CORROSION

UNDERSTANDING THE BASICS

ASM INTERNATIONAL

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Preface

Most people are familiar with corrosion in some form or another. Whether it is a rusty nail in a backyard fence, corroded fenders and/or mufflers on our automobiles, or a perforated underground water pipe, it is safe to say that corrosion is all around us. It is costly to prevent or repair, and it is generally not pleasing to look at. In the industrial workplace, corrosion is certainly one of the most common causes of failure of engineered components and structures. The complexities of corrosion phenomena challenge corrosion scientists, chemists, mechanical, civil, and metallurgical engineers, coating specialists, and maintenance and operating personnel.

In order to better understand corrosion, it is important to first examine the basic concepts that influence the corrosion process; hence, the title of this publication—*Corrosion: Understanding the Basics*. Included in these 12 chapters are practical discussions on the following:

- Thermodynamic and electrochemical principles of corrosion
- Recognition and prevention of various forms of corrosion
- Types of corrosive environments commonly encountered and environmental variables that can increase or decrease corrosion rates
- Corrosion characteristics of metals and alloys and nonmetallic materials
- Methods of corrosion prevention, including design considerations, materials selection, coatings, inhibitors, and cathodic and anodic protection
- Corrosion testing and monitoring
- Techniques for diagnosing corrosion failures

Although the book is primarily intended for professionals who are not corrosion experts, it should also serve as a quick and useful corrosion-control guide for corrosion engineers.

Assisting in the preparation of this book was Larry Korb from Rockwell International. Larry, who is a Fellow of ASM International and longtime member and former chairman of the ASM Handbook Committee, meticulously reviewed each chapter. I have long been in awe of my friend's exhaustive knowledge of materials and their failure mechanisms (including corrosion), and his keen insight into the editorial process. It is always an honor and a privilege to work with Mr. Korb.

I also wish to acknowledge the contributions of Nalco Chemical Company (Naperville, IL). Many of the photographs illustrating the different modes of corrosion were supplied by Nalco. These originally appeared in two excellent books on failure analysis authored by Nalco engineers Harvey M. Herro (an ASM member) and Robert D. Port. I am indebted to Ms. Connie Szewczyk, a Communications Specialists with Nalco, for supplying these photographs.

Thanks are also extended to Kenneth B. Tator and Alison B. Kaelin from KTA-Tator Inc. (Pittsburgh, PA). Ken supplied an extensive table that reviewed the advantages and limitations of organic coating resins. Alison prepared material on environmental, health, and safety considerations for the coatings industry. Their contributions appear in Chapter 9.

The efforts of the ASM staff are also duly noted. In particular, I would like to thank Scott Henry and Bonnie Sanders from the Publications Department and Eleanor Baldwin and her coworkers from the ASM Library for the help and support throughout the project

Last, I would be remiss in not acknowledging the fact that several chapters in the book were adapted from the ASM Materials Engineering Institute (MEI) course on corrosion that was prepared by Dr. Joe H. Payer from Case Western Reserve University (Cleveland, OH). Chapters 2 and 3, as well as the description of electrochemical test methods in Chapter 11, were based on Dr. Payer's work.

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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.

