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by J.W. Oldfield and B. Todd

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Reverse Osmosis — which stainless steel to use?

by B Todd and J W Oldfield

Reverse osmosis (RO) plants are used for treating a wide variety of water compositions, including seawater. Stainless steels★ are well suited to the requirement of RO as their resistance to aqueous corrosion is high, so avoiding potential membrane-scaling ions contaminating the process.

Unfortunately, some stainless steels are prone to pitting and crevice corrosion in certain waters — notably those containing chlorides. Great care is needed in selecting the optimum grade of stainless steel for a particular water so as to avoid costly corrosion failures without specifying too highly alloyed and expensive a material.

The purpose of this paper is to describe the behaviour of stainless steels in aqueous environments and to assist in the selection of suitable alloys for particular conditions.

Corrosion characteristics of stainless steels in aqueous environments

Stainless steels are essentially iron-chromium alloys containing sufficient chromium to enable the alloy to develop a protective film. Although the ferritic iron-chromium stainless steels are used commercially they are less readily fabricated and welded than the austenitic iron-nickel-chromium alloys and the largest tonnage of these alloys is in those grades, usually containing 18 per cent chromium and about 10 per cent nickel.

In fresh or saline waters at or near neutral pH levels the protective film on stainless steels renders them virtually immune to general corrosion. For all practical purposes the corrosion rate can be taken as zero and no corrosion allowance need be provided.

The same is true for fast flowing conditions and tests[1] in seawater show negligible attack even at 40m/s.

Unfortunately this protective film can break down in waters containing chlorides. This breakdown is localised so that the general surface remains unchanged whilst deep pits form in those areas where breakdown occurs.

This localised attack is particularly likely to occur in crevices, *ie* areas where the surface of the stainless steel is shielded from full exposure to the corrosive environment by, for example, deposits from the water, overlapping metal surfaces, gaskets, etc.

Within such crevices oxygen in the water is rapidly consumed and this gives rise to an electrochemical cell in which the external fully exposed surfaces act as a cathode whereas the metal surface within the crevice becomes an anode.

In this anodic region, acidity, together with the concentration of aggressive ions such as chlorides rapidly builds up and when the *p*H has fallen to a level at which the passive film breaks down, corrosion occurs — often at rates of more than a millimetre per month.

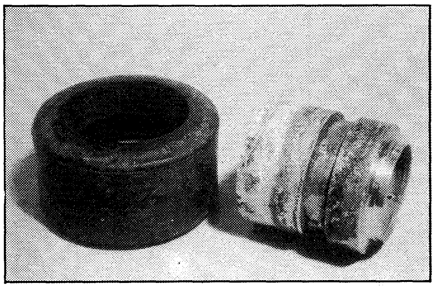

Fig. 1 — Crevice corrosion of type 316 stainless steel

Fig 1 shows crevice corrosion on a Type 316 connector from a seawater RO plant.

Effect of composition on crevice corrosion

The passive film on stainless steels is improved when the alloy contains molybdenum. Molybdenum is an expensive alloying element and as it tends to form ferrite in the steel, it is necessary to increase the nickel content to maintain an austenitic structure.

In recent years nitrogen has been found to be beneficial in stainless steels as it is a strong austenite former and also increases the resistance to crevice corrosion. Most recently-developed stainless steels with improved pitting and crevice corrosion resistance contain nitrogen.

The relative effect of chromium, molybdenum and nitrogen on crevice corrosion can be assessed from the wide used PRE_N — pitting resistance equivalent as follows:—
$PRE_N = Cr\% + 3.3\ Mo\% + 16\ N\%$

Thus stainless steels, to have high resistance to crevice corrosion, should have high chromium, molybdenum and nitrogen contents and should have sufficient nickel to maintain an austenitic structure.

Nitrogen also has the benefit of increasing strength, particularly proof stress, so that thinner piping can be used to withstand the high pressure in RO plants, so reducing cost.

