

**Versatile Corrosion Resistance of INCONEL\* alloy 625 in Various  
Aqueous and Chemical Processing Environments**

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**Abstract**

INCONEL® alloy 625 is a nickel–chromium–molybdenum alloy that is used for its high strength, excellent fabricability and weldability, and outstanding corrosion resistance. The outstanding and versatile corrosion resistance of INCONEL alloy 625 under a wide range of temperatures and corrosive environments is the primary reason for its wide acceptance in chemical processing and other applications. This paper will present laboratory and field data related to the resistance of alloy 625 to various aqueous media causing localized corrosion, stress corrosion cracking and other forms of attack. Also the versatility of the alloy for use in oxidizing, carburizing, chlorinated solvents and simulated waste incinerator type environments containing halide species, will be demonstrated.

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## Introduction

INCONEL alloy 625, UNS N06625, is an austenitic solid solution strengthened nickel–chromium–molybdenum alloy containing niobium. The high alloy content of alloy 625 enables it to withstand a wide variety of severe corrosive environments. In mild environments, such as ambient atmosphere, fresh and seawater, neutral salts and alkaline media, there is almost no attack. In more severe corrosive environments, chromium provides resistance to oxidizing chemicals, whereas, the high nickel and molybdenum contents make the alloy resistant to nonoxidizing environments. The high molybdenum content also makes this alloy very resistant to pitting and crevice corrosion. The added niobium (3 to 4%) acts to stabilize the alloy against sensitization during welding, thereby preventing subsequent intergranular attack. Also, the high nickel content provides freedom from chloride-ion stress corrosion cracking. This combination of corrosion resistant characteristics has made the alloy one of the most widely used materials by the chemical and aerospace industries.

In this paper the versatility of alloy 625 as a useful material in various corrosive environments will be demonstrated. The data are taken from published literature and current laboratory results comparing the performance of the alloy with various commercial materials. The paper is divided into two sections: (1) aqueous and (2) high temperature corrosion. The nominal composition of the alloy is listed in Table I along with some of the more important commercial alloys referred to in the paper.

**Table I. Nominal Composition of Alloys**

Alloy	UNS No.	Fe	Ni	Cr	Mo	Al	Ti	Si	Mn	C	Others
617	N06617	1.5	Bal	22.0	9.0	1.2	0.3	0.5	0.5	0.07	12.5 Co
625	N06625	3	Bal.	21.5	9.0	0.2	0.2	0.6	0.5	0.06 Max.	4 Nb
825	N08825	Bal.	42.0	21.5	3.0	0.2	0.9	0.4	0.7	0.03	2.2 Cu
020/20-Cb3®	N08020	Bal.	34.0	20.0	2.5	–	–	–	–	.06 Max	3.4 Cu, 0.5 Nb
B2	N10665	2 Max	Bal.	1 Max	28	–	–	.10 Max	1 Max	.02 Max	1 Co Max.
718	N07718	18.5	52.5	19	3.0	.5	.9	.2	.2	.04	5.1 Nb
C-276	N10276	5	Bal.	15.5	16	–	–	.08 Max	1 Max	.02 Max	4 W, 2.5 Co Max .35 V Max
G-3	N06985	19.5	Bal.	22	7	–	–	.4	.8	.015 Max	5 Co Max 1.9 Cu 1.5 W Max Nb + Ta = .3
G	N06007	19.5	Bal.	22	6.5	–	–	1 Max	1.5	.05 Max	Nb + Ta = 2 2Cu 2.5 Co Max 1 W Max
K-500	N05500	1	65.5	–	–	2.7	.6	.2	.8	.1	29.5 Cu
X-750	N07750	7	73	15.5	–	.7	2.5	.2	.5	.04	1 Nb
X	N06002	18.5	Bal.	22	9	–	–	1 Max	1 Max	.10	1.5 Co Max .6 W Max
MP-35N®	R30035	–	35	20	10	–	–	–	–	–	35 Co
230®	–	3	61	22	2	.3	–	–	0.6	0.1	14 W, 5 Co, .02 La

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## Aqueous Corrosion

### Uniform Corrosion

Uniform corrosion, sometimes also called general corrosion, is a type of corrosion attack that is uniformly distributed and proceeds at approximately the same rate over the entire metal surface. Tests are designed to evaluate the resistance of alloys to uniform corrosion mainly to aid in the selection of materials. These tests are generally conducted in various acids to take into account many situations that may occur. Table II shows the general corrosion resistance of various alloys, including alloy 625, in different non-oxidizing and oxidizing acids. As the data indicates, some alloys that are good in non-oxidizing acids (e.g. alloys C-276 and B2) may not be good in oxidizing acids. However, alloy 625 is among the most resistant alloys to uniform corrosion and may be used both in the non-oxidizing acids and oxidizing (acidic, Cl-) environments.

**Table II. Corrosion Resistance (Corrosion Rate in Mills Per Year; 24-Hour Exposure)**

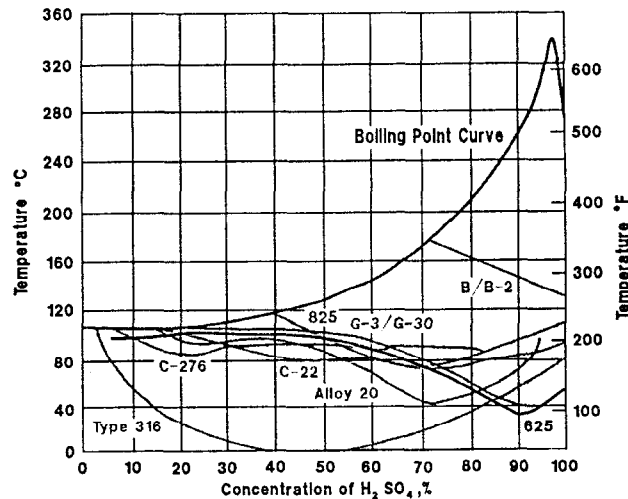
Alloy	Boiling Nonoxidizing Acids					Boiling Oxidizing Environments	
	40% HCOOH	10% HCl	10% H <sub>2</sub> SO <sub>4</sub>	55% H <sub>3</sub> PO <sub>4</sub>	85% H <sub>3</sub> PO <sub>4</sub>	10% HNO <sub>3</sub>	50% H <sub>2</sub> SO <sub>4</sub> + 2.5 % Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>
304	180	> 12,000*	2,200	400	9,500	1.0	46
316	30	> 12,000*	400	18	450	1.0	36
317	**	9,000	360	**	**	0.5	28
200	10	8,000	130	500	**	> 12,000*	8,000
600	10	4,400	360	**	1,800	**	**
825	8	1,000	18	6	35	0.6	11
G-3	2	1,000	24	5	24	0.8	11
625	7	620	44	10	110	1.0	23
C-276	3	220	16	7	18	18.0	260
B-2	0.4	7	2	3.5	3.5	> 12,000*	**

\*Specimen Dissolved

\*\* Not Tested

(Ref. 1)

Uniform corrosion data related to the temperature and concentration of sulfuric acid (2) is plotted in Figure 1, in the form of isocorrosion lines, for alloy 625 and other alloys. The isocorrosion lines indicate a corrosion rate of 0.5 mm/yr (20 mils/year). The data shows the applicability of alloy 625, corroding at a rate of less than 20 mpy, in all concentrations of sulfuric acid at various temperatures below the isocorrosion line indicated. Figure 1 shows that alloy 625 possesses comparable corrosion resistance to other highly corrosion resistant alloys in sulfuric acid.



