Guidelines for Using Stainless Steel in the Water and Desalination Industries

ERIN D. MACKEY[1] AND THOMAS F. SEACORD[2]

[1]Brown and Caldwell, Walnut Creek, Calif.
[2]Carollo Engineers, Boise, Idaho

Stainless steels are corrosion-resistant, but to take full advantage of their corrosion-resistant properties, stainless steel piping and components must be properly specified, installed, and operated. The recommendations included in this article are intended to arm engineers and operators with a screening-level tool for avoiding misapplication. To properly select the right grade of stainless steel for the various environmental conditions existing in different areas of the process, equipment, piping, and conveyance systems must be defined, including chlorides, pH, free chlorine in solution, bacteria, and temperature. Considering the environments that occur during idle, startup, normal operations, and shutdown conditions within treatment and conveyance facilities is also important. Once the stainless steel is specified and manufactured, proper care over its shipping, installation, and operation must be taken to protect the integrity of the materials to minimize corrosion.

Stainless steel is widely used in critical components of drinking water, wastewater, and water reuse treatment and conveyance systems, including well casings, reverse osmosis (RO) and other membrane treatment equipment, ultraviolet (UV) disinfection systems, and ozone generators. Stainless steels are corrosion-resistant. However, contrary to popular belief, they are prone to failures from corrosion, including intergranular corrosion as a result of welding, stress corrosion cracking, and microbiologically induced corrosion (MIC). Thus, to take full advantage of the corrosion-resistant properties of stainless steel, piping and components must be properly specified, handled, installed, and operated.

BACKGROUND

Engineers have few available resources that are tailored to water treatment and intended for selecting stainless steel materials and specifying the appropriate methods to use when handling these materials during construction. Engineers and operators want a high enough grade of stainless steel for the required corrosion protection, but they do not want to use a higher and thus more expensive grade than is required. Furthermore, improper handling, installation, and operation can make the stainless steel susceptible to corrosion, negating some or all of the benefits from purchasing higher-cost, higher-performance materials.

With five families of stainless steel and more than 120 alloys and compositions, selecting the right stainless steel for any application is not a simple task. Furthermore, although information on the nature and use of stainless steel is abundant and comes from many sources, this information is not readily available to water and desalination industry professionals. The information does not come in a format that allows engineers and owners procuring stainless steel materials to easily incorporate recommendations into construction documents or to make operational decisions that may change the environment to which existing stainless steel materials are exposed. There is no general consensus in the industry to match or select stainless steel for typical applications in municipal infrastructure.

In response to these challenges, *Guidelines for the Use of Stainless Steel in the Water and Desalination Industries*, a jointly sponsored project of the US Bureau of Reclamation and the Water Research Foundation, was developed (Mackey et al. 2015). The guidelines presented in this project help water and desalination engineers accomplish three things: (1) properly specify the type of stainless steel used for different applications on the basis of water quality considerations; (2) properly specify construction standards that, if followed,

A full report of this project, *Guidelines for the Use of Stainless Steel in the Water and Desalination Industries* (#4431), is available for free to Water Research Foundation subscribers by logging on to www.waterrf.org.

can help extend the useful life of stainless steel materials to more than 20 years; and (3) identify appropriate operating conditions to avoid stainless steel corrosion as much as possible. This article is a primer on stainless steel corrosion and provides recommendations for its best use based on data in the peer-reviewed literature and corrosion experiments. Guidelines for the specification, preparation, and handling of stainless steel are presented in the report to facilitate the development of detailed stainless steel specifications.

What is stainless steel? A metallic alloy is any metal made of multiple elements, such as chromium, nickel, and molybdenum. Generally, a metallic alloy is considered "stainless" when its chromium content is greater than approximately 12% by weight, with iron as the majority of the balance.
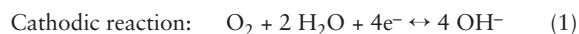
Higher alloyed stainless steels have more chromium, which provides corrosion resistance by forming a thin, adherent, and corrosion-resistant oxide film on a clean surface. When exposed to oxygen, whether in air or in water, this layer will naturally form to prevent corrosion (Tuthill 1994). The protective layer is less effective when the original oxide surface layer becomes damaged or scratched, although when exposed to oxygen again, the protective film will rapidly re-form. An important part of stainless steel preparation is passivation—i.e., removal of free iron compounds from the surface of the metal and the subsequent formation of a passive (inert) surface layer.

Stainless steel has five families, each characterized by its microstructure: martensitic, ferritic, austenitic, duplex (50/50 austenite/ferrite-mixed structure), and precipitation-hardened structures. The families are further characterized by their microstructures, which result from their particular compositions. Ferritic and martensitic alloys are iron–chromium alloys. Martensitic alloys can be hardened with heat treatment, while ferritic alloys cannot. Both ferritic and martensitic grades belong to the 400 series of stainless steels, which provide strength but only minimal corrosion resistance. Austenitic stainless steels are iron–chromium–nickel alloys, with nickel providing malleability and weldability. These materials belong to the 300 series of stainless steel alloys, which provide corrosion resistance in a variety of waters (e.g., brackish waters and high free chlorine waters; Avery et al. 1999). Duplex stainless steel is a mixture of two structures or phases, austenite and ferrite; the higher alloyed duplex materials are known as the superduplex alloys (Davidson & Redmond 1988); these have higher corrosion resistance. Lean duplex materials are a series of low-alloyed duplex materials that offer higher strength with resistance to stress corrosion cracking that is similar to the standard austenitic grades. The structure and strength of precipitation-hardened materials can be modified by heat treatment.

Mechanisms of stainless steel corrosion. As mentioned previously, stainless steel's protective film is less effective when the oxide surface layer becomes damaged or scratched, which can cause corrosion in those areas. Two main types of stainless steel corrosion are of particular

concern in water system applications—crevice corrosion and pitting corrosion—because they can lead to pinholes and stress corrosion cracking. Environmental factors play an important role in how quickly corrosion develops as well as in corrosion severity.

