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THE EFFECT OF VARIATIONS OF COBALT CONTENT ON THE CYCLIC OXIDATION RESISTANCE OF SELECTED Ni-BASE SUPERALLOYS

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SUMMARY

Cobalt levels were systematically varied in the Ni-base turbine alloys U-700 (cast), U-700 (PM/HIP), Waspaloy, Mar-M-247, IN-738, Nimonic-115, U-720, and SX-R-150. The cobalt levels ranged from 0 wt % to the nominal commercial content in each alloy. The alloys were tested in cyclic oxidation in static air at 1000, 1100 and 1150 °C for 500, 200 and 100 hr respectively. An oxidation attack parameter, K_a derived from the specific weight change versus time data was used to evaluate the oxidation behavior of the alloys along with x-ray diffraction analysis of the surface oxides. The alloys tend to form either Cr_2O_3/chromite spinel or Al_2O_3/aluminate spinel depending on the Cr/Al ratio in the alloys. Alloys with a ratio of 3.5 or higher tend to favor the Cr oxides while those under 3.0 form mostely Al oxides. In general the Al_2O_3/aluminate spinel forming alloys have the better oxidation resistance. Increased cobalt content lowers the scaling resistance of the high Cr alloys while a 5.0 wt % Co content is optimum for the Al controlling alloys. The refractory metals particularly Ta appear beneficial to both types of oxides perhaps due to the formation of the omni-present trirutile $Ni(Ta,Cb,Mo,W)_2O_6$. Both scales break down as increasing amounts of NiO is formed.

E-2952

INTRODUCTION

NASA Lewis Research Center undertook a long range program in support of the aerospace industry aimed at reducing the need for critical metals used in gas turbine engines. The program was termed "COSAM" - Conservation of Strategic Materials. One of the major objectives was to understand and possibly minimize the use of a critical element such as cobalt in high strength nickel-base superalloys (refs. 1 and 2). This study focuses on the role of cobalt on high temperatures cyclic oxidation on some typical alloys of interest.

Seven high temperature nickel-base superalloys were studied in high temperature cyclic oxidation. The alloys include: U-700 cast and powder metallurgy (P/M) hipped samples; hot worked Waspaloy; cast MAR-M-247; hot worked IN-738; hot worked Nimonic-115; hot worked U-720; and cast single crystal (SX) R-150. The alloys were varied in their cobalt levels from 0 to their normal commercial levels. The chemistries for each alloy are shown in table I (ref. 1). These superalloys represent a range of high-temperature, high strength Ni-base turbine alloys with a range of Cr to Al ratios from 15:1 for Waspaloy and near 7:1 for U-720, which can be hot worked, to alloys with Cr/Al ratios near 1, which must be cast.

PROCEDURE

The supplied test alloys were machined into oxidation test coupons each 1 by 2 by 0.23 cm with a 0.3 cm diameter hanger hole. The samples after cleaning and weighing were automatically cycled in static air furnaces as described in reference 3. In this study the samples were tested for 1 hr cycles consisting of 1 hr at either 1000, 1100, or 1150 °C in the furnace and a minimum of 20 min above the furnace at a temperature of near 65 °C. The samples were removed periodically for weighing.

The test times were 100, 200, and 500 hr at 1150, 1100 and 1000 °C respectively. These data are used to generated specific weight change/time values to evaluate the severity of the oxidation attack.

In addition to the weight change data, each sample and its collected spall were removed and analyzed by x-ray diffraction after 1,100, and when applicable 200 and 500 hr.

RESULTS AND DISCUSSION

ANALYSIS OF SPECIFIC WEIGHT CHANGE DATA

The oxidation behavior for each test sample can be determined from the specific weight change versus time data either by comparing the specific weight change at a given time or, more accurately by deriving an attack parameter, defined as K_a, from the fitted data which defines the overall oxidation resistance. The weight change/time data is fitted by multiple linear regression to:

$$\Delta W/A = k_1^{1/2} t^{1/2} - k_2 t \pm SEE \qquad (1)$$

where $k_1^{1/2}$ represents an oxide growth constant and k_2 an oxide spalling constant. SEE is the standard error of estimate. A rejection level of 0.90 is chosen for significance. This lead to an attack parameter defined as:

$$K_a = (k_1^{1/2} + 10.\ k_2) \qquad (2)$$

in certain cases a more appropriate estimating equation is a simple linear fit:

$$\Delta W/A = -k_2 t \pm SEE \qquad (3)$$

which modifies the attack parameter to:

$$K_a = (20.\ k_2) \qquad (4)$$

These equations, examples, and their rationale have been discussed previously in references 4 to 9.

In general the oxidation resistance can be rated as follows:

K_a < 0.20 excellent
0.20 to 0.50 excellent to good
0.50 to 1.00 good to fair
1.00 to 5.00 fair to poor
5.00 to 10.00 poor to catastrophic
>10.00 catastrophic

Where "excellent" means a low scale growth rate with minimal spall at one extreme while "catastrophic" means the sample is almost totally oxidized and usually converted to massive spall.

Selected specific weight change versus time curves for the various alloys are shown in figures 1 to 3. The individual data sets were fitted first to equation (1) by a multiple linear regression. If the significance level of either $k_1^{1/2}$ or k_2 did not exceed 0.90 it was dropped and the regression equation recalculated. Of the 127 runs for all alloys at the 3 test temperatures 99 give a good fit to (ref. 1) with the rejection level of 0.90. Fourteen runs had the first term drop out as not significant to the 0.90 level so (refs. 3 and 4) are used to estimate K_a. Twelve of the 127 runs were forced when $k_1^{1/2}$ is negative to a simple linear fit so again (refs. 3 and 4) are used rather than (refs. 1 and 2) to estimate K_a. Examples of these 3 types of fit are shown in table II. Finally 2 of the 127 runs were rejected outright as outliers. Table II summarizes this "fit" data for the 8 sets of alloys at each of the 3 test temperatures.

Tables III, IV, and V summarizes the specific weight change data and the derived constants from equations (1) to (4). Additional data of a statistical nature are tabled in the appendix separately for each of the three test temperatures. In addition to the $k_1^{1/2}$, k_2, and K_a derived parameters, specific weight changes at 100 hr and, where available, 200 and 500 hr are also listed to indicate sample behavior.

The K_a values derived for each set of alloys at each temperature are shown on log scale bar graphs in figures 4 to 6. The bars are grouped from low to high cobalt values from left to right on the plots. For each alloy series any replicates for a given alloy are also shown. The K_a rankings ranging from excellent to catastrophic are shown as horizontal lines.

The x-ray diffraction results from test sample surfaces are summarized in tables VI to VIII. There is a massive amount of data to be condensed because of the number of oxides found on these complex alloys. In general the alloys tend to be either Cr_2O_3/chromite spinel formers or Al_2O_3/aluminate spinel formers. Almost always present with either type is a tetragonal tri-rutile oxide with a d-lattice spacing on the (110) plane <3.30 Å. This is usually $Ni(Ta,Cb,Mo,W)_2O_6$ also termed tapiolite (ref. 10). Also found throughout the analyses was Cr titanate $Cr_2Ti_{13}O_{29}$, Ni titanate-(Ni,Co,Fe) TiO_3, and Ni Tungstate-$Ni(W,Mo)O_4$ and finally the alloys fail as massive NiO is detected. Occasionally a tri-rutile structure with a d-value >3.30 is detected. An alloy like MAR-M-247 with 1.5 Hf will indicate $HfO_2.ZrO_2$ is also detected in certain cases.

At 1000 °C the Al_2O_3/aluminate spinel forming MAR-M-247, Nimonic-115, SX-R-150 have the best cyclic oxidation resistance. There is no obvious Co effect although there are K_a minimums at 5 Co for MAR-M-247, at 10 Co for Nimonic-115, and at 6 Co for SX-R-150-all less than their commerical cobalt levels. U-700 (cast and P/M hipped), Waspaloy, IN-738 and U-720 all are Cr_2O_3/chromite spinel controlled at 1000 °C. Their oxidation rates are considerably higher than the alumina formers but there is no obvious Co effect.

At 1100 °C MAR-M-247 and Nimonic-115 alloys behave similarly to the 1000 °C test alloy except the K_a values are somewhat higher and critical NiO formation takes place at shorter times. The oxidation resistance is still generally good and again 5 Co is an apparent oxidation minimum for MAR-M-247 while the minimum for Nimonic-115 is also at 5 Co. SX-R-150 while still an apparent Al_2O_3/aluminate spinel former oxidizes massively to NiO and $NiWO_4$. This apparent anomolous behavior is difficult to explain based strictly on composition. The remaining alloys are basically chromia/chromite spinel formers at 1100 °C although alumnia and/or aluminates start to show up with longer times in both the U-700 series alloys. The oxidation resistance of the U-700, Waspaloy, IN-738, and U-720 generally fall into the poor category. The resistance is usually worse at the highest cobalt levels. NiO shows up at 100 hr on the U-700, IN-738, and U-720 series samples while Cr_2O_3 still controls at 100 hr for the Waspaloy. Even at 200 hr Cr_2O_3 still is quite strong for the Waspaloy while the other 3 chromia formers show mostly NiO present. This appears to be due to the high (19.5) Cr level in Waspaloy although U-720 with an 18 Cr level might be expected to behave in a similar manner.

