PEABODY’S
CONTROL OF PIPELINE CORROSION

SECOND EDITION

A.W. PEABODY

Edited by
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The Corrosion Society
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This book was originally published in 1967 by Sam Peabody and is the most quoted and used document in the corrosion industry for pipeline corrosion control and testing. When the original book was published, specific criteria for cathodic protection for underground pipelines were still under evaluation and consideration. Not until 1969 was the first documented standard approved by NACE International on criteria RP0169. The depth and vision that Peabody incorporated in the first version of the book has stood the test of time.

This revised version of the 1967 book is not an attempt to make radical changes to the original document. Much of the original text and concepts remain intact. We attempted, however, to incorporate original traditional elements of the book with updates and expanded discussions on equipment, testing techniques and criteria, coatings, survey methods, and data analysis.

An integral part of this revision is a CD-ROM that contains formulas of key design calculations, case examples of corrosion control designs which provide a set-by-step overview of how to design various components of cathodic protection systems, and an electronic copy of the revised book edition.

As described in the Preface of the original 1967 edition, every attempt has been made to check the accuracy of all statements and other data. However, it is unreasonable to assume that everything in this book is accurate and exact. Any suggestions will be considered when future editions of this book are prepared.
This updated version of NACE International’s book titled *Control of Pipeline Corrosion* is dedicated to the memory of its original author, A.W. (Sam) Peabody. Since its publication in 1967, the book has been translated into at least seven different languages and is considered by most as the definitive work on pipeline corrosion.

Sam received his bachelor’s degree from the University of Maine and pursued graduate studies at the Brooklyn Polytechnic Institute in New York. He worked for Ebasco Services Inc. (no longer in existence) for over 40 years until his retirement in 1980 as Director of Corrosion Engineering. He was an active member of NACE since 1947. His accomplishments, awards, and recognitions are too many to list here. His biggest legacy, especially to those of us who had the privilege of working for and with him, is that he was the perfect example of “a gentleman and a scholar.” He was an excellent teacher who always emphasized professional integrity, a quality he instilled in so many.
Contributors

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John A. Beavers is Vice President of Research at CC Technologies, a corrosion engineering and research company. He received B.S. and Ph.D. degrees in metallurgical engineering from the University of Illinois at Urbana-Champaign in 1973 and 1977, respectively. Dr. Beavers has directed and contributed to numerous research programs on corrosion performance of structural materials. These programs included failure analyses, critical literature reviews, and laboratory and field evaluations of metallic and non-metallic material. Dr. Beavers has utilized state-of-the-art electrochemical, surface analytical, and mechanical techniques for the evaluation of materials performance. A major emphasis of his research has been the mechanistic and practical aspects of corrosion and stress corrosion cracking (SCC) on underground pipelines. Dr. Beavers worked at Battelle Memorial Institute from 1977 to 1987, where he was a Senior Research Leader in the Corrosion Section. He joined CC Technologies in 1987.

Dr. Beavers has authored over 80 papers in the field of corrosion and has received two U.S. Patents. An active member of NACE, he was Chairman of the Research in Progress Symposium in 1994 and of the Publications Committee in 1991 and 1992.

*Editor’s Note: Sincere appreciation to John Beavers for investing a lot of time on a detailed and productive review of the final draft on the eve before printing.*

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Ronald L. Bianchetti is currently a Senior Engineer at East Bay Municipal Utility District (EBMUD) in Oakland, California. He received a B.S. in engineering in 1975 from the University of California, Davis and an MBA in 1981 from St. Mary’s College of California. He is a Registered Professional Engineer and has over 25 years of experience. Prior to holding his current position, Mr. Bianchetti worked in the private sector as a consultant in the corrosion industry from 1975 to 1992. His work includes planning, designing, testing, and the construction management of cathodic protection systems for underground pipelines, tanks, refineries, power plants, and marine structures. He has served in NACE International as Past Chairman of the Publications Committee, ad-hoc member to the Board of Directors, Past Western Region Chairman and Past Section Chair of the San Francisco Section.

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In 1996, Mr. Garrity received the Colonel George W. Cox Award for outstanding contributions to the field of underground corrosion control. He has published more than 20 papers in the field of corrosion control. Mr. Garrity delivered the plenary lecture at Corrosion’98.

