AC 2012-4630: INCORPORATING SUSTAINABILITY ISSUES INTO AN UNDERGRADUATE CORROSION COURSE

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Incorporating Sustainability Issues into an Undergraduate Corrosion Course

Abstract

Sustainability issues were introduced into an undergraduate corrosion course by means of special assignments and case studies. There are actually two courses; an undergraduate course called Corrosion Engineering, ME 349 and a graduate course called Corrosion, ME 387Q and they are taught together. In addition to the traditional types of assignments that focus on forms of corrosion and methods of testing for and mitigating corrosion, the course was redesigned to bring sustainability issues to the forefront; specifically with respect to undergraduate education.

Much attention was paid to topics in the news and in recent journal articles and a special section was added on corrosion issues associated with clean energy technologies. . Two case studies were also discussed; one in which a waste material, fly ash was added to concrete to improve its durability and another in which corroded pipes were used in low load-bearing architectural/structural applications.

A section on Materials Selection was introduced at the beginning of the course and then revisited near the end of the course; this time taking into account sustainability issues. A major focus was whether the choices should be changed or modified in order to address sustainability. These types of topics will be discussed in the paper, with emphasis on creating awareness about sustainability issues in every aspect of corrosion protection

Introduction

Corrosion is usually defined as the destructive result of chemical reactions between a metal (or alloy) and its environment; it returns the metal to its combined state [1]. Corrosion may be more broadly defined as the destruction or deterioration of a material because of reactions with its environment.

The overall objective in this course was to incorporate sustainable engineering into the corrosion engineering/corrosion course. Secondary goals included creating awareness of professional and contemporary issues in engineering practice. The central theme was based on identifying ways in which we can use the earth's resources more efficiently, produce less waste, and at the same time continue to provide the necessary goods and services for a growing global population. The focus was on creating awareness about sustainability issues in every aspect of corrosion protection.

Since this was an existing course, a list of topics already existed in the course catalogue. Therefore, it was decided to incorporate sustainability principles into the existing framework of the course. Emphasis was placed on corrosion protection as a means of corrosion reduction, as well as minimization. The list of topics is shown below. Topics that were modified to include sustainability issues include Topics, 2, 6, 14, 15 and 16.

Technical Content of ME 349 Corrosion Engineering/ ME 387Q Corrosion

1. Introduction-The Forms of Corrosion, the Technology of Corrosion and the Evaluation of Corrosion
2. Corrosion Protection by Materials Selection
3. Electrochemical Thermodynamics and Electrode Potentials
4. Electrochemical Kinetics of Corrosion
5. Passivity
6. Corrosion Issues Associated with Clean Energy Technologies
    - Solar
    - Wind
    - Biofuels
    - Carbon Capture and Sequestration
7. Polarization Methods to Measure Corrosion Rates
8. Galvanic and Concentration Cell Corrosion
9. Pitting and Crevice Corrosion
10. Effects of Metallurgical Structure on Corrosion
11. Environmentally Induced Cracking
12. Corrosion Related Damage by Hydrogen, Erosion and Wear
13. Failure Analysis
14. Corrosion in Selected Environments
    - Atmospheric Corrosion
    - Corrosion in Automobiles
    - Corrosion in Soils
    - Corrosion in Water Systems
    - Corrosion of Steel in Concrete
    - Corrosion in the Petroleum Industry
    - Corrosion in the Aircraft Industry
    - Corrosion in the Microelectronics Industry
15. Methods of Corrosion Protection: Anodic, Cathodic, Coatings, Inhibitors
16. Corrosion Protection by Materials Selection and Design
17. Report/Presentation on a Selected Corrosion Topic (Symposium Format)

The book used was Principles and Prevention of Corrosion by Denny Jones, Second Edition, Prentice Hall, 1996. It was supplemented with journal articles from Materials Performance, Corrosion, and the Journal of the Electrochemical Society as well as other reading material.

