Report No. BMI-1179
Chemistry - General
(TID-4500, 13th Ed.)

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Contract No. W-7405-eng-92

CORROSION OF HIGH-TEMPERATURE ALLOYS IN SULFUR-
BEARING CRACKED-AMMONIA ATMOSPHERES

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April 17, 1957

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CORROSION OF HIGH-TEMPERATURE ALLOYS IN SULFUR-BEARING CRACKED-AMMONIA ATMOSPHERES

G. Lee Ericson, Walter J. Braun, Frederick W. Fink,
and Robert S. Peoples

A representative selection of stainless alloys has been exposed in sulfur-bearing cracked-ammonia atmospheres containing 43 volume per cent water vapor. Experimentally controlled variables have included temperatures ranging from 1200 to 1800 F and sulfur levels ranging from zero to 350 grains per 100 ft³ of cracked ammonia. It has been found that high sulfur levels do not result in any significant change in the corrosion behavior of materials evaluated. Increasing the temperature resulted in some modifications of both physical properties and scaling resistance; however, these changes are a function of the temperature and not an effect of sulfur.

INTRODUCTION

One stage in the production of uranium at Mallinckrodt involves the reduction of UO_3 to UO_2 , using hot cracked ammonia as the reducing agent. A review of the reduction process will reveal that the cracked ammonia is introduced into the reducing chamber dry, and that water is produced during the reaction, reaching a maximum at the effluent end. In preliminary tests at Mallinckrodt Chemical Works, it was indicated that many of the heat-resisting alloys were susceptible to severe embrittlement and corrosion when in contact for extended periods with a cracked-ammonia atmosphere at temperatures approximating 1500 F. Subsequent experience in the operation of a screw reactor for the reduction of solid oxides by the hydrogen from cracked ammonia at about 1150 F verified the fact that this embrittlement could become a serious operating problem. It thus became necessary to make a search for materials of construction having the necessary physical and mechanical properties, as well as sufficient resistance to scaling to minimize product contamination.

A laboratory study under controlled test conditions was undertaken, therefore, to determine the utility of many of the high-temperature alloys in cracked-ammonia atmospheres at temperatures of 1200 and 1500 F. It was considered essential that the effects of the various factors, such as the free ammonia and the moisture contents of the atmosphere, as well as the purely thermal effects on the structures of the alloys, be isolated and studied individually.

The behavior of nineteen of the commercial high-temperature alloys in cracked-ammonia atmospheres at temperatures of 1200 and 1500 F, both with and without the presence of moisture, was reported in BMI-269, dated June 30, 1953. The results of this work indicated that Type 347 stainless steel was one of the better materials tested.

After the completion of the above work, a question arose in regard to the degree and extent of corrosion if sulfate were added to the system to enhance the kinetics of the process. Under these conditions, there would be a distinct possibility that construction materials would have to handle moist hot-cracked ammonia gases containing sulfur.

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The purpose of the research described herein was to determine what effects sulfur-bearing cracked-ammonia gas has on the corrosion resistance of selected materials.

Eighteen high-temperature alloys were exposed at 1200, 1500, 1700, and 1800 F, at nominal sulfur levels of 0, 80, and 350 grains per 100 ft³ of cracked ammonia, and with the addition of approximately 43 volume per cent water vapor. The sulfur additions, calculated on the basis of elemental sulfur, were made by dissolving sulfur dioxide in the water used for the moisture additions.

EXPERIMENTAL WORK

Test Equipment and Procedures

The test equipment consisted essentially of an ammonia cracker, from which the dissociated gases were introduced into sample-exposure furnaces. A sulphur dioxide solution of suitable concentration was pumped into the influent end of the sample furnaces to supply the required water and sulphur. A flow diagram of the system is presented in Figure 1. Details of a sample-exposure furnace and a tensile-sample holder along with a sulfurous acid pump are shown in Figure 2.