Crevice corrosion. Crevice corrosion forms when two halves of a tight metal-to-metal (or metal-to-other material) joint or multiple joints are immersed in an aqueous solution, creating an electrochemical cell. Depending on the degree of tightness, dissolved oxygen either penetrates or is kept from penetrating the crevice, which may weaken the oxide film trapped between the contacting surfaces (Kain et al. 1984). When this oxide layer weakens, chromium, iron, and nickel ions from the surface layers are diffused inside the crevice and combine with the hydroxyl ions diffusing from the bulk solution the stainless steel material is immersed in. This leaves an electrically unbalanced relationship, which causes an anode to form inside the crevice and a cathode to form on the metal's surface as follows:

Cathodic reaction: $\quad O_2 + 2\ H_2O + 4e^- \leftrightarrow 4\ OH^- \quad$ (1)

Anodic reaction: $\quad M = M^{n+} + ne^- \quad$ (2)

where e^- = electrons, M is the metal, M^{n+} is metal with a positive charge of n, and ne^- is *n* electrons. If significant concentrations of chloride are present (e.g., brackish waters) or free chlorine is present, this electrically unbalanced relationship can be exacerbated (Figure 1). As the pH inside the crevice drops, chloride ions from the bulk solution diffuse into the crevice to balance the anodic oxidation reaction by combining with the hydrogen ion. The decreasing pH increases the potential for the passive film to degrade and for crevice corrosion to begin.
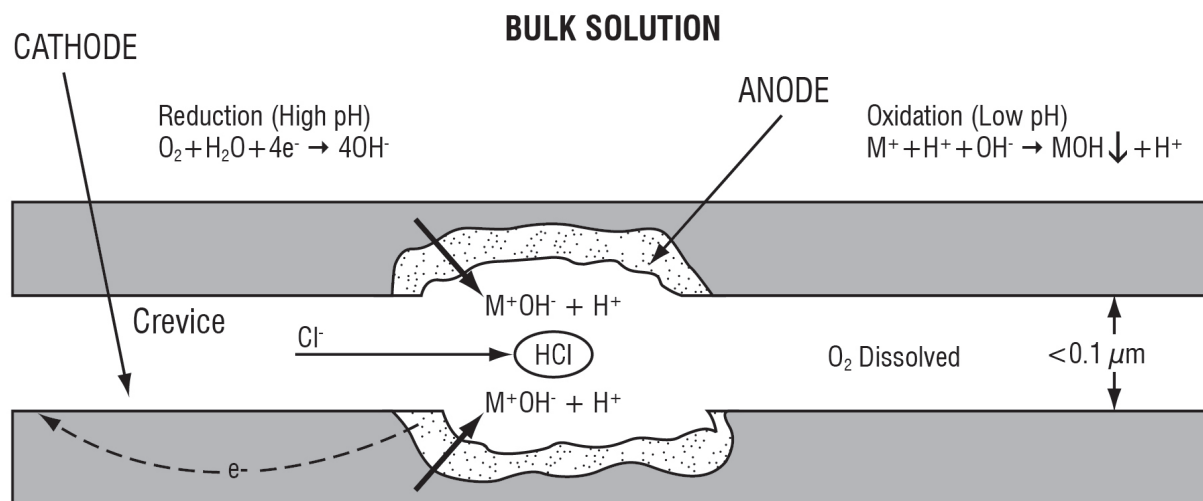
Inside the crevice, the anodic oxidation reaction consumes oxygen. However, by limiting the diffusion of dissolved oxygen in the confined space, the gap's tightness slows the reaction rate. At the crevice gap, chlorides and pH mostly initiate corrosion by accelerating the electrochemical reaction at the corrosion site (Oldfield 1984). In waters of normal bulk or free solution pH (6.5–8.0 pH), crevice corrosion is rare for

- Type 304/304L stainless steel with exposure to up to 200 mg/L chlorides when free chlorine concentrations are less than 2 mg/L and
- Type 316/316L stainless steel with exposure to up to 1,000 mg/L chlorides when free chlorine concentrations are less than 4 mg/L.

Furthermore, the dimension of the crevice gap is critical to crevice corrosion initiation, and environmental conditions influence the rate at which corrosion occurs, with crevice corrosion being less likely to occur under low-oxygen conditions (Nickel Development Institute 1987).

Pitting corrosion. Similar to crevice corrosion, pitting corrosion creates an adjacent anode and cathode, and

FIGURE 1 Illustration of crevice corrosion

BULK SOLUTION

CATHODE

Reduction (High pH)
$O_2 + H_2O + 4e^- \rightarrow 4OH^-$

ANODE

Oxidation (Low pH)
$M^+ + H^+ + OH^- \rightarrow MOH\downarrow + H^+$

Crevice

$M^+OH^- + H^+$

Cl^- HCl

$M^+OH^- + H^+$

O_2 Dissolved

$<0.1\ \mu m$

e^-

Source: Mackey et al. 2015. © Water Research Foundation 2015. Reprinted with permission.

$4e^-$—4 electrons, H^+—hydrogen ion, HCl—hydrogen chloride, H_2O—water, M^{n+}—metal with positive charge n, O_2—oxygen, OH^-—hydroxide

oxide breakdown begins in the presence of chloride ions. Figure 2 shows a cell forming, with oxygen evolution and chloride ingress. The chloride ion from the bulk solution penetrates the cell to form an electrochemically active cell environment, which can precipitate salt films at the bottom of the pit cell, increasing the chemical attack there while reducing the local pH. The drop in local pH accelerates the corrosion attack, where a very low pH regime inside the pit facilitates pitting (Nickel Development Institute 1987).

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

For a stainless steel alloy in an aggressive water environment, adding molybdenum, nitrogen, and chromium improves resistance to crevice corrosion and pitting corrosion.

ENVIRONMENTAL INFLUENCES ON CORROSION IN WATER TREATMENT

Microbes. Microbes are found in a variety of waters and soils that can sometimes be deleterious to stainless steels. Under stagnant and slow-flowing water conditions, slimes and bacterial films can attach to crevices and rough surfaces. Rough inside weld surfaces (root passes) result from poor welding that causes incomplete through-wall welds, allowing destructive microorganisms to attach.

Depending on the water source or soil characteristics, the bacteria can be either aerobic or anaerobic and, in some cases, can be facultative. In the initial stages, bacteria form a biofilm. The biofilm can cause a biomound and a hardened shell, or "tubercule," to form, which is essentially a concentration of microbial cells that form on metal surfaces. Tubercules often shelter corrosive microenvironments from the bulk process solutions that can accumulate and accelerate the corrosion attack and cause bulbous caverns to form in the pipe's cross section (Figure 2). After biomounds and tubercule(s) form, anodic and cathodic sites develop, forming a corrosion site that produces a corrosion cell.

FIGURE 2 MIC tubercule formed on a root weld
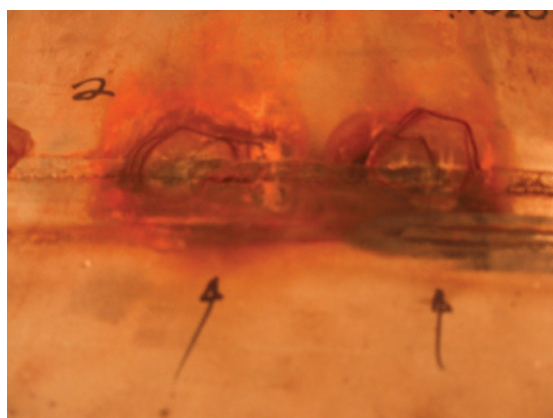
Source: Mackey et al. 2015. © Water Research Foundation 2015. Reprinted with permission.

