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THE CORROSION OF MONEL AND 70-30
CUPRONICKEL IN HYDROFLUORIC ACID

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THE CORROSION OF MONEL AND 70-30 CUPRONICKEL IN HYDROFLUORIC ACID

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Monel is shown to be suitable for the handling of 10 to 70 per cent hydrofluoric acid at 140 F and for handling 38 and 48 per cent acid at boiling; cupronickel also is useful over part of this range. Elimination of oxygen is necessary to achieve maximum corrosion resistance. Some accelerated interface attack was noted for 70-30 cupronickel. Welding of Monel is the preferable joining method. Silver solder joints are subject to embrittlement. Work hardening, annealing, and external stress do not significantly influence the corrosion of Monel. Galvanic coupling of Monel with silver or silver solder is to be avoided.

INTRODUCTION

Both aqueous hydrofluoric acid and gaseous hydrogen fluoride are handled in the process leading to the production of metallic uranium at the Mallinckrodt Uranium Refining Center. During this process, anhydrous hydrogen fluoride is used to hydrofluorinate brown uranium dioxide to green uranium tetrafluoride. The resultant water vapor, and the unreacted hydrogen fluoride are condensed at 140 F to a 70 per cent aqueous solution of hydrofluoric acid, although some condensate may be as dilute as 50 per cent hydrofluoric acid.

Originally Monel equipment was used to recover the condensed hydrofluoric acid, but the product was contaminated by corrosion products from this equipment. However, the installation of a silver liner in the condenser handling the off-gases resulted in a commercially marketable grade of 70 per cent hydrofluoric acid.

Future changes in the 70 per cent hydrofluoric acid market might make recovery of this acid less lucrative than other concentrations of acids. Thus, several materials have been evaluated for use in handling hydrofluoric acid of various concentrations.

The research presented in this report is an extension of that conducted previously and reported in Reports BMI-255 and BMI-268. In the previous work, silver was found to have superior corrosion resistance to hydrofluoric acid under all test conditions. The next most promising metals which were evaluated were Monel and 70-30 cupronickel, although neither metal is nearly so resistant as silver. It was found that these metals may be useful for handling hydrofluoric acid if the oxygen content of the acid vapors in contact with these metals is limited. Monel and the 70-30 cupronickel alloy have been shown to exhibit corrosion rates of 2 mils per month or less at 140 F if the oxygen content of the gas above the acid is limited to 1 per cent. At boiling temperatures, it is necessary to limit the oxygen content to 0.25 per cent, or less. A higher oxygen content greatly increases the corrosion rate.

This report describes the corrosion behavior of Monel and 70-30 cupronickel in hydrofluoric acid of various strengths at various temperatures, and the influences which

various factors have on the corrosion behavior of these two alloys. In addition, some comparative data were secured on the corrosion behavior of copper and mild steel.

SUMMARY

A laboratory investigation was made of several factors which might influence the corrosion resistance of Monel and 70-30 cupronickel alloys upon exposure to hydrofluoric acid. The most important consideration appears to be the amount of oxygen present in the vapors above the hydrofluoric acid which must be limited to 1 per cent at 140 F, and to less than 0.25 per cent at boiling acid temperatures in order that either of these alloys may be serviceable.

Monel appears to be uniformly resistant to hydrofluoric acid at concentrations between 10 and 70 per cent; 70-30 cupronickel offers comparable resistance except at a concentration of approximately 30 per cent, where maximum attack occurs. Copper is generally less satisfactory, and steel is unsuited for this application.

Minor variations in the composition of Monel have no significant effect upon its corrosion resistance. Welding is preferable to brazing with silver solder as a method of joining Monel. Work hardening, external stress, and various degrees of annealing and stress relieving have little effect upon the corrosion resistance of Monel exposed to hydrofluoric acid with limited access to oxygen.

Neither Monel nor 70-30 cupronickel suffers embrittlement upon exposure to hydrofluoric acid. The selective dissolution of copper from Monel has been observed, but this appears to be only a surface phenomenon with no great effect on the physical properties of the alloy.

Samples of Monel coupled to 70-30 cupronickel or to silver solder do not corrode at an excessive rate because of galvanic attack. The coupling of large areas of silver solder to relatively small areas of Monel could lead to excessive corrosion of the Monel, but would normally be avoided in equipment design.