Commercial anhydrous ammonia was introduced into the fused-silica cracker tube after pressure reduction (about 2 psig) where it contacted a catalyst consisting of porcelain chips impregnated with nickel. The temperature was maintained at approximately 1700 F, resulting in a residual uncracked ammonia content of approximately 0.1 per cent or less, calculated on a volume basis. The cracked-ammonia gas was introduced to the influent end of the sample-exposure furnace via a flowmeter at the rate of 100 ml per min. Water and sulfur dioxide were introduced jointly to give a water content of 43 volume per cent and the desired sulfur level. Measured quantities of sulfur dioxide were mixed with nitrogen and introduced into a thermostated reservoir. The concentration of the sulfur dioxide was determined by the temperature and the partial pressure of the gas. The sulfurous acid produced was pumped to the influent end of the sample furnace where it was vaporized by the heat of the furnace. The effluent gas was expelled through a bubble bottle to minimize back diffusion of air.

The samples used were in the form of sheet tensile specimens 8 by 3/4 in., with a reduced section 1/2 by 2-1/4 in. in the center. All specimens were the thickness of the stock available (0.040 to 0.100 in. thick). All edges were milled to close tolerances. Prior to exposure, the flat surfaces were abraded with 120-grit abrasive paper to remove scale and other surface contaminants. The specimens were degreased in acetone and weighed. After exposure, the samples were reweighed, the weight gain calculated, the hardness measured, and the ultimate and yield strengths determined. The percentage elongation was calculated.

The residual uncracked ammonia was determined by the following procedure: The effluent gas from the cracking furnace was bubbled at the rate of 100 ml per min through a gas scrubber containing standard acid (approximately 0.1 N H₂SO₄) for 1 to 4 hr. The remaining acid was neutralized with a standard base. The acid consumed was calculated to ml of ammonia, and to percentage of the original sample of cracked gas.

FIGURE 1. FLOW DIAGRAM OF EQUIPMENT FOR EXPOSING TENSILE SPECIMENS IN WET CRACKED-AMMONIA ATMOSPHERES WITH ADDED SULFUR

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FIGURE 2. PHOTOGRAPH OF A CONTROLLED-ATMOSPHERE
FURNACE SHOWING DETAILS OF THE TENSILE-
SAMPLE HOLDER AND SULFUROUS ACID PUMP

The concentration of the sulfurous acid solution was estimated by standard iodometric techniques.

The analysis of the off-gas was affected by the absorption of the sulfides and the unreduced sulfites in ammoniacal cadmium nitrate solution. Sulfides were determined from the precipitated cadmium sulfide, and sulfites were estimated from the soluble cadmium sulfite, both by iodometric procedures.

Four analyses of the off-gas from runs with added sulfur at 1700 F are presented in Table 1. From these data, it may be seen that the major portion of the sulfur injected as sulfur dioxide was reduced by the hot hydrogen to hydrogen sulfide. Portions of the initial sulfur were lost, probably through reactions with the piping and furnace linings. At 1200 F, small amounts of elemental sulfur were noted in the inlet end of the furnace tube directly below the water-sulfur dioxide injection line.

TABLE 1. ANALYSES OF OFF-GASES FROM CRACKED-AMMONIA RUNS WITH ADDED SULFUR DIOXIDE AT 1700 F

Time After Start of Run, hr	Sulfur Addition, grains per 100 ft ³ of cracked ammonia	Percentage of Sulfur Recovered as Hydrogen Sulfide	Percentage of Sulfur Recovered as Sulfur Dioxide	Percentage of Sulfur Accounted for by Analysis
40(a)	98	90	3.2	93.8
400(a)	98	98.3	0.6	98.9
350	77	77.1	4.2	81.3
100	400 to 500	71.4	0.5	71.9

(a) Data from the same run.