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Mark Lewis is Assistant Corrosion Engineer at the East Bay Municipal Utility District (EBMUD) in Oakland, California. He is a graduate of Kent State University and attended Bethany College in West Virginia. He has worked in the cathodic protection and corrosion engineering field since 1980, both within the United States and internationally. He is a Past Chairman of the San Francisco Bay Area Section of NACE International.

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Brenda J. Little, Senior Scientist for Marine Molecular Processes at the Naval Research Laboratory, has a Ph.D. in chemistry from Tulane University and a B.S. in biology and chemistry from Baylor University. She is a member of the American Chemical Society and the National Association of Corrosion Engineers (NACE International). She is a NACE International Fellow and the recipient of a 1999 NACE International Technical Achievement Award.

Dr. Little serves on the editorial board for Biofouling and is the author of one book, 20 book chapters, and over 80 peer-reviewed journal articles.

Steve McKim

Since 1989, Steve McKim has been Vice President of American Construction & Supply, Inc. Based in Mill Valley, California, his company specializes in cathodic protection construction services. Mr. McKim previously worked with Harco Corporation and Chevron USA. He has been in the corrosion industry since he graduated from the University of Illinois with a B.S. in mechanical engineering in 1983. He is a Past Chairman of the
Richard N. Sloan

The late Richard Sloan, was an authority in the field of pipeline coatings. He worked for over 45 years with a company that was first known as HC Price. (The company changed its name several times: HC Price, Ameron Price, Bredero Price, and Energy Coatings.) He attended Drexel University and graduated with a bachelor’s degree in Industrial Administration.

During his professional career, Richard Sloan taught various short courses in pipeline coatings, and was a speaker at numerous seminars on the subject. The late Mr. Sloan was an active and long-standing member of NACE, AWWA, and Western Pipeliners.

Michael J. Szeliga

Michael J. Szeliga, P.E., is the Chief Engineer for Russell Corrosion Consultants, Inc. He has more than 23 years of experience in corrosion control engineering. Much of his work has involved the analysis and control of stray current from DC-powered transit systems and from impressed current cathodic protection systems. A Licensed Professional Engineer in several states and certified by NACE International as a Corrosion Specialist and a Cathodic Protection Specialist, Mr. Szeliga has been and is the principal corrosion consultant for the design, construction, and maintenance of many light and heavy rail transit systems. He is presently chairman of the NACE (05)024X Committee on Interference Problems Associated with Rail Transit. Mr. Szeliga is also chairman of the ASTM subcommittee on stray current.

He has edited a book for NACE International titled *Stray Current Corrosion* and has published several articles on the subject.

Patricia Wagner

Patricia Wagner retired from the Naval Research Laboratory in 1998 after 14 years of extensive experience in microbiologically influenced corrosion. She is the coauthor of one book and the author of numerous articles on corrosion.

Publisher Note

Regarding the frequently used equations on the CD-ROM, NACE Press would like to extend its gratitude to Jeff Didas, who provided the original ideas and formulas, and to Jack Tinnea, who provided a technical review of the equations.
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Introduction to Corrosion

John A. Beavers

WHAT IS CORROSION?

One general definition of corrosion is the degradation of a material through environmental interaction. This definition encompasses all materials, both naturally occurring and man-made and includes plastics, ceramics, and metals. This book focuses on the corrosion of metals, with emphasis on corrosion of carbon and low-alloy steels used in underground pipelines. This definition of corrosion begs the question; why do metals corrode? The answer lies in the field of thermodynamics, which tells whether a process such as corrosion will occur. A second logical question is what is the rate of corrosion or how long will a pipeline last? Corrosion kinetics can help provide an answer to this question. Both topics are discussed in greater detail in Chapter 16. Chapter 1 contains an introduction to the subject of underground corrosion. A glossary of terms is included in Appendix A of this book to help with the sometimes confusing terminology.

A significant amount of energy is put into a metal when it is extracted from its ores, placing it in a high-energy state. These ores are typically oxides of the metal such as hematite (Fe₂O₃) for steel or bauxite (Al₂O₃·H₂O) for aluminum. One principle of thermodynamics is that a material always seeks the lowest energy state. In other words, most metals are thermodynamically unstable and will tend to seek a lower energy state, which is an oxide or some other compound. The process by which metals convert to the lower-energy oxides is called corrosion.

