Educational Article

Corrosion Control in Drinking Water Distribution Using Simple Methods

Part 1: Introduction to Corrosion — Terminology

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Abstract: Corrosion is a natural, thermodynamically driven process that results in a more stable state for the elements and compounds involved. Most metals corrode when they come into contact with drinking water, provided that certain conditions are met. Corrosion is an electrochemical process in which the metal's oxidation potential, its interaction with other conductive materials, and its surface condition play important roles. The water itself and its constituents are also significant, particularly dissolved oxygen, which acts as an oxidizing agent on metals.

Keywords: Corrosion, corrosion damage, corrosion phenomenon, corrosion protection, corrosion rate, corrosion type, electrochemical process, galvanic series, pitting corrosion, redox reaction, surface corrosion.

Foreword: What is the purpose of this series of articles?

The aim of this series of publications is to provide information on the possibilities of corrosion control in the drinking water distribution network and in drinking water installations. The importance of corrosion to the materials used in drinking water distribution and to drinking water itself is presented, methods of investigation are explained, and possible corrosion control strategies are discussed. The goal is to provide water utilities, industrial and commercial customers, and interested individuals with a deeper understanding of metal corrosion in drinking water.

1. What is corrosion?

Corrosion is a natural phenomenon in which materials undergo changes to their surface and structure through contact with the environment [1]. With the exception of precious metals, almost all metals corrode in water. This often means that the desired material properties are no longer guaranteed. In addition, corroded pipes often have increased surface roughness, which reduces their performance in terms of flow and pressure and leads to increased energy consumption during pumping. Corrosion does not only damage the material, but also the water transported in the pipes. Gases dissolved in drinking water, such as oxygen and carbon dioxide, supported by salts, attack metal pipes from the inside (Figure 1) and transfer metal ions into the water, contaminating the

transported water and, in the worst case, endangering the health of drinking water customers.

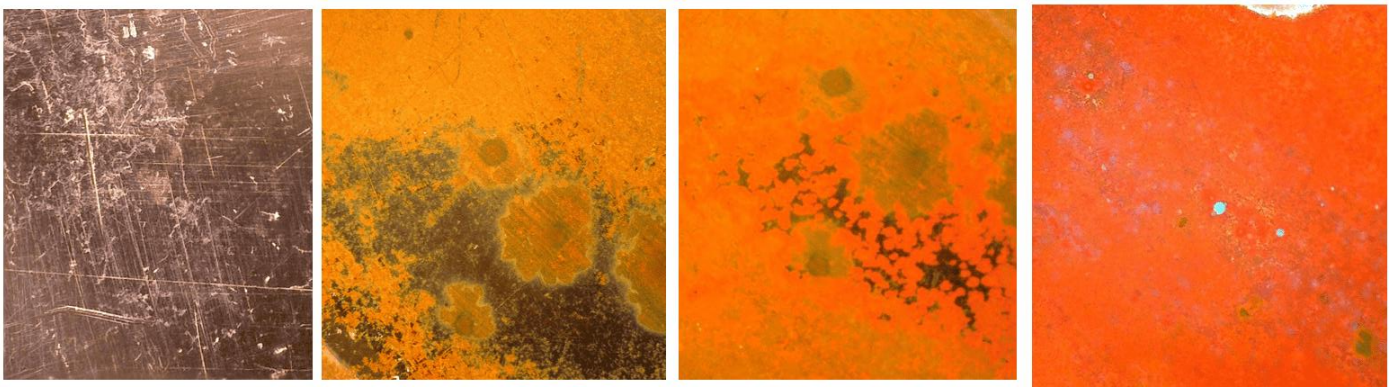


Figure 1. Corrosion of copper coupons in drinking water after 0, 3, 10 and 70 days (from left to right).

