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Corrosion of Several Metals in Supercritical Steam at 538°C

H. E. McCoy
B. McNabb

OAK RIDGE NATIONAL LABORATORY
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ABSTRACT

The corrosion of several iron- and nickel-base alloys in supercritical steam at 24.1 MPa (3500 psi) and 538°C has been measured to 7.92×10^7 sec (22,000 hr). The experiments were carried out in TVA's Bull Run Steam Plant. Corrosion was measured almost entirely by weight change and visual appearance; a few samples were evaluated by more descriptive analytical techniques. The corrosion rates of low-alloy ferritic steels containing from 1.1 to 8.7% Cr and 0.5 to 1.0% Mo differed by less than a factor of 2 in steam. Several modified compositions of Hastelloy N were evaluated and found to corrode at about equivalent rates. Of the alloys studied, the lowest weight gain in 3.6×10^7 sec (10,000 hr) was 0.01 mg/cm^2 for Inconel 718 and the highest 10 mg/cm^2 for the low-alloy ferritic steels.

INTRODUCTION

This study was motivated by the need of the Molten-Salt Reactor Program for a material for use in steam generators. Hastelloy N has excellent compatibility with molten fluoride salts, but it failed prematurely in a simulated superheated steam environment.[1] Thus, our program emphasized Hastelloy N, but included a total of over 80 alloys, mostly iron and nickel base. Because of our program to modify the chemical composition of Hastelloy N to obtain better resistance to embrittlement by irradiation and the fission product tellurium, several alloys with compositions slightly different from that of standard Hastelloy N were included in the study.

The tests were conducted in TVA's Bull Run Steam Plant in supercritical steam at 24.1 MPa (3500 psi) and 538°C. One test period included test times up to 5.4×10^7 sec (15,000 hr) and the data were reported previously.[2] A second test period covered an additional 2.52×10^7 sec (7000 hr) on many of the same test coupons and extended the total exposure time to 7.92×10^7 sec (22,000 hr).. Since the Molten Salt Reactor Program has again been discontinued, the results of the total steam corrosion will be presented in this report. Although the discussion will deal only with alloys selected to illustrate several important characteristics of steam corrosion, compositions and weight changes of all materials under investigation will be listed.

EXPERIMENTAL DETAILS

Test Facility

The facility used in this study is located in TVA's Bull Run Steam Plant.[3] This is a coal-fired plant with a supercritical steam cycle and a power generation capability of 980 MW. The facility is located about 5.49 m (18 ft) upstream from the turbine. The steam is extremely clean at this location containing less than 1 ppb O_2, less than 5 ppb Cu, less than 3 ppb Na, less than 15 ppb SiO_2, and less than 6 ppb Fe. Hydrazine is added to the feed water to scavenge oxygen, and the pH was controlled at 9.40 to 9.45 with ammonia. The electrical conductivity of the steam condensate is usually less than $3 \times 10^{-7}\ \Omega \cdot cm^{-1}$.

Although the stream was generally very pure, during at least one 1.44×10^7 sec (4000 hr) period the level of impurities was significantly higher. During this period all specimens gained very close to 0.5 mg/cm^2. Bull Run engineers pointed out that several condenser tube leaks had occurred in the previous year of operation, whereas in earlier years, few if any condenser leaks occurred. Since the cooling water in the condensers is at higher pressure than the condensing steam, untreated cooling water is introduced into the steam system hot well when a leak occurs. After replacement of condenser tubes, most of the specimens lost weight for a brief period. Perturbations in the weight change data due to this phenomenon will be pointed out as the data are presented.

A schematic of the test facility is shown in Fig. 1 and a photograph of the disassembled test assembly is shown in Fig. 2. The steam entered the 4-in.-diam sched 160 type 316 stainless steel test chamber at a flow rate of 0.12 to 0.13 kg/sec (16 to 17 lb/min). The initial sample holder was a cube 50.8 mm (2 in.) on each side and would accommodate 140 samples. A second sample holder was later added that would hold 72 specimens. Most of the samples were 12.7 mm wide × 50.8 mm long × 0.89 mm thick (1/2 in. wide × 2 in. long × 0.035 in. thick). Alumina washers 0.51 mm (0.020 in.) thick were placed between the specimens before they were bolted in place. Most of the space between the holder and the vessel was baffled to force flow across the samples at about 6.10 m/s (20 fps). Ten stressed instrumented specimens were located at the front of the chamber and four uninstrumented stressed specimens were located in the filter basket. The specimen geometry was chosen so that the stress was provided by the force of the steam on the inner wall. The wall thickness of the reduced section was varied from 0.25 to 0.75 mm (0.010 to 0.030 in.) to provide stresses of 531 to 193 MPa (77 to 28 × 10^3 psi). The front ten specimens had small capillary tubes that were heated by the steam when the tube specimen failed. A thermocouple attached to each capillary was recorded by a multipoint recorder and indicated when failure occurred. The steam passed through a metal filter to

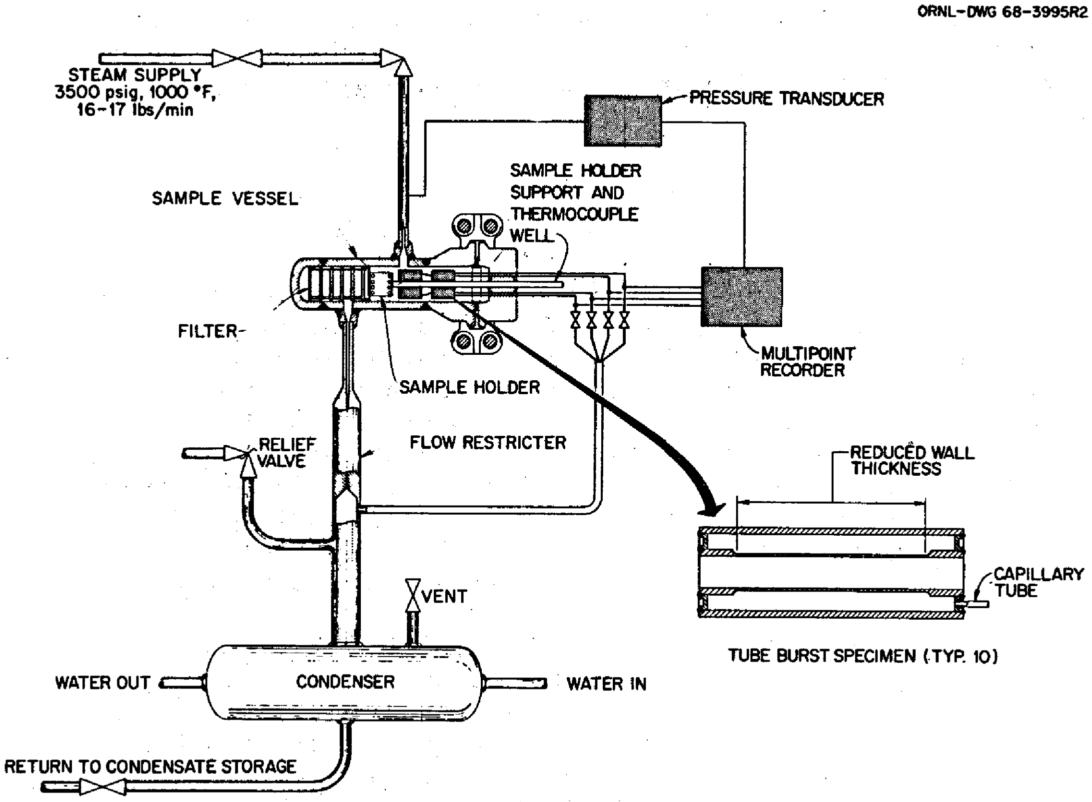

Fig. 1. Schematic of Test Facility Double-Walled Tube-Burst Specimen.

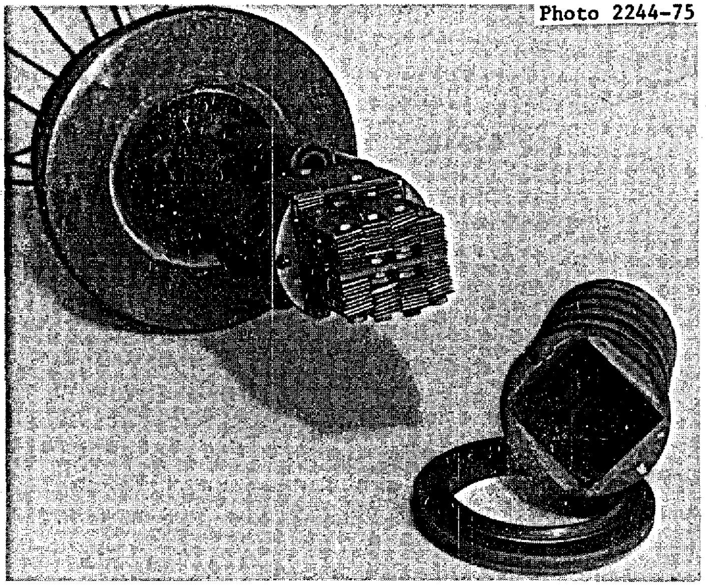

Fig. 2. Photograph of the Steam Corrosion Chamber After 19,000 hr of Exposure. Features to note are the stressed but uninstrumented specimens in the filter (foreground), the two groups of unstressed specimens, and the 10 instrumented stressed specimens. The stressed specimens have an outside diameter of 25 mm (1 in.) and a length of 76 mm (3 in.).

trap scale before it entered the small diameter flow restrictor. The restrictor reduced the steam pressure to near atmospheric pressure before reaching the condenser. The condensate was returned to condensate storage.

Test Materials

Chemical analyses of the test materials are given in Table 1. The first six alloys were commercial production materials. Alloys LC, MC, and NC were small melts of 2 1/4 Cr-1 Mo steel with variations in carbon content, and alloy 72768 is a commercial heat of 2 1/4 Cr-1 Mo steel. The other alloys down to "Hastelloy N modifications" were commercial production heats. Heats 185 through 237 were 2-lb laboratory melts. Hastelloy N heats 21541 through 73008 were small 50- to 100-lb melts that were vacuum melted and fabricated by commercial vendors. Hastelloy N heats 2477, 5065, 5067, 5085, 5095, 5101, and M1566 were large commercial heats of standard Hastelloy N.

All alloys were rolled to 0.89 m (0.035 in.) thick sheet. The rolling was done cold with intermediate anneals for softening; the finish of the exposed sample surface was generally typical of cold-rolled sheet. Samples were sheared, cleaned in acetone and alcohol, and annealed in argon for 1 hr at 927°C (the low-alloy ferritic steels), 1 hr at 1038°C (the stainless steels), or 1 hr at 1177°C (all other alloys).

Evaluation

Generally only weight change measurements were made. However, the samples were also examined visually for evidence of spalling, oxide color, etc. More extensive evaluation was carried out on a few specimens, including metallography to determine depth of oxide penetration and electron microprobe scans of oxide-metal interfaces to determine the compositions of the oxide and the metal beneath the oxide.

The stressed specimens were removed every 1000 hr for examination. Measurements were made of the inside diameter of each tube with a die test gage. In this way several points were obtained on the strain-time plot for each specimen. Any failed specimens were replaced before the assembly was returned to Bull Run. Some of the failed tubes were subjected to metallographic examination.

