A Comparison of the Properties of Corrosion-Resistant Alloys and Titanium: An Aid for Specifying the Most Cost Effective Materials for Demanding Applications

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While commercially pure (C.P.) titanium and titanium alloys offer excellent resistant to many commonly encountered corrosive media, these materials are currently in very limited supply. Thus, designers are being forced to consider alternate corrosion-resistant materials. Nickel-chromium-molybdenum corrosion-resistant alloys such as INCONEL alloys C-276, 22, and 686 and INCOLOY alloy 27-7MO are excellent candidates for this purpose.

Nickel and molybdenum are the controlling elements in determining the costs of such corrosion-resistant alloys. Alloys with higher contents of nickel and molybdenum will be found to be more costly than those with lesser contents. Thus, when a lower alloyed material like alloy 27-7MO can be used instead of the more highly alloyed C-276, 22, and 686 products, significant cost savings are possible.

This document presents data to support the use of corrosion-resistant alloys in the place of titanium and also data to help designers select the most cost effective alloy for an application. General corrosion data are provided in Tables 1 and 2. Mechanical and physical properties and chemical composition limits are presented in Table 3. Data specific to various industries and applications are presented in Table 4 to support the substitution of corrosion-resistant alloys for titanium. Similar data are presented in Table 5 to show where the lower cost alloy 27-7MO may be substituted for the more costly alloys C-276, 22, and 686. Information on all the alloy products manufactured by Special Metals is available on the company websites, www.specialmetals.com and www.specialmetalswelding.com.

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Table 1

A Comparison of the Aqueous Corrosion Resistance of Several Alloys in Various Applications
(Corrosion Rates in mpy)

Application / Test Environment	INCOLOY 25-6MO	INCOLOY 27-7MO	INCONEL C-276	INCONEL 22	INCONEL 686	Titanium Grade 2
General						
% Nickel / % Molybdenum	25 Ni / 6 Mo	27Ni / 7Mo	57Ni / 16Mo	58Ni / 13Mo	57Ni / 16Mo	N/A
Cost Ratio - alloy 25-6MO as base line	**1**	**1.1**	**2.0**	**2.1**	**2.3**	**2.1**
Pitting Resistance Equivalency Number [1]	35.8	43.0	45.2	46.5	50.8	N/A
Critical Pitting Temp (ASTM G48C)	70°C	>85°C	>85°C	>85	>85	
Critical Crevice Temp (ASTM G48D)	35°C	50°C	50°C	75	>85	
Critical Pitting Temp ("Green Death")	60°C	80°C	> Boiling	>120°C	>135°C	
Critical Crevice Temp ("Green Death")	45°C	65°C	90°C	120°C	135°C	
1% Boiling HCl - mpy	218	1.3	6.5	2.7	2	In test
5% HCl @ 122°F (50°C) - mpy	45	<0.1	0.5	<1	<1	
1% HCl @ 60C – mpy	0	0	0	0	0	0.6
3% HCl @ 60C – mpy	>50	<5	<1	<1	<1	39
5% HCl @ 60C – mpy	88	70	1	<1	1	118
15% HCl @ 35°C, Aerated – mpy	<50	<50	<5	5	<5	94
95% H2SO4 @ 122°F (50°C) – mpy	18	14	0.1	<1	<1	
10% H2SO4+2% HCl @122°F (50°C)-mpy	29	<0.1	<0.1			
10% H2SO4 @ 194°F (90°C) – mpy	33	1	<0.1	1	1	
10% H2SO4 @ 35C, Aerated – mpy	<5	<5	<5	<5	<5	47
40% H2SO4 @ 35C, Aerated – mpy	<5	<5	<5	<5	<5	335
10% H2SO4+10,000 ppm Cl^- @ 65°C – mpy	26	<0.5	0.5	<0.5	<0.5	In test
10% H2SO4+1,000 ppm Cl^- @ 65°C – mpy	26	0	1	<0.5	<0.5	
98% H2SO4+1,000 ppm Cl^- @ 65°C – mpy	57	49				
Resistance to hydrogen embrittlement and hydriding	Excellent	Excellent	Excellent	Excellent	Excellent	Poor

Table 2

A Comparison of the Aqueous Corrosion Resistance of Several Alloys in Various Applications (Corrosion Rates in mpy)

