



European Federation of Corrosion
and NACE International
Joint Publication
Number 63

The corrosion performance of metals for the marine environment: a basic guide

Edited by
Carol Powell & Roger Francis

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European Federation of Corrosion
1 Carlton House Terrace
London SW1Y 5AF
United Kingdom
+44 20 7451 7336

NACE International
1440 South Creek Dr.
Houston, Texas 77084-4906
+1 281-228-6200



Contents

	<i>Series introduction</i>	<i>ix</i>
	<i>Volumes in the EFC series</i>	<i>xi</i>
	<i>Preface</i>	<i>xvii</i>
	<i>U. Kivisäkk</i>	
1	Introduction <i>C. Powell</i>	1
2	Iron and carbon steel <i>R. Francis</i>	3
3	Stainless steels <i>R. Francis</i>	14
4	Copper alloys <i>C. Powell and P. Webster</i>	26
5	Nickel alloys <i>C. Powell and D. Jordan</i>	42
6	Aluminium alloys <i>C. Tuck</i>	51
7	Titanium alloys <i>R. W. Schutz</i>	61
8	Galvanic corrosion <i>R. Francis</i>	74

European Federation of Corrosion (EFC) publications: Series introduction

The European Federation of Corrosion (EFC), incorporated in Belgium, was founded in 1955 with the purpose of promoting European cooperation in the fields of research into corrosion and corrosion prevention.

Membership of the EFC is based upon participation by corrosion societies and committees in technical Working Parties. Member societies appoint delegates to Working Parties, whose membership is expanded by personal corresponding membership.

The activities of the Working Parties cover corrosion topics associated with inhibition, cathodic protection, education, reinforcement in concrete, microbial effects, hot gases and combustion products, environment-sensitive fracture, marine environments, refineries, surface science, physico-chemical methods of measurement, the nuclear industry, the automotive industry, the water industry, coatings, polymer materials, tribo-corrosion, archaeological objects and the oil and gas industry. Working Parties and Task Forces on other topics are established as required.

The Working Parties function in various ways, e.g. by preparing reports, organising symposia, conducting intensive courses and producing instructional material, including films. The activities of Working Parties are coordinated, through a Science and Technology Advisory Committee, by the Scientific Secretary. The administration of the EFC is handled by three Secretariats: DECHEMA e.V. in Germany, the Fédération Française pour les sciences de la Chimie (formerly Société de Chimie Industrielle) in France, and The Institute of Materials, Minerals and Mining in the UK. These three Secretariats meet at the Board of Administrators of the EFC. There is an annual General Assembly at which delegates from all member societies meet to determine and approve EFC policy. News of EFC activities, forthcoming conferences, courses, etc., is published in a range of accredited corrosion and certain other journals throughout Europe. More detailed descriptions of activities are given in a Newsletter prepared by the Scientific Secretary.

The output of the EFC takes various forms. Papers on particular topics, e.g. reviews or results of experimental work, may be published in scientific and technical journals in one or more countries in Europe. Conference proceedings are often published by the organisation responsible for the conference.

In 1987 the, then, Institute of Metals was appointed as the official EFC publisher. Although the arrangement is non-exclusive and other routes for publication are still available, it is expected that the Working Parties of the EFC will use The Institute of Materials, Minerals and Mining for publication of reports, proceedings, etc., wherever possible.

The name of The Institute of Metals was changed to The Institute of Materials (IoM) on 1 January 1992 and to The Institute of Materials, Minerals and Mining with effect from 26 June 2002. The series is now published by Maney Publishing on behalf of The Institute of Materials, Minerals and Mining.

P. McIntyre

EFC Series Editor

The Institute of Materials, Minerals and Mining, London, UK

EFC Secretariats are located at:

Dr B. A. Rickinson

European Federation of Corrosion, The Institute of Materials, Minerals and Mining,
1 Carlton House Terrace, London SW1Y 5AF, UK

Mr M. Roche

Fédération Européenne de la Corrosion, Fédération Française pour les sciences de la
Chimie, 28 rue Saint-Dominique, F-75007 Paris, France

Dr W. Meier

Europäische Föderation Korrosion, DECHEMA e.V., Theodor-Heuss-Allee 25,
D-60486 Frankfurt-am-Main, Germany

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Many types of metallic material are used in a wide range of applications in marine environments. The materials' resistance against corrosion is vital for marine structural integrity and in order to avoid failure. In the 1970s, 1980s and 1990s, a lot of valuable knowledge was gained about how to avoid corrosion in marine and seawater service offshore. Much of this information was published in journals and conferences at the time, but it is not readily found electronically. This knowledge decreased the risk for corrosion problems. However, during recent years, it seems that corrosion problems are appearing again and that today's engineers are not aware of the lessons learned earlier.

In order to collect basic information together, the Marine Corrosion Working Party of EFC started to work on a book on the subject of corrosion in offshore and other marine environments, covering the common problems and how to avoid them. Early in the work, it was obvious that it would be beneficial to broaden the work with participants from NACE International as well. Therefore it is very natural to have this publication as a joint publication with NACE International. I would like to thank the members of both EFC WP9 and NACE STG 44 who wrote chapters or offered valuable comments on the early drafts.

It is our hope that the contents of the book will be useful to all scientists and engineers who are involved in the selection of materials for marine service.

