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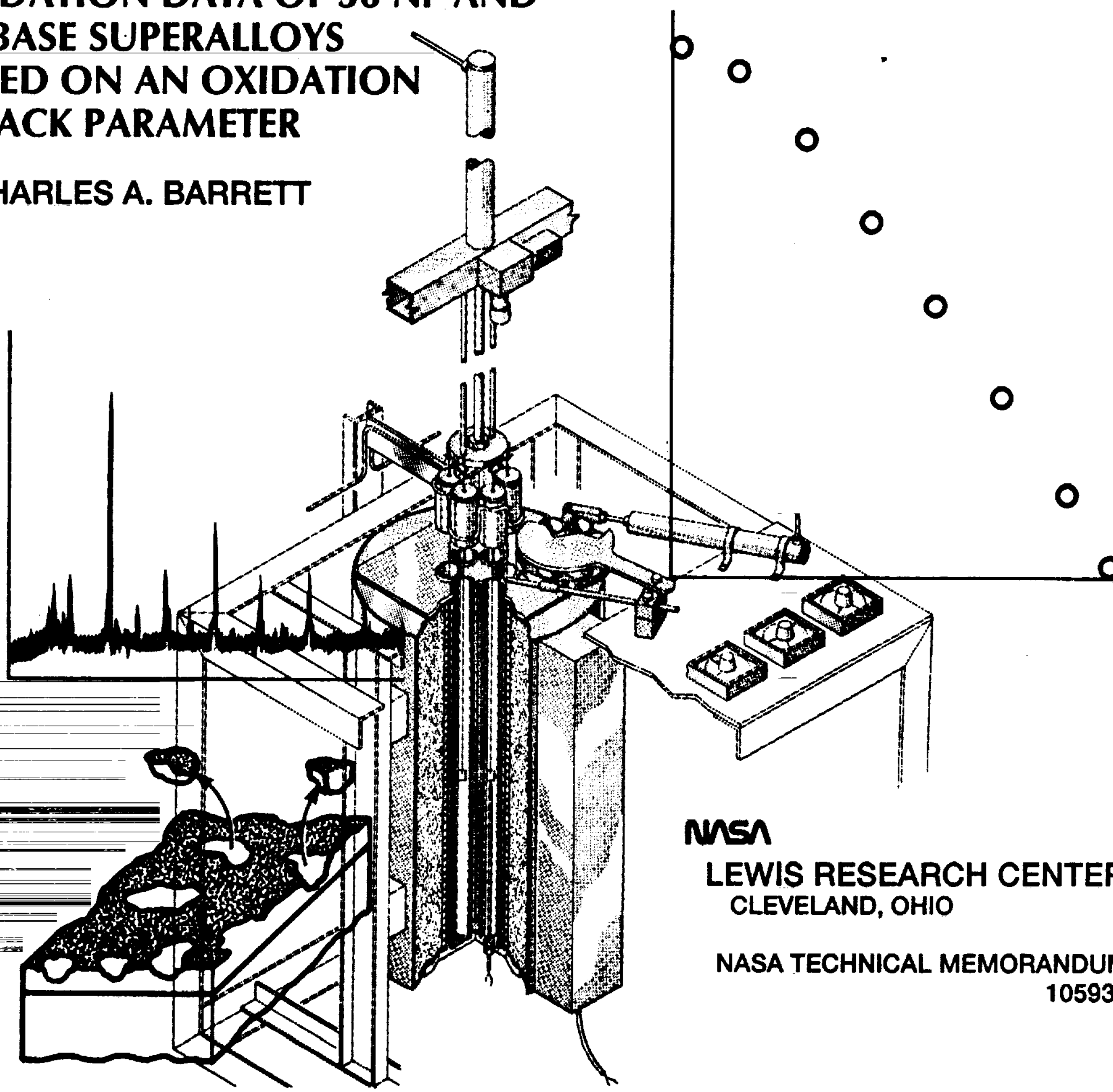

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A STATISTICAL ANALYSIS OF ELEVATED TEMPERATURE GRAVIMETRIC CYCLIC OXIDATION DATA OF 36 Ni- AND Co-BASE SUPERALLOYS BASED ON AN OXIDATION ATTACK PARAMETER

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SUMMARY

A large body of high temperature cyclic oxidation data generated from tests at NASA Lewis Research Center involving gravimetric/time values for 36 Ni- and Co-base superalloys was reduced to a single attack parameter, K_a, for each run. This K_a value was used to rank the cyclic oxidation resistance of each alloy at 1000, 1100, and 1150 °C. These K_a values were also used to derive an estimating equation using multiple linear regression involving $\log_{10}K_a$ as a function of alloy chemistry and test temperature. This estimating equation has a high degree of fit and could be used to predict cyclic oxidation behavior for similar alloys and to design an optimum high strength Ni-base superalloy with maximum high temperature cyclic oxidation resistance. The critical alloy elements found to be beneficial were Al, Cr and Ta.

INTRODUCTION

Cyclic oxidation data in the form of specific weight change/time values and x-ray diffraction results for retained scales as well as spalled oxide(s) has been collected in two recent NASA reports (refs. 1 and 2). These reports covered 36 high-temperature Ni- or Co-base superalloy turbine alloys (table I). These alloys were tested in standard NASA Lewis cyclic oxidation test rigs which have been described in detail in reference 3. Most of the samples tested in these studies were run in a standard mode of a 1.0 hr exposure in the hot zone and then automatically lifted out of the furnace for a minimum of 20 min. This standard cycle was repeated continuously with the sample removed at selected intervals for intermittent weighing to generate the specific weight ($\Delta W/A$) versus time curves. X-ray diffraction analysis was performed at selected intervals as well. In most cases the standard 1 hr cyclic tests for these alloys were 100 hr at 1150 °C, 200 hr at 1100 °C, or 500 hr at 1000 °C.

Most of these alloys, particularly at the higher test temperatures, showed an eventual sample specific weight loss due to scale spalling as the sample cools between heating cycles — more than offsetting the oxygen pickup during scale formation at the exposure temperature. The shape of these $\Delta W/A$ versus time curves closely resemble classic paralinear kinetic behavior (refs. 4 to 6).

This gravimetric cyclic oxidation data can be converted into a single attack parameter, K_a (see below) to rank the oxidation resistance at a given temperature. The higher this K_a value the poorer the resistance. Based on analysis of a large body of data generated by this laboratory, K_a values are ranked as follows (ref. 7):

$K_a \leq 0.20$ excellent
0.20 to 0.5 good
0.50 to 1.0 fair
1.0 to 5.0 poor
>5.0 catastrophic

The goals of this investigation are to derive the attack parameter, K_a for each individual alloy sample tested using the suitable model equation; compare the derived K_a values at 1000, 1100, and 1150 °C to rank the oxidation resistance of alloys; and thirdly, to attempt by regression analysis to derive an estimating equation for K_a (or more realistically $\log_{10}K_a$) as a function of test temperature and alloy composition. If the third goal is feasible the estimating equation will be used to estimate K_a for an alloy not included in this study and finally predict an optimum alloy composition for an alloy of this type.

ESTIMATING CORROSION ATTACK

All the specific weight change/time data and related kinetics are based on the simple mass balance equation at any time, t:

$$\Delta W/A = W_r - W_m \tag{1}$$

where $\Delta W/A$ is the sample's specific weight change value which is plotted against time in these type of handbook figures; W_r is the specific weight of the retained scale, and W_m is the accumulated specific weight of all the metal converted to oxide up to that time regardless whether the metal is still in the retained scale, or lost by any other process (e.g., scale spalling, and/or scale vaporization and/or scale erosion). This W_m value is the critical parameter in any corrosion process and always increases monotonically with time. The problem in any corrosion study is to somehow estimate W_m preferably as a function of time.

In most corrosion studies a test sample is run for a given time, removed from test and descaled and the thickness change measured. This value can be directly converted to a W_m value provided there is no significant alloy element concentration gradient or grain boundary penetration in the alloy. This is not a very practical method in high temperature oxidation studies since it effectively destroys the sample and is a difficult measurement to make particularly for complex alloys. An even more complex extension of this approach is to metallographically mount a cross section of the test sample and determine not only thickness change but any grain boundary attack. Special etching techniques or electron microprobe analysis can then be used to determine any diffusional effects. However, it would be more practical if some nondestructive technique to measure thickness change of the sample as a function of time could be developed, with these more complex and time consuming analysis serving to provide verification.

Another approach is to focus on the W_r value. Since it is assumed that the $\Delta W/A$ value can be derived for any time by simply weighing the sample at that time then if W_r can be determined then the W_m values can be readily solved using equation (1) for a series of times. For two limiting cases W_r presents no particular problem. In the first case typical of most high temperature isothermal studies no scale loss occurs. So the W_r value at any time is simply the $\Delta W/A$ value multiplied by a stoichiometric oxide constant (refs. 8 and 9). For example, in an isothermal parabolic oxidation process after time, t:

$$W_m = bk_p^{1/2}\, t^{1/2} - kp^{1/2}t^{1/2}$$

or

$$W_m = k_p^{1/2}\, t^{1/2}\,(b - 1) \tag{2}$$

where k_p is the parabolic scaling constant and b is the stoichiometric constant based on the composition of the scale.

In the other limiting case where the scale spalls to essentially bare metal, occasionally found in cyclic oxidation, equation (1) reverts to

$$-W_m = \sim \Delta W/A \tag{3}$$

where $\Delta W/A$ values are negative. This has been observed, for example, in burner rig oxidation studies where an insignificant amount of oxide remains (refs. 10 to 14).

There have been attempts at this laboratory and elsewhere to measure W_r directly using some physical method (e.g., β-back scatter, ultrasonic, or microwave technique). So far, however, no method has proven practical. Therefore, an indirect means of estimating W_m as a function of time must be found to analyze the large body of cyclic oxidation data.

One approach is to attempt to model the scaling/scale loss process using differential equations based on parabolic scale growth, occurring simultaneously with a linear scale loss. This model has been solved using the mass balance approach and requires only the constants k_p, k_ℓ, and the stoichiometric constant for the scale formed to be able to determine $\Delta W/A$, W_r, and most importantly W_m for any time t (refs. 4 to 6). But since k_p and particularly k_ℓ are not generally known, Barrett and Presler (ref. 9) derived a computer program to analyze paralinear behavior and determine $\Delta W/A$, W_r, and W_m values along with the k_p and k_ℓ values as a function of time using just two sets $\Delta W/A$, time inputs, and a stoichiometric constant. This program has been used successfully to analyze isothermal oxidation of chromia forming alloys where scale vaporization is significant (ref. 9). Attempts have also been made to use this COREST program to analyze cyclic oxidation behavior of the type of $\Delta W/A$ with time curves shown in the two turbine alloy reports but its success had been limited (refs. 14 and 15) but it is useful as a first approximation.

A more successful approach has been to actually model the cyclic oxidation process, cycle by cycle, on a computer. Any scale growth process, usually a parabolic rate constant, can be used as input. The nature of the spalling process should also be known. For chromia or alumina forming alloys it appears the rate of spalling is a fixed percent of the oxide thickness (ref. 16). As in the other methods the stoichiometric constants can usually be estimated quite easily. This computer program termed COSP (ref. 17) generates the $\Delta W/A$, W_r, and W_m versus time just as in COREST. This approach has been fairly successful with the more simple type heater alloys but has been more difficult to use in analyzing the cyclic oxidation behavior of more complex alloys like high temperature superalloys.

Another approach which has proven successful is to fit the specific weight change/time data to a simple quasi-paralinear equation by multiple linear regression:

$$\Delta W/A = k_1^{1/2}\, t^{1/2} \pm k_2 t \pm \sigma \tag{4}$$

Here $k_1^{1/2}$ and k_2 are constants analogous to the scale growth and scale spalling constants and σ is the standard error of estimate. If the fit is good enough (usually $R^2 > 0.90$) and $k_1^{1/2}$ is significant and positive and k_2 is statistically significant then the attack parameter K_a is defined as:

$$K_a = \left(k_1^{1/2} + 10|k_2|\right) \tag{5}$$

or

If $k_1^{1/2}$ is either not significant or negative and k_2 is significant then K_a is defined as

$$K_a = 20|k_2| \tag{6}$$

The rational behind these K_a derivations are discussed in references 7, 16, and 18 to 22. It has been shown that these K_a values are valid as estimators of oxidation resistance and are well correlated with both thickness change measurements and W_m estimates derived by both the COREST and COSP computer programs discussed above. This K_a estimation technique has the advantage that if the specific weight change/time data is in a computer data base for a given run the data can be automatically processed for a regression fit according to equation (4) and K_a computed according to equations (5) or (6) depending on the significance and sign of the coefficients $k_1^{1/2}$ and k_2. By this process fairly irregular kinetics can be evaluated. This K_a approach was chosen to analyze the large number of runs for the complex superalloys referred to in this report.

Derivation of K_a Values from the Cyclic Oxidation Data

A total of 323 runs based on the 36 alloys listed in table I of $\Delta W/A$ versus time data were individually analyzed according to equation (4) by multiple linear regression. This approach leading to K_a values for each run is detailed in Appendix A.

After discarding 8 outliers as described in the appendix a total of 315 valid K_a values were available to rank the alloys. These valid K_a values can be compared at each test temperature for each alloy as a series of bar graphs. For ease of description the 36 alloys tested were divided into two distinct groups and plotted in figures 1(a) to (c) and figures 2(a) to (c). In the first grouping, all Ni-base, the alloys were essentially alumina/aluminate scale formers. These alloys, 15 in number, contained 5 to 6 wt% Al and a minimum of 5 wt% Cr. The second grouping, containing both Ni- and Co-base alloys, were either Cr_2O_3/chromite or possibly MO scale formers. This group of 21 alloys contained either less than 5 wt% Al with Cr of 9 wt% or greater and were basically the Cr_2O_3/chromite scale formers. Or else they had quite high Al levels but no Cr and tended to form NiO as the surface oxide in spite of the high Al levels.

These two sets of alloys are plotted as a series of bar graphs in order of increasing Al content at the three test temperatures.

The coordinates are K_a values plotted on a log based scale. Also indicated are the rankings from excellent to catastrophic. The top of each bar is the maximum K_a value derived for that alloy at the given temperature. Any horizontal lines below the top represent replicates. This gives an indication of the scatter for each alloy. As expected, oxidation resistance decreases with an increase in test temperature and the number of alloys showing excellent to good oxidation resistance (i.e., $K_a \leq 0.2$ or ≤ 0.5) decreases with increasing temperature as well. Although these plots are quite informative they tend to be somewhat pessimistic because they focus more on maximum values than on average values. Based on these plots three alloys, all Al_2O_3/aluminate formers, have the best oxidation resistance. In decreasing order of resistance they are: (1) TRW-R, (2) B-1900, and (3) NASA-TRW-VIA.

Modeling Oxidation Attack, K_a as a f (Alloy Chemistry, Temperature)

In an earlier study (ref. 22) at this laboratory the derived oxidation attack parameter in the form of $\log_{10}K_a$ was used to study systematic variations in Co, Ta, Al, Cr, and Mo in a prototype Ni-base turbine alloy. The basic alloy content was Ni-1wt%Ti-2wt%W-1wt%Nb-0.1Zr-0.12C-0.01B. The alloy had five target levels each of Al (3.25, 4, 4.75, 5.50, and 6.25); Cr (6, 9, 12, 15, and 18); Co (0, 5, 10, 15, and 20); Mo (0, 1, 2, 3, and 4); and Ta (0, 2, 4, 6, and 8) all in weight percent. This series of alloys represented a 2^5 composite statistically designed experiment representing a total of 43 individual alloys. The samples were tested for 200 1-hr cycles at 1100 °C to derive the K_a values as described above. This design along with a suitable number of replicates enabled a second degree estimating equation to be derived by multiple linear regression as a function of the five composition variables.

This same basic approach was to be used to analyze statistically the 36 alloys with the valid 315 derived K_a values of this study. This analysis differs signifcantly from the above mentioned 2^5 statistically designed study as follows:

(1) It includes both Ni and Co-base alloys although the preponderance are Ni-base.

(2) There are 13 compositional variables as shown in table I - Cr, Al, Ti, Mo, W, Nb, Ta, C, B, Zr, Hf, V, and Re.

(3) The alloys were tested at two, three, or even four different temperatures.

(4) The compositions were essentially random (i.e., the alloy compositions were not systematically varied).

(5) An additional temperature term of the form $X_i = 1/T_k^\circ$ is required as well.

In addition the following simplyfing assumptions were made:

(A) Nominal alloy chemistries will be used even if multiple heats of the same alloys were tested.

(B) A fourteenth composition variable was added and was defined as the Co + Fe content in the Ni base alloys or the Ni + Fe content in the Co base alloys.

(C) The minor Cu content in the Mar-M-246 alloy was not included.

Note there were a number of replicate runs. In multiple regression analysis this allows the pure error variance to be separated from the residual error variance so the significance of the model may be tested with the lack of fit variance. This approach will be shown for the ultimate model derived in this analysis.

Initially only a first order model will be considered (i.e., the independent variables will be first degree only or linear - $x_1, x_2, \ldots$) using the basic 15 terms. Assume the model:

$$\log K_a = a + b_1 C_r + b_2 Al + b_3 NiCo + b_4 Ti + b_5 Mo + b_6 W + b_7 Nb + b_8 Ta$$
$$+ b_9 C + b_{10} B + b_{11} Zr + b_{12} Hf + b_{13} V + b_{14} Re + b_{15}(1/(temp + 273\ °C)) \pm \sigma \quad (7)$$

The multiple regression analysis stepwise procedure was used[1] which rejected any of the 15 terms not significant to the 0.15 level. The final estimating equation involved 11 significant terms with a suprisingly high R^2 value of just over 80 percent. The lack of fit (L.O.F) variance is highly significant implying as expected the model is not adequate. The summary table for this analysis is shown in Appendix C.

The next step is to build a model involving both first and second order terms. In most cases a second order equation is sufficient to model most estimating processes of this type. Thus the model equation would be of the form

$$\log K_a = a_1 + b_1 x_1 + b_{2.2} x_1^2 + b_{1.2} x_1 x_2 + b_2 x_2 + \ldots\ldots b_{15.15} x_{15}^2 \quad (8)$$

For $x_i = 15$ this would involve a possible 135 terms which would not be practical to run in a stepwise multiple regression analysis. Instead a series of subsets of x_i, x_i^2, $x_i x_i \ldots$ terms were used involving 20 to 25 of the 135 possible terms. The significant terms were then accumulated. A total of 23 likely terms were then used to derive a final estimating equation. A rejection level of $\alpha = 0.15$ was again used.

Table II summarizes this analysis. Including the coefficients for the final 14 term equation (9), fourteen of the 23 terms were found to be significant. These coefficients along with the intercept are listed in this table along with their significance levels. This technique also generated the predicted values for each sample run as well as log K_a values for any of the 36 alloys not tested at 1000 or 1100 °C.