EXPERIMENTAL WORK

A detailed description of the apparatus and procedures employed in this study of hydrofluoric acid corrosion has been reported previously in BMI-255 and BMI-268. The following sections describe briefly the equipment and procedures used for the work included in this report.

Apparatus and Procedures

140 F Tests in Hydrofluoric Acid Solutions

Each polyethylene reflux unit consisted of a 32-oz bottle with a 1-in. -ID water-cooled condenser tube sealed to the closure. The samples were supported at the vapor, interface, and liquid positions by polyethylene holders. Purge gas was introduced into the vapor space of the bottle and expelled through a back-diffusion trap at the top of the condenser. Purge-gas atmospheres were prepared by the addition of known quantities of oxygen to high-purity nitrogen. A purge rate of approximately 20 ml per min permitted replacement of the gas in the system every 40 min.

Commercial-grade hydrofluoric acid was used for exposures at 140 F, as it was felt that this represented the quality of acid likely to be handled in the acid-recovery system.

Boiling Hydrofluoric Acid Tests

For tests at temperatures above 180 F, reflux units were made from Teflon sheet and tubing. Threaded joints were sealed with Pennsalt HF resin cement. Instead of Teflon a water-cooled Karbate tube was used as a condenser to obtain better heat transfer. Details of these reflux units were included in BMI-268.

As with the polyethylene units, the vapor phase of the system was purged with high-purity nitrogen containing known amounts of oxygen. A purge rate of 20 ml per min was roughly equivalent to one complete volume change every 30 min.

Chemically pure acid was used for the boiling hydrofluoric acid exposures. This quality of acid represented that which probably would be encountered in the distillation column of the purification system.

Sample Preparation and Exposure

Specimens 2.0 by 0.5 by 0.065 in. were used for the experiments at 140 F, and 1.5 by 0.5 by 0.065-in. specimens were prepared for the boiling hydrofluoric acid work. Each specimen was abraded in two directions with 120-grit aluminum oxide paper. The specimens were degreased in cp acetone, weighed, and stored for at least 24 hr in a desiccator prior to use.

Heat-treatment and weld scales were removed from the Monel specimens by use of a two-step pickling procedure. This consisted of a 40-min immersion in a 12 w/o solution of hydrochloric acid containing 20 g per liter of cupric chloride, at 180 F, followed by immersion for 10 min in a 10 w/o solution of sulfuric acid containing 250 g per liter of sodium dichromate, at 100 F.

Tensile samples were exposed in tests in which physical properties were evaluated before and after corrosive exposure.

The exposure period for the 140 F tests was 35 days, except where otherwise stated. Samples were exposed for 4 days in boiling 38 and 48 per cent hydrofluoric acid.

Corrosion products were removed from copper-base alloys, when necessary, by a 1-min dip in 5 per cent potassium cyanide solution at 120 F.

EXPERIMENTAL RESULTS

The Effect of Hydrofluoric Acid Concentration

In the handling of hydrofluoric acid as a by-product of the hydrofluorination of uranium oxide, it is possible that acid concentrations of from 10 to 70 per cent would be encountered within the recovery system. Thus, it was felt necessary to secure corrosion information over this concentration range for use in the selection of suitable materials for recovery-system construction.

Previous work reported in BMI-268 has indicated the possible utility of Monel, copper, 70-30 cupronickel, and steel. To further evaluate these materials, samples were exposed at eight acid concentrations between 10 and 70 per cent, for 7 days, at 140 F. Each reflux unit was purged with nitrogen containing 1 per cent oxygen. Samples were exposed in the vapor, at the interface, and immersed in the liquid. The corrosion data presented in Figure 1 have been plotted from data recorded in Table A-1, in the Appendix.

The relatively uniform corrosion behavior of Monel throughout the concentration range may be readily seen from Figure 1. The most severe corrosive conditions exist in the vapor phase. It is to be noted that there is a decrease in the corrosion rate at 70 per cent acid.

Samples of 70-30 cupronickel were shown to have useful corrosion resistance, but were found to be particularly susceptible to attack within the concentration range from 30 to 38 per cent hydrofluoric acid. At a concentration of 48 per cent and higher, 70-30 cupronickel offers resistance equal to, or greater than, that shown for Monel. Non-uniform attack was observed at concentrations less than 50 per cent as a result of condensate flow down the sample surfaces. This is sometimes referred to as "streaming attack".

