Desalination and Water Treatment
www.deswater.com

31 (2011) 121–133
July

doi: 10.5004/dwt.2011.2362

Review of material selection and corrosion in seawater reverse osmosis desalination plants

Nicolas Larché[a*], Philippe Dézerville[b]

[a]*Institut de la Corrosion, 220 rue Pierre Rivoalon, 29200 Brest, France*
Tel. +33 2 98 051552; Fax +33 2 98050894; email: nicolas.larche@institut-corrosion.fr
[b]*Véolia Eau, 94410, Saint Maurice, France*
email: philippe.dezerville@veoliaeau.fr

Received 19 October 2010: Accepted in revised form 23 March 2011

ABSTRACT

Seawater desalination infrastructures require a careful material selection with high corrosion resistance. The high seawater temperatures in warm regions, where many desalination plants are developed, must be clearly considered regarding the corrosion of materials. To comply with the operational characteristics of seawater reverse osmosis (SWRO) process (high pressure, high chloride content and dissolved oxygen content at saturation values), the conventional material selection was stainless steel with sufficient pitting resistant equivalent number. However, many cases of corrosion failures of stainless steel in SWRO desalination units have been reported. In most cases the cause of the failures was attributed to the use of not enough alloyed grades. However, high alloy stainless steels are also susceptible to crevice and pitting corrosion in seawater. The operational corrosion risk will highly depend on the stainless steel composition, on the metallurgy (i.e. cast or wrought), on the service conditions, and on the geometrical configuration of the confined zones in contact with seawater. The present paper reviews the corrosion performance of metallic materials used for SWRO desalination plants. It focuses on the corrosion behaviour of several stainless steel grades. Recent corrosion failures of stainless steel pumps used in SWRO desalination plant in the Mediterranean Sea are also discussed.

Keywords: Metallic materials; Stainless steels; Corrosion; Seawater; Reverse osmosis desalination

1. Introduction

In seawater desalination plants, several forms of corrosion may be found to a greater or lesser extent depending on used materials and service conditions (temperature, seawater pre-treatment, velocity, etc). This includes general corrosion, localized corrosion (pitting and/or crevice corrosion), stress corrosion cracking, selective corrosion, bimetallic corrosion, erosion and/or impact corrosion. Details on the mechanisms of each corrosion form can easily be found in the literature [1–4] and it is not the purpose of the present review. In general, the failures found in seawater reverse osmosis desalination units concerns pumps, valves/fittings and piping systems, and it can be attributed to one or a combination of the following reasons: material selection not adapted to the media in service conditions, poor design and/or fabrication, abnormal corrosiveness of the media in contact with the devices, poor operation and/or poor maintenance [5]. In seawater reverse osmosis desalination plants, the corrosion induced by high tem-

* Corresponding author.

Presented at EuroMed 2010 — Desalination for Clean Water and Energy: Cooperation among Mediterranean Countries of Europe and MENA Region, 3–7 October 2010, David Intercontinental Hotel, Tel Aviv, Israel. Organized by the European Desalination Society.

peratures is avoided (processed at ambient temperature) but the high pressure used for the process may lead to severe geometrical configuration for stainless steels in terms of susceptibility to crevice corrosion. It is important to underline that "ambient temperature ranges" can be significantly different depending on the location of the desalination plant. For instance, in the Middle East, the ambient seawater temperatures can often be above 30°C and at these high "ambient" temperatures, the risk of pitting corrosion and crevice corrosion in seawater of any stainless steel grade is clearly increased compared to to the risk in seawater below 20°C [6–9]. The salinity, which can be significantly different from one seawater to another, should also be considered for material selection. The world maps of average seawater temperatures and salinities are shown in Fig. 1 and in Fig. 2, respectively. In addition, bioactivity of the seawaters may be different from one area to another and is expected to be more critical in tropical seawaters. The pH of seawaters varies from about 7.9 to 8.2 and even if larger variations can be found inside deep estuaries and productive coastal plankton blooms (7.3 and 8.6, respectively), the risk of general corrosion in this range of pH is not significant and cannot be considered as a critical parameter for stainless steel use.

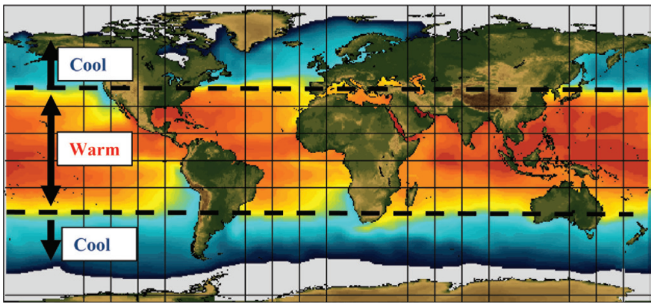

Fig. 1. Seawater temperature map showing areas of warmer water and areas of cooler water.

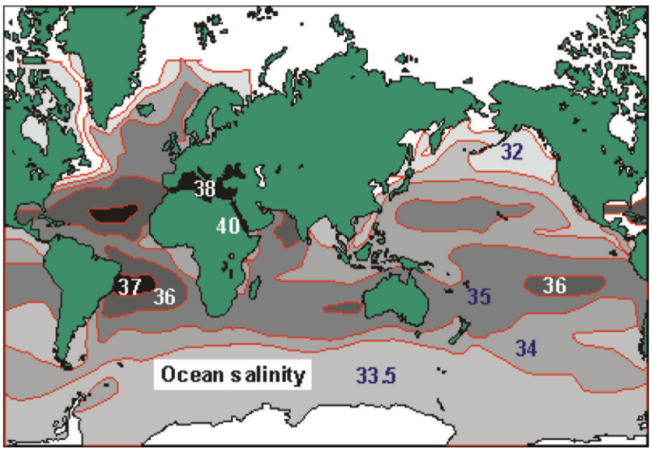

Fig. 2. World map of seawater salinity.

For most materials, corrosion is often most detrimental during shut-down periods, leading to stagnant seawater in contact with metallic parts. Seawater stagnation in seawater handling systems should definitely be avoided, especially for "passive" alloys such as stainless steel. It can easily lead to differential aeration cells and/or to the formation of deposits which can result in the breakdown of the passivity and a dramatic propagation of localized corrosion. For seawater handling systems which need to be regularly or sometimes stopped, it is thus strongly recommended to flush the systems with fresh water.

To comply with the operational characteristics of SWRO process (high pressure, high chloride content and dissolved oxygen content at saturation values) the conventional material selection has been stainless steels. There exists a large range of stainless steel grades and the simultaneous presence of Cr, Mo and N has obvious beneficial effect on their pitting and crevice corrosion resistance. Stainless steels are thus often characterized by a formula called PREN (Pitting Resistant Equivalent number) given by PREN = %Cr + 3.3%Mo + 16%N [10,11]. This formula leads to quasi-linear relationship between the PREN and the critical pitting or crevice corrosion temperature, which allows a global material ranking. However, the PREN must be used with care since this number does not consider other very important parameters such as the metallurgical quality. The composition of the main stainless steel grades used for seawater handling systems is given in Table 1.

