Opportunities and Challenges in Corrosion Education: Review of a National Research Council Assessment

by John R. Scully and Wesley L. Harris

Corrosion includes the destructive oxidation of metals and nonmetallic materials resulting in the degradation of function due to exposure of materials to corrosive operational environments. The need for prevention of the degradation of materials in engineered components has been addressed for many years. However, the need remains urgent and critical to the U.S. given existing as well as new threats to materials including harsh and extreme operating environments. Such degradation impacts the U.S. economy, health, and safety. The annual cost of such degradation is in the hundreds of billions of U.S. dollars.

An improvement in capability to better manage and reduce degradation of materials in engineered products requires a workforce educated and trained in the application of the tools, principles, and practices of corrosion engineering. The corrosion industry and government stakeholders, concomitant with university engineering leaders, are challenged to address our national need for the production of a strong, viable corrosion engineering workforce. In response to a request from the Department of Defense, at the direction of the U.S. Congress, the National Research Council formed a committee to assess the status of the U.S. university–industry engineering enterprise to produce the corrosion engineering workforce needed to ameliorate the effects of corrosion on materials in engineered products. The following article highlights some of the findings and recommendations of that assessment.

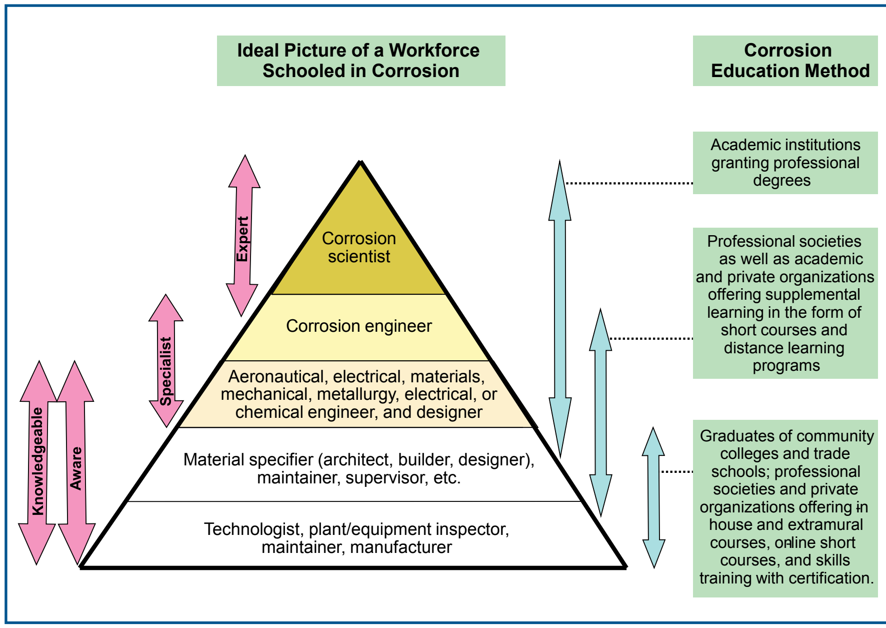

Fig. 1. *The corrosion workforce pyramid. The pyramid shows the various categories of corrosion professionals and the education they need. The green boxes on the right indicate the educational paths they follow. Adapted from J. R. Scully, presented at the 16th International Corrosion Conference, Beijing, China, September 2005.*[1]

The Existing State of Corrosion Education in the U.S.

The structure of the corrosion workforce is summarized in Fig. 1 which shows the various categories and levels that create the overall workforce.[2] The width symbolizes the relative numbers of trained workers estimated to be necessary in each category to support the needs of our complex technological society. For instance, only a few corrosion experts and specialists are needed to address new or vexing corrosion problems not readily solved by off-the-shelf solutions, standardized practices, specifications, or codes. These corrosion experts must possess the knowledge to address new corrosion mechanisms, new materials or coatings, unexpected or harsh environments that push materials to their performance limits, develop new tools to expand our knowledge and develop models and field sensors to monitor material health, and otherwise gauge the performance and degradation of materials.