Copper is shown to be subject to significantly greater attack than either Monel or 70-30 cupronickel. Also, it should be noted that excessive attack occurred at the interface location at the low acid concentration of 10 per cent, and that the interface sample disintegrated at the 38 per cent concentration level. Obviously, copper should be considered less satisfactory than Monel or 70-30 cupronickel for hydrofluoric acid service.

As would be expected, steel does not resist hydrofluoric acid attack within the concentration range of 10 to 70 per cent.

FIGURE 1. CORROSION DATA FOR METALS EXPOSED TO HYDRO-FLUORIC ACID AT CONCENTRATIONS BETWEEN 10 AND 70 PER CENT FOR 7 DAYS AT 140 F

One per cent oxygen in the nitrogen purge gas.

Localized Attack

A hardness and metallographic study of the Monel specimens, in both the as-received and annealed conditions, was made following exposure to hydrofluoric acid, to detect intergranular corrosion or selective dissolution of one of the alloy metals. No intergranular corrosion was noted for any of the specimens. There was some indication that copper was selectively dissolved from Monel leaving a spongy surface, as indicated by variations in the hardness measurements. Metallographic examination of these specimens indicated that this apparent "decuprification" did not penetrate deeper than 2 mils after 35 days' exposure to 70 per cent hydrofluoric acid at 140 F.

The Effect of Corrosion on Tensile Strength

To determine whether hydrofluoric acid attack results in embrittlement, tensile samples of Monel and 70-30 cupronickel were exposed to boiling acids of 38 and 48 per cent, and 70 per cent acid at 140 F. These data are recorded in Table A-2 in the Appendix.

No significant reductions in tensile strength were noted, indicating the absence of embrittlement under these exposure conditions. The selective removal of copper from Monel, followed by replating of the copper on the surface of the Monel was observed, but from the results of the tensile tests, it is concluded to occur only on the surface. The 70-30 cupronickel alloy was not observed to suffer such decuprification.

The Effect of Variations in Composition of Monel

As small variations in chemical composition always exist in different heats of an alloy, it was felt that the importance of these variations on the corrosion behavior of Monel should be determined. In addition to regular Monel, samples of "R" Monel, "326" Monel, Monel "60" weld rod, and Eutec-Rod "520" were included in the corrosion investigation.

Chemical analyses and corrosion data for specimens of the eight alloys exposed in 70 per cent hydrofluoric acid for 35 days at 140 F are presented in Table 1. The vapor phase of the reflux units was purged with nitrogen containing 1 per cent oxygen.

These chemical analyses do not seem to indicate the reason that Lot 5 Monel should be somewhat more corrosion resistant than Lots 2, 3, and 4 of the same alloy. Spectrographic analyses of the trace elements present also failed to explain this difference.

The Monel "60" weld rod, in the unwelded condition, was more resistant to hydrofluoric acid in the vapor phase than any of the six Monel alloys in sheet form, even though this weld rod has ten times the silicon content of the sheet stocks. Spectrographic evidence indicated that the Monel "60" weld rod contained significantly more aluminum and titanium than the sheet material. The presence of aluminum, silicon, and titanium would normally be expected to lower the corrosion resistance of Monel to hydrofluoric acid attack.

TABLE 1. CHEMICAL ANALYSES AND CORROSION DATA FOR MONEL ALLOYS EXPOSED IN 70 PER CENT HYDROFLUORIC ACID AT 140 F FOR 35 DAYS

1 Per Cent Oxygen in the Nitrogen Purge Gas

Material	Lot	Chemical Analysis (Balance Nickel), w/o					Corrosion Rate, mils per month		
		Copper	Iron	Manganese	Silicon	Carbon	Vapor Specimen	Interface Specimen	Immersed Specimen
"R" Monel ^(a)	1	29.3	1.65	1.08	0.02	0.15	2.51	1.45	1.70
Monel	2	31.8	1.34	1.13	0.12	0.15	2.53	2.56	2.00
Monel	3	29.4	2.26	1.04	0.10	0.15	2.64	1.64	1.82
Monel	4	29.7	2.19	1.05	0.15	0.15	2.64	2.09	1.71
Monel	5	31.6	1.37	1.01	0.12	0.15	1.47	1.22	0.83
"326" Monel ^(b)	6	37.6	1.30	1.03	0.10	0.15	4.36	5.77	3.07
Monel "60" weld rod ^(c)	--	30	2.5	1.0	1.5	0.15	0.79	1.4	1.6
Eutec-Rod "520"	--	--	--	--	--	--	3.7	2.0	1.8

(a) Low-silicon, free-machining Monel.

