OPTIMIZATION OF TIME-TEMPERATURE PARAMETERS FOR CREEP AND STRESS RUPTURE, WITH APPLICATION TO DATA FROM GERMAN COOPERATIVE LONG-TIME CREEP PROGRAM

by Alexander Mendelson, Ernest Roberts, Jr., and S. S. Manso

Lewis Research Center
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SUMMARY

By the use of orthogonal polynomials developed for discrete sets of data, the least-squares equations for determining the optimized stress-rupture parametric constants are obtained in nearly uncoupled form; thus the use of high-degree polynomials is permitted without the loss of significant figures. Optimum values of the constants can thereby be accurately obtained. The method is applied to the data obtained from the German cooperative long-time creep program by using a general parameter of which the Manson-Haferd and Larson-Miller parameters are special cases. Good correlation was obtained. An analysis is also made of creep data obtained for columbium alloy FS-85 with good results. A complete Fortran IV computer program is included to aid those wishing to use the method.

INTRODUCTION

One method of extrapolating short-time creep-rupture data to predict long-time life involves the use of a time-temperature parameter. This concept is based on the assumption that all creep-rupture data for a given material can be correlated to produce a single "master curve" wherein the stress (or log stress) is plotted against a parameter involving a combination of time and temperature. Extrapolation to long times can then be obtained from this master curve, which can presumably be constructed by using only short-time data. Three well-known parametric methods are the Larson-Miller, Manson-Haferd, and Dorn parameters (refs. 1 to 3). These parametric methods have the great advantage, at least in theory, of requiring only a relatively small amount of data to establish the required master curve.

More recently a general creep-rupture parameter was introduced by one of the authors (ref. 4) that includes most of the currently used parameters as special cases. The analysis in the present paper is therefore based on this general parameter.
A significant advance in the practical application of the parametric methods was the development of an objective least-squares method for determining the optimum values of the parametric constants without plotting and cross-plotting the data and without the use of judgment on the part of the analyst (ref. 5). This least-squares method involves, however, several practical difficulties that arise from the fact that in fitting the master curve by a polynomial, the set of linear algebraic equations for the coefficients (the normal equations) are very ill-conditioned. The determinant of these equations can be shown to be related to the Hilbert determinant (ref. 6), which rapidly approaches zero as its order increases. Thus for polynomials above the second degree, it is necessary to use double-precision arithmetic (16 significant digits or more) on the computer, and for the fifth degree and above the results become uncertain even with double-precision arithmetic. This difficulty is inherent in the normal least-squares equations and is not limited only to the stress-rupture problem.

The present report presents a method for avoiding the above difficulty by using orthogonal polynomials in the representation of the master curve (appendix A). The use of orthogonal polynomials for representing discrete sets of unequally spaced data is described in reference 6 and in more detail in reference 7. A further improvement can be obtained by performing a linear transformation on the stresses (or the logs of the stresses) so that all the values of stress (or log stress) lie between 2 and -2, as recommended in reference 7. As a result of these innovations, it became possible to perform all the computations in single-precision arithmetic (eight significant digits) up to 18th degree polynomials without appreciable round-off error.

In addition, this report contains a complete analysis, in which the general parameter was used, of all the data for three steels that were obtained by NASA through the cooperation of Dr. K. Richard of Faberwerke Hoechst in Frankfurt and that were investigated in a long-time cooperative creep program in Germany. Some of the data from the latter investigation are included in this paper.

Finally it is shown by means of a concrete example how the parameter techniques can be applied to creep data to predict long-time creep. For this purpose the data for columbium alloy FS-85, as reported in reference 8, are used.

A complete Fortran IV program, as used on the IBM 7094 computer in making the calculations, is presented in appendix B. This program can be used for the objective analysis of any set of creep-rupture data by the Larson-Miller, Manson-Haferd, or the more general parameter of reference 4.

**SYMBOLS**

A,B  linear transformation coefficients

a,b,c elements of coefficient matrix

D  standard deviation
K    degree of freedom
m    degree of polynomial
n    number of data points
P(σ) creep-rupture parameter
Q    polynomial
q    stress exponent
r    temperature exponent
S    sum of squares of residuals
T    temperature
Ta   temperature intercept
t    time to rupture
ta   time intercept
u    coefficient of polynomial function
X    scaled log stress
x    log stress
y    log time
ya   log time intercept
α,β  constants from recurrence relation
σ    stress
τ    \[ σ^q(T - T_a)^r \]

Subscripts:
max  maximum
min  minimum

PROCEDURE

General Parameter

The general creep-rupture parameter introduced in reference 4 has the fol-
lowing form

\[
P(\sigma) = \frac{\log t - \log t_a}{q - (T - T_a)^r}
\]  

(1)

where \( T_a, \log t_a, q, \) and \( r \) are material constants to be determined from the available experimental data. The parameter \( P(\sigma) \) is a function of the stress and, when plotted against stress, is referred to as a master curve (fig. 1, p. 9). If \( q = 0 \) and \( r = 1 \), the Manson-Haferd parameter is obtained. If \( q = 0, r = -1, \) and \( T_a = -460^\circ F \), the Larson-Miller parameter results. If \( q = 1 \) and \( r = 1 \), the stress-modified parameter suggested in reference 9 is obtained. Finally, if \( q = 0 \), equation (1) reduces to the parameter proposed by Manson and Brown (ref. 10).

The object is to find the best values of the constants \( q, \log t_a, T_a, \) and \( r \) so that the master curve best fits the data. To find these values, the method of least squares is used whereby the master curve is represented by a polynomial in the logarithm of the stress, and the best fit is obtained by minimizing the sum of the squares of the deviations (the residuals) of the data from the curve. The calculation procedure will now be described. The details of the derivation are given in appendix A, and a Fortran IV computer program using this method is given in appendix B.

Calculation Procedure

To simplify the notation, the following symbols are introduced:

\[
\begin{align*}
\tau &= \sigma q (T - T_a)^r \\
y &= \log t \\
x &= \log \sigma \\
y_a &= \log t_a
\end{align*}
\]

(2)

Then from equation (1) it follows that

\[
y = \sigma y_a + rQ(x)
\]

(3)

where in reference 5, \( Q(x) \) was represented by a simple polynomial of the form

\[
Q(x) = a_0 + a_1 x + a_2 x^2 + \ldots + a_m x^m
\]

(4)

The least-squares equations obtained sometimes led to difficulties as indicated in the INTRODUCTION. These difficulties can be avoided, however, by rewriting equation (4) in terms of polynomials that are orthogonal over the set of data, as defined in appendix A. Thus assume
where \( u_j \) is an unknown constant, \( m \) is the degree of the highest degree polynomial, and \( Q_j(x) \) is a polynomial of degree \( j - 1 \) that satisfies the orthogonality conditions described in appendix A. The use of orthogonal polynomials permits the solution of the least-squares equations directly in closed form, thus the loss of a large number of significant digits is avoided. The method of calculating \( Q_j \) will be discussed in appendix A.

