CORROSION COSTS AND PREVENTIVE STRATEGIES IN THE UNITED STATES

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PURPOSE OF THIS STUDY

Previous studies have shown that corrosion is very costly and has a major impact on the economies of industrial nations. A 1975 benchmark study by Battelle-NBS pointed out the severe impact on the U.S. economy. The estimates based on the Battelle-NBS study are that the cost of corrosion in the United States alone was approximately $70 billion, which was 4.2 percent of the gross national product (GNP). A limited study in 1995, updating the 1975 figures estimated the total cost of corrosion at approximately $300 billion. However, that study did little more than apply a multiplication factor to the 1975 cost that was equivalent to the GNP growth from 1975 to 1995.

Through discussions between NACE International (The Corrosion Society) representatives, members of Congress, and the Department of Transportation (DOT), an amendment for the cost of corrosion was included in the Transportation Equity Act for the 21st Century (TEA-21), which was passed by the U.S. legislature in 1998. The amendment requested that a study be conducted in conjunction with an interdisciplinary team of experts from the fields of metallurgy, chemistry, economics, and others, as appropriate. Subsequently, the Federal Highway Administration (FHWA) initiated a systematic study to estimate the total metallic corrosion cost and to provide preventive strategies to minimize the impact of corrosion. In the period from 1999 to 2001, CC Technologies Laboratories, Inc. conducted the study in a cooperative agreement with FHWA and NACE International.

OBJECTIVES AND SCOPE

The primary objectives of this study were:

1. Develop an estimate of the total economic impact of metallic corrosion in the United States.
2. Identify national strategies to minimize the impact of corrosion.

The work to accomplish these objectives was conducted through the following main activities:

- Determination of the cost of corrosion based on corrosion control methods and services.
- Determination of the cost of corrosion for specific industry sectors.
- Extrapolation of individual sector costs to a national total corrosion cost.
- Assessment of barriers to progress and effective implementation of optimized corrosion control practices.
- Development of implementation strategies and recommendations for the realization of cost-savings.

APPROACH

A critical review of previous national studies was conducted. These studies have formed the basis for much of the current thinking regarding the corrosion costs to the various national economies. The earliest study was reported in 1949 by Uhlig, who estimated the total cost to the economy by summing materials and procedures related to corrosion control. The 1949 Uhlig report, which was the first to draw attention to the economic importance of corrosion, was followed in the 1970s by a number of studies in various countries, such as the United States, the United Kingdom, and Japan. The national study by Japan conducted in 1977 followed the Uhlig methodology. In the United States, Battelle-NBS estimated the total direct cost of corrosion using an economic input/output framework. The input/output method was adopted later by studies in two other nations, namely by Australia in 1983 and Kuwait in 1995. In the United Kingdom, a committee chaired by T.P. Hoar conducted a national study in 1970 using a method where the total cost was estimated by collecting data through interviews and surveys of targeted economic sectors.

Although the efforts of the above-referenced studies ranged from formal and extensive to informal and modest, all studies arrived at estimates of the total annual cost of corrosion that ranged from 1 to 5 percent of each country's GNP.

In the current study, two different approaches were taken to estimate the cost of corrosion. The first approach followed a method where the cost is determined by summing the costs for corrosion control methods and contract services. The costs of materials were obtained from various sources, such as the U.S. Department of Commerce Census Bureau, existing industrial surveys, trade organizations, industry groups, and individual companies. Data on corrosion control services, such as engineering services, research and testing, and education and training, were obtained primarily from trade organizations, educational institutions, and individual experts. These services included only contract services and not service personnel within the owner/operator companies.

The second approach followed a method where the cost of corrosion was first determined for specific industry sectors and then extrapolated to calculate a national total corrosion cost. Data collection for the sector-specific analyses differed significantly from sector to sector, depending on the availability of data and the form in which the data were available. In order to determine the annual corrosion costs for the reference year of 1998, data were obtained for various years in the last decade, but mainly for the years 1996 to 1999. For many of the sectors, the information is public and could be obtained from government reports and other publicly available documents. Discussions with industry experts provided the basis of the industry sector data collection. Corrosion cost information from the private industry sectors was more difficult to obtain. This stemmed from the fact that either the information was not readily available or could not be released because of company policies. In this case, information from publicly available industry records on operation and maintenance cost was obtained and, with the assistance of industry experts, corrosion-related costs were estimated.

The industry sectors for corrosion cost analyses represented approximately 27 percent of the U.S. economy gross domestic product (GDP), and were divided among five sector categories: infrastructure, utilities, transportation, production and manufacturing, and government.

The total cost of corrosion was estimated by determining the percentage of the GDP of those industry sectors for which direct corrosion costs were estimated and extrapolating these numbers to the total U.S. GDP. The direct cost used in this analysis was defined as the cost incurred by owners or operators of the structures, manufacturers of products, and suppliers of services.

The following elements were included in these costs:

- Cost of additional or more expensive material used to prevent corrosion damage.
- Cost of labor attributed to corrosion management activities.
- Cost of the equipment required because of corrosion-related activities.
- Loss of revenue due to disruption in supply of product.
- Cost of loss of reliability.
- Cost of lost capital due to corrosion deterioration.

For all industry sectors studied in this report, the direct corrosion costs were determined. For highway bridges, a life-cycle cost analysis was performed in which both the direct and indirect costs of corrosion were addressed. Indirect costs are incurred by individuals other than the owner or operator of the structure. Measuring and valuing indirect costs are generally complex assessments, and several different methods can be used to evaluate potential indirect costs. Owners or operators can be made to assume the costs through taxation, penalties, litigation, or payment for clean-up of spills. In such cases, these expenses become direct costs. In other cases, costs are assumed by the end-user or the overall economy. In the case of highway bridges, indirect costs, such as traffic delays during bridge maintenance, repair, and rehabilitation, are more difficult to turn over to the owner or operator of the structure. Once assigned a dollar value, the indirect costs are included in the cost of corrosion management of the structure and treated the same way as all other costs.