(b) High-copper, nonmagnetic Monel.

(c) Weld rod produced by the International Nickel Co. recommended for inert gas welding of Monel.

The Effect of Oxygen in the Purge Gas

The experimental work presented in BMI-268 indicated that the lowest corrosion rates for Monel exposed to hydrofluoric acid occurred under oxygen-free conditions. It has been noted that with oxygen present, the corrosion rates all tend to be higher.

Specifically, the corrosion of Monel is minimized at an oxygen concentration of 1 per cent or less, at a temperature of 140 F, while a concentration of 0.25 per cent or less is required at boiling temperatures.

Localized attack resulting from condensate return, referred to as "streaming attack" is accelerated by the presence of oxygen in the vapor.

The experimental work presented in this report was conducted with an oxygen concentration in the purge gas of 1 per cent, thus representing approximately the maximum concentration that may be tolerated with reasonable corrosion behavior of the alloys studied.

Galvanic Effects on Corrosion

Couple effects on the corrosion of Monel exposed to hydrofluoric acid were evaluated by welded, brazed, and mechanically coupled specimens.

Welding

Samples were prepared by welding two pieces of Monel sheet stock. The welding was done by the Heliarc method, using Monel "60" weld rod, and procedures recommended by the International Nickel Company^{(1)*}. The sample surfaces were cleaned prior to welding to remove contaminants which could result in embrittlement.

Comparative corrosion data for welded and unwelded samples exposed in hydrofluoric acid are presented in Table 2. These data, along with visual examinations of the samples, indicate that the weld and heat-affected areas are essentially as resistant to attack by hydrofluoric acid as the unwelded Monel, and are free from localized attack.

Brazing

Corrosion samples were prepared by joining two pieces of Monel with silver solder. Brazing was evaluated for use as a possible substitute for welding in the repair of Monel equipment. Of the several silver solders available, only those with compositions of silver-15 w/o copper-5 w/o phosphorus**, and silver-28 w/o copper*** were sufficiently corrosion resistant for consideration.

*References are at the end of the report.

**Sil-Fos.

***BT Silver Solder.

TABLE 2. CORROSION DATA FOR WELDED MONEL SHEET-STOCK SAMPLES
EXPOSED TO 70 PER CENT HYDROFLUORIC ACID FOR 35 DAYS
AT 140 F

1 Per Cent Oxygen in the Nitrogen Purge Gas

Alloy	Lot	Corrosion Rate, mils per month					
		Vapor Specimen		Interface Specimen		Liquid Specimen	
		Welded	Unwelded	Welded	Unwelded	Welded	Unwelded
"R" Monel	1	1.74	2.51	1.99	1.45	1.47	1.70
Monel	2	0.46	2.53	0.91	2.56	0.71	2.00
Monel	3	3.09	2.64	2.30	1.64	2.15	1.82
Monel	4	3.59	2.64	2.08	2.09	2.03	1.71
Monel	5	0.65	1.47	0.68	1.22	0.61	0.83

Monel specimens brazed together by either of these two silver solders showed good corrosion resistance when exposed to boiling 48 per cent hydrofluoric acid for 4 days, with 0.25 per cent oxygen in the nitrogen purge gas. Similar brazed specimens became embrittled when exposed for 35 days at 140 F in 70 per cent hydrofluoric acid, with 1 per cent oxygen in the nitrogen purge gas. This embrittlement was apparently caused by selective dissolution of copper from the solder joint, leaving a porous mass of silver. The Monel adjacent to the brazed joints was preferentially attacked, indicating that galvanic attack occurred. Although there was no significant galvanic attack on samples exposed for 4 days in boiling 48 per cent acid, there was evidence from visual observations of the samples that longer exposures would have resulted in similar embrittlement.

The results of these tests indicate that welding is to be preferred over brazing as a method of fabrication or repair of Monel equipment intended for the handling of hydrofluoric acid.

Galvanic Coupling

Monel samples were electrically coupled with both 70-30 cupronickel and silver solder by attachment with Monel bolts. Corrosion data for coupled and uncoupled samples exposed in 38, 48, and 70 per cent hydrofluoric acid are presented in Table 3.

