CHAPTER 1

The Effects and Economic Impact of Corrosion

CORROSION is a natural process. Just like water flows to the lowest level, all natural processes tend toward the lowest possible energy states. Thus, for example, iron and steel have a natural tendency to combine with other chemical elements to return to their lowest energy states. In order to return to lower energy states, iron and steel frequently combine with oxygen and water, both of which are present in most natural environments, to form hydrated iron oxides (rust), similar in chemical composition to the original iron ore. Figure 1 illustrates the corrosion life cycle of a steel product.

Fig. 1  The corrosion cycle of steel
The Definition of Corrosion

Corrosion can be defined in many ways. Some definitions are very narrow and deal with a specific form of corrosion, while others are quite broad and cover many forms of deterioration. The word corrode is derived from the Latin *corrodere*, which means “to gnaw to pieces.” The general definition of corrode is to eat into or wear away gradually, as if by gnawing. For purposes here, corrosion can be defined as a chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties.

The environment consists of the entire surrounding in contact with the material. The primary factors to describe the environment are the following: (a) physical state—gas, liquid, or solid; (b) chemical composition—constituents and concentrations; and (c) temperature. Other factors can be important in specific cases. Examples of these factors are the relative velocity of a solution (because of flow or agitation) and mechanical loads on the material, including residual stress within the material. The emphasis in this chapter, as well as in other chapters in this book, is on aqueous corrosion, or corrosion in environments where water is present. The deterioration of materials because of a reaction with hot gases, however, is included in the definition of corrosion given here.

To summarize, corrosion is the deterioration of a metal and is caused by the reaction of the metal with the environment. Reference to marine corrosion of a pier piling means that the steel piling corrodes because of its reaction with the marine environment. The environment is air-saturated seawater. The environment can be further described by specifying the chemical analysis of the seawater and the temperature and velocity of the seawater at the piling surface.

When corrosion is discussed, it is important to think of a combination of a material and an environment. The corrosion behavior of a material cannot be described unless the environment in which the material is to be exposed is identified. Similarly, the corrosivity or aggressiveness of an environment cannot be described unless the material that is to be exposed to that environment is identified. In summary, the corrosion behavior of the material depends on the environment to which it is subjected, and the corrosivity of an environment depends on the material exposed to that environment.

It is useful to identify both natural combinations and unnatural combinations in corrosion. Examples of natural or desirable combinations of material and environment include nickel in caustic environments, lead in water, and aluminum in atmospheric exposures. In these environments, the interaction between the metal and the environment does not
usually result in detrimental or costly corrosion problems. The combination is a natural combination to provide good corrosion service.

Unnatural combinations, on the other hand, are those that result in severe corrosion damage to the metal because of exposure to an undesirable environment. Examples of unnatural combinations include copper in ammonia solutions, stainless steel in chloride-containing environments (e.g., seawater), and lead with wine (acetic acid in wine attacks lead). It has been postulated that the downfall of the Roman Empire can be attributed in part to a corrosion problem, specifically the storage of wine in lead-lined vessels. Lead dissolved in the wine and consumed by the Roman hierarchy resulted in insanity (lead poisoning) and contributed to the subsequent eventual downfall. Another anecdote regarding lead and alcoholic beverages dates back to the era of Benjamin Franklin. One manifestation was the “dry bellyache” with accompanying paralysis, which was mentioned by Franklin in a letter to a friend. This malady was actually caused by the ingestion of lead from corroded lead coil condensers used in making brandy. The problem became so widespread that the Massachusetts legislature passed a law in the late 1700s that outlawed the use of lead in producing alcoholic beverages.

The Effects of Corrosion

The effects of corrosion in our daily lives are both direct, in that corrosion affects the useful service lives of our possessions, and indirect, in that producers and suppliers of goods and services incur corrosion costs, which they pass on to consumers. At home, corrosion is readily recognized on automobile body panels, charcoal grills, outdoor furniture, and metal tools. Preventative maintenance such as painting protects such items from corrosion. A principal reason to replace automobile radiator coolant every 12 to 18 months is to replenish the corrosion inhibitor that controls corrosion of the cooling system. Corrosion protection is built into all major household appliances such as water heaters, furnaces, ranges, washers, and dryers.