In this series of articles, we will focus on metals, but other materials also corrode, such as glass, which is attacked by the alkaline conditions in the dishwasher, or plastics, which become brittle when exposed to sunlight. Most metals used in engineering are not thermodynamically stable under Earth's environmental conditions. They oxidize—at varying rates—into a stable mineral form. The most common oxidizing agent involved in corrosion is oxygen, which makes up 21% of the Earth's atmosphere. The water within a metal pipeline forms a distinct corrosion system characterized by specific environmental conditions that are more or less corrosive depending on the water's composition. The major factors are discussed below. The fact that some metals or alloys, although thermodynamically unstable, are stable in practice is due to the phenomenon of passivation. In this process, the metal surface is coated with a layer of oxidation products, called scale that is stable under environmental conditions and prevents oxygen from reaching the metal, thus inhibiting corrosion. For example, stainless steel is coated with a very hard and resistant corrosion layer of chromium oxide that is so thin that it is not visually noticeable. However, if salty water is allowed to dry on stainless steel, it will be attacked. While iron dissolves in dilute sulfuric acid to form hydrogen, when concentrated sulfuric acid is transported in iron containers, a dense, stable layer of iron oxide forms on the metal's surface, protecting the material below. These examples show that the specific environmental conditions are very important for the corrosion of metals.

Corrosion is also an important economic issue that deserves more research and development resources. It is estimated that annual corrosion damage accounts for approximately 3-4% of the world's gross national product, or between 12 and 20 billion euros for Germany alone in 2023. According to scientific studies, 15 to 30% of these costs could be avoided [2].

2. Corrosion terms

In technical terms, corrosion is classified as material degradation, just like excessive stress caused by high temperatures or mechanical loads. Sustained mechanical stress leads to wear. Corrosion, on the other hand, is caused by chemical, physical, or electrochemical processes [3], with electrochemical corrosion playing a significant role in the context of drinking water systems. These terms are defined in EN ISO 8044 [4]:

The prerequisite for corrosion is a **corrosion system** consisting of the metals and a corrosive environment (medium and operating conditions).

Corrosion is the process that leads to a measurable change in the workpiece. The **corrosion rate** indicates how quickly the corrosion process takes place.

A **corrosion phenomenon** is a measurable change caused by corrosion. This can involve a change in the surface (increased roughness or discoloration), increased resistance, or a current-voltage anomaly. The browning of water in unprotected steel pipes and the detection of metals in the water are also manifestations of corrosion.

Corrosion damage refers to the impairment of a component's function resulting from corrosion (affecting its fitness for service). Examples include pitting in drinking water pipes, the rusting of components such as valves or stems, and increased surface roughness, which impairs component function and leads to the aforementioned rise in flow resistance. Progressive corrosion of components culminates in **corrosion failure**; this term describes the loss of function of a technical system due to the effects of corrosion. For more detailed information, please refer to the literature [3,4].

The most common type of corrosion is **surface corrosion**, such as the corrosion of cast iron or low-alloy steel pipes used for drinking water. This type of corrosion involves the extensive oxidation of metals. The oxidized metals grow as scale on the pipe walls, or they migrate into the water and are carried along with the water flow. An example of this is lead corrosion. The pipe gradually loses thickness until leaks occur. Reactions with water and other substances can also produce scale in the form of poorly soluble compounds that deposit on the metal. In the best case, protective layers form that guard the metal against further corrosion (passivation). For instance, compact rust layers in cast iron and steel pipes can ensure over 100 years of service (Figure 2a). These pipes often have a scale layer several centimeters thick on the inside that is mechanically stable, and the drinking water they transport often shows no increased iron content or other hygienic problems. The examination of such a pipe under different operating conditions will be reported in the fourth article.

(a) **(b)**

Figure 2. (a) Surface corrosion on a 200 mm (DN 200) steel drinking water pipe after nearly 100 years of operation. **(b)** Pitting corrosion on copper pipes. Leaks are indicated by white arrows.

Pitting is a type of localized corrosion (see Figure 2b), which penetrates deep into the material and causes damage much faster than surface corrosion. It mainly occurs in passivated metals, such as copper and stainless steel. The presence of metal partially covered with corrosion products that generate a local electrochemical element is important for its occurrence. Additionally, low pH, high concentrations of free chlorine, low acid capacity, and unfavorable operating conditions favor pitting.