Table III is an analysis of variance (ANOVA) summary table to partition the variability (i.e., sum of squares) to test the goodness of fit of the 14 term model equation. This is possible because of the large number of replicate terms which represent pure error. This enables the residual error found in regression analysis to be separated into pure error and lack of fit. The F- ratio of $MS_{L.O.F}$ to MS_{error} is roughly 1.26. Thus the L.O.F term is not significant to the $\alpha = 0.05$ level. This indicates the model estimating equation is adequate for predictive purposes. The R^2 value is close to 0.85 which is quite high for this type of estimation. Even if a better model estimating equation could be found involving more of the 135 possible second order terms or involving even higher order terms or possibly other variables not included in the model only an R^2 value of 0.886 could have been achieved because of the pure replicate error. On this basis the estimated equation explains just over 95 percent of the possible variability that could be modeled.

Figures 3(a) to (c) and figures 4(a) to (c) show the derived K_a estimates from the 14 term estimating equation on a $\log_{10}$ bar graph scale for each alloy at 1000, 1100, and 1150 °C for the two alloy groupings. These values are listed in tables IV and V. Also shown on the same bar graphs are the

[1]The SAS statistical computer package (version 5) for the VM main frame operating system was used for all data analysis in this study.

average observed K_a values[2] for each alloy for ready comparison. At 1000 °C only 11 of the 36 alloys were tested, so 25 alloys represent just the predicted values. At 1100 °C 34 of the 36 alloys were tested, while at 1150 °C all 36 alloys were run. In general the mean and predicted values fall in or near the same rating category. The overall agreement between the predicted and average K_a values appear good.

Figure 5 shows a plot of the regression standard residuals plotted against the predicted values for all the 315 runs. The random nature of the residuals are a good indicator of the validity and unbias nature of the regression equation. A scatter diagram of the predicted log K_a values ploteed against the log of their observed values is shown in figure. 6. The data was fitted by simple linear regression and gives a resultant diagonal straight line with a slope near unity. Also shown are the + or − 2.5 standard deviation lines which would include 95 percent of the data points. This is a further validation of the 14 term regression equation to estimate log K_a values.

A further check on efficency of the estimating equation is how well it predicts K_a values for a similar alloy not included in the original 36 alloy data base. The alloy chosen was NASAIR-100 which has a nominal composition in weight percent of Ni-9Cr-5.8Al-0.5 Co-10.5 W-3.3Ta-1.2Ti-1 Mo-0.03 max Zr -0.006 C- 0.002 B. Two samples were tested for 100 1 hr cycles at 1150 °C. Also a single sample was tested at 1200 °C even though this was outside the temperature test range by 50 °C. Table VI summarizes the K_a derivations for these cyclic runs. From the estimated log K_a values from the 14 term estimating equation (9) and the derived log K_a values from the computed K_a values derived from the oxidation rate constants. The agreement appears quite good. At 1150 °C both actual log K_a values are within 1-1/2 sigma units, while at 1200 °C the values are within one sigma unit of each other. This leads further credence as to the validity of the 14 term estimating equation as well as the overall approach.

Implications for Alloy Chemistry From The Model Estimating Equation

The final 14 term estimating equation (9) summarized in table III has certain obvious implications from the alloy chemistry standpoint. There are only three terms with beneficial negative coefficients which lower the K_a estimates. These improve the cyclic oxidation resistance of this type of Ni-based or Co-based superalloy. Both Al and Cr improve the resistance and so does Ta as long as Al is present. Alloy elements which are neutral (i.e., have no effect) on the cyclic oxidation resistance at least within the alloy ranges (i.e., sample space) of the 36 alloys tested are C, B, and Zr. This also applies to Co in Ni-based or Ni in Co-based alloys.

This leaves Ti, Hf, V, Re, Nb, Mo, and W to be evaluated from the coefficients. Nb is the most obvious element to omit since has a positive interaction with Ti, Ta and Hf. This then allows 1.0-percent Hf to be alloyed since it is neutral without Nb. Rhenium and V should also be eliminated. Tungsten, Mo, and Ti should probably also be dropped since they are all involved with positive terms. However, since around 1.0-percent Ti is usually alloyed to this type of Ni-base superalloy for reasons other than oxidation resistance it should be fixed at roughly 1 percent. One percent Hf could be added also as long as Nb is not present.

This could lead to a typical prototype turbine alloy of Ni-10Co-0.9Ti-1Hf-0.1C-0.015B-0.1Zr with XAl-YCr-ZTa. It is then possible to use the estimating equation to optimize the composition within certain alloy constraints. If Mo and W are required for any reason they should be kept as low as possible.

[2]The average K_a's are defined as the antilog of the average of the log K_a values for each alloy at each temperature.

This is assumed to be a Group I alloy - a basic alumina/aluminate former which has an Al content constrained between 5 and 6 wt%. The Cr contents for this type of alloy that varies between 5 and 13 wt% while Ta when present ranges between 2 and 9 wt%. The role of Cr in helping to stabilize the protective alumina/aluminate scale in heater alloys and Ta in forming the tri-rutile oxide Ni (Ta) O_4 which also confers protection in more complex alumia/aluminate forming alloys have been discussed elsewhere (refs. 8 and 7). This statistical analysis tends to confirm these earlier conclusions. The optimum contents of Al, Cr, and Ta were determined using the above constraints and generating a series of contour plots from the 14 term estimating equation at 1100 °C. A factor was added (2.5×0.352155) to give a 95 percent confidence interval so that the alloy would have excellent cyclic oxidation resistance (i.e., log $K_a \leq -0.7$). The criterion chosen was such that the total Cr + Al + Ta content would be at a minimum. On this basis the composition for the "best" cyclic oxidation resistance should be 6Al–5Cr-8.6Ta. Thus a typical ideal alloy should be Ni-10Co-6Al-5Cr-8.6Ta-0.9Ti-1Hf-0.15C-0.015-0.05Zr. This high strength superalloy would satisfy all the compositional constraints of a group I alumina/aluminate forming alloy with good cyclic oxidation resistance and contain no deletereous alloy additions implicit from the 14 term estimating equation.

SUMMARY OF RESULTS

As a result of statistical analysis of 323 cyclic oxidation runs in static air for 36 Ni- and Co- base high strength superalloys in the 1000 to 1150 °C range using an oxidation attack parameter, K_a derived from $\Delta W/A$, time data the following results were obtained:

(1) Using multiple linear regression analysis with log K_a as the dependent variable a second degree estimating equation can be derived as a function of nominal alloy composition and test temperature based on 315 K_a values with a high degree of fit.

(2) The derived 14 term estimating equation has an R^2 value of close to 85 percent and the numerous replicate runs show the maximum possible R^2 would be close to 89 percent due to 11 percent pure error and only 4 percent lack of fit. This indicates this particular 14 term model is adequate and can be used to predict oxidation results and design alloys with a high degree of confidence.

(3) Based on the coefficients of the regression equation Cr and Al are considered beneficial, and Ta is beneficial when Al is present. Nb is deleterious when Ta, Ti, and Hf are present and should be omitted. Mo and W should be at a minimum since they adversely affect Al and Cr, respectively. Re, V, and Ti should not be alloyed if possible. Ni in Co-base alloys and Co in Ni-base alloys appear innocuous as does C, B, and Zr within the range of their nominal compositions of the 36 alloys studied.

(4) The same estimating equation appeared equally valid for either Ni- or Co-base alloys and for both alumina/aluminate formers or chromia/chromite formers.

(5) Of the 36 alloys studied (see table I) the five best all group I alumina/aluminate formers can be ranked as follows from best to worse (low K_a to high) based on the estimating equation computed at 1100 °C:

(a) B-1900
(b) B-1900 + H_f
(c) NASA-TRW-VIA
(d) TRW-R
(e) TAZ 8A

(6) The estimating equation was used to calculate K_a values for NASAIR-100 a related alloy and compared to K_a values derived from cyclic oxidation tests at 1150 and 1200 °C. The actual and derived K_a's agreed well within the 95 percent confidence interval.

(7) An optimum Ni-base alloy with maximum possible cyclic oxidation resistance along with a minimum total alloy content with good mechanical properties was designed using both the log K_a 14 term estimating equation and the compositional constraints implicit in table I. This alloy in weight percent was the alumia/aluminate former alloy:

Ni-10Co-5Cr-6Al-8.6Ta-0.9Ti-0.15C-0.015B-0.05Zr.

CONCLUSIONS

1. A cyclic oxidation attack parameter, K_a derived from gravimetric/time data which has proven useful in the past to quantitatively rank cyclic oxidation resistance for a number of heater type alloys was successfully to evaluate the cyclic oxidation resistance of a large number of complex Ni- and Co-base high strength superalloys.

2. Using $\log_{10} K_a$ as the dependent variable an estimating equation involving alloy chemistry and test temperature was derived from the experimentally derived K_a values using multiple linear regression. This allowed the oxidation resistance of the alloys studied as well as similar alloys to be successfully predicted and ranked.

3. The estimating equation can be used to design comparable alloys based on alloy composition and test temperature.

APPENDIX A - DERIVATION OF INDIVIDUAL K_a VALUES

A total of 323[1] runs based on the 36 alloys in table I of the $\Delta W/A$ versus time data from references 1 and 2 were individually analyzed according to equation (4), by multiple linear regression.

$$\Delta W/A = k_1^{1/2} t^{1/2} + k_2 t \pm \text{S.E.E.}$$

Where $\Delta W/A$ is the specific weight change at any time, t in hours, $k_1^{1/2}$ is a growth constant that when squared is analogous with the parabolic scaling constant, k_p; and k_2 is a linear coefficient and S.E.E. is the standard error of estimate on the $\Delta W/A$ estimates. The significance level for each coefficient is tested to the 10 percent significance level. If both are significant and $k_1^{1/2}$ is postivie then an attack parameter, K_a is defined as:

$$K_a = \left(k_1^{1/2} + 10|k_2|\right)$$

But if $k_1^{1/2}$ is either negative or not significant then K_a is re-defined as

$$K_a = 20|k_2|$$

The other limiting case is when there is no linear component such as spalling, scale vaporization, excessive scale growth etc., K_a reduces to simply $K_a = k_1^{1/2}$ or for diffusion controlled scaling $K_a = k_p^{1/2}$. Here k_p is the conventional isothermal parabolic scaling constant.

The runs analyzed ranged in temperatures from 1000 to 1150 °C. The times analyzed were at 1000 °C were 500 hr, 1100 °C - 200 hr and 1150 °C - 100 hr. The times may be shorter if the specific weight charges are extreme (> 100 mg/cm^2) usually with associated massive scale spall.

The total of 323 cyclic oxidation sample runs involving 36 alloys were analyzed as described above using regression analysis on the specific weight change/time data. K_a values were then computed from the appropriate $k^{1/2}$ and/or k_2 constants. Table A-I summarizes the class of K_a values derived for each alloy at each temperature. There were 20 runs at 1000 °C, 128 at 1100 °c and 172 at 1150 °C. There were also three runs at 1093 °C (2000 °F). An examination of these 323 K_a values led to dropping 8 of these values. Seven were inferred to be statistical outliers (runs 204-3, 336-4, 472-6, 324-4, 656-1, 657-4, and 664-6). In addition run 481-6 was dropped because its $\Delta W/A$ values were positive but gave too poor a fit to any of the standard model equations to drive K_a.

The individual K_a values are listed in table A-II. Of the 315 valid runs 231 follow the type I paralinear model the remaining 84 are of the type III type showing a linear weight loss. In general the individual regression fits are quite good to models I or III with R^2 values usually well over 90 percent. Of the 315 valid runs, 25 had R^2 values under 90 percent. Of these, 16 had R^2 values in 80 to 90 percent range, 5 in the 70 to 80 percent range, 3 in the 60 to 70 percent range, and 1 in the 50 to 60 percent

[1]Included also are 28 runs not listed in references 1 and 2, but plotted in the Appednix B of this report.

range. In the overall analysis, however, these three values with the lowest R^2 model fits in the 50 to 70 percent range were not even close to being statistical outliers so they were retained for the overall analysis. These valid K_a values can then be used for further comparison and analyses.

APPENDIX B - SUPPLEMENTAL CYCLIC OXIDATION PLOTS

Figures B-1 to B-28 show the additional 28 alloy runs not included in references 1 and 2. The K_a values were derived as described in the body of the text. The test cycles were 1 hr in static air.

APPENDIX C - BASIC LINEAR OXIDATION MODEL

A summary of the simplest linear model involving 11 significant terms of the original 15 first order terms listed in the main body of the text are shown in tables C-I and C-II. A reasonable R^2 is derived as indicated in table C-I. However, table C-II indicates the residual sum of squares when partitioned into true error (i.e. replicate) and lack of fit error the simplest model is not adequate. This led to the more complex final model which included second degree terms.

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TABLE I.—NOMINAL ALLOY COMPOSITION FOR HIGH-TEMPERATURE TURBINE ALLOYS

Alloy	Composition, wt%													Comments
	Ni	Co	Cr	Al	Ti	Mo	W	Cb	Ta	C	B	Zr	Hf	
Alloy 625	Balance	-------	22.5	0.2	0.2	9.0	-----	See Comments	See Comments	0.05	-----	-----	-----	Cb + Ta = 3.65[1]
Alloy 718	↓	-------	19.0	.5	.9	3.05	-----	See Comments	See Comments	.04	0.005	-----	-----	With 18.5 wt% Fe; Cb + Ta = 5.30[2]
Astroloy		15.0	15.0	4.4	3.5	5.25	4.0	-----------	-----------	.06	.03	0.06	-----	Similar to U-700
B-1900		10.0	8.0	6.0	1.0	6.0	.1	0.1	4.3	.1	.015	.08	-----	[a]4
B-1900 + Hf		10.0	8.0	6.0	1.0	6.0	.1	.1	4.3	.1	.015	.08	1.0	
IN-100		15.0	10.0	5.5	5.5	3.0	-----	-----------	-----------	.18	.015	.05	-----	With 1.0 wt% V; [a]3
IN-713LC		-------	12.0	5.9	.6	4.5	-----	2.0	-----------	.05	.010	.10	-----	[a]4
IN-738		8.5	16.0	3.4	3.4	1.75	2.6	.9	1.75	.17	.010	.10	-----	[a]6; includes one hot-worked alloy with ~ 0 Cb
IN-792		9.0	12.7	3.2	4.2	2.0	3.9	-----------	3.9	.21	.02	.10	.75	[a]4
IN-939		19.0	22.0	2.0	3.6	-----	2.0	1.0	1.5	.15	.01	.10	-----	
MAR-M-200		10.0	9.0	5.0	2.0	-----	12.5	2.7	-----------	.15	.015	.05	-----	
MAR-M-200 + Hf		10.0	9.0	5.0	2.0	-----	11.5	1.0	-----------	.15	.015	.05	1.5	[a]2
MAR-M-211		10.0	9.0	5.0	2.0	2.5	5.0	2.7	-----------	.15	.015	.05	-----	
MAR-M-246		11	11	5.0	1.5	-----	-----	-----------	2.0	.09	.01	.01	-----	With 0.1 wt% Cu
MAR-M-247		10.0	8.2	5.5	1.0	.6	10.0	-----------	3.0	.16	.02	.09	1.5	[a]2
MAR-M-421		9.5	15.8	4.3	1.8	2.0	3.8	2.0	-----------	.15	.015	.05	-----	[a]2
NASA-TRW-VIA		7.5	6.1	5.4	1.0	2.0	5.8	.5	9.0	.13	.02	.13	.40	With 0.5 wt% Re[b]; [a]3
Nimonic 115		14.0	14.6	4.9	4.0	3.5	-----	-----------	-----------	.16	.015	.001	-----	
NX-188		-------	<10	8.0	-----	18.0	-----	-----------	-----------	.04	-----	-----	-----	3
René 41		11.0	19.0	1.5	3.1	10.0	-----	-----------	-----------	.09	.01	-----	-----	
René 80		9.5	14.0	3.0	5.0	4.0	-----	-----------	-----------	.17	.015	.03	-----	
René 120		10.0	9.0	4.3	4.0	2.0	7.0	-----------	3.8	-----	.015	.07	-----	
René 125		10.0	9.0	5.0	2.5	2.0	7.0	-----------	3.8	.10	.02	.05	1.50	[a]4
R-150-SX		12.0	5.0	5.5	-----	1.0	5.0	-----------	6.0	-----	-----	-----	-----	With 3.0 wt% Re and 2.2 wt% V
TAZ-8A		-------	6.0	6.0	-----	4.0	4.0	2.5	8.0	.125	.004	1.0	-----	[a]2
TRW-R		8.0	8.0	5.3	.8	3.0	4.0	.3	6.0	.05	.015	.12	1.00	
TRW-1800		.6	13.0	6.0	.6	-----	9.0	1.5	-----------	.09	.07	.07	-----	
U-520		12.0	19.0	2.0	3.0	6.0	1.0	-----------	-----------	.05	.005	-----	-----	
U-700		18.5	15.0	4.3	3.5	4.5	-----	-----------	-----------	.07	.03	.08	-----	[a]7; includes three bar stock alloys; varying Co levels[c]
U-710		15.0	18.0	2.5	5.0	3.0	1.5	-----------	-----------	.10	.012	-----	-----	
U-720		15.0	18.0	2.5	5.0	3.0	1.2	-----------	-----------	.04	.03	.03	-----	
Waspaloy		13.5	19.5	1.3	3.0	4.3	-----	-----------	-----------	.08	.006	.06	-----	
WAZ-20		-------	-----	6.5	-----	18.5	-----	-----------	-----------	.15	-----	.15	-----	
MAR-M-509	10.0	Balance	23.5	-----	.2	-----	7.0	-----------	3.5	.60	-----	.50	-----	
WI-52	-----	Balance	21.0	-----	-----	-----	11.0	2.0	-----------	.45	-----	-----	-----	With 2.0 wt% Fe[4]
X-40	10.5	Balance	25.5	-----	-----	-----	7.5	-----------	-----------	.50	-----	-----	-----	

[a]Represents number of vendors and/or different heats tested.
[b]A modified form of VIA was tested where; 0.5 Re was replaced with an additional 0.5 Hf.
[c]U-700 alloys had Co levels of 14.5 to 19.0 wt%.

[1]Cb = 1.8; Ta = 1.85.
[2]Fe - 18.5 listed as CoNi; Cb - 2.0; Ta = 3.30.
[3]Cr = 0.
[4]Fe = 2.0 listed as CoNi.

