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**ELEVATED-TEMPERATURE, STRAIN-CONTROLLED FATIGUE DATA
ON TYPE 304 STAINLESS STEEL:
A COMPILATION, MULTIPLE LINEAR REGRESSION MODEL,
AND STATISTICAL ANALYSIS**

by

D. R. Diercks and D. T. Raske

APPLIED TECHNOLOGY

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Materials Science Division

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ABSTRACT

The available elevated-temperature, strain-controlled, uniaxial fatigue data on Type 304 stainless steel (474 data points) are tabulated, and variables that influence cyclic life are divided into first- and second-order categories. The first-order variables, which include strain range, strain rate, temperature, and hold time, were used in a multiple linear regression analysis to describe the observed variation in fatigue life for zero and tension hold-time data. Goodness of fit, with respect to these variables, as well as the appropriateness of the transformations used are discussed. Prediction intervals are estimated, and comparisons between the regression equation curves and the data from which they were obtained are made. The second-order variables include the laboratories at which the data were generated, the different heats from which the test specimens were fabricated, and the heat treatments that preceded testing. These variables were statistically analyzed to determine their effect on fatigue life. The results are discussed, and the heats and heat treatments that are most resistant to fatigue damage under these loading and environmental conditions are identified.

I. INTRODUCTION

In the past decade, a considerable quantity of elevated-temperature [430°C (806°F) and above] low-cycle fatigue data have been obtained on AISI Type 304 stainless steel.¹⁻¹⁴ Most of these data were obtained in support of the structural design of the liquid-metal fast-breeder reactor. The present report describes the results of an extensive effort to collect the appropriate data, analytically describes the observed variation of cyclic life as a function of the principal test variables, and makes statistical inferences concerning the significance of test variables not included in the regression model.

II. DATA BASE

Data considered in the present analysis were obtained from hourglass or, in a few cases, uniform-gauge specimens cycled under axial loading strain-controlled conditions. The basic total axial strain versus time waveforms

considered are shown in Fig. 1, as well as the associated load versus time waveforms. Figure 1a shows the case of continuous cycling through a constant strain range $\Delta\epsilon_t$ at a constant strain rate $\dot{\epsilon}$. The corresponding load versus time waveform is not linear since yielding typically occurs with each strain reversal. In the second type of loading, a specified hold time t_h at constant peak tensile strain (or at peak compressive strain or both) is programmed into each strain cycle, as seen in Fig. 1b. Significant load relaxation can occur during the hold time in elevated-temperature tests. For this reason, the load response to this imposed strain waveform is often referred to as "cyclic relaxation." Detailed information on specimen design, testing procedures, and loading waveforms may be found in Conway et al.⁹ and Slot et al.¹⁰

The results of the data-collection effort are summarized in Tables I and II. Table I contains 436 data points from zero and tension hold-time (cyclic-relaxation) tests, and Table II contains 38 points from compression and tension plus compression hold-time tests. All tests were conducted in an air environment. The sources of the data are listed, and footnote a in the tables indicates the types of data included and not included in the analysis. Data generated for waveforms other than continuous cycling at constant total axial strain rate and cyclic relaxation (hold time at constant total axial strain) are not included, with the exception of some General Electric Company (GE) data generated at constant total diametral strain rate. In all cases, the tabulated strain-range and strain-rate values refer to axial strain.

III. REGRESSION ANALYSIS

The quantity of compression and tension plus compression hold-time data in Table II and the variety of test conditions represented were considered insufficient to permit the development of a meaningful analytical description. However, the 436 zero and tension hold-time data points in Table I were judged to form an adequate base for a multiple linear regression analysis. The cyclic life N_f (i.e., the number of cycles required to cause complete specimen failure) was selected as the dependent variable, and the independent variables chosen were total axial strain range $\Delta\epsilon_t$, in percent;* total axial strain rate $\dot{\epsilon}$, in s^{-1} ; test temperature T_c , in degrees celsius; and tensile hold time t_h , in minutes. The following transformations on the independent variables were employed:

$$S = \log_{10} (\Delta\epsilon_t/100),$$

$$R = \log_{10} (\dot{\epsilon}),$$

$$T = T_c/100,$$

and

$$H = \log_{10} (t_h + 1).$$

* An analysis was also performed using the plastic strain range $\Delta\epsilon_p$ rather than the total strain range as one of the independent variables, but a somewhat poorer correlation resulted.

These transformations were chosen for two reasons. First, previous experience had shown that they result in a decrease in the number of terms required in the correlations with cyclic life. Second, the transformed variables all have absolute values between 0 and 10 for the data considered. The untransformed variables have a much greater range of values and would have resulted in awkwardly large and small values for the regression coefficients obtained. The transformation on tension hold time is such that it drops out of the regression equation when $t_H = 0$.

The problem of choosing the appropriate transformation for the dependent variable N_f was somewhat more difficult. In performing a regression analysis, transformations on the dependent variable are generally made with three objectives in mind:¹⁷ (a) to simplify the fitting equation obtained, (b) to obtain a distribution of residuals that does not vary systematically with the dependent variable (i.e., stabilize the variance), and (c) to obtain an approximately normal distribution of residuals. The transformation on N_f that most nearly satisfies these criteria is $(\log_{10} N_f)^{-1/2}$. This transformation was found to be superior to the transformations $\log_{10} N_f$, $(\log_{10} N_f)^{-1}$, and $(\log_{10} N_f)^{1/2}$, as will be discussed. Thus, in the regression analysis performed, $(\log_{10} N_f)^{-1/2}$ was assumed to be a polynomial function of S , R , T , and H as defined above. First-order interactions of the independent variables and cross-product terms of two independent variables were included in the equation, but cross products of three or more variables were excluded to keep the number of potential variables to a manageable level.

"Cyclic-life" values from several tests terminated before failure were included in the regression analysis, since these data were considered to provide a useful lower bound on life. However, Battelle-Columbus Laboratories (BCL) test SS-6 at 538°C was not included, since it was felt that this test had been terminated long before probable failure and its inclusion would unduly distort the model. C. E. Jaske, who conducted this test, concurred in this judgment.¹⁸ Thus, 435 data points were used to perform the analysis.

The regression analysis was conducted on an IBM 370/195 digital computer using the Statistical Analysis System (SAS), a proprietary software package documented by Service.¹⁹ The Stepwise and Maximum R^2 Improvement procedures* were used to select the appropriate variables to be included in

* In the Stepwise and Maximum R^2 Improvement procedures, the independent variables (or specified combinations of the independent variables) are added one by one to the model. The first variable used in the model is the one that produces the largest R^2 statistic. Each successive variable modifies the model, on the basis of producing the greatest increase in R^2 , until the "best" n-variable model is obtained. The total number of independent variables in the final model is determined by statistical comparisons.

the model. The analytical model obtained to describe the data of Table I was

$$\begin{aligned}
 (\log_{10} N_f)^{-1/2} = & 1.2055 + 0.6600 \cdot S \\
 & + 0.1804 \cdot S^2 - 0.008143 \cdot S^4 \\
 & + 0.000253 \cdot R \cdot S^4 + 0.000218 \cdot T \cdot S^4 \\
 & - 0.0005466 \cdot R \cdot T^2 - 0.005557 \cdot R \cdot T^2 \\
 & - 0.002939 \cdot H \cdot R^2 + 0.01197 \cdot H \cdot T \\
 & - 0.0005164 \cdot H^2 \cdot T^2 .
 \end{aligned} \tag{1}$$

The correlation coefficient R for this 11-term model is 0.9781. By way of comparison, the $(\log_{10})^{1/2}$ transformation required a 15-term model to produce a comparable value of the correlation coefficient, the $(\log_{10} N_f)^{-1}$ transformation required a 16-term model, and the $\log_{10} N_f$ transformation required more than 20 terms.

Table III lists the standard errors for the regression coefficients of Eq. (1) and the significance level at which a given coefficient has a value of zero, i.e., the independent variable associated with this coefficient does not belong in the model. Thus, a significance level of 0.01 means that a 1% probability exists that the associated variable is included in the model erroneously. All variables included in the model are significant at the 0.02 level. Confidence intervals for the regression coefficients may be computed from the standard error values using t -statistics.

IV. EXAMINATION OF RESIDUALS

We have shown that the $(\log_{10})^{-1/2}$ transformation results in a simpler regression equation than the other transformations considered. We will now show that this transformation results in a distribution of residuals that is sufficiently normal about zero and has constant variance. These last two considerations will become important when estimates of prediction intervals are made. In addition, normality of the residuals will be assumed in some of the other statistical analyses to be performed.

First consider the normality of the residuals. Figure 2 is a plot of the percent of residuals on a normal probability scale versus residual value for the Eq. (1) model. The residual is defined as

$$(\log_{10} N_{\text{obs}})^{-1/2} - (\log_{10} N_{\text{comp}})^{-1/2} ,$$

where N_{obs} is the experimentally observed cyclic life, and N_{comp} is the life computed from Eq. (1). The residual plot corresponds closely to the standard normal line for a population that has a zero mean (μ) and a standard deviation (σ) of 0.01348. This σ value is the same as the sample standard deviation s computed for the residuals. A χ^2 goodness-of-fit test was also performed to compare the observed distribution of residuals about zero with that expected for a normal distribution. The value of χ^2 was found to be 21.6 with 15 degrees of freedom. Approximately 12% of the samples from a normal population would be expected to have a χ^2 value this large. This distribution of residuals was judged to be sufficiently close to a normal distribution that meaningful statistical inferences can be made.

Homogeneity of error variance can be verified by plotting the residuals as a function of the dependent variable. Figure 3 shows such a plot, with $(\log_{10} N_{\text{comp}})^{-1/2}$ as the abscissa. The error variance appears to be approximately constant, i.e., the width of the scatter band does not vary significantly with the value of $(\log_{10} N_{\text{comp}})^{-1/2}$. A similar plot, but with $(\log_{10} N_{\text{obs}})^{-1/2}$ as the abscissa, again shows no systematic variation (Fig. 4). The other transformations on cyclic life that were considered resulted in residual plots displaying obvious dependences of error variance on transformed life.

The above residual plots are used to demonstrate the appropriateness of the $(\log_{10})^{-1/2}$ transformation on the dependent variable. Plots of residual values versus the independent variables included in the regression model and potential variables not included in the model may be used to show that the terms included in the model are appropriate. Such plots versus S, R, T, and H (Figs. 5-8) show no systematic variation, indicating that the dependence of cyclic life on these variables is properly taken into account in the regression model. On the other hand, residual plots versus testing laboratory, material heat number, and heat treatment (Figs. 9-11) tend to show systematic variations. The dependence of cyclic life on the latter set of variables will be discussed in Sec. VII.

