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A High Temperature Cyclic Oxidation Data Base for Selected Materials Tested at NASA Glenn Research Center

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INTRODUCTION

A cyclic oxidation database has been established covering approximately 30 years of weight change data run at NASA Lewis Research Center (now Glenn Research Center at Lewis Field). These data consist mostly of nickel, iron and cobalt base alloys exposed in static air for various cycle times at fixed test temperatures. Materials include stainless steels, heater alloys, inconels, superalloys, intermetallic compounds, coating alloys, and silicon-base ceramics. Despite the wide variety of materials tested, a standard experimental approach has been followed over the years, allowing for an efficient consolidation of all the results into a modern, PC-compatible, database format. The intention of this database is to allow full access to NASA-GRC cyclic oxidation data. Thus, the purpose of this monograph is to serve as an explanatory companion. It not only covers operational and organizational features of the database, but also provides a background for many of the test programs included in the data fields. In addition to describing the database, various ways of using this data to estimate the corrosion attack are discussed, and examples of analyzing cyclic oxidation behavior with the database are given. This database involves close to 1000 commercial and experimental alloys.

This database contains a file folder termed CYCLES on a read only CD of 36.9 MB with 735 files.* This folder consists of 732 Cyclic Oxidation Run files in Microsoft EXCEL format that hold a total of 4003 sample tests. The three additional files are: (1) A composition file which lists the chemical compositions of the materials tested, (2) An IndexRun file which contains the run number, material designations, test temperature, cycle time, and length of test, and (3) An IndexRef file which indicates which materials were analyzed in a series of NASA studies referenced at the end of this text.

TESTING AND DATABASE ORGANIZATION

The test rigs and furnaces used in deriving this cyclic data are described in detail in a series of reports (refs.1, 3, 4, 6, 7, 8, 12, 16, 17, and 18). A schematic of the test setup is shown in figure 1. A bank of up to thirteen such or similar furnaces is usually in operation at this laboratory. In all the cyclic tests except for very long cycle times of 1000 hours, the length of heating and cooling cycles are controlled by reset timers. In a typical test, up to six hanger wires, centered by spall shields in six individual circularly arrayed ceramic tubes, suspend the samples vertically. The

* CD is available upon request. Contact: Materials Durability Branch, NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135.

samples are lowered and raised by pneumatic cylinders activated when the timers time out. When the desired number of test cycles is reached as pre-set on the cycle control, the samples can be removed for weighing and examination. The samples are then re-hung for further testing typically with the same cycle duration but the number of cycles can be set to any desired number. This process is repeated until the desired total test time (i.e., cycles) is reached. Most of the samples tested, whether rectangular or disk shape coupons, are machined to roughly 0.5 inches (1.27 cm.) wide so as not to snag on the top edges of the furnace tubes as the samples are lowered into the furnace. They are usually ground as coupons to a 32 microinch rms finish and glass bead blasted prior to test. Exceptions are noted in the comments column of the IndexRun file discussed in the next section.

For example, in a typical test the furnace temperature is 1100 °C, six alloy coupons are suspended by yttria dispersed platinum wire. The heating timer is set at 60 minutes; the timer controlling the time out of the furnace (i.e., the cooling period) is set at 20 minutes. The counter control is set to generate test times of 1, 5, 10, 25, 50, 75, 100, 125, 150, 175, and 200 hours. The samples are weighed at these times and specific weight change data can be derived using the original sample area and the initial sample weight. These specific weight change data values as a function of time (or cycles) for a given alloy constitute the fundamental data of this database.

It should be noted that during each test each sample was analyzed by X-ray diffraction at selected intervals for both the retained scale and collected spalls. This generated a very large amount of data that was too cumbersome to handle as a database. These analyses were used in conjunction with the specific weight change data. Their use is detailed in the references cited in the IndexRef file discussed in a later section.

This database consists of 4003 individual alloy test runs at selected temperatures. This database is set up as a Microsoft EXCEL spreadsheet keyed by run number and a tube position number ranging from one to six based on the six test positions in the standard furnace set-up. Thus, each record in the database represents a given run with up to six sample tests at a selected temperature. The individual exposure times may vary as samples are removed, lost or added. Occasionally the position number may exceed a value of six if samples are removed and staggered time-wise or if more than one sample is supported on the same position wire.

The individual runs are designated as R1 to R212 for the more recent tests since the EXCEL database was initiated in early 1988. Older data beginning with test data from early 1970 was also entered in the EXCEL database starting in the early 1990's. These earlier data, designated as old run 1, etc. were given a prefix of R1000. Thus old run 1 is the earliest and is specified as R1001. Table's I and II show a typical new and old run. It is important to note that the run number and sample position are the key elements in defining the run conditions. The pertinent run conditions are not always shown on the individual "Run" tables but are listed on a special IndexRun file table discussed below for the complete run database. The plot of the run data with specific weight change in milligrams (mgm) per square centimeter for each sample is plotted against time in hours and is embedded in each individual "Run" table. Prior to embedding, the plots were generated by SigmaPlot software.

A certain set of runs designated in the R700's was tested in a different manner (refs. 9 and 45). These alloy samples were tested for ten-1000 hour cycles in a large box furnace in static air with the coupons hung from a tiered quartz lattice as shown in figure 2. For analytical reasons, the data was still processed in groups of six using dummy run numbers. The quartz lattice rack containing the samples was manually inserted and removed for each cycle between sample weighings.

Another special set of run numbers is in the R900's, which represents ceramic tests. These were tested in the vertical six tube automatic cycling furnaces like the metal samples except that, having no hanger hole, the small rectangular bars were tested contained in small suspended alumina cups (for silicon carbide) or in small platinum wire baskets (for silicon nitride).

As an EXCEL database, any set of critical parameters can be searched and sorted using the standard EXCEL tools of Find, Sort and Filter. These parameters are test temperature (degrees centigrade), test cycle time (defined as "tau (τ)", in hours), and test time (in cycles and/or hours). Also the test alloys can be found and sorted. Each alloy tested was given a code number "XXYYZZ" as detailed in table III. The first digits "XX" denote the base of the alloy; the second set "YY" gives the type of alloy; and the third set "ZZ" is the individual alloy number. For example, the nickel base alloy Hastelloy X superalloy is designated as 2-3-15, 2 for nickel base, 3 for superalloy and 15 for this particular alloy of this grouping

For ease in accessing the large database, an index file table termed IndexRun was set up as an EXCEL file in the CYCLES folder. How it can be used is discussed in the next section.

COMMENTS ON THE VARIOUS AUXILARY TABLE FILES

THE INDEXRUN FILE

The IndexRun Table file in the CYCLES folder is used to find a specific sample alloy run. In general the records in this table are sorted first by base: Fe-, Ni-, Co- etc. (XX), then by type (YY), and then by a specific material number (ZZ). These records are in turn listed in order of ascending temperature (Temp), then the length of exposure cycle at test temperature (tau), and finally the total number of hours exposed in the furnace at test temperature (Total Hours). The test data for a given specimen alloy run are found in the "Cycles" folders under individual Run Number files listed in sequence from R1 to R99 which represent 732 run files containing 4003 individual sample runs. A page of this file is shown in table IV.

This IndexRun file in EXCEL format can be searched for any desired piece of information using the standard Edit procedures either as this file exists or first using the Data procedure to re-Sort or Filter the file. For example, this file could be re-sorted alphabetically by Coded Alloy name or specific groups of data could be separated from the file (e.g., Nickel-base alloys tested at 1100 °C). Once the desired Run Number and Tube Number are noted, simply click on the Run Number Icon in the Cycles data base folder to bring up the run with its data along with a plot of the specific weight data as a function of time.

The IndexRun file also contains a brief Comments column. For instance, exceptions to a standard practice are noted in the Comments column. Most of the samples tested whether rectangular or disk shape coupons are machined to roughly 1.27 cm wide so as not to snag on the top edges of the furnace tubes as the samples are lowered into the furnace. They are usually ground as coupons to a 32 rms finish and glass bead blasted prior to test. Exceptions are noted in the Comments column.

In addition, a number of experimental cyclic oxidation programs are included in the coded alloy column and/or the Comments column. For example, ASMA alloys listed were part of a program in the late 1970's to develop an austenitic alloy comparable to a 304-type stainless steel with a minimum Cr content (refs. 6, 13, 14). Also in the Comments column is the notation COSAM, which refers to an alloy development program in the 1980's to modify a series of Ni-base superalloys by reducing the Co content (refs. 26, 28, and 29). Other comments include Small, which means a small tear-drop shape sample about 0.318 cm thick was cut from the end of a Mach 0.3 burner rig test bar with a 0.318 cm hanger hole with a surface area of just under 3 square centimeters. The standard samples were roughly 7.5 square centimeters in area.

All the samples tested for ten-1000 hour cycles are flagged in the Comments column by the term "Long Time Cycle". These long time test samples as mentioned above were given dummy run numbers from 701 to 746 and dummy tube numbers of 1 to 6 so as to be consistent with the rest of the sample database.

The samples when raised out of the furnace are enclosed. They are held high enough above the furnace in a spall shield so the samples cool to about 70 degrees centigrade. The term Water-cooled found in the Comments for a few special runs has cooling water running through the spall shields so the samples reach close to 25 degrees centigrade. This difference in cooling temperature did not appear significant to oxidation/scale spalling behavior. Also in certain tests the surface of the samples might be varied by polishing the sample surface or in a few cases using a light chemical etch though with negligible effect. Other comments are self-explanatory. For

example, the phrase “for Mich Tech” means samples of Ni-Cr-Al alloys with Zr additions were run in cyclic testing and supplied to Michigan Technology University to study the Zr effect on these alloys.

THE COMPOSITION FILE

Also in the CYCLES folder is the Composition file listed here in ascending order by the base “XX”, then by type “YY” and then by number. They can also be sorted alphabetically by Alloy (i.e., material). The chemical compositions may be given in weight % (i.e., w/o) or atomic % (i.e., a/o). The last column in the table lists other elements not generally found in an alloy of this type. These materials can likewise be located by clicking on the Find… icon in the EXCEL edit procedure. A typical page of this file is shown in table V.

THE INDEXREF FILE

An additional EXCEL file in the CYCLES folder termed IndexRef was set up to connect any of the individual materials to the references that utilized the cyclic data. A partial list is shown in table VI. The materials are sorted in alphabetical order by Alloy as shown in the fifth field. Also listed in this table are the material code numbers (columns 2, 3, and 4) along with an internal ID number (column 1). In column 6 are the numbered references in the literature wherein cyclic oxidation data of these materials are discussed. Two additional columns list the elemental base and general type of alloy or ceramic. These references are listed at the end of the text.

Table VII outlines the contents of the Cycles folder and the three descriptive files described above.