Soils. Like water, soil serves as an environmental medium for the corrosion of stainless steel materials. In buried stainless steel, crevice corrosion, pitting, and MIC attack are all common. Soil chemistry, stainless steel alloy composition, stray current, and construction and fabrication practices all influence the type of corrosion that occurs. Corrosion resistance depends mainly on the soil's characteristics—resistivity, acidity, and chloride and sulfate content.

Chlorine and chloramine. Along with oxygen, chlorine is the primary oxidant in cooling waters, potable waters, and treated wastewaters. Chlorine can be added to water in several forms, such as chlorine gas, liquid sodium hypochlorite, and calcium hypochlorite granules.

Chlorine dissociates in bulk aqueous environments to form hypochlorous acid and hypochlorite, which are very effective for disinfection of suspended bacteria and viruses but are not particularly effective for disinfection of biofilms. Where chlorinated solutions are alkaline, meaning their pH values are between 7.0 and 8.5–9 (the typical range for potable water), most stainless steels can resist the threat of pitting or crevice corrosion.

Free chlorine can react with ammonia and ammoniated compounds to form chloramines. The extent to which free chlorine converts to chloramine will affect the water's corrosivity. As more free chlorine converts to chloramines, the condition is less corrosive. When combined with high free chlorine concentrations, chloride has a synergistic effect on corrosion. Figures 3–7 present general guidelines for selecting different steels as a function of chlorine and chloride concentrations, though no simple chlorine or chloride threshold guarantees there will not be corrosion at lower concentrations.

Dissimilar metals and galvanic corrosion. Two metals electrically connecting with each other while immersed in an aqueous environment create an electric cell that allows for galvanic corrosion to occur. The potential is expressed as voltage. The corrosion potential (voltage value) of each metal is determined by comparing it with a known standard, such as platinum or a saturated calomel half cell (the other half being the alloy evaluated), which is typically immersed in seawater. The metal with the highest voltage is the cathode (corrosion protected), while the other is the sacrificial anode. The greater the difference in voltage potential, the greater the driving force for galvanic corrosion.

A solution's ionic strength and electrical conductivity can also influence the system's corrosion characteristics, meaning high-concentration chloride solutions have higher ionic strengths and electrical conductivities than demineralized water solutions. The first defense for galvanic corrosion is to prevent joining or connecting two dissimilar metals in the design phase; if that is not feasible, then any other means of electrical isolation may be used, such as dielectric coatings and 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 ensure that flange bolts do not contact the dissimilar metals. Other factors that can affect galvanic corrosion include anode-to-cathode ratio, the presence of aggressive ions facilitating the galvanic reaction, and resistance to current flow in the conducting materials and in the connection between them.

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

- 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 corrosion at the weld. The 308L type of steel with a small overall surface area of weld versus the more passive 316L with a large area of general material body will provide a very high cathode-to-anode ratio and result in a high current density. This can cause severe and rapid galvanic corrosion.
- If there are hard-facing overlays for the rotating-seal faces of marine tail shafts, it is important to pay close attention to each alloy's position.

Carbon in the form of graphite-containing gaskets, O-ring seals, packing, and graphite-lubricated gaskets can initiate severe galvanic corrosion of stainless steels, which means that using graphite that is in contact with stainless steel can be problematic.

CONSTRUCTION AND FABRICATION INFLUENCES

In addition to environmental factors, construction and fabrication methods can significantly influence stainless steel's ability to prevent corrosion. Welding methods, contact between different metals, cleaning, passivation, and surface finishes may all influence the metal's ability to form and maintain a protective chromium oxide film on its surface. The presence and geometry of crevices may also have an effect. Furthermore, if the material is improperly handled during delivery (i.e., handling and packing during transport) or installation (i.e., handling and preparation during installation), the metal surface can be damaged or contaminated.

GUIDELINES FOR SPECIFYING AND SELECTING STAINLESS STEEL

Most stainless steel corrosion can be anticipated and avoided. Good design; appropriate material selection; proper specification and control over material quality, fabrication, and construction methods; and correct commissioning and operating practices can ensure a long service life. The following guidelines can help engineers and end users select, procure, and use stainless steel materials to improve service life in a cost-effective way. The guidelines are broken into the following parts:

- General background information and recommendations
- Methods for specifying the quality of materials to be incorporated into the work

- Methods for specifying the proper construction and operation conditions to protect the integrity of the stainless steel materials

This organization follows the MasterFormat[1] structure, a specification outline commonly used in the construction industry and by engineers developing design documents and specifications for construction projects. To make decisions on process changes and to determine whether existing stainless steel materials are suitable, this article includes decision trees to help end users evaluate pertinent water chemistry and material compatibility issues (Figures 3–7). The full details and list of other specifications used to construct this section are included in Mackey et al. (2015).

Part 1: general requirements. Following the commonly used specification outline, the "general requirements" section provides background information, reference standards, and administrative/procedural requirements for stainless steel pipe or equipment specifications. Because stainless steel–containing parts can be wrought (i.e., formed from flat sheets of metal), extruded tubular material, cast (i.e., molten metal poured in a casting to form a shape), or machined, the necessary background information pertinent to a purchasing specification will vary greatly. These general requirements are detailed in Mackey et al. (2015).

Part 2: product requirements. This section describes the quality of materials to be incorporated into the work, including the names of acceptable manufacturers where appropriate. Quality requirements may include finishing techniques to use. Key design and specification recommendations on a number of critical topics are included.

Other important product elements that should have corrosion resistance considered in their specifications include wall thickness, fittings and joints, fasteners, post-fabrication surface finishing, and water or soil chemistry where applicable. Detailed information on these topics can be found in Mackey et al. (2015).

Material and manufacturing. To identify the grade of stainless steel and manufacturing process suitable for the intended service, the designer should consider a number of factors. One factor is whether the specifier allows the supplier to furnish the most economical stainless steel grade that meets requirements. For example, for wrought plate or tubular products, Type 316L (PREN = 25) is a commonly specified austenitic alloy that fluctuates in price on the basis of market forces.

The comparative pitting resistance between corrosion-resistant alloys is established using a mathematical relationship based on the critical influence of key alloying elements common to various stainless steel alloys. This mathematical relationship is known as the pitting resistant equivalent number, or PREN. The higher the PREN, the more resistant the alloy generally is to pitting. The most common definition of the PREN formula is %Cr + 3.3 × %Mo + 16 × %N. It is important to note that PREN resistance is a guideline and should be considered in concert with application-specific conditions, such as free chlorine and chloride resistance data for brackish water applications.

Conversely to wrought plate or tubular products, some lean duplex alloys (e.g., LDX 2101, PREN = 27) are equally resistant to pitting, may be less expensive, and may be more available at certain times. Allowing for either alloy type might lower costs. Similarly, stainless steel cast products (e.g., valves and fittings) may be more available in 316 than in 304. Thus, if the designer allows the substitution of 316 for 304, this may also reduce cost or delivery time without sacrificing quality.