V. PREDICTION INTERVALS

In Sec. IV, it was established that the distribution of residuals about zero is approximately normal, with a standard deviation of 0.01348 that is essentially independent of observed and computed life. Thus, the transformed experimentally observed lives can be considered to be normally distributed about the mean value computed from Eq. (1), with the same standard deviation of 0.01348.¹⁷ The determination of confidence intervals for a new experimental observation, or prediction intervals, is then straightforward. For a normal distribution, 95% of the observations may be expected to fall within an interval of 1.960 standard deviations to each side of the mean. Thus, the 95% confidence interval for a new observation as a function of computed life from Eq. (1) is defined by $(\log_{10} N_{\text{comp}})^{-1/2} \pm 0.02643$. If an additional test were to be run under a given set of conditions for which the computed value of cyclic life was N_{comp} , then one would expect the observed cyclic life N_{obs} for that test to fall within the indicated range about N_{comp} 95% of the time. Note that the prediction intervals are functions of N_{comp} only and not of the other test variables.

A plot of $\log N_{\text{obs}}$ versus $\log N_{\text{comp}}$ for the 435 data points used in the regression analysis is shown in Fig. 12. The dashed line corresponds to $N_{\text{obs}} = N_{\text{comp}}$, and the solid lines above and below the dashed line define the 95% prediction interval for a new observation. Because of the $(\log_{10})^{-1/2}$ transformation on N_{comp} employed, the prediction interval is much wider at long lives than at short lives and is slightly skewed in the direction of longer lives. This feature of the transformation reflects the actual scatter present in the data, as seen in Fig. 12. For a total of 435 data points, one would expect ~22 points to fall outside the 95% confidence interval, with 11 to each side. In the present analysis, 14 points fell above the upper prediction limit and 9 below the lower prediction limit.

VI. COMPARISONS OF REGRESSION CURVES WITH EXPERIMENTAL DATA

It is of interest to compare the fatigue-life curves defined by Eq. (1) with the experimental data from which the equation was obtained for various combinations of the independent variables. Such comparisons are shown as logarithmic plots of total strain range versus cycles to failure in Figs. 13-33. The solid and dashed curves are computed from Eq. (1) for the conditions indicated, and the data points shown correspond to the experimental data of Table 1. It should be noted that the curves have been extended beyond the available data base in many cases to illustrate how they extrapolate. An attempt was made to obtain a functional form for Eq. (1) that extrapolated in a reasonable manner, but no life-predictive capabilities outside the data base are claimed. It will be shown that, in some cases, extrapolation beyond the data base can result in unrealistic cyclic life predictions. Thus, significant extrapolation of Eq. (1) cannot be recommended as a reliable procedure.

Figures 13-21 show the influence of strain rate on life in zero hold-time tests at various temperatures. The data and the curves clearly reflect the increasing dependence of cyclic life on strain rate with increasing temperature. A slight tendency appears to exist for the fitted curves to understate the strain-rate effect at 593°C and overstate it at 816°C, but the departures from the experimental data are not serious. In general, the curves of Eq. (1) describe the experimental data quite well and interpolate in a reasonable fashion.

The effects of tension hold time at constant strain rate ($\dot{\epsilon} = 4 \times 10^{-3} \text{ s}^{-1}$) on cyclic life are shown in Figs. 22-29. The curves do not show the expected tendency for hold-time effects to increase with an increase in temperature. However, this can partly be explained by the lack of data at the lowest and highest temperatures, thus making the curves unreliable in these regions. At 816°C, where no tension hold-time data are available, the 10- and 600-min tension hold-time curves may be seen to coincide and both lie to the right of the 60-min curve. This physically unrealistic result illustrates the dangers associated with extrapolating Eq. (1) beyond the data base. In the temperature range of 538 to 650°C, where most of the data lie, the agreement between the fitted curve and the experimental data is generally good. However, even in this region the influence of hold time on cyclic life does not show the expected temperature dependence.

In Figs. 30-33, the fitted curves are compared with tension hold-time data generated in tests for which the cyclic strain rate was $4 \times 10^{-3} \text{ s}^{-1}$. Intuitively, one would expect this decrease in strain rate to result in a slight decrease in cyclic life when compared with similar hold-time data generated at a cyclic strain rate of $4 \times 10^{-3} \text{ s}^{-1}$ (Figs. 22-29). However, the fitted curves of Figs. 30-33 tend to show the opposite effect, especially at the lower temperatures and strain ranges. Again it must be pointed out that the data are rather sparse. In addition, all but two of the data points of Figs. 30-33 were generated on aged specimens. Aging will be seen, in Sec. VII, to enhance life somewhat, and this may be perturbing the results described here.

The fatigue design curves for inelastic analysis contained in Case 1592 of the ASME Boiler and Pressure Vessel Code⁹ were obtained from laboratory data (essentially all of which are included in this analysis) by applying a safety factor of 20 on life or 2 on strain range, whichever is more conservative.¹ It is of interest to compare the regression curves and lower prediction limits obtained here with the Code Case 1592 design curves. Such a comparison is made in Fig. 34 for a temperature of 650°C (1202°F).^{*} The degree of conservatism in the design curve may be seen to decrease with a decrease in strain range, but even at the lowest strain range the design curve falls more than five standard deviations to the left of the regression equation curve. In comparison, the 99.8% lower prediction limit curve lies just over three standard deviations to the left of the regression curve. It should be pointed out that normality of the distribution of the data about the mean has not been demonstrated in the extreme tails of the distribution [beyond about three standard deviations (Fig. 2)], and one should be cautious when making quantitative estimates of probabilities in this region. It should also be noted that the lowest strain range for which data are available under a 650°C zero-hold condition is 0.25% for a total strain rate of $4 \times 10^{-3} \text{ s}^{-1}$ and 0.58% for a strain rate of $4 \times 10^{-4} \text{ s}^{-1}$. The $1 \times 10^{-3} \text{ s}^{-1}$ strain-rate curve of Fig. 34 has been extended to the 0.25% strain-range value. This mild extrapolation may be considered acceptable for the purposes of Fig. 34, but, as noted previously, significant extrapolations of the regression equation beyond the data base of Table I should be avoided.

VII. EFFECT OF SECOND-ORDER VARIABLES

In this section, the effects of the second-order, or qualitative, variables excluded from the analytical model of cyclic fatigue life are investigated. These variables include the four laboratories at which the data were generated, the different heats from which the test specimens were fabricated, and the heat treatments that preceded testing.

The testing laboratories were considered as a possible source of variation in the data because of certain intangible differences in testing procedures that generally exist among them. The reason for analyzing the original heats for these data is to investigate the effect of the variations in chemical composition and/or residual elements on fatigue life. As for heat treatment, the goal is to identify the processes that are most beneficial in resisting fatigue damage under these loading and environmental conditions.

The investigation of these variables consisted of a statistical analysis on the residual values of the transformed fatigue lives. Residuals offer a convenient means of comparing the fatigue behavior of different samples because deviations from values obtained for all the samples provide

* Because the Code uses only one design curve for the temperature range of 538-650°C, this curve would represent the least conservative case for this temperature range.

a quantitative measure of fatigue performance. The transformation on fatigue life is such that negative residual values are associated with longer observed lives than predicted by the model.

Sample means and variances constituted the variables studied, using the following assumptions and analyses:

a. Samples representing specific data for a given laboratory, heat, and heat treatment from the normal population of residuals obtained by the regression analysis ($n = 435$, $\mu = 0$, $\sigma = 0.01348$) were assumed to be normally distributed with mean $\bar{x}$ and variance s^2 .

b. Those heat treatments that resulted in similar microstructural features were assumed to be identical. Because of this, the data for the following heat treatments were combined: 2, 3, and 4; 5 and 8; and 14 and 15 (Table I).

c. Pairs of samples were compared by testing the assumption that the mean values of the residuals in the sample were equal. This is the null hypothesis $\bar{x}_i = \bar{x}_j$ (for $i \neq j$), and it was tested using the t test.²² The t -statistic was computed and compared with values from Student's t -distribution for $n_i + n_j - 2$ degrees of freedom. The level of significance, α , of the tests was 5%. Thus, a 5% probability exists that the null hypothesis would be rejected erroneously. All tests were two-sided; therefore, the values from the t -distribution were taken at the 0.025 level. This gave a confidence level ($\gamma = 1 - \alpha$) of at least 95% when different sample means were detected. The probability of a Type-II error, i.e., not detecting a real difference in the means at $\alpha = 5\%$, was also determined.²³ The probability of this error is strongly dependent on the sample size, and the test is generally not very sensitive when small samples ($n < 20$) are compared. The sample variances were also compared using the F -distribution. When this test indicated that the variances were unequal, an approximate t -statistic was used.²²

d. When two or more samples were judged equal in mean and variance, they were combined to provide a new, larger sample, which increased the sensitivity of the statistical tests and decreased the Type-II error probability.

e. To present the results of this analysis in a format that clearly illustrates the basis for the conclusions reached in the text, the samples discussed are plotted as normal probability density functions in terms of their mean $\bar{x}_i$ and standard deviation s_i .

A. Interlaboratory Variability

Possible interlaboratory variation in results was the first to be investigated because, if present, it would certainly obscure the effects of the other variables. For convenience, the source laboratories were assigned the following numerical designations: 1 — Argonne National Laboratory; 2 — Aerojet Nuclear Company (ANC), now Edgerton, Germeshauser, and Grier, Inc.; 3 — General Electric Company — Nuclear Systems Program; and 4 — Battelle-Columbus Laboratories.

Comparisons of the residuals from these four laboratories were made for specific heats and heat treatments. This was necessary to eliminate any

possible effect of these variables on the analysis. The results are shown in Fig. 35 as normal distributions, using the sample mean and variance to determine these curves. The solution-annealed data from laboratory 2 were insufficient to permit a comparison with the other three laboratories (Fig. 35a). Therefore, solution-annealed and aged data from laboratory 2 were compared with similar data from laboratory 1 (Fig. 35b). Although quantitative conclusions cannot be deduced from these curves, they do indicate that the data from laboratory 1 had considerably less scatter than the other data. In contrast, the data from laboratory 4 exhibit the most scatter and have a large positive mean residual, indicating the observed fatigue lives are shorter than predicted by the model.

The results of the statistical analysis suggest that the data from laboratories 1-3 could be combined for the study of heat-to-heat and heat-treatment variability. The data from laboratory 4 were significantly different from those of laboratory 1, and, for this reason, the laboratory 4 data were excluded from these analyses.

B. Heat-to-heat Variability

Only those heats from Table I for which sufficient data existed to provide statistically meaningful results were investigated. These consisted of heats 1-5 and 7 in the solution-annealed and aged condition and heat 6 in the as-fabricated condition. Statistical comparisons of these data indicated large and significant differences between heats. However, evidence indicated that the cause of these differences might be attributed to the tensile hold-time data.^{2,3,4} This possibility was investigated by separating the data into groups consisting of continuous cycling and hold-time waveforms. Because of the many different tensile hold times reported for the data used in this study, no distinction of individual values was attempted. Furthermore, only those data from laboratories 1 and 2 in the solution-annealed and aged condition were used (an exception was the as-fabricated data from heat 6).

