Preventing Corrosion
from Wearing Our Future Away

Adam Winkleman
Erik B. Svedberg*
National Materials Advisory Board
Washington, D.C.

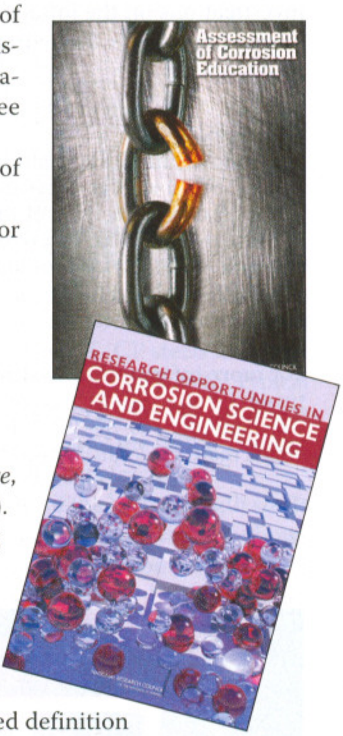
Robert E. Schafrik*, FASM
GE Aircraft Engines
Cincinnati, Ohio

David J. Duquette*, FASM
Rensselaer Polytechnic Institute
Troy, N.Y.

**Member of ASM International*

The National Academies recently released two reports on corrosion science entitled "Research Opportunities in Corrosion Science and Engineering" [1] and "Assessment of Corrosion Education" [2], prepared by two different committees under the National Materials Advisory Board (NMAB), consisting of leading experts in the field of corrosion science from academia, government laboratories, and industry. This article highlights some of the key findings and recommendations of these two National Research Council (NRC) reports. Three areas discussed include:

- The need for an expanded definition of corrosion and the cost of corrosion to our society
- Identification of the current issues and methods of combating or preventing corrosion and a review of the efforts of various government agencies supporting corrosion research
- A summary of the grand challenges in corrosion research and development and the need for corrosion science education expressed by the committees of these studies



The potential for great discovery is pushing the field of corrosion science and engineering forward, and a grave threat that institutional knowledge might be lost is pulling the field backwards; both issues are working toward renewing interest in corrosion science.

What is corrosion?

The origin of the word corrosion is from the Latin word *corrodere*, meaning "to gnaw to pieces," (a similar origin as the word "rodent"). Currently, corrosion is defined as the slow deterioration by being eaten or worn away, which is inclusive of all literary meanings both physical (e.g., rust) and abstract (e.g., relationships or emotions). With respect to matter, corrosion historically referred to the destructive oxidation of metals, as metal structures were the dominant material of the industrial age. As other materials (specifically plastics, ceramics, and composites) are more widely used, an updated definition for deterioration of materials is needed. Currently, one accepted definition of corrosion of materials—the definition chosen by the Academies' most recent study—is the degradation or deterioration of any physical properties of a material by means of a chemical reaction with its environment.

Metallic oxidation is the most prevalent, most researched, and most taught form of corrosion. Corrosion by oxidation is typified by a process in which a metallic material reacts with oxygen and mediated by water to form a thermodynamically more stable compound; with respect to corrosion, this process is colloquially called rusting. Deterioration of materials can also occur through reactions with other species in the environment including sulfur, hydrogen, and light. For example, plastics and several classes of composite materials undergo physical degradation due to ambient ultraviolet (UV) irradiation from exposure to the sun.

Not all mechanisms for material degradation fall within this definition of corrosion as it requires the material to undergo a chemical reaction. Other mechanical degradation mechanisms, such as creep, wear, and fatigue, are not considered to be corrosion, although effects due to corrosion may accelerate these degradation modes.

The importance of corrosion and its cost to society

Corrosion permeates every aspect of our society. It is a natural phenomenon affecting all materials in structures important to our economic and national security and to our well being as a whole. Each component of the public infrastructure (for example, highways, airports, water supply, waste treatment, energy supply, and power generation) is part of a complex system requiring significant investment. Within that infrastructure, in both the private and public sectors, corrosion affects nearly every type of material and structure used. Corrosion, therefore, affects us in everyday life—in the manufacturing of products, the transportation of people and goods, the provision of energy, the protection of our health and safety, and the defense of the nation.

