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STRAINRANGE PARTITIONING LIFE PREDICTIONS OF THE LONG TIME METAL PROPERTIES COUNCIL CREEP-FATIGUE TESTS

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ABSTRACT

The method of Strainrange Partitioning is used to predict the cyclic lives of the Metal Properties Council's long time creep fatigue interspersion tests of several steel alloys. Comparisons are made with predictions based upon the Time- and Cycle-Fraction approach. The method of Strainrange Partitioning is shown to give consistently more accurate predictions of cyclic life than is given by the Time- and Cycle-Fraction approach.

NOMENCLATURE

$\Delta\varepsilon_{IN}$ = inelastic strainrange

$\Delta\varepsilon_{PP}$ = PP component of inelastic strainrange

$\Delta\varepsilon_{CP}$ = CP component of inelastic strainrange

F_{PP} = $\Delta\varepsilon_{PP}/\Delta\varepsilon_{IN}$

F_{CP} = $\Delta\varepsilon_{CP}/\Delta\varepsilon_{IN}$

N_{PP} = pure PP life, cycles to failure

N_{CP} = pure CP life, cycles to failure

n = number of rapid fatigue cycles per creep period

NOBS = observed number of combined creep-fatigue cycles to failure

NPRE = predicted number of combined creep-fatigue cycles to failure

N = Nth combined cycle

EF = equivalent factors on life (see Appendix)

SE = standard error of estimate

D_P = plastic tensile ductility = ln(100/(100 - $\%RA_P$))

D_C = creep rupture ductility = ln(100/(100 - $\%RA_C$))

RA = reduction of area

Num = number of tests

TSR = total strainrange during fatigue portion of cycle

T_f = time to failure, hours

INTRODUCTION

An important question facing the designer of engineering structures for long time service at elevated temperatures is the analytical procedure to be used to predict cyclic lives that are well in excess of those normally attained in the laboratory. A program intended to provide designers with useful information in predicting cyclic behavior at high temperatures was initiated a few years ago by the Metal Properties Council (MPC). This effort involved extensive testing of selected steels at elevated temperatures under interspersed creep-fatigue conditions and was carried out by the Materials Technology Corporation (MTC) of Ann Arbor, Michigan. A complete account of this program has been given by Curran and Wundt (1-4) along with life predictions using the Time- and Cycle-Fraction (TCF) method as used in ASME Code Case 1592 (5). The tests were designed to be conducted in such a manner as to be ideal for analysis by the TCF method.

The MPC data represent an extensive body of long time (up to

7000 hours) creep-fatigue results, and hence provide an opportunity to evaluate the ability of the Strainrange Partitioning method (SRP) to predict long hold time behavior.

Cyclic life predictions have previously been made by Saltsman and Halford (6) for one of the alloys (annealed 2.25Cr-1Mo) used in the MPC program. Those predictions were based upon short time (<100 hrs) SRP life relations established from cyclic creep-fatigue tests conducted in the authors' laboratory (7).

In the current study, we have applied the SRP method to all of the MPC interspersed creep-fatigue results. Details of the life predictions are discussed in the following sections. The SRP life predictions are compared with the predictions reported by Curran and Wundt (1-4) using the TCF approach.

Special appreciation is due Messrs Adolph O. Schaefer, Robert M. Curan and Boris Wundt of the MPC for making available to the authors the detailed results of the cyclic tests and the unpublished results of the materials characterization study.

METHOD OF STRAINRANGE PARTITIONING (SRP)

The SRP method has been proposed for predicting cyclic life in the high-temperature, creep-fatigue regime. This method was first presented in 1971 by Manson, Halford, and Hirschberg (7) and has been undergoing continued development since that time (8-11). One of the recent developments that is pertinent to the analysis of the MPC data are the Ductility Normalized-Strainrange Partitioning (DN-SRP) life relations and procedures (12).

In the absence of experimentally determined life relations, these equations enable the estimation of the four generic inelastic strainrange SRP life relationships (PP, PC, CC, and CP) from a knowledge of an alloy's tensile plastic ductility (D_P) and creep rupture ductility (D_C). These equations thus provide a method for estimating the reduction in cyclic life due to the harmful effects of long exposures at elevated temperatures as indicated by reduction in creep rupture ductility.

It was necessary to determine only the PP and CP life relations for analysis of the MPC results since the interspersion creep-fatigue tests contained only PP and CP type strainranges. The PP life relation for each material did not have to be estimated from the DN-SRP relation but rather could be determined from the continuous strain cycling (PP) tests conducted during the MPC test program. The CP life relation for each alloy was determined using the appropiate DN-SRP life relations and time dependent creep rupture data provided by the MPC. No tests were performed to permit the experimental determination of this life relation.

Although the MPC data were originally generated with the intent of evaluating only the TCF approach to creep-fatigue interaction, the results were well documented and in a format compatible with the application of the SRP method.

In making a life prediction using SRP, three basic steps are followed.

(a) The PP, PC, CC, and CP life relations must be established either by experiment or by an estimation procedure such as the DN-SRP equations.

(b) The magnitude of the inelastic strainrange must be known, either by direct measurement, or by calculation using constitutive equations. The inelastic strainrange is then partitioned into its various components (PP, PC, CC, CP).

(c) Finally, a life prediction is obtained using an appropriate damage rule, such as the interaction damage rule, to assess the damage contribution of each partitioned strainrange component. The predicted life is calculated by solving the damage rule equation.

Each of these steps will be applied to the MPC creep-fatigue interspersion test results in the ensuing sections with the recognition that the steps are somewhat simplified since only two components (PP and CP) of the inelastic strainrange are involved.

MPC CREEP-FATIGUE INTERSPERSION TESTS

The alloys, heat treat conditions, and test temperatures involved in the the MPC interspersion program are summarized below.

a) 1Cr-1Mo-0.25V,	Normalized and Tempered,	540C(1000F)
b) 1Cr-1Mo-0.25V,	Normalized and Tempered,	485C(900F)
c) 2.25Cr-1Mo,	Annealed,	540C(1000F)
d) 2.25Cr-1Mo,	Normalized and Tempered,	540C(1000F)
e) 2.25Cr-1Mo,	Quenched and Tempered,	485C(900F)
f) Type 304 Stainless,	Solution Annealed,	650C(1200F)
g) Type 304 Stainless,	Solution Annealed,	565C(1050F)

In the MPC creep-fatigue interspersion tests, one combined cycle, Fig. 1, consists of a creep period of either 23 or 47 hours at a constant tensile stress followed by a rapid reversal of strain back to the point of zero inelastic strain, followed by a preselected number of interspersed rapid fatigue cycles at a fixed total strainrange about a zero mean strain. At the beginning and end of each combined cycle, the net strain is nominally zero. Thus, strain ratcheting is not present in these tests.

It should be noted that the number of interspersed fatigue cycles reported in (1-4) is one-half cycle greater than the values reported herein. This extra half cycle is accounted for in the present analysis as being the half cycle of plastic strain that reverses the tensile creep strain obtained during the hold period. It is emphasized that all of the strains are accounted for in the SRP analysis presented.

ANALYSIS OF MPC TESTS

SRP Life Relations

Only two of the four generic SRP life relations are needed to predict the lives of the MPC creep-fatigue interspersion tests since only PP and CP strainranges were present. A noteworthy feature of SRP in this case is that the life relations could be determined from existing data.

PP Life Relation

The PP life relation for each alloy was determined from data from the MTC fatigue tests and the interspersion tests. Additional strain-controlled fatigue tests (3) were performed by MTC (3) during the interspersion testing using specimens identical to those used in the interspersion tests. However, the inelastic strainrange values were never reported for these fatigue tests. Therefore, the relationship between total strainrange and inelastic strainrange had to be established using total strainrange values and the corresponding inelastic strainrange values reported for the rapid cycling portion of the interspersion tests. The validity of this approach was verified by comparing these results with the cyclic data reported in (13) and the unpublished MPC cyclic data.

The PP life relations were obtained directly from these data and are shown in Figs. 2(a-e). Since only two or three data points are available for each dataset, a least squares curve fit is not justifiable and in fact could be misleading. Previous experience was used as a guide for fixing a straight line of constant slope through the limited data. For the 1Cr-1Mo-0.25V steel and the 2.25Cr-1Mo steel, a slope of -0.8 was used and is consistant with values reported by Jaske and Mindlin (13), Brinkman et al (14), and Ellis et al (15) for annealed 2.25Cr-1Mo, and by Levin (16) for 1Cr-1Mo-0.25V. This steep slope is appropiate in only the large strain regime which is considered in this paper. For Type 304 stainless steel, a constant slope of -0.6 was used based upon the findings of Saltsman and Halford (17) for Type 304 and 316 stainless steels.

Although the PP data are sparse, they were obtained near the strainrange levels of direct interest to the current analysis. The PP line is based on short time data only. No tensile ductility data after high temperature long-time exposure are available to estimate the effects of exposure on this life relation (12).

CP Life Relation

Two DN-SRP equations have been proposed for use in estimating the CP life relation, one for conditions that produce transgranular cracking and the other for conditions that produce intergranular cracking during creep (10).

$$N_{CP} = D_C(5\Delta\varepsilon_{IN})^{-1.67} \qquad \text{(Transgranular)}$$

$$N_{CP} = D_C(10\Delta\varepsilon_{IN})^{-1.67} \qquad \text{(Intergranular)}$$

Examination of the fractures of creep rupture specimens for each alloy revealed that only the Type 304 stainless steel suffered intergranular cracking; the other alloys failed by transgranular cracking. Plots of the creep rupture ductility as a function of rupture time are presented in Figs. 3(a-e). A line is drawn through the limited data that fall within the extremes of time to failure observed in the MPC creep-fatigue tests. These data were obtained from (13) and from unpublished data supplied to the authors by the MPC (Table A1, Appendix).

As first suggested by Manson (9), the creep rupture ductility used in the DN-SRP equations is the ductility measured in a conventional creep rupture test for the same time to failure as is experienced in the cyclic test being analyzed. For example, if the lifetime of a cyclic test is known, say 1000 hours, the 1000 hour creep rupture ductility would be used in the DN-SRP equation for calculating the cyclic life. In the more typical case, the time to failure is not known when cyclic life is being predicted. Here an iterative procedure is used until the calculated time to failure agrees with the estimated time to failure (and the associated creep rupture ductility).

Partitioning of Strainranges

Partitioning the inelastic strains of the hysteresis loop associated with the creep period is a matter of simply examining the detailed test results. The inelastic strainrange is the width of the hysteresis loop ABCA (Fig. 1) at zero stress, and the CP strainrange component is taken as the amount of creep strain accumulated under the constant stress. The PP component is the difference between the inelastic strainrange and the CP component.

The hysteresis loop ,CDEC, traversed during the interspersed fatigue cycling is also shown in Fig. 1. It is assumed that the straining rate is high enough to exclude creep effects and thus the entire inelastic strainrange for this hystersis loop is PP.

One combined creep-fatigue interspersion test cycle has three contributions to damage - the PP and CP strainrange components of the inelastic strainrange produced immediately prior to and during the creep portion, and the PP strainrange produced as a result of the interspersed fatigue cycling portion. A calculation of the expected cyclic life can be made from a knowledge of the magnitudes of these three strainranges and a knowledge of the material's PP and CP life relations at the temperature of interest.

Life Predictions

The analytic details of how damage is summed using the interaction damage rule of SRP is presented in the Appendix. The number of observed cycles to failure is defined as the number of completed combined cycles to failure.

The SRP life predictions were made using two slightly different analytical procedures.

SRP 1 - Damage during the creep period was summed on each and every cycle using the instantaneous PP or CP strainrange values as dictated by the cyclic hardening or softening characteristics of the material. Examples of cyclic variations in the inelastic strainrange during the creep periods are shown in Figs. 4(a-g) for each of the seven datasets. Typically, the inelastic strainrange increased during the latter portion of the tests, reflecting the steadily increasing creep rates as the tests progressed. In some cases, the creep rates increased by over an order of magnitude from the first to the last cycle. It was because of these large variations that a cycle-by-cycle analysis was made.

