Selection of Materials for Use in Desalination Plants: A Corrosion Literature Review Paper

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Abstract

In recent years, the availability of fresh drinking water has become more and more important, especially for metropolises located in areas without an adequate natural source of fresh water. This dilemma has led to a rise in the number of desalination plants across the globe and efforts to improve their efficiency. Engineers have the opportunity to make the biggest impact on both of these factors by selecting proper materials for heat exchanger pipes, pumps, water boxes, venting systems, etc. When engineers are selecting materials, it is important they consider the heat exchange properties, corrosion resistance, and cost of the materials. The most important aspect to consider is the corrosion resistance because of the highly corrosive chloride environment. The most practical material for use in desalination plants is high alloyed stainless steels.

Introduction

The efficiency of desalination plants is vital to their sustainability. Proper materials selection is critical to control the initial and maintenance costs of a desalination plant. In this paper, the viable options for materials will be discussed based on their resistance to corrosion and their cost-effectiveness.

In the 1960s and early 1970s, non-ferrous alloys were typically used for the piping in desalination plants.[1] Some of these alloys include 70/30 cupro-nickel, 90/10 cupro-nickel, admiralty, and aluminum brass.[2] These materials were used in desalination plants because of their antifouling characteristics and good heat exchange properties. However, copper alloys are very susceptible to corrosion when exposed to polluted seawater or high water velocities.[3] The combination of these two weakness could lead to catastrophic failure. Because of the deficiencies of copper-base alloys, alternatives were sought.

Currently, stainless steels are the most widely used material in desalination plants. The ideal material for use in desalination plants is titanium because it suffers little to no corrosion in saltwater environments.[4] However, titanium is far more expensive than stainless steels. There are advancements being made to improve the corrosion resistance of stainless steels. Highly alloyed ferritic and austenitic stainless steels are being tested in salt water in comparison to titanium. The stainless steels are normally alloyed with chromium, nickel, molybdenum, and nitrogen to improve their corrosion resistance.[5]

To narrow the selection of materials, a designer must be aware of the all types of corrosion to which materials will be subjected in desalination plants. The types of corrosion that will be explored here are uniform attack, galvanic corrosion, crevice-corrosion and pitting, and erosion-corrosion.

Uniform Attack

Uniform attack occurs equally over the entire surface of material exposed to the catalyst of corrosion.[6] In metals, this type of deterioration is an oxidation-reduction reaction. During an oxidation reaction, metals lose their valence electrons; the site at which this occurs is called the anode.[6] These lost electrons become a part of another chemical in a reaction called reduction. The location at which reduction occurs is called the cathode.[6]

Metals that become passive in a saltwater environment should be selected to combat uniform attack in desalination plants. Passivity occurs when a metal forms a thin, adherent oxide film that causes the material to become completely inert.[6] Passivity is common to the following materials: chromium, iron, nickel, and titanium.[6] When titanium is exposed to a water-based environment, it forms a thin titanium oxide film that reforms almost instantly if damaged.[7] This passive layer is why titanium performs well in saltwater environments.

Galvanic Corrosion

Galvanic corrosion occurs when electrical coupling is created between two metals or alloys that are exposed to an electrolyte.[6] An electrolyte is a solution through which electric current can be transmitted by the motion of ions.[6] In desalination plants, the salt water acts as the electrolyte. In this environment, the more active metal will act as the anode and experience the corrosion whereas the inert (cathodic) metal will not. The degree to which a metal is inert or cathodic can be determined by the Galvanic Series, shown in Figure 1. Corrosion can be anticipated and prevented when engineers use this data.