Of far more serious consequence is how corrosion affects our lives during travel from home to work or school. The corrosion of steel reinforcing bar (rebar) in concrete can proceed out of sight and suddenly (or seemingly so) result in failure of a section of highway, the collapse of electrical towers, and damage to buildings, parking structures, and bridges, etc., resulting in significant repair costs and endangering public safety. For example, the sudden collapse because of corrosion fatigue of the Silver Bridge over the Ohio River at Point Pleasant, OH in 1967 resulted in the loss of 46 lives and cost millions of dollars.
Perhaps most dangerous of all is corrosion that occurs in major industrial plants, such as electrical power plants or chemical processing plants. Plant shutdowns can and do occur as a result of corrosion. This is just one of its many direct and indirect consequences. Some consequences are economic, and cause the following:

- Replacement of corroded equipment
- Overdesign to allow for corrosion
- Preventive maintenance, for example, painting
- Shutdown of equipment due to corrosion failure
- Contamination of a product
- Loss of efficiency—such as when overdesign and corrosion products decrease the heat-transfer rate in heat exchangers
- Loss of valuable product, for example, from a container that has corroded through
- Inability to use otherwise desirable materials
- Damage of equipment adjacent to that in which corrosion failure occurs

Still other consequences are social. These can involve the following issues:

- Safety, for example, sudden failure can cause fire, explosion, release of toxic product, and construction collapse
- Health, for example, pollution due to escaping product from corroded equipment or due to a corrosion product itself
- Depletion of natural resources, including metals and the fuels used to manufacture them
- Appearance as when corroded material is unpleasing to the eye

Of course, all the preceding social items have economic aspects also (see the discussion that follows, “Economic Impact of Corrosion”). Clearly, there are many reasons for wanting to avoid corrosion.

The Many Forms of Corrosion

Corrosion occurs in several widely differing forms. Classification is usually based on one of three factors:

- **Nature of the corrodent**: Corrosion can be classified as “wet” or “dry.” A liquid or moisture is necessary for the former, and dry corrosion usually involves reaction with high-temperature gases.
- **Mechanism of corrosion**: This involves either electrochemical or direct chemical reactions.
- **Appearance of the corroded metal:** Corrosion is either uniform and the metal corrodes at the same rate over the entire surface, or it is localized, in which case only small areas are affected.

Classification by appearance, which is particularly useful in failure analysis, is based on identifying forms of corrosion by visual observation with either the naked eye or magnification. The morphology of attack is the basis for classification. Figure 2 illustrates schematically some of the most common forms of corrosion.

Eight forms of wet (or aqueous) corrosion can be identified based on appearance of the corroded metal. These are:

- Uniform or general corrosion
- Pitting corrosion
- Crevice corrosion, including corrosion under tubercles or deposits, filiform corrosion, and poultice corrosion
- Galvanic corrosion
- Erosion-corrosion, including cavitation erosion and fretting corrosion
- Intergranular corrosion, including sensitization and exfoliation
- Dealloying, including dezincification and graphitic corrosion
- Environmentally assisted cracking, including stress-corrosion cracking, corrosion fatigue, and hydrogen damage

In theory, the eight forms of corrosion are clearly distinct; in practice however, there are corrosion cases that fit in more than one category. Other corrosion cases do not appear to fit well in any of the eight categories. Nevertheless, this classification system is quite helpful in the study

![Fig. 2 Schematics of the common forms of corrosion](image-url)
of corrosion problems. Detailed information on these eight forms of corrosion can be found in Chapter 4.

Completeness requires further distinction between macroscopically localized corrosion and microscopic local attack. In the latter case, the amount of metal dissolved is minute, and considerable damage can occur before the problem becomes visible to the naked eye. Macroscopic forms of corrosion affect greater areas of corroded metal and are generally observable with the naked eye or can be viewed with the aid of a low-power magnifying device. Figure 3 classifies macroscopic and microscopic forms of localized corrosion.

**Methods to Control Corrosion**

There are five primary methods of corrosion control:

- Material selection
- Coatings
- Inhibitors
- Cathodic protection
- Design

Each is described briefly here and in more detail in subsequent chapters.

**Material Selection**

Each metal and alloy has unique and inherent corrosion behavior that can range from the high resistance of noble metals, for example, gold...
and platinum, to the low corrosion resistance of active metals, for example, sodium and magnesium. Furthermore, the corrosion resistance of a metal strongly depends on the environment to which it is exposed, that is, the chemical composition, temperature, velocity, and so forth.