Table 1. Chemical Analyses of Test Materials

Alloy	Concentration, wt %																			
	Ni	Mo	Cr	Fe	Mn	C	Si	P	S	Cu	Co	V	W	Al	Ti	B	Nb	Hf	Zr	Other
Armco Iron[a]				Bal	0.017	0.012		0.005	0.025											
Low-Alloy Ferritic																				
1.1 Cr	0.25	0.49	1.1	Bal	0.42		0.64				<0.05	<0.02	<0.05	<0.05	<0.02					
1.9 Cr	0.20	0.54	1.9	Bal	0.46		0.17													
2.0 Cr	0.32	0.88	2.0	Bal	0.40		0.25													
4.2 Cr	0.36	0.47	4.2	Bal	0.40		0.35													
8.7 Cr	0.35	0.97	8.7	Bal	0.44		0.50													
LC	0.05	0.98	2.3	Bal	0.51	0.009	0.58	0.002	0.009											
MC	<0.05	1.14	2.4	Bal	0.38	0.030	0.27	0.019	0.025											
HC	0.21	0.91	2.2	Bal	0.44	0.120	0.40	0.010	0.015											
72768	0.16	0.95	2.2	Bal	0.44	0.09	0.38	0.011	0.011											
12-5-3 Maraging	12.7	2.80	5.1	Bal	0.05		0.10							0.3						
Stainless Steels																				
Type 502[a]		0.5	5.0	Bal		0.1														
17-7 PH	7.10		17.0	Bal		0.07								1.15						
Type 201	5.23		16.55	Bal	7.28	0.076	0.54	0.34	0.006											0.059 N
Type 304[a]	8.0		18.0	Bal		0.03														
Type 309[a]	13.5		23.0	Bal		0.2														
Type 310[a]	20.5		25.0	Bal		0.25	1.5													
Type 316	13.01	2.8	17.0	Bal	1.74	0.027	0.65	0.016	0.017	0.10	0.15									
Type 321[a]	10.5		18.0	Bal		0.08									0.4					
Type 347[a]	11.0		18.0	Bal		0.08											0.4			0.4 Ta
Type 406			13.0	Bal		0.15								4.0						
Type 410[a]			12.5	Bal		0.15														
Type 446[a]			25.0	Bal		0.20														0.25 N
Ni-280	Bal	0.0002	0.002	0.003	<0.0001	0.34	0.005			<0.001	0.002	<0.0001	<0.0001	0.3	<0.0001		<0.0001		<0.0001	
Monel[a]	60.0			3.5	3.5	0.5				23				0.5						
Copper[a]								0.02		9949										
Inconel 600	78.0		14.5	7.0		0.05														
Inconel 601	60.5		23.0	14.1	0.5	0.05	0.25		0.007					1.35						
Inconel 718	53.0	3.0	18.0			0.05								0.50	1.0		5.0			
Incoloy 800	31.3		20.1	46.2	0.84	0.04	0.38		0.008	0.50				0.24	0.36					
Hastelloy B	Bal	27.0	<0.2	5.2	0.96		0.3			0.01	0.48	0.2		<0.05	<0.01				<0.05	
Hastelloy C	Bal	16.0	16.0	5.8	0.75		0.48			0.01	1.2	0.1	5.0	0.2	<0.01				<0.05	
Hastelloy S	Bal	14.7	14.5	0.90	0.04	0.007	<0.01				0.22			0.2						0.01 B
Hastelloy W	60.0	25.0	5.0	5.5		0.08					1.0	0.30								
Hastelloy X		8.6	22.0	19.0	0.64		0.60			0.02	2.0	0.05	0.5	0.2	<0.01				<0.05	
Haynes Alloy 25	10.0	0.5	20.0	1.4	1.0	0.1	0.7	0.015	0.01	0.02	Bal	<0.02	15.2	0.1	0.02				<0.05	
Haynes Alloy 188	22.0		22.0	3.0	1.25	0.15					Bal		15.0							
Rene 62	Bal	9.0	15.0	22.0	0.25	0.05	0.25							1.25	2.5		2.25		0.01	
Hastelloy N Modifications:																				
185	Bal	11.0	5.9	3.8	0.46	0.05	0.10				<0.03		<0.1	<0.05	0.91			<0.1	0.98	
186	Bal	10.0	5.4	3.5	0.45	0.05	0.09				<0.03		<0.1	0.84	0.88			<0.1	<0.05	
188	Bal	13.0	7.3	4.5	0.49	0.05	0.15				<0.03		<0.1	0.95	<0.02			1.1	<0.05	
231	Bal	12.0	7.0	4.2	0.03	0.05	0.12				<0.03			<0.05	<0.02		<0.05	1.3	<0.05	1.2 Y
232	Bal	13.0	8.0	4.5	<0.02	0.05	0.12				<0.03			<0.05	<0.02		<0.05	1.2	<0.05	
234	Bal	16.0	7.2	4.0	<0.02	0.05	0.13				<0.03			<0.05	<0.02		<0.05	<0.1	<0.05	
236	Bal	11.0	7.0	4.0	0.5	0.05	0.13				<0.03			1.0	<0.02		<0.05	<0.05	0.5	
237	Bal	12.0	6.7	4.3	0.49	0.05	0.13				<0.03			<0.05	0.04		1.03	<0.1	<0.05	
2477	Bal	16.2	7.0	4.2	0.055	0.057	0.047	0.008	0.004	0.01	0.05	<0.01	0.03	0.02	0.03	0.0002	<0.0005	<0.001	<0.001	
5065	Bal	16.5	7.1	4.0	0.55	0.07	0.58	0.005	0.004	0.007	0.05	0.20	0.1	<0.03	<0.01	0.001	<0.05	<0.1	<0.1	
5067	Bal	17.2	7.4	4.0	0.48	0.06	0.43	0.005	0.007	0.01	0.09	0.30	0.6	0.01	0.01	0.004				
5085	Bal	17.0	7.0	3.6	0.64	0.06	0.65	0.004	0.003	0.01	0.15	0.20	0.07	0.05	<0.01	0.004	<0.05		<0.002	
N1 5095	Bal	16.39	7.2	3.87	0.54	0.07	0.68	0.001	0.007	0.01	0.15				0.02		0.002			
N2 5101	Bal	16.39	6.92	3.91	0.44	0.05	0.63	0.001	0.009	0.01	0.09				0.02		0.007			
21541	Bal	11.6	7.3	0.04	0.16	0.05	0.017	0.001	0.002	0.01	<0.10	<0.10	1.98	0.03	0.005	0.0007			<0.005	
21542	Bal	12.1	7.21	0.041	0.16	0.06	0.014	0.001	0.004	0.01	<0.10	<0.10	2.05	<0.10	<0.10	0.0005	0.96		<0.005	
21543	Bal	12.4	7.31	0.038	0.08	0.05	0.019	<0.001	0.004	0.01	<0.10	<0.10	<0.10	<0.02	<0.003	0.0002	0.70		<0.005	
21544	Bal	12.6	7.3	<0.10	0.13	0.06	<0.03	<0.01	0.003	0.01	<0.10	<0.10	<0.10	<0.10	<0.10	0.0005			0.44	
21545	Bal	12.0	7.18	0.034	0.29	0.05	0.015	0.001	<0.002	0.01	<0.10	<0.10	<0.10	0.02	0.49	0.00007			0.01	
21546	Bal	12.3	7.29	0.046	0.16	0.05	0.009	0.001	<0.002	0.01	<0.10	<0.10	<0.10	0.02	0.10	0.0002			0.005	
21554	Bal	12.4	7.39	0.097	0.16	0.065	0.01	0.004	<0.002					0.03	0.003	0.0002			0.35	
21555	Bal	12.4	7.18	0.065	0.16	0.052	0.008	0.003	<0.002					0.02	0.003	0.0007			0.05	
M1566	Bal	16.0	7.5	5.0	0.5	0.06					0.5									
68688	Bal	13.8	7.91	4.98	0.52	0.079	0.38	0.042	<0.002	0.023	0.08				0.013	0.0002	<0.05	<0.05	<0.05	
68689	Bal	13.7	7.6	4.8	0.47	0.081	0.53	0.01	<0.002	0.02	0.075				0.36	0.0002	<0.05	<0.05	<0.05	
69344	Bal	13.0	7.4	4.0	0.56	0.109	0.5	0.001	0.004	0.03	0.06	<0.01	<0.01	0.24	0.77	0.00001	1.7	<0.01	0.001	
69345	Bal	13.0	7.5	4.0	0.52	0.078	0.5	0.001	0.01	0.02	0.07	<0.01	0.03	0.27	1.05	0.00006	<0.01	0.92	0.3	
69641	Bal	13.9	6.9	0.30	0.35	0.06	0.02	0.001	0.003	0.01	<0.03	0.02		<0.03	1.30	0.0001	<0.05	0.70	0.01	
69648	Bal	12.8	6.9	0.30	0.24	0.04	0.05	0.001	0.003	0.02	<0.03	0.10		<0.05	0.92	0.00008	1.95	0.08	0.02	
69714	Bal	12.4	8.0	0.10	0.35	0.012	<0.05	0.001	0.004	0.05	0.05	<0.01	0.01	0.17	0.80	0.00001	1.6	<0.01	<0.01	
70727	Bal	11.7	7.5	0.05	0.37	0.04	<0.05	0.004	0.001	<0.01	<0.01	<0.01	0.01	<0.03	2.1	0.00006	<0.1	<0.01	<0.01	
70785	Bal	12.2	7.0	0.16	0.27	0.057	0.09	0.002	0.004	0.02	0.03	0.003	0.003	0.14	1.1	0.002	0.097	<0.003	0.01	
70786	Bal	12.2	7.2	0.41	0.48	0.044	0.08	0.002	0.01	0.02	0.05	0.008	0.003	0.13	0.82	0.0005	0.62	0.003	0.06	
70787	Bal	12.5	7.0	0.18	0.43	0.041	0.09	0.002	0.004	0.02	0.05	0.003	0.003	0.17	0.90	0.0005	0.12	0.77	0.07	
70788	Bal	12.5	7.2	0.43	0.43	0.027	0.10	0.002	0.004	0.02	<0.02	0.008	0.003	0.18	1.36	0.0004	0.07	0.30	0.01	
70795	Bal	13.0	7.8	0.04	0.63	0.054	0.03	<0.005	0.005	0.003	0.005	0.001	<0.005	0.06	1.49	0.002	0.005	0.42	0.017	
70796	Bal	12.4	7.3	0.05	0.64	0.043	0.02	<0.005	0.005	0.003	0.005	0.002	<0.005	0.10	0.04	0.0005	0.04	0.75	0.024	
70797	Bal	12.5	7.0	0.29	0.38	0.055	0.02	<0.005	0.003	0.003	0.005	0.002	<0.005	0.07	0.59	0.0002	0.98	0.75	0.035	
70798	Bal	12.8	7.5	0.26	0.53	0.038	0.02	0.002	0.005	0.003	0.005	0.003	<0.005	0.07	0.71	0.0001	0.94	0.32	0.011	
70835	Bal	12.1	7.8	0.68	0.58	0.053	0.05	0.001	0.004	0.005	0.10	<0.01	<0.01	0.10	0.71	0.002	2.6	<0.01	<0.005	
71114	Bal	12.5	7.14	0.062	0.02	0.05	0.026	0.002	0.005	0.007	0.07			0.07	1.75	0.002			<0.03	
71583	Bal	12.4	7.35	0.13	0.03	0.05	0.055	0.002	0.004	0.015	0.10			0.2	1.44				<0.03	
72115	Bal	11.9	7.03	0.07	0.07	0.091	0.09	0.003	0.002							<0.001		0.72	0.2	
72503	Bal	12.9	6.79	0.32	0.01	0.066	0.01	0.0008	0.002					0.1	1.94	<0.001				
72604	Bal	11.5	6.69	0.07	0.07	0.09	0.09	0.003	0.003							<0.001		0.30	0.02	
73008	Bal	12.4	7.63	0.18	0.45	0.078	0.06							0.03	2.1	<0.003				

[a] Nominal composition, all others are actual analyses.

Errors

The specimens were weighed on a standard four-place balance with an accuracy of ±0.0001 g. The specimens had surface areas of 12 to 14 cm^2, so the uncertainty in weight corresponded to almost 0.01 mg/cm^2. This error does not include small pieces of loose material that may have been adhering to the specimen or small amounts of oxide that may have been knocked off during disassembly. Efforts were made to minimize these sources of error, but they are likely still present.

The stresses imposed on the tube burst specimens were affected by uncertainties in tube dimensions. The uncertainty in the wall thickness was about ±0.0127 mm (±0.0005 in.). When the nominal wall thickness was 0.254 mm (0.010 in.), this uncertainty introduced an error in the stress of ±5%. When the wall thickness was 0.762 mm (0.030 in.), this uncertainty was about ±2%.

Experimental Observations

Weight gain results on all materials tested in steam are given in the Appendix.

Low-Alloy Ferritic Steels

Five alloys containing from 1.1 to 8.7% Cr and 0.5 to 1.0% Mo (Table 1) were exposed to steam for 14,000 hr at 538°C and these results were presented previously[2] and are shown in Table A1. These specimens were lost during the one year in which the program was inactive, and it was necessary to begin testing with a new group of specimens. These specimens were exposed 7000 hr, and the data for the second series are shown in Fig. 3 along with the scatterband for the first series. The extremes of the scatterband for the first series were defined by alloys containing 1.1% Cr (lowest weight gain) and 1.9% Cr (highest weight grain). These same alloys are near the extremes for the second series, and the data from the two series generally agree very well.

The behavior in air was vastly different from that noted in steam. After only 1000-hr exposure all alloys except the one containing 8.7% Cr had begun to spall, and after 13,000-hr exposure all alloys had lost weight.[2]

Two samples from the steam series were examined metallographically and typical photomicrographs are shown in Fig. 4. The microstructures of the specimen containing 1.1 and 8.7% Cr were quite similar. The oxide, which consists of two distinct layers had a total thickness of about 50 μm. The microstructure of the metal surface was altered to a depth of about 10 μm. Microprobe scans of these specimens showed that the oxide layer nearest the metal contained detectable quantities of

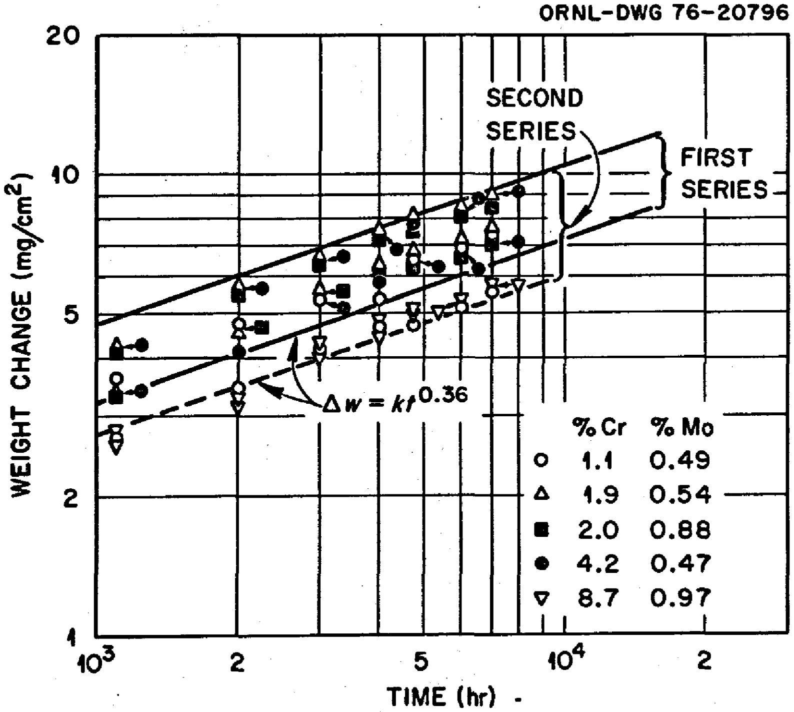

Fig. 3. Influence of Chromium Content on the Weight Change of Annealed Low-Alloy Ferritic Steels in Supercritical Steam at 538°C and 24.1 MPa (3500 psi).

Fe, Cr, Mo, and Si with Fe and Cr being the predominant constituents. Only iron was detected in the outermost oxide. The two alloys chosen for metallographic examination had very similar weight gains and gained the least weight of the series. Note in Table 1 that these alloys were the highest in silicon and that silicon was detectable in the oxide film. In light of these observations and previous work that showed silicon to reduce the oxidation rate of steel,[4,5] it is quite likely that the higher silicon content of these two alloys resulted in their superior corrosion resistance.

The weight changes observed with several heats of 2 1/4 Cr-1 Mo steel are shown in Fig. 5. The scatterbands from the observations of steels containing from 1.1 to 8.7% Cr are shown and the data for the four heats of 2 1/4 Cr-1 Mo steel fall within the scatterbands. The low carbon heat had the lowest oxidation rate, but we do not know a basis for attributing this to its low carbon content. These same alloys were exposed in the 50% cold-worked condition. The data from these specimens are presented in Fig. 6. A comparison of Figs. 5 and 6 shows that cold working did not have a detectable effect on corrosion. (These data are also tabulated in Table A2.)

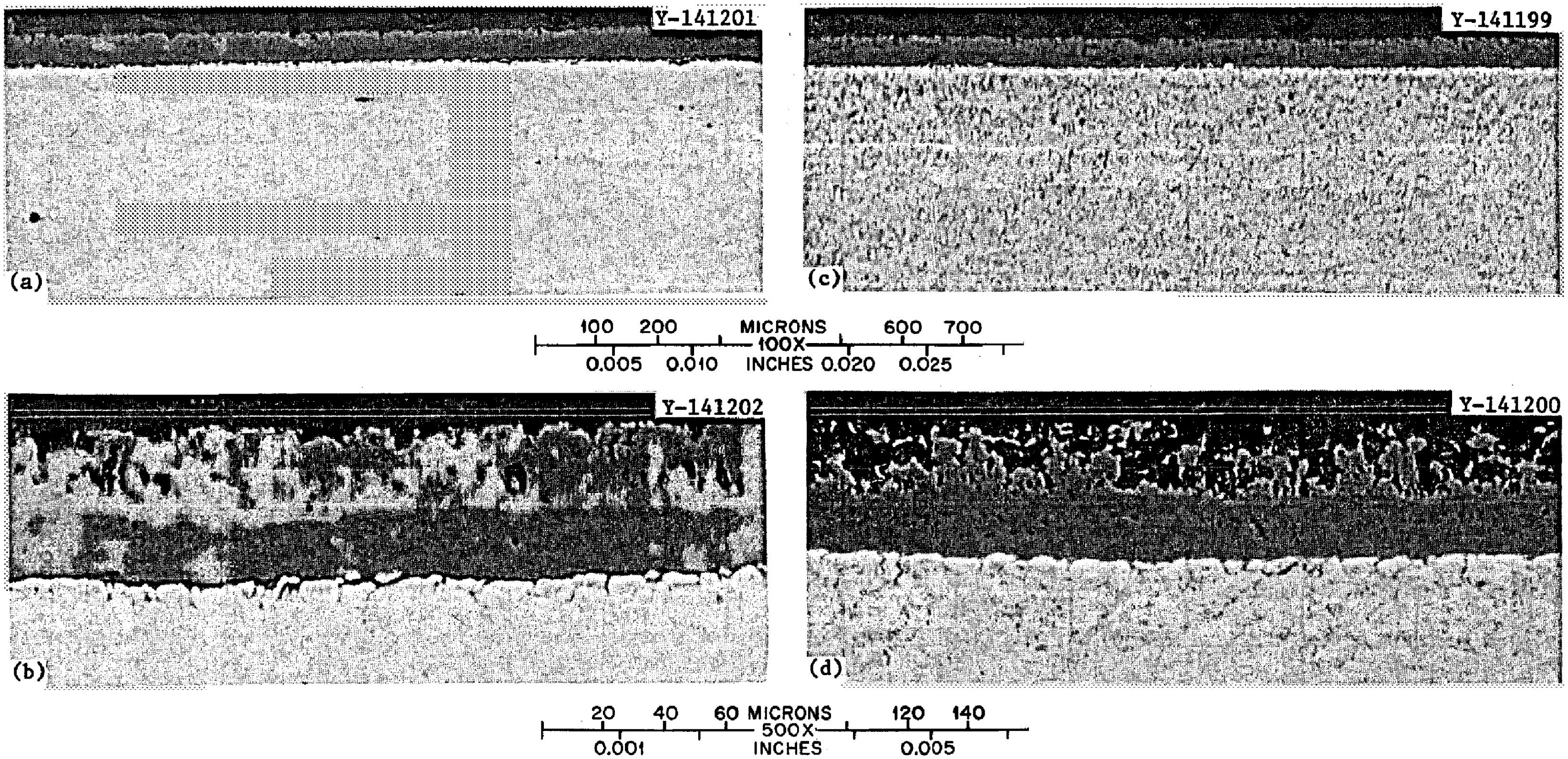

Fig. 4. Photomicrographs of Low-Alloy Ferritic Steel Exposed to Steam at 538°C and 24.1 MPa (3500 psi) for 7000 hr. (a) and (b) Alloy containing 1.1% Cr. (c) and (d) Alloy containing 8.7% Cr. All specimens as polished; however, specimen shown in (c) and (d) was etched slightly by moisture in the ambient air.

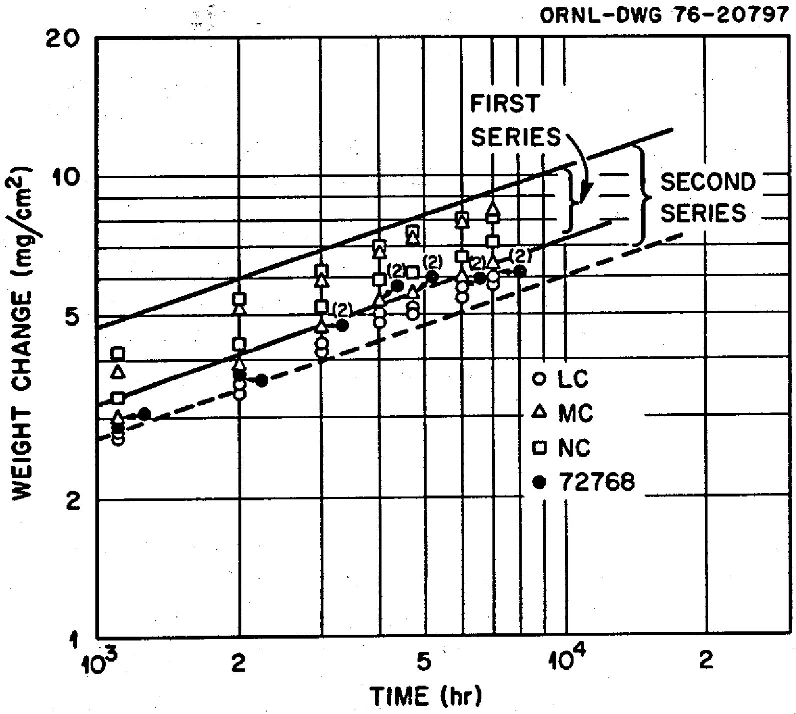

Fig. 5. Weight Changes of Several Heats of 2 1/4 Cr-1 Mo Steel in Solution-Annealed Condition Exposed to Supercritical Steam at 538°C and 24.1 MPa (3500 psi).