The corrosion of Monel is not significantly increased by coupling with the 70-30 cupronickel alloy, but it is increased by coupling with silver solder. Silver solder is cathodic to Monel in hydrofluoric acid at concentrations of 38, 48, and 70 per cent. It may be seen that at an acid concentration of 48 per cent, the corrosion of Monel is increased nearly fivefold when coupled with silver solder. However, even with this increase, the corrosion rate was 2.6 mils per month, which is not considered serious. These results indicate that large areas of silver, or its alloys, should not be coupled to relatively small areas of Monel, in equipment design.

The Effects of Physical Properties on Corrosion

Experiments were performed to determine the effects of work hardening, annealing, and external stress on the hydrofluoric acid corrosion of Monel and 70-30 cupronickel.

Work Hardening

To determine the effect of hardness on hydrofluoric acid corrosion of Monel, samples from five lots of sheet stock were work hardened by ball peening one-half of each specimen. In addition, samples from Lots 2 and 5 were first soft annealed and then cold reduced 70 per cent by rolling, resulting in a hardness increase from approximately 67 to 96 Rockwell B.

Corrosion data for samples exposed in 70 per cent hydrofluoric acid at 140 F, and in boiling 38 per cent acid are included in Tables A-3 and A-4, in the Appendix.

TABLE 3. CORROSION DATA FOR MONEL GALVANICALLY COUPLED TO 70-30 CUPRONICKEL AND SILVER SOLDER EXPOSED TO HYDROFLUORIC ACID

Alloy Coupled to Monel	Hydrofluoric Acid Concentration, per cent	Temperature, F	Oxygen Concentration in Nitrogen Purge Gas, per cent	Coupled	Corrosion Rate ^(b) , mils per month	
					Monel	Other Alloy
70-30 Cupronickel	70	140	1.0	No	1.7	0.7
	70	140	1.0	Yes	1.6	0.88
Silver-28 w/o copper ^(a)	70	140	1.0	No	0.87	2.2
	70	140	1.0	Yes	1.1	2.4
Silver-28 w/o copper ^(a)	48	Boiling	0.10	No	0.53	0.41
	48	Boiling	0.10	Yes	2.6	0.03
Silver-28 w/o copper ^(a)	38	Boiling	0.10	No	1.7	0.32
	38	Boiling	0.10	Yes	3.0	0.10

(a) BT silver solder.

(b) All samples exposed in the liquid phase.

These data do not indicate any significant increase in corrosion as a result of the work hardening.

Annealing

It was thought that some degree of annealing might impart improved corrosion resistance to Monel. Specimens were subjected to four heat treatments ranging from stress equalizing at 575 F to soft annealing for 1 hr at 1500 F. Reductions in hardness ranging from 6 to 13 points Rockwell B were obtained.

Corrosion data for the above annealed samples exposed in 70 per cent hydrofluoric acid at 140 F, and in boiling 38 per cent acid are presented in Table A-5, in the Appendix.

These data do not indicate significant improvement in the corrosion resistance of Monel in hydrofluoric acid as a result of the annealing or the stress-equalization treatments.

External Stress

Specimens of Monel and 70-30 cupronickel were stressed in specially designed Teflon jigs to approximately the yield strength of the alloys. These were exposed in 70 per cent hydrofluoric acid at 140 F for 35 days. The corrosion data are presented in Table A-6 in the Appendix.

No stress cracking was observed in either alloy, and the corrosion rate was found to be essentially the same for stressed and unstressed samples. Visual examinations of the 70-30 cupronickel specimens indicated the possibility that the stressed pieces may have received slightly greater attack than similarly exposed unstressed specimens.

REFERENCE

- (1) Nickel and Nickel Alloys (Reference Manual), International Nickel Company, Section M.

WJB:FWF:GLE/mmk

APPENDIX

TABLE A-1. CORROSION DATA FOR MONEL, COPPER, 70-30 CUPRONICKEL, AND STEEL EXPOSED TO VARIOUS CONCENTRATIONS OF HYDROFLUORIC ACID AT 140 F FOR 7 DAYS