ESTIMATING CORROSION ATTACK

The purpose of establishing this database was to estimate the corrosion attack of these high temperature materials and, if possible, determine the kinetics of the cyclic oxidation process for predictive purposes. Also an attempt was to be made to particularly rank the alloys tested. In general, the alloys are to be protected by the formation of alumina (Al_2O_3) and/or chromia (Cr_2O_3) scales. Therefore, they should contain significant additions of Al and/or Cr. The SiC or Si_3N_4 ceramics tested are protected by the formation of silica (SiO_2). The formation of these protective oxides is likewise affected by other alloying elements or impurities present in these materials. Hence, most of the studies conducted on these alloys or ceramics focused on composition as well as temperature, time and cycle time.

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

$$\Delta W/A = W_r - W_m \qquad (1)$$

Where Δ W/A is the sample’s accumulated specific weight change value which is plotted against time in these type of data plots; W_r is the specific weight of the retained scale up to t in hours, and W_m is the accumulated specific weight of all the metal converted to oxide up to that time regardless of 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 one of the critical parameters 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 some corrosion studies a test sample is run for a given time, removed from test, descaled, and the thickness change measured. This value can be directly converted to a W_m value provided there is no significant alloy 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 also 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 the $\Delta W/A$ value is obtained experimentally then, if W_r can be determined, the W_m values can be readily determined using equation (1) for a series of times. For two limiting cases, W_r estimates present 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.3 and 53). For example, for isothermal parabolic oxidation after time, t:

$$W_m = b\,(k_p^{0.5})\,(t^{0.5}) - (k_p^{0.5})\,(t^{0.5})$$

or

$$W_m = (k_p^{0.5})\,(t^{0.5})\,(b - 1) \qquad (2)$$

Where k_p is the parabolic scaling constant and b is the stoichiometric constant based on the composition of the scale (i.e., the molecular weight of the oxide formed divided by molecular weight of oxygen in the oxide).

In the other limiting case where the scale spalls to essentially bare metal (i.e., $W_r = 0$) occasionally found in cyclic oxidation, equation (1), where the $\Delta W/A$ values are negative, reverts to:

$$-W_m = \sim \Delta W/A \qquad (3)$$

This has been observed, for example, in burner rig oxidation studies where an insignificant amount of oxide remains on the sample (refs. 11, 50 to 52).

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

One approach was 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 method and requires only the constants k_p, k_l, the linear loss rate of the oxide and the stoichiometric constant b as defined above for the scale formed to be able to determine $\Delta W/A$, W_r, and most importantly W_m for any time t (refs. 54 to 56). But since k_p, and particularly k_l are not generally known, Barrett and Presler (ref. 57) derived a computer

program to analyze paralinear behavior (i.e., parabolic scale growth combined with linear scale loss) and determine the gravimetric variables as a function of time as well as k_p and k_l using just two sets of $\Delta W/A$, 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. 57). Attempts have been made to use this COREST program to analyze cyclic oxidation behavior of the type of $\Delta W/A$ with time curves shown in a number of database plots. Its success has been limited but it is useful as a first approximation (refs. 4 and 11).

A more successful approach has been to actually model the cyclic oxidation process, cycle by cycle, on a computer. Any scale growth process, usually defined by a parabolic rate constant derived from isothermal oxidation tests, can be used as input. The nature of the spalling process should also be inferred. For chromia or alumina forming alloys it appears the fraction spalled is a fixed constant Q_0 times the oxide thickness (ref. 21). As in other methods the stoichiometric constants can usually be estimated from x-ray diffraction data. This computer program termed, COSP (ref. 37), generates $\Delta W/A$, W_r, and W_m values just as in the COREST program. This approach has been fairly successful with the more simple type of heater alloys but has been more difficult to use in analyzing the cyclic oxidation behavior of more complex alloys like high temperature superalloys. This COSP program (ref. 37) written in MS-DOS includes input for other possible scale growth kinetics (e.g., cubic, logrithmic, etc.) and other possible spalling models, all of which are some function of scale thickness. It also includes a Monte Carlo method where a unit area of scale can be divided into n segments and each segment randomly spalls to bare metal or doesn't spall at the end of a given heating cycle according to an overall spalling probability. Thus, for example for n =1000 and Q_0=0.006 cm^2/mg at any time t, the surface of the 1000 segments with an overall Q_o value of 0.006 will have a few spots of bare metal, a few segments that possibly never spalled and many possibilities in between. This program has recently been upgraded as WinCOSP written for Windows 98 (ref. 58). It probably comes closest to modeling the actual scale growth/spalling process. The usual procedure is to infer a model based on the initial growth portion of the curve to estimate k_p at the appropriate scale growth model and iterate spall constants (i.e., Q_0 values) to try to match the actual specific weight change/time curves.

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

$$\Delta W/A = (k_1^{0.5})\,(t^{0.5}) +/- (k_2 t) +/- (s) \qquad (4)$$

Here $k_1^{0.5}$ and k_2 are constants analogous to the scale growth and scale spalling constants and s is the standard error of estimate. Note k_2 is always negative for scale loss by whatever process whether spalling, vaporization or erosion. It can be positive if the sample is growing by fretting (i.e., serial cracking). By this latter process the sample can double or triple in size. If the fit is good enough (usually $R^2 > 0.90$) and $k_1^{0.5}$ is significant and positive and k_2 is statistically significant, then an attack parameter K_a is defined as:

$$K_a = (k_1^{0.5} + 10|k_2|) \qquad (5)$$

Or if $k_1^{0.5}$ is either not significant or negative and k_2 is significant then K_a can be defined as:

$$K_a = 20|k_2| \qquad (6)$$

The rational behind these K_a derivations is discussed in references 12, 16, 21, 22, 23, 25, and 26. 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 mass balance approach discussed above (refs. 3 and 4). This K_a estimation technique has the advantage that if the specific weight change/time data is in a computer data base such as described herein the data can be automatically processed for a regression fit according to equation (4) and K_a computed with equations (5) or (6) depending on the significance and sign of the coefficients $k_1^{0.5}$ and k_2. This process can evaluate fairly irregular kinetics. This K_a approach or a modification in addition to those referenced above was chosen to analyze a large number of runs for complex superalloys. Also see in more recent reports (refs. 40, 45 to 48).

EXAMPLES OF ANALYZING CYCLIC OXIDATION WITH THE DATABASE

Run 127 (R127) can be used as an example of how this data can be analyzed using the current technique(s) described in the previous section. Table VIII lists the critical data for this run and figure 3 shows the associated specific weight change time plot. Going to the IndexRun(s) file shows it consists of three sample runs of the iron-base FeCrAl ferritic heater alloy Kanthal AF. These 3 replicate samples were run in tube positions 1, 2, and 3 for 500 one-hour heating cycles at 1200 ºC. This was a special setup where the spall shield was water cooled so the samples were at room temperature within the twenty minute cooling cycle. Going to the Cycles folder and clicking on the R127.xls icon brings up the data and plots of the specific weight change data in mgms per square centimeter versus time in hours (see table VIII). An inspection of this data indicates the shape of the accumulated specific weight change / time curves appear to approximate paralinear behavior. It should be noted the three sets of observed data show significant downward jogs at 300 and 400 hours where the samples were handled for x-ray diffraction of the in situ scales. The three sets of data were fitted by non-linear regression to the equation of the form referred to above using SigmaPlot version 7.1 using the paralinear equation:

$$\Delta W/A = (k_1^{0.5})\,(t^{0.5}) +/- (k_2 t) +/- (s) \qquad (4)$$

Here k_1 represents the parabolic scale growth constant, k_2 is a linear scale loss constant and t is time. The derived constants are as follows with s the standard error of estimate in mg/cm^2 and R^2, the coefficient of determination and $R^2_{adj,}$ the adjusted coefficient of determination.

	$k_1^{0.5}$	k_1	k_2	s	R^2	R^2_{adj}
127-1	0.205521	0.042109	–0.00477045	0.0687	0.983395	0.983063
127-2	0.194827	0.037958	–0.00452844	0.0691	0.980965	0.980585
127-3	0.188209	0.035423	–0.00476479	0.0764	0.968545	0.967916

Figure 4(a), (b), and (c) shows these fits for the observed and predicted values and indicates the excellent fits for each of the three sets. The relative rank or rating of the degree of oxidation resistance has been defined as K_a. Here K_a is defined as:

$$K_a = (k_1^{0.5} + \ 10\,|k_2|) \qquad (5)$$

The respective K_a values are as follows: 127-1 = 0.252909, 127-2 = 0.233010, and 127-3 = 0.235857. Based on the previous studies the oxidation ranking falls just short of excellent (K_a < or = 0.2) in the "good" range (K_a >0.2 but <0.5) (ref. 40 and 45).

WinCosp can be used in the next step to analyze the same three sets of the run 127 data. Here parabolic scale growth and uniform scale spalling are modeled on a cycle by cycle basis summed successively over the total number of cycles. Depending on the amount of spall after each cooling cycle scale growth is accelerated due to the increased oxidation rate due to in effect projecting back to an earlier part of the parabolic growth curve. The further back the projection the greater the instantaneous growth rate. The details of this approach are discussed in refs. 37 and 58. The results of a few trial and error fits are shown in figure 5(a), (b), and (c) and appear to give a fairly good fit to the observed data. Many additional results can be derived from this method including estimates of the total metal consumed in the scaling and spalling process as a function of time as long as the same type of scale controls. Here this would be the Al as αAl_20_3.

A major question in cyclic oxidation tests of this type is how to define failure. Usually alumina forming alloys, such as heater alloys or in other alloys that protect by forming chromia(Cr_2O_3), start to fail when spinel(s) start to form containing the base metal oxide (e.g., CoO,NiO, or FeO). In paralinear oxidation this is generally in the downward linear portion of the specific weight change curve, crossing the zero weight gain origin time axis. When enough of these base metal oxides are present along with other deleterious oxides in more complex alloys (e.g., TiO_2, MoO_3, WO_3, etc.) true failure is indicated by "breakaway" where the weight change/time curve breaks sharply downward accompanied by severe spalling. As a rule of thumb time values where the specific weight change exceeding a negative 5.0 mg/cm^2 can be considered as time to incipient failure.

However, actual time to breakaway is a more meaningful value. Tests may not be run to reach breakaway so extrapolation to the time to cross the zero-weight change axis or to a value of –5 mg/cm^2 might be a simpler criterion. Further complicating a definition of failure is if the specific weight change curve remains parabolic (e.g., pure Ni) but has a very high k_p. Or the alloy is complex enough that the scaling rate is linear—either positive or negative (e.g., complex turbine superalloys). Adding to the complexity of defining failure is the vaporization of chromia scale controlling alloys as their operating temperature approaches 1000 ºC. The volatility of oxides of W, Mo, and Re can also lead to failure. Further complicating factors defining failure is the deleterious role of tramp sulfur in an alloy or water vapor in the atmosphere as well as the beneficial effect of small amounts of reactive metals or elements like Zr, Hf, La, Y, and Si in the alloys whether added or picked up in processing.

All of the above discussion and analysis show that cyclic oxidation is a very complex process with ongoing studies still modifying testing and analytical techniques.