At 1150 °C MAR-M-247 and Nimonic-115 series still show fair cyclic oxidation resistance and are mostly Al_2O_3/aluminate spinel formers. MAR-M-247 starts out as a complex NiO/<3.30 tri-rutile/$NiWO_4$/Cr_2O_3/HfO_2 former. At 100 hr aluminate spinel/Al_2O_3 shows up as well. The Nimonic-115 series indicates mostly Cr_2O_3/chromite spinel/$NiTiO_3$ after 1 hr for the 5, 10, and 15 cobalt levels. The 0 Co indicates only Al_2O_3 after 1 hr but chromite spinel along with NiO, Al_2O_3 and aluminate spinel. At the 5, 10, and 15 Co levels only Al_2O_3, aluminate spinel and <3.30 tri-rutile are observed. For both alloy systems the minimum in K_a values are at the 5 Co level.

U-700 (cast and P/M), Waspaloy, IN-738, and U-720 all are strong Cr_2O_3 formers after 1 hr along with <3.30 tri-rutile and in some cases $Cr_2Ti_{13}O_{29}$ and chromite spinels. At 100 hr U-700 becomes a strong NiO/chromite spinel former but with some Al_2O_3/aluminate spinel showing up as well along with $NiWO_4$ at the higher cobalt levels. Waspaloy is somewhat similar but without any Al_2O_3/aluminate spinel being detected. For IN-738 NiO becomes dominant along with Cr_2O_3/chromite spinel, and to a lesser extent $NiTiO_3$ and <3.30 tri-rutile. U-720 is similar to IN-738 except $NiWO_4$ shows up as well but as a minor phase. In general even for the 100 hr test the K_a value indicates poor to catastrophic oxidation resistance with the poorest resistance at the highest cobalt value. The SX-R-150 alloy series is in the high catastrophic range even though the alloys are initially Al_2O_3/aluminate spinel formers but rapidly forms massive NiO as they did at 1100 °C.

In general the cyclic oxidation behavior tends to fall into two categories. Three of the alloy sets: SX-R-150, Nimonic-115, and MAR-M-247 with Cr to Al ratios of 0.91, 2.98, and 1.49 tend to form Al_2O_3/aluminate spinels as the controlling oxide. Waspaloy, U-720, and IN-738 with Cr:Al of 15.0, 7.20, and 4.71 tend to form Cr_2O_3/chromite spinels as the controlling scale. While U-700, with a Cr to Al ratio of 3.49, seems to be close to the borderline as far as oxide control is concerned but usually forms Cr_2O_3/chromite spinel. These trends tend to be verified by both the derived K_a values and the x-ray diffraction results.

These tendencies are shown schematically in figure 7. With increasing time the tendency of the scales is to break down to NiO. This appears to take longer for the Al_2O_3/aluminate formers. With increased temperature the time for breakdown to NiO decreases. This tendency for NiO formation is negated slightly by the increased inclination for Al_2O_3 formation vis a vis Cr_2O_3 formation with temperature (ref. 11). With increasing temperature Co seems to accelerate NiO formation when Cr_2O_3/chromite scales control. For Al_2O_3/aluminate control Co seems to give consistent minimums in K_a values near 5.0 percent for all three test temperatures. This study also seems to reinforce previous studies conducted at this laboratory that the refractory metals (Cb,Mo,W and particularly Ta) are beneficial at certain optimum concentrations. This may be due to the formation of the tri-rutile structure which appears to stabilize particularly the Al_2O_3/aluminate spinel oxides (refs. 6, 9, and 10).

CONCLUSIONS

(1) The cyclic oxidation behavior of selected Ni-base γ/γ' superalloys depends primarily on their Cr and Al contents particularly on the Cr/Al ratios.

(2) If the ratios are greater than 3.5, as typified by U-720, Waspaloy and IN-738, the alloys tend to form the protective Cr_2O_3/chromite spinel while alloys with ratios of <3.0, like Mar-M-247 and Nimonic-115, tend to form protective Al_2O_3/aluminate spinel. U-700 with a ratio between the two can form either type.

(3) The oxidation attack parameter K_a derived from the specific weight change/time data indicates the Al_2O_3/aluminate spinel is more protective and longer lasting than the Cr_2O_3/chromite spinel.

(4) These scales tend to breakdown as increased amounts of NiO are formed.

(5) In these alloys tri-rutile $Ni(Ta,Cb,W,Mo)_2O_6$ was associated with formation of both protective oxides. When present, $Ni(W,Mo)O_4$ seemed to trigger the deleterious NiO.Ta appears particularly beneficial.

(6) Increasing Co levels are associated with higher K_a values and increased NiO formation in the high Cr/Al alloys. In the low Cr/Al alloys a minimum in K_a values occurs near 5 Co at the three test temperatures.

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TABLE I. - NOMINAL COMPOSITIONS AND VARIATIONS IN COBALT LEVELS IN NICKEL-BASE SUPERALLOYS SELECTED FOR THE COSAM PROGRAM

	Weight percent											
	Co	Cr	Al	Ti	Mo	W	Ta	Hf	B	Zr	C	Cr/Al
U-700	18.5	15.0	4.3	3.5	5.2	----	---	---	0.03	----	0.08	3.49
Waspaloy	13.5	19.5	1.3	3.0	4.3	----	---	---	.006	.06	.08	15.0
MAR-M-247	10.0	8.2	5.5	1.0	.6	10.0	3.0	1.5	.020	.09	.16	1.49
IN-738	8.5	16.0	3.4	3.4	1.8	2.6	1.8	---	.010	.10	.17	4.71
Nimonic-115	14.0	14.6	4.9	4.0	3.5	----	---	---	.017	.001	.16	2.98
U-720	14.7	18.0	2.5	5.0	3.1	1.24	---	---	.031	.031	.04	7.20
SX-R-150[a]	12.0	5.0	5.5	---	1.0	5.0	6.0	---	-----	-----	----	.91

[a]3Re-2.2V

VARIATIONS IN COBALT LEVELS

U-700-cast	0.1, 4.3, 8.6, 12.8, 17.0
U-700-powder met/hipped	0, 4.3, 8.6, 12.8, 17.0
Waspaloy-hot worked	0, 4.5, 9.0, 13.5
MAR-M-247-cast	0.1, 5.0, 9.8
IN-738-hot worked	0, 4.0, 8.0
Nimonic-115-hot worked	0, 5.0, 10.0, 15.0
U-720-hot worked	0, 7.5, 14.7
SX-R-150-cast	0, 6.0, 12.0

TABLE II. - SUMMARY OF REGRESSION CURVE FITS FOR SELECTED NICKEL-BASE SUPERALLOYS TESTED IN CYCLIC OXIDATION AT 1000°, 1100° AND 1150 °C

	1000 °C			1100 °C			1150 °C		
	Paralin-ear	Linear	Force-lin.	Paralin-ear	Linear	Force-lin.	Paralin-ear	Linear	Force-lin.
U-700 cast	6	0	0	7	1	1	6	2	0
U-700 P/M	6			2	3	1	3	2	0
Waspaloy	9			7[a]	0	0	8	1	0
MAR-M-247	6			4	0	3	4	1	2
IN-738	3			3	0	0	3	0	0
Nimonic-115	5			1	2	1	1	0	3
U-720	4			3	0	0	3	0	0
SX-R-150	3			2	0	1	1	2	0
Totals	41	0	0	29	6	7	29	8	5

[a]2 of 9 samples poor fits-rejected as outliers.