Many cases of corrosion failures of stainless steel in SWRO desalination units have been experienced [5] and are in obvious correlation with the reported failures from the offshore industry [8,13,14]. In most cases, the causes of the failure was attributed to the use of not enough alloyed grades such as UNS S31603 (316L), S31703 (317L) and N08904 (904L) which are highly susceptible to pitting and crevice corrosion in seawater at ambient temperatures. These stainless steel grades with relatively low PREN should clearly not be used for any applications in contact with seawater unless specific and well designed protection (e.g. cathodic protection) is applied. More alloyed stainless steel grades with PREN above 40 are also susceptible to crevice corrosion in seawater and the operational corrosion risk will highly depend on the service conditions (e.g. temperature, chlorination, oxygen content), on the metallurgy (e.g. cast or wrought alloys) and on the geometrical configuration of the confined zones in contact with seawater. For instance, several cases of crevice corrosion of flanges made of UNS S31254 (254SMO) and UNS S32750 (SAF2507), the PREN of which are above 40, have been experienced in natural seawater [14]. In seawater handling systems, the geometrical configuration between two tightened flanges is known to be severe in terms of crevice corrosion. In such applications, the crevice corrosion initiation and propagation will highly depend on the seawater temperature, the seawater treatment (e.g.

Table 1
Composition of some stainless steels used in seawater applications (Balanced Fe) from ASTM A240/A240M [12]

N°UNS	Other designation	Cr	Ni	Mo	N	Other	PREN1	Type
S30403	304L	18–20	8–12	–	0.10	–	20–22	Austenitic
S31603	316L	16–18	10–14	2.0–3.0	0.10	-	24–29	
N08904	904L	19–23	23–28	4.0–5.0	0.10	Cu 1.0–2.0	34–41	
S31803	2205	21–23	4.5–6.5	2.5–3.5	0.08–0.20		31–38	Duplex
S32205		22–23	4.5–6.5	3.0–3.5	0.14–0.20		34–38	
S32550	52N, 255	24–27	4.5–6.5	2.9–3.9	0.10–0.25	Cu 1.5–2.5	35–44	Super duplex
S32750	2507	24–26	6.0–8.0	3.0–5.0	0.24–0.32	Cu 0.5	38–47	
S32760	Zeron100	24–26	6.0–8.0	3.0–4.0	0.20–0.30	Cu 0.5–1.0 W 0.5–1.0	37–44	
S31254	254SMO	19.5–20.5	17.5–18.5	6.0–6.5	0.18–0.22	Cu 0.5–1.0	42–45	Super austenitic
N08367	Al6XN	20–22	23.5–25.5	6.0–7.0	0.18–0.25	Cu 0.75	43–49	
S34565	4565	23–25	16–18	4.0–5.0	0.4–0.6	Cb 0.10	44–51	
S31266	B66	23–25	21–24	5.2–6.2	0.35–0.60	Cu 1.0–2.5 W 1.5–2.5	46–54	

1 – PREN = %Cr+3,3%Mo+16%N

chlorination), the surface state of flanges and the nature of the gasket between flanges. It is also important to underline that PREN is just an empirical number which links the composition of the alloy to the pitting corrosion resistance performed in a standard test such as the ASTM G48 A or B [15], which can be completely different from real service conditions. This number does not consider metallurgical aspects which are known to be of major importance for corrosion resistance of stainless steels. Hence, material selection should not be only based on PREN or from ASTM G48 tests. For instance, a wrought alloy and a cast alloy with a same composition (i. e. with the same PREN) will not have the same crevice corrosion resistance in seawater: the cast version will exhibit higher crevice corrosion susceptibility than the wrought version due to a more heterogeneous metallurgy.

From the reported field corrosion cases and more recent investigations, especially from the offshore industry, the critical temperature for the use of highly alloyed stainless steels is sometimes given below 20°C for some seawater applications involving tight crevices [16,17]. If stainless steel is often the right choice for seawater handling systems, it appears clearly that the selection of the grade considering the service conditions and the geometry of the units must be performed with very special care.

2. Review of structural material selection for seawater reverse osmosis (SWRO) desalination plants

Several types of materials are used in desalination units and corrosion resistance is not necessarily the first criteria of material selection for seawater handling systems. Criteria such as mechanical performance, machinability, weldability, cost, etc. often influence the final material selection. Thus it seems important to briefly review the properties of materials commonly used for seawater applications in terms of corrosion resistance and the possibility for them to be implemented in SWRO desalination plants.

2.1. Carbon steel

Carbon steel is one of the most used material for seawater structures due to its good mechanical properties, good machinability, good weldability and rather low cost. However, carbon steel is highly susceptible to general corrosion. The influence of dissolved oxygen content, flow velocity and temperature are known to have a very important influence on the corrosion rates of carbon steel (see Fig. 3 which illustrate the influence of the temperature and the flow velocity on the corrosion rate of carbon steel [18,19]).

The use of carbon steel might be acceptable in case of seawater deaeration with dissolved oxygen content below 10 ppb [20]. In aerated seawater, these materials should not be used without specific protection such as organic coatings associated with cathodic protection. If cathodic protection is applied on coated steel, it is essential to check if the used organic coatings are compatible with the cathodic protection. Cathodic protection induces a local pH increase on protected surfaces, and non-adapted coatings could lead to delamination at the paint/steel interface.

Carbon steels are also susceptible to bimetallic corrosion when coupled to “corrosion resistant” stainless

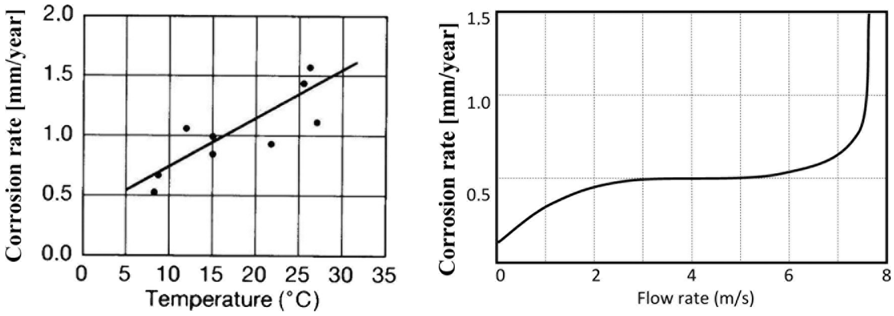

Fig. 3. Average corrosion rate of carbon steel in aerated seawater [mm/year] depending on the temperature (a) [18] and the flow rate at ambient temperature (b) [19].

steels. This was quantified in an investigation at the Institut de la Corrosion where carbon steel was coupled to superduplex stainless steel in non-chlorinated and chlorinated seawater with negligible flow rate at 6°C and 30°C [21]. The effects of cathode to anode ratios, temperature and chlorination on galvanic corrosion of carbon steel are shown in Fig. 4. The bimetallic corrosion rates were very high with cathode to anode ratio of 10:1 at 6°C and at 30°C in natural seawater. In 0.5 ppm-chlorinated seawater, the bimetallic corrosion of carbon steel clearly decreased because chlorination prevents the development of the biofilm on the cathodic surfaces, leading to a decrease in the efficiency of the cathodic reduction.

