THE WORLD
CORROSION
ORGANIZATION

Global Needs for Knowledge Dissemination, Research, and Development in Materials Deterioration and Corrosion Control

By

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in cooperation with
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Foreword

Corrosion has been the subject of scientific study for more than 150 years. It is a naturally occurring phenomenon commonly defined as the deterioration of a material (usually a metal) or its properties because of a reaction with its environment. Like other natural hazards such as earthquakes or severe weather disturbances, corrosion can cause dangerous and expensive damage to everything from pipelines, bridges, and public buildings to vehicles, water and wastewater systems, and even home appliances. Unlike weather-related disasters, however, there are time-proven methods to prevent and control corrosion that can reduce or eliminate its impact on public safety, the economy, and the environment.

The science of corrosion prevention and control is highly complex, exacerbated by the fact that corrosion takes many different forms and is affected by numerous outside factors. Corrosion professionals must understand the effects of environmental conditions such as soil resistivity, humidity, and exposure to salt water on various types of materials; the type of product to be processed, handled, or transported; required lifetime of the structure or component; proximity to corrosion-causing phenomena such as stray current from rail systems; appropriate mitigation methods; and other considerations before determining the specific corrosion problem and specifying an effective solution.

With its many forms, causes, and associated prevention methods, corrosion obviously is highly complex and requires extensive expertise and significant resources to control. The 2001 U.S. Federal Highway Administration-funded cost of corrosion study, "Corrosion Costs and Preventive Strategies in the United States,"[1] determined the annual direct cost of corrosion to be a staggering $276 billion—or 3.1% of the gross domestic product (GDP). Other studies done in China, Japan, the U.K., and Venezuela showed similar to even more costly results, leading to an estimated worldwide direct cost exceeding $1.8 trillion. Corrosion is so prevalent and takes so many forms that its occurrence and associated costs never will be completely eliminated; however, all studies estimate that 25 to 30% of annual corrosion costs could be saved if optimum corrosion management practices were employed.

A critical component to obtaining a thorough understanding of the science and prevention of corrosion is knowledge sharing between individuals and societies throughout the world. A serious corrosion problem in one location, such as failure of a ship hull or underground gas pipeline, may have already been solved by colleagues in another part of the world. This urgent need for global collaboration has led to the establishment of the leading entity for raising public awareness of corrosion, identifying best practices, providing expertise, and establishing global standards—the World Corrosion Organization (WCO).

Founded in 2006 by the Australasian Corrosion Association (ACA), the Chinese Society for Corrosion and Protection (CSCP), the European Federation of Corrosion (EFC), and NACE International–The Corrosion Society, the WCO is an international association of societies and organizations involved with corrosion management and control. WCO members meet on a regular basis to work on important initiatives to minimize the effect of corrosion in every country. To help achieve its goals, the WCO recently applied for acceptance as a nongovernmental organization (NGO) within the United Nations.

The WCO has a major role in ensuring that governments, industry, academia, and the general public understand that by following appropriate strategies and obtaining sufficient resources for corrosion programs, the best engineering practices can be achieved. The payoff includes increased public safety, reliable performance, maximized asset life, environmental protection, and more cost-effective operations in the long run.

1 Introduction

Corrosion has a huge economic and environmental impact on virtually all facets of the world's infrastructure, from highways, bridges, and buildings to oil and gas, chemical processing, and water and wastewater systems (Figure 1). In addition to causing severe damage and threats to public safety, corrosion disrupts operations and requires extensive repair and replacement of failed assets. The annual cost of corrosion worldwide is estimated to exceed $U.S.1.8 trillion,[2] which translates to 3 to 4% of the Gross Domestic Product (GDP) of industrialized countries.

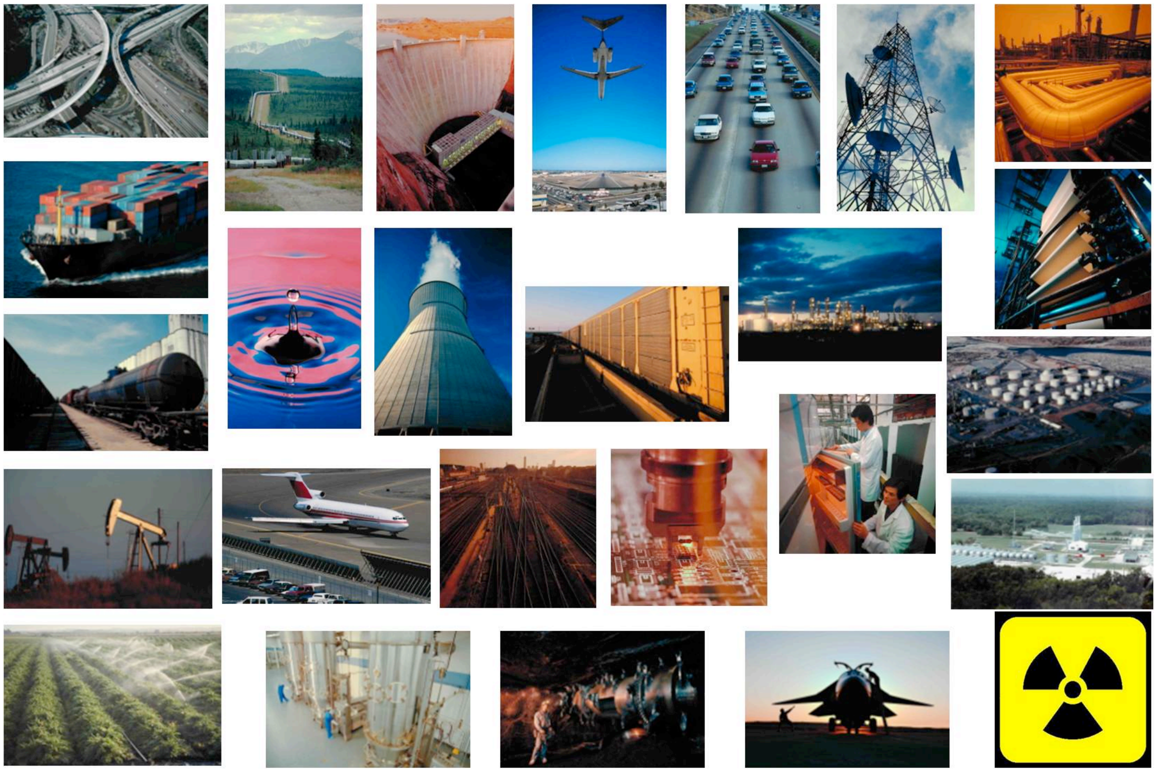

Figure 1: Areas that depend on reliable corrosion control.[3]

Fortunately, there are highly experienced corrosion professionals using innovative and long-proven technologies who can effectively control the effects of corrosion when given the proper resources. However, many decision-makers in industry and government do not understand the consequences or extent of corrosion and how critical it is to control it. They also do not appreciate the need for ongoing research and development (R&D) to further reduce the effects of corrosion on people, assets, and the environment.

This study demonstrates the need to educate the public on the importance of corrosion control, including R&D efforts into such areas as materials development and selection, innovative surface protection systems, and condition-based monitoring using sensors and remote data collection methods. Global standards are also needed to ensure compliance with best practices and share knowledge on effective corrosion control methodologies throughout the world.

The World Corrosion Organization (WCO) was founded so that corrosion associations and societies could join together to fight corrosion on a global basis. With 27 member organizations representing more than 50,000 corrosion scientists, engineers, and technicians from all over the world, the WCO is promoting education and training, technology exchange, and general corrosion awareness for the benefit of all society.

The WCO has the following primary goals as part of its strategic plan:

- Goal #1: To raise public awareness of corrosion and corrosion mitigation.
- Goal #2: To identify best practices in corrosion management.
- Goal #3: To facilitate the provision of corrosion expertise to governments, industries, and communities.
- Goal #4: To normalize corrosion-related standards worldwide.

Following are some of the activities being pursued as part of each goal:

Goal #1

- Establish a World Corrosion Awareness Day.
- Establish and maintain a public relations campaign from the WCO Web site: www.corrosion.org, with links to videos, reports, and other useful information from the various corrosion organizations.
- Implement a WCO Affiliate Organization Program.
- Encourage the involvement of the entire community in corrosion management.

Goal #2

- Work in conjunction with the International Corrosion Council (ICC) to encourage governments and industries to fund corrosion research.
- Encourage governments to provide financial incentives to industries to develop and implement corrosion mitigation programs.
- Develop and maintain a worldwide library of best practices.
- Emphasize the development of corrosion management practices focused on protection of the environment.

Goal #3

- Work with the ICC to establish links to worldwide directories of corrosion expertise and basic data.

Goal #4

- Harmonize existing corrosion standards.
- Actively contribute to the International Organization for Standardization (ISO) process.
- Normalize education and certification requirements.

To identify global needs for knowledge dissemination and R&D in materials degradation, the WCO organized and held workshops at conferences and meetings in various parts of the world in the fall of 2008, each of which was organized by one of its founding members:

- EUROCORR 2008, September 11 in Edinburgh, Scotland, organized by the European Federation of Corrosion (EFC).
- Corrosion Technology Week, September 16 in Salt Lake City, Utah, organized by NACE International.
- September 28 meeting in Beijing, China, organized by the Chinese Society for Corrosion Protection (CSCP).
- 17th International Corrosion Congress, October 9 in Las Vegas, Nevada, organized by NACE International together with the International Corrosion Council (ICC).
- Corrosion & Prevention 2008, November 18 in Wellington, New Zealand, organized by the Australasian Corrosion Association (ACA).