If equation (5) is substituted into equation (3), an equation with \( m + 5 \) unknown constants results for the case of the general parameter. For the case of the linear parameter there are \( m + 3 \) constants, and for the Larson-Miller parameter there are \( m + 2 \). It is necessary that the number of data points \( n \) always equals or exceeds the number of unknown constants.

The constants are determined so that equation (3) fits the data best in the least-squares sense. To accomplish this, the sum of the squares of the deviations is minimized; that is,

\[
S = \sum_{i=1}^{n} \left[ y_i - \sigma_i y_a - \tau_i Q(x_i) \right]^2
\]

(6)

is made a minimum. Because the equations are nonlinear in some of the unknown constants a trial and error procedure must be used. A set of values is assumed for \( q, r, \) and \( T_a \), and the corresponding best values of \( y_a \) and \( u_j \) are determined. A different set of values for \( q, r, \) and \( T_a \) is then chosen, and again the best values of \( y_a \) and \( u_j \) are calculated. Several sets of values of \( q, r, \) and \( T_a \) are tried, and the values corresponding to the overall best fit are determined. For the case of the linear parameter, only the value of \( T_a \) is varied (\( q \) is always equal to zero, and \( r \) is always equal to 1). For the Larson-Miller parameter, \( T_a \) is equal to \(-460^\circ F\), and no trial and error procedure is needed.

As a measure of the fit, the standard deviation \( D \), defined by

\[
D = \sqrt{\frac{S}{n - K}}
\]

(7)

is used, where \( K \) equals

\[
\begin{align*}
\text{general parameter} & \quad \text{m + 5} \\
\text{linear parameter} & \quad \text{m + 3} \\
\text{Larson-Miller parameter} & \quad \text{m + 2}
\end{align*}
\]

(8)

The smallest value of \( D \) will correspond to the best fit.
To determine the best values of \( y_a \) and \( u_j \) for a given set of values of \( T_a, q, \) and \( r, \) the following calculations are made. First, the logarithms of the stresses are scaled so that they lie in the range -2 to 2, as suggested in reference 7. The reason for this is discussed in appendix A. Thus define a variable \( X \) by

\[
X = Ax + B
\]

\[
A = \frac{4}{x_{\text{max}} - x_{\text{min}}}
\]

\[
B = -2 \frac{x_{\text{max}} + x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}
\]

The polynomials \( Q_j(x_i) \) are now calculated for each of the data points by using the following formulas:

\[
Q_{j+1} = (X - a_j)Q_j - \beta_jQ_{j-1} \quad m \geq j \geq 1
\]

\[
a_j = \frac{\sum_{i=1}^{n} x_i r_i^2 Q_j(x_i)}{\sum_{i=1}^{n} r_i^2 Q_j^2(x_i)} \quad m \geq j \geq 1
\]

\[
\beta_j = \frac{\sum_{i=1}^{n} x_i r_i^2 Q_j(x_i)Q_{j-1}(x_i)}{\sum_{i=1}^{n} r_i^2 Q_j^2_{j-1}(x_i)} \quad m \geq j > 1, Q_1 = 1, \text{ and } \beta_1 = 0
\]

where \( n \) is the number of data points, \( x_i \) is the scaled value of log for the \( i \)th data point, and \( r_i \) is equal to \( \phi(q(T_i - T_a))^r \) for the \( i \)th data point for the chosen values of \( T_a, q, \) and \( r. \)

It is to be noted that the degree of the polynomial \( Q(x) \) of equation (5) can be increased by merely computing the next polynomial in the series \( Q_{m+2} \) without having to recompute any of the previous ones. This is one of the advantages of using orthogonal polynomials.

Once the values of \( Q_j \) have been computed for each of the data points, \( y_a \) and \( u_j \) can be calculated as follows:
Let

\[ a_0 = \sum_{i=1}^{n} c_0^2 q_i \]

\[ a_j = \sum_{i=1}^{n} c_0^2 q_i x_i^2 \]

\[ b_j = \sum_{i=1}^{n} q_i^2 x_i^2 \]

\[ c_0 = \sum_{i=1}^{n} c_0 y_i \]

\[ c_j = \sum_{i=1}^{n} q_i y_i x_i^2 \]

where \( j = 1, 2, \ldots, m + 1 \).

Then

\[ y_a = \frac{c_0 - \sum_{j=1}^{m+1} \frac{a_j c_j}{b_j}}{a_0 - \sum_{j=1}^{m+1} \frac{a_j^2}{b_j}} \]

\[ u_j = \frac{c_j - a_j y_a}{b_j} \]

Note that if \( q = 0 \), \( a_0 \) equals the number of data points \( n \). Thus by means of equations (9) to (12), the best values of \( y_a \) and \( u_j \) to fit the data are found for a given choice of \( T_a, q, \) and \( r \). The Fortran IV program described in appendix B automatically scans all the desired values of \( T_a, q, \) and \( r \) and chooses the best set from all the submitted values as determined by the smallest value of the standard deviation \( D \), as defined by equation (7). The method can be illustrated by a simple example: consider a set of theoretical data, which fit the following equation exactly.
\[ \frac{9.5 - \log t}{T - 600} = 10^{-3}(7.02 + 0.467 \, x + 0.061 \, x^2 + 0.00928 \, x^3) \]  

(13)

Eight data points satisfying this equation are given in columns 2 to 6 of table I. For this data \( T_a = 600^\circ \) F and \( \log t_a = y_a = 9.5 \). Suppose, however, that these eight data points were obtained experimentally and that the values of \( T_a \) and \( \log t_a \) were not known. The problem then is to find the best values of \( T_a \) and \( \log t_a \) to fit the data by the linear parameter. These values can readily be found by using the equations of the previous section. First, from column 6 of table I:

\[ (\log \sigma)_{\text{max}} = 4.75051 \]

\[ (\log \sigma)_{\text{min}} = 1.81954 \]

Therefore from equations (9b)

\[ A = 1.36474 \]

\[ B = -4.48319 \]

and by means of equation (9a) the \( X_i \) were computed and are given in column 8.

For illustrative purposes three values of \( T_a \) were chosen, 500\(^\circ\), 600\(^\circ\), and 700\(^\circ\) F. For each of these values of \( T_a \), values of \( t_i, a_j, \beta_j, \) and \( Q_j(X_i) \) were computed by means of equations (2), (10), and (10a), and the values of \( a_j, b_j, \) and \( c_j \) were computed by equations (11). The results are tabulated for \( T_a = 600^\circ \) in columns 9 to 12 of table I and in table II up to a third degree polynomial.