RESULTS

The two methods used in this study to estimate the cost of corrosion to the United States are based on: (1) the cost of corrosion control methods and services, and (2) corrosion costs of specific industry sectors. Past studies have indicated that the second method is more likely to incorporate the majority of the major corrosion-related costs and the first method is likely to miss the significant cost of corrosion management, the cost for direct services related to the owner/operator, and the cost of loss of capital due to corrosion.

Method 1 – Corrosion Control Methods and Services

With this method, the annual direct cost of corrosion was estimated by adding the cost of corrosion control methods and services. The corrosion control methods that were considered include protective coatings, corrosion-resistant alloys, corrosion inhibitors, polymers, anodes, cathodic protection, and corrosion control and monitoring equipment. Other contributors to the total annual direct cost that were reviewed in this report are contract services (i.e., non-owner/operator services), corrosion research and development, and education and training.

Protective Coatings – Both organic and metallic coatings are used to provide protection against corrosion of metallic substrates. These metallic substrates, mostly carbon steel, will corrode in the absence of the coating, resulting in the reduction of the service life of the steel part or component. The total annual cost for organic and metallic protective coatings is $108.6 billion (see details below).

According to the U.S. Department of Commerce Census Bureau, the total amount of organic coating material sold in the United States in 1997 was 5.56 billion L (1.47 billion gal), at a cost of $16.56 billion. The total sales can be broken down into architectural coatings, product Original Equipment Manufacturers (OEM) coatings, special-purpose coatings, and miscellaneous paint products. A portion of each of these was classified as corrosion coatings at a total estimate of $6.7 billion. It is important to note that raw material cost is only a portion of a total coating application project, ranging from 4 to 20 percent of the total cost of application. When applying these percentages to the raw materials cost, the total annual cost of coating application ranges from $33.5 billion to $167.5 billion (an average of $100.5 billion).

The most widely used metallic coating for corrosion protection is galvanizing, which involves the application of metallic zinc to carbon steel for corrosion control purposes. Hot-dip galvanizing is the most common process, and as the name implies, it consists of dipping the steel member into a bath of molten zinc. Information released by the U.S. Department of Commerce in 1998 stated that about 8.6 million metric tons of hot-dip galvanized steel and 2.8 million metric tons of electrolytic galvanized steel were produced in 1997. The total market for metallizing and galvanizing in the United States is estimated at $1.4 billion. This figure is the total material costs of the metal coating and the cost of processing, and does not include the cost of the carbon steel member being galvanized/metallized.

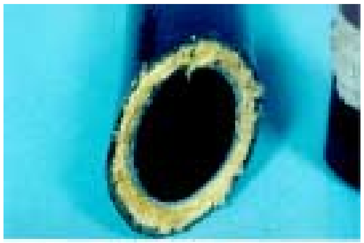
Corrosion-Resistant Alloys – Corrosion-resistant alloys are used where corrosive conditions prohibit the use of carbon steels and protective coatings do not provide sufficient protection or are economically not feasible. Examples of these alloys include stainless steels, nickel-base alloys, and titanium alloys. The total 1998 consumption cost of the corrosion-resistant metals and alloys is estimated at $7.7 billion (see details below).

According to U.S. Census Bureau statistics, 2.5 million metric tons of raw stainless steel were sold in the United States in 1997. With an estimated cost of $2.20 per kg ($1 per lb) for raw stainless steel, a total annual (1997) production cost of $5.5 billion was estimated. It is assumed that all production is for U.S. domestic consumption. The total consumption of stainless steel also includes imports, which account for more than 25 percent of the U.S. market. Thus, the total consumption of stainless steel can be estimated at $7.3 billion.

Where environments become particularly severe, nickel-base and titanium alloys are used. Nickel-base alloys are used extensively in the oil production and refinery and chemical process industries, where conditions are aggressive. Furthermore, there is increased use of these alloys in other industries, where high temperatures and/or severe corrosive conditions exist. With the average price for nickel-base alloys at $13 per kg in 1998, the total sales value in the United States was estimated at $285 million.

The primary use of titanium alloys is in the aerospace and military industry, where the high strength-to-weight ratio and resistance to high temperatures are properties of interest. However, titanium and its alloys are also corrosion-resistant to many environments and have, therefore, found application in oil production and refinery, chemical process, and pulp and paper industries. In 1998, it was estimated that 65 percent of titanium mill products were used for aerospace and 35 percent for non-aerospace applications. The total annual consumption price for titanium and titanium alloys for corrosion control applications is estimated at $150 million.

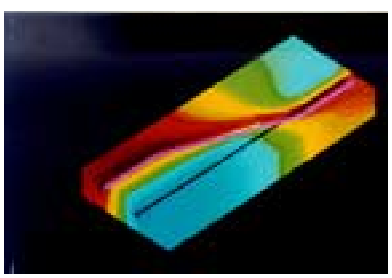
Corrosion Inhibitors – A corrosion inhibitor may be defined, in general terms, as a substance that when added in a small concentration to an environment effectively reduces the corrosion rate of a metal exposed to that environment. Inhibition is used internally with carbon steel pipes and vessels as an economic corrosion control alternative to stainless steels and alloys, coatings, or non-metallic composites. A particular advantage of corrosion inhibition is that it often can be implemented or changed *in situ* without disrupting a process. The major industries using corrosion inhibitors are oil and gas exploration and production, petroleum refining, chemical manufacturing, heavy manufacturing, water treatment, and the product additive industries. The total consumption of corrosion inhibitors in the United States has doubled from approximately $600 million in 1982 to nearly $1.1 billion in 1998.



Engineering Plastics and Polymers – In 1996, the plastics industry accounted for $274.5 billion in shipments. It is difficult to estimate the fraction of plastics used for corrosion control because, in many cases, plastics and composites are used for a combination of reasons, including corrosion control, light weight, economics, strength-to-weight ratio, and other unique properties. While corrosion control is a major market for many polymers, certain polymers are used mostly, if not exclusively, for corrosion control purposes. The significant markets for corrosion control by polymers include composites (primarily glass-reinforced thermosetting resins), polyvinyl chloride (PVC) pipe, polyethylene pipe, and fluoropolymers. The portion of polymers used for corrosion control is estimated at $1.8 billion.