Corrosion of most common engineering materials at near-ambient temperatures occurs in aqueous (water-containing) environments and is electrochemical in nature. The aqueous environment is also referred to as the electrolyte and, in the case of underground corrosion, is moist soil. The corrosion process involves the removal of electrons (oxidation) of the metal [Equation (1)] and the consumption of those electrons by some other reduction reaction, such as oxygen or water reduction [Equations (2) and (3), respectively]:
The oxidation reaction is commonly called the anodic reaction and the reduction reaction is called the cathodic reaction. Both electrochemical reactions are necessary for corrosion to occur. The oxidation reaction causes the actual metal loss but the reduction reaction must be present to consume the electrons liberated by the oxidation reaction, maintaining charge neutrality. Otherwise, a large negative charge would rapidly develop between the metal and the electrolyte and the corrosion process would cease.

The oxidation and reduction reactions are sometimes referred to as half-cell reactions and can occur locally (at the same site on the metal) or can be physically separated. When the electrochemical reactions are physically separated, the process is referred to as a differential corrosion cell. A schematic of a differential corrosion cell is given in Figure 1.1. The site where the metal is being oxidized is referred to as the anode or anodic site. At this site, direct electric current (defined as a positive flow of charge) flows from the metal surface into the electrolyte as the metal ions leave the surface. This current flows in the electrolyte to the site where oxygen, water, or some other species is being reduced. This site is referred to as the cathode or cathodic site. There are four necessary components of a differential corrosion cell.

1. There must be an anode
2. There must be a cathode
3. There must be a metallic path electrically connecting the anode and cathode. (Normally, this will be the pipeline itself.)
4. The anode and cathode must be immersed in an electrically conductive electrolyte (normally, moist soil).

Underground corrosion of pipelines and other structures is often the result of differential corrosion cells of which a variety of different types exist. These include differential
aeration cells, where different parts of a pipe are exposed to different oxygen concentrations in the soil, and cells created by differences in the nature of the pipe surface or the soil chemistry. Galvanic corrosion is a form of differential cell corrosion in which two different metals are electrically coupled and exposed in a corrosive environment. Further discussion of these differential corrosion cells is given below and in Chapter 16.

HOW DO WE DETECT CORROSION?

The electrochemical nature of the corrosion process provides opportunities to detect and mitigate corrosion of underground structures. We can monitor the voltages and the currents associated with the corrosion process. When a piece of metal is placed in an electrolyte, such as soil, a voltage will develop across the metal–electrolyte interface because of the electrochemical nature of the corrosion process. We cannot measure this voltage directly but, using a voltmeter, we can measure a voltage between two different metals that are placed in the soil. We also can measure the voltage difference between a metal and a reference electrode, commonly called a half-cell electrode. This voltage is referred to as a corrosion potential, an open circuit potential, or a native potential for that metal in the environment in which the measurement is being obtained. For soil environments, the most common reference electrode used is the copper–copper sulfate reference electrode (CSE).

Potential measurements can be used to estimate the relative resistance of different metals to corrosion in a given environment. Noble metals, such as gold and platinum, have more positive potentials and are more resistant to corrosion than are the more common engineering metals such as steel and aluminum. A galvanic series is a list of metals and alloys arranged according to their relative corrosion potentials in a given environment. Figure 1.1 shows a galvanic series for metals and other materials in neutral soils and water, indicating that carbon has the most positive potential of the materials listed and magnesium has the most negative potential. The potentials measured for the different metals in a galvanic series vary somewhat, depending on the nature of the environment, but the relative position of the metals is similar for natural environments such as soil and seawater.

Another use for corrosion potential measurements is to establish whether galvanic corrosion is likely to occur. When two metals are electrically coupled in an environment, the more negative (active) member of the couple will become the anode in the Introduction to Corrosion differential corrosion cell, and the more positive (noble) member of the couple will become the cathode in the cell. In general, the severity of the galvanic couple increases as the difference in potential between the two members of the couple increases, although this is not always the case. The galvanic series shown in Figure 1.1 indicates that, where copper is electrically coupled to mild steel in soil, the copper will become the cathode and the steel will become the anode, accelerating corrosion of the steel. A further discussion of galvanic corrosion is given in Chapter 16.