**Figure 1. Comparative Behavior of Several Nickel Base Alloys in Pure H<sub>2</sub>SO<sub>4</sub>. The Isocorrosion Lines Indicate a Corrosion Rate of 0.5 mm/yr (20 mils/yr).**  
(Ref. 2)

### Localized Corrosion

Pitting is a localized form of corrosion confined to a small area compared with the whole surface. Pitting and crevice corrosion or localized corrosion data as related to ppm chloride concentration and pH is graphed in Figure 2 for alloy 625 and other alloys. The data was obtained from field exposure of alloys in various SO<sub>2</sub> coal fired power plant scrubbing systems<sup>(3)</sup>. The areas below the line for each alloy represent the combination of pH and Cl<sup>-</sup> content where no severe pitting was observed. Alloy 625 possesses localized corrosion resistance that is superior to the alloys indicated in Figure 2.

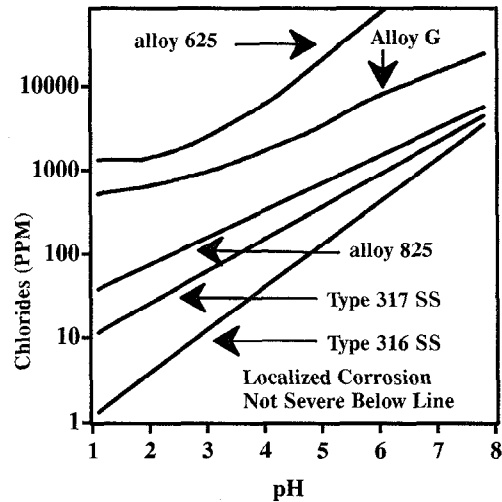


Figure 2. Corrosion Behaviour in SO<sub>2</sub> Scrubbing Environments (field tests)  
(Ref. 3)

Chromium and molybdenum have been found to be beneficial in promoting pitting resistance. Alloy 625 has a high chromium and molybdenum content, (21.5% Cr, 9% Mo), which accounts for its superior pitting resistance. An empirical relationship between the critical temperature for pitting to initiate and Cr and Mo contents of an alloy is displayed in Figure 3.<sup>(1)</sup> Alloys 625 and C-276 both possess high percentages of chromium and molybdenum and therefore rank the highest for pitting resistance as indicated from the data in Figure 3.

### Chloride Stress Corrosion Cracking

Nickel and nickel-base alloys are in general not subject to chloride stress-corrosion cracking as compared to stainless steels. The beneficial effect of nickel on the prevention of stress-corrosion cracking in boiling 42% MgCl<sub>2</sub> is shown in Figure 4.<sup>(3)</sup> The figure shows that alloys containing more than about 42-45% nickel will not crack in this environment. Alloy 625 contains 58%(min) nickel; thus, it will not crack in this environment. Among the environments in which stress-corrosion cracking can occur in alloy 625 are high temperature water and chlorides, listed in Table III with other environments that cause cracking.<sup>(4)</sup> Alloy 625 and various alloys were tested in an accelerated wet oxidation environment which consisted of a synthetic sewage with chlorides and fluorides, pH 3.2, and a temperature of 292°C(560°F), (Table IV).<sup>(5)</sup> Alloy 625 and the alloys listed which contain greater than 34% nickel are highly resistant to stress-corrosion cracking in this environment.

Table III. Environments in Which Stress Corrosion Cracking Has Been Observed in alloy 625

Heat Treatment	Environment in Which SCC Was Observed
Annealed	High Temperature Water, Degassed
Annealed	Polythionic Acid
Annealed	Oxygenated Water Plus Lead
Annealed	Water, 21 ppm O <sub>2</sub> , 316°C
Annealed	Steam, Cycled between 318 and 385°C(605-725 F), 10 ppm Cl <sup>-</sup> , 8 ppm O <sub>2</sub>
Cold Worked	288°C water, 100 ppm O <sub>2</sub>
Cold Worked and Aged at 204°C (400°F)	Water, saturated with H <sub>2</sub> S + 5% NaCl + 0.5% acetic acid, "NACE" solution, RT
Cold Worked and Aged at 500°C (932°F)	Water with 5% NaCl and 0.5% acetic acid, RT

(Ref. 4)

**Table IV. Stress Corrosion Cracking Data**

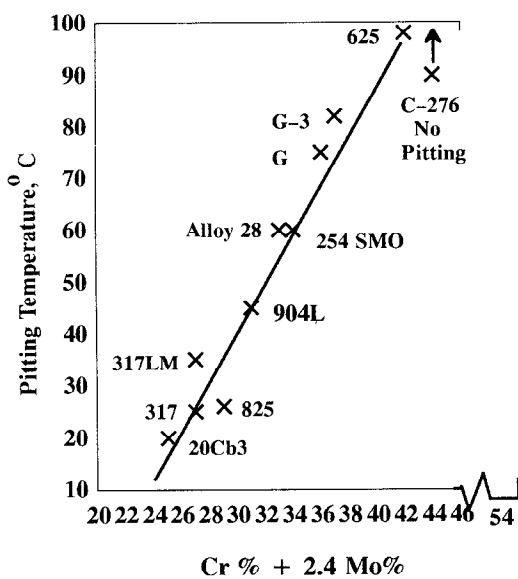
Alloy <sup>(a)</sup>	Stress Corrosion <sup>(b)</sup> Cracking in Liquid Phase
C-276	No Cracking
625	No Cracking
G	No Cracking
26-1	3 of 10 in 281 Hours
20-Cb3®	No Cracking
20-Cb3® Tube	1 of 10 in 440 Hours
825	1 of 9 in 295 Hours
Nitronic® 50	9 of 10 in 30 Hours
Nitronic® 10	8 of 10 in 16 Hours
Nitronic® 60	9 of 10 in 11 Hours
Nitronic® 33	9 of 10 in 11 Hours
316-L	10 of 10 in 12 Hours
304-L	10 of 10 in 12 Hours
316 Tube - Machined and Heat Treated	9 of 9 in 12 Hours
316 Tube - Machined	9 of 9 in 12 Hours
316 Tube	10 of 10 in 12 Hours

(a) Alloys listed in order of best to worst.