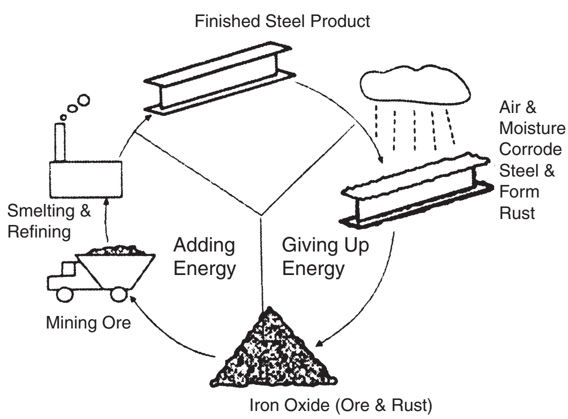

Fig. 1 The corrosion cycle of steel

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

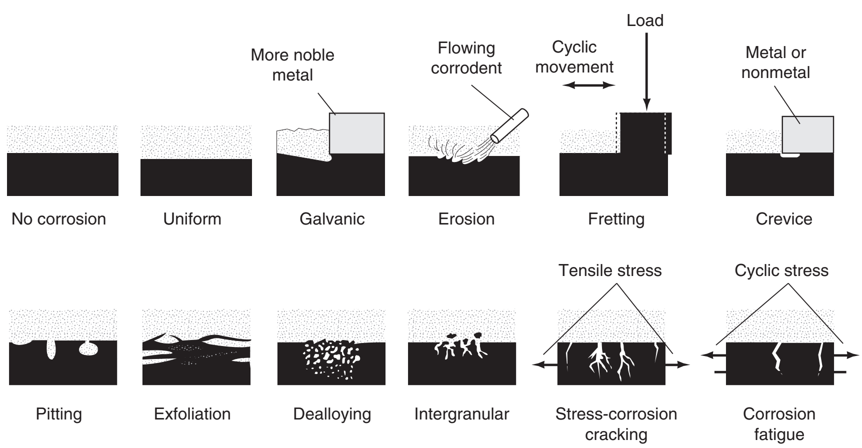

Fig. 2 Schematics of the common forms of corrosion

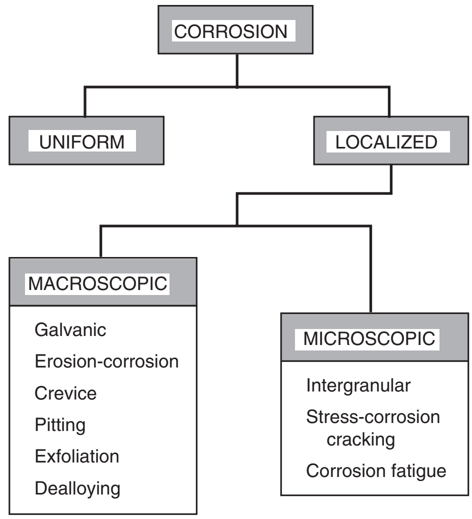

Fig. 3 Macroscopic versus microscopic forms of localized corrosion

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:

$$\frac{\text{corrosivity of environment}}{\text{corrosion resistance of metal}} \approx \text{rate of corrosive attack}$$

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 and 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 1 Opportunities in corrosion control

Opportunity	Examples	Implementation
Reduce corrosion costs	Lower maintenance and repair costs Extended useful lives of equipment and buildings Reduction of product loss from corrosion damage	Identify all corosion costs by review of total processes, equipment, and buildings Quantify corrosion costs Implement plan to reduce costs
Lower risk of failure	Safety Product liability Avoidance of regulation Loss of goodwill	Review process and products for exposure to risk Evaluate risk and consequences of failure Lower exposure by technology change
Develop new and expanded markets	Coatings Alloys Inhibitors Corrosion monitors	Apply emerging technology Develop competitive advantage by more corrosion-resistant product Transfer existing technology to other industries

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.

The panel found that the automotive sector probably had made the greatest anticorrosion effort of any single industry. Advances have been made in the use of stainless steels, coated metals, and more protective finishes. Moreover, several substitutions of materials made primarily for reasons of weight reduction have also reduced corrosion. Also, the panel estimates that 15% of previously unavoidable corrosion costs can be reclassified as avoidable. The industry is estimated to have eliminated some 35% of avoidable corrosion by improved practices.

In examining the aircraft, pipeline, and shipbuilding sectors, the panel reported that both gains and losses have occurred, most of them tending to offset each other. For instance, in many cases, the use of more expensive materials has reduced the need for corrosion-related repairs or repainting. Overall, it was thought that for the U.S. economy other than in motor vehicle and aircraft applications, total corrosion costs have been reduced by no more than 5% with a further reduction of unavoidable costs by about 2%.

The updated study shows that the total 1995 cost of metallic corrosion was reduced (from what it would have been in 1975 terms) by some 14%, or to 4.2% of the GNP. Avoidable corrosion, which was 40% of the total, is now estimated to be 35% but still accounts for slightly more than $100 billion per year. This figure represents the annual cost to the economy, which can be reduced by broader application of corrosion-resistant materials, improvement in corrosion-prevention practices, and investment in corrosion-related research. Table 2 compares the results of the 1978 and 1995 Battelle/NIST studies.

Factors Influencing Corrosion. Some of the factors that influence corrosion and its costs are shown in Fig. 4. Corrosion costs are reduced by the application of available corrosion technology, which is sup-

Table 2 Cost of metallic corrosion in the United States

Industry	Billions of U.S. dollars 1975	1995
All industries		
Total	82.0	296.0
Avoidable	33.0	104.0
Motor vehicles		
Total	31.4	94.0
Avoidable	23.1	65.0
Aircraft		
Total	3.0	13.0
Avoidable	0.6	3.0
Other industries		
Total	47.6	189.0
Avoidable	9.3	36.0

Source: *Economic Effects of Metallic Corrosion in the United States,* Battelle Columbus Laboratories and the National Institute of Standards and Technology (NIST), 1978, and Battelle estimates ported by technology transfer. New and improved corrosion technology results from research and development. The proper application of methods to control corrosion (e.g., coatings, inhibitors, and cathodic protection) reduces the cost of corrosion. The costs of corrosion tend to increase with such factors as deferred maintenance and extended useful lives of buildings and equipment. Increased corrosion costs are often realized when higher-performance specifications and more hostile environments are encountered.