Cathodic and Anodic Protection – The cost of cathodic and anodic protection of metallic structures subject to corrosion can be divided into the cost of materials and the cost of installation and operation. Industry data showed that the 1998 sales of hardware components totaled $146 million. The largest share of the cathodic protection market is taken up by sacrificial anodes at $60 million, of which magnesium has the greatest market share. Major markets for sacrificial anodes are the water heater market and the underground storage tank market. The cost of installation of the various cathodic protection components for underground structures varies significantly, depending on the location and the specific details of the construction. For 1998, the average total cost for installing cathodic protection systems was estimated at $0.98 billion (range: $0.73 billion to $1.22 billion). The total cost for replacing sacrificial anodes in water heaters and corrosion-related replacement of water heaters was estimated at $1.24 billion per year. Therefore, the total estimated cost for cathodic and anodic protection is $2.22 billion per year.

Corrosion Control Services – In the context of this report, services are defined as companies, organizations, and individuals that provide contract services for corrosion control purposes, while excluding corrosion-related activities that owners/operators may do in-house. By taking the NACE International membership as a basis, a total number of engineers and scientists that provide corrosion control services may be estimated. Based on a 16,000 membership in 1998 and the assumption that 25 percent provide contract corrosion control services, a total services cost of $1.2 billion was estimated.



Research and Development – Over the past few decades, less funding has been made available for corrosion-related research and development, which is significant in light of the costs of maintaining aging infrastructure. In fact, several government and corporate research laboratories have significantly reduced their corrosion research staff or have even closed down their research facilities. Moreover, less research and development funding has been available from either government or private sources. An estimate of an annual academic budget of $20 million was made, while no estimates were made for the cost of corporate corrosion-related research.

Education and Training – Corrosion-related education and training in the United States includes degree programs, certification programs, company in-house training, and general education and training. A few national universities offer courses in corrosion and corrosion control as part of their engineering curriculum. Professional organizations such as NACE International and SSPC (The Society for Protective Coatings) offer courses and certification programs that range from basic corrosion to coating inspector to cathodic protection specialist. NACE International offers the broadest range of courses and manages an extensive certification program. In 1998, NACE held 172 courses with more than 3,000 students, conducted multiple seminars, and offered publications, at a total cost of $8 million.

Summary – A total annual direct cost of corrosion by summing the costs of corrosion control methods and services was estimated at $121 billion, which is 1.38 percent of the U.S. GDP of $8.79 trillion in 1998. The largest portion (88.3 percent) of this cost is the organic coatings group at $107.2 billion. Notably, the categories of Research and Development and Education and Training indicated unfavorably low numbers.

Method 2 – Industry Sector Analysis

In this study, the U.S. economy was divided into five sector categories and 26 sectors, as follows:

Infrastructure:	Highway Bridges Gas and Liquid Transmission Pipelines Waterways and Ports Hazardous Materials Storage Airports Railroads
Utilities:	Gas Distribution Drinking Water and Sewer Systems Electrical Utilities Telecommunications
Transportation:	Motor Vehicles Ships Aircraft Railroad Cars Hazardous Materials Transport
Production and Manufacturing:	Oil and Gas Exploration and Production Mining Petroleum Refining Chemical, Petrochemical, and Pharmaceutical Pulp and Paper Agricultural Food Processing Electronics Home Appliances
Government:	Defense Nuclear Waste Storage

The cost of corrosion was estimated for each of the above categories. When summed, the total annual cost of corrosion for the industry sectors examined was $137.9 billion. The breakdown of these costs among the five sector categories is given in figure 1. Not all industries were examined in this study; therefore, the total economic impact on the U.S. economy would naturally be greater than the $137.9 billion given here.

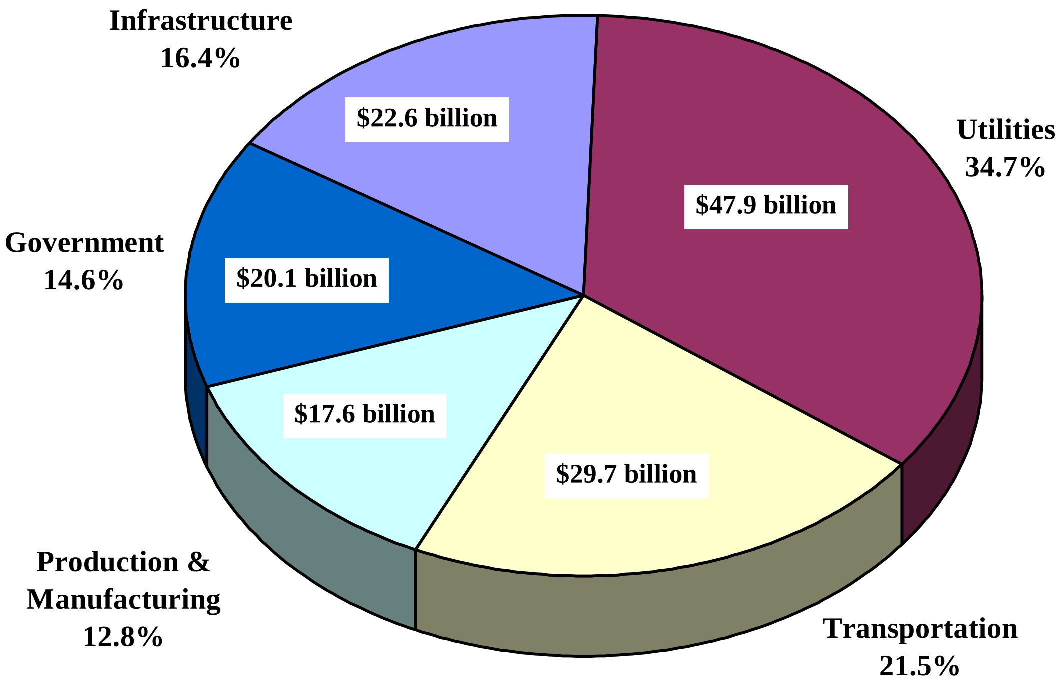
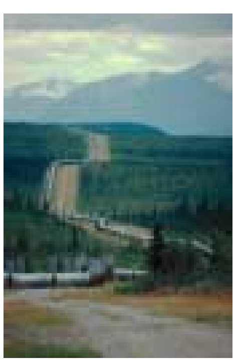


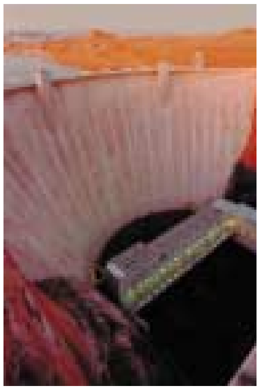
Figure 1. Cost of corrosion in sector categories analyzed in this study (total $137.9 billion/year).