The next level includes the various types of tertiary or post-tertiary engineers including mechanical, aerospace, chemical, civil, biomedical, and electrical engineers that are at the heart of engineering design practice. These engineers are most often responsible for the design of technological hardware, components, and systems. Such engineers, along with a few colleagues that graduate with a degree or emphasis in materials engineering, are those who usually make materials selection decisions. These engineers ideally would either be knowledgeable about materials and their corrosion based upon some basic level of materials engineering training including corrosion principles, or know when to engage other engineers that do. In other words, the NRC study emphasized that they must be "corrosion aware," at least know "what they don't know," and proactively involve a corrosion expert when the need arises. There also is a need for a dedicated corrosion engineer that can help select the best material or coating early in designs as well as choose the best protection strategy. Moreover, the ability to anticipate possible forms of corrosion, and their consequences affecting their designs would be highly desired.

The lower levels of the pyramid include all technicians and other workers that install, prepare, inspect, and otherwise implement and maintain the protection strategies designated for a given material-environment system. This includes builders and architects that add details to designs such as coatings and treatments. These practitioners must be skilled in the use of coatings, inhibitors, surface and environmental treatments, cathodic protection systems, as well as make repair decisions and otherwise conduct the day to day business of corrosion mitigation and avoidance on a plethora of technological system vulnerable to corrosion.

Today it is commonplace for many or most of the corrosion workforce to be drafted into the area often with little or no prior foundational training to complete their job assignments. Many of these workers are then trained on the job via extramural short courses and/or by lessons learned and trial and error learning methods. One of the findings of the National Academy study was that in many cases corrosion education of design engineers in any formalized setting was practically non-existent. In other cases, such as the knowledge based education of corrosion experts, the continuity of such education at Universities in the U.S. is threatened and under ever increasing stress due to the infrequent replacement of

(continued on next page)

retiring engineering faculty with expertise in corrosion with new faculty members following in the same field. This may go hand in hand with a shortage or decline of research funding to support corrosion research topics which enable the training and mentoring of future corrosion experts. Consequently, corrosion classes are often not offered at many universities. This contributes to the trend where corrosion experts are in many instances drafted into this role and trained on the job without formal education in corrosion.

In summary, corrosion training today occurs in a number of ways, perhaps somewhat inefficiently. The first question is what is the ideal workforce structure and optimal way to develop that workforce to meet the needs of a complex technological society? The next question concerns what comprises corrosion education in each category today, and how is it currently achieved as well as how should it be achieved? To frame this discussion, the National Academy study identified two distinctly different types of education as mentioned above: knowledge based and skills based.[1] In general, experts and specialists require a "knowledge based" education that focuses on training in fundamentals that may be applied to a variety of (perhaps unexpected or new) situations. Practitioners need a "skills based" education that enables them to perform a large number of predictable corrosion mitigation tasks. The latter are often guided by industry and governments standards, guidelines, specifications, and practices. Regarding the first question, the NRC study for the most part endorsed the need for the existing pyramid but questioned how well and whether enough trained engineers were being supplied to meet all the engineering needs that could reduce the costs and impacts of corrosion. It is useful to discuss the existing state of corrosion education in the context of undergraduate, graduate, and professional development type experiences to cover the various ways in which knowledge and skills based education occurs today and can be developed in the future.