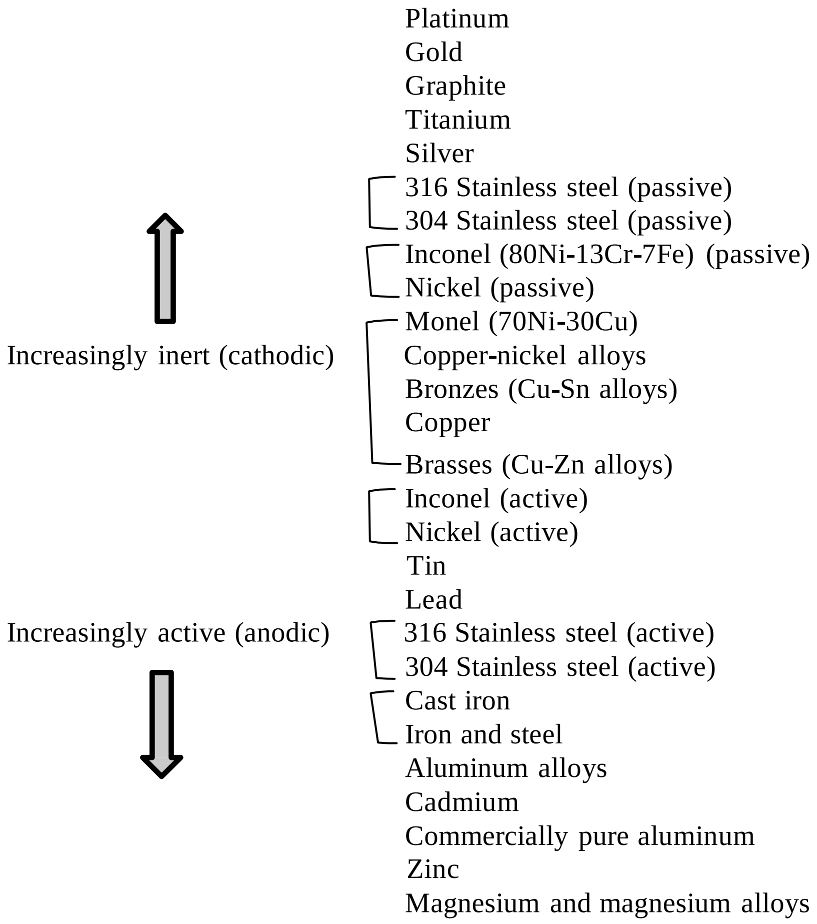


Figure 1 Galvanic Series[6]

To inhibit corrosion, the designer can choose two metals close together in the Galvanic Series, so they will react minimally with each other.[6] Galvanic corrosion can also be prevented by creating as large an anode area as possible, insulating reactive metals from each other, or introducing a third anodic metal that will receive all of the corrosive effects.[6] In desalination plants, engineers can easily prevent this type of corrosion by making educated choices about material selections and design.

Crevice-Corrosion and Pitting

Crevice-corrosion is electrochemical corrosion that occurs where there is a concentration of ions or dissolved gases.[6] Similarly, pitting is a localized attack that occurs when an oxidation-reduction reaction is concentrated in a pit or hole; pitting can be accelerated by the influence of gravity.[6] Both of these types of corrosion can lead to failure if unmonitored, and data shows that in multistage flash (MSF) desalination plants, 41% of all corrosion failure is due to pitting.[3]

Crevice-corrosion and pitting typically occur in a still environment, because concentrations of ions or dissolved gases are less likely to form in flowing liquids. Copper-based alloys, stainless steels, highly alloyed stainless steels, and titanium are all subject to crevice-corrosion and pitting when subjected to a high chloride environment. Copper alloys are very susceptible to these types of corrosion when the desalination plant is in a start-up or a shut-down period.[8] When salt water sits still, it can form a differential aeration environment.[8] Differential aeration is characterized by a concentration of dissolved oxygen where the oxygen acts as the anode and the metal is the cathode.