Infrastructure – The U.S. infrastructure and transportation system allows for a high level of mobility and freight activity for the nearly 270 million residents and 7 million business establishments. In 1997, more than 230 million motor vehicles, ships, airplanes, and railroad cars were used on 6.4 million km (4 million mi) of highways, railroads, airports, and waterways. Pipelines and storage tanks are part of the infrastructure as well. The annual direct cost of corrosion in the infrastructure category is estimated at $22.6 billion.

Highway Bridges: There are 583,000 bridges in the United States (1998). Of this total, 200,000 bridges are steel, 235,000 are conventional reinforced concrete, 108,000 bridges are constructed using prestressed concrete, and the balance is made using other materials of construction. Approximately 15 percent of the bridges are structurally deficient, primarily due to corrosion of steel and steel reinforcement. The annual direct cost of corrosion for highway bridges is estimated at $8.3 billion, consisting of $3.8 billion to replace structurally deficient bridges over the next 10 years, $2.0 billion for maintenance and cost of capital for concrete bridge decks, $2.0 billion for maintenance and cost of capital for concrete substructures (minus decks), and $0.5 billion for maintenance painting of steel bridges. Life-cycle analysis estimates indirect costs to the user due to traffic delays and lost productivity at more than 10 times the direct cost of corrosion maintenance, repair, and rehabilitation.

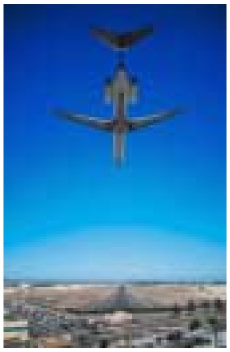


Gas and Liquid Transmission Pipelines: There are more than 528,000 km (328,000 mi) of natural gas transmission and gathering pipelines, 119,000 km (74,000 mi) of crude oil transmission and gathering pipelines, and 132,000 km (82,000 mi) of hazardous liquid transmission pipelines. For all natural gas pipeline companies, the total investment in 1998 was $63.1 billion, from which a total revenue of $13.6 billion was generated. For liquid pipeline companies, the investment was $30.2 billion, from which a revenue of $6.9 billion was generated. At an estimated replacement cost of $643,800 per km ($1,117,000 per mi), the asset replacement value of the transmission pipeline system in the United States is $541 billion; therefore, a significant investment is at risk, with corrosion being the primary factor in controlling the life of the asset. The average annual corrosion-related cost is estimated at $7.0 billion, which can be divided into the cost of capital (38 percent), operation and maintenance (52 percent), and failures (10 percent).



Waterways and Ports: In the United States, 40,000 km (25,000 mi) of commercial navigable waterways serve 41 States, including all States east of the Mississippi River. Hundreds of locks facilitate travel along these waterways. In January 1999, 135 of the 276 locks had exceeded their 50-year design life. U.S. ports play an important role in connecting waterways, railroads, and highways. The Nation's ports include 1,914 deepwater ports (seacoast and Great Lakes) and 1,812 ports along inland waterways. Corrosion is typically found on piers and docks, bulkheads and retaining walls, mooring structures, and navigational aids. There is no formal tracking of corrosion costs for these structures. Based on figures obtained from the U.S. Army Corps of Engineers and the U.S. Coast Guard, an annual corrosion cost of $0.3 billion could be estimated. It should be noted that this is a low estimate since the corrosion costs of harbor and other marine structures are not included.

Hazardous Materials Storage: The United States has approximately 8.5 million regulated and non-regulated aboveground storage tanks (ASTs) and underground storage tanks (USTs) for hazardous materials (HAZMAT). While these tanks represent a significant investment and good maintenance practices would be in the best interest of the owners, Federal and State environmental regulators are concerned with the environmental impact of spills from leaking tanks. The U.S. Environmental Protection Agency set a December 1998 deadline for UST owners to comply with requirements for corrosion control on all tanks, as well as overfill and spill protection. In case of non-compliance, tank owners face considerable costs related to clean-up and penalties. The total annual direct cost of corrosion for HAZMAT storage is $7.0 billion, broken down into $4.5 billion for ASTs and $2.5 billion for USTs.

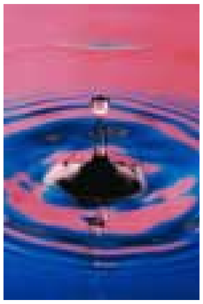


Airports: The United States has the world's most extensive airport system, which is essential to national transportation and the U.S. economy. According to 1999 Bureau of Transportation Statistics data, there were 5,324 public-use airports and 13,774 private-use airports in the United States. A typical airport infrastructure is complex, and components that might be subject to corrosion include the natural gas distribution system, jet fuel storage and distribution system, deicing storage and distribution system, vehicle fueling systems, natural gas feeders, dry fire lines, parking garages, and runway lighting. Generally, each of these systems is owned or operated by different organizations or companies; therefore, the impact of corrosion on an airport as a whole is not known or documented. However, the airports do not have any specific corrosion-related problems that are not described elsewhere in this report.

