ing in terms of rupture time or creep rate. An indication of the importance of the observed scatter may be had by determining at any one temperature the change in \( \log t \) or \( \log r \) for any range in the parameter at a constant stress level. Thus, differentiating relation [1] for constant temperature, one obtains

\[
\frac{d \log t}{T} = \frac{\alpha}{\beta} \tag{13}
\]

For the data examined, \( \alpha \) is of the order of 20. It is determined readily from Fig. 1 that a range of \( \Delta x/\alpha \) = 0.5 is not unusual. It follows therefore that even within a limited range of stress, relation [1] may lead to large errors when dealing with rupture times beyond \( 10^3 \) hr. A similar analysis applies in the case of creep rates less than \( 10^{-2} \) sec\(^{-1} \) where \( \alpha' \) is of the order of 30. 

Upon differentiating relation [2] at constant temperature it is found that

\[
\frac{d \log t}{\beta} = \left( \frac{\log \alpha - \log \xi}{\log A - \log \xi} \right) d\beta \tag{14}
\]

In this case, however, the error in interpolating rupture times is not excessive unless rupture times beyond about \( 3 \times 10^3 \) hr are encountered. This is estimated by assuming, for the steels discussed here, a value of 0.2 for

\[
\left( \frac{\log \alpha - \log \xi}{\log A - \log \xi} \right)
\]

and a range in \( \beta \) of about 1.3 at constant stress. Errors of several factors may be encountered under these conditions for rupture times in excess of approximately \( 3 \times 10^3 \) hr.

**SUMMARY**

In this paper the use of three different time-compensated temperature parameters in correlating creep-rupture results is discussed, and it is shown that the existence of a single-valued time-temperature function or the existence of a master curve relating rupture stress to these parameters is doubtful. A similar but shorter analysis of the creep problem leads to the same conclusion. In the light of these observations it is believed that an entirely new and more fundamental experimental approach is necessary to provide information which may indicate correlations between creep and creep-rupture properties determined under various conditions of initial stress and temperature. Such tests should include determination of the reproducibility of the experimental measurements so that the significance of any observed correlation can be established.

Whereas the results reported herein disprove the strict validity of the various parameters that have been suggested, it should not be concluded that parameter techniques are without value. In fact, they furnish an excellent means of summarizing many data in convenient form for purposes of comparison and, when judiciously used, yield valuable predictions. However, they should be used for this latter purpose only with a realization of the magnitude of the possible errors.

**BIBLIOGRAPHY**


**Discussion**

S. S. MANSON\(^*\) AND W. F. BROWN, JR.\(^*\) The writers regret to state that they do not agree with the authors either on the criterion used for checking the validity of time-temperature parameters nor with their conclusions. In addition, the writers wish to point out several technical inaccuracies.

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In the Introduction the authors state that in all previous evaluations “master curves” have been relied upon to prove the validity of the proposed parameter even though adequate empirical relations are available for a more rigorous analytical check.

The adequate empirical relations referred to by the authors are presumably based on representation of isothermal behavior by two intersecting straight lines. The approach used by Manson and Haferd in the authors’ reference (2) was decidedly not a reliance on master curves. It was recognized that small displacements of data points from the master curve could represent large errors in rupture time. The criterion used to establish the validity of the correlation was to use the master curve to reconstruct isothermal curves on a conventional log $\sigma$ versus log $t$ plot. The time errors were then seen directly by comparing the experimental data points with the calculated curves. Fig. 9 of this discussion illustrates the approach for DM steel. Each isothermal, it will be noted, was represented by the publisher (“Timken Digest for High Temperature Steels”) by two straight-line segments. The master curve is shown in the center of the figure. By assigning fixed values of temperature, the master curve was then used to reconstruct isothermals, as shown at the right in Fig. 9. The true measure of the extent of “correlation” is now seen as the deviations between the solid curves and the data points. These deviations are well within the limits of data scatter. The writers have analyzed suitable data for over 50 materials in the same manner as shown for DM steel.

Fig. 9 also serves to point out that the original stress-rupture data are equally well represented by a family of continuous curves as by a family in which each member consists of two straight lines. Although it has been common practice to draw isothermal stress-rupture curves as straight-line segments, this property has no basic significance. It is the writers’ belief—and convincing arguments could be brought to bear on this point—that the best representation of isothermals is not by straight lines. However, the pertinent point here is that the criterion of straightness cannot be used as the critical test of the validity of time-temperature parameters.