Another type of specific crevice-corrosion/pitting is fouling. Fouling is a localized corrosion induced by the concentrated chemicals produced by decomposing animal or plant life. The decomposing matter creates oxygen concentration cells and sulfide- and ammonia-containing compounds.[1,9] The concentration of oxygen and these compounds can be highly corrosive and can lead to failure if unmonitored. In desalination plants, fouling is a common issue because salt water is an ideal habitat for all types of marine life. Fouling can be prevented by precise and consistent filtering of the inflowing salt water.[8]

Crevice-corrosion and pitting can be prevented by many methods. To prevent crevice-corrosion during shut-down or still periods, pipes should be emptied, flushed with fresh water, and dried.[8] Crevice-corrosion can also be minimized by using welds instead of riveted or bolted joints that can create a pocket for the concentration of ions or dissolved gases. General crevice-corrosion and pitting can be prevented by keeping the salt water at high velocities.[4] High water velocities prevent the formation of high concentrations of ions or dissolved gases. However, high velocities lead to another type of corrosion, erosion-corrosion.

Erosion-Corrosion

Erosion-corrosion occurs when uniform attack is accelerated by such erosive forces as flowing water or sand abrasion.[6] In desalination plants, this corrosion is present in all of the pipes carrying flowing salt water. The materials selected for piping are generally resistant to the slow erosion-corrosion of constant flowing salt water. Table 1 shows that titanium is almost completely immune to erosion-corrosion.

Table 1 Erosion of commercially pure titanium[4]

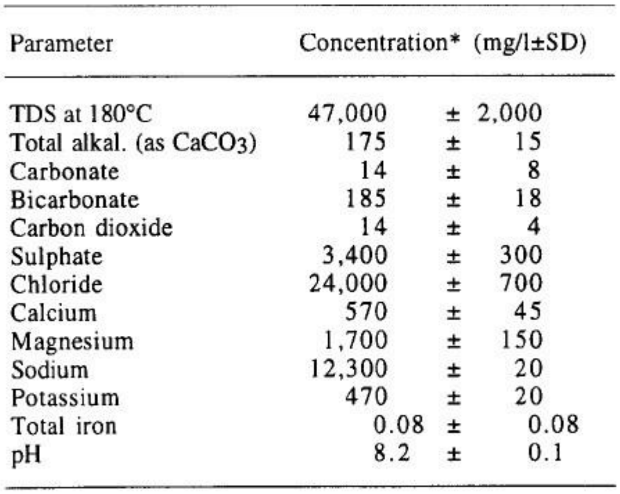
Test Environment	Amount of Erosion
Seawater at 7 m/s	None
Seawater at 36 m/s	0.008 mm/yr
Seawater with 40 g/160 mesh sand at 2 m/s	0.003 mm/yr
Seawater with 40 g/110 mesh sand at 2 m/s	0.013 mm/yr
Seawater with 4% 80 mesh emery at 4.1 m/s	0.008 mm/yr

Erosion-corrosion can be greatly accelerated if there is an obstruction in the pipe. The obstruction will cause turbulence in the piping, and the inner walls of the piping will be subjected to higher water velocities and more sand abrasion in certain areas. In desalination plants, these obstructions are typically marine life. This accelerated erosion-corrosion can be prevented by routine cleaning of the tubes.

The Al-Odwani, Al-Tabtabaei, and Abdel-Nabi Study

This study explored the viable options for construction materials for reverse osmosis (RO) desalination plants with a saltwater inlet source from the Arabian Gulf. This study was performed at the Desalination Research Plant in Doha, Kuwait. The composition of the Arabian Gulf seawater can be seen in Table 2.

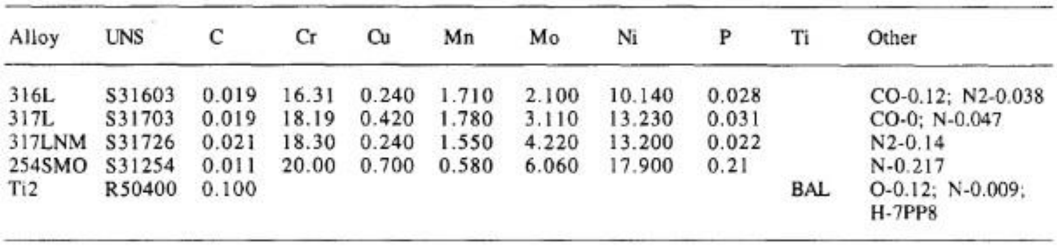
Table 2 Average seawater quality[5]