Five heats (1-3, 6, and 7) provided sufficient data to investigate the variation of the residuals from zero and nonzero hold-time tests. The results, with the exception of the as-fabricated data from heat 6, are shown in Fig. 36. Based on the sample means and variances, these results and the results of uniaxial creep tests from Sikka et al.^{2,4} indicate the following:

Heat 1. The hold-time data have a much lower fatigue life than predicted by the model. In addition, material from this heat also had poor uniaxial creep properties compared with other heats in this study. The continuous cycling and hold-time data differed in the residual mean value at a significance level of 2%, with a Type-II error probability of 10%. Therefore, with a confidence level of 98%, it can be concluded that this material will respond differently to zero and nonzero hold-time tests.

Heat 2. This material had fatigue lives slightly higher than predicted by the model for both continuous cycling and hold-time waveforms. It was not possible to distinguish any statistically significant difference in the mean values of samples from this heat subjected to the two waveforms. This means that the difference between the observed and predicted lives is similar for fatigue and creep-fatigue tests.

Heat 3. The material from this heat exhibited a considerably different response to the two loading waveforms. Under hold-time waveforms, the observed creep-fatigue lives were much longer than predicted, whereas the continuous cycling lives were similar to those of the other heats investigated in this study. Resistance to uniaxial creep was also reported to be high for this material. The confidence level at which the means differed for these loadings was 99.9%, with a Type-II error probability of 1%.

Heat 6. Data for this heat were excluded from Fig. 36 because the material was tested in the as-fabricated condition and therefore was not directly comparable to the other data. However, the mean values for samples from the two loading waveforms were virtually identical.

Heat 7. This material was similar to heat 3 in that it displayed large differences in response to the various loading waveforms. The hold-time test data had longer fatigue lives than the model predicted, and these results were consistent with the high uniaxial creep resistance observed. The t -test did not indicate a statistically significant difference in residual mean values for the samples cycled continuously and with hold times. This was due to the large variance and consequent overlap associated with these data.

The following conclusions regarding heat-to-heat variability are apparent from these results. Waveforms containing tensile hold times produced large variations in fatigue lives with respect to the lives predicted by the model for these heats. These variations were such that those heats with good uniaxial creep resistance also had longer fatigue lives, and those with poor creep resistance were accompanied by shorter fatigue lives than predicted. The confidence levels at which data from the creep-resistant heats (3 and 7) differed from the data for the heats more susceptible to creep damage (1 and 2) exceeded 98%, with Type-II error probabilities averaging 15%. No statistically significant differences were found in the data from heats 1-3, 5, and 7 tested under continuous cycling conditions. In addition, data for three zero hold-time tests from heat 4 with the same heat treatment had residuals with values within the range of mean values of these heats. Therefore, it is apparent that no significant heat-to-heat variations exist for continuous cycling waveforms, and data from these heats could be considered as identical in subsequent statistical analysis.

C. Heat-treatment Variability

From the previous results, continuous cycling data from laboratories 1-3 and heats 1-5 and 7 were combined to investigate the effect of heat treatment on fatigue life. As stated previously, the residual values were grouped with respect to the variable of interest (in this case, heat treatment), and the resultant values were statistically compared. Because of small sample sizes and consequent statistical inaccuracy, data from a number of heat treatments were not considered. Those samples that were of sufficient size to be accurately compared are shown as normal probability density functions in Fig. 37. Plots of the residuals for these heat treatments on a normal probability scale are shown in Figs. 38-41. The degree to which these samples conform to a standard normal line with the same mean and standard deviation can be observed in the figures.

Data from both the stress-relieved and solution-annealed plus aged heat treatments indicated longer mean fatigue lives than predicted by the model. These data had sample means and variances that were nearly identical. For material that was only solution annealed, the mean fatigue life was slightly less than predicted but considerably below the two previous treatments. For example, consider a case where the conditions of loading and environment would result in a fatigue life of 3000 cycles. Then, using the results shown in Fig. 37 with 3000 cycles represented by a residual of zero, material that was solution annealed would have a mean life of 2930 cycles. In contrast, the mean fatigue lives for material that was stress relieved or solution annealed and then aged would be 3420 and 3340 cycles, respectively. Thus stress relieving or aging after solution annealing would increase the mean fatigue life by an average of 13% at this nominal life.

The results of the statistical analysis indicate that the solution-annealed sample data differ from the stress-relieved and solution-annealed plus aged data with a confidence level exceeding 98%. The probability of Type-II errors were 35 and 10%, respectively. Consequently, either of these two heat treatments could be expected to result in better fatigue performance than solution annealing alone under these particular loading and environmental conditions, i.e., continuous cycling in air at a temperature between 430 and 816°C (806 and 1500°F). Earlier work at Argonne National Laboratory (ANL)⁶ has shown that specimens stress relieved or solution annealed and aged prior to testing have more carbide precipitation at the grain boundaries and coherent twin boundaries after testing than specimens initially solution annealed. Indeed, this work attributed longer fatigue lives to the more advanced carbide precipitation. It was also suggested that, in tests of long duration or higher temperatures, the differences in heat treatment would become obscured as a result of the precipitation induced by the time at temperature during the test. This hypothesis was statistically tested using tensile hold-time data from heat 1 in the solution-annealed and solution-annealed and aged conditions. No statistically significant difference in the effect of these heat treatments on fatigue life was observed. This is in contrast to the clear and significant difference observed for continuous cycling. Thus, the results of the present study support and confirm these conclusions.

Specific conclusions regarding comparisons of the as-fabricated data shown in Fig. 37 are uncertain because heat 6 could not be directly compared with the combined heats that constitute the base for the other heat-treatment data. Nevertheless, these data have a mean fatigue life that is considerably below the other heat treatments. In view of the previous heat-treatment effects on fatigue life, this result is not unexpected.

VIII. CONCLUSIONS

The goal of this investigation was threefold. First, the available elevated-temperature, strain-controlled, uniaxial fatigue data on Type 304 stainless steel were compiled, and the variables that influence cyclic life were separated into first- and second-order categories. Second, these data were used in an analytical model that describes the observed variation in

fatigue life as a function of the principal, or first-order, test variables. Third, the second-order variables excluded from the analytical model were statistically analyzed to determine their effect on fatigue life.

The results of this investigation suggest the following conclusions:

- a. A transformation of the form $(\log_{10})^{-1/2}$ applied to the dependent variable N_f was found to be most satisfactory for the purpose of multiple linear regression analysis.
- b. The analytical model from the regression analysis accurately describes the variation in mean fatigue life as a function of strain range, strain rate, temperature, and tensile hold time for the data investigated.
- c. Data from three of the four source laboratories exhibited no statistically significant difference in mean fatigue life for a given set of test conditions. Since one of these three laboratories (ANCO) began all of its tests with the initial half cycle of the strain waveform in tension and the other two laboratories (ANL and GE) in compression, this implies that the initial loading direction exerts no significant influence on observed life.
- d. The heat-to-heat variability was found to depend on the loading waveform used for testing. No significant heat-to-heat variations were found to exist for data tested with continuous-cycling waveforms. When the waveform contained a hold time at constant peak tensile strain, significant differences between heats were observed. These differences were such that the data on material from heats which were known to possess superior uniaxial creep resistance also had longer creep-fatigue lives, and those with poor uniaxial creep resistance had shorter lives than predicted by the analytical model.
- e. Heat treatments that produce carbide precipitation at the grain boundaries and coherent twin boundaries are the most resistant to continuous-cycling fatigue damage in air at temperatures between 530 and 816°C (800 and 1500°F).
- f. In creep-fatigue tests, the differences in heat treatments are obscured. This is thought to be due to the carbide precipitation induced by the time at temperature during the test.

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TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel¹

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN. ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	TEST. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	RPF
TEST TEMPERATURE = 430 C (806 F)											
2.19	1.72	.004400	0.0	754	2	1	GE		1070	1143	8
2.27	1.65	.004100	0.0	326;345	2	5	ANL	12A-10	2361	1291	1
1.13	0.81	.004500	0.0	514	2	1	GE		4432	5702	8
1.07	0.81	.004300	0.0	188;232	2	5	ANL	13A-9	16192	2604	1
0.79	0.53	.004600	0.0	422	2	1	GE		10917	16736	8
0.60	0.36	.004800	0.0	387	2	1	GE		31450	45863	8
0.60	0.36	.005000	0.0	390	2	1	GE		34160	46011	8
0.52	0.28	.004200	0.0	183;165	2	5	ANL	15A-7	61618	83729	1
TEST TEMPERATURE = 482 C (900 F)											
2.02	1.53	.004000	0.0	385;415	6	10	ANC	BT-100	680	1127	11
2.01	1.55	.004000	0.0	353;357	1	3	ANL	T-26	1299	1140	1
2.00	1.33	.004000	0.0	386;420	6	10	ANC	BT-72	594	1161	11
2.00	1.53	.004000	0.0	749	2	5	ANL	6C-11	1007	1161	1
1.95	1.48	.003900	0.0	758	2	5	ANL	7A-10	980	1204	1
1.00	0.69	.004000	0.0	248;234	1	3	ANL	T-34	6026	6023	1
0.99	0.59	.004000	0.0	281;274	6	10	ANC	BT-23	3809	6190	11
0.99	0.69	.004000	0.0	239;228	1	3	ANL	T-63	6601	6190	1
0.73	0.44	.004000	0.0	240;243	6	10	ANC	BT-24	7662	11405	11
0.73	0.46	.004000	0.0	206;206	1	3	ANL	T-364	16723	15287	7
0.60	0.36	.004000	0.0	194;185	1	3	ANL	T-157	27626	30184	1
0.50	0.21	.004000	0.0	208;208	6	10	ANC	BT-25	26176	62568	11
0.37	0.03	.004000	0.0	251;294	6	10	ANC	BT-26	692520	278723	11
0.33	0.01	.004000	0.0	165;194	6	10	ANC	BT-22	384324 ^g	559665	11

TABLE I. Summary of Elevated-temperature, Strain-controlling Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	REF
TEST TEMPERATURE = 482 C (900 F)											
1.98	1.51	.000400	0.0	362;377	1	3	ANL	T-328	880	919	7
0.99	0.65	.000400	0.0	256;262	1	3	ANL	T-325	8390	4652	7
0.60	0.33	.000400	0.0	216;208	1	3	ANL	T-130	26139	22831	1
1.48	1.51	.000039	0.0	372;370	1	3	ANL	T-27	955	720	1
0.99	0.61	.000040	0.0	611	1	3	ANL	T-292	4805	3544	7
0.98	0.62	.004000	0.6	T 274;280	6	10	ANC	BT-26	3818	4812	11
0.98	0.60	.004000	6.0	T 298;305	6	10	ANC	BT-27	3563	2123	11
0.59	0.29	.000390	10.0	490	1	3	ANL	T-166	5104	7090	2
2.02	1.52	.000040	45.0	T 823	1	3	ANL	T-95	388	336	1
0.99	0.61	.000040	45.0	T 635	1	3	ANL	T-87	1524	1303	2
1.98	1.54	.000040	600.0	T 796	1	3	ANL	T-178	123	126	2
TEST TEMPERATURE = 538 C (1000 F)											
3.96	3.41	.064000	0.0	855	2	1	GE	67-2	345	359	8
3.96	3.42	.032000	0.0	843	2	1	GF	67-1	347	331	8
2.94	2.50	.015000	0.0	800	2	1	BCL	SS-12	381	531	15
0.50	0.27	.008000	0.0	172;172	2	1	GE	67-3	43377	42365	8
3.96	3.42	.004000	0.0	421;421	2	1	GE	66-12	244	263	8
2.92	2.40	.004000	0.0	745	2	1	BCL	SS-1	390	454	15
2.04	1.63	.004000	0.0	717	2	1	BCL	SS-15	757	602	15
2.01	1.57	.004000	0.0	331;344	1	3	ANL	T-311	1100	936	7
2.01	1.57	.004000	0.0	342;345	2	5	ANL	60-10	1167	936	1
1.95	1.51	.004000	0.0	687	2	1	BCL	SS-5	612	995	15
1.01	0.53	.004100	0.0	217;212	2	1	ANL	3A-11	3951	4322	1
1.00	0.61	.004000	0.0	265;253	2	3	ANL	59-8	4252	4413	1
0.99	0.66	.004000	0.0	264;260	1	3	ANL	T-314	4951	4527	7