Finally, increased corrosion costs result from government regulations that prohibit the use of time-honored methods of protection because of safety or environmental damage. For example, in an effort to reduce smog, the elimination of lead-based paints on houses and bridges, chromate inhibiting paints on aircraft, and oil-based paints throughout industry has had severe repercussions. Substitute water-based paints have not, in many cases, afforded equivalent corrosion protection.

Cost Elements. Although costs vary in relative significance from industry to industry, several generalized elements combine to make up the total cost of corrosion. Some are readily recognized; others are less recognizable.

In manufacturing, corrosion costs are incurred in the product development cycle in several ways, beginning with the materials, energy, labor, and technical expertise required to produce a product. For example, a product can require painting for corrosion protection. A corrosion-resistant metal can be chosen in place of plain carbon steel, and technical services can be required to design and install cathodic protection on a product. Additional heat treatment can be needed to relieve stresses for protection against stress-corrosion cracking.

Other operating costs are affected by corrosion as well. Corrosion inhibitors, for example, often must be added to water treatment systems.

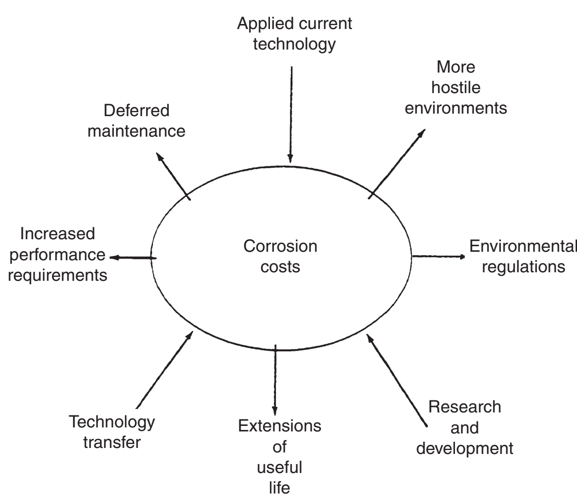

Fig. 4 Factors which increase or decrease the costs of corrosion

Portions of maintenance and repair costs can be attributed to corrosion, and corrosion specialists are often employed to implement corrosion-control programs.

Capital costs also are incurred because of corrosion. The useful life of manufacturing equipment is decreased by corrosion. For an operation that is expected to run continuously, excess capacity is required to allow for scheduled downtime and corrosion-related maintenance. In other instances, redundant equipment is installed to enable maintenance on one unit while processing continues with another unit.

For the end user or consumer, corrosion costs are incurred for purchases of corrosion prevention and control products, maintenance and repair, and premature replacement.

The original Battelle/NIST study identified ten elements of the cost of corrosion:

- Replacement of equipment or buildings
- Loss of product
- Maintenance and repair
- Excess capacity
- Redundant equipment
- Corrosion control
- Technical support
- Design
- Insurance
- Parts and equipment inventory

Table 3 lists examples under each of these categories.

Replacement, loss of product, and maintenance and repair are fairly straightforward. Excess capacity is a corrosion cost if downtime for a plant scheduled for continuous operation could be reduced were corrosion not a factor. This element accounts for extra plant capacity (capital stock) maintained because of corrosion.

Redundant equipment accounts for additional plant equipment (capital stock) required because of corrosion. Specific critical components such as large fans and pumps are backed up by identical items to allow processing to continue during maintenance for corrosion control.

The costs of corrosion control are straightforward, as are the technical support (engineering, research and development, and testing) costs associated with corrosion. Corrosion costs associated with design are not always as obvious. The last two cost elements, insurance and inventory, can be significant in specific cases.