The heat-resisting alloys exposed at the various temperatures are as listed below:

1200 F	1500 F	1700 F	1800 F
<u>Austenitic Stainless Steels</u>			
Type 304	Type 304	--	--
Type 304 ELC	Type 304 ELC	--	--
Type 309	Type 309	--	--
Type 310	--	Type 310	--
Type 316	Type 316	--	--
Type 321	--	--	--
Type 330	Type 330	Type 330	Type 330
Type 347	Type 347	Type 347	Type 347

<u>1200 F</u>	<u>1500 F</u>	<u>1700 F</u>	<u>1800 F</u>
<u>Miscellaneous Iron-Chromium-Nickel Alloys</u>			
Type 17-7 PH	--	--	--
Carpenter 20	--	--	--
Carpenter 20 + Nb	Carpenter 20 + Nb	Carpenter 20 + Nb	--
--	--	Type S-588	--
<u>Nickel-Base Alloys</u>			
Hastelloy C, quench annealed	Hastelloy C, quench annealed	Hastelloy C, quench annealed	--
Hastelloy C, stabilized and annealed	--	--	--
Hastelloy F	Hastelloy F	--	--
Inconel R	--	Inconel R	Inconel R
Inconel X	Inconel X	Inconel X	--
--	--	Nimonic 80-A	--
<u>Cobalt-Base Alloy</u>			
Haynes 25	--	Haynes 25	--

The nominal chemical compositions of the alloys tested are presented in Table 2.

DISCUSSION OF THE EXPERIMENTAL RESULTS

Weight-gain, tensile-strength, elongation, and hardness data for tensile samples exposed in wet cracked ammonia with and without added sulfur at 1200, 1500, 1700, and 1800 F are presented in Table A-1 in the Appendix, and these data are shown graphically in Figures A-1 through A-16, also in the Appendix.

The weight-gain data only for the above listed exposures are summarized in Figures 3, 4, and 5. Data at 1200 and 1500 F in atmospheres without added sulfur were secured from the work initially reported in BMI-269.

At 1200 F, the weight gains, as shown in Figure 3, are generally low, and average approximately 1/2 mg per in.² after a 500-hr exposure, with small increases after 2000 hr. The attack does not appear to be significantly influenced by the presence of sulfur (80 grains per 100 ft³ cracked ammonia) at this temperature. Surface scaling was slightly greater on the Type 321 stainless steel samples than of any of the other 16 alloys similarly exposed to the sulfur-containing atmospheres.

A microscopic examination of the exposed samples revealed that the alloys suffered only superficial surface attack. A comparison of the data shows that, with the exception of Type 17-7 PH, none of these alloys suffered a marked decrease in tensile strength and ductility as a result of the corrosion. It may be seen that the exposure of Type 17-7 PH resulted in a marked decrease in both yield and ultimate strengths, but

TABLE 2. NOMINAL CHEMICAL COMPOSITIONS OF ALLOYS TESTED

Material	Composition, w/o										
	C	Fe	Cr	Ni	Mo	Co	Nb	W	Si	Mn	Other
<u>Austenitic Stainless Steels</u>											
Type 304 stainless	0.08 max	Bal	18	8	-	-	-	-	1	2	-
Type 304 ELC stainless	0.04 max	Bal	18	8	-	-	-	-	1	2	-
Type 309 stainless	0.20 max	Bal	25	12	-	-	-	-	1	2	-
Type 310 stainless	0.25 max	Bal	25	20	-	-	-	-	1.5	2	-
Type 316 stainless	0.10 max	Bal	18	12	2-3	-	-	-	1	2	-
Type 321 stainless	0.08 max	Bal	19	9	-	-	-	-	1	2	Ti, 5 X C min
Type 330 stainless	0.25 max	Bal	15	35	-	-	-	-	1	2	-
Type 347 stainless	0.08 max	Bal	19	9	-	-	10 X C min	-	1	2	-
<u>Miscellaneous Iron-Chromium-Nickel Alloys</u>											
Type 17-7 PH	-	Bal	17	7	-	-	-	-	-	-	1 Al
Carpenter 20	0.07 max	Bal	20	25	2	-	-	-	-	-	3 Cu
Carpenter 20 + Nb	0.07 max	Bal	20	25	2	-	8 X C min	-	-	-	3 Cu
Type S-588	.42	Bal	18	20	4	-	5	3	1	1.5	-
<u>Nickel-Base Alloys</u>											
Hastelloy C	0.10	5	16	57	17	-	-	4	-	1	-
Hastelloy F	-	Bal	22	45	7	-	2	-	-	-	-
Inconel R	0.20	5-8	18-24	55-60	5-8	-	-	-	-	0.5-1.8	2-6 Cu
Inconel X	0.04	7	15	73	-	-	1	-	0.4	0.5	2.5 Ti, 1 Al
Nimonic 80-A	0.05 max	0.5 max	20	76	-	-	-	1 max	1 max	-	2.3 Ti, 1 Al
<u>Cobalt-Base Alloy</u>											
Haynes 25	0.12	1	20	10	-	51	-	15	1	1.5	-