General service in potable water treatment. For most conditions in potable water service, Type 304L has adequate corrosion resistance as long as the surface is kept clean and free of defects. Type 316L is a more conservative choice, with improved corrosion resistance in the presence of sediment and other deposits in higher concentrations of residual chlorine. The designer should use nickel–chromium–molybdenum (Ni-Cr-Mo) alloys, >6% Mo stainless steels, cement-lined steel, or ductile iron pipe immediately downstream of chlorine or potassium permanganate injection (Avery et al. 1999).
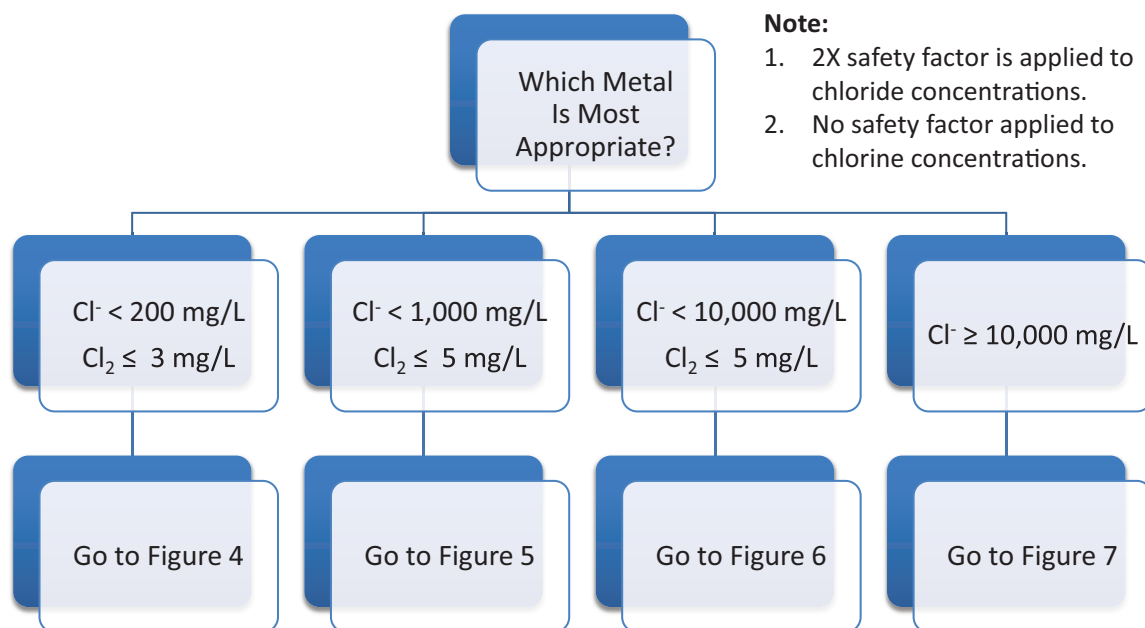
Chloride and free chlorine. The chloride concentration in water is an important part of determining stainless steel's resistance to crevice corrosion. The designer should also know that the presence of oxygen significantly increases the risk of crevice corrosion from chloride.

In fully de-aerated water, much higher chloride concentrations can be tolerated. Stainless steels are generally resistant to crevice corrosion in totally de-aerated waters, even seawater (Avery et al. 1999). However, chlorine and chlorides can have a synergistic effect, leading to more significant crevice corrosion at lower chloride concentrations (Avery et al. 1999). Table 1 contains guidelines for alloy selection based on chloride and chlorine concentrations at water temperatures typical for municipal water treatment applications.

Even without the synergistic influence of chloride on the ability of a free chlorine residual to accelerate corrosion, a chlorine residual in potable water can contribute to crevice corrosion. Type 304L becomes vulnerable to crevice corrosion when long-term chlorine exposure ranges from 3 to 5 mg/L, while 316L is more resistant. Corrosion testing has shown 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. Table 2 presents guidelines recommended for long-term exposure to chlorine in potable water (i.e., chloride ≤250 mg/L at ambient temperatures).

High temperatures. The designer should consider using heat-treated pipe (ASTM [American Society of Testing and Materials] A312) or tube (ASTM A269) rather than unannealed pipe or tube (ASTM A778) for materials used
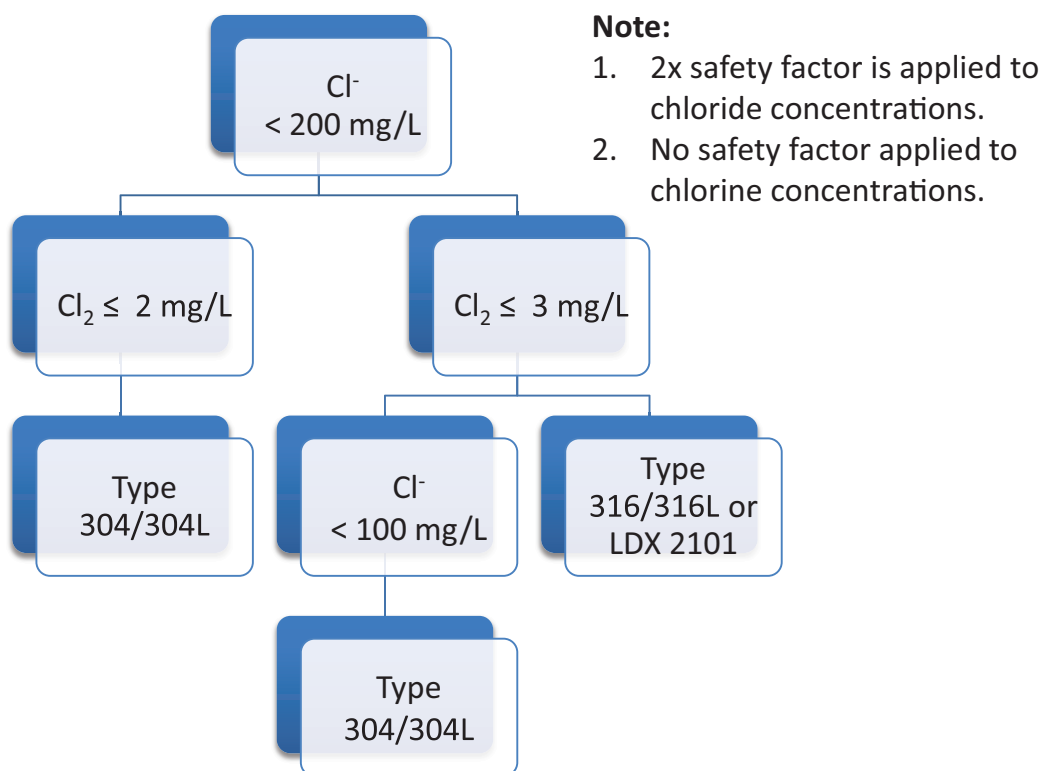
FIGURE 3 Decision tree 1: overview of material selection

Which Metal Is Most Appropriate?