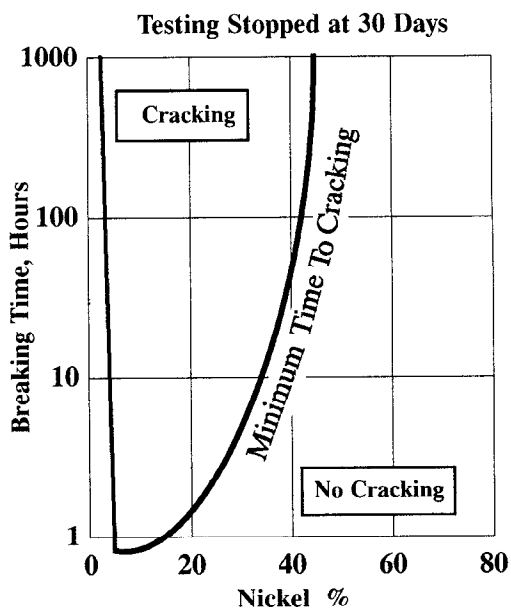
(Ref. 5)

(b) Wet Oxidation Environment

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**Figure 3. Critical Temperature for Pitting in 4% NaCl + 1% Fe<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> + .01 M HCl Versus Composition for Fe-Ni-Cr-Mo Alloys.**  
(Ref. 1)



**Figure 4. Stress Corrosion Cracking of Fe-Cr-Ni Alloy Wires in Boiling 42% Magnesium Chloride. (Copson U-Curve)**  
(Ref. 3)

## Sulfide Stress Cracking

Sulfide stress cracking (SSC) is a problem in the oil and gas industry. It usually results in a brittle failure of material under stress in water contaminated with hydrogen sulfide. SSC data is presented in Table V for alloy 625 and other alloys.<sup>(6)</sup> The tests were conducted at room temperature under constant load using a mixture of oxygen free water containing 3000 ppm dissolved H<sub>2</sub>S, 5% NaCl and 0.5% acetic acid (NACE solution). The threshold stress (stress required to initiate cracking) of alloy 625 is near the yield strength in both the annealed and cold rolled conditions. The threshold stress, however, is greater for some alloys, such as MP35N, in this environment.

Table V. Sulfide Stress Corrosion Cracking Data

Alloy	Condition	Yield Stress MPa (Ksi)	Tensile Stress MPa (Ksi)	Hardness HRC	Threshold Stress MPa (Ksi)
Titanium	A	527 ( 76.4)	659 ( 95.6)	20	516 ( 74.9)
MP35N®	CRA	2005 (290.8)	2046 (296.8)	51	1965 (285.0)
C-276	CR	1503 (218.0)	1631 (236.5)	41	1473 (213.6)
G	CR	1496(217.0)	1617 (234.5)	35	1470 (213.2)
K-500	CRA	1124(163.0)	1317 (191.0)	36	1101 (159.7)
625	A	558 ( 81.0)	979 (142.0)	20	546 ( 79.2)
625	CR	1327(163.0)	1355 (196.5)	39	1301 (188.7)
718	SA	986 (143.0)	1172 (170.0)	34	960 (139.3)
X-750	SA	1304 (150.0)	1318 (191.2)	37	1013 (147.0)
Nitronic® 50	CR	880 (127.6)	1076 (156.1)	26	862 (125.0)
3RE60	A	591 ( 85.7)	756 (109.7)	20	532 ( 77.1)
17-4 PH®	SA	858 (124.5)	974 (141.2)	30	86 ( 12.5)
Custom 450®	SA	579 ( 84.0)	945 (137.0)	25	290 ( 42.0)

A - Annealed

CRA- Cold Rolled and Annealed

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CR - Cold Rolled

SA - Solution Annealed and Aged

(Ref. 6)

## Hydrogen Embrittlement

Hydrogen embrittlement data developed by cathodic charging of various alloys with hydrogen followed by room temperature tension testing is presented in Figure 5.<sup>(6)</sup> The degree of susceptibility to hydrogen embrittlement was measured as a function of ductility loss. Alloy 625 possesses an intermediate ranking compared to the other alloys in Figure 5. Data developed in pressurized gaseous hydrogen is shown in Table VI.<sup>(7)</sup> Again, alloy 625 possesses an intermediate ranking compared to the other alloys in Table VI.

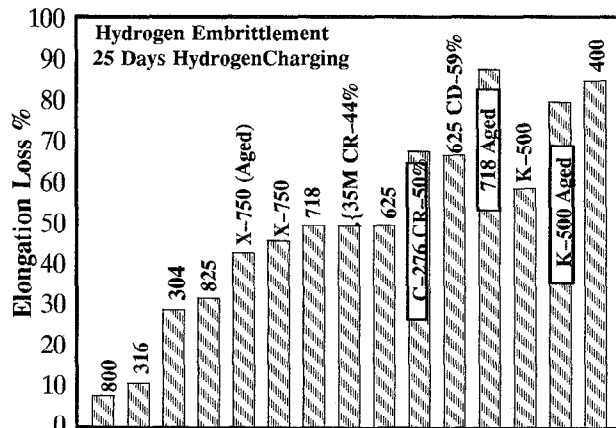


Figure 5. Loss in Ductility after 25 Days hydrogen Charging (Cathodic)

(Ref. 6)

**Table VI. Relative Resistance to Hydrogen Embrittlement Notched Strength Ratio (H<sub>2</sub>/He) at Room Temperature**

Alloy	H <sub>2</sub> Pressure (Ksi)	Strength Ratio
903	5	1.00
AISI 316	10	1.00
OFHC Copper	10	1.00
6061-T6	10	1.00
802	7	0.99
7075-T73	10	0.98
A-286	10	0.97
RA 330®	7	0.95
Be-Cu(Alloy 25)	10	0.93
AISI 310	10	0.93
AISI 347	5	0.91
ASTROLOY®	5	0.90
X	5	0.87
FM 718	7	0.86
AISI 1020	10	0.79
Ti-6Al-4V(Ann)	10	0.79
625	5	0.76
AISI 1042 (Norm)	10	0.75
HY 100	10	0.73
400	7	0.65
MP35N®	10	0.50
718	10	0.46
AISI 4140	10	0.40
RENE 41®	10	0.27
X-750	7	0.26
17-7 PH® (H 1050)	10	0.23
AISI 410	10	0.22
250 MARAGING	10	0.12

Source: B McPherson, NASA Marshall Space Flight Center, August 1986

(Ref. 7)

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### Intergranular Attack

Alloy 625 is stabilized against intergranular attack by precipitation of niobium carbides at a 927 to 1038°C (1700 to 1900°F) annealing temperature. Niobium carbides tie up carbon, making it less available to precipitate as chromium carbides in the grain boundaries. Chromium depletion near the grain boundaries is an effect of intergranular chromium carbide precipitation. This process occurs at certain temperatures and is known as sensitization. Sensitization of an alloy makes it susceptible to intergranular attack. Alloy 625 can be made susceptible to this attack by an improper annealing treatment which would inhibit the formation of niobium carbides thereby making carbon more available to precipitate intergranularly as chromium carbides by a subsequent sensitizing treatment. Corrosion rate data, in mpy, generated from the intergranular attack of alloy 625 due to sensitization of the grain boundaries, is presented in Figure 6.<sup>(8)</sup> The data was obtained by annealing samples at various temperatures followed by subjecting them to sensitizing temperatures in the range of 704 to 871°C (1300 to 1600°F) for one hour. The samples were then tested in boiling 65% nitric acid allowing the subsequent precipitation of Cr carbides at the grain boundaries when the

alloy is exposed to sensitizing temperatures of 704 to 871°C (1300 to 1600°F). At lower annealing temperatures, stabilizing Nb carbides are precipitated, thus a subsequent sensitizing heat treatment of 704° to 871°C (1300 to 1600°F) will cause little or no precipitation of Cr carbides at the grain boundaries.