This study summarizes the outcomes of these workshops and stresses the need for globally organized knowledge dissemination in the field of corrosion and corrosion control. It emphasizes that new knowledge must be acquired to make today's infrastructure safer and more reliable, and that extensive R&D is needed as an integral part of developing advanced technologies necessary to ensure the preservation of the earth's infrastructure and resources for future generations.

2 Needs for Knowledge Dissemination

The first evaluation of the cost of corrosion (the Hoar-Report[4]), which was conducted in the early 1970s, revealed that 3 to 4% of the GDP of industrialized countries is lost annually to corrosion. All similar evaluations performed later by different organizations basically came to the same conclusion. The last cost of corrosion study was published by the U.S. Federal Highway Administration (FHWA) in 2001[1] with support from NACE International. The findings clearly documented that in the United States, 3.14% of the GDP—equal to $276 billion—

is lost annually to corrosion. This sum includes only the direct costs for replacing damaged material and components. The indirect costs, such as loss of production, environmental impacts, transportation disruptions, injuries, and fatalities, were estimated to be equal to the direct costs. Corrosion costs worldwide are therefore on the order of $U.S. 552 billion.[2]

The Hoar Report emphasized that 25% of the annual cost of corrosion could be saved just by applying existing knowledge on corrosion control. Using this value to calculate possible worldwide savings (which was also supported by the FHWA report), $U.S. 450 billion in costs can be avoided each year. The return on investment is enormous, as the following example shows.

In its efforts to reduce corrosion on its military equipment and infrastructure the U.S. Department of Defense assessed in 2008[5] that the average return on investment from more than 80 corrosion mitigation projects carried out over three years is around 50:1. This underlines the paramount importance of knowledge dissemination in the field of corrosion and corrosion control.

This knowledge dissemination touches all fields of daily life and industrial branches. The issues include the following:

- **Infrastructure,** including building structures (onshore and offshore), transportation (roads, bridges, and tunnels), water distribution mains, energy distribution (electricity, gas, and oil), and communication systems and devices.
- **Transport methods,** including railways, automotive (materials technology, coating technology, clean exhaust technology by catalysts or filters), aerospace, and ships (diesel engines).
- **Energy production and storage,** including fossil fuels, nuclear fuels, biomass fuels, alternative energy sources, and hydrogen technology.
- **Raw materials,** including mining, metallurgy, recycling, and oil & gas for non-energy use.
- **Production technologies** in refineries, petrochemistry, chemistry, pulp & paper, and electronics.
- **Food,** including agriculture, food production technologies, and water cleanliness and availability.
- **Health,** including implant materials and technologies.
- **Safety and social integrity.**

Knowledge dissemination and technology transfer will be different in countries with different states of development. However, the aim in every case must be to raise the expertise in each country in the appropriate way. Education in corrosion and corrosion control needs to be tuned to the different levels in basic schools and universities.[6] As a next step, responsible bodies should be established or identified in each country to install local corrosion control management systems.

The aim is a network of independent experts worldwide who disseminate experiences (good and bad) and best practices.

A simple example demonstrates the impact of corrosion in everyday life on human health. This example was contributed by Prof. Lucien Bonou from Burkina Faso, Africa, at the WCO workshop during the 17th International Corrosion Congress[7] in September 2008. He examined the metal composition of cooking pots produced in his country from recycled aluminium alloys (Figure 2). He found that the material consisted of 32% iron and 10% copper. In addition, considerable amounts of other heavy metals were present (10% zinc, 2.5% lead, and 0.12% cadmium).

Figure 2: Corrosion-susceptible cooking pots from scrap containing aluminium alloys.[3]

This strange metal composition, which comes from using aluminium-containing scrap from parts of cars, drinking cans, tins, tubes, etc. (Figure 3), causes the pot metal to easily corrode from a reaction with the cooked food. As a result, heavy metal ions are released into the food and impair the health of the humans who consume it. It is therefore important to bring this problem into the public domain and take measures that only corrosion-resistant purer aluminium alloys be used for cooking pot manufacturing. This is a typical example where existing knowledge could solve the problem and prevent corrosion-related health hazards. It also shows that corrosion failures can occur not only within the material itself but within the medium it contacts (Figures 4 and 5).[8]

Figure 3: Aluminum containing scrap used for cooking pots.[3]

Figure 4: Corrosion failure of the material.

Figure 5: Corrosion failure at the medium.

Establishing a healthy environment and guaranteeing sound nutrition in every country is a huge, so far unsolved problem. The most important component to this is water, its abundant availability, and its healthy distribution. Water is a basic factor in nutrition (Figure 6). Therefore, distribution of water with defined purity and hygienic properties is an essential contribution to health and nutrition worldwide.

Figure 6: Drinking water—basics of nutrition.[9] Clockwise from top left: Availability, Distribution, Healthiness, and Cleanliness.

Water distribution requires piping, tanks, pumps, armatures, fittings, and plumbing systems. Which material to select is also a question of water quality and properties. For example, the European Drinking Water Directive,[10] in combination with the European Standard EN 12502,[11] gives advice and describes the boundary conditions for safe and healthy water distribution. The latter relates to the concentrations of metal ions in the water, which are restricted for ions and particulate compounds of the elements lead, copper, iron, nickel, zinc, cadmium, aluminium, and others. The metal ion concentration in the drinking water depends on the material selected, such as steel, galvanized steel, copper, brass, bronze, stainless steel, and plastic materials, and on the water quality with regard to dissolved solids and microorganisms. Thus, the pH of the water determines not only the likelihood of corrosion failures (e.g., by pitting) but also the corrosion-related content of metal compounds.[11] Based on these considerations, one could conclude that it is best to use plastic materials for water distribution and storage. However, plastic materials are not immune to degradation, and they may facilitate biofilm formation, causing hygienic and corrosion problems that are less likely to occur with metallic materials.

A wide field of corrosion control that only needs the application of present day knowledge relates to maintenance and inspection in industry. Several contributors at the various WCO workshops emphasized that assets are ruined by materials deterioration because of nonexistent or inappropriate corrosion management plans, inadequate maintenance, improper inspection (Figure 7),[12] lack of know how, lack of discipline, lack of consistencies, and the greatest problem—lack of corrosion awareness within the companies, including at the management and decision-making levels. Awareness and competence in corrosion control have to be supported and improved worldwide. Asset saving needs implementation of corrosion audits, corrosion assessment, and corrosion management. Promising examples of successful knowledge transfer from advanced countries to less advanced countries in corrosion, risk-based inspection, lifecycle analysis, appropriate corrosion control measures, and corrosion management systems are available and have been reported in the five WCO workshops. Thus, WCO aims to extend and broaden such networks through local experts and cooperation between corrosion societies.

Marine Environment

Mining Environment

Figure 7: Inadequate maintenance and corrosion inspection.[11]

One important concern discussed in the WCO workshops was the lack of basic education in corrosion and materials protection in university curricula, even in highly developed countries. Even more disappointing is that in places where corrosion education is included in the natural sciences or engineering curricula, or even established as separate studies, university leaders and faculty deans refuse to support this important subject. Available chairs for corrosion and corrosion control are no longer continued as such, but rather converted into positions for teaching "more future oriented" subjects such as biotechnology and nanotechnology. Such trends are observed specifically in Europe and the United States.[6,13] The WCO aims to foster the education of technologists and engineers who should be knowledgeable in corrosion, including undergraduate majors in the field of materials science and engineering (MSE); engineers who should be aware of corrosion, including undergraduate majors in non-MSE departments such as mechanical, civil, petroleum, and chemical engineering; corrosion experts (those earning an advanced degree specializing in corrosion); and practicing engineers with Bachelor's-level degrees.[6]

While this relates primarily to general education and transfer of existing knowledge, it is likewise important to support higher education to enable specialists in electrochemistry, corrosion, and materials science to increase knowledge of corrosion mechanisms and materials protection from the macro down to the nanoscale.[14] This is because corrosion prevention is only effective when the initiation of the corrosion process is prevented, which takes place in the nanoscale. Furthermore, it is evident that the longer the expected lifetime of a given structure, the smaller the surface defects that trigger the initiation and propagation of localized materials degradation. Under such conditions, defects of nanometric dimensions become more important. An advanced educational system must provide the knowledge base for more highly educated specialists to enable efficient and innovative research in the "nanoworld" of corrosion and corrosion prevention.

Another issue is the question of certified competence in the field of corrosion and corrosion control. Industries and government agencies look for contractors whose qualifications have been certified by independent bodies such as NACE International. But there are no agreed-upon, uniform standards for qualifying contractors or materials in the field of corrosion and its control. That is a real problem for companies operating in multiple countries and for industries and government agencies that must evaluate the qualifications of contractors educated and qualified in other countries.

Today, there are many organizations providing education programs in the field of corrosion and corrosion mitigation, but there is no consistency among those programs. Many are purely theoretical. Others focus on practical applications to the point of being a cookbook approach to handling each situation, but fail to give the student sufficient understanding to safely handle corrosion problems that require different approaches. The best programs combine classroom theory with hands-on field training.

Worldwide harmonization is needed in corrosion education, in certification, and also in corrosion-related standards. First steps have been made, but there are still many conflicting standards in Europe, between Europe and North America, between Japan and other countries, etc. This makes it difficult for companies operating in multiple countries to adopt a uniform set of standards throughout their organization. However, *standards* should not be confused with *regulations*. Regulations are adopted by government agencies and generally follow one or more consensus standards provided by professional organizations, but incorporate modifications that are specific to that country or region. It would be fine if the standards themselves were not in conflict. Therefore, WCO's goals include harmonizing of corrosion-related standards.