Ulf Kivisäkk, *Chairman of the EFC WP9 on Marine Corrosion*

Carol Powell

*Vice Chair of EFC Working Party 9 for Marine Corrosion**carol.powell@btinternet.com*

Seawater is not a simple solution of inorganic salts in water. It is a complex mixture containing many different salts, dissolved gases, trace elements, suspended solids, decomposed organic matter, and living organisms. Its composition can vary between wide limits; for example, the dissolved salt content of the Baltic Sea is about 7 g kg⁻¹, whereas the Persian Gulf has about 43 g kg⁻¹.

The temperatures of seawater range from 0 °C in the Antarctic to ~28 °C in the tropics [1]. Some shallow seas in equatorial regions can reach 40 °C, while 45 °C is typical of condenser outlet temperatures. Not only might seawater vary from location to location, but individual places can show changes in temperature and biological activity with the seasons.

As such, seawater can be an aggressive and unpredictable medium. For most metals and alloys, it is capable of causing degradation or *corrosion*. This can take the form of general thinning or more localised penetration in a variety of guises. The corrosion behaviour of metals in seawater is largely influenced by the oxygen content, seawater velocity, temperature, pollution, and marine organisms.

Organisms can occur on metals as microfouling (slimes) or macrofouling (e.g. sea grasses and mussels); both can have an influence on the corrosion behaviour of metals. Seawater is a good electrolyte and can potentially lead to galvanic corrosion of susceptible alloys if two or more are in electrical contact with each other and directly exposed to the seawater.

Alloys are mixtures of two or more different metals and many have the capability of improving the properties of the individual constituents. Service experience in seawater has developed over the years such that, with a reasonable understanding of the alloying additions and their effect, it is possible to have some estimation of their performance.

Corrosion of alloys is an electrochemical phenomenon and there is a trend to evaluate new alloy compositions in short-term laboratory trials rather than long-term live seawater exposures. Synthetic seawater standards are available for such evaluations, and the tests have their value, particularly in ranking similar alloys. However, the complex nature of seawater has made it difficult over the years to achieve realistic performance data from short-term testing, and it is still necessary to supplement this with long-term testing in natural seawater or service experience to fully understand how alloys perform.

The majority of alloys are susceptible to corrosion in seawater in one way or another. Their successful application relies on knowledge of the types of corrosion each alloy might be susceptible to and how to avoid potential problems by material selection, as well as good design, fabrication, and operational practices. Planned

regular maintenance or replacement regimes can be a solution to limited service lives and be more economical when the system is accessible and labour is cheap.

Higher-reliability materials are the alternative solution and often provide lower life-cycle costs than the cheaper first cost, less reliable systems. In an ideal world, 'fit and forget' solutions would predominate, but no material is a panacea, and economic pressures are always present to prevent selection of more expensive choices unless absolutely necessary.

The goal of this guide is to provide readers with a basic understanding of the types of alloy used in seawater. All alloy groups discussed can form a successful part of engineering solutions for handling or withstanding seawater, but this is only achieved by designing and operating to their strengths and circumventing their weaknesses. The chapters include the types of corrosion problem areas encountered, and this knowledge can assist in avoiding them either at the outset or, if a failure has already occurred, in the replacement of the component.

The terminology used assumes the reader has no prior knowledge of corrosion engineering. The intent is to allow engineers new to the marine industry to quickly obtain an overview of important practical issues. However, it need not exclude more experienced engineers interested in expanding their breadth of knowledge about alloys in seawater, or refreshing their knowledge.

The chapters cover the main alloy groups starting with steel as the most widely used construction material. Each subsequent chapter discusses applications, the typical alloys used, basic properties, and corrosion resistance for the various alloy groups. The final chapter specifically examines galvanic corrosion because, of all the corrosion mechanisms, this is perhaps the easiest to misunderstand and regularly causes significant problems. The guide also is a reminder that few systems or structures are made of single alloys, and their success is ultimately linked to assessing the systems or structure as a whole, as well as the individual components.

Each chapter represents a short overview of the topics, and explanations are easy to follow. If further details are required, a reference and/or bibliography section is included at the end of each chapter. Photographs have been omitted to keep the guide as economical as possible; however, pictures of most of the types of corrosion described can be found in a case history publication by the European Federation of Corrosion [2].

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Roger Francis

*Rolled Alloys, Unit 16, Walker Industrial Park, Walker Road, Blackburn BB1 2QE, UK**rfrancis@rolledalloys.com*

2.1 Introduction

This chapter reviews the corrosion of carbon and low-alloy steels, as well as cast irons, in the uncoated condition. There are a number of coatings used with carbon steel to extend its life, but a discussion of these is outside the scope of this guide. Carbon and low-alloy steels are the most widely used materials in the marine environment, for both structural components and pressure-retaining applications. Table 2.1 lists some of the major applications.

Carbon manganese steels cover a range of compositions depending on the ductility and strength required. They are usually the lowest cost metallic materials. When additional properties are required (e.g. higher strength, low-temperature ductility), small amounts of nickel, chromium, molybdenum, and copper may be added, either individually or in combination, to create special low-alloy steels. This guide does not propose to list all of the alloys here because they corrode in more or less the same manner in seawater.