FIGURE 3. WEIGHT-GAIN DATA FOR ALLOYS EXPOSED AT 1200 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE 4. WEIGHT-GAIN DATA FOR ALLOYS EXPOSED AT 1500 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE 5. WEIGHT-GAIN DATA FOR ALLOYS EXPOSED AT 1700 F AND 1800 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

500-hr exposure.

this was accompanied by an increase in ductility. At 1200 F, an increase in the ductility of this alloy and a decrease in strength are to be expected.

At 1500 F the weight gains appear, from Figure 4, to be approximately tripled over those recorded at 1200 F, with gains averaging about 1-1/2 mg per in.² after a 500-hr exposure. The data from BMI-269 for the samples exposed without added sulfur indicated that Type 347 stainless steel offered advantages because of its low weight gain, and relatively unchanged physical properties after exposure. Inconel X and Type 304 have the highest weight gains, and blistering was noted for Type 304. In the presence of sulfur (80 grains per 100 ft³ cracked ammonia), the corrosion appears to be slightly inhibited. Again, the lowest weight gain of the stainless-type materials is shown for Type 347 stainless steel, and the physical properties are comparable with those noted for the sulfur-free exposures. The highest gains are recorded for Inconel X. No localized attack, such as pitting, was observed on the surface of the ten alloys by examination at 20 diameters.

At 1700 and 1800 F, the weight gains, as shown in Figure 5, are again approximately double those at 1500 F, resulting in approximately a sixfold increase over the 1200 F data. The lowest weight gains of the stainless-type materials are recorded for Type 347 stainless steel at 1700 F, both in the sulfur-free and sulfur-containing atmospheres. However, at 1800 F, the lowest weight gain was noted for Type 330 stainless steel. The highest gains are shown for Inconel X and Nimonic 80-A. At these temperatures, the influence of sulfur is not striking, although slightly lower weight gains may be noted for Types 330, 347, and Illium R as the sulfur content is increased to 350 grains per 100 ft³ of cracked ammonia.

A limited amount of weight-loss data were secured for the samples exposed at 1700 F. The exposed samples were stripped by means of a fused-salt bath, after which they were reweighed. The loss, in relationship with the original weight, was calculated on a milligram per square inch basis. There do not appear to be sufficient data to draw definite conclusions. Considerable discrepancy may be noted between the weight-gain and weight-loss data.

From the data presented in this report, it would appear that the presence of sulfur in quantities up to 350 grains per 100 ft³ of cracked ammonia containing 43 volume per cent of water vapor does not increase the corrosion of any of the alloys subjected to tests at temperatures from 1200 to 1800 F. The changes in physical properties noted are considered to be the result of temperature, and it is felt that these changes would have occurred in sulfur-free cracked ammonia or in an inert atmosphere. These tests show that the more common stainless steels, such as Types 310 and 347, would be fully adequate for service under conditions similar to the test conditions investigated.

GLE:WJB:FWF:RSP/vlb

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APPENDIX

List of Symbols Used in Figures A-1 Through A-16

<u>Symbol</u>	<u>Material</u>
<u>Austenitic Stainless Steels</u>	
△	Type 304
▲	Type 304 ELC
×	Type 309
▣	Type 310
▲	Type 316
○	Type 321
⊕	Type 330
□	Type 347
<u>Miscellaneous Iron-Chromium-Nickel Alloys</u>	
P	Type 17-7 PH
▣	Carpenter 20
■	Carpenter 20 plus niobium
<u>Nickel-Base Alloys</u>	
▣	Hastelloy C, quench annealed
▣	Hastelloy C, stabilized and annealed
F	Hastelloy F
○	Inconel R
▣	Inconel X
◇	Nimonic 80-A
<u>Cobalt-Base Alloy</u>	
H	Haynes 25