The general relation between the rate of corrosion, the corrosivity of the environment, and the corrosion resistance of a material is:

\[
\text{corrosion resistance of metal} / \text{corrosivity of environment} \approx \text{rate of corrosive attack}
\]

For a given corrosion resistance of the material, as the corrosivity of the environment increases, the rate of corrosion increases. For a given corrosivity of the environment, as the corrosion resistance of the material increases, the rate of corrosion decreases. Often an acceptable rate of corrosion is fixed and the challenge is to match the corrosion resistance of the material and the corrosivity of the environment to be at or below the specified corrosion rate. Often there are several competing materials that can meet the corrosion requirements, and the material selection process becomes one of determining which of the candidate materials provides the most economical solution for the particular service.

Consideration of corrosion resistance is often as important in the selection process as the mechanical properties of the alloy. A common solution to a corrosion problem is to substitute an alloy with greater corrosion resistance for the alloy that has corroded.

**Coatings**

Coatings for corrosion protection can be divided into two broad groups—metallic and nonmetallic (organic and inorganic). With either type of coating the intent is the same, that is, to isolate the underlying metal from the corrosive media.

**Metallic Coatings.** The concept of applying a more noble metal coating on an active metal takes advantage of the greater corrosive resistance of the noble metal. An example of this application is tin-plated steel. Alternatively, a more active metal can be applied, and in this case the coating corrodes preferentially, or sacrificially, to the substrate. An example of this system is galvanized steel, where the sacrificial zinc coating corrodes preferentially and protects the steel.

**Organic Coatings.** The primary function of organic coatings in corrosion protection is to isolate the metal from the corrosive environment. In addition to forming a barrier layer to stifle corrosion, the organic coating can contain corrosion inhibitors. Many organic coating formulations exist, as do a variety of application processes to choose from for a given product or service condition.
**Inorganic coatings** include porcelain enamels, chemical-setting silicate cement linings, glass coatings and linings, and other corrosion-resistant ceramics. Like organic coatings, inorganic coatings for corrosion applications serve as barrier coatings. Some ceramic coatings, such as carbides and silicides, are used for wear-resistant and heat-resistant applications, respectively.

**Inhibitors**

Just as some chemical species (e.g., salt) promote corrosion, other chemical species inhibit corrosion. Chromates, silicates, and organic amines are common inhibitors. The mechanisms of inhibition can be quite complex. In the case of the organic amines, the inhibitor is adsorbed on anodic and cathodic sites and stifles the corrosion current. Other inhibitors specifically affect either the anodic or cathodic process. Still others promote the formation of protective films on the metal surface.

The use of inhibitors is favored in closed systems where the necessary concentration of inhibitor is more readily maintained. The increased use of cooling towers stimulated the development of new inhibitor/water-treatment packages to control corrosion and biofouling.

Inhibitors can be incorporated in a protective coating or in a primer for the coating. At a defect in the coating, the inhibitor leaches from the coating and controls the corrosion.

**Cathodic Protection**

Cathodic protection suppresses the corrosion current that causes damage in a corrosion cell and forces the current to flow to the metal structure to be protected. Thus, the corrosion or metal dissolution is prevented. In practice, cathodic protection can be achieved by two application methods, which differ based on the source of the protective current. An impressed-current system uses a power source to force current from inert anodes to the structure to be protected. A sacrificial-anode system uses active metal anodes, for example, zinc or magnesium, which are connected to the structure to provide the cathodic-protection current.

**Design**

The application of rational design principles can eliminate many corrosion problems and greatly reduce the time and cost associated with corrosion maintenance and repair. Corrosion often occurs in dead spaces or crevices where the corrosive medium becomes more corrosive. These areas can be eliminated or minimized in the design process. Where stress-corrosion cracking is possible, the components can be designed to operate at stress levels below the threshold stress for cracking.
Where corrosion damage is anticipated, design can provide for maximum interchangeability of critical components and standardization of components. Interchangeability and part standardization reduce the inventory of parts required. Maintenance and repair can be anticipated, and easy access can be provided. Furthermore, for the large items that are critical to the entire operation, such as primary pumps or large fans, redundant equipment is installed to permit maintenance on one unit while the other is operating. These practices are a sampling of rational design principles.