Undergraduate Corrosion Engineering Education

The NRC study found that undergraduate corrosion education was non-existent in many engineering schools. This was attributed insufficiently trained, willing, and interested faculty primarily due to a lack of research funding in corrosion. Indeed, numerous MSE department chairs pointed out that the presence of any sub-specialty in materials science in a given department and university was usually contingent on availability of research funding. Although the merit of having the availability of undergraduate classes contingent upon the research funding of the faculty may be questioned, it is indeed the situation at research universities in the U.S. and around the world. This situation is not unique. An analogous situation exists with respect to other traditional yet highly useful and necessary areas of materials science and engineering such as welding, casting, and even traditional fracture mechanics and metallurgy concentrations.[3]

Even in materials science and engineering programs that include corrosion oriented faculty, undergraduate technical training in corrosion is often not mandatory. A corrosion class, if offered at all, is presented as an optional technical elective. In many schools, even an introductory class in materials science and engineering is not required of all engineers despite availability as a technical elective. In introductory material science classes, corrosion coverage often consists of one or two lectures on materials degradation if fit in at all. Moreover, a materials selection approach to teaching materials engineering is sometimes used. Consequently, corrosion fundamentals are not introduced. Instead, corrosion takes the form of lists of corrosion properties which are not fully integrated with other topics such as mechanical properties that might be affected by corrosion. In the best case scenario where a structure–property–design oriented approach was used, corrosion was relegated to a chapter at the end of the book and/or simple tables presenting qualitative rankings.[4] These approaches miss the opportunity to provide a knowledge based education that would be deep, flexible and universal enough to be applied to future situations that defy off the shelf solutions. Today, even in the best case scenarios where a technical elective in corrosion based on fundamentals is offered by the small list of schools maintaining expertise in this area, only about 10-20 % of undergraduate engineers typically can fit such a course into their schedules. In some cases, these corrosion classes are taught by retired faculty with no replacement plan on the horizon. Moreover, there has been no dedicated corrosion engineering degree at U.S. universities, which might be useful given the need for some corrosion specialists to assist large teams of design engineers.

Graduate Corrosion Engineering Education

Traditionally, there have been two ways to educate this segment of the corrosion workforce. These include on-the-job training of engineers drafted into the corrosion field augmented by courses at a university, and/or short courses. The other educational route is by a formal tertiary education leading to an MS or PhD degree in corrosion with an intensive thesis dissertation on a focused corrosion subject. These degrees are mainly granted by materials science and engineering departments but some also come from chemical, mechanical, civil engineering, or chemistry programs.

The former educational process is often led by a mentor taking responsibility for this training. The NRC committee and those polled agreed that on the job training is an expensive, long-term, inefficient process leaving many gaps in corrosion knowledge in areas that are not addressed by either a short course, on-the-job training, or a mentor's knowledge. How 30 years of knowledge can be conveyed by retiring senior corrosion experts to novice engineers in a short period of time is a topic of great interest as the U.S. workforce ages and retires.[5] The latter type of education often occurs in a formal setting such as one of a few universities and is led by a few key professors who are active in corrosion research. Concerns with the latter, although somewhat anecdotal, include the belief that there is a shrinking number of corrosion faculty and also a decline in research funding for those faculty remaining in corrosion. The impression is that retiring corrosion experts are often not replaced in MSE departments and that the highly competitive materials science research field drives these decisions as mentioned above.[2] These concerns and the resultant lack of experts has great impact on all levels of the

> **"One of the greatest enduring challenges in engineering education today is to make broadly available and attract students to classes covering subjects such as materials science, applied electrochemistry, and corrosion of engineered materials."**