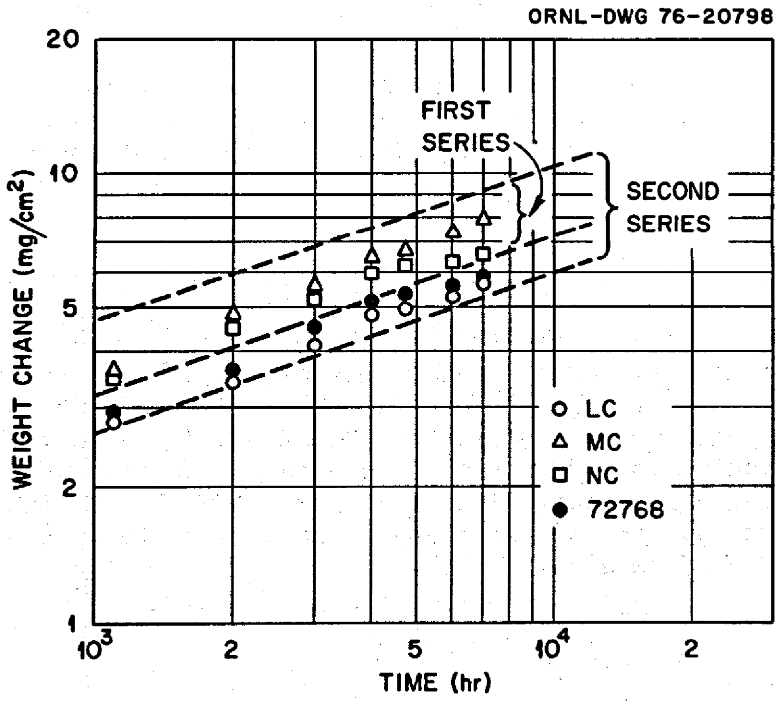

Fig. 6. Weight Changes of Several Heats of 2 1/4 Cr-1 Mo Steel in the Cold-Worked Condition Exposed to Steam at 538°C and 24.1 MPa (3500 psi).

Photomicrographs of three specimens of the 2 1/4 Cr-1 Mo steel are shown in Fig. 7. The three specimens examined were (1) standard alloy (heat 72768), annealed and air cooled, (2) standard alloy, cold worked 50%, and (3) normal carbon (NC) alloy, annealed and air cooled. The oxides on all three specimens were very similar to each other and to the alloys shown in Fig. 4. The oxide consisted of two layers and had an overall thickness of about 50 μm. The specimen underneath the oxide was affected to a depth of 10 μm or less. Electron microprobe spectral analysis showed that the oxide on each specimen nearest the metal contained detectable quantities of Fe, Cr, Mo, and Si with Fe and Cr being the major constituent. The outermost oxide layer contained only iron in detectable concentrations.

Hastelloy N

The weight changes of four heats of Hastelloy N exposed in steam are shown in Fig. 8. The variation among the four heats is about the same as the variation noted for duplication specimens of heat 5065. One of the heats, 2477, was vacuum melted, and the other three were air melted. The vacuum-melted heat was much lower in silicon and manganese than the air-melted heats, but this had no detectable effect on the corrosion rate in steam. After the first 4000-hr exposure, the weight change can be described by an equation of the form

$$\Delta W = Kt^{0.21} , \tag{1}$$

where ΔW is the weight gain in mg/cm^2, t is the time in hr, and K is a constant. The perturbation in rate after 15,000 hr is thought to be due to the condenser leaks in the plant and the attendant higher impurity levels in the steam. After the leaks were repaired, the rate of corrosion decreased.

Some Hastelloy N specimens from heat 5065 were given various surface treatments before exposure to steam. Six samples were solution annealed. Two of these were tested in the as-rolled and solution-treated condition, two others were electropolished, and two were abraded with 400 grit paper before exposure. Figure 9 shows that the weight changes were least for the electropolished material, intermediate for the as-rolled samples, and greatest for the abraded samples. Although the corrosion process may have been affected in a more complex way, the weight changes are qualitatively proportional to the "true" surface area.

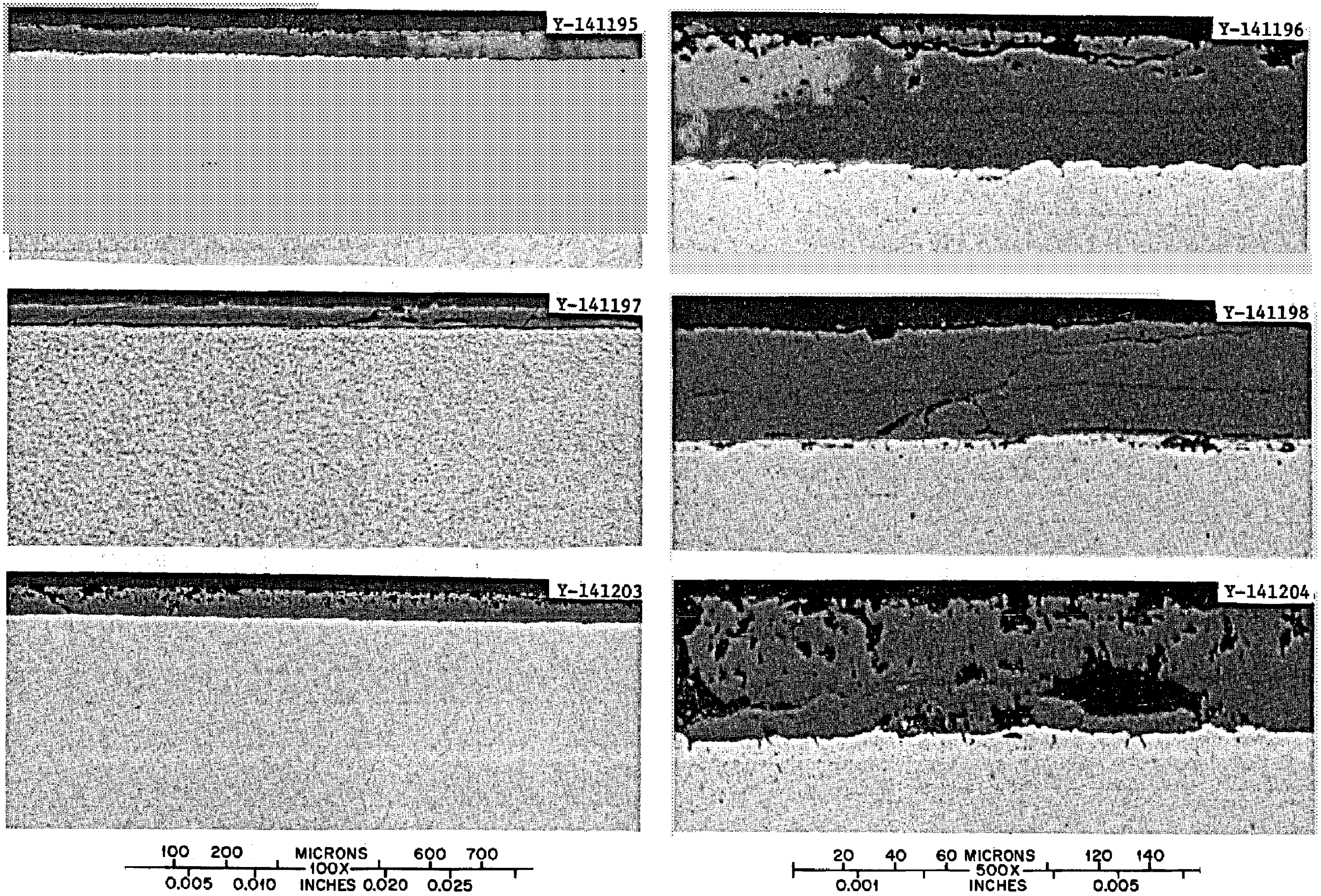

Fig. 7. Photomicrographs of 2 1/4 Cr-1 Mo Steel Exposed 7000 hr to Supercritical Steam at 538°C and 24.1 MPa (3500 psi). (a) and (b) Heat 72768, annealed at 927°C and air cooled. (c) and (d) Heat 72768, cold worked 50%. (e) and (f) Heat NC annealed at 927°C and air cooled. As polished.

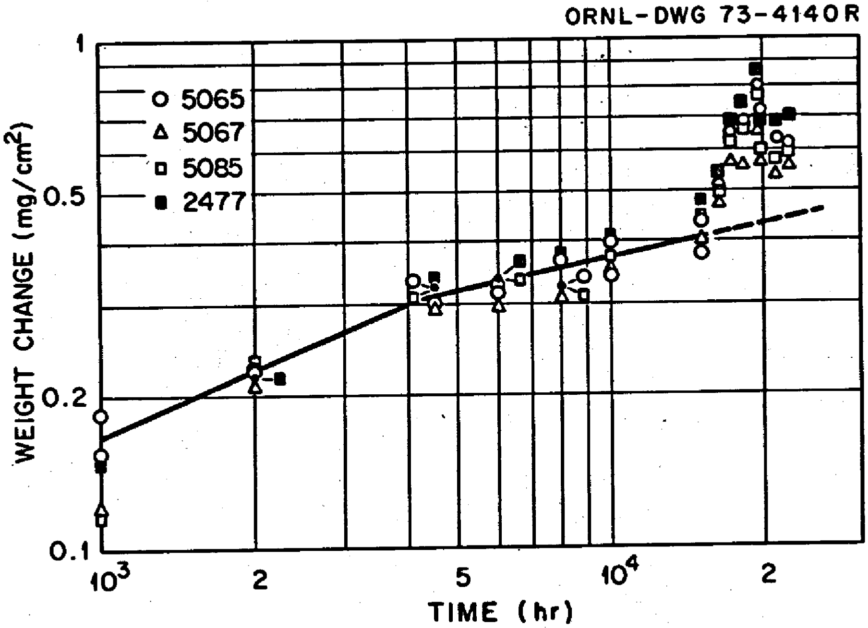

Fig. 8. Weight Changes of Several Heats of Annealed Hastelloy N Exposed to Supercritical Steam at 538°C and 24.1 MPa (3500 psi).

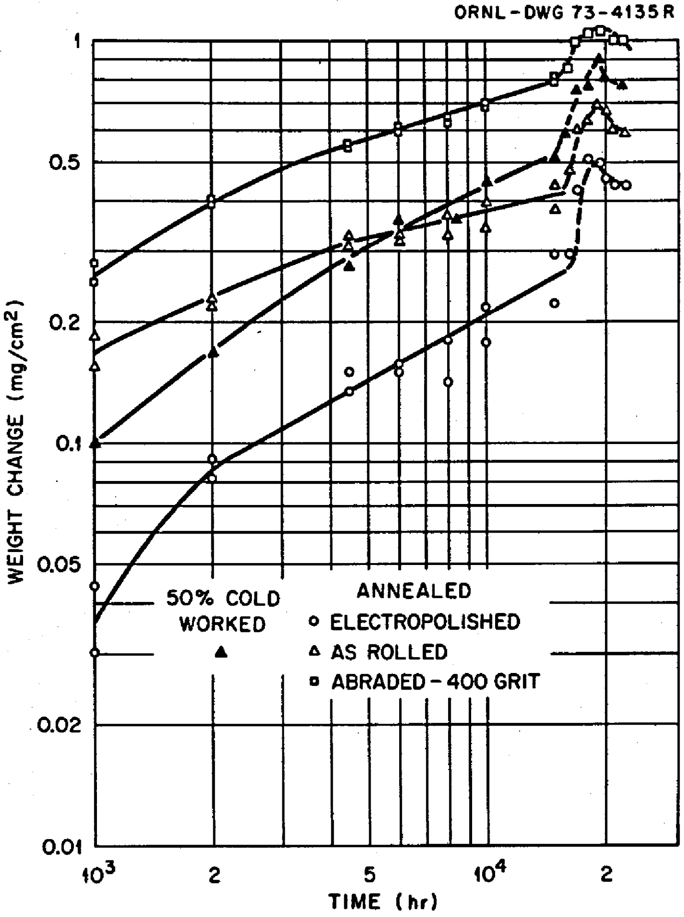

Fig. 9. Effect of Surface Finish on the Corrosion of Hastelloy N (Heat 5065) in Steam at 538°C and 24.1 MPa (3500 psi).

One specimen was cold worked 50% and tested with an as-rolled surface. The corrosion rate of this specimen was very near that of the annealed specimen with an as-rolled surface. Thus, cold working appears to have very little effect on the corrosion of Hastelloy N in steam. This is in agreement with the results of a prior study in which nickel-base alloys were noted to be less affected by cold working than high chromium steels.[6]

Specimens from small commercial heats of modified Hastelloy N containing from 0.10 to 2.1% Ti were exposed to steam, and the results are summarized in Fig. 10. Alloys containing 0.1% Ti (21546) and 0.49% Ti (21545) gained weight more rapidly than the standard alloy. However, the slope (weight change per unit time for greater than 2000 hr) was quite low for both these alloys and about equivalent to that for the standard alloy at long times. Alloys containing 0.92, 1.30, and 2.1% Ti gained less weight than standard Hastelloy N during 10,000 hr exposure. However, extrapolations to longer times would indicate that standard Hastelloy N and the alloys containing 0.10 and 0.50% Ti would gain less weight than the alloys containing more titanium. One alloy containing 0.7% Nb was also exposed and gained less weight than most of the titanium-modified alloys. The perturbation after long exposure times was due to the increased impurity level in the steam caused by the leaking condenser tubes. After the tubes were repaired, the specimen lost weight.

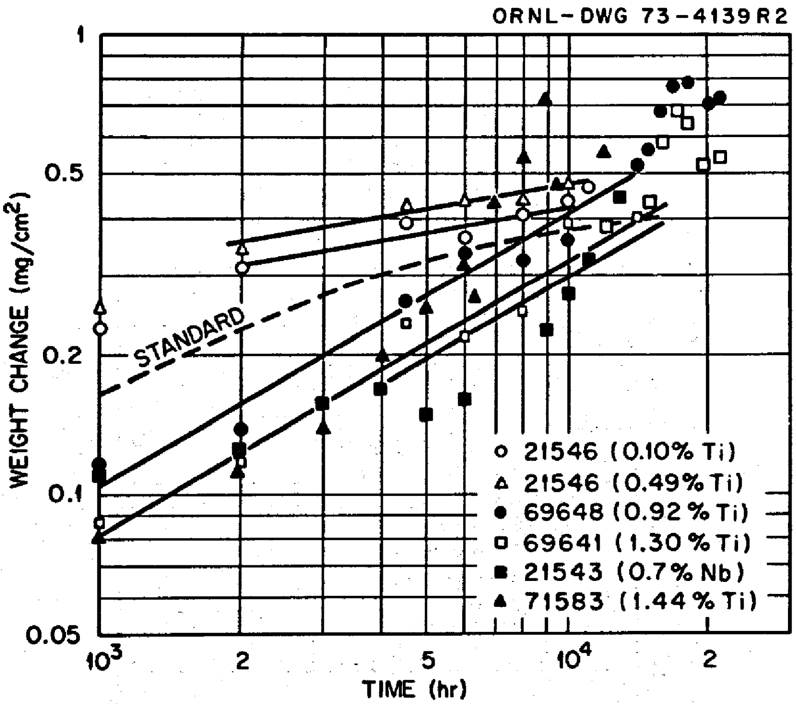

Fig. 10. Several Alloys of Hastelloy N Modified with Titanium and Niobium and Exposed to Supercritical Steam at 538°C and 24.1 MPa (3500 psi).

Several laboratory melts of Hastelloy N containing additions of Ti, Al, Zr, Hf, Y, Ce, and Nb were exposed to steam for 22,000 hr, and the weight changes are shown in Fig. 11. Maximum and minimum weight changes in these alloys differed by less than a factor of 2, but only the alloy containing 1.03% Nb gained less weight than the standard alloy. The perturbation after 15,000-hr exposure was due to leaking condenser tubes, and the specimen lost weight after the tubes were repaired.

Typical photomicrographs of two heats of standard Hastelloy N are shown in Fig. 12. The oxide was not of uniform thickness, but varied from a few to about 20 μm thick. Electronmicroprobe studies revealed that both the inner and outer oxides contained Cr, Mo, Ni, and a trace of Fe.

Four of the modified Hastelloy N specimens were examined metallographically and typical photomicrographs are shown in Fig. 13. The oxides on all these alloys appear quite similar in morphology to those formed on standard Hastelloy N. Electronmicroprobe scans of these samples revealed iron and nickel in the oxide of alloy 69648 (0.92% Ti), Fe, Ni, Cr, Ti, and Mo in the oxide of alloy 21543 (0.7% Nb), and nickel plus iron in the oxide of alloy 237 (1.03% Nb). The presence of iron in most of the oxides may have been attributable to the presence of iron particles in the steam. Since most of the steam circuit at Bull Run is constructed of low-alloy ferritic steels, large amounts of particulate iron are entrained in the steam and some deposit on the test specimens.