The values of \( y_a \) and \( u_j \) were then computed by using equations (12) for each of these three values of \( T_a \) by first assuming \( m = 2 \), then \( m = 3 \), and finally \( m = 4 \), corresponding to polynomials of second, third, and fourth degrees, respectively. For each of these cases the standard deviation \( D \) was computed from equation (7) with \( S \) being given by equation (6) and \( Q \) by equation (5). The results are summarized in table III. The least value of \( D \), signifying the best fit, is obtained for \( m = 3 \) and \( T_a = 600^\circ \) F. The corresponding value of \( y_a \) is 9.5. These values, of course, correspond to equation (13), from which the data were generated.

Application to Data from German Cooperative Long-Time Creep Program

As part of the German cooperative long-time creep program, a sufficient amount of material of each of three steels was supplied to NASA to permit the running of short-time tests necessary to predict the results at long times obtained in the German test program. The composition of these steels is shown in table IV.

The results of the NASA tests, which were used in the subsequent analysis,
Parameter, \( P = (T - x_w)/(\log t - 16.54) \)

Figure 1. - Master curve for steel K (27b KK), calculated from NASA data between 10 and 3700 hours.

are shown in table V. Table VI shows the results of the long-time German test program. The three steels will be designated briefly as steel K, steel C, and steel P.

With the use of the test data shown in table V a complete analysis was made by the previously described method. The general parameter discussed in the INTRODUCTION was used, and the best values were obtained for the parametric constants for each of the three steels.

All the data obtained for these steels are shown in tables V and VI. Many of the data points were obtained for purposes other than the application to time-temperature parameters, as described in this report. As already discussed in references 4 and 11, a much smaller amount of data is needed when an accelerated program is desired; however, since these data were already available, all the data indicated in tables V and VI were used to obtain the best possible parametric constants.

For all three steels the analysis showed the stress exponent \( q \) to be zero, but the temperature exponent \( r \) to be different for each of the three materials. For steel K the best value of \( r \) was 1, which indicated that the best fit is obtained by the linear parameter. For steel F a value of \( r \) of -1 was obtained, which indicated a parameter similar to the Larson-Miller parameter; however, the corresponding value of \( T_a \) was 200° F rather than -460° F used in the Larson-Miller parameter. For steel C the value of \( R \) was 2.5.

Figure 1 shows the results for steel K. Here the master curve consists of a plot of stress against the optimized parameter \( (T - 300)/(\log t - 16.54) \).

Figure 2 shows the isothermals computed by using the optimized parameters, as shown on each of the figures. The range of the NASA data used to obtain these parameters is also shown on each of the figures. The data points shown are the German results obtained to date. The predictions up to 100 000 hours from the NASA data based on the optimized parameters agree well with the German data, if scatter and differences in testing technique between the two organizations are considered.

Figure 3 shows a comparison for each of the three steels between the best linear parameter, the best Larson-Miller parameter, and the best general parameter. Although for some of the steels fair agreement can be obtained with one or the other of these parameters, it is clear that the general parameter is superior when all the materials are considered jointly. If any one of the special cases of this parameter is to be chosen for all materials, the linear
Predicted German data above 5 hr

(a) Steel K \((27b\, KK)\); parameter, \(P = (\log t - 16.54)/(T - 300)\).

(b) Steel C \((23b\, CK)\); parameter, \(P = (\log t - 8.87)/(T + 100)^{2.5}\).

(c) Steel P \((14a\, PA)\); parameter, \(P = (T - 200)(\log t + 11.13)\).

Figure 2. - Analysis of German steel data by generalized parameter with optimum constants (where \(T\) is temperature, and \(t\) is time to rupture).

Temperature for German data above 5 hr, °F

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>932</td>
<td>□</td>
</tr>
<tr>
<td>1022</td>
<td>□</td>
</tr>
<tr>
<td>1112</td>
<td>□</td>
</tr>
<tr>
<td>1202</td>
<td>□</td>
</tr>
<tr>
<td>1292</td>
<td>□</td>
</tr>
</tbody>
</table>

(a) Steel K \((27b\, KK)\).

(b) Steel C \((23b\, CK)\).

(c) Steel P \((14a\, PA)\).

Figure 3. - Analysis of German steel data by several parameters (where \(T\) is temperature, and \(t\) is time to rupture).
Application to Creep Data

Although there is no fundamental reason why the same parameter is capable of representing both creep and rupture data, it has nevertheless been found empirically (refs. 1 and 2) that the dual role of the same parameter leads to reasonable results. Experimental data for creep are much more limited, however, than that for rupture, and such data tend to contain more scatter; hence, analysis of creep data by the parametric approach has been limited in the past.

The method of the present report can be applied directly to creep data without any change. All that is necessary is to redefine $t$ as the time to attain a specified amount of creep rather than as the rupture time. Thus, it is assumed that for a given amount of creep, say 1 percent, a plot of $\log \sigma$ against a parameter, such as that given by equation (1), will produce a single master curve. For a different amount of creep, say 5 percent, a different master curve can be obtained, but it is assumed that the parametric constants, such as $\log t_a$ and $T_a$, remain the same and that they equal the values obtained from rupture data.

Calculations of this type were performed for columbium alloy FS-85. The creep tests were limited to runs of approximately 1000 hours; the data are

![Graph showing creep data analysis for columbium alloy FS-85.](image)
given in table VII, as taken from reference 8. Figure 4(a) shows the data for 5-percent creep strain, and figure 4(b) shows the master curves obtained for 1-, 2-, and 5-percent strain as well as the parametric constants obtained by the method of this report. While scatter in the creep data is high, the correlation must be regarded as good. In general, the points agree well with the master curve.

Although these results are encouraging, much more work is necessary before it can be concluded that the parametric approach is completely valid for creep data. If it is eventually concluded that the parametric approach is valid for creep data and in particular that the parametric constants are the same for both the creep and rupture processes, it is obvious that a great saving in test facilities and test program planning will result. It therefore seems very worthwhile in future studies to give more attention to the correlation and extrapolation of creep data by the parametric method.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 3, 1965.
ORTHOGONAL POLYNOMIALS AND LEAST-SQUARES DETERMINATION
OF PARAMETRIC CONSTANTS