Cast irons contain 2–4% carbon and the microstructure contains graphite as well as carbides. Ductile iron is the most common alloy, and it contains small additions of magnesium to spheroidise the graphite and increase ductility. In many respects, cast irons corrode similarly to carbon steels in seawater.

Austenitic cast irons contain 15–25% nickel and small additions of other elements. ASTM (A571) [1] UNS F43010 (Grade D-2M) is often used in castings for pump cases and valve bodies, as well as for centrifugally cast pipe. It has a lower corrosion rate in seawater than ductile cast iron, but it has a susceptibility to chloride stress corrosion cracking (SCC) in warm seawater (see section 2.4.3 *Stress corrosion cracking* later in this chapter).

Table 2.1 Typical carbon steel and cast iron applications in marine environments

Type	Alloy	Application
Structural	Carbon steel and cast iron	Platforms, jackets, ship hulls, vessels, piling and sheeting, towers, bridges, lock gates, gratings, ladders, cranes, lifts, and loaders
Pressure-containing	Carbon steel, low-alloy steels, cast iron, and austenitic cast iron	Piping, vessels, pumps, and valves

All carbon steels and cast irons corrode in aerated seawater, so they are low-initial-cost alloys, but have high maintenance/replacement costs unless protective measures are used. Offshore maintenance is very expensive and carbon steel is chiefly used with high quality coatings and/or cathodic protection (CP). When maintenance is simple and planned shutdowns are frequent, carbon steel may be a cost-effective option.

2.2 Corrosion in the atmosphere

In marine atmospheres, the corrosion rate of carbon and low-alloy steels can vary from 0.01 to 0.1 mm year⁻¹ depending on how close to the sea the exposed metal is located. In environments such as offshore platforms and ships' decks, where splashing is frequent, the corrosion rate is at the higher end of this range. Coupling to more noble (electropositive) metals can greatly increase the corrosion rate of carbon steel by galvanic corrosion at the junction to 1 mm year⁻¹ or more. Corrosion of carbon steel leads to unsightly rust staining that may contaminate other equipment and cause accelerated attack. For example, corrosion products of carbon steel have caused localised pitting of UNS S31603 (316L) stainless steel (SS).

Low-alloy steels generally perform similarly to carbon manganese steel. Carbon steel with ~0.5% copper is termed *weathering steel*, and in rural and urban areas, it can acquire an adherent and protective orange-coloured film. However, in marine atmospheres, the copper has no protective effect; the corrosion rate is no lower than that of carbon steel and may be greater (in particular for non-rinsed applications) [2].

There have been some recent developments in low-alloy steels for marine atmospheres. It is claimed that additions of silicon and aluminium give improved corrosion resistance to steels used for structures such as marine bridges over harbours [3].

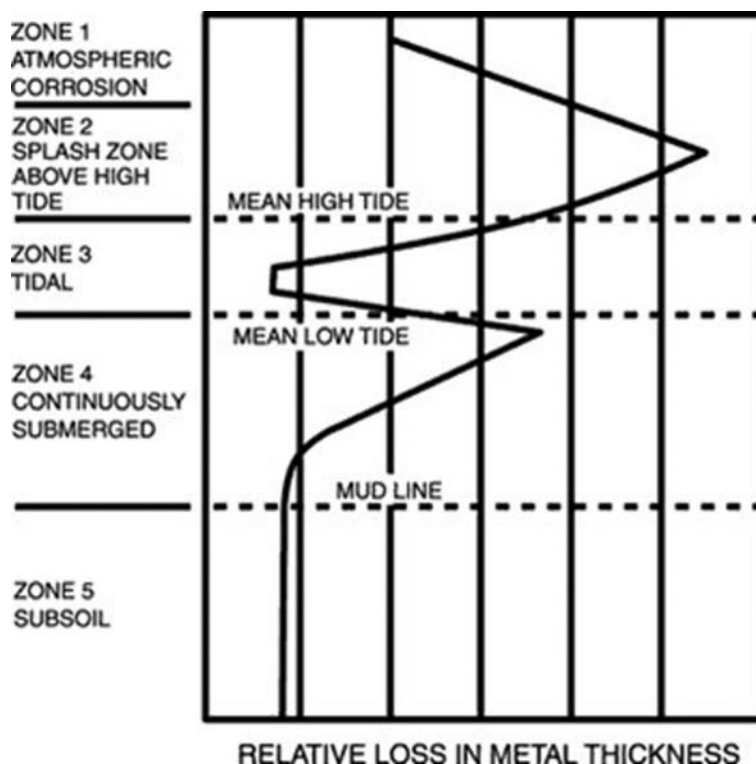
In most cases in which carbon steels and cast irons are used in marine atmospheres, high-quality coatings are needed for a useful, low maintenance life.

2.3 Splash zone

The intensity of corrosion of an unprotected steel structure in seawater varies markedly with position relative to the mean high and low tide levels (Fig. 2.1). Protection of a steel structure can be achieved by various means. Each corrosion zone shown in Fig. 2.1 must be considered separately. Generally accepted methods are CP, coating, and sheathing.

