purely arbitrary. At this point in the analysis, there is no way of determining strength effects due to the type of material involved. The following comments are based on the graphs .

a. The "parameter"-type data sets were not rated "Good" simply because there were not sufficient iso-stress data. In four cases however (see Table 2), the data were good enough to be rated "Fair." Unduly high standard deviations and abnormal constants were a major factor in the "Poor" ratings.

b. With only one exception, the curves for the parameter data for the Larson-Miller parameter with a constant C of 20 (Fig. 21A, B) fitted in well with the data for the stress-rupture time curves dicussed previously. One set of parameter data for pipe (Fig. 21B) appeared to meet all of the requirements for at least a rating of "Fair," but had a curve with unusual inflections. The reasons for this are not yet known.

c. When the Larson-Miller constants were optimized (Fig. 22A, B), the range in strengths appeared to increase. This was most apparent for the pipe (Fig. 22B). There were also more curves of the strength versus temperature with inflections.

d. The same general comments apply to the Manson-Haferd parameter values (Fig. 23A, B) as did to the Larson-Miller parameter with optimized constants. A major exception was the almost complete removal of inflections from the rupture-strength-temperature curves by the Manson Haferd parameter.

3. When the log of the minimum and average stresses for rupture in 100,000 hours (excluding "Poor" data) were plotted versus temperature (Fig. 24), the curves tended to break down at the higher temperatures. This is in contrast to Type 304 steel, where they tended to be straight lines. This reflects the marked increase in slope of log-stress versus log-rupture time curves above 1100°F for Grade 22 (2-1/4Cr - 1Mo) steel. In addition, the following was noted--

a. There was relatively little difference in the strengths from the different parameters. The general order was preserved, however, with the Larson-Miller parameter with a constant C of 20 giving the highest strengths, the Larson-Miller parameter with optimized constants giving intermediate strengths, and the Manson-Haferd parameter giving the lowest strengths.

b. There was very little difference between the parameter minimum and those from extrapolation of log-stress log-rupture time curves in the temperature range over which comparison was possible.

Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) Steel

Comparison of 100,000-hour Strengths from Parameters and Log-Log Extrapolation of Rupture Curves.

The data sets for which the 100,000-hour strengths from parameters could be directly compared with those from log-log curves (Fig. 25A, B, C) were quite limited except at 1000°F ($\sim$10,000 psi). All three parameters tended to give strengths at 1000°F which were somewhat higher than those from stress-rupture time curves. At lower temperatures (higher strengths), the parameters gave lower values. The Larson-Miller parameter with optimized constants may have resulted in the closest agreement with stress-rupture time curves.

When all of the parameter strength values, including those from short time parameter data, were cross plotted (Fig. 25D, E), the following characteristics were noted.

1. The Larson-Miller parameter with optimized constants tended to give higher values than when the constant was fixed at 20 (Fig. 25D). There also occurred a much wider band for this steel than was the case for Type 304 and Grade 22 steels.

2. The Larson-Miller parameter with optimized constants tended to give slightly higher values (Fig. 25E) than the Manson-Haferd parameter. The difference in strength levels between the two methods was quite small, particularly in comparison to that for Type 304 and Grade 22 steels. Also, for some reason, the data sets which apparently adapted poorly were also in a rather narrow range. However, as has usually been the case, the Manson-Haferd parameter tended to give high strengths for the data sets which adapted poorly.

The similarity of the strengths derived by the two methods for optimizing constants is significant. It should not be taken as a reflection of accurately predicted strengths, but is merely indicative of the fact that similar strengths result from the mathematics of the two parameters. The scatter at the higher strength levels (lower temperatures) which is shown by the top three graphs, A, B, and C, in Figure 25, is more indicative of the real problem. In many cases, the log stress-log rupture time curve at 1000°F was steeper than at lower or higher temperatures, and the adaptability of the data to the parameter methods became questionable.

The slightly high strengths at 1000°F obtained from the parameters apparently indicate that the stress-rupture time curves at this temperature flatten at long time periods. The low strengths obtained from parameters at the lower temperatures apparently reflect the influence of the abnormally steep slope of rupture curves at 1000°F on the predicted strengths at long time periods.

<u>Strengths from Parameters as a Function of Temperature</u>

As for the other two steels, the 100,000-hour strengths derived from the parameters were plotted against temperature (Figs. 26, 27, 28). Because the data were so extensive, two graphs were drawn for each parameter. Again as a matter of convenience and not as a significant variable, they were split between tube and bar, and pipe. The graphs revealed the following.

1. The range of strengths was far less when the Larson Miller parameter with a forced-fit constant of 20, rather than optimized constants, was used. (Figs. 26, 27).

2. The range for the strengths from the Larson-Miller and Manson-Haferd parameters with optimized constants (Figs. 27, 28), while much larger, were very similar. This is consistent with the good agreement of Figure 25E.

3. At a fixed temperature, the range in strengths obtained using the Larson-Miller parameter with a constant C of 20 was about the same as the differences in strengths that could occur between extrapolations with a constant of 20 and with an optimized constant. The differences between

the strengths from the Larson-Miller and Manson Haferd parameters with optimized constants was smaller than the range in strengths at a given temperature obtained from the Larson-Miller parameter with a constant of 20. However, the range in strengths at a given temperature from the two parameters with optimized constants was much greater than it was for the Larson-Miller parameter with a constant C of 20. Consequently, even though the two parameters with optimized constants gave very nearly the same strengths, they resulted in wide ranges in strengths at a given temperature. This emphasizes the fact that the comparisons between strengths by the different extrapolation methods is not indicative of the ranges in strength to be expected at a given temperature.

d. The most striking feature of these curves is the marked deviation from the minimum and average from log-stress log-rupture time curves. The stress-rupture time curves in all cases extrapolated to lower values than the parameters at 1000° and 1100°F. This reflects a possible flattening out of stress-rupture time curves at long time periods at these temperatures. The tendency for higher strengths than the stress-rupture time curves at 900°F suggest that a downward break may occur at longer time periods.

When the poorly adaptable data were eliminated, and "average" and minimum curves of 100,000-hour strengths were plotted as log-stress versus temperature (Fig. 29), the higher strengths at low temperatures and lower strengths at high temperatures from extrapolation of log stress-log rupture time curves were over-exaggerated. This occurred mainly because the strengths from parameters were very limited at 1000° to 1100°F, and those available were for relatively high-strength materials. Even though this bias was introduced, the concave upward curves, at least at 900° to 1000°F, are real. This type of curve was to be expected due to the preponderance of data sets where the slopes of log stress log rupture time curves tended to have lower gradients above and below than at 1000°F.

DISCUSSION

Extensive sets of stress-rupture data for three steels were subjected to extrapolation to 100,000 hours by parameters. Where possible, the strengths were compared with those obtained by extrapolation of log stress-log rupture time curves. The strengths determined by the different parameters were also compared. A rather qualitative evaluation of the adaptability of each data set to the extrapolation methods based on the type of results to be expected and on the mathematics of the methods was carried out.

In general, the parameters gave extrapolated strengths for 100,000 hours which were more reasonable than had been anticipated. Moreover, experience with the adaptability rating indicated rather definitely that proper selection of test data to meet the mathematical requirements of the parameters would considerably improve the extrapolated strengths. This may be the most important result and, consequently, analysis ought to be conducted to determine if it is correct. Certainly the results indicated that the optimization of constants for the parameters cannot be relied upon to give reasonable extrapolations unless there are controls for using only data which satisfy the mathematical requirements.

The prior presentations of the methods of data rating and comparisons of the 100,000-hour strengths indicated a number of the problems and possible solutions in using parameters to extrapolate rupture data to 100,000 hours. In view of the importance of the subject, these are brought together briefly below.

1. The degree of the polynomial must be such that it can be used to describe the rupture data in a realistic manner. Otherwise, the optimization process can lead to stress-parameter relationships that are not characteristic of the materials. Some sources of inconsistency seem to be as follows.

a. Stress-rupture time relationships which were complex, as may be reflected as changes in slope at a given temperature, or wide differences in slope of log stress-log rupture time curves at different temperatures.

b. Because the conditions described under (a) are more likely to be present if the tests cover a wide range of temperatures and times, the problem was often apparent in such cases. It was quite evident that the results would be improved if data adaptable to parameter methods and limited by consideration of the temperature at which the an extrapolation was to be carried out were used.

c. From the parametized data there was evidence that the constants for a given set of data might vary with temperature and time of testing. This could be expected from theoretical viewpoints. However, the observed effects which may be attributable to variations in constant values may also have resulted from the use of data which were not exactly compatible with the mathematics of the parameters.

d. Data scatter often caused problems. In such cases, it was generally evident that force-fitting of degree polynomial and constants could improve the results.

e. Inaccurate results were suspected in some cases. Certainly the optimization process was very sensitive to typographical errors in the data.

2. It would be very easy to conclude from the results of this investigation that in a number of cases force-fitting constants in the parameter equation would be a distinct improvement. This may not be true. However, at this point, it is not known if this is a correct way to procede. Only when data consistent with the mathematical requirements have been evaluated sufficiently to eliminate the problems discussed under (1) will this be clarified. Force-fitting constants tends to ensure that the data is parametized in a reasonable manner and that strengths will be fairly close to the expected

values. For this reason they seem to give better results in many cases than optimized constants. Actually, problems of adaptability mask whether or not constants are a function of chemical composition, heat treatment, product form, etc. The selection of data for mathematical compatibility could go a long way towards evaluating these factors. It is even possible that this procedure may lead to the establishment of standard constants. It this were achieved, it would be possible to utilize iso-temperature data for parameter extrapolation at lower temperatures.

3. There were a number of cases where short time, higher temperature tests were run to obtain parameter-type data. It seems clear from the results of this investigation that this may or may not give good results. There is a definite need to know whether or not the data adapts properly. At this point there is not sufficient background to judge whether or not there are severe discontinuities or other problems with the log stress-parameter curves developed in this manner. Certainly it could be misleading to blindly use such data for optimizing constants, or, for that matter, for forced-fit constants. As far as this investigation was concerned, the parameter-type data sets had the additional handicap of not providing values from extrapolation of stress-rupture time curves for comparative purposes.

4. The data available were gathered predominantly to enable the plotting of stress-rupture time curves. Consequently, they were not ideal for an evaluation by parametric extrapolation. At first this appeared to be a distinct handicap. However it should be recognized that the difficulties arising from this short-coming may have had the advantage of pointing to the optimum way to develop data for use with parameters, whereas ideal data could easily be misleading by not showing the potential problems.

5. There were several cases where the parametric data indicated significantly different strengths from the log stress-log rupture time curves. Perhaps it is even more important the the parameters indicated

that changes in slope occur in rupture curves at times longer than the tests, or even that rupture curves are curved instead of the straight lines usually drawn. There is definite need for long time data which will enable the determination of the correct type of extrapolation. It would also help to indicate which parameters are applicable under particular conditions for different materials. This assumes that there could well be better adaptability to the data in one case for one parameter and in another case for another parameter. There is a possibility that considerable progress could be made towards clarifying the questions by using parameters (using short time tests) to predict the results of actual longer time tests (>10,000 hours) in the data used for this investigation and, therefore, it is recommended that this be done.

There were other aspects with regard to the use of parameters which should be noted.

1. When the parameter constants change, the magnitude of the parameters for rupture in 100,000 hours at any given temperature change. The rupture test data are, however, fixed, which restricts the range of parameters. As a consequence of the mathematics, there can be differences in the range of temperatures for which the test data encompass extrapolated strengths of interest. This accounts for those cases where 100,000 hour strengths were reported for a given temperature for the Larson-Miller parameter with a constant C of 20, and not for optimized constants (or vice versa). It also accounts for values being reported for the Larson-Miller and not for the Manson-Haferd parameter, or vice versa.

2. It has been emphasized that parameter curves derived by the optimization process cannot be extrapolated beyond the range of stresses of the tests. This can only be done with any degree of confidence when the constants and shapes of curves are known.

3. "Force-fitting" such as that discussed previously should be carried out. Both of the computer programs in this investigation can be used in this manner.

4. The widespread use of the Larson-Miller parameter has provided enough experience to make it possible to judge when "optimized" constants are reasonable. In the course of this investigation, information was found which strongly indicated that a basis for judging "optimized" constants for the Manson-Haferd parameter also exists. A little more work would enable finalizing of this procedure.

SUMMARY AND CONCLUSIONS

The Larson-Miller and Manson-Haferd parametric methods were used to extrapolate rupture data for Type 304 (18Cr-8Ni) austenitic stainless steel, Grade 22 (2-1/4Cr - 1Mo) steel, and Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) steel by optimization of the parameter constants using a computer program. The parameter treatments were evaluated qualitatively and the derived 100,000-hour strengths were compared together with those obtained by straight line extrapolation of log stress-log rupture time curves and by the Larson-Miller parameter with a constant C of 20.

The results of the study emphasized the significance of the adaptability of the test data to the mathematical requirements of the individual methods used for extrapolation. It appeared that the 100,000-hour rupture strengths obtained by extrapolation with parameters when the data adapted well were closer to expected values than had been anticipated when the investigation began. Little confidence could be placed in the parametric extrapolation when the data did not adapt well. However, it was surprising to note how many of these data sets gave strengths close to those expected. Thus, the mathematics of the optimizing of constants in the Larson-Miller and Manson-Haferd parameters may or may not result in an "averaging" of constants and the log stress-parameter relationships. If this occurs, the resulting strengths are often close to the expected values, even if the adaptability of the data appears poor. The use of a fixed constant of 20 in the Larson-Miller parameter is a method of insuring an "averaging" of the data, or of producing log stress-parameter relationships considered characteristic of the material. Thus, it often gives what appear to be nearly correct values for data which adapts poorly simply because it forces the parametized data to behave in a reasonable manner.

The use of raw test data without regard to the adaptability to the mathematics of the particular parameter method, as was done in this investigation, cannot be relied upon to properly extrapolate the rupture strengths to long time periods. Most important, there was a strong indication that proper selection of test data to meet the mathematical requirements of parameters could lead to reliable extrapolation. Certainly the question of whether or not constants change with composition, heat treatment, product form, etc., cannot be evaluated without restricting the data used to that which meets these requirements. There may also be a need to control the degree of the polynomial in the procedure for optimizing constants to a greater extent than was done for this investigation.

In most cases, the range in extrapolated 100,000-hour strengths at a fixed temperature was much wider than the differences in strengths between parameters. The Manson-Haferd parameter gave lower strengths than the Larson-Miller parameter. The Larson-Miller parameter with a fixed constant of 20, gave higher strengths than when the constant was optimized, except for Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) steel. In general, the Larson-Miller parameter with optimized constants came closest to the strengths from extrapolation of stress-rupture time curves.

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Table 1

Summary of the 100,000-Hour Strength Levels for Types 304 and 304L Stainless Steels
Established by Straight-Line Extrapolation of Rupture Curves and by Three Parameter Methods

Extrapolation Methods:
L-L = Straight-Line Extrapolation of Log Stress-Log Rupture Time Curves
LM-20 = Larson-Miller Parameter with C = 20.0
L-M = Larson-Miller Parameter with an Optimized Constant
M-H = Manson-Haferd (Linear) Parameter with Optimized Constants

Data Rating (see p 7): G = Good; F = Fair; P = Poor; * = Slopes of the stress-rupture curves show apparent inconsistencies.

STRESSES (1000 psi) FOR RUPTURE IN 100,000 HOURS

Data Sheet	Extrapolation Method	Data Rating	Temperature, °F 950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1500
Type 304, Bar													
1	L-L	G				13.0				4.4			1.8
	LM-20	P	25.4	20.8	16.9	13.7	11.0	8.8	7.0	5.5	4.3		
	L-M	F	21.8	17.8	14.4	11.7	9.4	7.5	6.0	4.8			
	M-H	G	17.6	13.8	10.9	8.5	6.7	5.3	4.2				
15	L-L	G			16.0			7.4					
	LM-20	G	25.8	20.5	15.0	12.0							
	L-M	G	23.8	18.5	13.8	12.0							
	M-H	G	21.6	17.6	14.4								
19	L-L	G*			18.0			12.3			5.8		
	LM-20	P	29.9	25.7	22.3	19.0	15.5	12.2	9.6				
	L-M	P	27.7	23.4	19.5	16.1	13.2	10.7	8.6				
	M-H	G	24.0	21.7	19.5	17.4	15.3	13.3	11.3	8.8			
23	L-L	F						11.0			4.5		
	LM-20	F			19.5	16.0	12.9	10.0	7.7				
	L-M	F			20.1	16.4	13.4	10.6	8.0				
	M-H	F	19.7	18.2	16.5	14.8	13.0	11.2	9.3				

Table 1, continued

Data Sheet	Extrapolation Method	Data Rating	Temperature, °F 950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1500
40(Plate)	L-L	G				16.0				5.7			2.7
	LM-20	F	30.6	24.6	19.6	15.7	12.8	10.5	8.7	7.1	5.6		
	L-M	F	29.5	23.6	18.8	15.1	12.3	10.1	8.4	6.8	5.3		
	M-H	G	29.0	21.7	16.2	12.3	9.4	7.3	5.8				
A	L-L	G				12.1				4.8			
	LM-20	F	25.3	20.6	16.8	13.6	10.7	8.3	6.3	4.9	4.0		
	L-M	F	23.6	19.3	15.7	12.5	9.8	7.5	5.8	4.5			
	M-H	F	19.4	16.4	13.8	11.5	9.5	7.8	6.4	5.2	4.1		
B	L-L	G						6.9		3.9		2.8	1.6
	LM-20	P	25.9	20.4	16.2	12.8	10.1	8.0	6.3	5.0			
	L-M	F	21.3	17.0	13.6	10.9	8.8	7.0	5.6	4.5			
	M-H	G	18.3	14.5	11.5	9.1	7.2	5.8	4.6				
1H-H	L-L	P*		21.5		13.0							
	LM-20	P	30.7	24.0									
	L-M	P	20.8										
	M-H	P	23.8	20.3									
Type 304, Tube													
C-1	L-L	G				15.2		9.4					
	LM-20	G	29.3	23.4	18.7	14.9							
	LM	G	28.7	23.0	18.4	14.7							
	M-H	G	25.2	21.9	18.7	15.6							
D	L-L	F				18.3		10.8					
	LM-20	F	33.1	26.9	21.8	17.7							
	L-M	F	33.0	26.8	21.8	17.7							
	M-H	P	30.2	25.8	21.8	18.1							
E	L-L	P						12.1					
	LM-20	P	34.4	29.3	23.8								
	L-M	P	34.4	29.3	23.8								
	M-H		(Limited data)										

Table 1, continued

Data Sheet	Extrapolation Method	Data Rating	Temperature, °F 950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1500
Type 304S, Bar													
20S	L-L	G			24.0			11.5			4.7		
	LM-20	G	34.4	27.9	22.3	17.6	13.8	10.7	8.2	6.2			
	L-M	G	36.2	29.4	23.5	18.6	14.5	11.2	8.5	6.4			
	M-H	G	37.2	29.5	22.9	17.2	12.8	9.6	7.4				
21S	L-L	G*			16.5			11.7			4.8		
	LM-20	P	30.7	24.5	20.3	16.9	13.9	11.0	8.2				
	L-M	P	29.0	23.4	19.3	16.0	13.1	10.4	7.8				
	M-H	P	24.7	21.7	19.0	16.8	14.9	13.3	11.4	8.1			
Type 304L, Bar													
3L	L-L	G				10.0				2.7			1.3
	LM-20	F	22.1	17.3	13.4	10.2	7.8	5.9	4.5	3.5	2.8	2.2	
	L-M	G	19.2	14.7	11.0	8.2	6.3	5.0	4.1	3.5	2.9	2.2	
	M-H	G	15.3	11.3	8.5	6.4	5.0	3.9	3.1	2.6	2.1		
4L	L-L	G			18.6			8.2		4.9		3.2	1.5
	LM-20	P	25.9	21.2	17.2	13.8	11.0	8.7	6.9	5.3	4.1	3.1	
	L-M	P	25.6	20.9	16.9	13.6	10.8	8.6	6.7	5.2	4.0	3.0	
	M-H	F	22.0	16.1	11.6	8.4	6.0	4.4	3.3				
AL	L-L	G			15.0			8.4					
	LM-20	F	25.5	20.5	16.7	13.2							
	L-M	G	23.4	18.5	14.9	12.8							
	M-H	G	21.6	17.7	14.6	12.1							

Table 2

Summary of the 100,000-Hour Strength Levels for Wrought 2-1/4 Cr - 1 Mo Steels (Grade 22) Established by Straight-Line Extrapolation of Rupture Curves and by Three Parameter Methods

Extrapolation Methods
- L-L = Straight-Line Extrapolation of Log Stress-Log Rupture Time Curves
- LM-20 = Larson-Miller Parameter with C = 20.0
- L-M = Larson-Miller Parameter with an Optimized Constant
- M-H = Manson-Haferd (Linear) Parameter with Optimized Constants

Data Rating (see page 7): G = Good; F = Fair; P = Poor; O = Omit; * = Slopes of the stress-rupture curves show apparent inconsistencies.

STRESSES (1000 psi) FOR RUPTURE IN 100,000 HOURS

Data Sheet	Extrapolation Method	Data Rating	Temperature, °F						
			900	950	1000	1050	1100	1150	1200
TUBE - Annealed above or near top of critical temperature range									
1	L-L	G			11.0	8.0	6.1		
	LM-20	G	18.0		10.4	(8.0)			
	L-M	G	17.3	13.5	10.4				
	M-H	G	15.8	12.2	9.5				
3	L-L	G			12.8		8.2		
	LM-20	F	19.7		(12.6)				
	L-M	F	19.6	15.8					
	M-H	F	18.6	15.5					
5	L-L	G			11.3		8.0		
	LM-20	F	19.6		(12.5)				
	L-M	F	18.1	14.6					
	M-H	F	17.3	14.0					
6	L-L	G			12.5		8.4		
	LM-20	G	20.1		13.0	(10.4)			
	L-M	G	19.2	15.6	12.7				
	M-H	G	17.5	14.5	12.0				
7	L-L		Parameter Data						
	LM-20	P	18.0		(10.3)				
	L-M	P	18.2	13.8					
	M-H		Limited Data						

Table 2, continued

Data Sheet	Extrapolation Method	Data Rating	Temperature, °F 900	950	1000	1050	1100	1150	1200
8	L-L		Parameter Data						
	LM-20	P	18.0		(9.7)				
	L-M	P	16.7	12.4					
	M-H		Limited Data						
9	L-L		Parameter Data						
	LM-20	P	19.4		12.5				
	L-M	P	18.4	14.8					
	M-H		Limited Data						
18	L-L	G			10.0		6.7		2.5
	LM-20	G	18.0		11.1	8.3	5.9		
	L-M	G	17.0	13.7	10.7	8.1	5.8		
	M-H	G	16.0	13.1	10.7	8.5	6.0		
20	L-L	F*			10.1				
	LM-20	P	19.6		12.0				
	L-M	P	20.2	15.1	12.2				
	M-H	P	18.5	13.3					
TUBE - Annealed below or near bottom of critical temperature range									
25	L-L	G			11.8	8.7	4.8		
	LM-20	G	20.7		11.2				
	L-M	G	19.5	14.4	11.4				
	M-H	G	18.9	15.1	11.3				
26	L-L	G				9.3	7.2		
	LM-20	G	21.5		(12.7)				
	L-M	G	19.6	16.1					
	M-H	G	15.6						
27	L-L	F				8.5			
	LM-20	F	18.1		(10.3)	(7.7)	(5.3)		
	L-M	F	16.8						
	M-H	G	16.7						
28	L-L	G			10.1		5.7		1.9
	LM-20	G	19.3		11.0				
	L-M	G	17.4	12.8	9.9	7.4	4.9		
	M-H	G	17.4	12.8	9.1	6.0	3.8		
PIPE - Annealed above or near top of critical temperature range									
29	L-L	P			12.0				2.6
	LM-20	P	18.7		11.2	8.3	5.9		
	L-M	P	17.9	14.2	10.8	7.9	5.6		
	M-H	P	16.2	13.8	11.4	9.1	6.9		

Table 2, continued

Data Sheet	Extrapolation Method	Data Rating	Temperature, °F						
			900	950	1000	1050	1100	1150	1200
30	L-L	F			11.0				2.5
	LM-20	F	19.0		12.2	9.3	(6.4)		
	L-M	F	18.8	14.7	12.2	9.5			
	M-H	F	17.8	14.2	11.4	8.4			
31	L-L	F			13.4				2.1
	LM-20	P	23.1		13.3	9.5	6.1		
	L-M	P	19.2	14.1	11.3	8.1			
	M-H	P	24.8	18.2	14.3	10.8	7.3		
32	L-L	F			13.1		6.5		2.0
	LM-20	P	21.5		14.0	10.5	7.1		
	L-M	P	23.5	17.3	13.9	11.9	8.4		
	M-H	P		17.3	14.3	10.5	6.5		
33	L-L		Parameter Data						
	LM-20	F	(23.0)		14.4	10.8	7.4		
	L-M	F		19.6	14.3	11.1	7.6		
	M-H	F		17.4	14.1	10.7	6.6		
34	L-L		Parameter Data						
	LM-20	F	17.0		10.8	8.6	(6.9)		
	L-M	F	18.0	14.2	11.7	9.5	7.1		
	M-H	P		14.2	11.3	8.4			
35A	L-L		Parameter Data						
	LM-20	F	(22.0)		14.0	10.5	7.1		
	L-M	F	20.6	16.2	13.3	9.5			
	M-H	F	19.9	16.2	12.4	9.0			
35B	L-L		Parameter Data						
	LM-20	F	18.0		11.6	9.0	6.7		
	L-M	F		14.9	12.1	9.7	7.2		
	M-H	F		14.3	11.1	8.0			
36A	L-L		Parameter Data						
	LM-20	F	17.8	14.4	12.5	10.2			
	L-M	O							
	M-H	O							
36B	L-L		Parameter Data						
	LM-20	F		14.7	11.9	9.4			
	L-M	P		16.1	13.1	10.7	8.1		
	M-H	P		15.9	12.9	9.9			
37A	L-L		Parameter Data						
	LM-20	P		15.6	12.0	8.9	6.0		
	L-M	P		17.5	13.9	11.0	8.4		
	M-H	P		16.0	12.3	8.5	5.0		

Table 2, continued

Data Sheet	Extrapolation Method	Data Rating	Temperature, °F 900	950	1000	1050	1100	1150	1200
37B	L-L		Parameter Data						
	LM-20	P	19.3	15.8	12.7	9.9	7.5		
	L-M	P		18.8	15.2	12.5	9.8	6.5	
	M-H	P		17.4	14.6	11.3	7.6		
38A	L-L		Parameter Data						
	LM-20	P		14.8	12.2	9.3			
	L-M	O							
	M-H	P		15.6	12.0	8.1			
38B	L-L		Parameter Data						
	LM-20	P	14.8	11.6	9.0				
	L-M	P	16.3	12.2	9.1				
	M-H	P	14.5	11.0	8.4				
39	L-L		Parameter Data						
	LM-20	P	(18.6)		12.0	9.2	(6.7)		
	L-M	P		16.1	13.4	11.2	8.6		
	M-H	P	16.9	14.1	12.1	10.2	8.1		
A	L-L	F			12.0		7.0		
	LM-20	P	30.8		14.0	(9.5)			
	L-M	P	29.3	19.2	14.0				
	M-H	F	23.3	14.5					
B	L-L		Parameter Data						
	LM-20	P	26.1		16.0	11.5			
	L-M	P		26.6	21.9	17.4	13.3		
	M-H	P	29.4	25.3	21.4	17.9	14.6	11.7	
STP-5	L-L	F			12.6				
	LM-20	P	21.2		(12.6)				
	L-M	P	16.7						
	M-H	P	17.1						
BAR - Annealed above or near top of critical temperature range									
42	L-L	G			13.4		6.9		2.8
	LM-20	F	20.9		12.0	8.8	6.1		
	L-M	F	19.9	15.8	11.6	8.3	5.8		
	M-H	F	17.2	13.5	11.8	9.1	6.6	4.4	
BAR - Normalized and tempered									
48	L-L	G	30.0			13.2			2.1
	LM-20	P	29.5		14.6	9.1	5.3		1.65
	L-M	P	32.8	25.9	18.1	11.3	6.9	4.4	2.7
	M-H	P	29.0	21.1	14.3	8.9	5.2	2.7	1.4

Table 2, continued

Data Sheet	Extrapolation Method	Data Rating	900	950	1000	1050	1100	1150	1200
			Temperature, °F						
BAR - Annealed below or near bottom of critical temperature range									
49	L-L	G					5.3		
	LM-20	F			11.8	8.2			
	L-M	F			10.7	7.6			
	M-H	F		13.0	9.9	7.3			

( ) indicates outside of actual test stresses

Table 3

Summary of the 100,000-Hour Strength Levels for Wrought
1-1/4 Cr - 1/2 Mo - 3/4 Si Steels (Grade 11) Established by
Straight-Line Extrapolation of Rupture Curves
and by Three Parameter Methods

Extrapolation Methods	L-L =	Straight-Line Extrapolation of Log Stress-Log Rupture Time Curves
	LM-20 =	Larson-Miller Parameter with C = 20.0
	L-M =	Larson-Miller Parameter with an Optimized Constant
	M-H =	Manson-Haferd (Linear) Parameter with Optimized Constants
Data Rating (see page 7)		G = Good; F = Fair; P = Poor; O = Omit; * = Slopes of the stress-rupture curves show apparent inconsistencies.