SRP 2 - Damage during the creep period was assumed constant over the entire test and determined by the arithmetic average values for the PP and CP strainrange components over the life of the test.

Summing damage on a cycle-by-cycle basis is inherently the most precise procedure for determining the total damage during the creep periods. It is also the most laborious and would not be feasible in some situations. Then, average or typical strainrange values would have to be determined. To assess the magnitude of the effects of such an approximation, life predictions were made by using arithmetic average PP and CP strainrange values during the creep periods. The fatigue damage incurred during the rapid cycling portion of the combined cycle was estimated the same way for both types of SRP life predictions. The rapid cycling was done under strain control and the inelastic strainrange generally reached a stable value early and remained stable during most of the test. Thus, the fatigue damage incurred during this portion of the combined cycle was estimated using strainrange values established at half-life.

The life predictions made by SRP are compared with the life predictions reported by Curran and Wundt (4) using the TCF method. A summary of the test results and the TCF predictions are given in Tables 1(a-g) and plotted in Figs. 5(a-g).

The results of the SRP life predictions obtained by summing damage every cycle are given in Tables 2(a-g) and plotted in Figs. 6(a-g), and the predictions obtained by using average strainrange values are listed in Tables 3(a-g) and plotted in Figs. 7(a-g). The central 45 degree lines in Figs. 5-7 represent exact agreement between observed and predicted lives. These central lines are bracketed by two parallel lines which indicate a factor of two on life above and below the exact agreement lines.

Assessment of Life Predictions

The following criteria are used to evaluate the accuracy of the above life predictions.

(1) percentage of test lives predicted within factors of 2, 3, and 4 of the observed lives

(2) percentage of points under or over predicted

(3) standard error of estimate (SE) or equivalent factors on life (EF) (see Appendix)

Results of the SRP and TCF life predictions for the alloys, heat treat conditions, and test temperatures involved in the MPC program are given in Table 4. Table 4(a) gives an evaluation of the SRP life predictions obtained by summing damage every cycle (SRP-1). A review of this table shows that 86 percent of the tests are predicted within factors of 2, 95 percent within factors of 3, and 99 percent within factors of 4. There is a slight tendency to overpredict with 61 percent of the test lives being over predicted. The SE for these predictions is 0.215. The equivalent factors on life for this value of SE is 1.64.

The evaluation of the SRP life predictions using average strainrange values (SRP-2) is given in Table 4(b). Using this procedure 77 percent of the tests are predicted within factors of 2, 92 percent within factors of 3, and 97 percent within factors of 4. Eighty-two percent of the test are overpredicted, and the SE is 0.263. The equivalent factors on life is 1.83.

For comparison purposes, the evaluation of the TCF predictions is given in Table 4(c). Here only 66 percent of the tests are predicted withinzfactors of two, 91 percent within factors of 3, and 98 percent within factors of 4. Eighty-one percent of the tests are over predicted and the SE is 0.281. The equivalent factors on life is 1.91.

The life predictions for type 304 stainless steel at 1050F are overpredicted using both the SRP and TCF methods as shown in Figs. 5(g),6(g), and 7(g). The reasons for this are not clear at this time.

A summary of the results obtained by each life prediction method is given in Table 5. The SRP predictions obtained by summing damage every cycle (SRP-1) are significantly better than the predictions obtained using the TCF method. The SRP life predictions based on average strainrange values (SRP-2) are of equal or greater accuracy than those given by the TCF method.

DISCUSSION

Comparison of SRP with TCF Life Prediction Methods

The MPC tests were designed and conducted in a manner ideal for analysis by the TCF method. Despite this analysis advantage, the method did not necessarily give the best results as evaluated by the three criteria used in the previous section. Best results were obtained using the method of SRP and summing damage on a cycle-by-cycle basis (see footnote). The TCF method is easy to apply in this idealized test situation. However, when applied to more realistic creep-fatigue problems, it is generally recognized that this method has some serious limitations. Manson (18) has discussed in detail the virtues and limitations of the TCF method. Two limitations that apply directly to this analysis will be discussed briefly below.

The damage fraction due to the cyclic creep is based on the time to rupture obtained from a conventional static creep rupture test. This type of test, however, does not necessarily reflect the actual time to failure experienced under cycling loading. To overcome this shortcoming, Manson et al(20) proposed basing the creep damage fraction on a creep rupture curve obtained from cyclic

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A very recent paper by Batte et al (19) has been brought to the attention of the authors. Their work parallels the current study in several respects, in that they have applied life prediction methods (including SRP and TCF) to an analysis of long time (up to two years duration) creep-fatigue tests of a 0.5Cr-Mo-V steam turbine casing material. However, their conclusions are clouded by the fact that rather unorthodox modifications were made to the procedures for appling the TCF method. A more direct assesment of the method's capabilities using ASME Code Case 1592 procedures remains to be accomplished.

tests. This curve generally lies to the right of (i.e. longer lives for the same stress) the conventional static creep rupture curve (21).

Also, the time to rupture is highly sensitive to stress level. In situations where the stress is not known accurately or changes rapidly with time, it is difficult to determine the creep damage accurately. A common example of the latter case is a high-temperature tensile strain hold fatigue cycle which produces repeated stress relaxation. Jaske et al (22) conducted tests of this type using Incoloy 800 and Type 304 stainless steel. These tests involved tensile hold times from 10 to 300 minutes. The lives of these tests were then predicted using the TCF method. The creep damage fraction incurred during the hold period was determined using stresses measured during the relaxation period. The lives of these tests were overpredicted by a factor of about 3 at the one extreme and underpredicted by a factor of about 20 at the other. Manson (9), however, using SRP, was able to predict the lives of these same tests to within factors of two.

Ductility Normalized Equations

The creep rupture ductility values used in the SRP life predictions are based on an equal time to failure for both the cyclic and creep rupture tests. The validity of this approach is illustrated with the aid of Figs. 8(a-g). Here the ratio of observed to predicted life is plotted against time to failure. For the situation where the creep rupture ductility is little affected by exposure time, one would not expect the actual lives or the predictions to be affected by the duration of the test. This indeed is the case for 1Cr-1Mo-0.25V and annealed 2.25Cr-1Mo as seen in Figs. 8(a-c).

The creep rupture ductility of the remaining alloys, 2.25Cr-1Mo in the normalized and tempered and the quenched and tempered conditions and Type 304 stainless steel, are affected by exposure time as shown in Figs. 3(c-e). For the 2.25Cr-1Mo in both conditions the ratio of maximun/minimum ductilities for the times involved is about 1.6. For Type 304 stainless, this ratio is about 3.0. It is very important that such large changes in an alloy's strain absorption capability be accounted for in making life predictions.

The effects of basing the life predictions on short-time creep rupture ductility values is illustrated by the following example. For 2.25Cr-1Mo in the normalized and tempered condition, the ductility is constant at 1.60 up to about 600 hours and then decreases. The total time under creep loading for test specimen number 6B4E was 2824 hours*, and the corresponding creep rupture ductility is 0.97. Using this latter ductility value and summing damage every cycle, the damage fraction due to creep is 0.968, and the ratio of observed to predicted life is 0.99 (see Table 3(d)). If the life prediction had been based on the short time ductility of 1.60, the damage fraction due to creep would have been 0.587, and the ratio of observed to predicted life would have been 0.61. Obviously, the accuracy of the life prediction would suffer by using only the short time ductility value. This example, thus, illustrates the importance of using long time ductility values when predicting long time cyclic lives.

*failed 4 hours into the 61st cycle of 47 hours per cycle.

SUMMARY OF RESULTS

The SRP life prediction method has been used to predict the cyclic lives of the MPC creep-fatigue interspersion tests of several steel alloys. Since only the PP and CP components of inelastic strainrange are present in these tests, it was necessary to establish only the PP and CP life relations. The PP life relations were obtained directly from continuous cycling fatigue data generated as part of the MPC testing program whereas the CP life relations were estimated using creep rupture ductility data and the DN-SRP life relations.

A summary of the results obtained by each life prediction method is given in Table 5. The method of SRP gives consistently more accurate life predicitons than are given by the TCF approach. More specifically, in the case of the detailed SRP-1 analysis, the predictions are significantly more accurate than those obtained by the TCF method. When the less detailed SRP-2 analysis was made, the life predictions were still more accurate, although not significantly, than those obtained by the TCF method.

APPENDIX

Interaction Damage Rule

The interaction damage rule can be written in the following form to account for the damage incurred during both the creep portion and the interspersed rapid cycling portion of the combined cycle.

$$\underbrace{F_{CP}/N_{CP} + F_{PP}/N_{PP}}_{\text{Creep portion}} + \underbrace{n/N_{PP}}_{\text{Interspersed fatigue portion}} = \frac{1}{NPRE} \qquad (A1)$$

Each term on the left hand side is the damage per combined cycle for each type of strainrange component.

When half-life or average strainrange values are used, life can be predicted using equation (A1) since it is presumed that all cycles are the same. But, when a cyclic variation in strainrange is to be taken into account, the damage must be summed on a cycle-by-cycle basis until the summation of damage is equal to unity as indicated below.

$$\sum_{i=1}^{NPRE} \left(\frac{F_{CP}}{N_{CP}}\right)_i + \sum_{i=1}^{NPRE} \left(\frac{F_{PP}}{N_{PP}}\right) + \sum_{i=1}^{NPRE} \left(\frac{n}{N_{PP}}\right) = 1.0 \qquad (A2)$$

The predicted life, NPRE, is equal to the number of required summations.

The actual variations in strainrange of the MPC tests were known prior to making the life predictions. Hence these variations could be accounted for. The inelastic strainrange during rapid cycling generally stablized early and remained stable over most of the test. Thus the fatigue damage incurred during rapid cycling was estimated using the half-life values of inelastic strainrange. Based on the above, equation (A2) can be rewritten as follows.

$$\sum_{i=1}^{NOBS} \left(\frac{F_{CP}}{N_{CP}}\right)_i + \sum_{i=1}^{NOBS} \left(\frac{F_{PP}}{N_{PP}}\right)_i + \frac{n\,(NOBS)}{N_{PP}} = \frac{NOBS}{NPRE} \qquad (A3)$$

This equation was used for making SRP life predictions wherein damage was summed on an actual cycle-by-cycle basis.

Sample Calculation

The procedures followed in predicting the cyclic lives of the MPC tests will be illustrated with a sample calculation using average strainrange values for one of the tests and equation (A1).

The method of summing damage on a cycle-by-cycle basis will not be illustrated because the computations are too lengthy. However, the basic procedures are the same.

The test selected for analysis is 8B4E, Type 304 stainless steel at 650C (see Table 1(f)).

<u>creep portion</u>

$\Delta\epsilon_{PP} = 0.00034$ $\qquad F_{PP} = \Delta\epsilon_{PP}/\Delta\epsilon_{IN} = 0.064$

$\Delta\epsilon_{CP} = 0.00498$ $\qquad F_{CP} = \Delta\epsilon_{CP}/\Delta\epsilon_{IN} = 0.936$

$\Delta\epsilon_{IN} = 0.00532$

NOBS = 31 cycles

time to failure = 1490 hours

$D_C = 0.26$ (see Fig. 3(e)), intergranular cracking

Since this alloy experiences intergranular cracking during creep loading, the CP life relation for this mode of cracking must be used. Note that the pure CP life is determined as if the entire inelastic strainrange is of the CP type.

Thus $N_{CP} = (0.26)[10(0.00532)]^{-1.67} = 35$ cycles

The pure PP life is determined using the equation given in Fig. 2(e). Note again that the pure PP life is determined as if the entire inelastic strainrange is of the PP type.