SUMMARY

The cyclic oxidation test results for some 1000 high temperature commercial and experimental alloys have been collected in an EXCEL database. This database represents over thirty years of research at NASA Glenn Research Center in Cleveland, Ohio. The data is in the form of a series of runs of specific weight change versus time values for a set of samples tested at a given temperature, cycle time, and exposure time. Included on each run is a set of embedded plots of the critical data. The nature of the data is discussed along with analysis of the cyclic oxidation process. In addition examples are given as to how a set of results can be analyzed.

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Table I.—Typical New Cyclic Oxidation Run 165 with Corresponding Specific Weight Change / Time Plot (Note: No numerical prefix)

Tiitle:	**Cyclic Oxidation Run 165 Water Cooled 1200 C,100 Hr Cycles**												
Temp:	1200° C	tau:	100										
Tube	Material	Area	Wo	Code									
1	NiAl(Zr)	3.322	1.9061	2-12-149									
2	NiAl(Zr)	3.344	1.9298	2-12-149									
3	NiAl(Zr)	3.362	1.9740	2-12-149									
Cycles	Hours	W1	ΔW1/A	W2	ΔW2/A	W3	ΔW3/A	Average					
0	0	1.9061	0.00	1.9298	0.00	1.9740	0.00	0.00					
1	100	1.9117	1.69	1.9349	1.53	1.9789	1.46	1.56					
2	200	1.9123	1.87	1.9360	1.85	1.9801	1.81	1.84					
3	300	1.9116	1.66	1.9346	1.44	1.9790	1.49	1.53					
4	400	1.9118	1.72	1.9351	1.58	1.9792	1.55	1.62					
5	500	1.9098	1.11	1.9328	0.90	1.9770	0.89	0.97					
6	600	1.9079	0.54	1.9314	0.48	1.9752	0.36	0.46					
7	700	1.9075	0.42	1.9309	0.33	1.9743	0.09	0.28					
8	800	1.9042	-0.57	1.9281	-0.51	1.9714	-0.77	-0.62					
9	900	1.9028	-0.99	1.9272	-0.78	1.9706	-1.01	-0.93					

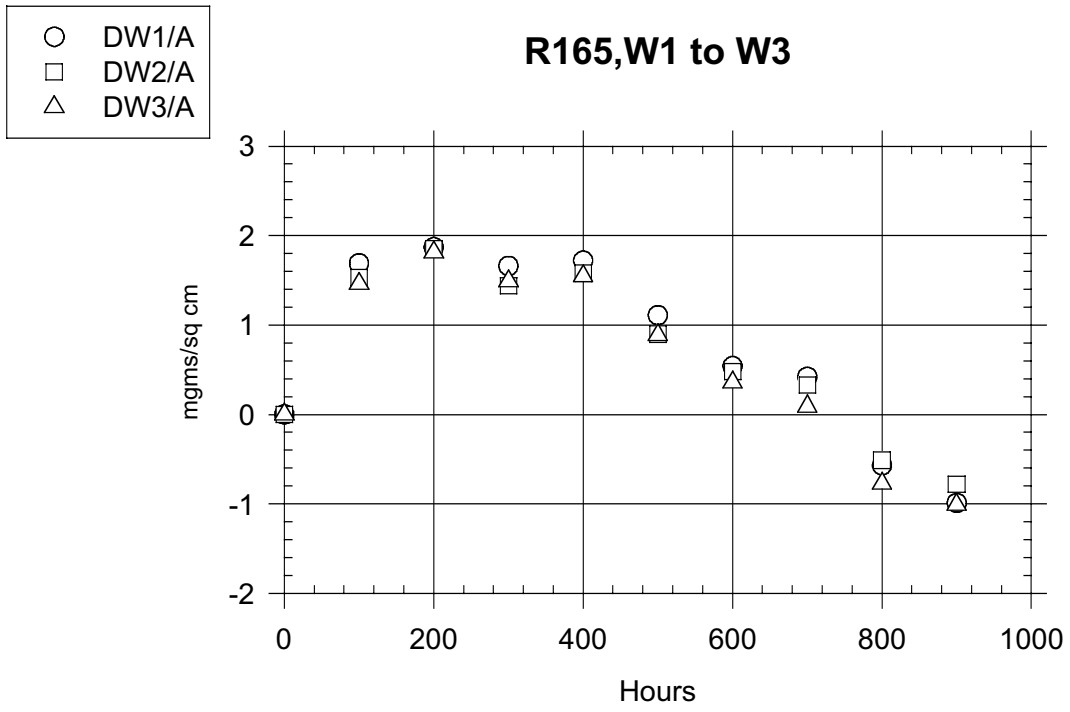


Table II.—Typical Old Cyclic Oxidation Run 39 with Corresponding Specific Weight Change / Time Plot (Note: Prefix of 1000)

Title:	Cyclic Oxidation Run 1039(Old Run 39) 1204 C, .5 Hour Cycles, Commercial Sheet Alloys											
Temp:	1204 C	τ:	0.5									
Tube	Alloy	Area	Wo	Code								
1	TD-NiCrFe	5.0854	0.6644	2-5-2								
2	TD-NiCrFe	5.0766	0.6636	2-5-2								
3	TD-NiCr	5.9187	3.1182	2-5-1								
4	TD-NiCr	5.9186	3.1575	2-5-1								
5	Tophet 30	6.4850	4.7808	2-2-10								
6	Tophet 30	6.5630	4.8277	2-2-10								
Cycles	Hours	W1	ΔW1/A	W2	ΔW2/A	W3	ΔW3/A	W4	ΔW4/A	W5	ΔW5/A	W6
0	0	0.6644	0.00	0.6636	0.00	3.1182	0.00	3.1575	0.00	4.7808	0.00	4.8277
1	0.5	0.6658	0.28	0.6651	0.30	3.1192	0.17	3.1585	0.17	4.7840	0.49	4.8302
2	1	0.6659	0.29	0.6651	0.30	3.1192	0.17	3.1586	0.19	4.7857	0.76	4.8317
10	5	0.6661	0.33	0.6658	0.43	3.1198	0.27	3.1590	0.25	4.7877	1.06	4.8349
20	10	0.6659	0.29	0.6653	0.33	3.1196	0.24	3.1585	0.17	4.7875	1.03	4.8344
30	15	0.6657	0.26	0.6647	0.22	3.1195	0.22	3.1582	0.12	4.7841	0.51	4.8330
40	20	0.6656	0.24	0.6642	0.12	3.1194	0.20	3.1580	0.08	4.7827	0.29	4.8317
50	25	0.6653	0.18	0.6636	0.00	3.1192	0.17	3.1575	0.00	4.7821	0.20	4.8317
60	30	0.6652	0.16	0.6631	-0.10	3.1193	0.19	3.1574	-0.02	4.7795	-0.20	4.8296
70	35	0.6648	0.08	0.6623	-0.26	3.1186	0.07	3.1566	-0.15	4.7770	-0.59	4.8273
80	40	0.6646	0.04	0.6618	-0.35	3.1187	0.08	3.1565	-0.17	4.7764	-0.68	4.8271
90	45	0.6643	-0.02	0.6614	-0.43	3.1183	0.02	3.1561	-0.24	4.7751	-0.88	4.8259
100	50	0.6641	-0.06	0.6611	-0.49	3.1183	0.02	3.1562	-0.22	4.7734	-1.14	4.8242
110	55	0.6644	0.00	0.6612	-0.47	3.1180	-0.03	3.1558	-0.29	4.7725	-1.28	4.8232
120	60	0.6639	-0.10	0.6605	-0.61	3.1180	-0.03	3.1554	-0.35	4.7704	-1.60	4.8219
130	65	0.6638	-0.12	0.6603	-0.65	3.1179	-0.05	3.1553	-0.37	4.7693	-1.77	4.8204

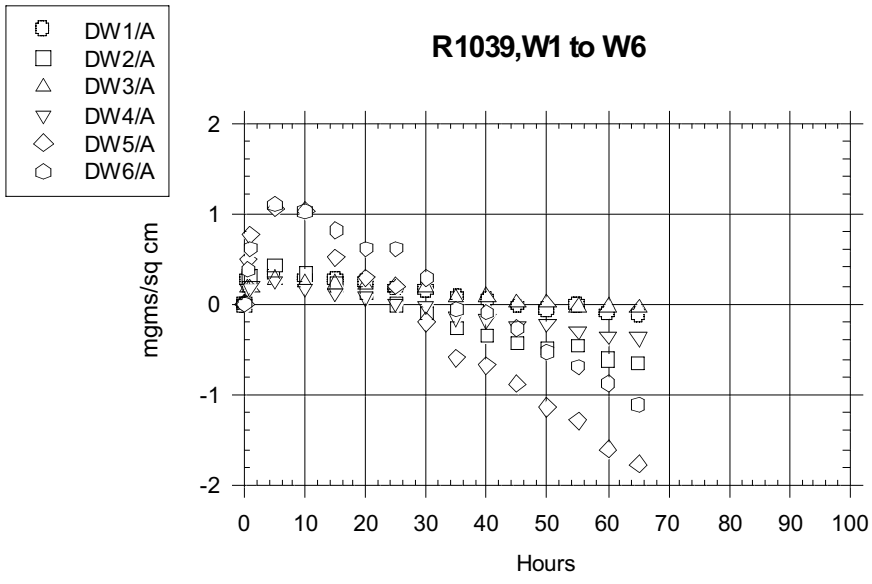


Table III.—Alloy Code Showing Base (XX), Type (YY) and Sample Number of the Materials Tested

XX Base	YY Type	ZZ Alloy Code Number
1 Iron	1 FeCrAl Heater Alloys	1 to 43
" "	2 Ferritic Alloys Including 400 Series Stainless Steels	1 to 25
" "	3 Austinitic Alloys Including 300 Series Stainless Steels	1 to 43
" "	4 Not Used	
" "	5 Experimental Modified 304 Stainless Steels to Conserve Cr	1 to 181
" "	6 Not Used ?	
" "	7 FeAl Intermetallics	1 to 19
" "	8 Superalloys	1 to 2
2 Nickel	1 Unalloyed Nickel	1 to 2
" "	2 NiCr Heater Alloys	1 to 11
" "	3 Superalloys	1 to 25
" "	4 Turbine Alloys	1 to 69
" "	5 TD-Ni or TD-NiCr's	1 to 4
" "	6 O.D.S. NiCrAl's	1 to 27
" "	7 Not Used	
" "	8 Experimental NiCrAl's	1 to 143
" "	9 Experimental Turbine Alloys	1 to 233
" "	10 Coated Turbine Alloys	1 to 5
" "	11 Not Used	
" "	12 NiAl Intermetallics - Less than 2% Cr	1 to 209
" "	13 Modified Experimental Wrought Turbine Alloys	2 to 36
3 Cobalt	1 Superalloys	1 to 5
" "	2 Turbine Alloys	1 to 4
" "	3 Experimental CoCrAl's	1 to 9
" "	4 CoCr	1 only
" "	5 CoAl Intermetallics	1 to 13
4 Niobium	1 Experimental NbAl-X Alloys	9 to 10
5 Chromium	1 Esssentially Unalloyed Cr	1 to 2
	2 Miscellaneous Cr Alloys	1 to 2
6 Titanium	1 Experimental TiAlX Alloys	1 to 13
7 Silicon	1 Si3N4 Ceramic	1 to 6
	2 SiC Ceramic	1 to 2