### Corrosion in Bleach Plant Environment

Pulp and paper bleach plant environment corrosion studies have been tabulated in Table VII.<sup>(9)</sup> Exposures in solutions ranging from pH 1.4 to 9.5 with up to 5500 ppm chlorides and 80°C (176°F) with strong chlorine-base oxidizers present, were made on 38 specimens each of 26 materials. There were eight chlorination stage, nine chloride dioxide stage, and three hypochlorite stage bleach plant environments. From the data indicated in Table VII, alloy 625 and some other highly corrosion resistant alloys rank first in corrosion resistance in bleach plant environments. The high chromium and molybdenum content (21.5%Cr, 9%Mo) of alloy 625 is responsible for alloy 625's pitting resistance in this environment and pitting resistance in general as was depicted in Figure 3.

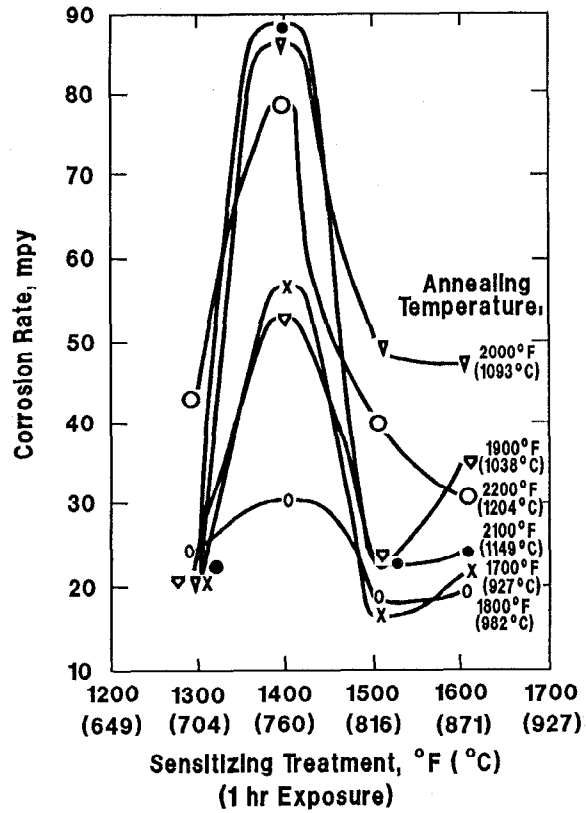


Figure 6. Effect of Annealing Temperature on Sensitization of Alloy 625. Specimens Were Annealed As Shown, Exposed to The Sensitizing Temperature for 1 Hr and Tested in Boiling 65% Nitric Acid. (Ref. 8)

Table VII. Corrosion Data in Pulp & Paper Bleach Plant Environments

Rank	Alloy	Total Depth Pitting (mils)	Rank	Alloy	Total Depth Pitting (mils)
1	G	-	9	AL-6X®	177
1	G-3	-	10	28	190
1	625	-	11	T-317X S/S	229
1	C-276	-	12	JS-700	247
1	Titanium GR-2	-	13	UHB-904L	250
1	Titanium 12	-	14	UHB-44LN	302
2	20Mo-6	5	15	825	311
3	AL 29-4®	7	16	254 SLX	414
4	SC-1	29	17	T-317LM® S/S	647
5	Schomac® 30-2	41	18	Nitronic® 50	658
6	Monit®	78	19	T-317L S/S	690
7	254-SMO	86	20	26-1	770
8	AL 29-4-2®	102	21	T-316L S/S	1158

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(Ref. 9)



## Sea Water Corrosion

Various alloys have been classified by rank of corrosion resistance to marine environments in Table VIII.<sup>(10)</sup> Alloy 625 stands among the best in marine environments owing again to its high chromium and molybdenum content.

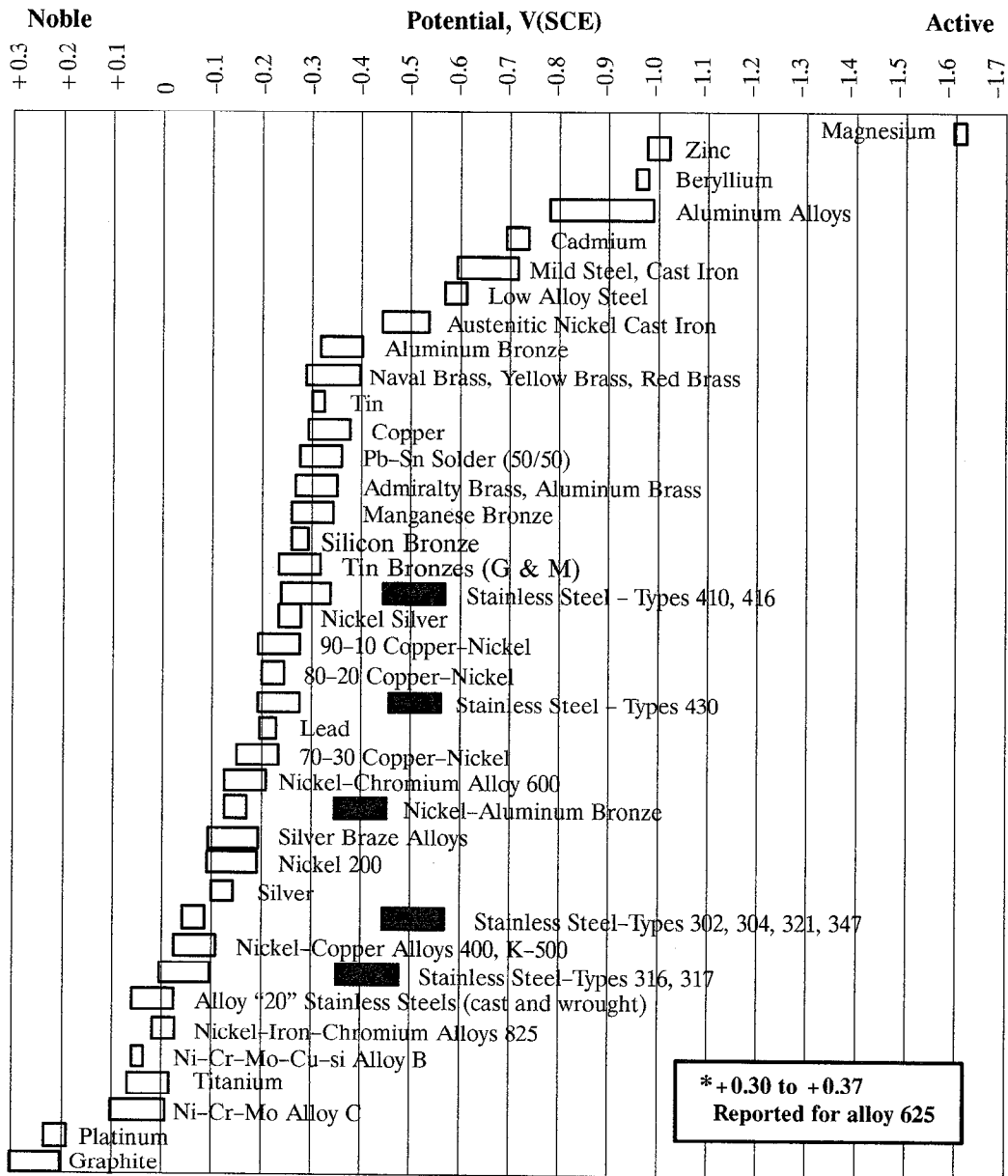
**Table VIII. Classification of Nickel Alloys Which May Find Special Application in Marine Environments**