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN ^b	STRESS RANGE, MPA ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	REF
TEST TEMPERATURE = 538 C (1000 F)											
0.96	0.63	.004000	0.0	524	2	1	BCL	SS-2	2876	4896	15
0.64	0.39	.004300	0.0	190;199	1	3	ANL	T-327	15416	15861	7
0.63	0.36	.004000	0.0	409	2	1	BCL	SS-21	10263	16490	15
0.39	0.20	.003100	0.0	153;144	2	1	ANL	3A-10	119358	106139	1
0.34	0.16	.004000	0.0	346	2	1	BCL	SS-4	31553	226122	15
0.27	0.04	.004000	0.0	332	2	1	BCL	SS-17	967734	978333	15
0.13	0.0	.004000	0.0	188	2	1	PCI	SS-6 ^h	1520257 ^g	1.09 x 10 ¹⁰	15
2.00	1.55	.000800	0.0	331;345	1	3	ANL	T-332	871	753	7
2.00	1.56	.000400	0.0	336;346	1	3	ANL	T-363	975	691	7
1.99	1.54	.000440	0.0	692	1	3	ANL	T-310	1016	707	7
1.02	0.68	.000410	0.0	262;268	1	3	ANL	T-322	4411	2930	7
0.61	0.34	.000410	0.0	205;209	1	3	ANL	T-324	17702	12560	7
0.63	0.35	.000250	0.0	214;217	1	3	ANL	T-336	16707	10432	7
1.99	1.54	.000040	0.0	351;355	1	3	ANL	T-303	469	521	7
1.00	0.62	.000040	0.0	292;298	1	3	ANL	T-301	2330	2177	7
0.60	0.28	.000040	0.0	246;239	1	3	ANL	T-293	21102	9214	7
0.50	0.24	.004000	1.0 T	200;200	2	1	GE	67-4	17320	20428	8
3.96	3.46	.004000	10.0 T	427;427	2	1	GE	66-11	141	124	8
2.22	1.80	.004000	10.0 T	752	2	1	BCL	SS-7	360	294	15
1.04	0.65	.004000	10.0 T	547	2	1	BCL	SS-22	1451	1068	15
1.01	0.65	.000040	10.0 T	565	1	3	ANL	T-352	1137	1311	7
2.20	1.80	.004000	30.0 T	745	2	1	BCL	SS-9	223	213	15
2.21	1.82	.004000	60.0 T	731	2	1	BCL	SS-8	184	174	15
1.01	0.69	.000040	50.0 T	258;267	1	3	ANL	T-357	922	714	7
1.00	0.67	.000040	500.0 T	248;256	1	3	ANL	T-391	390	268	7

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	REF
TEST TEMPERATURE = 566 C (1050 F)											
2.06	1.58	.004100	0.0	664	2	5	ANL	12A-7	1139	805	1
2.01	1.58	.004050	0.0	651	2	2	ANL	5A-5	1070	841	1
2.01	1.59	.004000	0.0	652	2	1	ANL	8A-5	1127	841	1
2.00	1.58	.004000	0.0	645	2	1	ANL	8A-7	990	850	1
1.01	0.68	.004000	0.0	504	2	2	ANL	5A-1	4320	3675	1
0.99	0.63	.004000	0.0	559	2	1	ANL	8A-1	2011	3853	1
0.99	0.70	.003900	0.0	443	2	5	ANL	13A-7	0708	3840	1
0.57	0.36	.004500	0.0	325	2	5	ANL	13A-10	42034	18804	1
0.51	0.28	.004000	0.0	351	2	2	ANL	5A-0	29112	27090	1
0.50	0.27	.004000	0.0	363	2	1	ANL	8A-0	17273	29132	1
0.50	0.29	.004100	0.0	157;170	2	5	ANL	7A-5	28880	29273	1
0.50	0.28	.004200	0.0	338	2	8	ANL	14A-10	29508	29413	1
0.50	0.28	.004000	0.0	189;150	2	1	ANL	8A-3	33098	29132	1
0.45	0.23	.003600	0.0	334	2	8	ANL	14A-11	97607	42866	1
0.40	0.19	.004000	0.0	157;154	2	6	ANL	4A-4	57452	72214	1
0.40	0.19	.004000	0.0	154;163	2	5	ANL	1A-0	09513	72214	1
0.35	0.13	.004000	0.0	161;172	2	2	ANL	5A-0	212400	136740	1
0.33	0.12	.003800	0.0	171;161	2	5	ANL	7A-5	302407	184492	1
0.28	0.07	.003700	0.0	166;163	2	5	ANL	4A-1	500718	486826	1
1.92	0.67	.000041	0.0	267;273	2	5	ANL	15A-9	1170	1659	1
1.02	0.71	.004100	1.0 T	514	2	5	ANL	7A-7	3027	2378	1
1.01	0.69	.004000	1.0 T	513	2	2	ANL	5A-5	3074	2352	1
0.47	0.23	.003800	12.6 T	382	2	5	ANL	15A-10	3701	4751	1
1.00	0.71	.004000	15.0 T	482	2	5	ANL	15A-11	1509	829	1
0.87	0.45	.003500	15.0 T	679	2	5	ANL	15A-0	375	1002	1
1.03	0.73	.004100	22.8 T	502	2	5	ANL	15A-5	000	611	1
1.95	1.65	.003900	170.0 T	553	2	5	ANL	15A-0	190	145	1
1.35	1.05	.002700	180.0 T	498	2	5	ANL	14A-1	230	223	1

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	REF
TEST TEMPERATURE = 566 C (1050 F)											
2.13	1.84	.004300	600.0	I 582	2	5	ANL	12A-12	93	102	
TEST TEMPERATURE = 593 C (1100 F)											
1.94	1.54	.039000	0.0	608	1	3	ANL	T-215	1041	1213	7
1.52	1.16	.040000	0.0	546	1	3	ANL	T-221	1849	2021	7
1.05	0.74	.042000	0.0	476	1	3	ANL	T-321	5487	4683	7
1.02	0.72	.041000	0.0	462	1	3	ANL	T-198	4882	4993	7
1.01	0.70	.040000	0.0	473	1	3	ANL	T-320	5090	5085	7
0.76	0.51	.040000	0.0	385	1	3	ANL	T-219	10512	10540	7
0.60	0.37	.039000	0.0	347	1	3	ANL	T-202	24062	20915	7
5.97	5.26	.004000	0.0	464;492	7	3	ANC	B-23	135	113	9
2.12	1.49	.004000	0.0	349;367	7	3	ANC	B-8	965	685	9
2.04	1.62	.004100	0.0	644	1	3	ANL	T-277	700	740	7
2.02	1.61	.004000	0.0	626	1	1	ANL	AA-2	737	751	1
2.02	1.59	.004000	0.0	656	1	1	ANL	T-17	753	751	1
2.02	1.60	.004100	0.0	629	1	3	ANL	AA-4	937	754	1
2.01	1.57	.004000	0.0	663	1	1	ANL	AA-1	766	758	1
2.01	1.40	.004000	0.0	373;395	6	10	ANC	BP-14	840	759	9
2.01	1.61	.004000	0.0	606	2	4	ANL	10A-5	941	758	1
2.01	1.67	.004200	0.0	631	1	1	ANL	T-14	1020	764	1
2.00	1.49	.004000	0.0	337;367	6	10	ANC	BT-92	590	765	9
2.00	1.60	.004000	0.0	612	2	5	ANL	60-6	841	765	1
2.00	1.48	.004000	0.0	322;349	2	3	ANC	A-233	1202	765	9
1.99	1.57	.004000	0.0	641	2	1	ANL	8A-8	800	772	1
1.93	1.56	.004000	0.0	656	3	3	ANL	845-10	1010	772	7
1.97	1.41	.004000	0.0	370;394	8	10	ANC	BT-73	594	787	9

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	REF
TEST TEMPERATURE = 593 C (1100 F)											
1.96	1.32	.004000	0.0	357;375	6	10	ANC	BT-14	915	795	9
1.96	1.47	.004000	0.0	313;325	2	11	ANC	A-225	940	795	9
1.95	1.48	.004000	0.0	307;325	2	3	ANC	A-232	885	803	9
1.94	1.41	.004000	0.0	382;379	8	10	ANC	BT-74	619	811	9
1.94	1.42	.004000	0.0	329;355	7	3	ANC	8-28	1170	811	9
1.55	1.21	.004200	0.0	560	1	3	ANL	T-29	1550	1220	1
1.52	1.12	.004000	0.0	596	1	3	ANL	AA-22	1708	1307	1
1.49	1.10	.004000	0.0	592	1	1	ANL	T-51	1025	1361	1
1.02	0.70	.004000	0.0	263;265	2	1	ANC	A-72	1950	3080	9
1.02	0.67	.004100	0.0	531	1	1	ANL	T-25	2853	3095	1
1.02	0.68	.004100	0.0	507	2	3	ANL	55-12	3740	3095	1
1.02	0.69	.004100	0.0	500	1	3	ANL	T-255	3820	3095	1
1.02	0.70	.004100	0.0	486	1	3	ANL	T-250	3938	3095	1
1.01	0.73	.004100	0.0	425	5	3	ANL	807-1	2091	3166	7
1.01	0.63	.004000	0.0	268;274	7	3	ANC	8-14	2145	3151	9
1.01	0.58	.004000	0.0	287;295	6	10	ANC	PP-07	2550	3151	14
1.01	0.71	.004000	0.0	459	2	4	ANL	10A-4	2674	3151	1
1.01	0.68	.004000	0.0	502	1	3	ANL	T-114	3451	3151	7
1.01	0.71	.004000	0.0	456	2	4	ANL	10A-11	3604	3151	1
1.01	0.69	.004000	0.0	494	1	3	ANL	T-145	3659	3151	7
1.01	0.69	.004000	0.0	494	1	3	ANL	T-125	3943	3151	7
1.01	0.69	.004000	0.0	481	1	3	ANL	AA-7	3950	3151	1
1.00	0.59	.004000	0.0	267;288	6	10	ANC	A105	2302	3225	9
1.00	0.65	.004000	0.0	529	1	1	ANL	AA-24	2551	3225	1
1.00	0.63	.004000	0.0	268;268	2	12	ANC	A-51	2757	3225	9
1.00	0.64	.004000	0.0	268;275	2	11	ANC	A-07	2904	3225	9
1.00	0.69	.004000	0.0	507	1	3	ANL	T-143	3006	3225	7
1.00	0.66	.004000	0.0	519	1	3	ANL	T-103	3019	3225	7