Parameter	Concentration* (mg/l±SD)		
TDS at 180°C	47,000	±	2,000
Total alkal. (as $CaCO_3$)	175	±	15
Carbonate	14	±	8
Bicarbonate	185	±	18
Carbon dioxide	14	±	4
Sulphate	3,400	±	300
Chloride	24,000	±	700
Calcium	570	±	45
Magnesium	1,700	±	150
Sodium	12,300	±	20
Potassium	470	±	20
Total iron	0.08	±	0.08
pH	8.2	±	0.1

The stainless steels 316L, 317L, 317LNMO, and 254SMO were compared to grade two titanium, Ti(2). The chemical composition of each can be seen in Table 3. Stainless steel 316L is the most commonly used grade of steel used in RO desalination plants.[5] Research has shown that higher contents of molybdenum and chromium increase the corrosion resistance of metals in a high chloride environment, so that led the researchers to test stainless steels 317L, 317LNMO, and 254SMO.

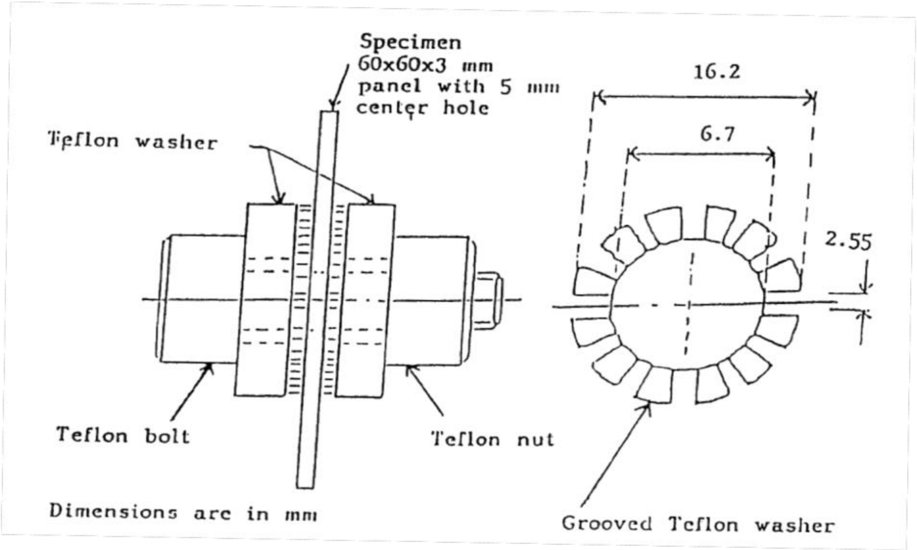
Table 3 Chemical compositions of the studied alloys[5]



Alloy	UNS	C	Cr	Cu	Mn	Mo	Ni	P	Ti	Other
316L	S31603	0.019	16.31	0.240	1.710	2.100	10.140	0.028		CO-0.12; N2-0.038
317L	S31703	0.019	18.19	0.420	1.780	3.110	13.230	0.031		CO-0; N-0.047
317LNM	S31726	0.021	18.30	0.240	1.550	4.220	13.200	0.022		N2-0.14
254SMO	S31254	0.011	20.00	0.700	0.580	6.060	17.900	0.21		N-0.217
Ti2	R50400	0.100							BAL	O-0.12; N-0.009; H-7PP8

Crevice-Corrosion Test Specifications

The samples of stainless steel and titanium were cut into 60x60x3 mm panels with a center hole having a diameter of 5 mm.[5] The samples were then cleaned, weighed, and fitted in a Teflon multiple crevice washer assembly. (See Figure 2.) The Teflon assemblies were fastened together by the indicated bolt and nut and tightened to a torque of 8 NM.