The authors would have presented a better case for the Manson-Haferd parameter if they had made proper selection of $T_a$ and $\log t_a$ for all their alloys. Of the five materials analyzed in this paper, the poorest correlations obtained by the authors are for steels G29 and T37. For both materials, they have selected negative values of $\log t_a$. Negative values of $\log t_a$ have never been encountered by the writers. A reanalysis of these two steels is shown in Figs. 10 and 11 of this discussion. Each of these figures shows the authors’ master curve, the master curve using new values of $T_a$ and $\log t_a$ and the isothermals derived from the new master curves. The new master curves now agree much better with the data, and if desired may be represented by two straight-line segments. Likewise the isothermals calculated using these master curves agree satisfactorily with the experimental data. This agreement is not construed as proof of the validity of the Manson-Haferd parameter but rather as evidence that these materials cannot be used to disprove its validity.

Convincing proof of validity of the Manson-Haferd parameter requires consideration of materials for which a large number of isothermal data is available (as presented in the authors’ reference 2). However, preferably the analysis should make use of constant nominal-stress data. Such data directly check the assumptions inherent in the parameter. A series of critical constant stress...
experiments on five materials were not mentioned by the authors. Fig. 12 of this discussion illustrates the constant stress results for DM steel. The solid lines represent correlation of the data by the linear parameter, and the agreement with the data points is seen to be very good. An attempt to correlate the data by other parameters, such as those of Larson-Miller and Dorn, led to considerable discrepancies. These critical tests may, in some measure, satisfy the need indicated by the authors in their Summary for a more fundamental experimental approach which may indicate correlations between creep-rupture properties, initial stress, and temperature.

The authors have attempted to provide some guidance to the reader as to the quantitative error in rupture time involved in each of the parameters. As already pointed out, their selection of values of $T_a$ and $\log t_a$ were not such as to produce the best correlation; however even using their analysis of errors, it is difficult to accept their conclusion. For

$$\log t_a - \log t = \frac{0.2}{\beta}$$

and for a range in $\beta$ of 1.3, as assumed by the authors, Equation [14] of the paper leads to the conclusion that the ratio between the experimental rupture time and the rupture time as indicated by the master curve is 1.8, independent of the rupture time (that is, it is no greater at times in excess of $3 \times 10^4$ hr than in any other time range). It is thus difficult to see how the authors conclude that errors of several orders of magnitude are involved at times in excess of $3 \times 10^4$ hours.

The authors throw doubt on the validity of the Manson-Haferd parameter by stating that a material would not exhibit stress-rupture properties at the point $(T_m, \log t_m)$. In reference (2) of the paper the following is carefully pointed out: "The point $(T_m, \log t_m)$ is not considered to have physical significance; it is considered only to be the point of convergence of the tangents to the curves of $\log t$ against $T$ in the time range from approximately 10 to 10,000 hr. Since there is relatively little curvature in this time range, the tangents represent a good approximation to the experimental curves, but no conclusions can be drawn about the linearity in longer time ranges." In the vicinity of $\log t_m$ the rupture time for all materials investigated is well over 1000 years. In the reference the possibility of curvature of constant stress lines even within the experimental time range is also considered, and a general method of data correlation is suggested when such curvature is noted. Manson and Haferd (2) and Manson and Brown also recognize the possibilities of anomalous behaviors in certain ranges of the variables. Thus, for example, it is pointed out that the linear parameter may not be applicable where major metallurgical transformations take place. Likewise, it is pointed out that 16-13-3 steel shows unusual curvature in a very limited temperature range. Very few such anomalies have been found for the materials, times, and temperature investigated. To define the limitations of the parameter we are presently investigating various materials over very wide ranges of stress and temperature.

The authors state that the usefulness of the Manson-Haferd parameter is limited by the large number of data necessary to evaluate the material constants. In our experience not more than 20 tests having an average duration of about 50 hr will establish the entire master curve for a given material. This represents 1000 hr of test time, about the same amount of time as is necessary to establish a single isothermal between 0.1 and 1000 hr by direct testing.

The authors in the body of their paper certainly paint a very dark picture of the validity of the various parameters. Their conclusion is in rather surprising contrast and emphasizes that, when judiciously used, the parameters yield valuable predictions. Some clarification would appear necessary as the "judicious use" of these parameters.

J. Miller. The authors have analyzed the parameter $T(C + \log t)$ and two other time-temperature parameters for correlating creep and rupture data. As a result of their analysis, they conclude that the validity of these parameters over wide ranges of variables is doubtful.

The paper is correct in implying that significant errors can result from injudicious use of time-temperature parameters. We agree that the relation expressed by the parameter $T(C + \log t)$ is not precise over large ranges of variables. In other words, 10,000-hr data cannot be predicted from 10-hr data in all cases with high accuracy.