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	REF
TEST TEMPERATURE = 593 C (1100 F)											
1.00	0.65	.004000	0.0	535	1	9	ANL	AA-5	3098	3225	1
1.00	0.71	.004000	0.0	447	5	3	ANL	807-6	3328	3225	7
1.00	0.66	.004000	0.0	518	1	3	ANL	T-35	3395	3225	1
1.00	0.69	.004000	0.0	482	2	1	ANL	9A-10	3519	3225	1
1.00	0.66	.004000	0.0	512	4	3	ANL	544-1	3870	3225	7
1.00	0.67	.004000	0.0	248;264	7	3	ANL	813-1	3979	3225	7
1.00	0.66	.004000	0.0	521	1	3	ANL	T-305	4310	3225	7
1.00	0.71	.004000	0.0	448	5	3	ANL	807-2a	4328	3225	7
0.99	0.62	.004000	0.0	269;294	6	10	ANC	BT-97	2119	3301	12
0.99	0.60	.004000	0.0	270;291	6	10	ANC	BT-05	2292	3301	9
0.99	0.61	.004000	0.0	266;275	7	1	ANC	9-3	2914	3301	9
0.99	0.64	.004000	0.0	539	1	3	ANL	T-310	3522	3301	7
0.99	0.59	.004000	0.0	256;265	6	13	ANC	BP-2	3602	3301	14
0.99	0.69	.003900	0.0	466	5	3	ANL	807-5	4022	3234	7
0.99	0.65	.004000	0.0	517	3	3	ANL	845-2	4370	3301	7
0.97	0.65	.003900	0.0	488	1	3	ANL	T-232	3491	3445	7
0.95	0.62	.004000	0.0	504	1	3	ANL	T-100	3870	3638	7
0.94	0.62	.003600	0.0	489	3	3	ANL	845-1	5003	3653	7
0.80	0.44	.004000	0.0	257;265	6	10	ANC	BT-88	2347	5570	9
0.76	0.47	.004100	0.0	449	1	1	ANL	AA-11	4853	6406	1
0.76	0.49	.004000	0.0	407	2	1	ANL	9A-12	6135	6373	1
0.75	0.47	.004000	0.0	426	1	3	ANL	AA-21	7002	6602	1
0.59	0.34	.004000	0.0	392	3	3	ANL	845-9	18605	13183	7
0.53	0.30	.004200	0.0	179;175	1	3	ANL	T-381	21585	18856	7
0.53	0.30	.004200	0.0	346	1	3	ANL	T-329	27900	18856	4
0.53	0.31	.004200	0.0	334	1	3	ANL	T-355	73753	18856	4
0.52	0.22	.004000	0.0	217;211	6	10	ANC	BT-01	15122	19898	9
0.52	0.28	.004000	0.0	168;187	2	1	ANC	A-200	17419	19898	9

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/s	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	REF
TEST TEMPERATURE = 593 C (1100 °F)											
0.52	0.28	.004100	0.0	359	1	3	ANL	T-302	37819	20006	4
0.51	0.27	.004000	0.0	183;178	1	1	ANL	T-10	10439	21270	1
0.51	0.22	.004000	0.0	204;218	6	10	ANC	BT-03	10333	21270	9
0.51	0.26	.004000	0.0	178;191	2	11	ANC	A-75	10018	21270	9
0.51	0.29	.004000	0.0	327	1	1	ANL	AA-9	25925	21270	1
0.51	0.31	.004100	0.0	312	1	3	ANL	AA-0	30498	21386	1
0.51	0.20	.004000	0.0	195;208	6	10	ANC	BP-23	38503	21270	9
0.50	0.21	.004000	0.0	190;205	7	1	ANC	8-4	16347	22791	9
0.50	0.29	.004000	0.0	323	1	1	ANL	AA-0	20834	22791	1
0.50	0.24	.004000	0.0	191;205	6	10	ANC	A1C8	24922	22791	9
0.50	0.23	.004000	0.0	188;194	7	3	ANC	8-19	20215	22791	9
0.50	0.31	.004000	0.0	297	2	4	ANL	10A-5	20832	22791	1
0.50	0.27	.004000	0.0	351	1	3	ANL	T-310	27552	22791	4
0.50	0.27	.004000	0.0	346	1	3	ANL	T-333	30507	22791	4
0.50	0.29	.004000	0.0	332	1	3	ANL	T-323	34052	22791	4
0.50	0.26	.004000	0.0	346	1	3	ANL	T-330	34620	22791	4
0.50	0.28	.004000	0.0	341	1	3	ANL	T-304	42040	22791	7
0.50	0.27	.004000	0.0	344	1	3	ANL	T-319	47003	22791	4
0.50	0.31	.004000	0.0	298	1	3	ANL	AA-5	34575	22791	7
0.50	0.28	.004000	0.0	324	1	1	ANL	T-15	30101	22791	1
0.49	0.26	.004000	0.0	352	1	3	ANL	T-334	23300	24482	4
0.43	0.25	.003900	0.0	340	2	1	ANL	8A-11	20053	20220	1
0.36	0.16	.004100	0.0	306	1	1	ANL	AA-12	52343	86664	1
0.35	0.15	.004000	0.0	148;175	2	1	ANC	A-207	37857	98520	9
0.35	0.15	.004000	0.0	201;181	6	10	ANC	PP-11	57000	98520	9
0.35	0.12	.004000	0.0	196;214	6	10	ANC	BT-12	81291	98520	9
0.35	0.17	.004100	0.0	278	1	3	ANL	AA-13	130937	99065	1
0.35	0.18	.004100	0.0	260	2	4	ANL	9A-11	540009	99065	1

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel¹ (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	REF
TEST TEMPERATURE = 593 C (1100 F)											
0.27	0.03	.0004000	0.0	156;207	6	10	ANL	BT-10	577570 ^g	413601	9
2.04	1.52	.000410	0.0	644	1	3	ANL	T-197	380	512	7
1.99	1.57	.000400	0.0	636	3	3	ANL	845-7	681	533	7
1.01	0.66	.000400	0.0	533	1	1	ANL	T-3	1516	2030	1
1.01	0.67	.000380	0.0	520	3	3	ANL	845-6	2935	2011	7
1.00	0.66	.000400	0.0	516	2	3	ANL	59-12	1740	2076	1
1.00	0.67	.000410	0.0	506	1	3	ANL	T-348	2595	2085	7
0.52	0.27	.000410	0.0	194;199	1	3	ANL	T-200	15016	12292	7
2.01	1.60	.000100	0.0	309;308	3	3	ANL	845-13	470	425	7
1.00	0.67	.000100	0.0	247;247	1	3	ANL	T-389	1697	1620	7
2.07	1.58	.000041	0.0	307;274	1	3	ANL	T-210	244	356	1
2.03	1.65	.000041	0.0	292;297	3	3	ANL	845-8	350	368	7
2.01	1.66	.000040	0.0	546	1	3	ANL	T-345	275	373	7
1.49	1.14	.000040	0.0	528	1	3	ANL	T-353	375	530	7
1.03	0.73	.000041	0.0	454	5	3	ANL	807-4a	1016	1305	7
1.02	0.69	.000041	0.0	255;250	5	3	ANL	807-3	1037	1332	7
1.01	0.71	.000040	0.0	212;230	5	3	ANL	807-3A	1165	1355	7
1.00	0.67	.000040	0.0	257;241	1	3	ANL	AA-25	851	1394	1
1.00	0.69	.000040	0.0	232;229	1	3	ANL	T-267	1105	1384	7
1.00	0.66	.000040	0.0	253;267	4	3	ANL	544-1a	1400	1334	7
1.00	0.68	.000040	0.0	501	5	3	ANL	807-1A	1650	1334	7
1.00	0.66	.000040	0.0	249;256	4	3	ANL	544-3	1558	1384	7
1.00	0.68	.000040	0.0	259;228	3	3	ANL	845-4	1707	1384	7
1.00	0.67	.000041	0.0	248;262	3	3	ANL	845-1a	1761	1390	7
0.99	0.69	.000039	0.0	452	1	1	ANL	T-7	1157	1408	1
0.97	0.64	.000039	0.0	258;253	7	3	ANL	813-2	1815	1472	7
0.74	0.45	.000041	0.0	452	1	3	ANL	T-340	2368	2410	7
0.59	0.32	.000041	0.0	411	1	3	ANL	T-355	5555	5251	7

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN ^b	STRESS RANGE, MPA ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	REF
TEST TEMPERATURE = 593 C (1100 F)											
0.50	0.25	.003040	0.0	194;183	1	2	ANL T-40		0487	8869	1
1.99	1.69	.003010	0.0	220;237	3	2	ANL 845-12		262	313	7
2.00	1.67	.003004	0.0	259;249	1	3	ANL T-218		204	275	7
1.98	1.66	.003004	0.0	238;252	3	3	ANL 845-11		251	279	7
1.01	0.73	.003004	0.0	211;211	1	3	ANL T-85		579	933	1
1.99	1.45	.004000	0.6 T	342;356	7	3	ANC 8-20		1068	609	9
1.93	1.54	.004000	0.6 T	319;330	6	12	ANC ET-8		807	614	14
1.97	1.48	.004000	0.6 T	355;380	8	10	ANC ET-70		545	620	9
1.01	0.64	.004000	0.6 T	278;300	6	10	ANC ET-99		1250	2295	12
1.01	0.66	.004000	0.6 T	242;259	6	13	ANC ET-10		3473	2295	14
1.00	0.64	.004000	0.6 T	269;271	2	12	ANC A-32		1190	2345	9
1.00	0.64	.004000	0.6 T	284;291	6	10	ANC A115		1484	2345	9
1.00	0.65	.004000	0.6 T	269;270	7	3	ANC 8-15		1050	2345	9
0.99	0.61	.004000	0.6 T	289;294	6	10	ANC ET-80		1458	2398	12
0.52	0.24	.004000	0.6 T	200;203	7	2	ANC 8-17		13393	12939	9
0.51	0.20	.004000	0.6 T	221;252	6	10	ANC ET-4		10750	13772	9
0.50	0.23	.004000	0.6 T	184;138	2	3	ANC A-250		12085	14691	9
0.50	0.21	.004000	0.6 T	202;204	7	1	ANC 8-7		12000	14631	9
0.35	0.15	.004000	0.6 T	220;201	6	10	ANC BP-10		18271	57562	9
2.05	1.68	.004100	1.0 T	613	1	3	ANL T-209		578	521	2
1.05	0.75	.004200	1.0 T	477	1	3	ANL T-331		1824	1850	4
1.01	0.70	.004000	1.0 T	491	2	4	ANL 10A-8		1040	1995	1
1.01	0.69	.004000	1.0 T	507	1	3	ANL T-282		1171	1995	4
1.01	0.71	.004000	1.0 T	488	1	1	ANL T-15		1325	1995	1
1.01	0.70	.004000	1.0 T	495	2	1	ANL 9A-1		1470	1995	1
1.01	0.69	.004000	1.0 T	518	1	1	ANL T-91		1019	1995	1
1.01	0.70	.004000	1.0 T	499	1	3	ANL T-315		1070	1995	4
1.01	0.72	.004000	1.0 T	457	1	3	ANL T-309		2255	1995	4