Thus $N_{PP} = [(0.00532/0.40)]^{-1.25} = 221$ cycles

<u>Interspersed fatigue portion</u>

$\Delta\varepsilon_{PP} = 0.0035$

n = 1 fatigue cycle per combined cycle

The fatigue life for this portion of the combined cycle is determined using the equation in Fig. 2(e).

Thus $N_{PP} = (0.0035/0.40)^{-1.25} = 2734$ cycles

All of the terms in Eq. (A1) are now known, and we can estimate the cyclic life of the test.

$$\frac{0.936}{35} + \frac{0.064}{221} + \frac{1}{2734} = \frac{1}{NPRE}$$

Thus NPRE = 36 combined cycles. This life is to be compared with the observed life of 31 cycles. Note that the CP component of the damage is much greater than the two PP components in this example.

Standard Error of Estimate

The standard error of estimate (SE) (23) can be used as a criterion for evaluating the accuracy of the life predictions and is given by the following general equation.

$$SE = \sqrt{\Sigma(\text{observed} - \text{predicted})^2/\text{Num}} \qquad (A4)$$

Logarithmic values of life are used. Thus Eq. (A4) becomes

$$SE = \sqrt{\Sigma(\log(NOBS) - \log(NPRE))^2/Num} \quad (A5)$$

By using logarithmic values of the observed and predicted lives, thus the SE is determined from the ratio of observed and predicted lives.

$$SE = \sqrt{\Sigma(\log(NOBS/NPRE))^2/Num} \quad (A6)$$

In order to give the reader a better comprehension of the magnitude of the scatter in the life predictions as measured by the SE, we propose relating it to a term we shall call "equivivalent factors on life" (EF). The EF is defined as the antilogarithm of the SE. Thus, if the SE for a series of tests is 0.301, the EF is 2.0.

Table A1, Unpublished MPC creep rupture data

Material	Spec No	Temp C	Stress* KSI	T_f HRS	% RA	D_c
2.25Cr-1Mo, Normalized and Tempered	602	540	40.00	60	78.9	1.56
	601	540	35.00	206	81.3	1.68
	603	540	30.00	1428	70.3	1.21
	605	540	27.00	4479	57.6	0.86
2.25Cr-1Mo, Quenched and Tempered	708	485	65.00	638	73.3	1.23
	711	485	60.00	1664	67.3	1.12
	712	485	55.00	4681	56.7	0.84
Type 304 Stainless Steel, Solution Anneal	816	650	27.35	166	30.5	0.41
	813	650	25.00	645	28.0	0.33
	814	650	22.50	2635	18.2	0.20
	811	650	20.00	5656	13.2	0.14
	---	565	35.80	2735	17.7	0.20
	---	565	30.00	23733	8.6	0.09

*1Ksi = 6.89 MPa

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Table 1 MPC Creep-fatigue interspersion test results and Time- and Cycle-Fraction method life predictions

(a) 1Cr-1Mo-0.25V, Normalized and Tempered, tested at 540C

Test No.	n	TSR %	Creep stress* Ksi	Hold time hr	Tr hr	Cycle fraction	Time fraction	NOBS/NPRE	NPRE cycles	NOBS cycles
1A1B	1	0.55	39.00	23	687	0.009	0.687	0.70	42	29
1A1A	1	1.50	39.00	23	523	0.063	0.523	0.59	38	22
1A3B	5	0.55	39.00	23	734	0.033	0.734	0.77	40	31
1A3A	5	1.50	39.00	23	345	0.148	0.345	0.49	28	14
1A3AA	5	1.50	39.00	23	506	0.222	0.506	0.73	28	21
1A5B	22	0.55	39.00	23	571	0.106	0.571	0.68	35	24
1A5A	22	1.50	39.00	23	349	0.606	0.340	0.97	15	14
1A5AA	22	1.50	39.00	23	275	0.476	0.275	0.75	15	11
1B4C	1	1.10	36.50	47	1175	0.038	0.392	0.43	58	24
1B4A	1	1.50	36.50	47	1410	0.084	0.470	0.56	54	29
1B2A	2	1.50	36.50	23	985	0.202	0.328	0.53	79	42
1B5A	22	1.50	36.50	23	471	0.865	0.157	1.02	20	20
1C4B	1	0.55	32.50	47	3992	0.025	0.399	0.42	198	84
1C4A	1	1.50	32.00	47	4118	0.251	0.412	0.66	131	87
1C2A	2	1.50	32.00	23	3019	0.625	0.302	0.93	140	130
1C3B	5	0.55	32.00	23	3621	0.169	0.362	0.53	296	157
1C5A	22	1.50	32.00	23	578	1.082	0.057	1.14	22	25
1C5B	22	0.55	32.00	23	3000	0.573	0.300	0.87	149	130
1D1A	1	1.50	27.50	23	4814	0.603	0.160	0.76	274	209
1D4A	1	1.50	27.50	47	7083	0.433	0.236	0.67	224	150
1D3A	5	1.50	27.50	23	1574	0.719	0.052	0.77	88	68
1D5A	22	1.50	27.50	23	576	1.082	0.019	1.10	23	25
1A00	0	0.00	39.00	23	620	0.000	0.620	0.62	42	26
1C00	0	0.00	32.00	23	3780	0.000	0.378	0.38	433	164
1A0B	0	0.00	39.00	23	671	0.000	0.671	0.67	209	140
1V0K	0	0.00	43.80	24	195	0.000	0.975	0.98	54	53

(b) 1Cr-1Mo-0.25V, Normalized and Tempered, tested at 485C

Test No.	n	TSR %	Creep stress* Ksi	Hold time hr	Tr hr	Cycle fraction	Time fraction	NOBS/NPRE	NPRE cycles	NOBS cycles
3B4B	1	0.55	49.50	47	1306	0.005	0.435	0.44	61	27
3B4A	1	1.50	49.50	47	1444	0.090	0.481	0.57	53	30
3B2A	2	1.50	49.50	23	988	0.210	0.329	0.54	78	42
3B3A	5	1.50	49.50	23	1149	0.539	0.383	0.92	53	49
3B5B	22	0.55	49.50	23	1119	0.129	0.373	0.50	96	48
3C4A	1	1.50	45.00	47	4120	0.261	0.412	0.67	129	87
3C4B	1	0.55	45.00	47	4531	0.017	0.453	0.47	204	96
3C2A	2	1.50	45.00	23	3353	0.725	0.335	1.06	137	145
3C2B	2	0.55	45.00	23	3434	0.044	0.343	0.39	385	149
3C3B	5	0.55	45.00	23	3716	0.105	0.372	0.48	338	161
3C3A	5	1.50	45.00	23	1992	0.946	0.198	1.15	75	86
3C5B	22	0.55	45.00	23	3066	0.356	0.307	0.66	201	133

(c) 2.25Cr-1Mo, annealed, tested at 540C

Test No.	n	TSR %	Creep stress* Ksi	Hold time hr	Tr hr	Cycle fraction	Time fraction	NOBS/NPRE	NPRE cycles	NOBS cycles
2A4E	1	0.55	22.50	47	3179	0.027	3.179	3.21	21	67
2A1A	1	1.50	22.50	23	3243	0.227	3.243	3.47	41	141
2A4B	1	2.30	22.50	47	2776	0.254	2.776	3.02	19	59
2A2B	2	2.30	22.50	23	1691	0.524	1.691	2.21	33	73
2A3B	5	0.55	22.50	23	2379	0.155	2.379	2.53	41	103
2A3A	5	1.50	22.50	23	1740	0.444	1.740	2.18	34	75
2A3AA	5	1.50	22.50	23	2186	0.568	2.186	2.75	35	96
2A6BB	11	2.30	22.50	23	914	1.289	0.914	2.20	18	39
2A5B	22	0.55	22.50	23	1971	0.523	1.971	2.49	34	85
2A5A	22	1.50	22.50	23	690	0.701	0.690	1.37	21	29
2A5AA	22	1.50	22.50	23	667	0.702	0.667	1.37	21	29
2B1A	1	1.50	19.50	23	4664	0.326	1.555	1.88	107	202
2B3A	5	1.50	19.50	23	2135	0.544	0.712	1.26	73	92
2A00	0	0.00	22.50	23	2281	0.000	2.227	2.23	43	99
2B00	0	0.00	19.50	23	5549	0.000	1.848	1.85	130	241
2A0H	0	0.00	22.50	23	2293	0.000	2.295	2.29	62	143
2P0K	0	0.00	26.00	24	750	0.000	2.500	2.50	16	39

(continued)

*1Ksi = 6.89 MPa

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(d) 2.25Cr-1Mo, Normalized and Tempered, tested at 540C

Test No.	n	TSR %	Creep stress* Ksi.	Hold time hr	Tr hr	Cycle fraction	Time fraction	NOBS/NPRE	NPRE cycles	NOBS cycles
6A1A	1	1.50	31.00	23	1161	0.112	1.161	1.27	39	50
6A4E	1	0.55	31.00	47	655	0.007	0.655	0.66	19	13
6A4B	1	2.30	31.00	47	1158	0.120	1.158	1.29	19	24
6A2B	2	2.30	31.00	23	1004	0.381	1.004	1.38	31	43
6A3E	5	0.55	31.00	23	755	0.059	0.755	0.81	39	32
6A3A	5	1.50	31.00	23	966	0.351	0.966	1.31	32	42
6A6B	11	2.30	31.00	23	446	0.776	0.466	1.24	15	19
6A5E	22	0.55	31.00	23	257	0.075	0.257	0.33	30	10
6A5EE	22	0.55	31.00	23	260	0.077	0.260	0.34	30	11
6A5A	22	1.50	31.00	23	326	0.468	0.327	0.78	18	14
6A5AA	22	1.50	31.00	23	346	0.501	0.346	0.85	18	15
6B4E	1	0.55	27.50	47	2824	0.030	0.941	0.97	62	60
6B1A	1	1.50	27.50	23	2530	0.244	0.843	1.08	101	110
6B3A	5	1.50	27.50	23	1419	0.499	0.473	0.96	63	61
6B5E	22	0.55	27.50	23	733	0.233	0.244	0.48	65	31
6B5A	22	1.50	27.50	23	397	0.560	0.132	0.70	24	17
6B5AA	22	1.50	27.50	23	346	0.502	0.115	0.62	24	15

(e) 2.25Cr-1Mo, Quenched and Tempered, tested at 485C

Test No.	n	TSR %	Creep stress* Ksi	Hold time hr	Tr hr	Cycle fraction	Time fraction	NOBS/NPRE	NPRE cycles	NOBS cycles
7A4E	1	0.55	62.50	47	1114	0.005	1.114	1.12	21	23
7A1A-2	1	1.50	62.50	23	735	0.098	0.735	0.83	37	31
7A4B	1	2.30	62.50	47	712	0.085	0.712	0.80	19	15
7A2B	2	2.30	62.50	23	686	0.274	0.687	0.96	30	29
7A3A	5	1.50	62.50	23	629	0.313	0.629	0.94	20	27
7A5E	22	0.55	62.50	23	759	0.097	0.749	0.85	38	32
7A5B	22	2.30	62.50	23	222	0.764	0.222	0.98	9	9
7B4E	1	0.55	57.00	47	2256	0.010	0.752	0.76	63	48
7B1A	1	1.50	57.00	23	1778	0.244	0.593	0.84	92	77
7B3E	5	0.55	57.00	23	2091	0.067	0.697	0.76	118	90
7B3A	5	1.50	57.00	23	1173	0.592	0.391	0.98	52	51
7B5E	22	0.55	57.00	23	1786	0.233	0.595	0.83	93	77