Note:
1. 2X safety factor is applied to chloride concentrations.
2. No safety factor applied to chlorine concentrations.

Cl^- < 200 mg/L $Cl_2 \leq$ 3 mg/L	Cl^- < 1,000 mg/L $Cl_2 \leq$ 5 mg/L	Cl^- < 10,000 mg/L $Cl_2 \leq$ 5 mg/L	$Cl^- \geq$ 10,000 mg/L
Go to Figure 4	Go to Figure 5	Go to Figure 6	Go to Figure 7

Source: Mackey et al. 2015. © Water Research Foundation 2015. Reprinted with permission.
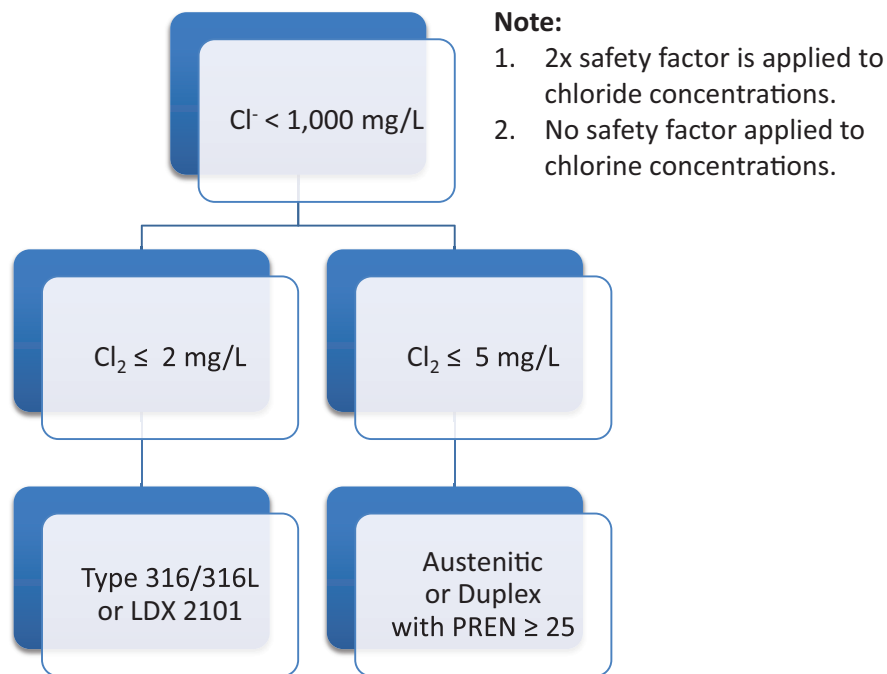
Cl^-—chloride, Cl_2—chlorine

FIGURE 4 Decision tree 2: for chloride concentrations <200 mg/L

Cl^- < 200 mg/L

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

$Cl_2 \leq$ 2 mg/L

$Cl_2 \leq$ 3 mg/L

Type 304/304L

Cl^- < 100 mg/L

Type 316/316L or LDX 2101

Type 304/304L

Source: Mackey et al. 2015. © Water Research Foundation 2015. Reprinted with permission.
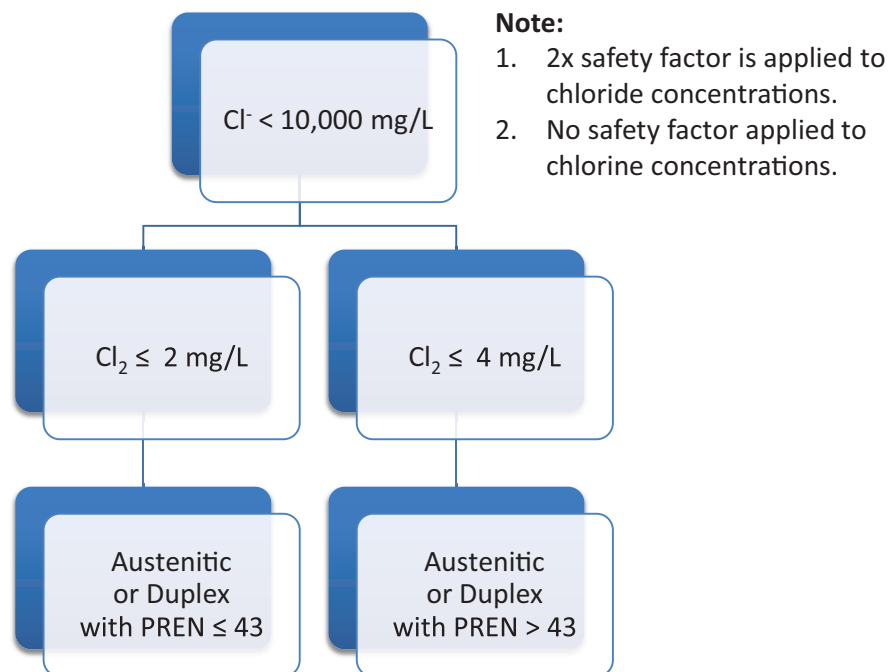
Cl^-—chloride, Cl_2—chlorine

FIGURE 5   Decision tree 3: for chloride concentrations between 200 and 1,000 mg/L

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

Cl⁻ < 1,000 mg/L

Cl₂ ≤ 2 mg/L   Cl₂ ≤ 5 mg/L

Type 316/316L or LDX 2101   Austenitic or Duplex with PREN ≥ 25

Source: Mackey et al. 2015. © Water Research Foundation 2015. Reprinted with permission.

Cl⁻—chloride, Cl₂—chlorine, PREN—pitting resistant equivalent number

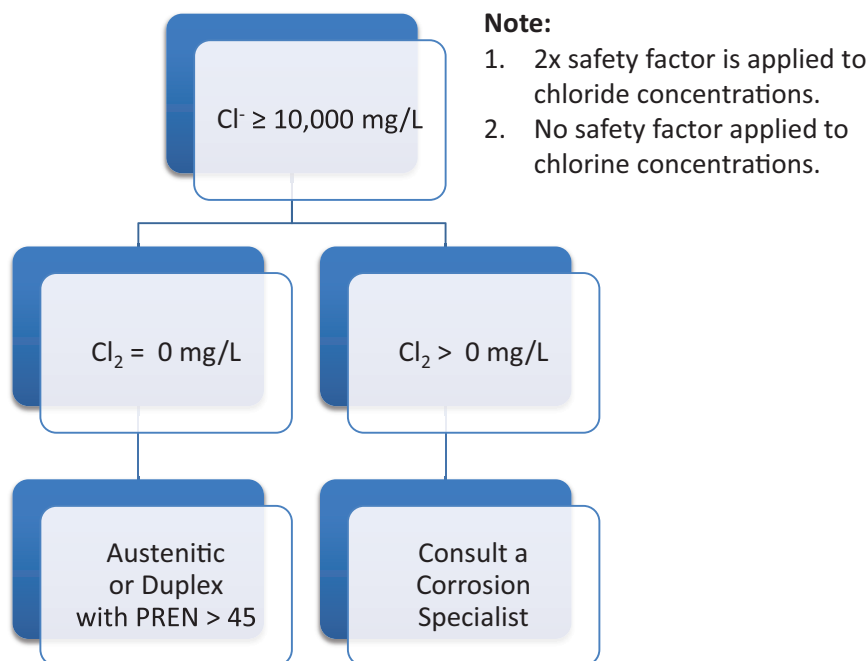**FIGURE 6**   Decision tree 4: for chloride concentrations between 1,000 and 10,000 mg/L