TABLE II.—MULTIPLE REGRESSION[a] RESULTS FOR LOG_{10} Ka AS A FUNCTION OF ALLOY COMPOSITION IN wt%, AND OF ABSOLUTE TEST TEMPERATURE IN $1/T_K$ BASED ON AN INITIAL SELECTION OF 23 MOST LIKELY 1st AND 2nd ORDER REACTIONS. NUMBER DATA VALUES n = 315

Zi = 23, Zf = 14

Significant terms, Z	Coefficient	t-statistic
Al-Ta	−0.03008490	−7.365
$1/T_K$	−28 733.83015	−11.020
Al^2	−.05162169	−9.088
Al·V	+.16395511	7.053
Cr	−.71873828	−5.241
Nb·Ta	+.05346153	7.115
$Cr·(1/T_K)$	+924.75130	4.850
Ti·Ta	+.01932161	2.432
Cr·W	+.003726623	5.878
Al·Mo	+.01273215	6.960
Ti·Nb	+.08140372	4.089
Nb·Hf	+.24155034	2.930
Ti	+.08344541	2.890
Re	+.21293029	1.739
a_o, intercept	22.75638644	

R^2 = 84.43% S.E.E. = 0.352155 Zi = 23
Al·Ta, $1/T_K$, Al^2, Al·V, Cr, Nb·Ta, $Cr·(1/T_K)$, Ti·Ta, Cr·W, Al·Mo, Ti·Nb, Nb·Hf, Ti, Re, Al, Mo, Nb, Ta, C, Zr, Hf, Cr^2, Ti·Zr

[a]Stepwise Regression–Variables are added one at a time starting with the most significant, the F–statistic for a variable must be significant to 0.15. After a variable is added, however, the stepwise method looks at all the variables already in the model and deletes any that does not produce an F–statistic significant to the 0.15 level.

TABLE III.—ANALYSIS OF VARIANCE (ANOVA)

SUMMARY FOR n = 315 DATA SET; Zf = 14

SHOWING SOURCES OF VARIATION INCLUDING LACK

OF FIT OF THE ESTIMATING EQUATION

Source	Degrees of freedom, d.f	Sum of squares	Mean squares
Model	14	201.66573	14.40469511
Residual	300	37.20395146	.12401317
Lack of fit	(67)	(9.8844261)	(.14752875)
Replication	(233)	(27.319525)	(.11725118)
Total	314	238.86968	

$$F - \text{Ratio} = \frac{\text{MS(LOF)}}{\text{MS(REPS)}} = \frac{0.14752875}{0.11725118} = 1.258^{a}$$

[a]The lack of fit term appears not be be significant since the F – Ratio for (1 – α) where α = 0.95 = 1.658 which exceeds the MS(LOF)/MS(REPS) ratio derived in this study. Therefore this model is considered satisfactory.

TABLE IV.—GROUP I ALLOYS – ALUMINA/ALUMINATE SCALE FORMERS COMPARISON OF PREDICTED Ka's FROM LOG Ka ESTIMATES FOR COEFFICIENTS LISTED IN TABLE II TO THE AVERAGE[a] OF THE OBSERVED Ka's FOR EACH ALLOY AT EACH TEST TEMPERATURE

Alloy	Wt%[b]			1000 °C		1100 °C		1150 °C	
	Al	Cr	Ta	Average Ka	Predicted Ka	Average Ka	Predicted Ka	Average Ka	Predicted Ka
MAR-M-200	5.0	9.0	----		0.9752	7.2548	14.3509	68.3329	47.7780
MAR-M-200 + Hf	5.0	9.0	----		1.0993	16.9870	16.1768	58.2881	53.8568
MAR-M-211	5.0	9.0	----		.7883	13.2160	11.6007	24.1583	38.6218
MAR-M-246	5.0	11.0	2.0		.0726	1.5534	.8376	18.0767	2.5006
René - 125	5.0	9.0	3.8		.1400	1.9005	2.0602	9.7719	6.8580
TRW-R	5.3	8.0	6.0	0.0555	.0323	.1063	.5365	.8302	1.8863
NASA-TRW-VIA	5.4	6.1	9.0		.0169	.3155	.3533	1.3698	1.3776
IN-100	5.5	10.0	----		1.8657	14.0391	24.3067	83.0396	76.6307
MAR-M-247	5.5	8.2	3.0	.0525	.0477	.5022	.7743	4.3845	2.6928
R-150-SX	5.5	5.0	6.0	3.5375	2.8480	45.0103	68.2400	314.856	282.519
IN-713 LC	5.9	12.0	----		.0924	.7146	.9439	1.2619	2.6685
B-1900	6.0	8.0	4.3	.0532	.0187	.1839	.3100	1.3843	1.0898
B-1900 + Hf	6.0	8.0	4.3		.0197	.4228	.3277	1.0774	1.1522
TAZ - 8A	6.0	6.0	8.0	.0972	.0252	.4243	.5244	2.2900	2.0534
TRW - 1800	6.0	13.0	----		.0968	.7309	.8746	3.6902	2.3416

[a]Observed Ka's are based on the antilog of the average of the Log Ka values for each alloy at each test temperatuare.

[b]Al, Cr, and Ta are the key elements in improving cyclic oxidation resistance.

TABLE V.—GROUP II ALLOYS - CHROMIA/CHROMITE AND NiO SCALE FORMERS - COMPARISON OF PREDICTED Ka's FROM Log Ka ESTIMATES FOR COEFFICIENTS LISTED IN TABLE II TO THE AVERAGE[a] OF THE OBSERVED Ka's FOR EACH ALLOY AT EACH TEST TEMPERATURE

Alloy	Wt%[b]			1000 °C		1100 °C		1150 °C	
	Al	Cr	Ta	Average Ka	Predicted Ka	Average Ka	Predicted Ka	Average Ka	Predicted Ka
MAR-M-509	0	23.5	3.5		10.2035	25.2623	25.6668	46.5804	38.7764
WI-52	0	21.0	----		16.1108	33.6529	54.9552	116.887	95.1412
X-40	0	25.5	----		12.4060	35.5703	24.4580	27.6292	33.1348
Alloy 625	0.2	22.5	1.9		3.9692	28.7153	11.2780	36.4196	17.9926
Alloy 718	0.5	19.0	3.3		8.3100	28.5671	36.1671	43.3921	69.8240
Waspaloy	1.3	19.5	----	4.7380	3.7067	5.7051	15.1791	23.1244	28.5170
René 41	1.5	19.0	----		4.6173		20.0954	33.0520	38.7982
IN-939	2.0	22.0	1.5		9.9811	32.5843	30.1413	55.3798	49.4148
U-520	2.0	19.0	----		3.9657	31.6500	17.2593	55.9731	33.3208
U-710	2.5	18.0	----		4.1103	33.7545	20.2068	48.908	41.1959
U-720	2.5	18.0	----	6.3587	3.9242	32.3348	19.2918	41.5751	39.3306
René 80	3.0	14.0	----		2.4992	37.3205	20.0015	60.3715	50.7086
IN-792	3.2	12.7	3.9		2.0481	21.9872	19.2034	49.8747	52.2593
IN-738	3.4	16.0	1.8	1.6985	3.1246	27.3451	19.5987	37.0869	44.5570
MAR-M-421	4.3	15.8	----		1.3436	9.5308	8.6353	34.9361	19.8471
René 120	4.3	9.0	3.8		.6020	6.8484	8.8588	14.9107	24.4930
U-700	4.3	15.0	----	1.1562	.7657	3.6784	5.4247	21.2444	13.0235
Astroloy	4.4	15.0	----		1.2896	3.2373	9.1370	61.7246	21.9361
Nimonic 115	4.9	14.6	----	.3982	.4071		3.0284	1.6397	7.4309
WAZ-20	6.5	----	----		.3425	20.0738	15.0883	82.7178	82.0313
NX-188	8.0	----	----		.0518	3.4403	2.2817	7.7592	12.4050

[a]Observed Ka's are based on the antilog of the average of the Log Ka values for each alloy at each test temperatuare.
[b]Al, Cr, and Ta are the key elements in inproving cyclic oxidation resistance.

TABLE VI.—COMPARISON OF OBSERVED AND PREDICTED Ka VALUES FOR A TYPICAL TURBINE ALLOY Ni-BASE NASAIR-100(Ni-9Cr-5.75Al-1.2Ti-1Mo-3.30Ta-10.5W-.03Zr) TESTED IN CYCLIC OXIDATION FOR ONE HR EXPOSURE CYCLES IN STATIC AIR AT 1150 AND 1200 °C

Run	Test temperature	Test time, hrs	$\Delta W/A$ final, mg/cm^2	Ka observed	Log Ka observed	Log Ka predicted[a]	Standard deviation,[a] σ	Deviation σ-units[b]
44-1	1150 °C	100	−33.54	5.8137	0.7645	0.2684	0.3522	1.408
44-3	1150 °C	100	−38.75	5.9583	0.7751	0.2685	0.3522	1.438
42-1	1200 °C	30	−48.14	12.2041	1.0865	0.7554	0.3522	0.940

[a]Based on the derived estimating equation, see table II.

$$^{b}\ \frac{(\text{log Ka observed} - \text{log Ka predicted})}{\text{Standard deviation}}$$

TABLE A-I.—CLASSIFICATION OF OBSERVED Ka VALUES DERIVED FROM INDIVIDUAL ΔW/A VERSUS TIME VALUES FOR EACH ALLOY RUN FOR A TOTAL OF 323 RUNS INCLUDING EIGHT PROBABLE OUTLIERS

Alloy	Number of samples tested at			Observed Ka, type		Number of outlier(s)[e] and reason(s)
	1000°C	1100 °C	1150 °C	Paralinear	Linear	
Alloy 625	0	1	1	2	0	0
Alloy 718	0	1	1	2	0	0
Astroloy	0	1	1	1	1	0
B-1900	1	8	30	23	16	1 $\sigma = 4.457$
B-1900 + Hf	0	3	3	0	6	1 $\sigma = 3.798$
IN-100	0	3[a]	13	11	5	0
IN-713 LC	0	1	2	0	3	0
IN-738	1	10	5	16	0	0
IN-792[b]	0	8	11	18	0	1 $\sigma = -3.972$, approximate parabolic $R^2 = 0.998$
IN-939	0	1	1	2	0	0
MAR-M-200	0	3	4	5	2	0
MAR-M-200 + Hf	0	6	8	12	2	0
MAR-M-211	0	3	3	5	1	2 $\sigma = -3.175$, $\sigma = -3.677$
MAR-M-246	0	1	1	2	0	0
MAR-M-247	2	5	5	9	3	1 $\sigma = -2.765$
MAR-M-421	0	1	1	2	0	0
NASA-TRW-VIA	0	6	13	15	4	0
Nimonic 115	2	1	1	2	2	1 $\sigma = -3.131$
NX-188	0	2	3	4	1	0
René-41	0	0	3	3	0	0
René-80	0	2	3	5	0	0
René-120	0	1	2	3	0	0
René-125	0	3	2	4	1	0
R-150-SX	2	1	1	3	1	0
TAZ-8A	1	11	11	20	3	0
TRW-R	1	2	2	1	4	0
TRW-1800	0	1	1	1	1	0
U-520	0	1	1	2	0	0
U-700	5	27	12	21	23	0
U-710	0	1	1	2	0	0
U-720	2	1	1	4	0	0
Waspaloy	3	5	5	12	1	1[c]
WAZ-20	0	2	3	3	2	0
MAR-M-509	0	2	3	5	0	0
WI-52	0	2[d]	7	3	6	0
X-40	0	1	7	8	0	0
Total	20	128	172	230	89	8

[a]An additional IN-100 sample tested at 1093 °C. paralinear behavior.
[b]One IN-792 sample showed almost pure parabolic behavior but was deemed an outlier.
[c]One Waspalloy sample (481-6) tested for 200 1. hr cycles at 1100 °c gave such a poor fit to any of 3 possible models-paralinear, linear or parabolic that it was automatically considered an outlier.
[d]Two additinal WI-52 samples tested at 1093 °C, paralinear behavior.
[e]Based on the model:
$\log Ka = a \cdot CoNi + b \cdot Ti + c \cdot Mo + d \cdot W \pm e \cdot Nb + f \cdot Ta + g \cdot C + h \cdot B + i \cdot Zr + j \cdot Hf + k \cdot V + l \cdot Al \cdot Cr + m \cdot Al^2 + n \cdot Cr^2 + o \cdot 1/T_K + p \cdot Cr + q \cdot Re \pm \sigma$
if $\sigma > \pm 2.5$ the sample is dropped as an outlier.

TABLE A-II.—INDIVIDUAL Ka VALUES AND ASSOCIATED SPECIFIC WEIGHT CHANGE DATA FOR EACH ALLOY SAMPLE RUN, n = 315

Alloy	Test temperature, °C	Run number	Test time, hr	Model type	$k_1^{1/2}$	k_2	Ka	R^2	Final ΔW/A
Alloy 625	1100	351-4	200	Paralinear	7.99315	−2.07222	28.7154	0.998	−293.20
Alloy 625	1150	352-4	100		7.69380	−2.87258	36.4196	.999	−208.10
Alloy 718	1100	351-3	200		8.17729	−2.03898	28.5671	.998	−284.60
Alloy 718	1150	352-3	100		8.67148	−3.47206	43.3921	.999	−255.70
Astroloy	1100	473-3	200		1.21721	−.20201	3.2373	.928	−30.25
Astroloy	1150	472-3	100	Linear	---------	−3.08623	61.7246	.992	−318.80
B-1900	1000	471-3	500	Paralinear	.03803	−.00151	.0531	.926	+.19
	1100	103-3	200	Paralinear	.07635	−.01044	.1808	.978	−.97
		103-4		Paralinear	.08866	−.01469	.2356	.951	−1.56
		186-6		Linear	---------	−.01597	.3193	.873	−2.52
		190-5		Linear	---------	−.00843	.1686	.832	−1.20
		276-6		Paralinear	.04583	−.00840	.1298	.983	−.97
		324-2			.06368	−.01226	.1863	.972	−1.40
		327-1			.03604	−.00924	.1284	.983	−1.21
	1150	41-1	100		.06418	−.03528	.4169	.999	−2.87
		78-1			.58862	−.24889	3.0775	.994	−19.91
		78-2			.65950	−.25321	3.1916	.995	−19.59
		95-1		Linear	---------	−.05565	1.1130	.995	−5.56
		95-2		Linear	---------	−.05231	1.0462	.995	−5.05
		101-3		Paralinear	.18539	−.04590	.6444	.996	−2.62
		101-6		Linear	---------	−.04207	.8414	.988	−3.97
		107-4		Linear	---------	−.06512	1.3025	.995	−6.80
		107-5		Paralinear	.40414	−.13133	1.7174	.997	−9.46
		123-1			.55939	−.16387	2.1981	.986	−12.11
		123-2			.72746	−.20699	2.7974	.982	−15.16
		123-3			.57362	−.13841	1.9577	.985	−9.12
		123-4			.15333	−.05408	.6941	.981	−4.35
		123-5			.32815	−.12461	1.5743	.989	−10.10
		123-6			.52619	−.12212	1.7474	.978	−7.93
		128-1		Linear	---------	−.07332	1.4665	.995	−7.08
		128-2		Linear	---------	−.05824	1.1648	.999	−5.62
		130-1		Paralinear	.71171	−.16798	2.3915	.976	−11.14
		130-2			2.32699	−.49507	7.2777	.981	−28.76
		130-3			.77096	−.20694	2.8404	.987	−14.43
		130-4			.21995	−.07800	1.0000	.999	−5.66
		130-5			.07632	−.06096	.6860	.998	−5.42
		130-6			.42854	−.15200	1.9485	.990	−11.99
		146-5		Linear	---------	−.04454	.8908	.986	−4.25
		204-4			---------	−.07026	1.4053	.947	−6.13
		221-1			---------	−.05004	1.0008	.990	−4.75
		221-5			---------	−.07562	1.5125	.997	−7.31
		321-2			---------	−.05778	1.1557	.995	−5.50
		328-1			---------	−.03415	.6830	.989	−3.27
		337-4			---------	−.03844	.7688	.994	−4.11
B-1900 + Hf	1100	190-4	200		---------	−.01208	.2416	.902	−1.94
	1100	326-3	200		---------	−.08729	1.7458	.983	−1.65
	1100	475-1	200		---------	−.00896	.1791	.959	−1.44
	1150	323-3	100		---------	−.0437	.874	.967	−3.85
	1150	474-1	100		---------	−.0664	1.327	.978	−7.80
IN-100	1093	100-1	100	Paralinear	6.9924	−2.1500	28.493	.999	−148.10

TABLE A-II.—Continued.

Alloy	Test temperature, °C	Run number	Test time, hr	Model type	$k_1^{1/2}$	k_2	Ka	R^2	Final ΔW/A
IN-100	1100	393-1	200	Paralinear	1.0514	−0.1415	2.466	0.985	−15.25
	1100	413-4	75	Linear	---------	−6.3439	126.878	.999	−462.4
	1100	469-1	200	Linear	---------	−.4421	8.842	.983	−63.34
	1150	41-6	100	Paralinear	5.3939	−1.0188	15.582	.955	−56.20
		95-3	75	Paralinear	21.2371	−6.4556	85.793	.997	−306.0
		95-6	75	Linear	---------	−5.2591	105.183	.999	−385.0
		105-1	90	Paralinear	4.1880	−7.9080	83.268	.999	−652.7
		105-2	100		13.8025	−7.9190	92.992	.999	−635.2
		127-1			41.1241	−7.9930	121.054	.983	−417.6
		127-2			14.9888	−10.7823	122.812	.999	−527.8
		127-3			18.2168	−3.8912	57.129	.989	−220.2
		127-4			16.6828	−3.4270	50.952	.984	−191.0
		127-5			28.0016	−5.2697	80.699	.968	−277.2
		127-6			23.6953	−4.3537	67.232	.953	−231.9
		414-4	60	Linear	---------	−7.3451	146.902	.999	−438.2
		470-1	45		---------	−11.8857	237.714	.999	−521.9
IN-713 LC	1100	473-5	200		---------	−.0357	.715	.997	−6.20
IN-713 LC	1150	41-4	100		---------	−.1386	2.772	.993	−12.98
IN-713 LC	1150	472-5	100		---------	−.0287	.575	.966	−2.52
IN-738	1000	674-3	500	Paralinear	1.0279	−.0670	1.698	.953	−12.65
	1100	324-1	200		9.4313	−1.3867	23.298	.976	−55.81
		413-2			11.9709	−1.6564	28.535	.964	−182.4
		469-6			2.4517	−.6258	8.710	.997	−95.13
		659-1			13.2680	−2.6506	39.774	.998	−338.4
		663-2			13.5724	−3.1061	44.634	.988	−183.3
		664-2			11.9394	−1.8196	30.135	.992	−199.50
		679-4			7.5608	−2.3929	31.490	.999	−363.60
		679-5			11.8385	−1.9061	30.900	.994	−215.80
		680-4			7.2468	−2.2193	29.440	.998	−332.70
		680-5			4.6310	−2.1713	26.344	.996	−357.9
	1150	41-2	100		8.5420	−1.8366	26.908	.965	−112.6
		321-1			9.9065	−2.2040	31.946	.976	−134.1
		414-2			11.7430	−2.6738	38.481	.983	−160.8
		470-6			13.4443	−2.9574	43.018	.986	−170.6
		658-1			5.5606	−4.3745	49.305	.999	−371.9
IN-792	1100	310-2	200		9.0621	−1.4302	23.364	.991	−161.9
		326-2			9.7766	−1.6063	25.841	.995	−184.5
		326-5			9.5023	−1.4302	23.804	.990	−156.30
		336-5			8.9258	−1.5386	24.312	.995	−184.4
		411-6			.0792	−1.2207	12.287	.973	−148.8
		469-4			10.0727	−1.5685	25.757	.983	−183.6
		657-5			9.4552	−1.3011	22.466	.965	−144.3
	1150	323-2	100		13.6102	−3.2478	46.088	.994	−192.1
		323-5			13.4964	−3.3138	46.634	.996	−196.2
		337-5			12.4612	−3.2332	44.794	.995	−205.0
		412-6			13.2188	−3.3625	46.844	.993	−208.5
		425-4			13.8841	−3.7341	51.225	.998	−233.2
		425-5			14.3983	−4.1172	55.570	.998	−264.5
		426-4			14.1476	−3.7264	51.411	.998	−229.6
		426-5			13.1177	−3.8563	51.681	.998	−251.4

TABLE A-II.—Continued.