There were 9 individual assignments in all, one group project, and one report/presentation (as well as two in-class exams and a final). Topics with a sustainability emphasis were Topics 2, 6, 14, 15, and 16. The topics of Materials Selection and Materials Selection and Design were deliberately covered twice, in Topics 2 and 16. Since this course is one that many graduate students take to supplement and enhance their research and since sustainability was a new emphasis for the course, there was no difference in the evaluation of the assignments that involved a sustainability focus for the undergraduate and graduate class. However, there was a difference in contribution to their overall grade in terms of their homework and reports/presentations as shown below.

Grading

ME 349		ME 387Q	
Two in-class exams	23% each	Two in-class exams	23% each
Homework	10%	Homework	5%
Report/Presentation	11%	Report/Presentation	16%
Final Exam	33%	Final Exam	33%

In order to provide some perspective for results that are to be presented later, some background information on corrosion is presented in the next section.

Corrosion Background Information

When corrosion takes place in metals or alloys, electrochemical reactions take place. These are reactions that can be divided into two or more partial reactions of oxidation and reduction. Corrosion can take many forms that are often listed as described in Jones [1]. Uniform corrosion is characterized by electrochemical reactions that proceed over the entire surface; often given in mpy or mils per year where a mil is 0.001 inch or mm/y, which is millimeters per year. Other types of corrosion include: galvanic or two-metal corrosion, selective leaching or dealloying, crevice corrosion, pitting, intergranular corrosion, environmentally induced cracking, and corrosion associated with fluid flow.

When a metal is placed in an electrolyte or corrosive medium, it achieves a corrosion potential (mixed potential, surface potential, open circuit potential) that falls between the half-cell electrode potentials of the anodic and cathodic reactions. This potential is referred to as Ecorr. This potential can be measured with a voltmeter with respect to a secondary reference electrode such as the Saturated Calomel Electrode (SCE) or Copper-Copper Sulfate Electrode (CSE). These potentials can also be referenced to the Standard Hydrogen Electrode (SHE). The corrosion potential is a very important parameter because testing of a metal under corrosive conditions usually begins at or near Ecorr.

One of the most well-defined forms of corrosion is uniform corrosion and an important parameter in the measurement of this type of corrosion is the polarization resistance, R sub p or Rp, which can be measured based on tests of linear polarization. The polarization resistance is important since it is inversely related to the corrosion rate for uniform corrosion.

The polarization resistance is defined as the slope of the potential-current density curve at the open circuit potential or corrosion potential (Ecorr). This parameter can be used for calculating the corrosion current and corrosion rate. The relationship between the current and voltage in the polarization curve is generally given by:

$$I = I_{corr}\left(e^{\frac{2.303(E-Eoc)}{\beta_a}} - e^{\frac{-2.303(E-Eoc)}{\beta_c}}\right)$$

where,

I is the measured cell current in amps,

I_{corr} is the corrosion current in amps,

E_{oc} is the open circuit potential in volts,

β_a is the anodic Tafel constant in volts/decade,

β_c is the cathodic Tafel constant in volts/decade.

Taking into account certain assumptions including uniform corrosion; a single anodic and cathodic reaction; and approximate values of the Tafel constants, the corrosion current can be related to the Tafel slopes by:

$$I_{corr} = \frac{\beta_a \beta_c}{2.303(\beta_a + \beta_c)} \cdot (\frac{1}{R_p})$$

Tafel slopes and the polarization resistance can be extracted from curve-fitting of the actual data based on the above equations. If the surface area of the metal is know, the cell current density and cell corrosion current density can be determined.

Classroom/Out-of-Classroom Activities

The activities related to sustainability included: (a) an individual assignment on material(s) choices for particular applications; (b) one group project on renewable energy (clean energy) issues; (c) a case study on the use of fly ash in concrete; a case study on the use of corroded drill pipe in walkways and other low load-bearing applications, and (d) one final project that was a report/presentation from each student on a corrosion issue (if possible, one with a sustainability focus).