<u>Figure 2</u> Multiple crevice washer assembly[5]

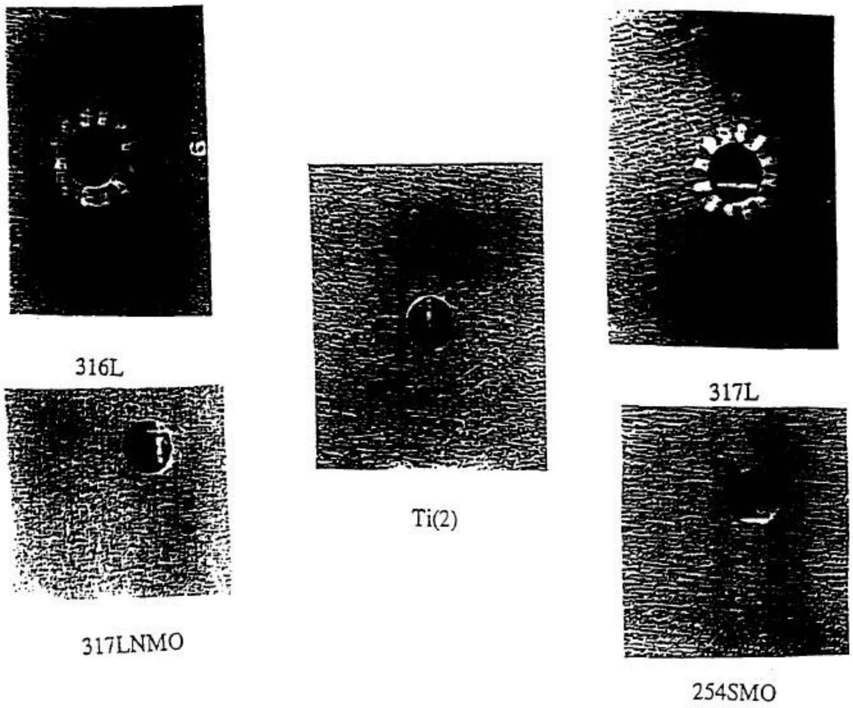
Two test groups were created by setting up the assembly twice for all of the metal samples. The two test groups were then exposed to the filtered Arabian Gulf seawater for 3,000 hours. The seawater was kept between 20°C and 30°C and at a pH of 6.5 to 6.7. The specimens were placed in a 100-liter plastic tank with a seawater flow rate of 100 liter/min. After 3,000 hours, the samples were removed from the seawater, removed from the Teflon fitting, and scrubbed with a nylon brush in deionized water.

Electrochemical Test Specifications

The open circuit potential (OCP) and electrochemical impedance spectroscopy (EIS) were tested in a filtered seawater feed with a pH of 6.8. The test group consisted of one of each of the following: Ti(2), 316L, 317L, 254SMO, and 317LNMO. The specimens were fitted into Teflon holders. The two counter electrodes were made of graphite, and the reference electrode was a saturated calomel electrode.

Results of the Al-Odwani, Al-Tabtabaei, and Abdel-Nabi Study

The crevice-corrosion test was concluded after 3,000 hours, and the severity of the corrosive attack was analyzed using a low-powered stereomicroscope as shown in Figure 3.



316L

317L

Ti(2)

317LNMO

254SMO

Figure 3 **External view of the creviced specimens**[5]

The 316L and 317L stainless steels showed the most susceptibility to crevice-corrosion with crevice attacks of maximum depth between 0.1 and 0.15 mm. When the chemical composition of molybdenum, chromium, nitrogen, and nickel were increased in 316L and 317L, their performance improved. The corrosion resistance of 317LNMO and 254SMO were similar to Ti(2). The use of 317LNMO and the use of 254SMO are thus both more economical than the use of titanium.

As illustrated in Figure 4, the OCP and EIS studies showed how the corrosion of the materials changed over time.