In addition to these ten categories, other less quantifiable cost factors, such as loss of life or loss of goodwill because of corrosion, can have a major impact. Single, catastrophic failures—for example, a corrosion-

Table 3 Elements of cost of corrosion

Element of cost	Example
Replacement of equipment or buildings	Corroded pressure vessel
Loss of product	Corrosion leak
	Corrosion contamination of product
	Corrosion during storage
Maintenance and repair	Repair corroded corrugated metal roof
	Weld overlay of chemical reaction tank
	Repair pump handling corrosive slurry—erosion and corrosion
	Scheduled downtime for plant in continuous operation, for example, petroleum refinery
Redundant equipment	Installation of three large fans where two are required during operation
Corrosion control	
Inhibitors	Injection of oil wells
Organic coatings	Coal tar on exterior of underground pipeline
	Paint on wooden furniture
	Topcoat on automobile—aesthetics and corrosion
	Zinc-rich paint on automobile
	Galvanized steel siding
Metallic coatings	Chrome-plated faucets—aesthetics and corrosion
Cathodic protection	Cathodic protection of underground pipelines
Technical support	Corrosion-resistant alloy development
	Materials selection
	Corrosion monitoring and control
Design	
Material of construction for structural integrity	Stainless steel for corrosive applications
	Stainless steel for high-temperature mechanical properties
Material of construction	High alloy to prevent corrosion products contamination, for example, drug industry
Corrosion allowance	Thicker wall for corrosion
Special processing for corrosion resistance	Stress relief, shot peening, special heat treatment (e.g., Al alloys) for corrosion
Insurance	Portion of premiums on policy to protect against loss because of corrosion (to cover charge of writing and administering policy, not protection amount)
Parts and equipment inventory	Pumps kept on hand for maintenance, for example, chemical plant inventory

Source: Ref 1

induced leak in an oil pipeline, with resulting loss of product and environmental contamination—can result in costly damage that is difficult to either assess or repair as well as massive legal penalties as "punative damage."

Sources of Information

Sources of information pertaining to corrosion and corrosion prevention are quite varied and include the following:

- Texts, reference books, and journals
- Videos and home study courses
- Software products
- Computerized databases

- Metals producers
- Trade associations and technical societies
- Consultants

Titles of several widely used textbooks on corrosion and a comprehensive bibliography relevant to corrosion are provided at the conclusion of this chapter (see the Selected References). Complementing print products are video training courses that are available from ASM International (formerly the American Society for Metals) and NACE International (formerly the National Association of Corrosion Engineers). Reference works that list corrodents in alphabetical order and give information for a variety of metallic and nonmetallic materials are particularly useful. Some provide only qualitative information such as "Resistant," "Unsatisfactory," etc., but others can give a more specific indication of the general corrosion rate. An example of the latter approach is *Corrosion Resistance Tables: Metals, Nonmetals, Coatings, Mortars, Plastics, Elastomers and Linings, and Fabrics* published by Marcel Dekker. In the *Corrosion Data Survey—Metals* and its companion volume, *Corrosion Data Survey—Nonmetals,* published by NACE International, the corrosion rate of a given material is plotted against temperature and corrodent concentration. Electronic versions of these products are also described in Chapter 8.

A number of technical journals on the subject of corrosion exist. Examples include *Corrosion,* and *Materials Performance,* published by NACE International, and *Oxidation of Metals,* published by Plenum Publishing Corp. Journals covering corrosion science and technology can also be found in numerous other metallurgical, surface engineering (coating), chemical, and electrochemical publications. The *Source Journals in Metals & Materials,* available in print or electronic format from Cambridge Scientific Abstracts (Beachwood, OH) lists dozens of journals devoted to corrosion.

Producers of metals and alloys publish considerable product data and educational information, as do trade associations such as the Nickel Development Institute, the Aluminum Association, the Copper Development Association, and the Specialty Steel Industry of North America. Addresses for these and other associations and societies are listed in the appendix to this chapter. Research organizations such as the LaQue Center for Corrosion Technology (Wrightsville Beach, NC) and the Electric Power Research Institute (Palo Alto, CA) also provide extensive corrosion information.

Several technical societies are involved with corrosion work. They serve as a source of technical literature, standards, reports, and software. They also sponsor technical symposia and have technical committees that cover a broad spectrum of corrosion problems. In the United States, the primary society devoted to corrosion is NACE Inter-

Table 4 NACE International technical committees

Committee	Activity
T-1	Corrosion control in petroleum production
T-2	Energy technology
T-3	Corrosion science and technology
T-5	Corrosion problems in the process industries
T-6	Protective coatings and linings
T-7	Corrosion by waters
T-8	Refining industry corrosion
T-9	Military, aerospace, and electronics equipment corrosion control
T-10	Underground corrosion control
T-11	Corrosion and deterioration of the infrastructure
T-14	Corrosion in the transportation industry

Table 5 ASTM committee G-1 on corrosion of metals

Subcommittee	Activity
G01.02	Terminology
G01.03	Computers in corrosion
G01.04	Atmospheric corrosion
G01.05	Laboratory corrosion tests
G01.06	Stress-corrosion cracking and corrosion fatigue
G01.07	Galvanic corrosion
G01.08	Corrosion of nuclear materials
G01.09	Corrosion in natural waters
G01.10	Corrosion in soils
G01.11	Electrochemical measurements in corrosion testing
G01.12	In-plant corrosion tests
G01.14	Corrosion of reinforcing steel
G01.99.01	Corrosion of implant materials

national. NACE was formed in 1943 with the aim of assisting the public and industry in the use of corrosion prevention and control to reduce the billions of dollars lost each year caused by corrosion. Table 4 lists NACE technical committees. NACE also sponsors a yearly international congress on corrosion.