The costs associated with corrosion, although largely hidden, are borne by every consumer, user, and producer. The direct economic costs are enormous, estimated to be 3.1% of the U.S. gross domestic product (GDP) [3]. Considering the 2009 GDP of about $14.1 trillion, this estimated percentage amounts to a cost in 2009 dollars of ~$437 billion [4]. The high costs arising from corrosion are not unique to American society, as many other developed countries throughout the world have similar burdens to maintain their infrastructure.

In addition to capital expenditures, corrosion has many indirect costs that include factors such as lost productivity due to outages, delays, failures, and litigation; and taxes and overhead on the cost of the corrosion portion of goods and services. NACE International, Houston, Tex., conservatively estimated the indirect cost to be equal to the direct cost; thus, the total cost due to corrosion represents ~6% of the GDP [4]. In addition to the direct and indirect costs, there are long-term effects of corrosion on safety, health, and the environment that are not readily quantifiable. Also difficult to quantify are missed-opportunity costs such as loss of readiness; that is, the nation's ability to respond to military, national security, and emergency situations. Whatever the real cost and lost opportunities are, corrosion severely impacts everyone's daily life, as well as the economic health and security of the nation.

Issues in corrosion science and engineering

Corrosion may be inevitable; however, there are ways to retard its kinetics and greatly reduce the economic burden on society. In broad terms (and in the eyes of the committee), the issues in corrosion science and engineering can be subdivided into four main categories of design, mitigation, detection, and prediction, which comprise key areas for research and development. The categories encompass the different approaches to solve the problems created by corrosion, which will enable improvements in our quality of life and reduce the cost of corrosion on society.

Design is the development of new materials that retard or inhibit corrosion, and includes the use of computational modeling to help increase the rate of discovery and the performance of desired material properties.

Mitigation, the most widely applied method, pertains to the protection and maintenance methodologies (e.g., painting) applied through the development and implementation of corrosion modeling tools, databases, design rules, and lessons learned.

Detection assesses corrosion damage and develops prognoses of the state and rate of material degradation (ideally using sensors and remote monitoring) to reduce maintenance costs and prevent sudden catastrophic failure.

Prediction models the life and performance of materials under multiple environmental and mechanical stresses, and can incorporate data from accelerated testing and other real-world sources.

Rusted steel parts.

Research on many aspects of corrosion over the past century led to mitigation techniques that enable our current standards of living. Better materials (slower corrosion rates), better protection (coatings), increased awareness (detection of the early stages of corrosion), and better organized and executed plans for combating corrosion or replacing corroded parts lead to dramatic improvements not possible without such research.

Current best practices and success stories for corrosion mitigation

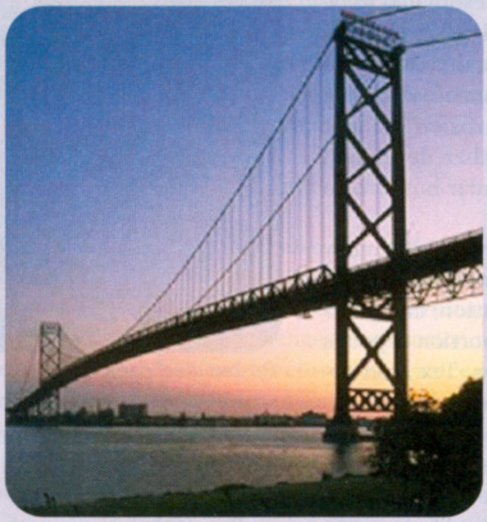
Of the approaches aimed at minimizing the costs arising from corrosion, mitigation received the most attention over the past decades. The goal of mitigation is to reduce the rate of degradation or deterioration of the physical properties and increase the functional life of the materials and their systems; thereby, reducing the need and associated costs for maintenance and/or replacement. To minimize the effects of corrosion, a mitigation strategy for each system must be tailored to the environment, composition, and structure of the chosen materials.