In SWRO processes where dissolved oxygen content is not controlled and flow velocities are high, the use of carbon steel for components in contact with seawater is clearly not recommended without both specific organic coating and cathodic protection.

2.2. Copper alloys

Copper alloys such as Admiralty brass, aluminium brass, CuNi90/10 or CuNi70/30 are widely used in sea-

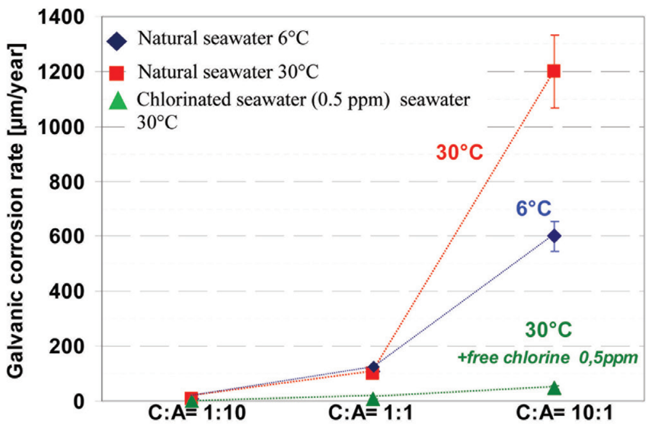

Fig. 4. Effect of cathode to anode ratios, temperature and chlorination on galvanic corrosion of carbon steel coupled to UNS S32750 (2507) superduplex stainless steel [21].

water handling systems but are not often used for the construction of SWRO units. Their typical compositions are given in Table 2.

Copper alloys are known to be naturally resistant to fouling due to the release of copper ions which have biocide properties. This property is particularly interesting in seawater applications to reduce cleaning operations without the use of biocide treatments (e.g. chlorination). To keep their biocide properties, copper alloys should not receive cathodic protection which would prevent the release of copper ions.

However copper alloys may exhibit selective corrosion during the "clean-up" of the installation and the release of copper ions may deteriorate membranes. This is the main reason why stainless steels have been preferred for the construction of SWRO units. In addition, copper alloys are highly susceptible to bimetallic corrosion when coupled to "corrosion resistant" stainless steels which are widely used in SWRO desalination plants. A study at the Institut de la Corrosion showed the strong influence of galvanic coupling between CuNi 90/10 and superduplex stainless steels on the localized corrosion of the copper alloy [21]. The extent of the corrosion is highly influenced by the surface ratio: the higher the cathode to anode ratio, the higher the corrosion of the anode. This is clearly illustrated in Fig. 5 where anode to cathode ratios of 1:10, 1:1 and 10:1 were tested in natural and chlorinated seawater at 6°C and 30°C. In natural seawater at 30°C, the 1:1 ratio was critical since it led to significant pitting corrosion, which was as dramatic as the pitting corrosion observed for the cathode to anode ratio of 10:1. At 6°C and in chlorinated seawater at 30°C, the 1:1 ratio did not lead to pitting corrosion (only low uniform corrosion). It is also shown that the chlorination clearly led to a decrease of the galvanic corrosion, except for cathode to anode ratio of 10:1 which was critical for all the tested conditions of exposure (severe pitting corrosion for all the tested conditions). Photographs of specimens after test are given in Fig. 6 where the maximum pitting corrosion depths are indicated.

Copper alloys can also be strongly affected by erosion

Table 2
Typical composition of 4 main copper based alloys used in seawater applications

Usual designation	N°UNS	Cu	Ni	Zn	Fe	Mn	Other
Admiralty brass	C44300	bal.	—	23–30	—	—	—
Aluminium brass	C68700	76–79.	—	bal.	—	—	Al=1.8–2.5 Ar=0.02–0.06
Cu-Ni 90/10 (1,5 Fe)	C70600	bal.	9–11	<0.5	1–2	0.5–1	—
Cu-Ni 70/30 (1,5 Fe)	C71640	bal.	29–33	<0.5	1–2	1.5–2.5	—

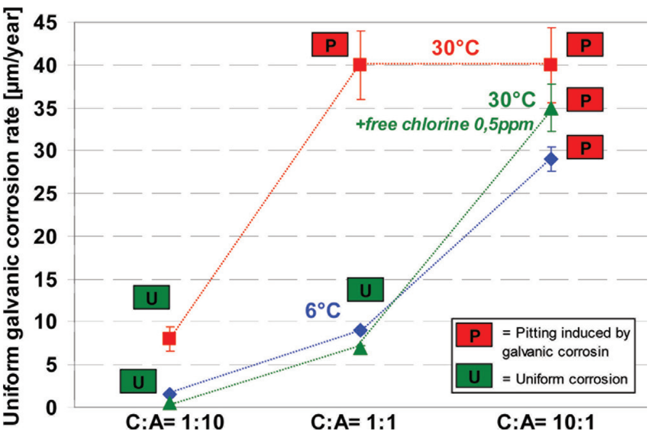

Fig. 5. Effect of cathode to anode ratios, temperature and chlorination on galvanic corrosion of copper–nickel 90/10 coupled to UNS S32750 (2507) superduplex stainless steel [21].

corrosion in systems where the flow rate is high. Standard recommendations to avoid erosion corrosion are given in Table 3 [22]. For copper–nickel alloys, the increase of nickel and iron contents will increase the erosion corrosion resistance. However it will also increase the susceptibility to pitting corrosion, especially in stagnant and/or polluted seawater. Seawater stagnation should clearly be avoided and sufficient flow rate must be ensured to avoid deposit which could lead to differential aeration cells and to localized corrosion under deposit. The pollution in seawater (e. g. sulfites) may also strongly affect the corrosion resistance of copper-based alloys in seawater [23,24].

However, copper–nickel alloys generally showed excellent corrosion resistance for many seawater applications (chlorinated or not) regarding that flow velocity, geometrical design, and galvanic coupling are controlled. Then the use of copper alloys in existing SWRO desalina-

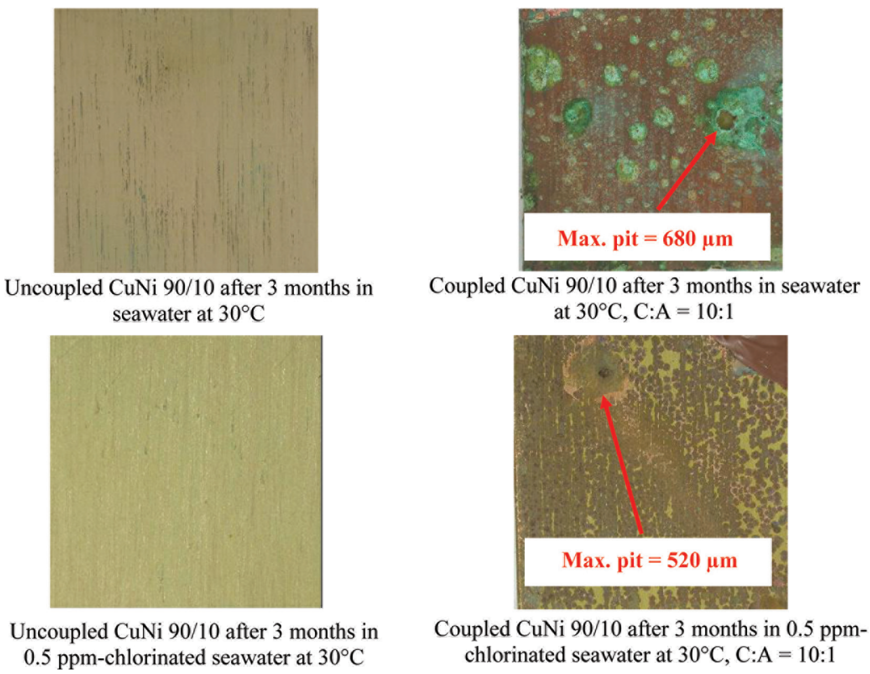

Fig. 6. Photographs of uncoupled and coupled copper–nickel 90/10 to UNS S32750 (2507) superduplex stainless steel (cathode to anode ratio = 10:1) in seawater at 30°C with and without chlorination. The duration of the exposure was 3 months.