Alloy	Remarks
<b>Class I: Most Resistant</b>	
C	Complete resistant except at welds
C-276	Low carbon (< .02 C) can be welded
625	Approaches alloy C in total resistance
MP35N®	Excellent, so far, in preliminary experiments
Chlorimet®-3	Cast alloy; excellent for pumps, etc.
Rene 41®	Good-to-excellent resistance to pitting
X	Good-to-excellent resistance to pitting
<b>Class II: Very Resistant</b>	
F G Inconel® R 700 718	Usually satisfactory; molybdenum content provides resistance to pitting.
<b>Class III: Resistant, Some Pitting</b>	
600 X-750 800 825 400 K-500	May be some pitting at sites where sea water is stagnant.

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(Ref. 10)

A galvanic series in sea water is presented in Figure 7 showing alloy 625 to be very noble compared to many of the other alloys. Thus, alloy 625 will usually behave as a cathode when in contact with other materials in sea water.<sup>(11,12)</sup>



Alloys are listed in the order of the potential they exhibit in flowing sea water. Certain alloys indicated by the symbol: ■ in low-velocity or poorly aerated water, and at shielded areas, may become active and exhibit a potential near - 0.5 volts.

\*(Ref. 12)

**Figure 7. Galvanic Series in Sea Water**

(Ref. 11)

Sea water corrosion-fatigue strength versus ultimate tensile strength for alloy 625 and various alloys is plotted in Figure 8.<sup>(13)</sup> Alloy 625 shows good corrosion-fatigue strength in sea water. The results of additional corrosion-fatigue tests on alloy 625 and other alloys in sea water are shown in Table IX.<sup>(14)</sup>

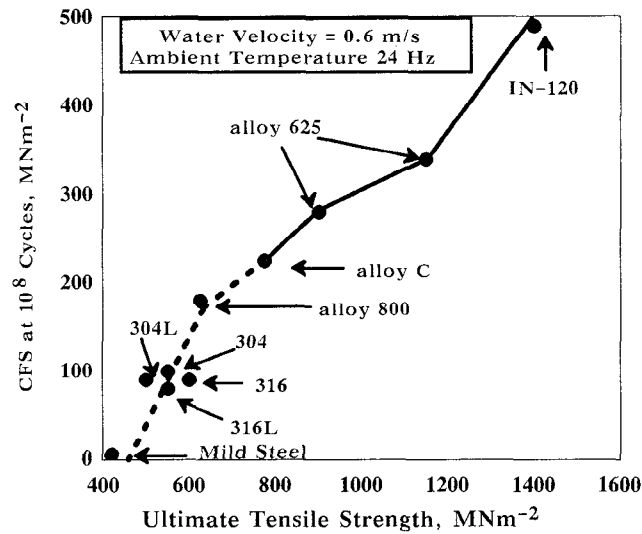


Figure 8. Variation of Corrosion-Fatigue Strength (CFS) with UTS of Rotating-bend Specimens of Various Alloys in Sea Water. (Ref. 13)

Table IX. 48-Day Corrosion Fatigue Strength (CFS) at  $10^8$  Cycles of Various Materials in Sea Water

Material	Ultimate Tensile Strength		CFS at 100 Megacycles in Sea Water	
	ksi	kgf/mm <sup>2</sup>	ksi	kgf/mm <sup>2</sup>
IN-120 (Experimental alloy)	205	144	70	49.2
718 (grain size = 0.01 mm)	189	133	60	42.2
625	149	105	50	35.1
718 (grain size = 0.068 mm)	189	133	40	28.2
625	129	91	40	28.2
718 (grain size = 0.152 mm)	-	-	32	22.5
C	108	76	32	22.5
K-500	176	124	26	18.3
800	89	63	24	16.9
18% Ni Maraging Steel (0.25 mm mild steel coating)	250	176	23	16.2
18% Ni Maraging Steel (Cathodic Prot. at 0.85V)	250	176	15	10.6
Ni-Al Bronze (cast) CA 955HT	115	81	15	10.6
AISI Type 304 Stainless Steel	79	56	15	10.6
AISI Type 316 Stainless Steel	85	60	14	9.8
AISI Type 304L Stainless Steel	75	53	14	9.8
AISI Type 316L Stainless Steel	79	56	13	9.1
Ni-Al Bronze (Cast) CA 955	87	61	12.5	8.8
Mn-Ni-Al Bronze (cast) CA 957	100	70	9	6.3
Mn Bronze (cast) CA 865	73	51	8	5.6
18% Ni Maraging Steel (Unprotected)	250	176	5	3.5
Mild Steel	60	42	2	1.4

(Ref. 13)

## High Temperature Corrosion

### Oxidation Test

Although alloy 625 is well known for aqueous corrosion resistance, it also has good resistance to oxidation and scaling at high temperatures. An oxidation test was conducted using air plus 5% added water vapor flowing at the rate of 500cc/min at 1000°C (1832°F) for 1008 hours. The water was added by bubbling air through water controlled at 33°C (91°F) to produce 5% water vapor. Periodically the samples were pulled out of the furnace and weighed after cooling to room temperature to obtain mass change data as a function of time. Figure 9 shows the mass change in air plus 5% water vapor at 1000°C for up to 1000 hours. The data indicates that alloy 625 is comparable to alloys 600 and 800 and better than alloy C-276 in oxidation at 1000°C.