TABLE III. - SUMMARY OF CYCLIC OXIDATION SPECIFIC WEIGHT CHANGE DATA INCLUDING DERIVED RATE AND ATTACK PARAMETERS AT 1000 °C

Alloy	Percent Co	Run no.	Specific weight change, mg/cm^2			$k_1^{1/2}$	k_2	K_a
			100 hr	200 hr	500 hr			
U-700-cast	~0.1	424-1	3.04	2.83	0.41	0.4851	0.02011	0.6862
	.1	452-2	2.85	1.57	-6.73	.7208	.04675	1.188
	4.3	424-2	3.23	1.87	-.67	.4840	.02329	.7169
	8.6	424-3	2.53	1.25	-2.24	.4440	.02312	.6751
	12.8	424-4	2.27	.64	-7.20	.5657	.03619	.9276
	17.0	424-5	2.13	.73	-4.38	.4720	.02892	.7612
U-700-(P/M)	0	447-2	2.87	2.88	0.30	0.5231	0.02470	0.7701
	4.3	447-3	2.29	1.35	-1.04	.4811	.02299	.7110
	8.55	447-4	1.60	.93	-4.25	.4170	.02343	.6514
	12.77	447-5	1.78	-1.35	-3.94	.2912	.02086	.4998
	17.0	447-6	1.61	.61	-7.15	.4038	.02434	.6472
Waspaloy	0	436-3	----	0.51	-76.46	3.029	0.2300	5.328
	0	615-6	2.75	2.65	-74.13	3.514	.2733	6.247
	4.5	436-4	----	2.42	-77.84	3.472	.2591	6.062
	4.5	480-4	3.08	2.97	-70.03	3.663	.2900	6.563
	9.0	436-5	----	1.28	-92.16	4.356	.3398	7.754
	9.0	480-5	2.84	3.64	-74.49	3.662	.2852	6.514
	13.5	436-6	----	1.62	-75.73	3.668	.2862	6.530
	13.5	480-6	2.42	2.77	-57.36	3.061	.2450	5.511
	13.5	615-5	1.34	2.15	-44.80	1.702	.1253	2.955
MAR-M-247	0.1	452-3	0.33	0.42	0.50	0.04138	0.0008771	0.05015
	.1	480-1	.31	.40	0.18	.05390	.002017	.07408
	5	452-4	.27	.31	.30	.03696	.001094	.04789
	5	480-2	.28	.27	.42	.03170	.0008846	.04055
	9.76	452-5	.33	.43	.46	.04708	.001215	.05923
	9.76	480-3	.30	.27	.24	.03427	.001221	.04648
IN-738	0	674-1	2.86	2.52	-12.38	1.005	0.06670	1.672
	4	674-2	3.19	1.89	-11.28	.9427	.06107	1.553
	8	674-3	3.68	1.52	-12.65	1.028	.06705	1.698
Nimonic-115	0	675-1	0.05	-0.17	-1.44	0.06846	0.005765	0.1261
	5	675-2	1.21	1.03	-3.35	.3182	.01786	.4967
	10	675-3	.50	.55	.65	.06514	.001709	.08222
	15	675-4	1.04	-.19	-1.47	.1930	.01242	.3171
	15	675-5	1.14	1.18	-4.60	.3220	.01779	.4999
U-720	0	674.4	2.25	-8.77	-70.44	2.915	0.2690	5.604
	7.5	674.5	2.77	-.56	-56.84	2.847	.2335	5.182
	14.7	674.6	2.80	-14.98	-77.59	2.959	.2821	5.776
	14.7	675-6	-.85	-7.34	-93.57	3.569	.3431	7.000
SX-R-150	0	615-1	0.16	0.27	-4.94	0.2002	0.1463	0.3465
	6	615-2	.16	.14	.25	.01349	Not sig[a]	.01349
	12	615-3	.31	.13	-16.78	.6394	.05139	1.153

[a]Special paralinear case (i.e., parabolic).

TABLE IV. - SUMMARY OF CYCLIC OXIDATION SPECIFIC WEIGHT CHANGE DATA INCLUDING DERIVED RATE AND ATTACK PARAMETERS AT 1100 °C

Alloy	Percent Co	Run no.	Specific weight change, mg/cm^2			$k_1^{1/2}$	k_2	K_a
			100 hr	200 hr	500 hr			
U-700-cast	~0.1	422-1	-11.69	-23.59		0.8799	0.1879	2.759
	.1	453-2	-20.54	-60.17		1.455	.3826	5.281
	4.3	422-2	-11.43	-23.97		-------	.1143	2.286
	8.6	422-3	-20.39	-48.90		.4837	.2639	3.123
	12.8	422-4	-31.65	-87.71		-------	.3530	7.060
	17.0	422-5	-41.59	-174.23		8.551	1.405	22.60
	17.0	437-2	-38.13	-186.38		10.93	1.662	27.54
	17.0	610-5	-25.52	-53.16		-------	.2383	4.765
	17.0	655-5	-10.82	-111.17		7.377	.9441	16.82
U-700-P/M	0	448-2	-13.02	-33.62		-------	0.1465	2.929
	4.3	448-3	-14.17	-37.19		-------	.1544	3.089
	8.6	448-4	-12.15	-39.47		-------	.1565	3.131
	12.8	448-5	-14.93	-109.76		5.641	.8016	13.66
	17.0	448-6	-12.10	-108.30		5.677	.7721	13.40
	17.0	610-6	-13.34	-17.31		-------	.1048	2.096
Waspaloy	0	437-3	-4.04	-24.26		1.512	0.2038	3.550
	0	614-6	-.92	-4.57		.3660	.04550	.8210
	4.5	437-4	-4.19	-28.77		1.843	.2431	4.274
	4.5	481-4	-2.28	-27.15		2.195	.2632	4.827
	9.0	437-5	-6.85	-49.97		3.564	.4604	8.168
	9.0	481-5	-.22	+1.11		- poor fit -		-------
	13.5	437-6	-2.86	-23.91		1.663	.2097	3.760
	13.5	481-6	.10	+.39		- poor fit -		-------
	13.5	614-5	-.72	-14.48		1.099	.1271	2.371
MAR-M-247	0.1	453-3	-3.36	-7.38		0.1437	0.04744	0.6183
	.1	481-1	.27	.12		.08980	.005592	.1457
	5	453-4	-2.49	-5.05		.04398	.02908	.2543
	5	481-2	.07	-.31		.09107	.007895	.1700
	9.76	453-5	-2.98	-5.30		--------	.02800	.5600
	9.76	481-3	-2.61	-4.92		.07888	.03204	.3997
	9.76	657-1	-1.04	-3.50		.2228	.03335	.5564
IN-738	0	662-6	-30.99	-139.07		7.243	1.096	18.21
	4	664-1	-4.44	-52.50		4.160	.5094	9.254
	8	664-2	-45.88	-199.49		11.94	1.820	30.14
Nimonic-115	0	664-3	-8.85	-20.28		0.3654	0.1267	1.633
	5	664-4	-.43	-.99		--------	.004836	.0967
	10	664-5	-3.13	-6.13		--------	.03142	.6284
	15	664-6	-.95	-1.01		--------	.00712	.1425
U-720	0	655-1	-83.50	-150.82		4.697	1.150	16.19
	7.5	655-2	-98.23	-242.90		10.17	19.65	29.82
	14.7	655-3	-135.17	-313.46		9.556	2.278	32.33
SX-R-150	0	614-1	-177.91	-243.81		--------	1.404	28.07
	6	614-2	-24.96	-180.74		13.36	1.797	31.33
	12	614-3	-381.61	-596.41[a]		3.777	4.124	45.01

[a]Value at 160 Hr-test terminated

TABLE V. - SUMMARY OF CYCLIC OXIDATION SPECIFIC WEIGHT CHANGE DATA INCLUDING DERIVED RATE AND ATTACK PARAMETERS AT 1150 °C

Alloy	Percent Co	Run no.	Specific weight change, mg/cm^2			$k_1^{1/2}$	k_2	K_a
			100 hr	200 hr	500 hr			
U-700-cast	~0.1	423-1	-30.50			--------	0.2570	5.140
	.1	454-2	-34.79			--------	.2919	5.839
	4.3	423-2	-50.07			2.333	.6793	9.127
	8.6	423-3	-104.39			6.677	1.501	21.69
	12.8	423-4	-197.77			16.33	3.513	51.46
	17.0	423-5	-230.72			16.44	3.922	55.66
	17.0	438-2	-243.21			15.21	3.965	54.86
	17.0	654-5	-214.42			14.14	3.559	49.72
U-700-(P/M)	0	449-2	-31.85			--------	0.2692	5.384
	4.3	449-3	-50.76			--------	.3984	7.968
	8.55	449-4	-64.70			3.565	.9398	12.96
	12.77	449-5	-142.16			11.64	2.395	35.59
	17.0	449-6	-174.85			15.04	3.100	46.04
Waspaloy	0	438-3	-94.17			8.070	1.692	24.99
	0	613-6	-155.16			--------	1.554	31.08
	4.5	438-4	-103.75			9.172	1.893	28.10
	4.5	482-4	-139.96			14.03	2.696	40.98
	9.0	438-5	-186.13			15.33	3.311	48.44
	9.0	482-5	-9.99			1.330	.2268	3.598
	13.5	438-6	-165.20			14.14	2.919	43.33
	13.5	482-6	-27.53			3.583	.6077	9.660
	13.5	613-5	-226.73			19.24	4.155	60.80
MAR-M-247	0.1	454-3	-15.26			--------	0.1596	3.193
	.1	482-1	.16			.1548	.01463	.3012
	5	454-4	-7.95			--------	.09237	1.847
	5	482-2	-2.65			--------	.02734	.5468
	9.76	454-5	-19.46			.4067	.2250	2.657
	9.76	482-3	-30.86			1.146	.4054	5.200
	9.76	656-1	-.30			.07611	.01139	.1901
IN-738	0	661-6	-116.59			6.789	1.661	23.40
	4	663-1	-187.51			15.20	3.288	48.08
	8	663-2	-183.28			13.57	3.106	44.63
Nimonic-115	0	663-3	-32.78			0.9616	0.4246	5.207
	5	663-4	-4.13			--------	.04835	.9670
	10	663-5	-8.93			--------	.1045	2.091
	15	663-6	-7.24			--------	.08198	1.640
U-720	0	654-1	-206.15			12.26	3.326	45.52
	7.5	654-2	-245.92			9.295	3.453	43.82
	14.7	654-3	-313.42			4.811	3.676	41.58
SX-R-150	0	613-1	-296.50			--------	2.998	59.97
	6	613-2	-427.42			--------	4.357	87.13
	12	613-3	-667.04[a]			--------	15.74	314.86

[a]Test discontinued after 45 hr.