Table 3
Maximum flow rate in copper-based piping systems to avoid erosion corrosion [22]

Copper alloy	Maximum flow rate (m/s)		
	Pipe diameter (mm)		
	< 100	100–250	>250
Admiralty brass	1.5	1.5	1.5
Aluminium brass	1.8	2.4	3.9
Cu-Ni 90/10 (1.5 Fe)	2.5	3.0	3.5
Cu-Ni 70/30 (1.5 Fe)	3.0	3.6	4.5

tion plants may be considered, regarding the following recommendations:

- check that the exact composition is conform to the standard requirements (a composition out of the typical range may have strong impact on the corrosion resistance)
- ensure that the flow rate of seawater is in the range defined in Table 3 and avoid zones of turbulence
- avoid galvanic coupling with any other metallic alloy
- ensure a "good" formation of the initial oxide layer, with flowing of "clean" seawater or soft water in the first days of utilisation
- avoid any prolonged stop which could lead to stagnant seawater in contact with the copper alloy
- ensure that copper ion release is compatible with the used membranes.

2.3. Stainless steels

Stainless steels are the conventional materials used for high pressure inlet piping to the RO membrane module, brine rejection pipe, product water outlet pipe and high pressure pumps. In seawater at ambient temperature, stainless steel containing at least 18% of Cr and at least 2% of Mo undergo practically negligible amount of general corrosion. The high chloride content of seawater can however lead to pitting and/or crevice corrosion if the selected stainless steel grade is not adapted.

2.3.1. Stainless steels with PREN below 35

Any stainless steel with PREN below 35 should definitely be avoided for seawater applications without specific protection (e.g. cathodic protection). In most desalination plants where UNS S31603 (316L) or UNS S31703 (317L) stainless steel were used, dramatic pitting and crevice corrosion occurred [5]. The only successful applications of UNS S31603 (316L) related to seawater pumps were pumps for which UNS S31603 parts were connected to less noble materials (e.g. carbon steel piping) which provided intentionally or not cathodic protection. Pitting and crevice corrosion were also several times reported for the more alloyed UNS N08904 (904L) stainless steel grade. The crevice corrosion propagation of some "low alloy" stainless steels was evaluated at the Institut de la Corrosion in seawater at different temperatures, chlorination levels and oxygen contents [25,26]. The crevice assemblies used for the investigation were based on the Crevcorr-type assembly involving plastic crevice formers tightened to the welded plate specimens with a torque of 3 Nm on M5 titanium bolts [27]. This assembly led to a "not severe" crevice geometry with calculated pressure under gasket of 3 N/mm². Photograph of the assembly is shown in Fig. 7 and some general results are given in Fig. 8. It is shown that all the tested alloys with PREN equal or below 26 exhibited severe crevice corrosion in aerated seawater at 20°C. The UNS S32205 with a PREN of 37 failed at 30°C. However, since the initiation and propagation of crevice corrosion strongly depend on the severity of the crevice, these data are only comparative and crevice corrosion may be initiated on UNS S32205 at lower temperature [28].

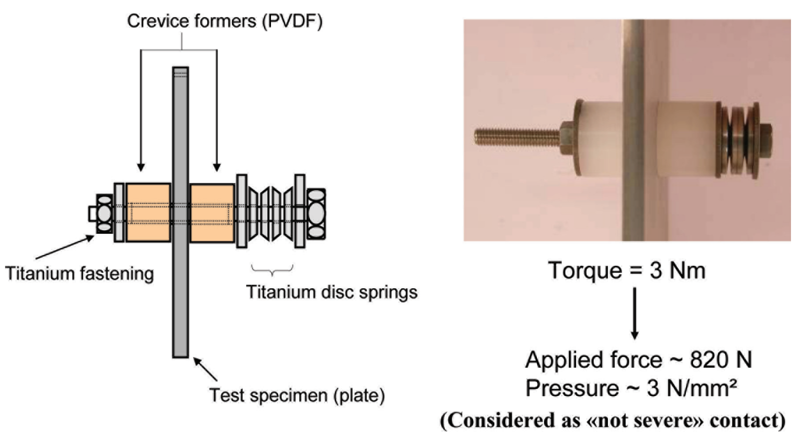

Fig. 7. Crevcorr-type assembly for crevice corrosion testing.

30° Aerated +free chlorine 0.5ppm	✖	✖	✖
30° Deaerated to 100ppb	●	●	●
30° Aerated	✖	✖	✖
20°C Aerated	✖	✖	●
5°C Aerated	✖	●	●
UNS. Trade name **PREN**	S30403 (304L) **20**	S31603 (316L) **26**	S32205 (2205) **37**

● No corrosion ✖ Crevice corrosion

Fig. 8. Results from crevice corrosion testing using Crevcorr-type assembly on welded stainless steel with PREN ranging from 20 to 37. Results only valid with the tested crevice geometry. Crevice geometry should be considered as "not severe" [25,26].

2.3.2. Stainless steels with PREN between 35 and 40

One of the most selected stainless steel grade for seawater applications such as desalination pumps was the duplex 2205 (UNS S31803 or UNS S32205) with PREN 35–38. This is due to a compromise between good mechanical properties, corrosion resistance and cost. However, it is now widely admitted that the critical crevice corrosion temperature of UNS S31803 or S32205 in seawater is clearly below 20°C, depending on the severity of the crevice geometry [13]. From both field and laboratory data, in seawater at 30°C and above, the risk of pitting and crevice corrosion with dramatic propagation is high for this stainless steel grade [6,7,13,25,26,29]. The use of stainless steel grades with PREN between 35 and 40 is thus not recommended in any seawater handling systems of SWRO desalination plants, without additional protection (e.g. carefully designed cathodic protection). Cathodic protection can be used on stainless steel and in that case it is strongly recommended to monitor and check the efficiency of the cathodic protection in critical parts of the protected structures. Special care must be paid in systems where a biofilm forms on the metallic surfaces since in that case, the current demand to remain in the protective potential range may be significantly increased and the efficiency of the cathodic protection must be checked (e.g. measurements of the potentials far from the sacrificial anodes).