3 R&D Needs for Today's and Future Challenges

3.1 General Remarks

Nutrition (including water), health, energy, infrastructure, availability of resources, environmental protection, social safety, and individual integrity are basic human needs. However, governments, industries, and communities that are challenged with satisfying these basic needs are generally not aware that success and achievements in these fields are inseparably connected with solutions of materials problems as well as materials degradation and protection. Therefore, it is important to initiate a global awareness that materials constitute the physical matter of all products and engineered systems and that materials properties (including corrosion resistance) frequently define the capabilities and limitations of a technology. It must become publicly accepted that materials preservation and corrosion control are fundamental and key enabling factors for all technologies. R&D in this field is, therefore, of paramount importance and must receive high priorities in financial support. It is the aim of this study to underline this statement with examples from many fields of public life and various industrial branches.

3.2 Nutrition and Health

As described in Section 2, the safe distribution and storage of water is paramount to ensuring sound nutrition. Best practices have been developed that allow the distribution of high-quality water with a low likelihood of corrosion failures. Figure 8 exemplifies some typical failures to be prevented.

However, R&D in materials corrosion and failure mitigation is still needed to reduce the metal ion release rate for a given class of metals; for example, by appropriate surface treatments or selection of materials composition. This relates also to appropriate water conditioning, because the type of conditioning used can determine the likelihood of plumbing corrosion failures. Water installation systems and plumbing techniques need to be improved. For plastic materials, lifetime prediction is an important goal of R&D, specifically the life-limiting effects of metal ions and disinfectants. Finally, leak-sensing techniques need to be improved.

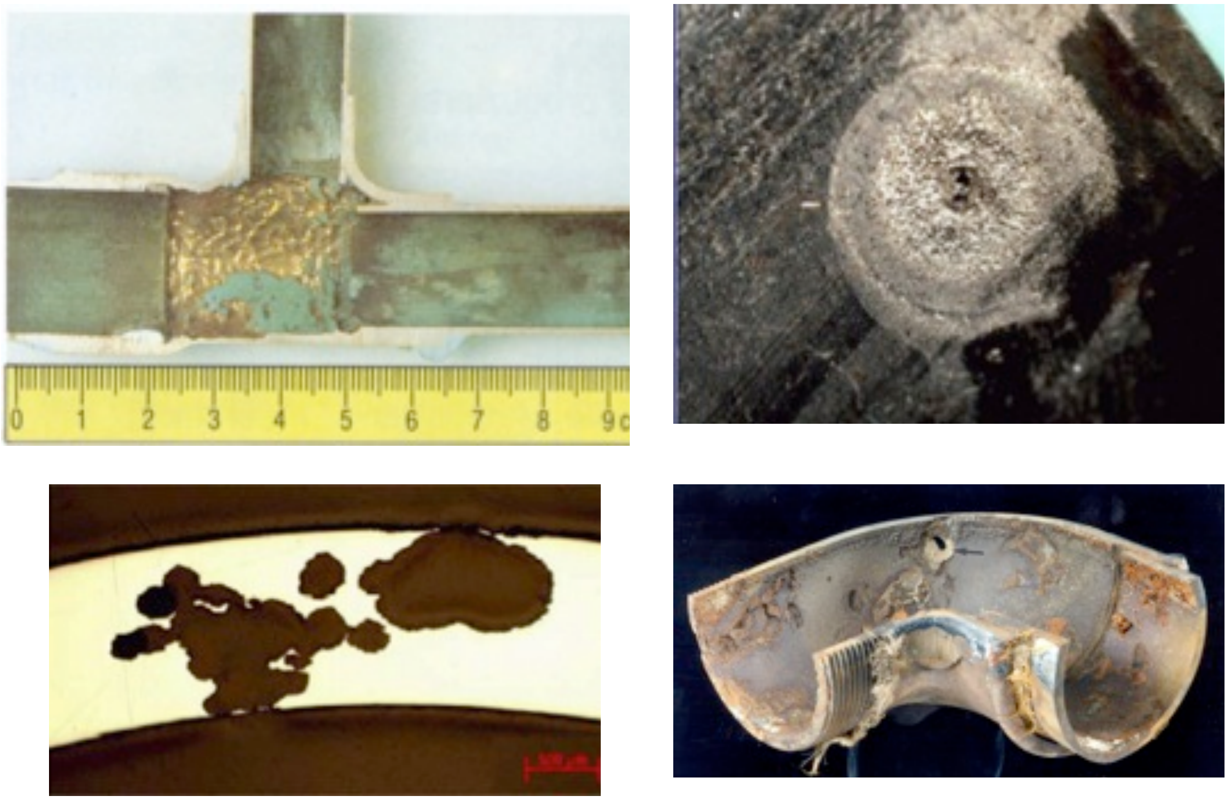

Figure 8: Corrosion failures in plumbing systems. Clockwise from top left: Erosion-corrosion of copper piping, pitting of stainless steel by chlorine disinfection (surface view), pitting of stainless steel by chlorine disinfection (cross section through pipe wall), and pitting of galvanized steel piping.

Another materials contribution to improve health is in the field of implant materials and technologies. In an aging world community, implants (metallic or non-metallic) will increase in importance (Figure 9). Implant materials demand a very specific property profile, among which corrosion behavior is one of the most important. Corrosion resistance is required when titanium and its alloys are used as dental materials. Improved corrosive metal dissolution will be needed when degradable implants are developed from magnesium for implanting in bones or in cardiovascular applications.[15] Thus, implant materials and technologies are additional fields where R&D needs the knowledge and expertise of corrosion experts.

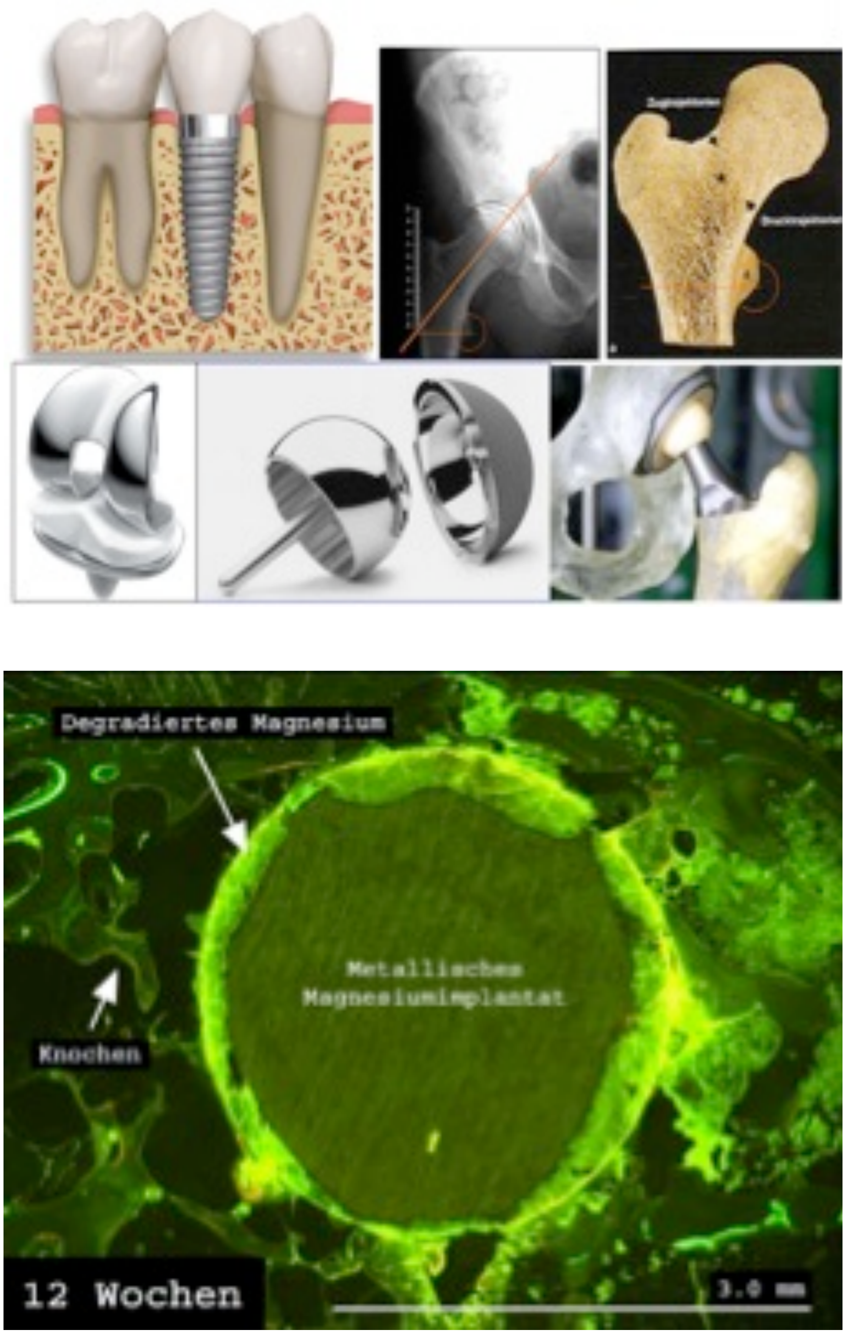

Figure 9: Examples of human implants.[15-20]

3.3 Energy Production and Storage

Worldwide energy production is based overwhelmingly on fossil fuels that include coal, oil, and gas (Figure 10). This will remain so at least for the next two or three decades because of the large supply and reasonable availability. However, burning fossil fuels produces carbon dioxide (CO_2), which is one of the major issues in global warming. The man-made atmospheric release of CO_2 during production of energy, as well as steel and concrete, needs to be reduced dramatically in the next decades. Different technologies must be applied to achieve this goal, and key words like “sequestration,” “capture,” and “storage” are frequently used. However, what is not discussed in public is that for each new technology, new corrosion problems arise as a result of new materials in new environments.