However, by proper use of this parameter, extremely valuable predictions can be made. As an illustration, in the accompanying Table 3, 10,000-hr rupture data reported in the U. S. Steel Bulletin on "Steels for Elevated Temperature Service" are compared with predicted values. The predicted values were obtained by plotting the 1000-hr strength as a function of $T(20 + \log t)$ and reading the 10,000-hr points from the resulting "master curves." In most cases the two values agree within experimental error although in some cases the difference is somewhat larger than normal experimentalscatter.

To obtain these data by the conventional method of extrapolating a log-log plot, a minimum of four or five specimens and

11 The DM steel reported in Fig. 12 of this paper is of somewhat different composition from that of Fig. 9 and consequently the stress-rupture properties of these two heats are different.
12 Reference (2) of paper, p. 5.
13 Thomson Laboratory, Small Aircraft Engine Department, General Electric Company, West Lynn, Mass.
about 4000 hr of testing time would be required for each material and temperature. In this example, the parameter method would therefore effect a saving of four to one in time.

It has been our experience in examining data on all types of alloys ranging from aluminum and magnesium to nickel and cobalt base that the parameter method will give more accurate results for equivalent testing times or that equivalent accuracy can be obtained with shorter times as compared with the log-log extrapolation method.

**Authors' Closure**

The discussions of Messrs. Manson and Brown and Mr. Miller are particularly welcome because of the association of these discussers with the procedures considered in the paper.

The initial point raised by Messrs. Manson and Brown, indicating that the validity of the linear parameter was investigated beyond the establishment of a master curve, is somewhat misleading. For example, the master curve for Steel DM in Fig. 9 shows that in only very few instances is more than one experimental point available at any stress level. The calculation of the log-stress log-rupture time curves from the master curve therefore depends entirely on interpolation. Reducing this procedure to its simplest form, it amounts to the calculation of a log-stress log-rupture time curve from each individual segment. It would seem that verification of the linear parametric procedure should be based on extensive extrapolations in both time and temperature. Our results clearly show that extrapolation over wide, but practical, limits in time and temperature leads to serious errors for the steels included in this paper.

The statement in the second point asserting that the criterion of straightness cannot be used in testing the validity of time-temperature parameters is, per se, meaningless without substantiation. It is commonly accepted for steels as well as many other materials that log-stress log-rupture time results can be satisfactorily approximated by straight line segments. It should be pointed out that one advantage of using straight line segments is that a simple linear relation between log stress and log rupture time can be easily obtained. Because creep and rupture at elevated temperatures are extremely complex phenomena, relationships between stress and rupture time cannot as yet be derived from purely fundamental concepts. Under such conditions as these it is generally accepted that empirical relations giving good agreement be employed. It should be pointed out, after all, that the parametric relation proposed by Manson and Haferd is empirical in nature.

It is stated by Messrs. Manson and Brown, in the third point raised, that proper selection of $T_a$ and log $\log_2 T_a$ were not made for steels G20 and T37. The procedure employed in determining the constants for these two steels was exactly the same as that employed for the other three steels and is completely discussed in the paper. It is regrettable, however, that Messrs. Manson and Brown did not describe briefly the procedure employed by them in obtaining the new constants which reduced the scatter somewhat in the master curves in Figs. 10 and 11 for these two steels. This point is somewhat disturbing because it seems that a great deal of experience is necessary to determine the proper material constants. Yet, according to Messrs. Manson and Brown in their closing discussion of their paper they state, “The selection of a point of intersection has not been found to be critical or to require great experience.” To pursue this point further, it may be observed from relation [8] in this paper that the slopes and intercepts of the line segments within the master curve depend on $T_a$ and log $\log_2 T_a$. It would seem then that if one could in some way determine the proper combination of $T_a$ and log $\log_2 T_a$, this should result in the least scatter in the master curve. The procedure for obtaining the optimum combination of the material constants is as yet obscure. This statement is made because, according to Manson and Haferd, the success of the linear parametric procedure for purposes of
extrapolation depends on the proper combination of $T_a$ and log $t_a$ rather than on the individual value of these constants. They even go so far as to suggest that a single value of $T_a$ be used for all materials. This suggestion, of course, cannot be taken seriously because for the two different heats of steel DM discussed by Messrs. Manson and Haferd, the computed values of $T_a$ differ a great deal.