A-1

FIGURE A-1. WEIGHT-GAIN DATA FOR ALLOYS EXPOSED AT 1200 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE A-1. (CONTINUED)

FIGURE A-2. ULTIMATE-STRENGTH DATA FOR ALLOYS EXPOSED AT 1200 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

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FIGURE A-2. (CONTINUED)

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FIGURE A-2. (CONTINUED)

FIGURE A-3. YIELD-STRENGTH DATA FOR ALLOYS EXPOSED AT 1200 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

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FIGURE A-3. (CONTINUED)

FIGURE A-3. (CONTINUED)

FIGURE A-4. ELONGATION DATA FOR ALLOYS EXPOSED AT 1200 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE A-4. (CONTINUED)

FIGURE A-4. (CONTINUED)

FIGURE A-5. HARDNESS DATA FOR ALLOYS EXPOSED AT 1200 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE A-5. (CONTINUED)

FIGURE A-6. WEIGHT-GAIN DATA FOR ALLOYS EXPOSED AT 1500 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE A-7. ULTIMATE-STRENGTH DATA FOR ALLOYS EXPOSED AT 1500 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE A-8. YIELD-STRENGTH DATA FOR ALLOYS EXPOSED AT 1500 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE A-9. ELONGATION DATA FOR ALLOYS EXPOSED AT 1500 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE A-10. HARDNESS DATA FOR ALLOYS EXPOSED AT 1500 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE A-11. WEIGHT-GAIN DATA FOR ALLOYS EXPOSED AT 1700 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE A-11. (CONTINUED)

----- No sulfur added
 ————— Approximately 80 grains sulfur per
 100 ft³ cracked ammonia
 - - - - - Approximately 350 grains sulfur per
 100 ft³ cracked ammonia

FIGURE A-12. ULTIMATE-STRENGTH AND YIELD-STRENGTH DATA FOR ALLOYS EXPOSED AT 1700 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE A-12. (CONTINUED)

FIGURE A-12. (CONTINUED)

FIGURE A-12. (CONTINUED)

FIGURE A-13. ELONGATION DATA FOR ALLOYS EXPOSED AT 1700 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE A-14. HARDNESS DATA FOR ALLOYS EXPOSED AT 1700 F IN WET CRACKED-AMMONIA ATMOSPHERES WITH AND WITHOUT ADDED SULFUR

FIGURE A-15.

WEIGHT-GAIN, ULTIMATE-STRENGTH, AND YIELD-STRENGTH DATA FOR ALLOYS EXPOSED AT 1800 F IN A WET CRACKED-AMMONIA ATMOSPHERE CONTAINING APPROXIMATELY 80 GRAINS SULFUR PER 100 FT³ CRACKED AMMONIA

FIGURE A-16. ELONGATION AND HARDNESS DATA FOR ALLOYS EXPOSED AT 1800 F IN A WET CRACKED-AMMONIA ATMOSPHERE CONTAINING APPROXIMATELY 80 GRAINS SULFUR PER 100 FT³ CRACKED AMMONIA

TABLE A-1. WEIGHT-GAIN AND PHYSICAL-PROPERTY DATA FOR ALLOYS EXPOSED AT 1200, 1500, 1700, AND 1800 F IN CRACKED-AMMONIA ATMOSPHERES CONTAINING ZERO, 80, OR 350 GRAINS OF SULFUR PER 100 FT³ CRACKED AMMONIA