STRESSES (1000 psi) FOR RUPTURE IN 100,000 HOURS

Data Sheet	Extrapolation Method	Data Rating	Temperature, °F						
			900	950	1000	1050	1100	1150	1200
TUBE - Annealed above or near top of critical temperature range									
4	L-L	G			11.0			7.0	
	LM-20	F	21.0	15.0	10.5				
	L-M	G	26.8	17.0	10.7				
	M-H	G	25.0	17.0	11.2				
10	L-L	G*			8.8		4.3		
	LM-20	F	22.5	14.3	9.1				
	L-M	G	27.4	15.9	10.6				
	M-H	G	22.2	15.3	10.8				
12	L-L	F			9.7		4.3		
	LM-20	F	25.0	16.0	10.0	(6.4)			
	L-M	F	27.1	15.4	10.4				
	M-H	F	22.6	15.7	10.7	7.3			
13	L-L	P			10.0				
	LM-20	P	29.0	18.5	(11.8)				
	L-M	O	16.9	12.4					
	M-H	P	28.6	16.1					
24	L-L	G			9.0	5.5	3.1		
	LM-20	G	27.0	15.0	(8.5)				
	L-M	G	29.5	16.0					
	M-H	G	28.4	13.7					

Table 3, continued

Data Sheet	Extrapolation Method	Data Rating	900	950	1000	1050	1100	1150	1200
			Temperature, °F						
34	L-L		Parameter Data						
	LM-20	P	27.0	16.5					
	L-M	P	23.8	13.4					
	M-H		Limited Data						
36	L-L	P			10.5				
	LM-20	G	30.5	18.0	10.5				
	L-M	G	26.3	13.9					
	M-H	G	21.7	14.2	10.3				
TUBE - Annealed within but near the lower critical temperature									
52	L-L	P			14.5	4.8			
	LM-20	P	27.0	16.0					
	L-M	P	35.7	25.0					
	M-H	P	34.8	22.6					
TUBE - Annealed below the critical temperature range									
54	L-L	G			10.4		5.8		
	LM-20	G	21.0	15.0	10.8				
	L-M	G	22.9	15.7	11.7				
	M-H	G	22.6	14.8	10.3				
55	L-L	P			10.4		6.4		
	LM-20	P	21.0	15.5	(11.3)				
	L-M	P	23.9	17.5					
	M-H		Limited Data						
56	L-L	P			10.4		5.8		
	LM-20	P	20.8	14.8	10.8				
	L-M	P	25.7	18.4	12.9				
	M-H		Limited Data						
59	L-L	G*			10.8				
	LM-20	P	20.4	13.0					
	L-M	P	31.3	18.3	11.1				
	M-H	P	31.6	16.6					
60	L-L	G			9.2		5.2		
	LM-20	P	21.0	13.8	10.0	7.2			
	L-M	P	22.9	14.6	10.2	7.7			
	M-H	P	21.6	12.6	9.0				

Table 3, continued

Data Sheet	Extrapolation Method	Data Rating	Temperature, °F 900	950	1000	1050	1100	1150	1200
PIPE - Annealed above or near top of critical temperature range									
68	L-L	P			7.7		3.1		
	LM-20	P	26.0	16.5	10.5	(6.6)			
	L-M	P	28.9	15.3	10.4				
	M-H	P	30.0	15.5	9.1				
69	L-L		Parameter Data						
	LM-20	P	20.6	15.2	11.2	7.8	(5.3)		
	L-M	P	24.2	17.0	12.0	8.6	6.2		
	M-H	?		22.7	16.2	11.6	8.4	6.1	
70	L-L		Parameter Data						
	LM-20	F	23.5	14.8	10.5	7.3	(5.2)		
	L-M	F		20.3	13.4	9.3	6.8		
	M-H	F	24.7	16.5	12.0	9.2	7.3		
71	L-L		Parameter Data						
	LM-20	P	20.0	14.4	10.3	7.5	(5.3)		
	L-M	O							
	M-H	P	14.2	11.7	9.9	8.3	6.8		
72	L-L		Parameter Data						
	LM-20	F	20.0	15.4	11.7	7.7	(5.0)		
	L-M	P	28.7	21.6	15.9	11.4	7.9		
	M-H	P	28.0	19.0	13.5	9.2	5.6		
73	L-L		Parameter Data						
	LM-20	P	23.6	14.8	11.3	8.1	(5.5)		
	L-M	O							
	M-H	O							
74	L-L	G	33.0		8.3		4.3		
	LM-20	P	22.5	14.8	10.2				
	L-M	P	18.4	11.8					
	M-H	P	17.0	12.0	9.1				
75	L-L	P	40.0		11.0		4.3		
	LM-20	P	28.6	17.5	10.7				
	L-M	P	29.8	17.3	10.5				
	M-H	P	28.9	16.1					
76	L-L	G	40.0		8.4		3.8		
	LM-20	F	28.8	16.5	9.5				
	L-M	P	38.4	25.7	15.5	8.4			
	M-H	P	38.4	27.0	17.3	9.9			

Table 3, continued

Data Sheet	Extrapolation Method	Data Rating	Temperature, °F 900	950	1000	1050	1100	1150	1200
PIPE - Normalized and tempered									
78	L-L		Parameter Data						
	LM-20	F	23.5	16.0	11.3	7.7	(5.4)		
	L-M	F		23.3	15.9	11.1	7.9		
	M-H	P		21.7	15.2	10.7	7.6		
79	L-L	G	24.0		9.6		4.7		
	LM-20	G	19.5	13.5	9.3	(6.4)			
	L-M	G	20.5	14.1	9.6				
	M-H	G	19.1	12.0	8.2				
80	L-L	G	33.0		7.1		4.7		
	LM-20	G	25.6	13.5	9.3	(6.4)			
	L-M	G	28.5	15.3	10.1	7.2			
	M-H	G	25.0	15.2	9.9	7.3			
81	L-L	G	37.0		7.1		4.0		
	LM-20	G	21.3	12.8	8.7	(6.0)			
	L-M	G	28.3	16.7	10.8				
	M-H	G	28.3	15.4	9.2				
82	L-L	F		22.0		7.4			
	LM-20	F	18.0						
	L-M	P	28.5	19.5					
	M-H	F	26.2	18.9					
BAR - Annealed above or near top of critical temperature range									
83	L-L	P	25.0						
	LM-20	O							
	L-M	O							
	M-H	O							
84	L-L	G			11.4		5.4		
	LM-20	P	26.5	17.2	11.0	(7.0)			
	L-M	P		21.3	15.3	9.5			
	M-H	P		20.9	14.8				
88	L-L	G*			7.8		5.5		
	LM-20	G	22.2	14.3	10.3	(7.5)			
	L-M	G	21.1	12.5	9.5	8.0			
	M-H	G	18.5	13.7	10.5	8.0			
89	L-L	F*			8.7		5.5		
	LM-20	F	22.0	14.4	10.5				
	L-M	G	20.1	13.7	10.4				
	M-H	G	17.8	13.3	10.3				

Table 3, continued

Data Sheet	Extrapolation Method	Data Rating	Temperature, °F 900	950	1000	1050	1100	1150	1200
BAR & PLATE - Normalized and tempered									
91	L-L	F*			6.5		3.4		
	LM-20	G	22.5	15.3	10.3				
	L-M	G	23.1	15.2	11.0				
	M-H	G	21.0	13.4	8.9				
93	L-L								
	LM-20	P	25.5	16.5	10.7	7.0	4.5		
	L-M	P	32.5	22.7	15.4	10.3	6.9	4.6	2.9**
	M-H	P	~~35.7~~	24.4	15.3	9.1	5.2	2.9	1.6

( ) indicates outside of actual test stresses

** 1250°F - 1.6

Table 4

Summary of the Optimized Stress-Rupture Parametric Constants for 304 and 304L Stainless Steels As Determined by the Application of the Larson-Miller and Manson-Haferd Parametric Methods

		Larson-Miller Parameter			Manson-Haferd Parameter			
Data Sheet	No. of Data Pts. (n)	Log-Time Intercept (Y_A)	Standard Deviation (D)	Degree of Polynomial (m)	Temp. Intercept (T_A)	Log-Time Intercept (Y_A)	Standard Deviation (D)	Degree of Polynomial (m)
Type 304, Bar								
1	18	-16.8	0.109	2	0	-14.8	0.094	3
15	9	-17.8	0.016	5	3050	-21.9	0.021	5
19	17	-14.2	0.159	7	1550	-0.6	0.078	4
23	6	-21.9	0.046	3	1550	-0.6	0.054	2
40	18	-18.9	0.127	4	550	-10.8	0.056	7
A	13	-17.7	0.094	4	3050	-17.8	0.096	3
B	26	-16.9	0.132	2	-500	20.8	0.108	3
1H-H	15	-9.0	0.207	6	1550	-1.6	0.167	3
Type 304, Tube								
C-1	8	-19.3	0.062	2	1550	-2.6	0.034	2
D	5	-19.9	0.084	1	2050	-10.0	0.109	1
E	4	-20.0	0.184	1				
Type 304S, Bar								
20S	14	-22.4	0.116	2	550	-12.8	0.097	7
21S	13	-17.8	0.228	3	1550	-1.6	0.130	4
Type 304L, Bar								
3L	14	-16.5	0.079	6	0	15.3	0.103	5
4L	36	-19.7	0.476	4	550	10.0	0.408	7
AL	10	-16.5	0.002	7	-1500	35.1	0.049	6

Table 5

Summary of the Optimized Stress-Rupture Parametric Constants for 2-1/4 Cr - 1 Mo Steels
As Determined by the Application of the Larson-Miller and Manson-Haferd Parametric Methods

		Larson-Miller Parameter			Manson-Haferd Parameter			
Data Sheet	No. of Data Pts. (n)	Log-Time Intercept (Y_A)	Standard Deviation (D)	Degree of Polynomial (m)	Temp. Intercept (T_A)	Log-Time Intercept (Y_A)	Standard Deviation (D)	Degree of Polynomial (m)
TUBE - Annealed above or near top of critical temperature range								
1	13	-19.8	0.062	2	0	17.8	0.060	6
3	7	-19.8	0.059	1	2550	-19.7	0.068	1
5	7	-17.9	0.051	3	-500	24.3	0.053	1
6	7	-18.1	0.085	1	-3000	56.3	0.093	1
7	4	-20.2	0.015	1				
8	4	-18.4	0.066	1				
9	4	-17.0	0.012	1				
18	12	-18.9	0.046	7	3050	-25.7	0.035	3
20	5	-20.5	0.024	2	550	10.4	0.151	1
TUBE - Annealed below or near bottom of critical temperature range								
25	12	-18.1	0.063	7	1550	-4.4	0.075	4
26	10	-17.4	0.044	2	550	8.7	0.031	6
27	9	-16.3	0.065	6	550	9.8	0.093	2
28	12	-18.3	0.081	5	550	10.7	0.071	5
PIPE - Annealed above or near top of critical temperature range								
29	12	-18.9	0.273	2	1550	-3.7	0.278	3
30	9	-20.0	0.021	6	0	19.0	0.105	3
31	10	-26.5	0.023	7	-1000	42.3	0.049	5
32	10	-24.5	0.127	4	550	13.0	0.133	4
33	6	-20.2	0.046	3	0	20.2	0.061	2
34	6	-22.0	0.005	3	550	12.0	0.072	2
35A	6	-17.6	0.046	2	-3000	58.4	0.080	2
35B	6	-22.2	0.044	3	550	11.5	0.040	2

Table 5, continued

Data Sheet	No. of Data Pts. (n)	Larson-Miller Parameter: Log-Time Intercept (Y_A)	Larson-Miller Parameter: Standard Deviation (D)	Larson-Miller Parameter: Degree of Polynomial (m)	Manson-Haferd Parameter: Temp. Intercept (T_A)	Manson-Haferd Parameter: Log-Time Intercept (Y_A)	Manson-Haferd Parameter: Standard Deviation (D)	Manson-Haferd Parameter: Degree of Polynomial (m)
36A	6	-2.3	0.052	2	1050	3.2	0.056	1
36B	6	-25.1	0.038	3	550	13.1	0.096	2
37A	6	-26.8	0.097	2	550	12.1	0.104	2
37B	6	-32.3	0.038	3	550	14.2	0.065	2
38A	6	-8.6	0.050	3	550	11.6	0.122	2
38B	6	-14.6	0.071	1	-3000	48.6	0.082	1
39	6	-27.8	0.114	3	2050	-11.7	0.173	1
A	11	-19.3	0.112	6	550	9.7	0.081	6
B	5	-32.8	0.139	2	2050	-19.0	0.182	1
STP-5	9	-12.7	0.089	6	-1500	33.4	0.200	2
BAR - Annealed above or near top of critical temperature range								
42	18	-19.1	0.168	5	1550	-3.3	0.118	7
BAR - Normalized and tempered								
48	22	-24.3	0.268	7	0	20.0	0.246	4
BAR - Annealed below or near bottom of critical temperature range								
49	5	-17.2	0.050	1	2550	-14.4	0.070	1

Table 6

Summary of the Optimized Stress-Rupture Parametric Constants for 1-1/4Cr - 1/2Mo - 3/4Si Steels
As Determined by the Application of the Larson-Miller and Manson-Haferd Parametric Methods

		Larson-Miller Parameter			Manson-Haferd Parameter			
Data Sheet	No. of Data Pts. (n)	Log-Time Intercept (Y_A)	Standard Deviation (D)	Degree of Polynomial (m)	Temp. Intercept (T_A)	Log-Time Intercept (Y_A)	Standard Deviation (D)	Degree of Polynomial (m)
TUBE - Annealed above or near top of critical temperature range								
4	8	-26.6	0.043	3	1550	-7.6	0.042	3
10	10	-24.2	0.019	7	1550	-5.6	0.042	6
12	14	-20.8	0.045	7	1550	-4.8	0.046	7
13	8	-12.9	0.091	3	550	11.0	0.109	1
24	12	-21.3	0.057	5	550	11.1	0.047	5
34	4	-16.8	0.246	1				
36	8	-17.1	0.063	3	1550	-3.5	0.077	3
TUBE - Annealed within but near the lower critical temperature								
52	8	-30.9	0.094	2	0	25.8	0.103	2
TUBE - Annealed below the critical temperature range								
54	9	-23.0	0.005	6	550	11.6	0.046	2
55	4	-22.3	0.053	1				
56	4	-27.0	0.044	1				
59	12	-30.0	0.121	7	550	13.4	0.112	7
60	12	-22.6	0.164	3	550	11.1	0.139	3
PIPE - Annealed above or near top of critical temperature range								
68	12	-20.6	0.032	7	550	11.6	0.031	7
69	6	-38.7	0.028	2	-3000	109.1	0.034	1
70	6	-27.9	0.077	2	2050	-14.9	0.085	2
71	6	-0.72	0.102	3	1550	-3.7	0.117	2
72	2 x 6	-34.5	0.139	2	550	13.8	0.156	3
73	2 x 6	-0.88	0.233	3	1550	9.0	0.250	3

Table 6, continued

Data Sheet	No. of Data Pts. (n)	Larson-Miller Parameter: Log-Time Intercept (Y_A)	Larson-Miller Parameter: Standard Deviation (D)	Larson-Miller Parameter: Degree of Polynomial (m)	Manson-Haferd Parameter: Temp. Intercept (T_A)	Manson-Haferd Parameter: Log-Time Intercept (Y_A)	Manson-Haferd Parameter: Standard Deviation (D)	Manson-Haferd Parameter: Degree of Polynomial (m)
74	11	-14.5	0.106	6	1550	-2.6	0.122	6
75	10	-20.0	0.211	3	550	-11.0	0.228	3
76	11	-36.1	0.079	6	2050	-28.8	0.080	6
PIPE - Normalized and tempered								
78	6	-32.7	0.053	1	-3000	+95.3	0.055	1
79	12	-22.0	0.089	2	550	10.9	0.079	3
80	12	-22.7	0.029	7	2550	-23.0	0.028	7
81	12	-26.6	0.215	4	550	12.6	0.227	4
82	10	-31.2	0.074	7	1550	-10.6	0.177	2
BAR - Annealed above or near top of critical temperature range								
83	6	+38.0	0.143	3	3050	-33.2	0.200	1
84	11	-34.9	0.250	3	550	15.5	0.213	3
88	8	-18.4	0.045	5	1550	-4.4	0.073	4
89	9	-18.5	0.007	6	2050	-11.2	0.005	5
BAR & PLATE - Normalized and tempered								
91	8	-20.9	0.054	3	550	10.9	0.059	3
93	28	-27.9	0.556	6	550	13.6	0.470	7

Table 7

Larson-Miller Optimized Constants and the Corresponding Standard Deviations for Various Degree Polynomials for Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) Steel

The two cases should be contrasted in that for Data Sheet 68, the standard deviation is high until the polynomial degree is increased to 7, whereas for Data Sheet 12, the standard deviation is low and has similar values for polynomial degrees of 4 to 7.

	LARSON-MILLER PARAMETER			
	Data Sheet 68 Data Rating: Poor		Data Sheet 12 Data Rating: Fair	
Degree of Polynomial (m)	Log-Time Intercept (Y_A)	Standard Deviation (D)	Log-Time Intercept (Y_A)	Standard Deviation (D)
2	-16.67	0.161	-20.28	0.079
3	-14.99	0.150	-19.33	0.079
4	-17.79	0.133	-20.56	0.048
5	-17.59	0.139	-19.88	0.048
6	-19.07	0.138	-20.21	0.046
7	-20.60	0.032	-20.78	0.045

Figure 1A. An example of the computer output for optimizing the constant for the Larson-Miller Parameter.

DATA FROM DATA SHEET NUMBER ONE 304 STAINLESS FROM TABLE VI
LARSON PARAMETER

CREEP/RUPTURE PARAMETERS ARE INVESTIGATED FOR
1 VALUE(S) OF T(A), 1 TEMPERATURE EXPONENT(S), 1 STRESS EXPONENT(S), AND 6 POLYNOMIAL(S)
USING 18 DATA POINTS

Q	R	M	T(A)	Y(A)	STD.DEV.	Q	R	M	T(A)	Y(A)	STD.DEV.
0.0	-1.00	2	-460.	-16.83	0.1086401						
0.0	-1.00	3	-460.	-16.76	0.1088223						
0.0	-1.00	4	-460.	-16.72	0.1116492						
0.0	-1.00	5	-460.	-16.71	0.1152014						
0.0	-1.00	6	-460.	-16.75	0.1201352						
0.0	-1.00	7	-460.	-16.63	0.1113287						

VALUES PRODUCING SMALLEST STANDARD DEVIATION

Q= 0.0 , R=-1.00, M= 2, T(A)= -460., Y(A)= -16.833, AND STANDARD DEVIATION = 0.1086401

TEMP	STRESS (*E-3)	LOG STRESS	TIME	CALCTD TIME	LOG TIME	CALC LOG TIME	DEV/SD	PARAMETER
1100.	45.0	4.653	1.4	1.9	0.161	0.275	1.050	0.2651E 05
1100.	40.0	4.602	5.5	5.2	0.740	0.715	0.238	0.2742E 05
1100.	40.0	4.602	6.3	5.2	0.799	0.715	0.780	0.2751E 05
1100.	30.0	4.477	55.0	58.3	1.740	1.766	0.235	0.2898E 05
1100.	24.9	4.396	357.0	269.6	2.553	2.431	1.122	0.3024E 05
1100.	21.0	4.322	1446.0	1065.3	3.160	3.027	1.221	0.3119E 05
1300.	30.0	4.477	0.4	0.4	-0.432	-0.348	0.774	0.2887E 05
1300.	25.0	4.398	1.5	1.7	0.176	0.229	0.487	0.2994E 05
1300.	20.0	4.301	9.5	8.3	0.978	0.920	0.528	0.3135E 05
1300.	15.0	4.176	51.0	61.4	1.708	1.788	0.739	0.3263E 05
1300.	11.0	4.041	337.0	493.5	2.528	2.693	1.525	0.3408E 05
1300.	9.0	3.954	1227.0	1830.3	3.089	3.263	1.599	0.3506E 05
1500.	15.0	4.176	0.8	0.8	-0.125	-0.112	0.117	0.3275E 05
1500.	13.0	4.114	1.9	1.8	0.272	0.266	0.051	0.3353E 05
1500.	10.0	4.000	12.7	8.8	1.104	0.945	1.462	0.3516E 05
1500.	7.0	3.845	84.3	68.5	1.926	1.836	0.830	0.3677E 05
1500.	5.3	3.724	332.0	319.7	2.521	2.505	0.150	0.3793E 05
1500.	4.2	3.623	1153.0	1114.6	3.062	3.047	0.136	0.3899E 05

Figure 1B. An example of the computer output for optimizing the constants for the Manson-Haferd Parameter.