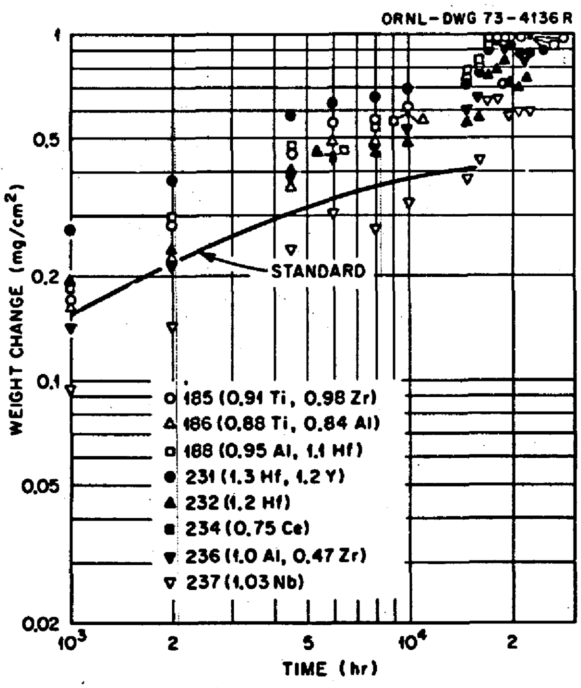

Fig. 11. Corrosion of Various Modified Compositions of Hastelloy N in Steam at 538°C and 24.1 MPa (3500 psi).

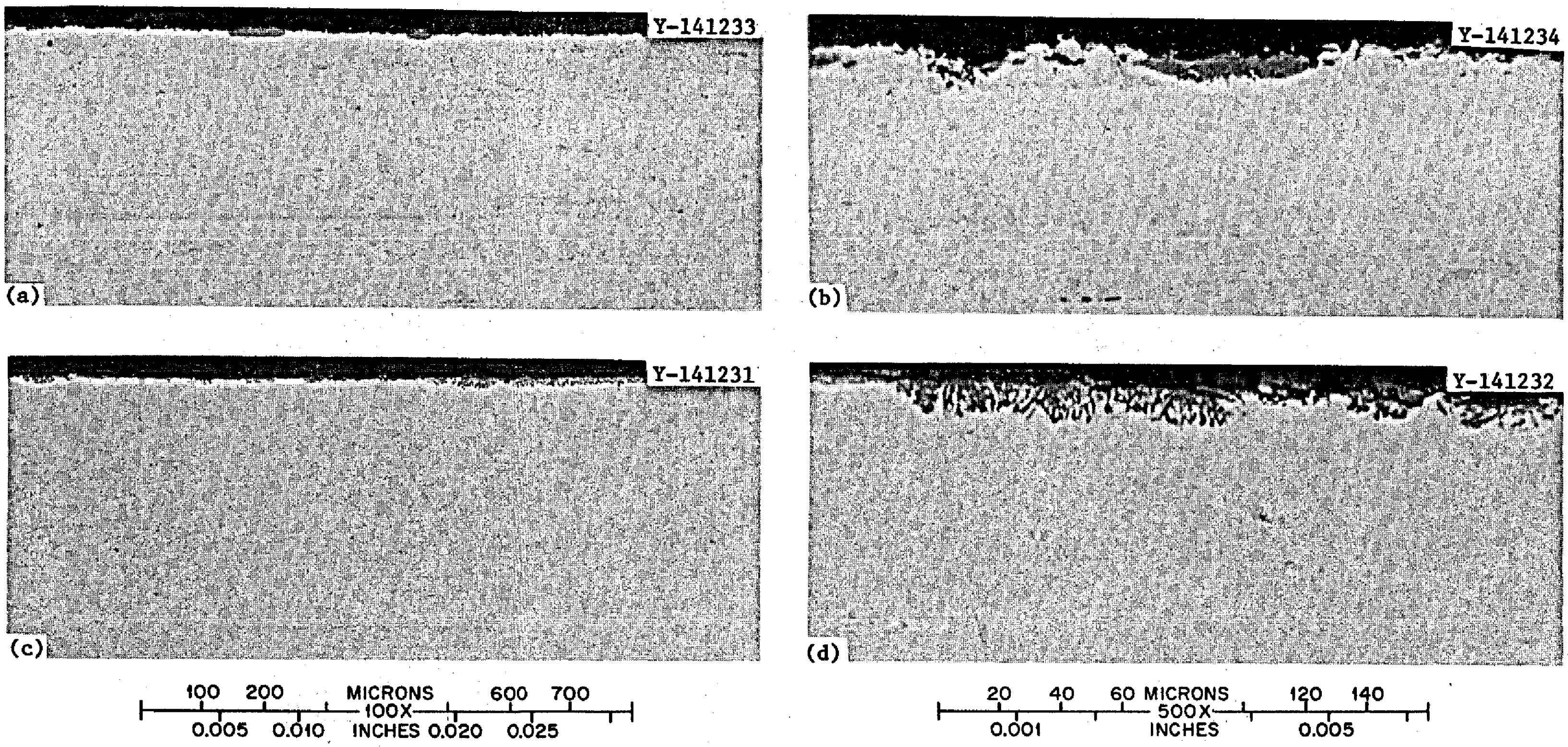

Fig. 12. Photomicrographs of Hastelloy N Exposed to Steam at 538°C and 24.1 MPa (3500 psi) for 22,000 hr. (a) and (b) Heat 5065. (c) and (d) Heat 2477. As polished,

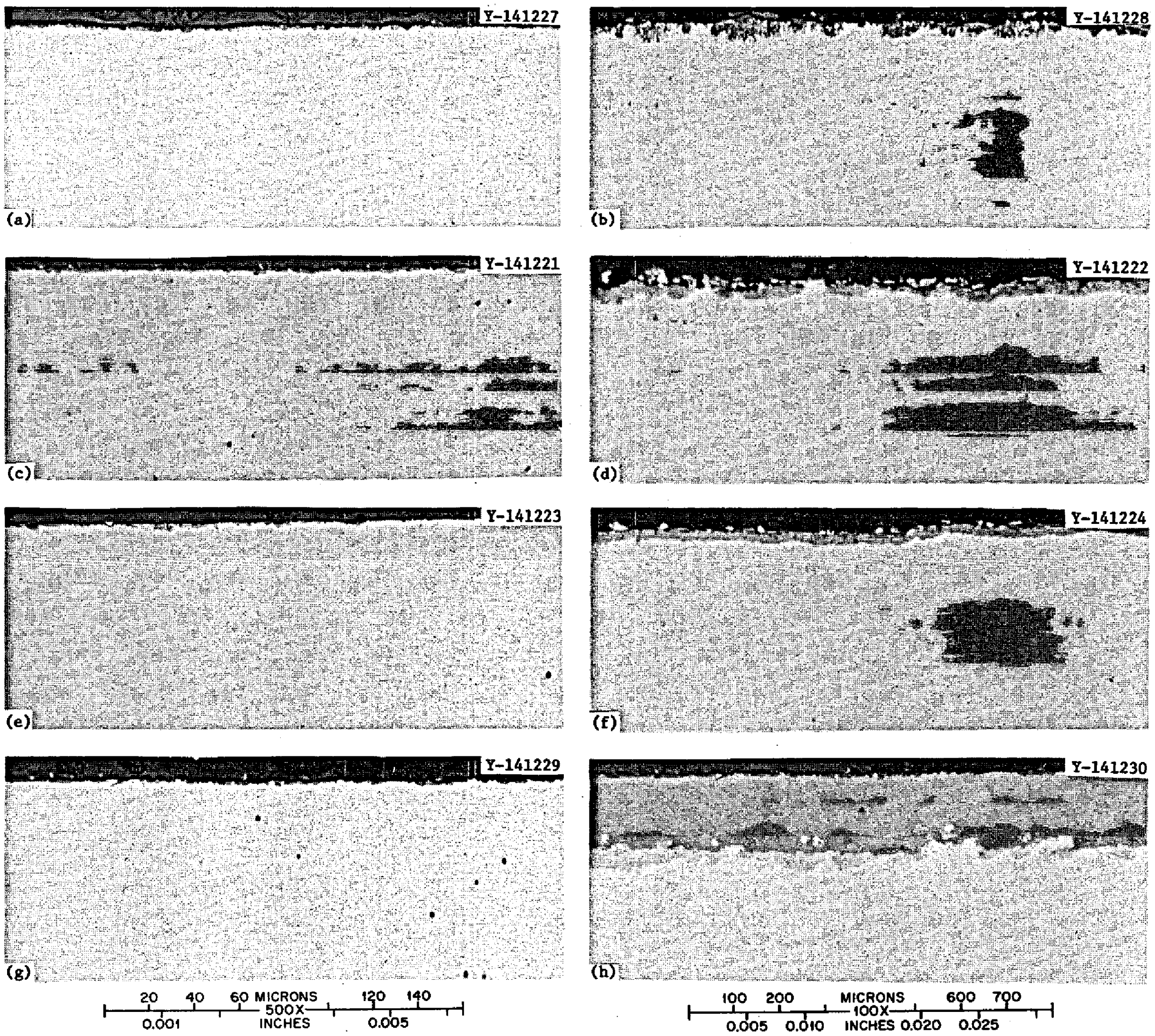

Fig. 13. Photomicrographs of Modified Hastelloy N Exposed to Super-Critical Steam at 538°C and 24.1 MPa (3500 psi). (a) and (b) Heat 69648 (0.92% Ti), 21,000 hr. (c) and (d) Heat 71583 (1.44% Ti), 12,000 hr. (e) and (f) Heat 21543 (0.7% Nb), 16,000 hr. (g) and (h) Heat 237 (1.03% Nb), 21,000 hr. As polished.

Stainless Steels

The data on stainless steels are given in Table A3 and the data for several selected steels are plotted in Fig. 14. These steels contain from 5 to 25% Cr, and type 502 stainless steel with 5% Cr has the highest oxidation rate. Type 17-7 PH steel contains 17% Cr plus 1.15% Al and has the lowest rate of weight change over the test period. The other four steels have about equal weight changes, but types 406 and 446 seem to be approaching a very low rate of weight gain.

Several of these same alloys were exposed in the cold-worked condition, and the observed weight changes of several of these alloys are shown in Fig. 15. Cold working reduced the corrosion rates of most steels studied by about a factor of 2, but had an even larger effect on type 201 stainless steel. This reduction of the corrosion rate of high chromium steels has been observed by other investigators.[7–9] The oxides on the annealed and cold-worked type 201 stainless steel specimens were subjected to x-ray diffraction after 6000-hr exposure to steam in an effort to determine a reason for the different oxidation behavior. The oxide on the annealed specimen consisted of Fe_3O_4 and α-Fe_2O_3, and the oxide on the cold-worked specimen was $MnFe_2O_4$ and α-Fe_2O_3. The most striking difference in the two specimens was that the matrix lines for the annealed alloy were those of an fcc cell with a lattice parameter of 3.5975 ± 0.0006 A, and those for the cold-worked specimen were those of a bcc cell having a lattice parameter of 2.875 ± 0.002 A plus a fcc cell having approximately the same lattice parameter as above. The bcc lines were not present in an as-cold-worked specimen, so the phase likely formed during exposure to steam at 538°C. This bcc phase is possibly responsible in some undetermined way for the superior oxidation resistance of the cold-worked materal. It is also possible that the formation of $MnFe_2O_4$ on the cold-worked specimen may have increased its oxidation resistance.

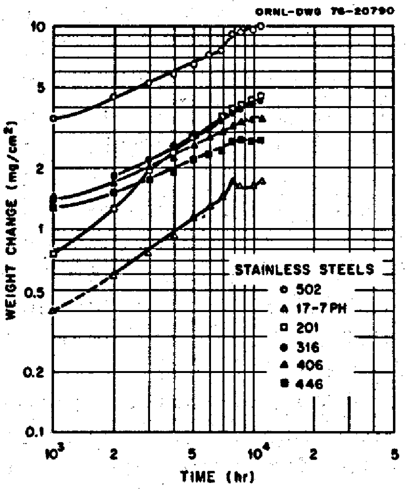

Fig. 14. Weight Changes of Solution Annealed Stainless Steels in Steam at 538°C and 24.1 MPa (3500 psi).

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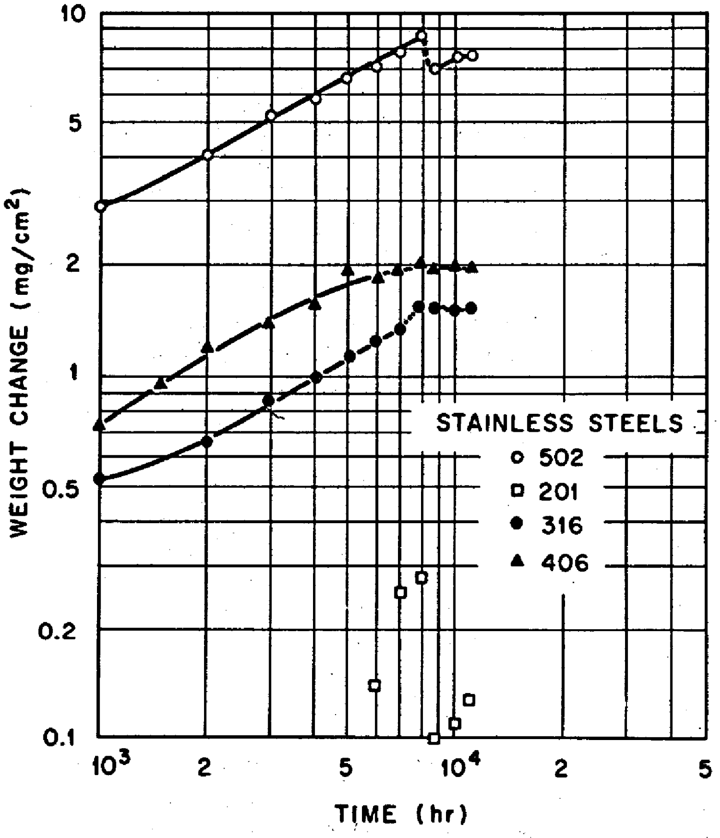

Fig. 15. Weight Changes of Cold-Worked (50%) Stainless Steels in Steam at 538°C and 24.1 MPa (3500 psi).

Six specimens of the stainless steel series were examined metallograhically and typical photomicrographs are shown in Fig. 16. The 502 stainless steel with only 5% Cr had an oxide film about 80 μm thick. Electronmicroprobe studies of the oxide on this specimen showed that the inner oxide contained iron and chromium and that only iron was detected in the outermost oxide. The oxides on the types 304 and 316 stainless steel specimens were quite similar to each other in morphology and were about 30 μm thick. Electronmicroprobe analysis showed that these specimens all had outer oxides in which only iron could be detected. The inner oxide of type 304 stainless steel contained iron, chromium, and nickel, and the inner oxide of type 316 stainless steel contained iron, nickel, chromium, and molybdenum. The photomicrographs of type 201 stainless steel show the marked effect of cold working on the rate of oxidation of this material. The oxide layer on the annealed material was about 40 μm thick and that on the cold-worked materials was hardly detectable. On the annealed specimen the oxide consisted of two distinct layers with the inner one containing Fe, Mn, Cr, and Ni and the outer one containing iron and manganese. The oxide layer on the cold-worked specimen was too thin to analyze by the electronmicroprobe analytical technique used.