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

Cl⁻ < 10,000 mg/L

Cl₂ ≤ 2 mg/L   Cl₂ ≤ 4 mg/L

Austenitic or Duplex with PREN ≤ 43   Austenitic or Duplex with PREN > 43

Source: Mackey et al. 2015. © Water Research Foundation 2015. Reprinted with permission.

Cl⁻—chloride, Cl₂—chlorine, PREN—pitting resistant equivalent number

FIGURE 7 Decision tree 5: for chloride concentrations ≥10,000 mg/L

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

Cl⁻ ≥ 10,000 mg/L

$Cl_2 = 0$ mg/L

$Cl_2 > 0$ mg/L

Austenitic or Duplex with PREN > 45

Consult a Corrosion Specialist

Source: Mackey et al. 2015. © Water Research Foundation 2015. Reprinted with permission.

Cl⁻—chloride, Cl_2—chlorine, PREN—pitting resistant equivalent number

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 to avoid sigma phase embrittlement.

Heat treatment of stainless steel pipe and tube. The designer must choose between unannealed or annealed (heat-treated) stainless steel products, which are both allowed by AWWA C220 (AWWA 2012). ASTM A778 covers unannealed pipe and tube, including tubular products with outside diameters between 3 and 48 in. as well as nominal wall thicknesses between 0.062 and 0.500 in. ASTM A778 also covers tubular products with other diameters or wall thicknesses as long as they meet the rest of the standard's requirements. ASTM A778 is the prevalent pipe standard used in the water industry and is adequate for most general service applications. The standard allows for field welding and modification without subsequent heat treatment.

Characteristics of unannealed pipes and fittings are as follows:

- Unannealed pipe is typically less expensive than heat-treated pipe and is often the first choice if it meets the application's requirements.
- 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 and rolled products), with nitrogen additions that meet the minimum mechanical properties offered by standard material.

ASTM A312 covers heat-treated pipe for austenitic stainless steel, and ASTM A790 covers heat-treated pipe for ferritic–austenitic (duplex) stainless steels. The companion standards for heat-treated fittings are ASTM A403 (austenitic) and ASTM A890 (duplex). The outside diameter and wall thickness dimensions are defined by ASME B36.19. More stainless steel alloys are covered by these standards, including all the extra-low-carbon grades included in ASTM A778.

Characteristics of heat-treated pipe and fittings are as follows:

- Heat-treated pipe is typically more expensive than unannealed pipe and fittings.
- Field welding requires post-weld field annealing to preserve corrosion protection for standard grade materials like 304 and 316. This is further reason to use low-carbon or dual-grade materials (e.g., 304L, 304/304L, 316L, and 316/316L).

ASTM A269 covers heat-treated tubes made of austenitic alloys. Tubing for special high-temperature applications is covered by ASTM A249. ASTM A789, A790, A928, and A358 cover additional grades of ferritic–austenitic

TABLE 1   Guidelines for alloy selection based on chloride and chlorine concentration

Service	Stainless Steel Grade	Pipe Manufacturing Process
For low chloride water service with chloride concentrations <200 mg/L and/or free chlorine <2 mg/L at ambient temperatures		
Piping ≥3-in. NPS	Type 304L stainless steel in accordance with ASTM A240	In accordance with ASTM A778
Piping <3-in. NPS	Type 304L stainless steel in accordance with ASTM A240	In accordance with ASTM A312
Chloride concentrations <1,000 mg/L and/or free chlorine <4 mg/L at ambient temperatures		
Piping ≥3-in. NPS	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 <3-in. 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
Chloride concentrations between 1,000 and 10,000 mg/L		
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
	Free chlorine <5 mg/L at ambient temperatures; austenitic or duplex grades of material with PREN ≥43[a]	In accordance with ASTM A312, ASTM A778, ASTM A790, or ASTM A928
Brackish water, seawater, and other waters with chloride concentrations between 10,000–20,000 mg/L and no free chlorine present		
All piping diameters	Austenitic and duplex grades of material with PREN > 43	In accordance with ASTM A312, ASTM A790, or ASTM A928
Chloride concentrations greater than 20,000 mg/L and no free chlorine[b]		
All piping diameters	Austenitic and duplex grades of material with PREN > 45	In accordance with ASTM A312, ASTM A790, or ASTM A928

ASTM—American Society of Testing and Materials, NPS—nominal pipe size, PREN—pitting resistant equivalent number

[a]Significant corrosion was observed at low chlorine concentrations for duplex stainless steel with PREN = 34. Significantly higher PREN-value steel may be warranted. Zeron 100 or similar high-PREN alloy may also be suitable.
[b]Combined chloride–free chlorine data are not available. Consult with a corrosion specialist when choosing materials for such conditions.

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

Welded joints. This discussion is restricted to circumferential weld joints used to connect pipe sections and fittings. Ideally, welding should be limited to shop welding when fabricating 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 (Figure 8), are typically more difficult in the field. Post-weld treatment to remove weld heat tint oxide is also difficult.

The designer should note the following minimum weld fabrication requirements for drinking water service:
- Use full-penetration welds, free of cracks, overlaps, and cold laps.
- Limit misalignment for manual welds to 1/16 in. or half the wall thickness, whichever is less.
- Limit weld reinforcement and root convexity to 1/16 in. or agreed-upon limit.
- Limit undercut to 1/32 in. or 10% of base metal thickness, whichever is less.

Cleaning. Cleaning includes all operations necessary to remove surface contaminants from stainless steel. These operations are performed to achieve maximum corrosion resistance of the metal, to minimize product contamination, and to achieve the desired appearance (ASTM A380).

Visual inspection at the job site should confirm that stainless steel items are free of paint, oil, grease, welding

TABLE 2   Guidelines for alloy selection based on chlorine concentration in potable water

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

PREN—pitting resistant equivalent number

flux, slag, heat-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 on interior surfaces (ASTM A380).