The spray and splash zone above the mean high-tide level is the most severely attacked region because of continuous contact with highly aerated seawater, and the erosive effects of spray, waves, and tidal actions. Corrosion rates as high as 0.9 mm year⁻¹ at Cook Inlet, Alaska, and 1.4 mm year⁻¹ in the Gulf of Mexico have been observed [4]. CP in these zones is ineffective because of the lack of continuous contact with the seawater (the electrolyte), and thus no current flows between the metals for much of the time. Coatings need to be very robust as the conditions can be damaging. Sheathing with neoprene, other rubber coatings, or nickel and copper alloys has been used successfully.

Corrosion rates for bare steel pilings, etc., can also be high at the position just below mean low tide, and are caused by galvanic effects because of the different levels of aeration that occur in the tidal region. This can be controlled by CP systems because the metal is continuously immersed.



2.1 Corrosion of carbon steel piling in seawater

2.4 Immersion

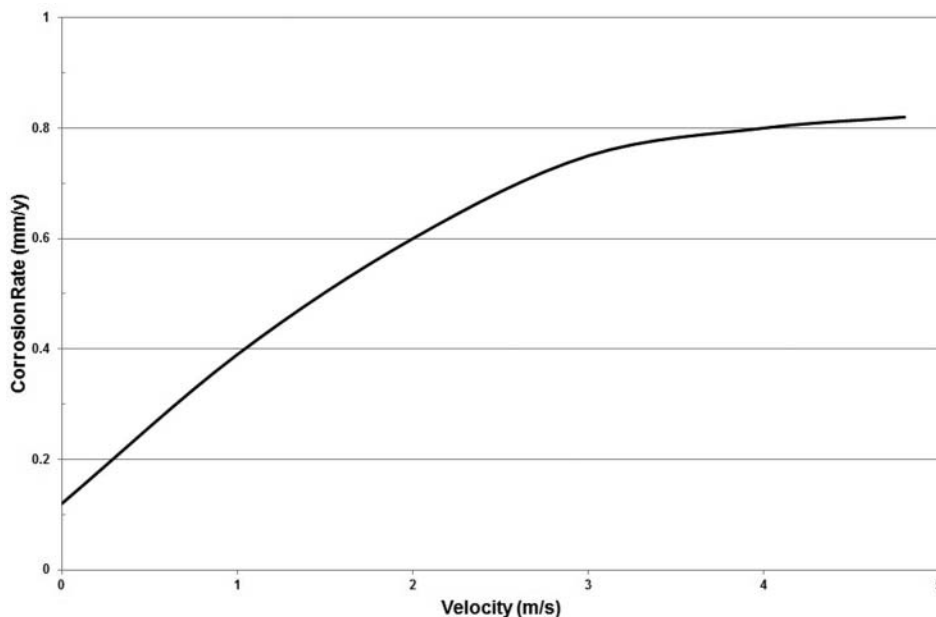
2.4.1 General corrosion

In quiescent seawater, the general corrosion rate of carbon steel and cast iron is $\sim 0.1 \text{ mm year}^{-1}$. However, cast iron and carbon steel can also undergo increased rates of corrosion under localised attack. General corrosion also increases as the seawater flow rate increases, as shown in Fig. 2.2 [5]. At a flow velocity of 4 m s^{-1} , the corrosion rate is approximately eight times that in quiescent seawater. Because austenitic cast iron contains nickel, it has a lower corrosion rate, typically $0.02 \text{ mm year}^{-1}$ in quiescent seawater.

When steels and irons corrode in seawater, the corrosion rate gradually decreases because the corrosion products restrict diffusion of fresh water to the metal surface. For this reason, long-term corrosion tests (1 year or more) tend to yield lower corrosion rates than short-term tests.

When carbon steel is used as a sacrificial anode, fragmentation rather than general corrosion has sometimes been reported for high-carbon manganese and low-alloy steels. Mild steel ($C < 0.1\%$) has been found to corrode more or less uniformly as an anode, although alloys with $C < 0.15\%$ are also reported as satisfactory.

Over time, the matrix of cast irons gradually corrodes, whereby the metallic constituents are selectively leached or converted to corrosion products, leaving the graphite particles intact, and the surface is slowly enriched in graphite (graphitic



2.2 Effect of velocity on the corrosion of carbon steel in seawater [4,5]

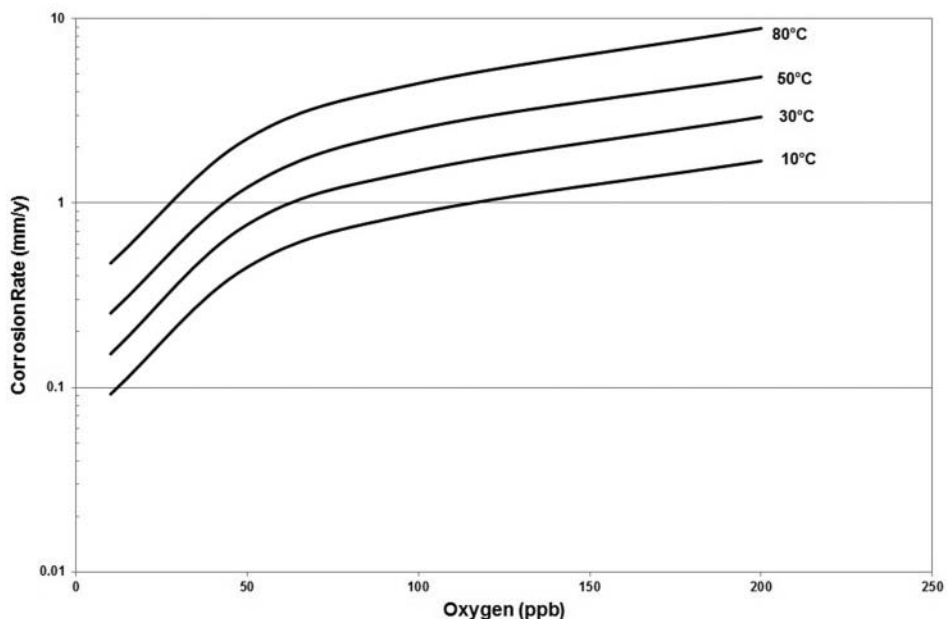
corrosion). This causes the potential to become more noble (electropositive), and heavily corroded cast iron can become the cathode in a galvanic corrosion cell. This is a slow process in seawater and generally takes 10 to 20 years. It does not affect austenitic cast irons, because the corrosion rate is lower and components are not in service long enough for significant graphitic corrosion to occur.