Application / Test Environment	INCOLOY 25-6MO	INCOLOY 27-7MO	INCONEL C-276	INCONEL 22	INCONEL 686	Titanium Grade 2
Marine						
Crevice Corrosion in 30°C Seawater for 60 Days (Max. Depth of Attack)		No Attack	0.02 mm			--
Synthetic Seawater@149°F(65°C)60 days	No Attack	No Attack	No Attack	No Attack	No Attack	--
Seawater @ 86°F (30°C) for 90 days with PTFE Crevice Device Installed	0.11" (0.28mm) Crevice Attack	No Attack				--
Natural Seawater, 1-2 ppm chlorine, 60°C, PTFE Crevice Device Installed	0.08 mm depth attack	--	--	--	No Attack	--
Saturated Boiling NaCl	Crevice Attack	No Attack	No Attack	None	None	Attack[4]
KCl+NaCl+MgCl2+CaCl2 Brine @ 113C	In test	In test	In test	In test	In test	Attack[5]
Synthetic Seawater, 1-2 ppm chlorine, 200°C					No Attack	No Attack
FGD						
Simulated FGD Inlet Condensate No. 1[2] - mpy	199 mpy	153 mpy	28 mpy	40 mpy	23 mpy	NR[8]
Simulated FGD Inlet Condensate No. 2[9] - mpy	--	--	54	12	14	--
Critical Pitting Temperature ("Green Death")	70°C	85°C	100°C	--	>135°C	--
Critical Crevice Temperature ("Green Death")	45°C	65°C	90°C	125°C	135°C	--
FGD Stack Condensate[7] @ 90°C – crevice depth	0.06 mm	In test	<.02 mm	<.02 mm	0	--
Pulp & Paper						
Chlorination- C stage pulp washer			No Attack[6]			No Attack[6]
Hydrogen Peroxide- 30% @ 140°F			<2 mpy			<20 mpy
Hydrogen Peroxide – 100% @ boiling			<2 mpy			<20 mpy
Phosphoric Acid						
85% Boiling H3PO4	30 mpy	27 mpy	13 mpy	16 mpy	18 mpy	
20% NaCl + 0.14% H3PO4 @ 95°C	Severe Pitting	No Attack				
Hydrofluoric Acid						
20% HF @ 50°C - mpy	220 mpy	140 mpy	12 mpy	17 mpy	8 mpy	NR
Oil and Gas						
Critical Pitting Temperature in Environment Relative to Sour Gas[3]	<60°C	80°C	>Boil	>Boil	>Boil	
NACE TM0177 - for hydrogen cracking	No Crack	No Crack	No Crack	No Crack	No Crack	Fail

Table 3

Physical and Mechanical Properties of INCOLOY alloy 27-7MO, INCONEL alloys C-276, 22 and 686, and Titanium

Physical & Mechanical Properties	INCOLOY 25-6MO	INCOLOY 27-7MO	INCONEL C-276	INCONEL 22	INCONEL 686	Titanium Grade 2
Density						
lb/cu.in.	0.290	0.289	0.321	0.311	0.315	0.163
g/cu. cm.	8.03	8.02	8.89	8.61	8.73	4.51
Mechanical Properties (Room Temperature)						
Specification - ASTM	B625,A240	A240	B575	B575	B575	B348
Minimum Specified UTS –ksi	94	112	100	100	100	50
Minimum Specified 0.2% YS - ksi	43	52	41	45	45	40
Minimum Specified Elongation - %	35	40	40	45	45	20
Limiting Chemical Composition						
Specification - ASTM	B625, A240	A240	B575	B575	B575	B348
Nickel	24.0-26.0	26.0-28.0	Balance	Balance	Balance	---
Chromium	19.0-21.0	20.5-23.0	14.5-16.5	20.0-22.5	19.0-23.0	---
Molybdenum	6.0-7.0	6.5-8.0	15.0-17.0	12.5-14.5	15.0-17.0	---
Tungsten	---	---	3.0-4.5	2.5-3.5	3.0-4.4	---
Copper	0.5-1.5	0.5-1.5	---	---	---	---
Iron	Balance	Balance	4.0-7.0	2.0-6.0	2.0 max	0.30 max
Manganese	2.0 max	3.00 max	1.0 max	0.50 max	0.75 max	---
Vanadium	---	---	0.35 max	0.35 max	---	---
Titanium	---	---	---	---	0.02-0.25	Balance
Cobalt	---	---	2.5 max	2.5 max	---	
Carbon	0.02 max	0.020 max	0.01 max	0.015 max	0.01 max	0.08 max
Nitrogen	0.15-0.25	0.3-0.4	---	---	---	0.03 max
Silicon	0.5 max	0.5 max	0.08 max	0.08 max	0.08 max	---
Sulfur	0.01 max	0.01 max	0.03 max	0.02 max	0.02 max	---
Phosphorus	0.03 max	0.03 max	0.04 max	0.02 max	0.04 max	---
Hydrogen	---	---	---	---	---	0.015 max
Oxygen	---	---	---	---	---	0.25 max
Residual Elements (each element)	---	---	---	---	---	0.1 max
Residual Elements (total)	---	---	---	---	---	0.4 max

Table 4

Industries and Environments in which INCOLOY alloy 27-7MO and INCONEL alloys C-276, 22 and 686 might replace Titanium