1 Per Cent Oxygen in the Nitrogen Purge Gas

Material	Sample Location	Corrosion Rate, mils per month						
		Hydrofluoric Acid Concentrations, per cent						
		10	20	30	38	48	60	70
Monel (Lot 2)	Vapor	2.1	2.0	2.8	3.5	2.3	1.5	0.27
	Interface	1.2	1.0	1.5	2.4	1.1	2.1	0.21
	Liquid	0.54	0.87	0.71	0.96	0.70	0.76	0.53
Copper	Vapor	5.1	2.8	4.7	5.1	5.3	6.2	2.9
	Interface	11.3	1.9	5.3	D	3.4	3.5	2.2
	Liquid	1.6	0.75	1.1	2.1	0.86	1.2	1.0
70-30 cupronickel	Vapor	2.4	1.5	8.2	4.4	1.3	2.0	1.2
	Interface	2.7	1.4	7.0	2.6	0.49	0.54	0.22
	Liquid	0.78	0.61	1.4	1.0	0.37	0.54	0.19
Steel	Vapor	9.5	--	--	--	--	1.3	1.3
	Interface	D	--	--	--	--	6.4	3.7
	Liquid	D	--	--	--	--	11.5	5.7

TABLE A-2. CORROSION AND TENSILE DATA FOR MONEL AND 70-30 CUPRONICKEL EXPOSED IN HYDROFLUORIC ACID

Alloy	Hydrofluoric Acid Concentration, per cent	Temperature, F	Exposure Time, days	Oxygen Concentration in Nitrogen Purge Gas, per cent	Corrosion Rate(a), mils per month	Tensile Strength, psi		Change in Tensile Strength, per cent
						Before Exposure	After Exposure	
Monel (Lot 2)	70	140	35	1.0	0.12	80,000	76,000	-5.0
	48	Boiling	4	<0.2	0.97	80,000	78,800	-1.5
	38	Boiling	4	<0.2	4.8	80,000	75,800	-5.3
Monel (Lot 5)	70	140	35	1.0	0.11	73,400	71,500	-2.6
	48	Boiling	4	<0.2	0.73	73,400	73,500	+0.14
	38	Boiling	4	<0.2	5.4	73,400	72,300	-1.5
70-30 cupronickel	70	140	35	1.0	0.06	59,000	61,000	+3.4
	48	Boiling	4	<0.2	0.73	59,000	58,000	-1.7
	38	Boiling	4	<0.2	--	59,000	56,200	-4.8

(a) Data averaged for five fully immersed specimens.

TABLE A-3. CORROSION DATA FOR AS-RECEIVED AND WORK-HARDENED MONEL EXPOSED IN 70 PER CENT HYDROFLUORIC ACID FOR 35 DAYS AT 140 F

1 Per Cent Oxygen in the Nitrogen Purge Gas

Monel Lot	Sample Location	As-Received Samples		Ball-Peened Samples ^(a)	70 Per Cent Cold-Reduced Samples	
		Hardness, Rockwell B	Corrosion Rate, mils per month	Corrosion Rate, mils per month	Hardness, Rockwell B	Corrosion Rate, mils per month
1(b)	Vapor	--	2.51	2.52	--	--
1(b)	Liquid	--	1.70	1.73	--	--
2	Vapor	67 to 71	2.53, 1.62	2.79	95 to 98	1.54
2	Liquid	67 to 71	2.00, 1.24	1.89	95 to 98	1.00
3	Vapor	--	2.64	3.19	--	--
3	Liquid	--	1.82	2.94	--	--
4	Vapor	--	2.64	2.59	--	--
4	Liquid	--	1.71	1.18	--	--
5	Vapor	65 to 69	1.47, 1.69	1.71	95 to 98	1.37
5	Liquid	65 to 69	0.83, 1.37	0.69	95 to 98	1.12

(a) Hardened by ball-peening one-half of each specimen; hardness not measured.

(b) "R" Monel.

TABLE A-4. CORROSION DATA FOR AS-RECEIVED AND WORK-HARDENED MONEL EXPOSED IN BOILING
38 PER CENT HYDROFLUORIC ACID FOR 4 DAYS

Oxygen Concentration in Nitrogen Purge Gas, per cent	Sample Location	As-Received Samples		70 Per Cent Cold-Reduced Samples	
		Hardness, Rockwell B	Corrosion Rate, mils per month	Hardness, Rockwell B	Corrosion Rate, mils per month
<u>Monel Lot 2</u>					
0.10	Vapor	67 to 71	2.37	95 to 98	2.02
0.10	Interface	67 to 71	0.56	95 to 98	0.89
0.10	Liquid	67 to 71	0.76	95 to 98	1.56
0.15 to 0.25	Vapor	67 to 71	1.86	95 to 98	3.68
0.15 to 0.25	Interface	67 to 71	0.77	95 to 98	0.78
0.15 to 0.25	Liquid	67 to 71	1.44	95 to 98	1.02
<u>Monel Lot 5</u>					
0.10	Vapor	65 to 69	2.39	95 to 98	1.14
0.10	Interface	65 to 69	0.59	95 to 98	0.46
0.10	Liquid	65 to 69	0.83	95 to 98	0.63
0.15 to 0.25	Vapor	65 to 69	1.50	95 to 98	0.22
0.15 to 0.25	Interface	65 to 69	0.71	95 to 98	0.80
0.15 to 0.25	Liquid	65 to 69	0.94	95 to 98	0.67