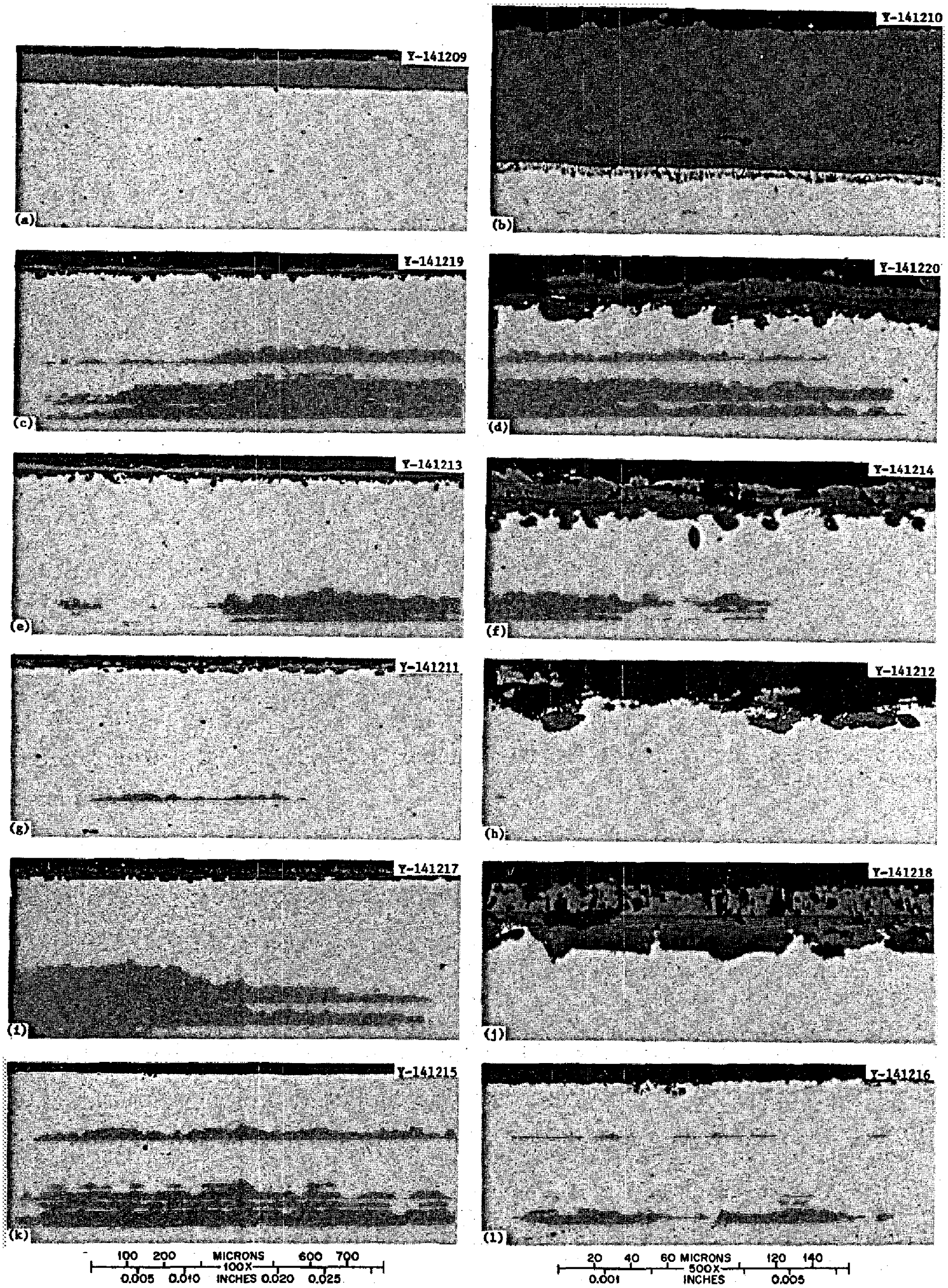

Fig. 16. Photomicrographs of Several Steels Exposed to Steam at 538°C and 24.1 MPa (3500 psi) for 11,000 hr (Type 304 Exposed 12,000 hr). (a) and (b) Annealed type 502. (c) and (d) As-received type 304. (e) and (f) Annealed type 316. (g) and (h) Cold-worked type 316. (i) and (j) Annealed type 201. (k) and (l) Cold-worked type 201. As polished.

Other Alloys

Several other alloys were exposed to steam and their weight changes are shown in Figs. 17 through 20. In Fig. 17 the behavior of Armco iron, Monel, Incoloy 800, and several nickel-base alloys is shown. Monel and Armco iron gained weight at a very high rate whereas Inconel 718 gained weight at a very slow rate. Inconel 600 fell at an intermediate level of weight gain, and Inconel 601 fell at a lower level. Incoloy 800 gained weight at a relatively high rate for the first 2000 hr, but the rate rapidly decreased to where the rate was proportional to time to about the one tenth power.

The weight changes of several Hastelloys are shown in Fig. 18 and the data cover about one-half log cycle. These alloys contain from 0.2% Cr (Hastelloy B) to 22% Cr (Hastelloy X), but the differences in weight change are not simply inversely proportional to the chromium content.

The weight changes of several alloys in the cold-worked condition are shown in Fig. 19. By comparison with the annealed data in Figs. 17 and 18, some assessment can be made of the effects of cold working. Cold working caused Hastelloy B to gain weight at a faster rate and slightly reduced the weight gain of Incoloy 800. The weight gain of Inconel 718 appeared to be increased slightly by cold working, but the values are still so low that inaccuracies in weighing make this conclusion rather tenuous. The weight gained in the first 1000 hr was increased by cold working for several of the Hastelloys, but the rate slowed to where weight changes were about equivalent after a few thousand hours for annealed and cold-worked material.

The weight changes of three alloys in the annealed and cold-worked conditions are shown in Fig. 20. Haynes Alloy 188 gained weight more rapidly in the cold-worked condition than in the annealed condition, but the difference was quite small after 10,000-hr exposure. The weight changes of all these alloys were quite low.

Three specimens from this series were examined metallographically and typical photomicrographs are shown in Fig. 21. Incoloy 800 had a very irregular oxide with the thickness in some areas as much as 10 μm. Examination by the electron microprobe showed that the inner oxide contained iron, nickel, and chromium, and that the outer oxide contained only iron in detectable quantities. This is in qualitative agreement with the observations of Tilborg and Linde.[10] Inconel 718 in the annealed condition formed a subsurface reaction product to a depth of about 15 μm during exposure to steam, but this product was not present in the material cold worked prior to exposure. The oxide was too thin to be analyzed on the annealed specimen, but analysis of the oxide on the cold-worked specimen revealed the presence of iron, nickel, and chromium.

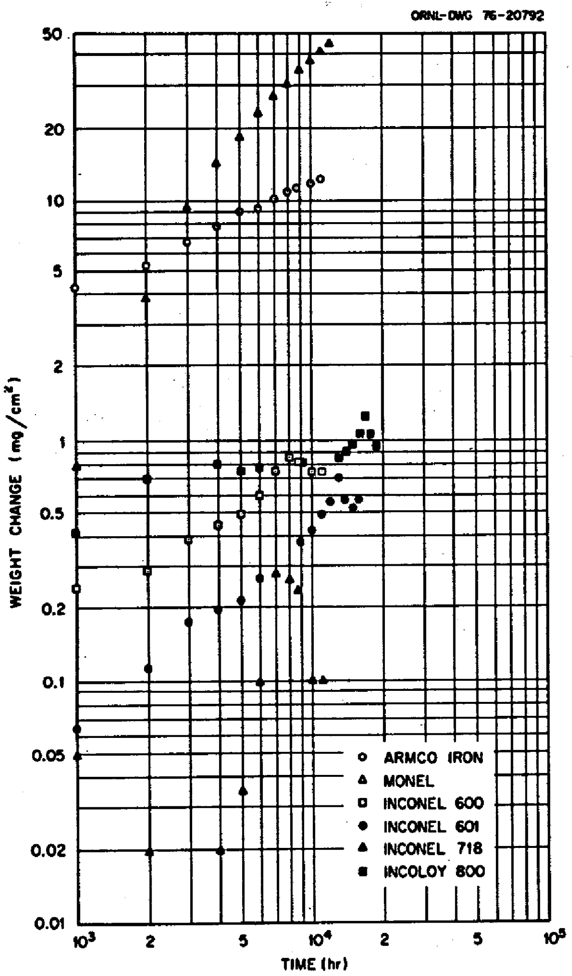

Fig. 17. Weight Changes of Several Solution-Annealed Alloys in Steam at 538°C and 24.1 MPa (3500 psi).

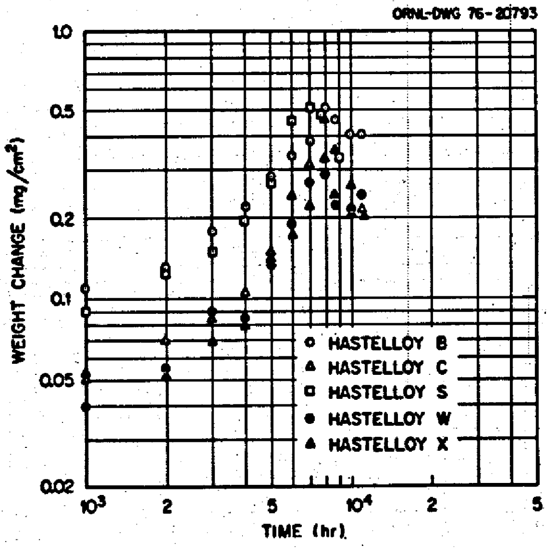

Fig. 18. Weight Changes of Several Nickel-Base Alloys in the Solution-Annealed Condition in Steam at 538°C and 24.1 MPa (3500 psi).

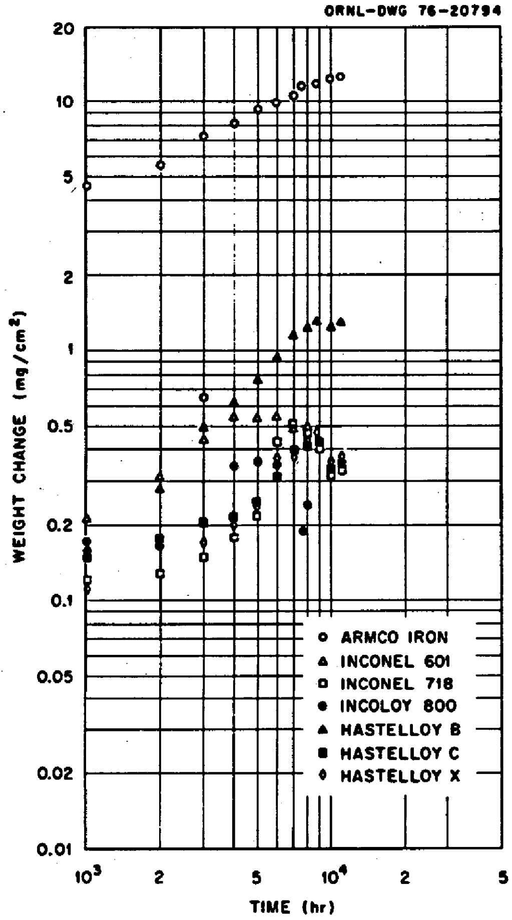

Fig. 19. Weight Changes of Several Alloys in the Cold-Worked Condition in Steam at 24.1 MPa (3500 psi) and 538°C.

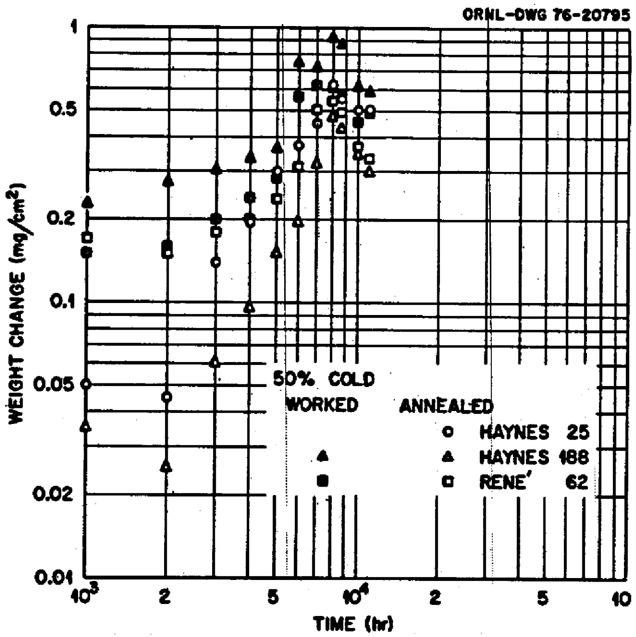

Fig. 20. Weight Changes of Three Alloys in Steam at 24.1 MPa (3500 psi) and 538°C in the Annealed and Cold-Worked Conditions.

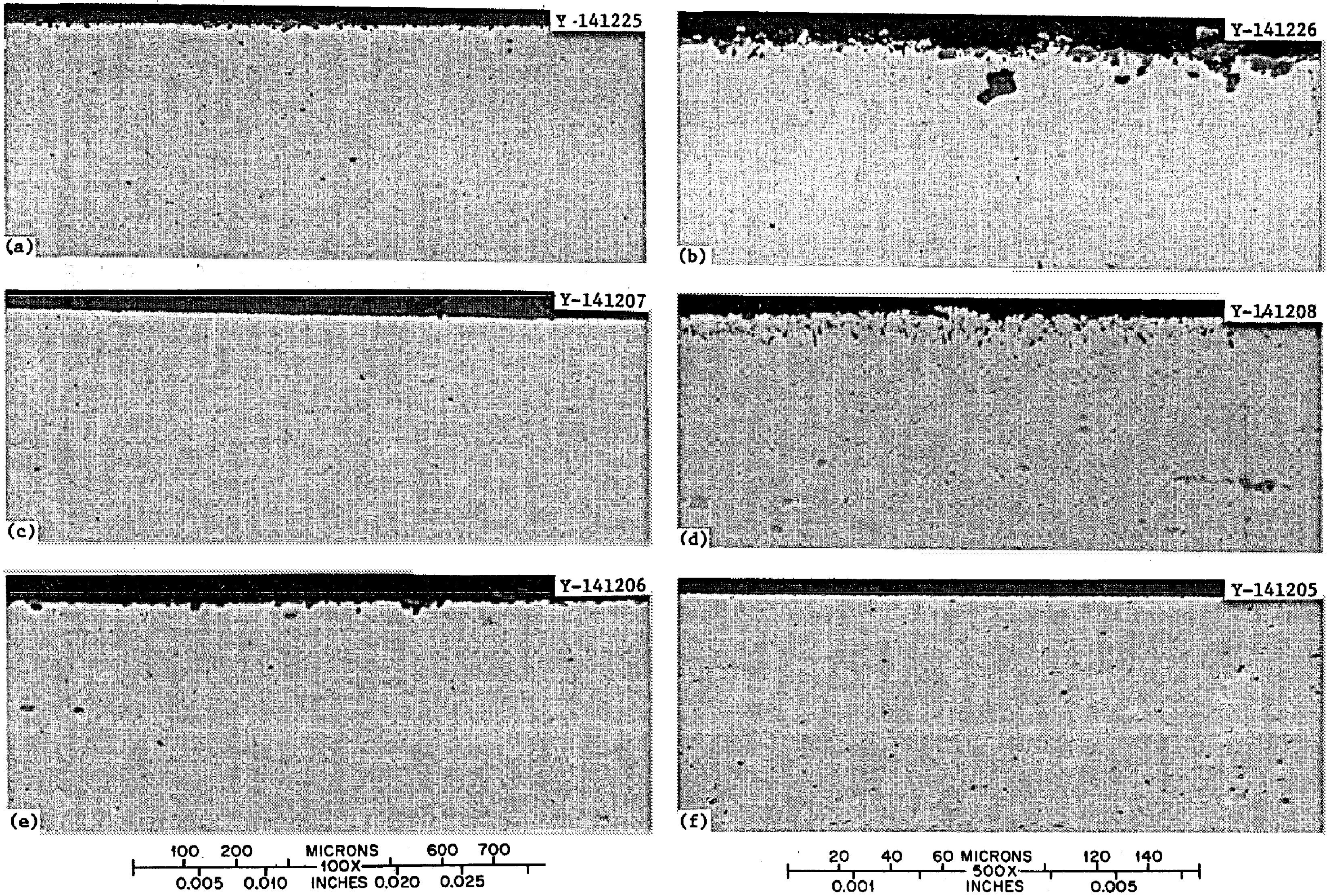

Fig. 21. Photomicrographs of Specimens Exposed to Steam at 538°C and 24.1 MPa (3500 psi). (a) and (b) Annealed Incoloy 800, 19,000 hr. (c) and (d) Annealed Inconel 718, 11,000 hr. (e) and (f) Cold-worked Inconel 718, 11,000 hr. As polished.

Tube Burst Results — Hastelloy N

Two heats of standard Hastelloy N tubing (N1 5095 and N2 5101) were evaluated in the stressed condition from 193 to 531 MPa (28.0 to 77.0×10^3 psi). The specimens of both heats in the annealed condition (1 hr at 1177°C) had shorter rupture times in steam than in argon. Specimens of heat N1 5095 tested in the as-received condition and stressed below 345 MPa (50.0×10^3 psi) in steam had rupture times equal to those of specimens tested in argon. Figure 22 shows the stress-rupture properties of heat N1 5095. Flaws in the specimens may have contributed to the scatter, but at stresses <345 MPa ($<50.0 \times 10^3$ psi), where wall thicknesses are heavier, there appears to be no significant effect of steam on the rupture time. Two of the specimens stressed at 193 and 280 MPa (28.0 and 40.6×10^3 psi) accumulated 15,000-hr exposure to steam at 538°C without rupture and three others at slightly higher stresses accumulated from 10,000 to 11,000 hr of exposure. Figure 23 shows the stress-rupture properties of heat N2 5101. Specimens in the annealed condition tested in steam had shorter rupture times than specimens tested in argon. Specimens in the as-received condition tested in steam had rupture times equal to or greater than specimens tested in argon. The longest rupture time of this heat was 12,000 hr for a specimen stressed at 336 MPa (48.8×10^3 psi) in steam at 538°C.