The corrosion of a seawater high pressure (HP) booster pump was recently investigated by Institut de la Corrosion and Véolia in a SWRO desalination plant in Mediterranean sea coast [30]. The typical composition of the booster pump is given in Table 4 and photographs of the corroded pump are given in Fig. 9 and in Fig. 10. Crevice corrosion at the gasket location and severe pitting corrosion on the open surface were observed. The seawater circulating inside the pump had a temperature between 20°C and 35°C with some stagnation periods. Regarding the rather high ambient temperatures and referring to the comments above, crevice and pitting corrosion was

Table 4
Typical composition of DIN 1.4468

Cr	Ni	Mo	N	C	S	P	Mn	Si
24.5 26.5	5.5 7.0	2.5 3.5	0.12 0.25	<0.05	<0.025	<0.03	<1.00	<1.00

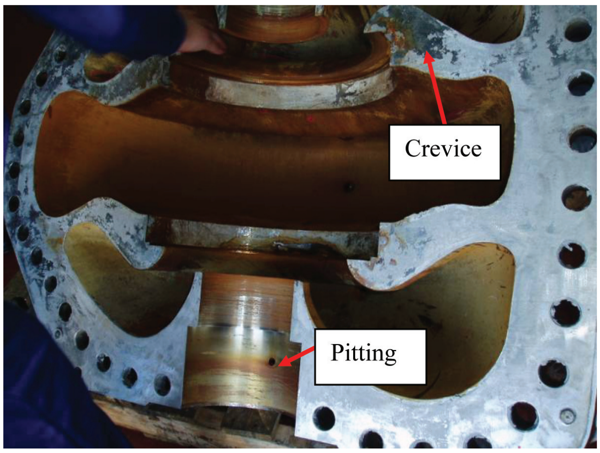

Fig. 9. Crevice and pitting corrosion of the casing of a HP booster pump (cast duplex stainless steel 1.4468).

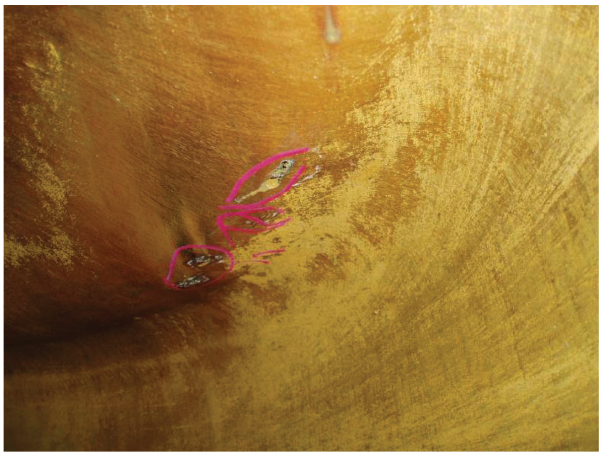

Fig. 10. Pitting corrosion of the casing of a HP booster pump (cast duplex stainless steel 1.4468).

clearly expected for such cast grade in the actual service conditions. The extremely severe extent of pitting corrosion on open surface was however attributed to the not adapted stagnation periods.

2.3.3. Stainless steels with PREN above 40 (superduplex and superaustenitic stainless steels)

Stainless steels with PREN above 40 are often called super stainless steel (superduplex or super austenitic stainless steel depending on the microstructure) and are often "wrongfully" mentioned to be fully corrosion resistant in seawater. About 25 years ago it was believed that highly alloyed stainless steel with PREN above 40 could be used in natural seawater at high ambient temperatures with no risk of crevice corrosion [31,32]. However many cases of pitting and crevice corrosion appeared in field service conditions [14] and today a lot of experience is available together with laboratory results, enabling more safe use of these materials. The critical pitting temperature (CPT) and the critical crevice temperature (CCT) often given from standard tests (i.e. ASTM G48-A and B, in 6%$FeCl_3$) must be used with care since seawater crevice corrosion is susceptible to occur at far lower temperature [5]. Since the conditions of exposure are completely different from real service conditions, this type of standard tests cannot be used alone for material selection in seawater handling systems. It may solely help at ranking materials. In some recent recommendations, the upper temperature limit for a safe use of stainless steels with PREN of 40 decreased below 20°C in some seawater applications where thigh crevices are involved [8].

2.3.4. Importance of the crevice geometry

Different high alloy stainless steels were evaluated for their crevice corrosion resistance in seawater in the frame of the join industry project performed at the Institut de la Corrosion [25, 26]. The standard CREVCORR-assembly was used for crevice corrosion testing but different torques (i.e. pressure under gaskets) and different surface roughness were evaluated, which means that different crevice geometries were evaluated. For the specimens tested with the recommended torque from standard CREVCORR test (e.g. 3 Nm corresponding to a pressure of about 3 N/mm²) no crevice corrosion occurred on the superaustenitic stainless steel UNS S31254 (254SMO) in 0.5 ppm-chlorinated seawater at 30°C. However, for the two other configurations involving higher pressure under gaskets (and sometimes lower roughness of plate alloys), crevice corrosion occurred systematically (Fig. 11). This result clearly underlines the importance of crevice geometry to define the limits of utilisation for each stainless steel grade.

2.3.5. Importance of the product form

It must be mentioned that due to elemental segregation and other factors (e. g. microstructure), cast grades have lower corrosion threshold values than the wrought grades [29,33]. For instance, the ASTM A890 Gr4A (= UNS J92205) is clearly expected to be more susceptible to crevice and pitting corrosion than its wrought equivalent UNS S31803 or UNS S32205. In addition, laboratory experiments clearly showed that once initiated, crevice corrosion propagated more dramatically in cast superduplex stainless steels compared to wrought superduplex stainless steels, in seawater from 15°C to 40°C [34]. In the same study it was shown that the tendency to repassivation was also much lower for cast versions. This is the reason why some pump manufacturers recently preferred the mechanized welding (of wrought materials) to replace the casting versions. Yakuwa et al. evaluated the crevice corrosion resistance of rolled (wrought) and cast duplex and super duplex stainless steels used for seawater pumps in different seawaters [6]. Averaged mass loss and crevice corrosion occurrence observed in the Arabian gulf with raw seawater and chlorinated seawater were plotted as a function of the tested PREN and results are given in Fig. 12 and in Fig. 13, respectively. It is clearly shown that cast materials, even with PREN above 40, exhibit much lower corrosion properties than their rolled (wrought) equivalent.

The corrosion of a seawater pump made of cast superduplex stainless steel was recently investigated by Institut de la Corrosion and Véolia in a SWRO desalination plant in Mediterranean sea coast [30]. The typical composition

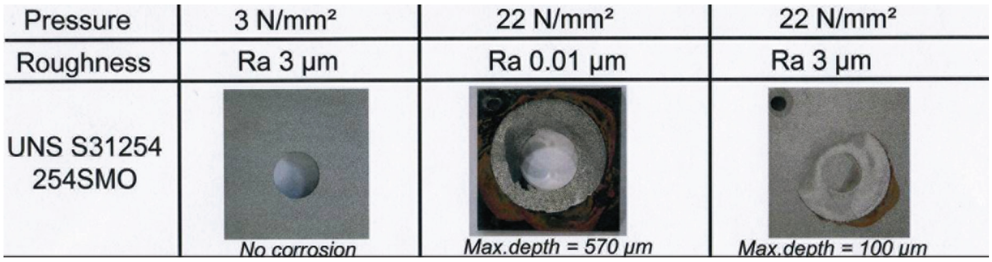

Fig. 11. Photograph of specimens at gasket location after 3 months of exposure in 0.5 ppm-chlorinated seawater, using different crevice geometries [25,26].