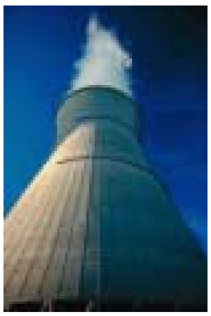
Railroads: In 1997, there were nine Class I freight railroads (railroads with operating revenues of more than $256.4 million). These railroads accounted for 71 percent of the industry's 274,399 km (170,508 mi) operated. There were 35 regional railroads (those with operating revenues between $40 million and $256.4 million and/or operating at least 560 km (350 mi) of railroad). The regional railroads operated 34,546 km (21,466 mi). Finally, there were 513 local railroads operating over 45,300 km (28,149 mi) of railroad. The elements that are subject to corrosion include metal members, such as rail and steel spikes; however, corrosion damage to railroad components is either limited or goes unreported. Hence, an accurate estimate of the corrosion cost could not be determined.

Utilities – Utilities supply gas, water, electricity, and telecommunications. All utility companies combined spent $42.3 billion on capital goods in 1998, broken down into $22.4 billion for structures and $19.9 billion for equipment. The total annual direct cost of corrosion in the utilities category is estimated to be $47.9 billion.

Gas Distribution: The natural gas distribution system includes 2,785,000 km (1,730,000 mi) of relatively small-diameter, low-pressure piping, which is broken down into 1,739,000 km (1,080,000 mi) of distribution main and 1,046,000 km (650,000 mi) of services. There are approximately 55 million services in the distribution system. A large percentage of the mains (57 percent) and services (46 percent) are made of steel, cast iron, or copper, which are subject to corrosion. The total annual direct cost of corrosion was estimated at approximately $5.0 billion.



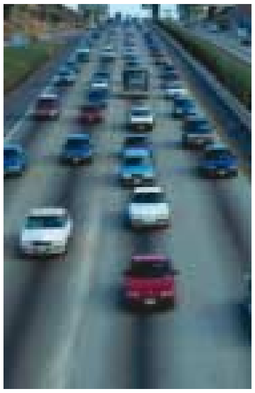
Drinking Water and Sewer Systems: According to the American Waterworks Association (AWWA) industry database, there are approximately 1,483,000 km (876,000 mi) of municipal water piping in the United States. This number is not exact, since most water utilities do not have complete records of their piping system. The sewer system consists of approximately 16,400 publicly owned treatment facilities that release some 155 million m^3 (41 billion gal) of wastewater per day (1995). The total annual direct cost of corrosion for the Nation's drinking water and sewer systems was estimated at $36.0 billion. This cost consists of the cost of replacing aging infrastructure and the cost of unaccounted-for water through leaks, corrosion inhibitors, internal mortar linings, external coatings and cathodic protection.



Electrical Utilities: The electrical utilities industry is a major provider of energy in the United States. The total amount of electricity sold in the United States in 1998 was 3.24 trillion GWh at a cost to consumers of $218 billion. Electricity generation plants can be divided into seven generic types: fossil fuel, nuclear, hydroelectric, cogeneration, geothermal, solar, and wind. The majority of electric power in the United States is generated by fossil fuel and nuclear supply systems. The total annual direct cost of corrosion in the electrical utilities industry in 1998 is estimated at $6.9 billion, with the largest amounts for nuclear power at $4.2 billion and fossil fuel at $1.9 billion, and smaller amounts for hydraulic and other power at $0.15 billion, and transmission and distribution at $0.6 billion.

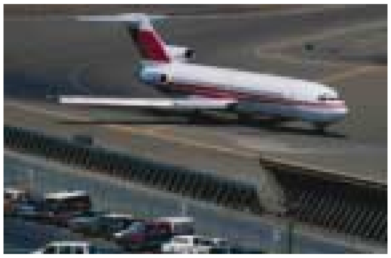
Telecommunications: The telecommunications infrastructure includes hardware such as electronics, computers, and data transmitters, as well as equipment shelters and the towers used to mount antennas, transmitters, receivers, and television and telephone systems. According to the U.S. Census Bureau, the total value of shipments for communications equipment in 1999 was $84 billion. An important factor for corrosion cost is the additional cost of protecting of towers and shelters, such as painting and galvanizing. In addition, corrosion of buried copper grounding beds and galvanic corrosion of the grounded steel structures contribute to the corrosion cost. For this sector, no corrosion cost was determined because of the lack of information on this rapidly changing industry. Many components are being replaced before physically failing because their technology becomes obsolete in a short period of time.

Transportation – The transportation category includes vehicles and equipment, such as motor vehicles, aircraft, railroad cars, and hazardous materials transport, which make use of U.S. highways, waterways, railroads, and airports. The annual cost of corrosion in the transportation category is estimated at $29.7 billion.



Motor Vehicles: U.S. consumers, businesses, and government organizations own more than 200 million registered motor vehicles. Assuming the average value of an automobile is $5,000, the total investment Americans have made in motor vehicles can be estimated at $1 trillion. Since the 1980s, car manufacturers have increased the corrosion-resistance of vehicles by using corrosion-resistant materials, employing better manufacturing processes, and designing corrosion-resistant vehicles. Although significant progress has been made, further improvement can be achieved in corrosion resistance of individual components. The total annual direct cost of corrosion is estimated at $23.4 billion, which is broken down into the following three components: (1) increased manufacturing costs due to corrosion engineering and the use of corrosion-resistant materials ($2.56 billion per year), (2) repairs and maintenance necessitated by corrosion ($6.45 billion per year), and (3) corrosion-related depreciation of vehicles ($14.46 billion per year).

Ships: The U.S. flag fleet consists of: the Great Lakes with 737 vessels at 100 billion ton-km (62 billion ton-mi), inland with 33,668 vessels at 473 billion ton-km (294 billion ton-mi), ocean with 7,014 vessels at 563 billion ton-km (350 billion ton-mi), recreational with 12.3 million boats, and cruise ship with 122 boats serving North American ports (5.4 million passengers). The total annual direct cost of corrosion to the U.S. shipping industry is estimated at $2.7 billion. This cost is broken down into costs associated with new ship construction ($1.1 billion), maintenance and repairs ($0.8 billion), and corrosion-related downtime ($0.8 billion).



