A Course in

CORROSION CONTROL

C. E. LOCKE and R. D. DANIELS
University of Oklahoma
Norman, Oklahoma 73069

WHY STUDY CORROSION? Corrosion is ubiquitous, expensive, dangerous, and wasteful of our resources. Costs directly attributed to corrosion are difficult to obtain and confirm. A National Bureau of Standards[1] report issued in 1966 stated that corrosion cost in the United States was $10 billion per year. Inflation, plant expansion, etc., may have pushed this cost to as high as $15 billion today. This is a tremendous cost that is not as visible to us as is raw material cost, labor cost, interest charges, etc. Just as good managers attempt to lower these latter costs, it behooves us to systematically attempt to lower the corrosion costs.

Corrosion can also be responsible for human suffering. Catastrophic failures caused by corrosion have occured in pipelines and process vessels. There have been several examples of process vessels exploding when the vessel walls were thinned or pitted by corrosion so that the normal operating conditions exceed the yield stress of the material.[2] Also, hydrogen generated by the corrosion reaction has been the source of process vessel explosions.[3, 4] The Office of Pipeline Safety in the 5th Annual Report to Congress showed that a total of 196 failures in gas distribution and transmission lines in 1972 were directly attributable to corrosion. From these corrosion caused leaks, 64 persons were injured and two were killed.[5]

The corrosion reaction returns metals to the combined state, from which they were won at no small expense. The combined form resulting from corrosion is widely distributed, not concentrated as are ore bodies, and is therefore lost to mankind. This is very wasteful of the world's resources.

All of these factors make a case for the importance of controlling corrosion. In order to control it, the engineer should have some understanding of the fundamentals and technology of corrosion and its control. The course entitled "High Temperature and Corrosion Resistance of Metals" is designed to accomplish this for the metallurgical and chemical engineering students at the University of Oklahoma. This course is taught in the School of Chemical Engineering and Materials Science and is taken by graduate and senior level students in chemical engineering and metallurgical engineering.

PLACE OF COURSE IN THE CURRICULUM

There are two levels of engineering courses in the undergraduate engineering program. Courses in one level, primarily the required courses, cover the topics a student must assimilate to be considered an engineer. For chemical engineers, thermodynamics, kinetics, and transport phenomena are examples of courses that fit this category. The courses in the other level cover topics that are not absolutely essential for every engineer to have in his bag. This does not downgrade the importance of the material, but it is possible to be a successful engineer without having covered it in school.

The corrosion course is considered to be in the latter category, in that a chemical or metallurgical engineer may do work without having been exposed to formal training in the subject. He will be a more well-rounded engineer by having studied corrosion, but it is not as essential or basic as a course in thermodynamics. The course is structured with these guidelines and categories in mind. This philosophy is transmitted to the students at the initial session of the course.

The need for an elective course in corrosion has been amply demonstrated over the years by the numbers of graduate engineers who have returned to the University for continuing education courses in corrosion. The University of Oklahoma currently offers a one-week intensive course in Corrosion Fundamentals on a schedule of three

Carl E. Locke, Assistant Professor of Chemical Engineering and Materials Science, joined The University of Oklahoma faculty in January, 1973. He has B.S., M.S., and Ph.D. degrees in chemical engineering from the University of Texas. His teaching and research interests are in corrosion and polymer properties. He has had eleven years of industrial experience which have included work in corrosion control. (Right)

Raymond D. Daniels, Professor of Chemical Engineering and Materials Science, has served on The University of Oklahoma faculty since 1958. He is also Executive Director of the University's Research Institute. He holds B.S. and M.S. degrees in physics and a Ph.D. in metallurgy from Case Western Reserve University. He is accredited by the National Association of Corrosion Engineers as a Corrosion Specialist. (Left)

times per year. In addition, the University of Oklahoma Corrosion Control Short Course, a two and one-half day course, taught primarily by representatives from industry, has been offered annually since 1953.

CORROSION COURSE OUTLINE

An outline of the topics covered in the course on High Temperature and Corrosion Resistance of Metals is given in Table 1. It is divided into two main topics: corrosion and oxidation; the difference between the two being presence of water in corrosion and its absence in oxidation. Of these two topics, corrosion receives the greater attention because of the variety of situations in which it occurs and the diverse characterizations of the damage associated with it.

The electrochemical basis of the corrosion reaction is developed beginning with a review of thermodynamics. The corrosion cell is compared to electrochemical devices such as the battery, fuel cell, and electrochemical cell for producing reactions. Bockris and Reddy[6] have interesting names for these: energy producer (battery, fuel cell); substance producer (electrochemical cell); energy waster, substance destroyer (corrosion cell). The corrosion cell is analyzed thermodynamically by means of the Nernst equation; half cell potentials and cell potentials are developed. The bane of students of electrochemistry, the IUPAC and American Sign conventions for half cell potentials are discussed and examples worked to show students that the overall cell potential is independent of half cell sign convention. The potential-pH diagrams (Pourbaix diagrams) are discussed, and their applications and limitations are illustrated.

The eight types of corrosion damage as classified by Fontana and Greene[7] are listed. The characteristics of each type, examples of the damage, and suggested preventative measures are discussed.

The kinetics of the corrosion reaction are introduced. Polarization behavior (activation and concentration) are shown to be a result of the kinetic limitations of the reactions. These fundamentals lead to the development of corrosion rate calculations and measurements from polarization behavior. Passivity is discussed at some length since it is so important to the stainless steels and some inhibitor mechanisms.

Five main methods of controlling corrosion are introduced to the students (cathodic protection, anodic protection, coatings, inhibitors, alloying). Each of these methods is related to the basic electrochemical thermodynamic and kinetic relationships described earlier in the course. Examples of each method are obtained from the current literature and discussed in class and a list of references is given to the students.