(f) Type 304 Stainless Steel, Solution Annealed, tested at 540C

Test No.	n	TSR %	Creep stress* Ksi	Hold time hr	Tr hr	Cycle fraction	Time fraction	NOBS/NPRE	NPRE cycles	NOBS cycles
8B4E	1	0.55	2.00	47	1490	0.011	0.497	0.51	61	31
8B4A	1	1.50	2.00	47	1414	0.119	0.471	0.59	51	30
8B2A	2	1.50	2.00	23	967	0.279	0.322	0.60	70	42
8B3E	5	0.55	2.00	23	1050	0.062	0.350	0.41	109	45
8B3A	5	1.50	2.00	23	630	0.394	0.210	0.60	45	27
8B5E	22	0.55	2.00	23	1012	0.250	0.337	0.59	70	44
8B5A	22	1.50	22.00	23	230	0.597	0.077	0.67	15	10
8C4E	1	0.55	17.00	47	4618	0.037	0.461	0.51	197	98
8C4A	1	1.50	17.00	47	2542	0.215	0.254	0.47	115	54
8C2A	2	1.50	17.00	23	1380	0.398	0.138	0.53	112	60
8C3E	5	0.55	17.00	23	2793	0.168	0.278	0.45	252	121
8C3A	5	[illegible]	17.00	23	1498	0.948	0.149	1.10	59	65
8C5E	22	0.55	17.00	23	1507	0.370	0.151	0.52	125	65
8C5A	[illegible]	1.50	17.00	23	391	1.013	0.039	1.05	16	17
8C00	0	0.00	17.00	23	6357	0.000	0.636	0.64	434	276

(g) Type 304 Stainless Steel, Solution Annealed, tested at 565C

Test No.	n	TSR %	Creep stress* Ksi	Hold time hr	Tr hr	Cycle fraction	Time fraction	NOBS/NPRE	NPRE cycles	NOBS cycles
9B4E	1	0.55	35.00	47	679	0.004	0.226	0.23	61	14
9B4A	1	1.50	35.00	47	1608	0.234	0.536	0.77	44	34
9B4AA	1	1.50	35.00	47	920	0.131	0.307	0.44	43	19
9B3A	5	1.50	35.00	23	186	0.202	0.062	0.26	30	8
9B3AA	5	1.50	35.00	23	245	0.252	0.082	0.33	30	10
9B3E	5	0.55	35.00	23	776	0.039	0.255	0.29	112	33
9B5E	22	0.55	35.00	23	359	0.072	0.120	0.19	78	15
9B5A	22	1.50	35.00	23	106	0.413	0.035	0.45	9	4
9C4EE	1	0.55	31.50	47	2529	0.017	0.253	0.27	196	53
9C4AA	1	1.50	31.50	47	2063	0.294	0.206	0.50	86	43
9C3E	5	0.55	31.50	23	3742	0.193	0.376	0.57	286	162
9C3A	5	1.50	31.50	23	736	0.807	0.074	0.88	36	32
9C5E	22	0.55	31.50	23	1018	0.214	0.102	0.31	139	44

*1Ksi = 6.89 MPa

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Table 2 SRP analysis of MPC test results summing damage every cycle

(a) 1Cr-1Mo-0.25V, Normalized and Tempered, tested at 540C

Test No.	Damage fractions fatigue PP	creep PP	period CP	NOBS/NPRE	NPRE cycles	NOBS cycles
1A1E	0.009	0.006	0.686	0.70	41	29
1A1A	0.047	0.007	0.973	1.03	21	22
1A3E	0.048	0.007	0.753	0.81	38	31
1A3A	0.167	0.009	0.623	0.80	18	14
1A3AA	0.229	0.008	1.138	1.38	15	21
1A5E	0.204	0.003	0.836	1.04	23	24
1A5A	0.680	0.008	0.736	1.42	10	14
1A5AA	0.592	0.005	0.765	1.36	8	11
1B4C	0.034	0.004	0.465	0.50	48	24
1B4A	0.067	0.006	0.533	0.61	48	29
1B2A	0.192	0.015	1.087	1.29	32	42
1B5A	1.088	0.006	0.224	1.32	15	20
1C4E	0.022	0.014	0.617	0.65	129	84
1C4A	0.213	0.012	0.525	0.75	116	87
1C2A	0.588	0.020	0.767	1.37	95	130
1C3E	0.218	0.015	0.367	0.60	261	157
1C5A	1.199	0.004	0.105	1.31	19	25
1C5E	0.601	0.012	0.132	0.75	174	130
1D1A	0.472	0.014	0.334	0.82	255	209
1D4A	0.375	0.011	0.267	0.65	230	150
1D3A	0.905	0.004	0.109	1.02	67	68
1D5A	1.214	0.005	0.110	1.33	19	25
1A00	0.000	0.007	0.678	0.68	38	26
1C00	0.000	0.019	0.332	0.35	467	164
1A0H	0.000	0.055	1.275	1.33	105	140
1VOK	0.000	0.132	2.098	2.23	24	53

(b) 1Cr-1Mo-0.25V, Normalized and Tempered, tested at 485C

Test No.	Damage fractions fatigue PP	creep PP	period CP	NOBS/NPRE	NPRE cycles	NOBS cycles
3B4E	0.005	0.017	1.067	1.09	25	27
3B4A	0.055	0.018	1.171	1.24	24	30
3B2A	0.170	0.019	0.397	0.59	72.	42
3B3A	0.580	0.040	1.100	1.72	29	49
3B5E	0.257	0.029	1.348	1.63	29	48
3C4A	0.204	0.034	0.899	1.14	77	67
3C4E	0.019	0.042	1.237	1.30	74	96
3C2A	0.557	0.065	0.778	1.40	104	145
3C2E	0.048	0.065	0.951	1.06	140	149
3C3E	0.130	0.078	1.236	1.44	111	161
3C3A	0.893	0.039	0.436	1.37	63	86
3C5E	0.663	0.045	0.558	1.27	105	133

(continued)

(c) 2.25Cr-1Mo, annealed, tested at 540C

Test No.	Damage fractions fatigue PP	creep period PP	CP	NOBS/NPRE	NPRE cycles	NOBS cycles
2A4E	0.017	0.006	1.391	1.41	47	67
2A1A	0.228	0.022	1.071	1.32	107	141
2A4B	0.173	0.011	1.217	1.40	42	59
2A2B	0.418	0.003	0.469	0.89	82	73
2A3E	0.199	0.011	0.797	1.01	102	103
2A3A	0.463	0.006	0.583	1.05	71	75
2A3AA	0.778	0.010	0.682	1.47	65	96
2A6BB	1.229	0.004	0.193	1.43	27	39
2A5E	0.630	0.010	0.612	1.25	68	85
2A5A	1.124	0.006	0.192	1.32	23	29
2A5AA	1.002	0.005	0.263	1.27	23	29
2B1A	0.327	0.009	0.501	0.84	241	202
2B3A	0.730	0.005	0.146	0.88	104	92
2A00	0.000	0.012	1.200	1.21	82	99
2B00	0.000	0.021	0.875	0.90	269	241
2A0M	0.000	0.029	1.281	1.31	109	143
2P0K	0.000	0.028	1.608	1.64	24	39

(d) 2.25Cr-1Mo, Normalized and Tempered, tested at 540C

Test No.	Damage fractions fatigue PP	creep period PP	CP	NOBS/NPRE	NPRE cycles	NOBS cycles
6A1A	0.099	0.005	0.491	0.59	84	50
6A4E	0.006	0.002	0.814	0.82	16	13
6A4B	0.091	0.002	0.606	0.70	34	24
6A2B	0.339	0.006	0.417	0.76	56	43
6A3E	0.053	0.003	0.835	0.89	36	32
6A3A	0.403	0.007	0.379	0.79	53	42
6A6B	0.800	0.002	0.084	0.89	21	19
6A5E	0.080	0.003	0.981	1.06	10	11
6A5EE	0.091	0.003	0.920	1.01	11	10
6A5A	0.624	0.002	0.057	0.68	21	14
6A5AA	0.561	0.003	0.195	0.76	17	13
6B4E	0.018	0.005	0.968	0.99	61	60
6B1A	0.213	0.004	0.203	0.42	261	110
6B3A	0.605	0.003	0.139	0.75	82	61
6B5E	0.278	0.008	0.944	1.23	25	31
6B5A	0.830	0.003	0.061	0.89	19	17
6B5AA	0.619	0.002	0.085	0.71	21	15

(continued)

(e) 2.25Cr-1Mo, Quenched and Tempered, tested at 485C

Test No.	Damage fractions: fatigue PP	Damage fractions: creep period PP	Damage fractions: creep period CP	NOBS / NPRE	NPRE cycles	NOBS cycles
7A4E	0.001	0.016	0.643	0.66	35	23
7A1A-2	0.058	0.015	0.471	0.54	57	31
7A4B	0.068	0.008	0.311	0.39	39	15
7A2B	0.229	0.019	0.560	0.81	36	29
7A3A	0.233	0.014	0.669	0.92	30	27
7A5E	0.090	0.014	0.485	0.59	54	32
7A5B	0.837	0.004	0.067	0.91	10	9
7B4E	0.012	0.012	0.266	0.29	165	48
7B1A	0.171	0.019	0.250	0.44	175	77
7B3E	0.030	0.027	0.395	0.45	199	90
7B3A	0.581	0.018	0.305	0.90	56	51
7B5E	0.164	0.018	0.300	0.48	160	77

(f) Type 304 Stainless Steel, Solution Annealed, tested at 650C

Test No.	Damage fractions: fatigue PP	Damage fractions: creep period PP	Damage fractions: creep period CP	NOBS / NPRE	NPRE cycles	NOBS cycles
8B4E	0.012	0.002	0.942	0.96	32	31
8B4A	0.088	0.002	0.735	0.83	36	30
8B2A	0.264	0.002	0.352	0.62	68	42
8B3E	0.059	0.004	1.388	1.45	31	45
8B3A	0.447	0.002	0.332	0.78	35	27
8B5E	0.310	0.003	1.565	1.88	23	44
8B5A	0.628	0.004	0.126	0.76	13	10
8C4E	0.034	0.001	0.703	0.74	133	98
8C4A	0.163	0.001	0.368	0.53	102	54
8C2A	0.338	0.002	0.213	0.55	109	60
8C3E	0.236	0.001	0.482	0.72	168	121
8C3A	0.915	0.001	0.196	1.11	58	65
8C5E	0.482	0.001	0.180	0.66	98	65
8C5A	1.114	0.000	0.028	1.14	15	17
8C00	0.000	0.002	0.746	0.75	369	276

(g) Type 304 Stainless Steel, Solution Annealed, tested at 565C

Test No.	Damage fractions: fatigue PP	Damage fractions: creep period PP	Damage fractions: creep period CP	NOBS / NPRE	NPRE cycles	NOBS cycles
9B4E	0.002	0.100	0.226	0.33	43	14
9B4A	0.147	0.015	0.499	0.66	51	34
9B4AA	0.093	0.076	0.208	0.46	42	19
9B3A	0.165	0.069	0.046	0.28	29	8
9B3AA	0.202	0.064	0.046	0.31	32	10
9B3E	0.017	0.067	0.143	0.23	145	33
9B5E	0.071	0.057	0.123	0.25	60	15
9B5A	0.484	0.063	0.037	0.58	7	4
9C4EE	0.011	0.054	0.552	0.62	86	53
9C4AA	0.186	0.043	0.265	0.49	87	43
9C3E	0.126	0.051	0.496	0.67	241	162
9C3A	0.637	0.045	0.122	0.80	40	32
9C5E	0.208	0.035	0.169	0.41	107	44

Table 3 SRP analysis of MPC test results using average strains during creep period