Natural seawater (in contact with air) contains $\sim 7 \text{ mg L}^{-1}$ dissolved oxygen when saturated at approximately 20°C , and this varies with temperature and depth [6]. In some cases, the seawater is deaerated, such as in multi-stage flash (MSF) desalination plants and seawater injection lines on offshore platforms. It is usual to express low levels of oxygen in parts per billion (ppb), where, for practical purposes, $1 \text{ ppb} = 0.001 \text{ mg L}^{-1}$.

If the dissolved oxygen is maintained at $\leq 20 \text{ ppb}$, the corrosion of carbon steel is low. In most land-based plants, this can be achieved and maintained. Offshore, however, 50 ppb is a more common oxygen level and on some platforms, the control is so poor that levels of 100 to 500 ppb are not uncommon for extended time periods. Under these conditions, carbon steel develops significant corrosion.

The effect of dissolved oxygen concentration and temperature on the corrosion rate of carbon steel is shown in Fig. 2.3 [7]. These data assume that no protective films are formed. There is a sharp increase in the corrosion rate from 10 to 50 ppb O_2 , and thereafter, a more gradual increase from 50 to 200 ppb O_2 . The increase in corrosion rate from 10 to 80°C at constant oxygen concentration is roughly the same order of magnitude as the increase produced by going from 10 to 50 ppb O_2 at 10°C . The results show the importance of keeping the dissolved oxygen content under control when carbon steel is used.

The use of galvanised steel pipe is sometimes suggested as an alternative to bare carbon steel, because it is readily available and is superior to bare carbon steel in fresh



2.3 Effect of dissolved oxygen and temperature on the corrosion of carbon steel [7]

water. Galvanised steel offers no advantages in seawater because the zinc corrosion products are soluble. The zinc corrodes in a few weeks or months and then it acts just like bare carbon steel [8].

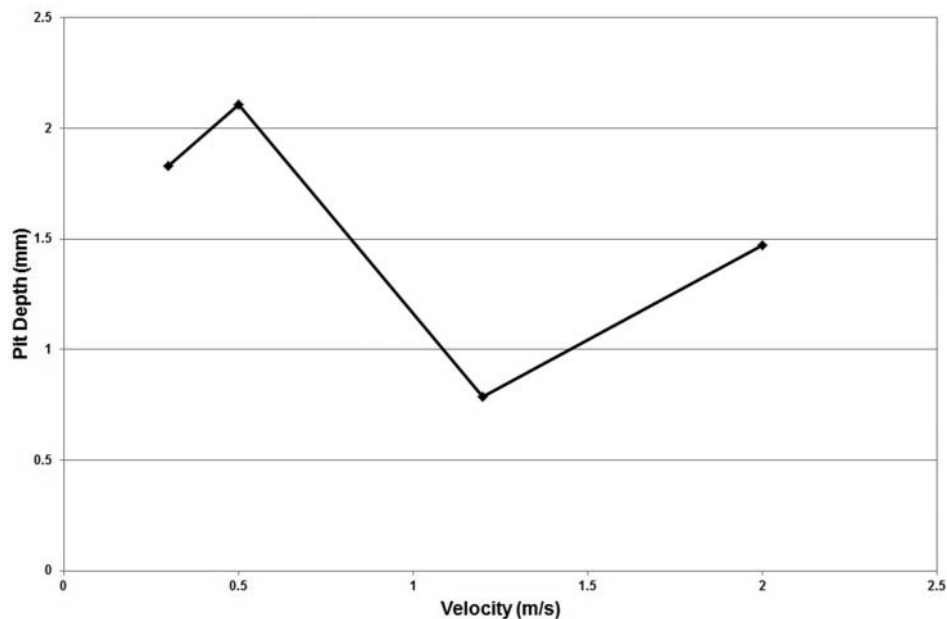
2.4.2 Pitting

Steels can undergo pitting to several times the depth of general corrosion under quiescent and flowing conditions. Hence, pitting corrosion is more likely to lead to leakage with carbon steel pipes [9]. The pit depth as a function of velocity is shown in Fig. 2.4. The effect of chlorine on the corrosion of carbon steel at various velocities is discussed later in section 2.4.7.