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	FOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAP	SPLC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	RPF
TEST TEMPERATURE = 593 C (1100 F)											
1.01	0.72	.004000	1.0 T	442	2	4	ANL	10A-7	2719	1995	1
1.01	0.74	.004000	1.0 T	442	2	4	ANL	10A-6	2961	1995	1
1.00	0.70	.004000	1.0 T	481	1	3	ANL	T-308	1528	2037	4
1.00	0.69	.004000	1.0 T	500	1	3	ANL	T-275	1500	2037	4
1.00	0.69	.004000	1.0 T	514	1	3	ANL	T-285	1593	2037	4
1.00	0.70	.004000	1.0 T	483	1	3	ANL	AA-10	1604	2037	1
1.00	0.70	.004000	1.0 T	486	1	3	ANL	T-307	1748	2037	4
1.00	0.70	.004000	1.0 T	477	1	3	ANL	T-320	2099	2037	4
1.00	0.70	.004000	1.0 T	496	4	3	ANL	544-2	2712	2037	7
1.00	0.69	.004000	1.0 T	499	3	3	ANL	845-3	3034	2037	7
0.99	0.68	.004000	1.0 T	515	1	1	ANL	T-72	1235	2082	1
0.99	0.72	.004000	1.0 T	437	5	3	ANL	807-2	2755	2082	7
0.50	0.28	.004000	1.0 T	360	2	3	ANL	62-6	10441	12111	1
0.49	0.29	.003900	1.0 T	316	2	4	ANL	10A-2	14970	12878	1
0.48	0.25	.003800	1.0 T	347	2	1	ANL	PA-9	9365	13725	1
1.04	0.74	.004000	5.0 T	457	3	3	ANL	845-25	2225	1031	7
1.03	0.72	.004000	5.0 T	496	3	3	ANL	845-25	2222	1050	7
2.00	1.55	.004000	6.0 T	332;344	6	13	ANC	BT-7	629	324	14
1.98	1.38	.004000	6.0 T	345;364	6	10	ANC	BT-15	382	329	9
1.97	1.52	.004000	6.0 T	306;328	2	11	ANC	A-223	309	331	9
1.95	1.41	.004000	6.0 T	328;357	8	10	ANC	ET-75	272	336	9
1.94	1.40	.004000	6.0 T	321;333	7	3	ANC	8-27	1008	339	9
1.02	0.73	.004000	6.0 T	266;260	6	10	ANC	PT-79	593	992	12
1.01	0.63	.004000	6.0 T	277;279	6	10	ANC	A102	651	1010	9
1.01	0.67	.004000	6.0 T	263;264	7	3	ANC	8-20	1708	1010	9
1.00	0.65	.004000	6.0 T	283;308	6	10	ANC	ET-31	790	1024	14
1.00	0.71	.004000	6.0 T	273;265	2	12	ANC	A-39	806	1029	9
1.00	0.63	.004000	6.0 T	262;255	7	1	ANC	P-6	1555	1024	9

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/s	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	REF
TEST TEMPERATURE = 593 C (1100 F)											
1.00	0.65	.004000	6.0	T 241;261	6	12	ANC	BT-1	2564	1029	14
0.52	0.24	.004000	6.0	T 178;181	2	3	ANC	A-251	5374	4306	9
0.51	0.28	.004000	6.0	T 187;192	2	3	ANC	A-254	5725	4535	9
0.50	0.19	.004000	6.0	T 214;248	6	10	ANC	BT-5	6245	4785	9
0.50	0.23	.004000	6.0	T 182;197	7	3	ANC	P-29	11685 ^g	4785	9
1.01	0.73	.004000	10.0	T 459	1	1	ANL	T-56	553	821	1
1.01	0.71	.004000	10.0	T 453	1	3	ANL	AA-25	635	821	1
1.00	0.72	.004000	10.0	T 231;235	1	3	ANL	T-371	700	826	6
0.99	0.72	.004000	10.0	T 223;236	3	3	ANL	845-14	1326	951	7
0.50	0.28	.004000	10.0	T 345	1	3	ANL	AA-26	5805	3517	1
2.00	1.66	.004000	15.0	T 605	1	3	ANL	T-44	237	244	1
1.00	0.74	.004000	15.0	T 441	1	3	ANL	T-36	666	713	1
0.60	0.39	.004200	15.0	T 345	1	3	ANL	T-38	2765	1911	1
1.98	1.40	.004000	30.0	T 316;346	6	10	ANC	BT-6	271	294	9
1.96	1.56	.004000	30.0	T 299;318	2	1	ANC	A-224	195	267	9
1.00	0.62	.004000	30.0	T 259;293	6	10	ANC	A1B16	503	553	9
1.00	0.66	.004000	30.0	T 256;229	7	3	ANC	R-22	1574	553	9
1.93	1.60	.004000	60.0	T 562	1	3	ANL	T-217	112	171	1
1.00	0.71	.004000	60.0	T 230;247	2	12	ANC	A-35	595	440	9
0.99	0.72	.003900	60.0	T 410	1	3	ANL	AA-27	555	446	1
0.99	0.75	.004000	60.0	T 255;243	2	11	ANC	A-76	415	447	9
3.55	0.34	.004400	60.0	T 328	1	3	ANL	T-244	1255	1261	3
1.01	1.73	.000040	60.0	T 550	1	3	ANL	T-54	102	172	1
1.02	0.72	.000041	60.0	T 509	4	3	ANL	544-4	751	474	5
1.01	0.72	.000040	60.0	T 241;268	4	3	ANL	544-3	575	492	6
1.01	0.79	.000040	60.0	T 397	5	3	ANL	544-4	874	433	5
1.00	0.73	.000040	60.0	T 209;264	4	3	ANL	544-6	557	492	7
1.00	0.78	.000040	60.0	T 391	3	3	ANL	845-5	767	492	5

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	TEST NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	REF
TEST TEMPERATURE = 593 C (1100 F)											
0.49	0.72	.000040	60.0	T 471	1	3	ANL	T-70	305	503	1
0.60	0.98	.000045	60.0	T 376	1	3	ANL	T-62	1031	1327	1
2.02	1.74	.004000	180.0	T 326	1	3	ANL	T-164	63	121	2
1.02	0.76	.004100	180.0	T 447	1	3	ANL	T-159	170	314	2
0.62	0.42	.004100	180.0	T 339	1	3	ANL	T-168	1251	682	3
0.59	0.41	.004000	180.0	T 321	1	3	ANL	T-93	1284	763	2
1.00	0.75	.000040	300.0	T 224;233	1	3	ANL	T-366	233	297	7
1.03	0.82	.004100	600.0	T 390	1	3	ANL	T-190	212	237	3
1.00	0.77	.004000	600.0	T 218;216	1	3	ANL	T-390	252	245	7
2.01	1.74	.000040	600.0	T 242;274	1	3	ANL	T-366	87	94	7
TEST TEMPERATURE = 650 C (1202 F)											
3.95	3.49	.032000	0.0	694	2	1	GE	66-7	303	269	8
1.98	1.62	.032000	0.0	536	2	1	GE	63-12	765	452	8
1.89	1.50	.025000	0.0	710	2	1	RCL	SS-15	744	436	15
3.95	3.47	.016000	0.0	712	2	1	GE	66-5	223	240	8
3.95	3.49	.016000	0.0	686	2	1	GE	66-4	292	240	8
2.73	2.30	.015000	0.0	674	2	1	RCL	SS-18	385	450	15
1.98	1.61	.016000	0.0	549	2	1	GE	62-7	705	821	8
0.49	0.70	.016000	0.0	435	2	1	GE	66-2	2904	3316	8
1.98	1.61	.008000	0.0	539	2	1	GE	63-11	734	712	8
0.49	0.28	.003000	0.0	322	2	1	GE	66-3	11136	17561	8
3.95	3.49	.004000	0.0	342;342	2	1	GE	66-6	184	192	8
2.10	1.71	.004200	0.0	579	2	1	GE		366	565	8
2.01	1.62	.004000	0.0	288;292	2	5	ANL	4A-3	701	604	1
2.01	1.62	.004000	0.0	290;291	2	5	ANL	6A-4	724	604	1

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	REF
TEST TEMPERATURE = 650 C (1202 F)											
2.00	1.70	.004000	0.0	219;224	2	1	ANL	3A-5	714	610	1
1.94	1.64	.004000	0.0	259;263	2	7	ANL	4A-5	775	615	1
1.95	1.58	.004000	0.0	281;281	2	1	GE	54-5	540	621	8
1.93	1.53	.004000	0.0	274;274	2	1	GE	53-11	592	621	8
1.93	1.59	.004000	0.0	579	1	2	ANL	T-357	722	621	7
1.61	1.24	.004300	0.0	268;272	2	5	ANL	1A-9	1018	917	1
1.11	0.79	.004400	0.0	481	2	1	GE		1740	1903	8
1.10	0.78	.004400	0.0	239;237	2	7	ANL	4A-8	2214	1933	1
1.01	0.75	.004000	0.0	184;186	2	7	ANL	3A-7	2406	2253	1
1.01	0.70	.004000	0.0	228;217	2	2	ANL	54-10	2420	2268	1
1.00	0.69	.004000	0.0	243;230	2	5	ANL	4A-6	2217	2315	1
1.00	0.71	.004000	0.0	231;209	2	2	ANL	54-9	3002	2310	1
0.99	0.68	.004000	0.0	229;232	1	3	ANL	T-372	2604	2367	7
0.84	0.60	.004200	0.0	194;190	2	1	ANL	3A-2	3504	3442	1
0.80	0.52	.004200	0.0	210;204	2	5	ANL	1A-8	3489	3865	1
0.76	0.46	.004000	0.0	415	2	1	BCI	SS-14	3881	4316	15
0.75	0.47	.004000	0.0	411	2	5	ANL	6A-2	4507	4457	1
0.59	0.33	.004700	0.0	387	2	1	GE		7320	8697	8
0.59	0.33	.004700	0.0	393	2	1	GE		7344	8697	8
0.52	0.28	.004000	0.0	171;171	2	1	GE	54-11	14020	12064	8
0.50	0.31	.004000	0.0	143;146	2	7	ANL	3A-6	9504	13624	1
0.50	0.27	.004000	0.0	173;173	2	1	GE	54-12	13400	13624	8
0.49	0.28	.004200	0.0	120;102	1	1	ANL	3A-1	21121	14719	1
0.49	0.27	.003900	0.0	165;162	1	5	ANL	T-375	25771	14426	7
0.47	0.25	.004000	0.0	365	2	1	BCI	SS-5	6882	16817	15
0.44	0.22	.004000	0.0	334	2	1	BCI	SS-10	12255	20734	15
0.40	0.18	.004000	0.0	163;158	2	5	ANL	1A-7	21524	29331	1
0.33	0.16	.004100	0.0	132;130	2	5	ANL	4A-3	64329	65000	1