TABLE VI. - SUMMARY OF X-RAY DIFFRACTION RESULTS OF SELECT Ni-BASE SUPERALLOYS AT 1000 °C FOR SURFACE OXIDE PHASES AFTER VARIOUS EXPOSURE TIMES IN CYCLIC OXIDATION. PHASE LISTED IN DECREASING ORDER OF INTENSITY

Alloy set	Percent Co	1 hr	100 hr	200 hr	500 hr
U-700 (cast)	~0.1	1,3	1,4,3	1,4,6,3	1,6,4,2
	4.3	1,3,2	1,4	1,4	1,4
	8.6	1,3,2	1,4,3	1,4,3	1,4
	12.8	1,3,2	1,4,3	1,3,4	1,4
	17.0	1,3,2	1,3,4	1,4,3	1
U-700 (P/M)	0	1,3,4	1,3,4	1,3,4	1,2,6,3
	4.3	1,3	1,3,4	1,3	1,6,4,3
	8.55	1,3	1,3,4	1,3	1,6,4,3
	12.77	1,3	1,3	1,2,6,3	1,4,2,6,3
	17.0	1,3	1,3,4	1,3	6,1,2,5,3
Waspaloy	0	1,3	1,4	1,4	6,1,4
	4.5	1,3	1,3,4	1,4,3,6	6,1,4
	9.0	1,3	1,3,4	1,3,4	6,1,4
	13.5	1,3	1,4	1,3,7	6,1,4
MAR-M-247	0.1	7/[a]7,2,1	2,1,7,3/[a]2,4,7,6	2,4,3/[a]2,1,7,3	2,7,3,1/[a]2,6,1,3,7
	5	7/[a]7,2,1,3	2,7,3,1/[a]2,4,7,1	2,7,4,3	2,7,3,1
	9.76	7,2,1,3	2,7,3,1,4	2,7,3,1	2,7,3,1
IN-738	0	1,3	1,3	1,3	1,3,6
	4	1,3	1,3,4	1,3,4	1,3
	8	1,3	1,3,4	1,3,4	1,6,3,2
Nimonic-115	0	2,1	2,1,4	1,2,4	2,1
	5	1,3	2,1,3,4	1,4,2,3	6,1
	10	1,3,2	2,1,3	2,3	3,2
	15	1,3,2	3,2,1,4	4,1,3	4,2,1,3/[a]6,1,4
U-720	0	1,3	1,3	1,6,3	6,4,1,3
	7.5	1,3	1,3	1,3,6	6,4,1,3
	14.7	1,3	1,3,4	1,6,3	6,1,4,3
SX-R-150	0	2,3,1	2,3/[a]2,3,6	2,3	6,2,3
	6	3,2,1	2,3	2,3	2,3
	12	2,3,1	2,3	2,3	2,6,3,1

Phases:
1 Cr_2O_3/Chromite spinel
2 Al_2O_3/Aluminate spinel
3 Tri-rutile-Ni(Ta,Cb,W,Mo)$_2O_6$
4 Titanates-(Ni,Co,Fe)TiO_3;$Cr_2Ti_{13}O_{29}$;TiO_2
5 Ni(W,Mo)O_4
6 NiO
7 Misc oxides - ZrO_2,HfO_2

[a]Replicate samples - significantly different results

TABLE VII. - SUMMARY OF X-RAY DIFFRACTION RESULTS OF SELECT Ni-BASE SUPERALLOYS AT 1100 °C FOR SURFACE OXIDE PHASES AFTER VARIOUS EXPOSURE TIMES IN CYCLIC OXIDATION. PHASE LISTED IN DECREASING ORDER OF INTENSITY

Alloy set	Percent Co	1 hr	100 hr	200 hr	500 hr
U-700 (cast)	~0.1	1,3	2,6,1,3,4	2,4,6,1,3	
	4.3	1,3	2,4,6,3	2,4,3,6,1	
	8.6	1,3	2,4,6,1,3	2,4,6,3,1	
	12.8	1,3	2,4,6,1	4,2,1,6,3	
	17.0	1,3	1,6,2,4,3	6,1,4/[a]6,1,4,3,2	
U-700 (P/M)	0	1,3	2,6,4,1,3	2,4,1,6	
	4.3	1,3	2,4,6,3,1	2,4,6,1	
	8.55	1,3	2,4,6,3,1	6,4,1,2,3	
	12.77	1,3	4,2,1,6,3	6,1,5	
	17.0	1,3	4,2,1,6,3	6,1,4/[a]4,6,2,1,3	
Waspaloy	0	1,3,4	1,4	1,3,6/[a]1,3,4	
	4.5	1,3,4	1,4,3	1,3,6	
	9.0	1,3	1,4	1,3,6	
	13.5	1,3	1,4	1,3,6	
MAR-M-247	0.1	6,1,5,3,7	2,6,3,7,5/[a]2,3,7,4	2,6,5,3,7/[a]2,3,7	
	5	1,5,3,7	2,3,6,7/[a]2,3,7,5	2,6,5,3,7/[a]2,3,7	
	9.76	1,5,3,7/[a]3,7,1	2,3,1,7,5	2,7,6	
In-738	0	1,3	6,1,4,3	6,1,3,2	
	4	1,3	1,3	6,1,3	
	8	1,3	6,1,3	6,1,4,3	
Nimonic-115	0	2,	2,1	1,2	
	5	1,3	2,3	2,1,3	
	10	1,3	2,3	2,3	
	15	1,3	2,3	2,3	
U-720	0	1,3	6,4,1,3	6,1,4,2,5,3	
	7.5	1,3	6,1,4,3	6,1,4	
	14.7	1,3	6,1,4,3	6,1,4,3	
SX-R-150	0	2,3,6	6,5,2,3	6,2,5,3	
	6	6,2,7	6,2,7,5	6,2,7	
	12	6,2,7	6,5,2,7	6,2,5,3[b]	

Phases:
1 Cr_2O_3/Chromite spinel
2 Al_2O_3/Aluminate spinel
3 Tri-rutile-$Ni(Ta,Cb,W,Mo)_2O_6$
4 Titanates-$(Ni,Co,Fe)TiO_3$;$Cr_2Ti_{13}O_{29}$;TiO_2
5 $Ni(W,Mo)O_4$
6 NiO
7 Misc oxides - ZrO_2,HfO_2

[a]Replicate samples - significantly different results
[b]Test terminated - 160 hr

TABLE VIII. - SUMMARY OF X-RAY DIFFRACTION RESULTS OF SELECT Ni-BASE SUPERALLOYS AT 1150 °C FOR SURFACE OXIDE PHASES AFTER VARIOUS EXPOSURE TIMES IN CYCLIC OXIDATION. PHASE LISTED IN DECREASING ORDER OF INTENSITY

Alloy set	Percent Co	1 hr	100 hr	200 hr	500 hr
U-700 (cast)	~0.1 4.3 8.6 12.8 17.0	1,3 1,3 1,3 1,3 1,3	6,4,1,2,3 6,4,1,2 6,1,4,5,2 6,1,2,5 6,1,2,5		
U-700 (P/M)	0 4.3 8.55 12.77 17.0	1,3 1,3 1,4,3 1,3 1,3,4	6,4,1 6,4,1 6,4,1 6,1,5 6,1,5		
Waspaloy	0 4.5 9.0 13.5	1,3 1,3,4 1,3,4 1,3,4	1,6,3 1,6,3/[a]6,1,5 6,1,4,5/[a]6,1 6,1,5		
MAR-M-247	0.1 5 9.76	6,3,5,1,7/[a]1,5,3,7 6,3,5,1,7/[a]1,5,3 1,3,5,7	2,3,7,4,1 2,3,7/[a]2,6,7,1 2,3,7,6,5		
In-738	0 4 8	1,3 1,3 1,3	6,1,4,3 6,1,4,3 6,1,4,3		
Nimonic-115	0 5 10 15	2 1,4,2,3,2,6,7 1,7,4,2 1,3,4	1,2,6 2,3 2,3 2,3		
U-720	0 7.5 14.7	1,3,7 1,3 1,3	6,4,1,2,5,3 6,1,4,2,5,3 6,1,4,5,3		
SX-R-150	0 6 12	2,3 6 6,2,3	6,5,2,3 2,6,5,3 6		

Phases:
1 Cr_2O_3/Chromite spinel
2 Al_2O_3/Aluminate spinel
3 Tri-rutile-Ni(Ta,Cb,W,Mo)$_2O_6$
4 Titanates-(Ni,Co,Fe)TiO_3;$Cr_2Ti_{13}O_{29}$;TiO_2
5 Ni(W,Mo)O_4
6 NiO
7 Misc oxides - ZrO_2,HfO_2; Tri-rutiles > 3.30

[a]Replicate samples - significantly different results

TABLE A-I. - SUMMARY OF STATISTICAL REGRESSION ANALYSIS RESULTS OF SPECIFIC WEIGHT CHANGE CYCLIC OXIDATION DATA FOR SELECTED ALLOYS AT 1000 °C. REJECTION LEVEL AT 0.90 LENGTH OF TEST-500. ONE HOUR EXPOSURE CYCLES.