(a) 1Cr-1Mo-0.25V, Normalized and Tempered, tested at 540C

Test No.	Strainrange values % fatigue $\Delta\varepsilon_{PP}$	creep period $\Delta\varepsilon_{IN}$	creep period F_{PP}	creep period F_{CP}	Damage fractions fatigue PP	creep period PP	creep period CP	$\frac{N_{OBS}}{N_{PRE}}$	NPRE cycles	NOBS cycles
1A1E	0.22	2.220	0.04	0.96	0.009	0.006	0.420	0.44	67	29
1A1A	1.03	3.180	0.04	0.96	0.047	0.007	0.582	0.64	35	22
1A3E	0.22	2.091	0.04	0.96	0.048	0.006	0.406	0.46	67	31
1A3A	1.32	3.315	0.07	0.93	0.167	0.009	0.323	0.56	25	14
1A3AA	1.04	3.778	0.04	0.96	0.229	0.008	0.740	0.98	21	21
1A5E	0.26	2.567	0.02	0.98	0.204	0.003	0.452	0.66	36	24
1A5A	1.05	3.959	0.05	0.95	0.680	0.008	0.526	1.21	12	14
1A5AA	1.14	4.675	0.03	0.07	0.592	0.005	0.557	1.15	10	11
1B4C	0.72	2.067	0.03	0.97	0.034	0.004	0.310	0.35	69	24
1B4A	1.09	2.021	0.04	0.96	0.067	0.006	0.359	0.43	67	25
1B2A	1.08	2.507	0.06	0.94	0.192	0.015	0.733	0.94	45	42
1B5A	1.15	1.739	0.07	0.93	1.088	0.006	0.186	1.28	16	20
1C4E	0.19	1.140	0.07	0.93	0.022	0.013	0.390	0.43	198	84
1C4A	1.14	1.097	0.06	0.94	0.213	0.012	0.381	0.61	144	87
1C2A	1.07	1.078	0.07	0.93	0.588	0.019	0.550	1.16	112	130
1C3E	0.20	0.637	0.08	0.92	0.218	0.016	0.270	0.50	311	157
1C5A	1.04	0.851	0.10	0.90	1.199	0.004	0.063	1.27	20	25
1C5E	0.16	0.399	0.14	0.86	0.601	0.012	0.095	0.71	183	130
1D1A	0.07	0.475	0.08	0.92	0.472	0.014	0.221	0.71	295	209
1D4A	1.16	0.549	0.07	0.93	0.375	0.011	0.204	0.59	254	150
1D3A	1.22	0.404	0.07	0.93	0.905	0.003	0.056	0.96	71	68
1D5A	1.05	0.719	0.14	0.86	1.214	0.005	0.050	1.27	20	25
1A00	--	2.365	0.05	0.95	0.000	0.007	0.415	0.42	62	26
1C00	--	0.601	0.11	0.89	0.000	0.019	0.250	0.27	609	164
1A0M	--	1.721	0.09	0.91	0.000	0.054	1.250	1.30	107	140
1VOK	--	4.403	0.19	0.81	0.000	0.013	2.038	2.17	24	53

(b) 1Cr-1Mo-0.25V, Normalized and Tempered, tested at 485C

Test No.	Strainrange values % fatigue $\Delta\varepsilon_{PP}$	creep period $\Delta\varepsilon_{IN}$	creep period F_{PP}	creep period F_{CP}	Damage fractions fatigue PP	creep period PP	creep period CP	$\frac{N_{OBS}}{N_{PRE}}$	NPRE cycles	NOBS cycles
3B4E	0.15	2.753	0.09	0.91	0.005	0.017	0.646	0.67	40	27
3B4A	0.90	2.873	0.08	0.92	0.055	0.017	0.779	0.85	35	30
3B2A	0.98	1.452	0.13	0.87	0.170	0.017	0.329	0.52	81	42
3B3A	1.11	2.373	0.13	0.87	0.580	0.038	0.870	1.49	33	49
3B5E	0.18	2.316	0.10	0.90	0.257	0.028	0.850	1.14	42	48
3C4A	1.10	1.452	0.12	0.88	0.204	0.032	0.692	0.93	94	67
3C4E	0.15	1.606	0.11	0.89	0.019	0.040	0.907	0.97	99	96
3C2A	0.94	1.089	0.19	0.81	0.557	0.062	0.655	1.28	114	145
3C2E	0.13	1.153	0.17	0.83	0.048	0.072	0.758	0.87	171	149
3C3E	0.13	1.235	0.17	0.83	0.130	0.074	0.921	1.13	143	161
3C3A	1.00	1.067	0.19	0.81	0.893	0.037	0.374	1.30	66	86
3C5E	0.17	0.825	0.19	0.81	0.663	0.041	0.377	1.08	123	133

(c) 2.25Cr-1Mo, annealed, tested at 540C

Test No.	Strainrange values % fatigue $\Delta\varepsilon_{PP}$	creep period $\Delta\varepsilon_{IN}$	creep period F_{PP}	creep period F_{CP}	Damage fractions fatigue PP	creep period PP	creep period CP	$\frac{N_{OBS}}{N_{PRE}}$	NPRE cycles	NOBS cycles
2A4E	0.28	2.954	0.02	0.98	0.017	0.006	1.350	1.38	49	67
2A1A	1.23	1.664	0.07	0.93	0.228	0.022	1.043	1.29	109	141
2A4B	1.98	2.980	0.04	0.96	0.173	0.012	1.186	1.37	43	59
2A2B	1.94	1.356	0.02	0.98	0.418	0.003	0.402	0.82	89	73
2A3E	0.39	1.641	0.05	0.95	0.199	0.011	0.761	0.97	106	103
2A3A	0.99	1.617	0.03	0.97	0.463	0.005	0.549	1.02	74	75
2A3AA	1.23	1.544	0.05	0.95	0.778	0.010	0.640	1.43	67	96
2A6BB	1.94	1.294	0.06	0.94	1.229	0.004	0.190	1.42	27	39
2A5E	0.35	1.572	0.05	0.95	0.630	0.010	0.580	1.22	70	85
2A5A	1.23	1.480	0.10	0.90	1.124	0.006	0.175	1.31	23	29
2A5AA	1.20	1.627	0.07	0.93	1.002	0.004	0.207	1.21	24	29
2B1A	1.23	0.833	0.05	0.95	0.327	0.009	0.482	0.82	247	202
2B3A	1.21	0.593	0.09	0.91	0.730	0.005	0.120	0.85	108	92
2A00	--	2.160	0.04	0.96	0.000	0.012	1.168	1.18	84	99
2B00	--	1.070	0.06	0.94	0.000	0.021	0.857	0.88	275	241
2A0M	--	1.674	0.07	0.93	0.000	0.029	1.278	1.31	109	143
2P0K	--	4.711	0.08	0.92	0.000	0.028	1.605	1.63	24	39

(continued)

(d) 2.25Cr-1Mo, Normalized and Tempered, tested at 540C

Test No.	Strainrange values % fatigue $\Delta\epsilon_{PP}$	creep period $\Delta\epsilon_{IN}$	F_{PP}	F_{CP}	Damage fractions fatigue PP	creep period PP	CP	NOBS/NPRE	NPRE cycles	NOBS cycles
6A1A	1.17	1.302	0.05	0.95	0.099	0.005	0.399	0.50	99	50
6A4E	0.38	3.963	0.02	0.98	0.006	0.002	0.536	0.54	24	13
6A4B	1.96	2.198	0.02	0.98	0.091	0.002	0.471	0.56	43	24
6A2B	2.03	1.408	0.05	0.95	0.339	0.006	0.560	0.70	61	43
6A3E	0.28	2.297	0.02	0.98	0.053	0.003	0.610	0.67	48	32
6A3A	1.14	1.371	0.07	0.93	0.403	0.007	0.330	0.74	57	42
6A6B	1.98	1.030	0.06	0.94	0.800	0.002	0.008	0.88	22	10
6A5E	0.28	4.851	0.02	0.98	0.080	0.003	0.635	0.72	15	11
6A5EE	0.31	4.986	0.02	0.98	0.091	0.003	0.665	0.76	14	11
6A5A	1.19	0.976	0.07	0.93	0.624	0.002	0.053	0.68	21	14
6A5AA	1.16	1.820	0.06	0.94	0.561	0.003	0.154	0.72	18	13
6B4E	0.26	1.405	0.03	0.97	0.018	0.005	0.714	0.74	81	60
6B1A	1.15	0.505	0.05	0.95	0.213	0.004	0.185	0.40	273	110
6B3A	1.17	0.559	0.06	0.94	0.605	0.003	0.123	0.73	84	61
6B5E	0.33	2.735	0.05	0.95	0.278	0.008	0.670	0.96	32	31
6B5A	1.28	0.889	0.11	0.89	0.830	0.003	0.053	0.89	19	17
6B5AA	1.12	0.954	0.08	0.92	0.619	0.002	0.054	0.68	22	15

(e) 2.25Cr-1Mo, Quenched and Tempered, tested at 485C

Test No.	Strainrange values % fatigue $\Delta\epsilon_{PP}$	creep period $\Delta\epsilon_{IN}$	F_{PP}	F_{CP}	Damage fractions fatigue PP	creep period PP	CP	NOBS/NPRE	NPRE cycles	NOBS cycles
7A9E	0.05	2.180	0.12	0.88	0.001	0.017	0.421	0.44	52	23
7A1A-2	0.86	1.632	0.11	0.89	0.058	0.014	0.327	0.40	78	31
7A4B	1.74	2.041	0.09	0.91	0.068	0.008	0.233	0.31	48	15
7A2B	1.55	2.022	0.12	0.88	0.229	0.019	0.425	0.67	43	29
7A3A	0.80	2.046	0.09	0.91	0.233	0.014	0.408	0.65	41	27
7A5E	1.10	1.602	0.10	0.90	0.090	0.014	0.328	0.43	74	32
7A5B	1.64	1.456	0.13	0.87	0.837	0.004	0.057	0.90	10	9
7B4E	0.17	0.818	0.14	0.86	0.012	0.012	0.200	0.22	214	48
7B1A	0.98	0.681	0.17	0.83	0.171	0.019	0.219	0.41	189	77
7B3E	0.06	0.766	0.18	0.82	0.030	0.027	0.313	0.37	244	90
7B3A	1.00	1.010	0.15	0.85	0.581	0.018	0.251	0.85	60	51
7B5E	0.08	0.718	0.15	0.85	0.164	0.018	0.243	0.42	181	77

(f) Type 304 Stainless Steel, Solution Annealed, tested at 650C

Test No.	Strainrange values % fatigue $\Delta\epsilon_{PP}$	creep period $\Delta\epsilon_{IN}$	F_{PP}	F_{CP}	Damage fractions fatigue PP	creep period PP	CP	NOBS/NPRE	NPRE cyclus	NOBS cycles
8B4E	0.35	0.532	0.06	0.94	0.012	0.001	0.841	0.85	36	31
8B4A	1.21	0.473	0.10	0.90	0.088	0.002	0.659	0.75	40	30
8B2A	1.26	0.287	0.18	0.82	0.264	0.002	0.333	0.60	70	42
8B3E	0.29	0.585	0.11	0.89	0.059	0.004	1.288	1.35	33	45
8B3A	1.30	0.383	0.15	0.85	0.447	0.002	0.316	0.76	35	27
8B5E	0.32	0.613	0.05	0.95	0.310	0.002	1.417	1.73	25	44
8B5A	1.19	0.477	0.33	0.67	0.628	0.002	0.100	0.74	14	10
8C4E	0.34	0.157	0.13	0.87	0.034	0.001	0.526	0.56	175	98
8C4A	1.23	0.175	0.07	0.93	0.163	<0.001	0.289	0.45	119	54
8C2A	1.18	0.171	0.27	0.73	0.338	0.002	0.194	0.53	112	60
8C3E	0.36	0.144	0.13	0.87	0.236	0.001	0.446	0.68	177	121
8C3A	1.18	0.149	0.18	0.82	0.915	0.001	0.194	1.11	59	65
8C5E	0.33	0.134	0.13	0.87	0.482	0.001	0.173	0.66	99	65
8C5A	1.22	0.138	0.28	0.72	1.118	<0.001	0.028	1.14	15	17
8C00	--	0.073	0.15	0.85	0.000	0.001	0.483	0.48	570	276