Alloy	Exposure Time, hr	Tempera- ture, F	Sulfur, grains per 100 ft ³ of cracked ammonia	Weight Gain, mg per in. ²	Weight Loss, mg per in. ²	Tensile Data		Elong- ation, per cent	Hardness, Rockwell B
						Yield	Ultimate		
						Strength, 0.2 Per Cent Offset, psi	Tensile Strength, psi		
Austenitic Stainless Steels									
Type 304	0	--	--	--	--	42,400	92,000	68	79
stainless steel	500	1200	81	0.7	--	39,400	91,500	61	81
	1000	1200	80	0.9	--	38,000	90,700	65	82
	1000(a)	1200	0	0.7(b)	--	47,600	88,700	53	83
	2000(a)	1200	0	0.8(b)	--	40,300	88,000	56	81
	500	1500	97	1.3	--	33,700	88,800	67	80
	1000	1500	97	1.7	--	35,100	87,700	63	81
	210(a)	1500	0	3.9(b)	--	38,300	90,600	60	79
	289(a)	1500	0	7.0(b)	--	34,800	89,600	65	72
	499(a)	1500	0	14.8(b)	--	34,100	87,800	59	69
	1010(a)	1500	0	22.5(b)	--	30,200	82,500	61	62
Type 304 ELC	0	--	--	--	--	31,600	84,200	74	71
stainless steel	460	1200	82	0.4	--	34,600	89,300	68	74
	1000	1200	81	0.6	--	31,400	82,700	64	73
	2000	1200	54	0.8	--	30,000	80,600	69	75
	500	1500	97	1.4	--	26,200	79,600	68	72
	1000	1500	97	1.8	--	27,200	80,000	72	75
Type 309	0	--	--	--	--	41,500	86,500	60	78
stainless steel	460	1200	82	0.7	--	37,400	85,000		79
	1000	1200	81	0.8	--	34,000	80,000	44	81
	2000	1200	54	1.1	--	37,600	71,500	48	82
	1000(a)	1200	0	0.6	--	39,100	82,900	43	81
	500	1500	97	1.6	--	35,100	86,000	49	80
	1000	1500	97	2.1	--	35,200	87,400	43	82
	511(a)	1500	0	3.0	--	33,800	84,600	45	76
Type 310	0	--	--	--	--	35,500	80,800	53	75
stainless steel	460	1200	82	0.6	--	36,600	83,900	47	81
	1000	1200	81	0.9	--	35,600	84,600	45	81
	2000	1200	54	2.0	--	35,800	83,900	46	82
	100	1700	0	2.5	--	32,100	81,200	51	73
	500	1700	0	4.4	9.2	31,400	80,200	48	73
	100	1700	100	4.8	--	35,500	82,400	47	77
	500	1700	77	5.0	11.	32,000	82,200	48	74
Type 316	0	--	--	--	--	31,500	80,400	52	71
stainless steel	460	1200	82	0.5	--	31,200	82,600	61	71
	1000	1200	81	0.7	--	30,100	81,300	55	70
	2000	1200	54	1.1	--	28,800	81,700	58	71
	500	1500	97	1.6	--	26,900	79,600	41	70
	1000	1500	97	2.1	--	27,200	80,000	45	73
	1145(a)	1500	0	4.2(b)	--	25,300	80,500	45	67
Type 321	0	--	--	--	--	50,600	93,700	48	80
stainless steel	500	1200	81	1.3	--	50,300	97,700	41	85
	1000	1200	80	1.5	--	48,400	96,900	43	85

TABLE A-1. (Continued)