Aircraft: In 1998, the combined commercial aircraft fleet operated by U.S. airlines was more than 7,000 airplanes. At the start of the jet age (1950s to 1960s), little or no attention was paid to corrosion and corrosion control. One of the concerns is the continued aging of the airplanes beyond the 20-year design life. Only the most recent designs (e.g., Boeing 777 and late-version 737) have incorporated significant improvements in corrosion prevention and control in design and manufacturing. The total annual direct cost of corrosion to the U.S. aircraft industry is estimated at $2.2 billion, which includes the cost of design and manufacturing ($0.2 billion), corrosion maintenance ($1.7 billion), and downtime ($0.3 billion).

Railroad Cars: In 1998, 1.3 million freight cars and 1,962 passenger cars were operated in the United States. Covered hoppers (28 percent) and tanker cars (18 percent) make up the largest segment of the freight car fleet. The type of commodities transported range from coal (largest volume) to chemicals, motor vehicles, farm products, food products, and ores and minerals. Railroad cars suffer from both external and internal corrosion. The total annual direct cost of corrosion is estimated at $0.5 billion, broken down into external coatings ($0.25 billion) and internal coatings and linings ($0.25 billion).

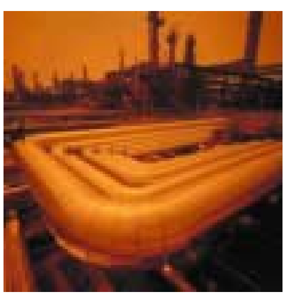
Hazardous Materials Transport: According to U.S. Department of Transportation, there are approximately 300 million hazardous materials shipments of more than 3.1 billion metric tons annually in the United States. Bulk transport over land includes shipping by tanker truck and rail car, and by special containers on vehicles. Over water, ships loaded with specialized containers, tanks, and drums are used. In small quantities, hazardous materials require specially designed packaging for truck and air shipment. The total annual direct cost of corrosion for hazardous materials transport is more than $0.9 billion. The elements of the annual corrosion cost include the cost of transporting vehicles ($0.4 billion per year), specialized packaging ($0.5 billion per year), and the direct and indirect costs of accidental releases and corrosion-related transportation incidents.

Production and Manufacturing – This category includes industries that produce and manufacture products of crucial importance to the U.S. economy and the standard of living in the United States. These include oil production, mining, petroleum refining, chemical and pharmaceutical production, and agricultural and food production. The total annual direct cost of corrosion for production and manufacturing was estimated at $17.6 billion.

Oil and Gas Exploration and Production: Domestic oil and gas production can be considered to be a stagnant industry, because most of the significant available onshore oil and gas reserves have been exploited. Oil production in the United States in 1998 consisted of 3.04 billion barrels. The significant recoverable reserves left to be discovered and produced are probably limited to less convenient locations, such as in deep water offshore, remote arctic locations, and difficult-to-manage reservoirs with unconsolidated sands. The total annual direct cost of corrosion in the U.S. oil and gas production industry is estimated at $1.4 billion, broken down into $0.6 billion for surface piping and facility costs, $0.5 billion in downhole tubing expenses, and $0.3 billion in capital expenditures related to corrosion.

Mining: In the mining industry, corrosion is not considered to be a significant problem. There is a general consensus that the life-limiting factors for mining equipment are wear and mechanical damage rather than corrosion. Maintenance painting, however, is heavily relied upon to prevent corrosion, with an annual estimated expenditure for the coal mining industry of $0.1 billion.

Petroleum Refining: The U.S. refineries represent approximately 23 percent of the world's petroleum production, and the United States has the largest refining capacity in the world, with 163 refineries. In 1996, U.S. refineries supplied more than 18 million barrels per day of refined petroleum products. The total annual direct cost of corrosion is estimated at $3.7 billion. Of this total, maintenance-related expenses are estimated at $1.8 billion, vessel turnaround expenses at $1.4 billion, and fouling costs are approximately $0.5 billion annually.

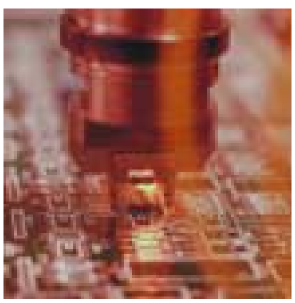


Chemical, Petrochemical, and Pharmaceutical: The chemical industry includes those manufacturing facilities that produce bulk or specialty compounds by chemical reactions between organic and/or inorganic materials. The petrochemical industry includes those manufacturing facilities that create substances from raw hydrocarbon materials such as crude oil and natural gas. The pharmaceutical industry formulates, fabricates, and processes medicinal products from raw materials. The total annual direct cost of corrosion for this industry sector is estimated at $1.7 billion per year (8 percent of total capital expenditures). No calculation was made for the indirect costs of production outages or indirect costs related to catastrophic failures. The costs of operation and maintenance related to corrosion were not readily available; estimating these costs would require detailed study of data from individual companies.

Pulp and Paper: The $165 billion pulp, paper, and allied products industry supplies the United States with approximately 300 kg of paper per person per year. More than 300 pulp mills and more than 550 paper mills support its production. The total annual direct cost of corrosion is estimated at $6.0 billion, with the majority of this cost in the paper and paperboard industry, and calculated as a fraction of the maintenance costs. No information was found to estimate the corrosion costs related to the loss of capital.

Agricultural: Agricultural operations are producing livestock and crops. According to the National Agricultural Statistics Service, there are approximately 1.9 million farms in the United States. Based on the 1997 Farm Census, the total value of farm machinery and equipment is approximately $15 billion per year. The two main reasons for replacing machinery or equipment include upgrading old equipment and replacement because of wear and corrosion. Discussions with experts in this industrial sector resulted in an estimate of corrosion costs in the range of 5 percent to 10 percent of the value of all new equipment. Therefore, the total annual direct cost of corrosion in the agricultural production industry is estimated at $1.1 billion.

Food Processing: The food processing industry is one of the largest manufacturing industries in the United States, accounting for approximately 14 percent of the total U.S. manufacturing output. Sales for food processing companies totaled $265.5 billion in 1999. Because of food quality requirements, stainless steel is widely used. Assuming that the stainless steel consumption and cost in this industry are entirely attributed to corrosion, a total annual direct cost of corrosion is estimated at $2.1 billion. This cost includes stainless steel usage for beverage production, food machinery, cutlery and utensils, commercial and restaurant equipment, appliances, aluminum cans, and the use of corrosion inhibitors.