The oxidation of metals is treated with emphasis on the processes involved and the controlling mechanisms in film formation and growth. The observed scaling rate laws are introduced and are related to the thermodynamic, kinetic, and mechanical factors. A very brief discussion of alloying elements for oxidation resistance is given at the end of the course.

HOMEWORK ASSIGNMENTS—ETC.

Because of the philosophy of the course as discussed above, this course does not have a large amount of homework. Problems are assigned covering the thermodynamics and kinetics of electrochemistry. Other assignments are given in which the corrosion literature is used by the students to write short reports on special examples of corrosion and on corrosion control methods.

The textbook, "Corrosion and Corrosion Control," by Uhlig[8] is used, but not exclusively. The course development does not follow the development in the text but nearly all subjects covered in the course are covered in the text. The book by Fontana and Greene[7] and the corrosion literature are used extensively for lecture preparation and supplemental references for the students.

INDUSTRIAL CONTACT

Corrosion technology has traditionally been and still is, to some extent, more advanced than corrosion science. Since contact with engineers currently involved with corrosion problems on a daily basis is very beneficial to the students, plant tours have become part of the course program. A tour of a petroleum company's technical center was arranged during this past semester. The students obtained first-hand examples of practical corrosion problems worked on by engineers and observed demonstrations of corrosion tests conducted in the laboratory. The tour was conducted late in the semester and the students saw examples of many topics discussed in class.

A student in the class discussed his experiences while employed in the maintenance division of another major oil company. He related experiences involving corrosion rate measurements, corrosion control applications, and corrosion control vendor contacts. The class seemed to benefit from these practical contacts.

An inspection trip was scheduled to observe the installation of a cathodic protection system, but the trip had to be cancelled because of a long period of wet weather which delayed the installation. The trip was scheduled through a cathodic protection system supplier and who seemed to be very pleased at the opportunity to have the students visit a worksite.

The course, High Temperature and Corrosion Resistance of metals, at the University of Oklahoma receives a practical emphasis. The fundamentals are covered as a foundation to understanding the causes and control of corrosion. The aim is to introduce the students to corrosion and interest them in this difficult, stimulating field of technology. □

REFERENCES

1. Stanley Lichtenstein, STR-3454, October, 1966, U. S. Department of Commerce, National Bureau of Standards, Washington, D.C., (Mat. Prot., April, 1967, p. 29).
2. H. M. Canavan, Corrosion, *17*, 22 (1961).
3. J. B. Lowe, Corrosion, *17*, 36 (1961).
4. J. R. Stephens and C. B. Livingston, Chem. Eng. Prog., *69* (4), 45-47 (1973).
5. Anon., Mat. Prot., *12*, 42 (1973).
6. J. O'M. Bockris and A. F. N. Reddy, "Modern Electrochemistry" Plenum Press, New York, 1970.
7. M. G. Fontana and N. D. Greene, "Corrosion Engineering," McGraw Hill, New York, 1967.
8. H. H. Uhlig, "Corrosion and Corrosion Control," John Wiley and Sons, New York, 2nd Edition, 1971.

TABLE 1
HIGH TEMPERATURE AND CORROSION RESISTANCE OF METALS

I. Introduction
- **A. Definitions**
- **B. Why study Corrosion**

II. Corrosion—Wet Atmosphere and Solutions
- **A. Fundamentals—Thermodynamics**
  - **1. Thermodynamics Review—Concentrate on free energy, chemical potential, fugacity, activity, activity coefficient.**
  - **2. Nernst Equation**
  - **3. Electrochemical Devices**
    - **a. Types of Devices**
      - **(1) Substance producer (electrochemical cell)**
      - **(2) Energy Producer (battery, fuel cell)**
      - **(3) Substance destroyer (corrosion cell)**
    - **b. Electrode Designation— Anode and Cathode**
  - **4. Half Cell Potentials—EMF Series**
    - **a. Hydrogen Electrode**
    - **b. IUPAC Sign Convention**
    - **c. American Sign Convention**
  - **5. Cell Potentials—Polarity—Corrosion Cells**
  - **6. Potential—pH Diagrams (Pourbaix Diagrams)**
  - **7. Galvanic Series**
- **B. Types of Corrosion Damage**
  - **1. Uniform Attack**
  - **2. Galvanic Couples**
  - **3. Crevice Corrosion**
  - **4. Pitting**
  - **5. Integranular Corrosion**
  - **6. Selective Leaching (parting, dezincification)**
  - **7. Erosion Corrosion (cavitation, fretting)**
  - **8. Stress Corrosion Cracking (hydrogen damage, corrosion fatigue)**
- **C. Fundamentals—Kinetics**
  - **1. Polarization Behavior (Activation and concentration polarization)**
  - **2. Mixed Potential Theory (Evans diagrams)**
  - **3. Overvoltage—(Tafel behavior)**
  - **4. Corrosion Rate Measurement for Polarization Rata (Tafel extrapolation, linear polarization)**
  - **5. Passivity (Anodic polarization behavior)**
  - **6. Predicting Corrosion Behavior**
- **D. Corrosion Control**
  - **1. Cathodic Protection**
  - **2. Anodic Protection**
  - **3. Coatings (organic, inorganic, metallic)**
  - **4. Inhibitors**
  - **5. Metals and Alloys**

III. Oxidation—High Temperature Deterioration of Metals
- **A. Thermodynamics**
- **B. Film Continuity**
- **C. Kinetic Laws**
- **D. Electrical Conductivity in Oxide Films**
- **E. Film Growth**
- **F. Alloying to Prevent High Temperature Oxidation**
- **G. Coating to Prevent High Temperature Oxidation (composites)**