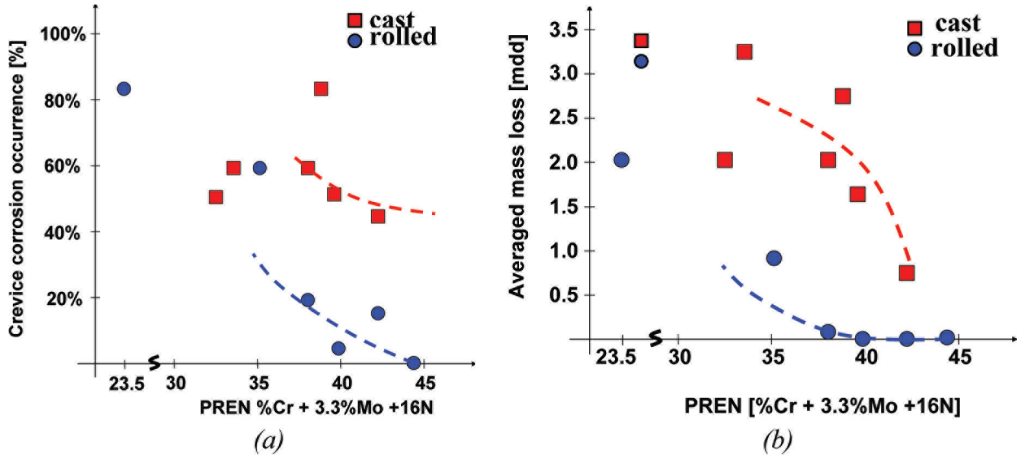

Fig. 12. Crevice corrosion occurrence (a) and mass loss (b) vs. PREN for rolled and cast stainless steels tested in the Arabian Gulf in raw seawater [6]. *mdd = mg/dm²/d.

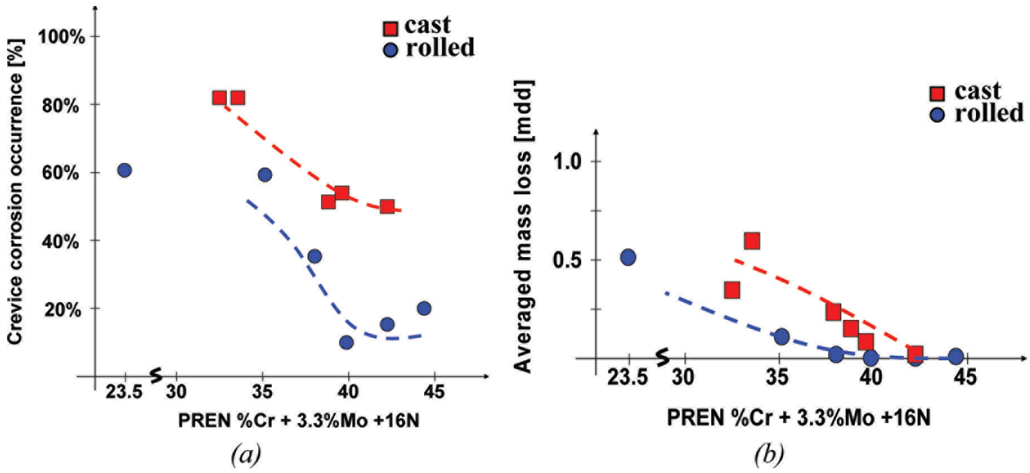

Fig. 13. Crevice corrosion occurrence (a) and mass loss (b) vs. PREN for rolled and cast stainless steels tested in the Arabian Gulf in chlorinated seawater [6].

of the pump is given in Table 5 and photographs of the corroded pump are given in Fig. 14 and Fig. 15. Crevice corrosion at gasket location and severe pitting corrosion on open surfaces were noticed. The seawater circulating inside the pump had temperature between 20 and 35°C with some stagnation periods. The seawater circulating inside the pump was analysed and did not revealed abnormal corrosiveness compared to typical Mediterranean seawater. Regarding the rather high ambient temperatures, crevice and pitting corrosion was expected for such cast grade. However, the extremely severe extent of pitting corrosion was attributed to un-adapted stagnation periods. The proposed solutions to stop or at least decrease corrosion in the existing desalination plant were:

- Change the "stop" procedure (e. g. permanent flow in the pumps or flush with fresh water)
- and install a specific cathodic protection for each pump.

Table 5
Typical composition of ASTM A890 Gr5A

Cr	Ni	Mo	N	C	S	P	Mn	Si
24.0 26.0	6.0 8.0	4.0 5.0	0.1 0.3	<0.03	<0.025	<0.03	<1.5	<1.00

If the cathodic protection is not efficient in very confined zones (e.g. external parts of flanges), welding of thin sheet of a corrosion resistant Ni-based material (i.e. UNS N06276, N06022, N06200 or N06059) could be used in the critical parts. In that case, adapted filler materials containing high amounts of Cr and Mo and adapted welding procedures must be used [35].

Fig. 14. Overview of the corroded pump made of cast super duplex stainless steel ASTM A890 Gr5A.

Other examples of crevice corrosion of both cast and wrought superduplex stainless steels installed in an SWRO desalination where the ambient temperature was high are given in Fig. 16. The importance of using good engineering practice for the welding of high alloy stainless steel is clearly illustrated in Fig. 17, where superduplex stainless steel pipes perforated after short operating period at welds that were not performed according standard practice.

2.4. Nickel-based alloys

Nickel-based alloys generally have very good corrosion resistance in seawater environments and are often selected for seawater handling systems where the "high" cost is justified. Regarding seawater applications, it exist three main families of Nickel-based alloys. The first one is the nickel–copper alloys (e.g. Monel®) with about 67% of Ni, 30% of Cu and balanced Fe. These alloys are susceptible to oxygen concentration cell corrosion, to pitting and crevice corrosion. Then these alloys may not present a great interest compared to stainless steel in SWRO applications. The second family called Inconel®, with higher Cr and Ni contents (about 16% and 76%, respectively) presents a greater interest in terms of corrosion resistance. The most used Inconel is the alloy UNS N06625 (alloy 625) with high pitting corrosion resistance in seawater (PREN = 47–56). In terms of seawater crevice corrosion resistance, the alloy 625 is better than "usual"

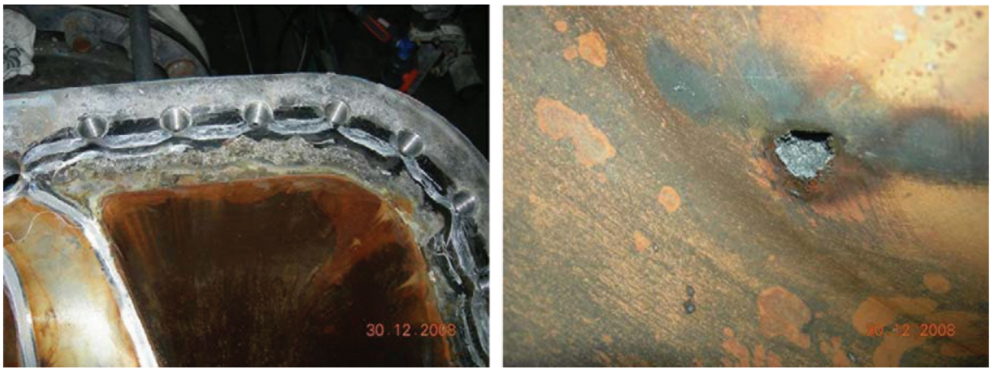

Fig. 15. Crevice (a) and pitting (b) corrosion of pump made of cast super duplex stainless steel ASTM A890 Gr5A).

