

Guidelines for the Use of Stainless Steel in the Water and Desalination Industries

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Subject Area: Infrastructure



Guidelines for the Use of Stainless Steel in the Water and Desalination Industries



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FOREWORD

The Water Research Foundation (WRF) is a nonprofit corporation dedicated to the development and implementation of scientifically sound research designed to help drinking water utilities respond to regulatory requirements and address high-priority concerns. WRF's research agenda is developed through a process of consultation with WRF subscribers and other drinking water professionals. WRF's Board of Trustees and other professional volunteers help prioritize and select research projects for funding based upon current and future industry needs, applicability, and past work. WRF sponsors research projects through the Focus Area, Emerging Opportunities, and Tailored Collaboration programs, as well as various joint research efforts with organizations such as the U.S. Environmental Protection Agency and the U.S. Bureau of Reclamation.

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A broad spectrum of water supply issues is addressed by WRF's research agenda, including resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide a reliable supply of safe and affordable drinking water to consumers. The true benefits of WRF's research are realized when the results are implemented at the utility level. WRF's staff and Board of Trustees are pleased to offer this publication as a contribution toward that end.

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EXECUTIVE SUMMARY

THE PROBLEM

Public agencies struggle with the cost of desalination and water treatment projects, and expect expensive stainless steel materials to last as long as the bond payment period for their capital improvement projects (typically 20 to 30 years). However, the misapplication of stainless steel, which can lead to premature corrosion, continues to be a costly and common problem. Engineers and owners lack the resources to understand how to properly select these materials and specify the appropriate methods for their construction.

OBJECTIVES

The central objective of this project was to develop guidelines for water and desalination engineers to help them:

1. Understand the types of stainless steel used for different applications based upon water quality considerations
2. Properly specify construction standards that, if followed, will help extend the useful life of stainless steel materials to a period greater than 20 years
3. Identify appropriate operating conditions such that stainless steel corrosion can be avoided to the greatest extent possible

BACKGROUND

Stainless steels are widely used in critical components of drinking water, wastewater, and water reuse systems, such as well casings, reverse osmosis (RO) and other membrane treatment equipment, ultraviolet (UV) disinfection systems, and ozone generators, to name a few. Although stainless steels are quite corrosion-resistant, contrary to popular belief, stainless steel can fail due to corrosion. For example, a common type of corrosion that can affect stainless steel is microbiologically induced corrosion (MIC). To take full advantage of its corrosion-resistant properties, stainless steel piping and components must be properly specified, installed, and operated.

There are five different families of stainless steel and over 120 alloys and compositions (Lamb 1999). Corrosion-related failures of stainless steel may occur due to inappropriate selection of stainless steel type for a given application, inadequate design, faulty operation procedures, or incorrect construction methods. At present, there is an abundance of information related to the nature and use of stainless steel available in the literature. This information, however, has not been readily available to water and desalination industry professionals, nor has it been presented in a format that is useful to engineers and owners seeking to procure stainless steel materials. It is difficult for decision-makers to easily incorporate recommendations into construction documents or make operational decisions that may change the environment to which existing stainless steel materials are exposed.

Guidelines specific to the water and desalination industries will help design engineers and stainless steel users select the correct stainless steel, specify appropriate fabrication methods, incorporate sound installation practices, and implement good operational procedures. These guidelines will help minimize corrosion while maintaining the reliability, purity, and safety of

water, wastewater, water reuse, and desalination treatment and conveyance systems (collectively referred to hereafter as “water treatment, desalination, and conveyance” applications).

APPROACH

To develop these guidelines, the research team gathered data from three distinct areas:

1. Literature Review: The mechanics of different types of corrosion were identified, and the water quality, construction standards, and other environmental issues that have caused stainless steel failures in the water and desalination industries were described (Chapter 2).
2. Utility Experiences: Water utilities and stainless steel fabricators were contacted regarding their experiences with stainless steel, including its potential for corrosion. The lessons from these experiences were summarized (Chapter 3).
3. Experimental Studies: Laboratory corrosion studies were conducted to fill in some of the data gaps in the literature on corrosion in the presence of elevated levels of free chlorine and/or chloride (Chapter 4).

The first four chapters of this report present material and corrosion fundamentals, and identify common construction or operational influences that result in stainless steel corrosion. Water quality influences on the corrosion of various stainless steel alloys were identified through published testing data, combined with new laboratory data developed through this project (presented in Chapter 4). This information was applied in Chapter 5, which presents guidelines for the use of stainless steels. The data collected in the first three steps were converted into easy-to-use guidelines that will assist engineers and end users in selecting, procuring, and using stainless steel materials that will result in service life that meets expectations in a cost-effective way.

RESULTS/CONCLUSION

Summary and Recommendations for Selecting Stainless Materials

The key issue for engineers to consider when selecting a stainless steel is to define the various environments that will exist in different areas of the process piping and conveyance systems (e.g., chlorides, pH, free chlorine in solution, bacteria). This includes consideration of the environments that occur during idle, start-up, normal operations, and shutdown conditions within both treatment and conveyance facilities.

Austenitic stainless steels and duplex stainless steels with a similar PREN (Pitting Resistance Equivalent Number, see Chapter 2) will have similar overall corrosion pitting resistance. This provides the design engineer a method for selecting grades of stainless steel that are compatible with the identified operating environments. A more aggressive operating environment (i.e., higher concentrations of chlorides and free chlorine) may lead the design engineer to select an alloy with a higher PREN. Alternatively, alloys among both varieties (austenitic and duplex) with similar PRENs may be selected for a given application.

Thought should be given to evaluating the interacting effects of chlorides and chlorine on the 300 series of austenitic and duplex stainless steel in the saline solutions typical of those handled by desalination plants.

Duplex stainless steel welds may not have the same degree of corrosion resistance as would be indicated by their base metal PREN. In contrast to duplex alloys, the corrosion resistance of

austenitic welds appear to be comparable to their base metal equivalent, as indicated by their PREN.

Utility and Fabricator Experiences with Stainless Steel Corrosion

Utility Experiences

The water quality and corrosion survey indicates that utilities primarily deal with low or moderate-level concentrations of chlorides (<1,000 milligrams per liter [mg/L]) and moderate pH values (approximately 6 to 8), most have some level of dissolved oxygen present, and most use 304/304L or 316/316L stainless steel. The following conclusions can be made based upon the utility surveys and case studies:

1. Workmanship errors such as scratches and gouges, weld spatter, and galvanic corrosion from incompatible metals (i.e., galvanized steel or carbon steel with stainless steel), were found to be the most common cause of stainless steel corrosion.
2. Operational practices influence the potential for corrosion. Stagnant and biologically contaminated water left in piping resulted in MIC (microbiologically induced corrosion, see Chapter 2) and ferric chloride coagulant addition accelerated corrosion problems.
3. Selecting the appropriate alloy will reduce corrosion caused by challenging water quality and environmental influences, such as chlorides, oxidants, and low pH values.

Fabricator Experiences

The following conclusions can be made based upon the fabricator surveys conducted:

4. Every fabricator that responded is certified to weld 300 series and duplex stainless steels. However, it is apparently less common for fabricators to be certified to weld super-austenitic stainless steels. Fabricators are often required to submit weld certifications. The frequency that fabricators recertify their welders varies.
5. Weld quality control is always performed, but the percentage of welds inspected varies, likely by project size.
6. Chemical passivation practice varies widely. Some fabricators are required to hold environmental permits for waste disposal and gas emissions. Some fabricators self-perform passivation, while others subcontract this work to a third party.
7. Not all fabricators are equipped to electropolish pipe. However, electropolishing is readily available from qualified subcontractors.

Corrosion Testing

The goal of this study was to fill in knowledge gaps left by previous studies, and determine the upper operating conditions for austenitic and duplex stainless steels when exposed to aqueous solutions with chloride and chlorine concentrations typical of those found in water and desalination industry applications. Other variables included temperature effects and various surface conditioning preparations, with an end objective to determine possible interacting corrosion effects between chlorides and chlorine.

Based on the published results of testing performed by others, 316L was defined as the base alloy for this study's test programs. In addition, tests were also performed using common duplex alloys. Corrosion rates observed during immersion tests demonstrated the significant impact of surface treatment on the ability of stainless steel alloys to resist chloride-induced crevice corrosion. The duplex alloys demonstrated a higher resistance to crevice corrosion than 316L, but even this resistance was limited by high chlorine and chloride concentrations and low pH solutions. In general, increasing free chlorine concentrations increased the rate and severity of crevice corrosion at all chloride concentrations.

Guidelines

The fundamentals and lessons learned from the literature, utility experiences, and experimental studies were assembled into easy-to-use guidelines that will assist engineers and end users to select, procure, and use stainless steel materials. The proper use of these guidelines will help the user achieve a service life for stainless steel treatment and conveyance components that meets expectations in a cost-effective way. Two approaches were taken in preparing these guidelines:

8. For selection and procurement of stainless steel materials, guidelines are presented in MasterFormat[®], a specification outline that is commonly used in the construction industry (Construction Specifications Institute, Alexandria, VA).
9. For decisions related to making process changes and determining if existing stainless steel materials are suitable, the report includes a decision tree to help the end user evaluate pertinent water chemistry and material compatibility issues.

APPLICATIONS/RECOMMENDATIONS

Use of these guidelines will help engineers and others develop designs, produce specifications, and incorporate operating procedures for water treatment, desalination, and conveyance facilities that preserve the integrity and functionality of integrated stainless steel components. Improved design and operation will reduce costs through fewer expensive repairs, preserve the environment through more “eco-friendly” approaches to field installation, and reduce the use of potentially hazardous maintenance and repair materials and procedures.

RESEARCH PARTNERS

This Emerging Opportunity project was co-sponsored by the Water Research Foundation and the United States Bureau of Reclamation (USBR), which provided funding through an agreement with Eastern Municipal Water District (Perris, CA). Additional funding was provided by The Nickel Institute and Corrosion Probe, Inc.

PARTICIPANTS

Utilities that participated in this project include:

- Weber Basin Water Conservancy
- Long Beach Water Department
- Irvine Ranch Water District

- Santa Cruz Water Department
- Zone 7 Water Agency, Alameda County
- Orange County Water District
- San Diego County Water Authority
- Tampa Bay Water
- Water Replenishment District of Southern California
- City of Goodyear

CHAPTER 1

INTRODUCTION

Stainless steels are widely used in critical components of drinking water, wastewater, and water reuse systems such as well casings, conveyance piping, reverse osmosis (RO) and other membrane treatment equipment, UV disinfection systems, and ozone generators, to name a few. The basic alloys used in these applications are 304/304L and 316/316L austenitic stainless steels. Although stainless steels are quite corrosion-resistant, contrary to popular belief, stainless steel can be prone to failures due to corrosion, including MIC. To take full advantage of its corrosion-resistant properties stainless steel piping and components must be properly specified, installed, and operated.

There are five different families of stainless steel and over 120 alloys and compositions (Lamb 1999). Corrosion-related failures may occur if the wrong type of stainless steel is chosen for a given application, or if the construction methods used in its application were not correct. Guidelines are needed to help stainless steel users in the water and desalination industries select the correct stainless steel and specify the appropriate fabrication methods and installation practices. These guidelines will help minimize corrosion while maintaining the reliability, purity and safety of water, wastewater, water reuse, and desalination treatment and conveyance systems (i.e., collectively referred to hereafter as “water treatment, desalination, and conveyance” applications).

OBJECTIVES

The purpose of this project is to develop a guidance document to assist engineers and consultants with properly specifying the type of steel most appropriate for a given water treatment, desalination, and conveyance applications. This guidance document will help prevent the misapplication of certain stainless steel alloys and help water systems avoid failures, water loss, and operational downtime due to use of improper stainless steel materials and/or fabrication and construction methods.

To develop these guidelines, the research team gathered data from three distinct areas:

1. Literature Review: The mechanics of the different types of corrosion were identified, and the water quality, construction standards and other environmental issues that have caused stainless steel failures in the water and desalination industries were described (Chapter 2).
2. Utility Experiences: Water utilities and stainless steel fabricators were contacted regarding their experiences with stainless steel, including its potential for corrosion. The lessons from these experiences were summarized (Chapter 3).
3. Experimental Studies: Laboratory corrosion studies were conducted to fill in some of the data gaps in the literature on corrosion in the presence of elevated levels of free chlorine and/or chloride (Chapter 4).

These fundamentals and lessons learned were converted into easy-to-use guidelines that can assist engineers and end users to select, procure, and use stainless steel materials that will result in service life that meets expectations in a cost-effective way (Chapter 5):

1. For selection and procurement of stainless steel materials, we have organized the guidelines into MasterFormat[®], a specification outline that is commonly used in the construction industry (Construction Specifications Institute, Alexandria, VA).
2. For decisions related to making process changes and determining if existing stainless steel materials are suitable, we have provided a decision tree to help the end user evaluate pertinent water chemistry and material compatibility issues.

CHAPTER 2

CORROSION CHEMISTRY IN STAINLESS STEEL

To understand stainless steel materials and what makes them resistant to corrosion, it is important to have a basic understanding of the types of corrosion that occur in water treatment, desalination, and conveyance applications. This chapter describes the basic types of stainless steels available for water applications and the basics of stainless steel corrosion chemistry and mitigation techniques.

REVIEW OF MATERIALS SCIENCE TERMINOLOGY

As indicated previously, the intended audience for these guidelines is engineers and consultants that provide services to the water and desalination industry. In order to understand the content of this document, it is important that the reader be familiar with some basic material science terminology. To this end, a glossary has been added at the conclusion of this report. Some basic terminology and concepts associated with stainless steel corrosion are reviewed here.

WHAT IS STAINLESS STEEL?

A metallic alloy (i.e., metal made of multiple elements such as chromium, nickel, and molybdenum) is generally considered to be “stainless” when its chromium content is greater than about 12 percent by weight, with the balance being iron, higher alloyed stainless steels have higher levels of chromium. Chromium provides corrosion resistance to these alloys by forming a thin, adherent, corrosion-resistant oxide film on a clean (e.g., pickled, wire/rotary brushed, or ground) surface (of the alloy). When exposed to oxygen, whether in air or even in water, this layer will naturally form and will help to prevent corrosion of stainless steel beneath it (Tuthill 1994). The effectiveness of this protective oxide layer can become compromised when the original oxide surface layer becomes damaged or scratched, but rapidly reforms its protective film in the presence of oxygen.

There are five families of stainless steel, each characterized by their structure: martensitic, ferritic, austenitic, duplex (50/50 austenite/ferrite mixed structure), and precipitation-hardened structures. The families are characterized by their microstructures, which result from their particular compositions. The properties typical to the different structures of stainless steel alloys are as follows:

1. Ferritic and martensitic alloys are iron-chromium alloys. Martensitic alloys are hardenable by heat treatment, while ferritic alloys are not. Both ferritic and martensitic grades belong to the 400 series of stainless steels, which provide strength but only minimal corrosion resistance.
2. Austenitic stainless steels are iron-chromium-nickel alloys (nickel provides malleability and weldability to this series of alloys). These materials are known as the 300 series of stainless steel alloys, which offer corrosion resistance to a wide variety of waters (Avery et al. 1999). L-grade 300 series grades such as 304L have guaranteed low carbon contents, which is important for welding. The L-grades however have slightly lower minimum yield and tensile strengths. Dual grade, such as 304/304L has both the guaranteed low carbon of the L-grade and the guaranteed minimum strength

- of the non-L grade. The molybdenum-containing 316/316L dual grade is also commonly available. The 300 series alloys have reasonable strength in the annealed condition, and can be made much stronger and harder by cold work, but this is not practical in most water applications. Higher alloyed austenitic stainless steels are recognized as the super-austenitic stainless, e.g., 254SMO, 654SMO, and AL6XN (Davidson and Redmond 1990).
3. Duplex stainless steel, as its name implies, is a mixture of two structures or phases, austenite and ferrite. Modern duplex alloys contain nitrogen, which not only adds strength and corrosion resistance, but also improves previous problems with weldability. Likewise, the higher alloyed duplex materials are known as the superduplex alloys (Davidson and Redmond 1988).
 4. A series of lowered alloyed duplex materials, commonly called "lean duplex", offers higher strength with corrosion resistance similar to the standard austenitic grades. Where their high strength can be utilized, they can be very cost effective, and potentially have wide application in the water industry.
 5. Precipitation-hardened materials are alloys whose structure and strength properties can be modified by heat treatment.

As previously discussed, stainless steel gains corrosion resistance from the thin, adherent and protective oxide film that forms naturally on its surface upon exposure to air or aerated conditions (e.g., water). The effectiveness of this protective film can become compromised when the oxide surface layer becomes damaged or scratched. These sites can become areas for crevice and pitting attack.

The plain chromium-containing ferritic stainless steels are generally less formable and more difficult to weld than their austenitic (nickel-containing) equivalents. Hence, such austenitic and duplex stainless steels are commonly used for water and desalination conveyance applications because they offer excellent corrosion resistance to a wide range of water chemistries, and are easy to fabricate and weld. However, martensitic and precipitation hardened alloys are used in water and desalination plant infrastructure, although not usually for components that require welding or fabrication. [Table 2.1](#) presents various types of stainless steel materials and their application based upon the alloy structures discussed in this section.

The stainless steels in [Table 2.1](#) are all iron-based alloys. The hardenable martensitic alloys are commonly produced in round bar forms suitable for bolting and fastener applications (410), whereas the ferritic stainless steels (430 and 409) are manufactured as flat rolled products suitable for welded tubing applications, typically in the automotive industry. Precipitation-hardened alloys find their applications as pump shafting and fastener materials for aerospace and marine applications.

Table 2.1
The categories of stainless steel

	Martensitic	Ferritic	Austenitic		Duplex	Lean duplex	Precipitation hardening
Typical grade *	Type 410	Type 430	Type 304	Type 316	Alloy 2205 †	LDX 2101 ^{® ‡}	Grade 17-4Ph
Percent chromium	10.5-12.5%	16-18%	18-20%	16-18%	21-23%	20-21%	15-17.5%
Typical application	Bolting & pump shafts, bearings turbine blades	Cooking utensils, turbine blades	Aqueous corrosion-resistant materials		Aqueous corrosion-resistant materials	Aqueous corrosion-resistant materials with low nickel fraction	Shafting & fasteners, turbine blades
Industry	General purpose	Appliances & automotive	Water industry		Water industry	Storage tanks	Aerospace & marine

* Presentation of alloys presented as “typical grade” is not an endorsement of the alloy or material. For example, there are multiple lean duplex alloys that would perform equally to LDX 2101^{® ‡} in similar environments. It is incumbent upon the owner or project engineer selecting the material to research alternative materials that may meet the project’s performance requirements.

† Registered trademark of Rolled Alloys Inc.

‡ Registered trademark of Outokumpu Stainless

Chloride and chlorine are two common water chemistry components that challenge the successful application of stainless steel. Austenitic and duplex stainless steels have the best combination of and fabrication properties, and corrosion resistance to handle chlorides and free chlorine. This makes these most suitable for widespread use in water and desalination applications. [Table 2.2](#) presents some examples of common alloys that may be used in the water and desalination industries in the context of chloride and chlorine concentration limits generally accepted. Crevice corrosion is unlikely at ambient temperatures at the suggested chloride or chlorine at concentrations shown in [Table 2.1](#). A service life of 20 years or more can generally be expected at these conditions. Chloramines (in place of free chlorine) may work in favor of stainless steel because of the higher associated pH values. At higher pH (≥ 8) and under deaerated conditions, crevice corrosion mechanisms are unlikely to occur for the stainless steel materials.

As indicated in [Table 2.2](#), laboratory trials (supported by field experience) suggest that for the majority of natural, raw, and potable waters with pH values in the range of 6.5 to 8.0, a more conservative approach to alloy selection may be appropriate, especially where chlorides and free chlorine are present together. Other factors, like pH and temperature, may also come into play when selecting materials. When the amount of free chlorine in solution exceeds 2 to 3 mg/L and the solution is aerated, a more cautious approach should be taken in alloy selection.

Table 2.2
Free chlorine and chloride tolerances of common stainless steel alloys
used in the water and desalination industries

Material	Concentration of free chlorine in feed water		
	0 mg/L	2 to 3 mg/L	3 to 5 mg/L
	Chloride concentration ¹		
304/304L stainless steel	< 250 mg/L	<100 mg/L	-
316/316L duplex 2205	< 1,000 mg/L	-	<250 mg/L
Alloy 2205	< 1,000 and up to 3,600 mg/L	-	-
Alloy 254SMO AL-6XN Ferralium 255	< 3,600 and up to 15,000 mg/L	-	-
Zeron 100 Alloy 2507 Ferralium 255 Alloy 654Mo	< 15,000 and up to 20,000 mg/L	-	-
Zeron 100; 654SMO	> 20,000 mg/L		

*The United States Environmental Protection Agency (EPA) has a (non-enforceable) secondary maximum contaminant limit (SMCL) of 250 mg/L. The European Drinking Water Directive and WHO guidelines limit the concentration of chloride in the presence of chlorine to 200 mg/L.

Handling water sources with extreme water quality conditions, like brine solutions and seawater, where the chloride content is in excess of 18,000 mg/L, or where the amount of free chlorine in solution is 7 mg/L or higher, typically require the use of the “super-austenitic” alloys (also referred to as the 6 percent or 7 percent molybdenum alloys) and “superduplex” stainless

steel alloys must also be considered (e.g., Zeron 100, 2507, and Ferralium 255). These materials are highly alloyed for improved corrosion resistance. The key elements used in these materials, in addition to chromium, are nitrogen, molybdenum, and sometimes tungsten. These elements are all melted together for integral alloying as the materials are manufactured.

CORROSION MECHANISMS

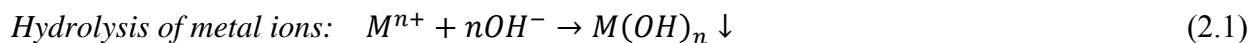
Aqueous corrosion is an electrochemical process with both anodic and cathodic reactions. Understanding the fundamentals of these reactions helps one understand the causes of corrosion and hence the rationale for selecting different materials to operate in specific environments.

Crevice Corrosion

Crevice corrosion is an electrochemical process dependent upon six stages and conditions (The Nickel Development Institute 1987).

Crevice Corrosion Stages

1. Formation of a crevice by a crevice former: The mechanism involves a well-shielded crevice, which creates an oxygen concentration differential between inside and outside the crevice. In addition, acidic corrosion products can form in the crevice itself through the ingress of chlorides.
2. Oxygen depletion: Very small amounts of corrosion that occur across the film soon consumes the oxygen within the crevice, stainless steel remains passive and the oxide film intact. Without more oxygen replenishment, the stainless steel film becomes weakened and subject to attack.
3. Hydrolysis of metal ions and decrease in pH: The few metal ions entering the moist environment in the crevice hydrolyze, depleting hydroxyl ions (OH^-) and the pH decreases. This process is shown in Equation 2.1.



4. Migration of the chloride ions into the crevice: Chloride ions (Cl^-) from the bulk solution migrate into the crevice to balance the charge resulting from depletion of the hydroxyl (OH^-) ions.
5. Initiation of crevice corrosion (Critical values both pH and chloride concentration): If pH decreases sufficiently and chloride ion concentration increases sufficiently to reach critical values (pH 2) for stainless steel, film breakdown and initiation will occur.
6. Propagation: If the critical values for pH and chlorides within a crevice are reached, initiation of corrosion occurs and propagation can proceed. The small shielded area is anodic to the large unshielded area outside the crevice. The galvanic effect favors deep penetration once initiation has occurred in normal saline waters (18,000 ppm chloride), waters. In deaerated water and in the absence of other reducible species, hydrogen reduction becomes the rate controlling reaction. In such deaerated waters, propagation proceeds so slowly, that crevice attack is seldom of practical significance. Gap shape and dimension play a significant role in the propagation of crevice corrosion. For 304 stainless steel, these gaps need to be 1 micron wide or less, for crevice corrosion initiation to occur.

Crevice corrosion is caused by the creation of an electrochemical cell between two halves of a very tight metal-to-metal joint when immersed in an aqueous solution (Figure 2.1). The tightness of the crevice either allows or prevents dissolved oxygen from penetrating the crevice and consequently may lead to the weakening of the oxide film trapped between the contacting surfaces (Kain, Tuthill, and Hoxie 1984). The weakening of this oxide layer leads to the diffusion of chromium, iron, and nickel ions from the surface layers and their combination with the hydroxyl ions diffusing from the bulk solution in which it is immersed. This is the cathodic reaction and can be described in the following manner:



This leaves an electrically unbalanced relationship, which results in the formation of a metal (M) hydroxide within the crevice. The cathode is the exterior surface of the metal.



As the pH drops and the chloride ion concentration increases, the potential for the passive film to degrade and crevice corrosion to begin increases. The anode is the interior surface of the crevice.

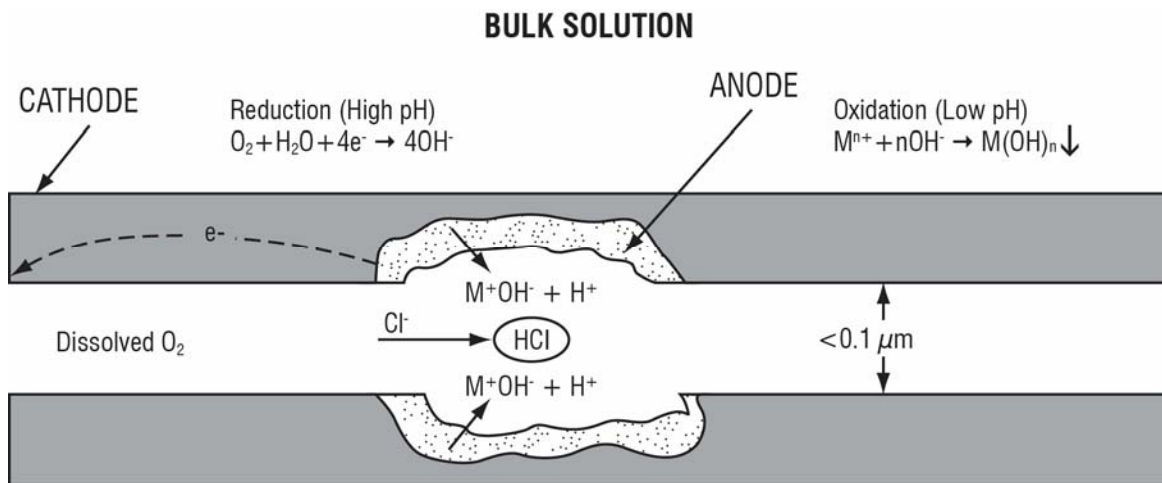


Figure 2.1 Illustration of crevice corrosion

Oxygen is consumed within the crevice but the tightness of the gap slows the reaction rate (being limited by diffusion of dissolved oxygen into the confined space). However, the smaller chloride ion diffuses more quickly, thus concentrating chloride ions in the crevice. Depending on the concentration, chloride ions can also combine with hydrogen to form hydrochloric acid or oxidizing metal chlorides in amounts significant enough to lower the pH in the crevice, increasing the rate at which the oxide film is degraded and the stainless steel is attacked (i.e., corroded).

At the crevice gap, chlorides and pH are the principal factors influencing initiation of corrosion (Oldfield 1984). In waters of normal pH (6.5 to 8.0 pH), crevice corrosion of Type 304/304L is rare up to 200 mg/L chlorides and equally rare for type 316/316L up to 1,000 mg/L chlorides.

Initial crevice formation can be human-initiated or caused by naturally present macro- or microorganisms. The presence of many of these organisms can be eliminated or avoided by design, fabrication, or operating procedures. Such methods include the following:

Man-Made Crevice Designs:

- | | |
|-------------------------------|--|
| 1. Stationary O-ring: | Avoid tight stationary crevices (man-made). |
| 2. Gasket surfaces: | Use hard red rubber gaskets. |
| 3. Non-metallic connectors: | Avoid. Use stainless metal couplings. |
| 4. Poor root pass pipe welds: | Use qualified welders and welding procedures and inspect afterward. |
| 5. Skip welds: | Use complete full penetration fillet weld or alternate welding sequence on either side of the joint to complete the joint for thin cross sections to avoid distortion. |
| 6. Paint; oil/grease; tape: | General cleanliness and removal of surface contamination. |
| 7. Bolted joints: | Avoid over-tightening fastener assembly. |

Natural Organisms (Crevice Formers):

- | | |
|---|---|
| 1. Adherent mussels and hard-shelled crustaceans: | Use copper-nickel trash bars; chlorinate |
| 2. Sticky sediments: | Use more resistant alloys; clean piping with pigging equipment. |
| 3. Colonies of bacteria: | Flush piping systems; Remove iron and manganese; chlorinate. |
| 4. Sediments and deposits: | Flush piping systems. |

In summary, for a stainless steel alloy in an aggressive water environment, resistance to crevice corrosion (and pitting corrosion, discussed subsequently) improves with increased addition of molybdenum, nitrogen, and chromium. The crevice gap dimension is the critical issue to crevice corrosion initiation. Environmental conditions influence the rate at which corrosion occurs. Crevice corrosion is less likely to occur under low-oxygen conditions (The Nickel Development Institute 1987).

Pitting Corrosion

Pitting creates a corrosion mechanism similar to crevice corrosion, where adjacent anode and cathodes are created and oxide breakdown begins in the presence of chloride ions. The difference is the penetration of attack, where the pit bottom (and anode) creates a pH environment that is more acidic than at the top of the pit, due the fact that the negative chloride ion is attracted to the anodic environment (the active pit bottom) where the chloride ions react with the release of metal ions to form metal chlorides (e.g., ferric chloride), which are known to be both highly acidic and accelerate the pitting reaction (Wagner 1992). The presence of more concentrated forms of chloride ions (lowering the pH) and/or the elevation of temperature accelerates this process.

Pitting occurs at the surface of metal substrates, around passive surfaces or at non-metallic inclusions, or where protective films breakdown. Pitting can be initiated at non-metallic inclusions, such as manganese sulfide, where cut ends expose these stringers (end grain attack) to aggressive environments, such as those containing chloride ions.

Figure 2.1 shows the formation of a cell with oxygen evolution and chloride ingress. The chloride ion from the bulk solution penetrates the cell to form an aggressive cell environment, which leads to the precipitation of salt films at the bottom of the pit cell. This increases the chemical attack at the bottom of the cell, while reducing the pH in this part of the cell. This accelerates the corrosion attack at the bottom of the cell, where the pH value of two exists for the pitting of stainless steels (The Nickel Development Institute 1987).

The comparative pitting resistance between the corrosion resistant alloys has been established using a mathematical relationship based upon the critical influence of key alloying elements that are common to various stainless steel alloys. A number of modified formulae have been developed. These tend to rank the corrosion resistant alloys with respect to consistency of performance in their ability to resist pitting. The formula for ranking materials is known as the PREN (Pitting Resistant Equivalent Number), with the most common definition being:

$$\text{PREN} = \% \text{Cr} + 3.3 \times \% \text{Mo} + 16 \times \% \text{N} \quad (2.4)$$

In this formula, the percent (by mass) contributions of key elements are empirically related to an alloy's ability to resist pitting. The higher the PREN, the more resistant the alloy is to the initiation of pitting.

Molybdenum (Mo) plays a large role in pitting resistance; nitrogen will also contribute significantly. In some PREN formulae, tungsten (W) is also recognized as playing a role in pitting resistance. Other elements such as nickel are influential in decreasing the propagation rate of pitting, but not the initiation. Factors other than the composition that influence the initiation of pitting include the presence of surface inclusions, other contaminants, the presence of heat tint, etc. The austenitic and duplex alloys are ranked in Table 2.3 using Equation 2.4 above, using a typical composition for the alloy.

Confidence in this mathematical ranking of alloys is supported by accelerated corrosion tests, as described in ASTM Specification G48 Method C (for pitting) and Method D (for crevice corrosion), which involves the total immersion of alloy coupons in 6 percent ferric chloride solutions over a series of temperature steps from 22 to 50°C for immersion periods of up to 72 hours at each step (ASTM 2011a). The alloy that shows no evidence of corrosion at the highest temperature is considered the alloy with the highest resistance to chloride attack by pitting or crevice corrosion. Crevice corrosion occurs at lower temperatures than pitting corrosion.

An alternative test method to evaluate pitting resistance involves the electrochemical initiation of pitting in stainless steels over a range of temperatures. This is described in ASTM G150, which uses a sodium chloride test solution (ASTM 2013e). The test results are obtained more rapidly than in the case for ASTM G48 testing (described in the previous paragraph), but the results in material ranking of alloys to pitting initiation are similar (ASTM 2011a).

Table 2.3
PREN values for different types of stainless steels

Common Name	UNS#*	Cr	Mo	N	W	PREN
<u>AUSTENITIC STAINLESS STEEL</u>						
304/304L	S30403	18.5	-	0.06	-	19.5
316/316L	S31603	17	2.2	0.06	-	25
<u>DUPLEX STAINLESS</u>						
Alloy 2304	S32304	23	-	0.13	-	25
LDX 2101® †	S32101	21.5	0.45	0.23	-	26.2
Alloy 2003® †	S32003	21	1.75	0.17	-	29
Alloy 2205	S32205	22.4	3.2	0.17	-	35.5
<u>SUPERDUPLEX ALLOYS</u>						
Alloy 2507	S32750	25	4	0.28	-	43
Ferralium® **	S32550	25.5	3.4	0.17	-	39
Zeron® 100 ††	S32760	25	3.5	0.25	0.75	41
<u>SUPER AUSTENITIC ALLOYS</u>						
254 SMO® †	S31254	20	6.25	0.20	-	43
AL6XN® †	N08367	21	6.5	0.22	-	46
Incoloy® 27-7™ ††	S31277	21.8	7.25	0.35	-	51
654 SMO® †	S32654	24.5	7.5	0.50	-	57

* Metal chemistries based upon average values presented in ASTM A 240 (ASTM 2015). Actual chemistries (and PREN values) may vary by manufacturer and production lot based upon the ranges shown in ASTM A 240.

† Trademarked materials have been studied for this report; no specific vendor endorsement is intended.

‡ The list of materials presented in this table is not comprehensive. There are other materials that may meet a project's requirements. It is incumbent upon the owner or project engineer selecting the material to research alternative materials that may meet the project's performance requirements.

** UNS- Unified Numbering System

†† Registered trademark of Outokumpu Stainless

‡‡ Registered trademark of Allegheny Technologies Incorporated

*** Registered trademark of Langley Alloys LTD

††† Registered trademark of Rolled Alloys Materials

‡‡‡ Registered Trademark of Special Metals

The advantage of the G150 method is that it accounts for the importance of temperature in pitting evaluation. Temperature plays a significant role in pitting for stainless steels. The Critical Pitting Temperature (CPT) is determined using this method and a Critical Pitting Index (CPI) represents the mean of various CPT values for a given metal.

As discussed previously, confidence in the mathematical PREN values for various alloys closely follow both the ASTM G48 and G150 methods (ASTM 2011a and 2013e, respectively). This was shown to be true in one study involving failures of flanges on offshore oil platforms in the North Sea, where chlorinated seawater test programs were undertaken to evaluate super-austenitic, duplex and superduplex stainless steels using both ASTM test methods (Drugli, Olav and Rouge 1993). Two testing programs were undertaken: The first program involved using the ASTM G48 method to determine the performance of the austenitic 6 percent molybdenum alloy to pitting attack versus various duplex alloys. A second test program involved testing girth welds of 2-inch Schedule 10 piping that either was welded to another section of Schedule 10 piping or was welded to a cast flange section. The results of this second testing program using 3 percent by weight sodium chloride solutions showed:

1. The 6 percent molybdenum alloy and duplex alloys fell in line with the predictable PREN values.
2. The 6 percent molybdenum alloy had higher Critical Pitting Index (CPI) values than the duplex alloys.
3. The weldments of the austenitic alloy were more corrosion-resistant than the weldments for the higher alloyed duplex stainless steels.
4. The cast austenitic and duplex stainless steels had lower mean CPTs than their welded plate counterparts. This means that cast stainless steels (welds are mini-castings) have reduced corrosion resistance compared to their wrought counterparts (plate, tube, pipe, etc.).
5. The primary location for pitting attack for the austenitic welds was at the weld fusion line. In the case of the duplex stainless steels, the pitting attack was in the weld itself, at the fusion line and in the heat-affected zone.

Of critical interest is the fact that the results of this testing lend credence to the use of the empirically derived PREN numbers.

ENVIRONMENTAL FACTORS THAT INFLUENCE CORROSION IN WATER TREATMENT

Microbiologically Induced Corrosion (MIC)

Microbes can be found in a variety of waters and soils, some of which can be deleterious to stainless steels. In the case of stagnant and slow flowing water conditions, slimes and bacterial films can attach themselves to crevices and rough surfaces, as in the case of rough inside weld surfaces (root passes), where poor welding has been performed and resulted in incomplete through-wall welds. Under stagnant conditions, this allows for attachment of slime formers, mold growers, microbial acid producers, sulfate producers, and metal ion oxidizers. Their rates of incubation and growth are then dependent upon the availability such water quality constituents as sulfates, iron, manganese or chlorides present in the feed water.

Depending upon the source of the water or soil characteristics, the bacteria can be either aerobic or anaerobic in nature. In the initial stages, bacteria form a biofilm, which leads to the formation of a biomound and eventually to the formation of a hardened shell, or tubercule, that interfaces with the internal metal surface. Anodic and cathodic sites develop and a corrosion site is formed to produce a corrosion cell. A tubercule is essentially a concentration of microbial cells that forms on metal surfaces. These tubercules shelter corrosive microenvironments from the bulk process solutions that can accumulate and accelerate the corrosion attack and can result in the formation of bulbous caverns through the cross-section of the pipe, plate, or containment vessel (Figure 2.2).

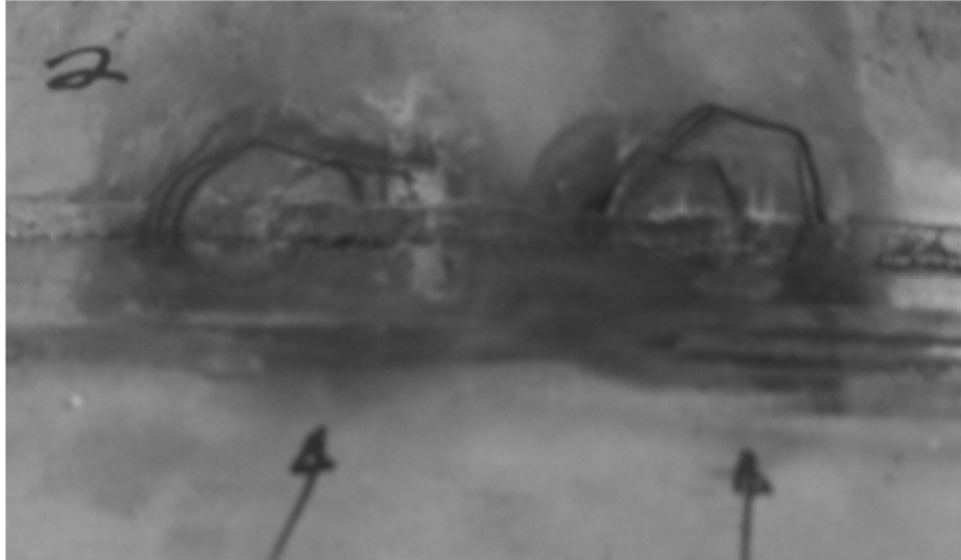


Figure 2.2 MIC tubercle formed on a root weld

The acids and chemical compounds that form inside the tubercle are separate and independent of the external water chemistry. Under aerated conditions oxygen-driven corrosion mechanisms typical of the metal ion-reducing bacteria (i.e., where iron oxide and manganese oxide are formed) dominate. Red-brown iron oxide films and black slimy manganese oxide films containing “sticky” polysaccharides form. Chloride ions can be absorbed into the biomass from the bulk water stream, which in turn accelerates the corrosion process. The added chloride ions facilitate the conversion of iron and manganese to their oxidized states. These acid chlorides, ferric chloride and manganic chloride are aggressive pitting agents to stainless steel. As more chlorides are absorbed into the corrosion process, the process becomes auto-catalytic, resulting in aggressive corrosion attack of the metal surfaces. The acid “looks” for seams or weaknesses in the pipe to attack, thereby deteriorating the integrity of the metal. In many cases, this results in wall penetration, with telltale signs of external weepage (Avery et al. 1996; Dickenson and Lewandowski 1996). These metal chlorides can become highly acidic.

Typical metal ion-reducing bacteria include *Gallionella* (manganese), *Sphaerotilus* and *Siderocapsa* (iron), among others. The bacterial polysaccharides provide the “glue” that allows the bacteria to form a colony on the metal surface, manganese or iron provide the terminal electron acceptor for cell metabolism, and water provides the environment. The chlorine added in water treatment acts as an oxidant, and further promotes corrosion by assisting in oxidizing the ferrous or manganous oxide, which themselves are not corrosive to the wall of the pipe. Chlorides from the water pass through the surface manganese oxides to form aggressive ferric and manganic chlorides under these surface deposits, eventually leading to pit initiation. These are well recognized as pit initiators to stainless steel (Tverburg, Pinnow, and Redmerski 1990).

Since microbial actions are related to pitting attack, material selection can influence the amount of microbial activity. Molybdenum has a significant role to play in the ranking of alloys and their resistance to crevice corrosion and pitting attack. Consequently, the specification of a higher molybdenum alloyed material or higher PREN alloy can be considered for replacement material, or chosen initially if the environmental conditions have been clearly defined. Other cost-

effective solutions can also be considered, including weld quality controls, bacterial filters (Yannoni, Kinsley, and Marston 1999), and periodic “shock” chlorination treatments.¹

Reviewing and understanding the potential issues caused by source water chemistry (chlorides, sulfate, manganese, and iron, including bacterial presence and pH) could go a long way towards formulating solutions to help mitigate MIC issues further downstream in the plant.

It is important to avoid allowing water to stagnate, especially after the equipment has undergone hydrostatic testing and when construction of well casings has been completed. In the case of hydrostatic testing, the test water should be drained, flushed out and the line or equipment blown dry (Kobrin et al. 1997). Alternatively, the vessel or piping being tested should be placed immediately back into service or circulated on a daily basis for at least one hour per day. The same consideration should apply to equipment or process lines that are going to be taken out of service for some time, or alternated in service with a duplicate piece of equipment.²

Soils

Like water, soil can serve as an environmental medium for corrosion of stainless steel materials to occur. Crevice corrosion, pitting and MIC attack are all common in buried stainless steel. In soils, corrosion is influenced by soil chemistry, stainless steel alloy composition, stray current, and construction and fabrication practices.

Soil chemistry greatly influences the potential for crevice corrosion and pitting of buried stainless steel piping. The corrosion resistance of stainless steel in soils is predicated primarily upon the alloy type, resistivity, acidity, and chloride and sulfate content of the soil. Depending on the chloride concentration and alloy type, various stainless steels can perform well without the need for coatings or other forms of protection in soils with resistivity values above 2,000 Ω -cm. Where coatings and other forms of protection are needed, consideration can also be given to using uncoated duplex stainless steel such as alloy 2205. Table 2.4 outlines a generally accepted corrosivity index and related alloy performance for soils according to soil resistivity values. These values are very similar to those reported in AWWA M11 for steel pipe (1989), which divides soils into four classes (Table 2.5).

Unlike steel piping products, stainless steel piping rarely needs to be coated either internally or externally. For long, buried stainless lines where the soil resistivity is < 2,000 Ω -cm, anodic or cathodic protection should be implemented. Where soil resistivity ranges from 2,000 to 10,000 Ω -cm, anodic or cathodic protection may be needed.

¹ Dosing waters entering water treatment plants with chlorine or potassium permanganate (often alternated by season) has provided some degree of protection from bacteria and zebra mussels, but this has not always been the answer. Chlorine injection has to be distributed centrally within the pipe or intake system to ensure that concentrated chlorine is not preferentially striking one side of the intake, which would result in localized corrosion.

² The ASME Code for Pressure Piping ASME B31.1 specifies, by rating, the quality of water that should be used for hydrostatic testing and the need for drainage immediately after testing (Sect. IV -3.4). However, it is recognized that high quality, clean waters are rarely available to most water plants, unless located adjacent to a power or process plant. Potable and treated waters would be preferred over raw waters. Seawater, untreated surface water, and well water should not be used.

Table 2.4
Corrosivity index for soils as a function of soil resistivity

Corrosivity	Soil resistivity	Acceptable alloys
Very corrosive	< 2,000 Ω-cm	duplex alloy
Aggressive	2,000 - 5,000 Ω-cm	316 may pit *, duplex
Mildly corrosive	5,000 - 10,000 Ω-cm	304 may pit *, 316, duplex
Slightly corrosive	10,000 - 20,000 Ω-cm	304, 316, duplex
Less corrosive	> 20,000 Ω-cm	304, 316, duplex
Not corrosive	30,000 - 100,000 Ω—cm	304, 316, duplex

Source: Data taken from Cunat 2001

* Anodic or cathodic protection may assist in improving the performance of those alloys that are noted “may pit.”

Table 2.5
AWWA M11 Soil Corrosivity Classes

Class	Soil type	Corrosivity	Resistivity
1	Sands and sandy loams	Lightly corrosive	6,000 - 10,000 Ω-cm
2	Loams (clay, silts)	Moderately corrosive	4,500 - 6,000 Ω-cm
3	Clays	Badly corrosive	2,000 - 4,500 Ω-cm
4	Peat, tidal marsh, clays	Aggressively Corrosive	< 2,000 Ω-cm

Source: Data taken from AWWA 1989

Soil resistivity is only one aspect of soil chemistry affecting the corrosion of buried stainless steel piping. The presence of chlorides and oxygen content have also been noted to affect corrosion rates for duplex materials. In one study, oxygen content assisted in reducing the corrosion potential for buried duplex materials (Sjögren et al. 2011). This is likely due to the participation of oxygen in the formation of a protective chromium oxide film. In this study, materials in a highly corrosive soil with low resistivity, high chloride concentration, and sulfate-reducing bacteria (SRB; typically found in marine clays and other anaerobic environments) performed better when buried 6 - 8 inches deep than when buried 24 inches deep. Oxygen content diminished with depth and therefore suggested that oxygen was beneficial in resisting corrosion in the buried piping.

In the case of soils and external MIC attack, the microbes involved are generally anaerobic (e.g., SRB). For iron and steel, general pitting attack will occur beneath the biomass, resulting in broad pits with terraced sides. The surface of these terraced pits can be shiny and reflective. The soil media for these biofilms is typically wet, clinging, clay containing sulfate radicals. SRB reduce the sulfate to sulfide, which along with the iron substrate produces a biomass and sulfurous acids that contribute to pitting. This suggests that bedding stainless steel pipe on sand or gravels to provide drainage will provide some protection against external MIC corrosion.

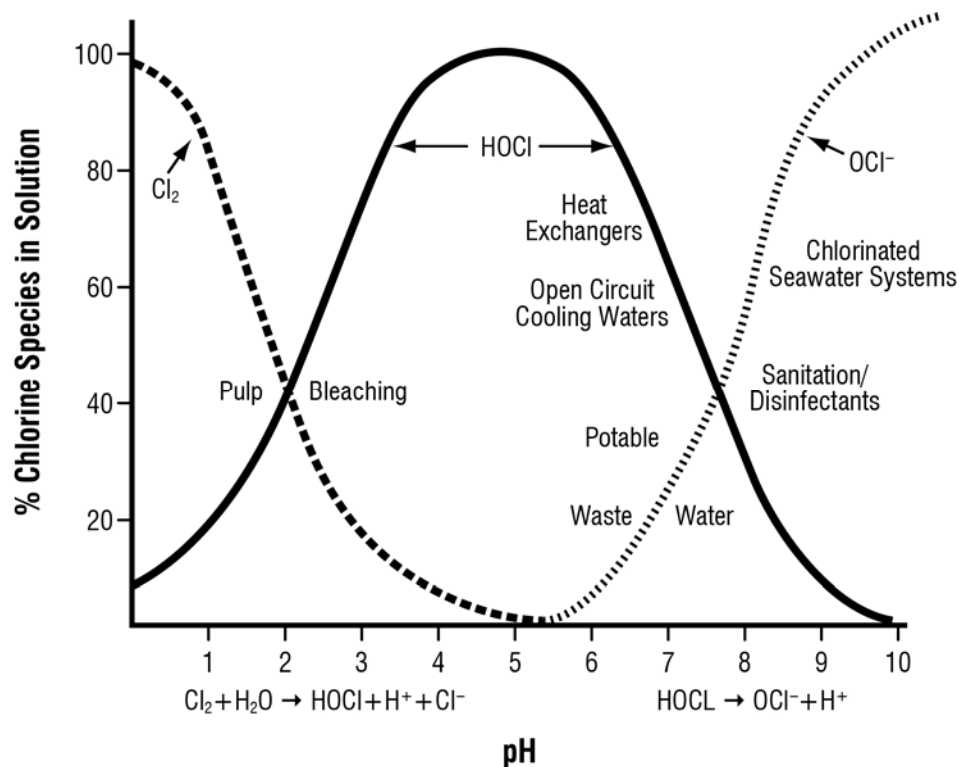
Stray electrical currents may cause corrosion of buried stainless steel (as well as carbon steel and cast iron). Stray electrical currents may result from nearby grounding electrodes for transformers, buried high-voltage cables, and overhead power lines. Development of stray currents

can be suppressed with proper electrical insulation of piping (e.g., using appropriate coatings and/or cathodic protection—impressed currents or sacrificial anodes).

Further information and an additional summary related to the selection and installation of buried pipe can be found in a summary presented in a recent AWWA Committee Report, which has been published in the *Journal AWWA* (AWWA 2012).

Chlorine and Other Oxidants

Next to oxygen, chlorine is the primary oxidant present in cooling waters, potable waters, and wastewaters. Chlorine is added to these waters as a disinfectant. Other, less common oxidants used in water treatment include potassium permanganate, ozone, chlorine dioxide, and bromine. Chlorine can be added to water in several different forms, such as chlorine gas, liquid sodium hypochlorite, and calcium hypochlorite granules. Chlorine dissociates to form hypochlorous acid and hypochlorite. As demonstrated in Figure 2.3, its speciation varies as a function of pH.



Source: Adapted from Jaques et al. 2000

Figure 2.3 Speciation of hypochlorite as a function of pH

These compounds are the most effective forms of chlorine for achieving disinfection. However, as more chlorine is added, the free chlorine (hypochlorous acid) concentration in solution increases. The free chlorine can react with ammonia and ammoniated compounds to form chloramines. Where these chlorinated solutions are alkaline in nature (pH values of 7.0 to 8.5, in the typical range of potable water), they can be handled by stainless steels without major concern for pitting or crevice corrosion. The extent to which the free chlorine is converted to chloramine

will affect the corrosivity of the water – with greater conversion of free chlorine to chloramines resulting in a less corrosive condition.

The data in Table 2.6 is based on research by International Nickel Inc. In this work, corrosion test coupons of Types 304/304L and 316/316L stainless steels were exposed to fresh and chlorinated waters from Lake Ontario. The data indicated that in the 3 to 5 mg/L residual chlorine range, Type 304/304L stainless steel becomes vulnerable to crevice corrosion or pitting of the base metal. Type 316/316L stainless steel can be expected to be more resistant to crevice corrosion in this free chlorine concentration range. Chlorinated fresh waters with up to 2 to 3 mg/L chlorine support the widespread use and selection of the austenitic stainless steels for construction in potable water treatment plants, fresh water-cooled condensers, and heat exchangers. In other words, where free chlorine concentrations will be within the range of 2 to 3 mg/L for much of the time, Type 316/316L stainless steel would be a suitable choice. At higher concentrations of free chlorine, higher alloyed materials should be used. However, further research is needed to establish appropriate concentrations of chlorine that may be suitable for these higher alloyed materials.

Table 2.6
Effect of chlorine on corrosion of stainless steel

Chlorine residual (mg/L)	Maximum depth of attack (mm)			
	Type 304 SS		Type 316 SS	
	Base plate	Crevice	Base plate	Crevice
0 ¹	0	0	0	0
0.8 - 1 [*]	0	0	0	0
2.0 [*]	0	0	0	0
3 - 5 [†]	<1 (0.03)	4-14 (0.1 - 0.4)	0	1 - 5 (0.03 - 0.1)

Source: Data taken from *Stainless Steel for Potable Water Plants*, Nickel Institute publication No. 10087 (available from NI website www.nickelinstitute.org).

* Water contained 23 mg/L of chloride.

† Water contains 790 mg/L of chloride.

For short periods of time, much higher doses of chlorine can be tolerated, such as for disinfection of distribution lines and tanks, as per AWWA standard C651 and C652 (AWWA, 2005 and 2002, respectively). The chlorine concentrations for these treatments are 25 to 50 mg/L chlorine for 24 to 48 hour exposures. In fact, these high levels of chlorine, for these short periods of time, appear to clean the metal surfaces and enhance the corrosion resistance of the normal protective oxide film on the austenitic stainless steels (Tuthill et al. 1998).

Saline Waters

As discussed previously, chloride concentrations play a key role in crevice and pitting corrosion. Brackish water, seawater, and brine discharges are high-chloride environments typical of desalination applications. These have the following general characteristics:

1. Brackish water: 3,600 – 18,000 mg/L chlorides,
2. Seawater: 18,000 - 20,000 mg/L chlorides, and
3. Hyper-saline (brine) discharges: >20,000 mg/L chlorides.