Selection of a stainless steel for a particular water

Many factors influence crevice corrosion, including composition of the steel and of the environment, temperature, flow rate, crevice dimensions (width and depth), etc. This leads to very wide scatter in tests results.

One of the authors[2] has developed a mathematical modelling technique to assess resistance to indication of attack. This technique takes account of many of the factors described above and enables predictions to be made about the behaviour of stainless steels under crevice corrosion conditions.

The technique involves simple quick electrochemical measurements which are used to derive a CCR (crevice corrosion resistance) factor which can be used, for example, to compare the resistance of different alloys.

Fig 2 gives a ranking of various stainless steels and nickel base alloys in seawater. The relative position of different alloys correlates well with exposure tests in seawater.

Although many test methods have been developed for comparing different alloys, the model has been developed to allow prediction of what level of CCR is needed for a particular set of conditions.

a) *CCR requirement for seawater*

Fig 3[1] shows how the initiation of crevice corrosion in seawater is affected by crevice gap in a 5mm deep crevice. (In this context the gap is defined as the volume of solution in the crevice divided by the internal area of the crevice; it is therefore an average gap).

This shows that for Type 316 stainless steel crevices narrower than about 0.4 microns will cause initiation. For the 25 per cent Ni, 20 per cent Cr, 4½ per cent Mo+Cu alloy UNS NO8904 the crevice would need to be narrower than about 0.25 microns to cause initiation.

Table 1 — Nominal composition of some standard stainless steels and nickel base alloys

Structure	*UNS Number*	*Usual Designation*	*Cr%*	*Ni%*	*Mo%*	*C% Max*	*Other*
Austenitic	S30400	304	18	10	—	0.08	—
Austenitic	S30403	304L	18	10	—	0.03	—
Austenitic	S31600	316	17	12	2.5	0.08	—
Austenitic	S31603	316L	17	12	2.5	0.03	—
Austenitic	S31700	317	19	13	3.5	0.08	—
Austenitic	S31703	317L	19	13	2.5	0.03	—
Duplex	S31803	2205L	22	5.5	3.0	0.03	0.15N
Austenitic	NO8904	904L	20	25	4.5	0.02	1.5 Cu Rem Fe
Austenitic	NO6625	Alloy 625	21.5	61	9.0	0.10	3.7 Nb+ Ta 5 Fe
Austenitic	NO6007	Alloy G	22	46	7.0	0.05	2 Nb+ 19 Fe

★ *See Table 1 for details of composition.*

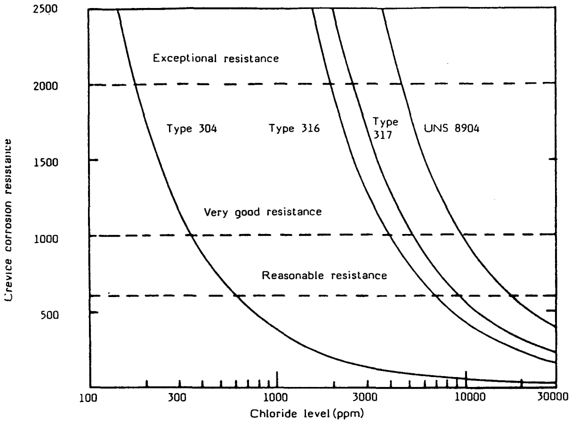

Fig 2 — Predicted crevice corrosion resistance of a range of stainless steels and nickel-base alloys in ambient temperature seawater.

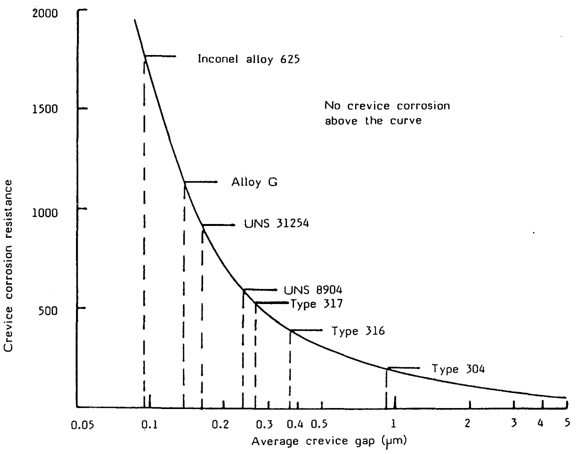

Fig 3 — Effect of crevice gap on initiation of crevice corrosion in ambient temperature seawater.