Electronics: Corrosion in electronic components manifests itself in several ways, and computers, integrated circuits, and microchips are being exposed to a variety of environmental conditions. Corrosion in electronic components is insidious and cannot be readily detected; therefore, when corrosion failure occurs, it is often dismissed as just a failure and the part or component is replaced. Particularly in the case of consumer electronics, devices would become technologically obsolete long before corrosion-induced failures would occur. However, in capital-intensive industries with significant investments in durable equipment with a considerable number of electronic components, such as the defense industry and the airline industry, there is a tendency to keep the equipment for longer periods of time and corrosion is likely to become an issue. Although the cost of corrosion in the electronics sector could not be estimated, it has been suggested that a significant part of all electric component failures is caused by corrosion.

Home Appliances: The appliance industry is one of the largest consumer products industries. For practical purposes, two categories of appliances are distinguished: "Major Home Appliances" and "Comfort Conditioning Appliances." In 1999, 70.7 million major home appliances and 49.5 million comfort conditioning appliances were sold in the United States, for a total of 120.2 million appliances. The cost of corrosion in home appliances includes the cost of purchasing replacement appliances because of premature failures due to corrosion. For water heaters alone, the replacement cost was estimated at $460 million per year, using a low estimate of 5 percent of replacement being corrosion-related. The cost of internal corrosion protection for all appliances includes the use of sacrificial anodes ($780 million per year), corrosion-resistant materials (no cost estimate), and internal coatings (no cost estimate). The cost of external corrosion protection using coatings was estimated at $260 million per year. Therefore, the estimated total annual direct cost of corrosion in home appliances is at least $1.5 billion.

Government – Federal, State, and local governments had a 1998 GDP of approximately $1.1 trillion ($360 billion Federal, $745 billion State and local). While the government owns and operates significant assets under various departments, the U.S. Department of Defense (DOD) was selected for analysis because of its significant impact on the U.S. economy. A second analyzed government sector is nuclear waste storage.

Defense: Corrosion of military equipment and facilities has been, for many years, a significant and ongoing problem. The corrosion-related problems are becoming more prominent as the acquisition of new equipment is decreasing and the reliability required of aging systems is increasing. The data provided by the military services (Army, Air Force, Navy, and Marine Corps) indicate that corrosion is potentially the number one cost driver in life-cycle costs. The total annual direct cost of corrosion incurred by the military services for systems and infrastructure is approximately $20 billion.

Nuclear Waste Storage: Nuclear wastes are generated from spent nuclear fuel, dismantled nuclear weapons, and products such as radio pharmaceuticals. The most important design item for the safe storage of nuclear waste is effective shielding of radiation. Corrosion is an important issue in the design of the casks used for permanent storage, which have a design life of several thousand years. A 1998 total life-cycle cost analysis by the U.S. Department of Energy for the permanent disposal of nuclear waste in Yucca Mountain, Nevada, estimated the total repository cost by the construction phase (2002) at $4.9 billion with an average annual cost (from 1999 to 2116) of $205 million. Of this cost, $42.2 million is corrosion-related.

Summary of Total Cost – The cost of corrosion was estimated for the individual economic sectors discussed above. The total cost due to the impact of corrosion for the analyzed sectors was $137.9 billion per year (see table 1). Since not all economic sectors were examined, the sum of the estimated costs for the analyzed sectors does not represent the total cost of corrosion for the entire U.S. economy. By estimating the percentage of U.S. GDP for the sectors for which corrosion costs were determined and by extrapolating the figures to the entire U.S. economy, a total cost of corrosion of $276 billion was estimated (see figure 2). This value shows that the impact of corrosion is approximately 3.1 percent of the Nation's GDP (see figure 3). This cost is considered to be a conservative estimate since only well-documented costs were used in this study. Other costs of corrosion were discussed (not estimated) in the individual sectors, but were left out due to lack of documentation.

The indirect cost of corrosion is conservatively estimated to be equal to the direct cost; giving a total direct plus indirect cost of $552 billion (i.e., 6 percent of the GDP). Evidence of the large indirect corrosion costs are: (1) lost productivity because of outages, delays, failures, and litigation, (2) taxes and overhead on the cost of the corrosion portion of goods and services, and (3) indirect costs of non-owner/operator activities.

Table 1. Summary of estimated direct cost of corrosion for industry sectors analyzed in this study.

CATEGORY	**INDUSTRY SECTORS**	**APPENDIX**	**ESTIMATED DIRECT COST OF CORROSION PER SECTOR**	
			$ x billion	**percent***
Infrastructure (16.4% of total)	Highway Bridges	D	8.3	37
	Gas and Liquid Transmission Pipelines	E	7.0	27
	Waterways and Ports	F	0.3	1
	Hazardous Materials Storage	G	7.0	31
	Airports	H	**	**
	Railroads	I	**	**
		SUBTOTAL	**$22.6**	**100%**
Utilities (34.7% of total)	Gas Distribution	J	5.0	10
	Drinking Water and Sewer Systems	K	36.0	75
	Electrical Utilities	L	6.9	14
	Telecommunications	M	**	**
		SUBTOTAL	**$47.9**	**100%**

Table1. Summary of estimated direct cost of corrosion for industry sectors analyzed in the study (continued).

CATEGORY	**INDUSTRY SECTORS**	**APPENDIX**	**ESTIMATED DIRECT COST OF CORROSION PER SECTOR**	
			$ x billion	**percent***
Transportation (21.5% of total)	Motor Vehicles	N	23.4	79
	Ships	O	2.7	9
	Aircraft	P	2.2	7
	Railroad Cars	Q	0.5	2
	Hazardous Materials Transport	R	0.9	3
		SUBTOTAL	**$29.7**	**100%**
Production and Manufacturing (12.8% of total)	Oil and Gas Exploration and Production	S	1.4	8
	Mining	T	0.1	1
	Petroleum Refining	U	3.7	21
	Chemical, Petrochemical, and Pharmaceutical	V	1.7	10
	Pulp and Paper	W	6.0	34
	Agricultural	X	1.1	6
	Food Processing	Y	2.1	12
	Electronics	Z	**	**
	Home Appliances	AA	1.5	9
		SUBTOTAL	**$17.6**	**100%**
Government (14.6% of total)	Defense	BB	20.0	99.5
	Nuclear Waste Storage	CC	0.1	0.5
		SUBTOTAL	**$20.1**	**100%**
		TOTAL	**$137.9**	

*Individual values do not add up to 100% because of rounding.
**Corrosion costs not determined.