Research using ASTM G48 and G150 has shown that the effect of chloride concentration on corrosion rates in stainless steel can be quantified by the PREN. An increasing PREN indicates an increasing resistance to pitting and crevice corrosion (ASTM 2011a and 2013e, respectively). [Table 2.7](#) presents some general guidelines for materials and PREN numbers that may be viewed as acceptable for these ranges of chloride concentrations.

Table 2.7
Materials and PREN range for use with high-chloride saline waters

Chloride concentration	Stainless steel materials	PREN range
1,000 – 10,000 mg/L	Austenitic or duplex grades of material	> 33
10,000 – 20,000 mg/L	Austenitic duplex grades of material	> 40
> 20,000 mg/L	Austenitic duplex grades of material	> 45

Sources: Data taken from ASTM 2011a and 2013e

Nickel-based alloys have been evaluated for geothermal environments (126,000 mg/L chlorides) and will not be reviewed as part of this report. More information on geothermal hyper-saline environments can be found in (Moeller and Cron 1998).

Under totally anaerobic conditions, less alloyed materials such as 316/316L stainless steel can be considered for well casings for the handling and disposal of saline solutions without concern for crevice corrosion (Hornburg 1994). However, any imperfection in fabrication that allows a crevice to be produced can result in rapid corrosion upon exposure to oxygen. The experience of reverse osmosis (RO) water supply well casings using PVC, FRP, and 316/316L stainless steel has been good, but the non-ferrous materials are limited by well depth and mechanical properties. For the discharge of brine streams, Alloy 2205 stainless steel has been used successfully under anaerobic disposal conditions. The duplex stainless steels offer higher strength capabilities and potentially allow the use of longer strings of casing. Wellhead controls and valves, and submersible pumps have also successfully used 316L stainless steel.

Use of higher alloyed superduplex stainless steel, such as Zeron 100, has been considered for slurry transmission pipelines from the plant to a final destination. It has good corrosion and wear resistance to these types of brine slurries.

Synergistic Effects of Chlorine, Chloride, and Temperature

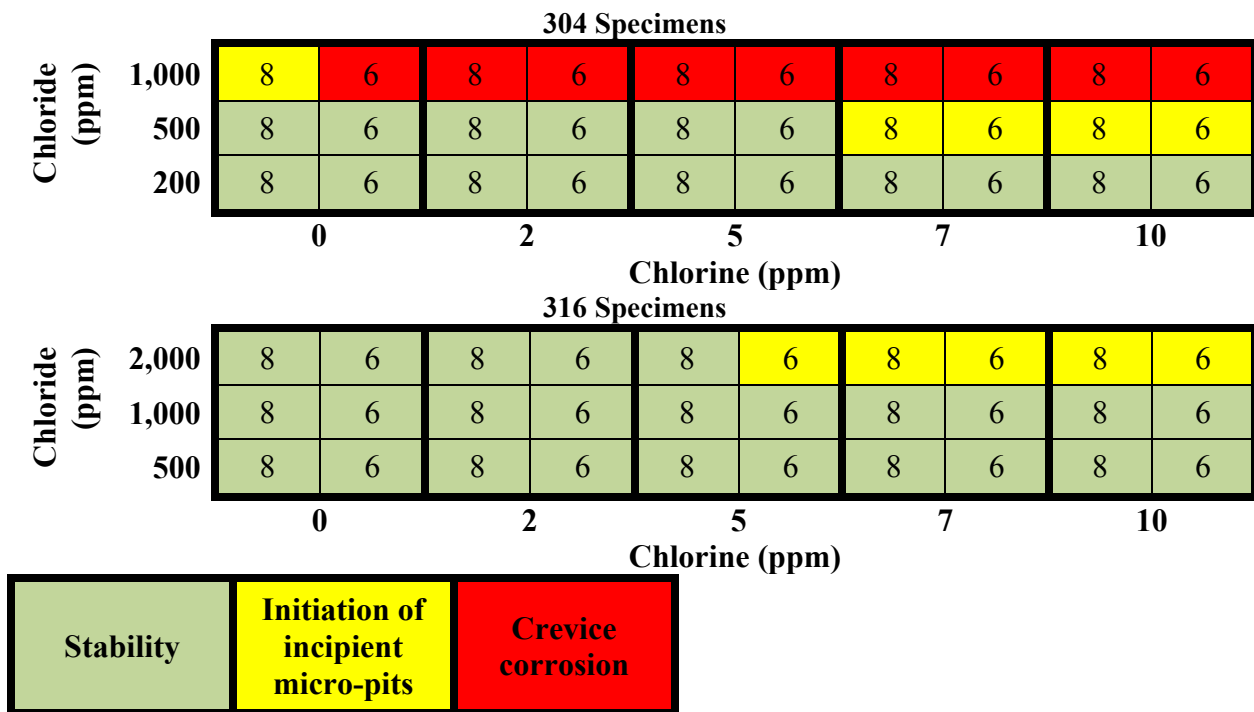
An emerging area of study is the synergistic effects of chlorine and chloride. New interest in this field has been spurred by observation of significant stainless steel failures when both chlorides and chlorine were present in concentrations that previous data (looking at the constituents separately) indicated should not have been cause for concern.

Recent studies presented in Europe addressed the corrosion tolerance of the austenitic and duplex stainless steels to chlorinated waters with varying concentrations of chlorides, pH, and temperature. One paper addressed the austenitic alloys, Types 304 and 316/316L, while the other addressed the behavior of the lean grades of duplex stainless steel and alloy 2205 under similar conditions, but at different temperatures (Mamang and Pettersson 2011 and Velpulanont et al. 2012, respectively).

The austenitic stainless steel study examined the range of 200 to 2,000 mg/L chlorides at chlorine concentrations ranging from zero to 10 mg/L free chlorine, both at pH 6 and 8 at 20°C for an exposure time of 60 days. The following summarizes the visual and optical microscopy evidence for the start of crevice corrosion (Mameng and Pettersson 2011):

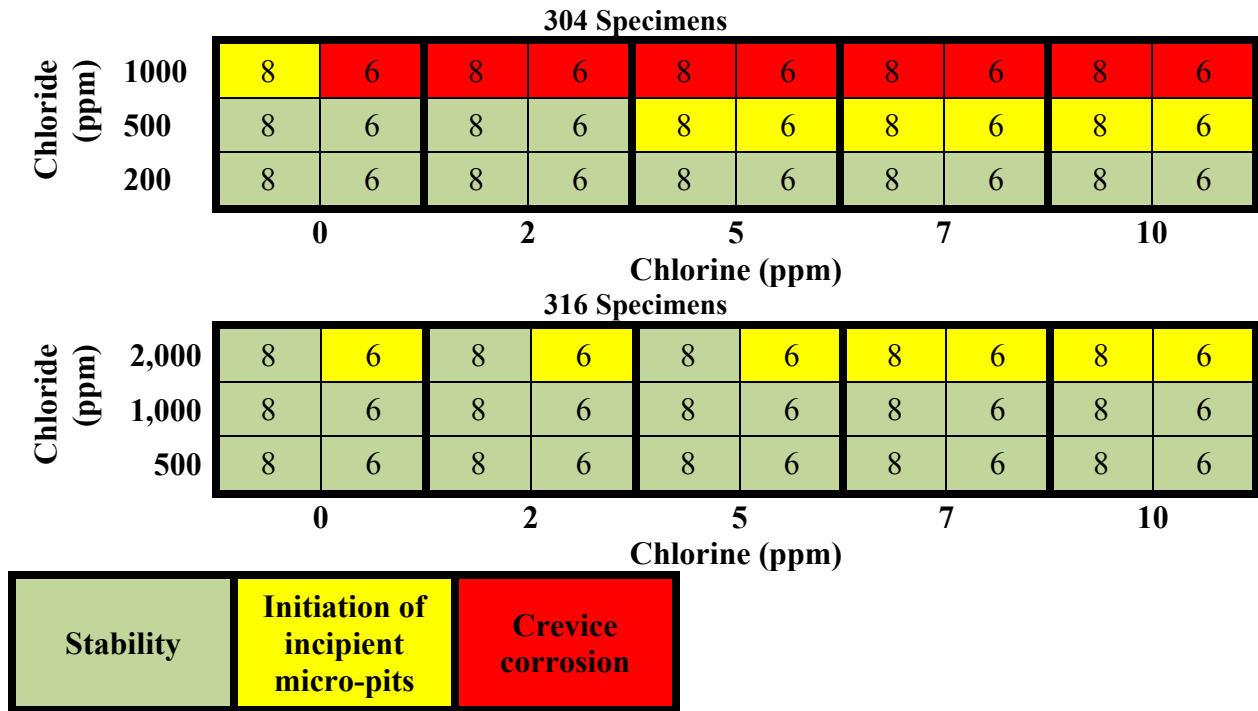
- The 304 stainless steel was resistant to chloride concentrations of up to 500 mg/L for both pH values (6 and 8) with free chlorine concentrations up to 5 mg/L. However, higher free chlorine concentrations in solution resulted in incipient pitting and indication for the commencement of crevice corrosion.
- Type 316/316L tolerance was higher than that for Type 304, which was to be expected with its higher PREN value. The Type 316/316L material was resistant to corrosion at chloride concentrations up to 2,000 mg/L and 5 mg/L free chlorine under all pH conditions, and up to 1,000 mg/L chlorides at 10 mg/L free chlorine at the pH 8 condition. Evidence of crevice attack was seen under the more acidic (pH 6) conditions with free chlorine levels higher than 5 mg/L.

These results are presented graphically in [Figures 2.4 and 2.5](#).



Source: Adapted from Velpulanont et al. 2012

Figure 2.4 Matrix map of risk of crevice corrosion on 304 and 316L stainless steel at various conditions based on visual results of 60-day exposures. Note: 8 and 6 represent the pH value of each condition.



Source: Adapted from Velpulanont et al. 2012

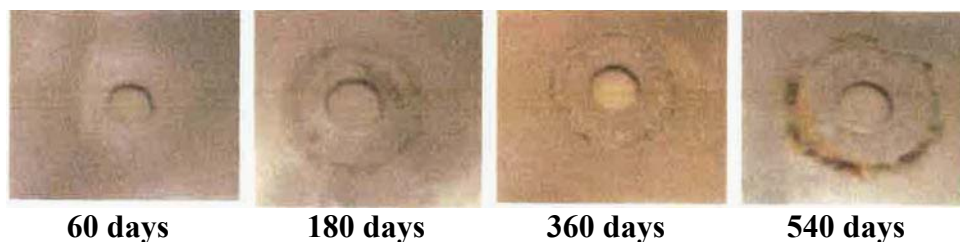
Figure 2.5 Matrix map of risk of crevice corrosion on 304 and 316L stainless steel at various conditions based on optical microscopy results of 60-day exposures. Note: 8 and 6 represent pH in each condition.

The duplex stainless steel study included welded specimens and the tests were run at higher temperatures – 30°C and 50°C for 30 days (Mameng and Pettersson 2011). The chloride content was limited to 250 mg/L and 500 mg/L, and the pH was held to between 6.5 and 7.5.

1. Alloy 2205 performed well at all temperatures with no pitting in the most aggressive of conditions (50°C; 500 mg/L chlorides; 1 mg/L free chlorine).
2. Type 316/316L stainless steel corroded at 50°C, 500 mg/L chloride, and 1 mg/L free chlorine in solution.
3. Type 304/304L stainless steel corroded under all conditions with more than 1.0 mg/L free chlorine. Pitting attack of the welds occurred under the same conditions as the base metal.
4. Results of lean grades of duplex varied. This was likely due to differences in the amounts of alloying constituents such as molybdenum and chromium and resulting in varied PREN values.

The results of these studies indicate there to be a temperature effect that becomes apparent when comparing Type 316/316L results at 20°C and 50°C (i.e., the relevant chlorine/chloride synergies for corrosion commencement).

These previous studies for austenitic and duplex materials (discussed above) were run for only 30 and 60 days, respectively. Additional 316/316L stainless steel crevice corrosion trials have been performed for 60, 180, 360, and 540 days under the most aggressive conditions (i.e., 2,000 mg/L chloride at pH 6 and chlorine levels of 10 mg/L; Velpulanont et al. 2012). As shown in Figure 2.6, although it is not visibly discernible at 60 days, crevice corrosion can initiate and propagate after lengthier exposures. This suggests that a more conservative approach should be taken in selecting materials for service in aggressive chlorinated waters. This approach has been adopted by the UK Drinking Water Inspectorate and the Environmental Protection Agency in their decisions for establishing maximum limits for chlorides and chlorine in drinking water.



Source: Eurocorr 2011

Figure 2.6 Visual comparison of extended exposure of 316L at 2,000 ppm chloride, pH 6 and 10

CONSTRUCTION AND FABRICATION INFLUENCES ON STAINLESS STEEL CORROSION

In addition to environmental factors such as water chemistry, soil chemistry, and biological materials, construction and fabrication methods can significantly influence the effectiveness of stainless steel at preventing corrosion. Connecting dissimilar metals, welding methods, cleaning, passivation, and surface finishes may all influence the ability of the metal to form and maintain a protective chromium oxide film on its surface. Additionally, the presence and geometry of crevices may also have an effect. Furthermore, despite measures taken during fabrication, if the material is improperly handled as it is being delivered or installed, the metal surface may be damaged or contaminated.

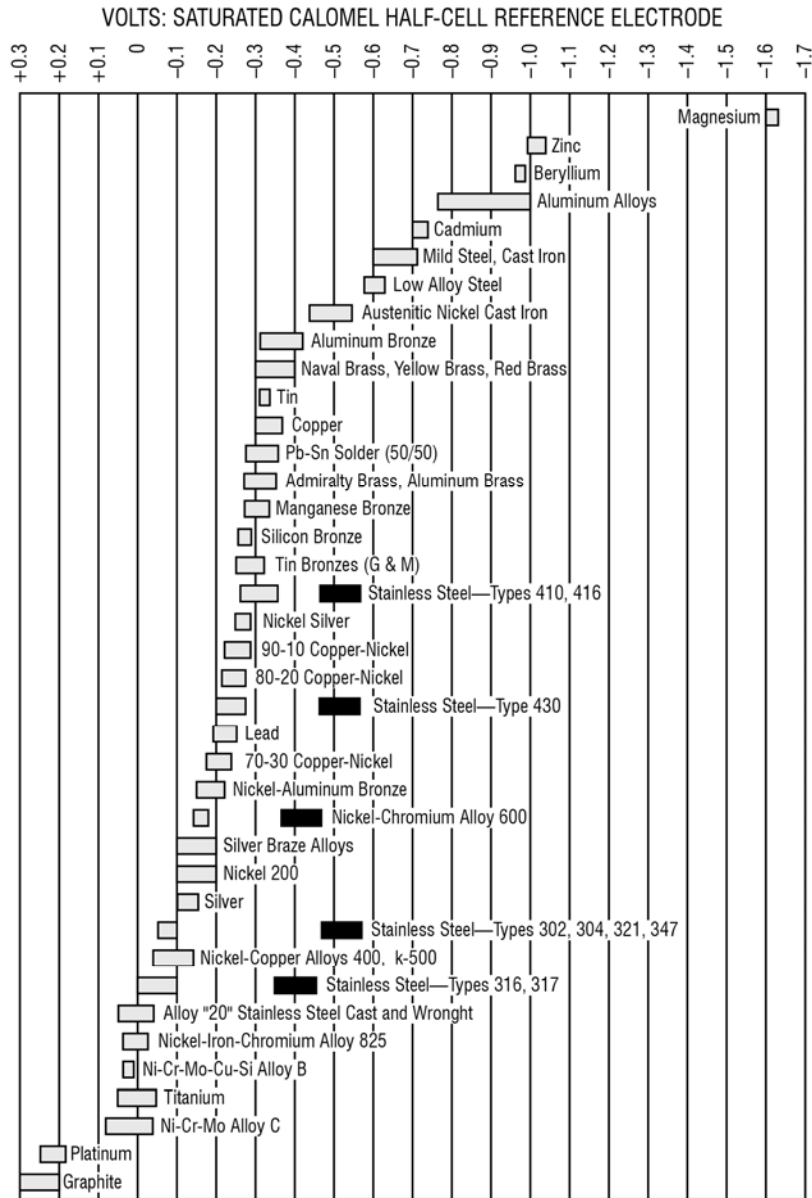
This section presents a discussion of key fabrication and construction practices that may influence corrosion of stainless steels.

Dissimilar Metals and Galvanic Corrosion

When two metals are connected to one another while immersed in an aqueous environment, an electric cell is created and galvanic corrosion can occur. The potential for this corrosion mechanism is expressed in terms of voltage. The corrosion potential (voltage value) of each metal is determined by comparing it to a known standard, such as platinum or a saturated calomel half cell (the other half being the alloy evaluated), all typically immersed in seawater. The metal with the highest voltage is the cathode (corrosion protected), while the other will become the sacrificial anode. This is why the copper fasteners in the great iron gates in Kyoto, Japan, have survived to

this day, while the iron nails in the copper hull of H.M.S. Alarm returned from her voyage from the West Indies in 1761 with most of her copper sheathing loose because of the iron nails holding the ship together had almost corrode away. Equipped with an understanding of this principle, design engineers are able to prevent much corrosion from occurring.

Figure 2.7 presents a ranking of different metals/alloys based upon their voltage potential when immersed in seawater (Tuthill et al. 1998). The metals/alloys presented in this figure may have some variances in their position to one another depending upon the immersed aqueous solution, but in general, the ranking in seawater is the standard ranking from which decisions are made (e.g., when to provide dielectric material separation, anodic or cathodic protection).



Source: Adapted from Tuthill et al. 1998

Figure 2.7 Corrosion potentials in seawater (8–13 ft/s, 50–80°F)

Note: alloys indicated by black boxes may exhibit a different potential in low-velocity or low-oxygen water.

With respect to the use of [Figure 2.7](#), the following guidelines should be considered:

1. The further apart the alloys are from one another in the table, the greater the driving force for galvanic corrosion.
2. The relative sizes of the anode and cathode are important. A small anodic area relative to the cathode (i.e., iron nails in copper hull of H.M.S. alarm) will corrode at a faster rate than an anodic area that is larger relative to the cathode (i.e., stainless steel fasteners in aluminum frame).
3. The ionic strength and electrical conductivity of a solution can also have an effect on the corrosion characteristics for the system (e.g., high concentration chloride solutions have high ionic strength and electrical conductivities relative to demineralized water solutions).
4. Galvanic corrosion cannot occur in the absence of an ionically conductive liquid environment, which is needed to complete the electrical circuit.
5. Protection of connections between dissimilar metals may be provided through the use of dielectric unions. Dielectric unions generally consist of a plastic liner that separates the two dissimilar metallic materials. These dielectric unions may include flange isolation kits that also contain isolators to make certain that the flange bolts are not contacting the dissimilar metals.

The various nickel chromium stainless steels can generally be coupled to one another without any serious galvanic effects. However, there are two important exceptions:

1. If Type 316L stainless steel is welded with Type 308L filler metal instead of Type 316L stainless steel, the weld metal will likely suffer severe localized corrosion.
2. Hard-facing overlays for rotating seal faces of marine tails shafts are other areas where close attention must be given to the position of the individual alloys with respect to one another.

Carbon, in the form of graphite containing gaskets, O-ring seals, packing and graphite-lubricated gaskets are very effective in initiating severe galvanic corrosion of stainless steels. Graphite in any form should never be used in contact with stainless steel.

Weld Fabrication

Improper welding techniques are a common cause of stainless steel corrosion. Corrosion associated with improper weld fabrication often occurs as a result of welding performed by welders with little experience in welding stainless steels. Even if welds are performed correctly, corrosion problems may follow as a result of improper control of and/or failure to remove heat tint from the heat affected area of the weld.

Welding Procedures and Welder Qualifications

To understand the importance of welder qualifications and following standard welding procedures, it is first important to understand the anatomy of a welded joint. As shown in

Figure 2.8, the material involved in a welded stainless steel joint comprises several main areas or components:

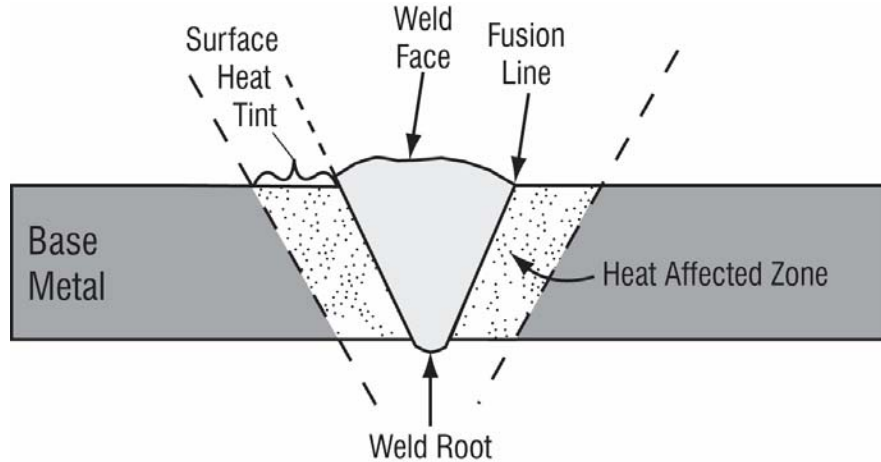


Figure 2.8 Weld Section

1. The Base Metal. This is the stainless steel (alloy) that will be joined to another stainless steel material by the welded joint.
2. The Fusion Line. This is where molten filler material solidifies at the base metal interface.
3. The Weld. This consists of molten base metal and filler material, if a welding process using a filler metal has been used. The filler metal is chosen based upon matching a chemistry, which provides the joint with comparable or better strength and/or corrosion resistance for that of the base metal. In some cases, an overalloyed filler metal may be used.
4. The Heat-Affected Zone (HAZ). This is the area of the base metal that is exposed to the heat from welding, but below the melting point. Surface heat tint (oxidation from the heat) may form in this area and, if not removed, can reduce the corrosion resistance.

Table 2.8 presents a summary of the consumable materials involved in a welded joint, including filler materials, electrode type, flux cored materials (for flux cored welding), and filler material to be used in welding stainless steel to carbon steel. Each consumable is selected based upon the type of stainless steel base material (alloy) that is being welded.

As discussed previously, employment of welders that lack the proper qualifications or experience can increase the likelihood of corrosion of welded stainless steel materials. These materials are more difficult to weld than lower grades of steel. Because a stainless steel weld is not as fluid as that for carbon steel under the welding arc, a stainless steel weld performed by an unqualified or inexperienced weld operator may not, in some instances, fully penetrate the weld joint, leaving an incomplete weld without a root pass. This is sometimes called a “paper weld.” It may result in pitting or MIC, especially where stagnant or slow moving water conditions exist. Welders unfamiliar with stainless steel techniques often fail to produce a fully penetrating root weld as a result of this lack of material fluidity.

Table 2.8
Welding consumables with base materials

	Base material (alloy)	Bare Wire	Welding electrode	Flux cored	Dissimilar welding with carbon steel
Austenitic	304L	ER308L	E308L-XX	304L	309L
	316L	ER316L	E316-XX	316L	
Lean duplex	2101, 2202 2304, 2003	ER2209	E2209-XX	E2209TO-X	E309MoL-XX
Duplex	2205	ER2209	E2209-XX	E2209TO-X	E309MoL-XX
Super austenitic	254SMO	ERNiCrMo-3* ERNiCrMo-13	ENiCrMo-3	NiCrMo-3	ERNiCrMo-3
	645SMO		ENiCrMo-13		ERNiCrMo-3
Superduplex	Alloy 2507 Zeron 100	Zeron 100	ER2594	E2595	

* Several other NiCrMo filler metals are also suitable. Consult manufacturer's data sheet

Even in cases where the material is welded from both sides in an attempt to produce a fully penetrated weld, if the root pass does not fully connect to the other (facing) weld, a separation inside the joint at the weld seam is left. This incomplete seam provides an ideal crevice. Should pitting or other crevice corrosion occur at and penetrate the weld seam, it can enable corrosion of the weld to further propagate. Both instances of improper weld fabrication demonstrate the need for qualified welders and weld quality control inspections. Welders should therefore receive training and certification through such organizations as the American Society of Mechanical Engineers (ASME; Section IX). Engineers specifying stainless steel fabrications should also require all field welds be checked for quality, until a statistically significant number of welds have been demonstrated as acceptable.

To control quality of a stainless steel weld, it is important that a welding procedure specification (WPS), along with requisite quality control testing (joint tests specification), be developed and followed for the joint or joints in question. Any welders working on these joints should be certified to this WPS. This qualification requirement is referred to as a "procedure qualification record" (PQR). When the WPS meets and passes the joint test specification criteria together with the PQR, both are referred to collectively as the "welder performance qualification" (WPQ; ASME 2012).

Pre-weld Fabrication

In preparation for a proper weld, there are a couple of steps that should be taken:

1. Mechanically clean or pickle the surface to be welded to remove the protective metal oxides and other surface discontinuities or imperfections. This may include grinding with iron-free abrasive wheels or rotary brushing using stainless steel heads. The stainless steel metal oxides have melting points above those of steel, which is why they need to be removed before welding. If these protective metal oxides remain on the surface of the metal to be welded, they have the tendency to become trapped in the solidifying molten weld metal. This diminishes the quality of the weld.
2. De-grease and chemically clean the surface that will be welded with a non-chlorinated solvent, such as acetone to remove grease, pencil marks, and general shop fabrication contamination. The grease and marking pencils may contain low melting point elements (e.g., sulfur, phosphorus) that will result in weld metal cracking.

Post Weld Fabrication

After welding has been completed, it is necessary to remove heat tint on the welded area. The heat tint is composed of a discolored layer that interferes with the reformation of the desired thin protective chromium oxide film, which provides the optimum corrosion resistance to the alloy surface. This type of post-weld cleaning is referred to as “pickling.” Pickling can be applied by brush using a pickling paste or gel, spraying using a pickling solution, or immersion in a pickling bath. The pastes or spray-on solutions are typically inorganic acids that are only effective at removing oxide scales in the absence of grease. The immersion technique is usually undertaken in a fabrication shop where the pickling solution is applied, neutralized (if required), and pressure sprayed with potable water. The clean parts can then be “passivated” in accordance with ASTM Standard A380 or Standard A967 before they are shipped for installation (ASTM 2013a and 2013b).³ Paste, gel, and spray pickling are usually done on site if field welding has been allowed by the engineer. In all cases, these surfaces should be thoroughly water washed or sprayed to remove excess pickling acid in order to prevent pitting attack by any excess acid left on the stainless steel part.⁴

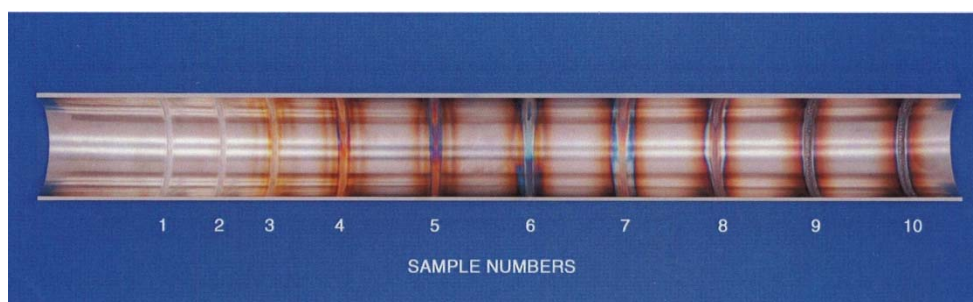
During the welding process, the molten weld needs to be protected from the atmosphere by inert gases, such as argon, helium, or argon/nitrogen on both the root and face of the weld. This becomes even more relevant when welding the higher alloyed materials, which require argon-helium gas mixtures for their protection. Dams, gates, and balloons can be used to trap and limit the loss of these protective gases in the root area of the weld while welding and completing the root pass. This is particularly useful for the larger pipe sizes (>12 inches), or for long runs of pipe being joined together. Duplex alloys require some important special considerations in welding. Manufacturers’ data sheets should be consulted.

³ Passivation, i.e., controlled oxidation and removal of iron contamination followed by the formation of a thin protective chromium oxide film, is discussed later in this chapter.

⁴ Pickling and passivation chemicals often require special environmental permits that are difficult to attain for field applications. Many stainless steel fabrication shops find it increasingly difficult to keep these permits as regulations and local jurisdictional requirements become increasingly stringent. Alternative, non-standard methods are frequently proposed and must be evaluated by an engineer. The effectiveness of these alternate methods is often not well documented. This subject requires additional research and will be discussed subsequently in this report.

Heat Tint

Control of heat tint is very important to maintaining the integrity of a piping system or tank, especially on the surfaces that are exposed to the process environment. Likewise, the smoothness of the root weld is important. Roughness produces areas that can lead to crevice corrosion or MIC when the flows are very slow or stagnant. The color of the heat tint indicates how impaired the component may be. As such, the design engineer should specify the protective gas chemistry to achieve a straw-colored tint for water applications (Figure 2.9). Chromium from the base metal will combine with the air or oxygen in the protective welding gases to form heat tint colors ranging from very light straw to blues and dark browns. A colored tint during welding indicates that the surface at the weld is losing chromium (and so will have reduced corrosion resistance). The presence of heat tint on welds indicates a susceptibility of stainless steel welds to corrosion attack.



Source: Figure reproduced from AWS D18.2:2009 with permission of the American Welding Society (AWS), Miami, Florida

Figure 2.9 Visual comparison guide for specifying weld discoloration criteria for sanitary welds in austenitic stainless steel tubes

Ten shades of heat tint are shown on mechanically polished Type 316L stainless steel in AWS specification D 18.2, where controlled oxygen additions were added to the purge gas (hydrogen-nitrogen) to produce the various shades of heat tint during welding. For potable waters, a number three (3) or four (4) level heat tint (straw color) with a maximum 50 mg/L oxygen contamination in the protective gases may prove acceptable for weld fabricated components. For saline water typical of desalination applications, a lower number is required to ensure adequate corrosion protection (Boulton and Avery 2004). This guide was intended to indicate what level of heat tint was acceptable if it could not be removed. However, it is best to maintain this maximum level of heat tint even if the heat tint will be removed afterwards, as not all removal techniques are fully effective.

A classic demonstration of the importance of heat tint removal (back to the base metal) for restoration of optimal corrosion resistance was reported by the University of Tennessee (Tuthill and Avery 1999). They performed polarization testing on welded Type 304 stainless steel samples using Type 308 welding wires. They allowed some samples to retain the heat tint due to welding and other samples to be cleaned free of scale, followed by the formation of a thin surface layer of oxidized chromium from the base metal. This cleaning and passivation was accomplished using rotating fiber brushes, pickling and electropolishing. The results showed that the material, clean and free of heat tint scale, exhibited the same passive/active corrosion characteristics as the base

metal, while the samples with heat tint exhibited corrosion at rates that exceeded that seen in the base metal.

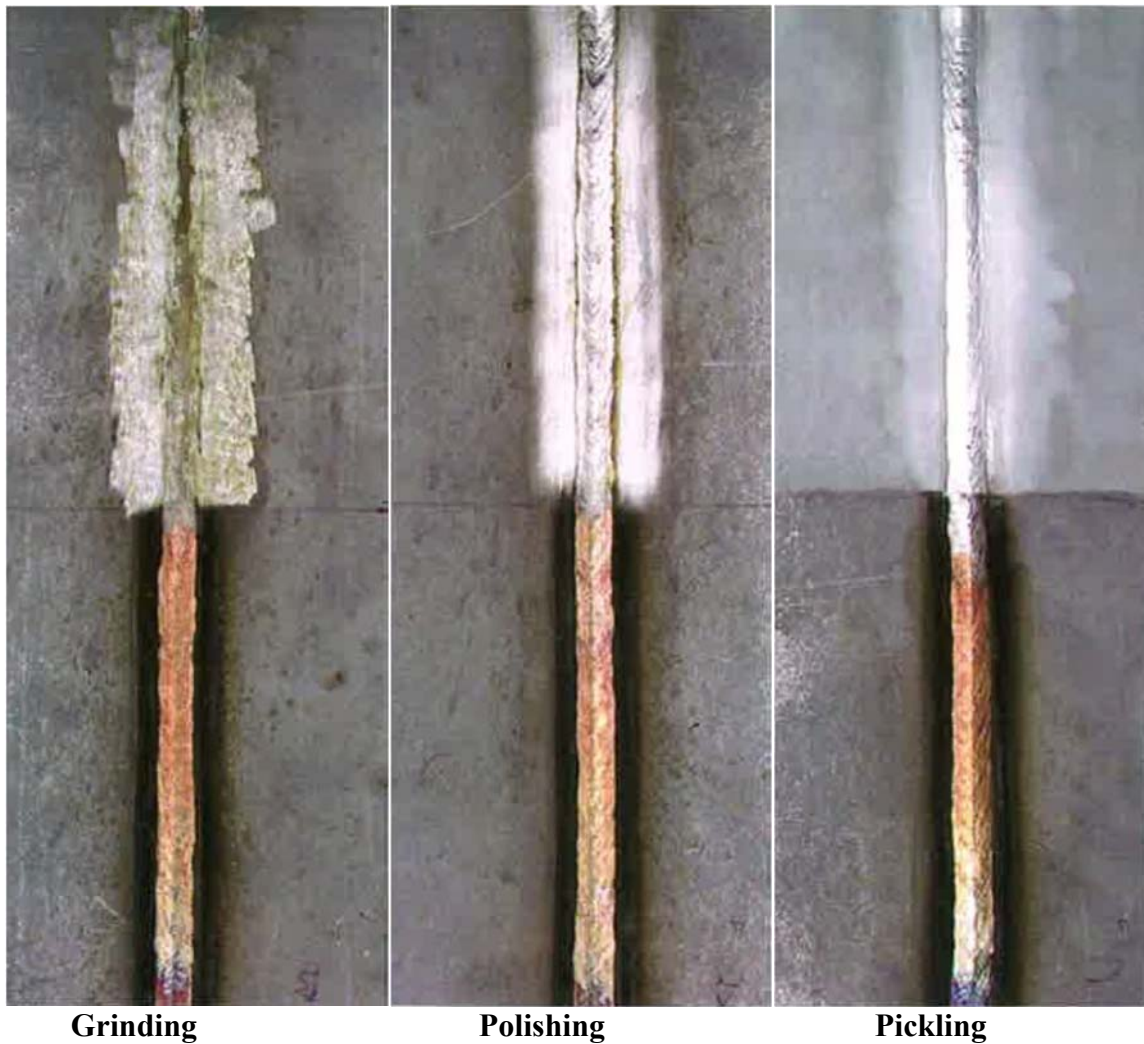
The greatest control over welding procedures are achieved in the fabrication shop, where all the tools are available to properly align pipe and feed inert gas to minimize heat tint formation. Post-weld heat tint removal is also best achieved in the fabrication shop, where piping spools can be fabricated and entire sections mechanically cleaned and pickled (chemically cleaned) in a 10 percent nitric–2 percent hydrofluoric acid bath as per ASTM A380 (ASTM 2013a), followed by a thorough water wash to rinse off the acid. The same controls are applied to the supply of fabricated straight lengths of longitudinally welded pipe, whether single welded or dual welded for heavier thickness.

Microbially Induced Corrosion at Weld Sites

In the presence of free chlorine, iron and manganese are oxidized to form ferrous and manganous hydroxides. These hydroxides precipitate on the of the pipe wall as a brown ferrous hydroxide film and black slimy films of manganous hydroxide. These films, by themselves, are not harmful to stainless steel. MIC can occur when they accumulate behind nodules or at discontinuities, caused by poor welding (incomplete root weld pass), or at heat tint areas adjacent to the weld where the loss of chromium from the metal surface due to poor welding gas coverage (heat affected zone – HAZ) has occurred. MIC is especially problematic in stagnant or slow moving water streams. Additional metal ions represent a food source for further colonization and growth. The free chlorine in solution supports continual oxidation of these metal ions and increased acidity within the cell, which results in pitting attack through the formation of ferric chloride and manganic chloride. Ferric chloride is a recognized pitting agent to the stainless steels.

Descaling

ASTM A380 refers to post weld mechanical cleaning (i.e., abrasive blasting, brushing, grinding, etc.) and pickling (i.e., chemical cleaning) as “descaling” (ASTM 2013a). Post weld descaling is important both from an aesthetic appearance and to ensure that the heat tint is removed. Removal of the scale (heat tint) allows the thin chromium oxide layer to be re-established for the corrosion protection of the stainless steel. Detailed cleaning guidelines and options can be found in ASTM A380. The choice of descaling method will depend upon type of contaminant to be removed, location, configuration of the part, and whether there is an aesthetic need for a particular appearance (Bornmyr 1995). For example, all weld spatter, arc strikes, and other surface contaminants should be removed by grinding smooth prior to pickling. Following pickling treatments, thorough jet spray washing with de-ionized water to remove the acids is critical to prevent further corrosion attack. Mechanical cleaning methods such as grinding, or use of flapper wheels and stainless steel brushes can be used prior to pickling (Figure 2.10).



Source: Bornmyr, A. 1995. *Handbook for Pickling and Cleaning of Stainless Steel*, 1st ed. Avesta, Sweden: AvestaPolarit Welding A.B.

Figure 2.10 Cleaning treatment comparisons

Passivation

Passivation is the further chemical treatment of stainless steel surfaces (where chromium predominates in the surface layers) to achieve increased ratios of chromium-to-iron in the protective oxide surface film. Passivation involves cleaning the surface of a stainless steel material with different concentrations of nitric acid or citric acid in buffer solutions to achieve a specific chromium-to-iron ratio with the oxide layer the metal's surface. Some of these treatments are described in the ASTM Specification A967 (ASTM 2013b). However, it should be noted that there is not full agreement on the terminology. To some individuals in the stainless steel industry, "passivation" is considered to include a chemically "controlled oxidation" step using an oxidizing acid. This facilitates the removal of iron surface contaminants. The chemical oxidation step is then followed by the formation of the protective chromium oxide film at the metal surface. Nitric acid

is an oxidizing acid, while citric acid is not. Therefore, it has been a point of contention within the industry as to the efficacy of citric acid as a chemical used for “passivation” as it does not control oxidation like nitric acid; it relies on oxygen from the atmosphere for formation of the chromium oxide film. By the “controlled oxidation” definition, treatment with citric acid to improve the integrity of the surface protective film is not truly “passivating.” Nevertheless, citric acid with buffers is an approved treatment for passivation by ASTM A967 (ASTM 2013b). Data, presented subsequently in this section demonstrates its efficacy. For the purposes of this report, “passivation” refers to cleaning with acid whether it is oxidizing or not (i.e., reformation of the chromium oxide film can be either passive or active chemical oxidation).

To show the difference between the acids used in passivation, a trial was run using 12 stainless steel 304L coupons. The coupons were ultrasonically cleaned, and divided into four equal sections. One of the groups of three samples was retained as the control sample (Ekstrand 2009). The other three groups were exposed to three different passivating treatments, as outlined in ASTM Standard Specification A967-99 (ASTM 2013b): 1) 30 percent nitric acid (minimum of 30 minutes in the temperature range of 79 to 90°F, or 26 to 32°C), 2) 10 percent citric acid (immersion 10 minutes in the temperature range of 120 to 140°F, or 49 to 60°C), and 3) 15 percent phosphoric acid (at room temperature for a 90-minute dwell time). All samples were allowed to dry and then placed in a desiccator for 72 hours. These were then analyzed using X-ray photoelectron spectroscopy to determine the chromium-to iron ratios in the outer surface oxide layer and also the chromium oxide--to-iron oxide ratios.

The results showed that all three acid treatments improved the chromium-iron ratios, as well as the oxide ratios. By inference, these treatments should be considered to offer improved corrosion resistance. In terms of ranking passivation efficiency, as presented in Table 2.9, the citric acid treatment was the most effective, followed by nitric acid, and then phosphoric acid. The citric acid treatment along with the use of other proprietary additions and buffering agents can be used to further enhance these chromium-iron ratios and hence achieve greater corrosion resistance.

Table 2.9
Acid treatments for the passivation of stainless steel to achieve favorable Cr/Fe ratios

Passivation treatment	Cr/Fe ratio	Cr ^{OX} /Fe ^{OX} ratio
Control	0.8 - 1	0.9 - 1.3
Nitric Acid	1.5	2 - 2.2
Citric acid	1.5 - 1.8	2.2 - 2.6
Phosphoric acid	1.2 - 1.4	1.5 - 1.9
Citric acid gel	1.7 - 2.1	2.5 - 3.2

Source: Ekstrand, B.J. 2009. *Comparison of Passivation Modalities – An Independent Analysis*. Costa Mesa, Calif.: AstroPak Corporation.

Note: Cr^{OX} and Fe^{OX} refer to chromium oxides and iron oxides, respectively.

Unlike citric acid, environmental permits are required to dispose of nitric acid passivation wastes. In this respect, the use of citric acid as a passivating chemical offers a distinct advantage. This is particularly true where passivation must be performed in the field; in the field, such a hazardous chemical use permit can be difficult or impossible to obtain. Even in the shop, many

stainless steel pipe fabricators are having an increasingly difficult time maintaining the required disposal permits to employ the nitric acid passivation treatment. Still, many in the industry view the “controlled oxidation” process that requires an oxidizing acid, like nitric acid, as critical to achieving adequate and true passivation. However, citric acid with buffers is a valid approach. It is an approved passivation treatment by ASTM (Specification A967; ASTM 2013b).

Auto-passivation is formation of chromium oxide at the metal surface by exposure to air or aerated waters after pickling (cleaning) to remove grease, oils, iron contaminants, and surface scale (heat tint). Generally, pickling followed by auto-passivation offers sufficient corrosion resistance for most potable and wastewater industry applications. However, desalination applications may require additional chemical treatment for passivation. The requirement for chemical passivation should be based on the specific application and environmental influences such as water chemistry parameters including: chloride, chlorine, pH and other variables already discussed. Chemical passivation is often a necessary final step for food process applications, and may apply to certain potable water applications too.

Surface Finishes

Electropolish and (iron-free) glass bead blasting are surface finishes that are sometimes applied to stainless steel pipes, vessels, and tanks. The application of these finishes certainly has an aesthetic value, but also provides a corrosion resistance benefit as these methods remove metal surface that may contain heat tint or iron impurities, change the depth and geometry of crevices, and provide a smoothness that makes it difficult for MIC bacteria to attach to the surface of the metal. Furthermore, the presence of a finished, smooth surface requires contractors to implement proper care when handling these materials or risk noticeably damaging the surface of the material. Neither electropolishing nor glass bead blasting should be confused with a mechanical polish, which can impart a near mirror-like finish to the metal. Both electropolish and glass bead blasting methods are considered more cost-effective alternatives to mechanical polishing for water treatment applications that remove a minimal amount of metal surface (typically 5 to 25 μm).

The following discussion presents some background information on both methods of surface finishing.

Electropolishing

Electropolishing is accomplished by submersion of stainless steel pipe, vessels, or tanks into an electropolishing bath. The bath size limits the size of material that may be treated at one time, thus requiring piping or vessels to be fabricated in multiple segments with joints that will not require further welding (i.e., flanged). Inside the bath, the polishing process is achieved electrically. The stainless steel surface is connected to a source of direct electric current (e.g., 12-V battery) and becomes the anode, while a copper wand or cleaning piece conforming to the shape to be cleaned (e.g., an angle section) becomes the cathode. The electropolishing bath solution is typically oxalic acid, acetic acid, or phosphoric acid, which is wiped on to the surface to be cleaned using the wand with a saturated rag wrapped around it.

More sophisticated electropolishing systems are commercially available. These systems polish the internal surfaces to provide a clean and smooth surface profile. Such techniques are commonly used in the electronic, pharmaceutical and food industries.

While the outsides of stainless steel parts are easily treated by an electropolishing electrode, interior treatment requires special procedures, including an electrode that will not deflect, touch

and damage the pipe or vessel wall. Therefore, only certain electropolishing shops are capable of treating long segments of interior stainless steel piping, which may provide a critical benefit at preventing crevice or MIC corrosion depending upon the application.

ASTM B912 presents a standard method for electropolishing of stainless steel (ASTM 2013b). This method should be preceded by the cleaning methods described previously in this document (i.e., ASTM A380; ASTM 2013a). For desalination applications, this method should be followed by chemical passivation using a 10 to 30 percent nitric acid solution in accordance with ASTM A967 (ASTM 2013b). For general water treatment applications, depending upon the water chemistry and environmental conditions that include chloride, chlorine, and microbiological concentrations, auto-passivation following the electropolishing process may be acceptable.

Sand, Grit, and Glass Bead Blasting (Peening)

Sand and grit blasting (peening) can be used to remove heat tint surface oxide and iron contamination. However, care must be taken to ensure that the blasting medium is totally free of iron particles and has not been used previously on carbon steel. Using low blasting pressures and small angle approach, a satisfactory surface finish can be accomplished since surface roughness is the limiting factor for a quality, desired finish.

Glass bead blasting (peening) is another method sometimes employed to provide surface finish to large stainless steel components that may not otherwise be electropolished, due to their shape and size. Similar to sand and grit blasting, this procedure involves spraying iron-free glass beads at the metal surface. The beads remove material from the surface of the metal and create a smooth, matte finish. Along with achieving this surface finish, the bead blasting procedure introduces compressive stresses, which improves the stress corrosion resistance and fatigue resistance of the stainless steel.

As with electropolishing, these peening methods should be preceded by cleaning using methods described previously in this document (i.e., ASTM A380; (ASTM 2013a). For desalination applications, this method should be followed by chemical passivation using a 10 to 30 percent nitric acid solution in accordance with ASTM A967 (ASTM 2013b). For general water treatment applications, depending upon the water chemistry and environmental conditions that include chloride, chlorine and microbiological concentrations, auto-passivation following the electropolishing process may be acceptable.

MATERIAL HANDLING AFTER FABRICATION AND DURING INSTALLATION

Once surfaces have been cleaned, chemically passivated or otherwise finished, and the stainless steel is ready for shipment and installation, the materials should be protected during handling to minimize surface damage. Steps that can be taken during shipment and installation to prevent damage and iron surface contamination include:

1. Covering stainless steel parts in foam and plastic wrapping.
2. Sealing (capping) and protecting pipe ends, including flanges from damage using wood and plastic fasteners.
3. Shipping the parts on wooden pallets with metal-free separations between any pallet nails and the piping (e.g., foam/plastic wrap of piping).
4. Prohibition of the storage of stainless steel components directly on the ground, especially on dirt, concrete and other hard, coarse surfaces. Use wooden pallets.

5. Prohibition of stacking and storing material around areas of construction where welding is being undertaken, so that molten weld metal cannot fall or become wind-blown to contaminate the clean surfaces of the stainless steel below. This type of contamination can ultimately result in iron staining.
6. Prohibition of walking on stored or stacked pipe.
7. Prohibition of lifting of stainless steel equipment with metal chains. Lift only with nylon straps strong enough to support the weight of the equipment.

STOCK MATERIALS AND FABRICATION OF STAINLESS STEEL PARTS

Cylindrical Components

Stainless steel-containing parts used within the water industry come in a variety of shapes and sizes. These may include castings, piping, tanks, pumps, valves, bolts and fasteners, to name a few finished components,

Cylindrical stainless steel products, equal or smaller than 16-inch diameter, start from a continuous coil of strip or sheet, which has been rolled to size, slit to finished width, prior to being formed and welded into pipe/tubing. The finished, welded product can be available in coil or as cut to length.

For sizes larger than 16-inch diameter, plate material up to 96-inch x 240-inch can be press rolled into segments for welding. [Figure 2.11](#) is an example of a rolled and welded construction (Type 316/316L, 120-inch diameter piping for handling ozone treated water).

Cylindrical Component-Piping

The common grades of 300 stainless steel can be ordered in one of three ways:

1. ASTM A778 allows welding with and without filler metal and has rather minimal testing requirements (ASTM 2009). When ordering to these requirements, it is suggested that the purchase order should request pickling after welding.
2. Series 300 welded pipe can be ordered to ASTM A312, which does not permit filler material to be used, except for repair welds (ASTM 2015b). ASTM A312 pipe may also require post weld annealing (i.e., limited to non-low carbon materials or high temperature applications). It is considered to be a better product for more aggressive environments. It covers seamless pipe, which can be used but is a more expensive product than welded pipe. There are applications where the seamless product can be superior to the welded product.
3. For heavy wall pipe where filler material is needed to make a proper through wall joint, ASTM A358 is used (ASTM 2014e). This specification offers many options related to heat treatments, welding, and testing.

Duplex stainless steels are not covered by the above specifications. ASTM A790 is the approximate equivalent to ASTM A312 and ASTM A928 is the approximate equivalent of ASTM A358 (ASTM 2010b, 2015b, and 2014e, respectively). There is not a duplex stainless steel equivalent for ASTM A778 (ASTM 2009).



Figure 2.11 120-inch diameter stainless steel piping (Vancouver, British Columbia) made from plate material

Fittings and Flanges

The specification for pipe fittings (elbows, tees, reducers, stub ends etc.) to match the A778 unannealed pipe is A774, which again has minimal testing requirements (ASTM 2009 and 2006, respectively). The specification for annealed pipe fittings is ASTM A403, which has many different options related to how the fitting is made and tested (ASTM 2014f). The equivalent duplex stainless steel fitting specification is ASTM A815 (ASTM 2014g).

Forged Fittings and Flanges, Both 300 Series and Duplex Alloys, are Covered in ASTM A182 Cast Shapes

Stainless steel castings allow the construction of complex shapes. With the most common stainless steel grades, the difference in corrosion resistance between the wrought and cast products is small. There are stainless steel casting equivalents to the austenitic, duplex, superduplex and super austenitic series of alloys. In addition, there are also two independent classes of castings: Ni-Resist and Ni-Hard. Both are used in the formation of pump and valve bodies, piston ring inserts, pump impellers, and associated cast equipment. The former class (Ni-Resist) is used for parts that will handle seawater and salt solutions and the latter class (Ni-Hard) is used for parts that will handle erosion slurries (Nickel Development Institute 1996 & 1998).

Table 2.10
Cast equivalents of wrought stainless steel counterparts

Cast Alloy	UNS# ¹	C	Mn	S	Si	Cr	Ni	Other
<u>AUSTENITIC</u>								
304	CF8	0.03	1.50	0.40	2.00	17.0 - 21.0	8.0 - 12.0	-
316	CF8M	0.03	1.50	0.40	2.00	17.0 - 21.0	8.0 - 12.0	-
304L	CF3	0.03	1.50	0.40	1.50	17.0 - 21.0	9.0 - 13.0	2.0 - 3.0
316L	CF3M	0.03	1.50	0.40	1.50	17.0 - 21.0	9.0 - 13.0	2.0 - 3.0
<u>DUPLEX</u>								
2205	CD3MN	0.03	1.50	0.020	1.00	21.0 - 23.5	4.5 - 6.5	0.10 - 0.30 N 2, 5 - 3.5 Mo 1.00 Cu
<u>SUPERDUPLEX</u>								
FERRALIUM 255	CD4MCu	0.04	1.00	0.04	1.00	24.5 - 26.5	4.75 - 6.0	1.75 - 2.25 Mo 2.75 - 3.25 Cu
ZERON 100	CD3MWCuN	0.03	1.00	0.025	1.00	24.0 - 26.0	6.5 - 8.5	0.20 - 0.30 N 3.0 - 4.0 Mo 0.50 - 1.00 Cu 0.5 - 1.0 W
2507	CE3MN	0.03	1.50	0.04	1.00	24.0 - 26.0	6.0 - 8.0	0.10 - 0.30 N 4.0 - 5.0 Mo
<u>SUPER-AUTENITIC</u>								
AL6XN	CD3MN	0.03	1.50	0.020	1.00	21.0 - 23.5	4.5 - 6.5	0.10 - 0.30 N 2.5-3.5 Mo 1.0 Cu
254SMO	CK3MCuN	0.025	1.20	0.010	1.00	19.5-20.5	17.5- 19.5	0.18-0.24 N 6.0-7.0 Mo 0.5-10 Cu'

Source: Data taken from Nickel Development Institute, 2001, Publication N° 11022.

Notes: UNS = Unified Numbering System

In a desalination plant, butterfly and check valve bodies are made from cast materials while the inner components are made from both cast and rod shapes. In the case of the Tampa Bay Desalination Plant:

The low-pressure butterfly valves (less than 120 psi) were specified to be EPDM-lined ductile cast iron, Type 316 stainless steel (grade CF8M), cast duplex stainless steel, and 6 percent molybdenum super-austenitic bodies. A metal butterfly disc was specified in nickel aluminum bronze for valve sizes up to 36 inches in diameter.

The high-pressure butterfly valves (>150 psi) were specified as austenitic stainless (type 316L stainless steel, grade CF3M) and austenitic-ferritic materials only, with Type 316L stainless (grade CF3M) being the lowest grade permitted.

In the case of the high performance swing check valve bodies, the same cast materials were allowed as for the butterfly valves.

Rod and Bar Shapes

Stainless steel rod and bar shapes are used in water treatment plants in parts that include pump shafts, fasteners, cables, chains, belt links and trash bars. These are made from a variety of stainless steel types, which are selected to match their need for corrosion resistance, strength, and/or ease of fabrication and machinability.