	INCOLOY 25-6MO	INCOLOY 27-7MO	INCONEL C-276	INCONEL 22	INCONEL 686	Titanium Grade 2
Chemical Process Industry						
5% HCl @ 122°F (50°C) - mpy	45	<0.1	0.5	<1	<1	
1% HCl @ 60C	0	0	0	0	0	0.6
3% HCl @ 60C	>50	<5	<1	<1	<1	39
5% HCl @ 60C	88	70	1	<1	1	118
15% HCl @ 35°C, Aerated	<50	<50	<5	5	<5	94
10% H2SO4+2% HCl @122°F (50°C)-mpy	29	<0.1	<0.1			
10% H2SO4 @ 194°F (90°C) – mpy	33	1	<0.1	1	1	
10% H2SO4 @ 35C, Aerated	<5	<5	<5	<5	<5	47
40% H2SO4 @ 35C, Aerated	<5	<5	<5	<5	<5	335
10% H2SO4+1,000 ppm Cl^- @ 65°C – mpy	26	0	1	<0.5	<0.5	
Marine						
Saturated Boiling NaCl	Crevice Attack	No Attack	No Attack	None	None	Attack
Sea Water applications in general	Attacked	No Attack	No Attack	No Attack	No Attack	No Attack
Oil and Gas						
NACE TM0177 - for hydrogen cracking	No Crack	No Crack	No Crack	No Crack	No Crack	Failed

Table 5

Industries and Environments in which INCOLOY alloy 27-7MO might replace INCONEL alloys C-276, 22 and 686

	INCOLOY 25-6MO	INCOLOY 27-7MO	INCONEL C-276	INCONEL 22	INCONEL 686	Titanium Grade 2
Chemical Process Industry						
1% Boiling HCl - mpy	218	1.3	6.5	2.7	2	In test
5% HCl @ 122°F (50°C) - mpy	45	<0.1	0.5	<1	<1	
1% HCl @ 60C – mpy	0	0	0	0	0	0.6
3% HCl @ 60C – mpy	>50	<5	<1	<1	<1	39
10% H2SO4+2% HCl @122°F (50°C)-mpy	29	<0.1	<0.1			
10% H2SO4 @ 194°F (90°C) – mpy	33	1	<0.1	1	1	
10% H2SO4 @ 35C, Aerated – mpy	<5	<5	<5	<5	<5	47
40% H2SO4 @ 35C, Aerated – mpy	<5	<5	<5	<5	<5	335
10% H2SO4+10,000 ppm Cl^- @ 65°C – mpy	26	<0.5	0.5	<0.5	<0.5	In test
10% H2SO4+1,000 ppm Cl^- @ 65°C – mpy	26	0	1	<0.5	<0.5	
Marine						
Crevice Corrosion in 30°C Seawater for 30 Days (Area Attacked / Max. Depth)	80 sq. mm. 0.01 mm	No Attack	1 sq. mm. 0.02 mm			--
Synthetic Seawater@149°F(65°C)60 days	No Attack	No Attack	No Attack	None	None	--
Seawater @ 86°F (30°C) for 90 days with PTFE Crevice Device Installed	0.11" (0.28mm) Crevice Attack	No Attack				--
Natural Seawater, 1-2 ppm chlorine, 60°C, PTFE Crevice Device Installed	0.08 mm depth attack	--	--	--	No Attack	--
NaCl – Saturated / Boiling	Crevice Attack	No Attack	No Attack	None	None	Attack[4]
Oil and Gas						
27-7MO is currently used as downhole wire line						
NACE TM0177 - hydrogen cracking	No Crack	No Crack	No Crack	No Crack	No Crack	Failed
FGD						
Absorber Vessel – 6% Mo & Higher alloys	Known to be Resistant	Known to be Resistant	Known to be Resistant	--	--	N/A
Inlet Ducting - best specified as alloy 686						
Outlet Ducting – alloy 27-7Mo should be acceptable– tests in progress						

Footnotes:

1 - PREN = %Cr + 1.5 (%Mo + %W) + 30 (%N)
2 - 60% H2SO4 + 2.5% HCl + 0.2% HF + 0.5% Flyash @ 80°C
3 - Critical Pitting Temperature of Cold Worked Wire in 6% $FeCl_3$ + 1% HCl
4 - Predicted from other work
5 - Titanium Grade 12
6 - No attack, <.15 mm localized attack and <1 mpy general attack (A. Garner)
7 - FGD stack condensate (6,145 ppm chloride, 115ppm nitrate, 2970 ppm sulfate), pH - 1.5
8 - NR = Not Recommended
9 - 60% H2SO4 + 0.5% HCl + 0.1% HF + 0.1% HNO_3 @ 85°C