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/s	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL	REF
TEST TEMPERATURE = 650 C (1202 F)											
0.31	0.15	.004000	0.0	227	2	1	DEL	SS-10	189591	86351	15
0.26	0.13	.004200	0.0	145;156	2	7	ANL	4A-11	220010 ^g	230504	1
0.25	0.11	.004000	0.0	105;105	2	1	GE	66-0	1000000 ^g	273986	8
2.10	1.76	.003420	0.0	507	2	1	GE		310	370	8
1.10	0.80	.000440	0.0	449	2	1	GE		800	1170	8
0.59	0.34	.000470	0.0	355	2	1	GE		3549	5114	8
2.08	1.80	.003042	0.0	419	2	1	GE		201	257	8
1.93	1.68	.000040	0.0	219;219	2	1	GE	63-2	310	275	8
1.09	0.82	.000043	0.0	398	2	1	GE		660	750	8
0.57	0.35	.000045	0.0	314	2	1	GE		2134	3136	8
0.57	0.30	.000046	0.0	323	2	1	GE		3124	3151	8
1.38	1.76	.000004	0.0	326	2	1	GE	63-c	307	193	8
1.93	1.64	.004000	0.1 T	272;284	2	1	GE	56-12	540	588	8
1.93	1.54	.004000	0.1 T	267;278	2	1	GE	57-2	570	588	8
2.06	1.76	.004000	1.0 T	496	2	5	ANL	12a-0	311	405	1
1.93	1.66	.004000	1.0 T	264;281	2	1	GE	57-1	329	432	8
1.93	1.60	.004000	1.0 T	264;281	2	1	GE	56-11	331	432	8
1.00	0.30	.004000	1.0 T	342	2	5	ANL	6A-0	930	1439	1
0.50	0.33	.004000	1.0 T	271	2	5	ANL	4A-2	3190	7146	1
0.49	0.29	.004000	1.0 T	151;158	2	1	GE	57-11	3869	7579	8
0.43	0.29	.004000	1.0 T	162;167	2	1	GE	57-9	3351	7579	8
3.45	3.64	.004000	10.0 T	309;309	2	1	GE	66-9	09	89	8
2.02	1.77	.004000	10.0 T	469	2	1	ANL	4A-7	233	216	1
2.00	1.71	.004000	10.0 T	254;254	2	1	GE	56-0	193	219	8
2.00	1.71	.004000	10.0 T	254;254	2	1	GE	56-1	201	219	8
1.00	0.79	.004000	10.0 T	382	1	1	ANL	7-00	320	607	1
0.29	0.78	.004000	10.0 T	189;189	2	1	GE	66-10	347	617	8
0.93	0.77	.003900	10.0 T	390	2	5	ANL	1A-11	640	626	1

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HFA ^a NO. ^d	HFA ^a TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	RFF
TEST TEMPERATURE = 550 C (1202 F)											
0.49	0.32	.004000	10.0 T	139;151	2	1	GE	57-12	1703	2367	8
0.49	0.31	.004000	10.0 T	151;151	2	1	GE	65-1	1713	2367	8
0.25	0.10	.004000	10.0 T	113;113	2	1	GE	63-3	8040	19295	8
2.03	1.73	.004000	30.0 T	232;232	2	1	GE	53-10	140	158	8
2.02	1.76	.004000	30.0 T	232;232	2	1	GE	53-12	165	163	8
0.49	0.33	.004000	30.0 T	148;148	2	1	GE	56-3	1210	1461	8
0.48	0.34	.004000	30.0 T	144;144	2	1	GE	56-2	802	1527	8
1.99	1.74	.000040	30.0 T	218;232	2	1	GE	57-10	142	151	8
1.96	1.75	.000040	30.0 T	192;208	2	1	GE	57-4	182	153	8
1.48	1.77	.004000	60.0 T	245;245	2	1	GE	54-2	144	145	8
1.93	1.78	.004000	60.0 T	223;223	2	1	GE	54-1	158	145	8
0.49	0.34	.004000	60.0 T	137;137	2	1	GE	65-4	995	1142	8
2.00	1.30	.004000	180.0 T	209;219	2	1	GE	57-7	120	120	8
1.98	1.78	.004000	180.0 T	219;219	2	1	GE	57-6	150	121	8
1.05	0.67	.004200	180.0 T	360	1	3	ANL	T-242	313	263	2
2.02	1.80	.000040	180.0 T	425	1	3	ANL	T-70	146	105	7
1.01	0.84	.000040	180.0 T	351	1	3	ANL	T-115	213	254	7
1.98	1.80	.004000	600.0 T	193;207	2	1	GE	66-1	149	106	8
2.01	1.81	.000040	600.0 T	401	1	3	ANL	T-99	07	84	1
TEST TEMPERATURE = 700 C (1292 F)											
2.41	2.05	.000800	0.0	256;281	2	15	ANC	20-E	245	266	10
1.01	0.70	.000800	0.0	217;232	2	15	ANC	18-E	882	1127	10
0.55	0.31	.000800	0.0	168;206	2	15	ANC	19-E	3905	4210	10
0.35	0.14	.000800	0.0	153;152	2	15	ANC	30-E	18964	18943	10
1.00	0.78	.004000	6.0 T	208;203	2	12	ANC	A-44	1180	554	13

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	SPEC. NO.	OBSERVED CYCLES TO FAIL	COMPUTED CYCLES TO FAIL ^f	REF
TEST TEMPERATURE = 700 C (1292 F)											
0.50	0.43	.000800	60.0 T	143;133	2	14	ANC	A-41	601 ^g	596	13
TEST TEMPERATURE = 816 C (1500 F)											
2.06	1.81	.004100	0.0	323	2	1	GF		260	236	8
2.02	1.78	.004000	0.0	305	2	5	ANL	7A-11	321	302	1
1.99	1.76	.004000	0.0	145;154	2	5	ANL	60-0	302	301	1
1.07	0.83	.004300	0.0	307	2	1	GE		764	806	8
0.57	0.36	.004500	0.0	271	2	1	GE		2477	2546	8
2.05	1.83	.000410	0.0	279	2	1	GF		145	168	8
1.06	0.86	.000420	0.0	256	2	1	GE		429	408	8
0.56	0.36	.000450	0.0	248	2	1	GE		1334	1182	8
0.56	0.36	.000450	0.0	259	2	1	GE		1351	1182	8
2.05	1.86	.000041	0.0	241	2	1	GE		130	103	8
1.05	0.87	.000042	0.0	233	2	1	GE		307	230	8
0.56	0.38	.000044	0.0	232	2	1	GE		788	591	8

TABLE I. Summary of Elevated-temperature, Strain-controlled Zero and Tension Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

^aIncluded are essentially all axial strain-controlled data obtained at temperatures of 430°C and greater at Argonne National Laboratory, Aerojet Nuclear Company, General Electric Company - Nuclear Systems Program, and Battelle-Columbus Laboratories. Also included are GE diametral strain-controlled data (data for which no test numbers are given). The following data are not included: block-loading, mean-strain, surface-finish-effects, cyclic-creep, weld metal, cold-worked, irradiated, and notched-specimen tests. All tests were conducted in an air environment.

^bT denotes hold time at constant peak tension strain.

^cFor hold-time tests, the stress values given are before relaxation. A single value corresponds to the total peak-to-peak stress range near $N_f/2$; when two numbers are given, the first is the tensile component of the stress range, and the second is the compressive component.

^dMaterial heat numbers are as follows:

1. 9T2796	5. X22807 (Type 304L stainless steel)
2. 55697	6. 600414
3. 346845	7. 8043813
4. 346544	8. 300380

^ePretest Heat treatments are as follows:

1. Solution annealed	8. Stress relieved 30 min at 760°C (1400°F)
2. Solution annealed and aged 1000 h at 566°C (1050°F)	9. Hot rolled
3. Solution annealed and aged 1000 h at 593°C (1100°F)	10. As-fabricated or as-welded
4. Solution annealed and aged 1000 h at 650°C (1202°F)	11. Aged 3096 h at 410°C (770°F)
5. Stress relieved 15 min at 760°C (1400°F)	12. Aged 8760 h at 400°C (752°F)
6. Stress relieved and aged 47 h at 566°C (1050°F)	13. Aged 8000 h at 593°C (1100°F)
7. Stress relieved and aged 160 h at 650°C (1202°F)	14. Aged 8760 h at 750°C (1382°F)
	15. Aged 9240 h at 750°C (1382°F)

^fCycles to failure computed from regression-analysis equation.

^gTest terminated before failure.

^hTest not included in regression analysis but is tabulated here for completeness.

TABLE II. Summary of Elevated-temperature, Strain-controlled, Compression and Tension Plus Compression Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	TEST NO.	OBSERVED CYCLES TO FAIL	REF
TEST TEMPERATURE = 593 C (1100 F)										
1.03	0.72	.004000	1.0 C	254;241	3	3	ANL	845-24	2747	7
1.01	0.70	.004000	1.0 C	477	2	1	ANL	9A-2	2973	1
1.01	0.72	.004000	1.0 C	463	1	1	ANL	T-18	2995	1
1.01	0.70	.004000	1.0 C	475	1	3	ANL	AA-14	3344	1
0.99	0.71	.004000	1.0 C	461	2	4	ANL	10A-1	2353	1
0.99	0.69	.004000	1.0 C	487	2	4	ANL	10A-10	2272	1
0.99	0.67	.004000	1.0 C	480	3	3	ANL	845-21	2401	7
1.01	0.71	.004000	2.0 C	242;245	1	3	ANL	T-376	2993	7
0.99	0.69	.003900	2.0 C	245;244	3	3	ANL	845-17	2659	7
1.02	0.72	.004000	4.0 C	477	4	3	ANL	544-5	2366	7
1.02	0.71	.004100	4.0 C	258;254	1	3	ANL	T-376	2453	6
1.00	0.71	.004000	4.0 C	248;237	3	3	ANL	845-18	2997	7
1.01	0.74	.004000	10.0 C	441	2	3	ANL	51-9	2910	1
1.03	0.72	.004000	10.0 C	231;224	3	3	ANL	845-15	2624	7
1.02	0.72	.004000	1.0 S	487	1	3	ANL	AA-17	2207	1
1.01	0.73	.004000	1.0 S	446	2	4	ANL	9A-12	2065	1
1.01	0.73	.004000	1.0 S	492	1	1	ANL	T-20	2082	1
1.00	0.70	.004000	1.0 S	483	2	1	ANL	9A-5	2432	1
1.00	0.74	.004000	1.0 S	443	2	4	ANL	10A-12	2276	1
0.99	0.72	.004000	1.0 S	432	2	4	ANL	10A-9	3157	1
0.99	0.69	.004000	1.0 S	240;250	3	3	ANL	845-19	2880	7
1.03	0.74	.004000	2.0 S	243;247	1	3	ANL	T-377	2177	6
0.99	0.71	.004000	2.0 S	476	2	3	ANL	845-20	2348	7
1.02	0.77	.004000	10.0 S	421	2	3	ANL	55-10	1470	1