Table IV.—Inex Run File (Sample Portion)

RunNumber	Tube	Base	XX	YY	ZZ	Coded Alloy Name	Temp	tau	Total Hours	Comments
1	1	Nickel-base	2	12	35	NiAl Beta 50.2+ trace Zr	1200	1	3500	Beta/gamma prime alloys
1	2	Nickel-base	2	12	37	NiAl Beta 46.8+ trace Zr	1200	1	1900	Beta/gamma prime alloys
1	3	Nickel-base	2	12	38	NiAl Beta 43.9+ trace Zr	1200	1	3500	Beta/gamma prime alloys
1	4	Nickel-base	2	12	39	NiAl Beta 39.9+ trace Zr	1200	1	1000	Beta/gamma prime alloys
1	5	Nickel-base	2	12	40	NiAl Beta 37.5+ trace Zr	1200	1	400	Beta/gamma prime alloys
1	6	Nickel-base	2	12	41	NiAl Beta/Gamma' 35.5+ trace Zr	1200	1	1000	Beta/gamma prime alloys
2	1	Nickel-base	2	12	37	NiAl Beta 46.8+ trace Zr	1200	1	1000	Beta/gamma prime alloys
2	2	Nickel-base	2	12	42	NiAl Beta/Gamma' 33.2+ trace Zr	1200	1	1000	Beta/gamma prime alloys ; same as run 20
2	3	Nickel-base	2	12	44	NiAl Beta/Gamma' 30.6+ trace Zr	1200	1	1000	Beta/gamma prime alloys ; same as run 20
2	4	Nickel-base	2	12	48	NiAl Beta/Gamma' 29.0+ trace Zr	1200	1	1000	Beta/gamma prime alloys ; same as run 20
2	5	Nickel-base	2	12	48	NiAl Beta/Gamma' 29.0+ trace Zr	1200	1	1000	Beta/gamma prime alloys ; same as run 20
2	6	Nickel-base	2	12	45	NiAl Beta/Gamma' 26.8+ trace Zr	1200	1	1000	Beta/gamma prime alloys ; same as run 20
3	1	Nickel-base	2	12	36	NiAl Beta 49.4-	1200	1	500	Beta/gamma prime alloys
3	2	Nickel-base	2	12	36	NiAl Beta 49.4-	1200	1	500	Beta/gamma prime alloys
3	3	Nickel-base	2	12	41	NiAl Beta/Gamma' 35.5+ trace Zr	1200	1	500	Beta/gamma prime alloys
3	4	Nickel-base	2	12	43	NiAl Beta/Gamma' 31.1-	1200	1	500	Beta/gamma prime alloys
7	1	Nickel-base	2	12	35	NiAl Beta 50.2+ trace Zr	1425	1	100	Beta/gamma prime alloys
7	2	Nickel-base	2	12	37	NiAl Beta 46.8+ trace Zr	1425	1	100	Beta/gamma prime alloys
7	3	Nickel-base	2	12	38	NiAl Beta 43.9+ trace Zr	1425	1	100	Beta/gamma prime alloys
7	4	Nickel-base	2	12	39	NiAl Beta 39.9+ trace Zr	1425	1	100	Beta/gamma prime alloys
7	5	Nickel-base	2	12	40	NiAl Beta 37.5+ trace Zr	1425	1	100	Beta/gamma prime alloys
8	1	Nickel-base	2	12	36	NiAl Beta 49.4-	1425	1	100	Beta/gamma prime alloys
8	2	Nickel-base	2	12	41	NiAl Beta/Gamma' 35.5+ trace Zr	1425	1	100	Beta/gamma prime alloys
9	1	Nickel-base	2	12	42	NiAl Beta/Gamma' 33.2+ trace Zr	1425	1	35	Beta/gamma prime alloys
9	2	Nickel-base	2	12	44	NiAl Beta/Gamma' 30.6+ trace Zr	1425	1	15	Beta/gamma prime alloys
9	3	Nickel-base	2	12	43	NiAl Beta/Gamma' 31.1-	1425	1	35	Beta/gamma prime alloys
10	1	Nickel-base	2	12	35	NiAl Beta 50.2+ trace Zr	1375	1	100	Beta/gamma prime alloys
10	2	Nickel-base	2	12	37	NiAl Beta 46.8+ trace Zr	1375	1	100	Beta/gamma prime alloys
10	3	Nickel-base	2	12	38	NiAl Beta 43.9+ trace Zr	1375	1	100	Beta/gamma prime alloys
10	4	Nickel-base	2	12	39	NiAl Beta 39.9+ trace Zr	1375	1	100	Beta/gamma prime alloys
10	5	Nickel-base	2	12	40	NiAl Beta 37.5+ trace Zr	1375	1	100	Beta/gamma prime alloys
10	6	Nickel-base	2	12	41	NiAl Beta/Gamma' 35.5+ trace Zr	1375	1	100	Beta/gamma prime alloys
11	1	Nickel-base	2	12	13	Ni-48.3Al-.1Zr - Hipped Std.-2	1300	1	40	NiAl with various Zr%;cracked
11	2	Nickel-base	2	12	50	NiAl Beta + 1.0 Zr	1300	1	60	NiAl with various Zr%;corner broke off
11	3	Nickel-base	2	12	51	NiAl Beta + .5 Zr	1300	1	100	NiAl with various Zr%
11	4	Nickel-base	2	12	52	NiAl Beta + .02 Zr	1300	1	100	NiAl with various Zr%
11	5	Nickel-base	2	12	7	NiAl Beta + .30 Zr	1300	1	100	NiAl with various Zr%
11	6	Nickel-base	2	12	55	NiAl Beta + .50 Zr	1300	1	100	NiAl with various Zr%
22	1	Nickel-base	2	12	13	Ni-48.3Al-.1Zr - Hipped Std.-2	1300	1	400	Beta HIP or Cast
22	2	Nickel-base	2	12	13	Ni-48.3Al-.1Zr - Hipped Std.-2	1300	1	400	Beta HIP or Cast
22	3	Nickel-base	2	12	12	Ni-38.1Al-.1Zr - Hipped Std.-3	1300	1	100	Beta HIP or Cast
22	4	Nickel-base	2	12	12	Ni-38.1Al-.1Zr - Hipped Std.-3	1300	1	100	Beta HIP or Cast
22	5	Nickel-base	2	12	55	NiAl Beta + .50 Zr	1300	1	100	Beta HIP or Cast
25	1	Nickel-base	2	12	97	NiAl-AlN	1300	1	100	AlN Cryomilled
25	2	Nickel-base	2	12	97	NiAl-AlN	1300	1	100	AlN Cryomilled
25	3	Nickel-base	2	12	13	Ni-48.3Al-.1Zr - Hipped Std.-2	1300	1	100	AlN Cryomilled
26	1	Nickel-base	2	12	13	Ni-48.3Al-.1Zr - Hipped Std.-2	1200	1	1500	AlN Cryomilled
26	3	Nickel-base	2	12	97	NiAl-AlN	1200	1	1500	AlN Cryomilled
26	5	Nickel-base	2	12	97	NiAl-AlN	1200	1	1500	AlN Cryomilled
27	1	Nickel-base	2	12	46	NiAl Beta 47.2+ trace Zr	1300	1	100	DoychakOld+Alloy2 HIP
27	3	Nickel-base	2	12	46	NiAl Beta 47.2+ trace Zr	1300	1	100	DoychakOld+Alloy2 HIP

Table V.—Composition File of the Materials Tested (Sample Portion)