Mitigation strategies are roughly classified as active or passive. Active techniques are systems that have competitive chemical reactions to prevent the loss of desired physical properties, and include external cathodic protection with or without coatings, sacrificial anodes, and inhibitors. Another active method minimizes the concentration of undesirable reactive species in the environment; this approach sometimes is used in boilers where oxygen and ionic species are removed while adding inhibitors. Passive techniques including material selection, organic and inorganic coatings, and metallic coatings (both barrier and sacrificial coatings) typically provide a physical barrier between the environment and the reactive material. None of the strategies for mitigation provides a silver bullet, and system design typically requires incorporating several techniques in any single solution.

The most common approach is developing passive techniques in which engineers intelligently design and select materials that will not undergo corrosion during the life of the system. Despite the fact that it is not thermodynamically possible to develop alloys that are totally immune to corrosion, there have been extraordinary developments with respect to heat- and corrosion-resistant alloys in the past century, and these developments have ac-

Meeting the challenges of corrosion: Education needs

Successful progress toward achieving the Corrosion Grand Challenges, or CGCs (see next page), lies in the ability of the nation's technology base to develop an engineering workforce that understands the physical and chemical bases for corrosion, as well as the engineering issues surrounding corrosion and corrosion abatement. An educated workforce in corrosion science and engineering will help create a sufficient framework to let the country substantially reduce the national cost of corrosion and increase the safety and reliability of the national infrastructure. For example, consider the role of engineering in bridge design and construction: one would not design a bridge without considering fatigue loadings, nor should one design it without considering the continuous degradation of its materials by the environment in which it operates.



Ambassador Bridge connecting Detroit, Mich., and Windsor, Ontario, Canada.

Both the public and private sectors appreciate the need for engineers educated in corrosion engineering who are able to account for corrosion during design and manufacture. The importance of corrosion education in today's world continues to increase as the limits of material behavior are stretched to improve the performance of engineered structures and devices. Employers recognize the need for employees competent in corrosion engineering, but as the NRC report reveals, they are not finding it in today's graduating engineers. The report identifies a deficiency in fundamental knowledge of corrosion engineering, little understanding of the importance of corrosion in engineering design, and a lack of know-how to control corrosion in the field. In fact, the problem is so critical that a principal concern of employers is that those making design decisions don't know what they don't know about corrosion. At the very least, it would benefit employers if they required that all engineers crafting design and materials selection decisions at least know enough about corrosion to understand when to bring in an expert.

In the NRC report "Assessment of Corrosion Education," the committee suggested several recommendations to meet the needs of both industry and the public sector with respect to training qualified engineers to solve current corrosion issues, as well to tackle the problems presented by the CGCs.

The primary recommendation in the report for industry and government agencies should be to strengthen the provision of corrosion education by developing a foundational corps of corrosion faculty. This can be achieved by supporting R&D in both the sciences and engineering and by providing incentives to universities (e.g., endowed chairs in corrosion control) to hire and maintain a strong faculty base.

Other recommendations for industry and government focus on strengthening the educational resources available. This is attainable by enabling the setting and updating of learning outcomes via publicizing skill sets for corrosion technologists, funding educational modules for corrosion courses, supporting faculty development through internships and sabbatical opportunities, and supporting cooperative programs between universities and government laboratories. Industry also can enable its employees to fill in skill-shortages with specific short courses.

At the university level, engineering departments should incorporate elective learning outcomes and coursework on corrosion into all engineering curricula. Improving the overall awareness of corrosion-control requires that more engineers have a basic exposure to corrosion, enough to "know what they don't know." Additionally, materials science and engineering (MSE) departments should establish required learning outcomes on corrosion into their curricula. All MSE undergraduate students should be required to take a course in corrosion control to improve the corrosion knowledge of graduating materials engineers.