TABLE II. Summary of Elevated-temperature, Strain-controlled, Compression and Tension Plus Compression Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

TOTAL STRAIN RANGE, %	PLASTIC STRAIN RANGE, %	TOTAL STRAIN RATE, 1/S	HOLD TIME, MIN. ^b	STRESS RANGE, MPa ^c	HEAT NO. ^d	HEAT TREAT ^e	LAB	TEST NO.	OBSERVED CYCLES TO FAIL	RFF
TEST TEMPERATURE = 650 C (1202 F)										
0.98	0.71	.003300	1.0 C	432	2	5	ANL	7A-2	1944	1
1.98	1.71	.000040	5.5 C	226;226	2	1	GE	65-12	258	8
1.98	1.70	.004000	30.0 C	264;264	2	1	GE	54-3	480	8
1.97	1.70	.004000	30.0 C	234;234	2	1	GE	52-11	409	8
1.00	0.77	.004000	1.0 S	345	2	8	ANL	7A-6	1714	7
0.49	0.32	.004000	1.0 S	137;137	2	1	GE	57-6	6916	8
0.49	0.31	.004000	1.0 S	144;144	2	1	GE	65-3	10266	8
1.98	1.71	.004000	3.0 S	233;233	2	1	GE	53-8	526	8
0.49	0.37	.004000	10.0 S	130;130	2	1	GE	65-10	7001	8
1.98	1.80	.004000	30.0 S	214;214	2	1	GE	53-9	380	8
1.98	1.84	.004000	30.0 S	220;220	2	1	GE	54-9	416	8
0.49	0.34	.004000	0.0	141;141	2	1	GE	65-1	4430	8
2.00	1.79	.004000	0.0	232;233	2	1	GE	65-9	336	8
1.98	1.77	.004000	0.0	230;230	2	1	GE	65-11	308	8

TABLE II. Summary of Elevated-temperature, Strain-controlled, Compression and Tension Plus Compression Hold-time Low-cycle Fatigue Data for Type 304 Stainless Steel^a (Contd.)

^aIncluded are essentially all axial strain-controlled data obtained at temperatures of 430°C and greater at Argonne National Laboratory, Aerojet Nuclear Company, General Electric Company - Nuclear Systems Program, and Battelle-Columbus Laboratories. The following data are not included: block-loading, mean-strain, surface-finish-effects, cyclic-creep, weld metal, cold-worked, irradiated, and notched-specimen tests. All tests were conducted in an air environment.

^bC denotes hold time at constant peak compression strain, and S denotes equal tension and compression (symmetrical) hold times.

^cFor hold-time tests, the stress values given are before relaxation. A single value corresponds to the total peak-to-peak stress range near $N_f/2$; when two numbers are given, the first is the tensile component of the stress range, and the second is the compressive component.

^dMaterial heat numbers are as follows:

1. 9T2796	3. 346845
2. 55697	4. 346544

^ePretest heat treatments are as follows:

1. Solution annealed
3. Solution annealed and aged 1000 h at 593°C (1100°F)
4. Solution annealed and aged 1000 h at 650°C (1202°F)
5. Stress relieved 15 min at 760°C (1400°F)
8. Stress relieved 30 min at 760°C (1400°F)

^fThe first number denotes hold time at peak tension strain per cycle, and the second number denotes hold time at peak compression strain per cycle.

TABLE III. Standard Errors and Significance Levels for
Coefficients of Eq. (1)

Independent Variable	Coefficient	Standard Error of Coefficient	Significance Level for Coefficient = 0
Intercept	1.2055	0.1259	<0.0001
S	0.6600	0.1735	0.0002
S^2	0.1804	0.0663	0.0067
S^4	-0.008143	0.002773	0.0035
$R \cdot S^4$	0.000253	0.000104	0.0151
$T \cdot S^4$	0.000218	0.000087	0.0123
$R \cdot T^2$	-0.0005466	0.0000399	<0.0001
$R \cdot H^2$	-0.005557	0.000567	<0.0001
$H \cdot R^2$	-0.002939	0.000385	<0.0001
$H \cdot T$	0.01197	0.00068	<0.0001
$H^2 \cdot T^2$	-0.0005164	0.0000802	<0.0001

Fig. 1. Typical Fully Reversed Test Waveforms. (a) Continuous-cycling strain-controlled test, and (b) strain-controlled test with tensile hold time. Neg. No. MSD-63057.

Fig. 2. Percent of Residuals That Have a Value Less Than or Equal to a Given Value vs That Value. The standard normal line for $\mu = 0$ and $\sigma = 0.01348$ is also shown. Neg. No. MSD-62753.

Fig. 3. Residual Values vs $(\text{log}_{10} N_{\text{comp}})^{-1/2}$. Neg. No. MSD-63640.

Fig. 4. Residual Values vs $(\text{log}_{10} N_{\text{obs}})^{-1/2}$. Neg. No. MSD-63645.

Fig. 5. Residual Values vs Total Strain Range. Neg. No. MSD-63648.

Fig. 6. Residual Values vs Strain Rate. Neg. No. MSD-63646.

Fig. 7. Residual Values vs Temperature. Neg. No. MSD-63647.

Fig. 8. Residual Values vs Tension Hold Time. Neg. No. MSD-63643.

Fig. 9. Residual Values vs Testing Laboratory. Neg. No. MSD-63641.

Fig. 10. Residual Values vs Heat Number. Neg. No. MSD-63644.

Fig. 11. Residual Values vs Heat Treatment. Neg. No. MSD-63642.

Fig. 12. Observed Cyclic Life vs Life Computed from the Regression Equation. The dashed line corresponds to equality of the two life values, and the solid lines define the 95% predicted interval for a given value of computed life. Neg. No. MSD-62657.

Fig. 13. Comparison of Regression Equation Curves for Various Strain Rates with Experimental Data for Type 304 Stainless Steel at 430°C (806°F). Neg. No. MSD-63629.

Fig. 14. Comparison of Regression Equation Curves for Various Strain Rates with Experimental Data for Type 304 Stainless Steel at 482°C (900°F). Neg. No. MSD-63614.

Fig. 15. Comparison of Regression Equation Curves for Various Strain Rates with Experimental Data for Type 304 Stainless Steel at 538°C (1000°F). Neg. No. MSD-63626.

Fig. 16. Comparison of Regression Equation Curves for Various Strain Rates with Experimental Data for Type 304 Stainless Steel at 566°C (1050°F). Neg. No. MSD-63625.

Fig. 17. Comparison of Regression Equation Curves for Various Strain Rates with Experimental Data for Type 304 Stainless Steel at 593°C (1100°F). The 0.004 s⁻¹ strain-rate data are shown in a separate plot (Fig. 18) for clarity. Neg. No. MSD-63618.

Fig. 18. Comparison of Regression Equation Curves for Various Strain Rates with Experimental Data for Type 304 Stainless Steel at 593°C (1100°F) and $\dot{\epsilon} = 0.004 \text{ s}^{-1}$. Neg. No. MSD-63624.

Fig. 19. Comparison of Regression Equation Curves for Various Strain Rates with Experimental Data for Type 304 Stainless Steel at 650°C (1202°F). Neg. No. MSD-63619.

Fig. 20. Comparison of Regression Equation Curves for Various Strain Rates with Experimental Data for Type 304 Stainless Steel at 700°C (1292°F). Neg. No. MSD-63623.

Fig. 21. Comparison of Regression Equation Curves for Various Strain Rates with Experimental Data for Type 304 Stainless Steel at 816°C (1500°F). Neg. No. MSD-63622.

Fig. 22. Regression Equation Curves for Various Tension Hold Times for Type 304 Stainless Steel at 430°C (806°F). No tension hold-time data are available at this temperature. Neg. No. MSD-63609.

Fig. 23. Comparison of Regression Equation Curves for Various Tension Hold Times with Experimental Data for Type 304 Stainless Steel at 482°C (900°F). Neg. No. MSD-63611.

Fig. 24. Comparison of Regression Equation Curves for Various Tension Hold Times with Experimental Data for Type 304 Stainless Steel at 538°C (1000°F). Neg. No. MSD-63621.

Fig. 25. Comparison of Regression Equation Curves for Various Tension Hold Times with Experimental Data for Type 304 Stainless Steel at 566°C (1050°F). Neg. No. MSD-63615.

Fig. 26. Comparison of Regression Equation Curves for Various Tension Hold Times with Experimental Data for Type 304 Stainless Steel at 593°C (1100°F). Neg. No. MSD-63610.

Fig. 27. Comparison of Regression Equation Curves for Various Tension Hold Times with Experimental Data for Type 304 Stainless Steel at 650°C (1202°F). Neg. No. MSD-63620.

Fig. 28. Comparison of Regression Equation Curves for Various Tension Hold Times with Experimental Data for Type 304 Stainless Steel at 700°C (1292°F). Neg. No. MSD-63617.

Fig. 29. Regression Equation Curves for Various Tension Hold Times for Type 304 Stainless Steel at 816°C (1500°F). No tension hold-time data are available at this temperature. Neg. No. MSD-63627.

Fig. 30. Comparison of Regression Equation Curves for Various Tension Hold Times and Two Strain Rates with Experimental Data for Type 304 Stainless Steel at 482°C (900°F). Neg. No. MSD-63628.

Fig. 31. Comparison of Regression Equation Curves for Various Tension Hold Times and Two Strain Rates with Experimental Data for Type 304 Stainless Steel at 538°C (1000°F). Neg. No. MSD-63612.

Fig. 32. Comparison of Regression Equation Curves for Various Tension Hold Times and Two Strain Rates with Experimental Data for Type 304 Stainless Steel at 593°C (1100°F). Neg. No. MSD-63613.

Fig. 33. Comparison of Regression Equation Curves for Various Tension Hold Times and Two Strain Rates with Experimental Data for Type 304 Stainless Steel at 650°C (1202°F). Neg. No. MSD-63616.

Fig. 34. Comparison of Lower Confidence Limits for a New Observation (Prediction Limits) with ASME Design Curve. Neg. No. MSD-63058.

Fig. 35. Normal Distribution Probability Density Functions for Residuals from Various Laboratories. Neg. No. MSD-63056.

Fig. 36. Normal Distribution Probability Density Functions for Zero and Nonzero Tensile Hold-time Data. Neg. No. MSD-63055

Fig. 37. Normal Distribution Probability Density Functions for Continuous-cycling Data with Various Heat Treatments. Neg. No. MSD-63054.

Fig. 38. Normal Probability Diagram of Residuals for Solution-annealed Data. Neg. No. MSD-63189.

Fig. 39. Normal Probability Diagram of Residuals for Solution-annealed and Aged Data. Neg. No. MSD-63188.

Fig. 40. Normal Probability Diagram of Residuals for Stress-relieved Data. Neg. No. MSD-63190.

Fig. 41. Normal Probability Diagram of Residuals for As-fabricated Data. Neg. No. MSD-63191.