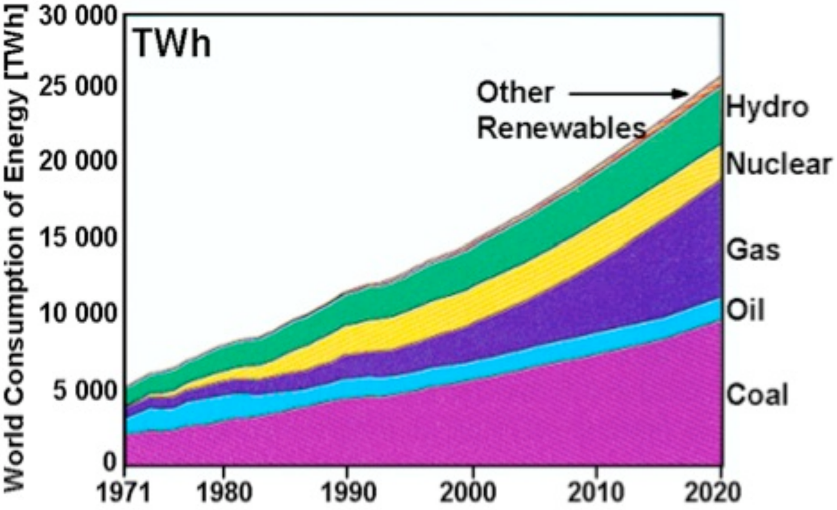

Figure 10: World consumption of energy (1971-2020).[21]

Take for example the large-scale underground storage of CO_2 (from power plant exhaust gases) in depleted gas reservoirs or aquifers, which is just getting into pilot status in several parts of the world (Figures 11 and 12).[22] Here, integrity of downhole tubing and cementing is strongly endangered by CO_2 corrosion due to much more severe environmental conditions than normally encountered in traditional oil and gas production (Figure 12). Approximately 60% of all oil and gas field failures are related to CO_2 corrosion (Figure 13).[23] In CO_2 underground storage (carbon capture and storage [CCS] technology), the CO_2 will probably be handled in the supercritical state. Severe corrosion problems must be envisaged because unknown concentrations of impurities such as oxygen, carbon monoxide (CO), and sulfur-containing gases like sulfur dioxide (SO_2) or hydrogen sulfide (H_2S) that are inevitably present in exhaust gases are expected to be corrosive for piping and other construction materials under such conditions. New and sustainable corrosion control concepts are needed to ensure integrity of equipment for much longer lifetimes than are usual today (e.g., more than 100 years).

Figure 11: Sites of proposed carbon capture and storage (CCS).[22]

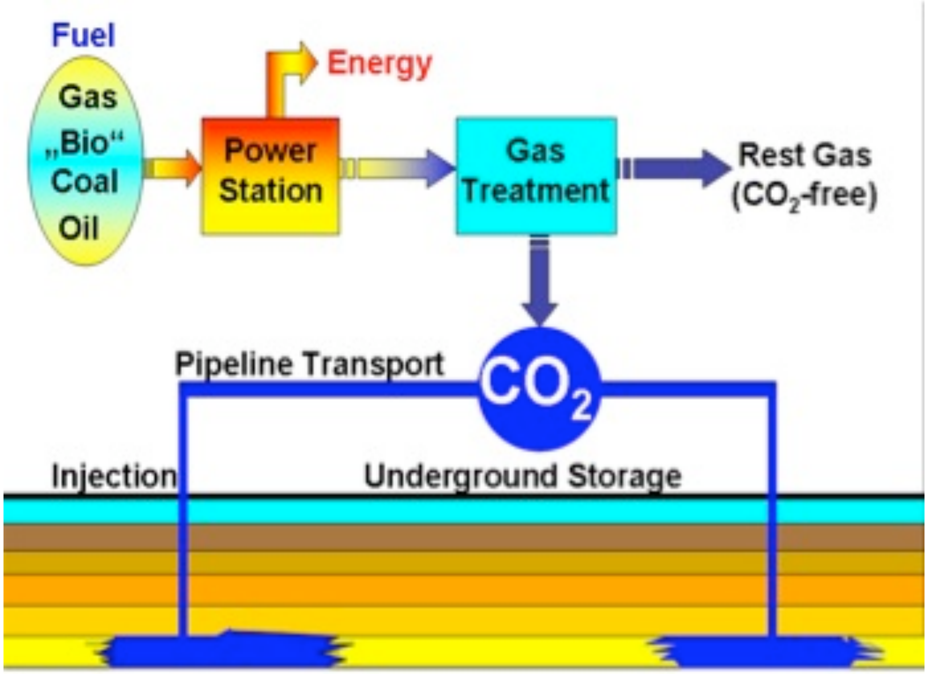

Figure 12: Energy production without CO_2 release into the atmosphere.

Figure 13: CO_2 corrosion of piping.

The use of biofuels in cars and trucks also presents corrosion problems. Because of its different chemical composition compared to classic diesel fuel, the materials for sealants, gaskets, and some components made from organic material have to be modified. Furthermore, coatings protecting the fuel tank need to be changed. Aluminium and aluminium alloys may experience severe pitting and carbon steel may experience stress corrosion cracking (Figures 14 and 15). These examples demonstrate that the decision on a technological change from fossil fuel to biofuel can be easily made at the management level. However, the real problems surface when the change is carried out. Again, materials and corrosion problems have to be solved first.

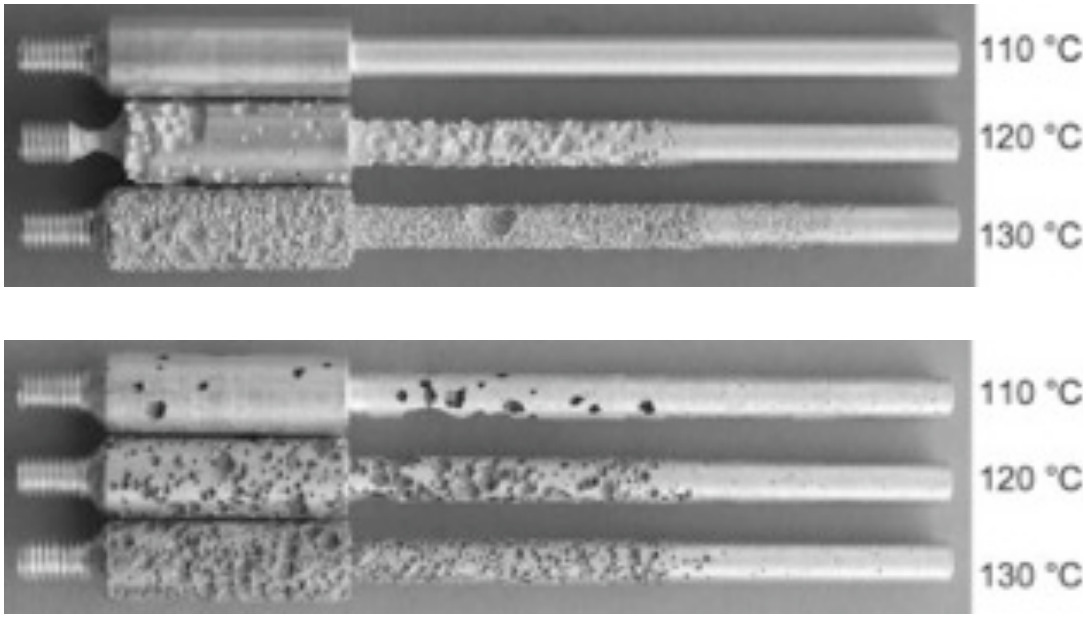

Figure 14: Pitting corrosion at aluminium and aluminium alloys in biofuel.[24]

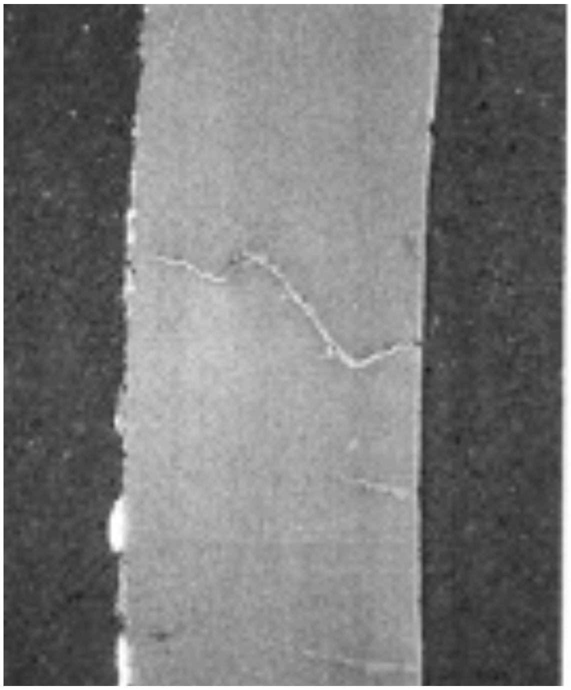

Figure 15: Stress corrosion cracking of and aluminum alloy in biofuel.[24] carbon steel in biofuel.[25]

What about alternative energy sources such as solar, wind, water, and geothermal energy? All technologies applied in energy production from alternate sources encounter materials and corrosion problems. In the photovoltaic technology, materials degradation occurs in photovoltaic elements and solar-powered heat exchanger piping will severely corrode without application of corrosion inhibitors that still keep their efficiency in high-temperature environments.