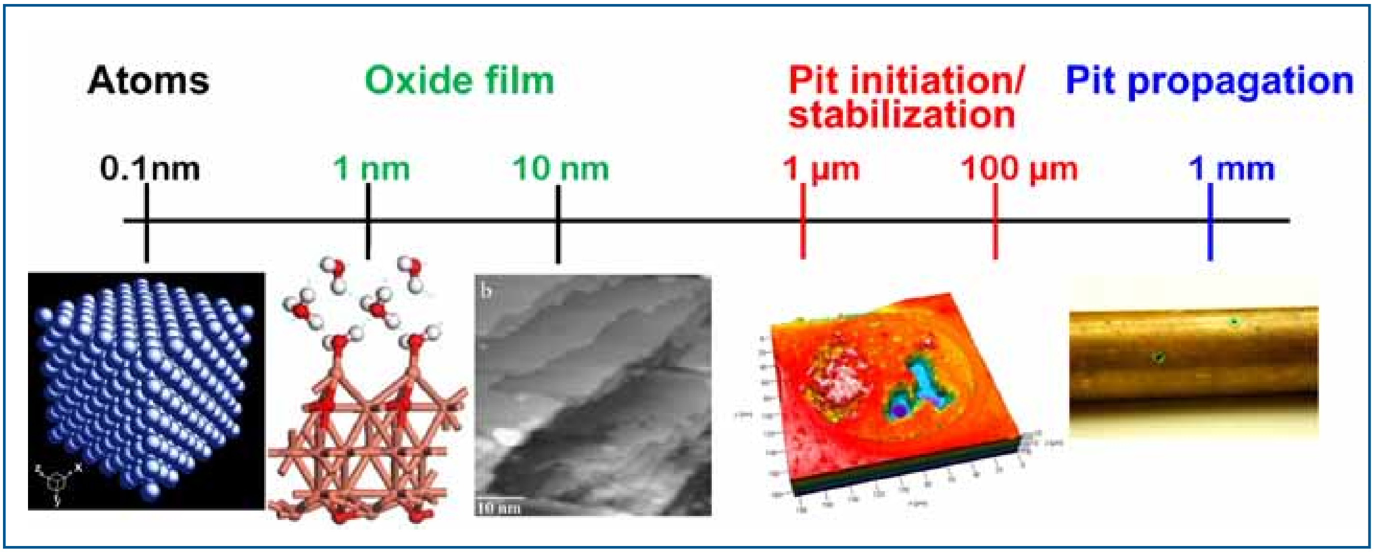

Fig. 2. *The length scales that must be considering to fully understand pitting corrosion.*[12]

corrosion workforce pyramid shown in Fig.1 by either directly controlling the supply of experts or, indirectly, by limiting the pool of potential new educators in corrosion. For instance, technical electives on corrosion would not be taught in many engineering schools because of a lack of qualified or interested lecturers.

Post-Graduate and Professional Corrosion Education

Opportunities exist now for post-graduate education and professional development in the form of short courses offered by technical societies, community colleges, and private companies. Corrosion technologists and builders have access to short courses ranging from day classes, evening classes, and week-long seminars. Standards organizations also offer classes covering standardized test techniques and protocols. The growing ability to present Web-based classes makes this process more facile. Such classes may be adequate for skills based education. The chief shortcomings are fragmentation of topics and the inevitable skills gaps that result, as well as the lack of knowledge based training to draw upon if situations are uncommon and judgments are necessary. A workforce trained utilizing on-the-job via professional development opportunities often lacks a foundation in core corrosion subjects. Another shortcoming is the inevitable non-optimal sequencing of classes controlled by many other factors such as work schedules. There is also the inconvenience and impracticality of semester-long classes should such comprehensive and long-term training be desired.

A Proposed Model and Recommendations Toward an Improvement Environment for Corrosion Education

There are both strategic and tactical recommendations for improvement in corrosion education at the various levels shown in Fig. 1. The NRC study pointed out that one key to the entire corrosion workforce relies on the training of a future generation of the knowledge based experts shown at the top of the corrosion pyramid (Fig. 1). This cadre of trained specialists will be responsible for corrosion research to help enable future technologies likely handicapped or hindered by new corrosion degradation challenges. For instance, a National Academy Grand Challenges in Engineering study[6] listed several technological challenges requiring significant engineering or scientific advances to insure a better standard of living for civilization. Many of these challenges have significant corrosion issues that cannot be solved with off-the-shelf corrosion knowledge. Of equal importance, a pool of corrosion experts is needed as instructors to teach the knowledge based education that can create of the next generation of both "corrosion aware" design engineers as well as experts and specialists that bring about the next wave of fundamental knowledge. Therefore, a recommended strategic goal would be to provide funding that would enable government and industry fellowships, endowed chairs or national centers in corrosion excellence which would help to ensure survival of knowledge based education programs in corrosion. At the same time, corrosion faculty must do a better job of disseminating the importance of corrosion more broadly outside of the corrosion subspecialty and link corrosion issues to engineering grand challenges. They should reach outside of the immediate corrosion community for broader dissemination. They must dispel the incorrect impression that off-the-shelf knowledge and the skills of today in corrosion are adequate for tomorrow.