ID	Alloy	XX	YY	ZZ	Base	Type1	Type2	Comment	PercentType	Proprietary	Fe	Ni	Co	Cr	Cu	Al	Ti	Hf	Zr	Y	Mo	W	Ta	Nb	Th
144	HOS-875	1	1	1	Iron-base	Commercial wrought	Ferritic alloy with Al	Heater Alloy	Wt%	NO	71.4	0.00	0	22.5	0	5.50	0	0.000	0.000	0	0	0	0	0	0
356	Kanthal A-1	1	1	2	Iron-base	Commercial wrought	Ferritic alloy with Al	Heater alloy	Wt%	NO	72	0.00	0.5	22	0	5.50	0	0.000	0.000	0	0	0	0	0	0
357	GE-1541	1	1	3	Iron-base	Commercial wrought	Heater/Sheet alloy		Wt%	NO	79.888	0.25	0	14.5	0	4.52	0	0.000	0.000	0.74	0	0	0	0	0
358	GE-2541	1	1	4	Iron-base	Commercial wrought	Heater/Sheet alloy		Wt%	NO	70.093	0.11	0	24.55	0	3.83	0	0.000	0.000	1.23	0	0	0	0	0
488	FeCrAlY MA-956	1	1	5	Iron-base	Dispersion strengthened	Ferritic alloy with Al	Y as Y2O3; also known as IN-956	Wt%	NO	75.18	0.40	0	18.9	0	4.40	0.5	0.000	0.000	0.6	0	0	0	0	0
410	Allegheny Lud. A-1	1	1	6	Iron-base	Commercial wrought	Superalloy		Wt%	NO	56.9	20.00	0	20	0	2.00	0	0.000	0.000	0	0	0	0	0	0
728	Fontana - O.S.U.	1	1	7	Iron-base	Experimental wrought	Ferritic alloy	Ohio State Univ. exp. alloy	Wt%	NO	87.45	0.00	0	6	0.5	6.00	0	0.000	0.000	0	0	0	0	0	0
773	Fecralloy A	1	1	8	Iron-base	Commercial wrought	Ferritic alloy with Al	from Henry Wiggin Ltd., England	Wt%	NO	80	0.00	0	15	0	5.00	0	0.000	0.000	0	0	0	0	0	0
783	NOZZL-(10 Ni)	1	1	9	Iron-base	Experimental cast	Ferritic alloy with Al	No Zr	Wt%	NO	0	74.50	0	20	0	5.00	0	0.000	0.000	0	0	0	0	0	0
586	NOZZl-Zr(10 Ni)	1	1	10	Iron-base	Experimental cast	Ferritic alloy with Al		Wt%	NO	64.3	10.00	0	20	0	5.00	0	0.000	0.200	0	0	0	0	0	0
550	Fe-15Cr-5Al-10Ni (Scratch)	1	1	11	Iron-base	MCrAl's experimental	Ferritic alloy with Al	Cast Leaves	Wt%	NO	70	10.00	0	15	0	5.00	0	0.000	0.000	0	0	0	0	0	0
551	Fe-15Cr-5Al-20Ni (Scratch)	1	1	12	Iron-base	MCrAl's experimental	Ferritic alloy with Al	Cast leaves	Wt%	NO	60	20.00	0	15	0	5.00	0	0.000	0.000	0	0	0	0	0	0
552	Fe-15Cr-5Al-30Ni (Scratch)	1	1	13	Iron-base	MCrAl's experimental	Ferritic alloy with Al	Cast leaves	Wt%	NO	50	30.00	0	15	0	5.00	0	0.000	0.000	0	0	0	0	0	0
553	Fe-15Cr-5Al-10Ni-.2Zr (Scratch)	1	1	14	Iron-base	MCrAl's experimental	Ferritic alloy with Al	Cast leaves	Wt%	NO	69.69	10.21	0	14.56	0	5.48	0	0.000	0.060	0	0	0	0	0	0
554	Fe-15Cr-5Al-20Ni-.2Zr (Scratch)	1	1	15	Iron-base	MCrAl's experimental	Ferritic alloy with Al	Cast leaves	Wt%	NO	59.54	20.45	0	15.08	0	4.76	0	0.000	0.170	0	0	0	0	0	0
555	Fe-15Cr--5Al-30Ni-.2Zr (Scratch)	1	1	16	Iron-base	MCrAl's experimental	Ferritic alloy with Al	Cast leaves	Wt%	NO	47.82	31.17	0	14.86	0	6.13	0	0.000	0.020	0	0	0	0	0	0
556	Fe-24Cr-10Ni-5Al-.2Zr (Scratch)	1	1	17	Iron-base	MCrAl's experimental	Ferritic alloy with Al	Cast leaves	Wt%	NO	60.8	10.00	0	24	0	5.00	0	0.000	0.200	0	0	0	0	0	0
557	Fe-19Cr--10Ni-5Al-.2Zr (Scratch)	1	1	18	Iron-base	MCrAl's experimental	Ferritic alloy with Al	Cast leaves	Wt%	NO	65.8	10.00	0	19	0	5.00	0	0.000	0.200	0	0	0	0	0	0
558	Fe-14Cr-10Ni-5Al-.2Zr (Scratch)	1	1	19	Iron-base	MCrAl's experimental	Ferritic alloy with Al	Cast leaves	Wt%	NO	70.8	10.00	0	14	0	5.00	0	0.000	0.200	0	0	0	0	0	0
688	Fe-22.5Cr-20Ni-5.5Al-.5Si	1	1	20	Iron-base	MCrAl's experimental	Ferritic alloy with Al	Ht. D-472;Ferritic to Austenite series	Wt%	NO	54.934	19.00	0	20	0	5.50	0	0.000	0.016	0	0	0	0	0	0
689	Fe-22.5Cr-28Ni-5.5Al-.5Si	1	1	21	Iron-base	MCrAl's experimental	Ferritic alloy with Al	Ht. D-473;Ferritic to Austenite series	Wt%	NO	43.031	27.50	0	21.4	0	7.50	0	0.000	0.019	0	0	0	0	0	0
690	Fe-22.5Cr-36Ni-5.5Al	1	1	22	Iron-base	MCrAl's experimental	Ferritic (Austenitic) alloy with Al?	Ht.D-485;Ferritic to Austenitic series	Wt%	NO	33.975	37.10	0	22.3	0	6.50	0	0.000	0.000	0	0	0	0	0	0
691	Fe-22.5Cr-36Ni-5.5Al-.5Si	1	1	23	Iron-base	MCrAl's experimental	Ferritic (Austenitic) alloy with Al?	Ht. D-486;Ferritic to Austenitic series	Wt%	NO	35.332	35.00	0	22.6	0	6.50	0	0.000	0.018	0	0	0	0	0	0
692	Fe-22.5Cr-44Ni-5.5Al-.5Si	1	1	24	Iron-base	MCrAl's experimental	Ferritic (Austenitic) alloy with Al?	Ht. D-487;Ferritic to Austenitic series	Wt%	NO	21.932	47.10	0	24.5	0	5.90	0	0.000	0.018	0	0	0	0	0	0
710	Fe-12Ni-10Cr-5Al D-534	1	1	25	Iron-base	MCrAl's experimental	Ferritic alloy with Al		Wt%	NO	72.45	12.00	0	10	0	5.00	0	0.000	0.000	0	0	0	0	0	0
1002	18SR + 2Mo	1	1	26	Iron-base	Experimental wrought	Ferritic alloy with Al	Automotive reactor program	Wt%	NO	75.749	0.00	0	17.91	0	2.19	0	0.000	0.000	0	2.02	0	0	0.58	0
712	Fe-20Ni-15Cr-5Al D-531	1	1	27	Iron-base	MCrAl's experimental	Ferritic alloy with Al		Wt%	NO	59.45	20.00	0	15	0	5.00	0	0.000	0.000	0	0	0	0	0	0
713	Fe-28Ni-15Cr-5Al D-532	1	1	28	Iron-base	MCrAl's experimental	Appears semi-austenitic	Ferrite no. = 1.1; slightly magnetic	Wt%	NO	51.45	28.00	0	15	0	5.00	0	0.000	0.000	0	0	0	0	0	0
897	Kanthal AF	1	1	29	Iron-base	Commercial wrought	Ferritic alloy with Al	Heater alloy;similar to Kanthal A-1	Wt%	NO	72.2	0.00	0.5	22	0	5.30	0	0.000	0.000	0	0	0	0	0	0
928	FeCrAlY Matrix	1	1	30	Iron-base	Experimental wrought	Ferritic alloy with Al	Basis for FeCrAlY + Alumina fibers	Atomic%	NO	67.94	0.00	0	24	0	8.00	0	0.000	0.000	0.06	0	0	0	0	0
929	FeCrAlY Matrix + Alumina fibers	1	1	31	Iron-base	Experimental wrought	Ferritic alloy with Al	FeCrAlY + Alumina surface fibers	Atomic%	NO	67.94	0.00	0	24	0	8.00	0	0.000	0.000	0.06	0	0	0	0	0
930	FeCrAl Matrix	1	1	32	Iron-base	Experimental wrought	Ferritic alloy with Al	Basis for FeCrAl + Alumina fibers	Atomic%	NO	68	0.00	0	24	0	8.00	0	0.000	0.000	0	0	0	0	0	0
931	FeCrAl Matrix + Alumina fibers	1	1	33	Iron-base	Experimental wrought	Ferritic alloy with Al	FeCrAl + Alumina surface fibers	Atomic%	NO	68	0.00	0	24	0	8.00	0	0.000	0.000	0	0	0	0	0	0
938	FeCrAlY MA-956 + Alumina Fibers	1	1	34	Iron-base	Dispersion strengthened	Ferritic alloy with Al	Embedded alumina fibers	Wt%	NO	75.18	0.40	0	18.9	0	4.40	0.5	0.000	0.000	0.6	0	0	0	0	0
997	GE-1540	1	1	35	Iron-base	Experimental wrought	Ferritic alloy with Al	Automotive reactor program	Wt%	NO	81	0.00	0	15	0	4.00	0	0.000	0.000	0	0	0	0	0	0
998	GE-1550 + 1.25Ta	1	1	36	Iron-base	Experimental wrought	Ferritic alloy with Al	Automotive reactor program	Wt%	NO	78.75	0.00	0	15	0	5.00	0	0.000	0.000	0	0	0	1.25	0	0
999	GE-1551 + 1.25Ta	1	1	37	Iron-base	Experimental wrought	Ferritic alloy with Al	Automotive reactor program	Wt%	NO	77.75	0.00	0	15	0	5.00	0	0.000	0.000	1	0	0	1.25	0	0
1000	GE-1551 + .5Ta	1	1	38	Iron-base	Experimental wrought	Ferritic alloy with Al	Automotive reactor program	Wt%	NO	78.5	0.00	0	15	0	5.00	0	0.000	0.000	1	0	0	0.5	0	0
1001	GE-1540 + 1.25Ta	1	1	39	Iron-base	Experimental wrought	Ferritic alloy with Al	Automotive reactor program	Wt%	NO	79.75	0.00	0	15	0	4.00	0	0.000	0.000	0	0	0	1.25	0	0
996	GE-1540 + 2Mo	1	1	40	Iron-base	Experimental wrought	Ferritic alloy with Al	Automotive reactor program	Wt%	NO	77.919	0.00	0	14.37	0	4.72	0	0.000	0.000	0	2.02	0	0	0.53	0
711	Fe-36Ni-15Cr-5Al D-533	1	1	41	Iron-base	MCrAl's experimental	Appears austenitic	Ferrite no. = .3 ; non-magnetic	Wt%	NO	43.45	36.00	0	15	0	5.00	0	0.000	0.000	0	0	0	0	0	0
354	FeCrAl-Alloy 2	1	1	42	Iron-base	MCrAl's experimental	Coating alloy	Certified Alloy master alloy;Ht. X-4034	Wt%	NO	72.54	0.00	0	22.1	0	4.80	0	0.000	0.000	0	0	0	0	0	0
355	FeCrAl-Alloy 3	1	1	43	Iron-base	MCrAl's experimental	Coating alloy	Certified Alloy master alloy;Ht. X-4035	Wt%	NO	72.8	0.00	0	21.5	0	5.00	0	0.000	0.100	0	0	0	0	0	0
563	Croloy 1/2	1	2	1	Iron-base	Commercial wrought	Ferritic alloy		Wt%	NO	97.955	0.00	0	0.65	0	0.00	0	0.000	0.000	0	0.55	0	0	0	0
564	Croloy 1-1/4	1	2	2	Iron-base	Commercial wrought	Ferritic alloy		Wt%	NO	96.82	0.00	0	1.25	0	0.00	0	0.000	0.000	0	0.55	0	0	0	0
566	Croloy 2-1/4	1	2	3	Iron-base	Commercial wrought	Ferritic alloy		Wt%	NO	95.62	0.00	0	2.25	0	0.00	0	0.000	0.000	0	1	0	0	0	0
132	Croloy 5	1	2	4	Iron-base	Commercial wrought	Ferritic alloy	Steam Plant Alloy	Wt%	NO	93.74	0.00	0	5	0	0.00	0	0.000	0.000	0	0.55	0	0	0	0
133	Croloy 7	1	2	5	Iron-base	Commercial wrought	Ferritic alloy	Steam Plant Alloy	Wt%	NO	91.07	0.00	0	7	0	0.00	0	0.000	0.000	0	0.55	0	0	0	0
134	Croloy 9	1	2	6	Iron-base	Commercial wrought	Ferritic alloy	Steam Plant Alloy	Wt%	NO	88.52	0.00	0	9	0	0.00	0	0.000	0.000	0	1.35	0	0	0	0
171	409 S.S.	1	2	7	Iron-base	Commercial wrought	Ferritic alloy		Wt%	NO	88.45	0.00	0	11	0	0.00	0.5	0.000	0.000	0	0	0	0	0	0
172	410 S.S.	1	2	8	Iron-base	Commercial wrought	Ferritic alloy		Wt%	NO	85.35	0.00	0	12.5	0	0.00	0	0.000	0.000	0	0	0	0	0	0
173	430 S.S.	1	2	9	Iron-base	Commercial wrought	Ferritic alloy		Wt%	NO	81.88	0.00	0	17	0	0.00	0	0.000	0.000	0	0	0	0	0	0
159	RA-26-1	1	2	10	Iron-base	Commercial wrought	Ferritic alloy	FeCr Ferritic Alloy	Wt%	NO	71.635	0.20	0	26	0	0.00	0.5	0.000	0.000	0	1	0	0	0	0
179	18SR	1	2	11	Iron-base	Commercial wrought	Ferritic alloy with Al		Wt%	NO	77.91	0.25	0	18	0	2.00	0.4	0.000	0.000	0	0	0	0	0	0
178	NASA-18T	1	2	12	Iron-base	Experimental wrought	Ferritic alloy with Al		Wt%	NO	76.546	0.00	0	18	0	2.00	0.5	0.000	0.000	0	0	0	1.25	0	0
175	Thermenol	1	2	13	Iron-base	Commercial wrought	Ferritic alloy with Al		Wt%	NO	80.65	0.00	0	0	0	16.00	0	0.000	0.000	0	3.3	0	0	0	0
177	TRW Valve	1	2	14	Iron-base	Commercial wrought	Ferritic alloy with Al		Wt%	NO	66.81	0.10	0	0	0	32.00	0	0.000	0.000	0	0.1	0.5	0	0	0
359	17-4 PH	1	2	16	Iron-base	Commercial wrought	Ferritic alloy		Wt%	NO	75.26	4.00	0	16	2.7	0.00	0	0.000	0.000	0	0	0	0	0	0
360	17-7 PH	1	2	17	Iron-base	Commercial wrought	Ferritic alloy with Al		Wt%	NO	72.81	7.10	0	17	0	1.00	0	0.000	0.000	0	0	0	0	0	0
452	AL-EX-20	1	2	19	Iron-base	Experimental wrought	Heater/Sheet alloy	High Mn, Low Cr	Wt%	NO	70.41	1.00	0	5	0	3.15	0	0.000	0.000	0	0	0	0	0	0
361	Incoloy-903	1	2	20	Iron-base	Commercial wrought	Superalloy	No Cr-?	Wt%	NO	41.9	38.00	15	0	0	0.70	1.4	0.000	0.000	0	0	0	0	3	0
585	Rawers	1	2	21	Iron-base	Experimental wrought	Ferritic alloy	U.S. Bur. of Mines	Wt%	NO	70.5	14.00	0	8	0	0.00	0	0.000	0.000	0	4.5	0	0	0	0
174	T439 S.S.	1	2	22	Iron-base	Commercial wrought	Ferritic alloy		Wt%	NO	79.25	0.50	0	18.25	0	0.15	1	0.000	0.000	0	0	0	0	0	0
565	Croloy 2	1	2	23	Iron-base	Commercial wrought	Ferritic alloy		Wt%	NO	96.32	0.00	0	2	0	0.00	0	0.000	0.000	0	0.55	0	0	0	0
567	Croloy 3 M	1	2	24	Iron-base	Commercial wrought	Ferritic alloy		Wt%	NO	94.94	0.00	0	3	0	0.00	0	0.000	0.000	0	0.93	0	0	0	0
995	18SR + .5 Ta	1	2	25	Iron-base	Experimental wrought	Ferritic alloy with Al	Automotive reactor program	Wt%	NO	77.54	0.17	0	17.74	0	2.10	0.44	0.000	0.000	0	0	0	0.45	0	0
164	304 S.S.	1	3	1	Iron-base	Commercial wrought	Austenitic stainless steel		Wt%	NO	67.92	10.00	0	19	0	0.00	0	0.000	0.000	0	0	0	0	0	0
362	304L S.S.	1	3	2	Iron-base	Commercial wrought	Austenitic stainless steel		Wt%	NO	67.97	9.00	0	20	0	0.00	0	0.000	0.000	0	0	0	0	0	0
165	309 S.S.	1	3	3	Iron-base	Commercial wrought	Austenitic stainless steel		Wt%	NO	60.3	13.50	0	23	0	0.00	0	0.000	0.000	0	0	0	0	0	0
160	RA-309	1	3	4	Iron-base	Commercial wrought	Austenitic stainless steel		Wt%	NO	60.635	14.00	0	23	0	0.00	0	0.000	0.000	0	0	0	0	0	0
166	310 S.S.	1	3	5	Iron-base	Commercial wrought	Austenitic stainless steel		Wt%	NO	50.75	20.50	0	25	0	0.00	0	0.000	0.000	0	0	0	0	0	0
161	RA-310	1	3	6	Iron-base	Commercial wrought	Austenitic stainless steel		Wt%	NO	52.935	20.00	0	25	0	0.00	0	0.000	0.000	0	0	0	0	0	0
167	316 S.S.	1	3	7	Iron-base	Commercial wrought	Austenitic stainless steel		Wt%	NO	65.42	12.00	0	17	0	0.00	0	0.000	0.000	0	2.5	0	0	0	0