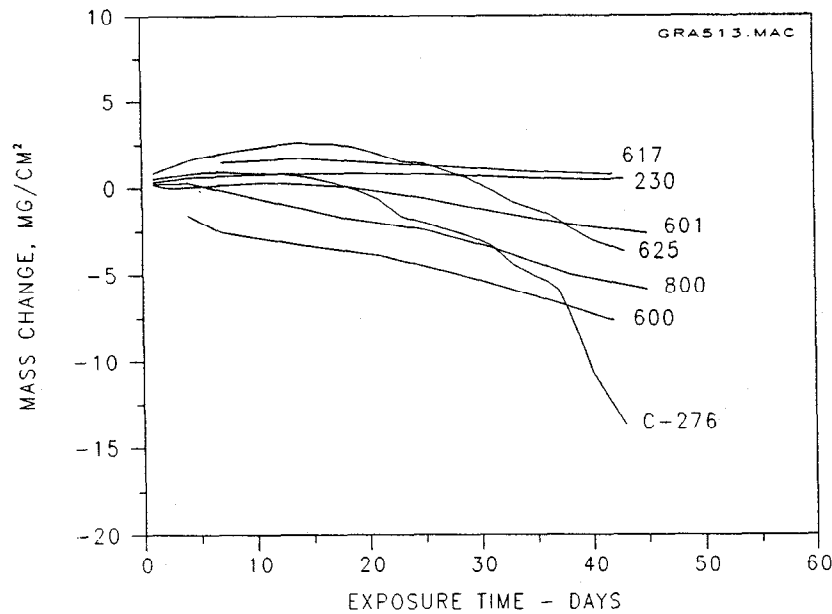


Figure 9. Mass Change As A Function of Exposure Time in Air Plus 5% Water Vapor at 1000°C for Various Commercial Alloys

A cyclic oxidation test is usually conducted on high temperature alloys such as alloys 601, 617 and MA 956 to check the scale adherence. In this case a cyclic oxidation test was conducted at 982°C (1800°F) in which the samples were heated to temperature in 15 minutes and cooled in air for 5 minutes. Samples were weighed after every 100 cycles to obtain the mass change. Figure 10 shows the mass change for samples exposed for 40 days (2880 cycles). The data shows excellent resistance of alloy 625 to cyclic oxidation indicating the ability of the alloy to retain a protective oxide coating under a drastic cyclic condition. Alloy 800 had to be stopped after about 1200 cycles.

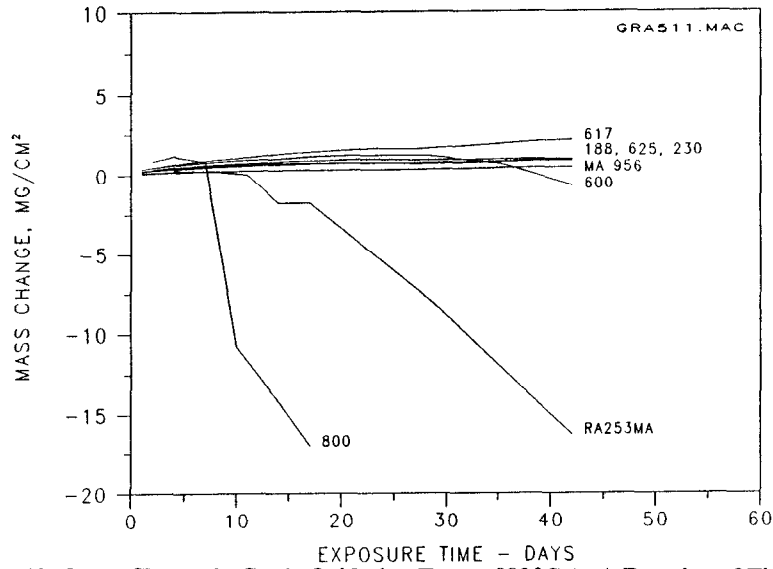


Figure 10. Mass Change in Cyclic Oxidation Test at 982°C As A Function of Time for Various Commercial Alloys. Note that alloy 625 is very resistant to cyclic oxidation.

### Carburization Resistance

Formation of stable oxide scale on the surface is a key to the carburization resistance of an alloy.<sup>(15-17)</sup> A test method was developed at Inco Alloys International, Inc. about 15 years ago to determine the relative high temperature carburization resistance of complex alloys used in ethylene furnaces.<sup>(18)</sup> The test method involves exposing samples of alloys to a mixture of hydrogen and 1 to 3% CH<sub>4</sub> at the temperature of interest. Samples are periodically removed for weighing by pulling the samples to the cold end of the test chamber and flushed with argon to minimize oxidation. Figure 11 shows mass change in H<sub>2</sub>-1%CH<sub>4</sub> at 1000°C (1832°F) for about 1000 hours for various commercial alloys. The data indicates that alloy 625 has good carburization resistance, comparable to alloys DS and 330 and better than alloy 800 and type 309 stainless steel. Figure 12 shows the mass change in a slightly oxidizing (pO<sub>2</sub> ~ 10<sup>-20</sup> atmospheres) carburizing environment, H<sub>2</sub>-5.5%CH<sub>4</sub>-4.5%CO<sub>2</sub>, at 1000°C (1832°F) for about 1000 hours. The data indicates that alloy 625 is comparable to alloys 600 and 230 and better than alloys 800 and 600 in this environment.

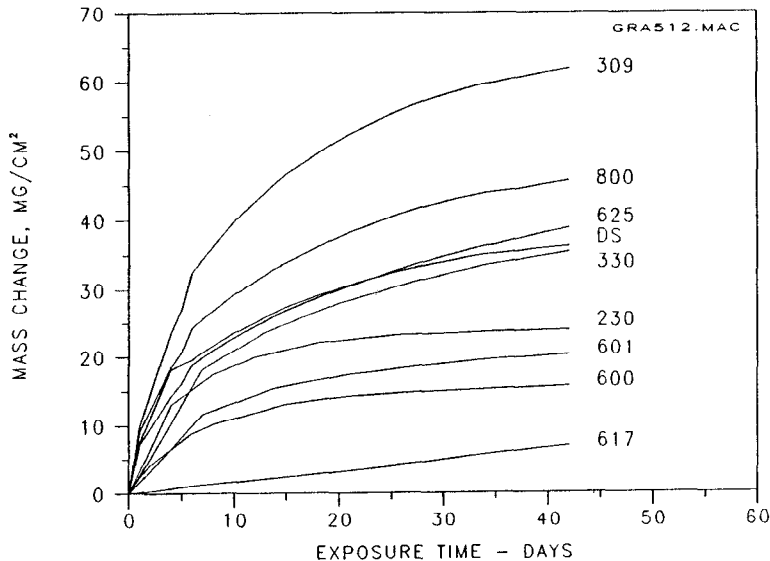


Figure 11. Mass Change As A Function of Exposure Time in H<sub>2</sub>-1%CH<sub>4</sub> at 1000°C for Various Alloys

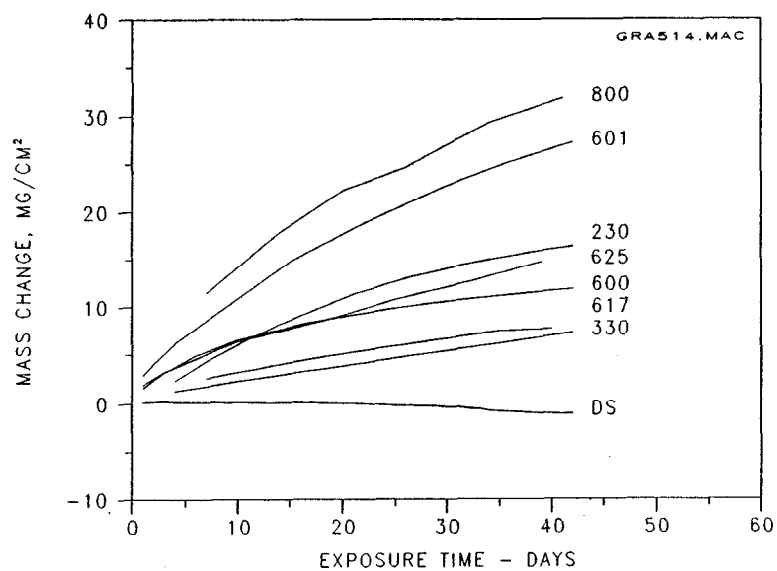


Figure 12. Mass Change As A Function of Exposure Time in  $H_2-5.5\%CH_4$  at  $1000^\circ C$  for Various Alloys