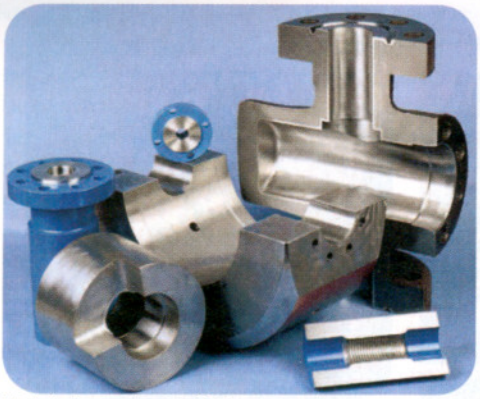
The above recommendations can be implemented relatively quickly. However, a longer term national corrosion policy is necessary. The NRC Committee believes this policy should have the vision of:

- Knowledge of the environmental degradation of all materials integrated into the education of engineers
- A mission to provide guidance and resources that will enable educational establishments to achieve the vision

To meet this need, the committee recommended the formation of a corrosion education and research council composed of government agencies, industry, and academia to develop a continuing strategic plan for fostering corrosion education with the appropriate resources for executing the plan.

celerated over the past few decades. Among the many success stories associated with these new materials, one of the most important is the development of the modern family of austenitic stainless steels.

An example of a systems approach to improving component life and reducing corrosion was achieved for automobiles, especially those in harsh environments. Specifically, car body panels are now routinely fabricated from two-sided galvanized steel, providing considerable protection against corrosion. A paint-primer layer applied by a cathodic electrodeposition process in combination with advanced metal pretreatments and galvanizing result in a nearly defect-free, highly protective coating system. Similarly, exhaust systems are made of relatively inexpensive, but long-lasting, stainless steel, while chrome trim has either been eliminated or galvanically isolated. These approaches mitigate corrosive destruction of the metallic components of the car during its expected life.



Nickel-base alloys offer improved stress corrosion cracking resistance.

Coil of galvanized steel strip.

Additionally, nonmetallic components incorporate mitigation strategies to ensure safety and increase life. Polymeric materials replaced metals in car bumpers and fenders to achieve both corrosion resistance and weight reduction. UV radiation- and heat-resistant polymers were required to accomplish this replacement. Enhanced resistance to UV degradation also is incorporated into the protective coatings on the entire car body. Each component of the automobile system is designed to incorporate a mitigation strategy to reduce the detrimental effects of corrosion, thus retaining the value, increasing the life, and reducing the overall maintenance costs and environmental impact of the car.

Corrosion research is aimed at understanding the specific details of the mechanisms of corrosion, and is driven by application needs. Mitigation, which is a corrosion engineering activity, is most successful when it is guided by a mechanistic understanding of corrosion.

Federal agencies in corrosion mitigation

Top-level priorities for federal investment are contained within each federal agency's strategic plan, budget requests to Congress, presidential speeches, and Congressional hearings. The top national priorities were categorized as: Infrastructure, Health and Safety, Energy, Environment, National Security, and Education. Federal agencies and departments associated with these national priorities have distinct roles in corrosion research.

The major federal agencies that invest in corrosion research are Dept. of Commerce/National Institute of Standards and Technology (DOC/NIST), the Departments of Defense (DOD), Energy (DOE), and Transportation (DOT), Department of Health and Human Services / Food and Drug Administration (HHS/FDA), NASA, and National Science Foundation (NSF). A brief examination by the NRC Committee of current research grants funded by NSF reveal a large number (40+) dealing with various aspects of corrosion research. However, there does not yet appear to be any clear themes to the corrosion research projects and no apparent program strategy regarding corrosion research. It is worth reiterating that the tasks of designing against corrosion and mitigating materials degradation do not have to be isolated even though each department will have different needs. Collaboration among departments and agencies can be augmented by collaboration with state government and private entities such as professional societies, industry consortia, and standards-making bodies.