Geothermal heat is a long-lasting energy source. The heat stored in the first 3,000 m of the earth crust could theoretically cover today's world energy demand for the next 100,000 years. However, the global accessibility of geothermal heat varies, which explains why the use of geothermal energy (Figure 16) is different in different countries. In Iceland, geothermal energy carries 56% of the total energy demand. In the Philippines, the contribution is 20%.[26] Corrosion of plant equipment and structures within and around geothermal power generation facilities can be a major problem due to the presence of salts, hydrogen sulfide (H_2S), and silicates in the geothermal water, which cause localized corrosion and scale formation in wells and casings and power generating equipment (Figure 17).[26] Materials selection is crucial and it needs long-term risk-based inspection to achieve significant cost savings. This has recently been demonstrated in the Philippines, currently the world's second largest producer of geothermal energy (3,000 MW). Continued corrosion mitigation activities will have a great impact in reducing the life cycle costs of local geothermal power generation operations.[26]

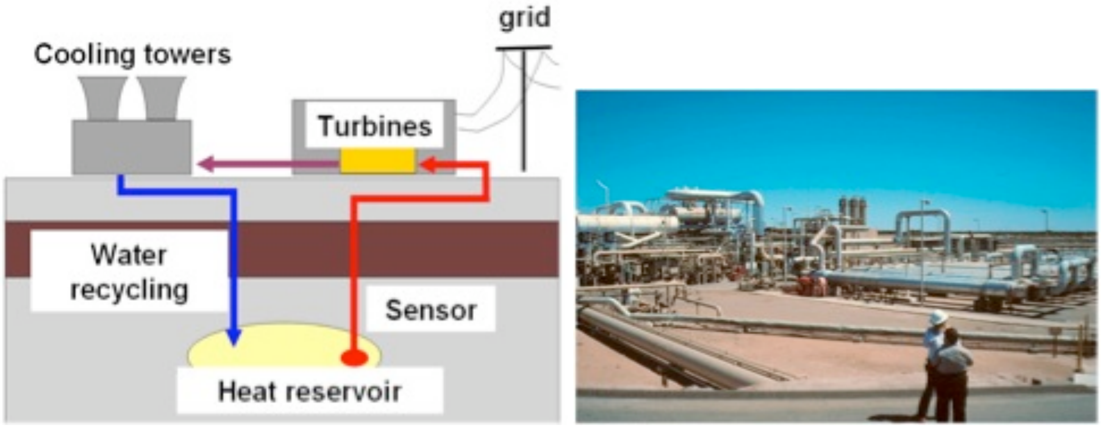

Figure 16: Geothermal power plant.

Figure 17: Corrosion of structural materials due to highly corrosive atmosphere in range of the plant.[26]

Wind energy parks (Figure 18) are presently installed at many places in the world. In Germany, about 20,000 windmills produce about 3% of the German electric energy. The installation of another 20,000 windmills is planned in the North and Baltic Seas in the next 10 years. Gigantic corrosion problems will arise due to the hostile environment in which offshore windmills have to work: corrosive seawater attacks fasteners, mast platforms, and anchoring, and there is mechanical impact from wind and waves. Tribological problems in the gear systems will have to be solved by materials selection, improved construction, and optimized lubrication. Comprehensive system monitoring, which still has to be developed, will be mandatory for failure prevention. Otherwise, no company will take the risk of insuring these systems. Failure of corrosion protection systems on offshore windmills will eliminate profit over the expected lifetime of the structure. This is because of the difficulty in scaffolding for repair work.

Figure 18: Wind energy parks onshore and offshore.

Tidal power plants are presently put forward as a cheap energy production technology. Tidal-driven underwater turbines (Figure 19) will operate in sea regions with high tidal potential.[27] These projects will be challenged by eminent materials and corrosion problems. Economical solutions for materials and materials protection will need extensive R&D efforts.

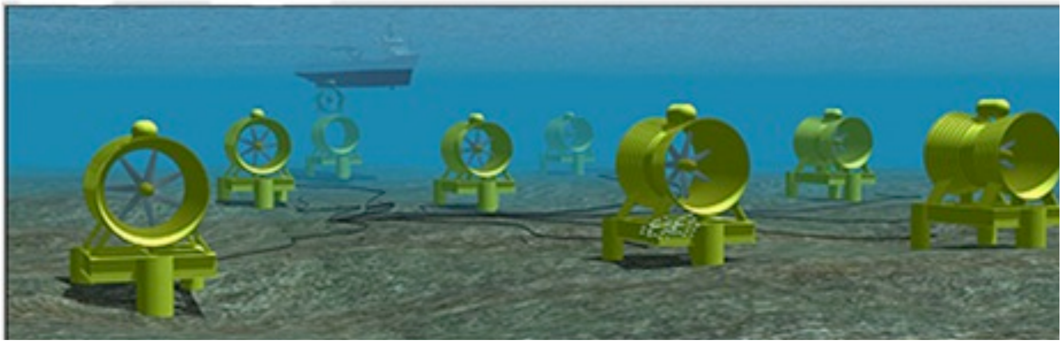

Figure 19: Giant tidal power scheme, built off the South Korean coast (300 units) and off the Welsh coast (eight units). The turbines will be deep in the water to avoid any danger to ships.[27]

Marine environments are long known to be very corrosive. The severity of corrosion varies according to the different marine zones (Table 1). Spanning from the lowest tidal mark in a given year to as many as 10 feet (3 m) above the year's highest tidal mark, the splash zone of a structure suffers the most severe corrosion.

Marine Zones	**Corrosion Rates of Steel in Offshore Service (mm/year)**
Seamud Zone	0.1
Immersion Zone	0.2
Tidal Zone	0.25
Splash Zone	0.4
Atmospheric Zone	0.1

Table 1: Steel corrosion rates in different marine zones.

The addition of nutrients for marine micro- and macro-organisms from sources such as agricultural products has resulted in the increase of microbiologically influenced corrosion (MIC), significantly aggravating the severity of corrosion in waters around wharfs and estuaries. Aerobic organisms attack the splash zone; anaerobic organisms, sulfate-reducing bacteria, and orange bloom cause corrosion problems in the tidal zone; and MIC is accelerated in the low water zone (Figures 20-22).[28] Accelerated low-water corrosion (ALWC), a newly observed and increasing phenomenon (Figure 21), leads to attack at from 10 to 20 times the expected corrosion rate close to the lowest astronomical tide levels, making it very difficult to observe. This appears to be caused by an “infection” of a new microbial strain that has evolved to survive in marine muds. This produces severe corrosion via metabolites such as H_2S. There is presently no effective solution apart from retrofitting structures with cathodic protection systems or full replacement, both at a very high cost. In any case, materials deterioration from these processes must be mitigated.

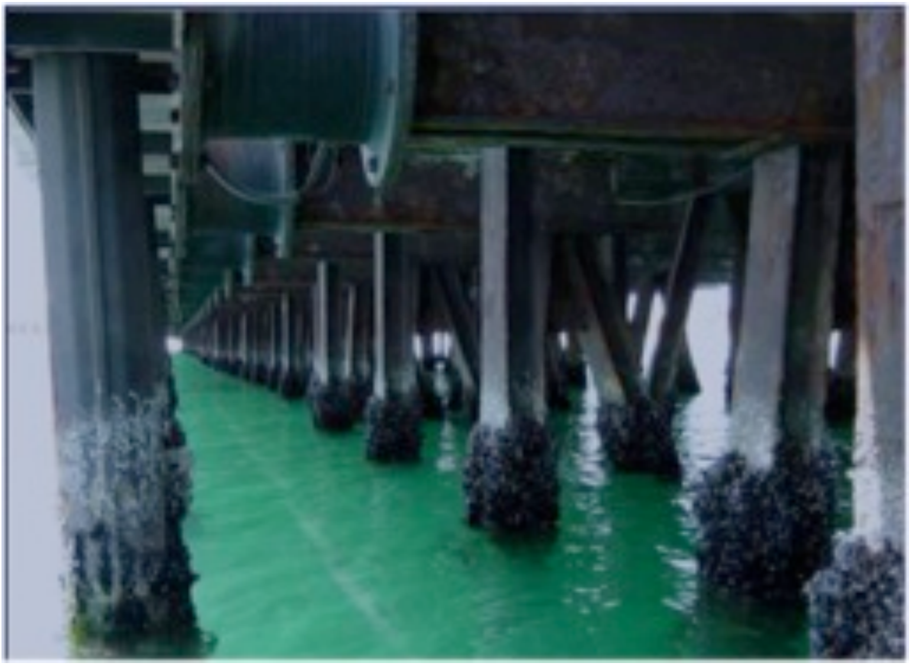

Figure 20: Marine corrosion of steel piles.[28]

Figure 21: Low water zone corrosion of sheet pilings.[29]

Figure 22: Pitting and wall perforation of steel piles by MIC.[28]

Cathodic protection—a technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell—is often used to control corrosion in marine environments, but it is not effective in preventing MIC. Coating and wallpapering are other options, but great experience and care is needed in the selection and application of the coating (Figure 23). R&D is necessary to optimize underwater and splash zone coatings and protection. This is also the case for steel-reinforced concrete piles (Figure 24).[29]

Figure 23: Underwater and splash zone coating.[29]