Rod and bar products are made from ingots that can be forged, extruded (like toothpaste), and drawn to final shapes (rounds, hexagon and other configurations). These preliminary rod and bar shapes can then be further fabricated into finished products. These shapes may need to be further machined to form grooves, such as those used to joint long pump shafts and fasteners. It is preferred to roll these grooves as opposed to cutting them since the metallurgical structure of the bolt is maintained rather than being machine cut across the grain structure of the bar, which can sometimes lead to thread burrs and other imperfections. This may not be practical in all cases, such as those involving pump or valve shafts but is quite practical for fasteners.

Figure 2.12 shows a selection of stainless steels graded by their relative strength and corrosion characteristics. The 400 series stainless steels offer good machinability properties at the expense of some ductility and formability, and relatively low corrosion resistance. There are also some special grades of stainless steel rod and bar shapes that are modified by the addition of nitrogen and/or manganese during the reforming process to maintain an austenitic structure. Nitrogen also contributes to the strength for these special stainless steels.

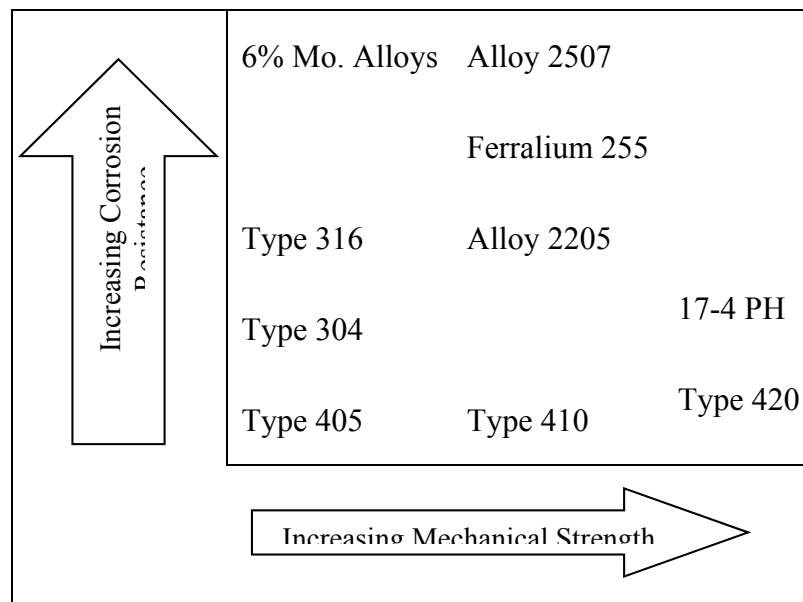


Figure 2.12 Corrosion resistance and mechanical strength of stainless steel rod and bar shapes

For rod products that have to withstand rotational loadings, such as in propeller shafts and pump shafts, corrosion fatigue properties are important. These materials also have to be capable of being machined and ground to tight tolerances matching those of bearings. The austenitic alloys have the best ductility, but the duplex and superduplex alloys offer higher strength and the same excellent corrosion resistance. Where high strength and moderate corrosion resistance (about the same as 304) is needed, the 17-4 PH alloy which can be heat-treated to varying strength levels should be considered.

Fasteners

Because of their diverse utility, fasteners are the most commonly used rod and bar shape in any water treatment plant. There is a variety of stainless steel fasteners used in any single water treatment plant application, ranging from Type 410 stainless steel (preferred for its strength) through to Type 316 stainless steel and 6 percent molybdenum bearing super-austenitic and the duplex alloys (preferred for their corrosion resistance). Inevitably, there are mix-ups in bolts for different flanges. The one or two misplaced bolts might corrode (e.g., 410 steel) while the rest remain comparatively uncorroded. These are obviously out of place with respect to the rest of the specified connection. To avoid these problems engineers and treatment plant managers and operators need to understand what makes a stainless steel bolt successful and how to select the appropriate bolts for different applications. To provide this understanding, the following information should be considered:

Stainless steel fasteners should be specified in accordance with ASTM F593 for bolts and ASTM F594 for nuts (ASTM 2013d and 2009b, respectively). These specifications cover Type 316 or 316L bolts in the cold worked condition and XM1 high manganese austenitic stainless steel nuts (5 to 8 percent manganese content). When forming the grooves for the bolt thread in the rod shape, a rolled groove is preferred to a cut groove so as to avoid burrs that may lead to crevice corrosion and/or galling.

The parallel standards ASTM A193 and ASTM A194 are for high temperature service applications (ASTM 2014a and 2014b, respectively). In these standards, the B8 class of bolting materials includes the austenitic grades of materials, with 316 stainless steel grades being classified as B8M series for both the nuts and bolts. However, nuts with high silicon-manganese content (7 to 9 percent manganese; 3.5 to 5 percent silicon) are classified as B8S, which have been used because of their ability to minimize galling when paired with other grades of austenitic stainless steel bolts.

Type 303 (sulfur) or 303 Se (selenium) rod shapes should not be considered as bolting materials for water service, despite their machining grade capabilities, due to their susceptibility to end-grain attack where the face of the rolled bar is cut. Stringers of sulfides or selenides are exposed and can result in pitting corrosion.

Type 316 stainless steel appears to be the standard fastener (nut and bolt) used in many potable and wastewater treatment plants, both for ductile cast iron flange connections and for stainless steel flanges, the sizes of which are covered by AWWA Standard C228 up through 72-inch diameters. Larger sizes are available, although the flange design is not covered by an industry standard. Standardization on one bolt alloy for multi-alloy connections is very practical, cost-effective, and avoids any misuse, especially during periods of downtime or maintenance. Technically, there is a benefit to the austenitic, super-austenitic and duplex bolting materials when the environment is aqueous. These are cathodic (corrosion protected) relative to a large number of

standard metallic flanges. Galvanic corrosion can be prevented by using dielectric insulating sleeves with the bolt and gaskets.

Stainless steel bolt materials are recognized for their galling characteristics, so some basic considerations in selection and pre-installation are appropriate (Lamb 1999).

1. Bolts should be inspected, cleaned and any burrs or other imperfections removed by light sanding. This will minimize the effects of galling. Additionally, roll threaded bolts are preferred over machine-threaded bolts; this will help retain the metallurgical structure of the bolt and reduce thread imperfections.
2. Consider the use of hardened washers to improve consistency in the bolt torque and pre-load relationship (e.g., silicon grade B8S stainless steel nuts with B8M grade stainless steel bolts). This difference in hardness assists in mitigating galling effects by facilitating a uniform load when tightening. A softer washer, such as aluminum bronze (different hardness between washer and bolt) will also help in reducing galling, but design care must be taken with the possible galvanic effect from the combination of different materials.
3. Ensure the bolting assembly is properly aligned, especially during installation. In the case of flanged joints, tighten using a cross bolting pattern.
4. The use of anti-seize lubricants will help reduce the tendency for materials to gall. Although molybdenum sulfide may be acceptable in many applications, this lubricant cannot be considered for water industry applications. ‘Never-seize’ or Teflon coatings can be considered. However, in all cases, the tensioning and torquing will be different from those of non-lubricated bolting connections.
5. Tightening and torquing should be undertaken at uniform rates. Torquing wrenches are available and should be used. They should be held perpendicular to the axis of the bolt to prevent galling.

CORROSION RESISTANCE TESTING METHODS

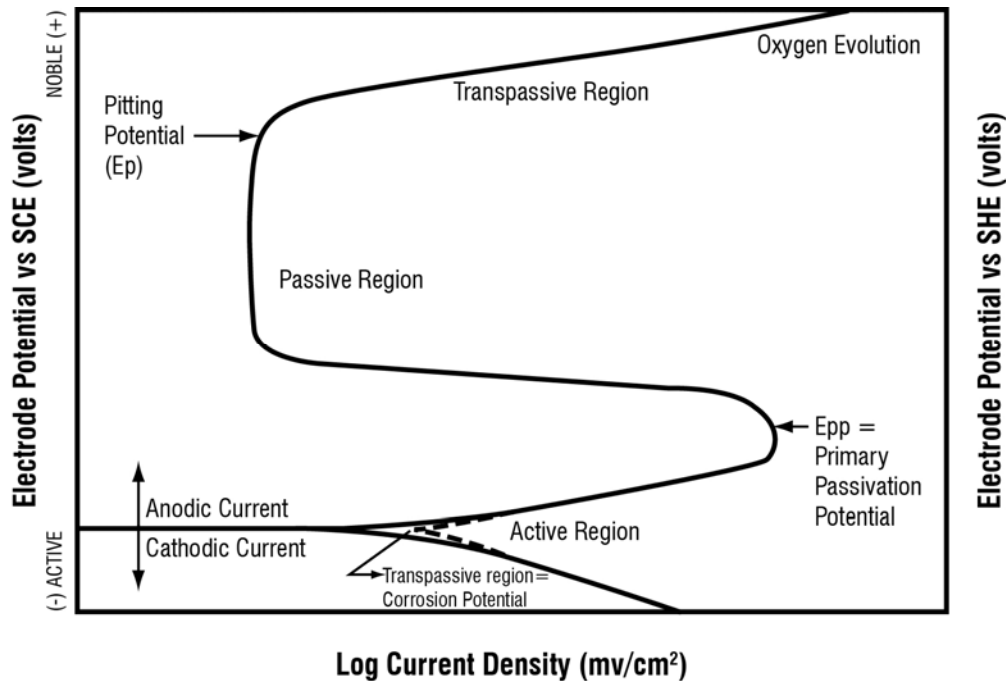
There are a number of testing methods used by engineers and material scientists to evaluate corrosion resistance of stainless steel materials. These methods primarily include immersion testing and potentiostatic methods. Of these methods, this document will focus on the potentiostatic method because these tests are performed quickly and have been demonstrated to have similar results to immersion tests that may require months or years to perform.

Potentiostatic Techniques

Most corrosion processes are electrochemical in nature and electrochemical tests have provided accelerated guidelines with regard to how metals will interact with specific aqueous environments. This provides the corrosion/design engineer with a tool to define the upper limits of performance for alloys in specific environments. For this project, we have attempted to define the upper application limits for the austenitic and duplex stainless steels exposed to chlorinated and oxidizing environments so that the correct, cost-effective materials can be selected for optimum performance (see Morris and Scarberry 1970).

The standard apparatus and assembly is outlined in ASTM G5 (ASTM, 2013f). A TFE-fluorocarbon compression gasket is placed in a holder and placed against the test specimen. The

assembly is then tightened with a mounting nut. The specimens are cleaned in accordance with test protocols. A reference electrode is added, which was a saturated calomel electrode is added. Following the specified procedures, a potential scan is run for 55-minutes and records the open circuit potential (OCP), known as the corrosion potential. Then start the potential scan, increasing the potential at a step rate of 50 mV every 5 minutes for 1 hour. The results are recorded on semi-logarithmic paper to develop the curve of voltage (V) against log current (log i). Depending upon the environment and the alloy being evaluated, there should be both active and passive corrosion regions in the resulting anodic curve (Figure 2.13).



Source: Adapted from Mameng and Pettersson 2011

Figure 2.13 Laboratory potentiostatic anodic polarization curve

The same assembly set up can be used for determining Electrochemical Critical Pitting Temperature Testing of Stainless Steels – ASTM Test G150-99. The samples, however, are prepared from 1-mm thick sheets that have a hole drilled at their center to allow attachment of the multi-crevice assembly. The Delrin multicrevice assembly holder contains 20 plateau and 20 grooves on one side of the specimen. The multicrevice assembly is manually tightened and placed in the potentiostatic assembly per ASTM G78 (ASTM 2008). Each plateau in contact with the metal surface is a site for a possible site of initiation for crevice corrosion.

The rapid scan potentiostatic technique allows for a drastic increase in the potential scan rate and enables primary passive potentials and anodic critical current densities to be measured before the specimens reaches a steady state. The shape of the anodic curve, typical of stainless steels, is in the form of an ‘S’, the inside of which yields a passive region with relatively no corrosion (see Figure 2.13). Outside of this passive region, corrosion will occur below the anodic curve and pitting will occur above the curve, ultimately leading to crevice corrosion attack. These regions are defined as the active, passive, and transpassive regions. The corrosion potential is that

point where the anodic and cathodic curves are projected as straight lines and intersect. By changing the shape of the anodic or cathodic curves using impressed currents, this anodic curved relationship becomes the basis for the design of anodic or cathodic protection of metal systems.

In recent potentiostatic research undertaken at the University of Sheffield, the upper limits for Types 304 and 316 stainless steel were evaluated when exposed to chlorides ranging from 200 to 2,000 mg/L, with and without 2 to 10 mg/L free chlorine, at 20°C (68°F), covering the pH range of 6 to 8 (Velpulanont et al. 2012). The guidelines set by the U.S. Environmental Protection Agency (EPA) limit the free chlorine levels to be 4 mg/L for drinking water (EPA 1989).

SUMMARY AND RECOMMENDATIONS FOR SELECTING STAINLESS MATERIALS

The overview presented in this section represents an approach to decision making with materials of construction, using several analytical approaches. The approach presented is based upon a material ranking system that accounts for the alloy's chemical composition using PREN. The PREN ranking correlates the various stainless steel alloys to one another when tested using the accelerated chemical testing in acidic, oxidizing ferric chloride solution, as defined in ASTM G48 "Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by the Use of Ferric Chloride Solution." Essentially, this test method determines the relative resistance to pitting and crevice corrosion for stainless steel materials when exposed to aggressive chloride environments.

Austenitic stainless steels and duplex stainless steels with similar PREN will have similar overall corrosion pitting resistance. This allows the design engineer a method for selecting grades of stainless steel that will meet his operating environments; e.g., refer to [Table 2.7](#) for handling brackish water environments (10,000 to 20,000 mg/L chlorides), the PREN to be met was determined to be >40 PREN and material selection was limited to the super-austenitic and superduplex alloys. The more aggressive the environment (i.e., higher concentrations of chlorides and free chlorine), the more conservative the engineer may want to be with the material selection by moving to a higher PREN value alloy. The material ranking allows the engineer to make a more informed material selection regarding the alloy's upper boundary of performance.

For potable waters (typically at pH 5 to 8), initial crevice corrosion testing could be undertaken in the field or in the laboratory using simple immersion techniques. However, simple immersion test techniques proved time consuming, which then led to the development of the accelerated immersion testing in ferric chloride and the development of testing protocols as outlined in ASTM G48. Later, rapid scan polarization testing methods were developed, which provided a corrosion chart from which corrosion characteristics for an alloy exposed to a specific solution could be determined. From this chart, engineers and metallurgists can determine the active and passive corrosion regions and determine the optimum upper limits of operation before pitting occurs on the alloy. The 300 series stainless steels and some duplex alloys have been tested using these techniques when exposed to specific environments, such as for exposure to chlorides, and the synergistic relationship between exposure to chloride in conjunction with free chlorine.

Thought should be given to evaluating the synergistic effects of chlorides and chlorine on the 300 series of austenitic and duplex stainless steel in the saline solutions (i.e., steel that comes into contact with high chloride and/or free chlorine solutions) typical of those being handled by desalination plants.

The alloys 304/304L, 316/316L, duplex and the lean grades of superduplex stainless steel (e.g., Ferralium 255) have acceptable corrosion resistance for when exposed to the EPA maximum chloride and chlorine concentrations. This work was based upon 30-day leaching (immersion) rates and means that all the 300 series austenitic and duplex alloys can be used for treated drinking water purposes without concern for pitting or crevice corrosion. However, it is important to note that none of these tests included an evaluation of elevated temperatures commonly seen in heat exchanger applications using potable water. Therefore, the industry would benefit from further testing which should include both elevated temperatures and higher chloride concentrations, typically seen in brackish and seawater applications.

The welds for the duplex stainless steel do not have the same quality of corrosion resistance as compared to their base metal PREN. The corrosion resistance of austenitic welds are comparable to that of their base metal equivalents.

Potentiodynamic polarization resistance provides critical current densities for stainless steels immersed in specific chlorinated solutions. This allows a determination of crevice corrosion and or pitting performance within an hour, for the designed/specific environment tested. Here, specific chloride and free chlorine concentrations can be rapidly analyzed, which could be specific to the environment typical for a desalination treatment plant. Two recent papers (Mameng and Pettersson 2011; Vepulanont et al. 2012) have attempted to delineate the outer boundaries (maximum chlorinated aqueous conditions) for the individual austenitic stainless steel and the duplex stainless steel materials exposed to various chloride/chlorine environments. The advantage to this corrosion testing technique is that the alloy sample can be exposed to the specific environment in which the alloy will operate and performance can quickly be evaluated.

The key issue for engineers to consider when selecting a stainless steel is to define the various environments that will exist in different areas of the process piping systems (e.g., chlorides, pH, free chlorine in solution, bacteria). Seawater or brackish waters will enter the plant, while purified water and heavily saline waters will exit the plant for storage/distribution or disposal, respectfully. This will demand a wide range of stainless steel alloys and castings for construction and material specification.

COMMON STANDARDS USED IN THE SELECTION AND SPECIFICATION OF STAINLESS STEEL

Table 2.11
AWWA Stainless Steel Standards

Standard	Description
C220	Stainless-Steel Pipe ½-inch (13 mm) and Larger
C221	Fabricated Steel Mechanical Slip-Type Expansion Joints
C223	Fabricated Steel and Stainless Steel Tapping Sleeves
C226	Stainless-Steel Fittings for Waterworks Service, Sizes ½-inch – 72-inch (13 mm – 1,800 mm)
C227	Bolted, Split Sleeved Restrained and Non-restrained Couplings for Plain End Pipe
C228	Stainless Steel Pipe Flanges for Water Service, Sizes 2-inch – 72-inch (50 mm – 1,800 mm)
C230	Stainless Steel Full Encirclement Repair and Service Connection Clamps

Source: Data from American Water Works Association, 6666 W. Quincy Avenue, Denver, Colorado 80235

Table 2.12**ASTM Important Standard Stainless Steel References**

Testing Specifications	<p>G3 – Conventions Applicable to Electrochemical in Corrosion Testing</p> <p>G5 – Standard Reference Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements</p> <p>G48 – Pitting and Crevice Corrosion of Stainless Steels and Related Alloys by the Use of Ferric Chloride Solution</p> <p>G51 – pH of Soil for Use in Corrosion Testing</p> <p>G59 – Method for Conducting Potentiodynamic Polarization Resistance Measurements</p> <p>G78 – Crevice Corrosion Testing of Iron-Base and Nickel-Base Stainless Alloys in Seawater and Other Chloride-Containing Aqueous Environments</p> <p>G150 – Electrochemical Critical Pitting Temperature Testing of Stainless Steels</p>
Material Specifications	<p>A182 – Forged or Rolled Alloy and Stainless Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service</p> <p>A240 – Chromium and Chromium-Nickel Stainless Steel Plate, Sheet and Strip for Pressure Vessels and for General Applications</p> <p>A312 – Seamless and Welded Austenitic Stainless Steel Pipes</p> <p>A358 – Electric-Fusion-Welded Austenitic Chromium-Nickel Stainless Steel Pipe for High-Temperature Service and General Applications</p> <p>A403 – Wrought Austenitic Stainless Steel Piping Fittings</p> <p>A774 – As-Welded Wrought Austenitic Stainless Steel Fittings for General Corrosive Service at Low and Moderate Temperatures</p> <p>A778 – Welded, Unannealed Austenitic Stainless Steel tubular Products</p> <p>A790/790M – Seamless and Welded Ferritic/Austenitic Stainless Steel Pipe</p> <p>A813 – Single or Double Welded Austenitic Stainless Steel Pipe</p> <p>A815 – Wrought Ferritic, Ferritic/Austenitic, and Martensitic Stainless Steel Piping Fittings</p> <p>A928 – Ferritic/Austenitic (Duplex) Stainless Steel Pipe Electric Fusion Welded with Addition of Filler Metal</p> <p>F593 – Stainless Steel Bolts, Hex Cap Screws, and Studs</p> <p>F594 – Stainless Steel Nuts</p>
Material Finishes	<p>A380 – Cleaning, Descaling and Passivation of Stainless Steel Parts, Equipment and Systems</p> <p>A967 – Chemical Passivation Treatments for Stainless Steel Parts</p>

Source: data from ASTM International, 100 Barr Harbor Drive P.O. Box C700, West Conshohoken PA.19428-2959.

CHAPTER 3

UTILITY AND FABRICATOR EXPERIENCES WITH STAINLESS STEEL CORROSION

In an effort to understand what stainless steel corrosion problems are prevalent in the drinking water industry, information was collected from water agencies and industrial manufacturers based on their own experiences. This data was used to determine where more emphasis should be placed in the guidelines (Chapter 5). This exercise included conducting utility and stainless steel fabricator surveys and reviewing corrosion reports. The results are summarized here.

PART 1 – SURVEY OF UTILITY EXPERIENCES WITH STAINLESS STEEL CORROSION

A survey of water utilities was performed. The survey data collected helps to compare facilities that have corrosion problems based on their water quality parameters, type(s) of oxidants used, and stainless steel type.

Survey Methodology

An eight-question utility survey was prepared (provided in Appendix A). The survey was structured to cover three critical topics: 1) Do you have stainless steel corrosion problems?, 2) If so, what kinds of problems do you see?, and 3) What type of water quality do you have? Some questions were multi-part. Extent of response depended upon the answers provided to the previous portions of the question. As shorter surveys generally have better response rates, the survey was intentionally kept brief to allow completion in ten minutes. Portions of the survey allowed for more open-ended responses should the participant wish to provide more information.

The survey was posted on Survey Monkey in March 2013 and potential respondents were contacted via email that same month. The survey closed in July 2013. The respondent group consisted of water utility contacts from agencies in the United States that the Research Team knew had stainless steel equipment and potentially challenging water quality.

The utility survey was sent to over 700 utility representatives from 151 agencies. Utility contacts included engineering managers, lead operators, and facility managers. In some cases, multiple individuals were contacted at an agency in an effort to improve the response rate.

This survey effort demonstrates the difficulty of obtaining good survey data using a passive survey instrument. At the close of the survey, a total of 25 utility responses were received. In terms of total number of agencies contacted, this translates into response rate of 16 percent. Most responses were received from California and Florida, with a few from three other states. One international response (from the Middle East) was also received. As expected, the majority of responses were from utilities using high total dissolved solids (TDS) or high hardness groundwater (Figure 3.2).

Utility Survey Results

Figure 3.1 presents the distribution of survey respondents based on their location. The overwhelming majority of respondents, 84 percent, were from either Florida or California—the states that contain the majority of desalination facilities in the United States.

The distribution of source water types reported by the responding utilities is presented in Figure 3.2. The majority of respondents treat groundwater in their facilities. Of these facilities, 28 percent are softening fresh groundwater and 24 percent are treating brackish groundwater.

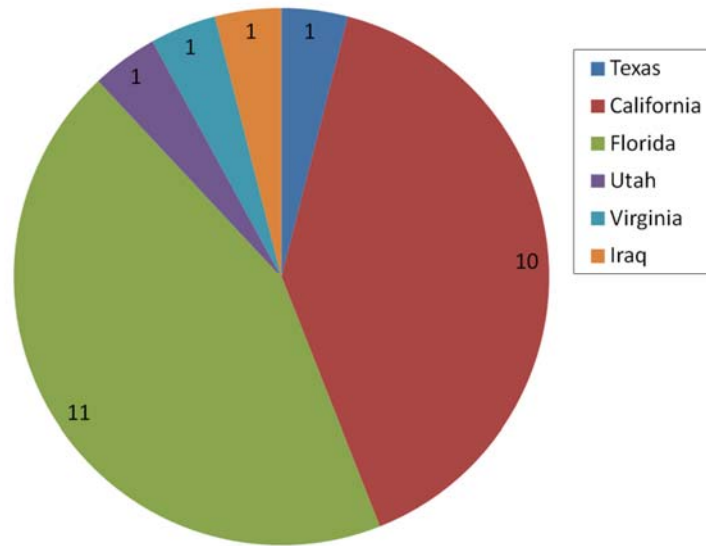


Figure 3.1 Distribution of utility survey respondents by state/country

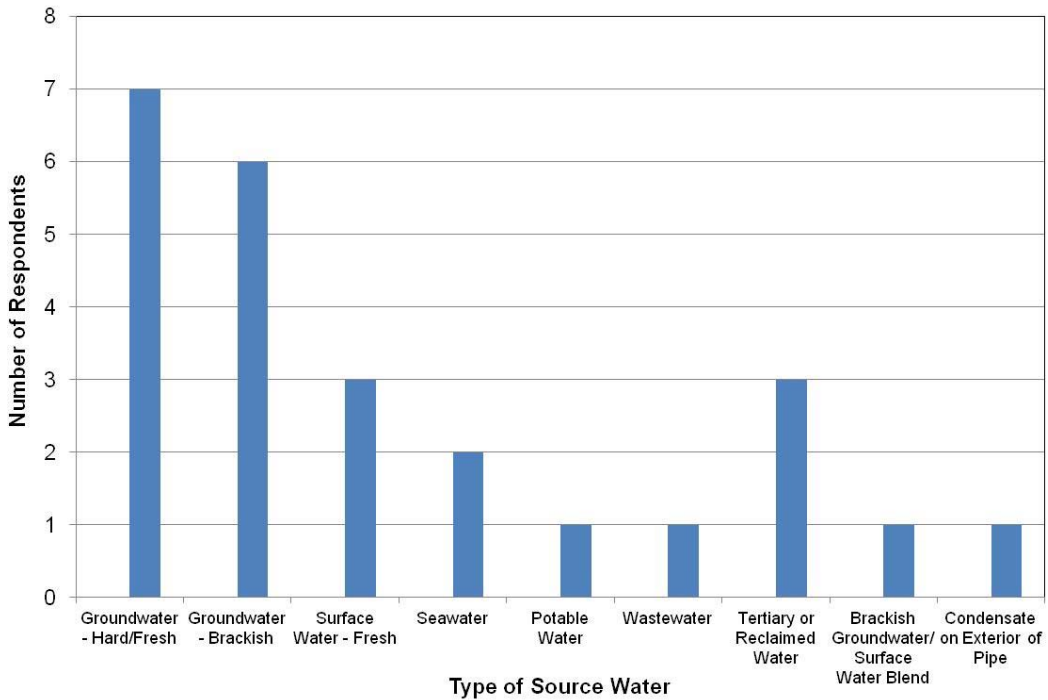


Figure 3.2 Distribution of source water types

All of the respondents that knew what type of stainless steel piping they have in their facility (23 out of 25) have some 316/316L stainless steel in their facilities. Half of those facilities employ some amount of 304/304L piping as well. Figure 3.3 presents the distribution of types of stainless steel reported by the responding utilities. Figure 3.4 presents the type of surface finishing used in the various facilities. Forty percent of responding utilities have different types of surface finishes throughout their facility. Chemical passivation is the most common surface treatment, used in 34 percent of responding utilities.

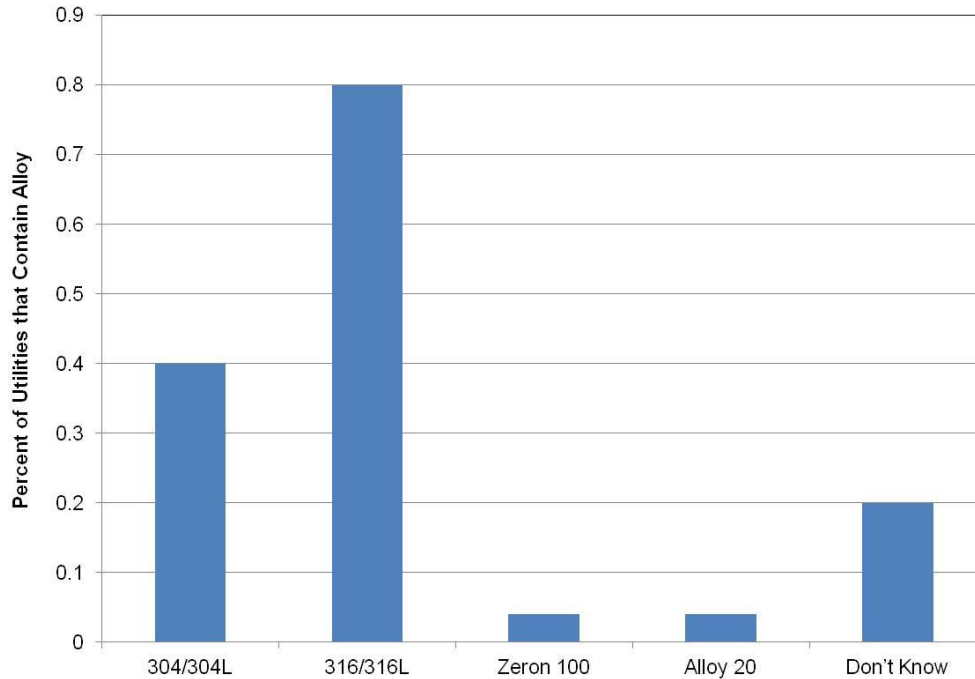


Figure 3.3 Types of stainless steel used in respondent utilities

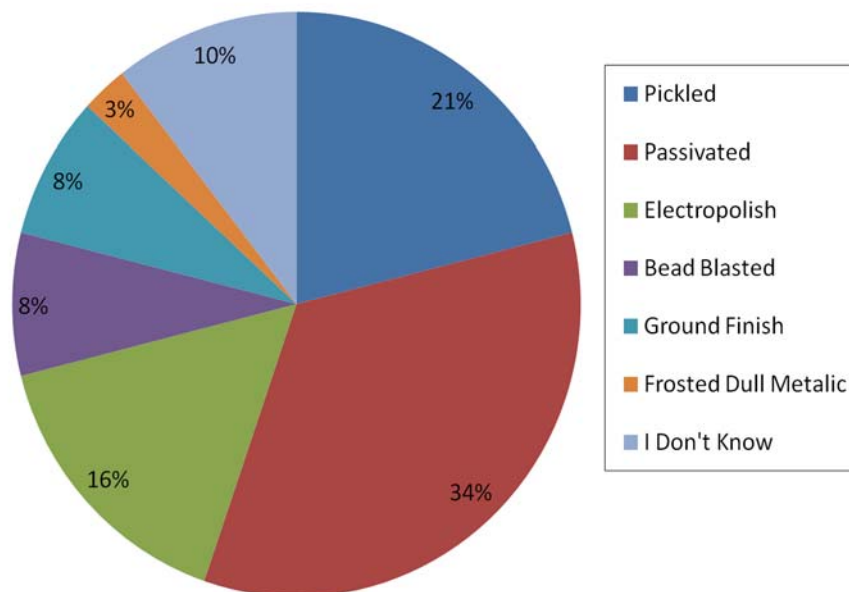


Figure 3.4 Distribution of surface finishing types

Figure 3.5 presents the age of stainless piping in the responding facilities. The majority of the stainless pipe was ten years old or less. More than 95 percent was twenty years old or less.

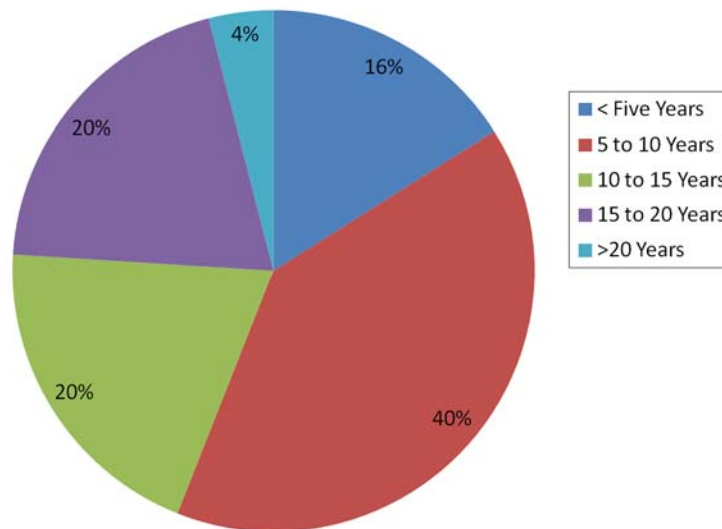


Figure 3.5 Age of steel piping in responding facilities

Corrosion Problems

Of the 25 responding utilities, ten stated that they have experienced stainless steel corrosion problems. Figure 3.6 presents a distribution of the location of the corrosion. The most commonly reported problems included “general ‘corrosion’ on exterior surfaces” and “pinhole leaks at welds” were most commonly reported. “General corrosion” does not distinguish between general surface corrosion and corrosion at joints or fittings, so further conclusions cannot be made.

As shown in Figure 3.7, corrosion events were most commonly attributed to MIC; however, 30 percent of the utilities did not know why they were seeing corrosion problems. One respondent listed dielectric corrosion caused by dissimilar metals, hydrogen sulfide gases, and condensate forming on the outside of the pipe as causes of corrosion. From this data, it appears that the cause of corrosion most readily identifiable by the average respondent is MIC.

In terms of welding practices, half of the respondents to this question reported that field welding was performed at their facility (Figure 3.8); however, only one of those utilities reported that the heat tint was properly removed after the field welding was completed. An interesting note is that of the utilities that had field welding performed, only the respondent that stated the heat tint was removed reported any corrosion at the welds.

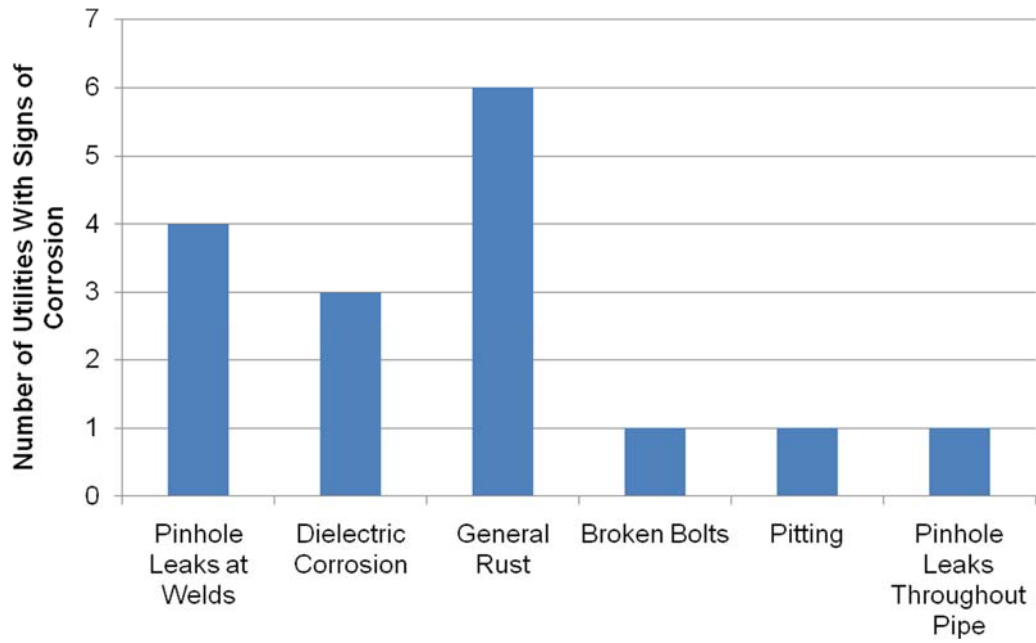


Figure 3.6 Location of corrosion event

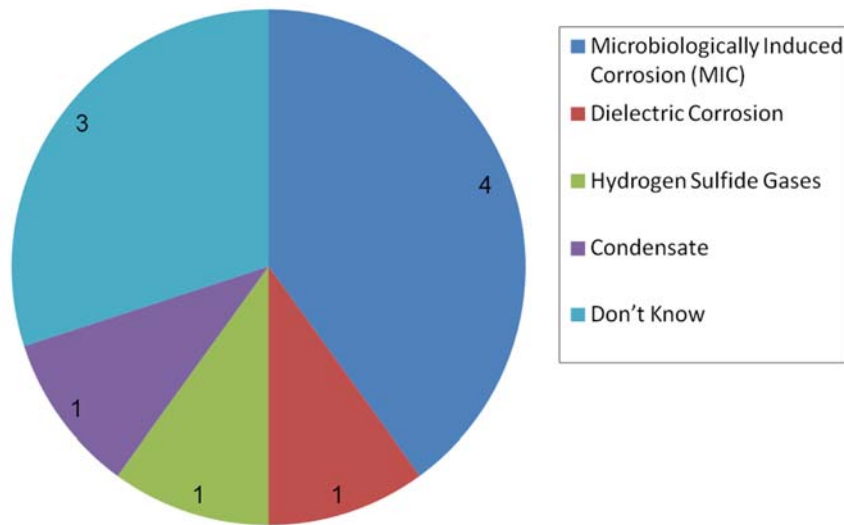


Figure 3.7 Causes of corrosion incidents

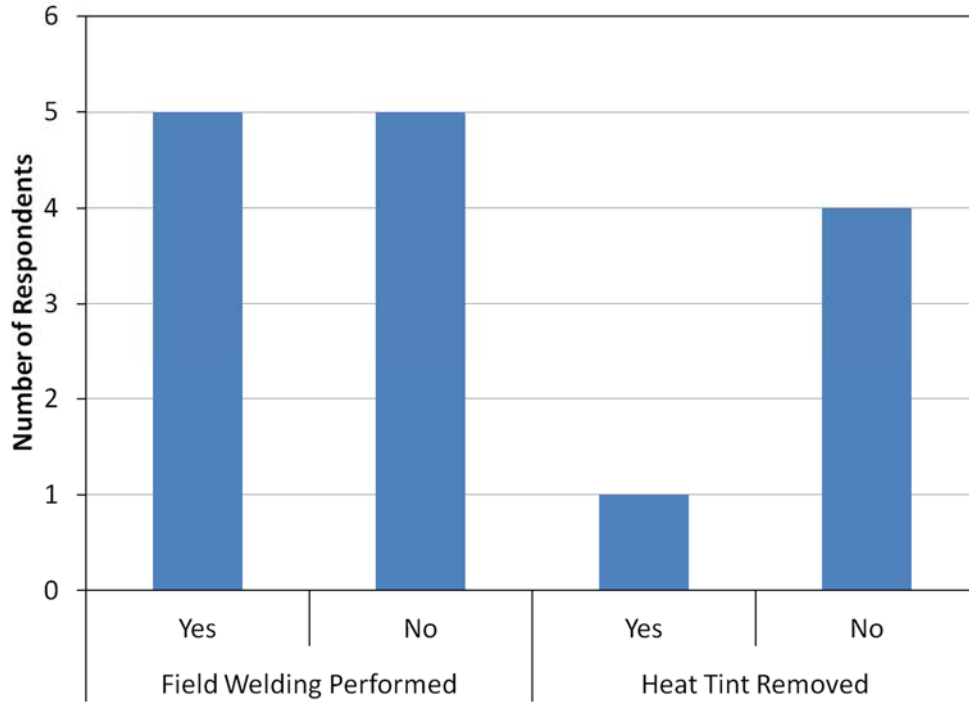


Figure 3.8 Field welding responses

Water Quality

Figures 3.9 through 3.17 present a comparison between utilities that did report corrosion and utilities that did not report corrosion based on different water quality characteristics and types of oxidants used in their facilities.

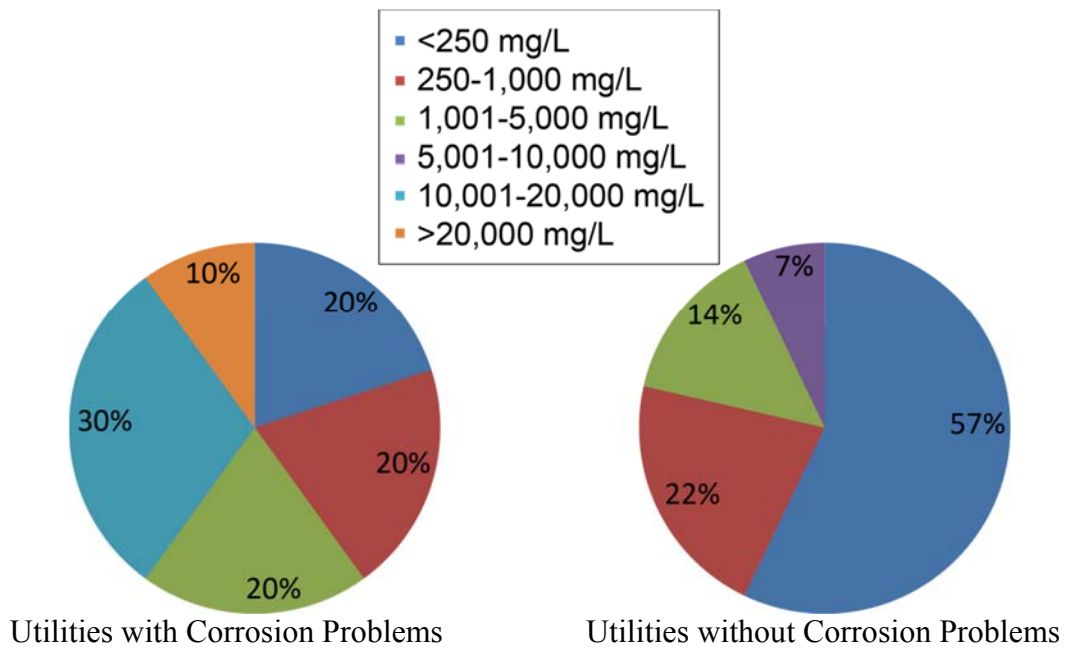


Figure 3.9 Distribution of chloride concentrations at responding utilities

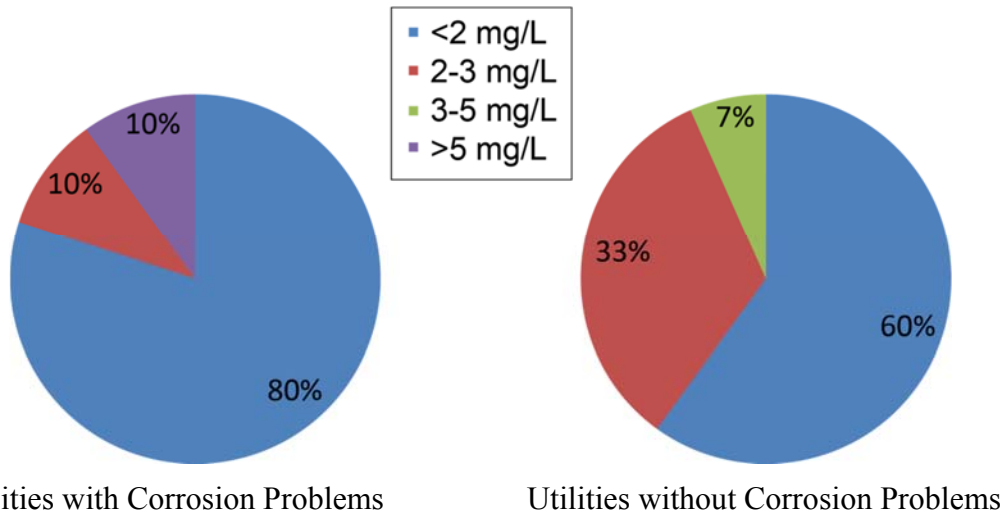


Figure 3.10 Distribution of chlorine concentrations at responding utilities

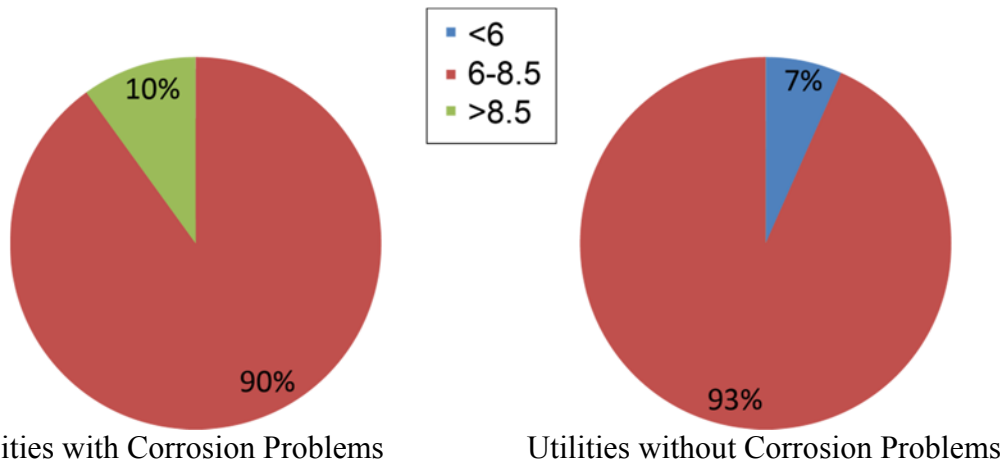


Figure 3.11 Distribution of pH levels at responding utilities

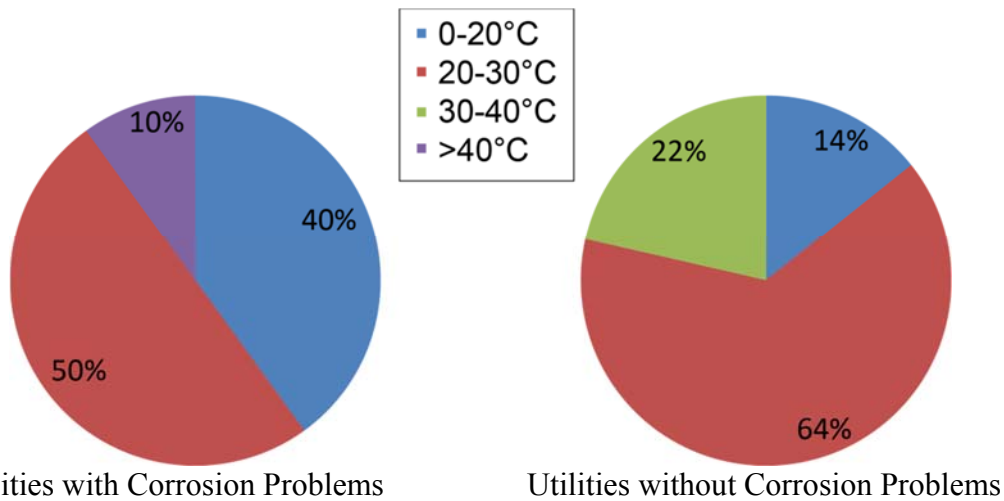


Figure 3.12 Distribution of water temperatures at responding utilities

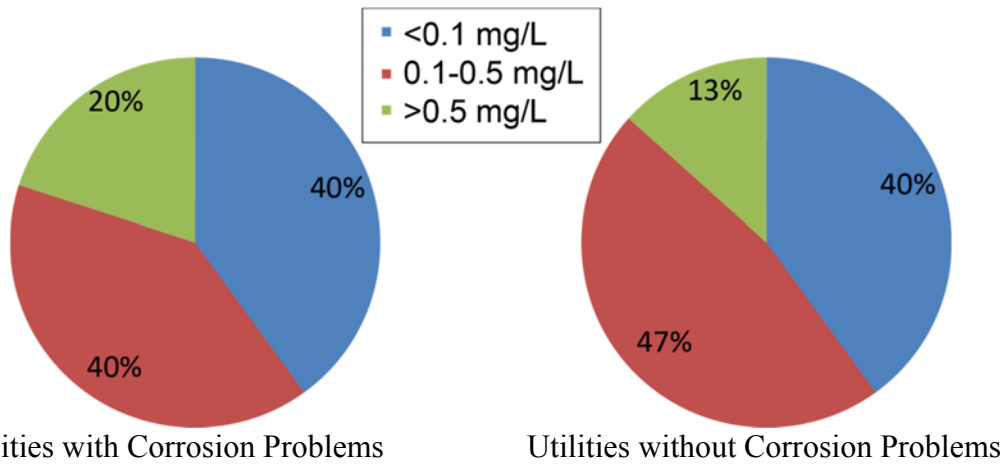


Figure 3.13 Distribution of dissolved oxygen concentrations at responding utilities

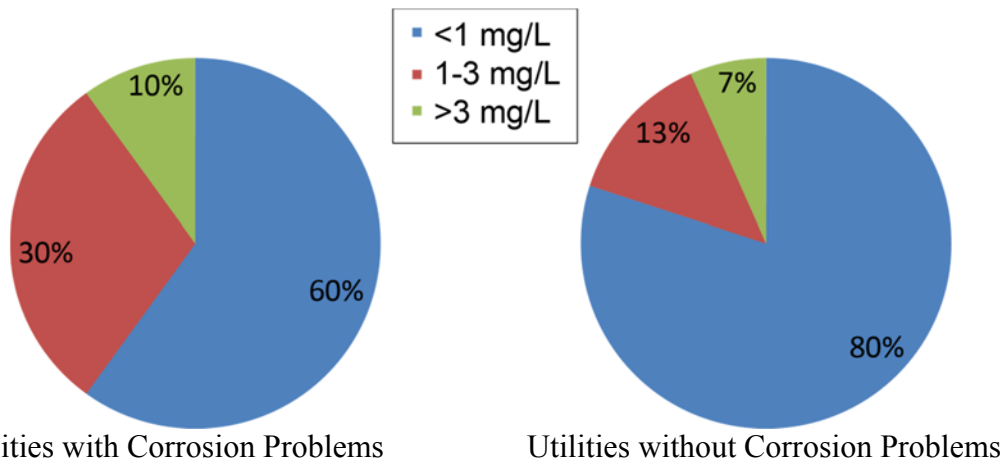


Figure 3.14 Distribution of iron concentrations at responding utilities

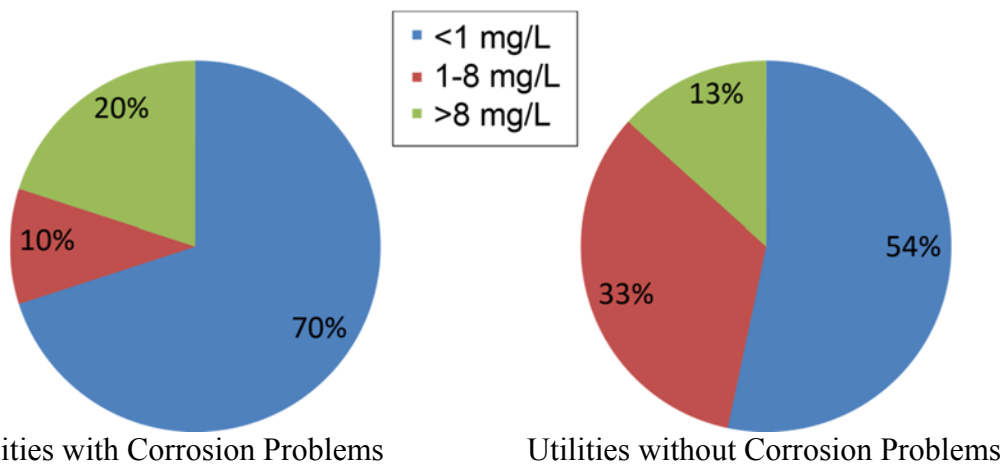


Figure 3.15 Distribution of hydrogen sulfide concentrations at responding utilities

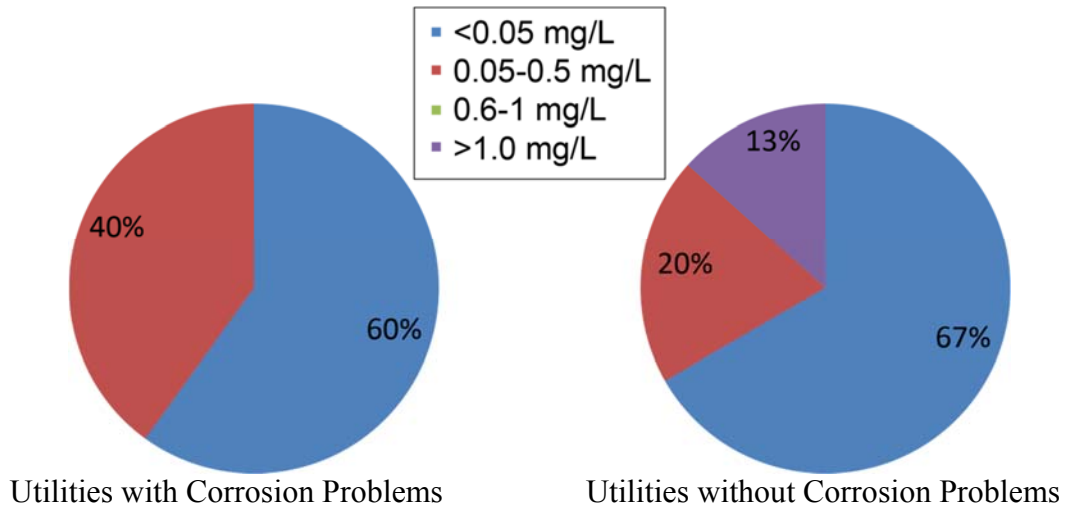


Figure 3.16 Distribution of manganese concentrations at responding utilities

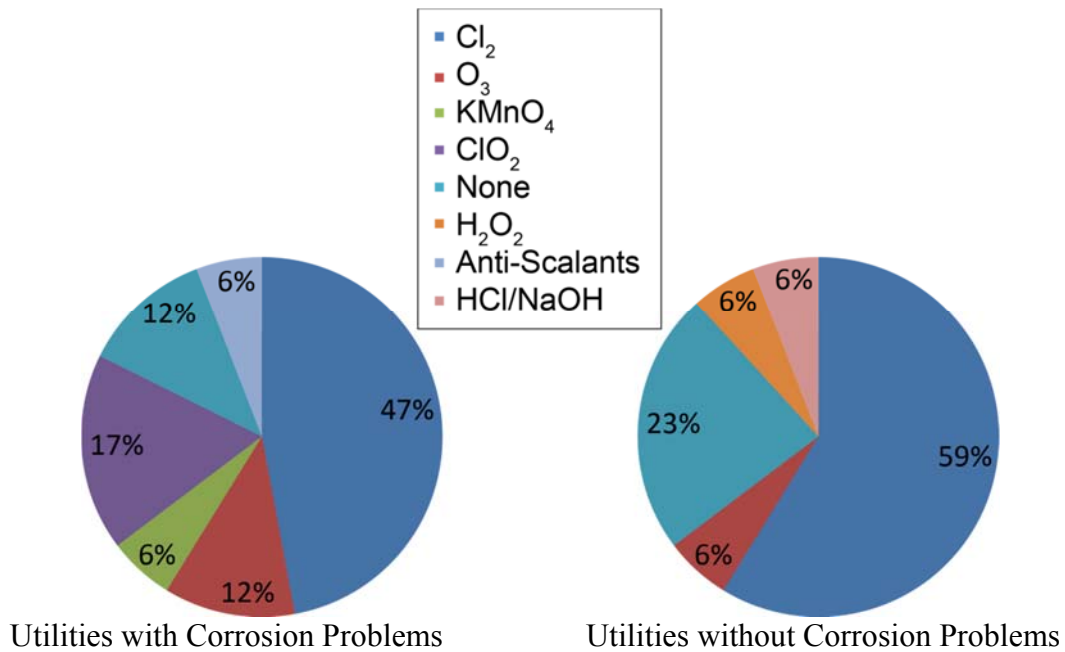


Figure 3.17 Distribution of oxidant usage at responding utilities

It is important to remember that the sample size from this survey is very small (25). Some of the bins have only one respondent and results can be easily swayed trying to interpret data from a sample of this size. Generally, the results were in line with expectations with respect to water quality and welding:

- All utilities with high levels of chlorine (>5 mg/L) reported corrosion. Most utilities with low levels of chlorine (<2 mg/L) reported little or no corrosion.
- Most utilities reporting corrosion had high levels of chloride (>250 mg/L). All utilities with very high chloride levels (>10,000 mg/L) reported corrosion.