Corrosion in drinking water pipes is caused by **electrochemical processes**. When two different metals, such as copper and zinc, are immersed in oxygen-saturated water, an electrical voltage is produced between them. When they are electrically connected, a current flows. During this reaction, the less noble metal (zinc) oxidizes, dissolving as a zinc cation and leaving behind two electrons (anode process). These electrons flow through the electrical connection to the more noble metal (copper), leading to the reduction of oxygen on its surface. The less noble zinc anode dissolves. This process is called a **reduction-oxidation reaction, or redox reaction for short**. A redox process can also occur on a metal surface in contact with water (e.g., in a pipe) if the electrodes are spatially separated yet electrically connected and have a sufficient potential difference to trigger an electrochemical process. The following conditions lead to the formation of local elements or corrosion elements:

- when different metals are combined with physical or chemical irregularities on their surfaces, deposits, or scale;
- with deposits or scale on the metal;
- between crystallites of a polycrystalline structure in alloys;
- when the electrolyte concentration differs locally;
- when the concentration of reactive gases (e.g., oxygen) differs locally;
- in the case of air bubbles at phase boundaries;
- when the pH values and thus potentials change.

For **electrochemical corrosion** to occur, the following conditions must be met:

- **an anodic partial reaction, such as metal dissolution;**
- **a cathodic partial reaction, such as oxygen reduction;**
- **an electrically conductive connection between the two reaction sites;**
- **and an ion-conducting medium, in this case water and its ingredients.**

3. Factors influencing the corrosion process

The half-cell potentials of the elements can be arranged according to their oxidation potential. The more electropositive or noble an element is, the more difficult it is to oxidize. Accordingly, all half-cells can be classified into a **galvanic series** according their **electrochemical potential** (see Table 1). Measurements under standard conditions (temperature 25 °C, 1 mol/L for concentrations in solution and a pressure of 1.013 bar for gases) are referred to as **standard potentials**. The potentials change under other conditions, and can be calculated using the Nernst equation, which will be discussed in the third article. In the table, the nobler elements are above hydrogen, which by definition, has a potential of 0 V at all temperatures. The oxidizing power decreases from top to bottom in the series. Table 1 shows that chlorine and oxygen are more oxidizing than any of the listed metals.

Table 1. Galvanic series of the elements.[1]

Element/Element symbol	Oxidized form	Transferred electrons	⇌ Reduced form	Standard potential (E °) (V)
Chlorine (Cl)	Cl_2	+ 2 e^-	⇌ $2Cl^-$	+1.36
Oxygen (O)	$O_2 + 2\ H_2O$	+ 4 e^-	⇌ 4 OH^-	+1.21
Copper (Cu)	Cu^{2+}	+ 2 e^-	⇌ Cu	+0.337
Copper (Cu)	Cu^{2+}	+ e^-	⇌ Cu^+	+0.167
Hydrogen (H)	2 H^+	+ 2 e^-	⇌ H_2	0
Iron (Fe)	Fe^{3+}	+ e^-	⇌ Fe^{2+}	−0.036
Lead (Pb)	Pb^{2+}	+ 2 e^-	⇌ Pb	−0.126
Nickel (Ni)	Ni^{2+}	+ 2 e^-	⇌ Ni	−0.250
Iron (Fe)	Fe^{2+}	+ 2 e^-	⇌ Fe	−0.44