Alloy	Exposure Time, hr	Temperature, F	Sulfur, grains per 100 ft ³ of ammonia	Weight Gain, mg per in. 2	Weight Loss, mg per in. 2	Tensile Data			Elongation, per cent	Hardness, Rockwell B
						Yield Strength, 0.2 Per Cent Offset, psi	Ultimate Tensile Strength, psi			
Type 330 stainless steel	0	--	--	--	--	34,300	83,100	45		70
	460	1200	82	0.4	--	48,500	93,600	32		87
	1000	1200	81	0.6	--	43,800	88,500	25		87
	2000	1200	54	0.6	--	44,200	90,800	31		88
	500	1500	97	1.3	--	37,900	86,500	34		83
	1000	1500	97	2.4	--	38,000	84,400	28		83
	100	1700	0	4.9	--	31,500	82,900	33		75
	500	1700	0	6.6	--	29,000	80,800	34		72
	100	1700	100	4.2	67.0	34,700	84,800	39		78
	500	1700	90	4.1	--	31,800	83,600	38		76
	100	1700	350	1.8	13.0	33,200	81,800	38		82
	500	1700	350	1.2	22.0	31,500	83,400	38		77
Type 347 stainless steel	100	1800	80	2.1	45.	28,100	77,100	33		75
	500	1800	80	2.7	27.	26,800	77,800	37		73
	0	--	--	--	--	48,200	92,300	51		84
	460	1200	82	0.4	--	49,700	95,700	49		86
	1000	1200	81	0.5	--	48,200	94,300	45		85
	2000	1200	54	0.7	--	45,200	92,800	46		88
	1000(a)	1200	0	0.8	--	50,300	92,600	39		86
	2000(a)	1200	0	1.1	--	43,700	92,400	42		85
	500	1500	97	1.2	--	35,900	90,200	50		87
	1000	1500	97	1.7	--	36,400	91,500	48		83
	210(a)	1500	0	1.4	--	37,700	89,300	47		81
	289(a)	1500	0	1.7	--	35,700	89,200	50		81
Miscellaneous Iron-Chromium-Nickel Alloys	499(a)	1500	0	2.1	--	33,800	87,800	48		79
	1010(a)	1500	0	2.1	--	34,300	88,200	49		72
	100	1700	0	3.1	--	36,100	89,400	54		73
	500	1700	0	4.6	33.	34,600	87,900	50		74
	100	1700	100	2.6	--	36,900	88,400	51		75
	500	1700	80	2.9	9.8	38,200	89,100	51		76
	100	1700	350	2.1	12.0	37,600	88,700	50		82
	500	1700	350	0.1	16.0	35,500	88,200	51		80
	100	1800	80	5.3	78.	30,300	80,700	46		75
	500	1800	80	7.5	36.	24,400	79,000	54		78
Type 17-7PH	0	--	--	--	--	215,000	222,000	4		115
	500	1200	81	0.5	--	77,500	129,000	16		101
	1000	1200	80	0.9	--	75,500	133,000	14		102
Carpenter 20	0	--	--	--	--	52,600	92,400	39		87
	500	1200	81	0.6	--	54,600	97,800	33		90
	1000	1200	80	0.8	--	54,200	100,000	28		93
Carpenter 20 + Nb	0	--	--	--	--	53,600	93,800	39		87
	460	1200	82	0.5	--	56,900	97,000	39		90
	1000	1200	81	0.7	--	53,500	98,700	33		91
	2000	1200	54	0.8	--	54,100	103,600	28		92
	500	1500	97	1.1	--	44,700	98,700	30		94
	1000	1500	97	1.9	--	45,800	100,000	27		95
	100	1700	0	1.7	--	43,200	90,700	39		83
	500	1700	0	2.8	8.6	40,800	90,200	34		84
	100	1700	100	1.5	--	44,400	91,300	36		86
	500	1700	77	2.5	5.8	42,900	91,500	40		84

TABLE A-1. (Continued)