2.4.3 Stress corrosion cracking

Carbon steel and cast irons do not usually develop SCC in seawater. Although austenitic cast irons have a lower general corrosion rate in seawater ($\sim 0.02 \text{ mm year}^{-1}$) than grey cast iron, they are susceptible to chloride SCC, particularly in warm seawater.

Traditionally, austenitic cast iron components have lasted for at least 10 years, even in warm climates like the Middle East. In recent years, however, failures of pump cases have occurred within 1 to 6 years [10]. The shortest times to failure were on as-cast parts, while stress-relieved parts lasted a little longer. This reduction in life probably results from commercial pressures, because castings used to be grossly over-designed, but with increasing pressure to reduce costs, wall thicknesses are being reduced, with a consequent increase in the stress at critical locations.



2.4 Effect of velocity on the pit depth of carbon steel after 14 months in seawater [9]

The number of failures in some countries, such as Saudi Arabia, has led to the use of more resistant materials, such as superduplex stainless steel. Note that in colder climates, such as the UK, where the seawater is typically 5 to 15 °C, pumps and valves in austenitic cast iron have lasted more than 20 years. However, coupling to a galvanically more noble metal can stimulate corrosion and could lead to SCC, even in cooler waters. Stresses in modern castings are usually higher than in the past, so the likelihood of SCC, even at moderate temperatures, is greater.

2.4.4 Hydrogen embrittlement

The normal potential of carbon and low-alloy steels in aerated seawater is about –550 mV SCE (saturated calomel electrode) and this is too electropositive to generate hydrogen. However, under the influence of CP, or coupling to more electronegative metals such as zinc, the potential can be –900 mV SCE or more negative, and hydrogen is then evolved. This does not cause a problem for most steels, but hydrogen embrittlement (HE) can occur with high-strength steels, such as those used for high-strength bolting or in jack-up rigs. This is avoided by using impressed current CP, low-voltage anodes, or Shottky diode limited conventional anodes, so the potential is about –850 mV SCE [11,12].

2.4.5 Fouling/microbiologically influenced corrosion

In natural seawater, carbon steel rapidly becomes covered with a thin fouling layer, followed quickly by attachment of shellfish and weeds. In some regions, this can happen very rapidly. In the Gulf of Mexico, a NPS 8 (200 mm nominal diameter)

pipe became so full of fouling after 22 months that it had to be replaced [13]. Fouling of structures can also be severe enough to affect the mechanical loading.

When chlorine is added to the seawater to control fouling, this problem is eliminated, but there are consequent increases in pitting and general corrosion as described in section 2.4.7 *Chlorine/hypochlorite* later in this chapter.

When flow rates are high, approximately 2 m s^{-1} and above, there is less likelihood of attachment of fouling, but this varies according to different geographical locations, partly because of the differences in seawater temperature, and partly because of varying microbiological activity. At low flow velocities, suspended matter may settle onto the tube; as a result, the region beneath the deposits quickly becomes anaerobic. This stimulates the activity of organisms such as sulphate-reducing bacteria (SRB). These well-known causes for pitting corrosion of carbon steel may cause penetration of a pipe wall.

2.4.6 Accelerated low-water corrosion

The phenomenon of accelerated low-water corrosion (ALWC) was identified about 50 years ago and appears to be slowly spreading around the world. This is because there is a microbial involvement and it is thought that shipping may be spreading the bacteria involved in this form of attack [14].

ALWC affects sheet and tube piling and occurs between the mean low-water mark and the low astronomical tide mark. Corrosion rates can be 0.5 mm year^{-1} per side and because piling is normally installed uncoated, with a modest corrosion allowance, it is clear the life span of a piling can be drastically shortened.

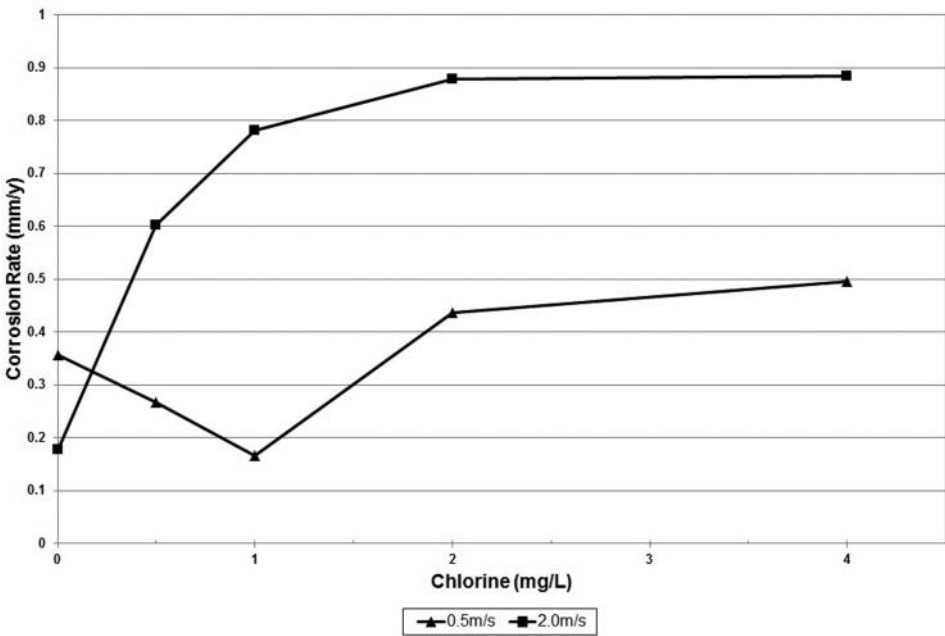
The mechanism is thought to be a form of microbiologically influenced corrosion (MIC) and involves SRB becoming active beneath deposits and marine growths on the surface. The hydrogen sulphide can attack the carbon steel, but some can also diffuse into aerobic regions where sulphur-oxidising bacteria convert the hydrogen sulphide to sulphuric acid that further exacerbates attack of the steel. Although it is mostly seen on the seawater side of pilings, it can also occur on the landward side if there is sufficient seawater ingress and significant numbers of SRB [14].