Alloy	Percent Co	Run No.	$k_1^{1/2}$	k_2	R^2	S.E.E	Final ΔW/A values, mg/cm^2	
							Observed	Calculated
U-700-cast	~0.1	424-1	0.4851	0.02011	0.995	0.18	0.41	0.79
	.1	452-2	.7208	.04675	.949	.72	-6.73	-7.26
	4.3	424-2	.4840	.02329	.967	.38	-.67	-.82
	8.6	424-3	.4440	.02312	.956	.37	-2.24	-1.63
	12.8	424-4	.5657	.03619	.931	.65	-7.20	-5.45
	17.0	424-5	.4720	.02892	.979	.28	-4.38	-3.91
U-700-(P/M)	0	447-2	0.5231	0.02470	0.953	0.51	0.30	-0.66
	4.3	447-3	.4811	.02299	.902	.54	-1.04	-1.92
	8.55	447-4	.4170	.02343	.833	.71	-4.25	-2.39
	12.77	447-5	.2912	.02086	.781	.81	-3.94	-3.92
	17.0	447-6	.4038	.02434	.634	1.19	-7.15	-3.14
Waspaloy	0	436-3	3.029	0.2300	0.744	11.57	-76.46	-29.20
	0	615-6	3.514	.2733	.834	9.99	-74.13	-58.10
	4.5	436-4	3.472	.2591	.734	13.01	-77.84	-51.90
	4.5	480-4	3.663	.2900	.885	8.77	-70.03	-63.07
	9.0	436-5	4.356	.3398	.852	12.64	-92.16	-72.48
	9.0	480-5	3.662	.2852	.848	9.92	-74.49	-60.68
	13.5	436-6	3.668	.2862	.854	10.56	-75.73	-61.11
	13.5	480-6	3.061	.2450	.900	6.96	-57.36	-54.04
	13.5	615-5	1.702	.1253	.667	6.75	-44.80	-24.61
MAR-M-247	0.1	452-3	0.04138	0.0008771	0.988	0.04	0.50	0.49
	.1	480-1	.05390	.002017	.976	.05	.18	.20
	5	452-4	.03696	.001094	.981	.04	.30	.28
	5	480-2	.03170	.0008846	.913	.08	.42	.27
	9.76	452-5	.04708	.001215	.991	.04	.46	.45
	9.76	480-3	.03427	.001221	.954	.05	.24	.16
IN-738	0	674-1	1.005	0.06670	0.921	1.31	-12.38	-10.87
	4	674-2	.9427	.06107	.947	.96	-11.28	-9.46
	8	674-3	1.028	.06705	.953	.95	-12.65	-10.54
Nimonic-115	0	675-1	0.06846	0.005765	0.968	0.10	-1.44	-1.35
	5	675-2	.3182	.01786	.762	.67	-3.36	-1.82
	10	675-3	.06514	.001709	.990	.05	.65	.60
	15	675-4	.1930	.01242	.825	.38	-1.47	-1.89
	15	675-5	0.3220	0.01779	0.542	1.12	-4.60	-1.70
U-720	0	674-4	2.915	0.2690	0.984	3.49	-70.44	-69.32
	7.5	674-5	2.847	.2335	.890	7.25	-56.84	-53.06
	14.7	674-6	2.959	.2821	.978	4.48	-77.59	-74.94
	14.7	675-6	3.569	.3431	.973	6.10	-93.57	-91.75
SX-R-150	0	615-1	0.2002	0.01463	0.686	0.75	-4.94	-2.84
	6	615-2	.01349	Not sig.[a]	.920	.05	.25	.30
	12	615-3	.6394	.05139	.827	2.01	-16.78	-11.40

[a]Special paralinear case (i.e., parabolic).

TABLE A-II. - SUMMARY OF STATISTICAL REGRESSION ANALYSIS RESULTS OF SPECIFIC WEIGHT CHANGE CYCLIC OXIDATION DATA FOR SELECTED ALLOYS AT 1100 °C. REJECTION LEVEL AT 0.90 LENGTH OF TEST-200. ONE HOUR EXPOSURE CYCLES.

Alloy	Percent Co	Run No.	$k_1^{1/2}$	k_2	R^2	S.E.E	Final ΔW/A values, mg/cm^2	
							Observed	Calculated
U-700-cast	~0.1	422-1	0.8799	0.1879	0.988	1.65	-23.59	-25.13
	.1	453-2	1.455	.3826	.992	2.98	-60.17	-55.94
	4.3	422-2	-Force-	.1143	.986	1.68	-23.97	-22.86
	8.6	422-3	.4837	.2639	.996	1.83	-48.89	-45.94
	12.8	422-4	Not sig.	.3530	.978	6.62	-87.71	-70.60
	17.0	422-5	8.551	1.405	.982	12.51	-174.2	-160.1
	17.0	437-2	10.93	1.662	.982	13.46	-88.97	-91.09
	17.0	610-5	Not sig.	.2383	.993	2.54	-53.16	-47.65
	17.0	655-5	7.377	.9441	.914	13.93	-111.2	-84.50
U-700-P/M	0	448-2	Not sig.	0.1465	0.984	2.34	-33.62	-29.29
	4.3	448-3	Not sig.	.1544	.970	3.38	-37.19	-30.89
	8.6	448-4	Not sig.	.1565	.961	3.91	-39.47	-31.31
	12.8	448-5	5.641	.8016	.906	14.34	-109.8	-80.54
	17.0	448-6	5.677	.7721	.869	15.74	-108.3	-74.14
	17.0	610-6	-Force-	.1048	.931	3.52	-17.31	-20.96
Waspaloy	0	437-3	1.512	0.2038	0.950	2.43	-24.26	-19.37
	0	614-6	.3660	.04550	.938	.54	-4.57	-3.92
	4.5	437-4	1.843	.2431	.941	3.08	-28.77	-22.56
	4.5	481-4	2.195	.2632	.934	3.03	-27.16	-21.60
	9.0	437-5	3.564	.4604	.961	4.51	-49.97	-41.68
	9.0	481-5	-Poor fit-					
	13.5	437-6	1.663	.2097	.930	2.72	-23.91	-18.42
	13.5	481-6	-Poor fit-					
	13.5	614-5	1.099	.1271	.869	2.01	-14.48	-9.88
MAR-M-247	0.1	453-3	0.1437	0.04744	0.998	0.20	-7.38	-7.46
	.1	481-1	.08980	.005592	.900	.10	.12	.15
	5	453-4	.04398	.02908	.996	.21	-5.05	-5.19
	5	481-2	.09107	.007895	.757	.11	-.31	-.29
	9.76	453-5	Not sig.	.02800	.993	.30	-5.30	-5.60
	9.76	481-3	.07888	.03204	.993	.27	-4.92	-5.29
	9.76	657-1	.2228	.03335	.998	.09	-3.50	-3.52
IN-738	0	662-6	7.243	1.096	0.972	11.16	-139.1	-116.8
	4	664-1	4.160	.5094	.949	5.33	-52.50	-43.06
	8	664-2	11.94	1.820	.992	10.01	-199.5	-195.1
Nimonic-115	0	664-3	0.3654	0.1267	0.999	0.20	-20.28	-20.18
	5	664-4	Not sig.	.004836	.915	.18	-.99	-.97
	10	664-5	Not sig.	.03142	.992	.36	-6.13	-6.28
	15	664-6	-Force-	.007126	.736	.53	-1.01	-1.43
U-720	0	655-1	4.697	1.150	0.989	10.43	-150.8	-163.5
	7.5	655-2	10.17	1.965	.996	8.73	-242.9	-249.2
	14.7	665-3	9.556	2.278	.999	6.67	-313.5	-320.4
SX-R-150	0	614-1	-Force-	1.404	0.982	23.78	-243.8	-280.7
	6	614-2	13.36	1.797	.979	13.64	-180.7	-170.4
	12	614-3	3.777	4.124	.999	8.52	-596.4	-612.0

TABLE A-III. - SUMMARY OF STATISTICAL REGRESSION ANALYSIS RESULTS OF SPECIFIC WEIGHT CHANGE CYCLIC OXIDATION DATA FOR SELECTED ALLOYS AT 1100 °C. REJECTION LEVEL AT 0.90 LENGTH OF TEST-200. ONE HOUR EXPOSURE CYCLES.