(g) Type 304 Stainless Steel, Solution Annealed, tested at 565C

Test No.	Strainrange values % fatigue $\Delta\epsilon_{PP}$	creep period $\Delta\epsilon_{IN}$	F_{PP}	F_{CP}	Damage fractions fatigue PP	creep period PP	CP	NOBS/NPRE	NPRE cycles	NOBS cycles
9B4E	0.14	0.835	0.78	0.22	0.002	0.033	0.232	0.27	52	14
9B4A	1.03	0.397	0.43	0.57	0.147	0.013	0.487	0.65	53	34
9B4AA	1.11	0.574	0.68	0.32	0.093	0.021	0.265	0.38	50	19
9B3A	1.00	0.902	0.83	0.17	0.165	0.023	0.090	0.20	29	8
9B3AA	0.99	0.663	0.82	0.18	0.202	0.018	0.080	0.30	33	10
9B3E	0.11	0.365	0.71	0.29	0.017	0.018	0.149	0.18	180	33
9B5E	0.17	0.464	0.79	0.21	0.071	0.014	0.078	0.16	93	15
9B5A	1.19	1.493	0.89	0.11	0.484	0.029	0.059	0.57	7	4
9C4EE	0.17	0.385	0.58	0.42	0.011	0.026	0.549	0.59	91	53
9C4AA	1.03	0.340	0.54	0.46	0.186	0.016	0.308	0.51	84	43
9C3E	0.14	0.156	0.57	0.43	0.126	0.017	0.405	0.55	296	162
9C3A	0.98	0.290	0.60	0.40	0.637	0.010	0.172	0.82	39	32
9C5E	0.17	0.205	0.62	0.38	0.208	0.008	0.135	0.35	126	44

TABLE 4. SUMMARY OF LIFE PREDICTIONS

(a) SRP-1, Damage Summed Over Cycle

Material	Temp. C	No. of Tests	Percentage of Tests within Factors of 2	3	4	Predictions under	over	SE
1Cr-1Mo-0.25V, Normalized and Tempered	540	26	92	100	---	50	50	0.180
1Cr-1Mo-0.25V, Normalized and Tempered	485	12	100	---	---	92	8	0.147
2.25Cr-1Mo, Annealed	540	17	100	---	---	76	24	0.115
2.25Cr-1Mo, Normalized and Tempered	540	17	94	100	---	18	82	0.142
2.25Cr-1Mo, Quenched and Tempered	485	12	58	92	100	0	100	0.285
Type 304 Stainless, Solution Annealed	650	15	100	---	---	27	73	0.166
Type 304 Stainless, Solution Annealed	565	13	38	62	92	0	100	0.402
		112	86	95	99			

(b) SRP-2, Avg. Strainrange Values Used

Material	Temp. C	No. of Tests	Percentage of Tests within Factors of 2	3	4	Predictions under	over	SE
1Cr-1Mo-0.25V, Normalized and Tempered	540	26	69	96	100	31	69	0.258
1Cr-1Mo-0.25V, Normalized and Tempered	485	12	100	---	---	50	50	0.124
2.25Cr-1Mo, Annealed	540	17	100	---	---	71	29	0.112
2.25Cr-1Mo, Normalized and Tempered	540	17	94	100	---	0	100	0.188
2.25Cr-1Mo, Quenched and Tempered	485	12	33	83	92	0	100	0.371
Type 304 Stainless, Solution Annealed	650	15	87	100	---	27	73	0.199
Type 304 Stainless, Solution Annealed	565	13	46	62	85	0	100	0.462
		112	77	92	97			

(c) TCF Method

Material	Temp. C	No. of Tests	Percentage of Tests within Factors of 2	3	4	Predictions under	over	SE
1Cr-1Mo-0.25V, Normalized and Tempered	540	26	85	100	---	12	88	0.212
1Cr-1Mo-0.25V, Normalized and Tempered	485	12	58	100	---	17	83	0.267
2.25Cr-1Mo, Annealed	540	17	29	82	100	100	0	0.364
2.25Cr-1Mo, Normalized and Tempered	540	17	82	100	---	35	65	0.213
2.25Cr-1Mo, Quenched and Tempered	485	12	100	---	---	8	92	0.076
Type 304 Stainless, Solution Annealed	650	15	73	100	---	13	87	0.247
Type 304 Stainless, Solution Annealed	565	13	23	46	85	0	100	0.466
		112	86	95	99			

Table 5: Summary of accuracy of life predictions using Strainrange Partitioning and the Time- and Cycle-Fraction methods.

Method	Factors of 2 %	Factors of 3 %	Factors of 4 %	Predicted under %	Predicted over %	SE
SRP-1	86	95	99	39	61	0.[illegible]5
SRP-2	77	92	97	27	73	0.263
TCF	66	91	98	28	72	0.281

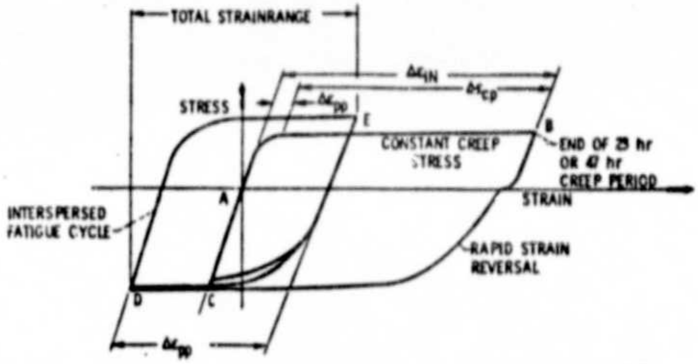


Figure 1 - Schematic Hysteresis Loops Associated with MPC Creep-Fatigue Interspersion Tests. Partitioned Strainranges Indicated on Loops.

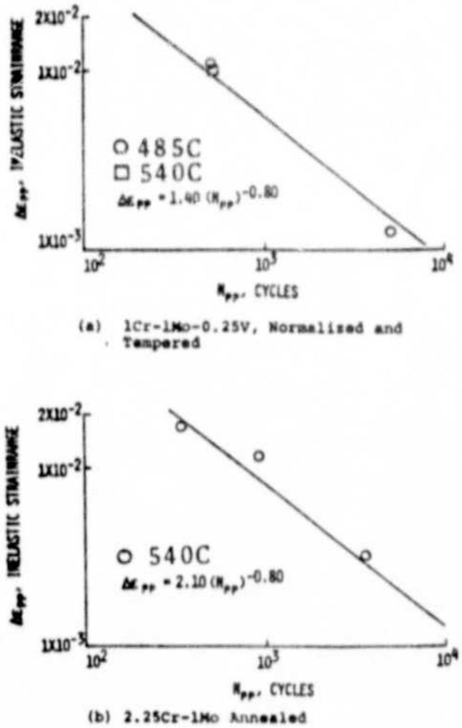
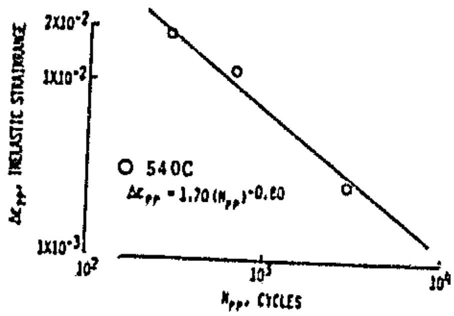
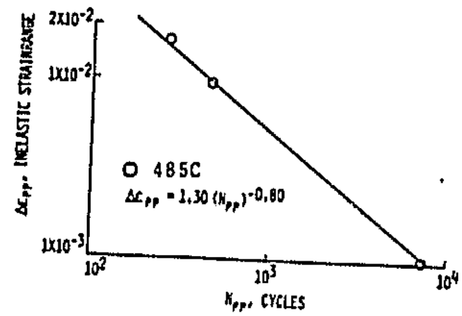


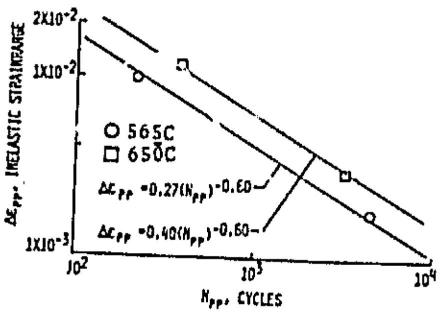
Figure 2 - PP Life Relations for MPC Alloys.



(c) 2.25Cr-1Mo, Normalized and Tempered

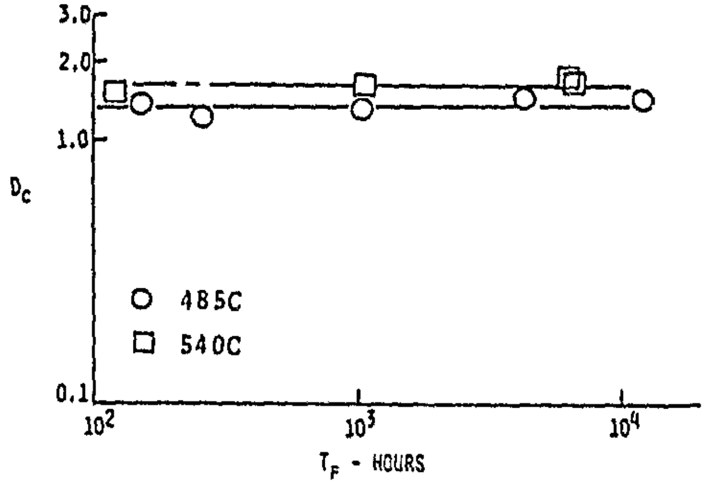


(d) 2.25Cr-1Mo, Quenched and Tempered

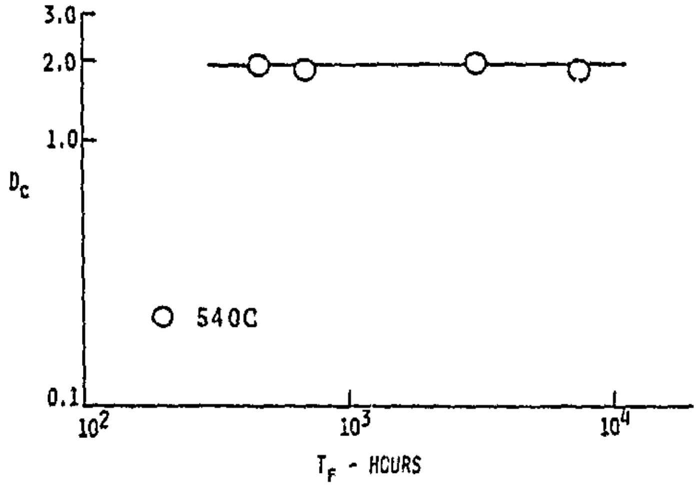


(e) Type 304 Stainless Steel, Solution Annealed

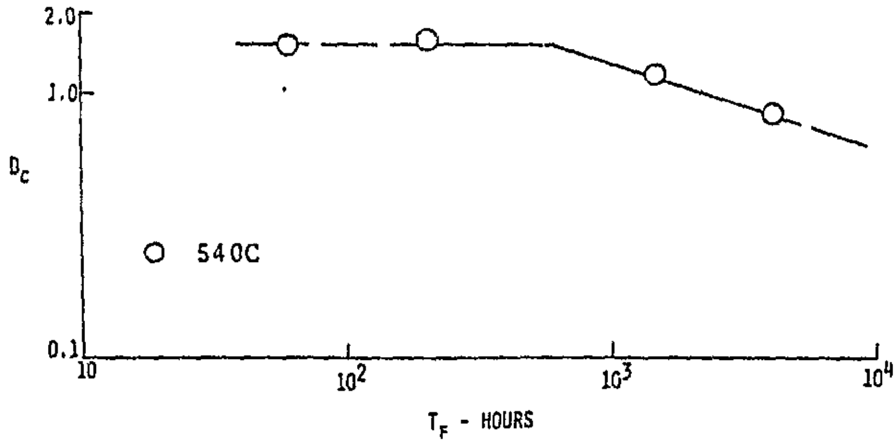
Figure 2 - Concluded.