Knowledge-based Education

Corrosion experts and specialists must be well versed in materials engineering, chemistry and electrochemistry, and fracture mechanics in the case of chemo-mechanical corrosion modes such as fretting, film rupture, and environmental fracture. Depending on focus, additional topics such as surface science, polymer science, colloid chemistry, fluid mechanics, and electrical engineering are quite useful. The follow-on NRC study pointed out the multi-scale nature of corrosion phenomena (Fig. 2).[7,8,9] Events and processes in corrosion must be understood at the atomic, micrometer, millimeter, and centimeter length scales.[9] These processes control many corrosion properties and behavior at the macro-scale. In addition, corrosion events occur on time scales from less than picoseconds through many years. The length and time scale "bridge challenge" is an educational issue common to the corrosion field as well as other topics in applied electrochemistry.[10]

A knowledge based education on many of these topics is provided now by several major universities in the U.S. and around the world with formal corrosion programs with intensive education of "in resident" graduate students. A two year master's degree or three to five year PhD program is usually required.[11] To sustain funding over the period necessary to produce graduates with this type of knowledge based education, funding agencies may need to adapt new approaches in addition to the traditional research streams.

(continued on next page)

(continued from previous page)

Some funding should be established in the form of dedicated centers, dedicated faculty fellowships, or student training grants such as the National Science Foundation's research experience for undergraduates. One recently established DoD University Corrosion Collaboration is making a strong effort to fulfill this recommendation. Knowledge-based training in electrochemistry, chemistry, and applicable materials valuable to the corrosion workforce may also come from closely related areas such as battery, fuel cell, photo-electrochemical, electro-synthesis, nanofabrication, and chemical and petroleum engineering. However, few students in these other areas have access to a corrosion engineering or science graduate class. Ideally, this could be facilitated by improved distance learning relationships between schools and engineering departments such that the few schools with the teaching expertise in corrosion could supply it more broadly to the engineering community.

There are also a few programs which enable industry and government lab personnel to spend a year at a university in order to complete post tertiary training in corrosion. These programs should be expanded and include both faculty and student professional participation. The issue of job knowledge management and transfer remains an issue whose effectiveness and limitations are worth discussing further.[4]

At the undergraduate level it is recognized that the expanding number of technical electives recommended to engineering students creates intense competition between material/corrosion classes. One recommendation was to introduce learning outcomes into their curricula and to require corrosion control classes in curricula. One school teaches a combined corrosion, battery, fuel cell technical elective of broad engineering school interest. This class is taught in live classes and simultaneously around the school's home state through a blackboard type Web-based approach which enables broad access. Another strategy would be to teach classes of high industry interests such as corrosion in a compressed format such as over one month that could be placed in between semesters or quarters and also enable working professionals to further their development with fewer scheduling conflicts. Yet another idea would be to more fully integrate corrosion into almost every chapter of other materials science and engineering classes. One example is to fit corrosion into a course structure that focuses on optimization of material properties governed by materials structure, composition, and processing.[3] The effects of corrosion on optimization or degradation of each property (*e.g.*, strength, fatigue endurance limit, fracture toughness, etc.) could be integrated with that subject and appear in each chapter. In addition, at least one university is establishing a Corrosion Engineering bachelor's degree that enables in depth study of corrosion fundamentals, mitigation strategies, and the design of corrosion protection systems. Lastly, the creation of educational modules that could be offered and distributed to other universities that do not offer corrosion classes was recommended. Expected corrosion learning outcomes and skill sets should be listed and periodically updated for the entire engineering and science communities. All of these measures would help to create a workforce of design engineers, and those that perform materials code and specification compliance that are "corrosion aware" if not knowledgeable about corrosion.