Opportunities in Corrosion Control

The massive costs of corrosion provide many opportunities to users, manufacturers, and suppliers. Opportunities exist to reduce corrosion costs and the risks of failure, and to develop new, expanded markets. Examples of these opportunities and the means to implement a program to capitalize on the opportunities are presented in Table 1.

The costs of corrosion vary considerably from industry to industry; however, substantial savings are achievable in most industries. The first step in any cost-reduction program is to identify and quantify the present costs of corrosion. Based on this analysis and a review of the present status of corrosion control in the industry, priorities can be determined and the most rewarding cost-reduction projects pursued.

Risk of corrosion failure can be lowered in the producer’s facility and in its products. Both process and products can be analyzed to identify the areas where corrosion failures can occur. Once identified, the risk of failure can be evaluated from the perspectives of impact on safety, product liability, avoidance of regulation, and loss of goodwill. Where risks

<table>
<thead>
<tr>
<th>Opportunity</th>
<th>Examples</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce corrosion costs</td>
<td>Lower maintenance and repair costs</td>
<td>Identify all corrosion costs by review of total processes, equipment, and buildings</td>
</tr>
<tr>
<td></td>
<td>Extended useful lives of equipment and buildings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduction of product loss from corrosion damage</td>
<td>Implement plan to reduce costs</td>
</tr>
<tr>
<td>Lower risk of failure</td>
<td>Safety</td>
<td>Review process and products for exposure to risk</td>
</tr>
<tr>
<td></td>
<td>Product liability</td>
<td>Evaluate risk and consequences of failure</td>
</tr>
<tr>
<td></td>
<td>Avoidance of regulation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Loss of goodwill</td>
<td>Lower exposure by technology change</td>
</tr>
<tr>
<td>Develop new and expanded markets</td>
<td>Coatings</td>
<td>Apply emerging technology</td>
</tr>
<tr>
<td></td>
<td>Alloys</td>
<td>Develop competitive advantage by more corrosion-resistant product</td>
</tr>
<tr>
<td></td>
<td>Inhibitors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Corrosion monitors</td>
<td>Transfer existing technology to other industries</td>
</tr>
</tbody>
</table>
are too great, technological changes can be implemented to reduce the risk. Evaluation also can identify areas where technological advances are required in the industry.

Increased consumer awareness of corrosion provides a competitive advantage for products with improved corrosion resistance. Through the application of existing or emerging technologies to products or services, advances are being made in all methods for corrosion control: material selection, coatings, inhibitors, cathodic protection, and design. Market opportunities are to be found in the transfer of existing technology to other industries.

### The Economic Impact of Corrosion

Corrosion of metals costs the U.S. economy almost $300 billion per year at current prices. Approximately one-third of these costs could be reduced by broader application of corrosion-resistant materials and the application of best corrosion-related technical practices. These estimates result from a recent update of findings of the 1978 study *Economic Effects of Metallic Corrosion in the United States*. The study was performed by Battelle Columbus Laboratories and the National Institute of Standards and Technology (NIST) and published in April 1995.

The original work, based upon an elaborate model of more than 130 economic sectors, found that in 1975, metallic corrosion cost the United States $82 billion, or 4.9% of its gross national product (GNP). It was also found that 60% of that cost was unavoidable. The remaining $33 billion (40%) was incurred by failure to use the best practices then known. These were called “avoidable” costs.

Over the last two decades, economic growth and price inflation have increased the GNP more than fourfold. If nothing else had changed, the costs of metallic corrosion would have risen to almost $350 billion annually by 1995, $139 billion of which would have been avoidable. However, 20 years of scientific research and technological change, much of which was initiated because of the 1978 study, have affected these costs.

The Battelle panel updated the earlier results by judgmentally evaluating two decades of corrosion-related changes in scientific knowledge and industrial practices. In the original study, almost 40% of the 1975 metallic corrosion costs were incurred in the production, use, and maintenance of motor vehicles. No other sector accounted for as much as 4% of the total, and most sectors contributed less than 1%. The aircraft sector, for instance, was one of the next largest contributors and accounted for just more than 3%. Pipelines, a sector to which corrosion is a recognized problem, accounted for less than 1% of the total cost.