Fig. 16, (a) Crevice corrosion of a cast superduplex stainless steel at gasket location, (b) crevice corrosion of a wrought superduplexduplex stainless steel at a "Victaulic-type" connection.

Fig. 17. Perforating pitting corrosion at welds on superduplex stainless steel pipes. In these cases, welding was not performed according good engineering practices.

superduplex and superaustenic stainless steels (e.g. UNS S31254 and S32750). However, when severe crevice geometries are involved, the UNS N06625 may also be susceptible to crevice corrosion and the superaustenitic UNS S31266 (B66) with PREN of 50 was shown to exhibit better crevice corrosion resistance [36].

The Hastelloys® (third family) are definitely the most corrosion resistant nickel-based alloys in seawater, with approximately 16% of Cr and additional 16% of molybdenum (Mo) as alloying elements. The most used hastelloy® alloys for seawater handling systems are the UNS N10276 (C276), N06022 (C22) and N06200 (C2000) or N06059 (alloy 59). In most seawater applications, these alloys can be used safely with very low risk of pitting or crevice corrosion. Due to the rather high cost of these alloys, critical parts of seawater handling systems can be protected with the cladding or the welding of thin Hastelloy sheets. The composition of the most used nickel based alloys in seawater is given in Table 6.

2.5. Titanium alloys

Titanium and titanium alloys are definitely the best corrosion resistant materials in seawater since it is fully immune at ambient temperature and above. All the systems handling seawater in a SWRO desalination plant could be made of titanium without risk of corrosion. The limited use of titanium in seawater handling systems is due to the cost, the availability to make the systems and sometimes the mechanical properties. The risk of galvanic corrosion induced by the coupling of titanium to dissimilar metal is not increased compared to the use

Table 6
Composition of some nickel-based alloys used in application applications

N°UNS	Usual designation	Ni	Cr	Mo	Cu	Fe	PREN1	Other
N04400	Monel400	≥63			28–34	≤2,5	—	
N06625	625	Bal.	20–23	8–10	≤0.5	≤5	46.5–56	Nb, Al, Ti
N10276	C276	Bal.	14.5–16.5	15–17	≤0.5	4–7	74–72	W, Co
N06022	C22	Bal.	22	13		3	65	W, Co, V
N06200	C2000	Bal.	23	16	1.6	—	76	
N06059	Alloy 59	Bal.	23	16	—	—	76	

1 – PREN = %Cr+3.3%Mo+16%N

Remark: The name "Ni-resist" alloys has been given to a series of cast iron to which sufficient nickel has been added to produce an austenitic structure similar to that of the austenitic stainless steels. Even if "Ni-resist" alloys have significant advantages compared to unalloyed cast iron in terms of increased velocity tolerance and galvanic compatibility with adjacent dissimilar materials, past experience with HP SWRO pumps from Ni-resist was dramatic. Without protection, "Ni-resist" alloys are clearly not recommended for use in any component in the pre-treatment area, additive systems or water supply systems [5].

of stainless steel or nickel-based alloys [37]. However the risk of biofouling leading to the ennoblement of the electrochemical potential still exists on titanium [1].

2.6. Plastics

Many plastics proved to be excellent material construction for some seawater applications. It can be polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), fibre reinforced polyester, fibre reinforced vinylester, fibre reinforced epoxy, etc. The C-PVC can sustain moderate pressures and is largely used for potable water applications. The main limitation for the use of plastic material is the strength. Threaded joints in plastic pipes are not recommended because they drastically lower bending strength. The strength will also decrease with the temperature. Thus, plastics are optimal materials for use in SWRO systems at ambient temperature where the low modulus of elasticity of plastic can be tolerated. However, fibre reinforced type of plastic may often be recommended because of its additional strength and increased modulus of elasticity over unreinforced plastics.

Special care must be paid in case of contacts between plastics and passive metallic materials such as stainless steel. If the contact geometry between the plastic and the metallic are too severe (very small confined zones with seawater ingress) the risk of crevice corrosion in the metallic material will not be negligible and will depend on the intrinsic corrosion resistance of the metallic material.

2.7. Gasket materials

As previously mentioned in this document, there is a "severe" crevice geometry between flanges and gasket materials used for watertightness. In seawater handling systems, the risk of developing crevice corrosion on passive materials such as stainless steel is generally significant (depending on water treatment, temperature and/or chlorination). The severity of the crevice between flanges and gasket materials is also very depending on the nature of the gasket material. In some cases, a right selection of gasket materials can prevent the initiation of crevice corrosion. The general recommendations concerning gasket material selection are as followed [38]:

For low pressure systems (up to 10 bar)

- Avoid the use of PTFE or graphite loaded gaskets
- Use gaskets made of synthetic rubber, rubber bonded aramid or synthetic fibre

For high pressure systems (10–100 bar)

- Avoid the use of PTFE coated gaskets
- Graphite- containing gaskets are acceptable provided the graphite is sealed from the seawater and is never wetted (condition which might be difficult to ensure)
- Only metals compatible with high alloy stainless steel should be used for spiral wound gaskets

3. Conclusions

The general requirements for alloys selection in SWRO systems are: adequate strength, fabricability and weldability to enable components to support high pressure and to be manufactured economically, and good corrosion resistance in aerated seawater for plant integrity. The most corrosion resistant solution, which is also the most costly, is to have most elements of a SWRO desalination plant made of titanium or corrosion resistant nickel-based alloys such as UNS N06022, N06276, N06059 or N06200. However, for cost consideration and technical feasibility, stainless steels were generally preferred. Depending on product form and on the selected grade, stainless steels can be dramatically affected by pitting and crevice corrosion regarding the service conditions including seawater characteristics and maintenance operations. From a corrosion resistance point of view, wrought materials should always be preferred to cast materials. Concerning maintenance operation of stainless steel components, any stagnation of seawater in contact with metallic structures must be avoided. All seawater handling systems which need to be regularly or sometimes stopped should be flushed with freshwater or should be connected with an alternative circuit which allows a permanent circulation of seawater. It exist many grades of stainless steels and the selection must be carefully adapted to the service conditions and the geometry of the seawater handling system. To protect critical parts of SWRO components such as flanges at gasket localisation, welding of thin sheet of a nickel based corrosion resistant material could be performed (e.g. UNS N06022, N06276, N06059 or N06200).

Copper–nickel alloys are widely used in seawater handling systems but are not often recommended for the construction of SWRO units since their use must be performed with very special care to avoid failures (galvanic corrosion, erosion–corrosion, release of copper ions susceptible to affect the RO membranes). With a careful design, copper–nickel alloy could however be a good candidate for piping systems.