#### Performance of Alloy 625 in Chlorine Containing Environments

Chlorine is a key component in a number of industrial process environments such as mineral chlorination, ethylene dichloride and vinyl chloride monomer production, aluminum smelting and refining, fuel element reprocessing and heat recovery systems. High temperature halide corrosion has also been noted in fossil fuel boilers, coal gasification equipment<sup>(19)</sup> gas turbines<sup>(20-22)</sup> and in municipal and chemical waste incinerators.<sup>(23,24)</sup> Krause<sup>(24)</sup> has shown that municipal waste can contain as high as 0.5% halides on a dry basis. Most of the laboratory studies simulating waste incineration environments have been restricted to temperatures ranging from  $120^\circ C$  to  $650^\circ C$  ( $248^\circ F$  to  $1202^\circ F$ ). Since nickel and nickel-base alloys have a long established reputation for their resistance to halogen attack dating back to the work of Brown et. al.,<sup>(25)</sup> it was deemed useful to extend the temperature range of laboratory data in simulated HCl environments. The temperature range selected for this study was  $593^\circ C$  to  $927^\circ C$  ( $1100^\circ F$  to  $1700^\circ F$ ). This temperature range is typical of the flue gas temperature in the studies of both Fluck<sup>(26)</sup> and Krause.<sup>(24)</sup> Boiler internals and flue stacks, if not tubes, could certainly be expected to experience thermal exposure in this temperature range. The simulated atmosphere selected for this study was  $N_2-10\%CO_2-9\%O_2-4\%HCl-130ppm HBr-100ppm SO_2$ .

Exposures were made in a 100 mm diameter mullite tube in a horizontal electrical resistance furnace. The test specimens were in the form of pins, 7.6mm diameter by 19 mm length. The nominal chemical compositions of some of the alloys used in this study are shown in Table I. The specimens of all the alloys were exposed to the 4% HCl environments at 593, 704, 816 and  $927^\circ C$  (1100, 1300, 1500 and  $1700^\circ F$ ). The gas composition mentioned above was prepared by mixing a purchased gas mixture of  $N_2-SO_2-CO_2-O_2$  with gaseous HCl and HBr. The final gas composition was metered into the mullite tube with electronic flow controllers at a total flow rate of 500 cc/min.

The metal loss data for the alloys tested in  $N_2-10\%CO_2-9\%O_2-4\% HCl-130ppm HBr-100ppm SO_2$  at 593, 704, 816 and  $927^\circ C$  (1100, 1300, 1500 and  $1700^\circ F$ ) for 300 hours is shown in Table X. At the conclusion of the test, all the alloys exhibited negative mass changes suggesting either spalling, vaporization losses or both. The rate of metal loss tended to increase with increasing temperature. The high-iron alloys showed higher mass losses at  $704^\circ C$  ( $1300^\circ F$ ) than at  $927^\circ C$

(1700°F). Metallographic examination (see Figure 13 as an example of attack) showed that high iron alloys had experienced extensive internal oxidation, perhaps triggered by molten  $\text{FeCl}_2$  (M.P. of  $696^\circ\text{C}$  ( $1285^\circ\text{F}$ )). The morphology of corrosion scale at high temperature ( $927^\circ\text{C}$ ) was distinctly different from that at low temperature. At high temperature, voids could frequently be seen that were more pronounced in iron rich alloys. Typical microstructures from Type 316 stainless steel and alloy 625 after exposure at  $704^\circ\text{C}$  ( $1300^\circ\text{F}$ ) and  $927^\circ\text{C}$  ( $1700^\circ\text{F}$ ) illustrating the above mentioned effects are shown in Figures 13 to 16. If one considers the need for excellent resistance to corrosion over the whole temperature regime of  $593^\circ\text{C}$  to  $927^\circ\text{C}$  ( $1100^\circ\text{F}$  to  $1700^\circ\text{F}$ ) these laboratory tests indicate that the nickel-base alloys become essential in order to avoid  $704^\circ\text{C}$  ( $1300^\circ\text{F}$ ) liquid phase corrosion. These alloys—600, 601, 617, 625 and 690—do well, with alloys 600 and 625 showing the best resistance to corrosion at the more elevated temperature.

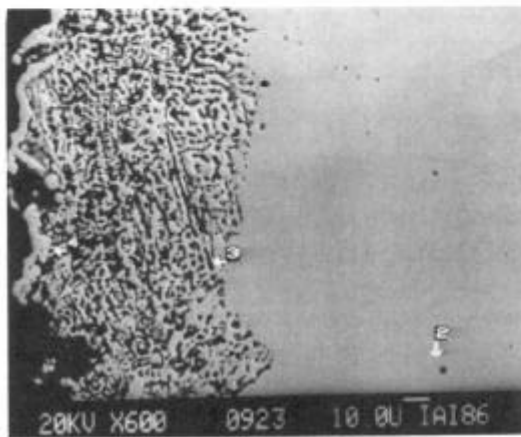


Figure 13. SEM Micrograph from Near Surface Region of Type 316 Stainless Steel Sample Exposed to 4% HCl Environment at  $704^\circ\text{C}$  for ( $1300^\circ\text{F}$ ) for 300 Hours.

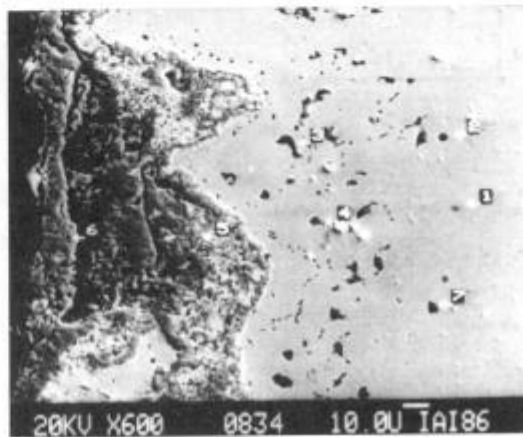


Figure 14. SEM Micrograph from Near Surface Region of Type 316 Stainless Steel Sample Exposed to 4% HCl Environment at  $927^\circ\text{C}$  for ( $1700^\circ\text{F}$ ) for 300 Hours.