Alloy	Test temperature, °C	Run number	Test time, hr	Model type	$k_1^{1/2}$	k_2	Ka	R^2	Final $\Delta W/A$
IN-792	1150	428-4	100	Paralinear	13.9847	−3.6630	50.615	0.998	−225.0
IN-792	1150	428-5	100		17.1251	−4.4736	61.861	.997	−273.8
IN-792	1150	470-4	100		12.3665	−3.2108	44.474	.992	−203.4
IN-939	1100	327-3	200		12.3857	−2.0199	32.584	.996	−227.6
IN-939	1150	328-3	100		15.8826	−3.9472	55.380	.996	−233.2
MAR-M-200	1100	310-3	200		1.7693	−.3701	5.470	.994	−52.16
	1100	391-1	200		1.1751	−.3713	4.888	.999	−58.06
	1100	391-2	200		5.1989	−.9083	14.281	.989	−50.55
	1150	225-1	75	Linear	---------	−5.0986	101.972	.998	−369.2
		225-2	75	Linear	---------	−5.0528	101.056	.999	−368.2
		392-1	100	Paralinear	11.2087	−2.6179	37.388	.984	−165.2
		392-2	100		16.4969	−4.0094	56.591	.994	−243.3
MAR-M-200 + Hf	1100	310-4	200		5.7798	−.8618	14.398	.994	−95.85
		310-5			6.3588	−.8557	14.916	.974	−94.95
		391-3			7.5777	−1.0607	18.185	.984	−115.7
		391-4			10.9500	−1.3809	24.758	.944	−35.11
		391-5			6.4031	−.8243	14.646	.957	−90.17
		391-6			7.1013	−.9866	16.967	.983	−107.0
	1150	225-3	100		4.6373	−4.2870	47.507	.999	−380.3
		225-4			5.2434	−1.0455	15.698	.982	−58.81
		225-5		Linear	---------	−3.9051	78.102	.999	−385.0
		225-6		Linear	---------	−4.4577	89.153	.999	−439.9
		392-3		Paralinear	22.2491	−5.1485	73.734	.997	−295.0
		392-4			20.9305	−5.2509	73.439	.998	−313.7
		392-5			23.0734	−4.6244	69.317	.985	−242.8
		392-6			21.4160	−4.6941	68.357	.993	−261.4
MAR-M-211	1100	324-4	115		51.5721	−9.4149	145.721	.983	−524.9
	1100	473-6	200		.3227	−.08759	1.199	.989	−14.62
	1150	321-4	100		1.4392	−.39142	5.353	.979	−27.93
	1150	478-1	100		32.1709	−7.6849	109.019	.995	−452.8
MAR-M-246	1100	325-3	200		.2656	−.1288	1.553	.994	−24.44
MAR-M-246	1150	322-3	100		5.0692	−1.3008	18.077	.975	−92.89
MAR-M-247	1000	452-5	500		.0471	−.0012	.059	.991	+.46
	1000	480-3	500		.0343	−.0012	.046	.954	+.24
	1100	453-5	200	Linear	-------	−.0280	.560	.993	−5.30
		481-3		Paralinear	.0789	−.0320	.399	.997	−4.92
		657-1		Paralinear	.2228	−.0334	.556	.998	−3.50
		657-2		Paralinear	.1964	−.0259	.456	.994	−2.52
		657-3		Linear	-------	−.0282	.564	.979	−4.86
	1150	454-5	100	Paralinear	.4067	−.2250	2.657	.996	−19.46
		482-3		Paralinear	1.1464	−.4054	5.200	.995	−30.86
		656-2		Paralinear	2.9041	−.6259	9.163	.995	−35.68
		656-3		Linear	-------	−.1459	2.919	.973	−14.21
MAR-M-421	1100	325-1	200	Paralinear	3.8911	−.5640	9.531	.944	−74.11
MAR-M-421	1150	322-1	100		12.0706	−2.2866	34.936	.940	−128.7
NASA-TRW-VIA	1100	103-1	200		.2144	−.0198	.412	.988	−.94
		103-2			.1933	−.0174	.367	.982	−.77
		103-6			.1118	−.0111	.223	.874	−.54
		190-6			.0528	−.0154	.207	.992	−2.32
		473-4			.1981	−.0258	.456	.939	−1.88

TABLE A-II.—Continued.

Alloy	Test temperature, °C	Run number	Test time, hr	Model type	$k_1^{1/2}$	k_2	Ka	R^2	Final ΔW/A
NASA-TRW-VIA	1100	659-6	200	Paralinear	0.0991	−0.0212	0.311	0.963	−2.41
	1150	41-3	100		.4364	−.0838	1.274	.991	−3.87
		78-6			.4543	−.1233	1.687	.991	−8.27
		101-4			.4176	−.0750	1.168	.999	−3.26
		105-5			.1437	−.0564	.708	.997	−4.13
		129-1		Linear	-------	−.0367	.734	.995	−3.81
		129-2		Linear	-------	−.0382	.763	.983	−3.77
		129-3		Paralinear	0.8529	−.1894	2.747	.996	−11.01
		129-4			.5891	−.1357	1.946	.999	−7.68
		129-5			.1439	−.0533	.677	.992	−4.20
		129-6			1.3212	−.2894	4.215	.999	−15.81
		204-5		Linear	-------	−.0877	1.754	.998	−8.96
		472-4		Paralinear	.2585	−.1205	1.463	.998	−9.82
		658-6		Linear	-------	−.0768	1.536	.996	−7.35
Nimonic 115	1000	675-4	500	Paralinear	.1930	−.0124	.317	.825	−1.47
Nimonic 115	1000	675-5	500	Paralinear	.3220	−.0178	.500	.542	−4.60
Nimonic 115	1150	663-6	100	Linear	-------	−.0820	1.640	.962	−7.24
NX-188	1100	393-2	200	Paralinear	.8623	−.2386	3.248	.990	−39.06
	1100	413-3	200		.5128	−.3131	3.644	.997	−58.45
	1150	102-3	100		.5371	−.4188	4.725	.999	−37.87
		102-6			2.1865	−.8314	10.500	.997	−61.88
		414-3		Linear	-------	−.4708	9.416	.998	−48.39
René 41		100-5		Paralinear	10.2068	−2.6283	36.490	.998	−156.4
René 41		137-3			8.2779	−2.4160	32.438	.995	−150.9
René 41		137-6			8.5318	−2.1973	30.505	.998	−130.4
René 80	1100	232-3	200		10.6738	−2.9182	39.856	.999	−426.4
	1100	659-2	200		13.7574	−2.1189	34.946	.993	−234.3
	1150	108-3	100		14.0964	−5.2980	67.077	.999	−380.0
	1150	108-6	100		12.8420	−5.0996	63.838	.999	−373.9
	1150	658-2	100		6.6785	−4.4707	51.386	.999	−370.6
René 120	1100	232-6	200		2.9670	−.3887	6.854	.984	−38.57
René 120	1150	108-4	100		4.6319	−1.0219	14.851	.996	−57.63
René 120	1150	108-5	100		4.9019	−1.0068	14.970	.994	−53.30
René 125	1100	325-4	200		1.4998	−.1942	3.442	.959	−20.97
	1100	659-3	200	Linear	-------	−.0190	.380	.997	−3.92
	1100	659-3	200	Paralinear	2.1047	−.3141	5.246	.967	−38.76
	1150	322-4	100		3.0903	−.6214	9.304	.981	−34.69
	1150	658-4	100		2.7092	−.7554	10.263	.990	−52.21
R-150-SX	1000	615-3	500		.6394	−.0514	1.153	.827	−16.78
	1000	678-6	500		5.8266	−.5024	10.850	.922	−148.1
	1100	614-3	160		3.7768	−4.1233	45.010	.999	−596.4
	1150	613-3	45	Linear	-------	−15.7428	314.856	.993	−667.0
TAZ-8A	1000	471-6	500	Paralinear	.0851	−.0012	.097	.994	+1.40
	1100	232-2	200		.7243	−.0823	1.547	.955	−7.40
		324-3			.3521	−.0095	.447	.999	+2.95
		413-1			.1172	−.0094	.211	.648	−.06
		413-6			.4530	−.0235	.688	.992	+1.31
		469-2			.3932	−.0184	.578	.998	+1.84
		473-2			.1203	−.0063	.184	.981	+.43
		657-6			.0401	−.0046	.086	.748	−.19

TABLE A-II.—Continued.

Alloy	Test temperature, °C	Run number	Test time, hr	Model type	$k_1^{1/2}$	k_2	Ka	R^2	Final ΔW/A
TAZ-8A	1100	679-3	200	Paralinear	0.2292	−0.0042	0.272	0.999	+2.38
		679-6			.7115	−.0478	1.190	.953	−.45
		680-3			.3893	−.0133	.522	.999	+2.79
		680-6			.3805	−.0135	.516	.999	+2.60
	1150	321-3	100		.7966	−.0748	1.545	.965	−.08
		414-1		Linear	-------	−.0156	.311	.908	−1.32
		414-6		Paralinear	.8835	−.0666	1.549	.988	+1.66
		425-3			5.6342	−.8719	14.353	.877	−41.81
		425-6			3.5610	−.4959	8.520	.743	−21.76
		426-3			2.7443	−.3985	6.729	.915	−15.43
		426-6			2.2947	−.2956	5.251	.723	−10.80
		428-3			2.8832	−.4323	7.206	.941	−17.29
		428-6			2.1823	−.2880	5.062	.822	−10.02
		472-2		Linear	-------	−.0134	.269	.79-	−.91
		656-6		Linear	-------	−.0144	.288	1.883	−1.16
TRW-R	1000	471-5	500	Paralinear	.0415	−.0014	.056	.946	+.31
	1100	325-2	200	Linear	-------	−.0056	.112	.991	−1.07
	1100	475-2	200		-------	−.0050	.101	.927	−.85
	1150	322-2	100		-------	−.0267	.534	.965	−2.46
	1150	474-2	100		-------	−.0645	1.290	.963	−8.26
TRW-1800	1100	659-5	200	Paralinear	.1807	−.0550	.731	.999	−8.65
TRW-1800	1150	658-5	100	Linear	-------	−.1845	3.690	.988	−17.07
U-520	1100	351-5	500	Paralinear	13.8059	−1.7844	31.650	.971	−172.8
U-520	1150	352-5	200		18.1022	−3.7871	55.973	.992	−197.1
U-700	1000	424-5	500		.4720	−.0289	.761	.979	−4.38
		436-1			.8972	−.0618	1.515	.760	−17.72
		436-2			.6738	−.0430	1.104	.885	−9.28
		447-6			.4038	−.0243	.647	.634	−7.15
		452-1			1.4341	−.1073	2.508	.970	−34.22
	1100	251-1	200	Linear	-------	−.1083	2.167	.961	−27.48
		251-2		Paralinear	1.0491	−.2553	3.602	.937	−47.83
		266-1		Linear	-------	−.0945	1.890	.935	−18.64
		269-1			-------	−.0880	1.760	.959	−21.46
		310-6			-------	−.2893	5.785	.861	−46.18
		324-6			-------	−.1160	2.319	.965	−29.06
		326-6			-------	−.0815	1.630	.945	−16.65
		422-5		Paralinear	8.5510	−1.4050	22.601	.982	−174.2
		437-1		Linear	-------	−.0931	1.861	.974	−17.69
		437-2		Paralinear	10.9300	−1.6620	27.550	.982	−88.97
		448-6		Paralinear	5.6767	−.7721	13.398	.869	−108.3
		453-1		Linear	--------	−.0811	1.623	.917	−13.28
		469-5			--------	−.0786	1.5717	.863	−11.53
		477-6			--------	−.1101	2.2014	.969	−21.86
		610-1			--------	−.2296	4.5926	.985	−42.50
		610-2			--------	−.0545	1.091	.846	−7.87
		610-3			--------	−.0755	1.510	.951	−17.31
		610-4		Paralinear	.5479	−.1315	1.863	.972	−21.16
		610-5		Linear	--------	−.2383	4.765	.993	−53.16
		610-6		Linear	--------	−.1048	2.096	.931	−17.31
		655-4		Paralinear	12.0917	−1.9223	31.314	.991	−214.9

TABLE A-II.—Continued.

Alloy	Test temperature, °C	Run number	Test time, hr	Model type	$k_1^{1/2}$	k_2	Ka	R^2	Final ΔW/A
U-700	1100	655-5	200	Paralinear	7.3772	−0.9441	16.819	0.914	−111.2
		656-6	200	Paralinear	6.7959	−1.8583	25.379	.999	−271.3
		679-1	200	Linear	--------	−.1278	2.556	.956	−32.13
		679-2	100		--------	−.0938	1.876	.936	−19.72
		680-1			--------	−.1230	2.460	.973	−23.97
		680-2			--------	−.0854	1.708	.940	−15.05
	1150	321-6			--------	−.4705	9.411	.941	−60.56
		323-6			--------	−.4260	8.520	.964	−51.14
		423-5		Paralinear	16.4400	−3.9220	55.660	.992	−230.7
		438-1			2.0961	−.6998	9.095	.958	−58.16
		438-2			15.2100	−3.9650	54.860	.995	−243.2
		449-6			15.0393	−3.0999	46.038	.970	−174.8
		454-1			2.2690	−.6897	9.166	.938	−57.77
		470-5		Linear	-------	−.3743	7.486	.960	−45.27
		476-6		Linear	-------	−.5407	10.814	.925	−71.45
		654-4		Paralinear	14.7616	−3.6417	51.179	.992	−217.5
		654-5			14.1388	−3.5586	49.725	.995	−214.4
		654-6			9.3159	−3.4349	43.665	.999	−246.5
U-710	1100	324-5	200		11.6597	−2.2095	33.755	.997	−270.2
U-710	1150	321-5	100		9.4443	−3.9464	48.908	.999	−294.1
U-720	1000	674-6	500		2.9558	−.2821	5.777	.978	−77.59
	1000	675-6	500		3.5686	−.3431	7.000	.973	−93.57
	1100	655-3	200		9.5565	−2.2778	32.335	.999	−313.5
	1150	654-3	100		4.8115	−3.6764	41.575	.999	−313.4
Waspaloy	1000	436-6	500		3.6677	−.2862	6.530	.854	−75.73
	1000	480-6	500		3.0613	−.2450	5.511	.900	−57.36
	1000	615-5	500		1.7020	−.1253	2.955	.667	−44.80
	1100	393-5	200		9.0460	−1.9120	28.166	.999	−248.5
		437-6			1.6630	−.2097	3.760	.930	−23.91
		473-1			1.7550	−.2465	4.220	.968	−30.25
		614-5			1.0993	−.1271	2.371	.869	−14.48
	1150	438-6	100		14.1400	−2.9190	43.330	.985	−165.2
		470-2			11.7414	−4.4294	56.035	.999	−318.9
		472-1			4.082	−.7967	12.049	.992	−41.06
		482-6			3.5827	−.6077	9.660	.980	−27.53
		613-5			19.2421	−.4156	23.398	.995	−226.7
WAZ-20	1100	232-5	200		3.6298	−1.0868	14.498	.991	−155.5
	1100	413-5	200		9.3657	−1.8428	27.794	.999	−240.6
	1150	102-4	100	Linear	-------	−5.8479	116.958	.999	−568.3
	1150	102-5	100	Linear	-------	−5.2145	104.291	.999	−505.3
	1150	414-5	100	Paralinear	6.8340	−3.9566	46.400	.999	−322.5
MAR-M-509	1100	310-1	200		9.3065	−1.3218	22.524	.990	−137.1
	1100	326-4	200		10.3614	−1.7972	28.333	.999	−211.2
	1150	102-1	100		9.6676	−1.8752	28.420	.987	−97.87
	1150	102-2			17.2012	−3.3339	50.540	.981	−177.5
	1150	323-4			21.8875	−4.8477	70.364	.996	−265.2
W1-52	1093	120-1			9.7830	−4.3592	53.375	.999	−327.5
	1093	120-2			2.3512	−3.8348	40.699	.998	−346.4
	1100	393-3	200	Linear	-------	−3.7798	75.596	.998	−579.6
	1100	469-3	200	Paralinear	14.5889	−.0392	14.981	.999	−559.0

TABLE A-II.—Concluded.

Alloy	Test temperature, °C	Run number	Test time, hr	Model type	$k_1^{1/2}$	k_2	Ka	R^2	Final ΔW/A
W-152	1150	99-1	100	Linear	-------	−6.2106	124.212	0.999	−608.2
		99-2		Linear	-------	−6.8008	136.016	.999	−663.3
		105-4		Paralinear	9.9264	−7.6869	86.795	.999	−650.6
		105-5		Paralinear	8.8308	−7.2813	81.644	.999	−623.7
		128-4	75	Linear	-------	−5.8658	117.317	.982	−387.4
		128-5	75	Linear	-------	−5.8844	117.689	.993	−419.0
		470-3	45	Linear	-------	−9.0172	180.344	.999	−405.7
X-40	1100	393-4	200	Paralinear	15.2770	−2.0293	35.570	.971	−206.3
	1150	95-4	100		15.5662	−2.3280	38.846	.994	−186.0
		95-5			1.7174	−.3388	5.106	.816	−25.44
		105-3			11.4739	−2.2589	34.063	.983	−121.8
		105-6			10.8964	−2.1528	32.424	.989	−113.6
		128-3	45		5.5343	−1.6776	22.310	.950	−42.54
		128-6	100		15.5855	−3.4410	49.995	.995	−188.6
		146-3	100		15.1885	−3.5114	50.303	.996	−197.9

TABLE C—I—MULTIPLE REGRESSION[a] RESULTS FOR LOG_{10} Ka AS A FUNCTION OF ALLOY COMPOSITION IN wt%, AND OF ABSOLUTE TEST TEMPERATURE IN $1/T_K$ BASED ON AN INITIAL SELECTION OF 15 1[st] ORDER VARIABLES. NUMBER OF DATA VALUES n = 315.