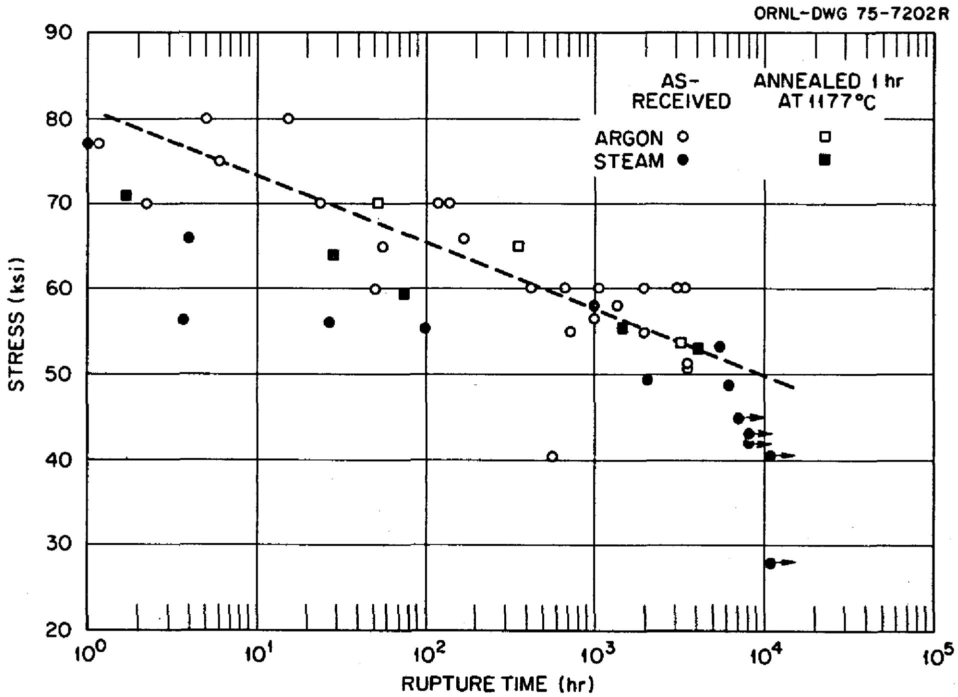

Fig. 22. Rupture Life of Hastelloy N (Heat N1 5095). Tubes stressed in argon and steam environments at 538°C.

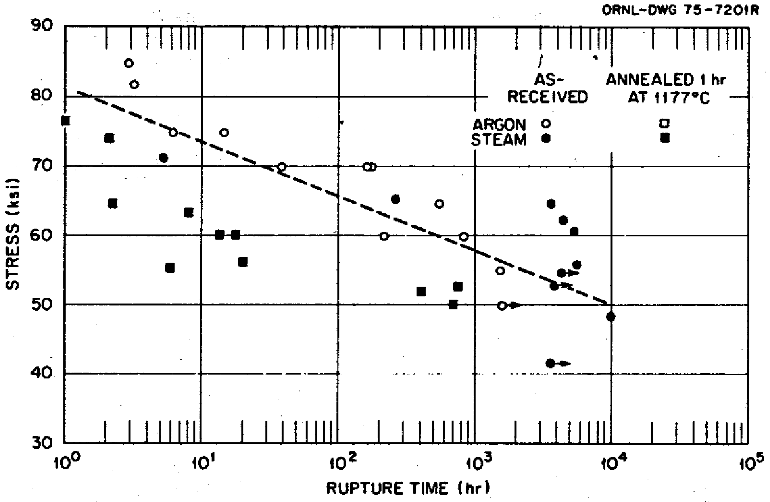

Fig. 23. Rupture Life of Hastelloy N (Heat N2 5101). Tubes stressed in argon and steam environments at 538°C.

The minimum creep rates of both heats of material were plotted as a function of stress in Fig. 24. The creep rates were calculated from plots of diametral strain, $\Delta D/D$ vs time, which were based on measurements of the internal diameter of the specimens at 1000-hr intervals. There is considerable scatter in the data because of difficulty in measuring the internal diameters at the point of maximum strain, but the figure is useful as an indication of the strain rates expected in this stress range. Buildup of scale on the inside diameter exposed to steam also constributes to the inaccuracy of this method since the apparent strain is reduced as the scale thickens.

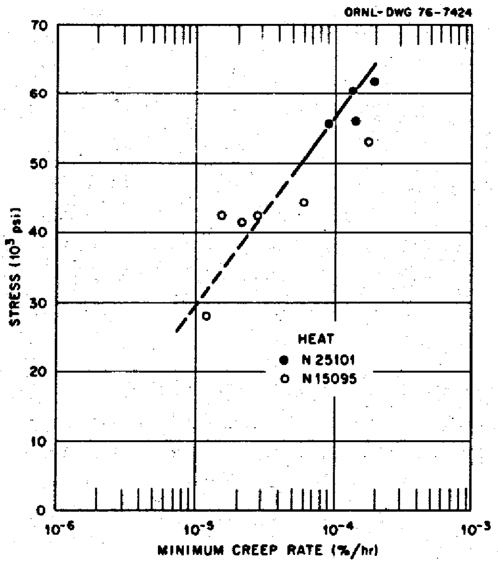

Fig. 24. Creep Properties of Hastelloy N at 538°C in Steam Environment.

Four typical fractured specimens are shown in Fig. 25. In each case the outer protective tube has been machined off. The three short-term test specimens (1.65 to 75.3 hr) exhibited relatively ductile tearing fracture indicative of a very high strain rate at the moment of fracture. The specimen from the 2089-hr test had a lower ductility failure.

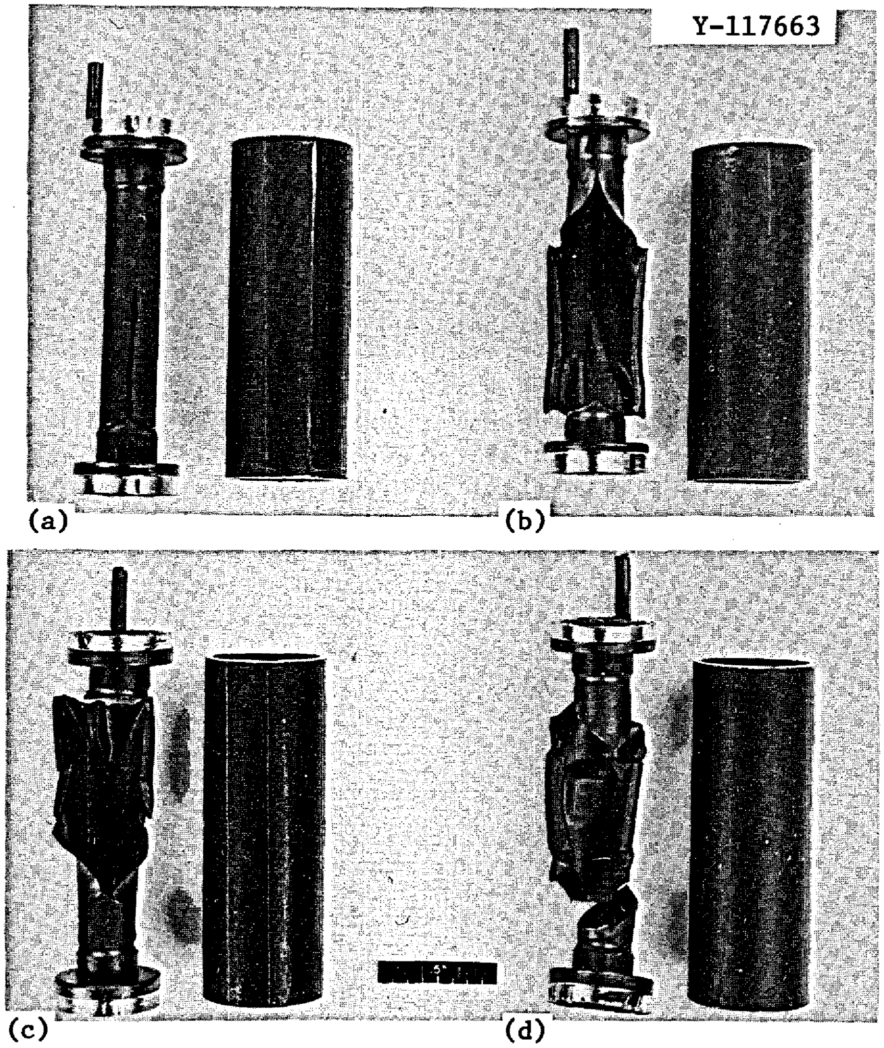

Fig. 25. Photographs of Four Specimens Failed in Steam. See Fig. 1 for a schematic drawing of the assembled specimen. (a) SN 64, 340 MPa (49,340 psi), rupture at 2088.75 hr. (b) SN 118, 410 MPa (59,500 psi), rupture at 75.3 hr. (c) SN 111, 441 MPa (64,000 psi), rupture at 28.75 hr. (d) SN 106, 489 MPa (70,940 psi), rupture at 1.65 hr.

SUMMARY

The corrosion of several alloys in supercritical steam at 538°C and 24.1 MPa (3500 psi) was measured for times up to 22,000 hr. Various post-test examinations were performed, and the following important observations were made.

1. All the alloys formed tenacious, nonspalling oxides when tested in steam.

2. The corrosion rates of five ferritic alloys containing from 1.1 to 8.7% Cr and 0.5 to 1.0% Mo and four heats of 2 1/4 Cr-1 Mo steel containing from 0.009 to 0.12% C were equal to within a factor of 2.

3. Cold working prior to exposure did not have a detectable effect on the corrosion of 2 1/4 Cr-1 Mo steel.

4. The oxide layer formed on the ferritic steel was about 50 μm thick and consisted of two distinct layers. The layer next to the metal contained detectable quantities of Fe, Cr, Mo, and Si, and the outermost oxide contained only iron.

5. The corrosion rate of Hastelloy N in steam increased with increasing surface roughness.

6. Although rather large changes were made in the composition of Hastelloy N, the corrosion rate was altered by no more than a factor of 2.

7. The oxide on Hastelloy N was quite irregular with the thickness in different locations varying from a few to 20 μm. The surface of the oxide was quite high in iron, and this was likely due to the deposition of particulate iron from the steam circuit.

8. The corrosion rates of several steels containing from 5 to 25% Cr varied by an order of magnitude. The highest corrosion rate was exhibited by type 502 with 5% Cr and the least by type 17 — 7 PH with 17% Cr and 1.15% Al.

9. Cold working cause a large reduction in the corrosion rate of type 201 stainless steel. This reduction was associated with either the formation of a bcc phase or the spinel $MnFe_2O_4$ that formed on the cold-worked material. Cold working has a lesser effect on the other high-chromium steels, but generally decreased the corrosion rates.

10. Oxides on the stainless steels generally consisted of 2 distinct layers. The layer closest to the metal contained all principal constituents of the alloy, and the outer oxide contained only iron in detectable quantities.

11. Several iron- and nickel-base alloys were tested. Inconel 718 had the lowest weight gains, and Incoloy 800 had the lowest corrosion rate with a dependence on $(\text{time})^{0.1}$.

12. The inner oxide on Incoloy 800 contained iron, nickel, and chromium, and the outer oxide contained only iron in detectable quantities. The oxide on Inconel 718 contained iron, nickel, and chromium.

13. Inconel 718 in the annealed condition formed a subsurface reaction product to a depth of about 15 μm, but this product was not present in the cold-worked material.

14. Although some small difference existed in the behavior of annealed and cold-worked nickel-base alloys, the effects were reasonably small.

15. The stress-rupture properties of Hastelloy N were lower in steam than in argon at short rupture times, but were equivalent at long rupture times.

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APPENDIX

Collected Weight Change Data for Various Metals and Alloys Exposed to Supercritical Steam at 24.1 MPa (3500 psi) and 538°C

Table A1. Weight Change Data for First Set of Specimens of Low-Alloy Ferritic and Maraging Steels

Alloy	Specimen	Area (cm^2)	Weight Gain, mg/cm^2, at Various Times in hr										
			670	1,000	2,000	2,482	4,000	4,482	6,000	8,000	10,000	13,000	14,000
Cr 1.1[a]	172	13.6924		3.14	3.78			5.12	6.00	6.47	6.80		9.12
	173	13.6444		3.21									
	205	13.6221	2.31			4.22	4.96		5.37	5.60	6.22	7.74	
Cr 1.9[a]	202	13.5654	3.97			6.30	7.98						
	208	13.6392	4.28			7.95	8.53		8.89	8.89	9.78	11.71	
	163	13.6274		4.94									
	164	13.6355		4.93	5.98			7.57	8.90	9.31	9.81		12.03
Cr 2.0[a]	166	13.6369		3.93									
	167	13.6287		3.40	4.32			5.80	6.93	7.37	7.63		9.60
	203	13.5638	2.90			4.63	5.91						
	209	13.5759	2.73			4.51	5.77		6.08	6.53	7.31	8.96	
Cr 4.2[a]	204	13.5999	3.76			6.14	7.74		8.07	8.64	9.97	11.88	
	169	13.6329		3.98	5.13			6.83	7.97	8.48	8.96		10.41
	170	13.5955		4.49	6.89								
Cr 8.7[a]	175	13.6411		3.77									
	176	13.6668		3.73	4.56			5.98	7.03	7.43	7.68		9.71
	206	13.6558	2.74			5.81	6.27		6.27	6.57	7.29	8.79	
12-5-3[b]	207	13.5928	3.97			6.61	8.91		9.73	10.22	11.33	13.99	
	178	13.5173		6.33									
	179	13.4833		6.16	7.37			9.48	11.04	11.77	12.13		15.48

[a] Low-alloy ferritic steel annealed 1 hr at 927°C in argon.

[b] 12-5-3 maraging steel annealed 1 hr at 816°C in argon.

Table A2. Weight Change Data for Second Set of Specimens of Low-Alloy Ferritic and Maraging Steels

Alloy	Condition[a]	Specimen	Area (cm^2)	Weight Gain, mg/cm^2, at Various Times in hr						
				1100	2000	3000	4000	4700	6000	7000
LC	A	481	13.9030	2.88	3.40	4.10	4.88	4.98	5.34	5.72
LC	A	482	13.8512	2.75	3.42	4.14	4.84	4.99	5.35	5.73
LC	B	483	13.9548	2.68	3.39	4.19	4.86	5.04	5.45	5.82
LC	B	484	13.8130	2.75	3.53	4.28	4.98	5.14	5.60	6.03
MC	A	489	13.6378	3.20	4.16	4.99	5.73	5.91	6.37	6.85
MC	A	490	13.8373	4.08	5.43	6.15	7.00	7.46	8.35	9.01
MC	B	491	13.9548	2.96	3.86	4.64	5.35	5.50	5.96	6.39
MC	B	492	13.8650	3.77	5.14	5.91	6.82	7.34	7.90	8.38
NC	A	485	13.7092	3.08	3.85	4.52	5.18	5.30	5.70	6.12
NC	A	486	13.6301	3.96	5.10	6.02	6.88	7.22	7.21	7.41
NC	B	487	13.5783	3.31	4.35	5.22	5.99	6.17	6.67	7.17
NC	B	488	13.7993	4.18	5.41	6.15	6.93	7.40	7.88	8.23
72768	A	517	13.6437	2.92	3.59	4.52	5.07	5.32	5.56	5.90
72768	A	518	13.6165	2.96	3.65	4.52	5.10	5.37	5.60	5.95
72768	B	519	13.6956	2.96	3.69	4.64	5.28	5.54	5.80	6.16
72768	B	520	13.7200	2.85	3.59	4.61	5.20	5.45	5.70	6.08
Cr 1.1	A	493	11.0218	3.84	4.81	5.63	6.33	6.47	6.92	6.58
Cr 1.1	A	494	13.7718	3.75	4.97	5.56	6.24	6.70	7.17	6.90
Cr 1.1	B	495	13.4363	2.69	3.45	4.11	4.67	4.79	5.15	5.51
Cr 1.1	B	496	13.6437	3.62	4.74	5.39	5.39	6.47	6.90	7.34
Cr 1.9	A	497	13.7611	3.55	4.69	5.55	6.25	6.41	6.88	7.33
Cr 1.9	A	498	13.7337	4.35	5.78	6.60	7.38	7.78	8.32	8.70
Cr 1.9	B	499	13.8159	3.42	4.63	5.57	6.31	6.49	6.99	7.52
Cr 1.9	B	500	13.9780	4.29	5.74	6.58	7.48	8.00	8.59	8.96
Cr 2.0	A	501	13.7365	3.14	4.20	4.99	5.56	5.70	6.07	6.40
Cr 2.0	A	502	13.6573	4.14	5.37	6.20	6.91	7.37	7.89	7.94
Cr 2.0	B	503	13.7092	3.49	4.72	5.63	6.22	6.34	6.74	7.25
Cr 2.0	B	504	13.7092	4.09	5.49	6.37	7.15	7.59	8.10	8.43
Cr 4.2	A	505	13.6845	3.84	4.47	5.61	6.26	6.64	6.85	7.15
Cr 4.2	A	506	13.6301	4.45	5.72	6.58	7.34	7.75	8.18	8.48
Cr 4.2	B	507	13.7337	4.30	5.65	6.49	7.36	7.83	8.47	8.93
Cr 4.2	B	508	13.5130	3.35	4.13	5.30	5.97	6.37	6.70	7.10
Cr 8.7	A	509	13.7092	3.03	3.67	4.14	4.79	5.08	5.41	5.65
Cr 8.7	A	510	13.5621	3.05	3.70	4.17	4.82	5.12	5.45	5.72
Cr 8.7	B	511	13.7092	2.63	3.26	4.15	4.73	5.05	5.33	5.70
Cr 8.7	B	512	13.7611	2.58	3.21	4.04	4.61	4.91	5.18	5.55
12-5-3	A	513	13.6546	6.14	7.60	9.40	10.7	11.3	12.0	12.7
12-5-3	A	514	13.7993	5.97	7.31	9.26	10.5	11.1	11.8	12.5
12-5-3	C	515	13.5016	3.63	4.87	6.65	7.86	8.39	9.04	9.79
12-5-3	C	516	13.6325	3.43	4.64	6.39	7.66	8.18	8.80	9.56

[a] A = Cold worked, B = annealed 1 hr at 927°C in argon, and C = annealed 1 hr at 816°C in argon.