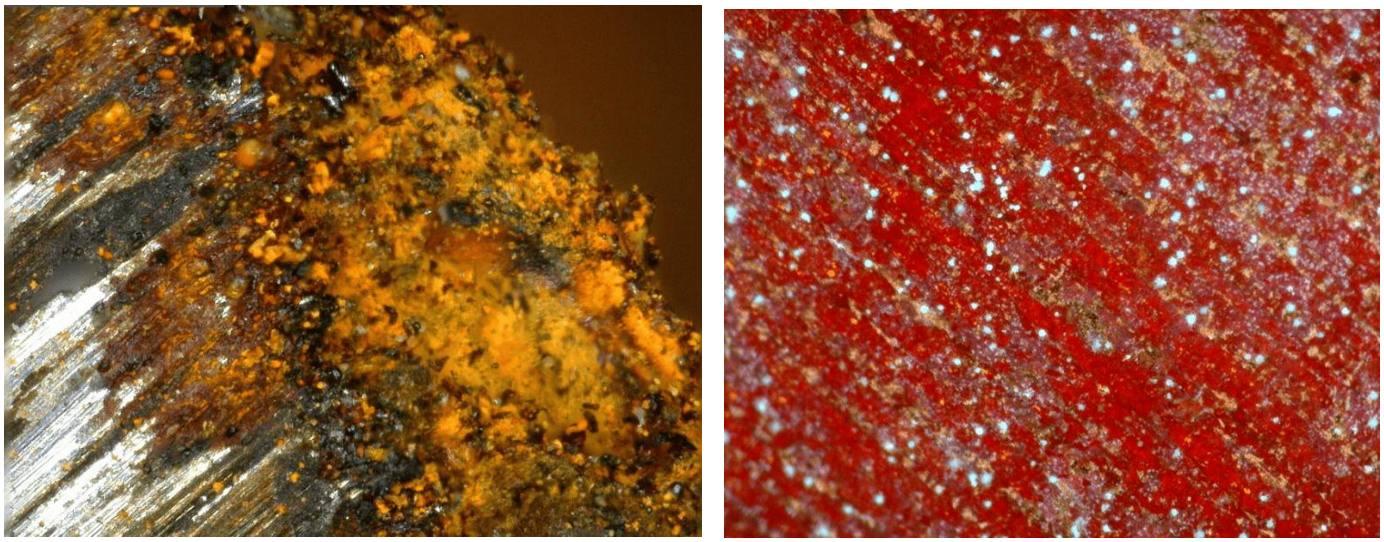
Chromium (Cr)	Cr^{3+}	+ 3 e^-	⇌ Cr	−0.74
Zinc (Zn)	Zn^{2+}	+ 2 e^-	⇌ Zn	−0,763
Aluminum (Al)	Al^{3+}	+ 3e^-	⇌ Al	−1.78

[1] Data taken from, updated [5].

Redox reactions, including corrosion, often involve multiple species, e.g., Cu(0), Cu(I), and Cu(II) for copper or Fe(0), Fe(II), and Fe(III) for iron. All of the metals listed in Table 1 are not stable in pure water at pH 7. However, they can form covering layers of oxides that passivate the surface, e.g., chromium forms a thin, hard layer of chromium(III) oxide that also protects stainless steels from further corrosion.

Corrosion is caused by the corroding material, the medium, and the direct connection of different metals or alloys with different oxidation potentials (i.e., **galvanic corrosion**).

Other factors that influence metal corrosion include surface condition, such as roughness and cracks; grain boundaries; metal inclusions; and coatings. Figure 3 illustrates how the surface affects corrosion. The partially bright, low-alloy steel in Figure 3a shows various inhomogeneous iron oxide corrosion products growing along the drawing grooves. The copper sheet's surface is mostly covered with red copper(I) oxide, while the grooves are covered with light blue copper(II) minerals (Figure 3b).



(a) **(b)**

Figure 3. Coupons corroded by drinking water at 50x magnification **(a)** low-alloyed steel, **(b)** copper.

Corrosivity refers to an environment's ability to cause corrosion. Different oxygen concentrations, low pH values, and high salt concentrations can promote corrosion. Conversely, high pH values, low salt concentrations, and low total inorganic carbon (TIC), phosphate and silicate reduce corrosion.

Because the composition of each drinking water is unique, the **corrosion properties** of each water will differ with the same materials and operating conditions. Oxygen is the most significant oxidizing agent in drinking water. The addition of disinfectants, such as chlorine or chlorine dioxide, also promotes corrosion because they are oxidizing agents. While today's drinking water is almost always oxic (has an oxygen content above 3 mg/L), raw water can be anoxic ($c(O_2) \leq 3$ mg/L). In the absence of oxygen, other species act as oxidants, such as nitrates and sulfates. Nitrites, ammonium, and hydrogen sulfide may form as reduction products. Currently, drinking water with oxygen concentrations of > 3.2 mg/L is used to create a stable corrosion layer for unprotected iron materials [6].

An increase in temperature always increases the corrosion rate. Unfavorable operating conditions, such as high flow velocities and stagnation, often lead to accelerated

corrosion. Air bubbles and sediment deposits are problematic because they promote localized corrosion.

3. Thermodynamics and kinetics of corrosion

The driving force of electrochemical corrosion is the achievement of a thermodynamically favorable state that is low in energy and disordered. In other words, the enthalpy strives for a minimum and the entropy strives for a maximum. A material that does not corrode under given thermodynamic conditions is considered immune. Metallic pipes and installation materials used for drinking water are rarely immune. For instance, metallic iron in oxygen-saturated water produces amorphous iron oxide hydrate, commonly known as "rust."