- The three utilities that reported the use of chlorine dioxide also reported corrosion problems. One utility uses potassium permanganate, and that utility also cited corrosion problems.
- All of the utilities with water temperatures above 40°C experienced corrosion.
- There was no clear trend with respect to pH, iron concentration, dissolved oxygen level, or manganese concentration.

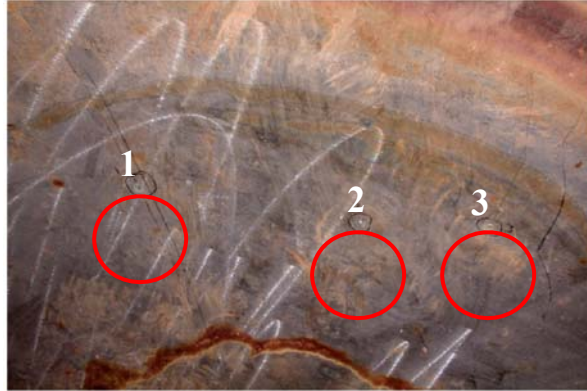
PART 2 – UTILITY CASE STUDIES – TYPICAL STAINLESS STEEL CORROSION EXPERIENCES

Several of the responding utilities also submitted stainless steel corrosion reports that they had previously completed as a result of past problems or to evaluate materials for future applications. The three reports detail different causes and symptoms of corrosion. This section gives a brief summary of the reports submitted by the utilities.

Utility 1. Zone 7 Water Agency, Del Valle Water Treatment Plant

A leak was discovered in one of the dissolved air flotation (DAF) saturator tanks at the Del Valle Water Treatment Plant (DVWTP). The DAF system was placed into operation in 2007 and the leak was discovered in the summer of 2009. Inspection of the tank revealed four separate areas of corrosion:

- There was pitting corrosion from the inside of the tank (Figure 3.18). The pits marked one and three, both were found to lie on distinct scratches. The pit marked two was found to lie on an area of weld spatter.
- Galvanic corrosion where 2-inch galvanized pipe nipples were attached to the tank (Figure 3.19). The use of galvanized pipe directly connected to a stainless steel system creates a dielectric connection and is not recommended.
- Mounds of corrosion were found where the tank shell was welded to the bottom head (Figure 3.20). Mounds like the one seen in Figure 3.20 can form over small pits, however, no pits were found in these locations.
- Crevice corrosion was found where the rubber gasket meets the manway opening on the tank (Figure 3.21). This corrosion was found to measure approximately 5/16-inch across the 1-inch surface with a depth of up to 3/64-inch.



Source: Courtesy of Zone 7 Water Agency

Figure 3.18 Pitting Corrosion on the inside of the tank at the DVWTP



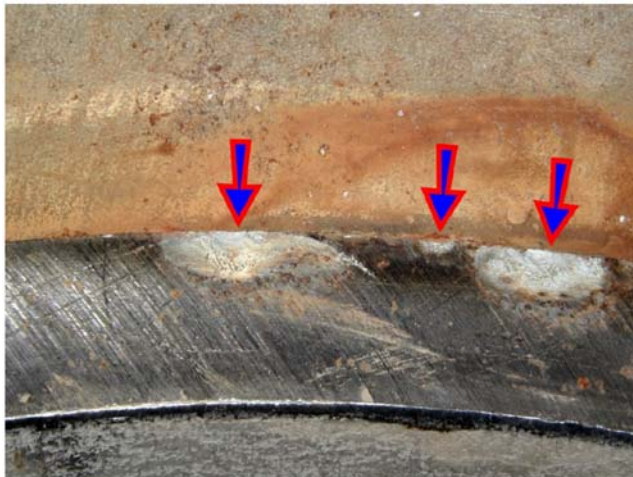
Source: Courtesy of Zone 7 Water Agency

Figure 3.19 Galvanic corrosion from a connection between dissimilar metals (galvanized pipe and stainless steel tank) at the DVWTP



Source: Courtesy of Zone 7 Water Agency

Figure 3.20 Corrosion found at a circumferential weld at the DVWTP



Source: Courtesy of Zone 7 Water Agency

Figure 3.21 Crevice corrosion found at manway opening at the DVWTP

Cleaning and Repair

The following procedure was recommended to repair the tank before placing it back into service.

- Surface cleaning and finishing. Blend all scratches, gouges, and weld spatter with a medium to fine grit abrasive. This method will not retard continuing growth of existing pits, but will help avoid the initiation of new pits.
- Weld repair of bottom head corrosion pits. Clean all pits discovered during the inspection process to the metal surface, then weld and blend to match the adjoining surfaces.

- Replacement of galvanized steel piping. Replace all galvanized steel pipe nipples with stainless steel materials.
- Manway flange corrosion repair. There are no remediation methods that will eliminate the formation of corrosion in these locations. The crevices found are likely to continue to grow. To retard growth, these crevices should be cleaned and filled with a non-metallic rebuild material that is suitable for stainless steel. One commercially available product is Chesterton ARC 858.

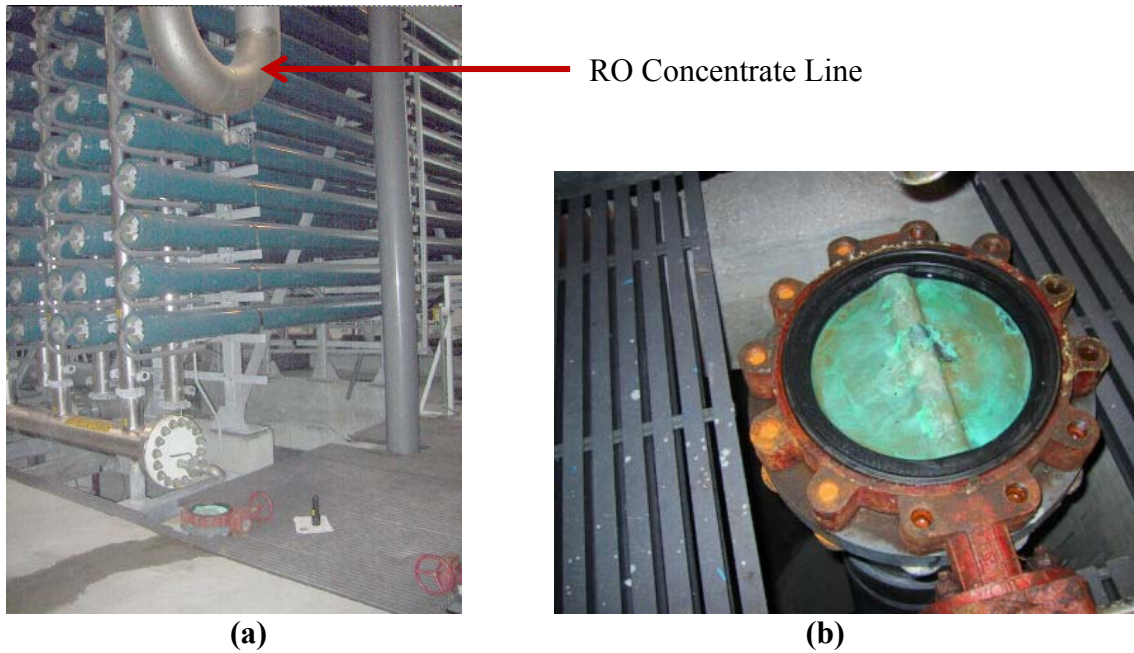
Conclusions

The corrosion found at the DVWTP is a result of poor workmanship (i.e., scratches, gouges, and weld splatter), and material selection for the DAF saturation tank. From this experience, the importance of thorough inspection of all welds and work installation is demonstrated.

Utility 2. Tampa Bay Desalination Plant, Apollo Beach, FL

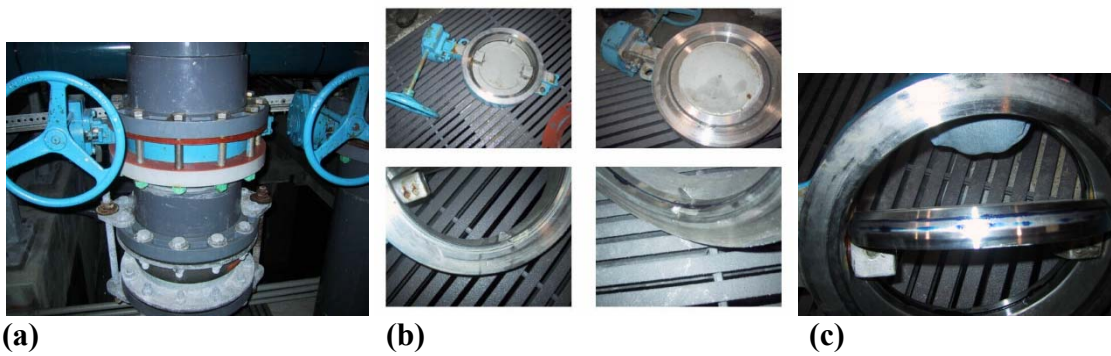
Corrosion of stainless steel materials was found throughout the Tampa Bay Desalination Plant (TBDP). The problems observed are summarized here:

- The cleaning line butterfly valves have nickel-aluminum-bronze discs and cast ductile iron bodies. These valves should be expected to provide good corrosion resistance to the cleaning solution. However, a leak from the RO concentrate line above the valve (Figure 3.22a) contributed to the corrosion of the disk surface seen in Figure 3.22b.
- It has been recommended that blind flange covers be used in these locations during periods of inactivity. In addition, Type 316 stainless steel butterfly valves would have been preferred in this location.
- The permeate valve on Train #3 also leaked when closed. These valves (Figure 3.23a, b, and c) showed no apparent corrosion. However, rust staining was found on the valve. This staining was caused by the presence of a carbon steel washer in the actuator mechanism.
- Mixed fastener types and materials were found throughout the TBDP (Figure 3.24a-e). All fasteners at the TBDP should be Type 316 SS. This will avoid fastener material inconsistencies and also consolidate the stocks on hand.



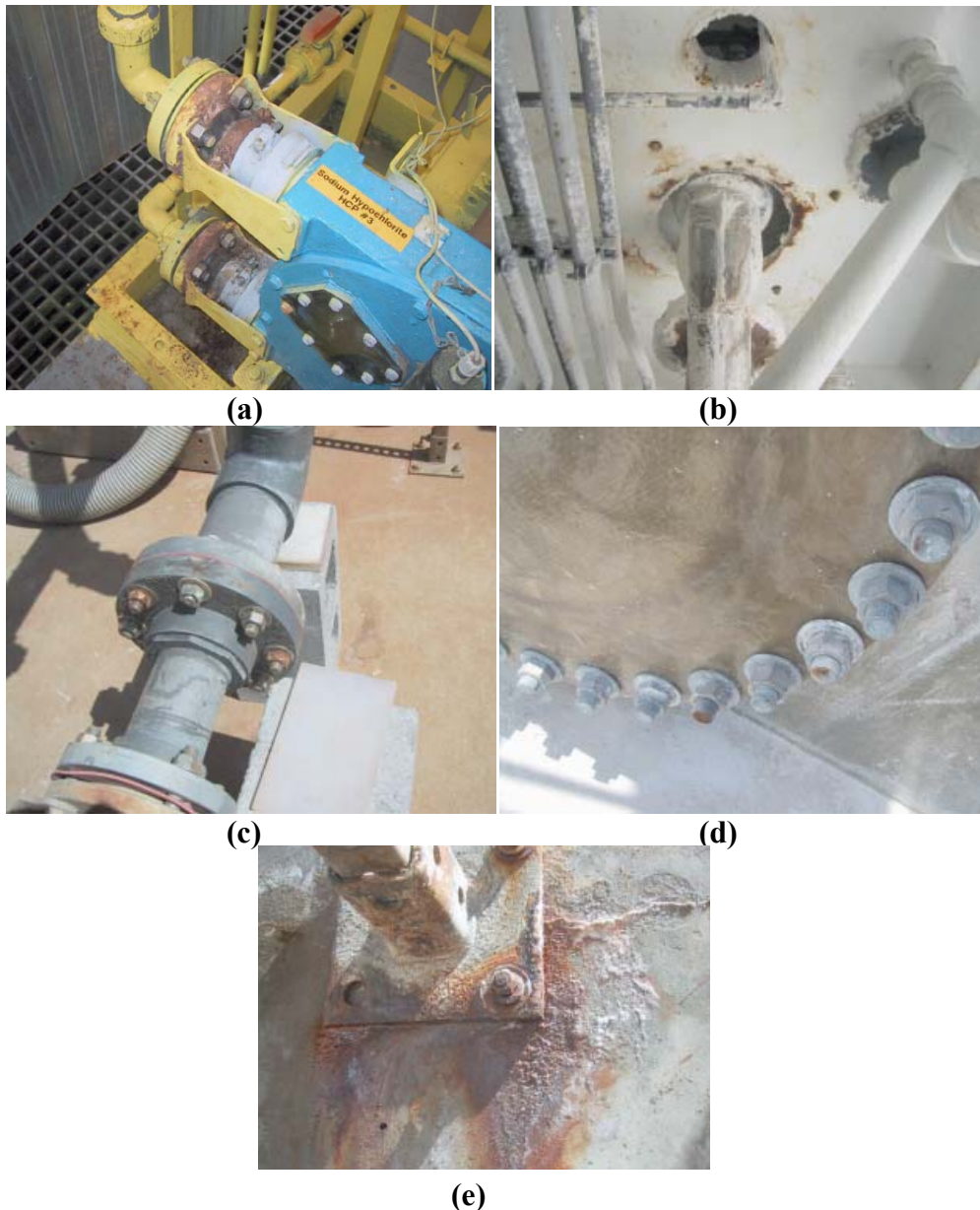
Source: Courtesy of Tampa Bay Desalination Plant

Figure 3.22 Corrosion of butterfly valve (a) in CIP line; (b) a close-up of the disc surface at the TBDP



Source: Courtesy of Tampa Bay Desalination Plant

Figure 3.23 Leaking permeate valve with rust staining from carbon steel washer



Source: Courtesy of Tampa Bay Desalination Plant

Figure 3.24 Corrosion issues throughout the facility from the use of inappropriate dissimilar metals and fasteners at the TBDP

- The interconnecting pipes on the RO trains were all connected with galvanized steel grooved couplings, using carbon steel bolting materials. All of the couplings and their fasteners exhibited some degree of corrosion (Figure 3.25). Future replacement of all couplings and fasteners with Type 316 stainless has been recommended.



Source: Courtesy of Tampa Bay Desalination Plant

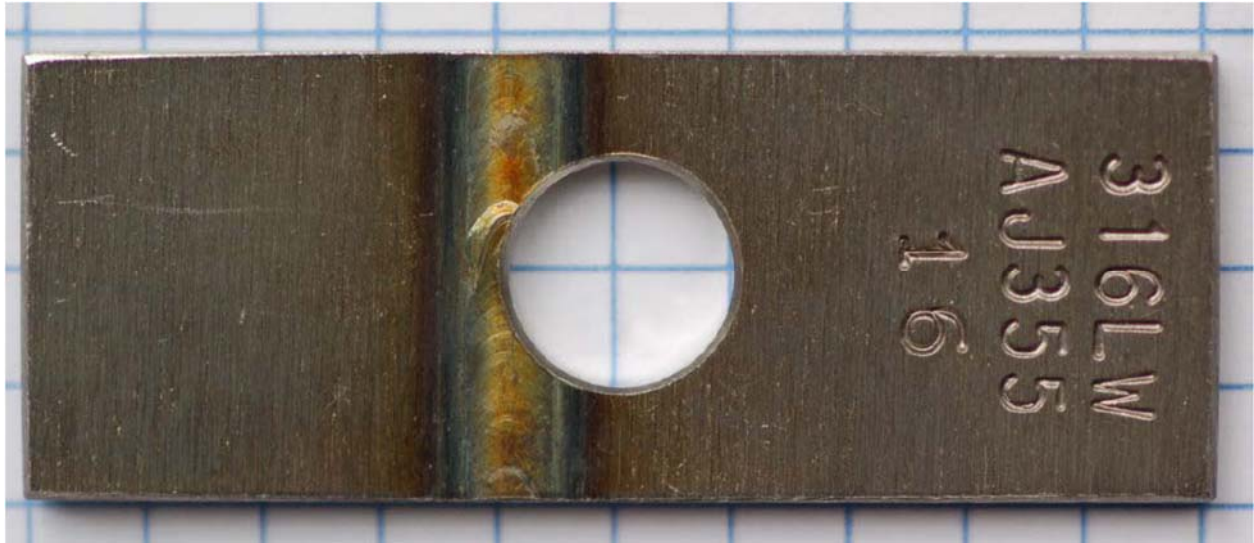
Figure 3.25 Corrosion at galvanized steel grooved couplings within the TBDP

Utility 3. Municipal Water District of Orange County, Fountain Valley, CA

Prior to the design and construction of a new seawater desalination facility the Municipal Water District of Orange County (MWDOC) conducted a study to determine the most suitable stainless steel alloy to be used. The study examined the effects of source water on the following materials:

- 316L
- 70Cu-30Ni (CDA715)
- 2507 Duplex Stainless
- 2205 Duplex Stainless
- Ni-Al-Bronze Alloy (CDA630)
- AL6XN

Each of the metal coupons was prepared by including an autogeneous weld bead that was not passivated (Figure 3.26). The samples were removed from the solution and inspected at intervals of 3,6,16, and 22 months.



Source: Courtesy of the Municipal Water District of Orange County

Figure 3.26 Example of a prepared coupon before exposure to source water

After removal from the source water solution, each of the coupons was ultrasonically agitated for two minutes, cleaned in an acid bath, and rinsed before being weighed. The samples were weighed to determine if there was any significant weight loss due to corrosion. Only the copper alloys, CDA715 and CDA630, showed a statistically significant weight loss during the test.

The coupons were analyzed for pitting using a slightly modified version of the ASTM G46 test. Each of the coupons were subdivided into 50 square blocks and examined at 20X magnification. The specimens were rated per the charts in ASTM G46 (ASTM 2013g). [Table 3.1](#) presents the results seen after 6 months in solution.

The results did not change significantly after 6 months; therefore, results were not recorded for 16 and 22 months. A progression of the corrosion on the CDA630 alloy coupons is presented in [Figure 3.27](#).

Table 3.1

Localized corrosion ratings after 6 months

Alloy	Parent material	Heat affected zone	Weld
316L	Crevice Attack	Crevice Attack	Crevice Attack
2205	No Attack	No Attack	Crevice Attack
2507	No Attack	No Attack	No Attack
AL6XN	No Attack	No Attack	No Attack
Ni-Al-Bronze (CDA630)	Pitting & Crevice	Pitting & Crevice	Pitting & Crevice
70Cu-30Ni (CDA715)	Blotchy General Corrosion	Blotchy General Corrosion	Pitting General Corrosion

* Frequency, Severity (higher number indicates more frequent and larger pits)



Source: Courtesy of the Municipal Water District of Orange County

Figure 3.27 Corrosion progressions in the CDA630 alloy coupons

The conclusions from this study were that:

- Copper base alloys are not suitable for this seawater desalination application due to rapid pitting and general corrosion.
- 316L and Alloy 2205 both experienced crevice attack on the weld and heat affected zone.
- The 2507 and AL6XN performed the best in this study. No corrosive attack was witnessed on these two alloys.

Utility 4. Weber Basin Conservancy District, Layton, UT

Corrosion was found in the stainless steel piping and fittings associated with an ozone system at the Weber Basin Conservancy District (WBCD). Corrosion was caused by two sources.

- Microbial Induced Corrosion (MIC) – Inspected pipes from the WBCD had signs of pitting corrosion that started at the outer diameter and worked inward to the inside of the pipe. Samples of the corrosion debris were analyzed and were found to have elevated concentrations of manganese. The elevated manganese concentration is a

symptom of MIC, which is the likely source of the pitting. Untreated water left stagnant in piping is a common source of MIC, and is the possible source in this instance.

- Localized Crevice Corrosion- Localized crevice corrosion was found in the piping and stainless steel tanks at the WBCD. The corrosion was seen as deposits of rust at locations where high turbulence would be expected. The debris from these samples had high iron oxide concentrations as well as halide concentrations such as chloride and iodide. A likely reason for this is that the plant was using ferric chloride as a coagulant up stream of the stainless steel piping. The presence of the chloride as well as low pH (~5) conditions acted as an accelerant for the corrosion. Because of the iron oxide deposits, an increase in sub-deposit corrosion was seen.

Case Study Conclusions

The following conclusions can be made from the case studies presented:

- Workmanship errors such as, scratches and gouges, weld spatter, and contact between incompatible metals (i.e., galvanized steel or carbon steel with stainless steel), were found to be the most common cause of stainless steel corrosion in case studies. This emphasizes the importance of proper specifications and inspections of all work done before the equipment into service.
- Proper operation of the facilities is also important. At the WBCD stagnant water left in piping as well as the ferric chloride coagulant addition resulted in the acceleration of corrosion.
- Selecting the appropriate alloy for the water quality is also important. The study performed by the MWDOC demonstrated a wide range of corrosion for different alloys.

Stainless steel corrosion can be reduced by proper alloy selection, workmanship, and operation. Guidelines for the use of stainless steel in the water and desalination industries should establish and reinforce good practices for engineers and end-users to follow in these areas.

PARTS 1 AND 2 – UTILITY EXPERIENCES CONCLUSIONS

The intent of evaluating water utility experience was to characterize materials currently in use as well as the most common types and causes of corrosion. The data collected indicated where more emphasis should be placed in developing guidelines for the use of stainless steel in water and desalination industry applications. The following conclusions can be made based upon the utility surveys and case studies. Where appropriate, implications to the development of guidelines for the use of stainless steel are noted.

- Workmanship errors such as, scratches and gouges, weld spatter, and direct contact between incompatible metals (i.e., galvanized steel or carbon steel with stainless steel), were found to be the most common cause of stainless steel corrosion.
- Implication: When developing guidelines for the use of stainless steel, emphasis should be placed on specifying proper material fabrication, handling, and inspections. Use of compatible materials or dielectric unions should also be emphasized.

- Operational practice can influence the potential for corrosion. Stagnant water left in piping resulted in MIC and ferric chloride coagulant addition accelerated corrosion problems.
- Implication: When developing guidelines for the use of stainless steel, emphasis should be placed on operational practices to avoid stagnant water and use of chemicals that may accelerate stainless steel corrosion.
- Selecting the appropriate alloy for the water quality can mitigate corrosion caused by water quality and environmental influences. Chlorides, oxidants, and pH were all important influences.
- Implication: When developing guidelines for the use of stainless steel, emphasis should be placed on chlorides, oxidants and pH when determining the appropriate alloy to be used or when considering changes in operating conditions to an existing system.

The water quality and corrosion survey indicates that utilities are primarily dealing with moderate-level concentrations of chlorides (<1,000 mg/L) and moderate pH values, most have some level of dissolved oxygen present, and most used 304/304L or 316/316L stainless steel. Forty percent reported corrosion problems. Corrosion problems included pinhole leaks at welds (40 percent), at connections to dissimilar metals (30 percent) and general "corrosion" on exterior metal surfaces (60 percent). Besides "I don't know/other", MIC was the most commonly reported reason for corrosion (44 percent).

PART 3 – SURVEY OF FABRICATOR PRACTICES

Survey Methodology

A survey of stainless steel welders and fabricators was conducted to gather data on welding practice and qualifications, and common surface treatment methods employed.

The survey was posted on Survey Monkey in March 2013 and potential respondents were contacted via email that same month. The survey closed in July 2013. The survey was sent to 32 stainless steel manufacturer representatives from 35 different companies. Follow-up calls were made two months later to contact potential participants who had not yet responded to the survey invitation.

This active recruiting of survey participants significantly raised the response rate above that of the utility survey. At the close of the survey period, a total of 12 fabricator responses had been received. Only eight responded to the questions on pickling and passivation, and only three responded to the questions on electropolishing. In terms of total number of fabricators contacted, this translates into response rate of 36 percent.

Fabricator Survey Results

Figure 3.28 presents the distribution of survey respondents based on their location. Half the respondents were from California and the other half were distributed among the Midwest and the South.

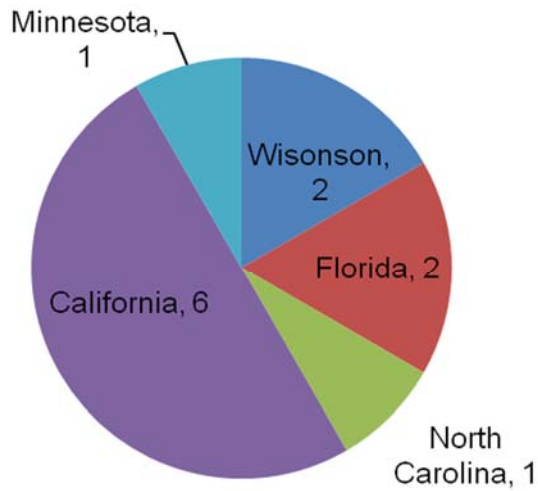


Figure 3.28 Distributions of fabricator shops respondents by State

Welding

Figure 3.29 presents a distribution of different types of stainless steels that the respondents are certified to weld. Every fabricator that responded is certified to weld 300 series and duplex stainless steels. Fabricators that are certified to weld super-austenitic stainless made up the smallest percentage, but this was still two-thirds of all the respondents.

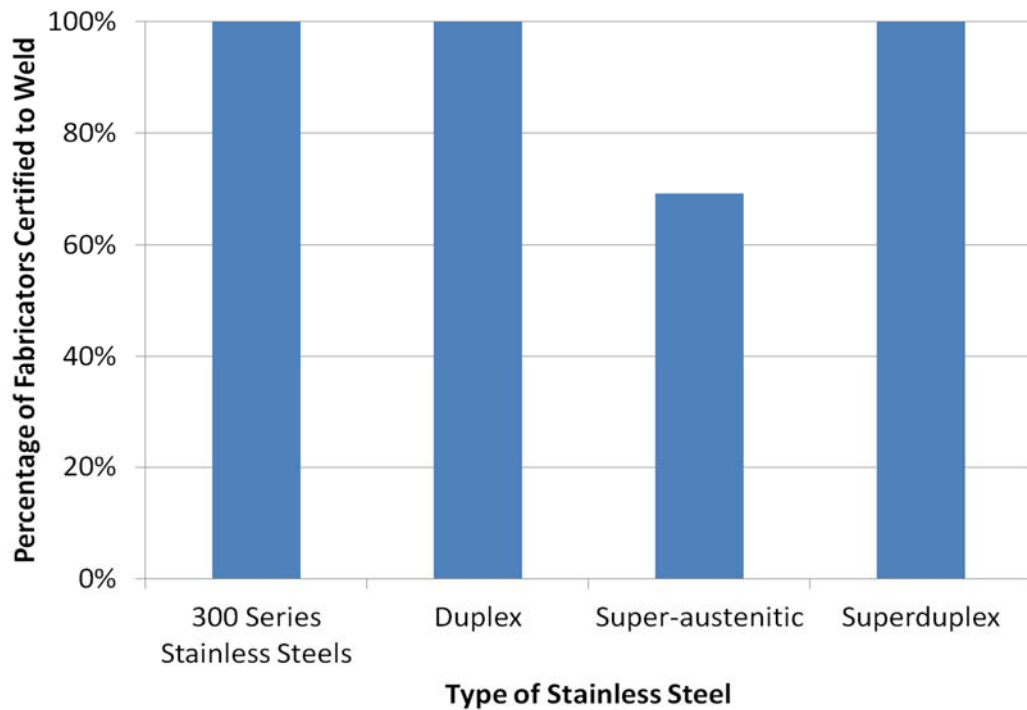


Figure 3.29 Distribution of stainless steel alloys respondent fabricator shops are certified to weld

Figure 3.30 displays how often the fabricators require their welders to become recertified. The most frequent intervals were every 6 and 12 months. Two of the respondents (17 percent) do not require recertification as long as the welder does not have a period of inactivity of more than three months. Half of the respondents stated that they are required to submit welder certifications for review as part of the specifications process more than 75 percent of the time (Figure 3.31). Not one respondent answered that they never need to submit welder certifications.

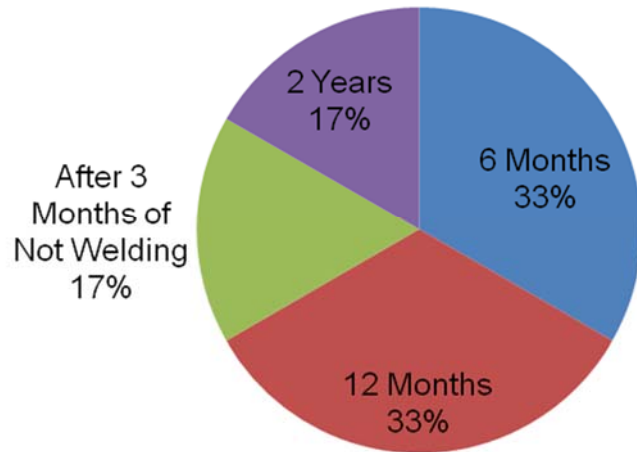


Figure 3.30 Welder recertification frequencies

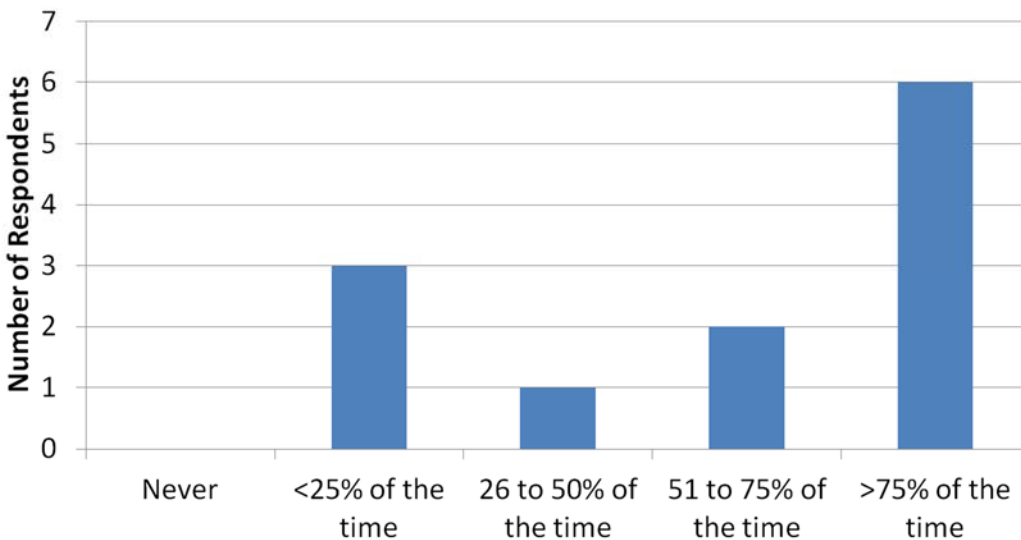


Figure 3.31 Percentage of projects that require welder certifications to be submitted

Figure 3.32 presents the frequency of projects that require fabricators to perform quality control (QC) checks on their welds. None of the respondents answered never to this question, but half of them responded that they need to perform QC checks less than 25 percent of the time.

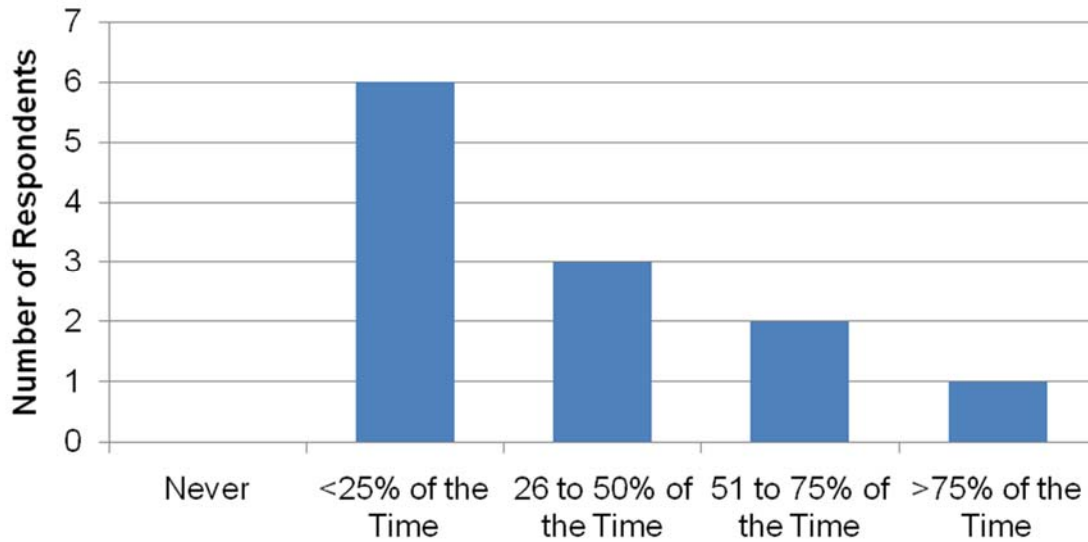


Figure 3.32 Percentage of projects that require QC checks to be performed on welds

Fifty-eight percent of all fabricators responded that they use ASTM-312 for material specifications when purchasing pipe. The rest of the respondents use ASTM-778 for material specifications (Figure 3.33).

Pickling, Passivation, and Electropolishing

Only eight (67 percent) of the respondents perform pickling and passivation chemical treatments after fabrication. Of these fabricators, three of them sub contract these services out to others. Therefore, the following section is based on the responses of only five fabricators. Table 3.2 presents the chemical passivation treatment methods that are used by the responding fabricators. There was no trend in treatment chemical use among the respondents.

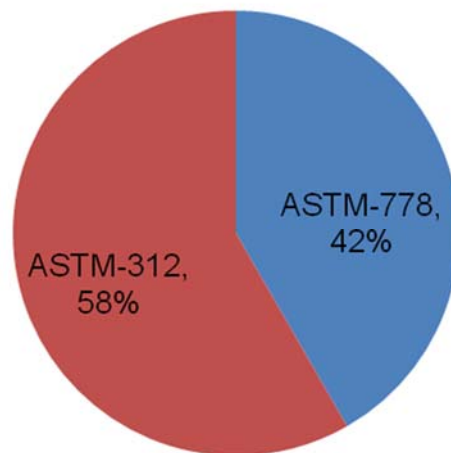


Figure 3.33 Material specifications used when purchasing pipe

Table 3.2
Use of passivation treatment chemicals by responding fabricators

Treatment method	Number of fabricators
10% Nitric Acid-2% Hydrofluoric Acid	2
30% Nitric Acid (Immersion of 30 Minutes, Temperature Range of 79-90°F)	2
10% Citric Acid (Immersion of 10 minutes, Temperature Range of 120-140°F)	2
15% Phosphoric Acid (90 Minute Dwell Time at Room Temperature)	2
15% Nitric Acid-3% Hydrofluoric at 120°F	1

Only two of the fabricators that perform chemical passivation treatment hold environmental permits; one for waste and water, and the other for gas and hazardous materials.

Electropolishing

The three respondents that perform electropolishing can perform electropolishing on both the inside and outside of pipes greater than three inches in diameter. Figure 3.34 presents the length and diameter of pipe that each of the three fabricators can process in their facilities.

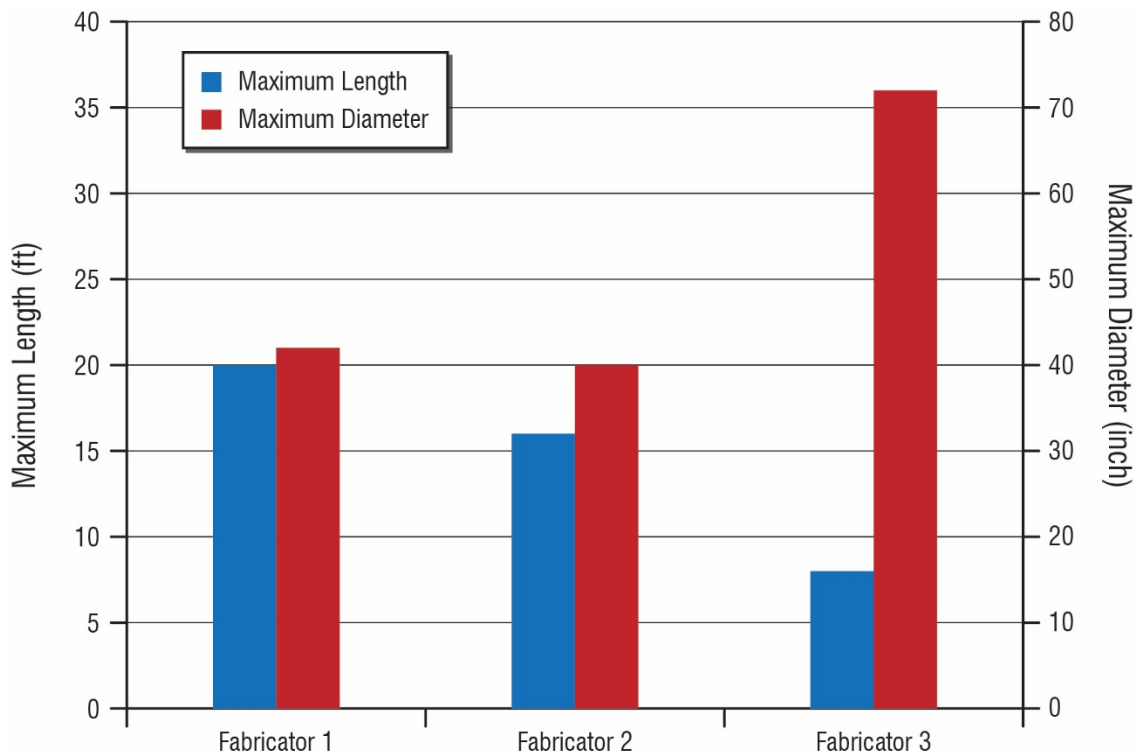


Figure 3.34 Description of respondents' electropolishing capabilities

PART 3 – SURVEY OF FABRICATOR PRACTICES CONCLUSIONS

The following conclusions can be made based upon the fabricator surveys conducted. Where appropriate, implications to the development of guidelines for the use of stainless steel are noted:

- Every fabricator that responded is certified to weld 300 series and duplex stainless steels, however, it is apparently less common for fabricators to be certified to weld super-austenitic stainless. Fabricators are often required to submit weld certifications. The frequency that fabricators recertify their welders varies.
- Implication: When developing guidelines for the use of stainless steel, consider the material type and frequency of welder certification. The cost of the material and size of the project may influence the welder's certification frequency.
- Weld quality control is always performed, but the number of welds inspected does vary, likely by project size.
- Implication: When developing guidelines for the use of stainless steel, quality control documentation should be available for review. The cost of the material and size of the project may influence the number of welds that should be reviewed for quality control.
- Chemical passivation practice varies widely. Some fabricators are required to hold environmental permits for waste disposal and gas emissions. Some fabricators self-perform passivation, others subcontract this work to a third party.
- Implication: When developing guidelines for the use of stainless steel, it should be noted that there are a variety of chemical passivation treatments that are included in ASTM A967. Not all of these treatments may be equally affected by the availability of environmental permits. In addition, if a fabricator does not have the appropriate facilities (or permits) to perform chemical passivation, it can be subcontracted to a third party.
- Not all fabricators are equipped to electropolish pipe. When fabricators cannot perform electropolishing required by specification, they will need to subcontract this service (this service is readily available). Fabricators that can perform electropolishing can accommodate diameters greater than 3-inches up to (and in one case greater than) 20-inches while performing this finish on both the inside and outside of the pipe. Not all fabricators can perform electropolish on long lengths of pipe.
- Implication: When developing guidelines for the use of stainless steel, it should be noted that electropolish can be performed inside and outside of a variety of pipe lengths and diameters greater than 3-inches.

CHAPTER 4 CORROSION TESTING

NOTE: This chapter describes the corrosion testing done as part of this work. The technical details are included to document the experimental protocol and results. The details may be of interest mainly to a corrosion specialist audience. The results and conclusions from this work have been incorporated into the recommendations provided in Chapter 5.

The goal of this laboratory study was to determine the upper operating conditions for austenitic and duplex stainless steels when exposed to aqueous solutions with chloride and chlorine concentrations typical of those found in water and desalination industry applications. Other variables included temperature effects and various surface conditioning preparations (i.e., polishing, grinding, pickling and electro-polishing), with an end objective to determine possible synergistic corrosion effects between chlorides and chlorine.

The basic corrosion mechanisms investigated were pitting attack and crevice corrosion using both cyclic potentiodynamic polarization testing and immersion testing. The short-term (24-hour) polarization tests were run to determine the active/passive corrosion characteristics for alloys exposed to specific chlorinated environments, while long term immersion testing (30 – 60 – 90 days) provided long-term exposure data.

The stainless steel grades used in these experiments, Types 304/304L, 316/316L, 2205 duplex stainless steel and one lean grade of duplex stainless steel all met the requirements specified by the EPA Drinking Water Standard as laid out in the ANSI/NSF 61 Standard.

PAST ELECTROCHEMICAL STUDIES

Extensive work has been undertaken to determine the optimum stainless steel for the handling of different chlorinated waters. Most of this work covers the application of Types 304/304L and 316/316L, which has been found to be acceptable for the handling of drinking waters. The results of two important studies on this topic and their influence on the test protocol developed in this work are discussed below.

A study by Mameng and Pettersson (2011) investigated the resistance of new lean grades of stainless steels and Alloy 2205 duplex stainless steel, as compared to the 300 series stainless steels, which are the basic materials of construction used in the water and desalination industry today. Electrochemical corrosion tests were done under a variety of water quality conditions, varying pH, chlorine, and chloride concentrations. The results were as follows:

- 316L and 2205 stainless steels performed well in chlorinated environments at 30°C and up to 1 mg/L as Cl₂ at pH values of 6.5 to 7.5.
- LDX 2101® duplex stainless steel performed as well as 304L stainless steel under all test conditions, up to and including: 30°C; 0.5 mg/L as Cl₂ free chlorine, and 200 mg/L chloride.
- 304L showed pitting in environments with a chloride concentration of 500 mg/L and a free chlorine concentration of 1 mg/L at 50°C.

- In the most severe conditions (50°C—high temperature environments), 316L and 2205 proved more suitable than the lean grades of duplex stainless steels.

Based on the results of this study and recognizing that the acceptable upper limits for 304L have already been determined, 316L was defined as the base alloy for our study's test programs.

SCHEMATIC POLARIZATION CURVE

Potential at Passive Breakdown (Trends)

The second report, published by Vepulanont et al. (2012) evaluated the 300 stainless steel series' (304/304L and 316/316L) resistance to crevice and pitting corrosion in aqueous environments when exposed to a temperature of 20°C with chloride concentrations of 200, 500, and 1,000 mg/L combined with free chlorine concentrations of 0, 2, 5 and 10 mg/L as Cl₂. The pH was held at 6-8, typical of potable waters.

There was no evidence of 304/304L pitting or suffering crevice corrosion when exposed to 200 mg/L chloride, although there was some sign of initial pitting observed under a low powered optical microscope when exposed to water with the following characteristics: 500 mg/L chloride, 7 mg/L as Cl₂ free chlorine, pH 8.

By contrast, 316/316L showed evidence of surface discoloration, with some evidence of initial, incipient pitting when viewed under a low powered optical microscope in an environment of 2,000 mg/L chlorides; zero chlorine; pH 6. Acidity (pH) appeared to have an effect on initiation of pitting corrosion. There was insufficient evidence to suggest any synergistic impact between chlorides and free chlorine on crevice corrosion in this work. However, there appeared to be some identifiable upper limits for 304L and 316L under chlorinated conditions. As expected, chlorine, chlorides and pH had less of an effect on 316L than 304L. The following recommendations can be made based on this work:

- Using a safety factor of two, a chloride concentration of 250 mg/L appeared to be a maximum realistic limit for 304L stainless steel (no evidence of pitting or crevice corrosion) for the handling of drinking waters at 20°C. At 500 mg/L chloride and pH 8, a free chlorine concentration of 7 mg/L as Cl₂ was the upper performance limit.
- Chlorine concentrations have a greater effect on crevice corrosion, although concentrations less than 10 mg/L as Cl₂ did not seem to impact results.
- 2,000 mg/L chloride would be an acceptable upper limit for 316L stainless steel, but a more conservative lower limit based upon longer term immersion testing and evidence of incipient pitting at these chloride levels may be needed.
- 1,000 mg/L chlorides appears to be a maximum realistic limit for 316L stainless steel along with a free chlorine concentration of 3 to 5 mg/L as Cl₂ at 20°C, using a safety factor of 2 on the chloride concentration.

Immersion tests were run for a total of 540 days to evaluate the impact of time with corrosion performance. The results are summarized in [Table 4.1](#) below. The 316/316L specimens were exposed to the following environment: pH 6, 2000 mg/L chloride and 10 mg/L chlorine. Although not discernable, after 60 days crevice corrosion can initiate and propagate after longer periods of exposure time, which suggests that conservative approaches be taken when defining upper practical operational limits for materials.

Table 4.1
Inspection results from long-term stainless steel corrosion testing

Exposure time	Visual inspection	Optical microscope
30 days	surface discoloration	incipient pitting
60 days	surface discoloration	crevice initiation
180 days	crevice initiation	not reported
360 days	crevice corrosion	crevice corrosion
540 days	aggressive crevice attack under the plateau	N/A

Source: Vepulanont et al. 2012

Research Needs

Duplex stainless steel (alloy 2205) and superduplex stainless steel (alloy 2507) have played a role in handling brackish water and seawater, but their upper limit of performance has not been defined to allow a cost-effective selection of material for these environments. Therefore, polarization studies were undertaken to cover this range of waters, including the 3 percent, 4 percent, and 6 percent molybdenum super austenitic and superduplex alloys.

Surface finishing is another area of interest in determining the effects of corrosion and the benefits to be gained. This work also evaluated the corrosion susceptibility of different commercial grade alloy finishes to determine their relative abilities to improve corrosion resistance of the common 300 series stainless steels when exposed to waters containing chloride and chlorine.

All of the laboratory work described here was performed by Corrosion Testing Laboratories (Newark DE).

PHASE 1 – SHORT-TERM POTENTIOSTATIC TESTING

Experimental Approach

This study evaluated the pitting and crevice corrosion resistance of austenitic (i.e., 316/316L) and duplex stainless steels in handling brackish and saline waters with high chloride concentrations in the presence of varying concentrations of free chlorine. Electrochemical corrosion testing (per ASTM G5 and G61; ASTM 2014f and 2014d, respectively) was performed to help identify the exposure tolerances.

The test solution pH proved hard to control during the electrochemical testing. Bleach that was added resulted in pH increase and subsequent efforts to adjust the pH proved difficult due to the low buffering capacity of the test solution. Both the 3,600 and 10,000 mg/L as Cl₂ chlorine solutions had pH values higher than the target pH at the conclusion of testing. The pH of the 3,600 mg/L chloride samples' increased to 6.2 and the pH of the 10,000 mg/L chloride samples' increased to 7 to 7.5.

It was recognized that 304/304L had an upper tolerance limit of 500 parts per million (ppm) chlorides. With this premise, 316/316L was considered to be the baseline austenitic stainless steel for this electrochemical study. The duplex stainless steels (alloy 2205), superduplex stainless steel (alloy 2507) and super-austenitic alloys were expected to perform well in the high salinity (i.e., high chloride) environments.

Test Solutions

The test solutions were prepared using commercially available sea salts meeting ASTM D 1141 and laboratory prepared de-ionized water. The chloride ion concentration for each solution (i.e., 3,600 mg/L or 10,000 mg/L chlorides) was confirmed using inductively coupled plasma (ICP) analysis. The test temperature was held at 30°C.

The test solution was adjusted to pH 6 using dilute sulfuric acid prior to commencement of each test. The test water was de-aerated prior to the addition of chlorine. Household bleach (sodium hypochlorite) was used to achieve the desired chlorine concentration; the dosage was verified with test strips and a spectrophotometer.

The pH remained relatively stable (6.0 to 6.2) for the 3,600 mg/L chloride test concentration, while pH stability for the 10,000 mg/L chloride started at a pH ranging from 5.0 to 5.2 and ended each test at a range of pH 7.0 to 7.5.

Test Specimen Preparation

Test specimens were prepared from nominal ¼-inch plate, which measured approximately ¾ inch square with a through hole for mounting crevice washers. One edge of the specimen was drilled and tapped for mounting to an electrode holder. The samples were ground to a uniform finish using successively finer abrasive paper, ending with 600-grit paper. The test specimens were assembled with PTFE fluorocarbon crevice formers and titanium hardware following the guidelines of ASTM G-48, Method D. The assembly was tightened to a torque of 40 in-oz. using a calibrated torque driver. The assembled specimens were attached to a standard ASTM G5 type of electrode holder for testing (ASTM 2014f). A typical assembled test specimen and the polarization cell testing apparatus are pictured in [Figures 4.1a](#) and [4.1b](#).



Figure 4.1a Typical crevice assembly



Source: Courtesy of Corrosion Testing Laboratories, Inc.

Figure 4.1b Test polarization cell

Electrochemical Test Method

Cyclic potentiodynamic polarization testing followed the guidelines of ASTM G5 and G61 (ASTM 2014f and 2014d, respectively). The alloys were initially exposed to all combinations of the following conditions:

- Chloride concentrations: 3,600 and 10,000 mg/L.
- Free chlorine concentrations: 0, 1, 3 and 5 mg/L as Cl₂.
- pH: 6.
- Temperature: 30°C.

The alloys tested included: Duplex 2205; superduplex 2507 and superaustenitic 254SMO (duplicate samples). The compositions of these materials are shown in [Table 4.2](#) below.

Table 4.2
Chemical composition for alloys being tested (wt %) in the short-term experiments

Alloy	Cr	Ni	Mo	Cu	N	Mn	Si	C	Fe
316L	17.33	11.32	2.08	-	-	1.59	0.31	0.02	Bal
2205	22.47	5.50	3.05	-	0.16	1.82	0.26	0.02	Bal
2507	25.57	6.82	3.76	0.14	0.26	0.47	0.21	0.023	Bal
254SMO	19.9	18.2	6.11	0.75	0.205	0.48	0.49	0.016	Bal

The test cell was similar to the standard cell described in ASTM G5, which includes a platinum counter electrode, a saturated calomel electrode (SCE) as the reference electrode, and an air-cooled condenser to minimize evaporative losses (ASTM, 2014f). The test sample was mounted and tightened between PTFE-fluorocarbon gaskets. Approximately 800 mL of test solution was poured into the test vessel and test vessel placed into a constant temperature bath maintained at 30°C. Fresh solution was used for each test. The test solution was de-aerated using bottled nitrogen gas for one hour prior to the addition of chlorine. The free chlorine concentration was verified using test strips. The gas sparge pipe was moved into the vapor space and the gas flow adjusted to maintain a nitrogen blanket in the test vessel. There was no agitation of the test solution. The test specimen was immersed and a Gamry Instruments PC14 potentiostat connected to the electrodes. The open circuit potential (OCP) was monitored for one hour prior to initiating the potential scan. The potential scan was initiated at -300mV of the final open circuit. A scan rate of 1mV/second was used throughout the test. The scan proceeded in the forward (electro-positive) direction until approximately one volt (1V) was reached or until breakdown occurred and the corrosion current increased 100- fold above the stable passive current. Once one of these conditions was met, the scan was reversed in the electro-negative direction until the corrosion current was less than the stable passive current of the forward scan or the open circuit potential had been reached. After exposure, the test specimens were disassembled and visually evaluated for the presence of pitting or crevice corrosion.