DATA FROM DATA SHEET NUMBER ONE 304 STAINLESS FROM TABLE VI
LINEAR PARAMETER

CREEP/RUPTURE PARAMETERS ARE INVESTIGATED FOR
13 VALUE(S) OF T(A), 1 TEMPERATURE EXPONENT(S), 1 STRESS EXPONENT(S), AND 5 POLYNOMIAL(S)
USING 18 DATA POINTS

Q	R	M	T(A)	Y(A)	STD.DEV.
0.0	1.00	3	3050.	-16.31	0.2188904
0.0	1.00	4	3050.	-16.26	0.2272200
0.0	1.00	5	3050.	-16.26	0.2351903
0.0	1.00	6	3050.	-16.36	0.2462490
0.0	1.00	7	3050.	-16.22	0.2478953
0.0	1.00	3	2550.	-11.11	0.2469180
0.0	1.00	4	2550.	-11.08	0.2562181
0.0	1.00	5	2550.	-11.08	0.2644721
0.0	1.00	6	2550.	-11.17	0.2763554
0.0	1.00	7	2550.	-11.05	0.2790733
0.0	1.00	3	2050.	-5.85	0.3134493
0.0	1.00	4	2050.	-5.83	0.3252296
0.0	1.00	5	2050.	-5.83	0.3332350
0.0	1.00	6	2050.	-5.91	0.3464745
0.0	1.00	7	2050.	-5.82	0.3522062
0.0	1.00	3	1550.	-0.12	0.6971333
0.0	1.00	4	1550.	-0.21	0.6765336
0.0	1.00	5	1550.	-0.20	0.7021044
0.0	1.00	6	1550.	-0.32	0.6734859
0.0	1.00	7	1550.	-0.34	0.7139049
0.0	1.00	3	1050.	2.77	0.7251322
0.0	1.00	4	1050.	3.05	0.6082904
0.0	1.00	5	1050.	3.20	0.4729552
0.0	1.00	6	1050.	3.25	0.4881289
0.0	1.00	7	1050.	3.23	0.5081378
0.0	1.00	3	550.	9.04	0.1179971
0.0	1.00	4	550.	9.01	0.1133510
0.0	1.00	5	550.	9.00	0.1163102
0.0	1.00	6	550.	8.96	0.1173517
0.0	1.00	7	550.	8.96	0.1244705
0.0	1.00	3	0.	14.83	0.0942310
0.0	1.00	4	0.	14.80	0.0954036
0.0	1.00	5	0.	14.80	0.0999805
0.0	1.00	6	0.	14.75	0.1040663
0.0	1.00	7	0.	14.73	0.1064580
0.0	1.00	3	-500.	20.03	0.1029074
0.0	1.00	4	-500.	19.99	0.1056310
0.0	1.00	5	-500.	19.99	0.1107616
0.0	1.00	6	-500.	19.95	0.1163847
0.0	1.00	7	-500.	19.91	0.1171401
0.0	1.00	3	-1000.	25.19	0.1111541
0.0	1.00	4	-1000.	25.14	0.1146317
0.0	1.00	5	-1000.	25.13	0.1200835
0.0	1.00	6	-1000.	25.10	0.1264805
0.0	1.00	7	-1000.	25.03	0.1266674
0.0	1.00	3	-1500.	30.34	0.1174083
0.0	1.00	4	-1500.	30.26	0.1213511
0.0	1.00	5	-1500.	30.25	0.1270151
0.0	1.00	6	-1500.	30.22	0.1338920
0.0	1.00	7	-1500.	30.12	0.1338460
0.0	1.00	3	-2000.	35.47	0.1221534
0.0	1.00	4	-2000.	35.37	0.1264256
0.0	1.00	5	-2000.	35.36	0.1322328
0.0	1.00	6	-2000.	35.34	0.1394022
0.0	1.00	7	-2000.	35.21	0.1392561
0.0	1.00	3	-2500.	40.56	0.1258413
0.0	1.00	4	-2500.	40.47	0.1303029
0.0	1.00	5	-2500.	40.46	0.1362278
0.0	1.00	6	-2500.	40.43	0.1436408
0.0	1.00	7	-2500.	40.30	0.1434314
0.0	1.00	3	-3000.	45.75	0.1286936
0.0	1.00	4	-3000.	45.60	0.1333537
0.0	1.00	5	-3000.	45.59	0.1393656
0.0	1.00	6	-3000.	45.56	0.1469451
0.0	1.00	7	-3000.	45.40	0.1467000

Figure 1B, continued

DATA FROM DATA SHEET NUMBER ONE 304 STAINLESS FROM TABLE VI
LINEAR PARAMETER

VALUES PRODUCING SMALLEST STANDARD DEVIATION

Q= 0.0 , R= 1.00, M= 3, T(A)= 0., Y(A)= 14.831, AND STANDARD DEVIATION = 0.0942310

TEMP	STRESS (*E-3)	LOG STRESS	TIME	CALCTD TIME	LOG TIME	CALC LOG TIME	DEV/SD	PARAMETER
1100.	45.0	4.653	1.4	1.6	0.161	0.216	0.584	-0.1334E-01
1100.	40.0	4.602	5.5	5.5	0.740	0.738	0.024	-0.1281E-01
1100.	40.0	4.602	6.3	5.5	0.799	0.738	0.649	-0.1276E-01
1100.	30.0	4.477	55.0	72.4	1.740	1.860	1.269	-0.1190E-01
1100.	24.9	4.396	357.0	304.4	2.553	2.483	0.734	-0.1116E-01
1100.	21.0	4.322	1446.0	981.3	3.160	2.992	1.787	-0.1061E-01
1300.	30.0	4.477	0.4	0.3	-0.432	-0.498	0.707	-0.1174E-01
1300.	25.0	4.398	1.5	1.7	0.176	0.223	0.503	-0.1127E-01
1300.	20.0	4.301	9.5	10.0	0.978	1.000	0.232	-0.1066E-01
1300.	15.0	4.176	51.0	71.5	1.708	1.854	1.555	-0.1010E-01
1300.	11.0	4.041	337.0	429.7	2.528	2.633	1.120	-0.9464E-02
1300.	9.0	3.954	1227.0	1206.7	3.089	3.082	0.077	-0.9033E-02
1500.	15.0	4.176	0.8	0.7	-0.125	-0.142	0.186	-0.9971E-02
1500.	13.0	4.114	1.9	2.0	0.272	0.290	0.194	-0.9706E-02
1500.	10.0	4.000	12.7	10.2	1.104	1.007	1.024	-0.9152E-02
1500.	7.0	3.845	84.3	75.6	1.926	1.878	0.503	-0.8604E-02
1500.	5.3	3.724	332.0	335.6	2.521	2.526	0.049	-0.8207E-02
1500.	4.2	3.623	1153.0	1198.3	3.062	3.079	0.178	-0.7846E-02

Figure 2A. An example of the computer output for the Larson-Miller Parameter of the program designed to calculate strength values from stress-parameter data.

PARAMETRIC ANALYSIS OF STRESS-RUPTURE DATA, BY THE UNIVERSITY OF MICHIGAN HIGH TEMPERATURE METALLURGY GROUP. THIS IS COPY 4 OF 4.

ANALYSIS FOR: DATA FROM DATA SHEET NUMBER ONE 304 STAINLESS FROM TABLE VI

RANGES OF THE 18 ORIGINAL DATA ANALYZED:	LOWEST	HIGHEST
STRESS (KSI)	4.20	45.00
TIME (HR)	0.4	1446.
TEMPERATURE (DEG. F)	1100.	1500.

THE OPTIMIZED STRESS-RUPTURE PARAMETRIC CONSTANTS PRODUCED BY THE USE OF ORTHOGONAL POLYNOMIALS IN A SLIGHTLY MODIFIED VERSION OF THE MENDELSON-ROBERTS-MANSON FORTRAN IV PROGRAM (NASA TECHNICAL NOTE TN D-2975) ARE LISTED BELOW:

PARAMETER TYPE = LARSON, STRESS EXPONENT Q = 0.0, TEMPERATURE EXPONENT R = -1.0, TEMPERATURE INTERCEPT T(A) = -460.0, LOG TIME INTERCEPT Y(A) = -16.833435, AND FOR THIS SET OF DATA THESE CONSTANTS PRODUCED A STANDARD DEVIATION OF 0.1086401.

MULTIPLE POLYNOMIAL REGRESSION FOR POLYNOMIALS FROM ORDER 1 TO 6, USING DOUBLE-PRECISION (64-BIT WORD SIZE) ARITHMETIC PRODUCED THE FOLLOWING STANDARD DEVIATIONS FOR EACH ORDER OF POLYNOMIAL OF THE FORM LOG(STRESS IN KSI)=FUNCTION(PARAMETER) INVESTIGATED:

ORDER OF POLYNOMIAL =	1	2	3	4	5	6	
STANDARD DEVIATION =	0.0185867	0.0151675	0.0155798	0.0157622	0.0161009	0.0167464	10.0 MEANS NEAR-SINGULAR

AND USING THE SMALLEST STANDARD DEVIATION AS THE CRITERION FOR 'BEST,' THE ENTIRE 'BEST' EQUATION IS GIVEN BELOW:

LOG OF STRESS IN KSI = (0.301D 01) + (0.288D-01)P + (0.831D-03)P^2 + (0.0)P^3 + (0.0)P^4 + (0.0)P^5 + (0.0)P^6

(WHERE P, AS LARSON PARAMETER, IS DIVIDED BY 1000.)

USING THE ABOVE EQUATION, THE FOLLOWING TABLE OF STRESSES TO PRODUCE RUPTURE AT THE SPECIFIED TIMES AND TEMPERATURES WAS CALCULATED. NOTE THAT A STRESS OF ZERO INDICATES THAT THE CALCULATED STRESS WAS OUT OF THE RANGE OF THE ORIGINAL DATA ANALYZED.

TIME IN	T	E	M	P	E	R	A	T	U	R	E	S
HOURS	950.	1000.	1050.	1100.	1150.	1200.	1250.	1300.	1350.	1400.	1500.	1600.
10.	0.0	39.053	33.177	28.089	23.701	19.930	16.703	13.951	11.613	9.634	6.563	4.411
100.	36.026	30.285	25.362	21.160	17.588	14.564	12.015	9.875	8.085	6.595	4.339	0.0
1000.	28.114	23.294	19.220	15.793	12.923	10.531	8.546	6.907	5.559	4.455	0.0	0.0
10000.	21.773	17.771	14.439	11.678	9.402	7.535	6.012	4.774	0.0	0.0	0.0	0.0

USING THE OPTIMIZED STRESS-RUPTURE PARAMETRIC CONSTANTS FROM THE MODIFIED VERSION OF THE MENDELSON-ROBERTS-MANSON NASA TN D-2975 PROGRAM, THE FOLLOWING PARAMETER VALUES WERE CALCULATED FOR THE TIMES AND TEMPERATURES INDICATED:

TIME IN	T	E	M	P	E	R	A	T	U	R	E	S
HOURS	950.	1000.	1050.	1100.	1150.	1200.	1250.	1300.	1350.	1400.	1500.	1600.
10.	0.266D 05	0.275D 05	0.284D 05	0.294D 05	0.303D 05	0.313D 05	0.322D 05	0.331D 05	0.341D 05	0.350D 05	0.369D 05	0.388D 05
100.	0.280D 05	0.290D 05	0.299D 05	0.309D 05	0.319D 05	0.329D 05	0.339D 05	0.349D 05	0.359D 05	0.369D 05	0.389D 05	0.409D 05
1000.	0.294D 05	0.304D 05	0.315D 05	0.325D 05	0.335D 05	0.346D 05	0.356D 05	0.367D 05	0.377D 05	0.388D 05	0.408D 05	0.429D 05
10000.	0.308D 05	0.319D 05	0.330D 05	0.341D 05	0.352D 05	0.362D 05	0.373D 05	0.384D 05	0.395D 05	0.406D 05	0.428D 05	0.450D 05

THE ORIGINAL DATA USED FOR THE ABOVE ANALYSES FOLLOWS:

TEMPERATURE, DEG F =	1100.	1100.	1100.	1100.	1100.	1100.	1300.	1300.	1300.	1300.
STRESS IN KSI =	45.000	40.000	40.000	30.000	24.900	21.000	30.000	25.000	20.000	15.000
LOG OF KSI STRESS =	1.6532	1.6021	1.6021	1.4771	1.3962	1.3222	1.4771	1.3979	1.3010	1.1761
PARAMETER VALUE =	0.265D 05	0.274D 05	0.275D 05	0.290D 05	0.302D 05	0.312D 05	0.289D 05	0.299D 05	0.313D 05	0.326D 05

TEMPERATURE, DEG F =	1300.	1300.	1500.	1500.	1500.	1500.	1500.	1500.
STRESS IN KSI =	11.000	9.000	15.000	13.000	10.000	7.000	5.300	4.200
LOG OF KSI STRESS =	1.0414	0.9542	1.1761	1.1139	1.0000	0.8451	0.7243	0.6232
PARAMETER VALUE =	0.341D 05	0.351D 05	0.327D 05	0.335D 05	0.352D 05	0.368D 05	0.379D 05	0.390D 05

Figure 2B. An example of the computer output for the Manson-Haferd Parameter of the program designed to calculate strength values from stress-parameter data.

PARAMETRIC ANALYSIS OF STRESS-RUPTURE DATA, BY THE UNIVERSITY OF MICHIGAN HIGH TEMPERATURE METALLURGY GROUP. THIS IS COPY 1 OF 4.

ANALYSIS FOR: DATA FROM DATA SHEET NUMBER ONE 304 STAINLESS FROM TABLE VI

RANGES OF THE 18 ORIGINAL DATA ANALYZED:	LOWEST	HIGHEST
STRESS (KSI)	4.20	45.00
TIME (HR)	0.4	1446.
TEMPERATURE (DEG. F)	1100.	1500.
PARAMETER VALUE	-0.130-01	-0.7846D-02

THE OPTIMIZED STRESS-RUPTURE PARAMETRIC CONSTANTS PRODUCED BY THE USE OF ORTHOGONAL POLYNOMIALS IN A SLIGHTLY MODIFIED VERSION OF THE MENDELSON-ROBERTS-MANSON FORTRAN IV PROGRAM (NASA TECHNICAL NOTE TN D-2975) ARE LISTED BELOW:

PARAMETER TYPE = LINEAR, STRESS EXPONENT Q = 0.0, TEMPERATURE EXPONENT R = 1.0, TEMPERATURE INTERCEPT T(A) = 0.0, LOG TIME INTERCEPT Y(A) = 14.831466, AND FOR THIS SET OF DATA THESE CONSTANTS PRODUCED A STANDARD DEVIATION OF 0.0942310.

MULTIPLE POLYNOMIAL REGRESSION FOR POLYNOMIALS FROM ORDER 1 TO 6, USING DOUBLE-PRECISION (64-BIT WORD SIZE) ARITHMETIC PRODUCED THE FOLLOWING STANDARD DEVIATIONS FOR EACH ORDER OF POLYNOMIAL OF THE FORM LOG(STRESS IN KSI)=FUNCTION(PARAMETER) INVESTIGATED:

WHERE A STD. DEVIATION OF 10.0 MEANS NEAR SINGULAR MATRIX							
	ORDER OF POLYNOMIAL =	1	2	3	4	5	6
	STANDARD DEVIATION =	0.0555035	0.0129223	0.0128069	10.0000000	10.0000000	10.0000000

AND USING THE SMALLEST STANDARD DEVIATION AS THE CRITERION FOR 'BEST,' THE ENTIRE 'BEST' EQUATION IS GIVEN BELOW:

```
LOG OF
STRESS                                          2                    3                     4                  5                6
IN KSI=(-0.4043D 01) +( 0.9320D 03)|P| +(-0.5045D 05)|P| +( 0.9440D 06)|P| +( 0.0      )|P| +( 0.0      )|P| +( 0.0      )|P|
                      (WHERE P, ORIGINALLY NEGATIVE, WAS USED AS |P|)
```

USING THE ABOVE EQUATION, THE FOLLOWING TABLE OF STRESSES TO PRODUCE RUPTURE AT THE SPECIFIED TIMES AND TEMPERATURES WAS CALCULATED. NOTE THAT A STRESS OF ZERO INDICATES THAT THE CALCULATED STRESS WAS OUT OF THE RANGE OF THE ORIGINAL DATA ANALYZED.

TIME IN HOURS	T 950.	E 1000.	M 1050.	P 1100.	E 1150.	R 1200.	A 1250.	T 1300.	U 1350.	R 1400.	E 1500.	S 1600.
100.	0.0	40.220	34.326	29.029	24.379	20.371	16.966	14.103	11.715	9.734	6.748	4.719
1000.	36.582	30.601	25.369	20.897	17.142	14.029	11.472	9.386	7.690	6.315	4.297	0.0
10000.	26.584	21.535	17.352	13.941	11.191	8.989	7.235	5.840	4.731	0.0	0.0	0.0
100000.	17.609	13.837	10.862	8.535	6.725	5.320	4.228	0.0	0.0	0.0	0.0	0.0

USING THE OPTIMIZED STRESS-RUPTURE PARAMETRIC CONSTANTS FROM THE MODIFIED VERSION OF THE MENDELSON-ROBERTS-MANSON NASA TN D-2975 PROGRAM, THE FOLLOWING PARAMETER VALUES WERE CALCULATED FOR THE TIMES AND TEMPERATURES INDICATED:

TIME IN HOURS	T 950.	E 1000.	M 1050.	P 1100.	E 1150.	R 1200.	A 1250.	T 1300.	U 1350.	R 1400.	E 1500.	S 1600.
100.	0.135D-01	0.128D-01	0.122D-01	0.117D-01	0.112D-01	0.107D-01	0.103D-01	0.987D-02	0.950D-02	0.917D-02	0.855D-02	0.802D-02
1000.	0.125D-01	0.118D-01	0.113D-01	0.108D-01	0.103D-01	0.986D-02	0.947D-02	0.910D-02	0.876D-02	0.845D-02	0.789D-02	0.739D-02
10000.	0.114D-01	0.108D-01	0.103D-01	0.985D-02	0.942D-02	0.903D-02	0.867D-02	0.833D-02	0.802D-02	0.774D-02	0.722D-02	0.677D-02
100000.	0.103D-01	0.983D-02	0.936D-02	0.894D-02	0.855D-02	0.819D-02	0.787D-02	0.756D-02	0.728D-02	0.702D-02	0.655D-02	0.614D-02

THE ORIGINAL DATA USED FOR THE ABOVE ANALYSES FOLLOWS:

TEMPERATURE, DEG F =	1100.	1100.	1100.	1100.	1100.	1100.	1300.	1300.	1300.	1300.
STRESS IN KSI =	45.000	40.000	40.000	30.000	24.900	21.000	30.000	25.000	20.000	15.000
LOG OF KSI STRESS =	1.6532	1.6021	1.6021	1.4771	1.3962	1.3222	1.4771	1.3979	1.3010	1.1761
TIME IN HOURS =	1.45	5.50	6.30	55.00	357.00	1446.00	0.37	1.50	9.50	51.00
PARAMETER VALUE =	-0.133D-01	-0.128D-01	-0.128D-01	-0.119D-01	-0.112D-01	-0.106D-01	-0.117D-01	-0.113D-01	-0.107D-01	-0.101D-01

TEMPERATURE, DEG F =	1300.	1300.	1500.	1500.	1500.	1500.	1500.	1500.
STRESS IN KSI =	11.000	9.000	15.000	13.000	10.000	7.000	5.300	4.200
LOG OF KSI STRESS =	1.0414	0.9542	1.1761	1.1139	1.0000	0.8451	0.7243	0.6232
TIME IN HOURS =	337.00	1227.00	0.75	1.87	12.70	84.30	332.00	1153.00
PARAMETER VALUE =	-0.946D-02	-0.903D-02	-0.997D-02	-0.971D-02	-0.915D-02	-0.860D-02	-0.821D-02	-0.785D-02

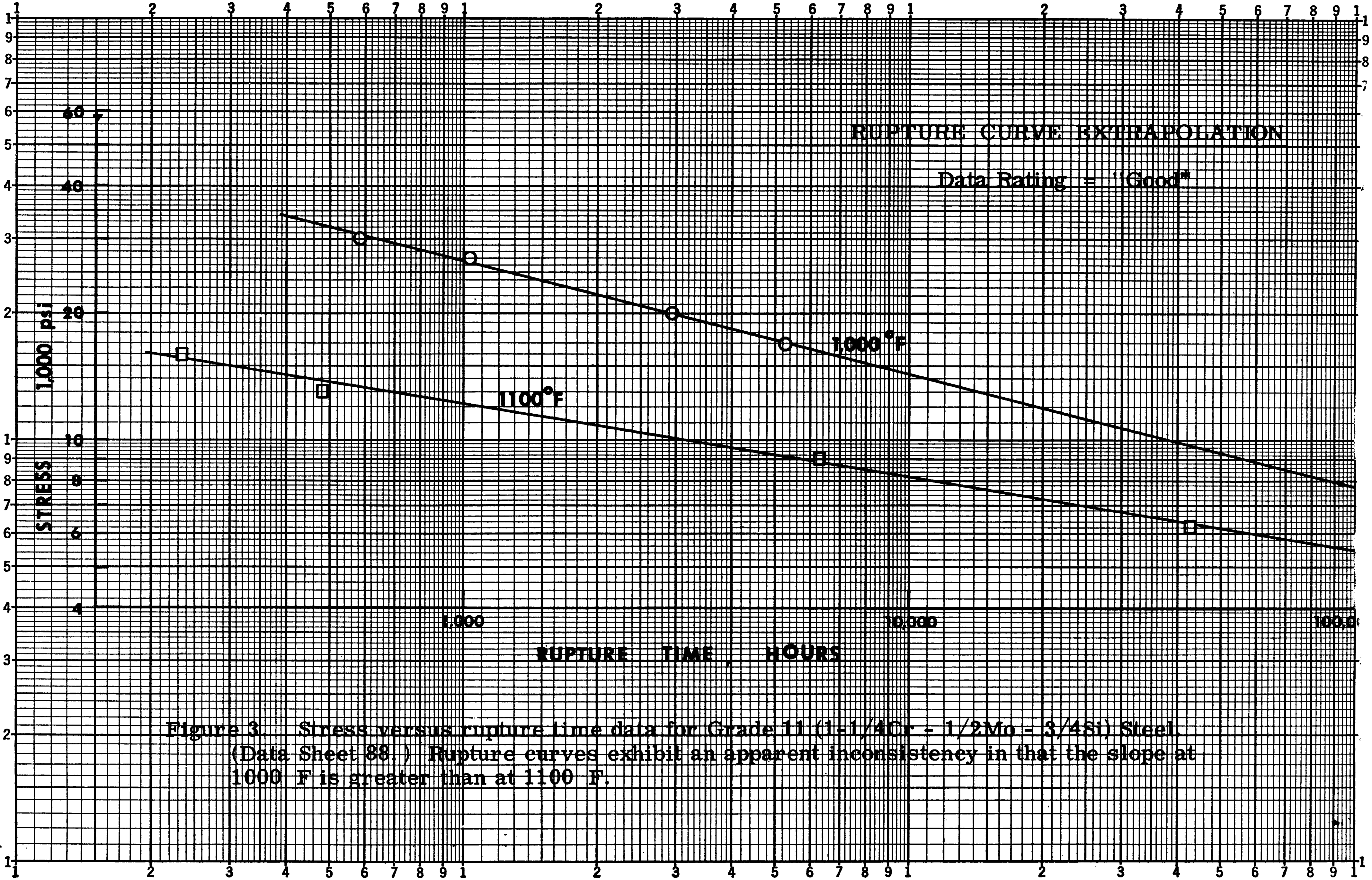


Figure 3. Stress versus rupture time data for Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) Steel. (Data Sheet 88.) Rupture curves exhibit an apparent inconsistency in that the slope at 1000 F is greater than at 1100 F.

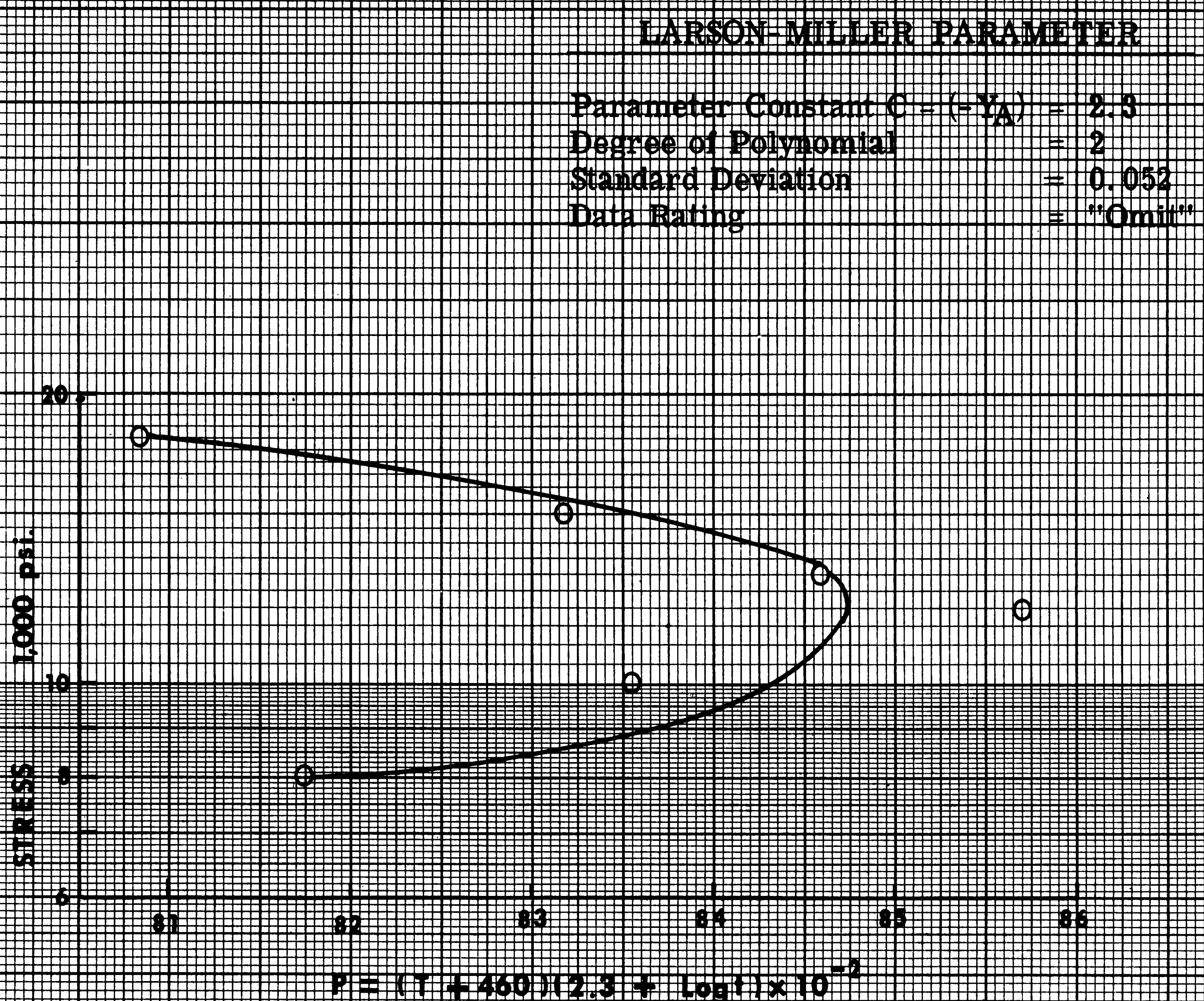


Figure 4A. Stress versus Larson-Miller Parameter values, determined by optimization of the constant. Grade 22 (2-1/4Cr - 1 Mo) Steel, Data Sheet 36A. This parameter data was not considered because the curve has an unreasonable shape. (For a given parameter value, two rupture-stress values can be obtained.)