Descaling. Descaling removes heavy, tightly adherent oxide films caused by hot-forming, heat treatment, welding, and other high-temperature operations. Descaling can be mechanical or chemical, which is referred to as "pickling" (ASTM A380). Mechanical grinding is an effective way to remove localized scale, such as the scale produced from welding (ASTM A380).

Most pickling solutions will loosen weld and heat-treating scale but may not remove them completely. As a result, the designer should use intermittent scrubbing as required to ensure a completely cleaned surface. The designer should avoid over-pickling after any chemical descaling treatment and thoroughly rinse and water-jet spray the component to remove excess acid before it can cause acid attack on the base metal (ASTM A380).

Preventing or removing all heat tint from welds is critical when maximum resistance to MIC or crevice corrosion is required (Tuthill 1994). ASTM standards require pipe and fittings to be free of scale; however, they do not explicitly require that all heat tint be removed. AWWA C220 (AWWA 2012) requires that "the pipe shall be free from scale and contaminating iron particles. Contaminating iron particles and heat tint shall be removed . . .". In the heat-affected zone (HAZ) of welds, heat tint is scale and, if this standard is not included, the specification should include a requirement similar to the AWWA C220 language.

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

Passivation. The term "passivation" is commonly applied to several different operations or processes relating to stainless steels. Unless otherwise specified, this definition of passivation is taken to mean a specified requirement for passivation under ASTM A380 (see §1.1.1.2). There are three potential definitions of the term, as defined in ASTM A380:

- Removal of exogenous iron or iron compounds from the surface of a stainless steel by means of a chemical dissolution
- 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, to enhance 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. To avoid ambiguity, the designer should precisely define the intended meaning.

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

Electropolishing. Electropolishing is a form of passivation used occasionally in water industry applications in which fabricated stainless steel materials are the anode for a current passed through an acid electrolyte. Performed before cleaning and descaling, electropolishing smooths, polishes, deburrs, and cleans stainless steel parts, resulting in a smooth, high-luster finish. Electropolishing is not, however, the same as mechanical polishing, which results in a mirror-like finish. It is also less expensive than mechanical polishing. Electropolishing offers the following benefits:

- It greatly reduces the potential for MIC because it is more difficult for bacteria to adhere well 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 will likely cause corrosion, easily show.
- The polished look is aesthetically attractive and enhances the appearance of the finished facility.

Source quality control. Establishing specifications to hold materials to the defined standards is a critical first step in

FIGURE 8   Full penetration weld fabrication examples
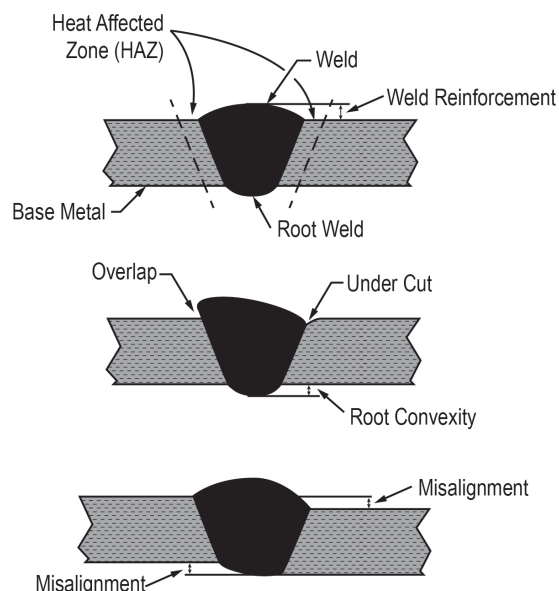
Source: Mackey et al. 2015. © Water Research Foundation 2015. Reprinted with permission.

minimizing stainless steel corrosion. Once the specifications are in place, the manufacturer can provide written certification under the requirements of the governing standard that the materials conform to the standard's requirements.

To protect the stainless steel surface's integrity, the following shipping and handling procedures are recommended:

- Encapsulate all flanges and pipe ends in dense foam.
- Securely strap all elements to pallets with nylon straps. Using metallic straps should be prohibited.
- Cap ends of tube, pipe, fittings, and valves with non-metallic plugs.
- Load pallets so no stainless steel material bears the weight of pallets above.
- Have the purchaser inspect materials on delivery and reject material because of improper shipping methods or damage during shipment.

Part 3: execution requirements. *Design*. Stainless steel failures in drinking water applications due to MIC are common. High-chloride services, such as brackish water, seawater, and RO concentrate applications, also pose special corrosion challenges for stainless steel. Thus, the design must provide ways to avoid conditions that promote MIC and provide resistance to chloride-crevice corrosion, pitting, and stress corrosion cracking. Helpful design recommendations include the following:

- Avoid stagnant water conditions. Drain promptly and completely after completing hydrostatic testing and shutting down the facility.
- Design stainless steel pipe systems and vessels so they drain completely.
- Avoid dead legs, low points, and areas that cannot be drained completely.
- Use reference standards and specify practices that require full-penetration welds with smooth internal contours.
- Require post-field weld descaling and passivation.
- Consider the use of electropolished stainless steel in areas or applications susceptible to MIC or high chloride concentrations.
- Select stainless steel materials with an appropriate PREN for the chloride concentration using the guidelines provided in this section or seek expert advice.
- Provide isolation between dissimilar metals to eliminate galvanic corrosion.

Field welding. Writing specifications that prohibit field welding wherever possible is strongly recommended. If there are compelling reasons to permit field welding, following these guidelines is suggested:

- Require that all field welding complies with the same requirements as shop fabrication welding and post-weld finish treatment.
- Require that 100% of field welds are subject to radiographic testing. This requirement may be relaxed after a statistically significant number of field welds are demonstrated to be acceptable.

Field quality control. Pipe should be visually inspected for welding defects such as crevices, pits, cracks, protrusions, and oxidation deposits. Any defects should be repaired. Additionally, welds in liquid oxygen and ozone service piping should be examined and inspected in accordance with ASME B31.3.

Protection. Following these rules provides suitable protection that preserves the appearance and finish of stainless steel:

- Do not allow bare cables, chains, hooks, metal bars, or skids to come in contact with stainless steel.
- Store stainless steel materials away from other metals.
- Do not store stainless steel materials in contact with the ground.
- Do not store stainless steel outside without protection, such as plastic wrap.
- Do not use wrapping or protection that might absorb water and stain the surface of the stainless steel, such as cardboard.
- With electropolished stainless steel, use disposable latex gloves or an equivalent. Do not handle with bare hands or gloves contaminated with oils, metals, or other materials.

Decision trees for selecting stainless steel materials for drinking water. The decision trees presented in Figures 3–7 serve as guidelines for selecting stainless steel for different free chlorine–chloride environments. It is important to note that the use of these guidelines does not guarantee that selecting steels according to these decision trees will prevent corrosion. However, like the specification guidelines presented in the previous sections, these decision trees are based on the best available science to minimize corrosion.