Alloy	Exposure Time, hr	Temperature, F	Sulfur, grains per 100 ft ³ of cracked ammonia	Weight Gain, mg per in. ²	Weight Loss, mg per in. ²	Tensile Data		Elongation, per cent	Hardness, Rockwell B
						Yield Strength, 0.2 Per Cent Offset, psi	Ultimate Tensile Strength, psi		
Type S-588	0	--	--	--	--	97,800	123,000	20	102
	100	1700	0	3.8	--	63,300	102,000	15	99
	500	1700	0	4.1	27.	62,000	97,300	17	97
	100	1700	100	2.4	--	73,400	92,400	15	101
	500	1700	77	3.1	13.	60,000	100,000	17	99
<u>Nickel-Base Alloys</u>									
Hastelloy C, quench annealed	0	--	--	--	--	54,000	121,000	55	91
	500	1200	82	0.3	--	68,100	109,000	10	96
	1000	1200	81	0.4	--	76,700	117,000	7	102
	2000	1200	54	0.5	--	95,700	138,000	3	107
	1000(a)	1200	0	0.4	--	No data	189,000	1	114
	2000(a)	1200	0	0.6	--	158,000	189,000	1	116
	500	1500	97	1.2	--	80,700	146,000	6	110
	1000	1500	97	1.8	--	80,000	142,000	5	110
	684(a)	1500	0	1.5	--	108,000	163,000	5	111
	1237(a)	1500	0	1.9	--	144,000	151,000	3	110
	100	1700	0	3.2	--	61,700	115,000	6	103
	500	1700	0	4.0	35.	60,400	122,000	8	103
	100	1700	100	2.7	--	74,200	145,000	11	105
	500	1700	77	3.6	30.	61,800	122,000	6	103
Hastelloy C, stabilized and annealed	0	--	--	--	--	78,200	120,000	5	99
	500	1200	82	0.4	--	89,200	111,000	2	102
	1000	1200	81	0.5	--	85,300	105,000	0	103
	2000	1200	54	0.5	--	100,000	127,000	0	106
Hastelloy F	0	--	--	--	--	59,000	107,000	44	91
	500	1200	82	0.4	--	62,200	114,000	18	97
	1000	1200	81	0.6	--	93,200	141,000	10	105
	2000	1200	54	0.8	--	96,000	157,000	10	103
	500	1500	97	1.9	--	64,100	130,000	19	103
	1000	1500	97	2.7	--	61,700	127,000	15	104
Illium R	0	--	--	--	--	60,300	123,000	40	94
	500	1200	82	0.4	--	60,900	121,000	32	94
	1000	1200	81	0.2	--	59,600	120,000	30	94
	2000	1200	54	0.8	--	57,400	118,000	27	94
	1000(a)	1200	0	0.5	--	66,700	120,000	32	95
	2000(a)	1200	0	0.6	--	60,300	121,000	31	91
	100	1700	0	3.1	--	61,200	135,000	38	88
	500	1700	0	5.4	11.0	47,600	112,000	38	86
	100	1700	100	3.6	--	52,200	117,000	37	89
	500	1700	80	4.9	12.0	52,600	116,000	34	86
	100	1700	350	2.4	5.6	53,500	119,000	39	90
	500	1700	350	5.5	13.0	52,000	115,000	34	93
	100	1800	80	4.1	9.3	52,300	117,000	40	90
	500	1800	80	11.	14.	46,700	107,000	33	90

TABLE A-1. (Continued)

Alloy	Exposure Time, hr	Temperature, F	Sulfur, grains per 100 ft ³ of cracked ammonia	Weight Gain, mg per in. ²	Weight Loss, mg per in. ²	Tensile Data		Elongation, per cent	Hardness, Rockwell B
						Yield Strength, 0.2 Per Cent Offset, psi	Ultimate Tensile Strength, psi		
Inconel X	0	--	--	--	--	45,900	114,000	56	85
	500	1200	82	0.7	--	136,500	189,000	16	111
	1000	1200	81	0.9	--	130,000	181,000	19	111
	2000	1200	54	1.2	--	135,000	184,000	15	107
	500	1500	97	3.8	--	88,200	156,000	23	108
	1000	1500	97	5.6	--	77,700	148,000	21	106
	1145(a)	1500	0	6.7	--	65,700	138,000	27	103
	100	1700	0	7.7	--	100,000	161,000	27	105
	500	1700	0	16.	125.	84,000	154,000	26	105
	100	1700	100	5.2	--	100,000	162,000	28	106
	500	1700	77	11.	161.	101,000	163,000	30	105
Nimonic 80-A	0	--	--	--	--	106,000	166,000	29	108
	100	1700	0	8.4	--	85,000	139,000	21	102
	500	1700	0	14.	160.	78,800	117,000	9	102
	100	1700	100	4.7	--	83,800	144,000	20	101
	500	1700	77	14.	98.	85,400	143,000	24	102
Cobalt-Base Alloys									
Haynes 25	0	--	--	--	--	81,400	158,000	47	102
	500	1200	82	0.3	--	103,000	140,000	9	108
	1000	1200	81	0.4	--	116,000	139,000	7	110
	2000	1200	54	0.5	--	121,000	142,000	3	110
	1000(a)	1200	0	0.4	--	120,000	133,000	2	110
	100	1700	0	3.3	--	79,700	138,000	4	109
	500	1700	0	5.9	29.	78,800	126,000	3	108
	100	1700	100	1.8	--	85,800	158,000	10	110
	500	1700	77	3.7	17.	81,200	149,000	7	108

(a) Data taken from BMI-269 for comparison.

(b) Blistered.