A set of polynomials $Q_j(x)$ are said to be orthogonal over an interval
with respect to the weighting function $\tau(x)$ if they satisfy the following
relation

$$\int_{x=x_1}^{x=x_2} \tau^2(x)Q_j(x)Q_k(x)dx = 0 \quad j \neq k \quad (A1)$$

Similarly a set of polynomials can be defined to be orthogonal over a set of n
discrete points $x_i$ by the following relation

$$\sum_{i=1}^{n} \tau_i^2 Q_j(x_i)Q_k(x_i) = 0 \quad j \neq k \quad (A2)$$

It can be shown (ref. 6), that all orthogonal polynomials satisfy a three-term
recurrence relation of the form

$$Q_{k+1} = (x - a_k)Q_k - \beta_k Q_{k-1} \quad k \geq 1 \quad (A3)$$

Thus by starting with $Q_1 = 1$ and $\beta_1 = 0$ an infinite set of orthogonal poly-
nomials can be generated by means of equation (A3) if values for $a_k$ and $\beta_k$
are known. These can be determined from the orthogonality conditions (eqs.
(A1) or (A2)). From the relation (A2) it follows that

$$\sum_{i=1}^{n} \tau_i^2 Q_k(x_i)Q_{k+1}(x_i) = 0 \quad (A4a)$$

and

$$\sum_{i=1}^{n} \tau_i^2 Q_{k+1}(x_i)Q_{k-1}(x_i) = 0 \quad (A4b)$$

When the recurrence relation (A3) is used to eliminate $Q_{k+1}$, there is obtained

$$\sum_{i=1}^{n} \tau_i^2 Q_k \left[ (x_i - a_k)Q_k - \beta_k Q_{k-1} \right] = 0 \quad (A5a)$$
When the orthogonality condition (A2) is used, equations (A5a) and (A5b) reduce to

\[ \sum_{i=1}^{n} \tau_i^2 (x_i - \alpha_k) Q_k^2 = 0 \]  \hspace{1cm} (A6a)

\[ \sum_{i=1}^{n} \tau_i^2 (x_i Q_k Q_{k-1} - \beta_k Q_{k-1}^2) = 0 \]  \hspace{1cm} (A6b)

Solving equations (A6) for \( \alpha_k \) and \( \beta_k \) gives

\[ \alpha_k = \frac{\sum_{i=1}^{n} x_i \tau_i^2 Q_k^2}{\sum_{i=1}^{n} \tau_i^2 Q_k^2} \]  \hspace{1cm} (A7a)

\[ \beta_k = \frac{\sum_{i=1}^{n} x_i \tau_i^2 Q_k Q_{k-1}}{\sum_{i=1}^{n} \tau_i^2 Q_{k-1}^2} \]  \hspace{1cm} (A7b)

Thus a set of orthogonal polynomials can be generated that are orthogonal over a finite set of discrete values of the variable \( x \). Note that these values need not be equally spaced, a condition that is obviously necessary for stress-rupture data.

Scaling of Polynomial Argument

From the recurrence relation (A3) with \( Q_1 = 1 \), it follows that the leading term of \( Q_{k+1}(x_i) \) is \( x_i^k \). Therefore, depending on the values of \( x_i \), the values of \( Q_{k+1}(x_i) \) can become very large or very small. This procedure can lead to a loss of significant figures in performing the calculations. It is shown in reference 7, by comparison with the Chebyshov polynomials, that if \( x \) is scaled so that all the values of \( X_1 \) lie between 2 and -2, the polynomial
values \( Q_j(X_i) \) will all be of approximately uniform size. To perform this scaling, let \( x_{\text{max}} \) be the maximum value of \( \log \sigma \) and \( x_{\text{min}} \) be the minimum value of \( \log \sigma \); then let

\[
X = A \log \sigma + B \quad (A8)
\]

\[
2 = A x_{\text{max}} + B \quad (A9a)
\]

\[
-2 = A x_{\text{min}} + B \quad (A9b)
\]

and solving for \( A \) and \( B \) results in equations (9b).

It has been found in practice that scaling the values of \( x \) as indicated does indeed preserve the significance of the calculations.

**Least-Squares Procedure**

In terms of the orthogonal polynomials, equation (3) can be written

\[
y = c^q y_a + \tau \sum_{j=1}^{m+1} u_j Q_j(X) \quad (A10)
\]

To find the best values of \( y_a \) and \( u_j \) that fit the data, the sum of the squares of the residuals is minimized. Thus let

\[
S = \sum_{i=1}^{n} \left[ y_i - c^q y_a - \tau \sum_{j=1}^{n} u_j Q_j(X_i) \right]^2 \quad (A11)
\]

Then in order to find the values of \( y_a \) and \( u_j \) that will make \( S \) a minimum, \( S \) is differentiated in turn with respect to \( y_a \) and each \( u_j \), and the resulting equations are set equal to zero. When this is done, the following set of equations is obtained:

\[
\begin{align*}
\sum a_0 y_a & + a_1 u_1 + a_2 u_2 + \ldots + a_{m+1} u_{m+1} = c_0 \\
a_1 y_a & + b_1 u_1 + 0 + \ldots + 0 = c_1 \\
a_2 y_a & + 0 + b_2 u_2 + \ldots + 0 = c_2 \\
& \vdots \ \vdots \ \vdots \\
a_{m+1} y_a & + 0 + 0 + \ldots + b_{m+1} u_{m+1} = c_{m+1}
\end{align*}
\]

(Al2)

where
\[ a_0 = \sum_{i=1}^{n} \sigma_i^2 q_i \]
\[ a_j = \sum_{i=1}^{n} \sigma_i q_i Q_j(x_i) \quad j = 1, 2 \ldots m + 1 \]
\[ b_j = \sum_{i=1}^{n} \tau_i Q_j^2(x_i) \quad j = 1, 2 \ldots m + 1 \]
\[ c_0 = \sum_{i=1}^{n} \sigma_i^2 \tau_i y_i \]
\[ c_j = \sum_{i=1}^{n} \tau_i y_i Q_j(x_i) \quad j = 1, 2 \ldots m + 1 \]

It is to be noted that the only nonzero elements in the coefficient matrix of equations (A12) are the diagonal elements and the elements of the first row and first column. All the other elements are zero because of the orthogonality properties of the polynomials used. This is one of the major advantages in using orthogonal polynomials. In the usual case of data fitting, all the elements of the first row and first column, except for the first element, would also be zero; and the equations would be completely uncoupled, each \( u_j \) being computed completely independent of the others, without the necessity of solving any sets of equations with the resultant loss of significant figures. In this particular case because of the added constant \( y_a \), the equations are not completely uncoupled, but they are very nearly uncoupled and can readily be solved. Thus for any equation after the first

\[ u_j = \frac{c_j - a_j y_a}{b_j} \quad (A14) \]

Substituting into the first equation and solving for \( y_a \) give immediately

\[ y_a = \frac{c_0 - \sum_{j=1}^{m+1} \frac{a_j c_j}{b_j}}{a_0 - \sum_{j=1}^{m+1} \frac{a_j^2}{b_j}} \quad (A15) \]
APPENDIX B