> **The committee strongly felt that engineering classes in corrosion with specific learning outcomes should be available to undergraduate engineers who will practice design, undergraduate materials engineers who will perform materials selection, and graduate level engineering students specializing in corrosion.**

Skills-based Education

This segment of the workforce can continue to be trained by distance learning, short courses, and compressed duration educational programs. This approach is especially viable as a short term or tactical measure but is not seen to be the long-term solution. Many opportunities already exist. Distance learning opportunities at universities and through technical societies alike are rapidly expanding such that full time enrollment in residence is no longer required. The biggest concerns here include cost, location skills gaps, and sub-optimal sequencing of classes which are typically lacking. These could be handled by online MS degree programs such as those offered by some European corrosion centers. Here, the student has an advisor or mentor to recommend class sequences to optimize learning and skills building. Today, coordination is lacking between technical societies and universities. However, in the most ideal case for students, there would be coordination between knowledge- and skills-based education in a complementary fashion with a unified goal of enhancing professional development.

In summary, corrosion education requires several strategic initiatives and some practical measures to improve the education and training that each level of the corrosion workforce can receive. (Fig. 1).

Conclusions

Corrosion has an impact on safety, reliability, and the economy over a broad range of technological applications from national defense and infrastructure to health and the welfare of populations. Successful corrosion engineering application may save billions of dollars annually in the U.S. alone and help meet the engineering grand challenges of the future.[13] However, a highly trained corrosion workforce is needed to accomplish these goals.

The current level of effectiveness of corrosion engineering curricula in the U.S. is not sufficient to address the nation's need to improve safety, reliability, and reduce costs due to corrosion. To remedy this situation, corrosion engineering education, training, and research must be addressed at several levels: (1) short-term initiatives by universities, government, and industry and (2) long-term initiatives jointly taken by the federal government and the U.S. corrosion research community. The corrosion workforce pyramid may be improved if industry and government can strengthen the provision of corrosion engineering education to produce more corrosion faculty and research, as well as infuse corrosion into all undergraduate engineering curricula. The formation of a national council on corrosion engineering to address the national need for effective corrosion engineering application, education and research may also improve the workforce pyramid.[14] Such a national council should consist of members from government, industry, and academia. The national corrosion council would develop a vision, mission, and a dynamic strategic plan with funding resources for a systemic corrosion education enterprise.[15]

About the Authors

Wesley L. Harris is the Charles Stark Draper Professor of Aeronautics and Astronautics and the Director of the Lean Sustainment Initiative at MIT. Before his appointment as Associate Provost, Prof. Harris served as head of MIT's Department of Aeronautics and Astronautics from 2003 to 2008. He earned his BS in aerospace engineering at the University of Virginia, and his MA and PhD in aerospace and mechanical sciences at Princeton University, on whose Board of Trustees he later served (2001-2005). Wes has been elected to membership in the National Academy of Engineering, the Cosmos Club, and the Confrerie des Chevaliers du Tastevin. He is also an elected fellow of the American Institute of Aeronautics and Astronautics, the American Helicopter Society, and the National Technical Association, in recognition of his achievements in engineering, engineering education, management, and advancing cultural diversity. He may be reached at weslhar@mit.edu.