Table A3. Weight Change Data for Specimens of Stainless Steels

Stainless Steel Type	Specimen	Condition[a]	Area (cm^2)	Weight Gain, mg/cm^2, at Various Times in hr											
				1,000	2,000	3,000	4,000	5,100	6,000	7,000	8,000	8,700	10,000	11,000	12,000
502	372	Annealed	13.7092	3.71	4.77	5.43	6.05	6.84	7.52	8.20	9.75	9.90	10.28	10.61	
502	373	Annealed	13.0605	3.29	4.23	4.95	5.49	6.19	6.64	7.09	8.26	8.56	8.94	9.48	
502	405	Cold Worked 50%	13.8650	2.91	4.05	5.14	5.74	6.51	7.11	7.77	8.65	7.02	7.46	7.65	
17-7 PH	374	Annealed	13.9202	0.50	0.66	0.83	0.98	1.19	1.32	1.44	1.75	1.65	1.65	1.69	
17-7 PH	375	Annealed	13.8598	0.33	0.51	0.67	0.84	1.08	1.23	1.41	1.65	1.60	1.61	1.67	
201	352	Annealed	13.5782	0.71	1.16	1.81	2.20	2.70	3.02	3.39	3.77	3.96	4.16	4.34	
201	353	Annealed	13.5727	0.81	1.35	2.08	2.49	2.98	3.29	3.75	3.97	4.10	4.35	4.55	
201	354	Cold Worked 50%	13.6137	0.04	0.04	0.07	0.04	0.05	0.14	0.21	0.24	0.18	0.11	0.13	
201	355	Cold Worked 50%	13.7611	0.03	0.03	0.05	0.03	0.07	0.15	0.27	0.32	0.02	0.02	0.03	
304	349	As-Received	13.6554	0.79	1.11	1.25	1.47	1.64	1.83	2.05	2.24	2.60[b]	2.54[c]	2.45	2.50
309	359	Annealed	13.7911	1.60	2.05	2.53	2.72	2.95	3.09	3.23	3.45	3.46	3.34	3.37	
309	360	Annealed	13.4095	1.69	2.06	2.48	2.67	2.90	3.01	3.17	3.43	3.39	3.29	3.31	
310	361	Annealed	13.5377	0.57	0.91	1.10	1.20	1.31	1.43	1.56	1.74	1.60	1.51	1.49	
310	362	Annealed	13.5377	0.83	1.10	1.29	1.40	1.50	1.58	1.71	1.84	1.73	1.70	1.69	
316	363	Annealed	13.5893	1.34	1.71	2.07	2.39	2.79	3.06	3.35	3.75	3.89	4.07	4.25	
316	364	Annealed	13.1245	1.44	1.87	2.27	2.61	2.96	3.20	3.49	3.80	3.97	4.15	4.37	
316	365	Cold Worked 50%	13.5512	0.52	0.66	0.85	1.00	1.14	1.23	1.34	1.56	1.55	1.51	1.54	
321	366	Annealed	13.4699	0.75	1.05	1.39	1.69	2.09	2.31	2.61	3.13	3.33	3.56	3.82	
321	367	Annealed	13.4320	0.67	0.93	1.22	1.47	1.84	2.03	2.29	2.76	2.91	3.05	3.28	
347	334	Annealed	13.2688	0.67	1.05	1.17	1.33	1.42	1.52	1.61	1.73	1.94	1.71	1.70	1.71
347	335	Annealed	13.3337	0.55	0.78	0.92	1.09	1.19	1.25	1.37	1.55	1.81	1.45	1.44	1.46
406	368	Annealed	13.7580	1.56	1.92	2.28	2.51	2.85	3.02	3.17	3.42	3.48	3.53	3.61	
406	369	Annealed	13.6301	1.25	1.54	1.86	2.09	2.45	2.62	2.80	3.07	3.16	3.16	3.24	
406	406	Cold Worked 50%	13.5830	0.73	0.96	1.20	1.40	1.58	1.97	1.86	1.97	2.03	2.00	2.02	
410	336	Annealed 927°C	13.7768	2.39	2.80	3.03	3.48	3.80	4.11	4.37	4.77	5.23	5.27	5.44	5.69
410	337	Annealed 927°C	13.5450	2.53	3.03	3.22	3.68	4.02	4.36	4.61	5.02	5.46	5.51	5.70	5.98
446	370	Annealed	12.8269	1.03	1.30	1.58	1.77	2.00	2.09	2.18	2.50	2.49	2.39	2.43	
446	371	Annealed	14.0554	1.52	1.82	2.03	2.16	2.38	2.56	2.72	2.97	2.87	2.78	2.79	

[a] Annealed 1 hr in argon at 1038°C unless otherwise specified.

[b] 9000 hr.

[c] 9700 hr.

Table A4. Weight Change Data for Specimens of Nickel 280 Annealed 1 hr in Argon at 800°C

Specimen	Area (cm^2)	Weight Gain, mg/cm^2, at	
		400 hr	1518 hr
266	13.8262	4.44	54.43
267	13.8262	3.33	77.11
268	13.9680	4.30	72.95
269	13.7880	5.25	75.29

Table A5. Weight Change Data for Specimens of Various Metals and Alloys

Material	Specimen	Condition[a]	Area (cm^2)	Weight Gain, mg/cm^2, at Various Times in hr															
				1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	8,700	10,000	11,000	12,000	13,000	13,700	15,000	16,000
Armco Iron	356	Annealed 927°C	13.6683	4.44	5.52	7.06	8.06	9.17	9.59	10.19	10.97	11.39	11.90	12.30					
	357	Annealed 927°C	13.6241	4.33	5.37	6.88	7.87	9.06	9.62	10.25	11.08	11.41	11.94	12.43					
	358	Cold Worked 50%	13.7063	4.66	5.68	7.22	8.24	9.38	9.97	10.57	11.47	11.89	12.45	12.97					
Monel	332	Annealed 800°C	13.6301	0.62	2.81	7.89	12.96	17.28											
	333	Annealed 800°C	13.6301	1.19	4.59	9.50	14.42	18.54	23.33[b]	27.38	30.52	35.08[c]	38.22[d]	42.21	45.79				
Copper	466	Annealed 800°C	13.5783	0.34	−0.13	−0.94	−1.61	−2.72	−3.71	−5.45[d]	−5.45	−7.65[c]							
	467	Annealed 800°C	13.5554	0.22	−0.18	−1.17	−1.80	−2.60	−3.68	−4.46[d]	−4.46	−6.23[c]							
Inconel 600	388	Annealed 1176°C	13.5130	0.26	0.30	0.41	0.46	0.52	0.58	0.69	0.87	0.80	0.78	0.77					
	389	Annealed 1176°C	13.5265	0.24	0.27	0.37	0.43	0.49	0.62	0.87	0.86	0.85	0.71	0.74					
Inconel 601	316	Annealed 1176°C	13.7337	0.06	0.11	0.17	0.17	0.19	0.25			0.36[c]	0.42[e]	0.50	0.56	0.73	0.57	0.52	0.57
	317	Annealed 1176°C	13.7611	0.07	0.12	0.20	0.22	0.24	0.31			0.40[c]	0.45[e]	0.51	0.59	0.71	0.60	0.55	0.59
	468	Cold Worked 50%	13.7546	0.21	0.31	0.44	0.55	0.54	0.55	0.48	0.50								
Inconel 718	390	Annealed 1176°C	13.5644	0.05	0.02	0.00	0.02	0.03	0.10	0.30	0.29	0.25	0.10	0.10					
	391	Annealed 1176°C	13.7195	0.05	0.02	−0.02	0.00	0.04	0.10	0.28	0.25	0.22	0.10	0.10					
	412	Cold Worked 50%	13.3954	0.12	0.13	0.15	0.18	0.22	0.42	0.51	0.49	0.40	0.32	0.34					

[a] Annealed 1 hr in argon at the indicated temperature.

[b] 6,100 hr.

[c] 9,000 hr.

[d] 6,700 hr.

[e] 10,100 hr.

Table A6. Weight Change Data for Specimens of Incoloy 800 and Hastelloys B and C

Alloy	Specimen	Condition[a]	Area (cm^2)	Weight Gain, mg/cm^2, at Various Times in hr																	
				1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	8,700	10,000	11,000	13,000	14,000	15,000	16,000	17,000	17,700	19,000
Incoloy 800	198	Annealed 1037°C	13.6339	0.50[b]	0.80[c]		0.95														
	199	Annealed 1037°C	13.6200	0.41	0.71		0.82	0.82	0.84		0.90				0.92	0.95	1.03	1.15	1.43	1.11	1.00
	200	Annealed 1037°C	13.6350	0.42	0.68		0.81	0.71	0.71		0.75				0.80	0.86	0.92	1.03	1.24	1.01	0.89
	201	Annealed 1037°C	13.5310	0.51	0.81																
	469	Cold Worked 50%	13.8543	0.17	0.17	0.65	0.35	0.36	0.35	0.19[d]	0.24										
Hastelloy B	376	Annealed 1176°C	12.6206	0.10	0.11	0.16	0.19	0.27	0.34	0.36	0.47	0.42	0.38	0.40							
	377	Annealed 1176°C	13.6480	0.12	0.16	0.21	0.25	0.30	0.34	0.40	0.56	0.50	0.43	0.43							
	407	Cold Worked 50%	13.3631	0.16	0.29	0.49	0.62	0.76	0.94	1.16	1.26	1.32	1.25	1.29							
Hastelloy C	378	Annealed 1176°C	13.5241	0.06	0.08	0.10	0.13	0.16	0.23	0.30	0.44	0.35	0.26	0.24							
	379	Annealed 1176°C	13.5621	0.04	0.06	0.07	0.08	0.14	0.25	0.32	0.51	0.35	0.26	0.22							
	408	Cold Worked 50%	13.6220	0.15	0.17	0.21	0.21	0.25	0.32	0.40	0.43	0.41	0.32	0.35							

[a] Annealed 1 hr in argon at the indicated temperature.

[b] 670 hr.

[c] 2,482 hr.

[d] 6,700 hr.

Table A7. Weight Change Data for Specimens of Various Superalloys

Alloy	Specimen	Condition[a]	Area (cm²)	Weight Gain, mg/cm², at Various Times in hr										
				1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000
Hastelloy S	417	Annealed	13.7229	0.09	0.14	0.15	0.20	0.27	0.44	0.55	0.50[b]	0.34		
	418	Annealed	13.7229	0.09	0.12	0.15	0.19	0.27	0.46	0.47	0.46[b]	0.32		
Hastelloy W	380	Annealed	12.8533	0.04	0.05	0.09	0.10	0.15	0.21	0.31	0.20	0.22[c]	0.22	0.25
	381	Annealed	13.2794	0.04	0.06	0.09	0.07	0.12	0.17	0.23	0.38	0.23[c]	0.21	0.23
	409	Cold Worked 50%	13.3134	0.11	0.16	0.20	0.23	0.30	0.38	0.49	0.59	0.62[c]	0.60	0.66
Hastelloy X	382	Annealed	13.8476	0.06	0.06	0.09	0.11	0.15	0.17	0.22	0.33	0.23[c]	0.20	0.22
	383	Annealed	13.7953	0.04	0.04	0.05	0.05	0.15	0.18	0.22	0.33	0.25[c]	0.21	0.20
	410	Cold Worked 50%	13.7063	0.12	0.14	0.17	0.21	0.24	0.35	0.38	0.47	0.46[c]	0.35	0.36
Haynes 25	384	Annealed	13.4209	0.03	0.01	0.10	0.16	0.28	0.34	0.40	0.58	0.49[c]	0.46	0.48
	385	Annealed	13.5889	0.07	0.08	0.18	0.23	0.37	0.41	0.50	0.66	0.60[c]	0.54	0.52
Haynes 188	386	Annealed	13.2926	0.03	0.01	0.05	0.08	0.14	0.18	0.32	0.46	0.41[c]	0.32	0.28
	387	Annealed	14.0295	0.04	0.04	0.07	0.11	0.16	0.21	0.32	0.49	0.44[c]	0.38	0.31
	413	Cold Worked 50%	13.7684	0.23	0.27	0.30	0.33	0.36	0.75	0.71	0.92	0.87[c]	0.60	0.58
Rene 62	392	Annealed	13.6678	0.18	0.16	0.19	0.22	0.25	0.33	0.55	0.55	0.51[c]	0.40	0.37
	393	Annealed	13.8791	0.15	0.14	0.17	0.18	0.23	0.30	0.46	0.54	0.48[c]	0.29	0.30
	411	Cold Worked	13.7580	0.15	0.16	0.20	0.24	0.29	0.56	0.62	0.61	0.57[c]	0.45	0.50

[a] Anneals are for 1 hr in argon at 1176°C.

[b] 7,700 hr.

[c] 8,700 hr.

Table A8. Weight Change Data for Specimens of Modified Hastelloy N Laboratory Heats[a]

Heat	Specimen	Area (cm^2)	Weight Gain, mg/cm^2, at Various Times in hr														
			1,000	2,000	4,482	6,000	7,000	8,000	10,000	15,000	16,100	17,000	18,000	19,000	19,700	21,000	22,000
185	87	13.6149	0.14														
185	88	13.6431	0.21	0.29	0.49	0.54		0.59	0.65	0.74	0.81	0.98	1.01	1.11	1.00	0.99	1.02
185	89	13.6603	0.20	0.32													
185	90	13.6048	0.12	0.24	0.41	0.55		0.53	0.58								
186	91	13.5903	0.21	0.24													
186	92	13.6285	0.12	0.21	0.36	0.49		0.48	0.59								
186	521	13.6410	0.05	0.14	0.36[b]	0.28	0.27										
188	37	13.6213	0.29	0.40	0.62	0.57		0.68	0.71	0.78	0.84	0.99	1.05	1.15	0.99	0.95	1.00
188	38	13.5819	0.09	0.19	0.32	0.32		0.40	0.46								
231	35	13.6267	0.12	0.21	0.28	0.29											
231	36	13.6386	0.26	0.43													
231	105	12.5198	0.27	0.38	0.58	0.62		0.65	0.69	0.72	0.79	0.93	1.06	1.09	0.94	0.89	0.89
232	103	13.5416	0.18	0.22	0.39	0.43		0.44	0.47	0.55	0.59	0.78	0.80	0.84	0.72	0.71	0.72
232	104	13.5230	0.21	0.24	0.39	0.46		0.47	0.50								
236	101	13.6424	0.11	0.17	0.35	0.41		0.45	0.52	0.60	0.66	0.88	0.89	0.93	0.84	0.84	0.85
236	102	13.6070	0.18	0.26	0.43	0.46		0.49	0.54								
237	99	13.6422	0.10	0.15	0.24	0.28		0.29	0.33	0.38	0.43	0.65	0.65	0.73	0.58	0.59	0.60
237	100	13.6359	0.10	0.14	0.23	0.32		0.26	0.32								

[a] Annealed 1 hr in argon at 1176°C.

[b] 4,700 hr.