CONCLUSIONS AND RECOMMENDATIONS

Without readily available resources that help engineers understand the right ways to select stainless steel materials and to specify appropriate construction methods, stainless steel will continue to be misapplied, leading to premature corrosion. The recommendations included in this article arm engineers and operators with the right tools for avoiding misapplication, helping them preserve stainless steel conveyance systems.

When selecting a stainless steel, engineers must define the various environments existing in different areas of the process equipment, piping, and conveyance systems, including chlorides, pH, free chlorine in solution, bacteria, and temperature. Engineers must also consider environments that occur during idling, startup, normal operations, and shutdown conditions within treatment and conveyance facilities. Furthermore, once the stainless steel is specified and manufactured, proper care over its shipping, installation, and operation must be taken to protect the integrity of the stainless steel materials to minimize corrosion.

ACKNOWLEDGMENT

ENDNOTE

[1]MasterFormat®, Construction Specifications Institute, Alexandria, Va.

ABOUT THE AUTHORS

Erin D. Mackey is a supervising engineer at Brown and Caldwell, 201 N. Civic Dr., Ste. 300, Walnut Creek, CA 94526 USA; emackey@brwncald. com. She is a technical specialist in drinking water and reuse and leads the Northern California One Water practice for Brown and Caldwell.

Thomas F. Seacord is vice-president and chief technologist for desalination at Carollo Engineers, 12592 W. Explorer Dr., Ste. 200, Boise, ID 83713 USA; tseacord@carollo.com.

https://doi.org/10.5942/jawwa.2017.109.0044

PEER REVIEW

Date of submission: 08/10/2016
Date of acceptance: 12/21/2016

RESOURCES

ASME (American Society for Mechanical Engineers), 2009. ASME Standard B31.3, Process Piping Guide. ASME, New York.

ASME, 2004. ASME Standard B36.19, Stainless Steel Pipe. ASME, New York.

ASTM, 2016. ASTM A249: Standard Specification for Welded Austenitic Steel Boiler, Superheater, Heat-Exchanger, and Condenser Tubes. ASTM International, West Conshohocken, Pa. https://doi.org/10.1520/A0249_A0249M-16A.

ASTM, 2016. ASTM Standard A312: Standard Specification for Seamless, Welded, and Heavily Cold Worked Austenitic Stainless Steel Pipes. ASTM International, West Conshohocken, Pa. https://doi.org/10.1520/A0312_A0312M-17.

ASTM, 2016. ASTM Standard A403: Standard Specification for Wrought Austenitic Stainless Steel Piping Fittings. ASTM International, West Conshohocken, Pa. https://doi.org/10.1520/A0403_A0403M-16.

ASTM, 2016. ASTM Standard A778: Standard Specification for Welded, Unannealed Austenitic Stainless Steel Tubular Products. ASTM International, West Conshohocken, Pa. https://doi.org/10.1520/A0778_A0778M-16.

ASTM, 2016. ASTM Standard A789: Standard Specification for Seamless and Welded Ferritic/Austenitic Stainless Steel Tubing for General Service. ASTM International, West Conshohocken, Pa. https://doi.org/10.1520/A0789_A0789M-17.

ASTM, 2016. ASTM Standard A790: Standard Specification for Seamless and Welded Ferritic/Austenitic Stainless Steel Pipe. ASTM International, West Conshohocken, Pa. https://doi.org/10.1520/A0790_A0790M-16.

ASTM, 2015. ASTM Standard A269: Standard Specification for Seamless and Welded Austenitic Stainless Steel Tubing for General Service. ASTM International, West Conshohocken, Pa. https://doi.org/10.1520/A0269_A0269M-15A.

ASTM, 2015. ASTM Standard A358: Standard Specification for Electric-Fusion-Welded Austenitic Chromium-Nickel Stainless Steel Pipe for High-Temperature Service and General Applications. ASTM International, West Conshohocken, Pa. https://doi.org/10.1520/A0358_A0358M-15.

ASTM, 2014. ASTM Standard A403: Standard Specification for Wrought Austenitic Stainless Steel Pipe Fittings. ASTM International, West Conshohocken, Pa. https://doi.org/10.1520/A0403_A0403M-16.

ASTM, 2014. ASTM Standard A928: Standard Specification for Ferritic/Austenitic (Duplex) Stainless Steel Pipe Electric Fusion Welded with Addition of Filler Metal. ASTM International, West Conshohocken, Pa. https://doi.org/10.1520/A0928_A0928M-14.

ASTM, 2013. ASTM Standard A380: Standard Practice for Cleaning, Descaling, and Passivation of Stainless Steel Parts, Equipment, and Systems. ASTM International, West Conshohocken, Pa. https://doi.org/10.1520/A0380_A0380M-13.

ASTM, 2013. ASTM Standard A890: Standard Specification for Castings, Iron-Chromium-Nickel-Molybdenum Corrosion-Resistant, Duplex (Austenitic/Ferritic) for General Application. ASTM International, West Conshohocken, Pa. https://doi.org/10.1520/A0890_A0890M.

ASTM, 2013. ASTM Standard A967: Standard Specification for Chemical Passivation Treatments for Stainless Steel Parts. ASTM International, West Conshohocken, Pa. https://doi.org/10.1520/A0967_A0967M-13.

REFERENCES

Avery, R.E.; Lamb, S.; Powell, C.A.; & Tuthill, A.H., 1999. Stainless Steel for Potable Water Treatment Plants. Technical paper, May 1999 Series Paper #10087. The Nickel Institute, Toronto.

AWWA, 2012. AWWA C220-12 Stainless-Steel Pipe, 1/2 in. (13 mm) and Larger. AWWA, Denver.

Davidson, R.M. & Redmond, J.D., 1988. Practical Guide to Using 6 Mo Austenitic Stainless Steel: NiDI Technical Series #10 032. The Nickel Institute, Toronto.

Kain, R.M.; Tuthill, A.H.; & Hoxie, E.C., 1984. The Resistance of Type 304 and 316 Stainless Steels to Crevice Corrosion in Natural Waters. *Journal of Materials for Energy Systems*, 5:4:205.

Mackey, E.D.; Seacord, T.F.; & Lamb, S., 2015. *Guidelines for the Use of Stainless Steel in the Water and Desalination Industries*. Water Research Foundation, Denver.

Nickel Development Institute, 1987. Guidelines for the Selection of Stainless Steels for Marine Environments Natural Waters and Brines, Publ. N 11003. The Nickel Institute, Toronto, Ont.

Oldfield, J., 1984. Prediction of Crevice Corrosion Resistance of Stainless Steels in Aqueous Environments; a Corrosion Engineering Guide. Proc. 12th International Corrosion Conference, Houston, Tex.

Tuthill, A.H., 1994. Stainless Steel Piping. *Journal AWWA*, 86:7:67.