TABLE A-5. CORROSION AND HARDNESS DATA FOR AS-RECEIVED AND ANNEALED MONEL EXPOSED TO HYDROFLUORIC ACID

Annealing Data(a)	Hydrofluoric Acid Concentration, per cent	Exposure Temperature, in F	Oxygen Concentration in Nitrogen Purge Gas, per cent	Exposure Time, days	Corrosion Rate, mils per month					
					Samples in Vapor		Samples at Interface		Samples in Liquid	
					Monel Lot 2	Monel Lot 5	Monel Lot 2	Monel Lot 5	Monel Lot 2	Monel Lot 5
As-received	70	140	1.0	35	1.62	1.69	1.10	1.23	1.24	1.37
Stress equalized, 3 hr at 575 F	70	140	1.0	35	1.10	1.16	1.71	1.35	0.80	0.79
Stress equalized, 1 hr at 1000 F	70	140	1.0	35	1.52	1.55	--	1.17	0.99	1.08
Open annealed, air quenched, 25 min at 1500 F	70	140	1.0	35	1.43	1.11	1.63	1.22	1.13	0.98
Open annealed, air quenched, 1 hr at 1500 F	70	140	1.0	35	--	2.80	--	2.08	1.33	1.14
As-received	38	Boiling	0.10	4	2.37	2.39	0.56	0.59	0.76	0.83
Stress equalized, 3 hr at 575 F	38	Boiling	0.10	4	1.07	1.62	1.05	0.69	1.34	1.87
Stress equalized, 1 hr at 1000 F	38	Boiling	0.10	4	2.78	2.01	1.13	0.78	1.98	1.34
Open annealed, air quenched, 25 min at 1500 F	38	Boiling	0.10	4	2.00	1.61	0.87	0.83	1.52	1.14
Open annealed, air quenched, 1 hr at 1500 F	38	Boiling	0.10	4	3.30	1.97	1.65	0.74	1.79	0.86
As-received	38	Boiling	0.15 to 0.25	4	1.86	1.50	0.77	0.71	1.44	0.94
Stress equalized, 3 hr at 575 F	38	Boiling	0.15 to 0.25	4	1.86	1.87	0.99	0.66	1.75	0.57
Stress equalized, 1 hr at 1000 F	38	Boiling	0.15 to 0.25	4	3.30	2.53	1.18	0.72	1.63	2.37
Open annealed, air quenched, 25 min at 1500 F	38	Boiling	0.15 to 0.25	4	2.30	2.72	0.83	1.01	1.80	0.84
Open annealed, air quenched, 1 hr at 1500 F	38	Boiling	0.15 to 0.25	4	1.89	1.22	0.71	1.34	1.22	2.23

(a)

Heat Treatment	Hardness, Rockwell B	
	Monel	Monel
	Lot 2	Lot 5
As received	71	67
Open annealed, 25 min at 1500 F	65	62
Open annealed, 1 hr at 1500 F	62	54

TABLE A-6. CORROSION DATA FOR STRESSED AND UNSTRESSED MONEL EXPOSED IN 70 PER CENT HYDROFLUORIC ACID AT 140 F FOR 35 DAYS

1 Per Cent Oxygen in the Nitrogen Purge Gas

Monel Lot	Sample Location	Corrosion Rate, mils per month	
		Unstressed Samples	Stressed Samples
1(a)	Vapor	2.51	1.43
1(a)	Interface	1.45	1.58
1(a)	Liquid	1.70	0.59
2	Vapor	2.53	1.07
2	Interface	2.56	2.41
2	Liquid	2.00	0.71
4	Vapor	2.64	0.92
4	Interface	2.09	2.61
4	Liquid	1.71	0.86
5	Vapor	1.47	2.39
5	Interface	1.22	3.28
5	Liquid	0.83	0.98

(a) "R" Monel.