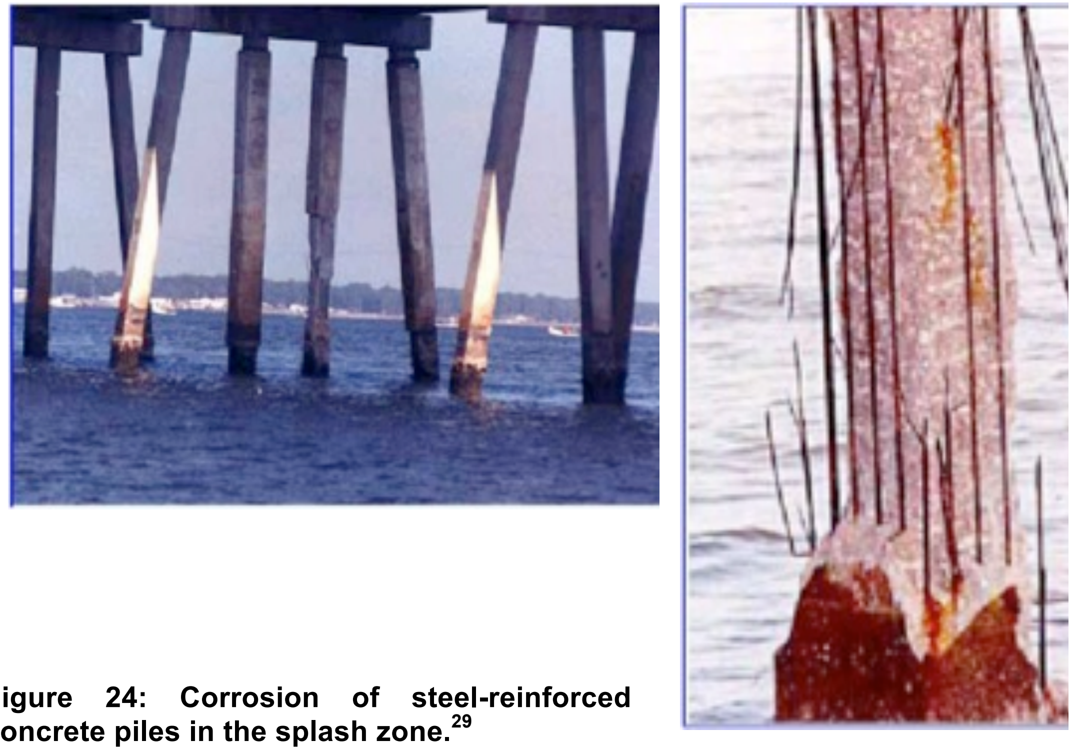

Figure 24: Corrosion of steel-reinforced concrete piles in the splash zone.[29]

Another great challenge is the development of efficient and environmentally friendly anti-fouling coatings for ships. It is estimated that biofouling of ship hulls by barnacles and other sea life increases fuel consumption by 8%. Based on an estimated fuel consumption of 350 million tons for the shipping industry worldwide in 2007, an excess of 28 million tons of fuel were consumed because of ship hull biofouling. In addition, it has been estimated that ships emitted 1,120 million tons of CO_2 in 2007.[29] Properly designed and applied anti-biofouling coatings could make a significant contribution to reduce environmental pollution.

The nuclear power industry also faces materials and corrosion problems both in fission and fusion technologies. The number of nuclear power plants is rapidly increasing worldwide because this kind of energy production does not contribute to global warming. The highest growth rates are presently occurring in China and Russia. By 2020, up to 4% of the total energy production in China will come from nuclear power plants. The percentage seems small; however, it equates to 40,000 MW of energy.[30] Some countries today rely on nuclear power for up to 80% of their energy needs, including France. On the other hand, the disadvantages of nuclear power—the large initial investment, fear of nuclear leakage, and problems with waste disposal—have retarded its development in other countries. Although much fundamental research has been done in the nuclear industry in advanced countries, in-field accidents and leaks indicate that there are flaws in field operation and that additional research is required.

Three main areas have been identified that require increased corrosion science knowledge and understanding in the nuclear industry:[31]

- How to extend the life of nuclear power plants from 30-40 years as initially planned to 50-60 years and even longer without compromising safety
- How to accurately predict the long-term behavior of metallic materials considered for nuclear waste disposal, where safe storage is needed for thousands of years
- How to analyze and select materials for use at the very high temperatures expected in Generation IV nuclear power plants in environments that include gas (helium), supercritical water, liquid metals, and salts

Present research issues in publications from 2007 and 2008 include:[31]

- Stress corrosion cracking of steel pipelines
- Inhibitor selection for cooling water and chemical decontamination media
- Erosion-corrosion in piping
- Non-destructive corrosion testing methods
- Software tools for calculating corrosion rate
- Atmospheric corrosion inside retired reactor vessels
- Corrosion cracking of heat-exchanger tubes
- Corrosive conditions in cooling systems
- Corrosion fatigue monitoring for steam generators
- Low-temperature chloride-induced atmospheric stress corrosion cracking of stainless steel for nuclear waste disposal

New technological approaches for safe production and final storage demand new materials and corrosion control solutions. Huge R&D programs are needed, which should be executed on an international basis. However, this is not enough—there also is a shortage of trained and experienced inspectors and others knowledgeable in nuclear plant corrosion control. Increased educational efforts in this field must be an integral part of the strategy for future safe use of nuclear power as an energy source.

One way to optimize energy savings is for energy production units to operate as efficiently as possible. Higher efficiencies in power plants are obtained with higher gas temperatures. One of the operating goals involves “700 °C thermal power plants.”[32] This goal is only achievable with appropriate materials and innovative surface protection methods that remain effective under such extreme environmental conditions.[33] Thermal barrier coatings have been developed that allow materials temperatures up to 1,000 °C and surface temperatures up to 1,350 °C.[34] However, lifetime prediction and the extension of operating conditions to even higher temperatures in industrial systems are important issues that need intensive R&D activities.

This contrasts with the belief in recent years that a broad understanding of high-temperature corrosion mechanisms has already been achieved and that this knowledge can simply be applied in industrial situations without incurring corrosion problems. A more thorough analysis, however, reveals that in most cases the industrial conditions are far too complex for such an approach. A number of synergistic effects may prevent reliable prediction of corrosion and the lifetime of the components in use. Furthermore, a number of new technologies has created a demand for new research because of environmental considerations. Operating temperatures need to increase to optimize thermal efficiency and reduce the emission of pollutants. Examples include different types of thermal energy conversion systems, such as high-temperature fuel cells (solid oxide fuel cells) and combustion/gasification of more aggressive fuels (waste, biomass, etc.). Also, new groups of materials like intermetallics have led to a significant demand for research on understanding the corrosion phenomena involved and to develop specific protection measures.[35]

3.4 Transportation

Saving energy, raw materials, and resources is a multidisciplinary challenge in many fields of technology. A good example is the low consumption, low environmental impact, low cost “€3,000 Car” that is presently under development in the automotive industry (Figure 25). Its realization is only possible with joint multi-disciplinary efforts in materials functionality. New solutions are needed for construction materials, joining processes, motor design, fuel composition, exhaust cleanliness, surface protection, passenger safety, and much more. New ideas and new technologies (among them cost-effective, environmentally neutral, longlasting, and effective corrosion control) need careful and coordinated amalgamation to shape a sustainable future for the transportation needs of a fast-growing world population.

Wish list for the
3.000-Dollar Car:

- low consumption
- low environmental impact
- high safety
- low cost

New solutions still needed for

- construction materials
- joining processes
- motor design
- fuel composition
- exhaust cleanliness
- surface protection
- passenger safety
- easy-to-use

Figure 25: Wish list for a €3,000 Car—a contribution to saving energy, raw materials, and resources.

3.5 Infrastructure

In recent years the deterioration of infrastructural installations such as buildings; roads; bridges; tunnels; train tracks; water distribution mains; energy distribution systems for electricity, gas, and oil; and communication systems and devices has become very obvious. Public safety is more and more at risk and in some cases lives have been lost from failure to adequately address the corrosion issues (Figure 26). In the United States, the cost of corrosion related to bridges alone amounts to about $ 8.3 billion per year (Figure 27).[1,36]

Figure 26: Highway 35W-Mississippi Bridge collapse in Minneapolis on August 1, 2007.[37-38]

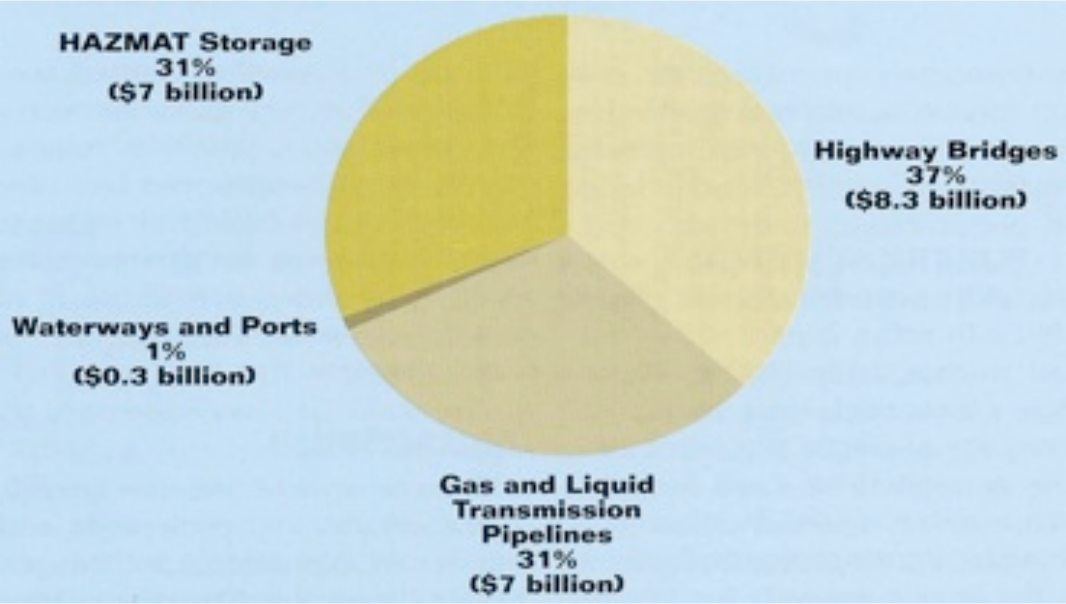

Figure 27: Annual cost of corrosion to the U.S. infrastructure (total: $22.6 billion).[1]