The collected electrochemical data was plotted and analyzed using software provided by Gamry Instruments. The data was analyzed for basic behavior including breakdown potential and the presence of a hysteresis loop. Corrosion rates were calculated from the electrochemical data following the practices of ASTM G102, also referred to as a Tafel Analysis (ASTM 2010a).

After testing, the solution pH was found to have increased. The 3,600 mg/L chloride solution had experienced only a minor change from the initial 6.0 up to 6.2. A more significant change was observed in the 10,000 mg/L chloride solutions with final pH values ranging from 7.0 to 7.5. It was found that the combination of de-aeration and the addition of chlorine resulted in the increased pH values. Attempts to stabilize the pH at 6.0 in the 10,000 mg/L solution proved tedious and impractical as very minor additions of either base or acid resulted in large swings in pH between 7 and 5.2.

Results and Discussion

No transpassive corrosion was observed in the electrochemical data for 2205, 2507, or 254SMO under the conditions of these tests. General corrosion rates were also similar for each alloy. One data plot is presented in [Figure 4.2](#) below representing typical results obtained. Key-point data and data plots are presented in Appendix B.

The breakdown potential (E_b) was never clearly identified and a complete hysteresis loop was not achieved for any of the scanned samples, except for 316/316L stainless steel. No transpassive behavior was identified from the plotted scans, which indicated that general corrosion was the predominant corrosion mechanism. The scans (data plots) were basically the same for the superduplex 2705 and 6% molybdenum alloy 254SMO, when exposed to both 3,600 mg/L and 10,000 mg/L chloride levels. Key-point data and data plots are presented in Appendix B.

A visual inspection of the exposed specimens also showed no discernable crevice corrosion, as illustrated in [Figure 4.3](#).

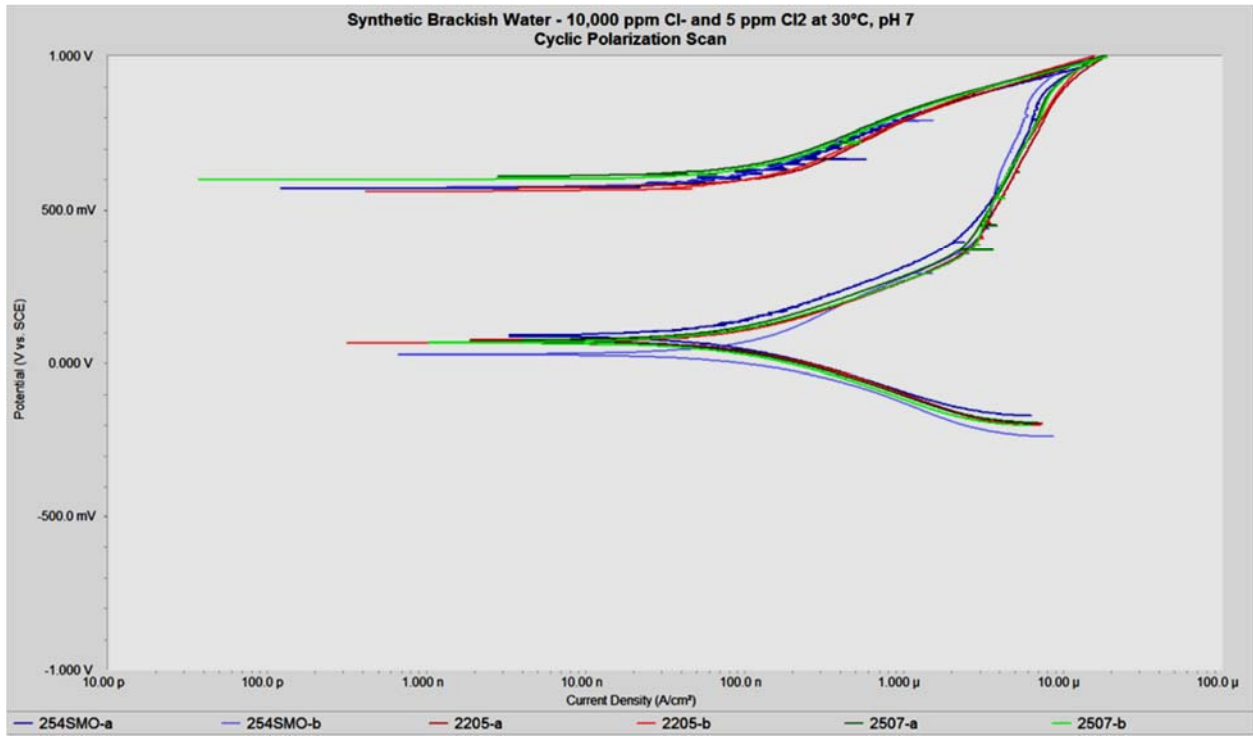


Figure 4.2 Typical data plot showing overlay of all specimens exposed to 10,000 mg/L chloride and 5 mg/L as Cl₂ free chlorine at pH 7 and 30°C



Figure 4.3 Typical appearance of exposed specimens; 11X magnification

Since the original test matrix did not help identify the upper limit for 2205, additional tests were performed to better understand the limits of 2205 in simulated brackish water with 10,000 ppm chlorides. In addition, it helped define parameters for consideration in future test programs.

An Alloy 316/316L test specimen was included in this next test, along with an Alloy 2205 test specimen in order to validate the test method. The test environment was selected to be 10,000 ppm chloride, 5 mg/L Cl₂, at 30°C and with a pH 5.2. Delrin® crevice assemblies were torqued to 40 in.-oz.

These test conditions are summarized in [Table 4.3](#) below and subsequently discussed in more detail.

The first two tests were performed to validate the test method. The 10,000 mg/L chloride with 5 mg/L free chlorine solution at 30°C was selected as the test environment. Since testing at a pH of 6.0 was elusive in this solution, these two tests were performed at a pH of 5.2, which was stable throughout the test. Single tests of Alloys 2205 and 316L were performed.

The 2205 specimen performed similarly to the previous testing, with no breakdown or post-test evidence of localized corrosion. The 316L specimen experienced passive breakdown and subsequent transpassive corrosion, [Figures 4.4](#) through [4.6](#). The results validated the test program, but did not identify the upper limit of exposure to corrosion for duplex 2205 stainless steel.

Table 4.3
Second phase of short-term corrosion tests – conditions and results

Alloy	Chloride (mg/L)	Free chlorine (mg/L as Cl ₂)	pH	Assembly torque *	Temp.	Observations
2205	10,000	5	5.2	40 in.-oz.	30°C	Performed to confirm previous results. Results were confirmed—no corrosion observed.
316L	10,000	5	5.2	40 in.-oz.	30°C	Performed to confirm previous results. Results were confirmed—corrosion was observed.
2205	10,000	0	2.0	40 in.-oz.	30°C	No corrosion was observed.
2205	10,000	0	2.0	14 to 16 in.-lbs.	30°C	No corrosion was observed.
2205	10,000	0	2.0	75 in.-lbs.	30°C	No corrosion was observed.
2205	10,000	0	2.0	75 in.-lbs.	50°C	Corrosion was observed.

* A measurement of the crevice tightness. The three tightness levels shown are common to various industry standard methods (ASTM G48 and ASTM G78; ASTM 2011a and 2008, respectively). Crevice tightness has been linked to corrosion rates.

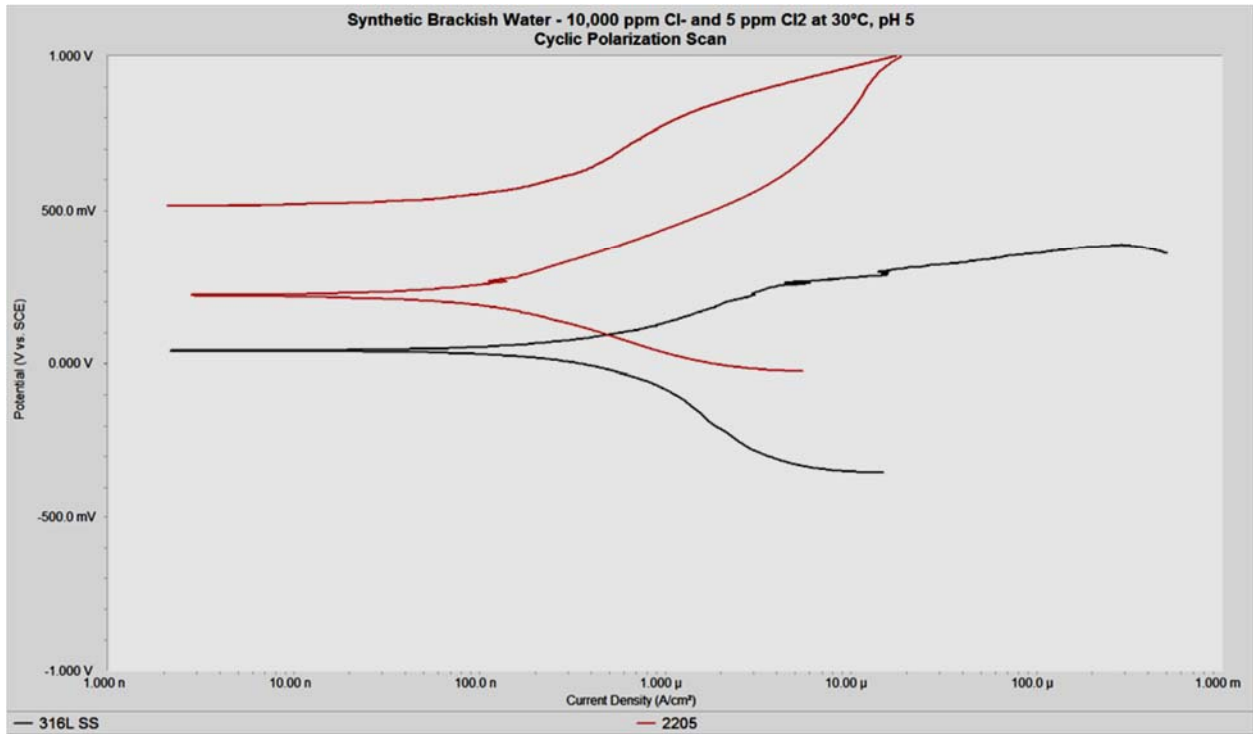


Figure 4.4 Data plots of 2205 (red) and 316L (black) exposed to 10,000 mg/L chloride, no free chlorine, pH 5, at 30°C.



Source: Courtesy of Tampa Bay Desalination Plant

Figure 4.5 Specimen AQR2 (left, 316L) and AVM16 (right, 2205) after exposure to 10,000 mg/L chloride, no free chlorine, pH 5, at 30°C. Crevice corrosion is present in lighter areas



Source: Courtesy of Tampa Bay Desalination Plant

Figure 4.6 Close-up of crevice corrosion, 25X original magnification

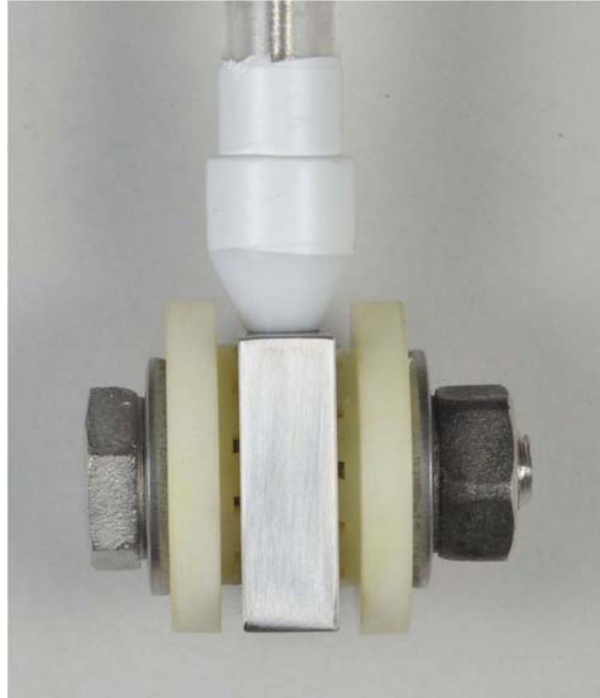
The next set of tests were performed in an attempt to identify the conditions that would initiate crevice corrosion on a 2205 specimen in a synthetic brackish water solution containing 10,000 mg/L chloride. Five conditions were identified for evaluation:

- Solution pH.
- Tightness of the crevice.
- Surface condition.
- Temperature.
- Time.

The lowering of test pH to 5.2 was based on the water's stability (i.e., buffering capacity) when running the earlier polarization tests at 10,000 mg/L chloride (pH 6 was difficult to maintain at these chloride concentrations). Solution pH was also adjusted to 2.0 to simulate the acidic environment that can be present inside a crevice.

A search of ASTM and MTI standards identified three torque levels commonly used in crevice corrosion testing, 40 in.-oz., 14-16 in.-lbs., and 75 in.-lbs.). This necessitated the use of Delrin® crevice spacers, rather than using the PTFE fluorocarbon spacers, in order to achieve the proposed higher levels of torque.

Three tests were performed at 30°C and a pH 2. Delrin® crevice formers were used for the higher torque values (Figure 4.7). Although there was a rapid increase in current initiating at approximately +750 mV in each test, there was no hysteresis in the return curve or visible transpassive corrosion on the test specimens after the test. A Tafel analyses indicated an increasing corrosion rate with increasing applied torque to the crevice assembly.

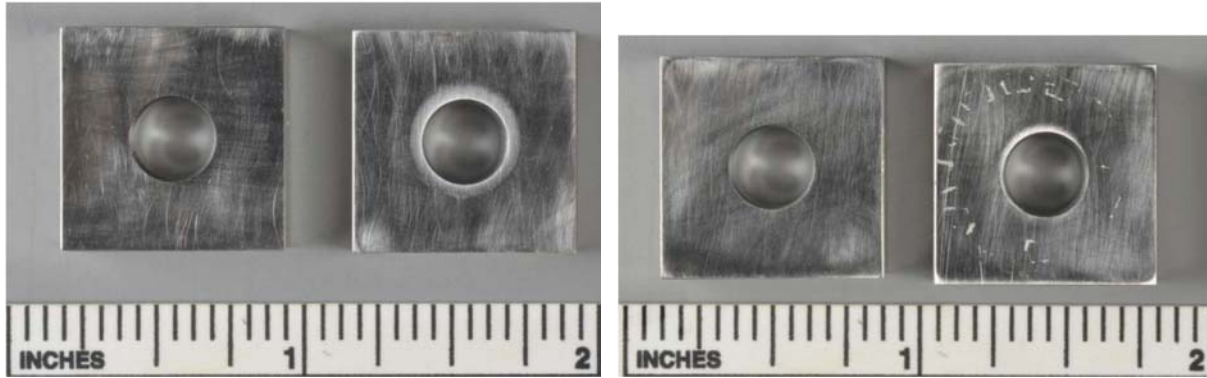


Source: Courtesy of Tampa Bay Desalination Plant

Figure 4.7 Typical crevice assembly using Delrin® crevice washers

The test temperature was increased to 50°C and one test performed at pH 2, with a torque of 75 in.-lbs. Passive breakdown was initiated at approximately +480 mV. Upon reversal of the applied potential, the current remained high forming a large hysteresis loop. Numerous sites of transpassive (crevice) corrosion were observed on the 2205 test sample (see [Figures 4.8 through 4.10](#)).

After exposure, the test specimens were disassembled and inspected for the presence of pitting or crevice corrosion, both visually and by low power magnification (25 times). There was no evidence of crevice corrosion for any of the combinations of variables, except under the most severe conditions (50°C, pH 2, Delrin® washers; and the highest torque). Multiple sites of crevice corrosion were visually evident on Alloy 2205 when exposed to these conditions.



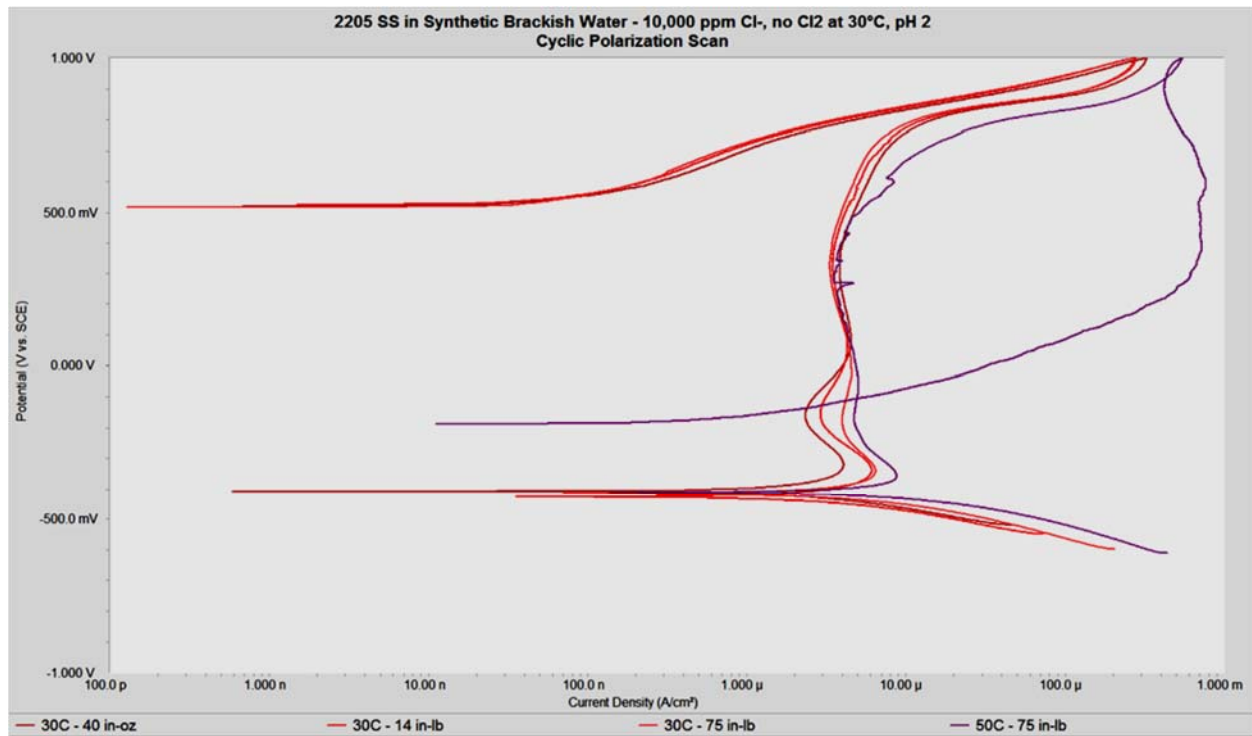
Source: Courtesy of Tampa Bay Desalination Plant

Figure 4.8 2205 test specimens exposed in the additional tests. (Note visible crevice attack (light areas at right, exposed at 50°C.)



Source: Courtesy of Tampa Bay Desalination Plant

Figure 4.9 Close-up of crevice corrosion on Alloy 2205, 25X magnification



Source: Courtesy of Tampa Bay Desalination Plant

Figure 4.10 Data plots representing the additional tests of 2205 at 10,000 ppm chloride (Note hysteresis loop (purple) exposed at 50°C.)

Conclusions

- Preliminary results indicated no observed corrosion in the duplex materials, which was somewhat unexpected. As a result, further testing was performed to identify the exposure tolerances of Duplex 2205 SS. The following information was obtained: No trans-passive corrosion was observed for any of the materials in the baseline test matrix; i.e., no apparent pitting or crevice corrosion. Each alloy performed similarly when exposed to any combination of the environmental conditions. No apparent synergies were observed when free chlorine and chlorides were evaluated together.
- Lowering the pH increased the corrosion rates on Duplex 2205 SS.
- Increasing the applied torque on the crevice assemblies also increased the corrosion rates on Duplex 2205.
- Type 316L SS is susceptible to crevice corrosion in static brackish water with a chloride concentration of 10,000 mg/L, free chlorine of 5 mg/L, at 30°C and a pH of 5.0.
- Duplex 2205 SS may be resistant to crevice corrosion in static brackish water with chloride concentrations up to 10,000 mg/L, free chlorine up to 5 mg/L, at 30°C and the pH range of 5.2 to 7.0. Immersion testing is needed to confirm this, with exposure of at least 60 days (see Phase 2 test results).
- Duplex 2205 SS may be resistant to crevice corrosion in static brackish water with chloride concentrations up to 10,000 mg/L, no free chlorine, at 30°C in pH range of 2.0

to 7.0. Immersion testing is needed to confirm this, with exposure of at least 60 days (see Phase 2 test results).

- Duplex 2205 is susceptible to crevice corrosion in static brackish water with a chloride concentration equal to or greater than 10,000 mg/L at a temperature of 50°C and a pH of 2.0.

Due to the nature of these tests, time for corrosion initiation was not investigated. That work was done in Phase 2.

Implications for Future Work

The original test matrix failed to initiate crevice corrosion in any of the materials being evaluated, Duplex 2205 and 2507 and Austenitic 254SMO stainless steels.

Additional testing of 2205 using harsher conditions did initiate crevice corrosion but at much lower pH (2.0) and higher temperature (50°C) than was used in the original test matrix for the 10,000 ppm chloride synthetic brackish water solution.

These results indicated that further testing was warranted to gain a better understanding of the limits of exposure of these alloys in brackish water based on a longer timeframe. Hence, Phase 2 testing (long-term immersion tests) was performed. This data is presented in the next section.

PHASE 2 – LONG-TERM IMMERSION TESTING

This test program (30-, 60-, and 90-day immersion testing) was initiated to evaluate the performance of four stainless steel grades (316/316L; 2205; 2507 and 254SMO) in brackish water of varying chloride concentration, with and without chlorine treatment. In addition, the 316/316L stainless steel specimens were used to evaluate the performance of various surface finishes or treatments in four of the test conditions.

The test matrix is shown in [Table 4.4](#) below. The first four tests (316/316L) were designed to evaluate specific surface treatments and their benefits, plus one autogenously welded (no filler metal) test coupon. The surface conditions were as follows:

- 120 grit abrasive grind.
- 120 grit abrasive grind plus hydrogen peroxide H₂O₂ passivation.
- 120 grit abrasive grind plus electropolish
- As welded: evaluating the base metal, heat affected zone (HAZ), and weld.

Table 4.4
Long-term immersion test matrix

Environmental conditions			Alloy type tested			
Chloride (mg/L) [†]	pH	Free chlorine (mg/L Cl ₂)	316/316L	2205	2507	254SMO
3,600	5	0	X	X		
		5	X	X		
10,000	5	0	X	X		
		5	X	X		
15,000	5	0		X	X	X
		5		X	X	X
	2	0		X	X	X
		5		X	X	X
20,000	5	0			X	X
		5			X	X
	2	0			X	X
		5			X	X

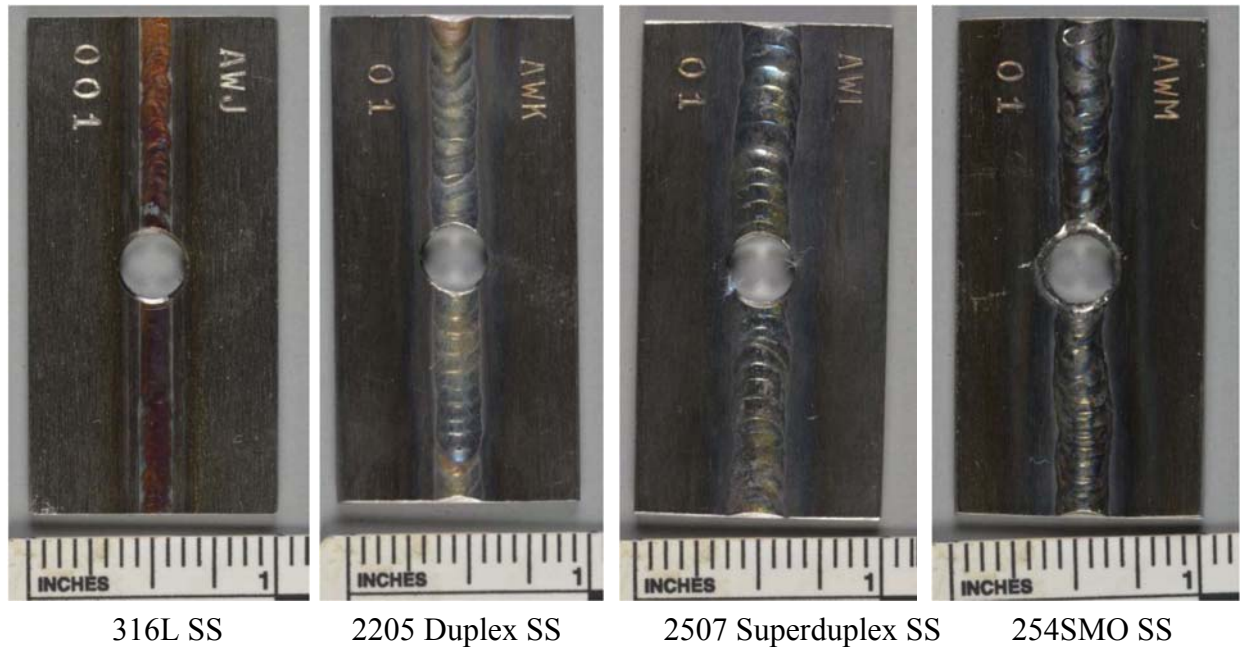
* Test temperature was held at 40°C.

† Total immersion: assemblies were tightened to 75 in-lb, using Delrin[®] crevice formers.

‡ Chlorinated waters were circulated at 1 ft/sec.

Weld Specimen Procedure

Test specimens were procured from The Metal Samples Company (Munford, Alabama). Each specimen was stamped with a unique identification code that includes a 3-letter alloy code and a sequential number. Metal Samples Co. also provided mill certificates for the base metal and weld filler metals used. The 316L specimens were autogenously welded while the 2205, 2507, and 254SMO specimens were butt welded with appropriate filler metal. Welded samples were received by Corrosion Testing Laboratories in the as-welded condition (Figure 4.11). All of the butt weld test samples were inspected to ensure that the weld bead was raised above the plate surface. Similarly, sized weld beads were present on all specimens. A summary of the primary alloying elemental compositions has been tabulated below (Table 4.5).



Source: Courtesy of Tampa Bay Desalination Plant

Figure 4.11 Typical appearance of as-received test specimens

Table 4.5
Test specimen elemental composition based on supplied mill test reports

Alloy/CTL Code	Form	Cr	Ni	Mo	Cu	N	C	Fe	Nb
316L-AWJ	Base	16.98	10.05	2.04	0.426	0.10	0.020	Bal.	-
2205-AWK	Base	22.63	4.78	3.01	-	0.171	0.027	Bal.	-
	2209 Filler	22.94	8.80	3.15	0.05	0.143	0.01	Bal.	-
2507-AWL	Base	25.60	6.8	3.81	0.200	0.290	0.021	Bal.	-
	25104 Filler	25.17	9.49	3.90	0.099	0.24	0.012	Bal.	-
254SMO-AWM	Base	19.90	17.90	6.09	0.73	0.195	0.011	Bal.	-
	I625 Filler	22.64	64.43	8.66	0.02	-	0.01	0.30	3.5

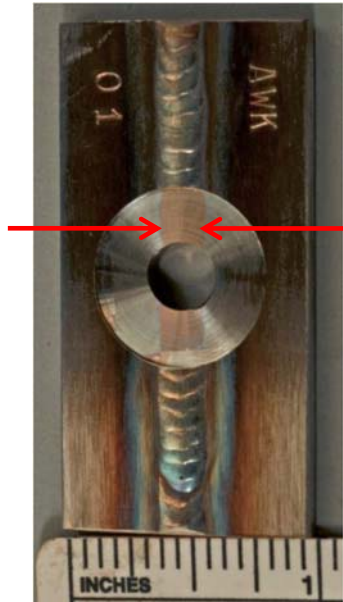
* Bal. = balance of remaining material (summing to 100%).

One specimen of 2205 duplex stainless steel was machined and the machined surface etched to identify the remaining weld filler metal. Using the etch as an indicator, a visual examination confirmed that there was sufficient weld metal on the machined surface for testing.

The various post-weld surface finishes on the 316/316L welded specimens were applied at the corrosion test laboratory. One set was left in the as-welded condition, heat tint still visible. A second set was ground flush on 120-grit paper to remove the heat tint. A third set was ground flush

and passivated in Avesta 630, an H₂O₂-based solution. A fourth set was ground flush and electropolished.

The 2205, 2507 and 254SMO specimens had a flat circular area machined to provide a suitable surface for attachment of the crevice washers. The machined surface was subsequently ground using 240 grit abrasive to remove shallow machining marks (see [Figure 4.12](#)).



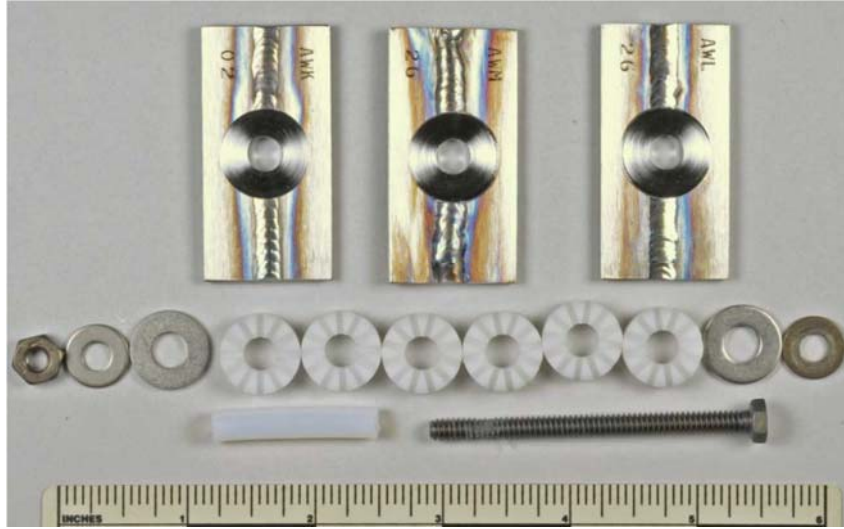
Source: Courtesy of Tampa Bay Desalination Plant

Figure 4.12 Machined surface etched to reveal remaining weld metal (arrows)

After fabrication, each specimen was cleaned, weighed to the nearest 0.0001 gram and measured to the nearest 0.01 mm. One specimen of each alloy was kept as an unexposed reference.

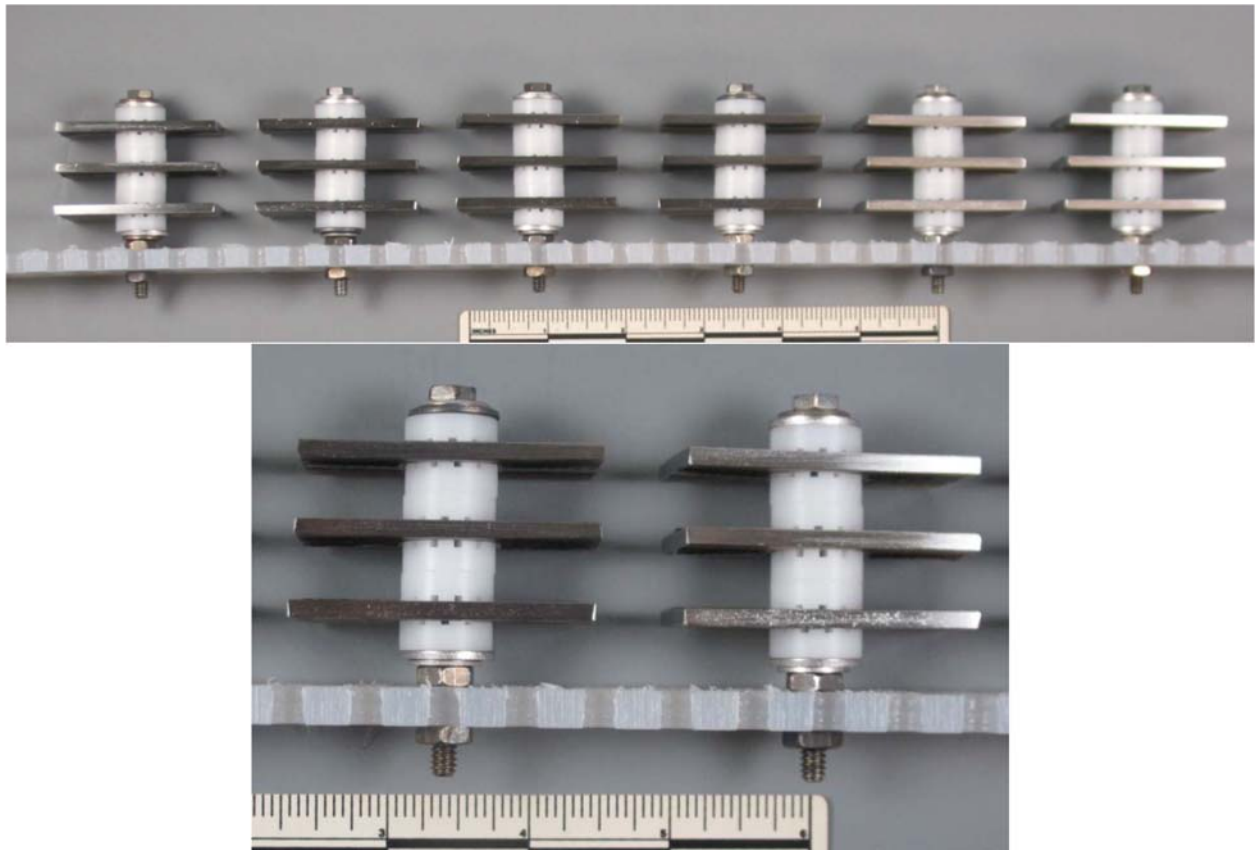
The crevice assembly consisted of a test specimen sandwiched between two Delrin® crevice formers, held in place with titanium hardware and PTFE insulators (see [Figures 4.13](#) and [4.14](#)). Non-metal crevice formers were used for the experiments to produce tighter crevices, which more readily promote crevice corrosion initiation. Each crevice former had twelve raised surfaces that contacted the test specimen forming pie-shape crevices. The crevice formers were positioned such that artificial crevices were formed on the weld metal, HAZ, and base metal of each specimen. The assembly followed the guidelines of ASTM G78 (ASTM 2008). Up to three specimens were placed in one assembly and the assembly tightened to 75 in.-lbs. (8.5 N-m).

The crevice assemblies were attached to a polypropylene rack ([Figure 4.14](#)). Each rack contained multiple assemblies, as required for the various exposures. The assembled racks were inserted into the appropriate test vessels.



Source: Courtesy of Tampa Bay Desalination Plant

Figure 4.13 Crevice assembly showing three specimens, six crevice washers, Ti bolt, PTFE insulating tube, and Ti washers and nut



Source: Courtesy of Tampa Bay Desalination Plant

Figure 4.14 Typical crevice assembly and rack

The Test Solutions

The test solutions were prepared using synthetic sea salts that meet the requirements of ASTM D1141 (purchased from Lake Products Company, Inc.) and laboratory prepared de-ionized water that met the requirements of ASTM D1193 Grade IV. The salt concentrations were adjusted to obtain the desired chloride concentrations, which were verified by ion chromatography.

The solutions that had free chlorine were prepared using household bleach. These solutions were dosed daily to maintain a concentration of 5 mg/L as Cl₂ free chlorine. The concentration of free chlorine was measured using commercial test strips that had been verified by spectrophotometry. Solution pH was adjusted with hydrochloric acid to obtain and maintain the desired pH of either 2 or 5.

During exposure, six solutions were dosed with bleach daily and the pH adjusted as needed. The pH of the six non-chlorinated solutions was monitored on a weekly basis and adjusted as required. Evaporative losses were replaced with deionized water.

Test Vessels

The test vessels were fabricated using clear PVC pipe to make a vertical column that could hold the test specimens (Figure 4.15). The column was placed above a 6-gallon reservoir that contained the test solution (20 liters) and a circulating pump, as is shown in the schematic and photograph below. The test solution was introduced into the bottom of the column flowing upward and exiting out the top and returning to the reservoir. The reservoir was internally heated using a titanium immersion heater connected to a digital temperature controller that was verified accurate at the test temperature of 40°C. There was one test set-up for each test condition (total of 12). Test specimens exposed to similar test conditions were placed in the same test vessel.

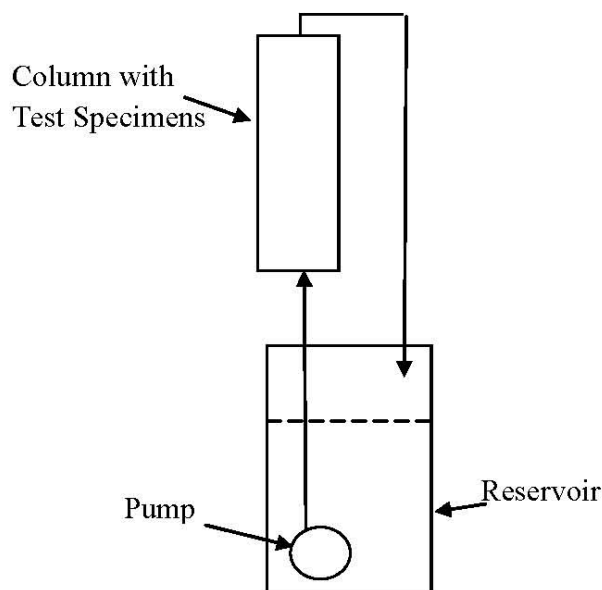


Figure 4.15 Test vessels, schematic on left and photo of exposure column on right

Exposure Procedure

The test specimens were assembled into racks, and the assemblies were inserted into the appropriate columns. The test solutions were added to the reservoirs and heated to 40°C. Once at temperature, the circulation was initiated at a flow rate of <1 ft/s. The test was maintained for 30 days with periodic monitoring of the test solutions.

During exposure, the solution chemistry (i.e., free chlorine, pH) was checked and adjusted daily. Chloride concentrations were also routinely analyzed and adjusted. Any evaporative losses were made up with deionized water. The test solutions were replaced with fresh solution every 30 days.

After the first 30-day exposure period the columns were opened, the racks lifted up and the 30-day specimens removed from each column. The racks were then immediately returned to exposure. Shortly thereafter, the test solutions were replaced. The circulation pumps were turned off and the columns removed from the reservoirs. The old solution was discarded and the reservoir was rinsed and dried before addition of the fresh solution. The column was then reinstalled and the exposure re-initiated. Each solution change required approximately 10 minutes. During this time, the test specimens remained in the columns and, although they were not immersed, remained wet until the exposure was re-initiated. The same procedure was followed after the subsequent exposure periods (i.e., 60 and 90 days total exposure).

Test Specimen Evaluation

Upon removal from exposure, the samples were rinsed with de-ionized water. As soon as possible, thereafter, the specimens were cleaned following the guidelines of ASTM G1. The cleaned specimens were dried and re-weighed and the mass loss used to calculate a general corrosion rate. Each specimen was then evaluated optically for the presence of crevice corrosion. Corrosion was evaluated based on the number of crevice sites and crevice depth. The number of crevice sites (maximum of 24 per specimen) was determined at 10X optical magnification. The maximum depth of attack was measured using the Microscopical Method described in ASTM G46, *Standard Practice for Examination and Evaluation of Pitting Corrosion* (ASTM 2013g). The exposed specimens were then photographed. Any corrosion events in non-creviced areas was considered pitting corrosion rather than crevice corrosion.

RESULTS

Thirty-Day Test Period

During this test period, evaporative losses of approximately 400 mL per week were observed. This was made up with de-ionized water. After the first 14 days of exposure, the concentration of the chlorinated 3,600-ppm chloride solution had increased slightly to 3,900 ppm. The concentration was adjusted back to 3,600 ppm by the addition of de-ionized water. The remaining solutions did not experience any significant change in concentration. After the first 30 days of exposure, the first set of specimens was removed from each test vessel.



Figure 4.16 Test specimen assembly consisting of 316L SS specimens after 90 days of exposure; Note rust stains on crevice washers

Sixty-Day Test Period

During this test period, evaporative losses of approximately 400 mL were made up weekly with de-ionized water. During this exposure period (Day 45), the concentration of the chlorinated 3,600 ppm chloride solution had increased slightly, to 3,700 ppm. The concentration was adjusted back to 3,600 ppm by the addition of de-ionized water. The remaining solutions did not experience any significant change in concentration. After 60 days of exposure, the second set of specimens was removed from each test vessel.

Ninety-Day Test Period

During this test period, evaporative losses of approximately 400 mL were made up weekly with de-ionized water. During this exposure period (Day 75), the concentration of the chlorinated 3,600-ppm chloride solution had increased slightly to 3,700 ppm. The concentration was adjusted back to 3,600 ppm by the addition of de-ionized water. The remaining solutions did not experience any significant change in concentration. After 90 days of exposure, the final set of specimens was removed from each test vessel terminating the test (See [Figure 4.16](#)).

Corrosion Observations

In review, six (6) test specimens of each material were exposed to various test conditions as described earlier. Two (2) specimens were exposed for each time interval, 30 days, 60 days, and 90 days.

The exposed specimens were cleaned and evaluated as described above. In general, crevice corrosion was observed in each test condition to varying degrees depending on alloy, chloride concentration, pH, and chlorination. The results have been summarized in [Tables 4.6](#) through [4.39](#). Photographs of the exposed specimens after 30, 60, and 90 days exposure are presented in Appendix C. Results related to these tables and figures are described below.

Type 316L SS

These test specimens experienced crevice corrosion within 30 days in every test condition that they were exposed to. There was very little difference in the number of crevice sites per specimen between the as-welded, ground, and the ground-passivated specimens. The electropolished specimens also experienced crevice corrosion in each test condition but fewer crevice sites were observed on each specimen than on the other 316L specimens (Tables 4.6 through 4.15).

Pitting corrosion was observed in the non-creviced area of the weld on both 90-day as-welded specimens exposed to the chlorinated 10,000 mg/L chloride solution.

2205 Duplex SS

3,600 mg/L Chloride. Crevice corrosion was observed on both specimens exposed for 60 days to the non-chlorinated solution but not on the 30 or 90-day specimens. In the chlorinated solution, crevice attack was observed on five of the six specimens exposed. The crevice attack was primarily located in the weld metal or the HAZ (Tables 4.6 through 11).

10,000 mg/L Chloride. Crevice corrosion was observed on three specimens (one 60-day and both 90-day specimens) exposed to the non-chlorinated solution. In the chlorinated solution, crevice attack was present on four specimens (both specimens exposed for 60 and 90-days) of the six specimens exposed. There were more initiation sites and deeper crevice attack on the specimens exposed in the chlorinated solution (Tables 4.12 through 17).

15,000 mg/L Chloride- pH 5. Crevice corrosion was observed on two specimens (one 30-day and one 90-day specimen) exposed to the non-chlorinated solution. In the chlorinated solution, crevice attack was observed on all six specimens (Tables 4.18 through 23).

15,000 mg/L Chloride- pH 2. Crevice corrosion was observed on all six specimens exposed to both the non-chlorinated and the chlorinated solutions. The specimens exposed to the chlorinated solution had more initiation sites and deeper attack than those exposed to the non-chlorinated solution. (Tables 4.24 through 29).

Pitting Corrosion. Pitting corrosion was observed in the non-creviced areas of the weld on several of the 2205 specimens exposed to the chlorinated solutions. Examination of an unexposed specimen revealed the presence of small slag particles embedded in the surface of the weld metal, which could have served as initiation sites for at least some of the pits. This attack was not observed on the specimens exposed to the non-chlorinated solutions. Representative photographs are presented in Appendix C.

2507 Superduplex SS

15,000 mg/L Chloride- pH 5. Crevice corrosion was observed on one specimen (90-day specimen) exposed to the non-chlorinated solution. In the chlorinated solution, crevice attack was observed on three specimens. (Tables 4.18 through 23).

15,000 mg/L Chloride- pH 2. Crevice corrosion was not observed on any of the specimens exposed to the non-chlorinated solution and only one specimen (30-day specimen) exposed to the chlorinated solution. (Tables 4.24 through 29).

20,000 mg/L Chloride – pH 5. Crevice corrosion was not observed on any of the specimens exposed to the non-chlorinated solution. In the chlorinated solution, crevice attack was present on both specimens exposed for 90-days. (Tables 4.31 through 32).

20,000 mg/L Chloride – pH 2. Crevice corrosion was observed on two of the specimens (one 30- day and one 90-day specimen) exposed to the non-chlorinated solution. In the chlorinated solution, crevice attack was present on three specimens, one 30-day, one 60-day and one 90-day. (See Tables 4.33 through 39).

Superficial corrosion of the as-welded, non-creviced areas of several specimens exposed to the chlorinated solutions was observed.

254 SMO Super-austenitic SS

15,000 mg/L Chloride- pH 5. Crevice corrosion was not observed on any of the specimens exposed to the non-chlorinated solution. In the chlorinated solution, crevice attack was observed on three specimens (one 30-day and both 90 day specimen; Tables 4.18 through 23).

15,000 mg/L Chloride- pH 2. Crevice corrosion was observed on one of the specimens (60-day specimen) exposed to the non-chlorinated solution. In the chlorinated solution, crevice attack was observed on all six specimens (Tables 4.24 through 29).

20,000 mg/L Chloride – pH 5. Crevice corrosion was observed on one of the specimens (30-day exposure) exposed to the non-chlorinated solution. In the chlorinated solution, crevice attack was present on three specimens (one 30-day and both 90-day specimen; Tables 4.30 through 35).

20,000 mg/L Chloride – pH 2. Crevice corrosion was observed on two of the specimens (both 30-day specimens) exposed to the non-chlorinated solution. In the chlorinated solution, crevice attack was present on five specimens, one 30-day and both 60 and 90-day specimens (Tables 4.25 through 41).

Superficial corrosion of the as-welded, non-creviced areas of several specimens exposed to the chlorinated solutions was observed.

Table 4.6
Thirty-day evaluation; 3,600 mg/L Cl₂, pH = 5, No free chlorine

Alloy	Surface treatment	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
316L SS	As welded	AWJ-15	(0.02) [0.00]	5	(1.8) [0.046]	Weld HAZ
		AWJ-16	(0.02) [0.00]	3	(1.2) [0.030]	Weld HAZ
	120-grit ground	AWJ-39	(0.2) [0.00]	3	(1.5) [0.038]	Base, Weld HAZ
		AWJ-40	(0.01) [0.00]	2	(1.0) [0.024]	Base, Weld HAZ
	120-grit ground, then H ₂ O ₂	AWJ-63	(0.02) [0.00]	2	(2.0) [0.052]	Base, Weld HAZ
		AWJ-64	(0.01) [0.00]	7	(2.0) [0.040]	Base, Weld HAZ
	Electropolished	AWJ-88	(<0.01) [0.00]	1	(1.2) [0.030]	Base
		AWJ-89	(<0.01) [0.00]	1	(1.9) [0.048]	Base
	2205 Duplex SS	None	AWK-38	(<0.01) [0.00]	0	N/A
AWK-39			(<0.01) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.7
Sixty-day evaluation; 3,600 mg/L Cl⁻, pH = 5, No free chlorine

Alloy	Surface treatment	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
316L SS	As welded	AWJ-17	(0.01) [0.00]	5	(1.3) [0.034]	Weld HAZ
		AWJ-18	(0.01) [0.00]	3	(2.4) [0.062]	Base, Weld HAZ
	120-grit ground	AWJ-41	(0.1) [0.00]	3	(1.1) [0.026]	Base, Weld HAZ
		AWJ-42	(0.01) [0.00]	6	(2.7) [0.068]	Base, Weld HAZ
	120-grit ground then H ₂ O ₂	AWJ-65	(0.01) [0.00]	4	(2.6) [0.066]	Base, Weld HAZ
		AWJ-67	(0.01) [0.00]	5	(1.3) [0.034]	Base, Weld HAZ
	Electropolished	AWJ-90	(0.01) [0.00]	5	(2.2) [0.056]	Base, Weld, HAZ
		AWJ-91	(0.01) [0.00]	2	(1.4) [0.036]	Base
	2205 Duplex SS	None	AWK-40	(0.01) [0.00]	4	(0.7) [0.018]
AWK-41			(<0.01) [0.00]	1	(1.0) [0.026]	HAZ

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.8
Ninety-day evaluation; 3,600 mg/L Cl₂, pH = 5, No free chlorine

Alloy	Surface treatment	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
316L SS	As welded	AWJ-19	(0.01) [0.00]	8	(1.1) [0.028]	Base, Weld HAZ
		AWJ-20	(0.01) [0.00]	7	(2.1) [0.054]	Base, Weld HAZ
	120-grit ground	AWJ-43	(0.01) [0.00]	7	(1.0) [0.026]	Base, Weld HAZ
		AWJ-44	(0.01) [0.00]	9	(1.7) [0.044]	Base, Weld HAZ
	120-grit ground, then H ₂ O ₂	AWJ-68	(0.01) [0.00]	6	(2.3) [0.060]	Base, Weld HAZ
		AWJ-69	(0.01) [0.00]	6	(1.0) [0.026]	Base, Weld HAZ
	Electropolished	AWJ-92	(<0.01) [0.00]	7	(6.3) [0.016]	Base, Weld HAZ
		AWJ-93	(<0.01) [0.00]	3	(1.5) [0.038]	Base, Weld HAZ
2205 Duplex SS	None	AWK-42	(<0.01) [0.00]	0	N/A	N/A
		AWK-43	(<0.01) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.9
Thirty-day evaluation; 3,600 mg/L Cl⁻, pH = 5, Free chlorine = 5 mg/L as Cl₂

Alloy	Surface treatment	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [0.098]	Location of attack
316L SS	As welded	AWJ-21	(0.06) [0.00]	16	(3.9) [0.098]	Base, Weld HAZ
		AWJ-22	(0.07) [0.00]	19	(3.1) [0.080]	Base, Weld HAZ
	120-grit ground	AWJ-45	(0.02) [0.00]	17	(3.1) [0.078]	Base, Weld HAZ
		AWJ-46	(0.02) [0.00]	16	(3.1) [0.080]	Base, Weld HAZ
	120-grit ground, then	AWJ-70	(0.02) [0.00]	10	(1.4) [0.036]	Base, Weld HAZ
		AWJ-71	(0.03) [0.00]	18	(1.7) [0.044]	Base, Weld HAZ
	Electropolished	AWJ-94	(0.02) [0.00]	11	(1.9) [0.048]	Base, Weld HAZ
		AWJ-95	(<0.01) [0.00]	19	(<0.5) [<0.010]	Base, Weld HAZ
	2205 Duplex SS	None	AWK-44	(0.03) [0.00]	0	N/A
AWK-45			(<0.03) [0.00]	5	(3.7) [0.094]	Weld HAZ

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.10
Sixty-day evaluation; 3,600 mg/L Cl₂, pH = 5, Free chlorine = 5 mg/L as Cl₂

Alloy	Surface treatment	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack	
316L SS	As welded	AWJ-23	(0.09) [0.00]	20	(7.2) [0.182]	Base, Weld HAZ	
		AWJ-24	(0.10) [0.00]	18	(6.7) [0.170]	Base, Weld HAZ	
	120-grit ground	AWJ-47	(0.02) [0.00]	21	(4.2) [0.106]	Base, Weld HAZ	
		AWJ-48	(0.02) [0.00]	21	(4.0) [0.100]	Base, Weld HAZ	
	120-grit ground, then	AWJ-72	(0.02) [0.00]	18	(4.2) 0.106]	Base, Weld HAZ	
		AWJ-73	(0.02) [0.00]	19	(3.6) [0.092]	Base, Weld HAZ	
	Electropolished	AWJ-96	(<0.01) [0.00]	5	(1.6) [0.040]	Base, Weld HAZ	
		AWJ-97	(<0.01) [0.00]	9	(2.9) [0.074]	Base, Weld HAZ	
	2205 Duplex SS	None	AWK-46	(0.03) [0.00]	1	(1.1) [0.028]	HAZ
			AWK-47	(0.04) [0.00]	2	(1.3) [0.032]	HAZ

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.11
Ninety-day evaluation; 3,600 mg/L Cl⁻, pH = 5, Free chlorine = 5 mg/L as Cl₂

Alloy	Surface treatment	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack	
316L SS	As welded	AWJ-25	(0.29) [0.01]	23	(7.7) [0.196]	Base, Weld, HAZ	
		AWJ-26	(0.32) [0.01]	24	(6.5) [0.164]	Base, Weld, HAZ	
	120-grit ground	AWJ-49	(0.10) [0.00]	22	(11) [0.272]	Base, Weld, HAZ	
		AWJ-50	(0.09) [0.00]	24	(12) [0.312]	Base, Weld, HAZ	
	120-grit ground, then	AWJ-74	(0.07) [0.00]	21	(1.9) [0.048]	Base, Weld, HAZ	
		AWJ-75	(0.09) [0.00]	20	(12.3) [0.312]	Base, Weld, HAZ	
	Electropolished	AWJ-98	(0.02) [0.00]	9	(8.0) [0.206]	Base, Weld, HAZ	
		AWJ-99	(0.02) [0.00]	10	(7.2) [0.182]	Base, Weld, HAZ	
	2205 Duplex SS	None	AWK-48	(0.12) [0.00]	2	(0.5) [0.014]	Base*
			AWK-49	(0.14) [0.00]	2	(2.2) [0.056]	Weld, HAZ*

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

* Pitting corrosion observed in the non-creviced areas of the weld.