$[Z_i = 15, Z_f = 11]$

Significant terms, Z	Coefficient	t-statistic
Ta	-0.15488235	-9.666
$1/T_K$	-17 305.08365	-15.606
Al	-0.33925047	-7.333
Cr	-0.08308176	-4.459
Ti	+0.26407575	11.464
Nb	+0.24172264	4.789
C	+1.99987840	5.810
Re	+0.87295039	9.593
Zr	+0.37654324	2.415
Mo	+0.04526628	2.995
Hf	+0.17781791	2.309
a_o, intercept	14.77171564	

$R^2 = 80.04\%$ S.E.E. = 0.396669 $Z_i = 15$

Co/Ni, Cr, Al, Ti, Mo, W, Nb, Ta, C, B, Zr, Hf, V, Re, $1/T_K$

[a]Stepwise regression—variables are added one at a time starting with the most significant, the F-statistic for a variable must be significant to 0.15. After a variable is added, however, the stepwise method looks at all the variables already in the model and deletes any that does not produce an F-statistic significant to the 0.15 level.

TABLE C—II—ANALYSIS OF VARIANCE (ANOVA) SUMMARY FOR n = 315 DATA SET; $z_f = 11$ SHOWING SOURCES OF VARIATION INCLUDING LACK OF FIT OF THE ESTIMATING EQUATION

Source	Degrees of freedom, d.f.	Sum of squares	Mean squares
Model	11	191.19376	17.3812505
Residual	303	47.67592788	0.1573463
Lack of fit	(70)	(20.35603)	(0.29080575)
Replication	(233)	(27.319525)	(0.11725118)
Total	314	238.86968	

$$F - \text{ratio} = \frac{MS(LOF)}{MS(REPS)} = \frac{0.29080575}{0.11725118} = 2.480^a$$

[a]The lack of fit term appears to be significant since the F-ratio for $(1 - \alpha)$ where $\alpha = 0.95 = 1.658$ which does not exceed the MS(LOF)/MS(REPS) ratio derived for this first order model. Therefore this model is not considered satisfactory.

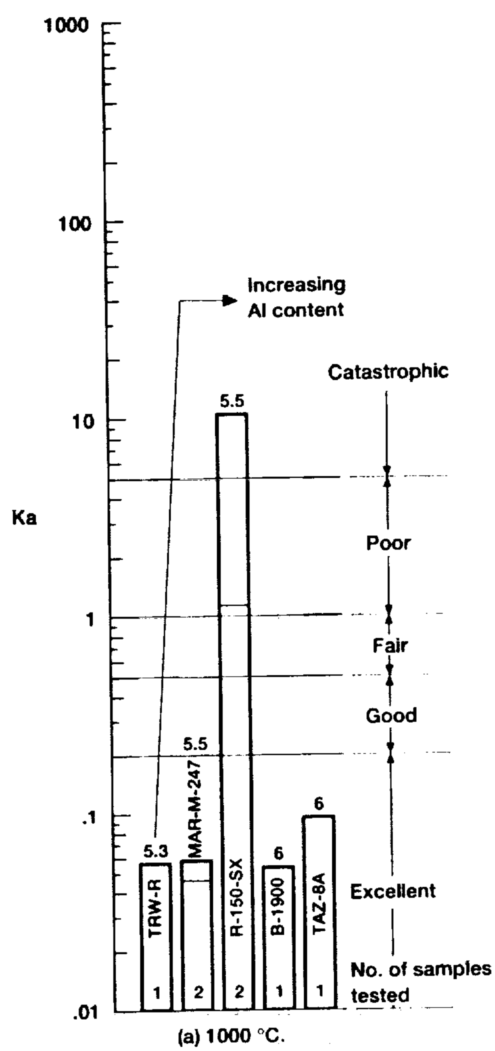
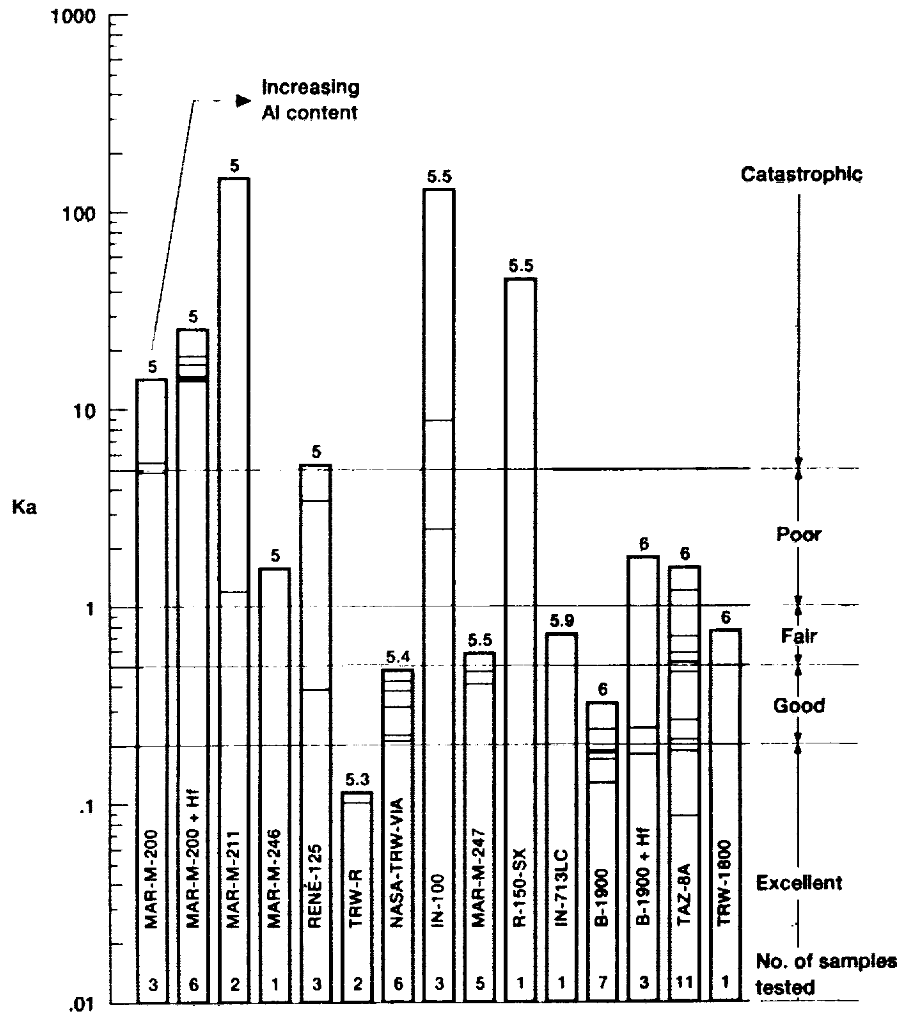
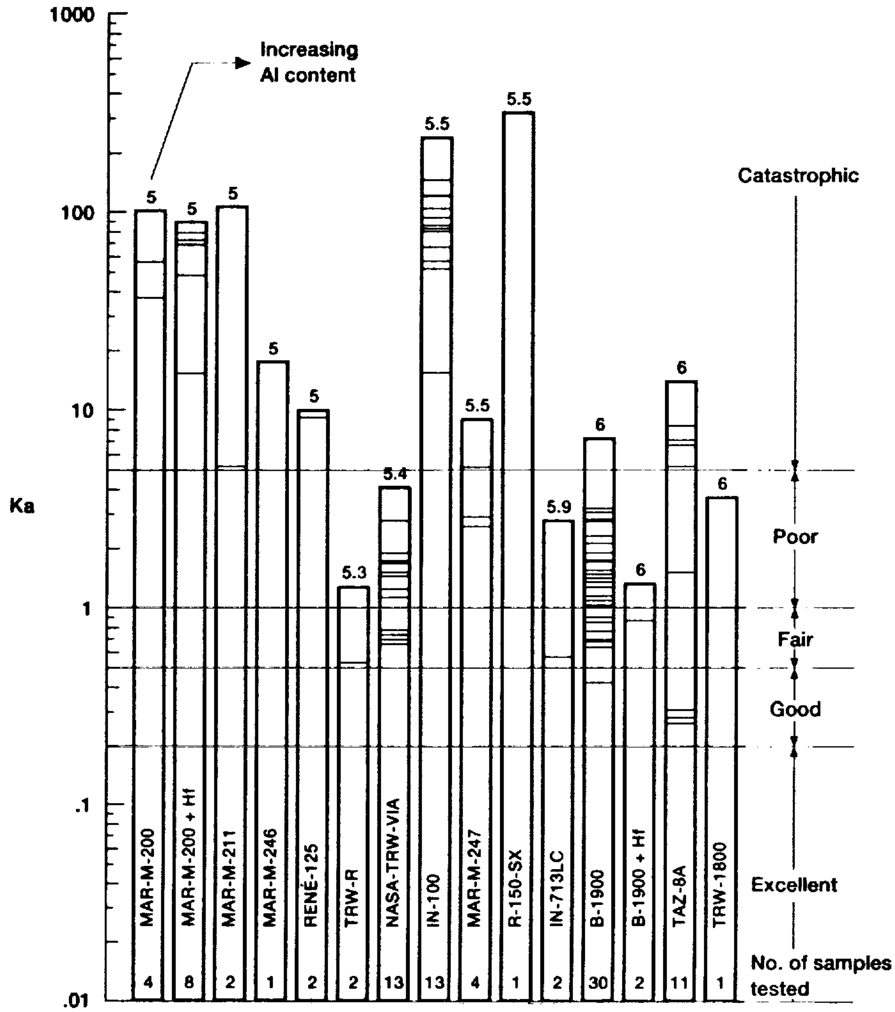


Figure 1.—Observed oxidation attack parameters - Ka's for Group I alumina/aluminate scale alloy formers tested at 1000, 1100 and 1150 °C respectively (multiple horizontal lines indicate replicates).



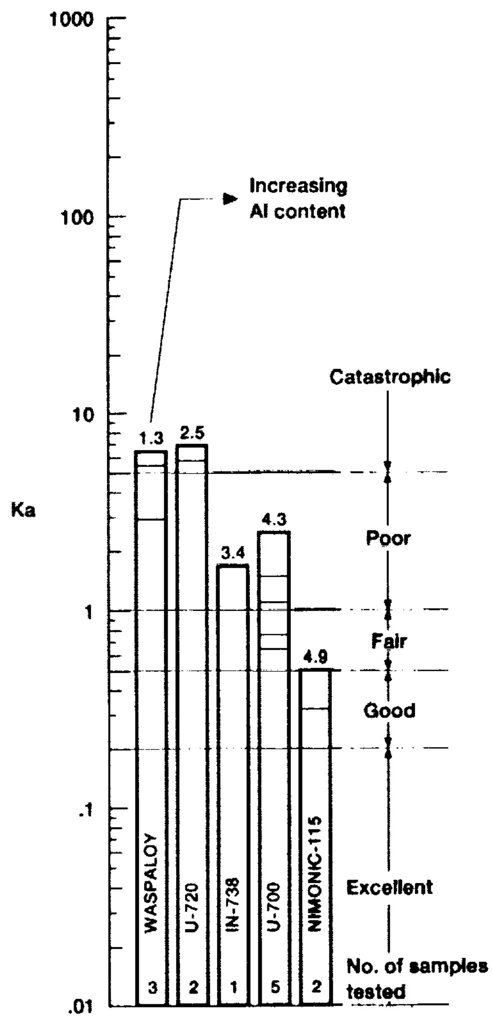
(b) 1100 °C.

Figure 1.—Continued.



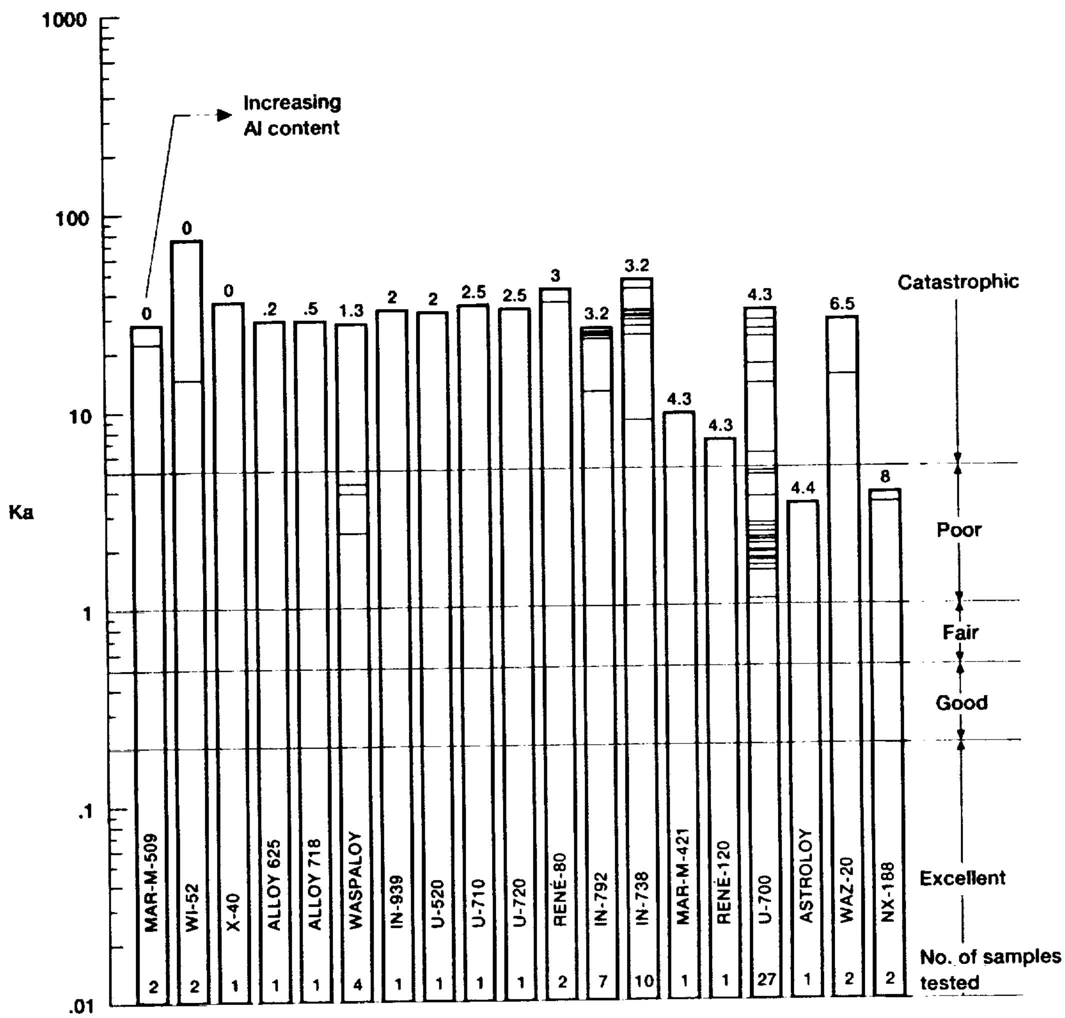
(c) 1150 °C.

Figure 1.—Concluded.



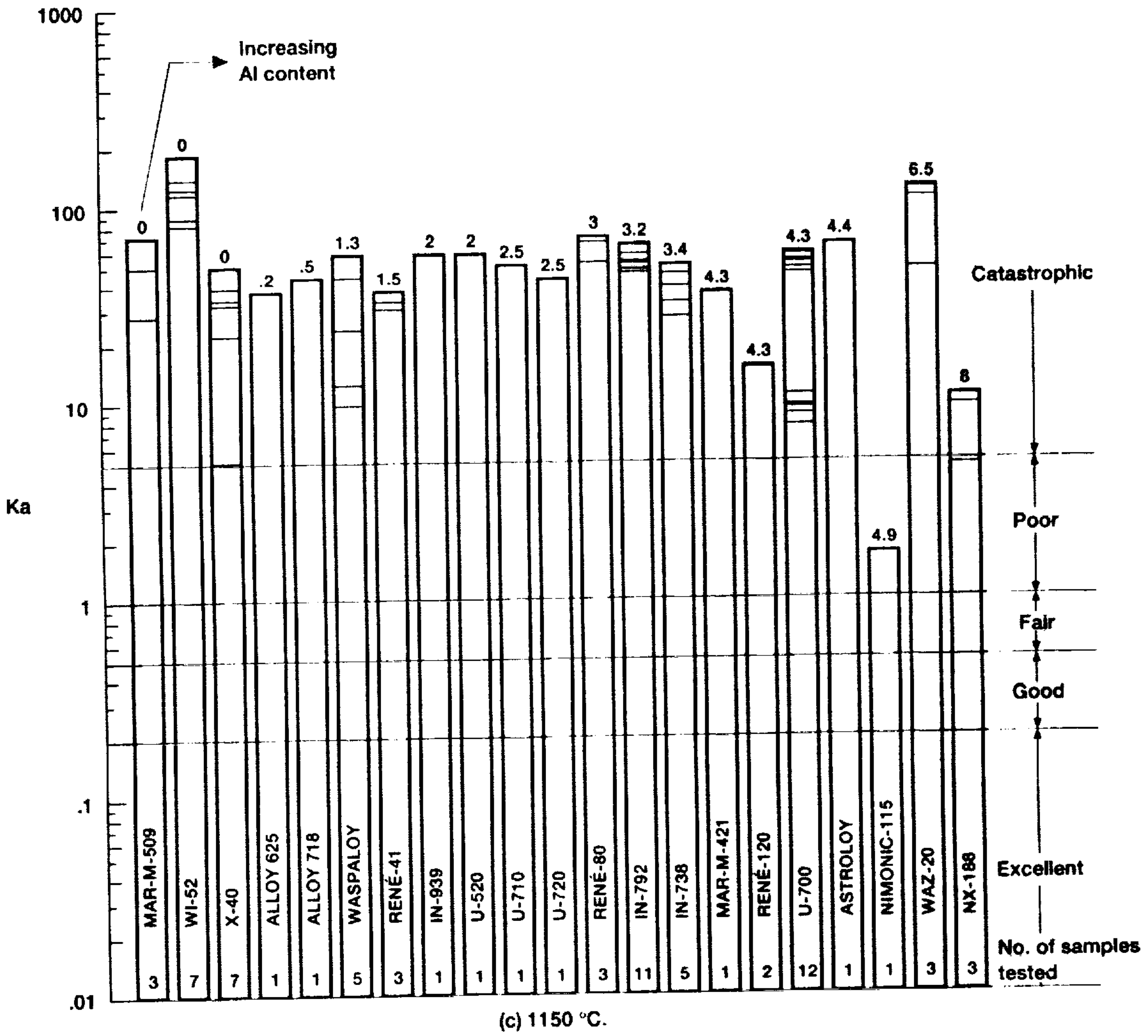
(a) 1000 °C.