(a) 1Cr-1Mo-0.25V, Normalized and Tempered

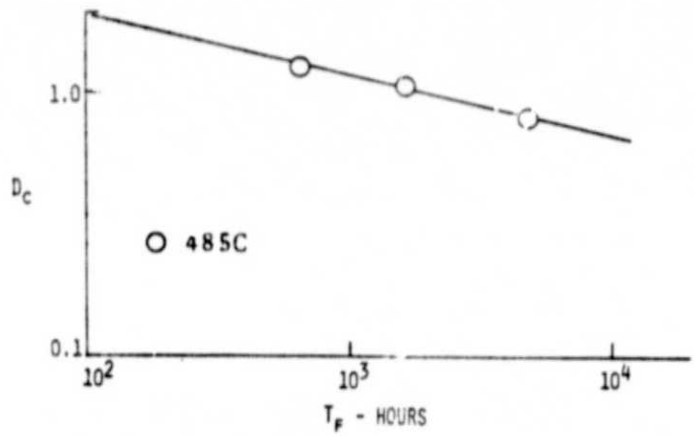


(b) 2.25Cr-1Mo, Annealed

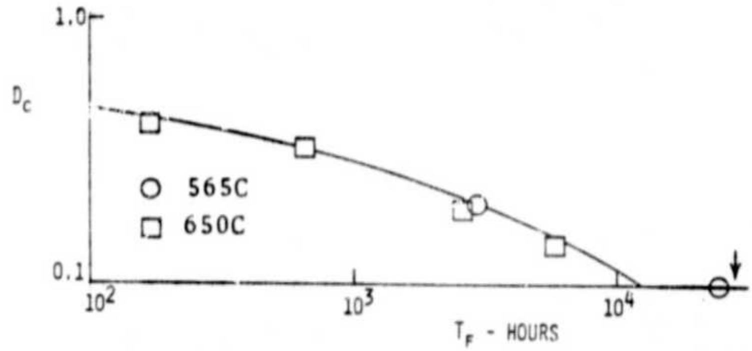


(c) 2.25Cr-1Mo, Normalized and Tempered

Figure 3 - Creep-Rupture Ductility for MPC Alloys.



(d) 2.25Cr-1Mo Quenched and Tempered



(e) Type 304 Stainless Steel,
Solution Annealed

Figure 3 – Concluded.

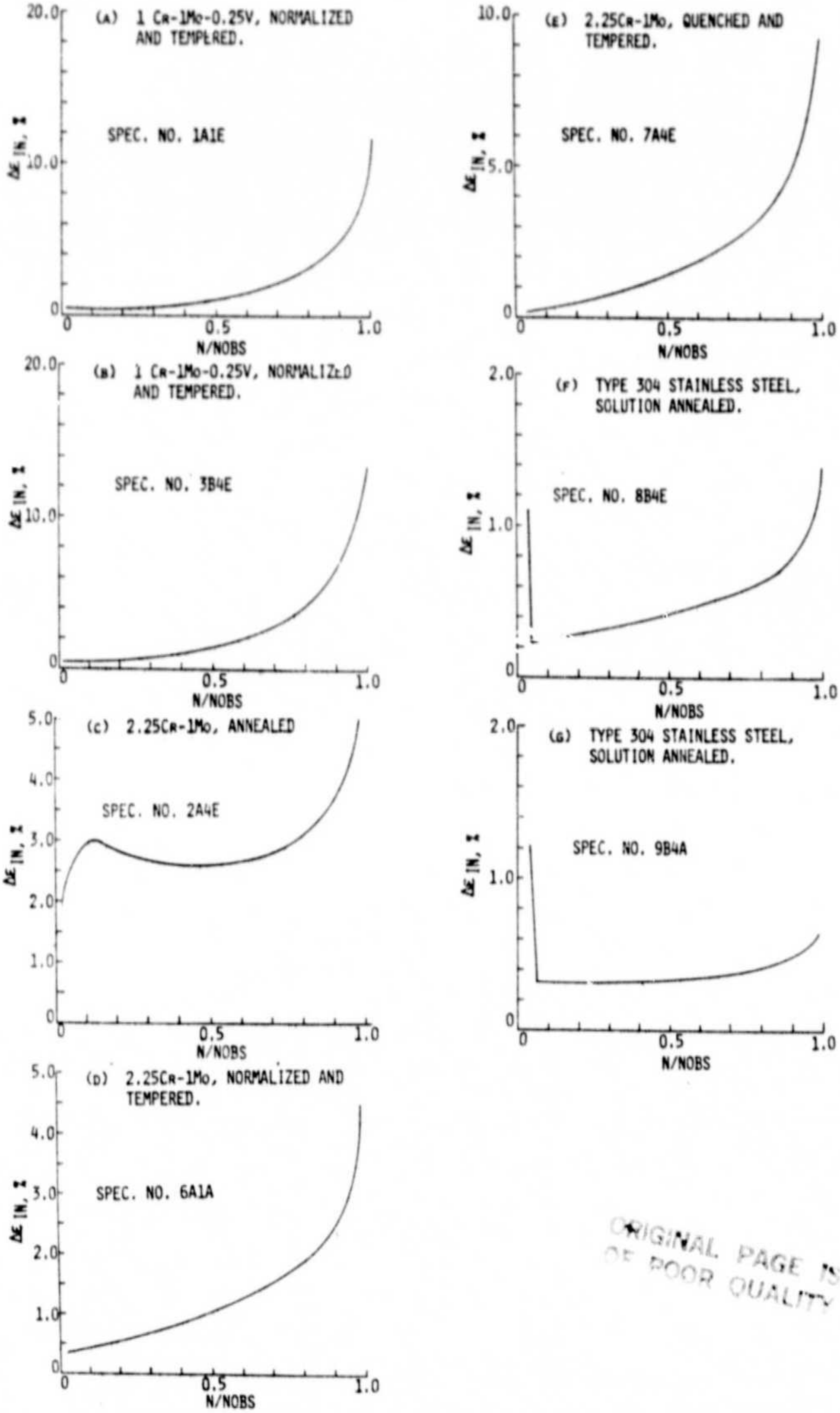
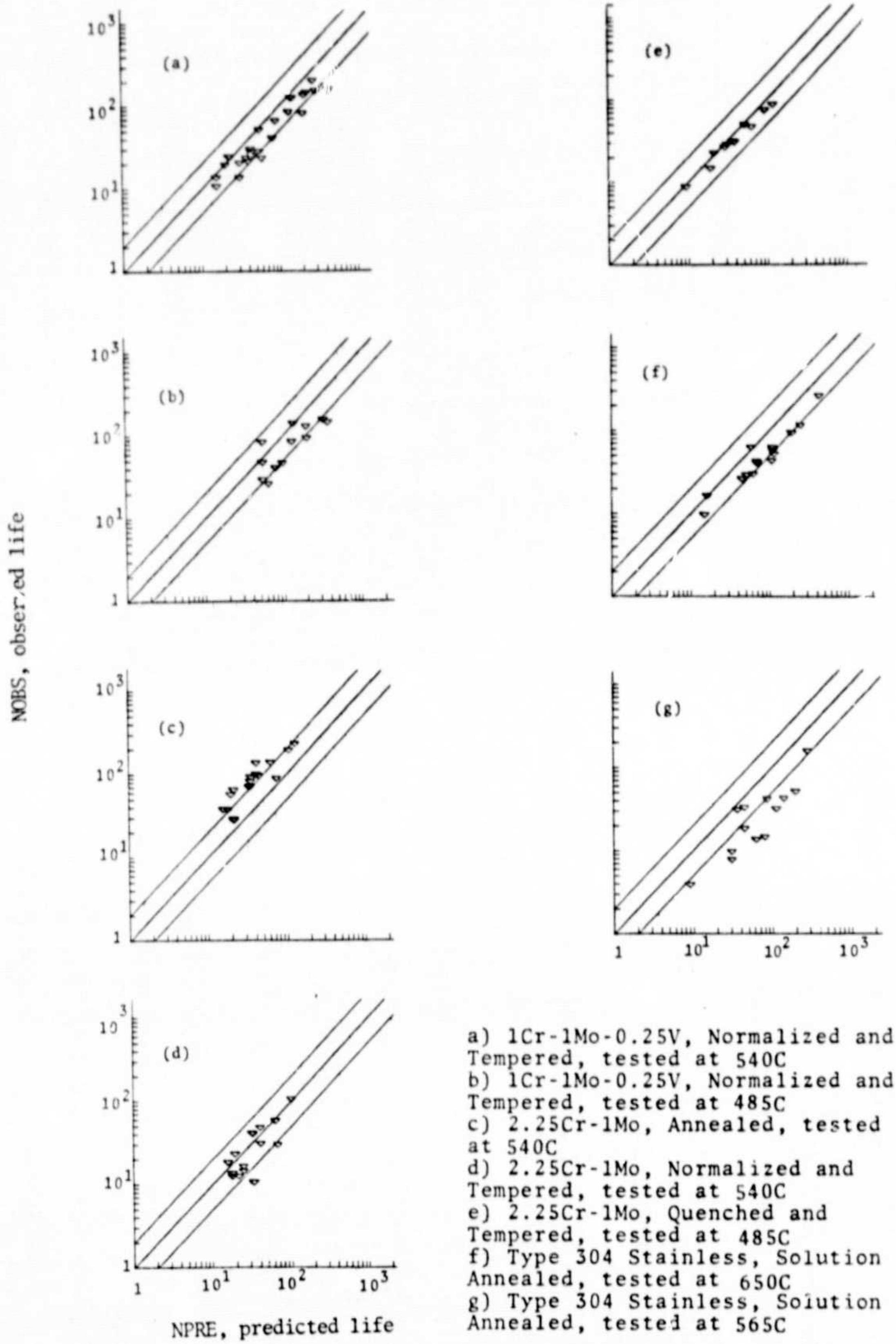
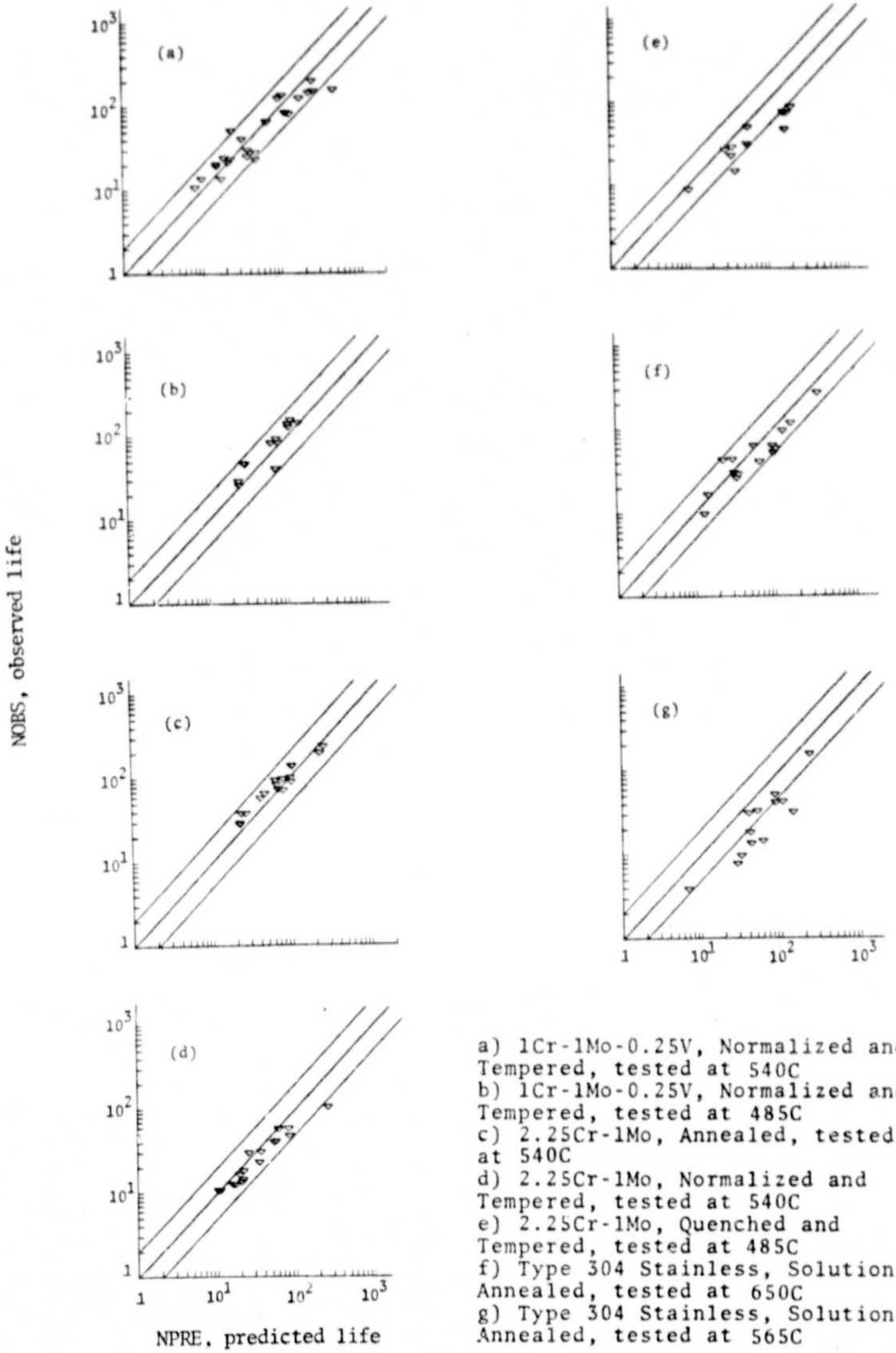