A number of methods for combating ALWC have been tried, with the most successful being high quality coatings and CP. With piling, not all areas may be sufficiently protected by impressed current CP and a hybrid solution, combining both impressed current and sacrificial anodes, is required in some cases.

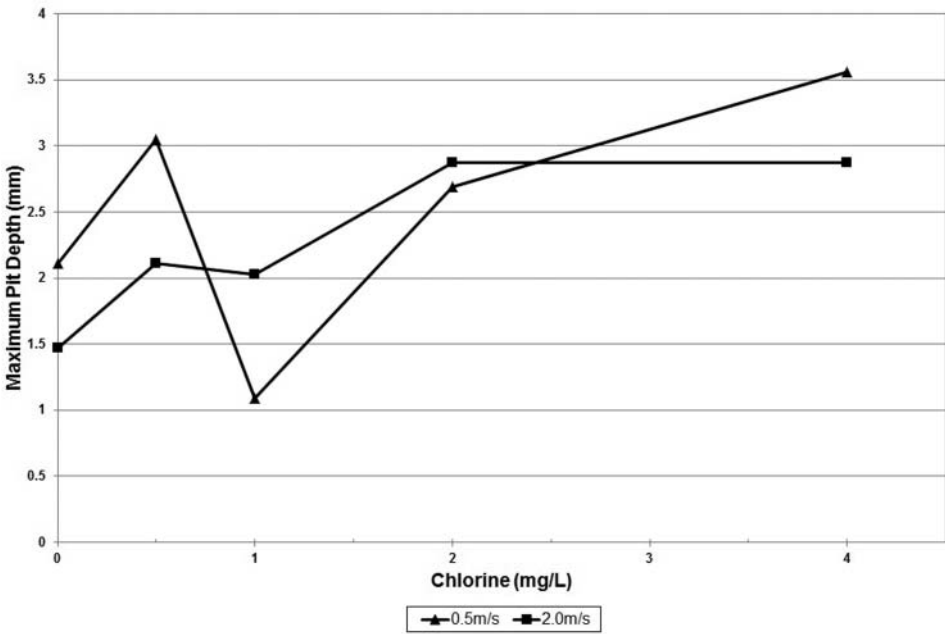
The whole phenomenon of ALWC, its causes and its prevention, has been reviewed and a document that includes an extensive bibliography was published by the International Navigation Association (PIANC) [14].

2.4.7 Chlorine/hypochlorite

Chlorine is added to seawater cooling systems to control macrofouling, such as that caused by weeds and shellfish. It also has the effect of keeping microfouling (slimes) at acceptable levels. The corrosion rate of carbon steel increases with chlorine concentration and velocity [9,15]. Figures 2.5 and 2.6 show the effect of chlorine on the general corrosion rate and pit depth, respectively, of carbon steel piping in seawater [9]. The exposure was for 14 months in the Gulf of Mexico with the seawater temperature varying from 12 to 29 °C.



2.5 Effect of chlorine on the corrosion rate of carbon steel after 14 months in seawater [9]



2.6 Effect of chlorine on the depth of pitting of carbon steel after 14 months in seawater [9]

The results show that pitting was deep and would lead to failure much more quickly than general corrosion. Figure 2.7 plots the safe continuous chlorine dose for no significant acceleration in corrosion vs. flow velocity using the maximum pit depth data [9]. This shows that, at 0.5 mg L^{-1} chlorine, the depth of pitting increases significantly above a flow velocity of 1 m s^{-1} . This design curve is not to eliminate pitting, but shows the chlorine/velocity level at which corrosion is no worse than without chlorine.