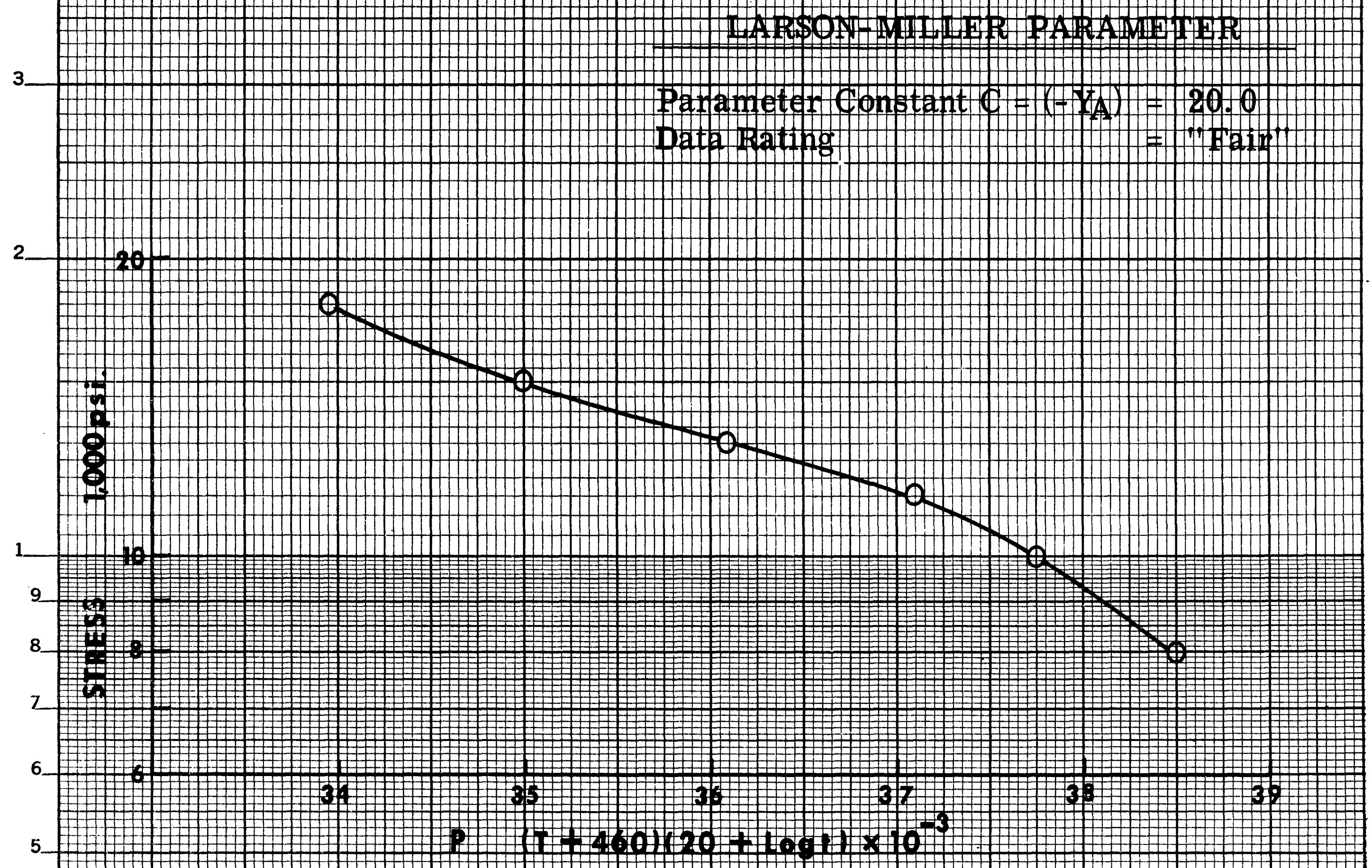


Figure 4B. Stress versus Larson-Miller Parameter values, determined by force fitting a constant of 20. Grade 22 (2-1/4Cr - 1 Mo) Steel, Data Sheet 36A. The force fitting improved the adaptability of the data in that the shape of the parameter curve is consistent with experience.

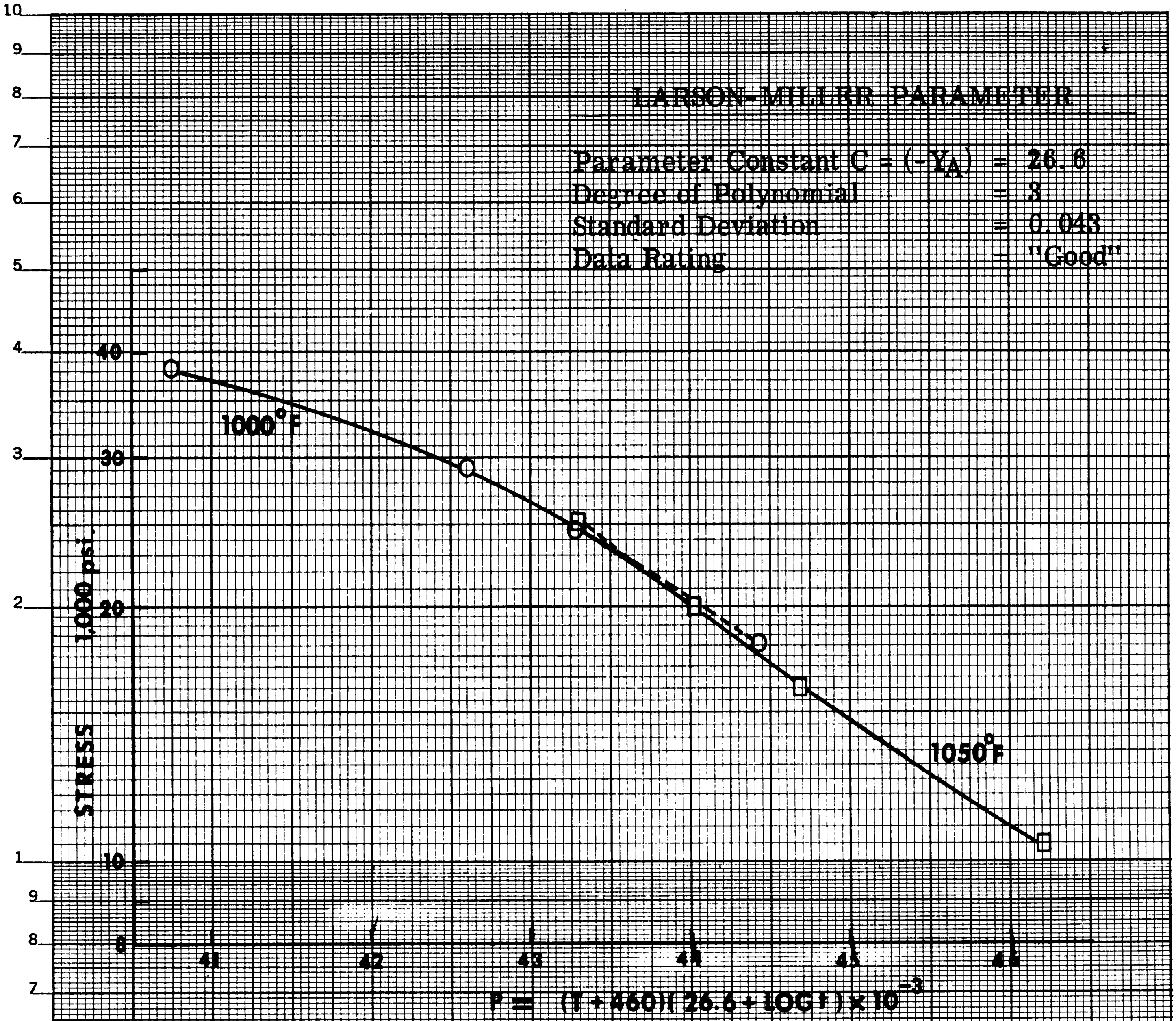


Figure 5. Stress versus Larson-Miller Parameter values, determined by optimization of the constant. Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) Steel, Data Sheet 4. Good adaptability of the rupture-test data has resulted in the parameter values from tests at 1000° and 1050°F being placed on a single curve.

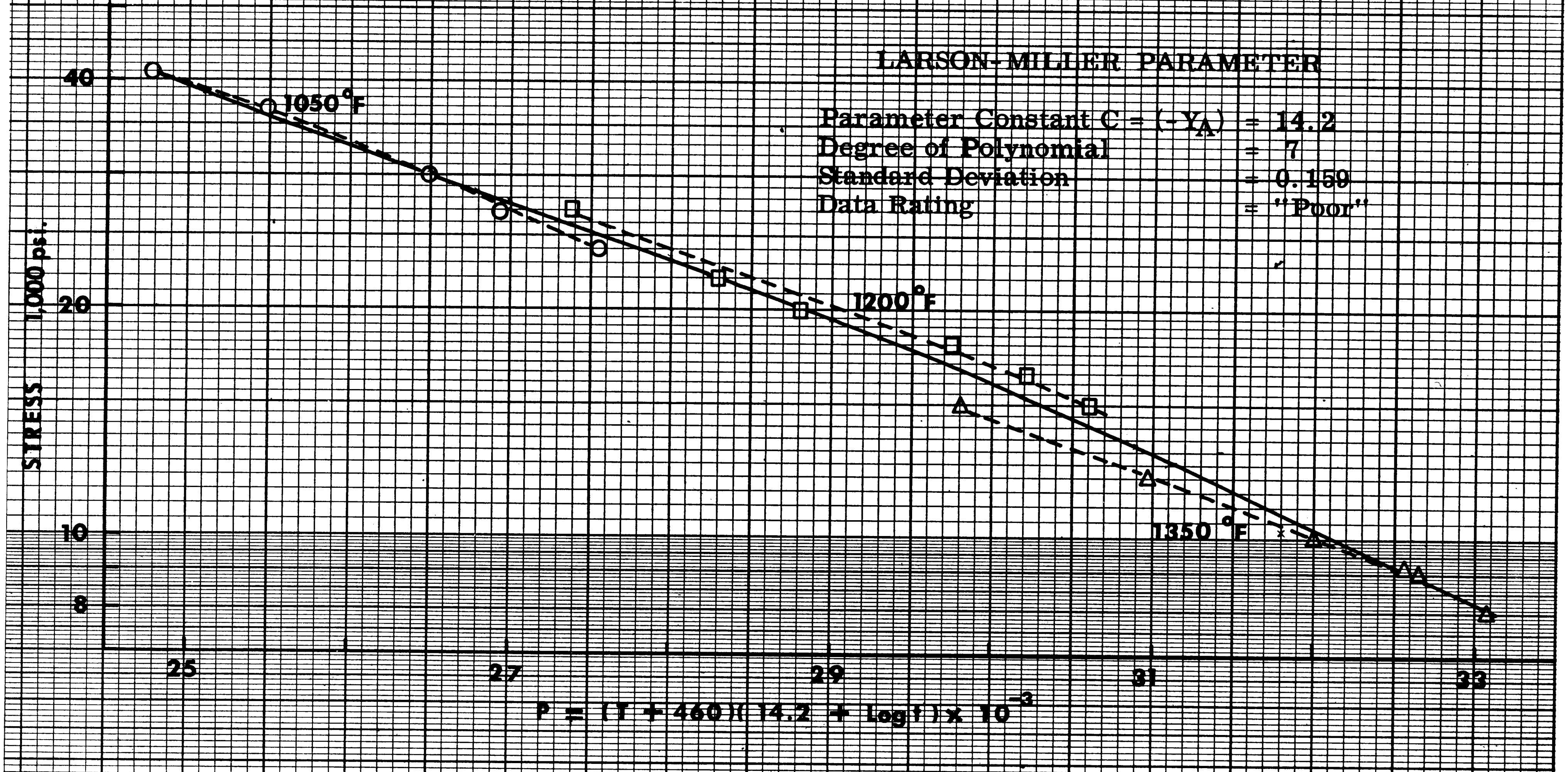


Figure 6. Stress versus Larson-Miller Parameter values, determined by optimization of the constant. Type 304 (18Cr - 8Ni) Austenitic Steel, Data Sheet 19. Poor adaptability of the data is evident from the mismatch of parameter curves for each of the three test temperatures.

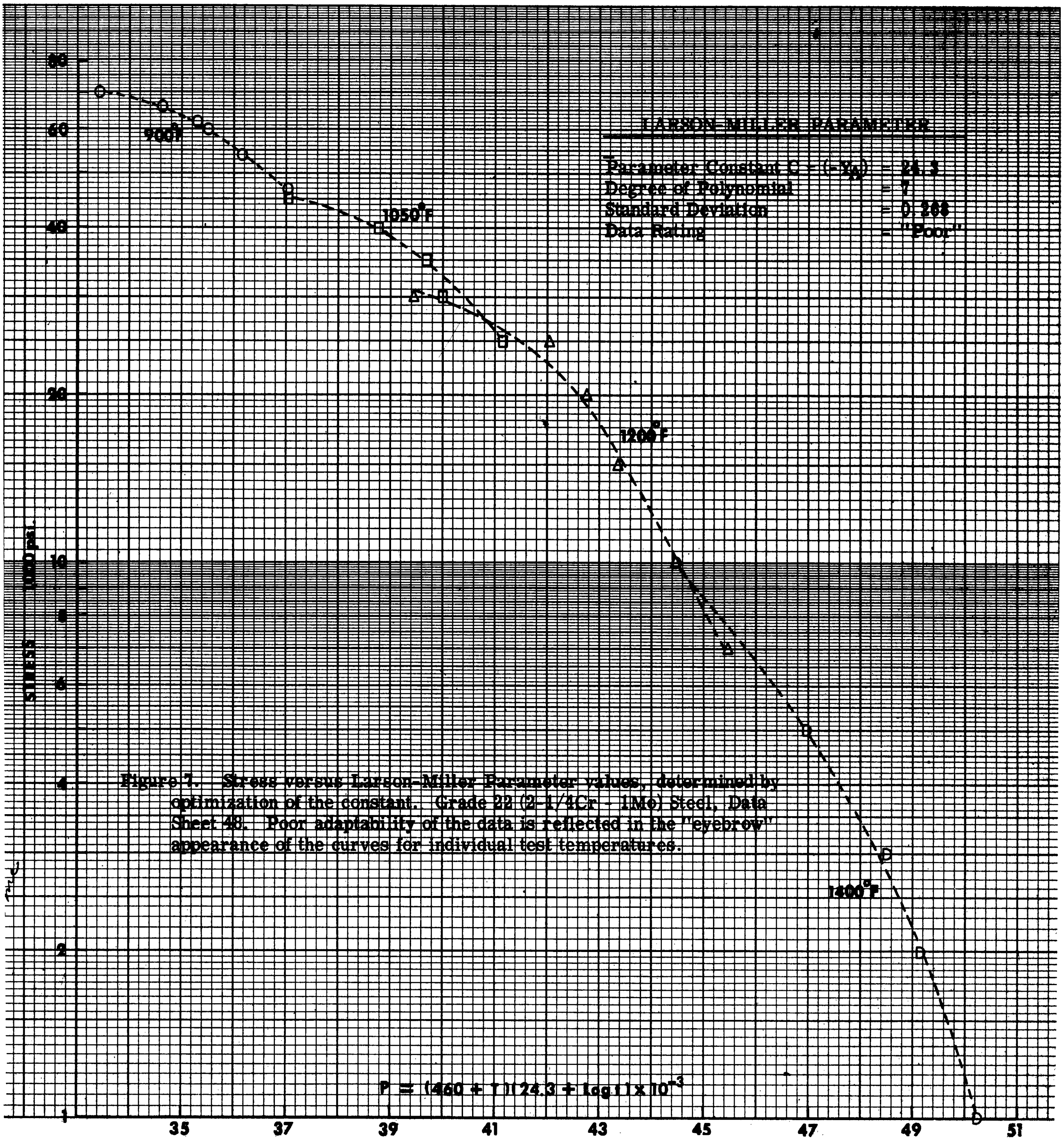


Figure 7. Stress versus Larson-Miller Parameter values, determined by optimization of the constant. Grade 22 (2-1/4Cr - 1Mo) Steel, Data Sheet 48. Poor adaptability of the data is reflected in the "eyebrow" appearance of the curves for individual test temperatures.

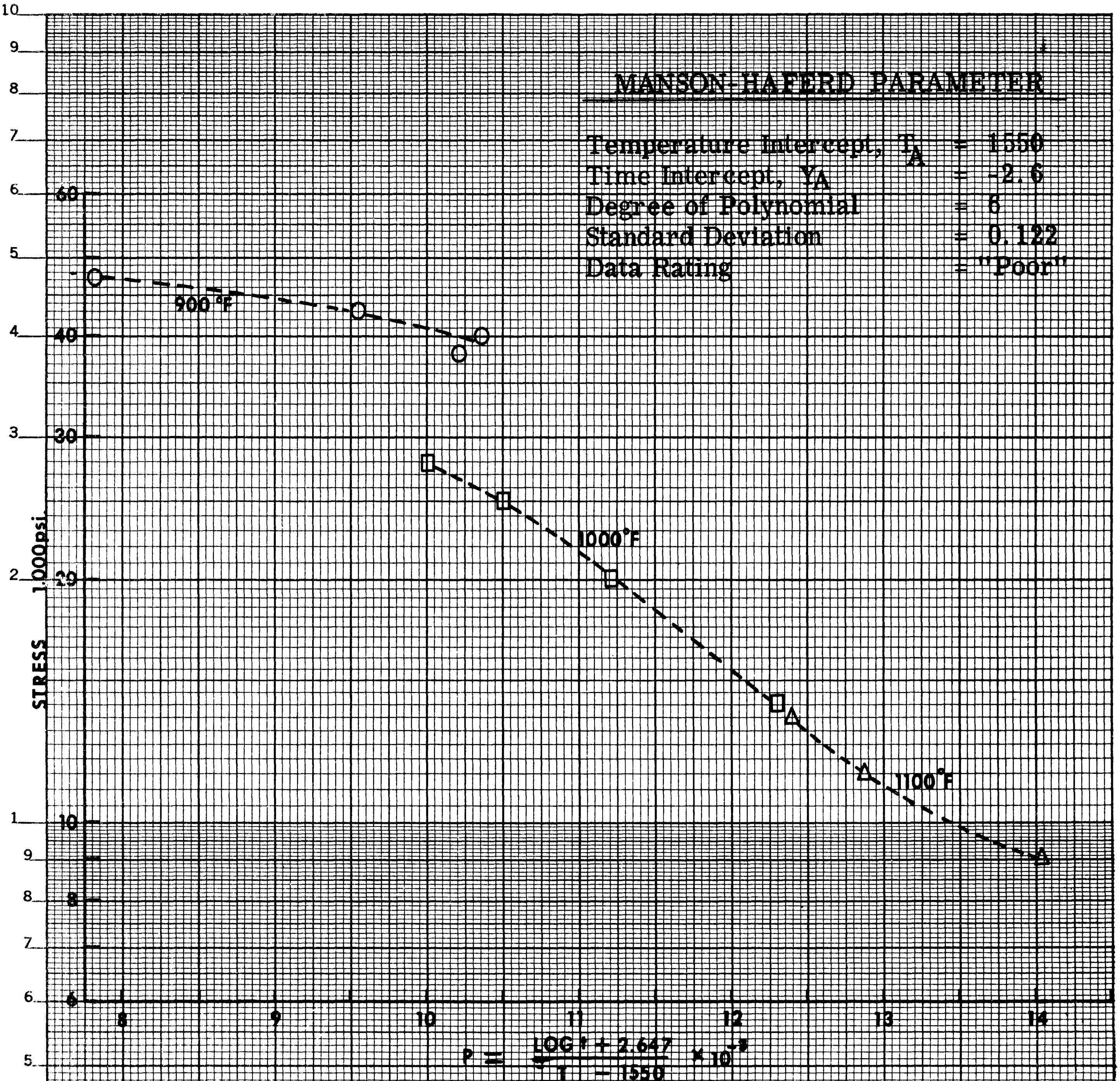


Figure 8. Stress versus Manson-Haferd Parameter values, determined by optimization of constants. Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) Steel, Data Sheet 74. Poor adaptability of the data is evident from the large mismatch between parameter curves for 900 °F and 1000 °F test data. Consideration of only the data at 1000 °F and 1100 °F would have led to a higher adaptability rating.

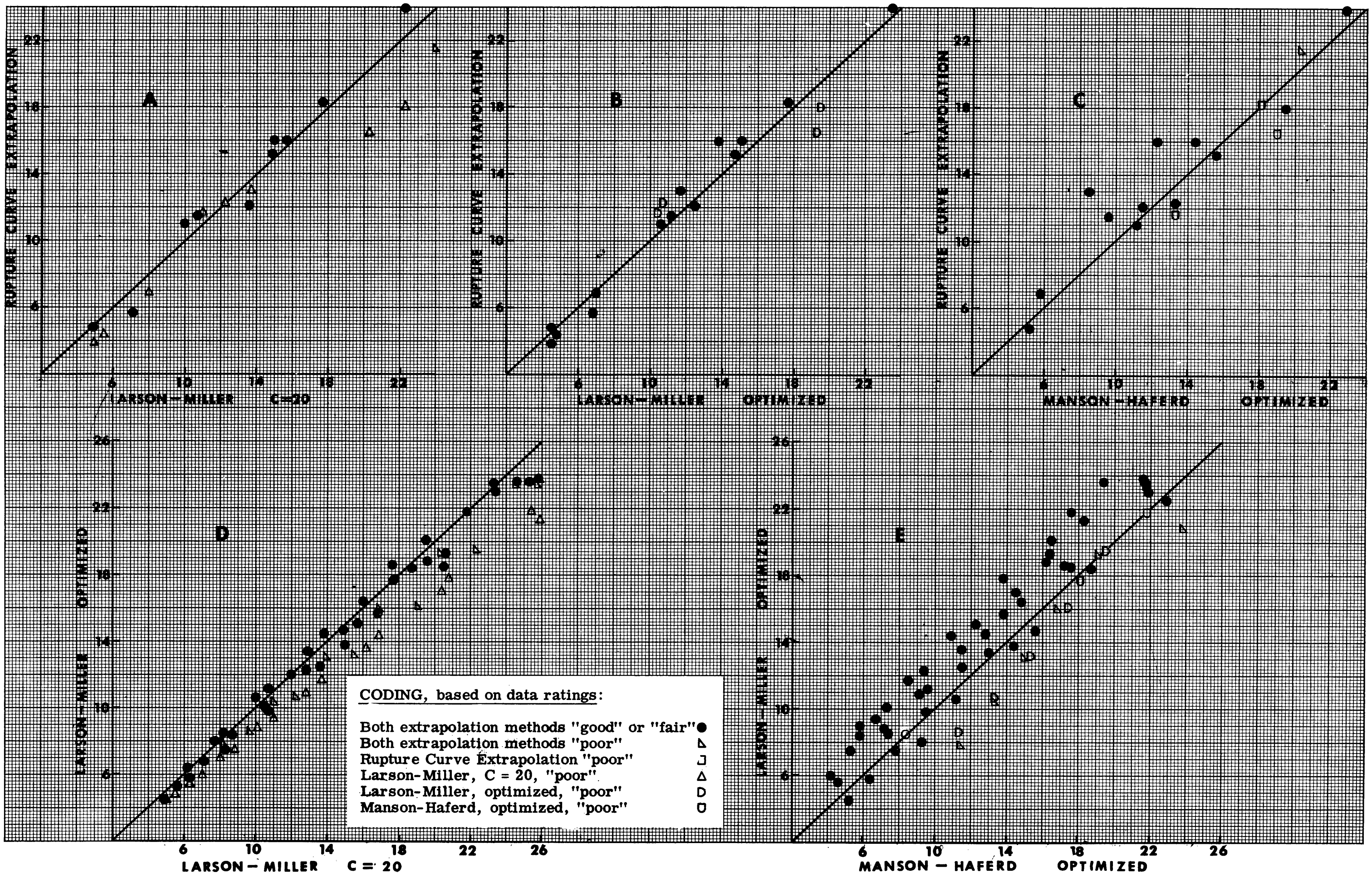


Figure 9 (A-E). Comparison of the stresses for rupture in 100,000 hours for Type 304 Austenitic Steel, obtained by extrapolation of rupture curves and by three parameter methods. Both ordinates and abscissas are 100,000-hour strengths in 1000 psi obtained by the indicated extrapolation methods.

Figure 10. 100,000-hour strengths as a function of temperature for Type 304 Austenitic Steel. Extrapolated strengths obtained using Larson-Miller Parameter with a constant C of 20.0.