FORTRAN IV PROGRAM

$ID YAG1202 ERNEST ROBERTS, JR. - 140 M-S - PAX 6132
$LIBSIO CONTINUE
$IBJOU SOURCE
$IBFIC PRMTAL LIST,REF,DLCK
C CREEP/STRESS-RUPTURE PARAMETER PROGRAM
C
C NOMENCLATURE IS AS FOLLOWS
C
C DD STANDARD DEVIATION
C KK DEGREE OF FREEDOM
C KM NUMBER OF VALUES OF M READ
C KQ NUMBER OF VALUES OF Q READ
C KK NUMBER OF VALUES OF K READ
C KTA NUMBER OF VALUES OF TTA READ
C M DEGREE POLYNOMIAL
C N NUMBER OF DATA POINTS
C PP PARAMETER
C Q STRESS EXPONENT
C QQ POLYNOMIAL
C R TEMPERATURE EXPONENT
C RATU ABST-Y-Y1/DD
C SIGMA STRESS
C SIGQ SIGMA**Q
C T TIME
C TA TIME INTERCEPT
C TAU SIGMA**Q*(TT-TTA)**R
C TAUSR TAU**2
C TIME CALCULATED T (10.**YY)
C TT TEMPERATURE
C TTA TEMPERATURE INTERCEPT
C X LOG SIGMA
C Y LOG T
C YA LOG TA
C YY CALCULATED LOG T

C ALL QUANTITIES IN COMMON WITH THIS PROGRAM AND THIS PAPER
C ARE REPRESENTED BY THE SAME SYMBOL, WITH REPEATED
C LETTERS INDICATING THE UPPER CASE AND GREEK LETTERS BEING SUBLITTLE
C OUT.
C
C PROGRAM EXTRAPOLATES CREEP/STRESS-RUPTURE DATA USING A
C GENERALIZED PARAMETER
C
C \[ PP = (Y/\sigma^Q - Y) / (T - T_A)^R \]
C
C SELECTS PARAMETER PRODUCING SMALLEST RESIDUAL AND OUTPUTS A
C COMPLETE TABLE. RESULTS OF ALL OTHER VALUES ARE SUMMARIZED IN
C A SHORTER TABLE.

*************INPUT*************

C TITLE CARD - MODE CARD, AND FIVE (5) SETS OF DATA. AT THE END OF
C EACH SET OF DATA MUST BE A CARD WITH THE WORD 'END' IN THE FIRST
C THREE COLUMNS. ALL DATA CARDS (EXCEPTING TITLE AND MODE CARDS)
C MUST HAVE BLANKS IN THE FIRST THREE COLUMNS. COLUMNS 73-80 ARE
C IGNORED.
C
C TITLE - ANY ALPHAMERIC INFORMATION--HEADS EACH PAGE OF OUTPUT
C MODE CARD - ONE OF THREE WORDS IN COLUMNS 1-6, 'LARSON', 'LINEAR',
C OR 'GENERAL'. THIS CARD DEFINES 'KK', THE DEGREE OF
C FREEDOM, USED IN CALCULATING GOODNESS OF FIT.
C
C DATA SET 1--VALUES OF TTA TO BE INVESTIGATED--ONE PER CARD
C
PRMT 1
PRMT 2
PRMT 3
PRMT 4
PRMT 5
PRMT 6
PRMT 7
PRMT 8
PRMT 9
PRMT 10
PRMT 11
PRMT 12
PRMT 13
PRMT 14
PRMT 15
PRMT 16
PRMT 17
PRMT 18
PRMT 19
PRMT 20
PRMT 21
PRMT 22
PRMT 23
PRMT 24
PRMT 25
PRMT 26
PRMT 27
PRMT 28
PRMT 29
PRMT 30
PRMT 31
PRMT 32
PRMT 33
PRMT 34
PRMT 35
PRMT 36
PRMT 37
PRMT 38
PRMT 39
PRMT 40
PRMT 41
PRMT 42
PRMT 43
PRMT 44
PRMT 45
PRMT 46
PRMT 47
PRMT 48
PRMT 49
PRMT 50
PRMT 51
PRMT 52
PRMT 53
PRMT 54
PRMT 55
PRMT 56
PRMT 57
PRMT 58
FORMAT (3X, F10.0) -- 50 VALUES MAXIMUM

DATA SET 2 -- VALUES OF TEMPERATURE EXPONENT, R, TO BE INVESTIGATED
    UNE PER CARD -- FORMAT (3X, F10.0) -- 20 VALUES MAXIMUM
PRMT 90

DATA SET 3 -- VALUES OF STRESS EXPONENT, W, TO BE INVESTIGATED
    UNE PER CARD -- FORMAT (3X, F10.0) -- 20 VALUES MAXIMUM
PRMT 91

DATA SET 4 -- DEGREES OF POLYNOMIAL, M, TO BE INVESTIGATED
    UNE PER CARD -- FORMAT (3X, F10.0) -- 20 VALUES MAXIMUM
PRMT 93

DATA SET 5 -- DATA POINTS IN THE ORDER TEMPERATURE, STRESS, AND
    TIME -- UNE PER CARD -- FORMAT (3X, F10.0)
    THE VALUE OF STRESS IS AUTOMATICALLY DIVIDED BY 1000
    FOR ALL CALCULATIONS EXCEPT FINDING THE LOG STRESS.
PRMT 95

--- 400 SETS MAXIMUM.  ---
PRMT 97

*************** REPEAT ***************

EACH OF THE FIVE SETS OF DATA MUST BE FOLLOWED BY A CARD HAVING
THE WORD END IN THE FIRST THREE COLUMNS.
ALL DATA CARDS (EXCEPTING TITLE AND MODE CARDS) MUST HAVE THE
FIRST THREE COLUMNS BLANK.
WITHIN EACH SET, DATA MAY BE IN ANY ORDER. IT WILL BE PROCESSED
IN THE ORDER PRESENTED TO THE MACHINE.

THE CALCULATIONS ARE PERFORMED IN FOUR (4) LOOPS.
GOING FROM INFERIEST TO OUTERMOST, THE QUANTITIES ARE VARIED
IN THE FOLLOWING ORDER
    DEGREE POLYNOMIAL, M
    VALUE OF ETA
    TEMPERATURE EXPONENT, R
    STRESS EXPONENT, W

THE OUTPUT TABLES UTILIZE LESS THAN 120 COLUMNS ON THE PRINTER
AND EXPECT NO CARRIAGE CONTROLS OTHER THAN 1, 0, + AND BLANK.
A LINE COUNTER IS INCORPORATED TO LIMIT OUTPUT TO 60 LINES PER
PAGE. FOR EACH NEW PAGE THE TITLE AND APPROPRIATE COLUMN HEADINGS
ARE PRINTED. PROGRAM ENDS WITH A TRANSFER TO THE INITIAL READ.

PAGE COUNTING AND ERROR TRAPS MUST BE PROVIDED BY THE OPERATING
SYSTEM.