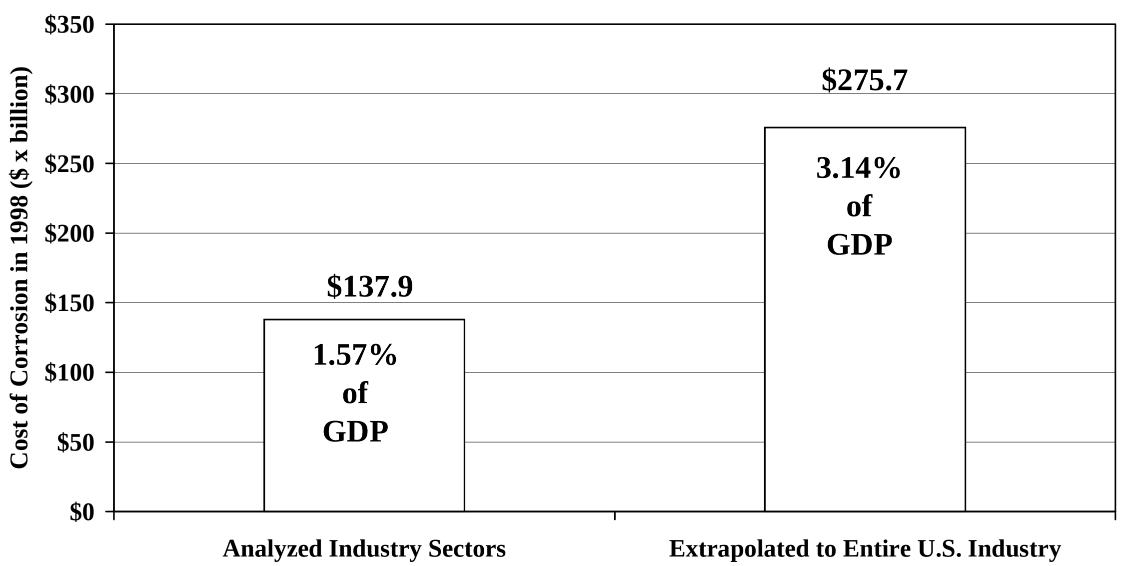


Figure 2. Comparison of total annual direct corrosion costs in analyzed sectors with total annual direct corrosion costs extrapolated to the entire U.S. industry.

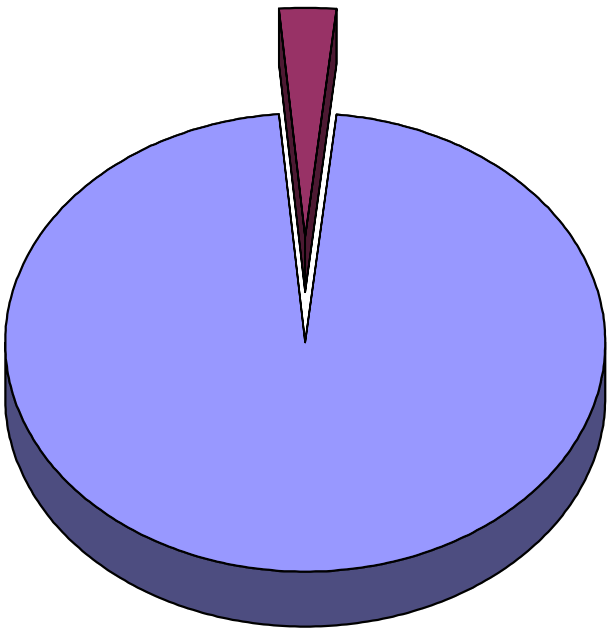


Figure 3. Impact of corrosion on the U.S. economy.

PREVENTIVE STRATEGIES

The current study showed that technological changes have provided many new ways to prevent corrosion and the improved use of available corrosion management techniques. However, better corrosion management can be achieved using preventive strategies in non-technical and technical areas. These preventive strategies include: (1) increase awareness of significant corrosion costs and potential cost-savings, (2) change the misconception that nothing can be done about corrosion, (3) change policies, regulations, standards, and management practices to increase corrosion cost-savings through sound corrosion management, (4) improve education and training of staff in the recognition of corrosion control, (5) implement advanced design practices for better corrosion management, (6) develop advanced life prediction and performance assessment methods, and (7) improve corrosion technology through research, development, and implementation.

While corrosion management has improved over the past several decades, the United States is still far from implementing optimal corrosion control practices. There are significant barriers to both the development of advanced technologies for corrosion control and the implementation of those technological advances. In order to realize the savings from reduced costs of corrosion, changes are required in three areas: (1) the policy and management framework for effective corrosion control, (2) the science and technology of corrosion control, and (3) the technology transfer and implementation of effective corrosion control. The policy and management framework is crucial because it governs the identification of priorities, the allocation of resources for technology development, and the operation of the system.

Incorporating the latest corrosion strategies requires changes in industry management and government policies, as well as advances in science and technology. It is necessary to engage a larger constituency comprised of the primary stakeholders, government and industry leaders, the general public, and consumers. A major challenge involves the dissemination of corrosion awareness and expertise that are currently scattered throughout government and industry organizations. In fact, there is no focal point for the effective development, articulation, and delivery of corrosion cost-savings programs.

Therefore, the following recommendations are made:

1. Form a Committee on Corrosion Control and Prevention of the National Research Council.
2. Develop a national focus on corrosion control and prevention.
3. Improve policies and corrosion management.
4. Accomplish technological advances for corrosion-savings.
5. Implement effective corrosion control.

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