Topics like wind energy, solar energy, biofuels, and carbon capture and sequestration are usually associated with sustainable engineering. Often these names are considered to be synonymous with sustainability; carefully thought out solutions to our current problems. However, each has its associated problems to overcome in order to be viable and sustainable. These issues were taken into account in the group project. Students were asked to identify and address corrosion issues where the choice of materials and the design of the materials system might lead to more efficiency and less waste than is currently encountered. Throughout the course, students were encouraged to think like a minimalist and consider using the proper choice of material for corrosion protection and also consider how that material could be manufactured and utilized more efficiently. In cases where additional protection needed to be provided (eg anodic protection, cathodic protection, coatings, inhibitors), they were asked to consider materials, procedures, and processes that would be effective, but at the same time would do the least harm to the environment. This is of particular concern in the case of inhibitors, since many of the most widely used and effective inhibitors are toxic.

One case study involved the utilization of fly ash (a waste product from the production of coal) in the production of concrete. Exerpts from two papers were presented to the class [2,3]. The other case study involved the use of corroded pipe for low load-bearing architectural/structural applications. The concern was the projected long-term durability of these pipes.

The final project was a report/presentation on a corrosion topic of the student's choice.

It would be desirable to have a focus on sustainability issues, but it was not a requirement, since many of the students chose to write about their senior design project, thesis, or dissertation topic. Nevertheless, they were encouraged to consider sustainability issues, even if that was not the primary focus of their paper. The paper was to be 3-5 pages for students in ME 349 and 5-7 pages for students in ME 387Q. The accompanying presentation was to be 3-4 minutes for students in ME 349 and 10-12 minutes for students in ME 387Q. The presentations were presented over a 3-hour period.

Results and Discussion

The results of incorporating sustainability engineering principles are indicated below for the specific topics.

Topic 2: Corrosion Protection by Materials Selection, Jones, 1996, Chapter 15
Assignment 1, Chapter 15
The answers are given in parenthesis and are based on Chapter 15 in the book by Jones.
The students were later asked to consider if, in fact, these were the best solutions and if there were possibly other materials they might consider, from a sustainability perspective.
Problem
15-1 Suggest the most appropriate alloys/materials for the following applications.
Include any recommended corrosion prevention measures.

a. knife blades which are resistant to rusting in household and commercial food processing (austenitic stainless steels)
b. buried storage tanks for automobile fuel storage (carbon steels: may need a coating and/or cathodic protection)
e. pipe to transport 50% nitric acid at 90 degrees C in a chemical process plant. (austenitic stainless steels)
f. truck tanks to transport 95% sulfuric acid (austenitic stainless steels; under certain circumstances, may be able to use carbon steel)
k. aircraft landing gear (aluminum alloys, possibly one in 7XXX series)
l. food processing equipment of minimum cost (austenitic stainless steels; aluminum alloys, possibly one in 5XXX series)

With respect to sustainability issues, some students suggested fiberglass or plastics for Problem 15-1 b, when the questions were revisited in Topic 16. It was observed that there was insufficient information available to make reasonable comparisons for all of the materials in all of the questions.

Topic 6: Corrosion Issues Associated with Clean Energy Technologies; References included Metals Handbook, 1987; Metals Handbook, 2003; Metals Handbook, 2005, Materials Performance, 2009-2011 issues, etc. They could also search the web.

Group Assignment (Group of at least 3; choose two topics, turn in group report, no longer than 3 pages)

Students could two choose from:
Solar

Wind
Biofuels
Carbon Capture and Sequestration

They needed to describe the state-of-the-art for these renewable energy sources or related energy issues eg carbon capture and sequestration. Then, they needed to emphasize present corrosion issues, anticipate future corrosion issues, and begin to think about and propose (if possible) solutions based on changes in material choices and/or system design. The group descriptions of renewable energy sources/energy related issues varied slightly, but some of the major corrosion problems are briefly summarized below.