PROGRAM WITH 1BSYS AND IOC3M WILL RUN ON A 16K MACHINE

LOGICAL TRGR1, TRGR2, TRGR3

DIMENSION TITLE(12), TABLE(6, 110), ITABLE(6, 110)

EQUIVALENCE (TABLE(1, 1), ITABLE(1, 1))

COMMON / DATA/SIGMA(201), T(201), TT(201)
    / TRYS(M(21), J(51), R(51), TTA(51))
    / DATA/SIGMA(200), TAU(200), TAUQ(200), X(200), XX(200), Y(200)
    / CALC/PP(200), RATIO(200), TIME(200), YY(200)
    / ENO/LN/YN/YN/JO/JEGR/EDEG/DEG
    / PLYKLN/OTHER1(L/G211), Y, OTHER2(65)

INPUT

WRITE (6, 999)
READ (5, 9001) (TITLE(K), K=1, 12)
READ (5,9001) DEGREE
K = 0
10
K = K+1
READ (5,9002) CHECK,TTA(K)
   IF (CHECK.NE.END) GO TO 10
   KTA = K-1
   K = 0
15
K = K+1
READ (5,9002) CHECK,K(K)
   IF (CHECK.NE.END) GO TO 15
   KK = K-1
   K = 0
20
K = K+1
READ (5,9002) CHECK,Q(K)
   IF (CHECK.NE.END) GO TO 20
   KJ = K-1
   K = 0
25
K = K+1
READ (5,9003) CHECK,M(K)
   IF (CHECK.NE.END) GO TO 25
   KM = K-1
   K = 0
30
K = K+1
READ (5,9004) CHECK,TT(K),SIGMA(K),T(K)
   IF (CHECK.NE.END) GO TO 30
   N=K-1
C
  END OF INPUT
C
  FIND LOG STRESS AND LOG TIME
C
   UO 100  K=1,N
   X(K)=ALOG10(SIGMA(K))+3.
   Y(K)=ALOG10(T(K))
100
   CONTINUE
C
  INITIALIZE CONSTANTS
C
   UO1=1,E5
   LINES=51
   IRGDR3=.FALSE.
   NTRY=0
C
  SCALE LOGS OF STRESS
C
  CALL SCALE
C
  FIND HIGHEST DEGREE POLYNOMIAL
C
   MAX = 0
   UO 110  K=1,KM
   MAX = MAX(MAX,M(K))
110
   CONTINUE
C
  MAJOR LOOP - CALCULATES ALL Y(K)S AND RESIDUALS
         WRITES SUMMARY TABLE
         FINDS SMALLEST RESIDUAL
C
   UO 500  K5=1,KW
C
  CALCULATE SIGMA**Q
C
   UO 112  K1=N
   SIGMA(K)=SIGMA(K)**Q(K5)
112
   CONTINUE
   UO 400  K4=1,KK
C
CALCULATE TAU AND TAU**2
C
C
UD 300 K3=1,KTA
C
UD 120 K=1,N
IUIFF=ABS(T(IK)-TAU(K3))
IF (IUIFF) 116,115,118
115 TAU(K)=0.
UD TU 119
118 TAU(K)=SIGU(K)*IUIFF**2(K4)
119 TAUSQR(K) = TAU(K)**2
120 CONTINUE
C
C
EVALUATE POLYNOMIALS
C
CALL POLY(MAX)
C
UD 200 K2=1, KM
C
DETERMINE Y(I)
C
CALL YSUBA (M(K2))
C
CALCULATE THEORETICAL LOG TIMES AND TIMES
C
CALL YTH(M(K2))
C
COMPUTE RESIDUAL
C
CALL RESID(M(K2))
C
MAKE ONE ENTRY IN SUMMARY TABLE
C
NTRY=NTRY+1
TABLE(I,NTRY)=w(K5)
TABLE(2,NTRY)=r(K4)
TABLE(3,NTRY)=M(K2)
TABLE(4,NTRY)=ITAI(K3)
TABLE(5,NTRY)=YA
TABLE(6,NTRY)=DD
TRGCR2=NTRY,EO.2,LINES
IF (TRGCR2) UD TU 170
GO TU 190
C
C
OUTPUTS ONE PAGE OF SUMMARY TABLE
C
C
OUTPUT TITLE AND HEADINGS FOR SUMMARY TABLE
C
C
WRITE (6,9005) (TITLE(K),K=1,12),DEGRF
IF (LISTS.EQ.51) WRITE (6,9006) KTA,KR, KU, KM,
WRITE (6,9007)
TRGCR1=NTRY.LE.LINES
LIMIT=LINES
IF (TRGCR1) LIMIT=NTRY
UD 180 K=1, LIMIT
WRITE (6,9008) (TABLE(I,K),I=1,2),ITABLE(3,K), (TABLE(I,K),I=4,6)
IF (TRGCR1) UD TU 180
KUL2=K+LINES
IF (TRGCR2) UD TU 175
IF (KUL2.GT.NTRY) UD TU 180
175 WRITE (6,9009) (TABLE(I,KUL2),I=1,2), ITABLE(3,KUL2),
L (TABLE(I,KUL2),I=4,6)
180 CONTINUE
NTRY=0
LINES=55
IF (TRGR3) GU TO 1000
C
SAVE VALUES PRODUCING SMALLEST RESIDUAL
C
190 IF (DD1.LE.0.0) GU TO 200
ML = M(K2)
TTA1 = TTA(K3)
R1 = R(K4)
Q1 = Q(K5)
YAI = YA
UD1 = DU
200 CONTINUE
300 CONTINUE
400 CONTINUE
500 CONTINUE
TRGR3 = .TRUE.
IF (NTKYE .NE. 0.0) GU TO 170
C
END MAJOR LOOP
C
OUTPUT OPTIMUM VALUES AND HEADING FOR FULL TABLE
C
1000 CONTINUE
1010 WRITE (6,9005) (TITLE(K),K=1,12),DEGREE
LINES = 5
1020 WRITE (6,9010) Q1, R1, M1, TTA1, YA1, DU1
LINES = LINES + 5
1030 WRITE (6,9011) LINES = LINES + 3
C
CALCULATE THEORETICAL TIMES, RATIOS OF DIFFERENCE, TO RESIDUAL, AND VALUES OF THE PARAMETER, FOR THE PARAMETER PRODUCING THE MINIMUM RESIDUAL
C
UG 1035 K = 1, N
TDIFF = ABS(TT(K) - TTA1)
SIGW(K) = SIGMA(K) * Q1
IF (TDIFF) 1032, 1031, 1032
1031 TAU(K) = 0.
UG TO 1034
1032 TAU(K) = SIGW(K) * TDIFF**K1
1034 TAU = TAU(K)**2
1035 CONTINUE
UD = DU1
CALL PULY(M1)
CALL YSUBA(M1)
CALL Y1H(M1)
CALL RAT101
CALL PARAM
C
OUTPUT FULL TABLE
C
K = 0
1040 K = K + 1
WRITE (6,9012) TT(K), SIGMA(K), X(K), T(K), TIME(K), Y(K), YY(K), 1
RAT1U(K), PP(K)
LINES = LINES + 1
IF (K.EQ.N) GU TO 1
IF (LINES .LT. 60) GU TO 1040
WRITE (6,9005) (TITLE(KKK), KKK =1,12), DEGREE
WRITE (6,9011)
LINES = 6
UG TO 1040
C
END OF PROGRAM
C
C FORMAT STATEMENTS FOR PROGRAM
C FORMATS FOR INPUT
C
9001 FORMAT (12A6)
9002 FORMAT (A3,F10.0)
9003 FORMAT (A3,12)
9004 FORMAT (A3,DPF10.0,3PF10.0,DPF10.0)
C FORMATS FOR OUTPUT
C
9005 FORMAT (1H1,20X,12A6/1H ,30X,A6,10H PARAMETER/1H)
C SUMMARY OF INPUT
C
9006 FORMAT (1H ,10X,45H RIP/EXP/RUPTURE PARAMETERS ARE INVESTIGATED FOR/ 11H ,12,18H VALUE(S) OF T(A),,I3,25H TEMPERATURE EXPONENT(S),,I3, 224H STRESS EXPONENT(S), AND ,I3,14H POLYNOMIAL(S)/1H ,10X,36H WISCH, 314,12H DATA POINTS/1H)
C HEADINGS FOR SUMMARY TABLE, ONE LINE OF SUMMARY TABLE
C
9007 FORMAT (1H ,2(2X,14H4,7X,1HR,6X,1HM,5X,4H(A),,5X,4HY(A),,4X, 1 8HSTU.DEV.,10X)/1H)
9008 FORMAT (1H ,0PF5.2,+8.2,15,F9.0,F10.2,1PE11.2)
9009 FORMAT (1H+,38X,0PF5.2,8.2,15,F9.0,F1C.2,1PE11.2)
C UPTIMUM VALUES
C
9010 FORMAT (1H10X44H VALUES PRODUCING SMALLEST STANDARD DEVIATION/3H0=PRMT
1F5.2,4H, R=F5.2,4H, M=I2,7H, T(A)=F6.0,7H, Y(A)=F9.3,11H, STU.DEV,PRMT
2=1PE9.2/1H0)
C HEADINGS FOR FULL TABLE, ONE LINE OF FULL TABLE
C
9011 FORMAT (5H TEMP,4X,6HSTRESS,3X,3HLLOG,6X,4HTIME,5X,6HCALLID,5X, 13HLLOG,3X,8HMCALC LOG,2X6HJEV/5D,3X9HPARAMETER/1H ,5X,6H(*-3),2X, 26HSTRESS,14X,4HTIME,5X,4HTIME,4X4HTIME/1H)
9012 FORMAT (1H ,0PF5.0,F8.1,F8.3,2F1C.1,3F9.3,1PF12.3)
C
9999 FORMAT (1H1)
C END
$SIBFIC PRMBLK LIST,REF,DECK
C SETS FIRST POLYNOMIAL TO UNITY AT ALL STATIONS AND STORES
C ALPHAMERIC CODE WORDS
C