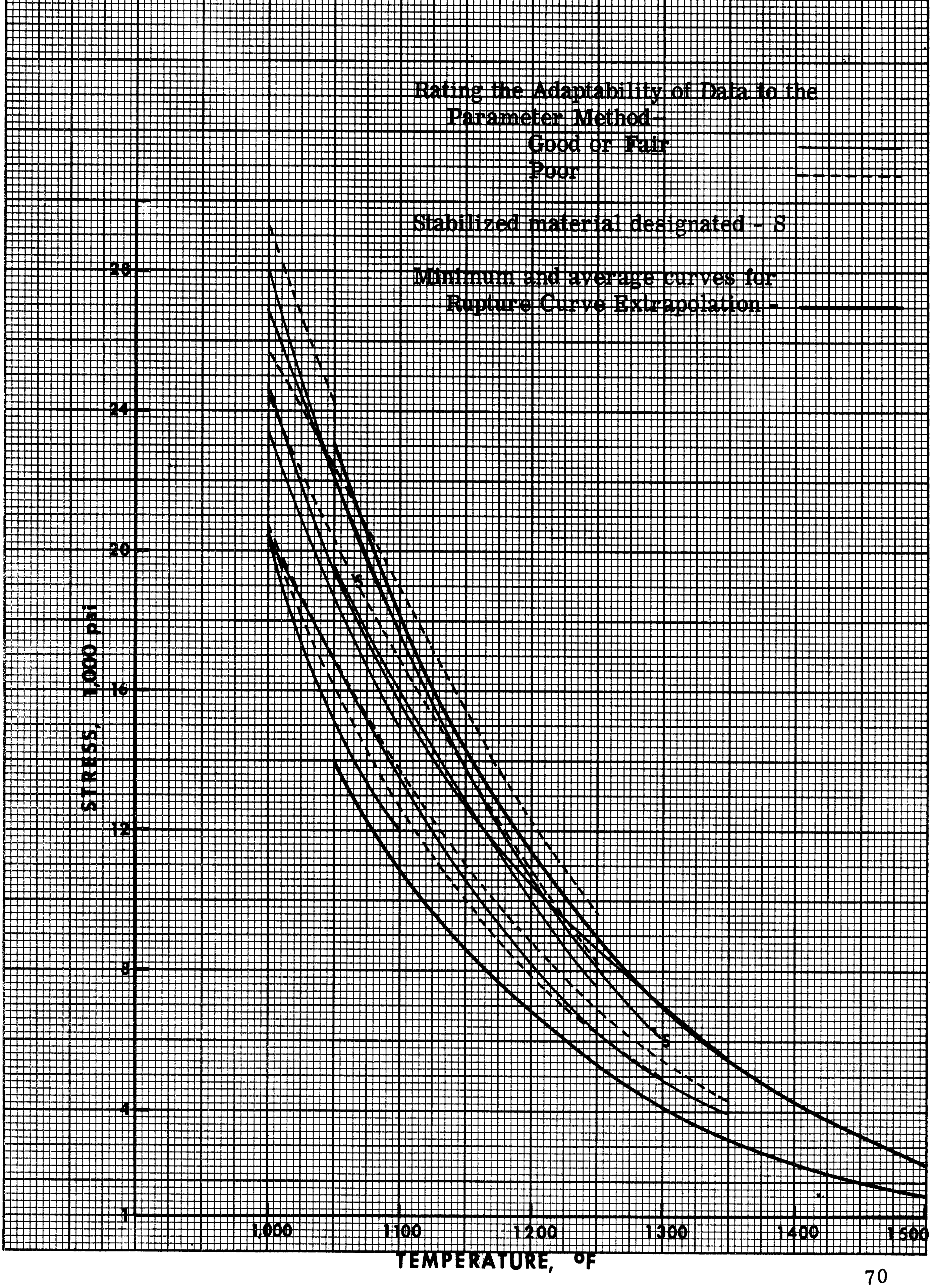


Figure 11. 100,000-hour strengths as a function of temperature for Type 304 Austenitic Steel. Extrapolated strengths obtained using Larson-Miller Parameter with an optimized constant.

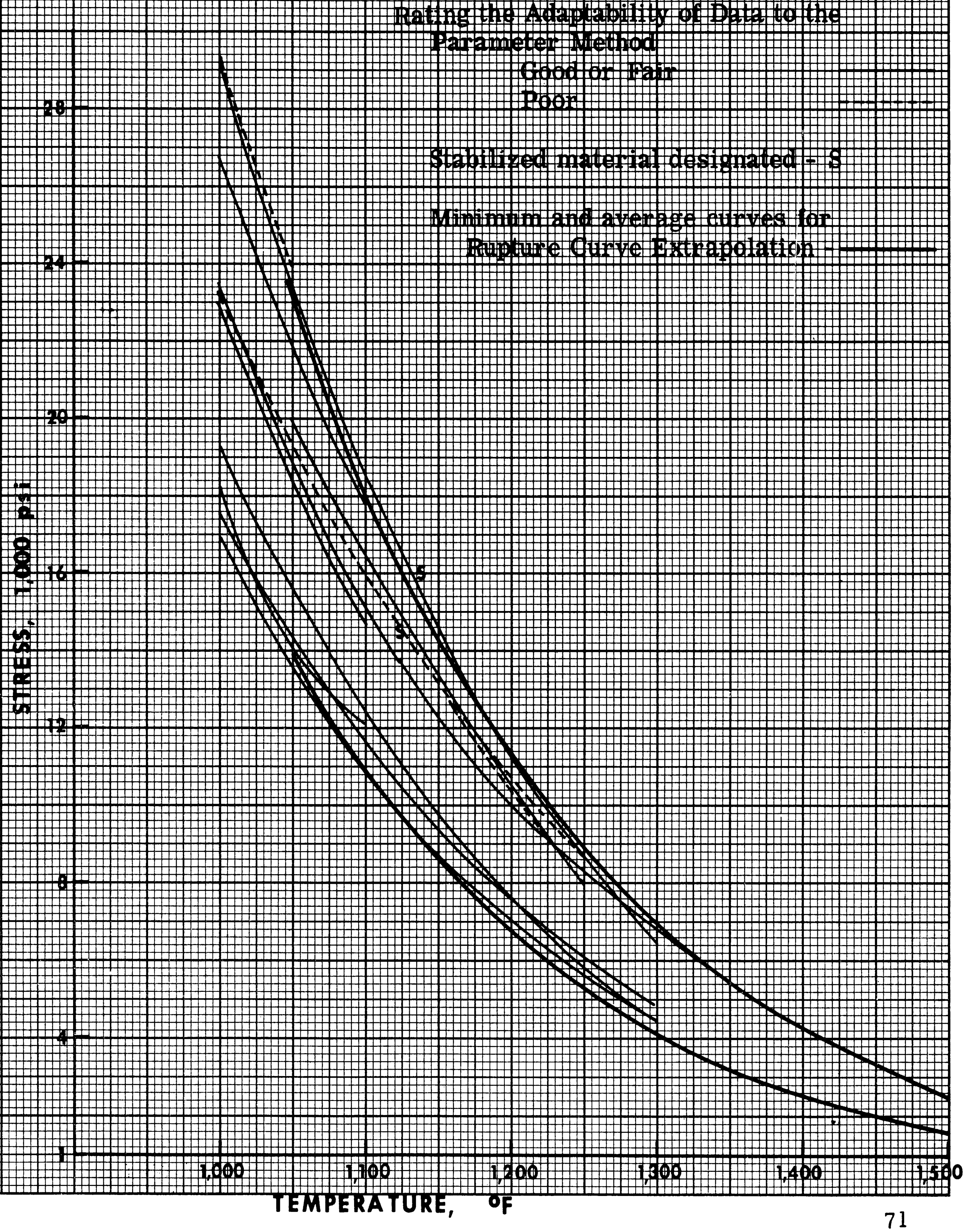


Figure 12. 100,000-hour strengths as a function of temperature for Type 304 Austenitic Steel. Extrapolated strengths obtained using Manson-Haferd (Linear) Parameter with optimized constants.

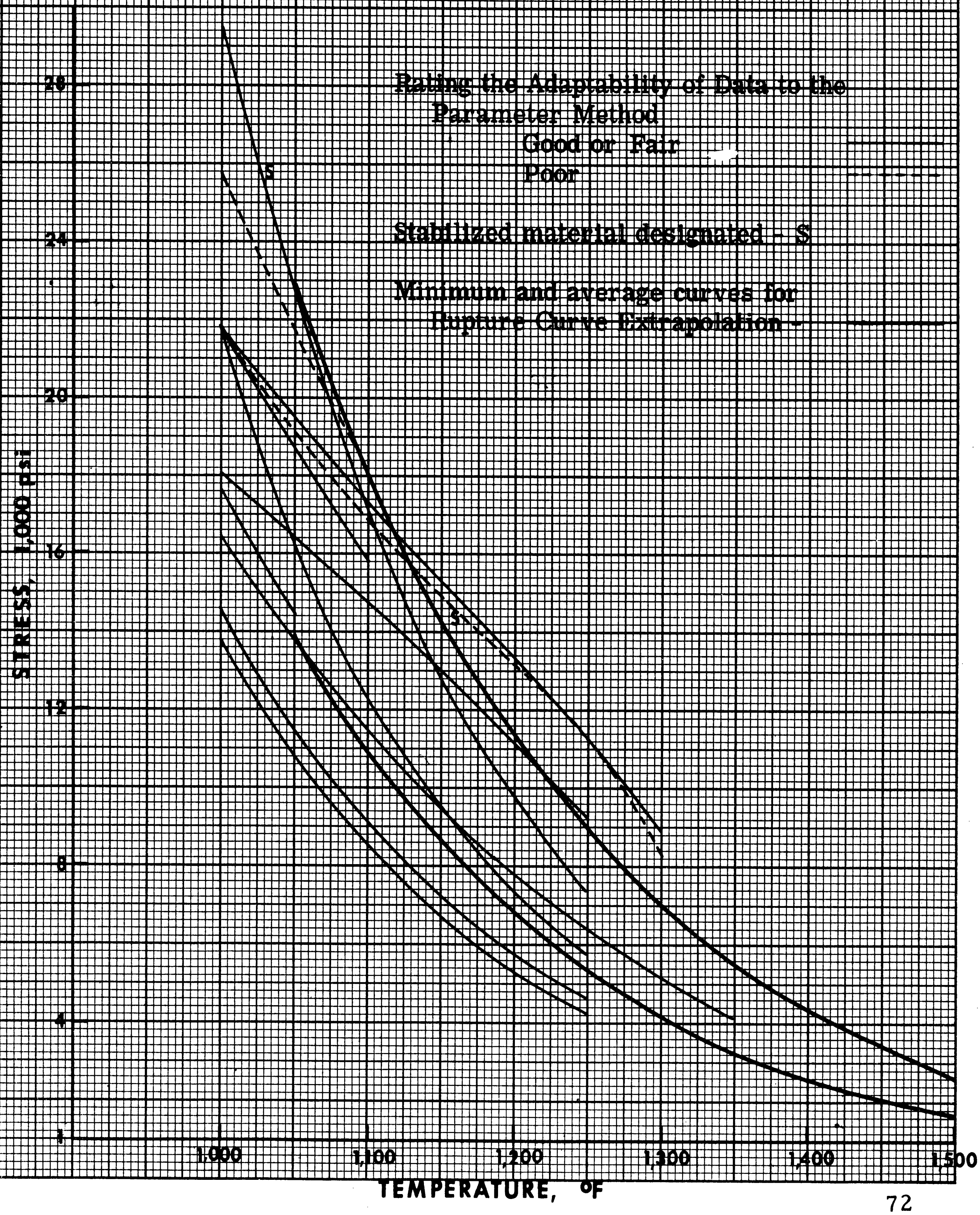


Figure 13. Average and minimum 100,000-hour strengths for Type 304 Austenitic Steel as a function of temperature. Strengths derived from the data sets with good and fair adaptability to the three parameter extrapolation methods.

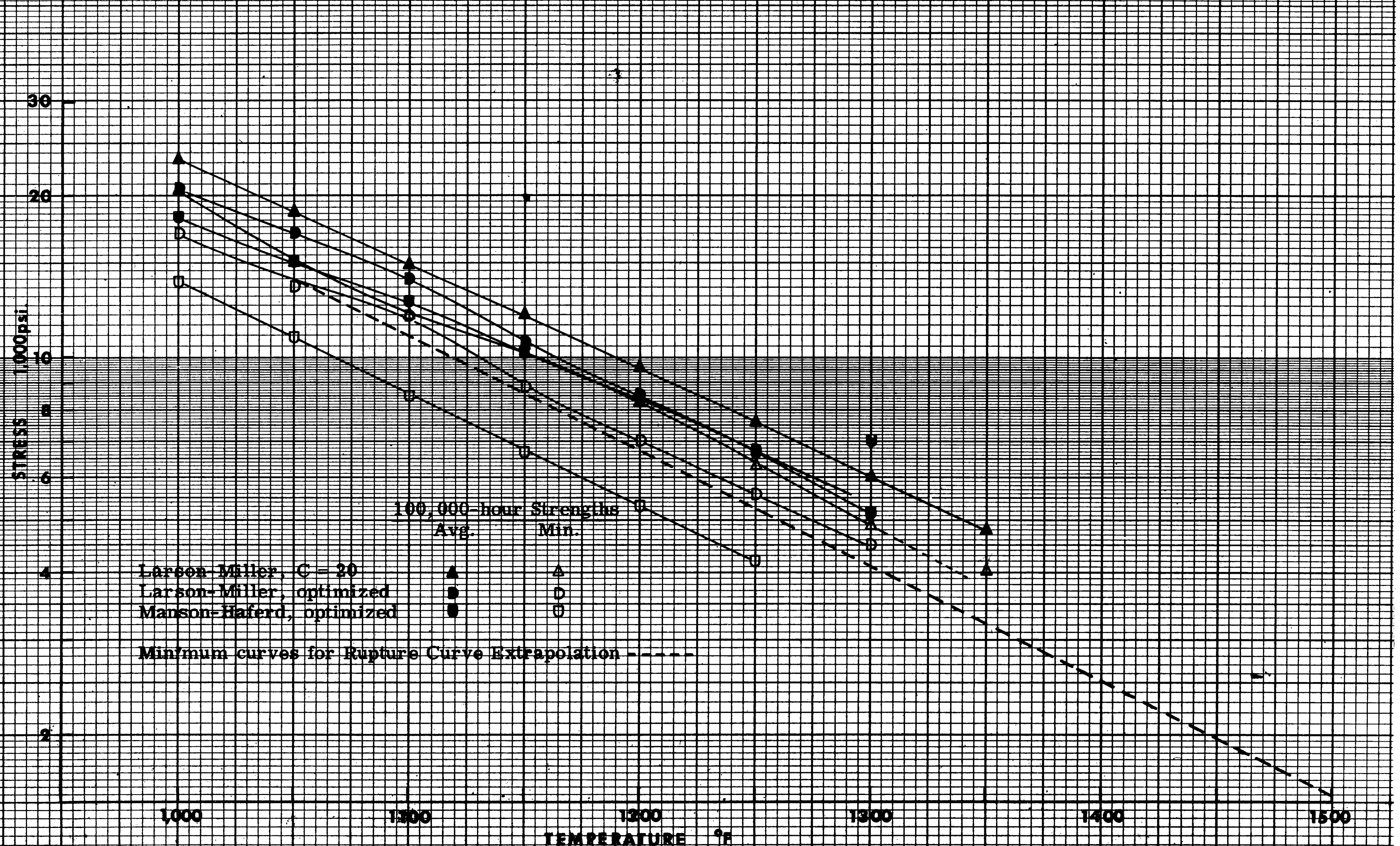


Figure 14. 100,000-hour strengths as a function of temperature for Type 304L Austenitic Steel. Extrapolated strengths obtained using Larson-Miller Parameter with a constant C of 20.0.

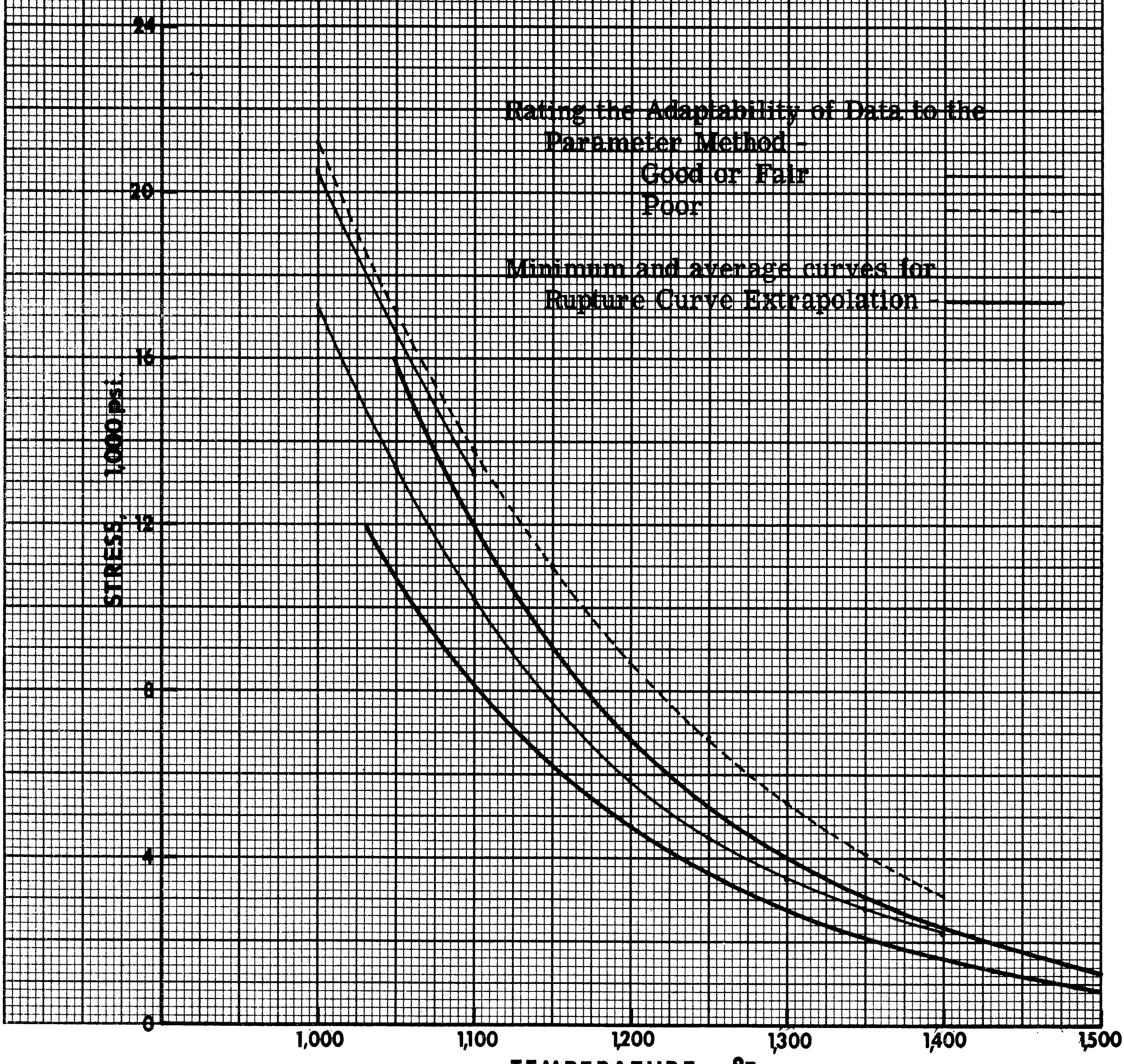
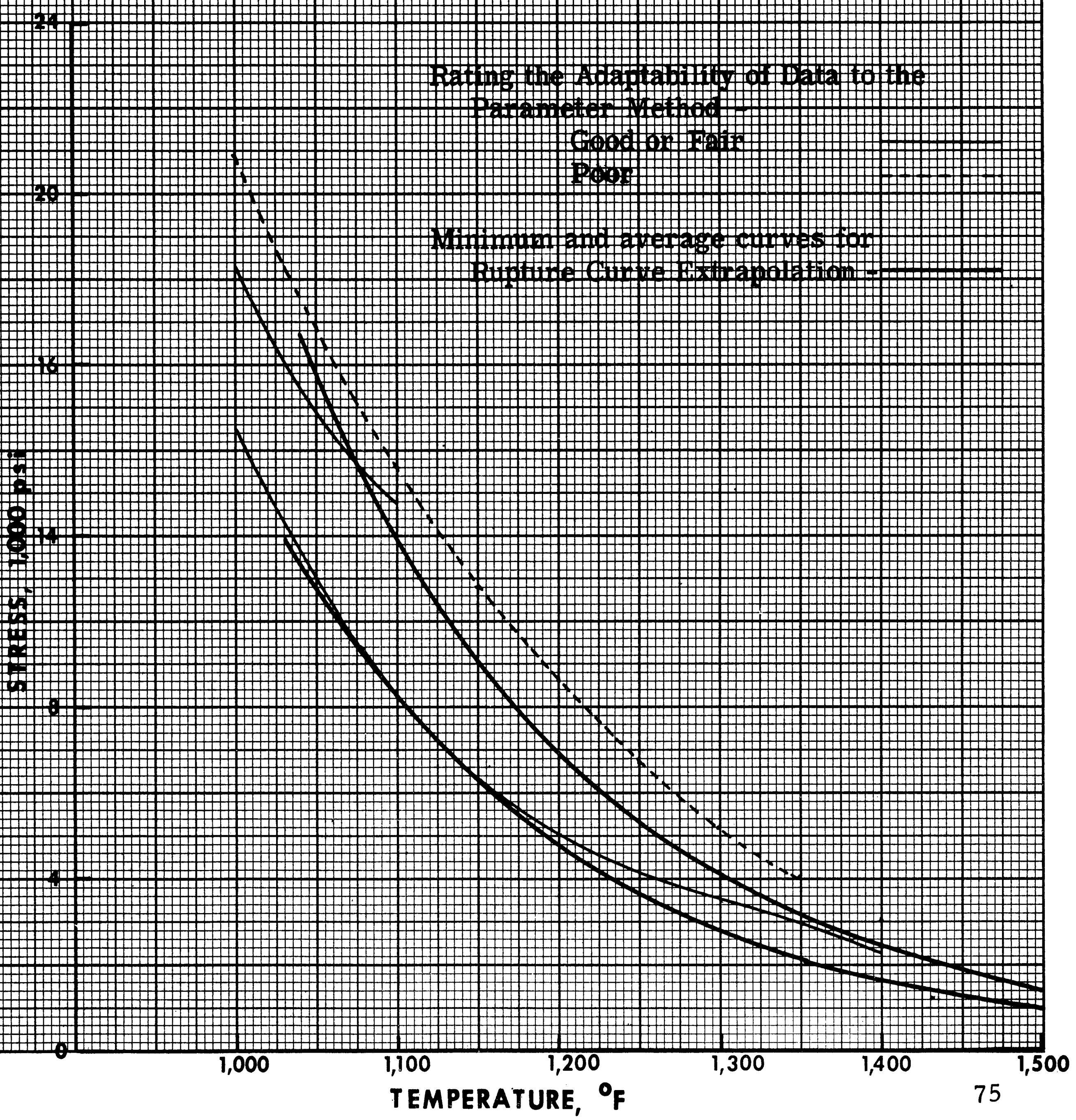


Figure 15. 100,000-hour strengths as a function of temperature for Type 304L Austenitic Steel. Extrapolation strengths obtained using Larson-Miller Parameter with an optimized constant.



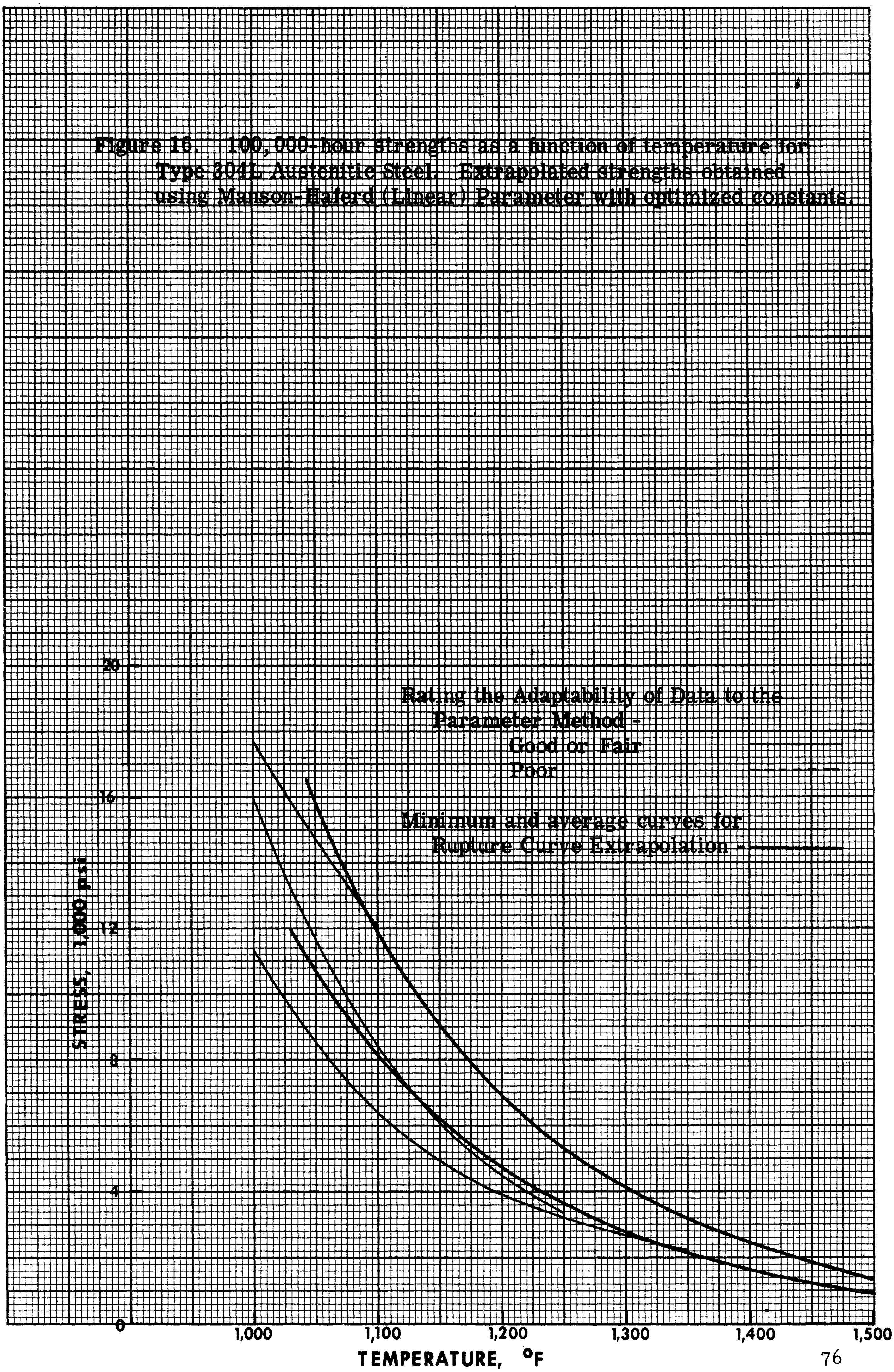


Figure 16. 100,000-hour strengths as a function of temperature for Type 304L Austenitic Steel. Extrapolated strengths obtained using Manson-Haferd (Linear) Parameter with optimized constants.