Figure 4 - Typical Examples of Cycle-to-Cycle Changes in Inelastic Strainrange with Repeated Creep Periods.



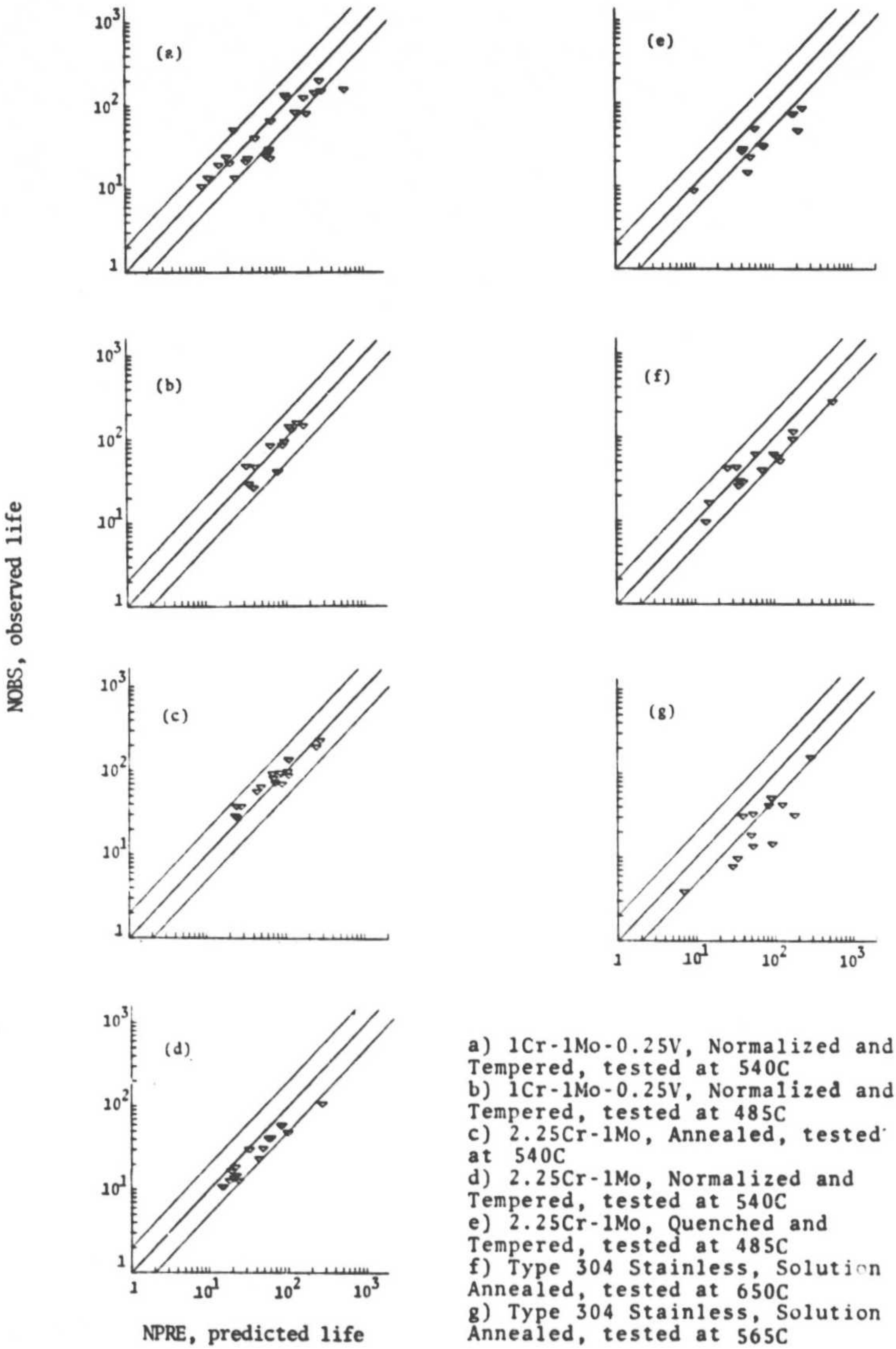
a) 1Cr-1Mo-0.25V, Normalized and Tempered, tested at 540C
b) 1Cr-1Mo-0.25V, Normalized and Tempered, tested at 485C
c) 2.25Cr-1Mo, Annealed, tested at 540C
d) 2.25Cr-1Mo, Normalized and Tempered, tested at 540C
e) 2.25Cr-1Mo, Quenched and Tempered, tested at 485C
f) Type 304 Stainless, Solution Annealed, tested at 650C
g) Type 304 Stainless, Solution Annealed, tested at 565C

Figure 5 - TCF Analysis of MPC Tests.



a) 1Cr-1Mo-0.25V, Normalized and Tempered, tested at 540C
b) 1Cr-1Mo-0.25V, Normalized and Tempered, tested at 485C
c) 2.25Cr-1Mo, Annealed, tested at 540C
d) 2.25Cr-1Mo, Normalized and Tempered, tested at 540C
e) 2.25Cr-1Mo, Quenched and Tempered, tested at 485C
f) Type 304 Stainless, Solution Annealed, tested at 650C
g) Type 304 Stainless, Solution Annealed, tested at 565C

Figure 6 - SRP Analysis of MPC Tests Summing Damage Every Cycle(SRP-1).



a) 1Cr-1Mo-0.25V, Normalized and Tempered, tested at 540C
b) 1Cr-1Mo-0.25V, Normalized and Tempered, tested at 485C
c) 2.25Cr-1Mo, Annealed, tested at 540C
d) 2.25Cr-1Mo, Normalized and Tempered, tested at 540C
e) 2.25Cr-1Mo, Quenched and Tempered, tested at 485C
f) Type 304 Stainless, Solution Annealed, tested at 650C
g) Type 304 Stainless, Solution Annealed, tested at 565C

Figure 7 - SRP Analysis of MPC Tests Using Ave. Strainrange Values(SRP-2).

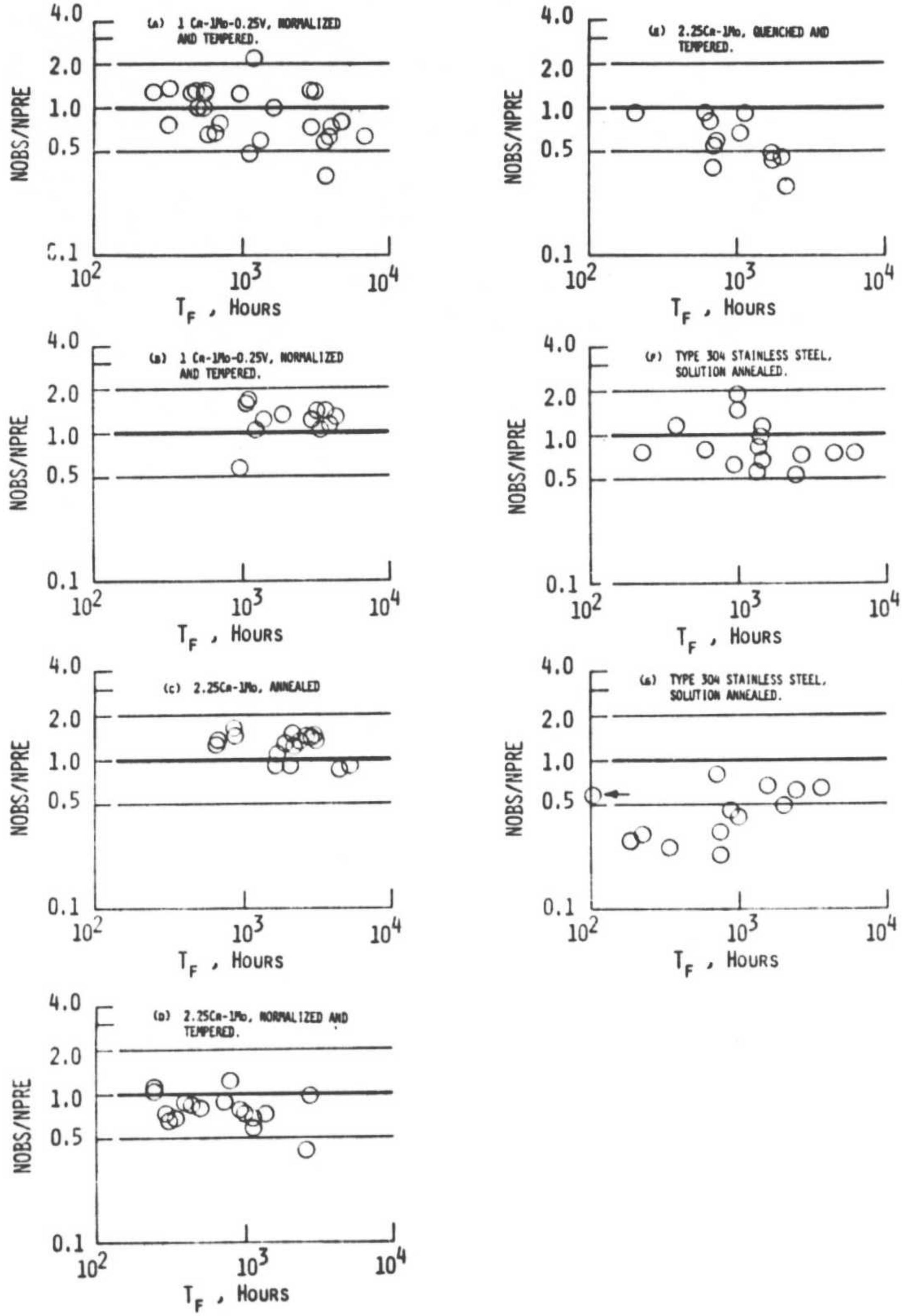


Figure 8 - Ratio of Observed to Predicted Life as a Function of Life of test.