Figure 2.—Observed oxidation attack parameters - Ka's for Group II chromia/chromite or NiO scale alloy formers tested at 1000, 1100 and 1150 °C respectively (multiple horizontal lines indicate replicates).



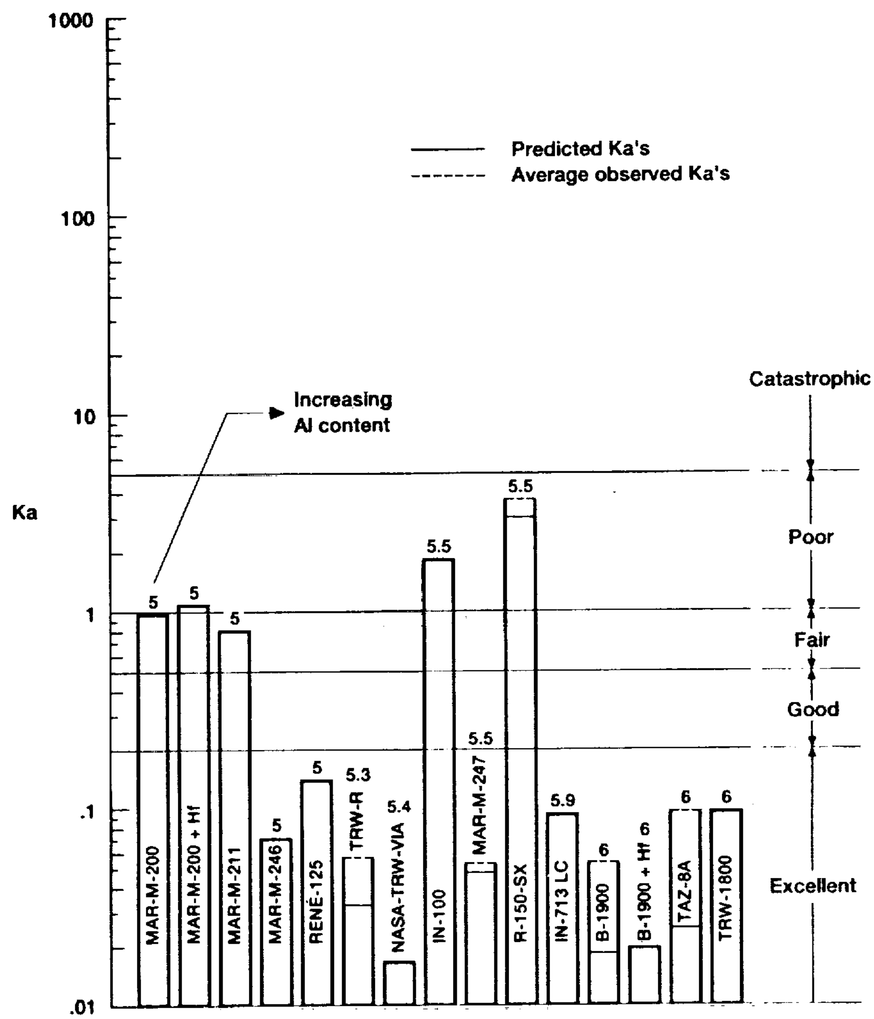
(b) 1100 °C.

Figure 2.—Continued.



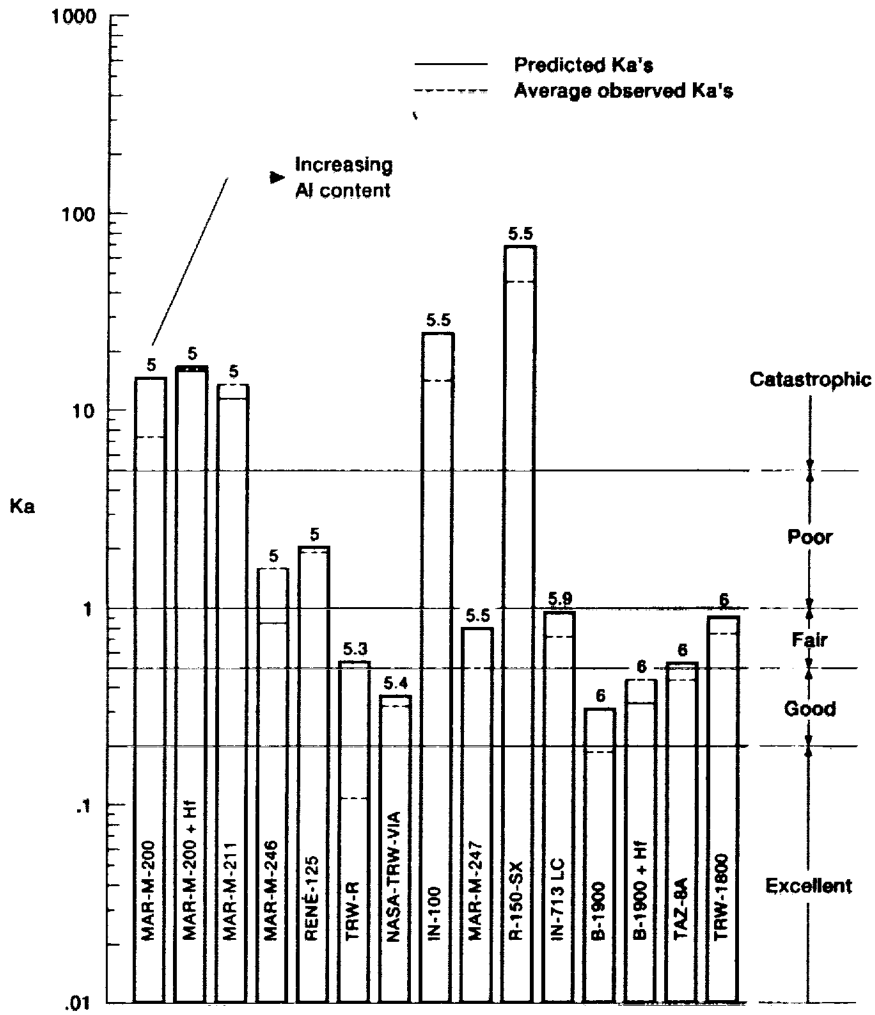
(c) 1150 °C.

Figure 2.—Concluded.



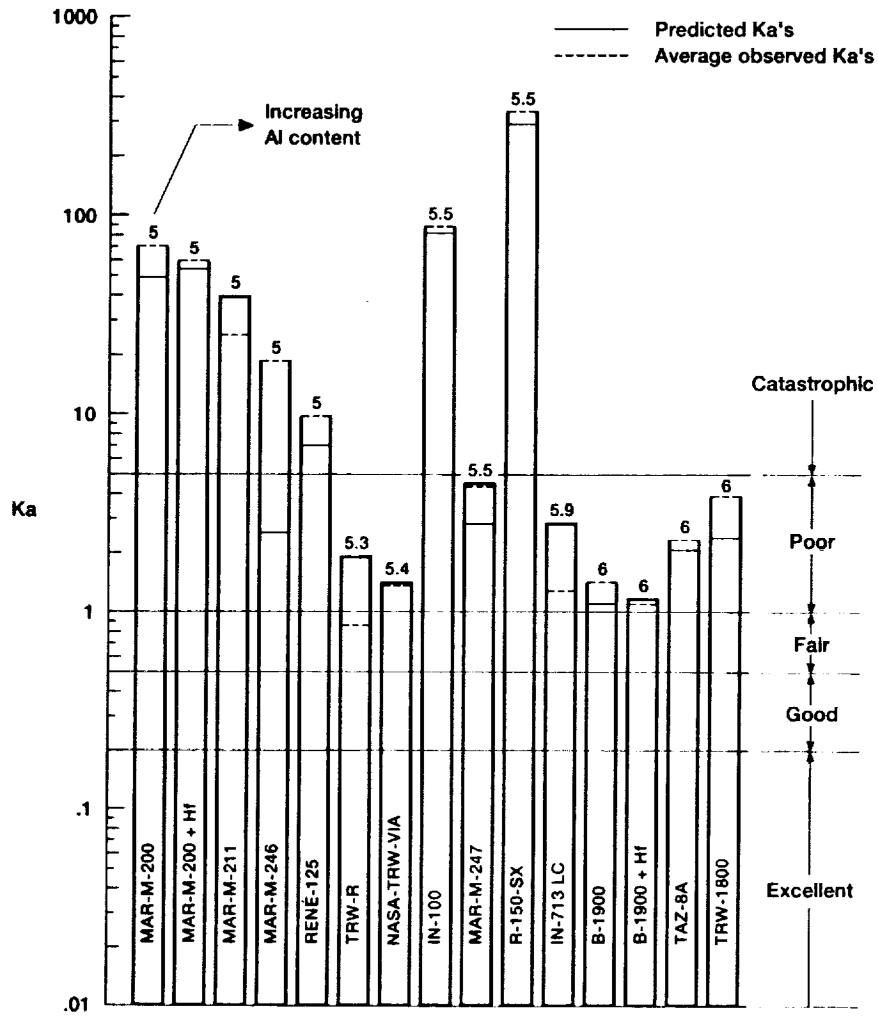
(a) 1000 °C.

Figure 3.—Comparison of the average observed and the predicted oxidation attack parameters, Ka's, for Group I alumina/aluminate scale alloy formers at 1000, 1100, and 1150 °C respectively.



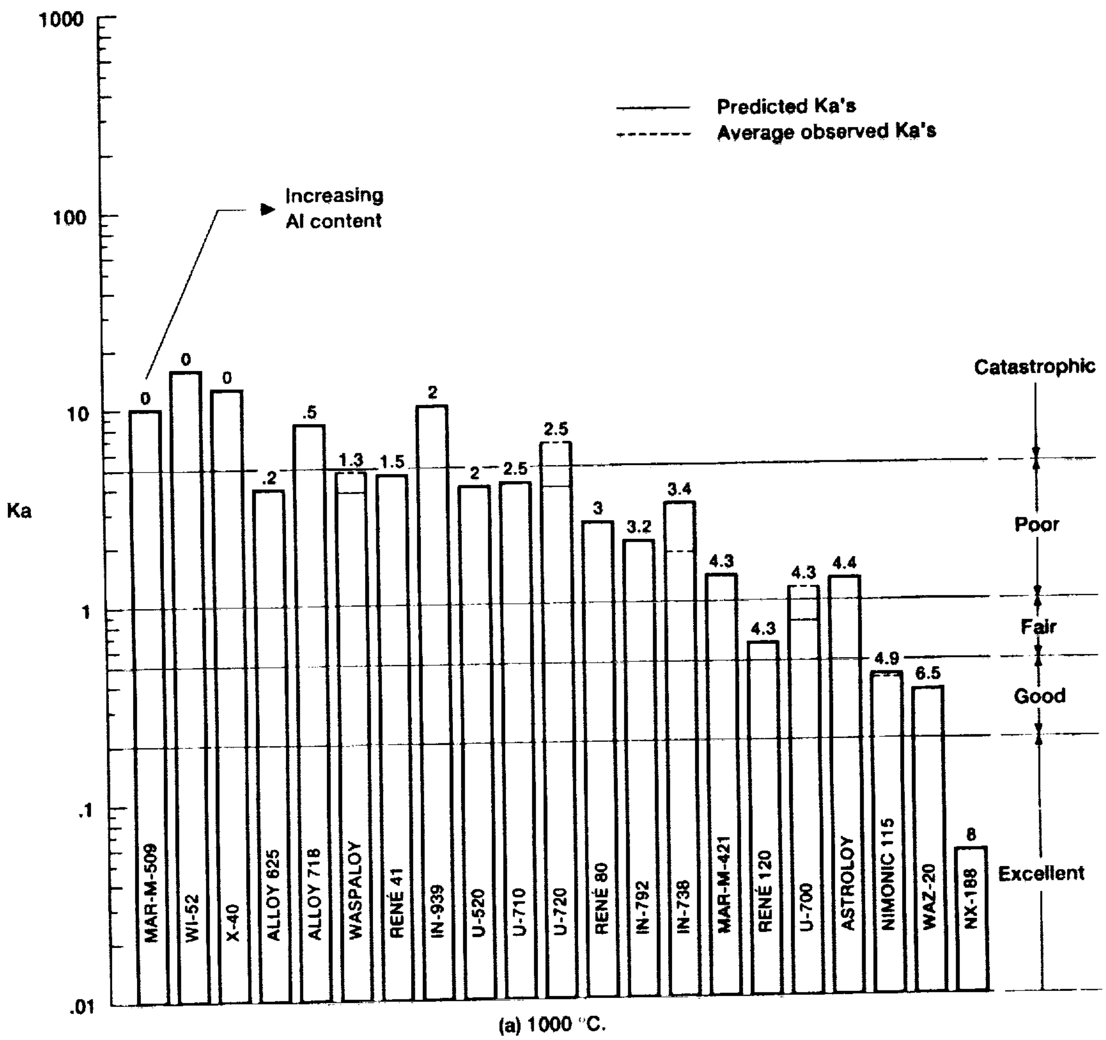
(b) 1100 °C.

Figure 3.—Continued.



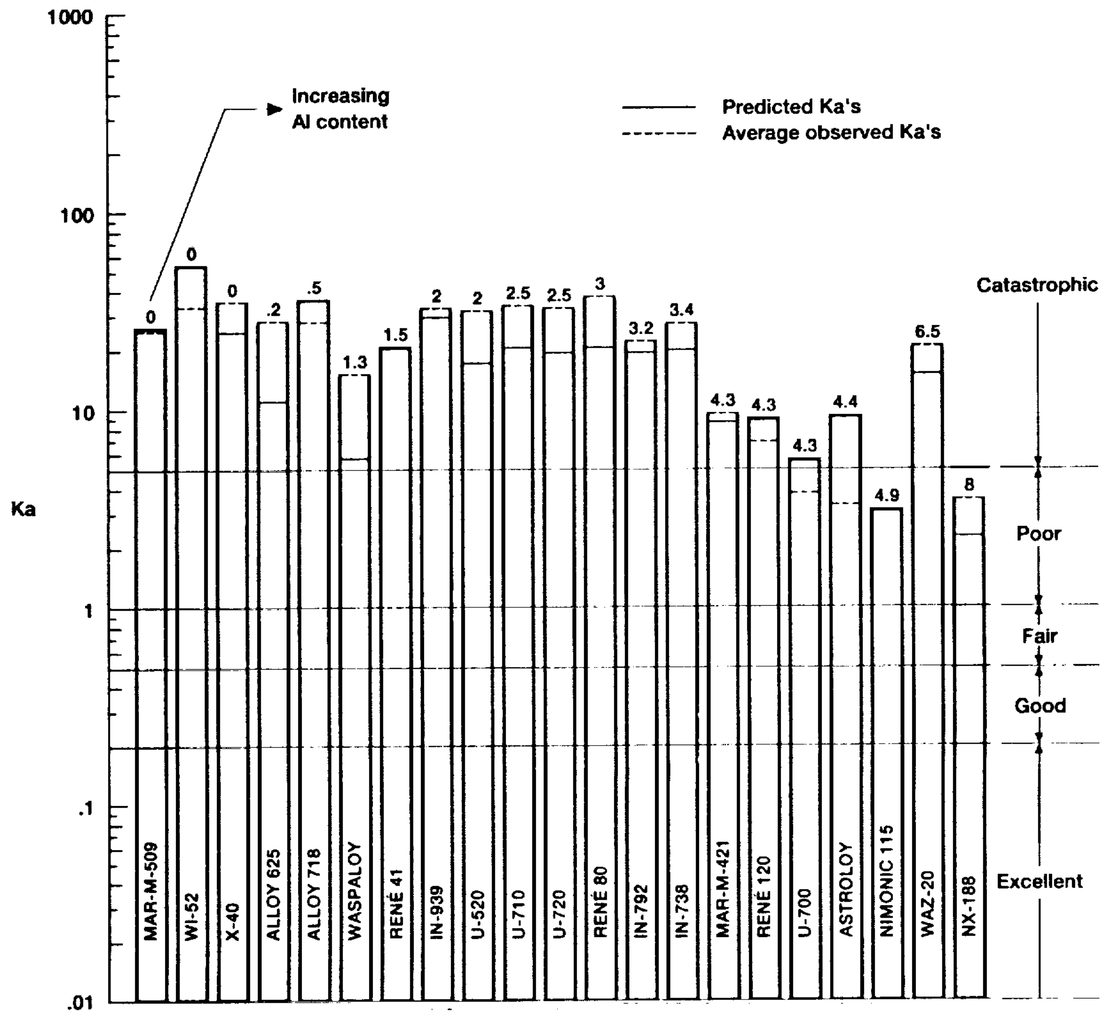
(c) 1150 °C.

Figure 3.—Concluded.



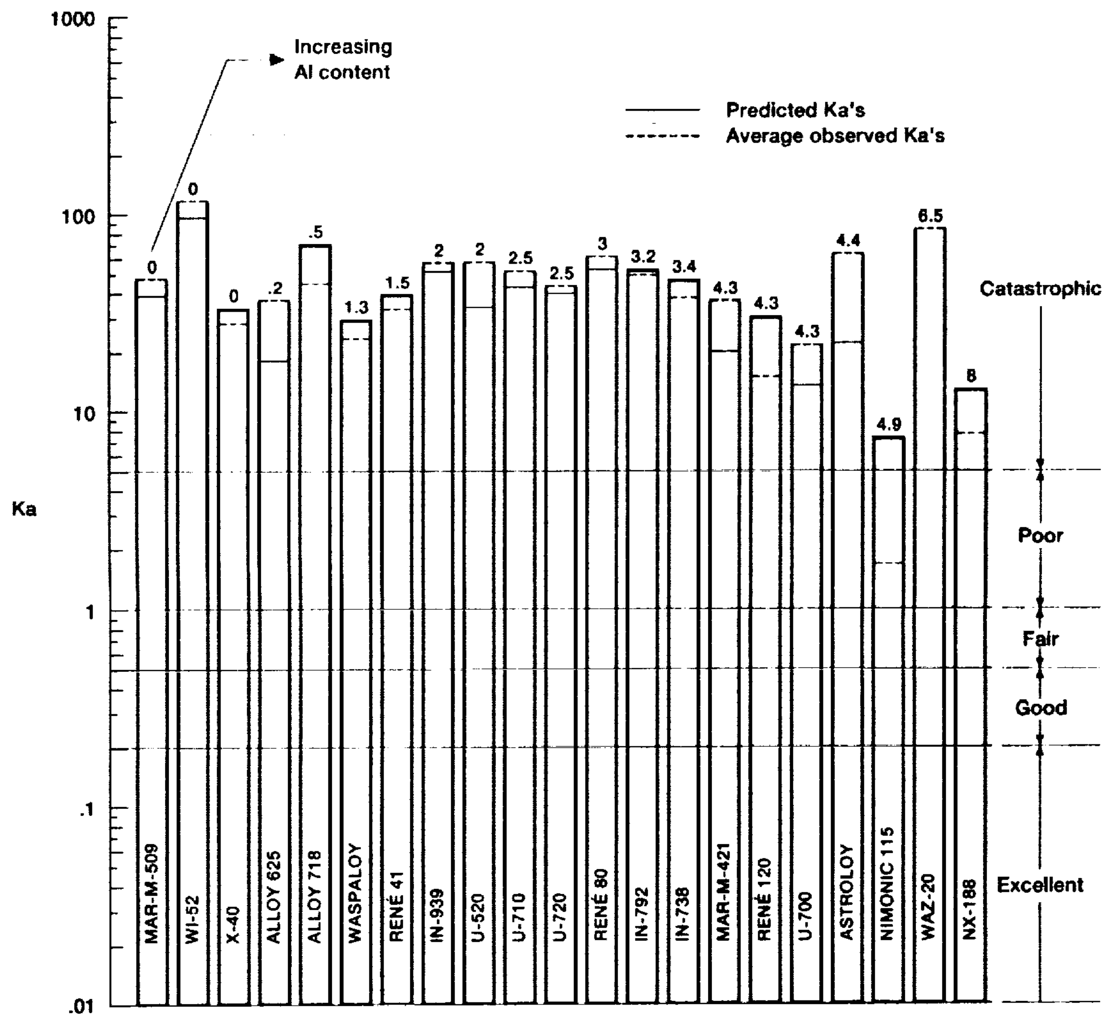
(a) 1000 °C.