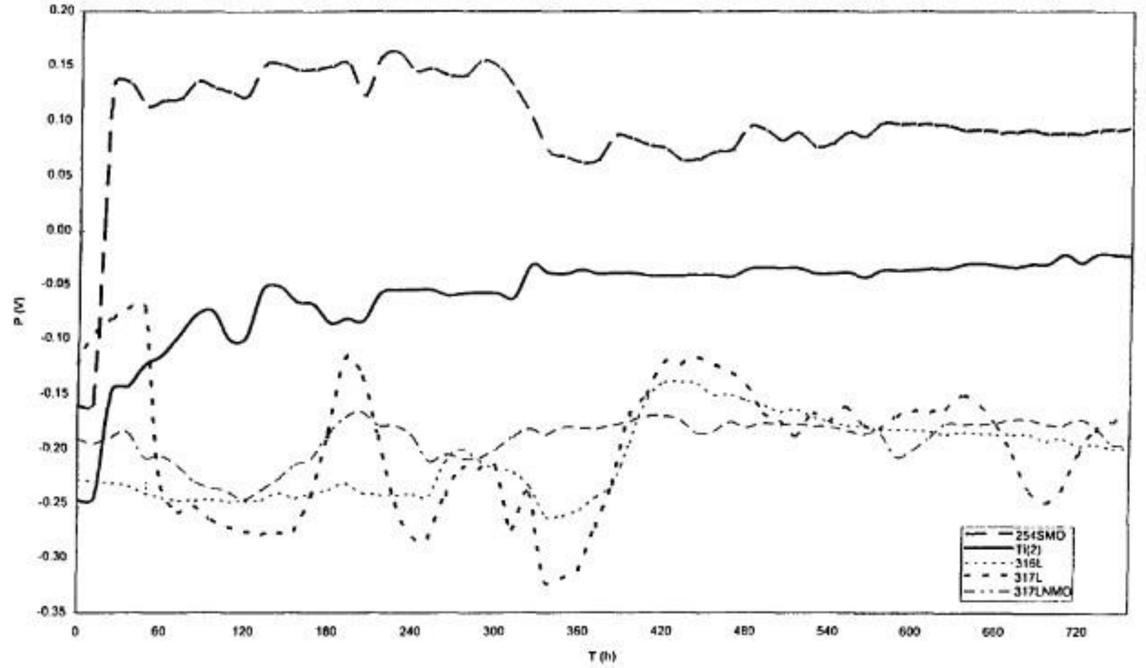


Figure 4 **Open circuit potential versus time**[5]

The 316L stainless steel showed signs that its passive film layer was being disrupted from T=0 to T=240 hr, because the OCP readings fluctuated around -220 mV. During the same time frame, the 317L stainless steel had very large changes in OCP. This may be evidence of the destruction and reforming of the passive layer and the competition of anodic and cathodic areas on the sample. The stainless steels 317LNMO and 254SMO had very steady OCP readings after 360 hours, indicating that their passive layers were very easily formed and maintained.

The results of this study showed that the stainless steels 254SMO and 317LNMO greatly outperformed the 316L and 317L in corrosion resistance. In the crevice-corrosion test, OCP test, and EIS test, it was shown that higher contents of chromium, nickel, molybdenum, and nitrogen improved the corrosion resistance of the stainless steel alloys. It was also shown that the Ti(2) was the most corrosion resistant; however, the titanium is not economically feasible. The overall cost of a desalination plant will still increase if stainless steels 254SMO and 317LNMO are used instead of 316L or 317L. However, over the course of a desalination plant's life, the use of 317LNMO will prove more cost-effective because of lower maintenance costs and improved product.[5]

Conclusion

When engineers are choosing the materials to be used in a desalination plant, they must consider many factors. The most difficult factor to design around is corrosion resistance. Materials in desalination plants are subject to uniform attack, galvanic corrosion, crevice-corrosion, pitting, and erosion-corrosion. There are some methods to lessen and/or prevent corrosion, but the most important factor is the selection of materials. The use of copper-based alloys, stainless steels, high alloyed stainless steels, and titanium was discussed. The Al-Odwani, Al-Tabtabaei, and Abdel-Nabi study showed that titanium performed best under the corrosive effects of Arabian Gulf seawater. However, the study concluded that the most economical material was the highly alloyed stainless steel 317LNMO. Current materials technology and market prices for certain metals make stainless steels the most economical material for use in desalination plants.

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