In a paper by Manson and Succop, they test results are presented in a plot of log rupture time against the temperature that indicate that the resulting straight lines are essentially parallel. The results employed in obtaining the straight lines include rupture times between 0.3 and 1819 hours. However, Mr. Manson and his co-workers have stated in each of their publications that because of divergence in the region of low rupture times, the material constants should be determined from experimental data in which rupture times below about 30 hours should be omitted. The results of Manson and Succop have been replotted and are shown in Fig. 13, but in order to retain sufficient experimental points, only data in which the rupture time was below 12 hours rather than 30 hours was omitted. One set of experimental points for a stress of 5000 psi was omitted entirely because only three experimental points remained. The results in Fig. 13 show that the straight lines converge at a negative value of log $t_a$ and further point to the fact that negative values of log $t_a$ are encountered in materials other than steels. Since, as pointed out by Manson and Haferd, the experimental points in plots of log $t$ against temperature are only approximately linear between 10 and 10,000 hours, the straight lines, which converge at the point $(T_a, \log t_a)$ are constructed as tangents to the experimental curves. Thus the location of the convergence, that is, whether log $t_a$ is positive or negative, depends on the type divergence from linearity of the experimental curves.

The results of Manson and Brown and Manson and Succop indicate that there is no set pattern to the type of divergence which may occur.

The fourth point raised by Messrs. Manson and Brown concerns the error encountered with the linear parameter within small ranges in stress for rupture times greater than $3 \times 10^4$ hours. The error encountered is of the order of several factors, as stated in the paper, and not of several orders of magnitude as stated in the preprint of this paper.

The next point raised by Messrs. Manson and Brown is of some importance because it throws some light on some limitations of the linear parametric procedure. If the point $(T_a, \log t_a)$ is not significant stresswise for values of $T_a$ within the creep range of temperatures, it follows that the experimental log $t$-temperature curves diverge from linearity at low values of rupture times. For some materials this divergence is found to occur appreciably below 1000 hours. It is then reasonable to state that for all materials which are investigated, the point of divergence should be established with certainty before attempting extrapolations. Mr. Manson and his co-workers have stated that little divergence from linearity is found for the log $t$-temperature curves in the approximate range between 10 and 10,000 hours. However, of all of the results published by Mr. Manson and his co-workers, the experimental results seem to seldom exceed 3000 hours. It would seem that the implication that the linear parameter can be used for extrapolations to 10,000 hours from short time results is not substantiated and requires more extensive proof. Any further light thrown on this point by the investigation now being conducted by Messrs. Manson and Brown will be received with interest.

The next point relating the necessary amount of testing to establish the material constants has in the past been of some concern to Messrs. Manson and Haferd. They have suggested that a single value of $T_a$ be used for all materials to reduce the amount of testing. Of greater importance is the fact, however, that the establishment of the so-called master curve gives very little indication of the limits within which extrapolations can be attempted, for example, the limitation imposed by divergence in the log $t$-temperature plot. To define these limitations for each new material more than 30 tests are indicated.

Concerning the final point raised by Messrs. Manson and Brown, it must be re-emphasized that the purpose of the present paper is to point out various limitations of the parametric procedures as well as to indicate some of the inconsistencies which exist among the parameters proposed. Our findings show that over practical ranges in stress or temperature, parametric procedures encounter serious limitations for purposes of extrapolation. For example, the use of the linear parameter for purposes of extrapolation, even over small ranges in stress and over a range of only several hundred degrees in temperature, results for the steels investigated in this paper to errors in rupture time of several factors of magnitude when rupture times greater than $3 \times 10^4$ hours are encountered. That parametric procedures have limitations is substantiated by the statement of Messrs. Manson and Brown in the authors' closure of their paper. They state, "The authors wish to emphasize that they feel none of the parameters so far presented, including their own, can truly represent the basic behavior of a complex alloy (such as a low-alloy steel) over extremely wide ranges of both time and temperature. It must be realized that the conception of a correlating parameter in the relatively simple forms thus far proposed is at best a tool which can permit the shortening of stress rupture testing times in ranges of practical application."

One application in which parametric procedures have been

![Fig. 13 Relationship Between the Logarithm of the Rupture Time and Temperature for Various Constant Initial Stresses (After Manson and Succop.)](image-url)
found particularly useful has been the summarizing of creeprupture results for purposes of comparison. Thus, for example, the Larsen-Miller parameter has been used to determine the approximate merits for high-temperature application of various alloys by comparing the master curves on a single plot. Such a procedure can also be used to determine the optimum heat-treatment for individual alloys. In using such procedures, there should be no attempt, however, to use such comparisons for predicting behavior over large ranges in time, stress, or temperature from limited results.

The authors agree with Mr. Miller that from a practical viewpoint, proper usage of parametric procedures as stated in the foregoing leads to useful approximate predictions. If the use of parametric procedures decreases the testing time, and, of course, this may depend on the approximate predictions desired, this fact is of importance from the practical viewpoint.