Table VI.—Index Reference File (Sample Portion)

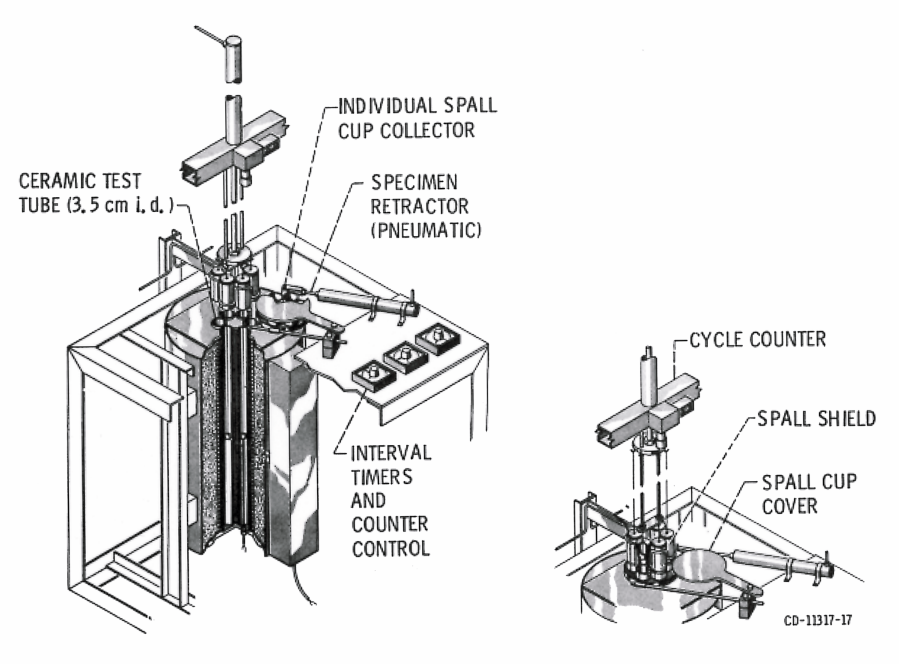
ID	XX	YY	ZZ	Alloy	References	Base	Type1
448	1	3	26	12RN72	23	Iron-base	Commercial wrought
359	1	2	16	17-4 PH		Iron-base	Commercial wrought
360	1	2	17	17-7 PH		Iron-base	Commercial wrought
179	1	2	11	18SR	9,45,46	Iron-base	Commercial wrought
995	1	2	25	18SR + .5 Ta		Iron-base	Experimental wrought
1002	1	1	26	18SR + 2Mo		Iron-base	Experimental wrought
364	1	3	22	19-9 DL	23	Iron-base	Commercial wrought
781	1	3	42	19-9 DL + .5 Al		Iron-base	Experimental wrought
782	1	3	43	19-9 DL + 1 Al		Iron-base	Experimental wrought
363	1	3	18	201 S.S.		Iron-base	Commercial wrought
451	1	3	25	253 MA	23	Iron-base	Commercial wrought
164	1	3	1	304 S.S.	9,45,46	Iron-base	Commercial wrought
428	1	5	181	304 S.S. master alloy-1		Iron-base	Experimental wrought
427	1	5	180	304 S.S. std.-1		Iron-base	Experimental wrought
362	1	3	2	304L S.S.		Iron-base	Commercial wrought
709	1	5	167	304S.S. Std. 2		Iron-base	Experimental wrought
165	1	3	3	309 S.S.	45,46	Iron-base	Commercial wrought
166	1	3	5	310 S.S.	9,45,46	Iron-base	Commercial wrought
559	1	3	41	316 L S.S.		Iron-base	Commercial wrought
167	1	3	7	316 S.S.	9,23,45,46	Iron-base	Commercial wrought
560	1	3	16	317 L S.S.		Iron-base	Commercial wrought
562	1	3	17	317 S.S.		Iron-base	Commercial wrought
168	1	3	8	321 S.S.	9,45,46	Iron-base	Commercial wrought
169	1	3	11	334 S.S.	45,46	Iron-base	Commercial wrought
170	1	3	12	347 S.S.	9,45,46	Iron-base	Commercial wrought
171	1	2	7	409 S.S.	9,45,46	Iron-base	Commercial wrought
172	1	2	8	410 S.S.	9,45,46	Iron-base	Commercial wrought
173	1	2	9	430 S.S.	9,45,46	Iron-base	Commercial wrought
366	1	8	1	A-286	23	Iron-base	Commercial wrought
452	1	2	19	AL-EX-20	23	Iron-base	Experimental wrought
410	1	1	6	Allegheny Lud. A-1	2,	Iron-base	Commercial wrought
77	2	4	38	Astroloy	33,40	Nickel-base	Commercial wrought
104	2	4	1	B-1900	1,11,24,28,33,40,45,46	Nickel-base	Commercial cast
662	2	4	28	B-1900 + .5 Si		Nickel-base	Experimental cast
663	2	4	29	B-1900 + 1.0 Si		Nickel-base	Experimental cast
49	2	4	2	B-1900 + Hf	24,33,40,47	Nickel-base	Commercial cast
126	3	1	5	Belgian P-3	45,46	Cobalt-base	Experimental wrought
127	3	1	4	Belgian S-57	9,45,46	Cobalt-base	Experimental cast
916	2	12	137	Beta NiAl + .1v/o ZrO2		Nickel-base	Intermetallics
917	2	12	138	Beta NiAl + .5 v/o Y2O3		Nickel-base	Intermetallics
921	2	12	142	Beta NiAl + 1.0 v/o Al2O3		Nickel-base	Intermetallics
918	2	12	139	Beta NiAl + 1.0 v/o HfO2		Nickel-base	Intermetallics
919	2	12	140	Beta NiAl + 1.0 v/o La2O3		Nickel-base	Intermetallics
920	2	12	141	Beta NiAl + 1.0 v/o TiO2		Nickel-base	Intermetallics
922	2	12	143	Beta NiAl + 1.0 v/o ZrO2		Nickel-base	Intermetallics
694	2	9	128	C.L.-10		Nickel-base	Experimental cast
695	2	12	93	C.L.-11		Nickel-base	Experimental cast
696	2	12	94	C.L.-12		Nickel-base	Experimental cast
697	2	12	95	C.L.-13		Nickel-base	Experimental cast
698	2	12	96	C.L.-14		Nickel-base	Experimental cast
714	2	12	15	C.L.-15		Nickel-base	Experimental cast
715	2	12	88	C.L.-16		Nickel-base	Experimental cast
716	2	12	89	C.L.-17		Nickel-base	Experimental cast
717	2	12	90	C.L.-18		Nickel-base	Experimental cast
718	2	12	91	C.L.-19		Nickel-base	Experimental cast
719	2	12	92	C.L.-20		Nickel-base	Experimental cast
365	1	3	23	CG-27	23	Iron-base	Commercial wrought
643	1	3	29	CG-27Mod.(0Cr-1.5Al)		Iron-base	Experimental wrought
647	1	3	30	CG-27Mod.(0Cr-3Al)		Iron-base	Experimental wrought
651	1	3	31	CG-27Mod.(0Cr-6Al)		Iron-base	Experimental wrought
640	1	3	38	CG-27Mod.(12Cr-1.5Al)		Iron-base	Experimental wrought
644	1	3	39	CG-27Mod.(12Cr-3Al)		Iron-base	Experimental wrought
648	1	3	40	CG-27Mod.(12Cr-6Al)		Iron-base	Experimental wrought
642	1	3	32	CG-27Mod.(4Cr-1.5A)		Iron-base	Experimental wrought
646	1	3	33	CG-27Mod.(4Cr-3Al)		Iron-base	Experimental wrought
650	1	3	34	CG-27Mod.(4Cr-6Al)		Iron-base	Experimental wrought
641	1	3	35	CG-27Mod.(8Cr-1.5Al)		Iron-base	Experimental wrought
645	1	3	36	CG-27Mod.(8Cr-3Al)		Iron-base	Experimental wrought
649	1	3	37	CG-27Mod.(8Cr-6Al)		Iron-base	Experimental wrought