Table A9. Weight Change Data for Specimens of Standard Hastelloy N Large Commercial Heats

Heat	Specimen	Condition[a]	Thickness (mm)	Area (cm^2)	Weight Gain, mg/cm^2, at Various Times in hr													
					1,000	2,000	4,482	6,000	8,000	10,000	15,000	16,100	17,000	18,000	19,000	19,700	21,000	22,000
2477	23		0.77	13.6662	0.15	0.21	0.34	0.33	0.38	0.41	0.48	0.54	0.69	0.75	0.86	0.68	0.68	0.70
2477	24		0.77	13.5224	0.13	0.25												
2477	55		0.25	12.8177	0.07	0.12	0.22	0.26	0.23	0.27	0.29	0.34	0.51	0.54	0.59	0.47	0.45	0.53
2477	56		0.25	12.7622	0.09	0.14	0.24	0.29										
2477	57		0.25	12.6151	0.10	0.17												
2477	58		0.25	12.4519	0.07	0.13	0.18	0.26	0.22	0.26								
2477	59		0.25	12.7940	0.07	0.09	0.25	0.26										
2477	60		0.25	12.6220	0.11	0.13												
2477	61	Cold Worked 50%	0.25	12.6409	0.13	0.15	0.27	0.31	0.36	0.42	0.50	0.55	0.70	0.73	0.81	0.73	0.72	0.75
2477	62	Cold Worked 50%	0.25	12.9948	0.15	0.18												
2477	63	Cold Worked 50%	0.25	12.9303	0.13	0.20	0.33	0.39										
2477	64	Cold Worked 50%	0.25	12.5853	0.10	0.17	0.28	0.36	0.36	0.45	0.52	0.58	0.76	0.77	0.90	0.76	0.76	0.79
5065	1		0.25	12.5543	0.14	0.20	0.29	0.32	0.29	0.33								
5065	2		0.25	12.5932	0.10	0.14	0.33	0.28	0.30	0.33	0.36	0.41	0.57	0.64	0.68	0.66	0.54	0.54
5065	3		0.51	12.9448	0.15	0.20	0.30	0.32	0.35	0.37	0.41	0.45	0.56	0.63	0.72	0.70	0.59	0.57
5065	4		0.51	12.9558	0.14	0.22	0.33	0.35	0.33	0.36	0.41	0.47	0.58	0.67	0.73	0.73	0.64	0.61
5065	5		0.77	13.4914	0.16	0.22	0.33	0.33	0.33	0.36	0.39	0.45	0.58	0.63	0.70	0.67	0.56	0.56
5065	6		0.77	13.5692	0.15	0.22	0.34	0.35	0.37	0.41	0.45	0.51	0.65	0.69	0.80	0.73	0.63	0.61
5065	7		1.52	14.5614	0.14	0.24	0.36	0.40	0.41	0.45	0.55	0.62	0.78	0.82	0.90	0.88	0.77	0.75
5065	8		1.52	14.5693	0.14	0.21	0.33	0.36	0.38	0.42	0.47	0.54	0.66	0.71	0.76	0.71	0.67	0.66
5065	9		0.77	13.5302	0.18	0.22	0.33	0.33	0.33	0.34	0.38	0.43	0.55	0.58	0.64	0.63	0.55	0.53
5065	10		0.77	13.6351	0.15	0.22	0.31	0.32	0.37	0.40	0.43	0.48	0.64	0.64	0.70	0.69	0.62	0.60
5065	11	Abraded	0.77	13.5960	0.29	0.40	0.56	0.60	0.63	0.70	0.81	0.87	1.01	1.04	1.08	1.08	1.04	1.03
5065	12	Abraded	0.77	13.5079	0.25	0.39	0.55	0.60	0.64	0.69	0.78	0.85	1.04	1.07	1.08	1.07	1.01	1.01
5065	13	Electropolished	0.77	13.3979	0.04	0.08	0.13	0.16	0.14	0.18	0.22	0.27	0.42	0.52	0.52	0.49	0.42	0.42
5065	14	Electropolished	0.77	13.2262	0.03	0.09	0.15	0.15	0.18	0.22	0.29	0.33	0.45	0.50	0.50	0.43	0.45	0.46
5065	15		0.25	12.5496	0.08	0.37	0.29	0.29										
5065	16		0.25	12.5359	0.07	0.18												
5065	17		0.25	12.5742	0.14	0.22	0.34	0.32										
5067	18		0.77	13.3301	0.14	0.22	0.30	0.31										
5065	19		0.25	12.4907	0.10	0.22	0.26	0.34										
5067	20		0.77	13.3419	0.12	0.21	0.30	0.30	0.31	0.35	0.40	0.47	0.56	0.56	0.66	0.56	0.54	0.56
5067	67		0.77	13.2601	0.12	0.20												
5067	68		0.77	13.1974	0.06	0.11	0.23	0.28	0.26	0.32								
5085	21		0.77	13.6078	0.12	0.23	0.32	0.32	0.32	0.37	0.44	0.49	0.65	0.66	0.79	0.60	0.57	0.59
5085	22		0.77	13.5278	0.13	0.18	0.34	0.34										
5085	65		0.77	13.7014	0.11	0.17	0.34	0.36	0.37	0.43								
5085	66		0.77	13.5821	0.13	0.18												
M1566	394		0.77	13.6297	0.09	0.09	0.18[b]	0.29	0.56	0.38	0.39[c]							
M1566	395		0.77	13.6678	0.11	0.12	0.22[b]	0.32	0.62	0.37	0.40[c]							
M1566	406	Cold Worked 50%	0.77	13.8262	0.12	0.15	0.33[b]	0.64	0.92	0.85	0.91[c]							

[a] Unless otherwise specified, annealed 1 hr at 1176°C in argon, tested with the surface in the as-rolled condition.

[b] 4,000 hr.

[c] 11,000 hr.

Table A10. Weight Change Data for Specimens of Modified Hastelloy N Commercial Heats[a]

Heat	Specimen	Area (cm^2)	Weight Gain, mg/cm^2, at Various Times in hr															
			1,000	2,000	4,482	5,000	6,000	8,000	10,000	13,000	14,000	15,100	16,000	17,000	18,000	18,700	20,000	21,000
21545	27	13.4661	0.19															
21545	28	13.4492	0.25	0.34	0.42		0.43	0.43	0.48									
21545	97	13.3940	0.13	0.22														
21545	98	13.4485	0.15	0.19	0.34		0.42											
21546	25	13.5637	0.23	0.31	0.40		0.37	0.41	0.44									
21546	26	13.5364	0.18															
21546	95	13.6380	0.23	0.29	0.40		0.45											
21546	96	13.5981	0.25	0.31														
21554	83	13.5252	0.21	0.31	0.49		0.59											
21554	84	13.5208	0.22	0.33														
21554	85	13.5629	0.19	0.28	0.43		0.56	0.52	0.60									
21554	86	13.5674	0.27															
21555	79	13.4514	0.25															
21555	80	13.5829	0.13	0.22	0.35		0.46											
21555	81	13.5219	0.11	0.18	0.29		0.35	0.36	0.41									
21555	82	13.4692	0.29	0.39														
68688	75	13.6022	0.12	0.18														
68688	76	13.5285	0.10	0.14	0.24		0.33											
68688	77	13.5245	0.04	0.13	0.24		0.30	0.27	0.33									
68688	78	13.5056	0.10															
68688	194	13.1127	−0.01	0.13[b]	0.25[c]	0.19	0.19	0.24		0.26	0.31	0.39	0.49	0.63	0.44[d]	0.40[e]		
68689	71	13.2735	0.12	0.18	0.31		0.41											
68689	72	13.5373	0.10	0.18	0.30		0.41	0.40	0.44									
68689	73	13.4412	0.13	0.19														
68689	74	13.4479	0.14															
68689	195	12.9800	0.03	0.13[b]	0.25[c]	0.17	0.18	0.26		0.29	0.34	0.44	0.54	0.61	0.55[d]	0.49[e]		
69641	160	13.4860	0.10															
69641	161	13.5752	0.09	0.12	0.24		0.22	0.25	0.39		0.40	0.44	0.60	0.69	0.65	0.55	0.52	0.55
69641	196	13.5937	0.04	0.17[b]	0.18[c]	0.21	0.27	0.32		0.38	0.43	0.53	0.60	0.60	0.52[d]	0.51[e]		
69648	157	13.5881	0.12	0.14	0.26		0.34	0.32	0.36		0.52	0.57	0.69	0.78	0.80	0.70	0.71	0.73
69648	158	13.5307	0.10															
69648	197	13.6013	0.03	0.18[b]	0.26[c]	0.24	0.29	0.36		0.45	0.51	0.57	0.70	0.84	0.74[d]	0.67[e]		

[a] Annealed 1 hr in argon at 1176°C.

[b] 2,482 hr.

[c] 4,000 hr.

[d] 17,700 hr.

[e] 19,000 hr.

Table A11. Weight Change Data for Specimens of Modified Hastelloy N Commercial Heats[a]

Heat	Specimen	Area (cm^2)	Weight Gain, mg/cm^2, at Various Times in hr															
			1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,100	11,000	12,000	13,000	13,700	15,000	16,000
21541	314	13.6926	0.12	0.14	0.19	0.22	0.18	0.20			0.26	0.28	0.34	0.41	0.59	0.26	0.20	0.22
21541	315	13.7063	0.11	0.18	0.20	0.23	0.20	0.20			0.30	0.32	0.38	0.45	0.60	0.33	0.26	0.26
21542	312	13.6926	0.02	0.06	0.09	0.13	0.12	0.12			0.18	0.23	0.29	0.37	0.53	0.25	0.19	0.19
21542	313	13.8022	0.10	0.12	0.16	0.17	0.16	0.19			0.21	0.25	0.33	0.40	0.57	0.28	0.21	0.23
21543	310	13.7611	0.09	0.12	0.15	0.15	0.14	0.15			0.22	0.27	0.33	0.35	0.40	0.17	0.06	0.06
21543	311	13.7748	0.12	0.14	0.17	0.19	0.16	0.17			0.24	0.28	0.33	0.42	0.51	0.19	0.08	0.09
21544	308	13.7200	0.24	0.35	0.36	0.31	0.19	0.23			0.36	0.43	0.51	0.60	0.79	0.78	0.60	0.63
21544	309	13.7959	0.17	0.26	0.31	0.36	0.28	0.27			0.41	0.48	0.57	0.62	0.91	0.83	0.62	0.63
21545	343	13.4363	0.19	0.25	0.27	0.31	0.31	0.34	0.46	0.48	0.60	0.48[b]	0.41	0.36				
21546	344	13.6956	0.27	0.34	0.34	0.39	0.41	0.45	0.56	0.58	0.71	0.61[b]	0.53	0.51				
21554	345	13.6301	0.13	0.17	0.20	0.27	0.31	0.38	0.47	0.54	0.90	0.78[b]	0.55	0.54				
21555	346	13.3827	0.07	0.12	0.13	0.19	0.25	0.28	0.38	0.40	0.56	0.52[b]	0.40	0.27				
70727	342	14.1173	−0.05	−0.04	−0.05	−0.03	−0.03	0.01	0.08	0.18	0.38	0.11[b]	0.09	0.11				
70785	306	13.7337	0.05	0.11	0.17	0.23	0.18	0.19			0.30	0.37	0.45	0.55	0.79	0.63	0.53	0.52
70785	307	13.7063	0.12	0.12	0.18	0.20	0.21	0.23			0.26	0.34	0.40	0.47	0.74	0.67	0.51	0.55
70786	304	13.7063	0.07	0.11	0.16	0.20	0.20	0.20			0.33	0.39	0.47	0.58	0.80	0.59	0.55	0.61
70786	305	13.7474	0.09	0.09	0.14	0.15	0.17	0.21			0.33	0.39	0.48	0.57	0.90	0.66	0.58	0.63
70787	302	13.7337	0.10	0.15	0.24	0.25	0.27	0.28			0.44	0.50	0.60	0.71	0.96	0.71	0.64	0.69
70787	303	13.6926	0.07	0.15	0.23	0.26	0.23	0.25			0.38	0.45	0.55	0.64	0.98	0.69	0.60	0.64
70788	300	13.7337	0.09	0.10	0.15	0.15	0.17	0.18			0.30	0.37	0.45	0.66	0.77	0.66	0.60	0.66
70788	301	13.7885	0.01	0.01	0.06	0.05	0.07	0.08			0.18	0.25	0.36	0.49	0.62	0.46	0.43	0.49
70795	298	13.6515	0.03	0.08	0.14	0.20	0.18	0.18			0.27	0.36	0.45	0.56	0.80	0.64	0.50	0.55
70795	299	13.6789	0.01	0.06	0.08	0.16	0.16	0.16			0.28	0.34	0.42	0.54	0.68	0.59	0.47	0.49
70796	296	13.8323	0.06	0.10	0.17	0.20	0.15	0.13			0.25	0.34	0.42	0.51	0.93	0.74	0.46	0.50
70796	297	13.8296	0.09	0.12	0.17	0.23	0.13	0.12			0.28	0.38	0.46	0.55	0.75	0.68	0.54	0.57
70797	294	13.7666	0.03	0.04	0.09	0.14	0.12	0.12			0.19	0.25	0.32	0.41	0.60	0.52	0.33	0.33
70797	295	13.7611	0.04	0.07	0.10	0.13	0.13	0.12			0.20	0.26	0.32	0.41	0.63	0.51	0.37	0.39
70798	292	13.7081	0.03	0.03	0.09	0.12	0.09	0.09			0.16	0.21	0.24	0.36	0.51	0.39	0.30	0.28
70798	293	13.6877	0.04	0.08	0.12	0.16	0.15	0.15			0.25	0.31	0.35	0.44	0.61	0.52	0.40	0.41
70835	290	13.9187	0.05	0.02	0.06	0.08	0.07	0.07			0.09							
70835	291	13.7819	0.04	0.04	0.09	0.09	0.09	0.08			0.14	0.17	0.22	0.31	0.54	0.35	0.27	0.28
70835	529	13.9030	0.11	0.31	0.41	0.46	0.41	0.35	0.35									
71114	338	13.7502	0.10	0.17	0.17	0.23	0.28	0.33	0.42	0.56	0.76	0.41[b]	0.43	0.45				
71114	339	13.4699	0.10	0.15	0.15	0.20	0.23	0.33	0.39	0.51	0.69	0.37[b]	0.41	0.45				
71583	340	13.6410	0.08	0.11	0.13	0.20	0.25	0.32	0.42	0.53	0.73	0.43[b]	0.46	0.54				
71583	341	13.5512	0.08	0.13	0.15	0.21	0.26	0.33	0.44	0.55	0.72	0.47[b]	0.50	0.58				
72115	396	13.7987	0.18	0.23	0.34	0.44	0.52	0.65	0.88	0.96	0.92[c]	0.82	0.86					
72115	397	13.7606	0.17	0.20	0.31	0.41	0.48	0.78	0.89	1.00	0.94[c]	0.73	0.75					
72115	414[d]	13.7200	0.18	0.29	0.42	0.51	0.59	0.70	0.82	0.94	0.93[c]	0.84	0.88					
72503	398	13.8469	0.12	0.14	0.22	0.27	0.36	0.50	0.66	0.71	0.72[c]	0.65	0.70					
72503	399	13.9060	0.11	0.12	0.20	0.27	0.35	0.44	0.59	0.64	0.64[c]	0.60	0.65					
72503	415[d]	13.7870	0.04	0.02	0.02	0.04	0.06	0.12	0.24	0.32	0.33[c]	0.27	0.25					
72604	400	14.0059	0.39	0.40	0.47	0.54	0.61	0.72	0.85	0.91	0.85[c]	0.75	0.72					
72604	401	13.9300	0.34	0.34	0.39	0.46	0.55	0.69	0.83	0.87	0.84[c]	0.70	0.71					
72604	416	12.4655	0.15	0.23	0.36	0.44	0.57	0.71	0.84	0.96	0.99[c]	0.97	0.99					
73008	530[d]	13.1383	0.00	0.05	0.12	0.15	0.17	0.18	0.19									
73008	531[d]	13.3845	0.08	0.25	0.25	0.34	0.32	0.31	0.32									
73008	532	13.5265	0.10	0.14	0.21	0.24	0.24	0.23	0.22									
73008	533	13.5265	0.23	0.44	0.47	0.62	0.62	0.58	0.57									

[a] Unless otherwise specified, annealed 1 hr at 1176°C in argon.

[b] 9,700 hr.

[c] 8,700 hr.

[d] Cold worked 50%.

Table A12. Weight Change Data for Specimens of Modified Hastelloy N Commercial Heats[a]

Heat	Specimen	Area (cm^2)	Weight Gain, mg/cm^2, at Various Times in hr						
			1,812	3,330	4,330	5,330	6,330	8,330	12,330
69344	258	13.6713	0.21	0.17	0.19	0.21	0.23	0.22	0.26
69344	259	13.6708	0.12	0.20	0.24	0.21	0.25	0.25	0.28
69344	522	14.0641	0.14[b]	0.23[c]	0.24[d]	0.21[e]	0.23[f]	0.25[g]	
69344	523	14.3600	0.18[b]	0.29[c]	0.33[d]	0.23[e]	0.25[f]	0.27[g]	
69345	260	13.6722	0.18	0.13	0.16	0.20	0.26	0.21	0.26
69345	261	13.6106	0.15	0.20	0.19	0.19	0.23	0.21	0.26
69345	524	14.0517	0.29[b]	0.26[c]	0.38[d]	0.37[e]	0.32[f]	0.30[g]	
69345	525	13.9051	0.32[b]	0.32[c]	0.40[d]	0.40[e]	0.32[f]	0.29[g]	
69714	262	13.6283	0.16	0.22	0.20	0.21	0.23	0.24	0.31
69714	263	13.6248	0.16	0.20	0.18	0.21	0.30	0.28	0.34
69714	526	13.6273	0.42[b]	0.43[c]	0.54[d]	0.57[e]	0.45[f]	0.43[g]	
69714	527	13.6956	0.34[b]	0.37[c]	0.46[d]	0.48[e]	0.39[f]	0.38[g]	
70727	264	13.6558	0.19	0.24	0.27	0.29	0.39	0.37	
70727	265	13.6675	0.19	0.20	0.18	0.20	0.27	0.26	0.33
70727	528	14.2668	0.25[b]	0.29[c]	0.41[d]	0.33[e]	0.23[f]	0.19[g]	

[a] Annealed 1 hr at 1176°C in argon.

[b] 2,000 hr.

[c] 3,000 hr.

[d] 4,000 hr.

[e] 5,000 hr.

[f] 6,000 hr.

[g] 7,000 hr.

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