ASTM (formerly the American Society for Testing and Materials) is also very active in the field of corrosion. The main committee is G-1 on corrosion of metals. Its scope is "the promotion of knowledge, the stimulation of research, the collection of engineering data, and the development of standard test methods, practices, guides, classifications, specifications and terminology relating to corrosion and methods for corrosion-protection of metals." A list of the subcommittees in G-1 is shown in Table 5.

Other societies having interests in corrosion are the American Institute of Mining, Metallurgical, and Petroleum Engineers; the American Petroleum Institute; the Electrochemical Society; the American Institute of Chemical Engineers; the American Welding Society; ASM International; the American Society of Mechanical Engineers; the Society for Protective Coatings (formerly the Steel Structures Painting Council); and SAE International (formerly the Society of Automotive Engineers). Most of these societies have symposia on corrosion at their various meetings.

Appendix: Addresses of Trade Associations and Technical Societies Involved with Corrosion

Aluminum Association, Inc.
900 19th St., NW
Suite 300
Washington, DC 20006

American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME)
345 E. 47th St., 14th Floor
New York, NY 10017

American Iron and Steel Institute (AISI)
1101 17th St., NW
Suite 1300
Washington, DC 20036-4700

American National Standards Institute (ANSI)
11 W. 42nd St., 13th Floor
New York, NY 10036

American Petroleum Institute (API)
1220 L St., NW
Washington, DC 20005

American Society of Mechanical Engineers (ASME)
345 E. 47th St.
New York, NY 10017

American Welding Society (AWS)
550 N.W. LeJeune Rd.
Miami, FL 33126

ASM International
9639 Kinsman Rd.
Materials Park, OH 44073-0002

ASTM
100 Barr Harbor Dr.
W. Conshohocken, PA 19428-2959

Canadian Institute of Mining, Metallurgy, and Petroleum (CIM)
Xerox Tower
Suite 2110
3400 de Maisonneuve Blvd., W.
Montreal, QC
Canada, H3Z 3B8

Canadian Standards Association (CSA)
178 Rexdale Blvd.
Rexdale, ON
Canada M9W 1R3

Copper Development Association (CDA)
260 Madison Ave.
New York, NY 10016

International Cadmium Association
12110 Sunset Hills Rd.
Suite 110
Reston, VA 22090

International Copper Association Ltd.
260 Madison Ave.
New York, NY 10016

International Lead Zinc Research Organization, Inc. (ILZRO)
2525 Meridian Parkway
P.O. Box 12036
Research Triangle Park, NC 27709

International Magnesium Association (IMA)
1303 Vincent Place
Suite 1
McLean, VA 22101

International Titanium Association (ITA)
1781 Folsom St.
Suite 100
Boulder, CO 80302-5714

Lead Industries Association, Inc.
295 Madison Ave.
New York, NY 10017

Materials Technology Institute of the Chemical Process Industries, Inc. (MTI)
1570 Fishinger Rd.
Columbus, OH 43221

NACE International
P.O. Box 218340
Houston, TX 77218-8340

National Institute of Standards and Technology (NIST)
Gaithersburg, MD 20899

Nickel Development Institute (NiDI)
214 King St., W.
Suite 510
Toronto, ON Canada M5H 3S6

SAE International
400 Commonwealth Dr.
Warrendale, PA 15096-0001

Society for the Advancement of Materials and Processing Engineering (SAMPE)
P.O. Box 2459
Covina, CA 91722

Specialty Steel Industry of North America (SSINA)
3050 K St., NW
Suite 400
Washington, DC 20007

Steel Founders' Society of America (SFSA)
Cast Metals Federation Building
455 State St.
Des Plaines, IL 60016

The Society for Protective Coatings (SSPC)
40 24th St.
6th Floor
Pittsburgh, PA 15222-4643

The Metallurgical Society (TMS-AIME)
420 Commonwealth Dr.
Warrendale, PA 15086-7514

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