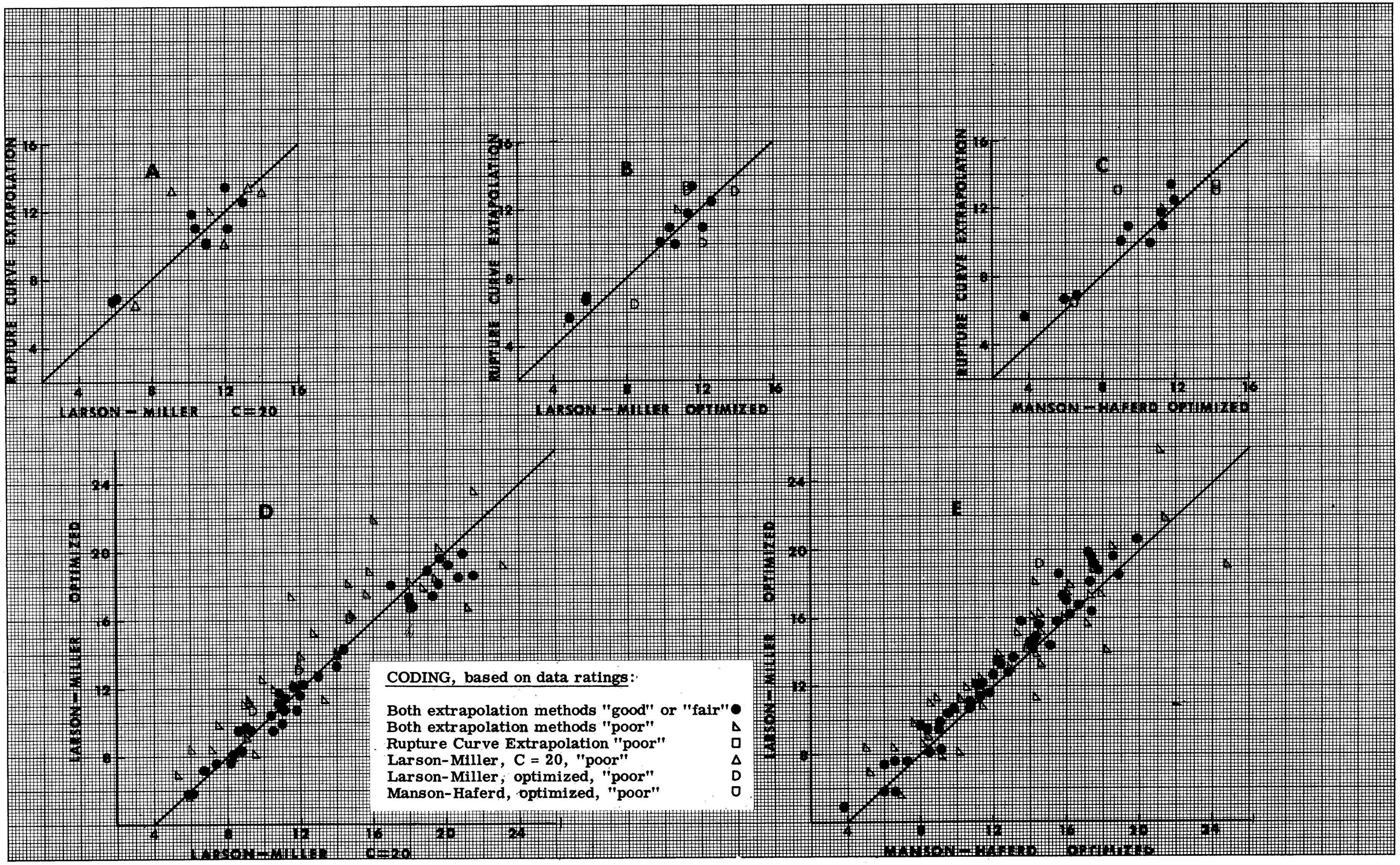


Figure 17 (A-E). Comparison of the stresses for rupture in 100,000 hours for Grade 22 (2-1/4Cr - 1Mo) Steel, obtained by extrapolation of rupture curves and by three parameter methods. Both ordinates and abscissas are 100,000-hour strengths in 1000 psi obtained by the indicated extrapolation methods.

Figure 18. 100,000-hour strengths as a function of temperature for Grade 22 (2-1/4Cr - 1Mo) Steel. Extrapolated strengths obtained using Larson-Miller Parameter with a constant C of 20.0. Only data sets for which values were obtained by extrapolation of stress rupture time curves are presented, i.e., "parameter"-type data are not included.

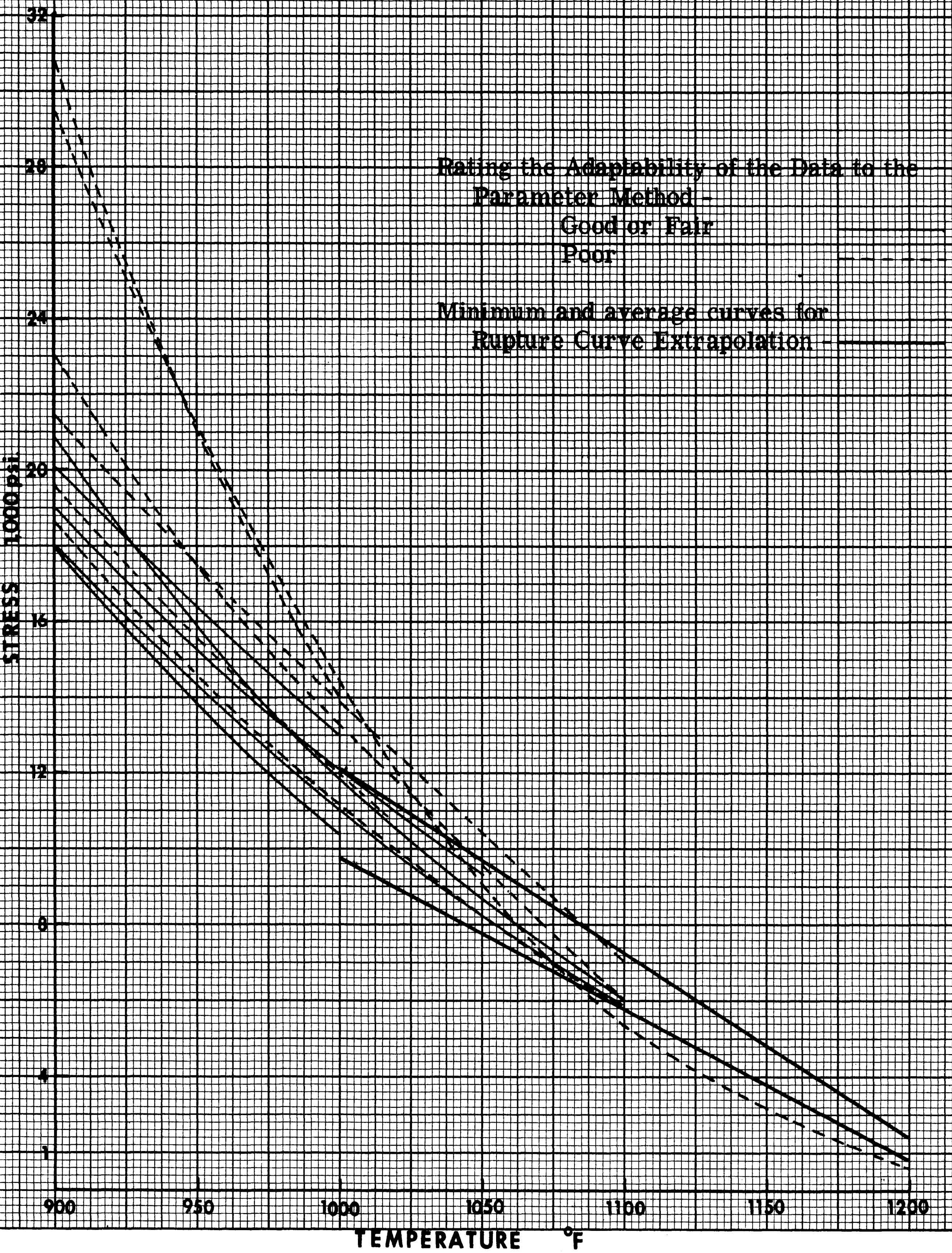


Figure 19. 100,000-hour strengths as a function of temperature for Grade 22 (2-1/4Cr - 1Mo) Steel. Extrapolated strengths obtained using Larson-Miller Parameter with an optimized constant. Only data sets for which values were obtained by extrapolation of stress rupture time curves are presented, i.e., "parameter"-type data are not included.

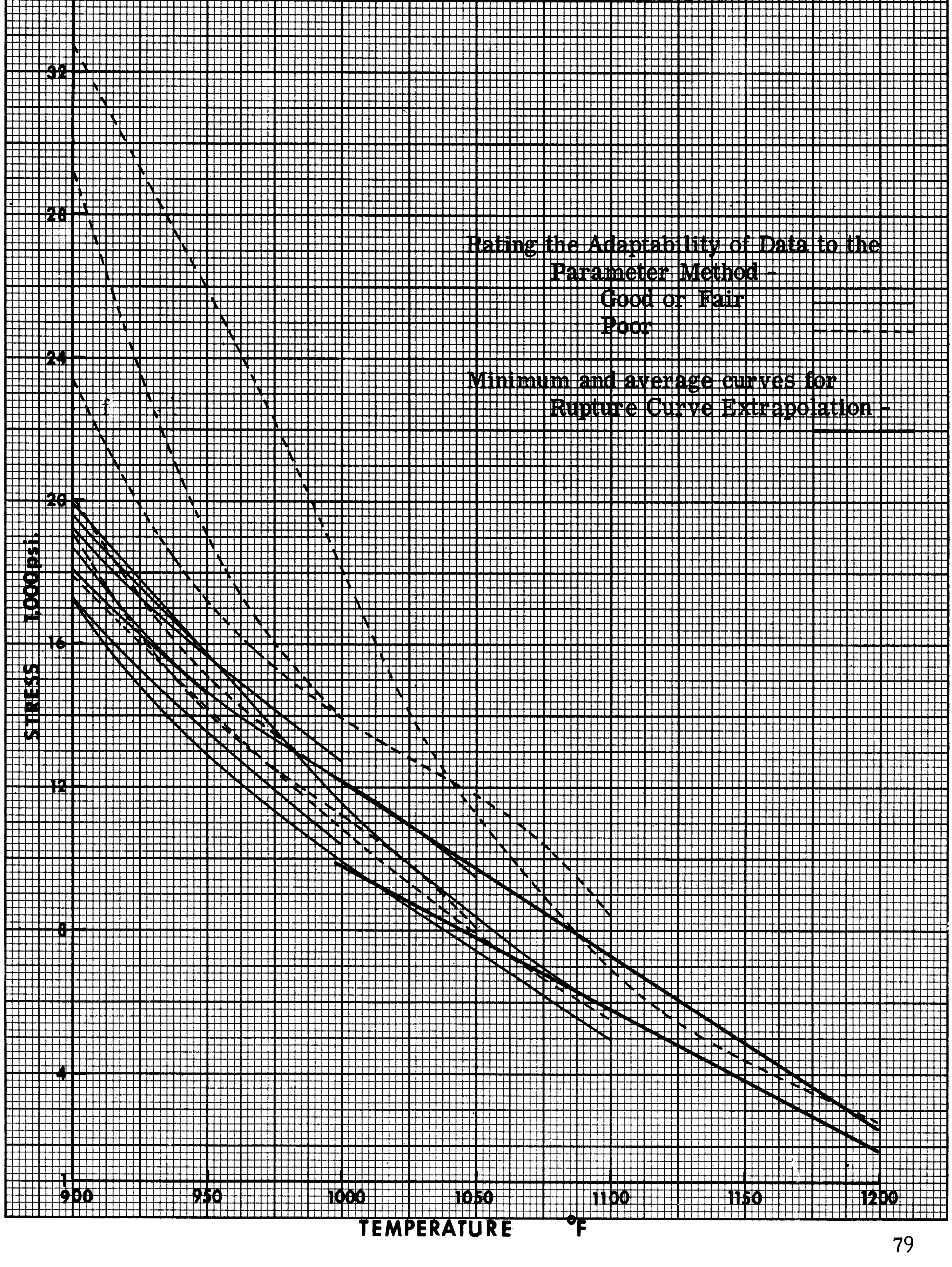


Figure 20. 100,000-hour strengths as a function of temperature for Grade 22 (2-1/4Cr - 1Mo) Steel. Extrapolated strengths obtained using Manson-Haferd (Linear) Parameter with optimized constants. Only data sets for which values were obtained by extrapolation of stress-rupture time curves are presented, i.e., "parameter-type" data are not included.

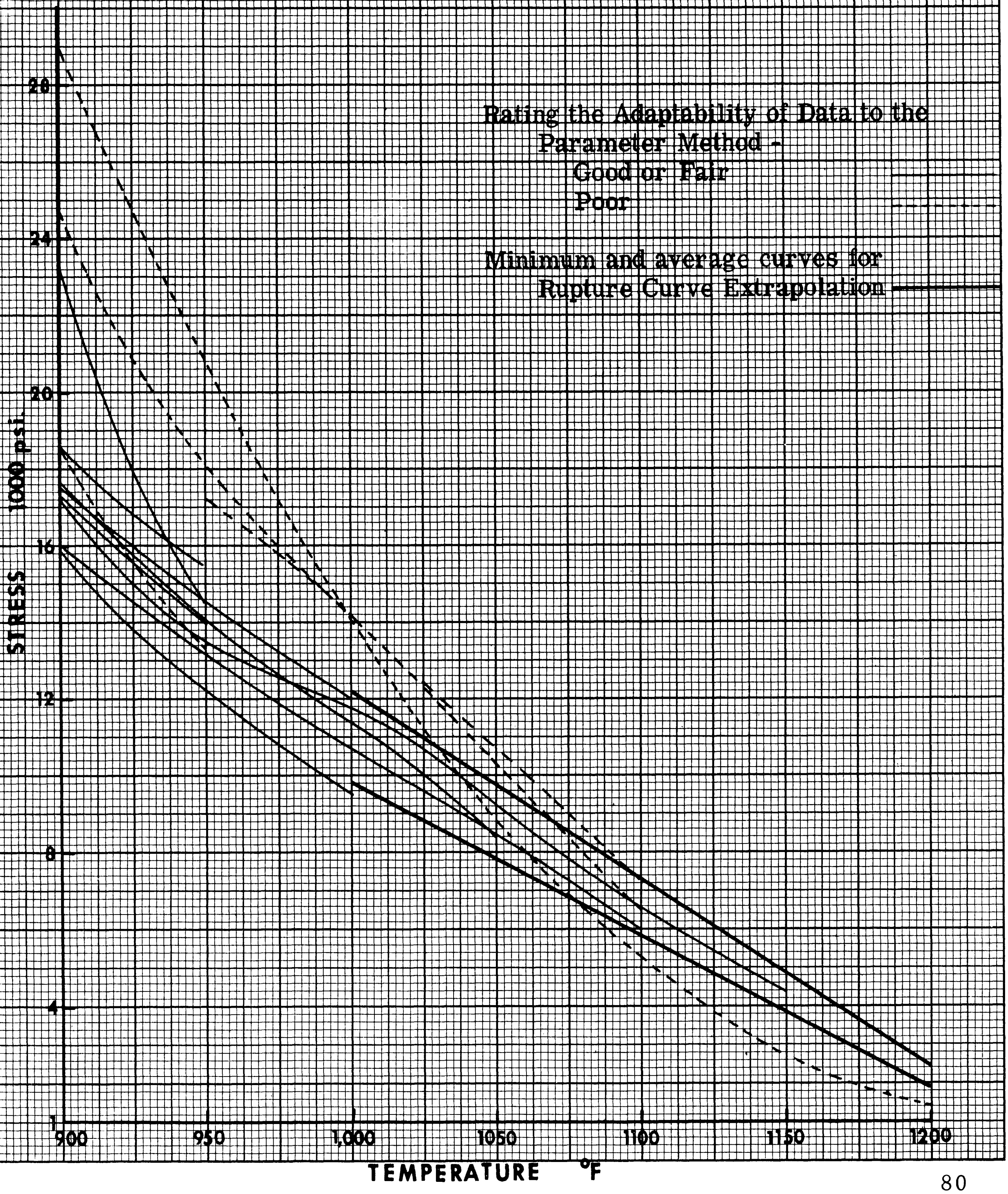
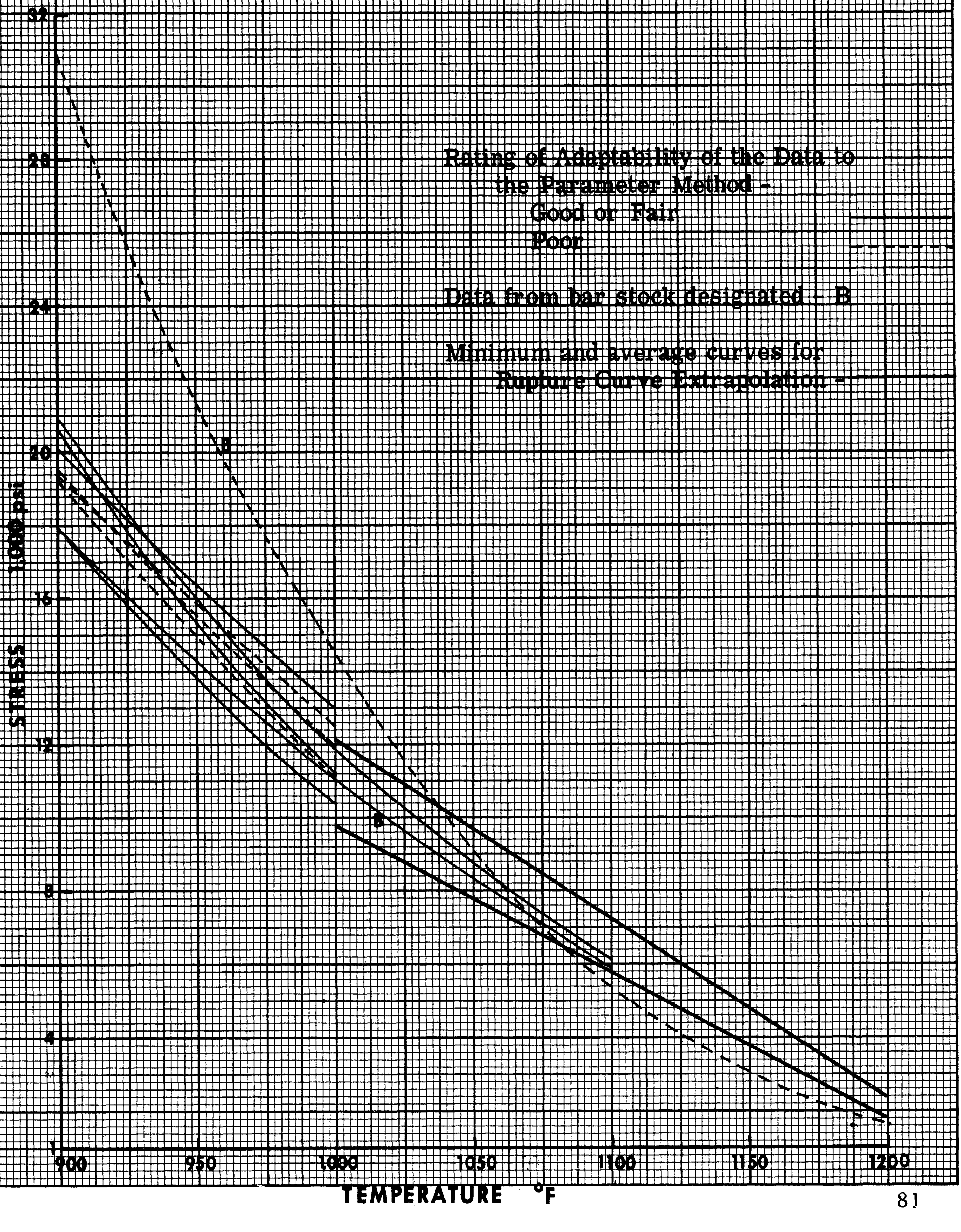


Figure 21A. 100,000-hour strengths as a function of temperature for bar and tube Grade 22 (2-1/4Cr - 1Mo) Steel. Extrapolation strengths obtained using Larson-Miller Parameter with a constant C = 20. 0.



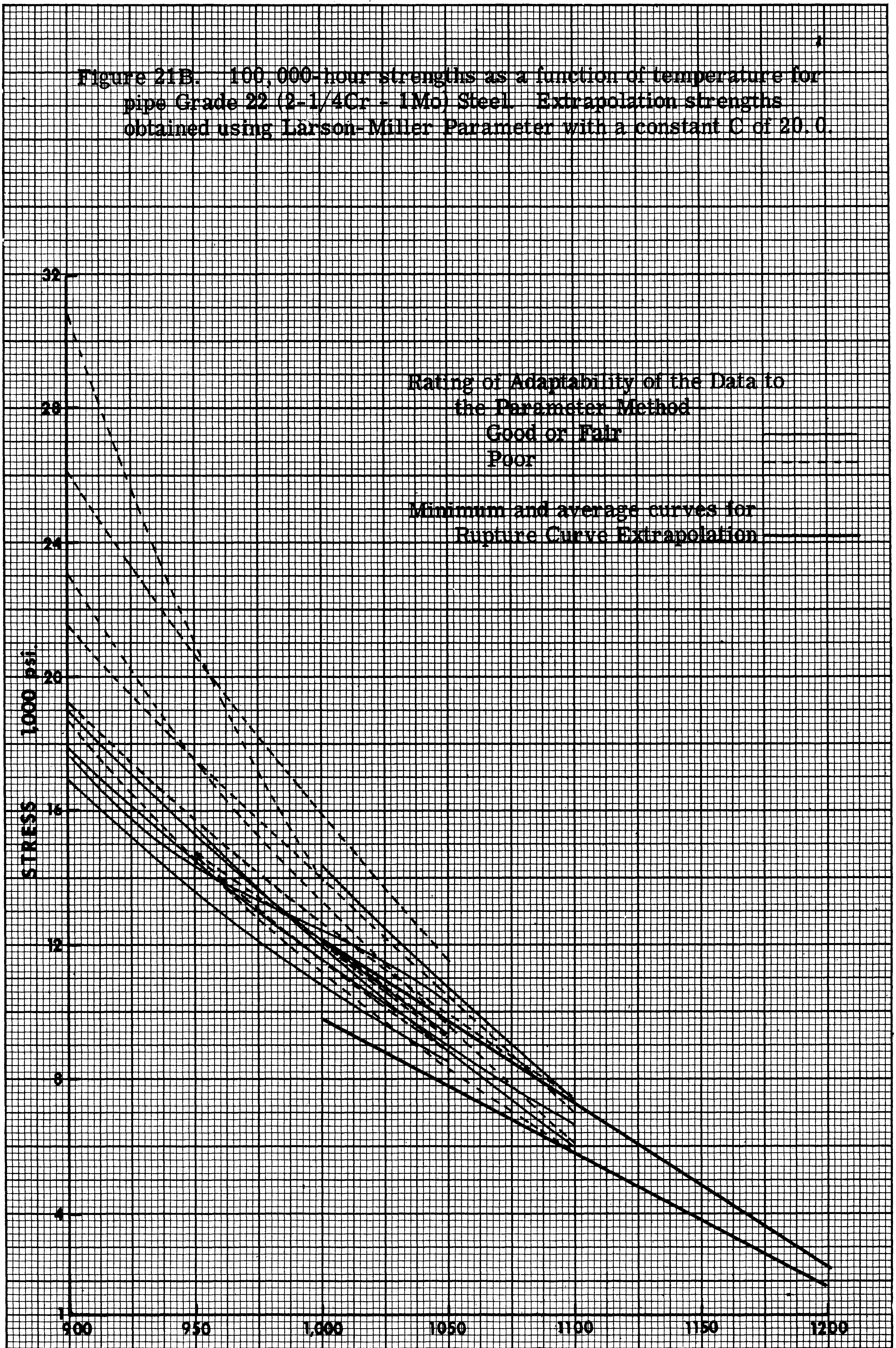


Figure 21B. 100,000-hour strengths as a function of temperature for pipe Grade 22 (2-1/4Cr - 1Mo) Steel. Extrapolation strengths obtained using Larson-Miller Parameter with a constant C of 20.0.

Figure 22A. 100,000-hour strengths as a function of temperature for bar and tube Grade 22 (2-1/4Cr - 1Mo) Steel. Extrapolation strengths obtained using Larson-Miller Parameter with an optimized constant.