Figure 4.—Comparison of the average observed and the predicted oxidation attack parameters, Ka's, for Group II chromia/chromite or NiO scale alloy formers at 1000, 1100 and 1150 °C respectively.



(b) 1100 °C.

Figure 4.—Continued.



(c) 1150 °C.

Figure 4.—Concluded.

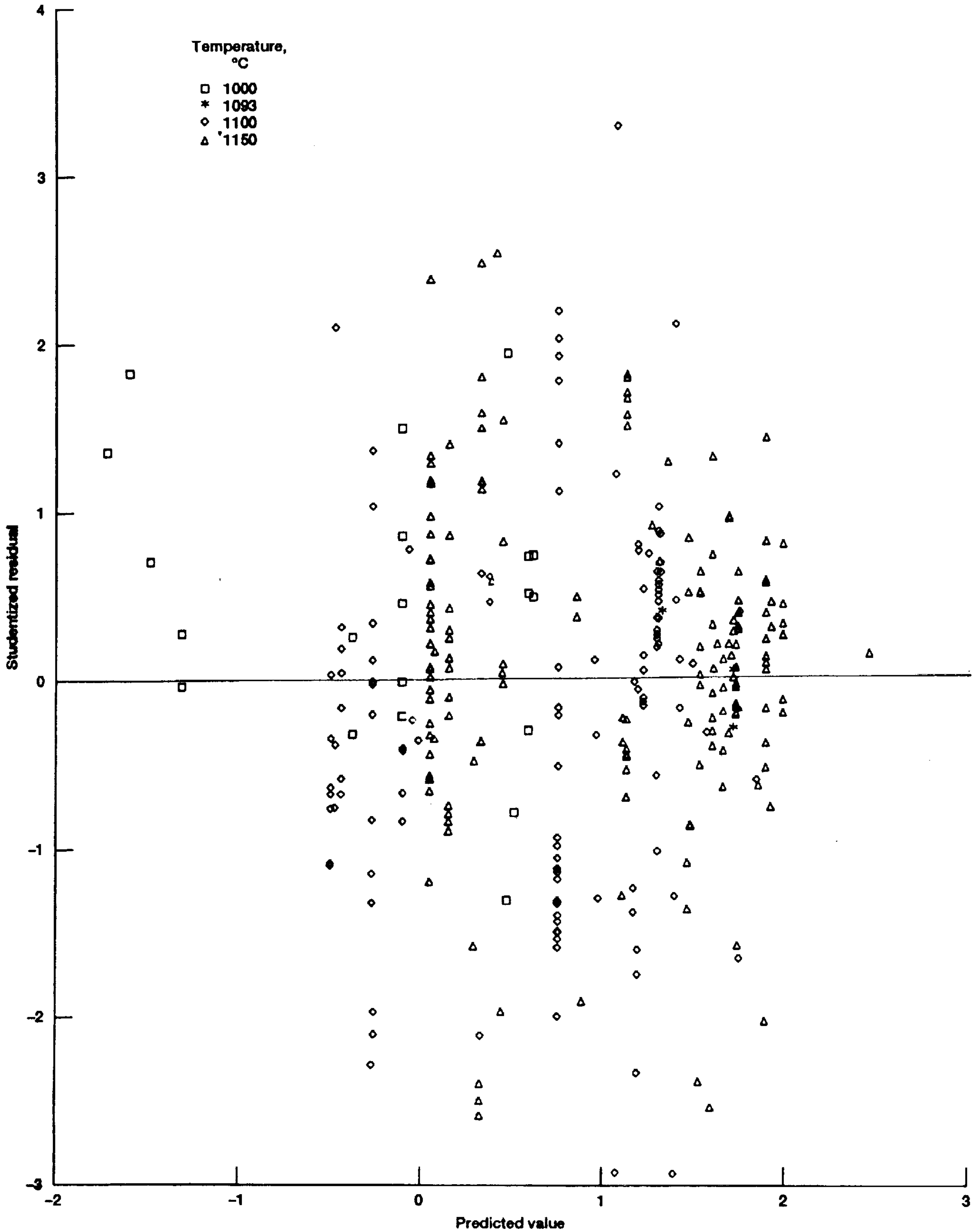


Figure 5.—Standardized residual values vs. 315 predicted log Ka values derived from a 14 term regression estimating equation involving alloy composition and temperature for 36 high strength Ni- and Co- base superalloys.

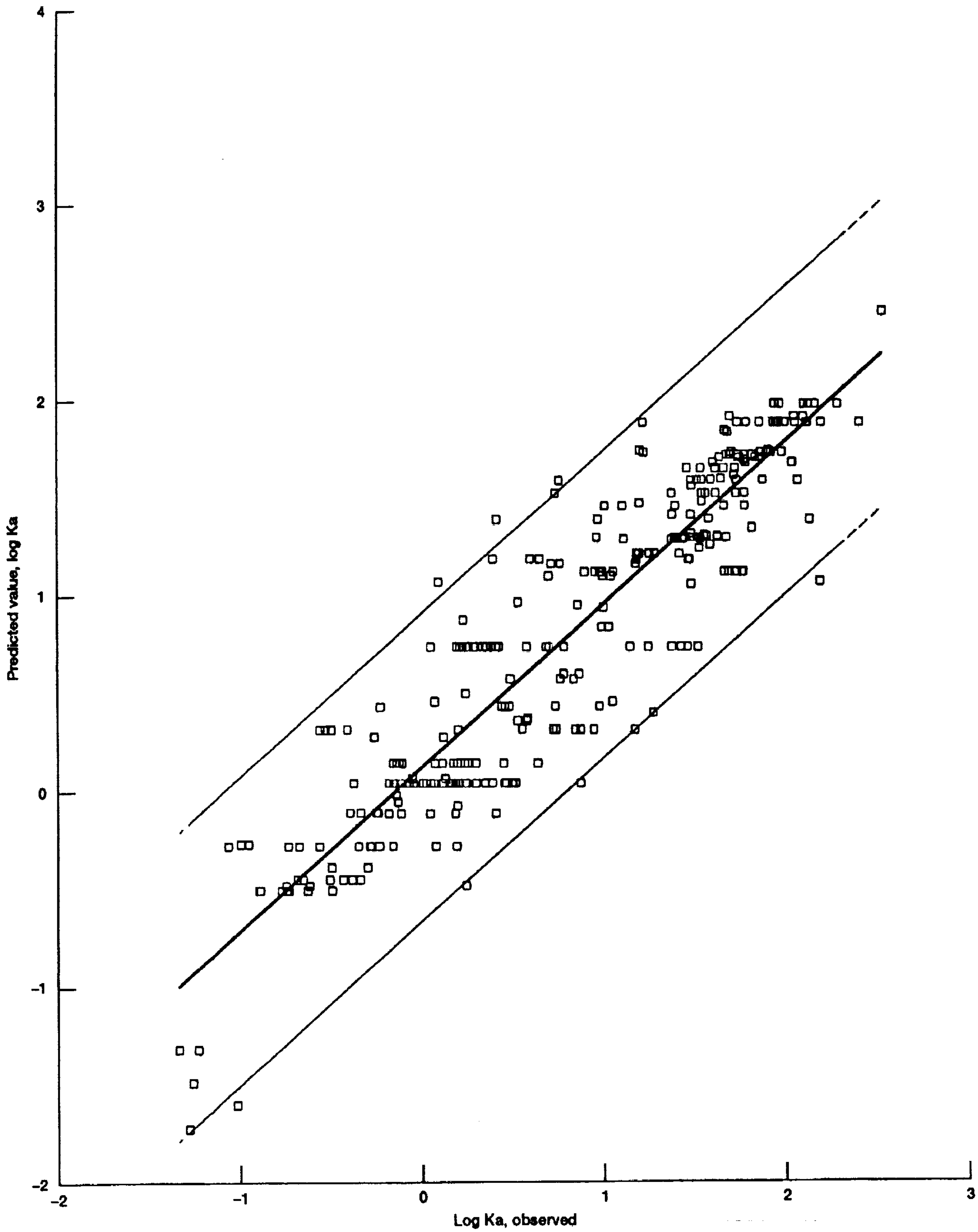


Figure 6.—Predicted log Ka values derived from a 14 term estimating equation involving alloy composition and temperature vs. observed log Ka values for 36 high strength Ni- and Co- base superalloys (the straight lines on this plot represent a simple linear regression fit of this data with ±2.5 standard deviation limits).

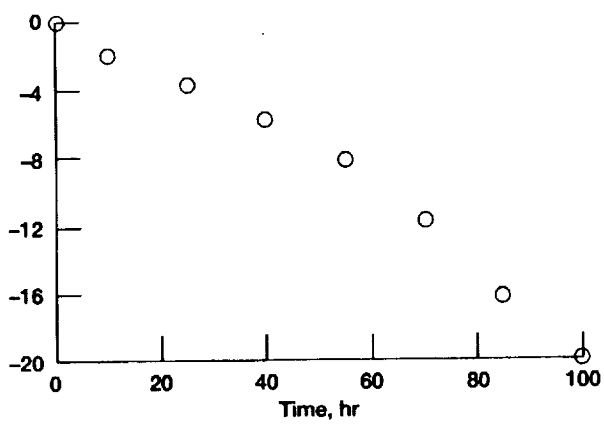


Figure B-1.—B-1900, 1150 °C, run 78-1.

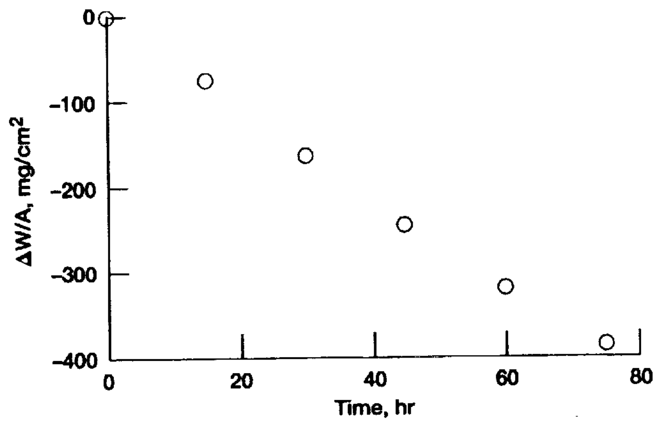


Figure B-2.—IN-100, 1150 °C, run 95-6.

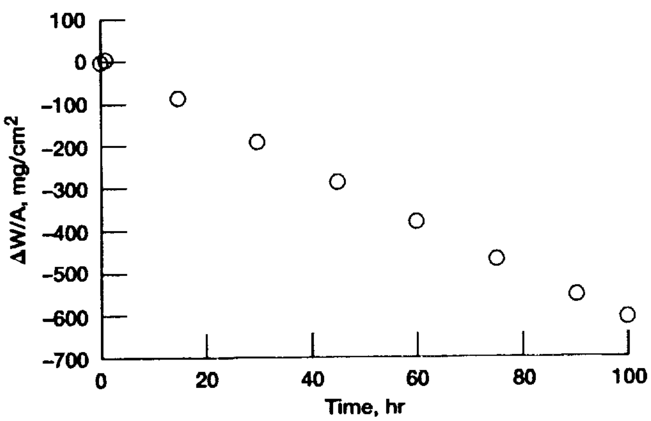


Figure B-3.—WI-52, 1150 °C, run 99-1.

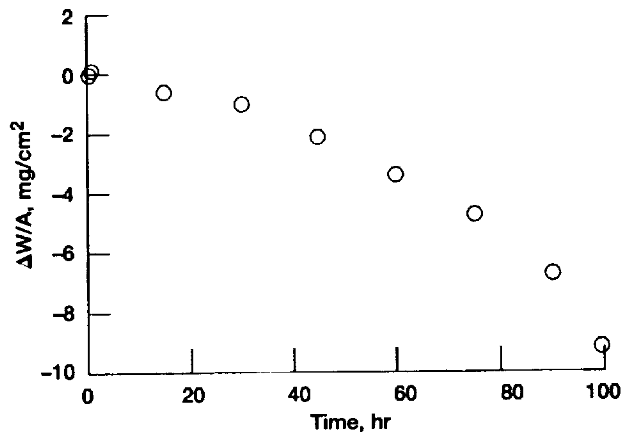


Figure B-4.—B-1900, 1150 °C, run 123-3.

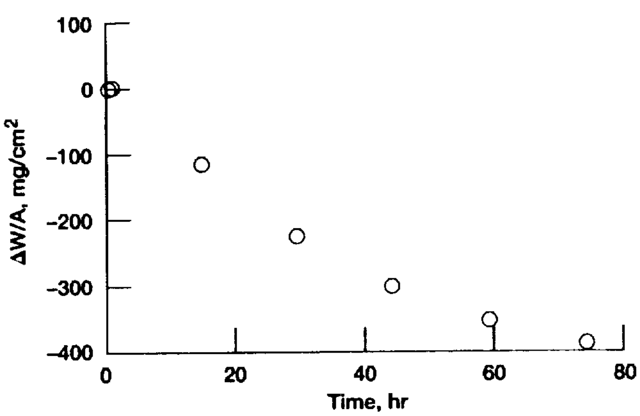


Figure B-5.—WI-52, 1150 °C, run 128-4.

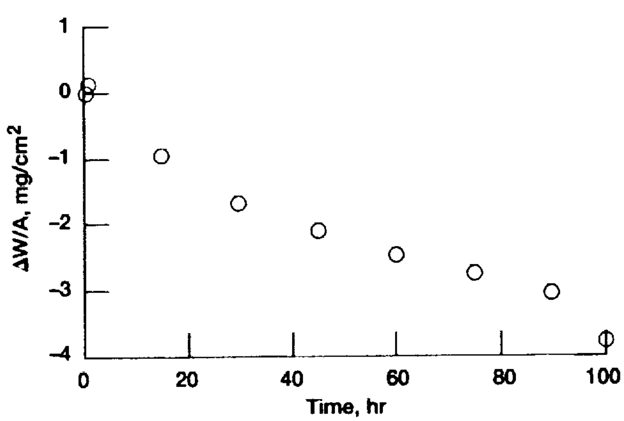


Figure B-6.—NASA-TRW-VIA, 1150 °C, run 129-2.

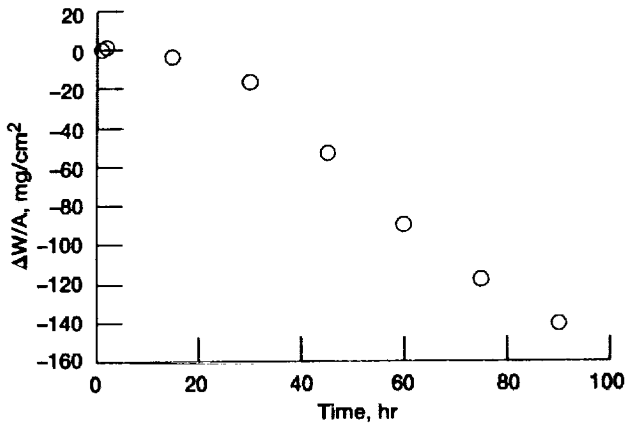


Figure B-7.—René-41, 1150 °C, run 137-3.

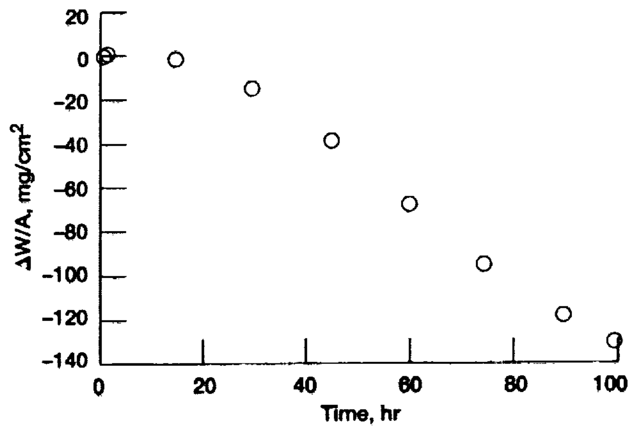


Figure B-8.—René-41, 1150 °C, run 137-6.

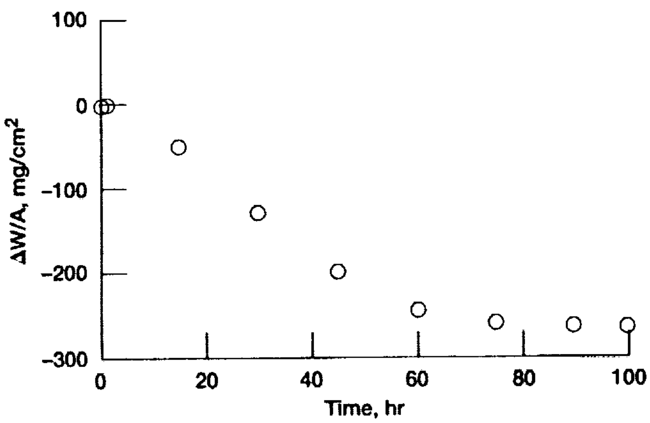


Figure B-9.—B-1900 + Hf, 1150 °C, run 204-3.