Grand challenges facing the corrosion community

Although much has been learned about the causes of corrosion, and several strategies for mitigation have been implemented, important corrosion R&D remains to be accomplished. Increased demands on systems to address societal needs require new materials exposed to increasingly aggressive environments. A strong link between fundamental research at the atomistic level and at the engineering level still needs to be established to advance innovative strategies in mitigating the ravages of corrosion damage on the nation's infrastructure. Research designed to address these national needs requires significant investment by several federal agencies and departments in collaboration with universities, national laboratories, and the private sector. The NRC report "Research Opportunities in Corrosion Science and Engineering" has as one of its tasks identifying the Corrosion Grand Challenges (CGCs), which are deemed to be the drivers and guiding principles to form the framework for prioritization of research and development activities. These challenges demand an integrated body of cross-disciplinary and interdisciplinary scientific and engineering research targeted at specific needs, coordinated to minimize duplication and to take advantage of synergism. The report concludes that the research demands can be conveniently expressed in four CGCs:

I Development of cost-effective, environment-friendly, corrosion-resistant materials and coatings
II High-fidelity modeling to predict corrosion degradation in actual service environments

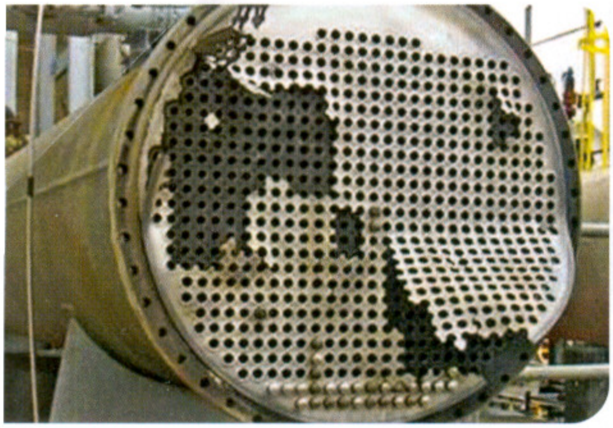
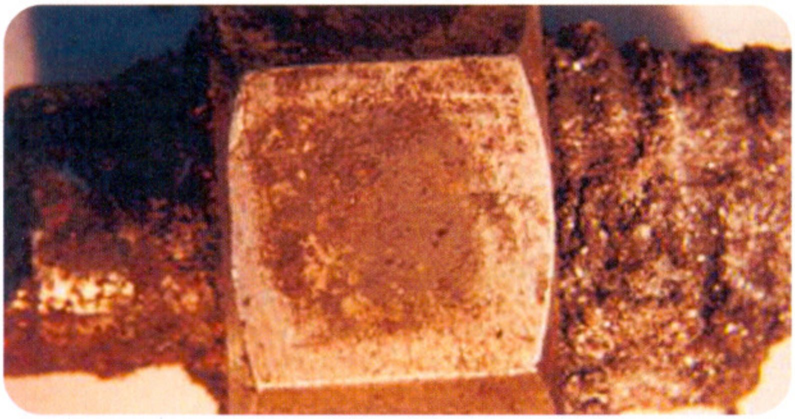


Photo of a heat exchanger failure.

Concrete damage from corroded rebar by salt in marine atmosphere.



Corroded bolt from galvanic corrosion. From Stress-Corrosion Cracking and Galvanic Corrosion of Internal Bolts from a Multistage Water Injection Pump, J. of Failure Analysis and Prevention, *Vol 8, No. 1, p 48-53, 2008.*

III Accelerated corrosion testing under controlled laboratory conditions; such testing would quantitatively correlate with the long-term behavior observed in service environments

IV Accurate forecasting of remaining service time until major repair, replacement, or overhaul becomes necessary; i.e., corrosion prognosis

CGC I, the ultimate proactive challenge, is to develop materials that resist corrosion for the entire life of the material in its given application. The remaining three CGCs effectively address the design and in-service life cycle of functional components.

CGC II leads to the development of modeling tools and databases that allow for calculating the degree of corrosion attack and the effort required to reduce its impact. These modeling tools and databases should account for particular applications given the material of interest, sufficient knowledge of the anticipated corrosive environment, and the different corrosion processes of concern. This capability allows quantitative consideration of the life cycle costs for different design solutions during the acquisition phase of a system.

CGC III attacks the complex issue of extrapolating (with high fidelity) expected field performance based on laboratory scale testing. The crux of the challenge is that there is a large mismatch between the time available for laboratory testing (typically on the order of months) and the time that a structural or functional component will be in service (typically many years). Therefore, laboratory testing must be accelerated, requiring a significant knowledge of the underlying mechanisms of corrosion and the expected corrosive environment including temporal variations in key environmental parameters.