BLOCK DATA
COMMON /PLYNML/QQ(21,200),OTHERS(85)/END/END/NAMES/NAMES(2)
DATA (QQ(I,K),K=1,200)/200*1.,/END/3HEND/,
1 /NAMES(K),K=1,2/12HLARSONLINEAR/
END
PRMB 1
PRMB 2
PRMB 3
PRMB 4
PRMB 5
PRMB 6
PRMB 7
PRMB 8

$SIBFIC PARM LIST,REF,DECK
C SUBROUTINE FOR EVALUATING THE PARAMETER AT EACH POINT
C

SUBROUTINE PARAM
COMMON /FDATA/SIGQ(200),TAU(200),OTHERS(600),Y(200)
1 /CALC/PP(200),OTHER1(600)/N/N
2 /PLYNML/OTHER2(4221),YA,OTHER3(63)

UO 10 K=1,N
PP(K) = (Y(K)-SIGQ(K)*YA)/TAU(K)
CONTINUE
RETURN
END
PRAM 1
PRAM 2
PRAM 3
PRAM 4
PRAM 5
PRAM 6
PRAM 7
PRAM 8
PRAM 9
PRAM 10
PRAM 11
PRAM 12
PRAM 13

$SIBFIC YTH LIST,REF,DECK
C SUBROUTINE FOR CALCULATING TIMES AND LOG TIMES FROM THE PARAMETER YTH
C

SUBROUTINE YTH(M)
COMMON /CALC/OTHERS(400),TIME(200),YY(200)
1 /FDATA/SIGQ(200),TAU(200),OTHER1(800)
2 /PLYNML/QQ(21,200),U(21),YA,OTHER2(63)

UO 10 K=1,N
YY(K) = 0.
M1 = M+1
UO 30 K=1,N
UO 20 J=1,M1
YY(K) = YY(K)+QO(J,K)*U(J)
CONTINUE
YY(K) = TAU(K)*YY(K)+SIGQ(K)*YA
TIME(K) = 10.*YY(K)
CONTINUE
RETURN
END
YTH 1
YTH 2
YTH 3
YTH 4
YTH 5
YTH 6
YTH 7
YTH 8
YTH 9
YTH 10
YTH 11
YTH 12
YTH 13
YTH 14
YTH 15
YTH 16
YTH 17
YTH 18
YTH 19
YTH 20
YTH 21
YTH 22
SUBROUTINE FUR CALCULATING RATIOS

COMMON /FDATA/Others(1000),Y(200)
1 /CALC/Others1(200),Ratio(200),Others2(200),YY(200)
2 /N/N/DD/DD

DO 10 K=1,N
   Ratio(K) = ABS(Y(K)-YY(K))/DD
10 CONTINUE
RETURN

SUBROUTINE RESID(M)

COMMON /FDATA/Others(1000),Y(200)
1 /CALC/Others1(600),YY(200)
2 /DD/DD/N/N/DEGREE/DEGREE/NAMES/FAMES(2)

IF (DEGREE.EQ.FAMES(2)) GO TO 20
IF (DEGREE.EQ.FAMES(1)) GO TO 10
   KK = 5
      GO TO 30
10   KK = 2
      GO TO 30
20   KK = 3
30   D = N-M-KK
   DD = 0.
      DO 40 K=1,N
         DD = DD+(Y(K)-YY(K))**2
40   CONTINUE
   DD = SQRT(DD/D)
RETURN
END
SUBRFTC  YSUBA  LIST,REF,DECK
C SUBROUTINE FOR EVALUATING Y(AM)
C THIS SUBROUTINE ALSO EVALUATES THE QUANTITIES, u, NECESSARY
C FOR DETERMINING THE THEORETICAL LOG TIMES.
C SUBROUTINE YSUBA(M)
C
COMMON /PLXMYL/ U(I,21),V(I,21),YA,AT(21),BT(21),CT(21),
1 /FDATA/SIGU(200),TAU(200),TAUSQR(200),OTHERS(400),
2 Y(200)/ N/N