Solar
- Corrosive effects on solar panels
- Degradation of metallic reflective coatings and/or reflective substrate materials
- Corrosion associated with the metal connectors

Wind
- Atmospheric, uniform and crevice corrosion of wind turbine blades
- Degradation of zinc or zinc/aluminum alloy coatings for corrosion protection
- Corrosion from extreme marine environments in offshore wind farms

Biofuels
- Stress corrosion cracking in pipelines leading to pipeline ruptures
- Filter clogging and injector issues
- Erosion from impinging particles
- Transportation and storage; specifically ethanol

Carbon capture and sequestration
- Piping to transport and store carbon dioxide
- Potential carbonic acid formation once carbon dioxide mixes with brines

Some of the students initially felt that certain technologies, such as solar energy and biofuels were without any corrosion problems. However, they soon recognized that this was not the case. They realized that identifying some of the current and potential issues would create awareness and allow some of the problems to be avoided or at least minimized. They often proposed more corrosion resistant materials, like stainless steels, titanium, zirconium and tantalum, but quickly realized that costs for some components like metal connectors in solar plates might be much too high.

Topic 14: Corrosion in Selected Environments, Jones, Chapter 11

Corrosion of Steel in Concrete
A case study, "Effect of Fly Ash Replacement on Corrosion of Steel in Concrete-An Update", [3], was presented in class. In that study, reinforced concrete specimens made using more than 25 mixes were subjected to cyclical salt water exposure. Exposure was accompanied by corrosion tests that were based on linear polarization resistance measurements for the 3 x 6 inch lollipop specimens (reinforced concrete specimens containing an embedded piece of rebar).

In reinforced concrete, the onset of corrosion is generally indicated by a decrease in Ecorr and an increase in 1/Rp. The results of more than a year of testing showed that there was generally a significant delay in the onset and severity of corrosion with fly ash replacement for cement. Figure 1 shows Ecorr and 1/Rp vs time data for a concrete (Mix 20) made with a water: cement ratio of 0.68. Note that the time to corrosion initiation was about 16 weeks. Figure 2 shows Ecorr and 1/Rp vs time data for a concrete (Mix 11) made with 35% cement replacement and a water:binder ratio of 0.69. The specimens made with Mix 11 did not experience significant corrosion activity over the more than 70 weeks of exposure and testing [2]. The paper showed that certain types and amounts of fly ash, a waste product, could be beneficial in minimizing corrosion and increasing concrete durability.

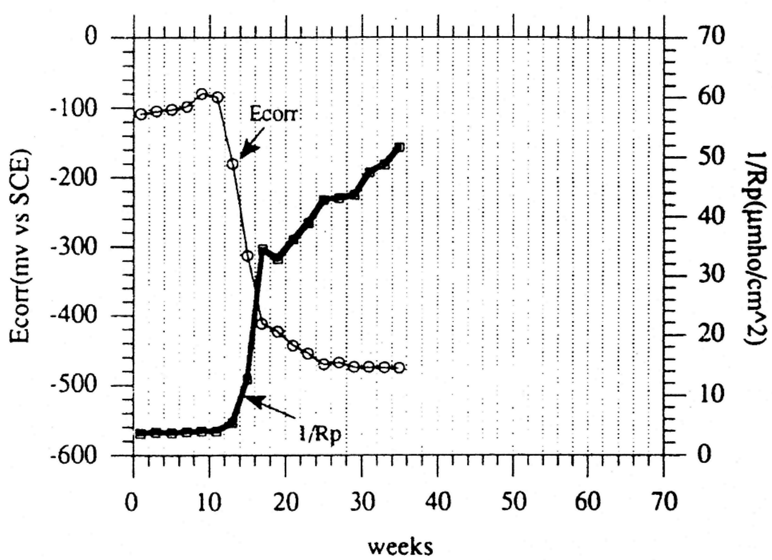

Figure 1 - Plot for Mix 20 [3]