Table VII.—Contents of the CYCLES Folder of the Excel Database

	EXCEL DATBASE : CYCLES - CONTENTS		
Cycles Folder	**Index Runs File**	**Composition File**	**Index Ref File**
732 Cyclic Oxidation Runs	Run Number	ID - Internal Control Number	ID - Internal Control Number
4003 Sample Runs	Tube	Alloy	XX - Base
	Base	XX - Base	YY - Alloy Type
	XX - Base	YY - Alloy Type	ZZ - Sample Number
	YY - Alloy Type	ZZ - Sample Number	Alloy
	ZZ - Sample Number	Base	References using the DATABASE
	Coded Alloy Name	Type1 - Descriptor	Base
	Test Teperature	Type2 - Additional Descriptor	Alloy Type Descriptor
	tau - Test Cycle(Hrs.)	Special Comment	
	Total Test Time(Hrs.)	Atomic or Weight Percent	
	Comments	Proprietary - Yes or No	
		Alloy Content - Fe to ….	

Table VIII.—Specific Weight Change Time Data for Cyclic Oxidation Run 127 for Use in Analyzing Oxidation Kinetics

Title:	Cyclic Oxidation Run 127 1200 C, 1.0 Hour Cycles							
Temp:	1200	**τ:**	1					
Tube	**Sample**	**Area**	**Wo**	**Code**				
1	AF-1	5.909	3.2231	1-1-29				
2	AF-2	6.057	3.3719	1-1-29				
3	AF-3	6.190	3.2924	1-1-29				
4	Empty							
5	Empty							
6	Empty							
	Hours	**W1**	**ΔW1/A**	**W2**	**ΔW2/A**	**W3**	**ΔW3/A**	**Average**
	0	3.2231	0.00	3.3719	0.00	3.2924	0.00	0.00
	1	3.2251	0.34	3.3739	0.33	3.2944	0.32	0.33
	5	3.2263	0.54	3.3751	0.53	3.2956	0.52	0.53
	10	3.2274	0.73	3.3762	0.71	3.2967	0.69	0.71
	20	3.2286	0.93	3.3774	0.91	3.2979	0.89	0.91
	30	3.2295	1.08	3.3783	1.06	3.2987	1.02	1.05
	40	3.2301	1.18	3.3789	1.16	3.2994	1.13	1.16
	50	3.2306	1.27	3.3794	1.24	3.2998	1.20	1.23
	60	3.2311	1.35	3.3798	1.30	3.3001	1.24	1.30
	70	3.2316	1.44	3.3803	1.39	3.3005	1.31	1.38
	80	3.2319	1.49	3.3806	1.44	3.3008	1.36	1.43
	90	3.2323	1.56	3.3808	1.47	3.3011	1.41	1.48
	100	3.2326	1.61	3.3812	1.54	3.3013	1.44	1.53
	110	3.2328	1.64	3.3813	1.55	3.3014	1.45	1.55
	120	3.2331	1.69	3.3815	1.58	3.3015	1.47	1.58
	130	3.2333	1.73	3.3818	1.63	3.3017	1.50	1.62
	140	3.2336	1.78	3.3820	1.67	3.3020	1.55	1.67
	150	3.2338	1.81	3.3822	1.70	3.3022	1.58	1.70
	160	3.2336	1.78	3.3821	1.68	3.3021	1.57	1.68
	170	3.2339	1.83	3.3823	1.72	3.3023	1.60	1.71
	180	3.2341	1.86	3.3825	1.75	3.3024	1.62	1.74
	190	3.2343	1.90	3.3827	1.78	3.3026	1.65	1.78
	200	3.2345	1.93	3.3829	1.82	3.3028	1.68	1.81
	210	3.2344	1.91	3.3829	1.82	3.3026	1.65	1.79
	220	3.2346	1.95	3.3830	1.83	3.3028	1.68	1.82
	230	3.2348	1.98	3.3832	1.87	3.3030	1.71	1.85
	240	3.2350	2.01	3.3834	1.90	3.3032	1.74	1.89
	250	3.2350	2.01	3.3832	1.87	3.3031	1.73	1.87
	260	3.2351	2.03	3.3833	1.88	3.3032	1.74	1.89
	270	3.2354	2.08	3.3836	1.93	3.3034	1.78	1.93
	280	3.2356	2.12	3.3838	1.96	3.3036	1.81	1.96
	290	3.2358	2.15	3.3840	2.00	3.3038	1.84	2.00
	300	3.2359	2.17	3.3841	2.01	3.3039	1.86	2.01
	310	3.2348	1.98	3.3836	1.93	3.3029	1.70	1.87
	320	3.2350	2.01	3.3838	1.96	3.3031	1.73	1.90
	330	3.2352	2.05	3.3839	1.98	3.3033	1.76	1.93
	340	3.2353	2.06	3.3841	2.01	3.3035	1.79	1.96
	350	3.2355	2.10	3.3843	2.05	3.3037	1.83	1.99
	360	3.2357	2.13	3.3845	2.08	3.3038	1.84	2.02
	370	3.2359	2.17	3.3846	2.10	3.3040	1.87	2.05
	390	3.2362	2.22	3.3850	2.16	3.3043	1.92	2.10
	400	3.2364	2.25	3.3852	2.20	3.3044	1.94	2.13
	410	3.2357	2.13	3.3841	2.01	3.3033	1.76	1.97
	420	3.2359	2.17	3.3842	2.03	3.3035	1.79	2.00
	430	3.2360	2.18	3.3844	2.06	3.3036	1.81	2.02
	440	3.2362	2.22	3.3845	2.08	3.3038	1.84	2.05
	450	3.2363	2.23	3.3847	2.11	3.3040	1.87	2.07
	460	3.2364	2.25	3.3848	2.13	3.3041	1.89	2.09
	470	3.2366	2.28	3.3849	2.15	3.3043	1.92	2.12
	480	3.2367	2.30	3.3850	2.16	3.3043	1.92	2.13
	490	3.2368	2.32	3.3852	2.20	3.3045	1.95	2.16
	500	3.2369	2.34	3.3853	2.21	3.3046	1.97	2.17



(a) Specimens at test temperature.

(b) Specimens cooled to ambient temperature.

Figure 1.—Schematic of NASA Glenn's standard cyclic oxidation test setup.

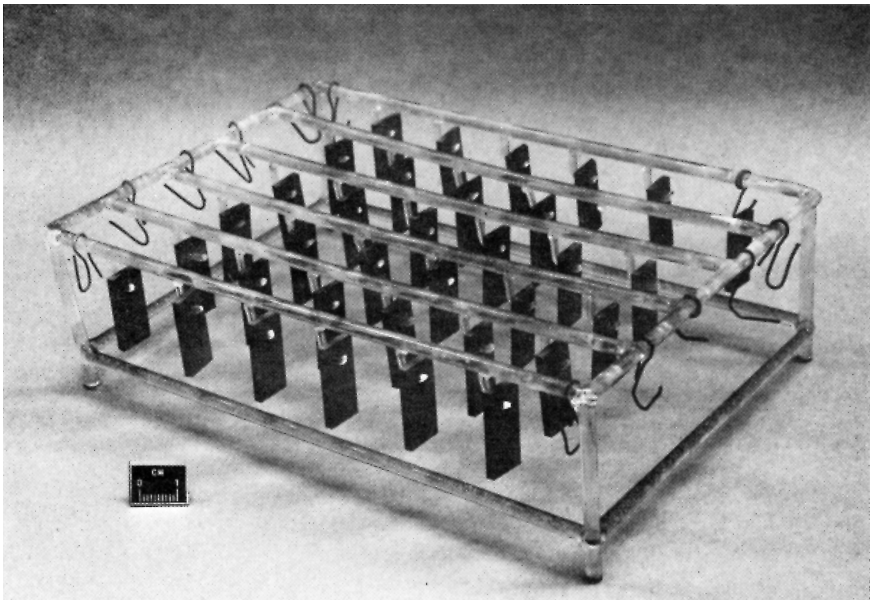


Figure 2.—Quartz tiered lattice to support test coupons for long time box furnace testing.

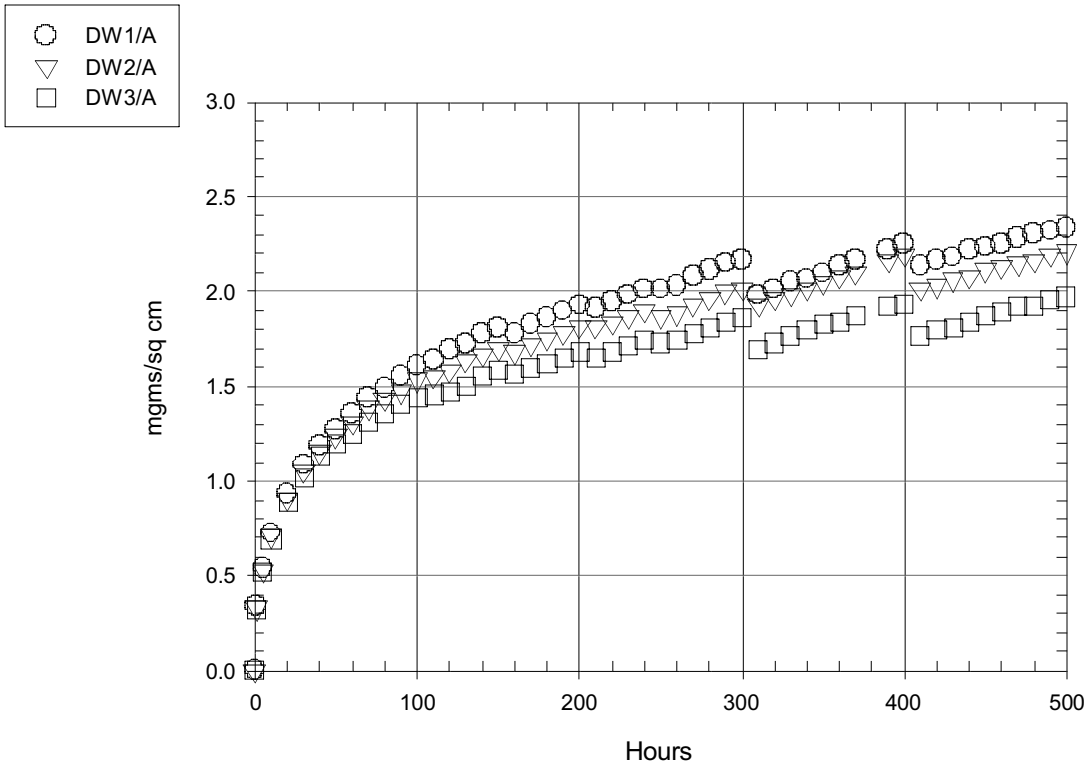


Figure 3.—Standard type plot embedded in each cyclic Run Data Table (Run 127).