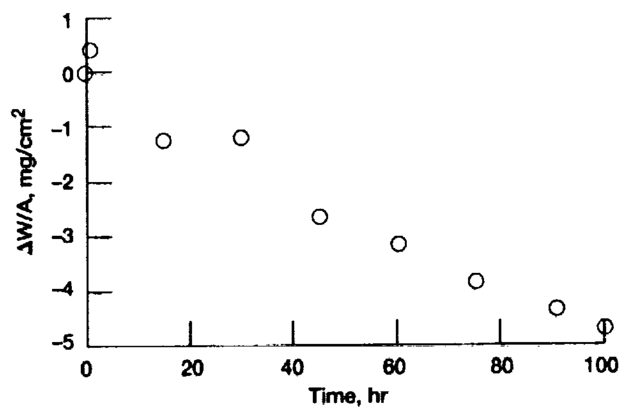


Figure B-10.—B-1900, 1150 °C, run 221-1.

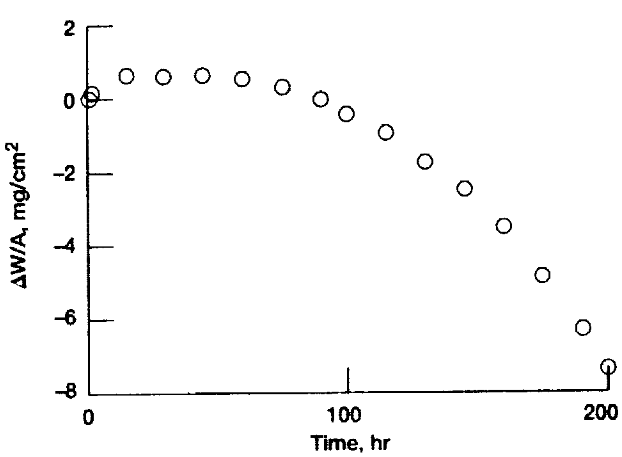


Figure B-11.—TAZ-8A, 1100 °C. run 232-2.

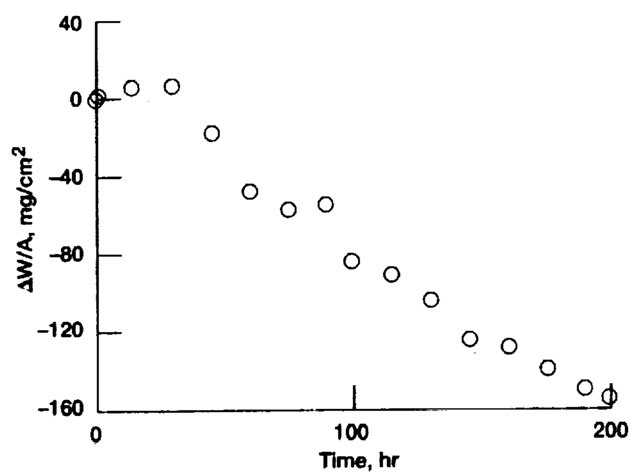


Figure B-12.—WAZ-20, 1100 °C, run 232-5.

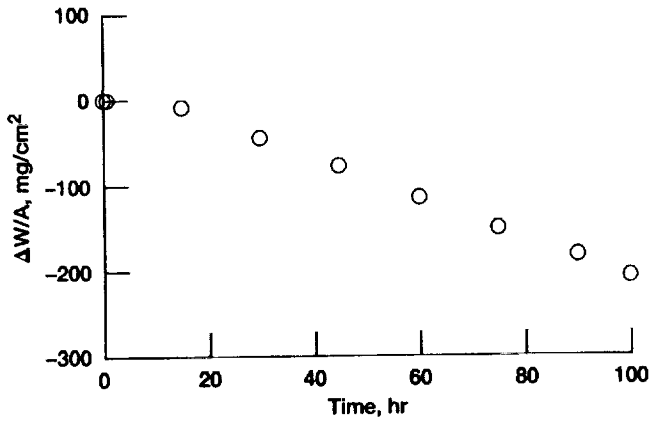


Figure B-13.—Alloy 625, 1150 °C, run 352-4.

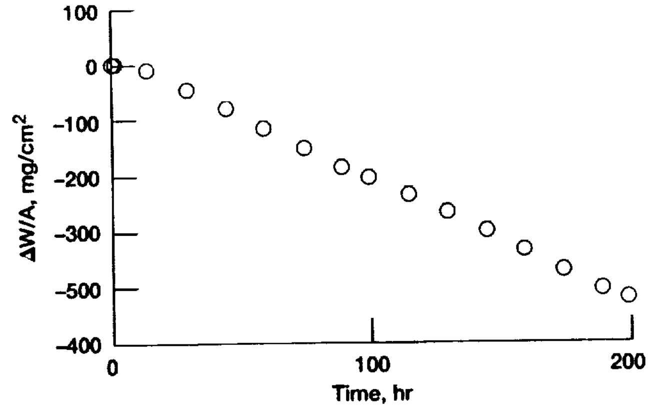


Figure B-14.—Alloy 625, 1150 °C, run 352-4.

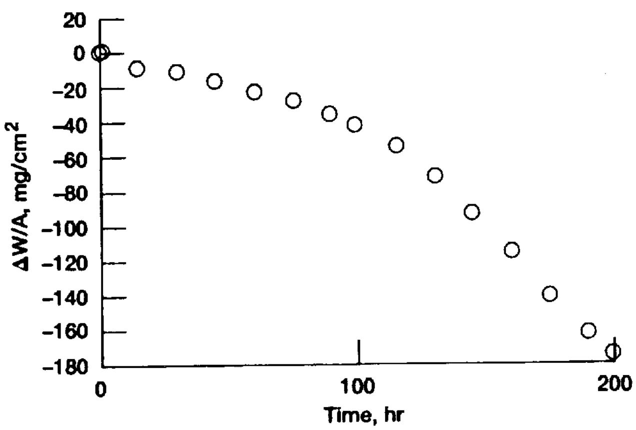


Figure B-15.—U-700, 1100 °C, run 422-5.

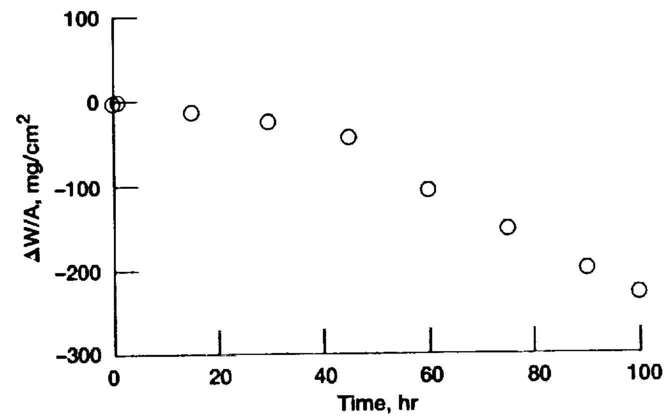


Figure B-16.—U-700, 1150 °C, run 423-5.

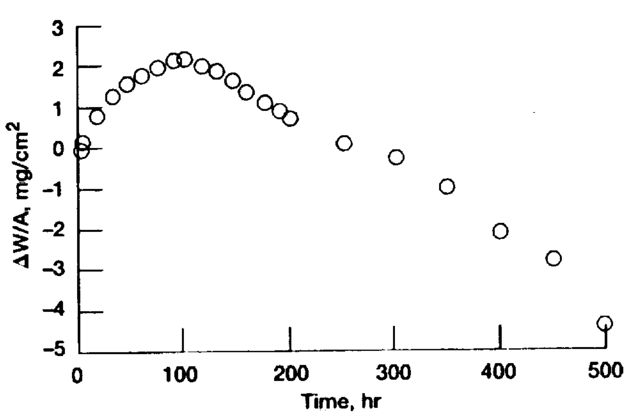


Figure B-17.—U-700, 1000 °C, run 424-5.

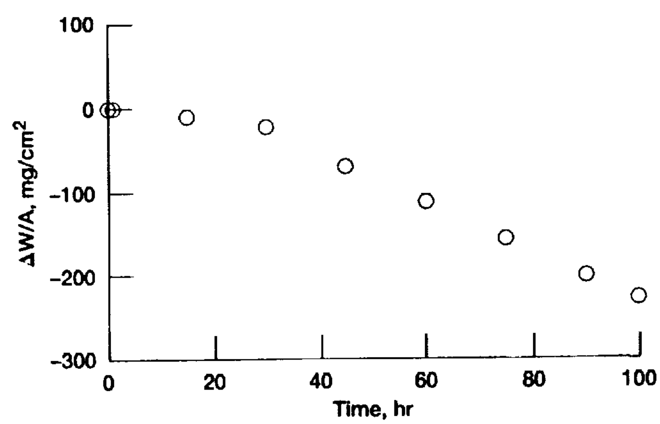


Figure B-18.—IN-792, 1150 °C, run 428-4.

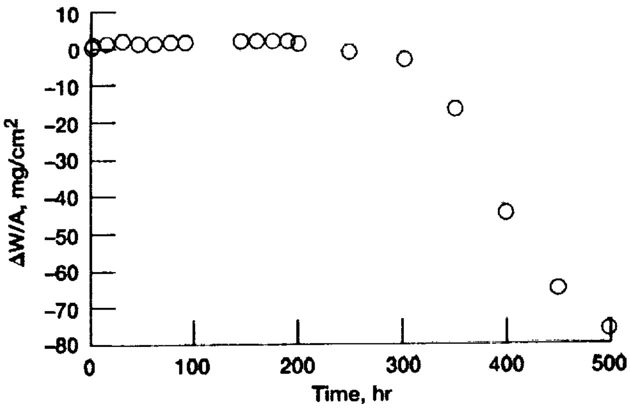


Figure B-19.—Waspaloy, 1000 °C, run 436-6.

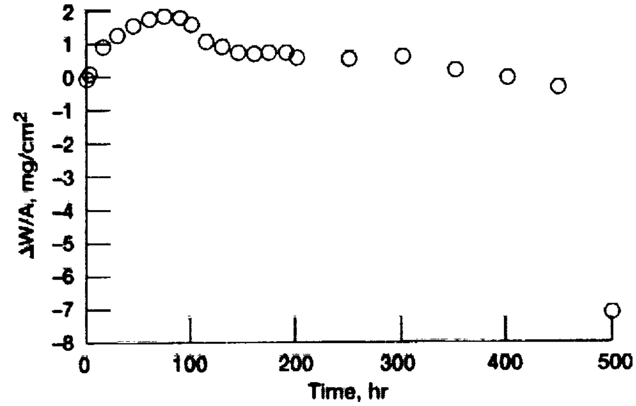


Figure B-20.—U-700, 1000 °C, run 447-6.

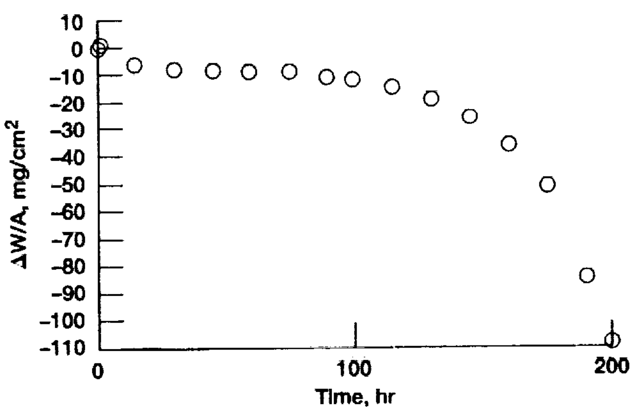


Figure B-21.—U-700, 1100 °C, run 448-6.

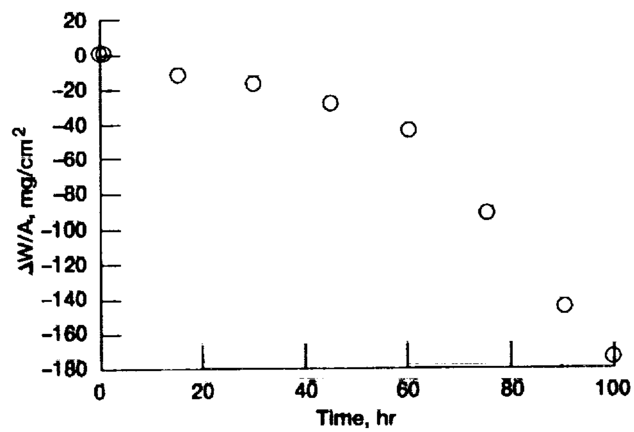


Figure B-22.—U-700, 1150 °C, run 449-6.

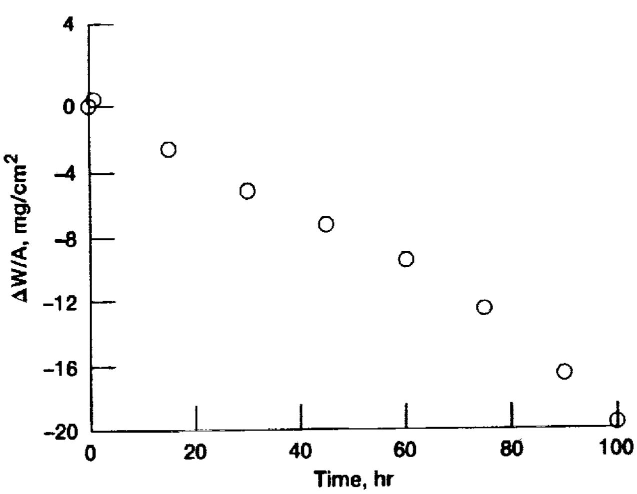


Figure B-23.—MAR-M-247, 1150 °C, run 454-5.

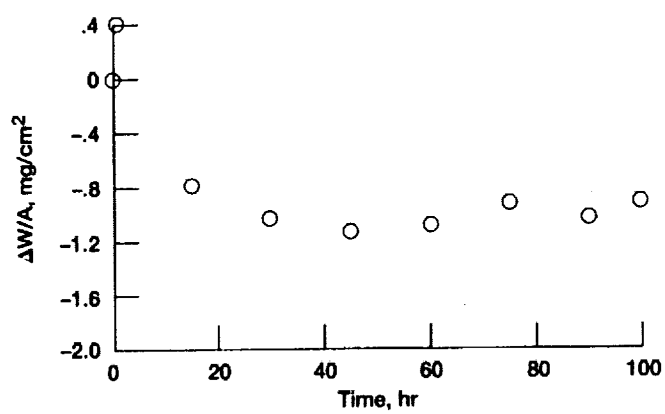


Figure B-24.—TAZ-8A, 1150 °C, run 472-2.

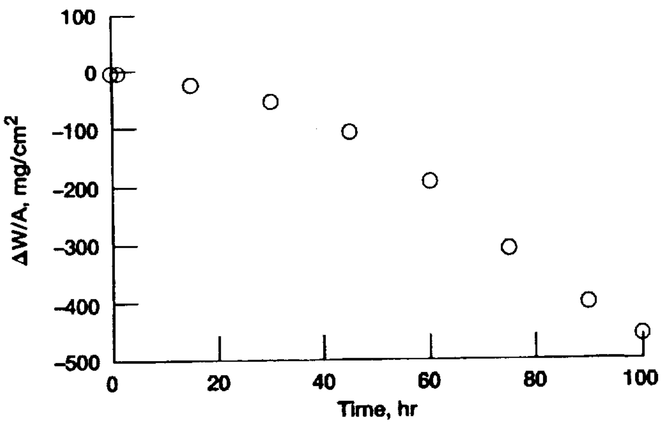


Figure B-25.—MAR-M-211, 1150 °C, run 478-1.

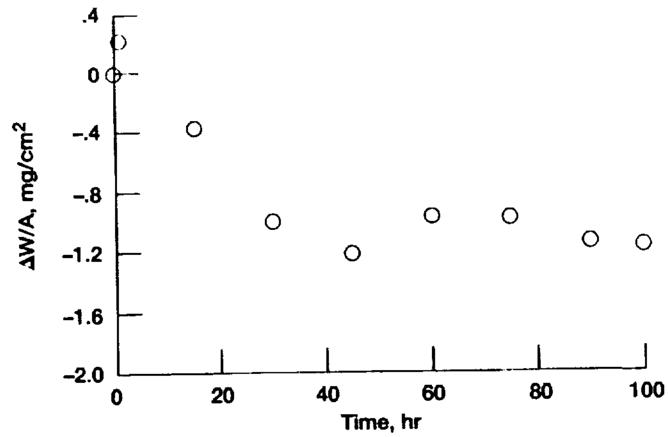


Figure B-26.—TAZ-8A, 1150 °C, run 656-2.

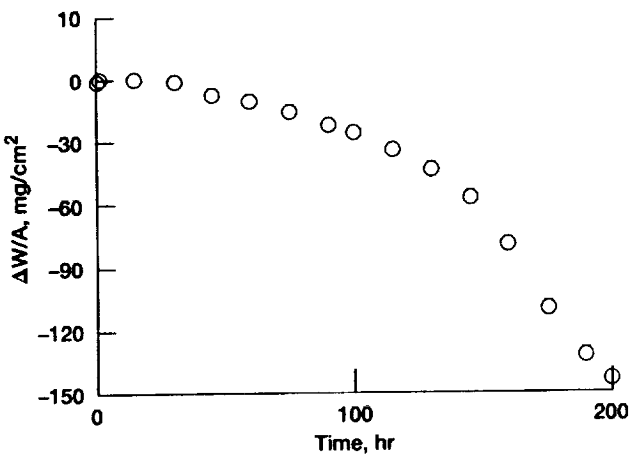


Figure B-27.—IN-792, 1100 °C, run 657-5.

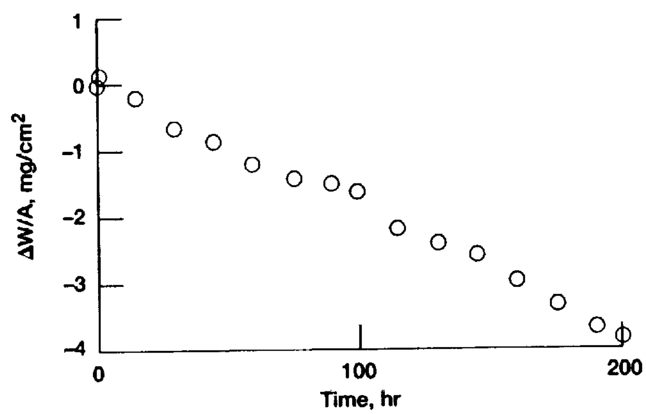


Figure B-28.—René-125, 1100 °C, run 659-3.

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A large body of high temperature cyclic oxidation data generated from tests at NASA Lewis Research Center involving gravimetric/time values for 36 Ni- and Co-base superalloys was reduced to a single attack parameter, K_a, for each run. This K_a value was used to rank the cyclic oxidation resistance of each alloy at 1000, 1100, and 1150 °C. These K_a values were also used to derive an estimating equation using multiple linear regression involving $\log_{10}K_a$ as a function of alloy chemistry and test temperature. This estimating equation has a high degree of fit and could be used to predict cyclic oxidation behavior for similar alloys and to design an optimum high strength Ni-base superalloy with maximum high temperature cyclic oxidation resistance. The critical alloy elements found to be beneficial were Al, Cr, and Ta.

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