C
AO = 0.
CO = 0.
DO 10  K=1,N
AO = AO+SIGU(K)**2
CO = CO+SIGU(K)*Y(K)
10 CONTINUE
M1 = M+1
DO 20  J=1,M1
A(J) = 0.
B(J) = 0.
C(J) = 0.
20 CONTINUE
DO 40  J=1,M1
DO 30  K=1,N
A(J) = A(J)+SIGU(K)*TAU(K)*SIGU(J,K)
B(J) = B(J)+TAUSQR(K)*SIGU(J,K)**2
C(J) = C(J)+TAU(K)*Y(K)*SIGU(J,K)
30 CONTINUE
40 CONTINUE
SUM1 = 0.
SUM2 = 0.
DO 50  J=1,M1
AOB = A(J)/B(J)
SUM1 = SUM1+AOB*C(J)
SUM2 = SUM2+AOB*A(J)
50 CONTINUE
YA = (CO-SUM1)/(AO-SUM2)
DO 60  J=1,M1
U(J) = (C(J)-A(J)*YA)/A(J)
60 CONTINUE
RETURN
END
SUBROUTINE FOR EVALUATING ORTHOGONAL POLYNOMIALS

ALL POLYNOMIALS UP TO MAXIMUM DESIRED DEGREE ARE EVALUATED AT EACH DATA POINT

THE FIRST POLYNOMIAL IS IDENTICALLY EQUAL TO UNITY

THESE VALUES ARE STORED BY A BLOCK DATA SUBROUTINE

SUBROUTINE POLY(M)

COMMON /FDATA/OOTHER1(400),TAUSQR(200),OTHER2(200),XX(200), UTHR3(200)
2 /PLYNL,QQ(21,200),OTHERS(45),ALPHA(20),UTHER1(200)
3 /N/N

S1 = 0.
S2 = 0.
S1 = S1+XX(K)*TAUSQR(K)
S2 = S2+TAUSQR(K)
CONTINUE

ALPHA(I) = S1/S2
S1 = S1+XX(K)*TAUSQR(K)
S2 = S2+TAUSQR(K)
CONTINUE
IF (M+1) RETURN
S1 = 0.
S2 = 0.
S3 = 0.
S4 = 0.
S1 = S1+XX(J)*QQ(J,K)
S2 = S2+QQ(J,K)
S3 = S3+XX(J)*QQ(J,K)
S4 = S4+QQ(J,K)
CONTINUE
ALPHA(K) = S1/S2
BETA(K) = S3/S4
QQ(K+1,J) = (XX(J)-ALPHA(K))*QQ(K,J)-BETA(K)*QQ(K-1,J)
CONTINUE
RETURN
END
SUBROUTINE FOR SCALING LOGS OF STRESS

THE SCALED VALUES LIE IN THE REGION -2 TO 2

COMMON /DATA/OTHER1(600),XX(200),OTHER2(200)/N/N

BIG = 0.
SMALL = 1.E5

BIG = AMAX1(BIG,X(K))
SMALL = AMIN1(SMALL,X(K))

CONTINUE
A = 4./(BIG-SMALL)
B = 2.*(BIG+SMALL)/(BIG-SMALL)

CONTINUE
RETURN
END

SCALE 1
SCALE 2
SCALE 3
SCALE 4
SCALE 5
SCALE 6
SCALE 7
SCALE 8
SCALE 9
SCALE 10
SCALE 11
SCALE 12
SCALE 13
SCALE 14
SCALE 15
SCALE 16
SCALE 17
SCALE 18
SCALE 19
SCALE 20
SCALE 21
REFERENCES


### Table I. - Calculation of Polynomials for Theoretical Data for Third Degree Polynomial

<table>
<thead>
<tr>
<th>Index, i</th>
<th>Temperature, $T_i$, °F</th>
<th>Time, $t_i$, hr</th>
<th>Stress, $\sigma_i$, psi</th>
<th>$\log t_i$</th>
<th>$\log \sigma_i$</th>
<th>$\sigma^4(T-T_a)$</th>
<th>Scaled $\sigma^4(T-T_a)$</th>
<th>Polynomial</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1100</td>
<td>4354.68</td>
<td>56 300</td>
<td>3.69501</td>
<td>4.75051</td>
<td>500</td>
<td>2.0</td>
<td>$Q_1$</td>
</tr>
<tr>
<td>2</td>
<td>1100</td>
<td>11385.9</td>
<td>19 800</td>
<td>4.05560</td>
<td>4.29666</td>
<td>500</td>
<td>1.5806</td>
<td>$Q_2$</td>
</tr>
<tr>
<td>3</td>
<td>1200</td>
<td>673.342</td>
<td>30 300</td>
<td>2.73612</td>
<td>4.46144</td>
<td>600</td>
<td>1.6329</td>
<td>$Q_3$</td>
</tr>
<tr>
<td>4</td>
<td>1200</td>
<td>2305.9</td>
<td>5 090</td>
<td>3.46539</td>
<td>3.70886</td>
<td>600</td>
<td>0.5743</td>
<td>$Q_4$</td>
</tr>
<tr>
<td>5</td>
<td>1300</td>
<td>117.731</td>
<td>12 900</td>
<td>2.06965</td>
<td>4.11059</td>
<td>700</td>
<td>1.1267</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
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### Table II. - Intermediate Calculations for Theoretical Data for Third Degree Polynomial

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<th>$c$</th>
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(Temperature intercept, $T_a$, 600° F.)
TABLE III. - FIT FOR SEVERAL VALUES OF LINEAR PARAMETER FOR THEORETICAL DATA

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<th>Deviation</th>
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TABLE IV. - COMPOSITION OF STEELS RECEIVED FROM GERMAN COOPERATIVE LONG-TIME CREEP PROGRAM

[As-received, 20-mm-diam. bar stock.]

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<th>Element</th>
<th>Composition, percent</th>
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<td></td>
<td>C (23b CK)</td>
</tr>
<tr>
<td></td>
<td>P (14a PA)</td>
</tr>
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<td></td>
<td>K (27b KK)</td>
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<td>Molybdenum</td>
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<td>Columbium and tantalum</td>
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**TABLE V. - NASA MAPPÉE DATA**

*(a) Steel K (27b KK)*

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<th>Time, t, hr</th>
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<th>Stress, σ, psi</th>
<th>Time, t, hr</th>
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(b) Steel C (25b CK)

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aData point used in parametric analysis.
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<th>Time, ( t ), hr</th>
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*Data point used in parametric analysis.*
### TABLE VI. - GERMAN RUPTURE DATA

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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