One-third of the ongoing cost of corrosion on U.S. highway bridges would be saved if existing, fully developed corrosion prevention technologies were applied to bridge decks and their substructures.[37] In the United States, this prompted the initiation of H.R. 1682, the "Bridge Life Extension Act 2008,"[36,39] which will require states to submit a plan for the prevention and mitigation of damage caused by corrosion when seeking federal funds to build a new bridge or rehabilitate an existing bridge. This includes careful construction, disclosure of planned corrosion prevention methods (e.g., application of cathodic protection), condition-based monitoring and maintenance, certification of the plan by a corrosion expert, and corrosion training for all bridge inspectors. In the U.K., the Highways Agency is mandating certification for qualified inspectors and applicators for protective coatings (paint) on highway structures via the U.K. Institute of Corrosion. This is the first such scheme in the world and is designed to iprove workmanship on site, but also importantly to extend life and thus reduce wolte-of-life costing for structures. Condition-based monitoring is another future challenge in R&D efforts to develop appropriate corrosion monitoring methods and devices.

The collapse of building structures is another example where proper corrosion protection measures could have saved lives and assets. Occurrences include the collapse of a Berlin Congress Hall roof that was caused by hydrogen-induced stress corrosion cracking of prestressed steel (Figure 28) and the collapse of suspended ceilings in swimming halls due to chloride-induced stress corrosion cracking (Figures 29 and 30).

Before collapse

After collapse

Cause of the collapse: stress corrosion cracking of prestressed steel in ring beam joint.

Figure 28: Collapse of the Berlin Congress Hall in 1980.[4]

Figure 29: Collapse of suspended ceilings in swimming halls due to inappropriate stainless steel fastening elements. Failure by stress corrosion cracking.[41]

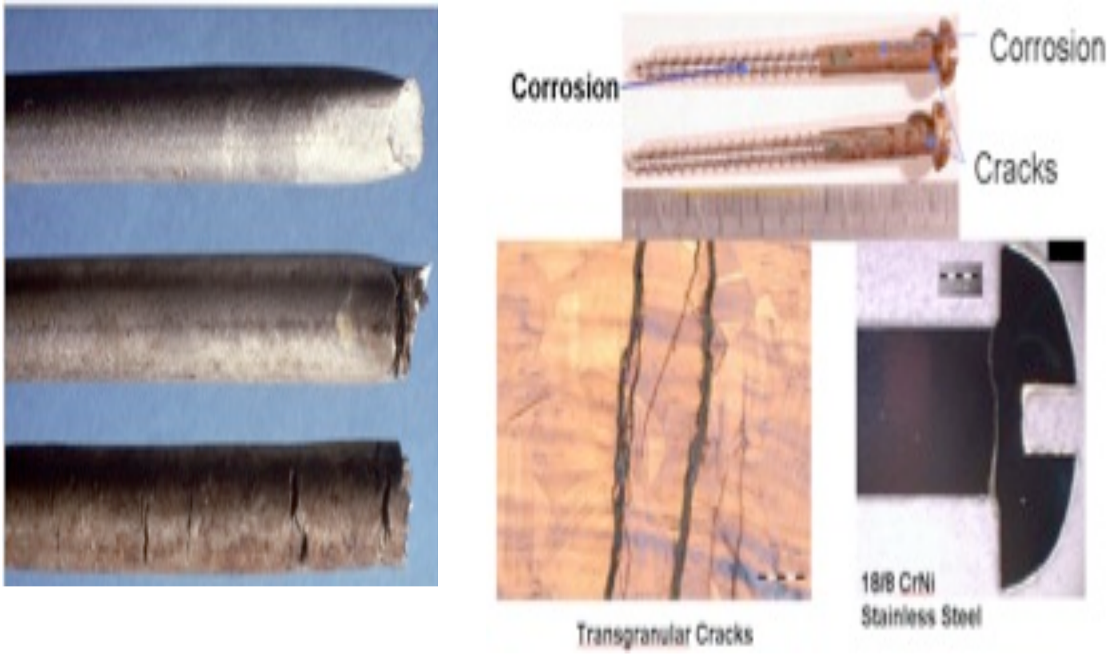

Figure 30: Stress corrosion cracking at fastening elements of suspended ceilings in the swimming halls of Uster (left)[42] and Denmark (right).[42] (See Figure 29.)

Failures of water distribution mains (Figure 31) are further examples of corrosion-related aging of infrastructure that are more frequently encountered by the public in recent years but which are rarely attributed to corrosion in the press. A survey carried out in Europe in 2004[42-43] revealed that due to corroded and broken water distribution mains, nearly 30% of the drinking water that leaves the water works may never reach the consumer (Figure 32). Appropriate condition monitoring would enable inspectors to pinpoint the sites of distribution system leaks. Figure 32 lists only four countries as examples. Similar situations are encountered in other countries with similar aging water distribution systems. Large investment in the U.K. water distribution networks mandated by the regulating agencies after local water shortages a few years ago reduced the average loss in distribution from leakages due to corrosion from over 25% to less than 20% in five years. The goal is for the average loss to decline to about 12 to 15% leakage, the current best practice in the U.K.

Figure 31: Broken water mains.

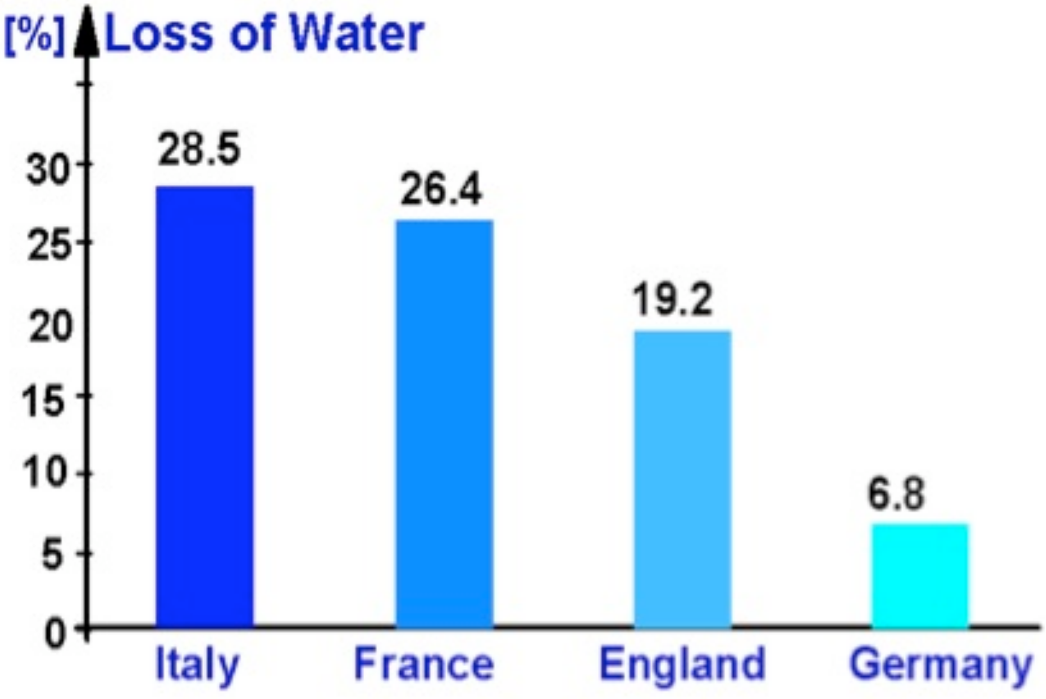

Figure 32: Water that left the water works but never reached the consumer.[42-43]

Condition monitoring and maintenance are vital to ensuring public safety as the world's infrastructure reaches the end of its design life and rapid deterioration occurs. New and reliable sensing techniques need to be developed that are suitable for more cases than currently available technologies. This requires research and resources to develop more reliable, versatile, and user-friendly corrosion monitoring sensors.

3.6 Raw Materials

In 2008, prices for many raw materials skyrocketed (Figure 33).[44-46] Examples are nickel, copper, chromium, molybdenum, aluminum, magnesium, crude oil, and natural gas. This prompts new technologies in mining, metallurgy, and oil production. Research is needed to evaluate corrosion-resistant alloys with lower concentrations of expensive alloying elements like chromium, nickel, and molybdenum. Optimum usage of these metals, combined with recycling materials, is essential for long-term sustainability. Recycling processes must be improved for steel, aluminium, magnesium, and other metals as well. Oil and gas production from deep, hot onshore and offshore wells (depths greater than 5,000 m) is challenged by immense materials and corrosion problems. Some fascinating technologies have been developed for use in subsea structures, but extreme materials and corrosion problems remain. These include severe corrosion in tubes, risers, and pipelines. In addition, there are growing efforts to extract oil from oil sands and shale. This practice involves hostile conditions for construction materials that cause severe corrosion failures. There will be little technological progress with these relatively new production methods without innovative solutions in materials protection and corrosion control.