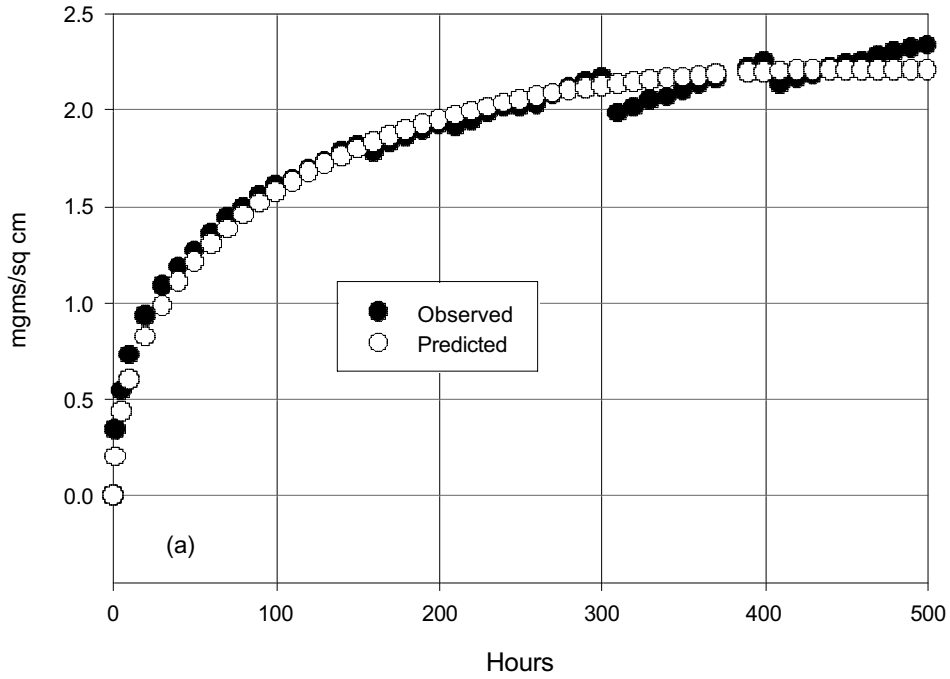
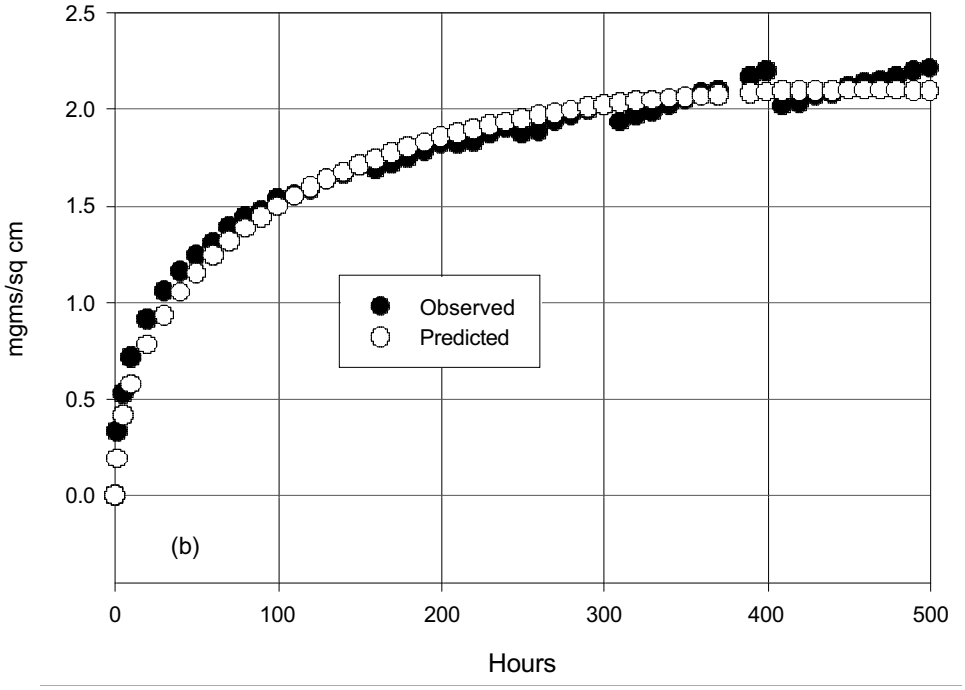


Figure 4.—Plots showing regression fits for observed and fitted data for Run 127, Samples 127–1, 127–2, and 127–3 using the Regression Model: $\Delta W/A = (k_p t)^{0.5} +/- k_l t$.



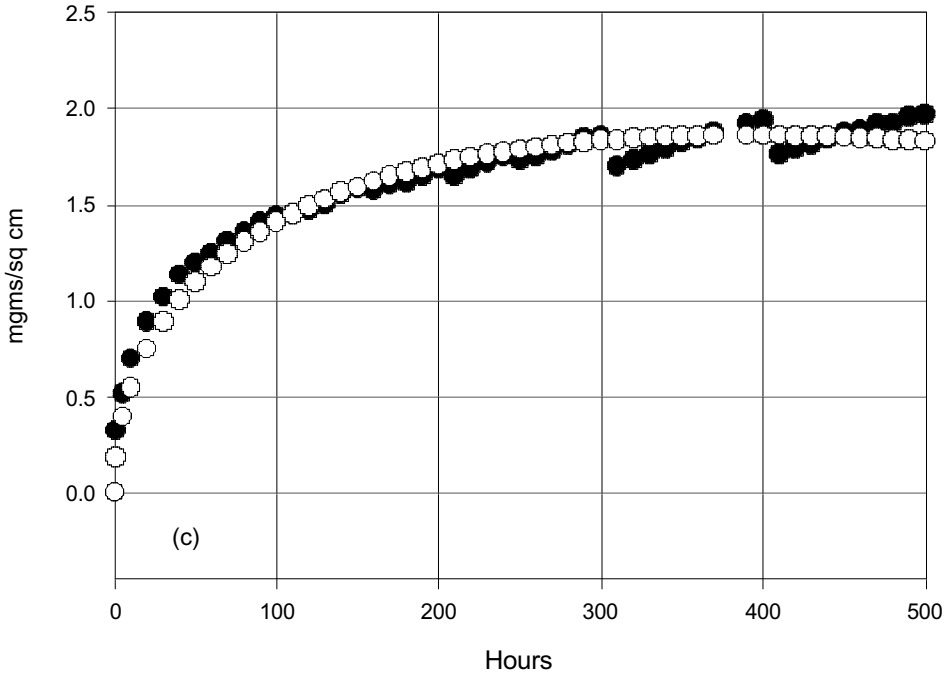


Figure 4. —Concluded. Plots showing regression fits for observed and fitted data for Run 127, Samples 127–1, 127–2, and 127–3 using the Regression Model: $\Delta W/A = (k_p t)^{0.5} +/- k_l t$.

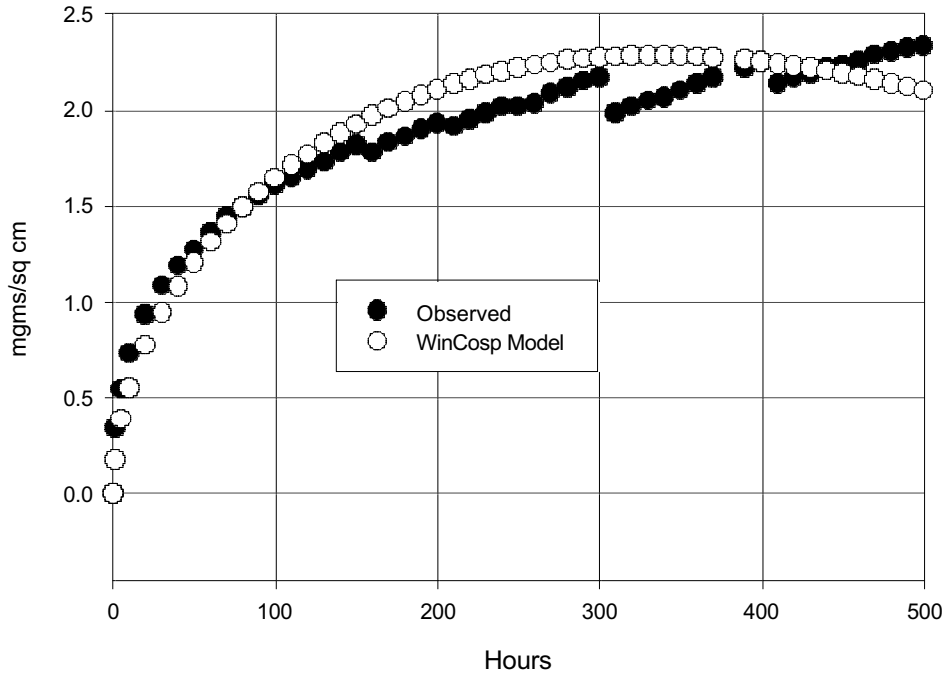


Figure 5.—Plots showing Model Fits using WinCosp Iteration for Run 127–1 assuming parabolic scale growth and scale spalling as a function of scale thickness.

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13. ABSTRACT ***(Maximum 200 words)***

The cyclic oxidation test results for some 1000 high temperature commercial and experimental alloys have been collected in an EXCEL database. This database represents over thirty years of research at NASA Glenn Research Center in Cleveland, Ohio. The data is in the form of a series of runs of specific weight change versus time values for a set of samples tested at a given temperature, cycle time, and exposure time. Included on each run is a set of embedded plots of the critical data. The nature of the data is discussed along with analysis of the cyclic oxidation process. In addition examples are given as to how a set of results can be analyzed. The data is assembled on a read-only compact disk which is available on request from Materials Durability Branch, NASA Glenn Research Center, Cleveland, Ohio

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