Alloy	Percent Co	Run No.	$k_1^{1/2}$	k_2	R^2	S.E.E	Final ΔW/A values, mg/cm^2	
							Observed	Calculated
U-700-cast	~0.1	423-1	Not sig.	0.2570	0.964	3.27	-30.50	-25.70
	.1	454-2	Not sig.	.2919	.965	3.67	-34.79	-29.19
	4.3	423-2	2.333	.6793	.977	4.54	-50.07	-44.66
	8.6	423-3	6.677	1.501	.945	19.79	-104.4	-83.32
	12.8	423-4	16.33	3.513	.981	21.60	-197.8	-188.1
	17.0	423-5	16.44	3.922	.992	13.08	-230.7	-227.8
	17.0	438-2	15.21	3.965	.995	11.12	-243.2	-244.4
	17.0	654-5	14.14	3.559	.995	10.35	-214.4	-214.5
U-700-P/M	0	449-2	Not sig.	0.2692	0.967	3.29	-31.85	-26.92
	4.3	449-3	Not sig.	.3984	.936	6.85	-50.76	-39.84
	8.55	449-4	3.565	.9398	.979	5.66	-64.70	-58.33
	12.77	449-5	11.64	2.395	.964	15.07	-142.2	-123.0
	17.0	449-6	15.04	3.100	.970	17.64	-174.8	-159.6
Waspaloy	0	438-3	8.070	1.692	0.990	5.57	-94.17	-88.45
	0	613-6	Not sig.	1.554	.779	52.68	-155.2	-155.4
	4.5	438-4	9.172	1.893	.990	23.42	-103.8	-97.61
	4.5	482-4	14.03	2.696	.985	10.00	-140.0	-129.3
	9.0	438-5	15.33	3.311	.991	10.96	-186.1	-177.7
	9.0	482-5	1.330	.2268	.993	.47	-9.99	-9.38
	13.5	438-6	14.14	2.919	.985	11.67	-165.2	-150.6
	13.5	482-6	3.583	.6077	.980	2.15	-27.53	-24.94
	13.5	613-5	19.24	4.155	.995	10.34	-226.7	-223.1
MAR-M-247	0.1	454-3	-Force-	0.1596	0.994	0.84	-15.26	-15.96
	.1	482-1	.1548	.01463	.792	.17	.16	.08
	5	454-4	-Force-	.09237	.965	1.16	-7.95	-9.24
	5	482-2	Not sig.	.02734	.982	.24	-2.65	-2.73
	9.76	454-5	.4067	.2250	.996	.81	-19.46	-18.44
	9.76	482-3	1.146	.4054	.995	1.42	-30.86	-29.07
	9.76	656-1	.07611	.01139	.839	.10	-.30	-.38
IN-738	0	661-6	6.789	1.661	.969	11.39	-116.6	-98.25
	4	663-1	15.20	3.288	.981	15.81	-187.5	-176.7
	8	663-2	13.57	3.106	.988	12.19	-183.3	-174.9
Nimonic-115	0	663-3	0.9616	0.4246	0.999	0.39	-32.78	-32.84
	5	663-4	-Force-	.04835	.943	.79	-4.13	-4.84
	10	663-5	-Force-	.1045	.943	1.70	-8.93	-10.45
	15	663-6	-Force-	.08198	.962	1.08	-7.24	-8.20
U-720	0	654-1	12.26	3.326	0.996	8.53	-206.1	-210.0
	7.5	654-2	9.295	3.453	.998	7.99	-245.9	-252.3
	14.7	654-3	4.811	3.676	.999	7.98	-313.4	-319.5
SX-R-150	0	613-1	Not sig.	2.998	0.999	6.55	-296.5	-299.9
	6	613-2	Not sig.	4.357	.999	7.46	-427.4	-435.7
	12	613-3	Not sig.	15.74	.993	42.10	-667.0[a]	-708.4

[a]Test discontinued after 45 hr.

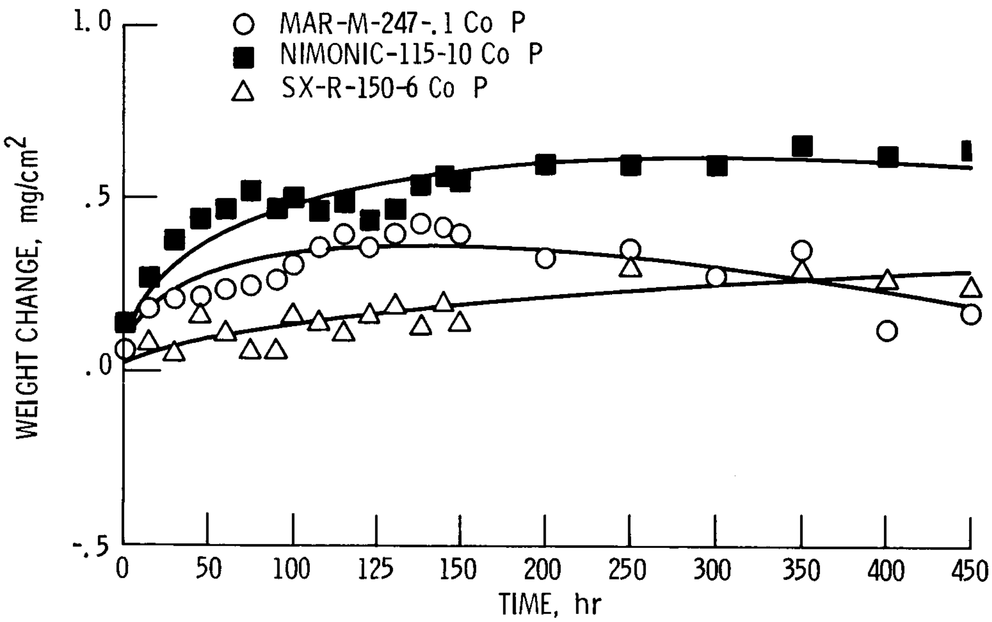


Figure 1. - Regression curve fits and observed cyclic oxidation specific weight change data for selected Ni-base superalloys at 1000 °C (P-paralinear fit).

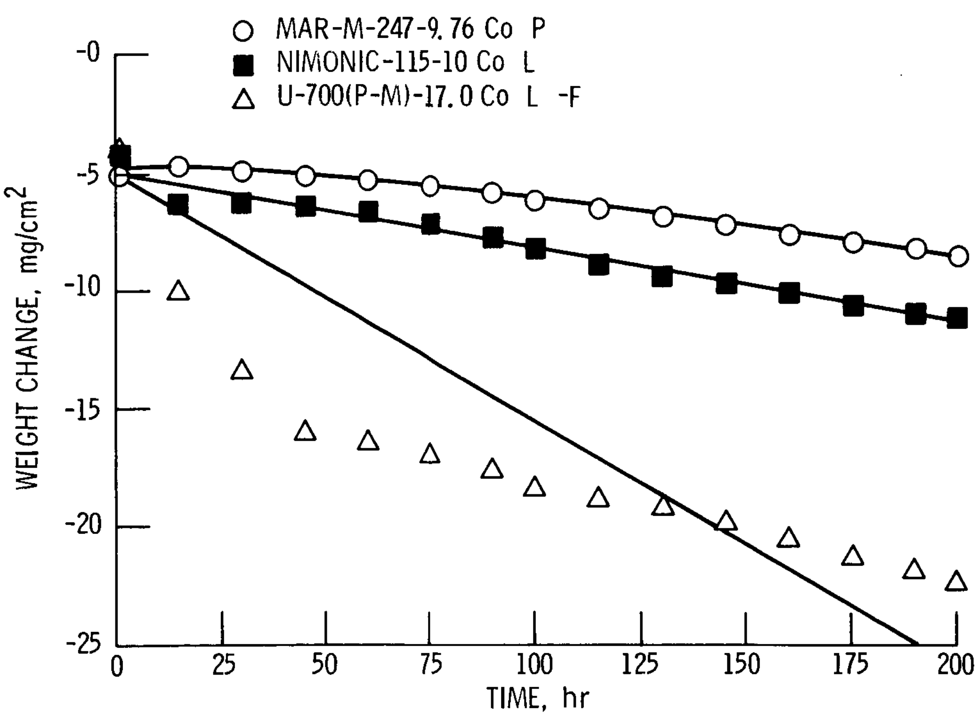


Figure 2. - Regression curve fits and observed cyclic oxidation specific weight change data for selected Ni-base superalloys at 1100 °C (P-paralinear fit; L-linear fit; F-force).