John R. Scully is the Charles Henderson Chaired Professor of Materials Science and Engineering at the University of Virginia (UVa). Prior to his appointment at UVa, he worked at Sandia National Laboratories and AT&T Bell Laboratories. He currently co-directs the Center for Electrochemical Science and Engineering in the Department of Materials Science and Engineering. He teaches a technical elective entitled Corrosion, Batteries, and Fuel Cells to undergraduate engineering students and Advanced Electrochemistry as well as Materials Characterization classes to graduate engineering students. His research is in the corrosion-metallurgy area. Scully is a Fellow of ECS, NACE, and ASM. He received the ECS H. H. Uhlig Award; the A. B. Campbell, H. H. Uhlig, and W. R. Whitney Awards from NACE; and the F. LaQue Award from ASTM. He is the technical Editor of *Corrosion*. He recently served on the National Research Council committees assembled to Assess Corrosion Education and Identify Research Opportunities in Corrosion Science and Engineering. He may be reached at jrs8d@virginia.edu.

References

1. J. R. Scully and R. G. Kelly, "Corrosion Education in the 21st Century," 16th International Corrosion Congress: Corrosion Tech. in the High Technology Era, Sept. 19-24, Beijing, China (2005).
2. Assessment of Corrosion Education, National Research Council of the National Academy, 500 Fifth Street, Washington DC, ISBN 978-309-11703-6, p. 33 (2009).
3. In the NRC study, several MSE department chairs stated that they would be reluctant to hire new faculty in corrosion stating that such candidates could not compete for funding.
4. M. Ashby, H. Shercliff, and D. Cebon, *Materials Engineering, Science, Processing, and Design*, Elsevier, Amsterdam (2007).
5. H. Hack, "Knowledge Transfer from Experienced to Novice Engineers," 2012 Plenary Lecture, NACE Corrosion Conference and ASM Baltimore Washington Section Meeting (2012).
6. Grand Challenges for Engineering, National Academy, 500 Fifth Street, Washington DC (2008).
7. Research Opportunities in Corrosion Science and Engineering, National Research Council of the National Academy, 500 Fifth Street, Washington DC, ISBN 978-0-309-16286-9, p. 69 (2011).
8. E. McCafferty, *Introduction to Corrosion Science*, Springer Science and Business, New York (2010).
9. Research Opportunities in Corrosion Science and Engineering, National Research Council of the National Academy, 500 Fifth Street, Washington D.C., ISBN 978-0-309-16286-9, p. 91 (2011).
10. (a.) R. C. Alkire and R. D. Braatz, *AIChE Journal*, **50**, 2000 (2004); (b.) R. Alkire and M. Verhoff, *Electrochim. Acta*, **43**, 2733 (1998); (c.) V. R. Subramanian and R. D. Braatz, *The Electrochemical Society Interface*, **19**(2), 37 (2010).
11. The optimal time period required for a high quality PhD in corrosion metallurgy is a pedagogical topic of discussion.
12. Courtesy of H. Cong, University of Virginia Center for Electrochemical Science and Engineering. Inlaid figures adapted from: C. D. Taylor and M. Neurock, in Current Opinion, *Solid State & Materials Science*, **9**(1-2), 49 (2005); J. Kunze, V. Maurice, L. H. Klein, H. H. Strehblow, and P. Marcus, *Solid State & Materials Science*, **9**, 49 (2005) and *Corrosion Science*, **46**, 245 (2004); and B. J. Marshall, Master's Thesis, Virginia Polytechnic Institute and State University, Blacksburg (2004).
13. Assessment of Corrosion Education, National Research Council of the National Academy, 500 Fifth Street, Washington DC, ISBN 978-309-11703-6, p. 9 (2009).
14. Assessment of Corrosion Education, National Research Council of the National Academy, 500 Fifth Street, Washington DC, ISBN 978-309-11703-6, p. 6 (2009).
15. Assessment of Corrosion Education, National Research Council of the National Academy, 500 Fifth Street, Washington DC, ISBN 978-309-11703-6, p. 7 (2009).