Table 2 — Typical analysis of some high alloy stainless steels commercially available

Designation	Producer	Cr%	Ni%	Mo%	Cu%	N%	PRE_N
AL-6XN	Allegheny	20.8	25	6.5		0.20	45.4
Uranus SB 8	Creusot-Loire	25	25	5	1.5	0.15	43.9
254 SMO (UNS S31254)	Avesta	20	18	6.1	0.7	0.20	43.3
A 965 (UNS S31254)	VEW	20	18	6.1	0.7	0.20	43.3
HR 8N	Sumitomo	21	24.5	5.8	0.8	0.2	43.3
AL-6X (UNS NO8366)	Allegheny	20.3	24.5	6.3			41.4
Cronifer 1925 HMO (UNS NO8925)	VDM	21	25	5.9		0.14	42.7
Sanicro 28 (UNS NO8028)	Sandvik	27	31	3.5	1.0		38.9
Alloy No. 20 MOD (UNS NO8320)	Haynes	22	26	5			38.8

Studies[3] have shown that average gaps in the range 0.2-0.5 microns are typical in practice. Less than 0.2 microns is unlikely and less than 0.1 micron almost impossible to achieve.

This means that the higher alloys shown in Fig 3, *ie* Inconel alloy 625*, Alloy G and UNS 31254 would all be acceptable in aerated seawater but that UNS 8904, Type 317 and Type 316 would not.

b) *Brackish Waters*

The wide variations in composition found in brackish ground waters from different sources[3] makes it unlikely that practical exposure tests would ever be carried out and a range of alloys in all these waters as the cost and time involved would be prohibitive. However, the modelling technique can be used to predict performance in different waters. Fig 4 shows how the ranking of different stainless steels varies with chloride content — the ion most likely to cause corrosion of stainless steels in aqueous environments.

In this instance indications of the degree of resistance have been marked on the ranking scale. 'Exceptional' resistance means that no corrosion should be encountered. 'Very good' resistance means that only under extremely severe crevice conditions would corrosion be expected whereas 'reasonable' resistance means that corrosion could occur in crevices normally encountered in the field.

Most brackish waters contain appreciable amounts of sulphates which are likely to be beneficial in terms of crevice corrosion as their presence in the water will reduce the build of chloride ions to levels necessary to cause break down of the passive film within the crevice.

The data in Fig 4 relate to sulphate-free waters and could be modified if appreciable quantities of sulphate are present.

High pressure components in RO plants

The high pressure piping, headers, connectors and membrane containment vessels in an RO plant contain many crevices so that materials selection must be based on crevice corrosion resistance.

For seawater applications, Fig 3 provides the necessary guidance. As crevices of 0.2 micron average gap can be expected then materials such as UNS 31254 Alloy G and Inconel alloy 625 are necessary. Materials such as Type 316 stainless steel, which are sometimes used are likely to suffer severe crevice corrosion within a few months — Fig 1 shows a typical failure from a seawater RO unit connector.

For the main components, alloys such as UNS 31254 are likely to be the most economic choice and several manufacturers now make alloys of this type — Table 2.

For brackish waters, Fig 4 provides suitable guidelines. If a material is selected on the basis of chloride content only, then if the water also contains sulphate, the materials choice based on these data will be somewhat conservative, depending on the relative amounts of chloride and sulphate.

Of interest for brackish waters are duplex stainless steels such as UNS 31803. These materials have a mixed austenite/ferrite structure and have high strength compared to austenitic grades — Table 3.