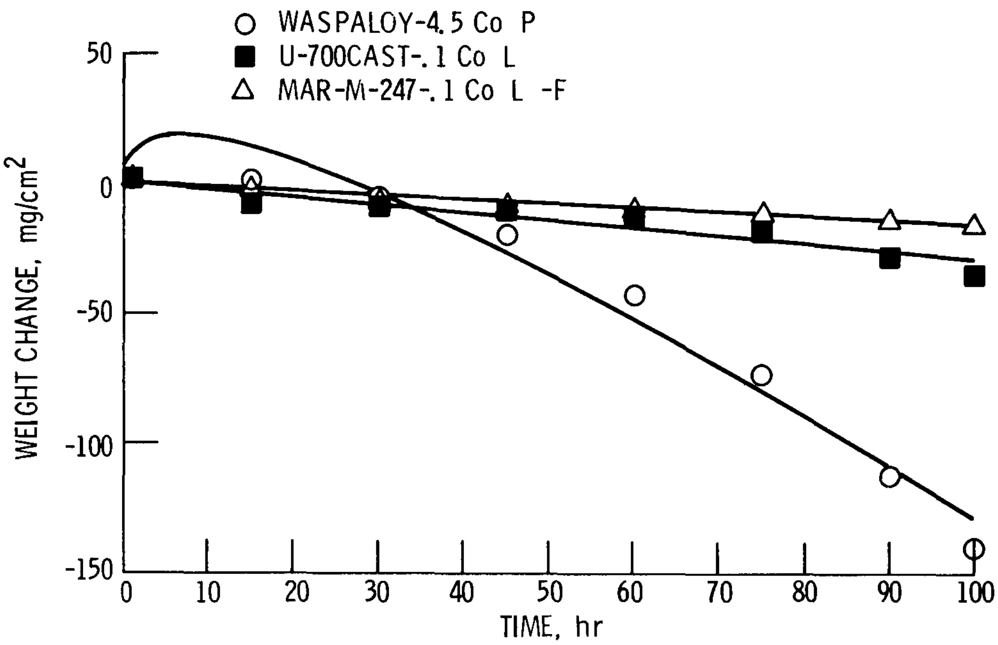


Figure 3. - Regression curve fits and observed cyclic oxidation specific weight change data for selected Ni-base superalloys at 1150 °C (P-paralinear fit; L-linear fit; F-force).

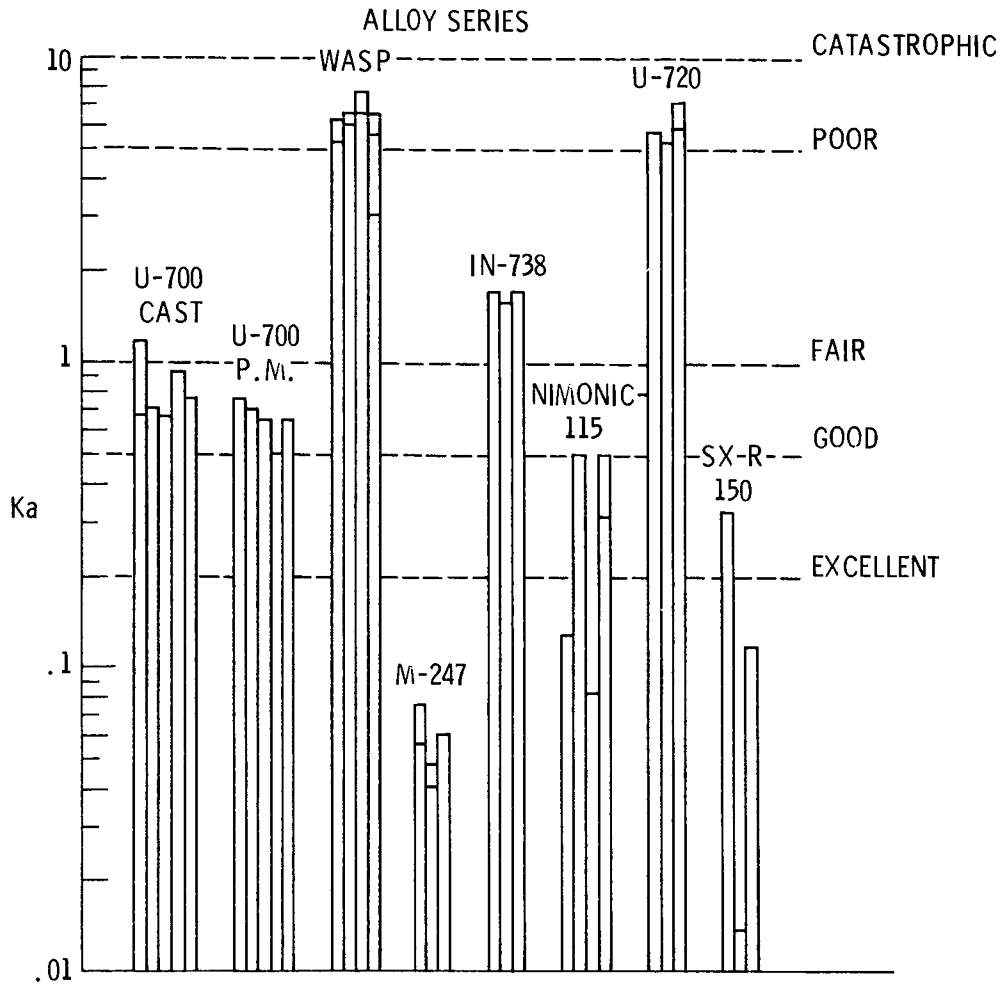


Figure 4. - Derived oxidation parameter Ka at 1000 °C for selected Ni-base superalloys (cobalt level increases - left to right).

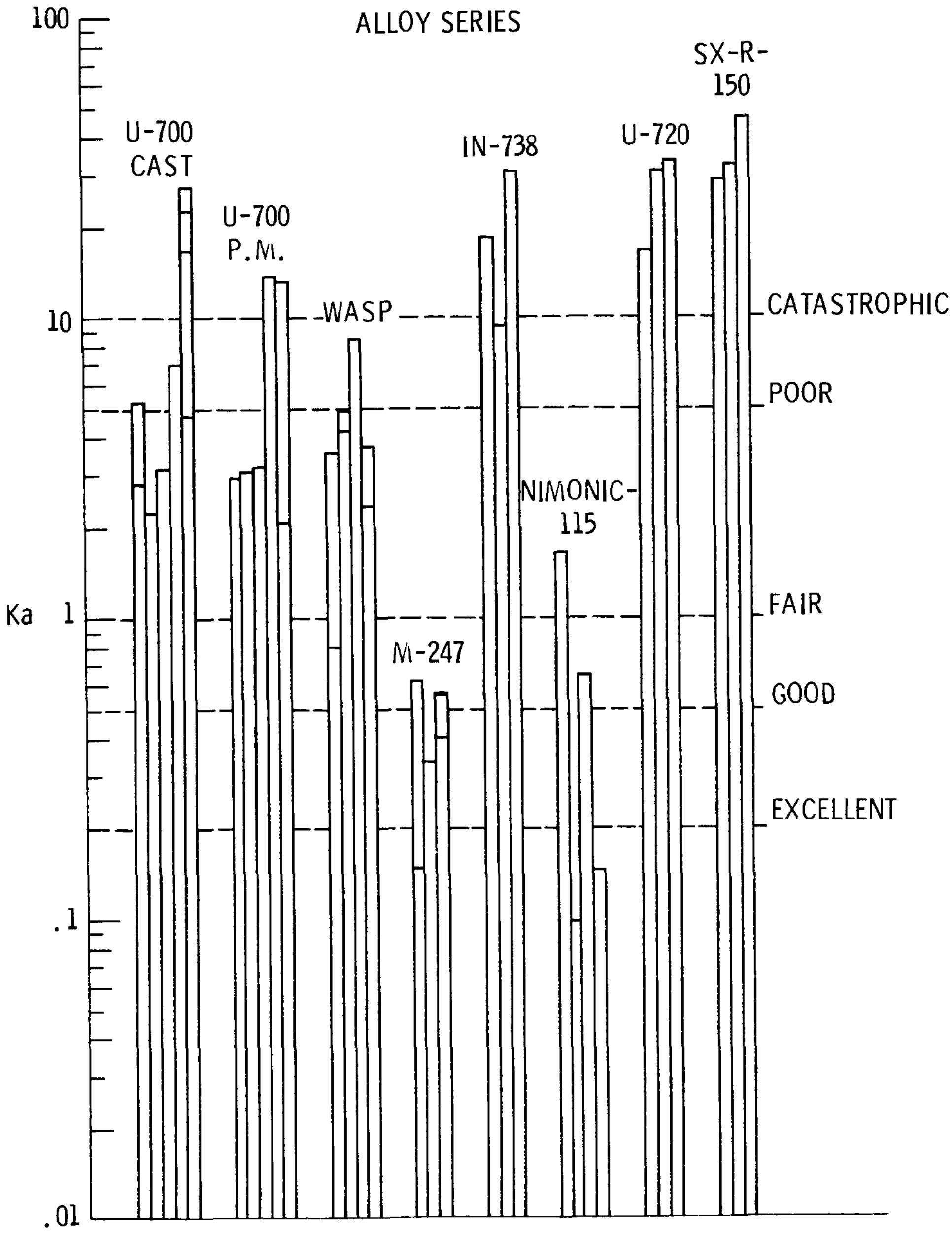


Figure 5. - Derived oxidation parameter Ka at 1100 ^{0}C for selected Ni-base superalloys (cobalt level increases - left to right).