Table 4.12
Thirty-day evaluation; 10,000 mg/L Cl⁻, pH = 5, No free chlorine

Alloy	Surface treatment	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
316L SS	As welded	AWJ-02	(0.03)	6	(2.0)	Base
		AWJ-03	[0.00]		[0.052]	HAZ
		AWJ-03	(0.03)	7	(2.0)	Base, Weld
		[0.00]	[0.050]		HAZ	
	120-grit ground	AWJ-27	(0.02)	7	(1.0)	Base
			[0.00]		[0.02]	HAZ
		AWJ-28	(0.01)	7	(0.9)	Base
			[0.00]		[0.022]	HAZ
	120-grit ground, then passivated	AWJ-51	(0.02)	4	(1.2)	Base
			[0.00]		[0.030]	HAZ
	AWJ-52	(0.01)	6	(1.3)	Base, Weld	
		[0.00]		[0.032]	HAZ	
Electropolished	AWJ-79	(0.02)	4	(2.3)	Base, Weld	
		[0.00]		[0.058]	HAZ	
	AWJ-80	(0.01)	6	(1.8)	Base	
		[0.00]		[0.046]	HAZ	
2205 Duplex SS	None	AWK-26	(<0.01)	0	N/A	N/A
			[0.00]			
		AWK-28	(<0.01)	0	N/A	N/A
			[0.00]			

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.13
Sixty-day evaluation; 10,000 mg/L Cl₂, pH = 5, No free chlorine

Alloy	Surface treatment	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
316L SS	As welded	AWJ-07	(0.02) [0.00]	6	(1.6) [0.040]	Base Weld HAZ
		AWJ-08	(0.02) [0.00]	6	(2.4) [0.062]	Base, Weld HAZ
	120-grit ground	AWJ-31	(0.01) [0.00]	8	(2.5) [0.064]	Base Weld HAZ
		AWJ-32	(0.01) [0.00]	10	(1.2) [0.030]	Base Weld HAZ
	120-grit ground, then passivated	AWJ-55	(0.01) [0.00]	5	(2.1) [0.054]	Base Weld HAZ
		AWJ-56	(0.01) [0.00]	6	(2.4) [0.060]	Base, Weld HAZ
	Electropolished	AWJ-77	(<0.01) [0.00]	3	(1.4) [0.036]	Weld HAZ
		AWJ-78	(0.01) [0.00]	8	(2.6) [0.066]	Base Weld HAZ
2205 Duplex SS	None	AWK-27	(<0.01) [0.00]	6	(1.5) [0.038]	Base, Weld HAZ
		AWK-29	(0.01) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.14
Ninety-day evaluation; 10,000 mg/L Cl⁻, pH = 5, No free chlorine

Alloy	Surface treatment	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
316L SS	As welded	AWJ-05	(0.02) [0.00]	9	(1.6) [0.040]	Weld, HAZ
		AWJ-06	(0.01) [0.00]	8	(2.4) [0.062]	Weld, HAZ
	120-grit ground	AWJ-29	(0.01) [0.00]	8	(2.5) [0.064]	Weld
		AWJ-30	(0.01) [0.00]	10	(1.2) [0.030]	HAZ
	120-grit ground, then H ₂ O ₂	AWJ-53	(0.01) [0.00]	7	(2.0) [0.064]	Weld
		AWJ-54	(0.01) [0.00]	10	(1.2) [0.030]	Weld
	Electropolished	AWJ-76	(0.01) [0.00]	4	(1.7) [0.044]	Base, Weld HAZ
		AWJ-81	(0.01) [0.00]	3	(1.4) [0.036]	Base, Weld HAZ
2205 Duplex SS	None	AWK-30	(<0.01) [0.00]	1	(1.0) [0.026]	HAZ
		AWK-31	(<0.01) [0.00]	1	(1.3) [0.032]	HAZ

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.15
Thirty-day evaluation; 10,000 mg/L Cl₂, pH = 5, Free chlorine = 5 mg/L as Cl₂

Alloy	Surface treatment	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
316L SS	As welded	AWJ-09	(0.21) [0.01]	20	(8.0) [0.202]	Base, Weld HAZ
		AWJ-10	(0.22) [0.01]	20	(7.2) [0.182]	Base, Weld HAZ
	120-grit ground	AWJ-33	(0.05) [0.00]	17	(4.2) [0.106]	Base, Weld HAZ
		AWJ-34	(0.07) [0.00]	13	(3.1) [0.079]	Base, Weld HAZ
	120-grit ground, then H ₂ O ₂	AWJ-57	(0.04) [0.00]	11	(2.9) [0.074]	Base, Weld HAZ
		AWJ-58	(0.05) [0.00]	15	(1.6) [0.040]	Base, Weld HAZ
	Electropolished	AWJ-86	(0.01) [0.00]	10	(3.5) [0.088]	Base, Weld HAZ
		AWJ-87	(0.01) [0.00]	10	(2.0) [0.054]	Base, Weld HAZ
2205 Duplex SS	None	AWK-32	(0.07) [0.00]	0	N/A	N/A
		AWK-33	(0.09) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.16
Sixty-day evaluation; 10,000 mg/L Cl⁻, pH = 5, Free chlorine = 5 mg/L as Cl₂

Alloy	Surface treatment	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
316L SS	As welded	AWJ-11	(0.26) [0.01]	21	(8.7) [0.220]	Base, Weld HAZ
		AWJ-12	(0.26) [0.01]	23	(9.3) [0.236]	Base, Weld HAZ
	120-grit ground	AWJ-35	(0.6) [0.00]	22	(5.0) [0.126]	Base, Weld HAZ
		AWJ-36	(0.7) [0.00]	19	(5.7) [0.144]	Base, Weld HAZ
	120-grit ground, then H ₂ O ₂	AWJ-59	(0.06) [0.00]	20	(4.7) [0.120]	Base, Weld HAZ
		AWJ-60	(0.05) [0.00]	17	(7.9) [0.200]	Base, Weld HAZ
	Electropolished	AWJ-84	(0.01) [0.00]	16	(3.3) [0.084]	Base, Weld HAZ
		AWJ-85	(0.01) [0.00]	12	(4.3) [0.110]	Base, Weld HAZ
2205 Duplex SS	None	AWK-34	(0.14) [0.09]	12	(4.3) [0.052]	Base, Weld HAZ
		AWK-35	(0.11) [0.00]	3	(4.3) [0.058]	Base, HAZ

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.17
Ninety-day evaluation; 10,000 mg/L Cl⁻, pH = 5, Free chlorine = 5 mg/L as Cl₂

Alloy	Surface treatment	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
316L SS	As welded	AWJ-13	(0.33) [0.00]	24	(7.2) [0.182]	Base, Weld* HAZ
		AWJ-14	(0.25) [0.00]	23	(3.5) [0.088]	Base, Weld* HAZ
	120-grit ground	AWJ-37	(0.10) [0.00]	22	(5.8) [0.148]	Base, Weld HAZ
		AWJ-38	(0.10) [0.00]	22	(4.9) [0.124]	Base, Weld HAZ
	120-grit ground, then H ₂ O ₂	AWJ-61	(0.09) [0.00]	21	(3.1) [0.080]	Base, Weld HAZ
		AWJ-62	(0.09) [0.00]	22	(3.1) [0.080]	Base, Weld HAZ
	Electropolished	AWJ-82	(0.03) [0.00]	22	(2.1) [0.54]	Base, Weld HAZ
		AWJ-83	(0.01) [0.00]	14	(7.2) [0.184]	Base, Weld HAZ
2205 Duplex SS	None	AWK-36	(0.15) [0.00]	4	(2.8) [0.072]	HAZ*
		AWK-37	(0.15) [0.00]	4	(6.2) [0.158]	Weld, HAZ*

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

* Pitting corrosion observed in the non-creviced areas of the weld.

Table 4.18
Thirty-day evaluation; 15,000 mg/L Cl₂, pH = 5, No free chlorine

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2205	AWK-02	(0.01) [0.00]	1	(0.6) [0.016]	HAZ
	AWK-03	(0.01) [0.00]	0	N/A	N/A
2507	AWL-26	(0.01) [0.00]	0	N/A	N/A
	AWL-27	(0.01) [0.00]	0	N/A	N/A
254SMO	AWM-26	(<0.01) [0.00]	0	N/A	N/A
	AWM-27	(<0.01) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.19
Sixty-day evaluation; 15,000 mg/L Cl₂, pH = 5, No free chlorine

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2205	AWK-04	(0.01) [0.00]	0	N/A	N/A
	AWK-05	(0.00) [0.00]	0	N/A	N/A
2507	AWL-028	(0.01) [0.00]	0	N/A	N/A
	AWL-029	(0.00) [0.00]	0	N/A	N/A
254SMO	AWM-28	(<0.01) [0.00]	0	N/A	N/A
	AWM-29	(<0.01) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.20
Ninety-day evaluation; 15,000 mg/L Cl₂, pH = 5, No free chlorine

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2205	AWK-06	(0.30) [0.00]	0	N/A	N/A
	AWK-07	(1.30) [0.01]	1	(1.8) [0.046]	HAZ
2507	AWL-30	(0.50) [0.00]	1	(0.8) [0.020]	Weld
	AWL-31	(0.30) [0.00]	0	N/A	N/A
254SMO	AWM-30	(0.30) [0.00]	0	N/A	N/A
	AWM-31	(0.50) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.21
Thirty-day evaluation; 15,000 mg/L Cl₂, pH = 5, Free chlorine = 5 mg/L as Cl₂

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2205	AWK-08	(0.21) [0.01]	1	(3.0) [0.076]	Weld HAZ
	AWK-09	(0.17) [0.00]	3	(3.0) [0.072]	HAZ
2507	AWL-32	(0.06) [0.00]	2	(<0.5) [0.010]	Weld HAZ
	AWL-33	(0.03) [0.00]	1	(1.2) [0.30]	Weld
254SMO	AWM-32	(0.01) [0.00]	0	N/A	N/A
	AWM-33	(0.01) [0.00]	1	(3.0) [0.078]	HAZ

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.22
Sixty-day evaluation; 15,000 mg/L Cl⁻, pH = 5, Free chlorine = 5 mg/L as Cl₂

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2205	AWK-10	(0.19) [0.00]	5	(4.3) [0.110]	HAZ, Base
	AWK-11	(0.11) [0.00]	3	(4.2) [0.108]	HAZ
2507	AWL-34	(0.01) [0.00]	0	N/A	N/A
	AWL-35	(0.01) [0.00]	0	N/A	N/A
254SMO	AWM-34	(0.01) [0.00]	0	N/A	N/A
	AWM-35	(0.01) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.23
Ninety-day evaluation; 15,000 mg/L Cl⁻, pH = 5, Free chlorine = 5 mg/L as Cl₂

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2205	AWK-12	(0.13) [0.00]	2	(1.9) [0.048]	HAZ, Base*
	AWK-13	(0.23) [0.01]	2	(3.0) [0.076]	HAZ*
2507	AWL-36	(0.01) [0.00]	1	(2.6) [0.066]	Weld
	AWL-37	(0.01) [0.00]	0	N/A	N/A
254SMO	AWM-36	(0.01) [0.00]	1	(0.8) [0.020]	HAZ
	AWM-37	(0.01) [0.00]	3	(0.9) [0.024]	Weld

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

* Pitting corrosion observed in the non-creviced areas of the weld.

Table 4.24
Thirty-day evaluation; 15,000 mg/L Cl₂, pH = 2, No free chlorine

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2205	AWK-14	(0.02) [0.00]	1	(<0.5) [0.010]	HAZ
	AWK-15	(0.03) [0.00]	1	(2.0) [0.046]	HAZ
2507	AWL-38	(0.02) [0.00]	0	N/A	N/A
	AWL-39	(<0.01) [0.00]	0	N/A	N/A
254SMO	AWM-38	(0.01) [0.00]	0	N/A	N/A
	AWM-39	(0.01) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.25
Sixty-day evaluation; 15,000 mg/L Cl₂, pH = 2, No free chlorine

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2205	AWK-16	(0.04) [0.00]	1	(2.4) [0.062]	HAZ
	AWK-17	(0.02) [0.00]	3	(2.0) [0.050]	HAZ
2507	AWL-40	(0.01) [0.00]	0	N/A	N/A
	AWL-41	(0.01) [0.00]	0	N/A	N/A
254SMO	AWM-40	(0.01) [0.00]	1	(<0.5) [<0.010]	HAZ
	AWM-41	(0.01) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.26
Ninety-day evaluation; 15,000 mg/L Cl₂, pH = 2, No free chlorine

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2205	AWK-18	(0.01) [0.00]	5	(2.5) [0.064]	Base, Weld HAZ
	AWK-19	(0.01) [0.00]	3	(1.9) [0.048]	Base, HAZ
2507	AWL-42	(0.01) [0.00]	0	N/A	N/A
	AWL-43	(<0.01) [0.00]	0	N/A	N/A
254SMO	AWM-42	(<0.01) [0.00]	0	N/A	N/A
	AWM-43	(0.01) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.27
Thirty-day evaluation; 15,000 mg/L Cl₂, pH = 2, Free chlorine = 5 mg/L as Cl₂

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2205	AWK-20	(0.34) [0.01]	7	(9.7) [0.246]	Base, Weld HAZ
	AWK-21	(0.52) [0.01]	10	(8.7) [0.220]	Base, Weld HAZ
2507	AWL-44	(0.04) [0.00]	1	(3.0) [0.076]	HAZ
	AWL-45	(0.02) [0.00]	0	N/A	N/A
254SMO	AWM-44	(0.02) [0.00]	1	(1.0) [0.026]	Weld HAZ
	AWM-45	(0.02) [0.00]	1	(<0.5) [<0.010]	HAZ

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.28
Sixty-day evaluation; 15,000 mg/L Cl⁻, pH = 2, Free chlorine = 5 mg/L as Cl₂

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2205	AWK-22	(0.28) [0.01]	6	(15.1) [0.384]	Base, Weld HAZ
	AWK-23	(0.46) [0.01]	6	(2.0) [0.052]	Base, Weld HAZ
2507	AWL-46	(0.03) [0.00]	0	N/A	N/A
	AWL-47	(0.04) [0.00]	0	N/A	N/A
254SMO	AWM-46	(0.02) [0.00]	4	(1.7) [0.044]	Weld HAZ
	AWM-47	(0.02) [0.00]	1	(1.8) [0.046]	HAZ

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.29
Ninety-day evaluation; 15,000 mg/L Cl⁻, pH = 2, Free chlorine = 5 mg/L as Cl₂

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2205	AWK-24	(0.21) [0.01]	7	(9.8) [0.25]	Base, Weld HAZ*
	AWK-25	(0.25) [0.01]	7	(7.5) [0.19]	Base, Weld HAZ*
2507	AWL-48	(0.04) [0.00]	0	N/A	N/A
	AWL-49	(0.04) [0.00]	0	N/A	N/A
254SMO	AWM-48	(0.03) [0.00]	1	(5.7) [0.146]	HAZ
	AWM-49	(0.02) [0.00]	3	(3.1) [0.08]	HAZ

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

* Pitting corrosion observed in the non-creviced areas of the weld.

Table 4.30
Thirty-day evaluation; 20,000 mg/L Cl⁻, pH = 5, No free chlorine

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2507	AWL-02	(<0.01) [0.00]	0	N/A	N/A
	AWL-03	(<0.01) [0.00]	0	N/A	N/A
254SMO	AWM-02	(<0.01) [0.00]	0	N/A	N/A
	AWM-03	(<0.01) [0.00]	1	(2.1) [0.054]	Weld

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.31
Sixty-day evaluation; 20,000 mg/L Cl⁻, pH = 5, No free chlorine

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2507	AWL-04	(<0.01) [0.00]	0	N/A	N/A
	AWL-05	(0.01) [0.00]	0	N/A	N/A
254SMO	AWM-04	(<0.01) [0.00]	0	N/A	N/A
	AWM-05	(<0.01) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.32
Ninety-day evaluation; 20,000 mg/L Cl₂, pH = 5, No free chlorine

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2507	AWL-6	(0.01) [0.00]	0	N/A	N/A
	AWL-7	(<0.01) [0.00]	0	N/A	N/A
254SMO	AWM-6	(<0.01) [0.00]	0	N/A	N/A
	AWM-7	(<0.01) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.33
Thirty-day evaluation; 20,000 mg/L Cl₂, pH = 2, Free chlorine = 5 mg/L as Cl₂

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2507	AWL-08	(0.02) [0.00]	0	N/A	N/A
	AWL-09	(0.02) [0.00]	0	N/A	N/A
254SMO	AWM-08	(0.03) [0.00]	1	(4.0) [0.098]	HAZ
	AWM-09	(0.02) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.34
Sixty-day evaluation; 20,000 mg/L Cl⁻, pH = 2, Free chlorine = 5 mg/L as Cl₂

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2507	AWL-010	(0.01) [0.00]	0	N/A	N/A
	AWL-011	(0.02) [0.00]	0	N/A	N/A
254SMO	AWM-010	(0.01) [0.00]	0	N/A	N/A
	AWM-011	(0.01) [0.00]	0	N/A	N/A

Table 4.35
Ninety-day evaluation; 20,000 mg/L Cl⁻, pH = 2, Free chlorine = 5 mg/L as Cl₂

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2507	AWL-12	(0.01) [0.00]	2	(1.9) [0.048]	Weld, HAZ
	AWL-13	(0.01) [0.00]	1	(5.1) [0.130]	Weld, HAZ
254SMO	AWM-12	(0.01) [0.00]	2	(3.5) [0.090]	Weld, HAZ
	AWM-13	(0.01) [0.00]	2	(2.0) [0.050]	Weld, HAZ

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.36
Thirty-day evaluation; 20,000 mg/L Cl₂, pH = 2, No free chlorine

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2507	AWL-14	(0.02) [0.00]	1	(2.4) [0.054]	Weld
	AWL-15	(0.02) [0.00]	0	N/A	N/A
254SMO	AWM-14	(0.02) [0.00]	2	(0.6) [0.016]	HAZ
	AWM-15	(0.02) [0.00]	1	(0.8) [0.020]	HAZ

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.37
Sixty-day evaluation; 20,000 mg/L Cl₂, pH = 2, No free chlorine

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2507	AWL-16	(0.01) [0.00]	0	N/A	N/A
	AWL-17	(0.01) [0.00]	0	N/A	N/A
254SMO	AWM-16	(0.01) [0.00]	0	N/A	N/A
	AWM-17	(0.01) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.38
Ninety-day evaluation; 20,000 mg/L Cl₂, pH = 2, No free chlorine

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2507	AWL-18	(0.01) [0.00]	0	N/A	N/A
	AWL-19	(0.01) [0.00]	2	(1.2) [0.030]	Weld
254SMO	AWM-18	(0.02) [0.00]	0	N/A	N/A
	AWM-19	(0.01) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.39
Thirty-day evaluation; 20,000 mg/L Cl₂, pH = 2, Free chlorine = 5 mg/L as Cl₂

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2507	AWL-20	(0.04) [0.00]	1	(1.0) [0.025]	Weld
	AWL-21	(0.066+) [0.00]	0	N/A	N/A
254SMO	AWM-20	(0.03) [0.00]	2	(3.0) [0.08]	Base
	AWM-21	(0.02) [0.00]	0	N/A	N/A

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.40
Sixty-day evaluation; 20,000 mg/L Cl⁻, pH = 2, Free chlorine = 5 mg/L as Cl₂

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2507	AWL-22	(0.04) [0.00]	0	N/A	N/A
	AWL-23	(0.05) [0.00]	3	(2.7) [0.068]	Weld, HAZ
254SMO	AWM-22	(0.02) [0.00]	1	(3.1) [0.078]	Base
	AWM-23	(0.03) [0.00]	1	(2.2) [0.056]	Weld, HAZ

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Table 4.41
Ninety-day evaluation; 20,000 mg/L Cl⁻, pH = 2, Free chlorine = 5 mg/L as Cl₂

Alloy	Sample ID	Corrosion rate: (mpy) [mmpy]	Number of crevice sites	Maximum depth of crevice attack: (mils) [mm]	Location of attack
2507	AWL-24	(0.04) [0.00]	1	(3.7) [0.094]	Weld
	AWL-25	(0.04) [0.00]	0	N/A	N/A
254SMO	AWM-24	(0.02) [0.00]	1	(<0.5) [0.010]	HAZ
	AWM-25	(0.03) [0.00]	2	(1.1) [0.028]	HAZ

mpy = mils per year, 1 mil = 0.001 inch, mmpy = millimeters per year

Discussion

All immersion tests were run in duplicate. Calculating corrosion rates assumes the mass loss was uniform. This did not occur, since the corrosion was mostly limited to the crevice corrosion formed by the washers and crevice depth. For instance, the number of corrosion sites, their depth and corrosion rate can rank the surface treatments in order of their corrosion performance, from worst to best:

1. As welded 316/316L
2. 120 grit & ground 316/316L
3. 120 grit & passivate (H₂O₂) 316/316L
4. Electropolished 316/316L
5. Alloy 2205

The corrosion resistance of the electropolished surface withstood environments at 3,600 mg/L chlorides at pH 5, zero chlorine at 40°F and for 60 days. The two other finishes, along with the al-welded 316/316L, performed reasonably well under the same conditions, but for 30 days duration only. There were marginal differences between the 120 grit prepared samples and as-welded 316/316L, but these specimens performed at 30 days duration only. When 5 mg/L chlorine was added to the environment, all of the samples suffered greater crevice corrosion attack, indicating a synergistic effect between chloride and chlorine, resulting in a more aggressive environmental condition.

The primary location for crevice attack was located in all three areas of the weldment, i.e., base metal, HAZ, and the weld. The 316/316L welded test samples, which had been autogenously welded (no filler metal), were attacked in all three weld locations.

A more accurate estimation of the resistance to crevice corrosion is the time to initiation, the number of initiation sites and maximum depth of penetration. [Table 4.42](#) below summarizes this data for time of first indication of crevice corrosion and severity, based upon on number of sites and depth of penetration.

Welded 316/316L stainless steel is susceptible to crevice corrosion in brackish water with 3,600 mg/L chloride. Removing the heat tint by grinding and subsequent passivation with commercial hydrogen peroxide did not significantly increase 316L's resistance to crevice corrosion. Electropolishing reduced the number of crevice initiation sites, but did not prevent crevice corrosion. The addition of chlorination at 5 mg/L free chlorine resulted in more aggressive crevice corrosion.

Welded Alloy 2205 exhibited more resistance to crevice corrosion than 316/316L, but was not immune even at 3,600 mg/L chloride concentration. Chlorination at 5 mg/L free chlorine resulted in more aggressive attack at each chloride concentration. Decreasing the pH in the 15,000 mg/L chloride resulted in crevice corrosion on all specimens exposed to this condition.

Welded 2507 superduplex stainless steel and welded austenitic 254SMO exhibited better resistance to crevice corrosion at 15,000 mg/L chloride concentration than Alloy 2205, particularly in the lower pH (pH 2) solutions, and especially without chlorination. These two alloys exhibit similar resistance to crevice corrosion in non-chlorinated solutions (15,000 and 20,000 mg/L chloride). However, in the chlorinated solutions, 2507 superduplex stainless steel performed better than the super-austenitic 254SMO.

Table 4.42
Crevice corrosion initiation time in days for surface conditioned
316/316L, duplex, superduplex, and super-austenitic stainless steels

Conditions/Alloy		316/316L							
Chloride (mg/L)	pH	Free chlorine (mg/L)	As-welded (days)	120 grit (days)	H ₂ O ₂ passivated (days)	Electro-polished (days)	2205 (days)	2507 (days)	254SMO (days)
3,600	5	0	30	30	30	30	60		
		5	30	30	30	30	30		
10,000	5	0	30	30	30	30	60		
		5	30	30	30	30	60		
15,000	5	0	-	-	-	-	30	90	>90
		5	-	-	-	=	30	30	30
	2	0	-	-	-	-	30	>90	60
		5	-	-	-	-	30	30	30
20,000	5	0	-	-	-	-	-	>90	30
		5	-	-	-	-	-	90	30
	2	0	-	-	-	-	-	30	30
		5	-	-	-	-	-	30	30

* **Numbers** refer to the shortest time frame required for crevice corrosion to occur. Not all samples at that time period or in subsequent time periods may exhibit crevice corrosion.

† **Color** provides a general sense of severity. **Red** is most severe (a greater number of samples at that time period and in subsequent time periods exhibit corrosion). **Purple** is less severe - observed corrosion is less severe at that time period and/or not all samples examined at that and/or subsequent time periods exhibited corrosion. **Green** is for no corrosion noted.

Conclusions

- Electrochemical test results did not reveal any evidence of hysteresis or transpassive behavior for any of the alloys when exposed to 3,600 and 10,000 mg/L chloride, except 316/316L.
- When acidifying the environment (pH 2), increasing torque values to 75 in.-lbs. and increasing the temperature to 50°C, numerous crevice sites were observed on Alloy 2205 and a large hysteresis curve was reported on the cyclic potentiodynamic polarization trace.
- The upper level of performance was determined to be 10,000 mg/L chloride for Alloy 2205.
- Lowering the pH increased the corrosion rates on Alloy 2205.
- Increasing the applied torque on the crevice assembly increased corrosion rates for Alloy 2205.
- 2507 superduplex stainless steel performed better than the super-austenitic 254SMO in the chlorinated solutions. Both exhibited better resistance to crevice corrosion at 15,000

mg/L chloride concentration than Alloy 2205, particularly in the pH 2 solutions, and especially without chlorination.

- The immersion phase of this study showed that the surface conditioning (ground: ground-passivated with hydrogen peroxide) offered limited benefits in corrosion protection to the 316/316L substrate.
- Electropolished 316/316L surfaces offered some benefits, especially through 60-day exposure.
- Chlorine provided a synergistic effect with chlorides on the corrosion resistance of 316/316L.

CHAPTER 5

GUIDELINES FOR STAINLESS STEEL USE

INTRODUCTION

The majority of stainless steel corrosion problems can be anticipated and are avoidable. Good design, appropriate material selection, and proper specification and control over material quality, fabrication, and construction methods, correct commissioning and operating practices all combine to give the material a long service life.

Previous sections of this report presented material and corrosion fundamentals and identified common construction or operational influences that result in stainless steel corrosion. Water quality influences on the corrosion of various stainless steel alloys were identified through published testing data combined with new laboratory data developed through this project (presented in Chapter 4).

At present, there is an abundance of this type of information available in the literature; however, to date it has not been readily available to water and desalination industry professionals, nor has it been presented in a format that is useful to engineers and owners seeking to procure stainless steel materials (e.g., to easily incorporate recommendations into construction documents) or make operational decisions that may change the environment to which existing stainless steel materials are exposed.

The purpose of this section is to convert these fundamentals and lessons learned into easy-to-use guidelines that can assist engineers and end users to select, procure, and use stainless steel materials that will result in service life that meets expectations in a cost-effective way. To accomplish this, we have taken two approaches:

1. For selection and procurement of stainless steel materials, we have organized the guidelines into MasterFormat[®], a specification outline that is commonly used in the construction industry (Construction Specifications Institute, Alexandria, VA).
2. For decisions related to making process changes and determining if existing stainless steel materials are suitable, we have provided a decision tree to help the end user evaluate pertinent water chemistry and material compatibility issues.

CONSTRUCTION SPECIFICATIONS INSTITUTE – MASTERFORMAT[®]

As described above, the guidelines are presented in an outline form consistent with the Construction Specifications Institute's (CSI) MasterFormat[®]. CSI is an organization that maintains and advances the standardization of construction language as it pertains to building specifications. CSI provides structured guidelines for specification writing in their Project Resource Manual. As presented in the Project Resource Manual, a construction specification is divided into three parts. A summary of these parts and their purposes is as follows:

- Part 1, General: Provides a summary, background information, reference standards, administrative and procedural requirements to the document user. Administrative and procedural requirements include quality assurance measures including qualifications, submittal requirements, and general design or fabrication requirements.

- Part 2, Products: Describes the quality of materials that are to be incorporated into the work, including, where appropriate, names of acceptable manufacturers. For stainless steel components, this may include pipe, vessels or cast machinery. Quality requirements may include finishing techniques that should be used. Ancillary features such as design requirements for joints, joint products, and bolts may also be included.
- Part 3, Execution: Describes, in detail, the preparation, and actions to be taken to incorporate the products into the project.

GUIDELINES FOR CSI MASTERFORMAT® PART 1, GENERAL REQUIREMENTS

Summary

Describe the intent of the specification. For example, indicate that the specification covers:

- Stainless steel pipe, tubing, and accessories.
- Stainless steel tanks or vessels.
- Stainless steel valves, pumps or other machinery.

The design requirements and reference standards are different for each of these types of use, so state the application up front.

Reference Standards

Reference standards are included to provide document users with information regarding the quality of materials or workmanship that is required. Selection of the appropriate reference standards varies based upon the type of stainless steel alloy and the alloy's product form (i.e., pipe, bar shapes, castings, etc.).

[Tables 5.1](#), [5.2](#), [5.3](#), and [5.4](#) summarize reference standards that are commonly used to specify the quality of stainless steel materials in municipal water applications.

Table 5.1
Reference standards for common stainless steel pipe and tubing

Common name	UNS No. (Wrought)	PREN*	Pipe			
			Material standard	Manufacturing standard	Design standard	Tube
AUSTENITIC STAINLESS STEEL						
304 **	S30400	20	ASTM A 240	≥ 3" ASTM A 778 < 3" ASTM A 312	General Service: AWWA C220 High Pressure, Desalination: ASME B 36.19	ASTM A 269
304L **	S30403	20	ASTM A 240	≥ 3" ASTM A 778 < 3" ASTM A 312	General Service: AWWA C220 High Pressure, Desalination: ASME B 36.19	ASTM A 269
316 **	S31600	25	ASTM A 240	≥ 3" ASTM A 778 < 3" ASTM A 312	General Service: AWWA C220 High Pressure, Desalination: ASME B 36.19	ASTM A 269
316L **	S31603	25	ASTM A 240	≥ 3" ASTM A 778 < 3" ASTM A 312	General Service: AWWA C220 High Pressure, Desalination: ASME B 36.19	ASTM A 269
DUPLEX STAINLESS STEEL						
LDX 2101®	S32101	27	ASTM A 240	ASTM A 790	ASME B 36.19	ASTM A 789
Alloy 2205	S31803	34	ASTM A 240	General Corrosive Service: ASTM A 790 Corrosive Service: ASTM A 928	ASME B 36.19	ASTM A 789
SUPERDUPLEX ALLOYS						
Alloy 2507	S32750	43	ASTM A 240	General Corrosive Service: ASTM A 790 Corrosive Service: ASTM A 928	ASME B 36.19	ASTM A 789
Ferralium	S32550	39	ASTM A 240	ASTM A 790	ASME B 36.19	ASTM A 789
Zeron 100	S32760	41	ASTM A 240	ASTM A 790	ASME B 36.19	ASTM A 789

(continued)

Table 5.1 (Continued)

Common name	UNS No. (Wrought)	PREN*	Pipe			Tube
			Material standard	Manufacturing standard	Design standard	
<u>SUPER-AUSTENITIC ALLOYS</u>						
AL6XN	N08367	46	ASTM A 240	ASTM A 312	ASME B 36.19	ASTM A 269
254 SMO	S31254	43	ASTM A 240	ASTM A 312	ASME B 36.19	ASTM A 269
654 SMO	S32654	57	ASTM A 240	ASTM A 312	ASME B 36.19	ASTM A 269
<u>OTHER</u>						
416	S41600	‡	†	†	†	†
17-4PH	S17400	‡	†	†	†	†
<u>SUPER ALLOYS</u>						
Hastelloy C-22	N06022	‡	ASTM B 575	ASTM B 619	ASME B 36.19	ASTM B 622
Hastelloy C-276	N10276	‡	ASTM B 575	ASTM B 619	ASME B 36.19	ASTM B 622

* PREN = Pitting Resistance Equivalent Number

** Types 304/304L and 316/316L stainless steels are also offered as “dual certified” material, which offers the material properties of low carbon stainless steel, making it suitable for welding (flat & rolled products), with nitrogen additions to provide and meet the minimum mechanical properties offered by standard material.

† For general water industry applications, this alloy is only used as bar stock in valves, pump shafts, bolts, etc.

‡ PREN is not applicable to super alloys, 416, or 17-4PH.

Table 5.2
Reference standards for common stainless steel pipe fittings

Common name	UNS No. (Wrought)	Cast name	UNS No. (Cast)	PRE N	Pipe flanges, fittings and valves	
					Manufacturing standard	Design standard
AUSTENITIC STAINLESS STEEL						
304 *	S30400	CF8	J92600	20	Wrought, < 3": ASTM A 403, Class WP Forged, all sizes: ASTM A 182	General Service: Fittings with welded ends: AWWA C226 Fittings with flanged ends ≥ 2": AWWA C228 High Pressure, Desalination Service: Fittings with welded ends ≥ 3": ASME B36.19 Fittings with flanged ends ≥ 3": ASME B16.5 Fittings < 3": ASME B16.11
304L *	S30403	CF3	J92500	20	Wrought, ≥ 3": ASTM A 774 Wrought, < 3": ASTM A 403, Class WP Forged, all sizes: ASTM A 182	General Service: Fittings with welded ends: AWWA C226 Fittings with flanged ends ≥ 2": AWWA C228 High Pressure, Desalination Service: Fittings with welded ends ≥ 3": ASME B36.19 Fittings with flanged ends ≥ 3": ASME B16.5 Fittings < 3": ASME B16.11
316 *	S31600	CF8M	J92900	25	Wrought, < 3": ASTM A 403, Class WP Forged, all sizes: ASTM A 182	General Service: Fittings with welded ends: AWWA C226 Fittings with flanged ends ≥ 2": AWWA C228 High Pressure, Desalination Service: Fittings with welded ends ≥ 3": ASME B36.19 Fittings with flanged ends ≥ 3": ASME B16.5 Fittings < 3": ASME B16.11

(continued)

Table 5.2 (Continued)

Common name	UNS No. (Wrought)	Cast name	UNS		Pipe flanges, fittings and valves	
			No. (Cast)	PREN*	Manufacturing standard	Design standard
316L*	S31603	CF3M	J92800	25	Wrought, $\geq 3''$: ASTM A 774 Wrought, $< 3''$: ASTM A 403, Class WP Forged, all sizes: ASTM A 182	General Service: Fittings with welded ends: AWWA C226 Fittings with flanged ends $\geq 2''$: AWWA C228 High Pressure, Desalination Service: Fittings with welded ends $\geq 3''$: ASME B36.19 Fittings with flanged ends $\geq 3''$: ASME B16.5 Fittings $< 3''$: ASME B16.11
DUPLEX STAINLESS						
LDX 2101	S32101	†	†	27	Wrought, all sizes: ASTM A 815 Forged, all sizes: ASTM A 182	Fittings with welded ends $\geq 3''$: ASME B36.19 Fittings with flanged ends $\geq 3''$: ASME B16.5 Fittings $< 3''$: ASME B16.11
Alloy 2205	S31803	CD3MN	J92205	34	Wrought, all sizes: ASTM A 815 Forged, all sizes: ASTM A 182	Fittings with welded ends: ASME B36.19 Fittings with flanged ends: ASME B16.5
Alloy 2507	S32750	CE3MN	J93404	43	Wrought, all sizes: ASTM A 815 Forged, all sizes: ASTM A 182	Fittings with welded ends: ASME B36.19 Fittings with flanged ends: ASME B16.5
Ferralium	S32550	CD3MCuN	J93373	39	Wrought, all sizes: ASTM A 815 Forged, all sizes: ASTM A 182	Fittings with welded ends: ASME B36.19 Fittings with flanged ends: ASME B16.5
Zeron 100	S32760	CD3MWCuN	J93380	41	Wrought, all sizes: ASTM A 815 Forged, all sizes: ASTM A 182	Fittings with welded ends: ASME B36.19 Fittings with flanged ends: ASME B16.5
AL6XN	N08367	CN3MN	J94651	46	Wrought, all sizes: ASTM B 366 Forged, all sizes: ASTM A 182	Fittings with butt welded ends: ASME B16.9 Fittings with threaded ends: ASME B16.11 Fittings with socket ends: ASME B16.11 Fittings with flanged ends: ASME 16.5

(continued)

Table 5.2 (Continued)

Common name	UNS No. (Wrought)	Cast name	UNS No. (Cast)	PRE N	Pipe flanges, fittings and valves	
<u>SUPERDUPLEX ALLOYS</u>						
<u>SUPER-AUSTENITIC ALLOYS</u>						
254 SMO	S31254	CK3MCu N	J93254	43	Wrought, all sizes: ASTM A 403 Forged, all sizes: ASTM A 182	Fittings with welded ends: ASME B36.19 Fittings with flanged ends: ASME B16.5
654 SMO	S32654	†	†	57	†	†
<u>OTHER</u>						
416	S41600	‡	‡ †	§	‡	‡
17-4PH	S17400	‡	‡ †	§	‡	‡
<u>SUPER ALLOYS</u>						
Hastelloy C-22	N06022	CX2MW	N26022	§	Wrought, all sizes: ASTM B 366 Forged, all sizes: ASTM B 564	Fittings with butt welded ends: ASME B16.9 Fittings with threaded ends: ASME B16.11 Fittings with socket ends: ASME B16.11 Fittings with flanged ends: ASME 16.5
Hastelloy C-27t	N10276	CW12MW	N30002	§	Wrought, all sizes: ASTM B 366 Forged, all sizes: ASTM B 564	Fittings with butt welded ends: ASME B16.9 Fittings with threaded ends: ASME B16.11 Fittings with socket ends: ASME B16.11 Fittings with flanged ends: ASME 16.5

** Types 304/304L and 316/316L stainless steels are also offered as “dual certified” material, which offers the material properties of low carbon stainless steel, making it suitable for welding (flat & rolled products), with nitrogen additions to provide and meet the minimum mechanical properties offered by standard material.

† No UNS designation or ASTM standards exist for fittings or cast materials.

‡ For general water industry applications, this alloy is only used as bar stock in valves, pump shafts, bolts, etc.

§ PREN is not applicable to super alloys, 416, or 17-4PH.

Table 5.3
Reference standards for common stainless steel cast shapes and equipment

Common name	UNS No. (Wrought)	Cast name	UNS No. (Cast)	PREN	Castings
AUSTENITIC STAINLESS STEEL					
304 *	S30400	CF8	J92600	20	ASTM A 351
304L *	S30403	CF3	J92500	20	ASTM A 351
316 *	S31600	CF8M	J92900	25	ASTM A 351
316L*	S31603	CF3M	J92800	25	ASTM A 351
DUPLEX STAINLESS					
LDX 2101	S32101	†	‡	27	†
Alloy 2205	S31803	CD3MN	J92205	34	General Application: ASTM A 890 Pressure Containing Parts: ASTM A 995
SUPERDUPLEX ALLOYS					
Alloy 2507	S32750	CE3MN	J93404	43	General Application: ASTM A 890 Pressure Containing Parts: ASTM A 995
Ferralium	S32550	CD3MCuN	J93373	39	General Application: ASTM A 890 Pressure Containing Parts: ASTM A 995
Zeron 100	S32760	CD3MWCuN	J93380	41	General Application: ASTM A 890 Pressure Containing Parts: ASTM A 995
SUPER-AUSTENITIC ALLOYS					
AL6XN	N08367	CN3MN	J94651	46	General Application: ASTM A 743 Severe Corrosion Applications: ASTM A 744
254 SMO	S31254	CK3MCuN	J93254	43	General Application: ASTM A 743 Severe Corrosion Applications: ASTM A 744
654 SMO	S32654	†	†	57	†
OTHER					
416	S41600	‡	‡ †	§	‡
17-4PH	S17400	‡	‡ †	§	‡
SUPER ALLOYS					
Hastelloy C-22	N06022	CX2MW	N26022	§	ASTM A 494
Hastelloy C-276	N10276	CW12MW	N30002	§	ASTM A 494

** Types 304/304L and 316/316L stainless steels are also offered as “dual certified” material, which offers the material properties of low carbon stainless steel, making it suitable for welding (flat & rolled products), with nitrogen additions to provide and meet the minimum mechanical properties offered by standard material.

† No UNS designation or ASTM standards exist for fittings or cast materials.

‡ For general water industry applications, this alloy is only used as bar stock in valves, pump shafts, bolts, etc.

§ PREN is not applicable to super alloys, 416, or 17-4PH.

Table 5.4
Reference standards for common stainless steel bar shapes & fasteners

Common name	UNS No. (Wrought)	PREN	Bar shapes	Fasteners
AUSTENITIC STAINLESS STEEL				
304*	S30400	20	ASTM A 276 ^{§§}	†
304L*	S30403	20	ASTM A 276	†
316*	S31600	25	ASTM A 276	Bolts (General Service): ASTM F 593, Group 2, Condition CW Bolts (High Pressure Service): ASTM A 193 Nuts (General Service): ASTM F 594, Group 2 Nuts (High Pressure Service): ASTM A 194
316L*	S31603	25	ASTM A 276	Bolts (General Service): ASTM F 593, Group 2, Condition CW Nuts (General Service): ASTM F 594, Group 2
DUPLEX STAINLESS				
LDX 2101	S32101	27	ASTM A 276	‡
Alloy 2205	S31803	34	ASTM A 276	‡
SUPERDUPLEX ALLOYS				
Alloy 2507	S32750	43	ASTM A 276	‡
Ferrallium	S32550	39	ASTM A 276	‡
Zeron 100	S32760	41	ASTM A 276	‡
SUPER-AUSTENITIC ALLOYS				
AL6XN	N08367	46	ASTM A 276	‡
254 SMO	S31254	43	ASTM A 276	‡
654 SMO	S32654	57	ASTM A 276	‡
OTHER				
416	S41600	**	ASTM A 582	§
17-4PH	S17400	**	ASTM A 564	§
SUPER ALLOYS				
Hastelloy C-22	N06022	**	ASTM B 574	‡
Hastelloy C-276	N10276	**	ASTM B 574	‡

* Types 304/304L & 316/316L stainless steels are also offered as “dual certified” material, which offers the material properties of low carbon stainless steel, making it suitable for welding (flat & rolled products), with nitrogen additions to provide and meet the minimum mechanical properties offered by standard material.

** PREN is not applicable to super alloys, 416, or 17-4PH.

† For general purposes, 304 and 304L fasteners are not recommended for water industry applications. See following note.

‡ For general purposes, when the fasteners are not submerged, 316 or 316L bolt material is acceptable. Where additional corrosion resistance is desired (e.g., submerged or corrosive atmosphere), fasteners fabricated from suitable material for the exposure are recommended. Otherwise, consult a corrosion engineer.

§ For general water industry applications, this alloy is only used as bar stock in valves, pump shafts, bolts, etc.

§§ There are 2 major specs for bar, one is A276 and the other is A479. These are valid for all the alloys down to and including 654SMO.

In addition to the basic reference standards indicated in [Table 5.1](#), it is necessary to define the governing design code and name the applicable reference standard in the specification.

- Pressurized tanks and vessels in drinking water applications are typically designed in accordance with ASME Boiler and Pressure Vessel Code, Section VIII.⁵
- Non-pressurized tanks are typically designed in accordance with an appropriate standard such as API 620.⁶
- Piping systems are designed in accordance with an appropriate standard:
 - Chemical piping, membrane filtration, and RO systems would typically be designed in accordance with ASME B16.3 Pressure Piping.
 - Potable water conveyance projects would typically be designed in accordance with AWWA M11 Steel Pipe—A Guide for Design and Installation.

The specifier should also decide whether to specify stainless steel pipe under one or more of the following standards.

1. ASME B36.19 Stainless Steel Pipe: Include this reference standard in the following cases.
 - a. Pipe sizes are 1/8-inch through 30-inch nominal pipe size.
 - b. Pipe wall thickness is defined by schedule (5S, 10S, 40S and 80S).⁷
 - c. Flanges are in accordance with ASME B16.5 with styles that include both flat-faced and raised-face.

Typical applications would include membrane filtration and RO facilities where AWWA standard valves are not usually used.

2. AWWA C220 Stainless-Steel Pipe, ½ In. (13 mm) and Larger: Include this reference standard in the following cases.
 - a. Pipe sizes/diameters typically associated with water works projects such as pump stations, transmission pipelines, and surface water treatment plants.
 - b. Pipe wall thickness is determined by the appropriate formulas in AWWA Manual M11 using stainless steel material properties (AWWA C220 § II.A).
 - c. Flanges are in accordance with AWWA C228, which allows only flat-faced flanges (AWWA C228 § 4.2.2).
 - d. AWWA standard valves with flat-faced flanges are used.

⁵ Section VIII provides requirements of pressure vessels operating at either internal or external pressures exceeding 15 psig; such vessels may be fired or unfired.

⁶ API 620 provides requirements for design and construction of tanks with pressures not more than 15 psig and temperatures not greater than 250°F that have a single vertical axis of revolution.

⁷ ASME B36.19§1 indicates that other pipe thicknesses are also commercially available with stainless steel materials in accordance with ASME B36.10 Welded and Seamless Wrought Steel Pipe.

Design Requirements

Stating design requirements prominently at the beginning of the specification helps to highlight them. Restrict this list to key issues requiring extra emphasis.

Piping Layout Drawings

Allow the fabricator the flexibility to lay out the piping in the manner that is most economical to fabricate in the shop, ship to the site, and assemble in the field while still meeting the design requirements. List design requirements that the pipe fabricator must demonstrate in his layout drawing submittals. Recommended design requirements include the following:

1. Pipe Section Length: Lay out and fabricate piping systems with piping sections as long as possible, while still allowing shop surface treatment and shipment, so that field joints are minimized.
2. Pipe Section Identification: Each pipe section must be marked with a unique identification mark that matches and indicates its location in the layout drawings (AWWA C220 § 6.1.).
3. Shop Fabrication: Fabricate piping sections in the shop and provide surface treatment to fabricated sections before shipping to the site.
 - a. At a minimum, shop surface treatment must include descaling (pickling) and passivation.
 - b. As discussed later in this section, shop surface treatment may also include electropolishing or shot peening (bead blasting).
4. Field Connections: Show joints and connections to maximize the size of piping sections and provide for the following.
 - a. Constructability,
 - b. Thrust restraint, flexibility, thermal effects, and piping support, and
 - c. Consideration for future field disassembly and equipment removal.
5. Dielectric Isolation: Show locations and methods of connections to dissimilar metals.
6. Field Welding: Ideally, welding should be limited to shop welding, where greater process control can be maintained. Field welding is discouraged because it ruins the shop finished surfaces in the vicinity of the weld. Design requirements should prohibit field welding unless there are compelling reasons requiring its use.

Tank Design Requirements

Typically, tank design codes require a corrosion allowance except in cases where corrosion effects can be shown to be negligible or entirely absent. Stainless steel alloys for tanks should be selected to allow exemption from corrosion allowance. When stainless steel failures occur, they are often due to localized pitting or crevice corrosion or stress corrosion cracking. A general corrosion allowance will not protect against these types of failure.⁸ If significant corrosion risk exists for a candidate stainless steel material then either another grade of stainless steel should be used or stainless steel is not an appropriate material for the intended service.

⁸ Stress corrosion cracking failures occur in austenitic stainless steel when temperatures exceed 140°F, there is stress, and chloride is present. Duplex stainless steels are not subject to this mechanism.

Like the requirements associated with piping, fabrication and welding on tanks is best controlled in a shop setting. Unlike piping, tanks can be very difficult to disassemble and remove should corrosion of welds cause tank failure. Therefore, field welding should be prohibited unless there are compelling reasons for its use.

Equipment Design Requirements

Stainless steel equipment used in the water industry such as pumps and valves will be made from a variety of cast, bar, and wrought materials. These materials should reference the appropriate design requirements for these components stated in [Tables 5.1](#) through [5.4](#). The stainless steel alloy used should be selected based upon the water chemistry and the life expected from the equipment. These alloys should be specified in “Part 2, Products” of an engineer’s CSI MasterFormat® specification for each component of the equipment that is being procured. However, some bar materials used for pump or valve shafts have lower PREN values that would otherwise be selected for application in a piping system that uses wrought material (refer to [Table 5.4](#)). These other, lower PREN materials are often used for bar shapes due to their higher strength (precipitation hardened stainless steels like 17-4PH) or machining properties (martensitic stainless steels like Type 416). In bar form, 17-4PH has a comparable corrosion resistance when compared to 304/304L wrought material, while Type 416 bar has significantly lower corrosion resistance than type 304/304L wrought material. For challenging applications that require both high corrosion resistance and mechanical properties such as high strength and hardness, special stainless steel alloys are available. Material selection should be based on good engineering judgment, PREN values, and the alloy manufacturer’s recommendations. Other non-stainless steel materials such as nickel-copper alloys may be considered for harsher environments.

Submittals

Submittals allow “paper” (i.e., hypothetical) construction prior to actual fabrication and installation. Submittal information is used both for confirmation that requirements are met and also that components and systems from different sources will successfully work together and within the site environment.

Drawings

Supplier submits detailed layout drawings in conformance with the design requirements. Drawing information includes the following:

1. Dimensions and alignments,
2. Locations of valves, fittings, and appurtenances,
3. Locations of pipe hangers and equipment supports,
4. Connection requirements of pipes, equipment, and structures,
5. Locations and details of welds, and
6. Thicknesses and dimensions of fittings and gaskets.

All supports and connections should be compatible with the stainless steels used or provided with dielectric isolation.

Product Data and Certifications

Includes equipment cut sheets, photographs, descriptions including welding procedures and stainless steel treatment and finishing procedures. Fabrication requirements vary with the intended service of the system. Supplier's submittal should demonstrate conformance with the appropriate requirements.

1. Oxygen and Ozone Service: Cleaning procedures in accordance with CGA Standard G-4.1.
2. Drinking Water Service: Compliance with NSF 61 - Drinking Water System Components - Health Effects.
3. Pressure Vessels: ASME Boiler and Pressure Vessel Code, Section VIII, Rules for Construction of Pressure Vessels, as applicable.

Submittals should include certifications appropriate to the stainless steel pipe or equipment specified.

1. Metallurgy: Manufacturer provides written mill certification under the requirements of the governing standard.
2. Welding: Submit welder and weld operator qualification certificates and welding procedures.
3. Pipe: The pipe purchaser may require an affidavit of compliance with the standard.
4. Fittings: The fitting purchaser may require an affidavit of compliance with the standard.

GUIDELINES FOR CSI MASTERFORMAT® PART 2, PRODUCT REQUIREMENTS

Material and Manufacturing

Identifying the grade of stainless steel and manufacturing process suitable to the intended service involves consideration of a number of factors. The specifier may allow the supplier to furnish the most economical stainless steel grade that meets the requirements. For example, for wrought plate or tubular products, Type 316L (PREN = 25) is a commonly specified austenitic alloy that fluctuates in price based on market forces while some lean duplex alloys (e.g., LDX 2101, PREN = 27) have equivalent resistance to pitting, may be less expensive and have greater availability at a given time. A specification that allows either may result in lower costs. Similarly, stainless steel components (e.g., valves and fittings) may be more available in 316 than in 304; therefore allowing substitution of 316 for 304 may also reduce cost and/or delivery time without sacrificing quality.

General Service in Potable Water Treatment

Type 304L has adequate corrosion resistance for most conditions in potable water service provided that the surface is maintained clean and free of defects. Type 316L is a more conservative choice and has improved corrosion resistance in the presence of sediment and other deposits when higher levels of residual chlorine exist. Use Ni-Cr-Mo alloys, ≥ 6 percent Mo stainless steels, or cement-lined steel or ductile iron pipe immediately downstream of chlorine or potassium permanganate injection (Avery et al, 1999).

Chloride and Chlorine

The chloride concentration in water is an important factor in determining the resistance of stainless steel to crevice corrosion. The designer should be aware that the presence of oxygen significantly increases the risk of crevice corrosion from chloride. Much higher chloride levels can be tolerated in fully de-aerated water. Stainless steels are generally resistant to crevice corrosion in totally de-aerated waters, even seawater (Ibid). However, the presence of chlorine can have a synergistic effect on crevice corrosion when chlorides are present, resulting in more significant crevice corrosion at lower chloride concentrations (Avery et al, 1999, Ibid). More information is available on the effect of chlorides in Chapters 2 and 4 of this report.

Resistance of stainless steel alloys to corrosion due to chloride is expressed as PREN, where $PREN = Cr\% + (3.3 \times Mo\%) + (16 \times N\%)$. PREN values are given for a number of standard alloys in Table 2.3. Guidelines for alloy selection based on chloride and chlorine concentrations are summarized in Table 5.5.