CGC IV addresses the critical need to monitor the actual deterioration of a component once it is in service, and then provide a reasonable forecast of the remaining time before a maintenance or replacement action is required. Underneath all these "applied issues" is a strong need to understand more completely the basic science behind the mechanisms of corrosion, which are also barriers to progress in CGC I-IV, and to disseminate broadly the information and knowledge that enable the grand challenges to be addressed in all their aspects.

The overarching vision of the NRC committee is that corrosion research will be advanced further and faster when corrosion behavior is included along with other materials properties in modern science and engineering practice, and when corrosion issues are addressed proactively rather than reactively. The full NRC report outlines several conclusions and recommendations for government agencies and provides a useful framework for structuring corrosion research opportunities. It is anticipated that this report will occasion a renewed critical interest in corrosion research by federal agencies, unquestionably resulting in significant benefit for the nation once the results of the research are implemented. Revitalization of the governmental and industrial corrosion research efforts will play an important role in reducing the costs of corrosion and better controlling the adverse affects.

Conclusions

This is an exciting, critical time in the history of corrosion science and engineering. The potential for great discovery is pushing the field forward, and a grave threat that institutional knowledge might be lost is pulling the field backwards; both issues are working toward renewing interest in corrosion science. Recent advances in scientific instrumentation enabling nanoscale and atomic characterization are opening opportunities to explore the fundamental mechanisms of corrosion processes that might yield insight not previously possible. Also, the computational power available today is unprecedented, allowing for complex modeling and simulation to be done at low cost at ever increasing rates. These new tools have the ability to revolutionize the speed of innovation and discovery, changing corrosion research from a predominantly "Edisonian" process to a rules-based, mechanistic approach.

The state of knowledge in corrosion science and engineering lies predominantly in an older generation that has amassed considerable years of fieldwork experience primarily with conventional metallic materials. It is therefore imperative to act now to energize and educate young scientists and engineers about corrosion to create a sufficiently skilled workforce (see sidebar). Otherwise the current generation of experts will retire and the basis of institutional corrosion knowledge will be lost, and the nation will also experience a reactive long, drawn out learning process of mitigating corrosion in new materials as they unexpectedly deteriorate in service. The public's rising expectations regarding safety and the financial need to reduce long-term capital costs should go far to emphasize the importance of understanding and developing corrosion design, mitigation, detection, and prediction strategies now.

We hope this article will increase awareness of the impact of corrosion on our society, enabling the collaboration between scientists and engineers to tackle the inherently interdisciplinary nature of corrosion science, and promote the importance of education in corrosion science for all engineers. For those who wish to further understand the issues described in this article, we recommend you read the full NRC reports for a more detailed explanation of the Grand Challenges and methods for improving corrosion education. ❍

References:

1. Research Opportunities in Corrosion Science and Engineering; available at www.nap.edu/catalog.php?record_id=13032.
2. Assessment of Corrosion Education; available at www.nap.edu/catalog.php?record_id=12560.
3. Corrosion Costs and Preventive Strategies in the United States (1999), Federal Highway Administration study performed by NACE International; available at www.corrosion-cost.com/pdf/main.pdf; accessed November 2010.
4. GDP data from www.bea.gov/national/index.htm#gdp.

For more information: Erik Svedberg, Ph.D., senior program officer, National Materials Advisory Board, Board on Manufacturing and Engineering Design, National Academies, 500 Fifth St., NW, Washington, DC 20001; tel; 202/334-2308; fax: 202/334-3718; email: esvedberg@nas.edu. Adam Winkleman, Mirzayan Science and Technology Policy Fellow, National Materials Advisory Board. Robert E. Schafrik, general manager, GE Aircraft Engines, Co-Chair of study. David J. Duquette, Professor of Metallurgical Engineering, Rensselaer Polytechnic Institute, Co-Chair of study. The NMAB and the Board on Manufacturing and Engineering Design merged to form the National Materials and Manufacturing Board.