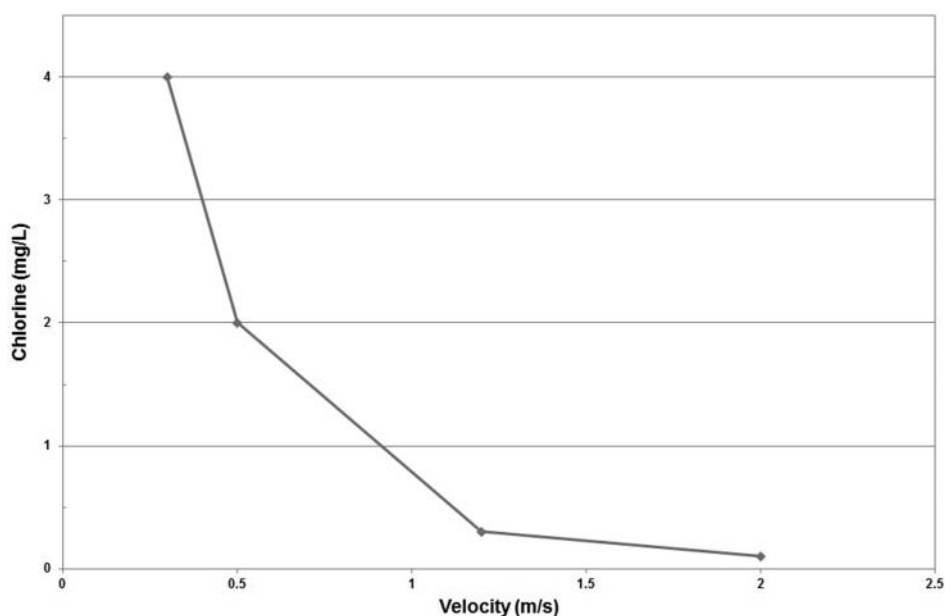
2.4.8 Galvanic corrosion

When cast iron and carbon steel are coupled to most metals, the corrosion rate increases, whereas the level of corrosion decreases for the coupled metals. This is because of galvanic effects and the cast iron or steel becomes the anode (see Chapter 8 on *Galvanic corrosion*). Because of their low cost, cast iron and carbon steel are frequently used as sacrificial anodes, for example, in the protection of brass tube plates in heat exchangers, and are purposely applied to corrode and decrease, or eliminate, the corrosion of the more vital component.

When cast iron corrodes, the graphite is left behind. Over a period of time, this means that the cast iron surface becomes soft and the component is much weaker. In addition, the graphite surface is highly cathodic to most metals, which can lead to accelerated galvanic corrosion of these metals.

2.4.9 Fabrication

One area that is often neglected when materials selection is considered is that of welds. This is one of the most common methods of joining, and the composition and structure of the weld metal may be quite different from that of the parent metal [16].



2.7 Safe continuous chlorine dose for carbon steel in seawater at 12 to 29 °C [9]

It is important, therefore, that the weld metal is not galvanically more susceptible to corrosion than the parent metal. Because the weld metal area is relatively small compared with the adjacent parent metal, any attack at the weld is greatly accelerated (see Chapter 8, *Galvanic corrosion*).

With carbon steel, problems of preferential corrosion of the weld metal usually result from the choice of welding consumables. High-silicon, low-nickel consumables give welds that are rapidly corroded in seawater, while the reverse (i.e. low-silicon, high-nickel) can produce welds that are acceptable. A common filler used to avoid preferential weld corrosion contains 0.6 to 1.0% nickel and 0.4% copper [16].

Another problem that sometimes occurs with carbon steel is preferential corrosion of the heat-affected zone (HAZ). If the welding is carried out with a heat input that is too low, then the HAZ can be hard and develop preferential corrosion in some aqueous media at room temperature. The solution is to weld with a higher heat input to produce a softer HAZ. This can be a problem with some alloyed steels, because welding produces a more coarse grain size than occurs in the parent metal [17].

Bond presented a paper reviewing the corrosion of carbon and low-alloy steel welds, the causes of problems, and the methods of avoidance [16]. Also described are potential problems with underwater weld repair and how to minimise them.

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Roger Francis

Rolled Alloys, Unit 16, Walker Industrial Park, Walker Road, Blackburn BB1 2QE, UK
rfrancis@rolledalloys.com

3.1 Introduction

Stainless steels provide a wide range of strengths and corrosion resistance in seawater environments. Some have limitations that restrict their use to marine atmospheres or require cathodic protection (CP). Others have been developed to a sophisticated level and have extremely high corrosion resistance in seawater. The degree of alloying, temperature, seawater flow, oxygen levels, chlorination, and welding considerations can all influence the performance of stainless steels, and are considered in relation to alloy selection and application.

3.2 Characteristics of stainless steels

Stainless steels have negligible general thinning in seawater because of a protective, predominantly chromium oxide film that forms immediately on their surface with exposure to air. Oxygen levels present in seawater normally allow the film to repair itself if damaged; in fact, oxygen levels as low as 10 ppb, such as those found in thermal desalination plants, are still sufficient for this to occur.

The film is maintained at very high flow rates, and seawater velocities in excess of 40 m s^{-1} can be accommodated [1]. In practice, however, flow rates in offshore stainless steel pipe systems are often limited to 7 to 10 m s^{-1} in stainless steels as a result of pumping costs and noise restrictions. Even so, the combination of good strength and erosion resistance reduces weight and is economical.

Good manufacturing and fabrication practices are paramount in obtaining the best performance from stainless steel, which is readily fabricated and welded [2–6]. Even the strong duplex stainless steels exhibit good ductility, and there are many suppliers and fabrication shops with experience working with these metals.

Under certain conditions in environments containing oxygenated chloride, the protective surface film on stainless steels can break down locally, leading to pitting, crevice corrosion, or chloride stress corrosion cracking (SCC). Alloy grades can be selected with increased additions of chromium, molybdenum, and nitrogen to significantly improve resistance to crevice corrosion and pitting. Higher nickel levels, or partial or full ferritic structures, increase resistance to chloride SCC compared with 300 series austenitic alloys. Therefore, the situation often faced during material selection is identifying the type of stainless steel that has the correct corrosion resistance required for any given marine environment.