Table 5.5
Guidelines for alloy selection based upon chloride and chlorine concentration

Service	Stainless steel grade	Pipe manufacturing process
<i>For low chloride water service with chloride concentrates below 200 mg/L and/or free chlorine less than 2 mg/L at ambient temperatures.</i>		
Piping 3-inch NPS and larger	Type 304L stainless steel in accordance with ASTM A240	In accordance with ASTM A778
Piping less than 3-inch NPS	Type 304L stainless steel in accordance with ASTM A240	In accordance with ASTM A312
<i>Chloride concentrations less than 1,000 mg/L and/or free chlorine less than 4 mg/L at ambient temperatures.</i>		
Piping 3-inch NPS and larger	Type 316L or LDX 2101 stainless steel in accordance with ASTM A240	Type 316L in accordance with ASTM A778 Type LDX 2101 in accordance with ASTM A790
Piping less than 3-inch NPS	Type 316L or LDX 2101 stainless steel in accordance with ASTM A240	Type 316L in accordance with ASTM A312 Type LDX 2101 in accordance with ASTM A790

(continued)

Table 5.5 (Continued)

Service	Stainless steel grade	Pipe manufacturing process
<i>Chloride concentrations between 1,000 and 10,000 mg/L.</i>		
All piping diameters	No free chlorine at ambient temperatures. Austenitic or duplex grades of material with PREN > 33	In accordance with ASTM A312, ASTM A790, or ASTM A928
	<i>Free chlorine <5 mg/L at ambient temperatures.</i> Austenitic or duplex grades of material with PREN \geq 43*	In accordance with ASTM A312, ASTM A778, ASTM A790, or ASTM A928
<i>Brackish water, seawater and other waters with chloride concentrations between 10,000 to 20,000 mg/L and no free chlorine present.</i>		
All piping diameters	Austenitic and duplex grades of material with PREN > 43	In accordance with ASTM A 312, ASTM A790, or ASTM A928
<i>Chloride concentrations greater than 20,000 mg/L and no free chlorine.†</i>		
All piping diameters	Austenitic and duplex grades of material with PREN > 45	In accordance with ASTM A312, ASTM A790, or ASTM A928

* Significant corrosion was observed at low chlorine concentrations for Duplex stainless steel with a PREN of 34. Significantly higher PREN value steel may be warranted. Zeron 100 may also be suitable.

† Combined chloride-free chlorine data not available. Consult with a corrosion specialist when choosing materials for such conditions.

Even without the synergistic influence of chloride, a chlorine residual in potable water can also contribute to crevice corrosion. Type 304L becomes vulnerable to crevice corrosion with long-term exposure in the 3 to 5 mg/L chlorine concentration range, while 316L is more resistant in this range. Corrosion testing (presented in Chapter 4) found that when 5 mg/L chlorine was added to the environment, all stainless steels tested (316L, 2205 Duplex, 2507 Superduplex, and 254SMO) were vulnerable to greater crevice corrosion attack. The guidelines presented in [Table 5.6](#) are recommended for long-term exposure to chlorine in potable water (i.e., chloride \leq 250 mg/L at ambient temperatures).

Table 5.6
Guidelines for alloy selection based upon chlorine concentration in potable water

Alloy	Performance
Type 304L stainless steel	Acceptable for service where residual chlorine in solution \leq 2 mg/L at ambient temperatures.
Type 316L stainless steel	Acceptable for service where residual chlorine in solution \leq 4 mg/L at ambient temperatures.
Alloy with PREN > 33	For residual chlorine levels > 4 mg/L, seek advice of metallurgist or corrosion consultant.

Types 304/304L and 316/316L are also affected by chlorine in moisture and vapor present above the water line. Staining and severe pitting have been reported for pipes constructed of these alloys that were connected to the head space of basins containing chlorinated water in potable water treatment plants. Use of these grades of stainless steel for vents and overflows for covered basins containing chlorinated water is not recommended.

Buried Service Lines

If stainless steel is buried in soil, consideration should be given to soil corrosivity and the materials chosen or protection system provided. The following guidelines (Tables 5.7 and 5.8) can be used but expert advice should be considered.

Table 5.7
Corrosivity index for soils as a function of soil resistivity

Corrosivity	Soil resistivity	Acceptable alloys
Very corrosive	< 2,000 Ω-cm	duplex alloy
Aggressive	2,000 - 5,000 Ω-cm	316 may pit ¹ , duplex stainless
Mildly corrosive	5,000 - 10,000 Ω-cm	304 may pit ¹ , 316, alloy 2205
Slightly corrosive	10,000 - 20,000 Ω-cm	304, 316, duplex stainless
Less corrosive	> 20,000 Ω-cm	304, 316, duplex stainless
Not corrosive	30,000 - 100,000 Ω-cm	304, 316, duplex stainless

Source: Data taken from Cunat 2001.

* Anodic or cathodic protection may assist in improving the performance of these alloys.

Table 5.8
AWWA M11 Soil Corrosivity Classes

Class	Soil type	Corrosivity	Resistivity
1	Sands and sandy loams	Lightly corrosive	6,000 - 10,000 Ω-cm
2	Loams (clay, silts)	Moderately corrosive	4,500 - 6,000 Ω-cm
3	Clays	Badly corrosive	2,000 - 4,500 Ω-cm
4	Peat, tidal marsh, clays	Aggressively Corrosive	< 2,000 Ω-cm

Source: data from AWWA 1989.

Unlike steel piping products, stainless steel piping rarely needs to be coated either internally or externally. For long, buried stainless lines where the soil resistivity is < 2,000 Ω-cm, anodic or cathodic protection should be implemented. Where soil resistivity ranges from 2,000 to 10,000 Ω-cm, anodic or cathodic protection may also be needed.

Gas Service

Consider the following stainless steel alloys (Table 5.9) as minimum requirements for piping in digester gas and oxygen-related service.

Table 5.9
Digester gas, oxygen and ozone service

Service	Stainless steel grade	Pipe manufacturing process
Piping 3-inch NPS and larger	Type 316L stainless steel in accordance with ASTM A240*	Type 316L in accordance with ASTM A269
Piping less than 3-inch NPS	Type 316L stainless steel in accordance with ASTM A240*	Type 316L in accordance with ASTM A312

* As opposed to stainless steel materials used in water service where pitting resistance equivalency has been demonstrated, there is no data to support the use of lean duplex material (e.g., LDX 2101) for digester gas, oxygen or ozone service. Type 316L stainless steel is a standard alloy used for this service.

High Temperature

Consider using heat-treated pipe (ASTM A312) or tube (ASTM A269) rather than unannealed pipe or tube (ASTM A778) for materials to be used in temperatures greater than 400°F. For temperatures greater than 800°F consider using grades of stainless steel other than 304L and 316L. Duplex stainless steels should not be used at temperatures above 550°F in order to avoid sigma phase embrittlement.

Pipe and Tube

The word “pipe” is used to apply to tubular products of dimensions commonly used for pipeline and piping systems. Because pipe is used to convey fluids, it is always cylindrical. Pipe is typically rigid and resistant to bending.

The words “tube” or “tubing” often refer to tubular products that may be used to convey fluids, but rigid tubes are often used as structural elements; such a tube may be rectangular or cylindrical. Non-rigid cylindrical tubing can be joined quickly by flaring or special coupling systems.

Stainless steel pipe and tube in the USA are manufactured to standardized dimensions.

- Pipe: For a given nominal pipe size (NPS), the outside diameter (OD) is fixed and wall thickness increases with schedule.
 - For NPS 1/8 to 12 inches the NPS and OD values are different.
 - For NPS \geq 14 inches the NPS and OD values are the same.
- Tube: the OD of tube is numerically identical to the nominal tube size (NTS) value for all sizes.

The designer must choose between unannealed or annealed (heat-treated) stainless steel products. The use of either product is allowed by AWWA C220.

Unannealed pipe and tube are both covered by ASTM A778. This standard covers tubular products with 3-inch through 48-inch in outside diameters that have nominal wall thicknesses of 0.062-inch through 0.500-inch. Tubular products having other diameters or wall thickness may be furnished under this standard provided that all other requirements of the standard are met. Characteristics of unannealed pipe, tubes, and fittings include the following:

- It is typically less expensive than heat-treated pipe and for this reason is generally the first choice if it meets the requirements of the application.
- ASTM A778 is the prevalent pipe standard used in the water industry and adequate for most general service applications.
- It allows field welding and modification without the need for subsequent heat treatment.
- Unannealed pipe and fitting material usage is restricted to extra low carbon alloys in the 300 series (e.g., 304L, 316L) and dual certified material (e.g., 304/304L, 316/316L). Dual certified material offers the material properties of extra low carbon stainless steel, making it suitable for welding (flat & rolled products), with nitrogen additions to provide and meet the minimum mechanical properties offered by standard material.

Heat-treated pipe is covered by ASTM A312 for austenitic stainless steel or ASTM A790 for ferritic/austenitic (duplex) stainless steels.⁹ Only pipe is covered by these standards and so the outside diameter and wall thickness dimensions are defined by ASME B36.19, which includes 1/8-inch through 36-inch NPS. Characteristics of heat-treated pipe and fittings include the following:

- It is typically more expensive than unannealed pipe and fittings.
- More stainless steel alloys are covered by these standards, including all the extra low carbon grades included in ASTM A778.
- Field welding requires post-weld field annealing to preserve corrosion protection for standard grade materials like 304 and 316, which is further reason to use low carbon or dual grade materials (e.g., 304L, 304/304L, 316L, 316/316L). The one exception where post weld annealing should be considered for low carbon or dual grade materials is for high temperature service, which is not a typical water industry application. It is used in applications with higher corrosiveness and higher temperatures than are suitable for unannealed extra low carbon alloys.

Heat-treated tubes made of austenitic alloys are covered by ASTM A269.¹⁰ This standard covers 1/4-inch heat-treated tubes and larger (inside diameter) and nominal wall thickness of 0.020-inch and heavier. Additional grades of ferritic/austenitic (duplex) stainless steels are covered by ASTM A789, A790, A928, and A358.

⁹ The companion standards for heat treated fittings are ASTM A403 (austenitic) and ASTM A890 (duplex).

¹⁰ Tubing for special high temperature applications is covered by ASTM A249 Standard Specification for Welded Austenitic Steel Boiler, Superheater, Heat-Exchanger, and Condenser Tubes.

Wall Thickness

Stainless steel piping and tubes that do not have a pressure rating or class. Selection of wall thickness for a particular application must consider such factors as:

- The theoretical bursting pressure,
- The type of connection,
- The spacing of pipe supports,
- The appropriate safety factor, and
- The allowable wall thickness variation due to manufacturing tolerances.

When the selection of wall thickness depends primarily upon capacity to resist internal pressure under given conditions, the designer must compute the exact value of wall thickness suitable for conditions for which the pipe is required, as prescribed in detail in the ASME Boiler and Pressure Vessel Code, ASME B31.3 Code for Pressure Piping, or other similar codes, whichever governs.¹¹

The nature of stainless steel allows the design of thin-wall piping systems without fear of early failure due to corrosion. *Stainless steel* pipe schedules are designated by an uppercase “S” to distinguish them from earlier *steel* (“s”) pipe schedules that were developed in the first half of the 20th century based upon commercially available sizes and historical practices.¹²

Stainless steel pipe schedule numbers are: 5S, 10S, 40S, and 80S. The *stainless steel* pipe wall thickness for a given NPS may or may not match the *steel* pipe wall thickness for the equivalent schedule number. In addition, wall thickness is not constant for a given schedule number; it may change from one NPS to another.

Stainless steel pipe wall thickness is determined either by schedule number or by gauge thickness, depending upon the governing ASTM standard:

- ASTM A312 or A790 (heat-treated) pipe always has wall thickness defined by schedule number. Maximum size is 30-inch NPS for the “S” schedule numbers.
- ASTM A778 (unannealed) pipe may have wall thickness defined by either
 - Schedule number in sizes up to 30-inch NPS (sometimes referred to as “schedule pipe”), or
 - Gauge thickness in sizes up to 48-inch NPS (sometimes referred to as “gauge pipe”).¹³

¹¹ ASME B36.19M§8. For pipe that is specified under AWWA C220, the wall thickness to meet the design requirements is determined by the appropriate formulas in AWWA Manual M11 using stainless steel material properties.

¹² *Steel* pipe NPS and wall thickness dimensions are defined for schedule numbers in ASME B36.10 Welded and Seamless Wrought Steel Pipe. *Stainless steel* pipe NPS and wall thickness dimensions are defined for schedule numbers in ASME B36.19 Stainless Steel Pipe. Some pipe thicknesses are also commercially available with stainless steel materials in accordance with ASME B36.10

¹³ ASTM A778 allows for fabrication of pipe larger than 48-inch NPS and some suppliers will produce larger sizes; such pipe would be gauge pipe.

For most general service applications in the drinking water industry, the following guidelines will apply in the selection of pipe wall thickness.¹⁴

- Less than 3-inch NPS.
 - For applications with internal pressures less than 1,000 psi gauge, minimum wall thickness corresponding to Schedule 10S.
 - For applications with internal pressures greater than 1,000 psi gauge but less than 2,000 psi gauge, use minimum wall thickness corresponding to Schedule 40S or more.
- A proprietary coupling system¹⁵ is reported by the manufacturer to be used with minimum wall thickness corresponding to Schedule 10S at up to 500 psi gauge or Schedule 5S at up to 300 psi gauge for ½-inch through 2-inch NPS.¹⁶
- Three-inch through 12-inch NPS.
 - For applications with internal pressures less than 400 psi gauge, minimum wall thickness corresponding to Schedule 10S.
 - For applications with internal pressures greater than 400 psi gauge but less than 800 psi gauge, minimum wall thickness corresponding to Schedule 40S.
 - For applications with internal pressures greater than 800 psi gauge but less than 1,100 psi gauge, minimum wall thickness corresponding to Schedule 80S.
- Fourteen-inch through 24-inch NPS¹⁷
 - For applications with internal pressures less than 300 psi gauge, use no less than minimum wall thickness corresponding to Schedule 10S.
 - For applications with internal pressures greater than 300 psi gauge but less than 450 psi gauge, use no less than minimum wall thickness corresponding to Schedule 40S.
 - For applications with internal pressures greater than 450 psi gauge but less than 600 psi gauge, use no less than minimum wall thickness corresponding to Schedule 80S.
- Twenty-six-inch through 36-inch NPS²²
 - For applications with internal pressures less than 300 psi, use minimum wall thickness corresponding to Schedule 40S or more.

In general, it is recommended that threaded pipe be avoided, though sometimes it is necessary (e.g., small diameter instrument fittings are all threaded). When threaded or grooved joints are used the pipes pressure rating is reduced because material is removed from the stainless steel. The pressure rating for the joint will depend upon the diameter of the pipe and actual coupling used (specified by the engineer). However, the following guidelines can generally apply relative to the pipe's pressure rating:

¹⁴ Exceptions include high temperature applications; many common stainless steel alloys have reductions in allowable stress at temperatures greater than 300 °F (see ASME B31.3 Table A-1). Other exceptions include applications where external loadings or pipe deflection requirements govern wall thickness selection.

¹⁵ Vic-Press, manufactured by Victaulic Company.

¹⁶ Note that Schedules 5S and 10S wall thicknesses do not permit threading in accordance with ASME B1.20.1.

¹⁷ ASME B36.19 does not provide for Schedule 40S in sizes larger than 24-inch NPS. However, ASME B36.10 provides for Schedule 40S in sizes up to 36-inch. Larger diameters may be fabricated based upon the methods provided in ASME B36.10 or B36.19, but they will not be “schedule” pipe as defined by these standards.

- Avoid threaded flange fittings. Instead, weld the flange or use a stub-end backing flange.
- Piping with threaded or grooved joints, diameters up to 12-inch.
 - For applications with pressures less than 250 psi gauge (cut groove) or less than 150 psi gauge (rolled grooves), use minimum wall thickness corresponding to Schedule 40S or more.
 - For pressures exceeding 250 psi gauge (cut grooves) or 150 psi gauge (rolled grooves), use minimum wall thickness corresponding to Schedule 80S or more.
- For pipe diameters exceeding these guidelines, consult the coupling manufacturer.

Fittings

Fittings include parts such as elbows, reducers, tees, reducers, wyes, laterals, crosses, and stub ends that are typically incorporated into a piping system. Fittings are specified by the ASTM standard that corresponds to the pipe or tube standard as indicated in [Table 5.2](#).

Where pipe is specified by AWWA C220, the matching fittings should be specified under AWWA C226, which allows either unannealed or heated treated fittings.

The designer must specify the fittings to match the pipe or tube standard and material. Likewise, the fitting schedule number or wall thickness must match the pipe or tube to which it will be joined.

Joints

Joints are connections between pipe or tube and any of the following:

- Pipes or tubes,
- Fittings,
- Piping appurtenances such as valves and strainers, or
- Equipment.

Flanged Joints

1. Connect to flanged valves and flanged pipe appurtenances with flanged pipe ends. Flange material should match the piping system material. Flange working pressure ratings are based on class.
 - a. Under AWWA C228, standard stainless steel flanges¹⁸ are available in the following classes:¹⁹
 - i. Pressure ratings are based on conditions and temperatures customarily found in water and wastewater applications. Maximum sustained operating pressure, plus any anticipated surge/transient pressures, should not exceed flange

¹⁸ Class SA, SB, SD, and SE flanges have the same diameter and drilling as AWWA D flanges and Class 125 cast-iron flanges (ASME B16.1); in size 24-inch and smaller, they also match ASME B16.5 150-psi standard for steel flanges (see AWWA 228 Table 1, Notes). Class SF flanges have the same diameter and drilling as AWWA F flanges and Class 250 cast-iron flanges (ASME B16.1); in sizes 24-inch and smaller, they also match ASME B16.5 300-psi standard for steel flanges (see AWWA 228 Table 2, Notes).

¹⁹ Pressure rating is at atmospheric temperature (AWWA 228 Tables 1 and 2).

pressure ratings. Test pressure should not exceed 125 percent of the design pressure.

- Class SA: 50 psi pressure rating in 2-inch through 72-inch NPS.
 - Class SB: 86 psi pressure rating in 2-inch through 72-inch NPS.
 - Class SD: 175 psi pressure rating in 2-inch through 12-inch NPS; 150 psi pressure rating in 14-inch through 72-inch NPS.
 - Class SE: 275 psi pressure rating in 2-inch through 72-inch NPS.
 - Class SF: 300 psi pressure rating in 4-inch through 48-inch NPS.
- ii. Except for blind flanges, these are slip-on flanges that are attached by means of double fillet welds. Specification of low carbon or dual-certified Type 304/304L and Type 316/316L, Type 321, or duplex stainless steel is recommended.²⁰
 - iii. All classes are flat-faced without projection or raised face. They will not mate to a raised-face flange.
- b. Under ASME B16.5, stainless steel flanges are available in the following sizes and pressure classes:
- i. Sizes are ½-inch through 24-inch NPS.
 - ii. Flange options are (See [Figure 5.1](#)):
 - Weld-neck flanges (sometimes referred to as butt weld flanges). These are typically used with high pressures or hazardous fluids. The butt weld may be examined by radiography or by the borescopic method described in ASTM A 1015.
 - Slip-on flanges. These are typically used because of their lower cost and ease of installation; they are attached by means of double fillet welds that are not practical to examine by radiography or by the borescopic method described in ASTM A 1015.
 - Socket-weld flanges. These are often used with applications involving high pressure but are limited to 2-inch NPS and smaller; they are attached by means of fillet welds that are not practical to examine by radiography or by the borescopic method described in ASTM A 1015.
 - Threaded flanges. These are available for 6-inch NPS or smaller and are typically restricted to temperatures not exceeding 250°F. However, threaded flanges are a potential site for crevice corrosion to occur (independent of chlorine or chloride concentrations) and their use should be avoided where practical.

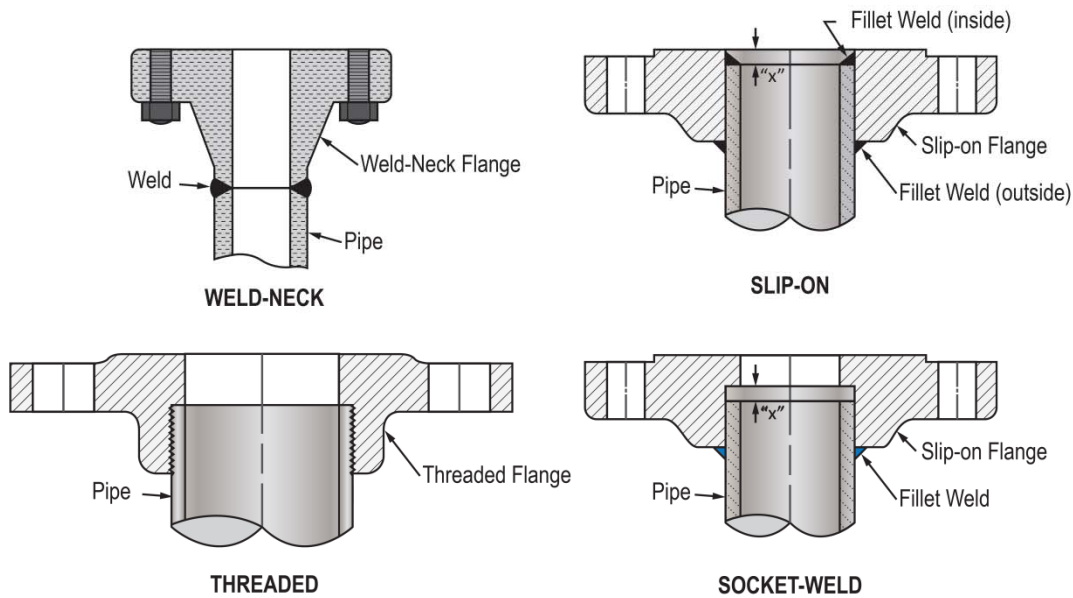
For general service in drinking water applications consider allowing both weld-neck and slip-on flanges so that the piping supplier has the flexibility to select from these options. Specify forged stainless steel with metal type matching the piping system.

Working pressure is a function of temperature and flange material for a given class; flanges are available in the following classes: 150, 300, 400, 600, 900,

²⁰ AWWA C228 § 4.3. Dual certification is defined as low carbon stainless steel, suitable for welding, with nitrogen additions to provide and meet the minimum mechanical properties offered by standard grades of stainless steel.

1500, and 2500. Refer to ASME B16.5 for complete information. The following examples of pressure ratings for various materials may be helpful:²¹

- Type 304 and 316 stainless steel flanges at temperatures between -20°F (-29°C) and 100°F (38°C).
 - Class 150 = 275 psi.
 - Class 300 = 720 psi.
 - Class 600 = 1,440 psi.
- Type 304L and 316L stainless steel flanges at temperatures between -20°F (-29°C) and 100°F (38°C).
 - Class 150 = 230 psi.
 - Class 300 = 600 psi.
 - Class 600 = 1,200 psi.



FLANGE OPTIONS

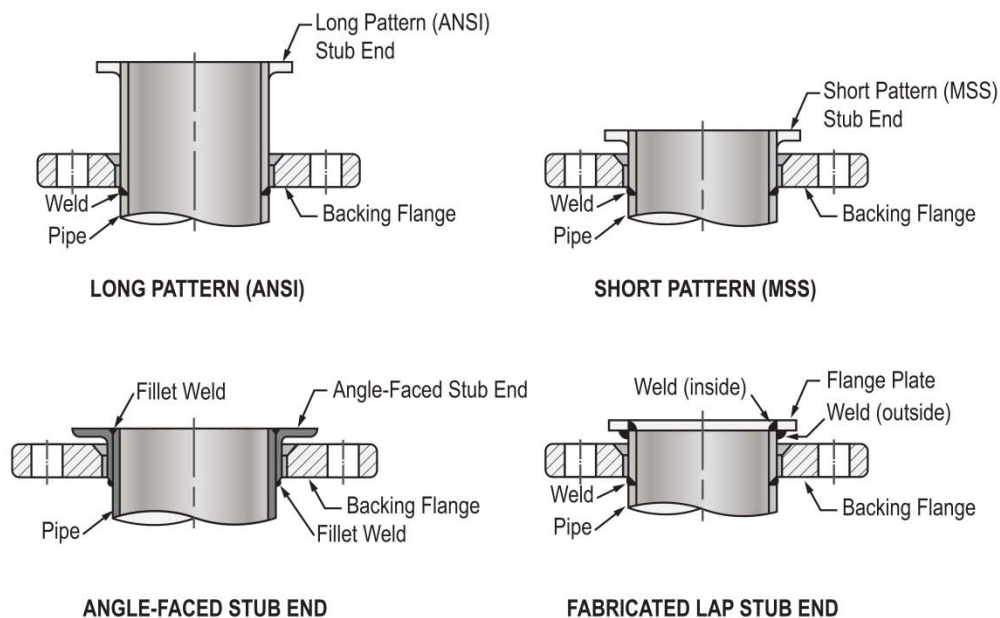
Figure 5.1 Flange options

2. Use pipe stub ends with backing flanges where welded pipe flanges are not required (e.g., where full-mechanical restraint is not required). Stub end connections are typically less expensive than welded flanges and offer the ability to rotate the backing flange to make field installation easier.²²
 - a. There are several basic types of stub end configurations for butt weld attachment to matching stainless steel pipe (Figure 5.2).

²¹ ASME B16.5 Table 2-2.1, Table 2-2.2, and Table 2-2.3.

²² The rotatable backing flange is sometimes referred to as a Van Stone (or Vanstone) flange.

- i. Lap-joint stub ends in accordance with ASME B16.9 are available as Class 150, 300, 400, 600, 900, 1500, and 2500. Two lengths are available under ASME B16.9:
 - Long pattern, sometimes referred to as ANSI.
 - Short pattern, sometimes referred to as MSS.²³
- ii. Fabricated lap stub ends are manufactured by welding a plate flange on the pipe stub end. When manufactured in accordance with ASME B31.3 they are available in the same pressure classes as lap-joint stub ends.
- iii. Angle-faced stub ends incorporate a rolled, cylindrical angle that slips on the end of the stub and is fillet welded.²⁴ They are typically manufactured to MSS or ANSI lengths.



TYPES OF STUB ENDS

Figure 5.2 Types of Stub Ends

- b. Backing flanges:
 - i. Backing flanges may be plate flanges in accordance with ASME B31.3 or lap joint flanges in accordance with ASME B16.5. In either case, they should be specified as the same class as the fitting. Stub ends must be machined, if necessary, so that the lap radius matches the backing flange.
 - ii. In environments where external corrosion is an issue (e.g., submerged, corrosive vapors present), use forged stainless steel backing flanges. Cast

²³ Manufacturers Standardization Society of the Valve and Fitting Industry.

²⁴ Rolled stainless angle face rings with backing flanges are allowed under AWWA C220 §4.9.2.1 when specified by the purchaser.

stainless steel flanges are also available, but may not offer the aesthetic appeal of forged flanges. Otherwise (and where aesthetics are not a concern), the designer may consider coated or galvanized carbon steel flanges as an economical choice. Coated ductile iron backing flanges are also an option where external corrosion is not a concern.

3. Gaskets: Gasket material can affect the potential for crevice corrosion of stainless steel flanges. Natural and synthetic elastomeric materials are less likely to promote conditions that result in crevice corrosion than PTFE or gaskets containing fibers. Gaskets containing carbon or graphite are not recommended; these have been known to result in even greater crevice corrosion.²⁵
4. Flange bolt tightness: Flange bolt tightness may influence the potential for crevice corrosion. When installing flange bolts, consult the gasket manufacturer's guidance on flange bolt tightness. In particular, the following installation considerations should be considered:
 - a. Use of a torque wrench to tighten flange bolts to the gasket manufacturer's recommendation.
 - b. Tighten all bolts in uniform increments (i.e., 1/3 turns), rotating around all the flange bolts so that no one bolt is over-tightened.
 - c. Using the torque wrench, check bolt tightness after 24 hours.

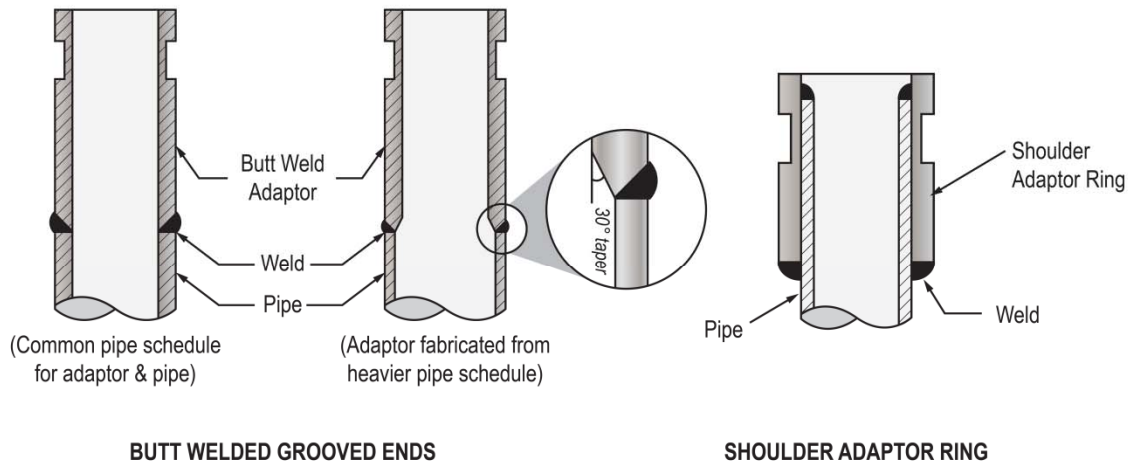
Grooved Couplings

Grooved couplings provide a fast and convenient method of assembling fabricated piping sections and components in the field. They also facilitate later removal of pipe sections for maintenance or equipment replacement. However, because of the relatively thin walls typically used for stainless steel pipe, special consideration of pressure rating is required when using grooved couplings.

1. Unless using fittings that are furnished by the grooved coupling manufacturer, it is suggested that grooved couplings are restricted to use with pipe schedules 40S and 80S.
2. There are several options for using grooved couplings with schedule 5S and 10S pipe (Figure 5.3).
 - a. Butt Welded Grooved End:
 - i. Schedule 40S and 80S end sections can be butt welded to schedule 5S and 10S pipe to allow cut grooves for piping systems composed of 5S and 10S.
 - ii. Specify a 30° from horizontal tapered interior diameter at the butt end of the higher schedule pipe to avoid an abrupt change of the inside diameter.
 - b. Shoulder Adapter Ring:
 - i. Some grooved couplings are compatible with an adapter ring with a cut groove that slips onto the pipe end and is fillet welded in place.
 - ii. The coupling manufacturer should be consulted regarding the type of adapter ring and coupling to be used with different pipe sizes and service applications.

²⁵ Kain, 1998.

3. Use grooved couplings made with stainless steel housings in environments where external corrosion would be an issue for galvanized or ductile iron (e.g., submerged surface, corrosive vapors). When external corrosion is not a concern, a designer may consider using galvanized fittings over ductile iron for aesthetic reasons.
4. Consider specifying grooved couplings with Type 651 silicon-bronze nuts to reduce galling and seizing and facilitate subsequent removal and re-installation.



TYPES OF GROOVED JOINTS

Figure 5.3 Type of Grooved Joints

Bolted Split-Sleeve Couplings

Split-sleeve couplings can be used to join plain-end stainless steel pipes of larger sizes than can be connected using standard grooved couplings.

1. Specify that bolted split-sleeve couplings meet the requirements of AWWA C227.
2. Require shop installation of any welded restraint rings or other pipe attachments so that they are part of the fabricated assembly prior to shop-applied surface finishing such as descaling and passivation.

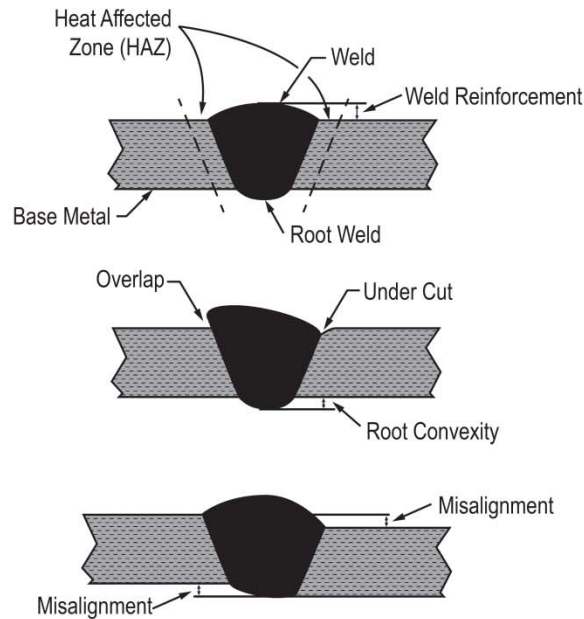
Welded Joints ²⁶

1. Ideally, welding should be limited to the shop welding undertaken to fabricate the piping sections. The fabricated sections are then descaled, passivated, and shipped to the field for assembly. Quality control issues, such as maintaining a protective inert gas shield and ensuring full penetration welds, are typically more difficult in the field as is post-weld treatment to remove weld heat tint oxide.
2. In general, the internal welds on piping 30-inches and smaller may be difficult to construct due to access and weld quality may suffer. However, if the joint is planned, internal welding near the opening is acceptable.
3. Circumferential butt welds should be full penetration, which is not the standard of care for many pipe fabrication shops (Tuthill 1994). AWWA C220 covers this by requiring complete joint penetration (CJP) butt joints, which is defined as penetration of weld metal through the thickness of the joint.²⁷ ASTM standards do not cover circumferential butt welds made in pipe fabricating shops and this requirement should be added to the specification if the AWWA standards are not used.
4. The following guidelines are recommended for circumferential welded joints in stainless steel pipe for drinking water service (Avery et al. 1999).
 - a. All circumferential pipe welds that are welded only from the OD should be made using gas tungsten arc welding (GTAW), or tungsten inert gas (TIG) for the root pass along with an internal inert gas purge to exclude oxygen in the weld root area. Control of heat input is important to minimize heat tint on the underside of the joint surface, exposed to the environment. Metal inert gas (MIG) can be selected for completion of the balance of the weld, depending on the cross sectional thickness of the joint.
 - b. Pipes 30-inch diameter and larger that are accessible for internal post-weld treatment: Remove heat tint by grinding and pickling the interior weld surface.
 - c. Pipes less than 30-inch diameter: The piping fabricator should be required to remove or prevent the formation of heat tint oxide using one of the following options.
 - i. Place welds so that they are accessible for internal grinding.
 - ii. Limit assembly length to accommodate pickling the fabricated unit.
 - iii. Prevent any significant heat tint oxide formation through very precise weld joint preparation and careful internal purging procedures. Automatic orbital welds can be made free of heat tint. The fabricator should be required to demonstrate the ability to make heat tint-free welds.
 - d. Use mechanical connections on joints where weld heat tint oxide removal or prevention is not practical.

²⁶ This discussion is restricted to circumferential weld joints used to connect pipe sections and fittings. Longitudinal welding (e.g., production of welded pipe) is governed by the reference pipe standards and is not the subject of this discussion of welded joints.

²⁷ AWWA C220 §4.4.2.1. The equivalent requirement for stainless steel fittings is AWWA C229 §4.2.3.3

5. Other minimum weld fabrication requirements (Figure 5.4) for drinking water service would include the following:²⁸
 - a. Require full penetration welds, free of cracks, overlaps and cold laps.
 - b. Limit misalignment for manual welds to 1/16-inch or half the wall thickness, whichever is less.
 - c. Limit weld reinforcement and root convexity to 1/16-inch or agreed-upon limit.
 - d. Limit undercut to 1/32-inch or 10 percent of base metal thickness, whichever is less.



WELD FABRICATION (FULL PENETRATION WELD EXAMPLE)

Figure 5.4 Weld Fabrication Examples

Threaded Joints

The use of threaded joints should be avoided in the water service applications due to the potential for crevice corrosion, independent of chlorine or chloride concentrations. Ideally, the use of threaded joints should be restricted to handling dry air or hydraulic fluid oils. Where practical, consider using welded or flanged fittings for instrument connections.

Tubing Joints

1. Use swage ferrule joints of the double acting ferrule design, providing both a primary seal and a secondary bearing force.
2. Flare type fittings are not acceptable.
3. Specify that tubing fitting materials are compatible with the stainless steel tubing.

²⁸ Ibid.

Fasteners

Stainless steel bolts should be used as fasteners with stainless steel materials such as flanges. Bolt threads should be sanded or brushed to remove any burrs. Specify rolled threads rather than machined threads to minimize surface burrs. The fastener material must not be less noble on the galvanic series than the material to be fastened (i.e., use the more noble metal for the part with the smaller surface area).²⁹ The following guidelines are applicable in most cases.

1. General service.
 - a. Bolts: Type 316, ASTM A193, Grade B8M, Class 1, heavy hex.
 - b. Nuts: Type 316, ASTM A194, Grade B8, heavy hex.
 - c. Washers: Type 316.
 - d. Surfaces descaled, pickled, and passivated in accordance with ASTM A380.
2. Brackish water membrane and RO applications.
 - a. Bolts: Type 316, ASTM F593, Group 2, Condition CW, heavy hex.
 - b. Nuts: use one of the following.
 - i. Type 316, ASTM A194, 8M, heavy hex nuts; use anti-seize compound formulated to prevent seizure and galling of stainless steel threads. Use this option if trouble-free removal of the nut is not critical.
 - ii. Type 651 silicon bronze heavy hex nuts will reduce galling and seizure of the threads. Consider using this option under the following conditions:
 - For applications that require occasional removal of nuts, such as grooved connectors or access flanges.
 - If a single metal appearance is not required for aesthetic purposes.
 - If non-galling fasteners are worth the higher cost of silicon bronze nuts.³⁰
 - iii. High manganese silicon stainless steel, ASTM F 593, B8S, heavy hex nuts. Consider using this option for the same reasons as silicon bronze but when a single metal appearance is desirable.
 - c. Washers: Type 316.
 - d. Surfaces descaled, pickled, and passivated in accordance with ASTM A380.
3. Use caution in specifying or designing pipe or equipment restraints. Avoid any contact between steel and stainless steel by one of the following methods:
 - a. Use all-stainless steel materials for pipe restraints, or
 - b. Isolate the stainless steel from steel contamination with protective pads or wraps.

Post-Fabrication Surface Finishing

Proper surface treatment of stainless steel is critical to achieve the desired corrosion resistance. This involves several steps that should be completed in the shop before fabricated pieces are transported to the job site.

Heat tint oxide in the weld HAZ is one of the major contributors to under-deposit corrosion and MIC in stainless steel used in potable water systems.³¹ Heat tint oxide can vary in color and

²⁹ Pp. 12-13, SSINA, 2014

³⁰ Note: There is a potential for galvanic corrosion unless the nuts are changed regularly.

³¹ Avery et al, 1999.

thickness ranging from a thin, light, or straw-colored oxide to a dark black oxide of appreciable thickness. The heavier the oxide, the more likely that it will contribute to the initiation of corrosion.

Following removal of heat tint oxides, it may be necessary to passivate the stainless steel surface in accordance with ASTM A967 or electro-polish it in accordance with ASTM B 912, especially if it is to be used for critical services in the handling of high-purity waters; e.g., pharmaceutical, electronic, and food industries. For general water service, the natural oxide film formation on surface areas following pickling treatment should be sufficient to reform the thin, protective chromium oxide film, typical of stainless steel.

Consult ASTM A380 *Standard Practice for Cleaning, Descaling, and Passivation of Stainless Steel Parts, Equipment, and Systems* for the appropriate surface finishing treatment or treatments needed for the particular application. The following basic requirements are typical for stainless steel used in water industry applications.

Cleaning

Cleaning includes all operations necessary for the removal of surface contaminants from stainless steel to: 1) achieve maximum corrosion resistance of the metal, 2) minimize product contamination, and 3) achieve the desired appearance (ASTM A380 2013).

Visual inspection at the job site should confirm that stainless steel items are free of paint, oil, grease, welding flux, slag, heating treating and hot-forming scale, dirt, trash, metal and abrasive particles and chips, and other gross contamination. Dust may be present on exterior surfaces but should not be present on interior surfaces (ASTM A380 2013).

Descaling

Descaling is the removal of heavy, tightly adherent oxide films resulting from hot-forming, heat treatment, welding, and other high-temperature operations. Descaling can be mechanical or chemical; chemical descaling is referred to as pickling (ASTM A380 2013).

1. Mechanical descaling methods: as required by stainless steel type or condition. Grinding is usually the most effective means of removing localized scale such as that which results from welding (ASTM A380 2013).
2. Chemical descaling methods (pickling): Most pickling solutions will loosen weld and heat-treating scale but may not remove them completely. Use intermittent scrubbing as required to ensure the surface is completely cleaned. Over-pickling must be avoided following any chemical descaling treatment, the component should be thoroughly rinsed and water jet sprayed to remove excess acid before it can cause acid attack of the base metal (ASTM A380 2013).

Preventing or removing all heat tint from welds is critical when maximum resistance to MIC and/or crevice corrosion is required (Tuthill 1994). ASTM standards require that pipe and fittings are free of scale but they do not explicitly require removal of all heat tint. AWWA C220 requires that “the pipe shall be free from scale and contaminating iron particles. Contaminating iron particles and heat tint shall be removed...” Heat tint in the HAZ of welds is scale and the specification should include a requirement similar to the AWWA C220 language if this standard is not included.

Specify that stainless steel materials are to be descaled after fabrication in accordance with ASTM A380 including the use of nitric-hydrofluoric acid per Table A2.1, Part I or cleaned with citric acid per Table A2.1, Part III.

Passivation

The term passivation is commonly applied to several distinctly different operations or processes relating to stainless steels. Define precisely the intended meaning to avoid ambiguity; the following are potential meanings of passivation listed in ASTM A380.

- Removal of exogenous iron or iron compounds from the surface of a stainless steel by means of a chemical dissolution.³²
- The process by which a stainless steel will spontaneously form a chemically inactive surface when exposed to air or other oxygen-containing environments.
- Chemical treatment with a mild oxidant, such as a nitric acid solution, for the purpose of enhancing the spontaneous formation of the protective passive film.
- Passivation *does not* indicate the separate process of descaling (including pickling) although descaling may be necessary before passivation can be effective.

Specify that stainless steel materials are to be passivated after fabrication in accordance with ASTM A380 with final cleaning per Table A2.1, Part II and in accordance with ASTM A967. The specified finish requirement should be to remove free iron, heat tint oxides, weld scale, and other impurities, and obtain a passive finished surface.

Specify testing of the passivated surface using Methods B, C or F described in ASTM A967 as appropriate for the application (none of these tests will be the right one for every application).

Electropolishing

Electropolishing is a form of passivation that is sometimes used in water industry applications, in which the fabricated stainless steel materials are treated as the anode for current passed through an acid electrolyte. Electropolishing is performed subsequent to cleaning and descaling. Electropolishing smooths, polishes, deburrs, and cleans stainless steel parts resulting in a smooth, high luster finish. However, electropolishing should be distinguished from mechanical polishing, which results in a mirror-like finish. Electropolishing is less expensive than mechanical polishing. Contractors have reported that, for a new water plant project, electropolishing can increase materials cost by approximately 10 percent. However, the same contractors have also reported that because electropolished piping is not welded in the field, their installation costs are reduced since joints consist of flanges, grooved couplings, bolted split sleeved couplings, etc.—i.e., a net savings can be realized in some cases.

³² Unless otherwise specified, it is this definition of passivation that is taken as the meaning of a specified requirement for passivation under ASTM A380 (see § 1.1.1.2)

Advantages offered by electropolishing include the following:

- It is ideal for reducing potential for MIC because it is more difficult for bacteria to adhere to the smooth surface.
- It provides a higher level of corrosion resistance in high-chloride (and high-chlorine) environments such as brackish and seawater RO applications.
- It forces the installer to “respect” the pipe, because abuse and damage, which likely result in corrosion, will easily show.
- The polished look is aesthetically attractive and enhances the appearance of the finished facility.

When electropolish is desired, specifications for electropolished stainless steel in water service should include the following.

1. Require electropolishing for the following stainless steel materials:
 - a. Pipe interior: All piping.
Note: not all fabrication shops can accomplish internal electropolishing for long lengths of piping.
 - b. Pipe exterior: All piping except concrete encased or buried piping.
 - c. List other materials as appropriate.
2. Procedures:
 - a. Following shop fabrication, prepare surfaces using preparatory and cleaning practices of ASTM A380.
 - b. Electropolish stainless steel components after fabrication in accordance with ASTM B912. Remove 5 μm ($\pm 1 \mu\text{m}$) from the surface.
 - c. Provide post dip in room temperature 10 to 30 percent nitric acid solution followed by a final rinse.
3. Finished surfaces: Free of imperfections such as pitting, etches, burn marks, or stains.

Shot Peening

Shot peening, sometimes referred to as bead blasting, is a cold working process that is sometimes used in water industry applications to produce a compressive residual stress layer and modify mechanical properties of metals by impacting a surface (with “shot”) using enough force to create plastic deformation (Outokumpu 2013). Shot peening has the following benefits when used with stainless steel:

- It reduces the potential for stress cracking corrosion and pitting (Avesta 2004 and Badran et al. 2008, respectively).
- It can help remove high temperature oxide as well as iron contamination.
- It provides a good surface finish for equipment that are too large for electropolishing (e.g., pump discharge heads or cartridge filter housings).

Shot peening is used primarily to increase the resistance to chloride stress cracking corrosion, which is not typically a significant issue in drinking water applications. Consequently, there is not a reference standard for shot peening that specifically applies to stainless steel used in water industry service. However, it is frequently used for high-chloride applications, such as in brackish water and seawater RO systems. When shot peening is desired, specifications for shot peening of stainless steel in water service would include the following.

1. Identify the surfaces to be treated by shot peening. State that the required surface treatment is a uniform finish with a matte or satin appearance.
2. Shot material should be stainless steel, glass, or ceramic that has not been previously used on carbon steel and that has not been significantly contaminated with scale and impurities from previous use on stainless steel.
3. Shot peening is not a substitute for pickling and passivation because it does not remove the chromium-depleted surface layer, which is best done by chemical means.
4. Shot peening is best performed in the shop after fabrication and should be followed by pickling and passivation for maximum corrosion resistance.³³
5. Sand blasting is not allowed as a substitute for shot peening because sand blasting operates by abrasion and can result in excessive cutting at localized points.

Cleaning for Ozone and Liquid Oxygen Service

Following pickling and passivation of the fabricated stainless steel materials, clean and seal piping sections in accordance with CGA Standard G-4.1.

Source Quality Control

1. Manufacturer provides written certification under the requirements of the governing standard that the materials supplied conform to the requirements of the standard.
2. Shipment to site.
 - a. Protect all flanges and pipe ends by encapsulating in dense foam.
 - b. Securely strap all elements to pallets with nylon straps. Use of metallic straps is prohibited.
 - c. Cap ends of tube, pipe, fittings, and valves with non-metallic plugs.
 - d. Load pallets so that no stainless steel materials bear the weight of pallets above.
 - e. Ensure that loaded materials do not exceed minimum height restrictions of shipping route (e.g., bridges and overpasses).
 - f. Purchaser inspects materials on delivery and may reject material due to improper shipping methods or damage during shipment.

³³ Cleaning and Descaling Stainless Steels, Nickel Development Institute, p 16.

GUIDELINES FOR CSI MASTERFORMAT® PART 3, EXECUTION REQUIREMENTS

Design

The designer is responsible for providing a system design that can be started up, operated, and maintained in ways that are consistent with the special requirements of stainless steel used in the drinking water industry.

There have been numerous reports of stainless steel failures in drinking water applications due to microbiologically induced corrosion (MIC). High chloride service such as brackish water, seawater, and RO concentrate applications also pose special corrosion challenges for stainless steel. The design must provide the means to avoid conditions that promote MIC and that provide resistance to chloride crevice corrosion and pitting. Design recommendations have been provided below:

- Avoid stagnant water conditions. Drain promptly and completely after hydrostatic testing is completed and when the facility is shut down.
- Dry piping where practical, or alternatively run the system for 1-2 hours per day for circular flow.
- Provide a design that allows the complete draining of all stainless steel pipe systems and vessels.
- Avoid dead legs, low points, and areas that cannot be drained completely during shutdown or standby.
- Apply special care in raw water systems. Ensure velocities minimize sediment deposits. Provide for inspection and sediment flushing.
- Use reference standards and specify practices that require full penetration welds with smooth internal contours.
- Require manufacturing and installation practices that prevent or remove heat tint oxide at welds.
- If field welds are necessary, require radiographic testing (or borescopic examination) and post-weld descaling and passivation.
- Consider using electropolished stainless steel in areas or applications susceptible to MIC or high chloride levels.
- Select stainless steel materials with an appropriate PREN for the chloride concentration using the guidelines provided in this section or seek expert advice.
- Avoid exposing stainless steel to chlorine vapor or air from the headspace of basins containing chlorinated water.
- Provide isolation between dissimilar metals to eliminate galvanic corrosion. Select appropriate fasteners of compatible stainless steel materials.

Field Welding

It is strongly recommended that the specifications prohibit field welding wherever possible. However, if there are compelling reasons to permit field welding then the following are suggested.

- Require that all field welding comply with the same requirements as shop fabrication welding and post-weld finish treatment.
- Require that 100 percent of field welds be subject to radiographic testing or borescopic examination as described in ASTM A 1015. This requirement may be relaxed after a statistically significant number of field welds have been demonstrated to be acceptable.

Field Quality Control

1. Visually inspect pipe for welding defects such as crevices, pits, cracks, protrusions, and oxidation deposits. Repair any defects.
2. Examine and inspect welds in liquid oxygen and ozone service piping in accordance with ASME B31.3.

Protection

1. Preserve the appearance and finish of stainless steel by providing suitable protection.
 - a. Do not allow bare cables, chains, hooks, metal bars, or skids to come into contact with stainless steel.
 - b. Storage:
 - Store stainless steel materials away from other metals.
 - Do not store in contact with ground.
 - Do not store outside without protection (e.g., plastic wrap) from airborne materials and pollutants.
 - Do not use wrapping or protection, which might absorb water and stain the surface of the stainless steel (e.g., no cardboard).
 - c. Protect stainless steel materials from carbon steel projections (e.g., no grinding of carbon steel in proximity).
 - d. Do not contact stainless steel with carbon steel wire brushes or tools. Do not use tools contaminated by previous use on carbon steel.
2. Electropolished stainless steel procedures.
 - a. Use disposable latex gloves or equivalent. Do not handle with bare hands or gloves contaminated with oils, metals, or other materials.
 - b. Clean, repair, or replace damaged, stained, scarred or dirty electropolished stainless steel to restore shop-finish quality.

Disinfection and Hydrostatic Testing

Stainless steel piping and materials require special consideration during startup, testing, and operations.

Disinfection

Type 304L and 316L stainless steel can tolerate higher levels of chlorine for shorter time periods than those indicated in [Tables 5.5](#) and [5.6](#). The following steps are recommended for disinfection of newly installed or modified stainless steel piping systems.

1. Disinfect using the continuous-feed method of AWWA C651 with the minimum chlorine concentration required to provide a residual of 10 mg/L as Cl₂ after 24 hours.
 - a. Dissolve all calcium/sodium hypochlorite granules completely before introducing the chlorine solution into the stainless steel system.
 - b. Do not place calcium or sodium hypochlorite granules directly into stainless steel piping or allow undissolved granules to contact stainless steel materials.
2. Pressurize stainless steel piping systems so that all gaskets and O-rings are seated before introducing chlorinated water into the system.
3. After disinfection, flush the hyper-chlorinated water from the system. Displace a minimum of three pipe volumes at the conclusion of the disinfection procedure.

Hydrostatic Testing and Shutdown

Problems with MIC often begin when water is left in stainless steel pipe or tanks following hydrostatic testing or when a facility is shut down. This is especially true with raw water.

1. Drain promptly and completely after hydrostatic testing or during shutdowns.
2. Circulate water regularly with an appropriate disinfectant residual if the system must be left full.

DECISION TREES FOR SELECTING STAINLESS STEEL MATERIALS FOR DRINKING WATER USE

The following decision trees can be used as guidelines for selecting stainless steel for different free chlorine-chloride environments. NOTE: Use of these guidelines does not constitute a guarantee that selecting steels according to these decision trees will prevent corrosion. However, like the specification guidelines presented in the previous sections, these trees are based on the best available science on minimizing corrosion, gathered and reported here in the previous chapters.