Drinking water systems are thermodynamically open. This means they exchange materials and energy with the environment, so they are subject to changing conditions. For instance, flowing water constantly supplies oxygen, which is consumed as corrosion progresses. Thus, thermodynamic equilibrium is never achieved in drinking water pipes. At best, quasi-stationary flow equilibria, or steady states, are achieved.

On the other hand, **kinetics deals with how quickly a reaction occurs.** If the corrosion rate is high enough, corrosion phenomena will occur. Figure 1 illustrates the corrosion of a copper sheet in contact with drinking water at 15°C over 70 days. After 10 days, the metal is fully covered in scale, a surface layer of corrosion products. Surface corrosion generally reduces the corrosion rate because the underlying metal can only be attacked after a delay. When a thermodynamically controlled reaction is prevented or slowed by a dense corrosion layer, the process is called **passivation**.

4. Corrosion control and corrosion protection

A systematic **corrosion control program** begins with an examination of system components, conveyed water, and operating conditions. It is followed by the selection of appropriate materials and the development and implementation of a corrosion control program to prevent or reduce corrosion. The program must be consistently monitored and observed for corrosion phenomena during operation. The program should be periodically reviewed and adjusted as necessary to minimize corrosion [7].

One important measure is **corrosion monitoring** of the metals and alloys used. Starting with the fourth article, simple **corrosion tests** for corrosion measurement are presented.

Corrosion protection includes all measures to reduce the corrosion damage. It is always an attempt to slow down or stop natural corrosion. Since the slowest possible corrosion of metals in drinking water is desirable, the question arises as to how this can be achieved. Measures can be taken on both the material and media side, as well as through cathodic protection, which can slow down or even stop corrosion.

On the material side, it is possible to use a nobler, electropositive materials. For example, cast iron impellers in pumps can be replaced with bronze or stainless steel ones. The use of alloys can influence corrosion; for example, if the oxidation potential is enhanced, or if the less noble metal can form a protective corrosion layer [3]. When installing new metal pipes, they should be electrically isolated from older pipes to prevent contact corrosion**.**

Coating a corrosive material prevents corrosion by a **protective layer**. For example, today's drinking water pipes made of cast iron or unalloyed or low-alloy steel have an internal coating of cement mortar and an external coating of zinc, covered with a bituminous or polymeric topcoat to protect against corrosion.

Cathodic protection is used in the drinking water sector, especially for large diameter transport pipes, to protect them from corrosion by the surrounding soil. The

material to be protected is subjected to a negative potential with respect to the electrodes in the surrounding soil so that the electrochemical corrosion potential is equalized and corrosion processes are stopped. The metal becomes inert and is protected from further corrosion. Alternatively, a sacrificial electrode, such as magnesium, can be used which is connected to the metal to be protected and corrodes in its place. Magnesium sacrificial electrodes are used in drinking water installations to protect the drinking water heater.

On the media side, the water should have a pH level greater than 7.0 (the maximum value according to the EU Drinking Water Directive is 9.5 [8]) and low salt concentrations to minimize corrosion. Ideally, water should contain as little oxygen as possible to limit corrosion. However, a minimum of 3.2 mg/L of oxygen is recommended for real drinking water networks in order to stabilize the top rust layers on older, unprotected cast iron and low-alloy steel pipes; otherwise, the scale can dissolve at low oxygen concentrations and contaminate the drinking water.

Corrosion inhibitors can also be added to the water to reduce corrosion. These inhibitors protect the areas of the material that are actively corroding, and their mechanism of action depends on the type of inhibitor. Cathodic, anodic, and neutral corrosion inhibitors are used depending on their mode of action. In the drinking water sector, for instance, silicates and phosphates are commonly employed, although their mechanisms are not fully understood. Furthermore, national requirements, if any, must be taken into account. In Germany, the German Federal Environmental Agency (UBA) maintains a list of approved treatment substances and disinfection methods as an appendix to the German Drinking Water Ordinance [9].

The next article discusses the properties of water that affect corrosion.

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