Lower corrosion resistant materials such as coated-carbon steel or stainless steels with PREN below 40 can be used in seawater handling systems under appropriate cathodic protection. It is then strongly recommended to monitor and check the efficiency of the cathodic protection in critical parts of the protected structures (i. e. far from the anodes) and special care must be paid in systems where biofilm forms on the metallic surfaces. In that case, the current demand to remain in the protective potential range may be significantly increased and the efficiency of the cathodic protection must be checked.

To avoid corrosion problems, low pressure circuits could be made of plastic with sufficient strength and chemical resistance to the handled aqueous media. Fiber-reinforced plastics may be used for higher pressure parts.

By selecting suitable materials, adapted protections and by appropriate control of plant operations, any corrosion problem in SWRO desalination plants could be predicted and managed.

References

[1] R. Francis, Galvanic Corrosion: A Practical Guide for Engineers, 2001.

[2] P. Marcus, ed., Corrosion Mechanisms in Theory and Practice, 2nd ed., 2002.

[3] R.H. Jones, ed., Stress-Corrosion Cracking Material Performance and Evaluation, ASTM International, 1999.

[4] Z. Szklarska-Smialowska, Pitting and Crevice Corrosion, 2005.

[5] A. Abu-Safiah, Material selection for the high pressure section of seawater RO plants. Desalination, 84 (1991) 279–308.

[6] H. Yakuwa, M. Miyasaka and K. Sugiyama, Evaluation of crevice corrosion resistance of duplex and super duplex stainless steels for seawater pumps. Corrosion, NACE Paper No. 09194, 2009.

[7] Material Selection Table for Seawater Service. Internal Communication of Arcelor Mittal.

[8] T. Havn, Material Selection and Engineering Evaluations, Seawater Systems. Aker Maritime, Norway, 2000.

[9] Material selection. NORSOK Standard M-001 rev-4, 2004.

[10] G. Herbsleb, Der Einfluß von Schwefeldioxid, Schwefelwasserstoff und Kohlenmonoxid auf die Lochkorrosion von austenitischen Chrom-Nickel–Stählen mit bis zu 4 Massen-% Molybdän in 1 M Natriumchlorid-Lösung. Materials Corrosion, 33(6) (1982) 334–340.

[11] P. Combrade, Crevice Corrosion of Metallic Materials. Corrosion Mechanisms in Theory and Practice, 2nd ed., 2002, p. 358.

[12] Standard Specification for Chronium and Chronium–Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications. ASTM A240/A240M – 04a, 2004.

[13] R. Johnsen, North Sea Experience with the Use of Stainless Steel in Seawater Applications. EFC Publication 10, The Institute of Materials, 1993.

[14] O. Strandmyr and O. Hagerup, Field experience with stainless steel materials in seawater systems. Corrosion'98, Houston, NACE, paper No. 707, 1998.

[15] ASTM G48-03, Standard Test Method for Pitting and Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solutions. American Society for Testing and Materials, 2003.

[16] T. Havn, Material engineering and fabrication experiences. paper 56, NACE Corrosion'95, 1995.

[17] NORSOK Standard M-001 rev-4.

[18] F.L. La Que, Marine Corrosion — Causes and Prevention, John Wiley and Sons, New York, 1975.

[19] G. Pini and J. Weber, Matériaux de construction de pompes pour le refoulement d'eau de mer et de liquides à haute teneur en chlorures. Revue technique Sulzer, 2 (1979) 69–80.

[20] E. Heitz and R. Manner, Corrosion studies under conditions of thermal desalination. II- The influence of oxygen content, ph value, flow rate and impurities on the corrosion rates of unalloyed and low alloyed steels. Werkstoffe Korrosion, 29 (1978) 783–791.

[21] N. Larché, Galvanic corrosion of materials for seawater applications. ARCOR financed project, 1st technical contribution to the T7 Marine Corrosion meeting, IC report 79055-1, 2009.

[22] Circuits Eau de Mer, Traitements et Matériaux, éd. Technip, 1993.

[23] C. Manfredi, S. Simison and S.R. De Sanchez, Selection of copper base alloys for use in polluted seawater. Corrosion Nace, 33(8) (1987).

[24] A.D. Sneddon and D. Kirkwood, The influence of fouling upon corrosion rates of steels and copper–nickel alloys in sea water. UK. Corrosion 88, Brighton, 1988, pp. 81–96.

[25] N. Larché and D. Thierry, Crevice corrosion of stainless steels for seawater applications. Joint Industry Project, confidential, 2009.

[26] N. Larché, D. Thierry, V. Debout, J. Blanc, T. Cassagne, J. Peultier, E. Johansson and C. Taravel-Condat, Crevice corrosion of duplex stainless steels in natural and chlorinated seawater. Duplex World 2010, Beaune, France, October 11–13, 2010.

[27] B. Espelid, Development of a New Crevice Corrosion Qualification Test for Stainless Steels. Stainless Steel World, 2003.

[28] U. Kivisakk, Crevice corrosion testing of stainless steel tubes. Corrosion'04, 2004.

[29] D.M. Aylor, R.A. Hays, R.M. Kain and R.J. Ferrara, Crevice corrosion performance of candidate naval ship seawater valve materials in quiescent and flowing natural seawater. NACE Corrosion paper No. 329, 1999.

[30] N. Larché, Field inspection of the corrosion in the SWRO desalination plant in the mediteranean sea. Comission report IC 89670-1, Institut de la Corrosion, Véolia Consultancy, 2009.

[31] A. Desestret and D. Catelin, Special stainless steels for use in seawater. Seminar on the Economic and Technological Aspects of the Protection of Steel against Corrosion, Genova, 7–11 May, 1984.

[32] C.V. Roscoe and K.J. Gradwell, The history and development of duplex stainless steels. Duplex Stainless Steel'86, Paper No. 34, 1986.

[33] J.M. Drugli, T. Rogne, R. Johnsen and S. Olsen, Corrosion testing of stainless steel weldments in seawater, NaCl, and FeCl3 solutions. NACE Corrosion paper No. 410, 1988.

[34] U. Steinsmo, S. Valen, P.O. Gartland and E. Bardal, Effect of temperature on propagation of crevice corrosion of high-alloyed stainless steels in natural seawater. 10th Europ. Corr. Cong., Paper No. 244, 1993.

[35] H. Skjellevick and H. Salbu, Ni-based alloys and weld overlays for seawater systems. Sea Water Corrosion of Stainless Steels - Mechanisms and Experiences, SINTEF, Paper No. 17, 1995.

[36] A.M. Grolleau, H. Le Guyader and V. Debout, Prediction of the service life of nickel based alloys N06625 and N06059 and super austenitic stainless steel S31266 in seawater using in-house crevice corrosion tests. Nace 2009, 2009.

[37] E.B. Shone and P. Gallagher, Galvanic compatibility of selected high alloy stainless steels in seawater. Corrosion in Seawater Systems, A.D. Mercer, ed., 1990, p. 40.

[38] R. Francis, Factors affecting gasket selection for stainless steels in seawater. Corrosion, NACE paper No. 07262, 2007.