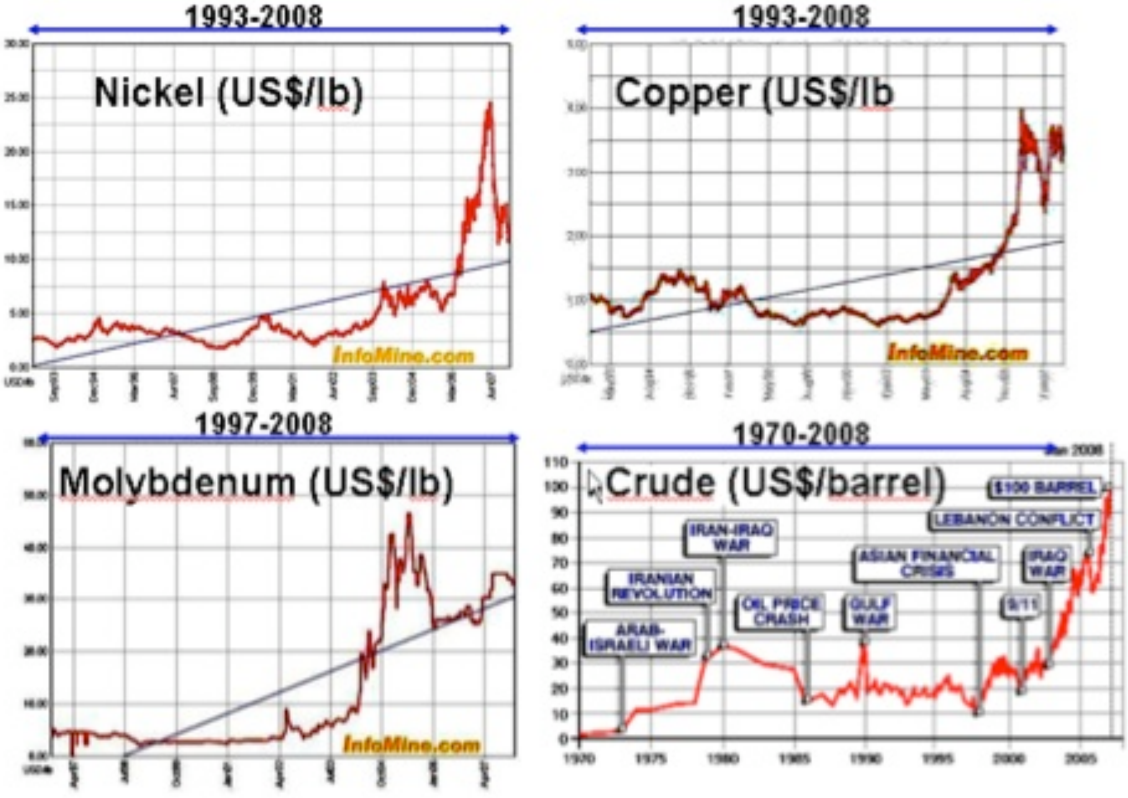

Figure 33: Increasing prices of raw materials.[44-46]

3.7 Production Technologies

New production technologies are under way in the petrochemical and chemical processing industries. Engineers are faced with unusual materials and corrosion problems for which solutions still have to be developed. The goal is to develop processes with low energy consumption and low environmental impact. Researchers are focusing on biotechnological and microreactor technologies, among others.

Another issue is to convert organic waste, including liquid manure, into innocuous products. One interesting method is the use of oxidation in supercritical water. This high-temperature/high-pressure process can cause severe corrosion problems, however. On the other hand, it is an environmentally more acceptable solution than waste incineration and, therefore, deserves more R&D efforts.

3.8 Cultural Heritage

Corrosion from the interaction between a material and the environment is also continuously destroying the world's cultural heritage. In many cases the rate of destruction is alarmingly fast (Figure 34).[47] There are not many buildings, art objects, or monuments that are as well protected as the Eiffel Tower in Paris, France. Every seven years, this steel monument is newly protected from atmospheric corrosion by another 50 tons of paint. The return on investment is realized by the attraction of 5.3 million tourists per year. This is an excellent example of how appropriate maintenance of elements of our cultural heritage can even be profitable.

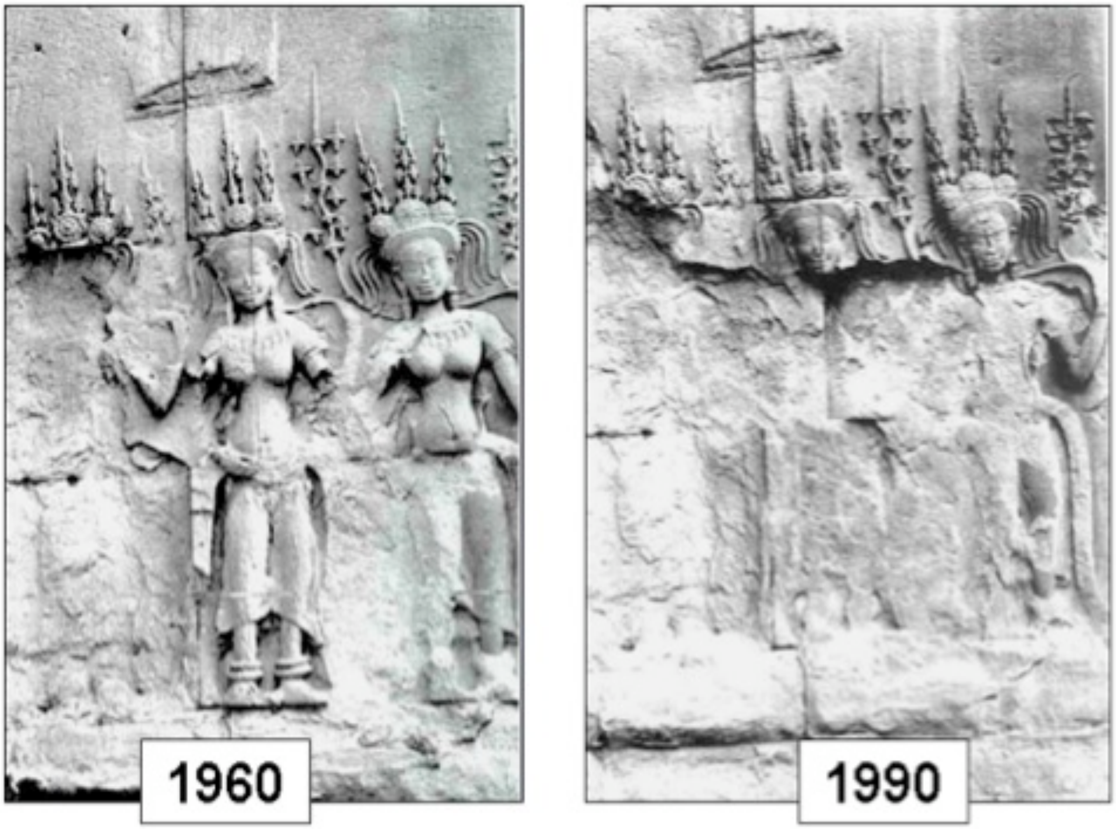

Figure 34: Weathering of stone artifacts in China.[47]

Unfortunately, in many places throughout the world, the objects of cultural heritage are gradually corroding away, caused by natural and human factors. Natural factors include sudden disasters such as hurricanes or earthquakes, changes in temperature and humidity, environmental pollution, sun radiation, water, oxygen, and attack by microorganisms. They cause materials degradation by weathering, discoloration, shrinkage, cracking, flaking, peeling, twisting, worm damage, mildew attack, and embrittlement. The end result is complete destruction of precious cultural relics. Human factors include the lack of adequate protective measures and protection management. In many countries, this means huge losses of cultural assets.

The WCO is committed to contributing to the preservation and protection of cultural relics with the combined knowledge of corrosion experts from all over the world. It is necessary to establish a multidisciplinary scientific system of cultural asset protection and to continuously perfect and harmonize the regulations and standards of these protection technologies. The principle is to maintain the original form of historic relics, minimize manual intervention, and keep their appearance as if it would be untreated. This makes it necessary to improve the scientific understanding of relic corrosion mechanisms and the impact of various environmental factors, search for options to control the environmental factors, explore new materials and methods for relic preservation, and integrate traditional skills and modern science and technology.

Preservation of cultural heritage is a multidisciplinary issue in which corrosion, materials protection, and surface modification play a crucial role. WCO offers its worldwide competence to ensure optimum efficiency in this area.

4. Conclusions

To satisfy the basic needs of the 6.3 billion people on this globe, including proper nutrition, clean water, good health, safe housing, dependable energy, effective communication, and mobility, many technological changes with global dimensions must be accomplished. While this concept is widely appreciated as such, there is often only a limited awareness of how critical it is to solve corrosion problems and what the real implications are to society.

It is the intention of this study to demonstrate with several examples that future technological challenges can only be met by immense R&D efforts worldwide in the fields of materials, surface protection, corrosion control, and condition-based monitoring. Progress in these disciplines is necessary to improve the capabilities and reduce the limitations of existing and upcoming technologies. Innovative approaches will determine whether energy efficiencies can be improved; whether communication, transportation, and civil infrastructure systems can be advanced in an environmentally benign way; and whether technical and public safety and security can be sustainably strengthened.

It appears that in literally all cases, key problems related to materials degradation and corrosion must be solved. This involves materials stability under new environmental conditions or functional adjustment of environments and materials surface properties by appropriate surface modification methods. This work must include efficient management of corrosion mitigation and service integrity. Condition-based monitoring will be one of the key factors to ensure service integrity. However, this can only be accomplished with innovative sensor devices that have yet to be developed. Global standards should be established to foster condition-based monitoring as a standard procedure.

The WCO is commited to working on these goals and making them attainable worldwide. With recognition by the United Nations as an NGO member, the WCO will receive the global attention that is necessary to be effective in its international efforts.

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