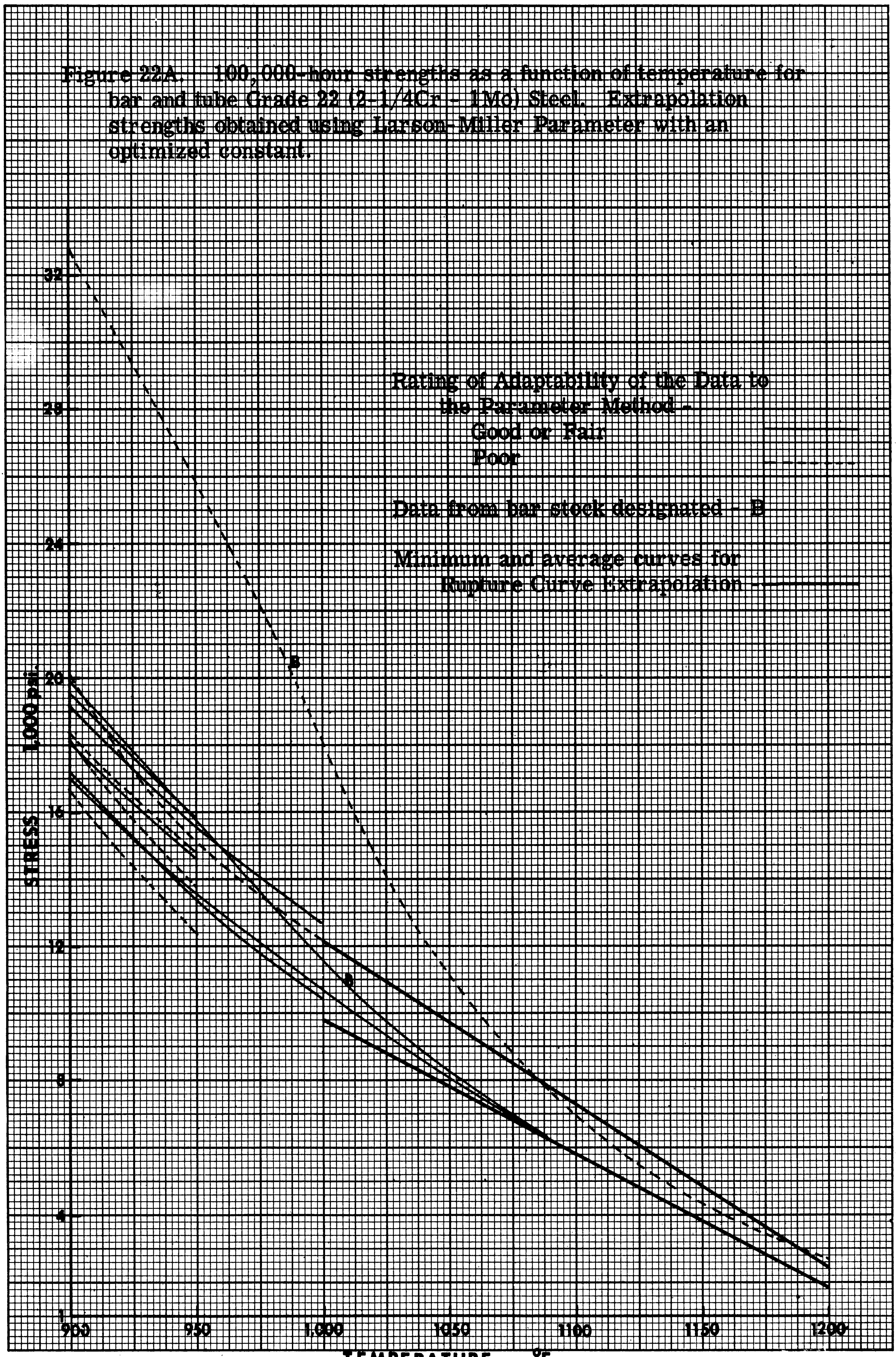


Figure 22B. 100,000-hour strengths as a function of temperature for pipe Grade 22 (2-1/4Cr - 1Mo) Steel. Extrapolation strengths obtained using Larson-Miller Parameter with an optimized constant.

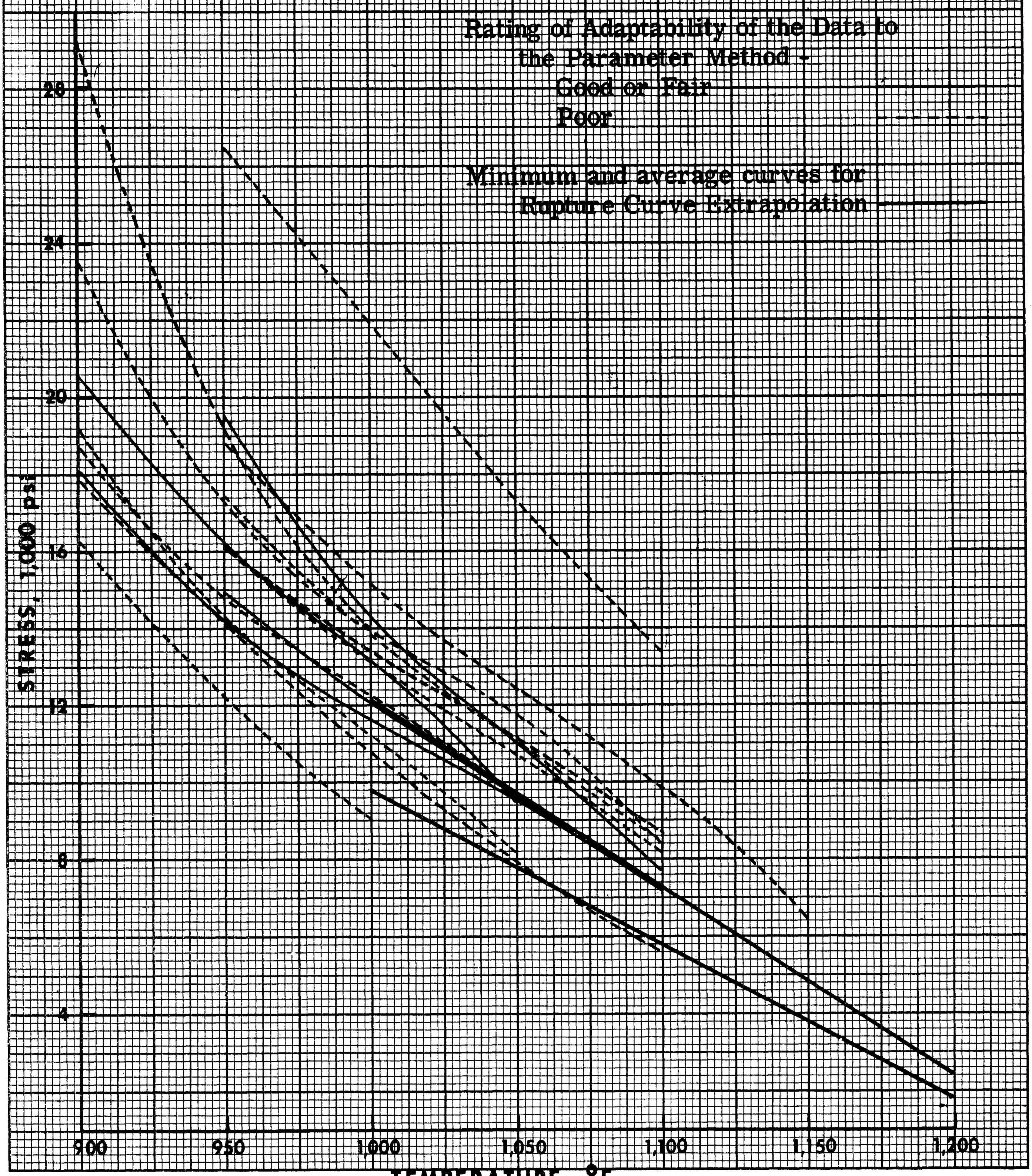


Figure 23A. 100,000-hour strengths as a function of temperature for bar and tube Grade 22 (2-1/4Cr - 1Mo) Steel. Extrapolation strengths obtained using Manson-Haferd (Linear) Parameter with optimized constants.

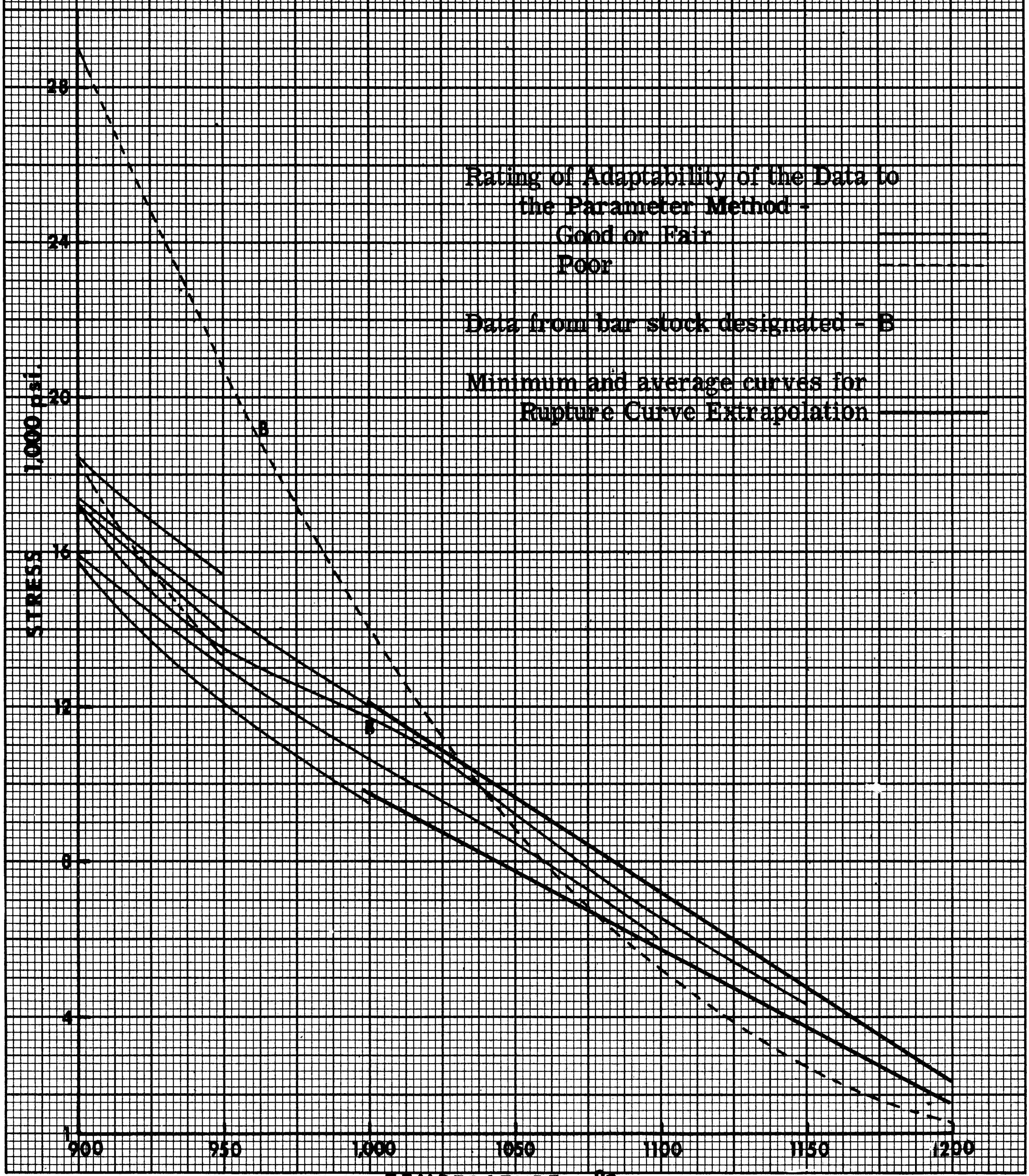
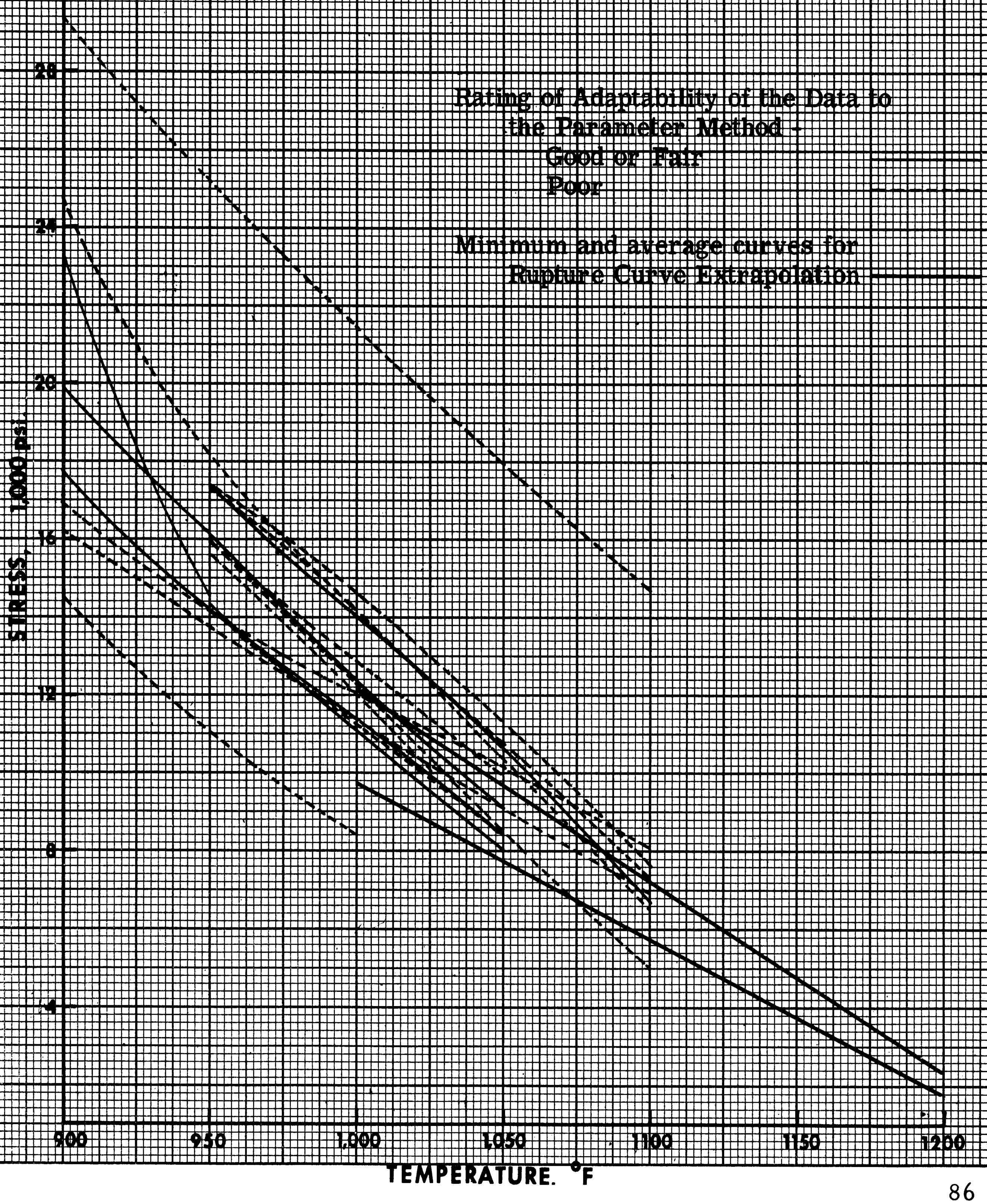


Figure 23B. 100,000-hour strengths as a function of temperature for pipe Grade 22 (2-1/4Cr - 1Mo) Steel. Extrapolation Strengths obtained using Manson-Haferd (Linear) Parameter with optimized constants.



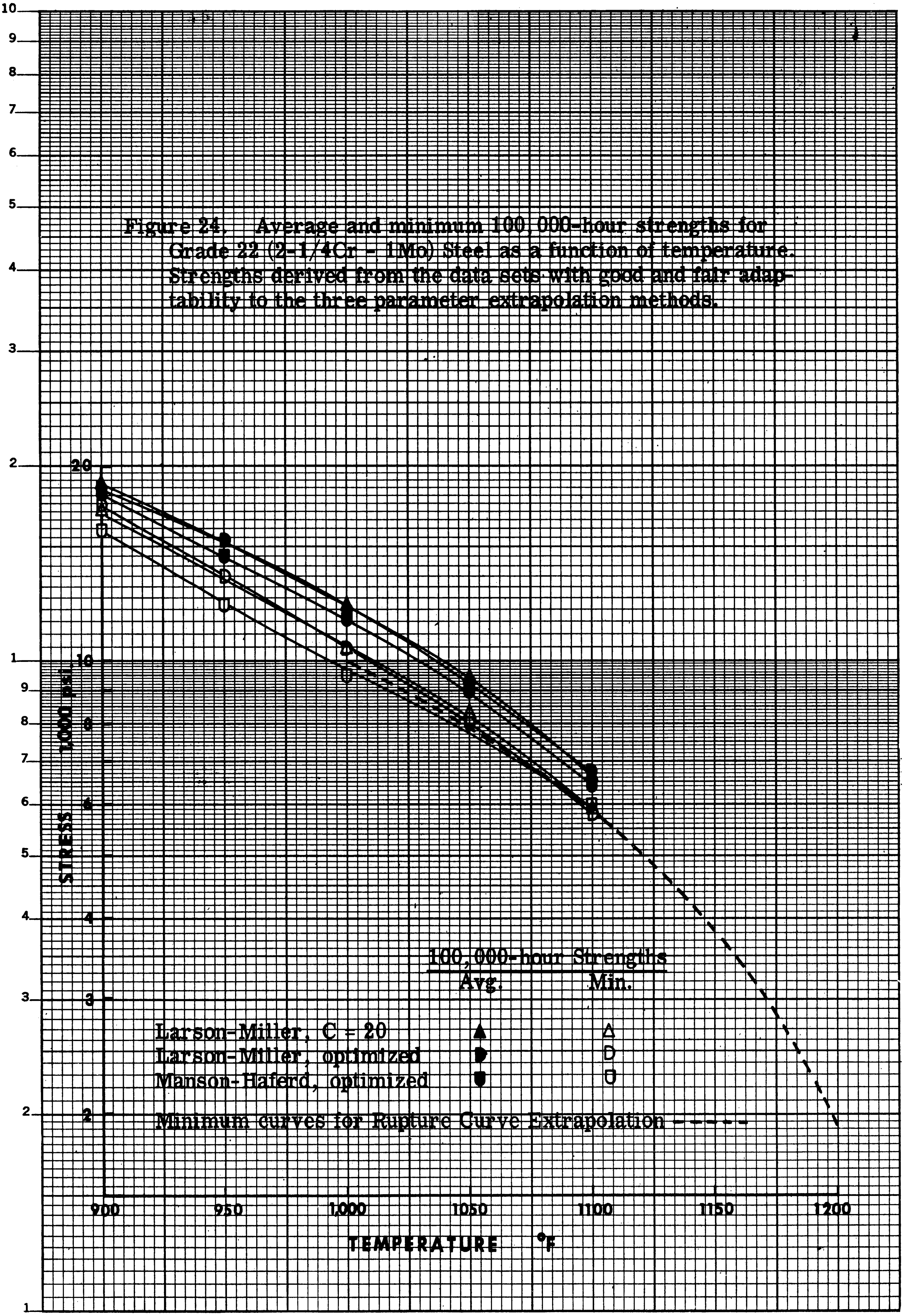


Figure 24. Average and minimum 100,000-hour strengths for Grade 22 (2-1/4Cr - 1Mo) Steel as a function of temperature. Strengths derived from the data sets with good and fair adaptability to the three parameter extrapolation methods.

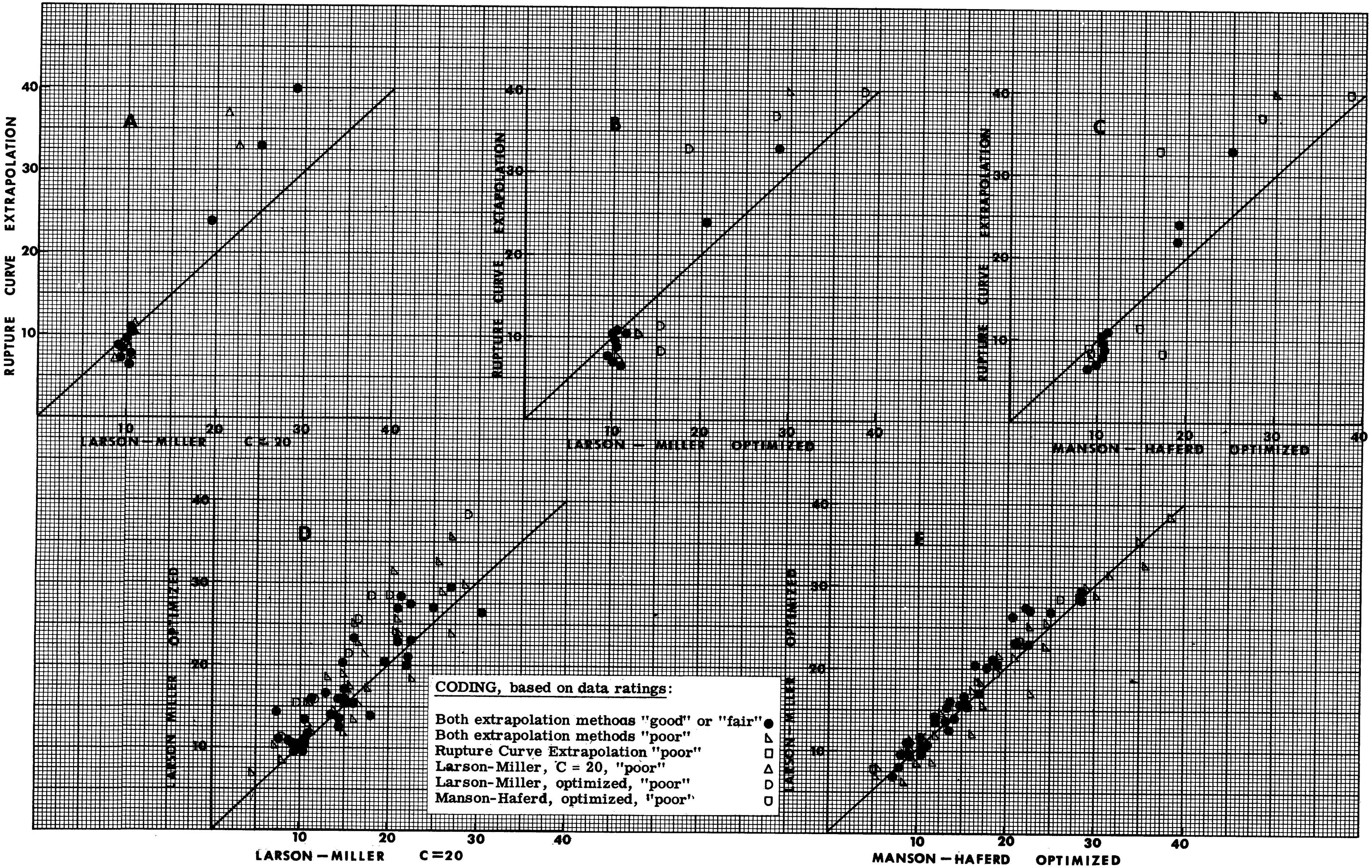


Figure 25 (A-E). Comparison of the stresses for rupture in 100,000 hours for Grade 11 (1-1/4Cr - 1/2Mo 3/4Si) Steel, obtained by extrapolation of rupture curves and by three parameter methods. Both ordinates and abscissas are 100,000-hour strengths in 1000 psi obtained by the indicated extrapolation methods.