Note:

1. 2x safety factor is applied to chloride concentrations.
2. No safety factor applied to chlorine concentrations

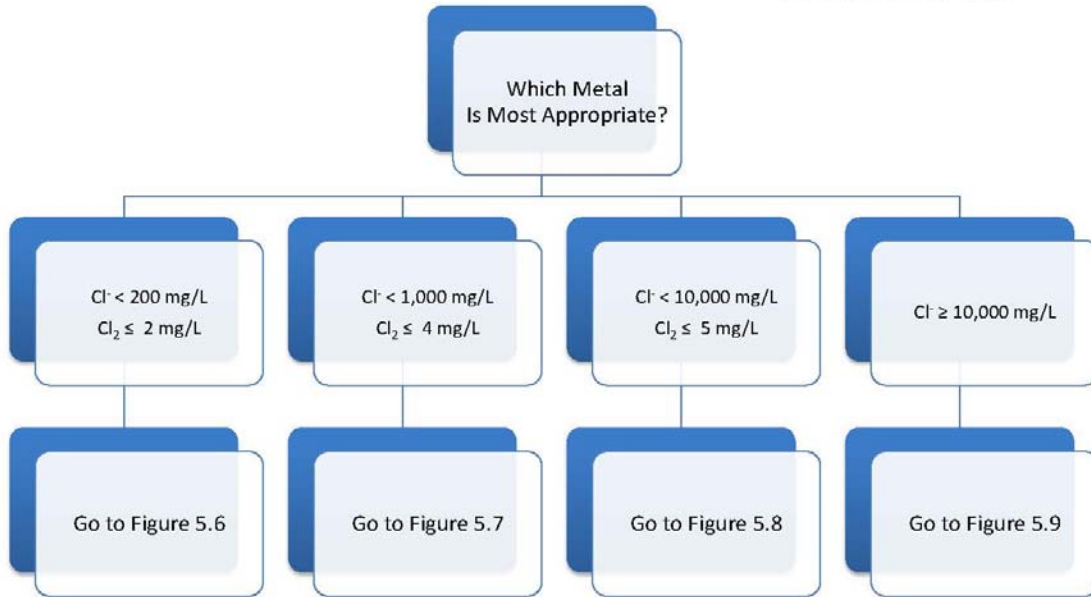


Figure 5.5 Decision Tree 1: Stainless steel recommendations based on chloride and free chlorine concentrations

Note:

1. 2x safety factor is applied to chloride concentrations.
2. No safety factor applied to chlorine concentrations

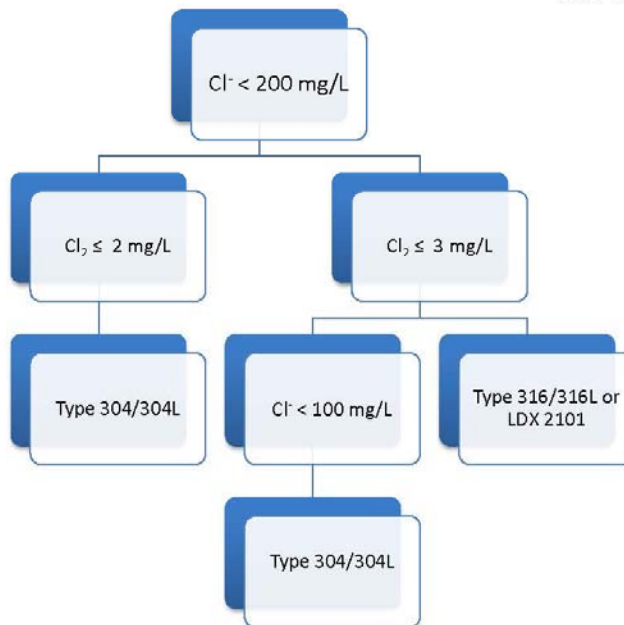


Figure 5.6 Decision Tree 2 for chloride concentrations <200 mg/L: Stainless steel recommendations based on chloride and free chlorine concentrations

Note:

1. 2x safety factor is applied to chloride concentrations.
2. No safety factor applied to chlorine concentrations

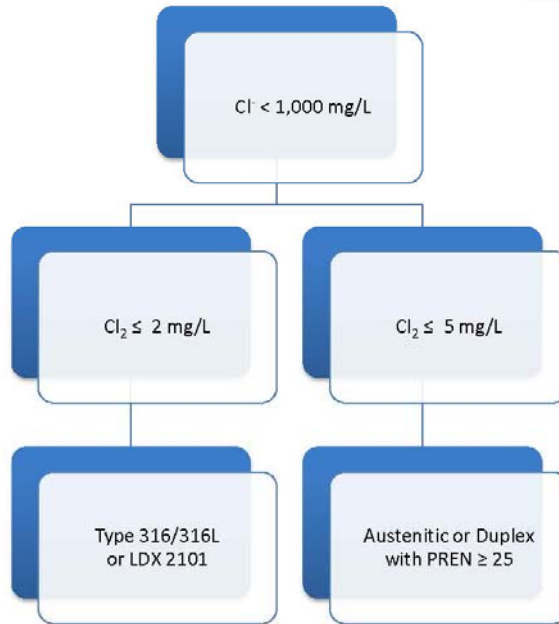


Figure 5.7 Decision Tree 2 for chloride concentrations between 200 and 1,000 mg/L: Stainless steel recommendations based on chloride and free chlorine concentrations

Note:

1. 2x safety factor is applied to chloride concentrations.
2. No safety factor applied to chlorine concentrations

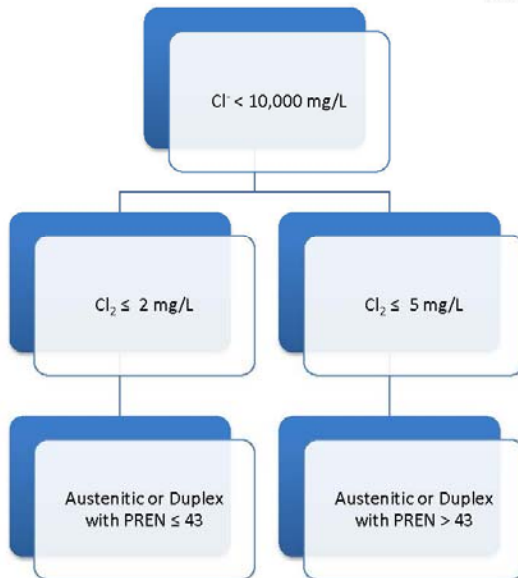


Figure 5.8 Decision Tree 2 for chloride concentrations between 1,000 and 10,000 mg/L: Stainless steel recommendations based on chloride and free chlorine concentrations

Note:

1. 2x safety factor is applied to chloride concentrations.
2. No safety factor applied to chlorine concentrations

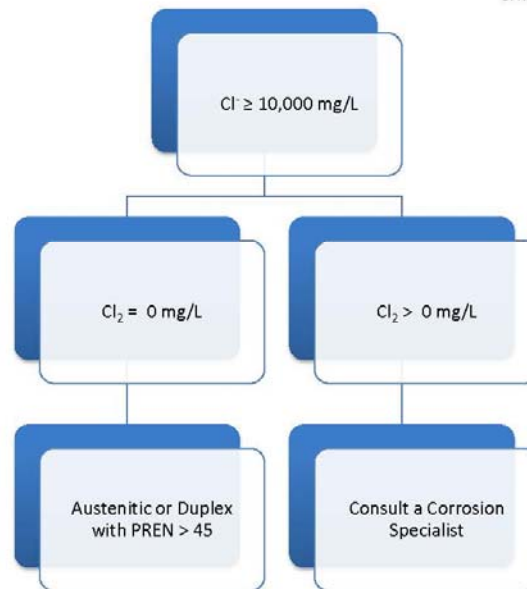


Figure 5.9 Decision Tree 2 for chloride concentrations $\geq 10,000$ mg/L: Stainless steel recommendations based on chloride and free chlorine concentrations

APPENDIX A
UTILITY AND FABRICATOR SURVEY QUESTIONS

SURVEY QUESTIONS

Utilities/Water Agencies

1. Location of Utility

State: _____

County: _____

2. What type of water is your stainless steel exposed to?

- | | |
|--|--|
| <input type="checkbox"/> Groundwater – hard/fresh | <input type="checkbox"/> Surface water – seawater |
| <input type="checkbox"/> Groundwater – brackish | <input type="checkbox"/> Potable water |
| <input type="checkbox"/> Seawater | <input type="checkbox"/> Wastewater |
| <input type="checkbox"/> Surface water – river | <input type="checkbox"/> Tertiary or reclaimed water |
| <input type="checkbox"/> Surface water – lake | <input type="checkbox"/> Other _____ |
| <input type="checkbox"/> Surface water – reservoir | |

3. *Specific to the answer given in question 2, please select which of the following ranges best describes the water quality your stainless steel is primarily exposed to:*

Chloride

- < 250 mg/L
- 251 to 1,000 mg/L
- 1,000 to 5,000 mg/L
- 5,001 to 10,000 mg/L
- 10,001 to 20,000 mg/L
- > 20,000 mg/L

pH

- < 6
- 6 to 8.5
- 8.5

Iron

Temperature

- 0 to 20 °C (32 to 68°F)
- 20 to 30 °C (68 to 86°F)
- 30 to 40 °C (86 to 104°F)
- 40°C (>104°F)

H₂S

- < 1 mg/L
- 1 to 3 mg/L
- > 3 mg/L

Chlorine

- < 2 mg/L
- 2 to 3 mg/L
- 3 to 5 mg/L
- 5 mg/L

Oxygen

- <0.1 mg/L
- 0.1 to 0.5 mg/L
- > 0.5 mg/L

< 1 mg/L

- 1 to 8 mg/L
- > 8 mg/L

Mn

- < 0.05 mg/L
- 0.05 to 0.5 mg/L
- > 0.6 to 1.0 mg/L
- > 1.0 mg/L

4. What type (s) of disinfectant(s)/oxidant(s) is your stainless steel exposed to?

- Chlorine
- Ozone
- ClO₂

- KMnO₄
- Other : _____

5. Stainless steel type used (check all that apply):

- 304/304L
- 316/316L
- Alloy 2205
- Other: _____
- I don't know

6. What type of surface finish does your stainless steel have (check all that apply)?

- Pickled
- Passivated
- Electropolish
- Bead blasted
- Ground finish
- AWWA 220
- ASTM 778
- Don't know.
Explain if able: _____

7. Age of stainless steel: _____ years

8. Have you had corrosion problems

- Yes
- No

a. **If yes:** Where has the corrosion problem presented itself:

- Pinhole leaks at welds
- Connection to dissimilar metals
- General "rust" on exterior metal surface
- Other: _____

b. **If yes:** Did the contractor perform field welding of the stainless steel piping?

- Yes
- No

i. **If yes:** was the heat tint removed?

- Yes
- No

1. **If yes:** What type of field control was used to prevent or remove heat tint? (Check all that apply)

- Inert gas
- Passivation liquid
Name: _____
- Passivation paste
Name: _____
- Mechanical grinding
- Don't know

c. **If yes:** What was the cause of the corrosion

- Microbiologically Induced Corrosion (MIC)
- Chlorides
- Chlorine,
- Dissimilar metals
- Other: _____
- Don't know,

9. Can we contact you for additional information?

Yes

No

a. if yes, provide address input form.

Yes/No

b. if yes, ask: do you have any reports involving your stainless steel corrosion that you would be willing to share?

c. I f yes, ask: would you be willing to host a corrosion testing program in association with this project?

Yes/No

SURVEY QUESTIONS

Fabricators

1. Location of Fabrication Shop
State: _____
Country: _____
2. Is your shop certified to weld the following groups of alloys? (check all that apply)
 - 300 Series stainless steels
 - Duplex (2205 & 2507 stainless steels)
 - Super austenitic alloys (i.e., 6 - % Mo alloys)
 - Super duplex stainless steels (e.g., Ferralium 255, Zeron 100)
3. How frequently are you required to submit stainless steel pipe/vessel welder certifications for review (as submittals to the customer or engineer) as part of an order?
 - Never
 - <20% of the time
 - 26 to 50% of the time
 - 51 to 75% of the time
 - >75% of the time
4. How frequently are your welders certified to the stainless steel materials?
 - About every 6 months
 - About every 12 months
 - I do not know
 - Other (please specify): _____
5. How frequently are you required to perform and submit quality control tests on your welds (as submittals to the customer or engineer) as part of an order?
 - Never
 - <20% of the time
 - 26 to 50% of the time
 - 51 to 75% of the time
 - >75% of the time
6. When not required to do otherwise by the customer's specification, what piping material specifications are used for purchasing pipe?
 - AWWA 220
 - ASTM 778
 - ASTM 312
 - Other
7. Do you perform pickling and passivation chemical treatments after fabrication?
 - Yes
 - No

a. If yes: What types of chemicals do you use for passivation treatments? (check all that apply)

- | | |
|---|---|
| <input type="checkbox"/> 10% Nitric Acid-2% Hydrofluoric Acid | <input type="checkbox"/> 15% Phosphoric Acid (at room temperature for 90 minute dwell time) |
| <input type="checkbox"/> 30% Nitric Acid (minimum of 30 minutes at temperature of 79 – 90°F) | <input type="checkbox"/> Hydrogen Peroxide |
| <input type="checkbox"/> 10% Citric Acid (immersion 10 minutes in the temperature range of 120-140°F) | <input type="checkbox"/> Oxalic Acid |
| | <input type="checkbox"/> Other (please specify): _____ |

b. If yes: What types of environmental permits do you require? Name Permits:

8. Do you perform electropolishing treatments?

- Yes No

a. If yes: What is the maximum length of pipe you can fit into your electropolish bath?
Maximum Length (feet) _____

b. If yes: What is the maximum diameter of pipe or vessel you can fit into your electropolish bath?

Maximum Diameter (inches) _____

c. If yes: Are you able to perform electropolishing on the inside and outside of pipes 3-inches in diameter and greater?

- Yes
 No

d. If yes: What is a typical request for surface removal by electropolishing?

- 5-micron
 10-micron
 10- to 20-micron
 25-micron
 Other: _____ micron

APPENDIX B PHASE 1 TEST DATA

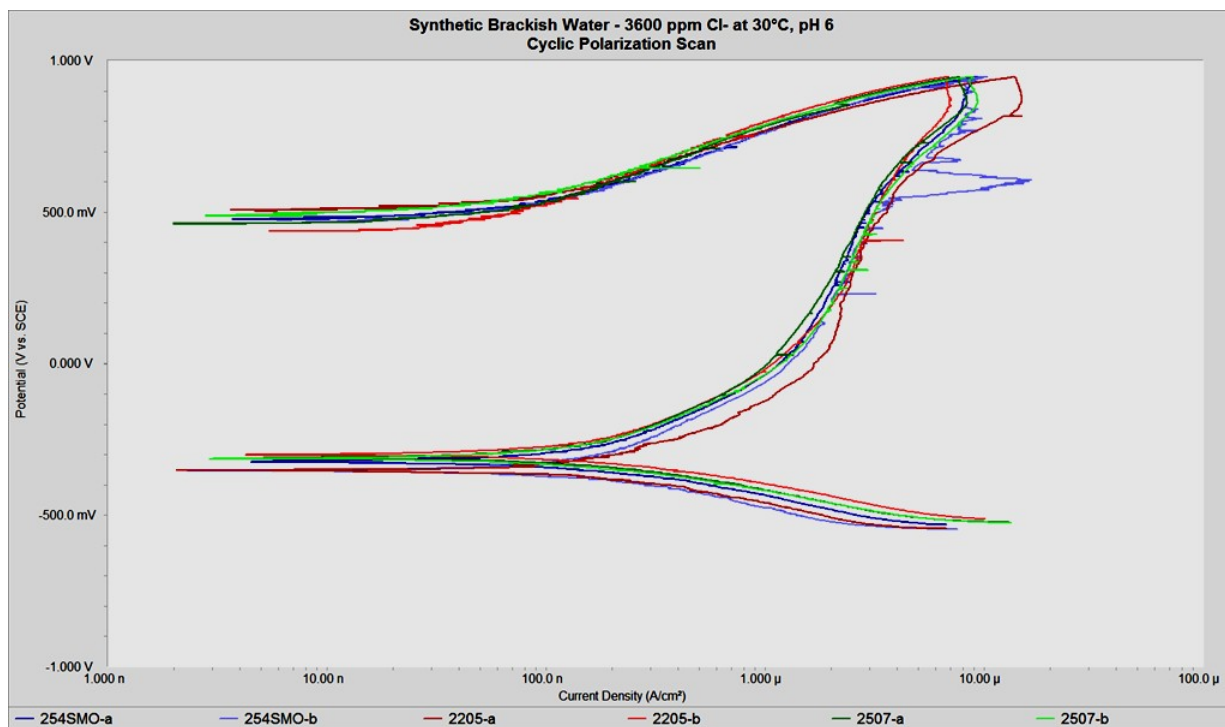
ROUND 1 OF TESTING

3,600 mg/L Chloride, 0 mg/L Chlorine, 30°C, pH 6

Sample	ID	E _{oc}	E _b	E _p	Hysteresis	I _{corr}	Corrosion Rate	Visible Crevice
2205	AVM1	-274	> +950	N/A	No	0.27	0.114	No
	AVM2	-241	> +950	N/A	No	0.25	0.105	No
2507	ACN1	-252	> +950	N/A	No	0.21	0.088	No
	AVN2	-254	> +950	N/A	No	0.18	0.073	No
254SMO	ABL1	-261	> +950	N/A	No	0.22	0.095	No
	ABL2	-276	> +950	N/A	No	0.22	0.095	No

Notes:

1. E values are in mV; I values are in micro-amps/cm² (10⁻⁶ Amps).
2. Corrosion rate is in mpy – mils per year, 1 mil = 0.001 inch.

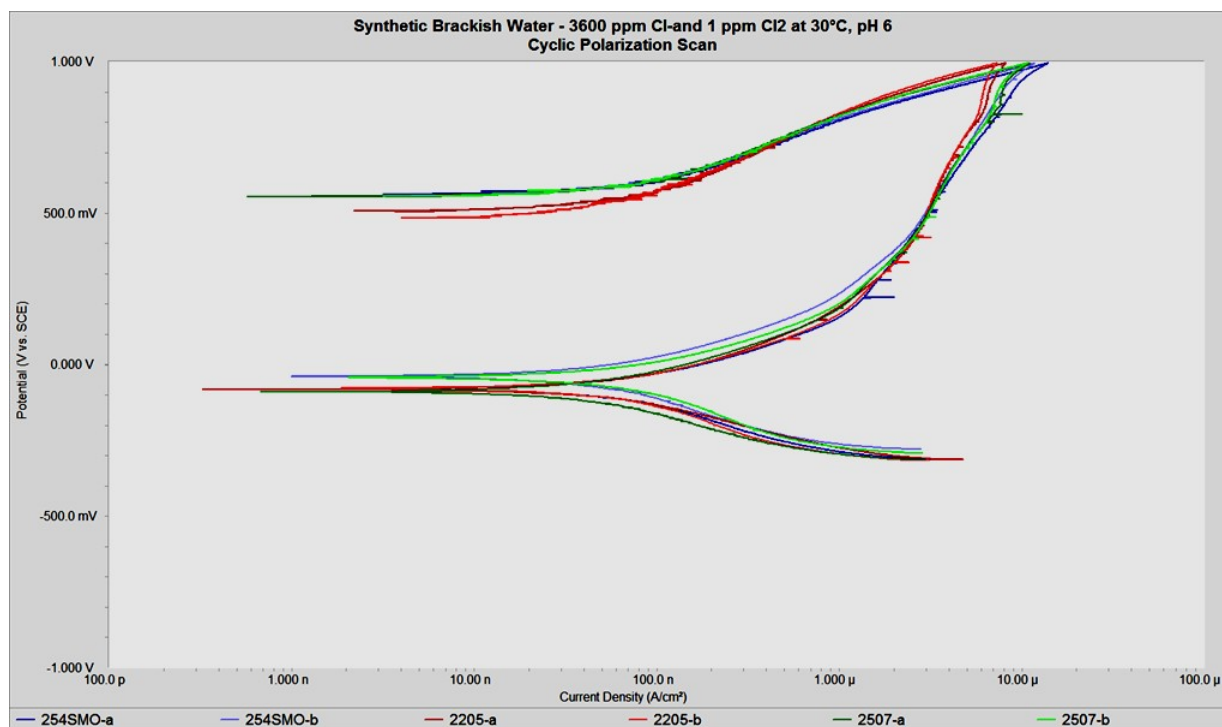


3,600 mg/L Chloride, 1 mg/L Chlorine, 30°C, pH 6

Sample	ID	E _{oc}	E _b	E _p	Hysteresis	I _{corr}	Corrosion Rate	Visible Crevice
2205	AVM5	-31	>+1000	N/A	No	0.09	0.040	No
	AVM6	-34	>+1000	N/A	No	0.09	0.036	No
2507	AVN5	-30	>+1000	N/A	No	0.08	0.034	No
	AVN6	-7	>+1000	N/A	No	0.13	0.054	No
254SMO	ABL5	-31	>+1000	N/A	No	0.08	0.035	No
	ABL6	+7	>+1000	N/A	No	0.06	0.027	No

Notes:

1. E values are in mV; I values are in micro-amps/cm² (10⁻⁶ Amps).
2. Corrosion rate is in mpy – mils per year, 1 mil = 0.001 inch.

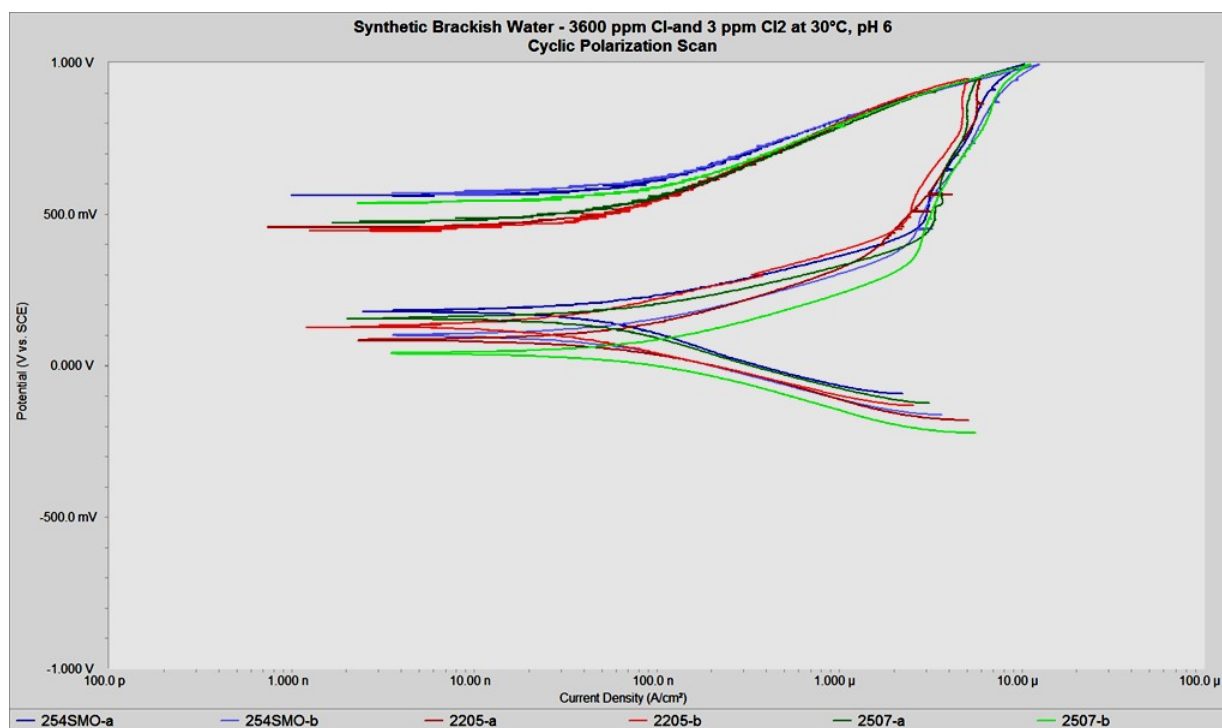


3,600 mg/L Chloride, 3 mg/L Chlorine, 30°C, pH 6

Sample	ID	E _{oc}	E _b	E _p	Hysteresis	I _{corr}	Corrosion Rate	Visible Crevice
2205	AVM3	+110	>+950	N/A	No	0.07	0.029	No
	AVM4	+161	>+950	N/A	No	0.03	0.012	No
2507	AVN3	+169	>+950	N/A	No	0.06	0.025	No
	AVN4	+66	>+1,000	N/A	No	0.09	0.040	No
254SMO	ABL3	+203	>+1,000	N/A	No	0.06	0.024	No
	ABL4	+129	>+1,000	N/A	No	0.06	0.025	No

Notes:

1. E values are in mV; I values are in micro-amperes/cm² (10⁻⁶ Amps).
2. Corrosion rate is in mpy – mils per year, 1 mil = 0.001 inch.

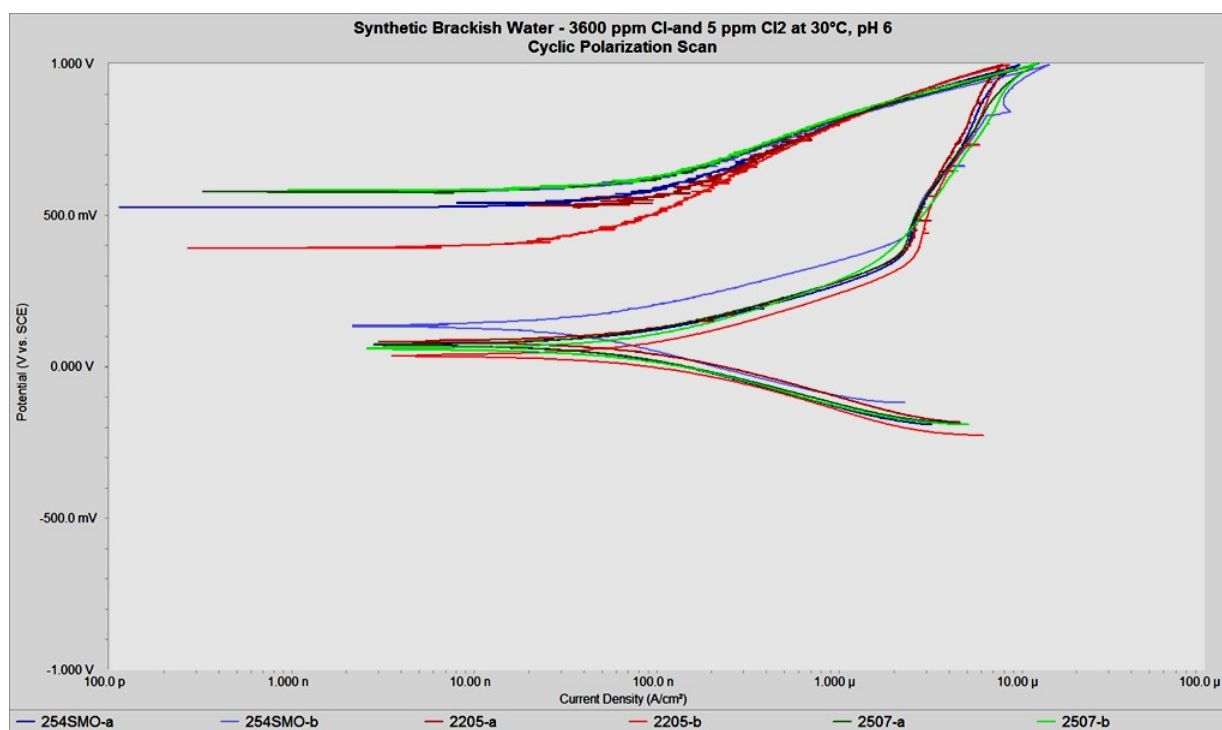


3,600 mg/L Chloride, 5 mg/L Chlorine, 30°C, pH 6

Sample	ID	E _{oc}	E _b	E _p	Hysteresis	I _{corr}	Corrosion Rate	Visible Crevice
2205	AVM7	+106	>+1,000	N/A	No	0.08	0.035	No
	AVM8	+61	>+1,000	N/A	No	0.09	0.039	No
2507	AVN7	+105	>+1,000	N/A	No	0.06	0.026	No
	AVN10	+99	>+1,000	N/A	No	0.08	0.035	No
254SMO	ABL7	+98	>+1,000	N/A	No	0.07	0.029	No
	ABL8	+174	>+1,000	N/A	No	0.04	0.017	No

Notes:

1. E values are in mV; I values are in micro-amperes/cm² (10⁻⁶ Amps).
2. Corrosion rate is in mpy – mils per year, 1 mil = 0.001 inch.

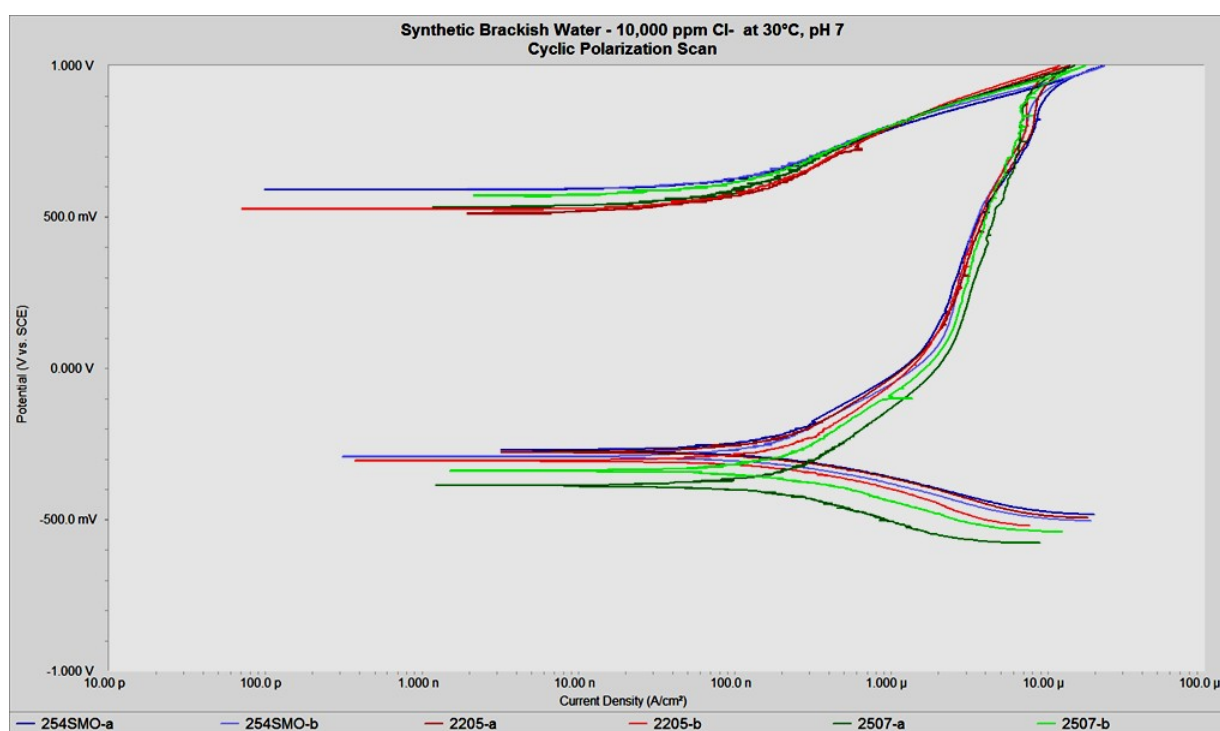


10,000 mg/L Chloride, 0 mg/L Chlorine, 30°C, pH 7

Sample	ID	E _{oc}	E _b	E _p	Hysteresis	I _{corr}	Corrosion Rate	Visible Crevice
2205	AVM9	-221	>+1,000	N/A	No	0.24	0.099	No
	AVM10	-249	>+1,000	N/A	No	0.28	0.119	No
2507	AVN8	-310	>+1,000	N/A	No	0.28	0.117	No
	AVN9	-269	>+1,000	N/A	No	0.24	0.102	No
254SMO	ABL9	-209	>+1,000	N/A	No	0.21	0.091	No
	ABL10	-231	>+1,000	N/A	No	0.19	0.085	No

Notes:

1. E values are in mV; I values are in micro-amperes/cm² (10⁻⁶ Amps).
2. Corrosion rate is in mpy – mils per year, 1 mil = 0.001 inch.

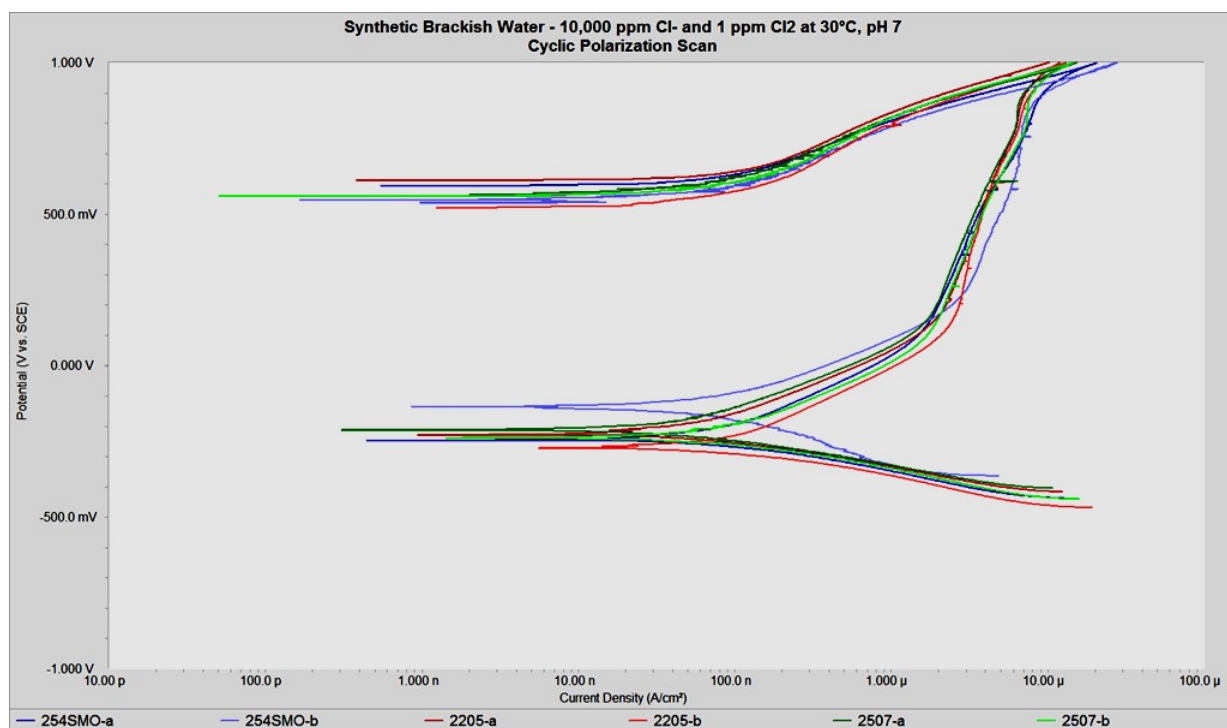


10,000 mg/L Chloride, 1 mg/L Chlorine, 30°C, pH 7

Sample	ID	E _{oc}	E _b	E _p	Hysteresis	I _{corr}	Corrosion Rate	Visible Crevice
2205	AVM11	-117	>+1,000	N/A	No	0.06	0.023	No
	AVM12	-169	>+1,000	N/A	No	0.10	0.043	No
2507	AVN11	-126	>+1,000	N/A	No	0.05	0.021	No
	AVN11	-164	>+1,000	N/A	No	0.09	0.039	No
254SMO	ABL11	-137	>+1,000	N/A	No	0.08	0.036	No
	ABL12	-83	>+1,000	N/A	No	0.09	0.041	No

Notes:

1. E values are in mV; I values are in micro-amps/cm² (10⁻⁶ Amps).
2. Corrosion rate is in mpy – mils per year, 1 mil = 0.001 inch.

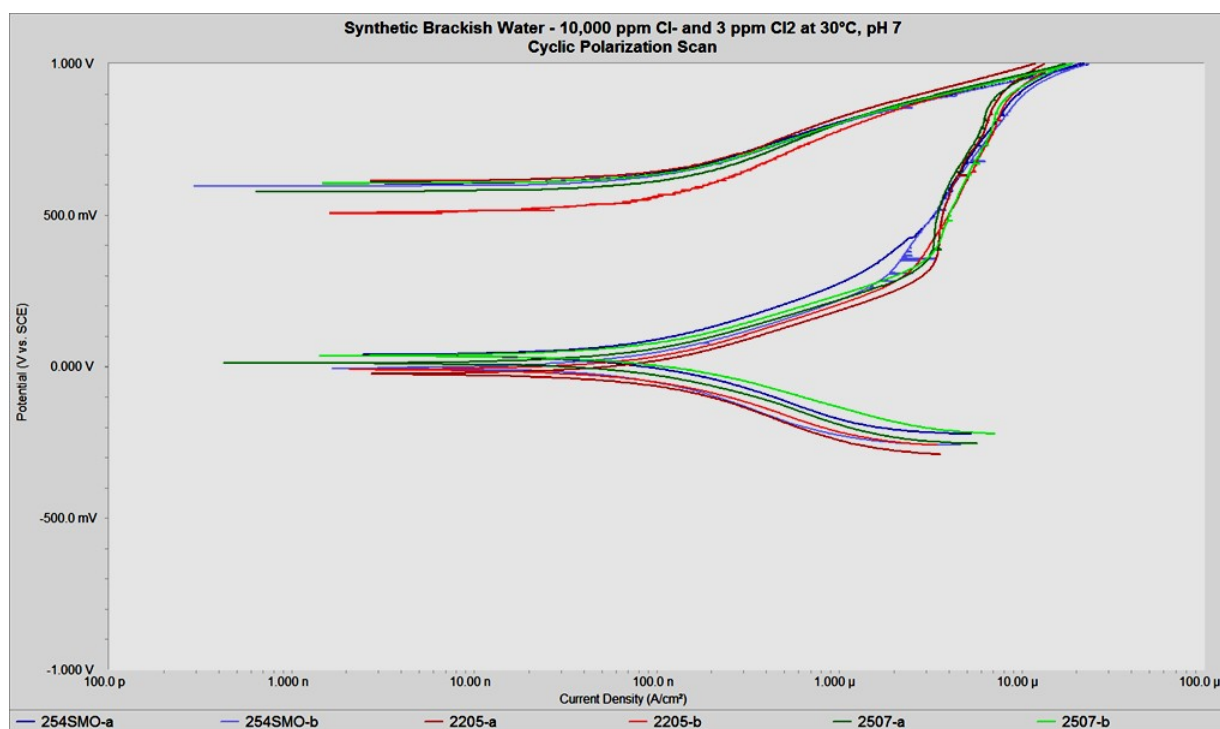


10,000 mg/L Chloride, 3 mg/L Chlorine, 30°C, pH 7

Sample	ID	E _{oc}	E _b	E _p	Hysteresis	I _{corr}	Corrosion Rate	Visible Crevice
2205	AVM13	+10	>+1,000	N/A	No	0.11	0.045	No
	AVM14	+35	>+1,000	N/A	No	0.11	0.044	No
2507	AVN13	+46	>+1,000	N/A	No	0.09	0.038	No
	AVN14	+79	>+1,000	N/A	No	0.10	0.043	No
254SMO	ABL13	+78	>+1,000	N/A	No	0.10	0.043	No
	ABL14	+40	>+1,000	N/A	No	0.09	0.041	No

Notes:

1. E values are in mV; I values are in micro-amps/cm² (10⁻⁶ Amps).
2. Corrosion rate is in mpy – mils per year, 1 mil = 0.001 inch.

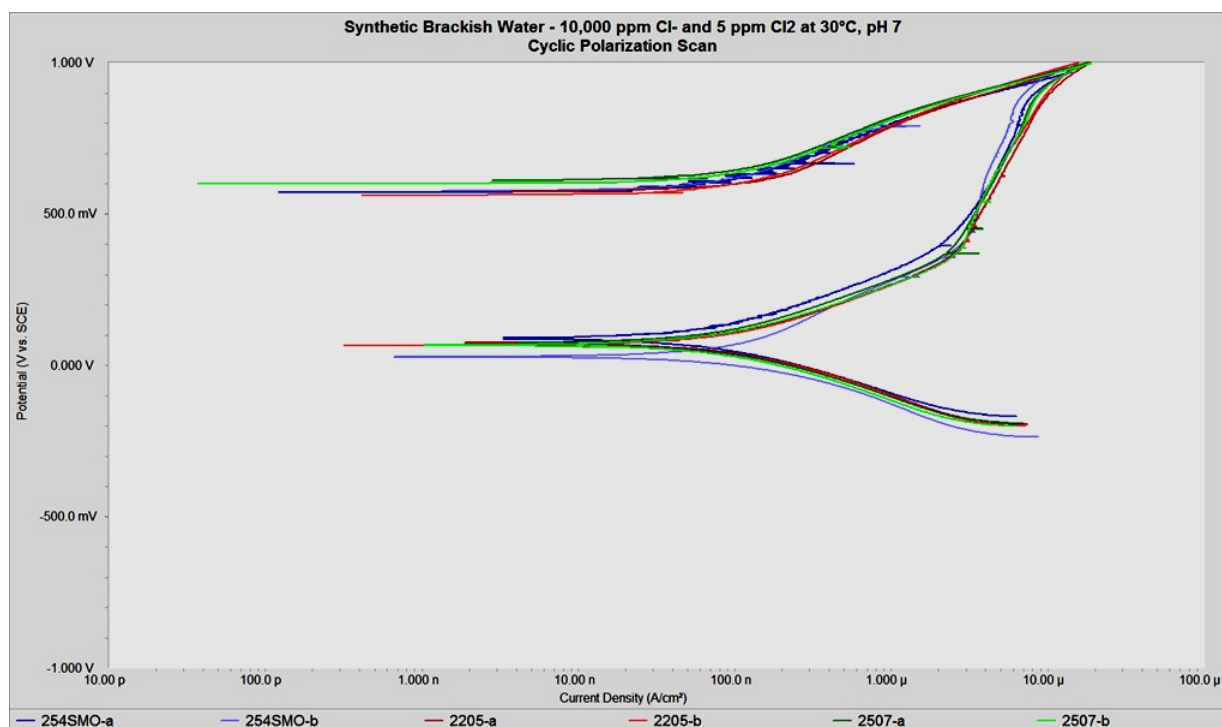


10,000 mg/L Chloride, 5 mg/L Chlorine, 30°C, pH 7

Sample	ID	E _{oc}	E _b	E _p	Hysteresis	I _{corr}	Corrosion Rate	Visible Crevice
2205	AVM15	+104	>+1,000	N/A	No	0.11	0.048	No
	AVM16	+99	>+1,000	N/A	No	0.11	0.048	No
2507	AVN15	+108	>+1,000	N/A	No	0.09	0.038	No
	AVN16	+99	>+1,000	N/A	No	0.09	0.038	No
254SMO	ABL15	+125	>+1,000	N/A	No	0.08	0.035	No
	ABL16	+61	>+1,000	N/A	No	0.13	0.055	No

Notes:

1. E values are in mV; I values are in micro-amperes/cm² (10⁻⁶ Amps).
2. Corrosion rate is in mpy – mils per year, 1 mil = 0.001 inch.



ROUND 2 OF TESTING

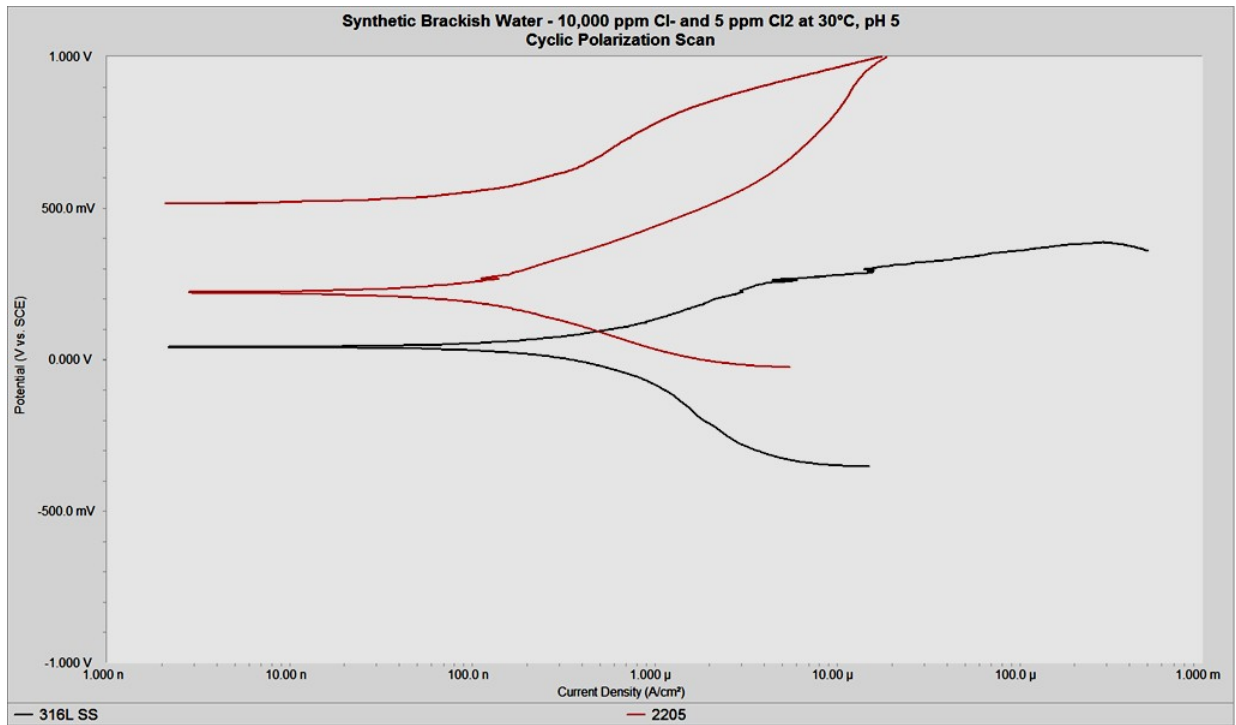
10,000 mg/L Chloride, 5 mg/L Chlorine, 30°C, pH 5.2

Sample	ID	E _{oc}	E _b	E _p	Hysteresis	I _{corr}	Corrosion Rate	Visible Crevice
2205	AVM16*	+276	> +1,000	N/A	No	0.13	0.055	No
316L	AQR2	-54	+265	ND	Yes	0.60	0.253	Yes

Notes:

1. E values are in mV; I values are in micro-amps/cm² (10⁻⁶ Amps).
2. Corrosion rate is in mpy – mils per year, 1 mil = 0.001 inch.

*Specimen refinished after previous exposure.

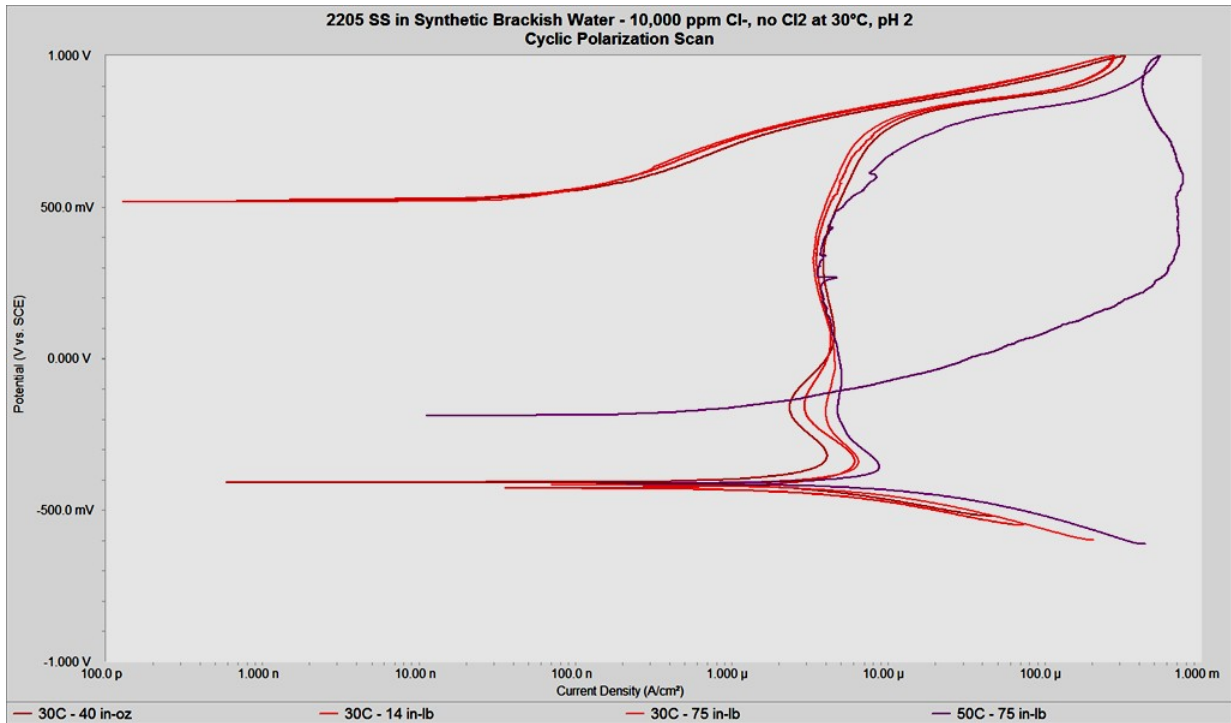


10,000 mg/L Chloride, 0 mg/L Chlorine, 30°C, pH 2, Alloy 2205

Test	Sample ID	E _{oc}	E _b	E _p	Hysteresis	I _{corr}	Corrosion Rate	Visible Crevice
30°C, 40 in.-oz. torque	AVM17	-221	+78 ³	N/A	No	2.21	0.93	No
30°C, 14 in.-oz. torque	AVM18	-249	+780 ³	N/A	No	2.89	1.2	No
30°C, 75 in.-lb. torque	AVM19	-299	+780 ³	N/A	No	3.63	1.5	No
50°C, 75 in.-lb. torque	QVM20	-313	+484	-1.0	Yes	6.0	2.5	Yes

Notes:

1. E values are in mV; I values are in micro-amps/cm² (10⁻⁶ Amps).
2. Corrosion rate is in mpy – mils per year, 1 mil = 0.001 inch.
3. Not a true breakdown since there was no hysteresis and localized corrosion was not observed on the test specimen.



GLOSSARY

Alloy	A metal made up of multiple elements.
Annealed	An alloy in its softest (most ductile) condition.
Anode	The source of a positive charge. An electron acceptor.
Austenitic stainless steel	Stainless steel with primarily austenite (face centered cubic) grains. The 300 series SS are austenitic.
Base metal	Metals to be welded.
Cast	Solidified structure formed from molten metal.
Cathode	The source of electrons or an electron donor. It may accept positive charge.
Charpy Notch Test	A mechanical test that determines the toughness of an alloy.
Crevice corrosion	Corrosion that occurs between two surfaces with a tiny gap in-between.
Ductility	Property that allows the metal to be deformed.
Duplex stainless	A two-phase alloy with approximately equal amounts of austenite and ferrite.
Embrittlement	Loss of ductility.
Field passivation	Acid or mechanical removal of surface imperfections, including heat tint, on site, with the formation of a thin and tightly adherent protective oxide layer.
Ferritic stainless steel	Chromium-iron stainless steel.
Forged	Hot or cold shaping operation in rod and bar manufacturing.
Heat Affected Zone (HAZ)	The region immediately adjacent to the molten weld.
Ingot	A mass of metal cast in a convenient shape for shaping, remelting or reforming.
Malleable	Ability to be easily mechanically formed.
Martensitic stainless steel	Chromium-high carbon content stainless steel.
Microbiologically Induced Corrosion (MIC)	Attack of metals by microbes which are given the opportunity to colonize under slow moving or stagnant water conditions, and form tubercles beneath which aggressive acids can form and attack the alloy.
Molar	moles per liter.

Paper Weld	A field weld, which on the surface looks of high quality, but lacks complete weld penetration of the tube/pipe wall.
Passivate	Natural formation of an oxide film on a clean stainless steel surface.
Pickling	Acid cleaning to remove heat tint and other surface discontinuities.
Pitting	Significant corrosion of a metal (e.g., stainless steel) in a localized site on the surface.
RMS surface finish	Root mean square is a measure of smoothness for a metal surface.
Rolled	Manufacturing method to flatten metal, or mechanically bend a plate into a circular form ready for welding.
Root weld	The backside of the weld (toe of the weld in cross section)
Sigma phase	An undesirable metal phase, which lacks ductility.
Stainless steel	Steel whose chromium content is greater than 12% by weight.
Transpassive corrosion	General corrosion that occurs under highly oxidizing conditions, rare in stainless steels.
Unannealed	An alloy in its as-worked condition. I.e., after welding, cold or hot forming.
Weldment	This is the total weld area impacted by the welding process.
Wrought	Metal that has been mechanically processed and thermally treated.

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ACRONYMS

”	inch(es)
°C	degrees Celsius
°F	degrees Fahrenheit
%wt	percent by weight
Ω-cm	ohm-centimeter (a unit of resistivity measurement)
μm	micron
ASME	American Society of Mechanical Engineers
AWS	American Welding Society
C	carbon
Cl ⁻	chloride
Cu	copper
CJP	complete joint penetration
CPI	Critical Pitting Index
CPT	Critical Pitting Temperature
Cr	chromium
Cu	copper
DAF	dissolved air flotation
DVWTP	Del Valle Water treatment Plant
E _b	breakdown potential, usually expressed in units of milivolts
EPA	Environmental Protection Agency (United States)
Fe	iron
ft/s	feet per second
GTAW	gas tungsten arc welding
HAZ	heat affected zone
in.-lbs.	inch-pounds
in.-oz.	inch-ounce
ICP	inductively coupled plasma
mg/L	milligrams per liter
M	metal or molar
MIC	microbially induced corrosion (or microbiologically induced corrosion)
MIG	metal inert gas (welding)
Mo	molybdenum
mpy	mils per year (1 mil = 0.001 inches)
mmpy	millimeters per year
mV	millivolt

N	nitrogen
N-m	Newton-meter
Nb	niobium (also known as columbium)
Ni	nickel
OCP	open circuit potential
OD	outer diameter
PQR	Procedure Qualification Record
PREN	pitting resistant equivalent number
PVC	polyvinyl chloride
QC	quality control
RMS	root mean square
RO	reverse osmosis
SRB	sulfate-reducing bacteria
SMCL	secondary maximum contaminant limit
TBDP	Tampa Bay Desalination Plant
TIG	tungsten inert gas (welding)
UNS	Unified Numbering System
V	volts
WPC	weld performance certification
WPQ	welder performance qualification
WPS	welding procedure specification
XPS	x-ray photoelectron spectroscopy