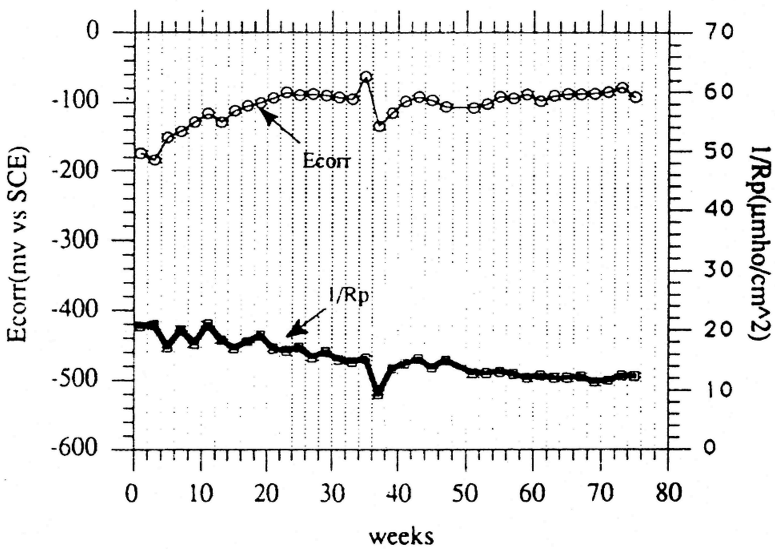

Figure 2 - Plot for Mix 11 [3]

Re-use of Corroded Pipe
In this case study, cut pieces (from pipes like those that were to be re-used) were subjected to exposure to salt water conditions over a period of months, followed by stress-strain testing. It was demonstrated that the behavior of these materials was not severely compromised after corrosion, leading to the conclusion that, at least for these types of pipes and for low load-bearing applications, the long-term durability was sufficient.

Topic 16: Corrosion Protection by Materials Selection and Design, Chapter 15 in Jones (see Topic 2)

Topic 17: Report/Presentation (Presentations presented in symposium format)

ME 349/ME 387Q Symposium Presentations
(Presentations with a significant sustainability focus are in parenthesis)

(Corrosion of Offshore Wind Turbines)
(An Overview of Corrosion and Corrosion Protection in Waste to Energy Boilers)
Prevention of Primary Water SCC in Steam Generator Tubes
(Corrosion from Ethanol)
Corrosion on Boats
Coastal Corrosion
Corrosion of Golf Clubs
Corrosion of Medical Implants within the Human Body
Natural Gas Pipeline Corrosion
Corrosion from Hydrogen Sulfide Gas in the Oil and Gas Industry
Corrosion by Sour Gas
(Corrosion Inhibitors in Sour Oil and Gas Wells)

Delamination of Refinery Equipment
Heat Exchanger Corrosion
Spark Plug Corrosion
Corrosion in Space
Use of Coatings for Corrosion Prevention
Coatings for Architectural Applications
Microbiologically Influenced Corrosion (MIC)
Microbial Corrosion in Concrete
Examination of Deicing Salts on Civil Structures and Automobiles
Corrosion in Reinforced Concrete
Carbonation of Concrete and Corrosion of Reinforcing Steel
Novel Rebar Corrosion Detection Techniques
Corrosion Detecting Conductivity Sensor
The Use of Epoxy Coated Rebar in Bridge Decks
Epoxy Coatings of Rebar in the Concrete-Industry vs Academia Opinions
(Corrosion Tendencies of Calcium Aluminate Cement)
(Alkali-Silica Reactions and Reinforcement Corrosion in Concrete-A Complex Relationship)

Conclusions

Sustainability engineering principles were successfully introduced into a corrosion course by means of special assignments and case studies. The main focus was on creating awareness of sustainability issues.

It should be noted that in many cases, there was limited quantitative information that could be used to answer specific questions definitively. Since the course was first modified, Autodesk Inc, a leader in engineering software [4] and Granta Design, a leader in materials information technology [5] have combined resources to provide much more information that will be useful when this course is taught in the future.

References

1. Jones, D.A. Principles and Prevention of Corrosion, Second Edition, Prentice Hall, 1996.
2. Wheat, H.G., "Effect of Fly Ash Replacement on Corrosion of Steel in Concrete-An Update, " Proceedings of the Second International Conference on Sustainable Construction, Ancona, Italy, June 28-30, 2010.
3. Zhang, H. and Wheat, H.G., "Electrochemical Testing of Steel-Reinforced Concrete," in Corrosion and Corrosion Protection of Steel in Concrete, R.N. Swamy, Ed., Sheffield Academic Press, 1994.
4. http://usaautodesk.com
5. www.grantadesign.com