Table 3
UNS 31803 (22% Cr 5½% Ni 3% Mo+N)

	Proof Strength MPa (Min^{m})	UTS MPa (Min^{m})
	450	650
(316L)	170	485

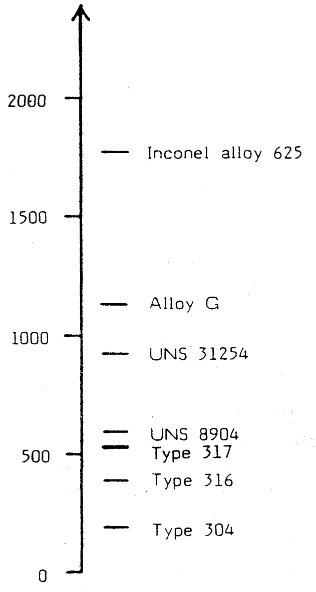

Fig 4 — Predicted crevice corrosion resistance of stainless steels in waters of varying chloride content

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* *Trademark.*

In the unwelded condition this alloy can have crevice corrosion resistance approaching that of UNS 8904. However, it is difficult to produce matching properties (strength and corrosion resistance) in weldments so that for welded construction it can be considered similar to Type 316L but with much higher strength.

This alloy has replaced FRP (fibre reinforced plastic) membrane containment pressure vessels in some designs of RO plant[4] to overcome cracking and codification problems.

Economic use of stainless steels for high pressure systems

Although corrosion considerations dictate the appropriate grade of alloy to use, it is important to design the system to take best advantage of the properties of stainless steels.

Most flow velocities in pipe systems have been derived from experience with carbon-steel or copper base alloys, both of which suffer serious corrosion if certain velocity limits are exceeded. In the case of stainless steels, no such limitation exists and provided pressure drop and noise levels are acceptable, then only cavitation (which normally would not occur in high pressure systems) would set a limit.

Offshore piping systems in high alloy stainless steels are designed[5] at 7m/s to reduce pipe diameter, wall thickness and cost.

In the case of seawater RO systems the high alloy stainless steels which are necessary to provide sufficient crevice corrosion resistance fortunately have higher strength — particularly proof strength — than the standard grades. Advantage can be taken of this by designing to modern Codes based on proof strength.

In any pipe system fabrication costs represent a sizeable proportion of the total cost. As fabrication costs are closely related to pipe diameter and thickness, those costs are also reduced where pipe size and thickness are reduced.

To achieve overall economies on a pipe system, the following points should be observed:—

Select the correct grade of stainless steel to suit the environment.

Use as high a flow rate as possible to minimise pipe diameter.

Use a design code based on proof strength.

Consider life cycle rather than initial cost.

Failure to observe any one of these points will result in unnecessary expense and in some cases, poor reliability.

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NiDI

North America

Nickel Development Institute
7 King Street East – Suite 1200
Toronto, Ontario, Canada
M5C 1A2
Telephone 416 362 8850
Telex 06-218565
Fax 416 362 6346

Europe

Nickel Development Institute
European Technical Information Centre
The Holloway, Alvechurch
Birmingham, England
B48 7QB
Telephone 0527 584 777
Telex 51-337125

Japan

Nickel Development Institute
11-3, 5-chome, Shimbashi
Minato-ku, Tokyo
Japan
Telephone 03 436 7953
Telex 72-2422386
Fax 03 436 7734

Central & South America

Nickel Development Institute
c/o Instituto Brasileiro de Informação do Chumbo, Níquel e Zinco
Av. Nove de Julho, 4015
Caixa Postal 6691
São Paulo-SP, Brasil
Telephone 011 887 2033
Telex 38-1125479

India

Indian Nickel Development Institute
c/o Indian Lead Zinc Information Centre
N° 7 Shopping Centre, Block B-6
Safdarjung Enclave
New Delhi 110 029, India
Telephones 600973 & 604230
Telex 81-314162

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