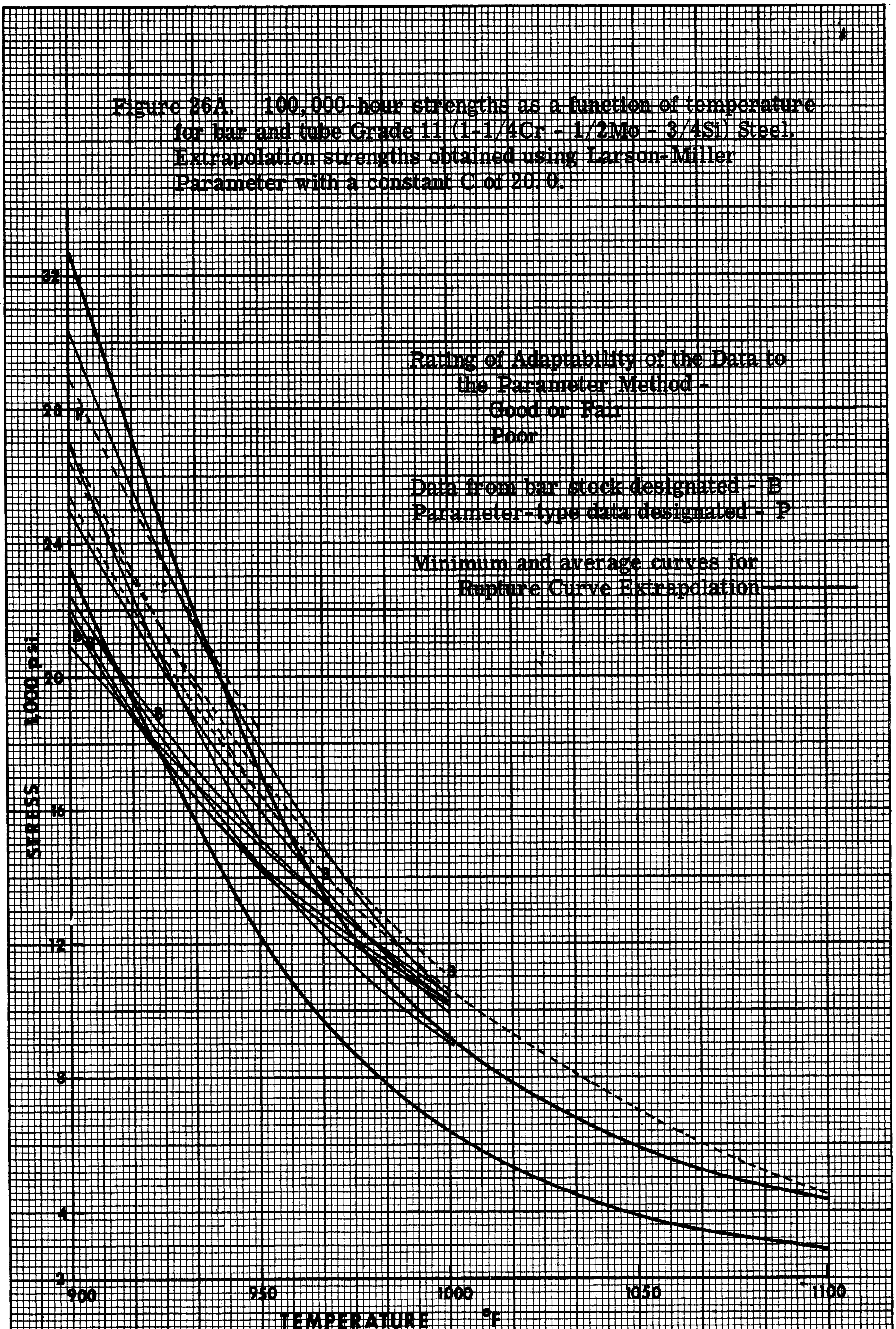
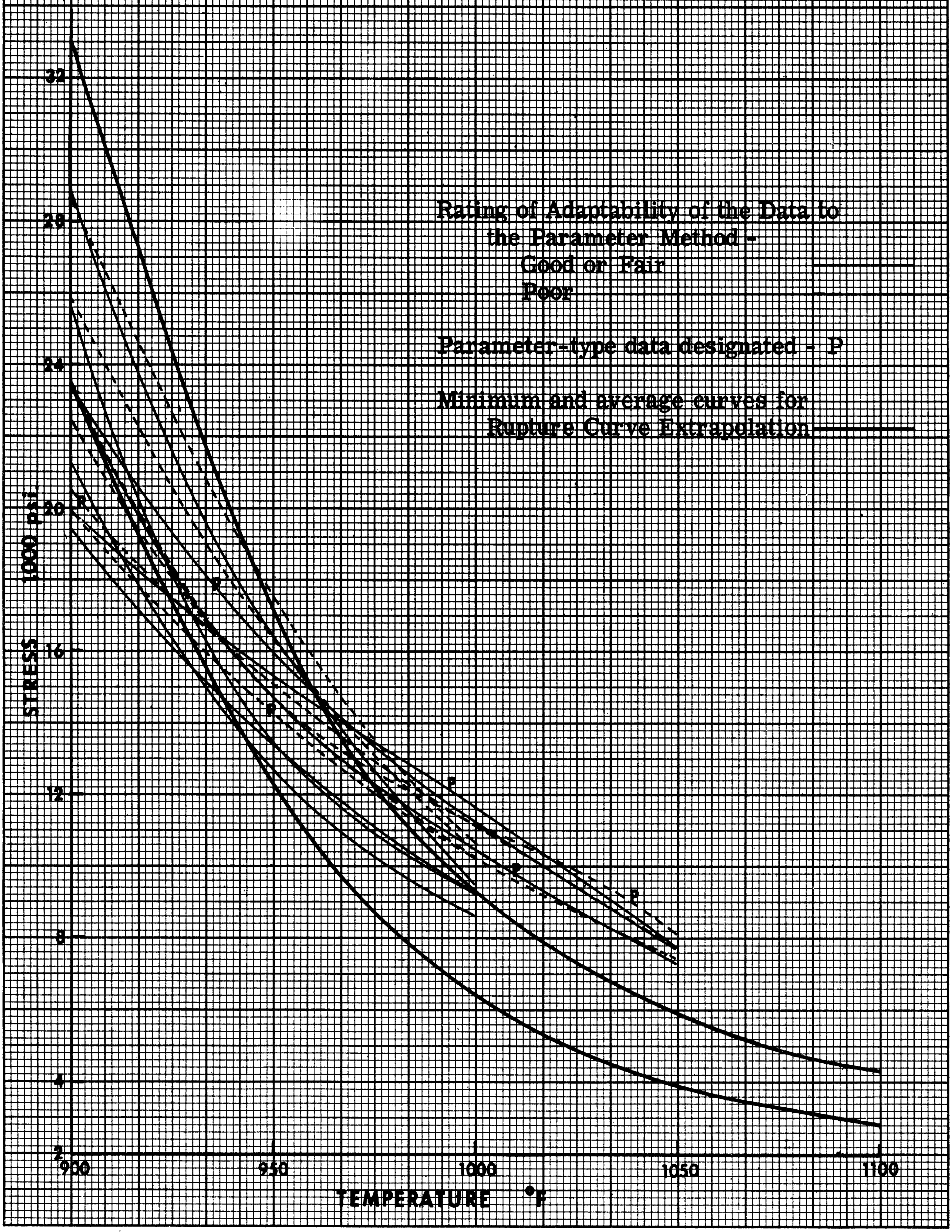


Figure 26A. 100,000-hour strengths as a function of temperature for bar and tube Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) Steel. Extrapolation strengths obtained using Larson-Miller Parameter with a constant C of 20.0.

Figure 26B. 100,000-hour strengths as a function of temperature for pipe Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) Steel. Extrapolation strengths obtained using a Larson-Miller Parameter with a constant C of 20.0.



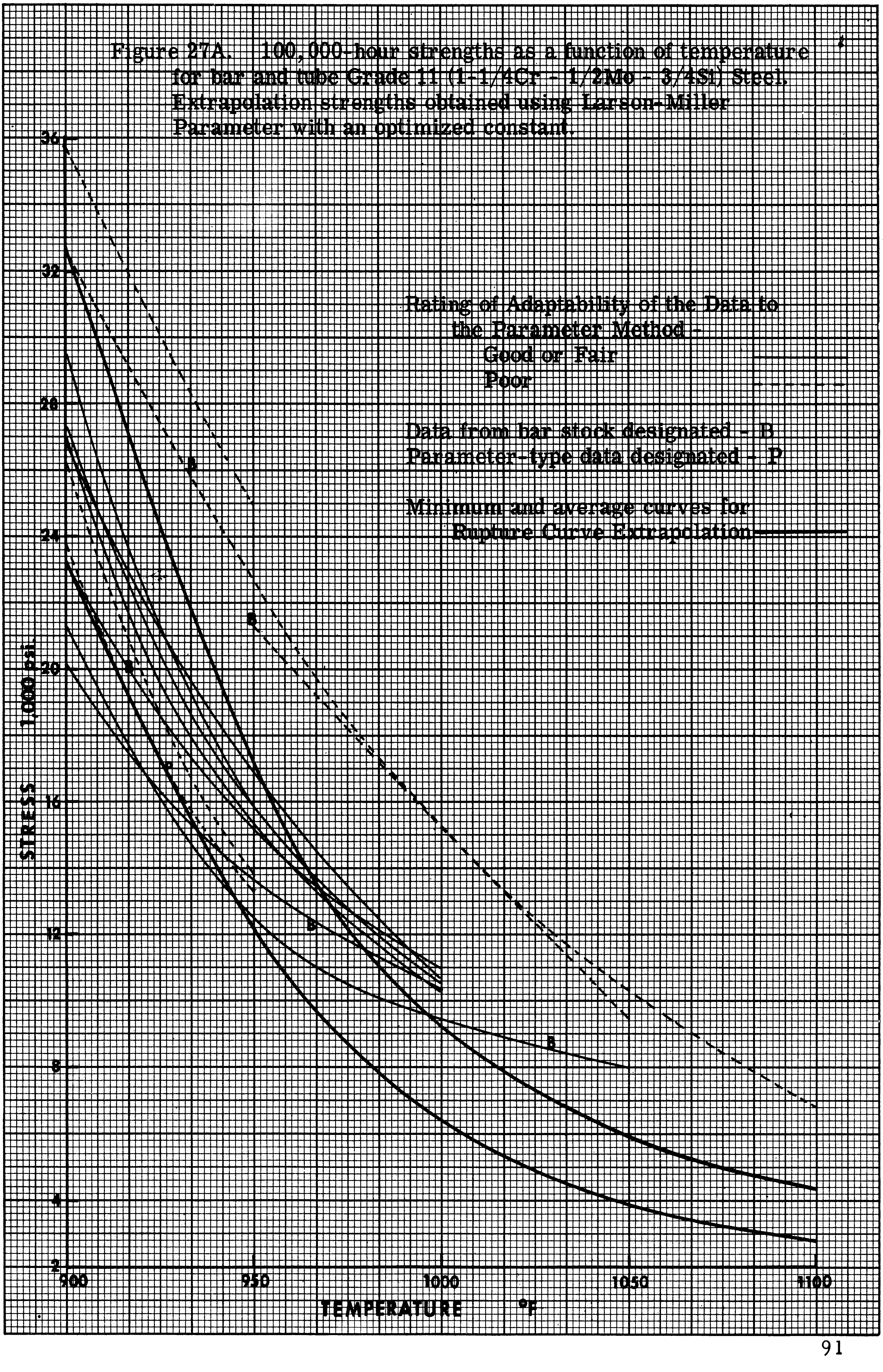


Figure 27A. 100,000-hour strengths as a function of temperature for bar and tube Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) Steel. Extrapolation strengths obtained using Larson-Miller Parameter with an optimized constant.

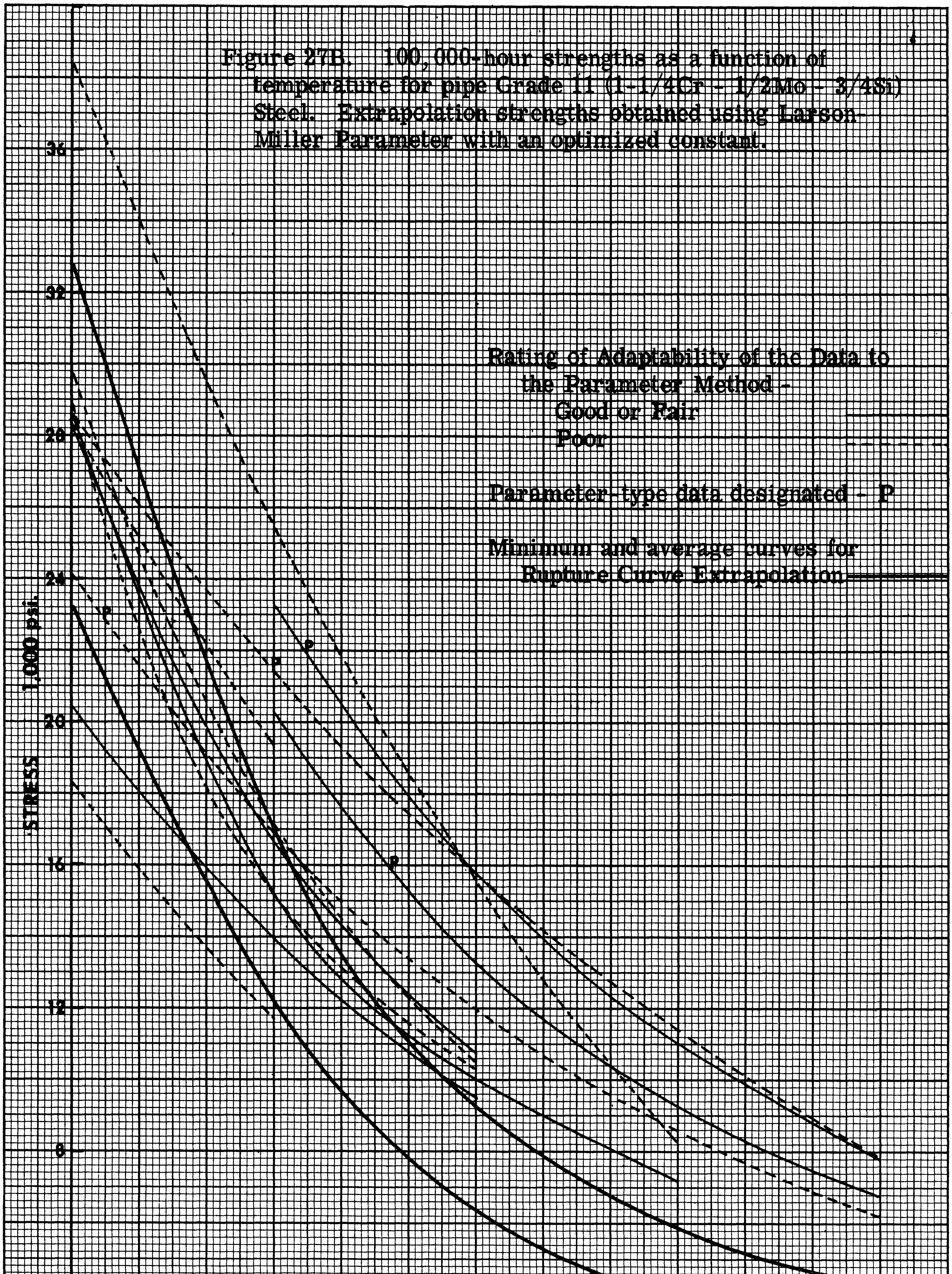
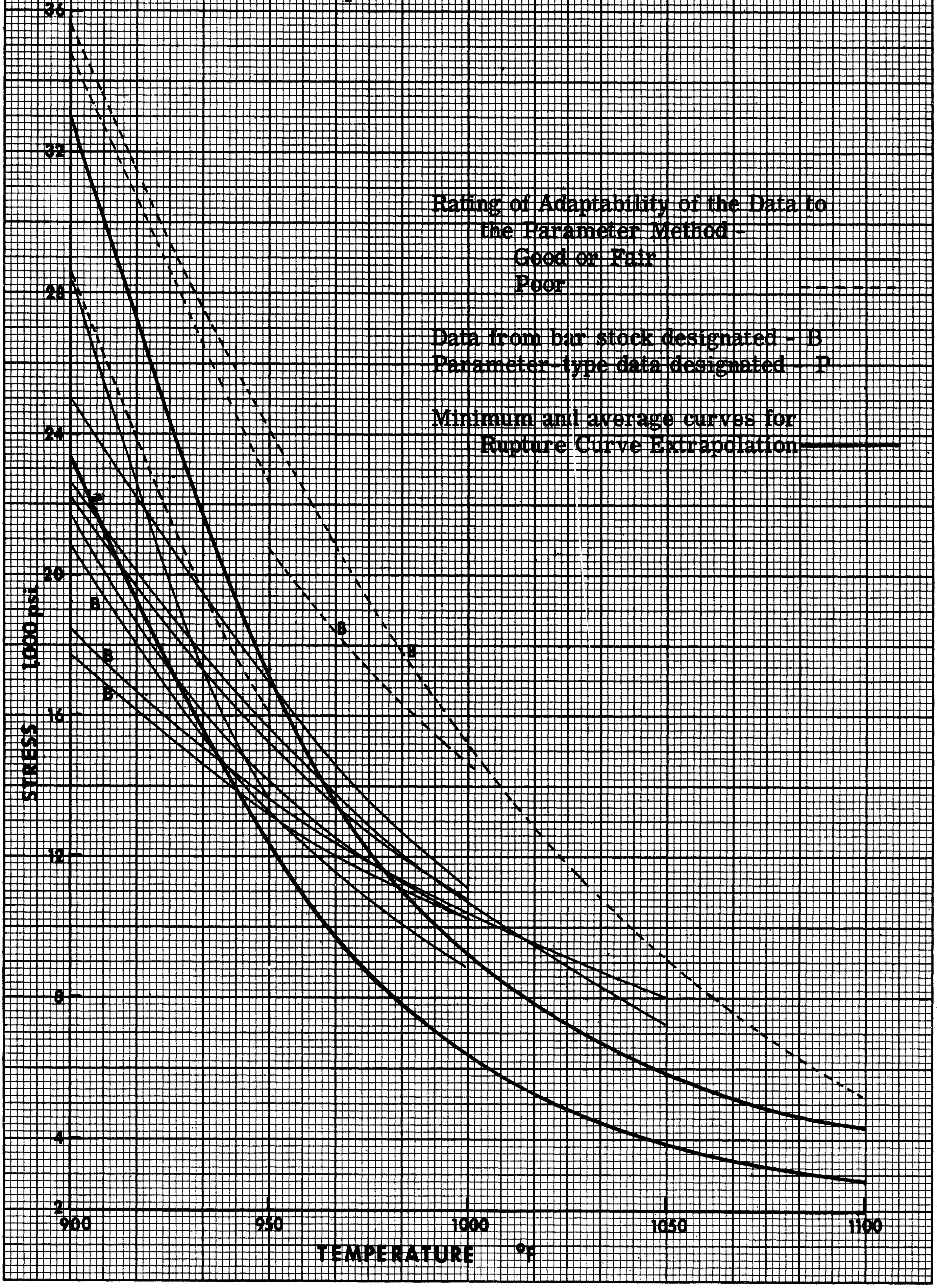


Figure 27B. 100,000-hour strengths as a function of temperature for pipe Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) Steel. Extrapolation strengths obtained using Larson-Miller Parameter with an optimized constant.

Figure 28A. 100,000-hour strengths as a function of temperature for bar and tube Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) Steel. Extrapolation strengths obtained using Manson-Haferd (Linear) Parameter with optimized constants.



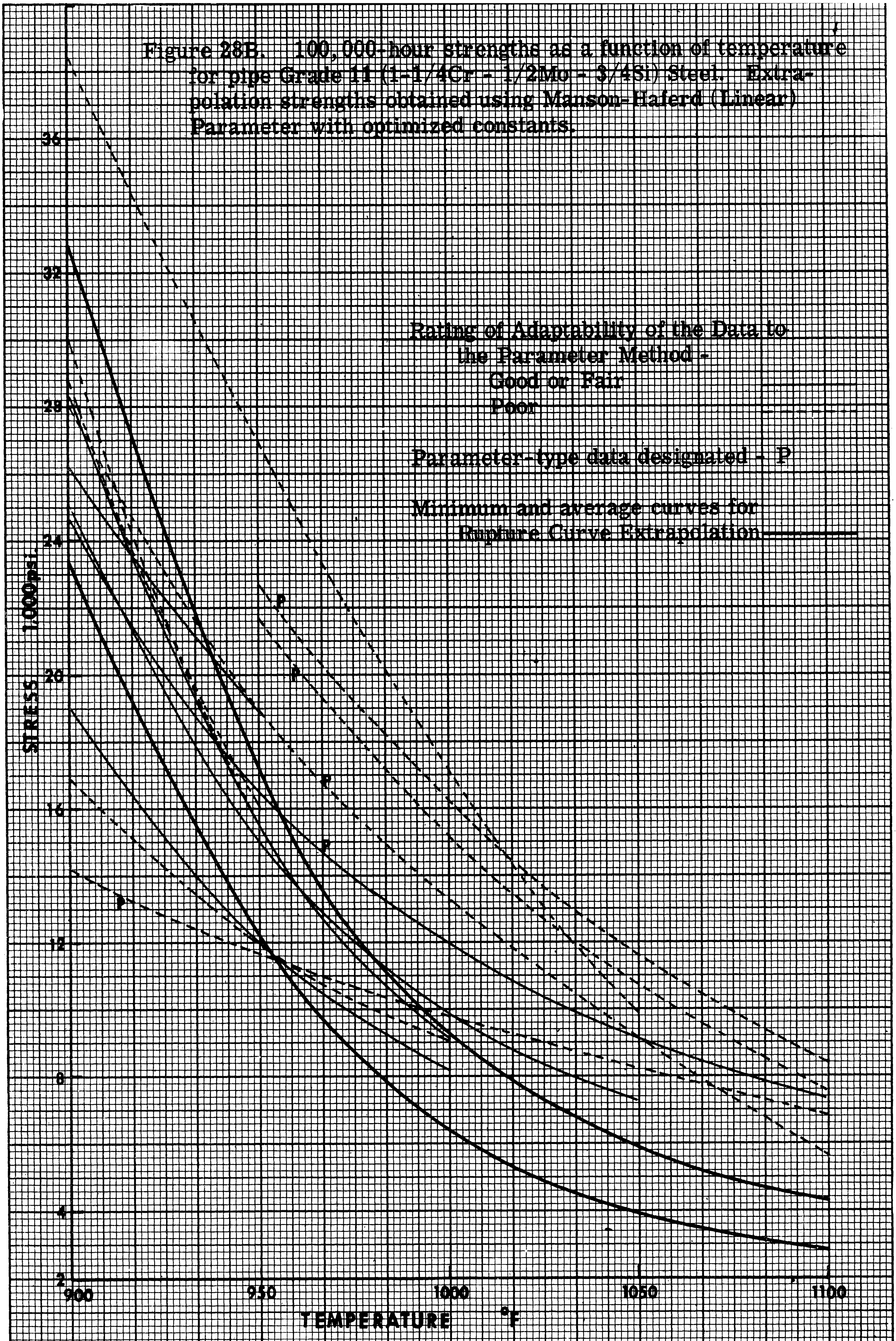


Figure 28B. 100,000-hour strengths as a function of temperature for pipe Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) Steel. Extrapolation strengths obtained using Manson-Haferd (Linear) Parameter with optimized constants.
Rating of Adaptability of the Data to the Parameter Method -
Good or Fair
Poor
Parameter-type data designated - P
Minimum and average curves for Rupture Curve Extrapolation
P
STRESS 1,000 psi.
36
32
28
24
20
16
12
8
4
2
900
950
1000
1050
1100
TEMPERATURE °F

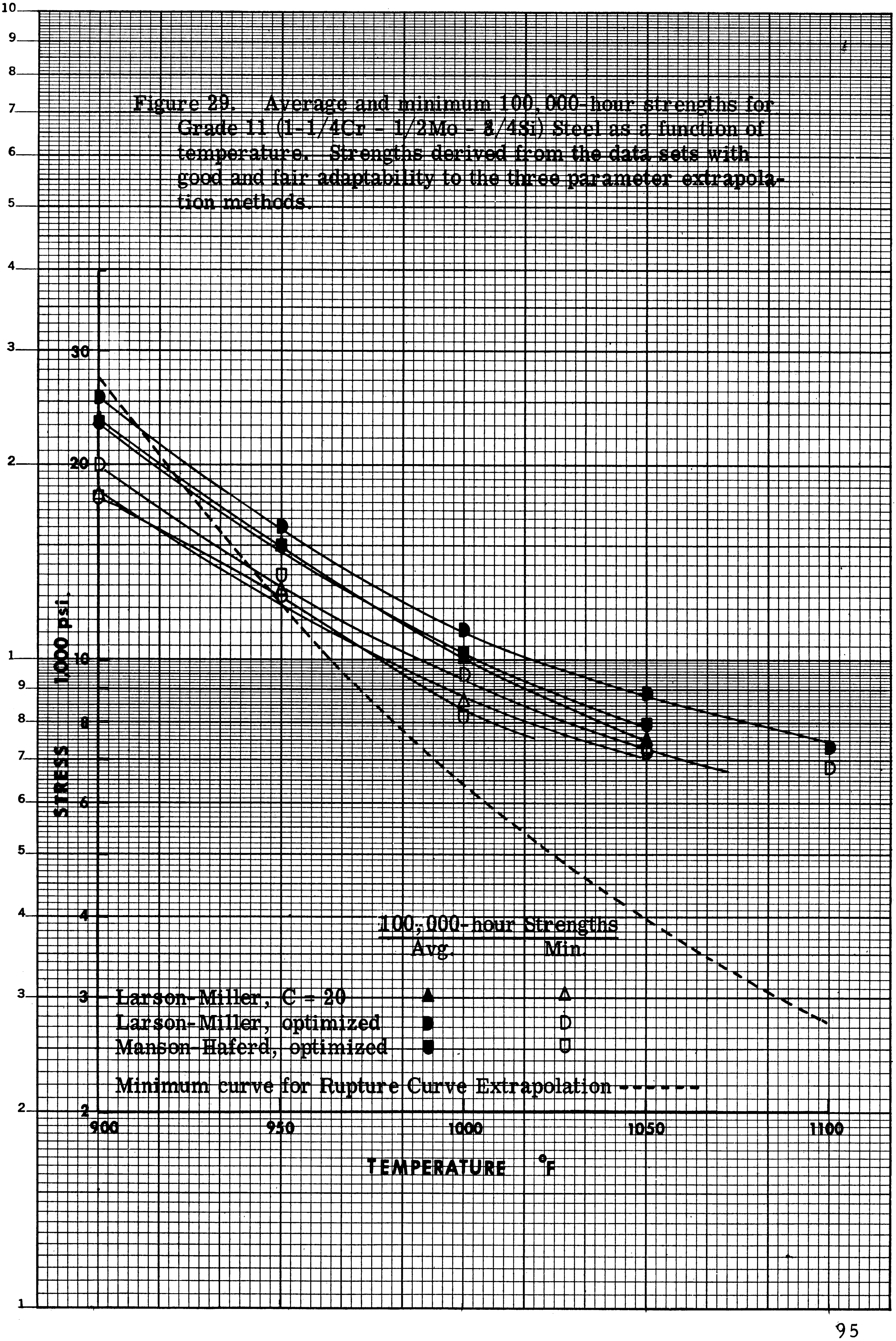


Figure 29. Average and minimum 100,000-hour strengths for Grade 11 (1-1/4Cr - 1/2Mo - 3/4Si) Steel as a function of temperature. Strengths derived from the data sets with good and fair adaptability to the three parameter extrapolation methods.