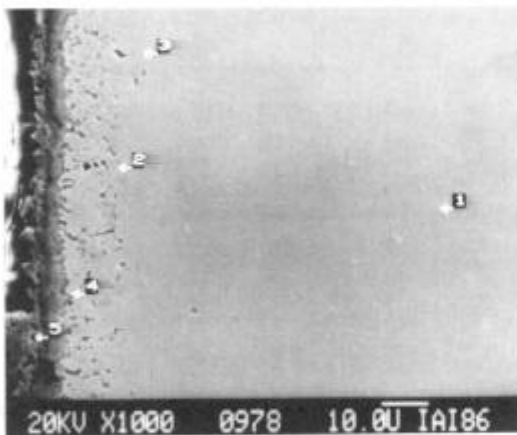


Figure 15. SEM Micrograph from Near Surface Region of INCONEL alloy 625 Sample Exposed to 4% HCl Environment at  $704^\circ\text{C}$  for ( $1300^\circ\text{F}$ ) for 300 Hours.

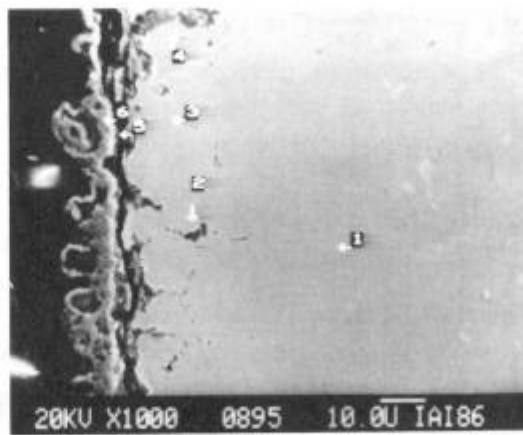


Figure 16. SEM Micrograph from Near Surface Region of INCONEL alloy 625 Sample Exposed to 4% HCl Environment at  $927^\circ\text{C}$  for ( $1700^\circ\text{F}$ ) for 300 Hours.

**Table X. Mass Change Data for Selected Alloys in N<sub>2</sub> -10% CO<sub>2</sub> - 9% O<sub>2</sub> - 4% HCl - 130 ppm HBr - 100 ppm SO<sub>2</sub> Environment after 300 Hours Mass Change - mg/cm<sup>2</sup>**

Alloy	593° C (1100° F)	704° C (1300° F)	816° C (1500° F)	927° C (1700° F)
309	-2.62	-117.89	-	-77.70
316	-5.48	-152.08	-32.75	45.74
347	-1.61	-327.80	-221.65	-68.36
600	-0.32	-0.98	-6.93	-10.18
601	-0.05	-2.19	-7.24	-29.53
617	-0.51	-8.38	-10.81	-44.64
625	-0.52	-2.06	-5.86	-5.91
690	-0.13	-1.12	-14.27	-24.21
800	-0.53	-245.22	-6.63	-18.98
825	-1.53	-127.34	-8.52	-25.89

#### **Material for a Heat Exchanger**

In recent times increased emphasis is being placed on safe disposal of chlorinated solvents. Combustion, particularly on-site incineration is an effective way to safely dispose of these materials instead of hauling of solvents on public thoroughfares. Also, cost is much lower for on-site combustion. Taking these factors into consideration, a combustion system was chosen by an industrial waste incinerator operator for handling chlorinated solvents generated from a coating operation.<sup>(27)</sup> The system consists of a blower that draws the methanol and methylene chloride fumes, containing 97% air, from the coater into the U-bend of the preheater/exchanger. The gas stream is separated into distinct, totally isolated alternating passages formed by the fixed plates. The gas leaving the heat exchanger is heated to 427° C (800° F). The preheated gas enters a natural gas fired combustor where the temperature is maintained between 927 and 982° C (1700 and 1800° F). The combustion gases then pass through a fire tube boiler. The gases leave the boiler at 760° C (1400° F) and pass through the hot side of the pre-heater/exchanger which reduces the temperature of the gases to 316° C (600° F). The gases then pass through a scrubber and into the atmosphere. The original heat exchanger was constructed out of Type 309 stainless steel. First inspection of the heat exchanger after about six months of operation indicated extensive scaling of the thin plates. Nearly all of the original thickness, 0.48mm of the plate has been oxidized and the remainder had suffered internal attack.

Because of the time constraints, a decision was made to install another type 309 SS heat exchanger and at the same time include a test rack of coupons of various alloys in the gas stream ahead of the exchanger for evaluation of alternative materials. The rack of coupons consisted of Types 304, 309 and 316 stainless steels and INCONEL alloys 600, 625 and INCOLOY alloys 800 and 825, and INCO alloy C-276. The rack was exposed to the operating environment for 300 hours). Metallographic analysis of the rack coupons indicated higher corrosion and internal attack for alloys 800 and 825 and Type 304, 309 and 316 stainless steels (5 to 12 mils (0.13 to 0.30 mm) in 300 hours). Alloys 600, 625 and C-276 showed very little corrosion (< 2 mils (< 0.05 mm) in 300 hours). This was similar to the results obtained from the laboratory corrosion study as indicated earlier.

Based on the test rack data alloys 600, 625 and C-276 were judged to be acceptable candidates. Alloy C-276 was ruled out because of its cost and limited availability. Alloys 600 and 625 could be considered equivalent because alloy 600 was corroded only slightly more than alloy 625 and the disadvantage of having a slightly higher corrosion rate could at least partially be offset by its lower cost. The final decision was made to use **alloy 625** on the basis that a slightly longer life could be expected,



which would amortize purchase and installation costs over a longer period of time. In addition, alloy 625 has better resistance to pitting and crevice corrosion in the event of acid condensate exposure during down time. After the installation of alloy 625 heat exchanger, first inspection was conducted after about five months of operation. All of the heat transfer surfaces showed a uniform gray oxide with no evidence of spalling. Based on this excellent corrosion performance, the exchanger is expected to last 5 to 8 years, as compared to the one year life for 309 SS. A recent contact with the company personnel indicated that no problem related to the exchanger has been encountered. Another new system is being designed for similar application and alloy 625 is being specified as the heat exchanger material.

### Conclusions

Due to its high nickel, chromium, niobium and molybdenum contents, alloy 625 has good overall aqueous corrosion resistance in a wide range of highly aggressive environments. In many environments the resistance of alloy 625 to aqueous corrosion is comparable to alloys such as G-3, C-276, 622 and C-22. It is resistant to general corrosion and intergranular attack in many environments found in the chemical processing industries. It is highly resistant to pitting and crevice corrosion in applications such as flue gas desulfurization. It is highly resistant to corrosion and fatigue failures in sea water where it is often used in naval applications. Alloy 625 resists aggressive environments which can cause chloride and sulfide stress corrosion cracking and hydrogen embrittlement in oil country tubular goods. Alloy 625 also resists general and localized corrosion in the pulp and paper industries.

Alloy 625 has good high temperature gaseous oxidation resistance comparable to alloys 800 and 600 and better than alloy C-276. Alloy 625 has excellent resistance to cyclic oxidation comparable to alloys 600, 188, 230 and 617. Alloy 625 has good resistance to both reducing and oxidizing carburization environments.

Alloy 625 showed the best resistance to environments containing 4% HCl at various temperatures from 593°C to 927°C (1100°F to 1700°F). In the field evaluation of commercial alloys in a chlorinated solvent incinerator, alloy 625 performed extremely well. The heat exchanger made of alloy 625 is still doing well after 3 years of service.

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