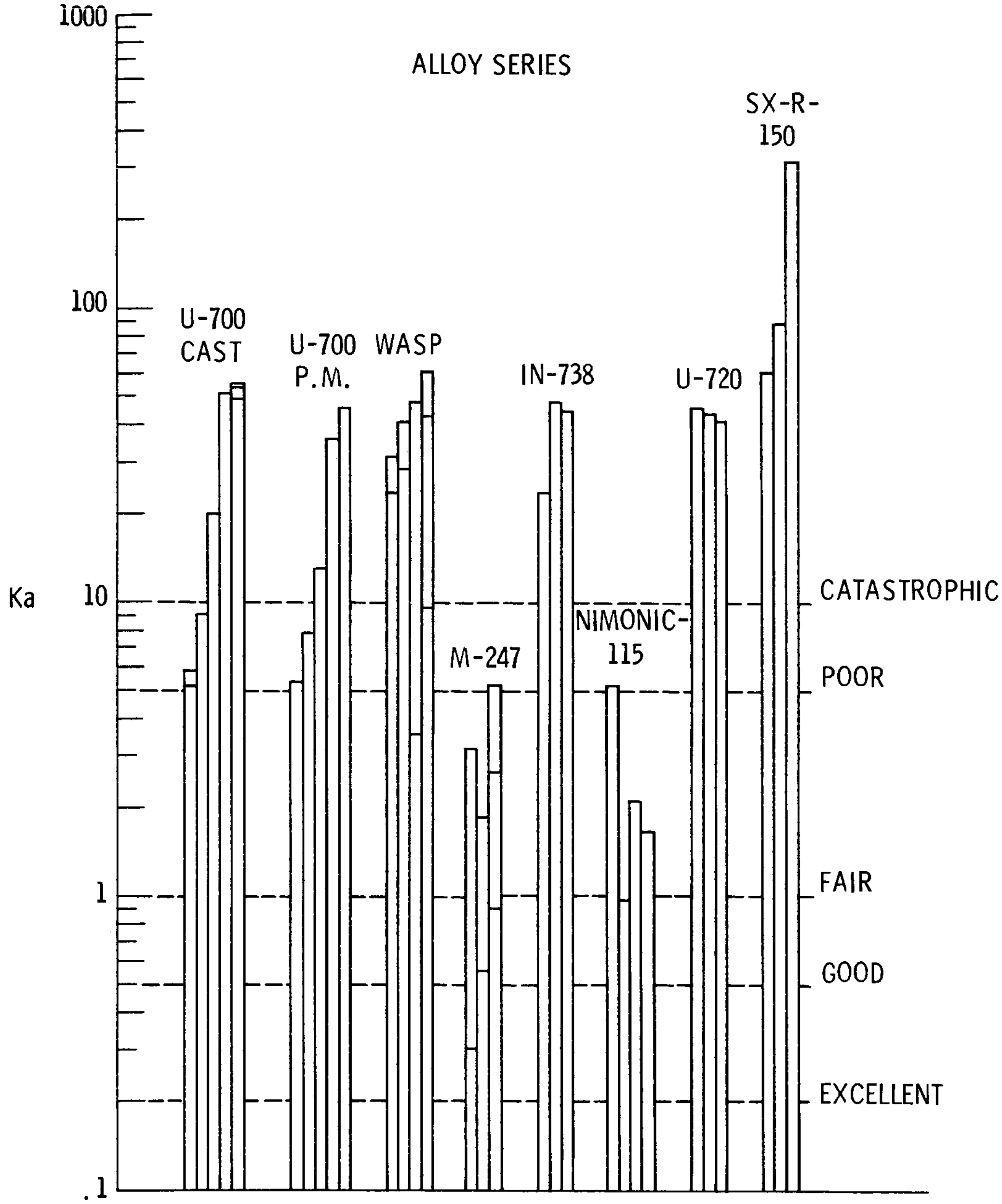
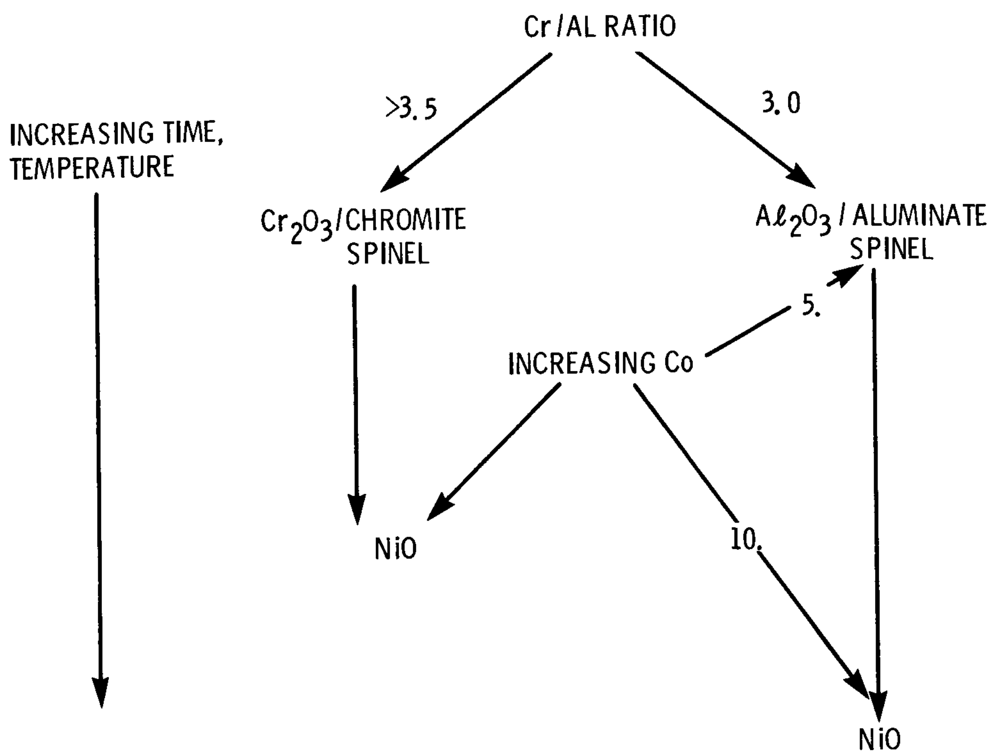


Figure 6. - Derived oxidation parameter Ka at 1150 $^{\circ}C$ for selected Ni-base superalloys (cobalt level increases - left to right).



Cr/Al RATIOS	U-700	3.5:1	IN-738	4.7:1	SX-R-150	0.9:1
	WASPALOY	15:1	NIMONIC-115	3.0:1		
	MAR-M-247	1.5:1	U-720	7.2:1		

Figure 7. - Alloy scaling tendencies on high strength Ni-base superalloys.

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15. Supplementary Notes

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16. Abstract

Cobalt levels were systematically varied in the Ni-base turbine alloys U-700 (cast), U-700 (PM/HIP), Waspaloy, Mar-M-247, IN-738, Nimonic-115, U-720, and SX-R 150. The cobalt levels ranged from 0 wt % to the nominal commercial content in each alloy. The alloys were tested in cyclic oxidation in static air at 1000, 1100 and 1150 °C for 500, 200 and 100 hr respectively. An oxidation attack parameter, K_a derived from the specific weight change versus time data was used to evaluate the oxidation behavior of the alloys along with x-ray diffraction analysis of the surface oxides. The alloys tend to form either Cr_2O_3/chromite spinel or Al_2O_3/Aluminate spinel depending on the Cr/Al ratio in the alloys. Alloys with a ratio of 3.5 or higher tend to favor the Cr oxides while those under 3.0 form mostely Al oxides. In general the Al_2O_3/aluminate spinel forming alloys have the better oxidation resistance. Increased cobalt content lowers the scaling resistance of the high Cr alloys while a 5.0 wt % Co content is optimum for the Al controlling alloys. The refractory metals particularly Ta appear beneficial to both types of oxides perhaps due to the formation of the omni-present tri-rutile $Ni(Ta,Cb,W,Mo)_2O_6$. Both scales break down as increasing amounts of NiO is formed.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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