Table 1.1 Practical Galvanic Series for Materials in Neutral Soils and Water
<table>
<thead>
<tr>
<th>Material</th>
<th>Potential Volts (CSE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon, Graphite, Coke</td>
<td>+0.3</td>
</tr>
<tr>
<td>Platinum</td>
<td>0 to -0.1</td>
</tr>
<tr>
<td>Mill Scale on Steel</td>
<td>-0.2</td>
</tr>
<tr>
<td>High Silicon Cast Iron</td>
<td>-0.2</td>
</tr>
<tr>
<td>Copper, Brass, Bronze</td>
<td>-0.2</td>
</tr>
<tr>
<td>Mild Steel in Concrete</td>
<td>-0.2</td>
</tr>
<tr>
<td>Lead</td>
<td>-0.5</td>
</tr>
<tr>
<td>Cast Iron (Not Graphitized)</td>
<td>-0.5</td>
</tr>
<tr>
<td>Mild Steel (Rusted)</td>
<td>-0.2 to -0.5</td>
</tr>
<tr>
<td>Mild Steel (Clean and Shiny)</td>
<td>-0.5 to -0.8</td>
</tr>
<tr>
<td>Commercially Pure Aluminum</td>
<td>-0.8</td>
</tr>
<tr>
<td>Aluminum Alloy (5% Zinc)</td>
<td>-1.05</td>
</tr>
<tr>
<td>Zinc</td>
<td>-1.1</td>
</tr>
<tr>
<td>Magnesium Alloy (6% Al, 3% Zn, 0.15% Mn)</td>
<td>-1.6</td>
</tr>
<tr>
<td>Commercially Pure Magnesium</td>
<td>-1.75</td>
</tr>
</tbody>
</table>

\[\text{a}\text{Typical potential normally observed in neutral soils and water, measured with respect to copper sulfate reference electrode.}\]

Table 1.1 also shows that the potential of mild steel can differ depending on whether the surface is clean or covered with mill scale. The potential of steel also is a function of soil properties, including pH, ion concentration, oxygen, and moisture content. The potential differences that develop on underground pipelines and other structures as a result of these factors can result in severe corrosion. Further discussions of these differential corrosion cells are given in Chapter 16.

Potential measurements are commonly used on underground pipelines to detect the presence of these types of differential corrosion cells. An electrical connection is made to the pipe, and the potential of the pipe is measured with respect to a reference electrode placed over the pipe. This process is shown schematically in Figure 1.2. Normally, the reference electrode is connected to the negative lead of a digital voltmeter to obtain a negative reading. As shown in Table 1.1, most potentials in soils are negative. With this type of measurement, the most negative regions of the structure are the anodes and are undergoing accelerated corrosion due to the differential corrosion cells.
Current measurements also can be used to detect differential corrosion cells if the anodes and cathodes are large. These large cells create long-line currents that can be detected by measurements made over the pipe or other underground structure. Through Ohm’s law \(V = IR\), where \(V\) is the voltage, \(I\) is the current, and \(R\) is the resistance) we know that current flow in the soil will create a voltage gradient. This gradient can be detected by placing identical reference electrodes over the pipe and measuring the voltage difference. The voltage measurements can be used to indicate the direction of the differential cell current. The anodic and cathodic sites on the pipeline can be located by performing a series of cell-to-cell potential measurements taken along the pipeline. Another possible source of current flow in the ground is stray currents. These issues are discussed further in Chapter 5.

**HOW DO WE MITIGATE CORROSION?**

The principal methods for mitigating corrosion on underground pipelines are coatings and cathodic protection (CP). Although each will be treated in greater detail in the following chapters, these two methods are briefly described here.

Coatings normally are intended to form a continuous film of an electrically insulating material over the metallic surface to be protected. The function of such a coating is to isolate the metal from direct contact with the surrounding electrolyte (preventing the electrolyte from contacting the metal) and to interpose such a high electrical resistance that the electrochemical reactions cannot readily occur. In reality, all coatings, regardless of overall quality, contain holes, referred to as holidays, that are formed during application, or during transport or installation of mill-coated pipe. Holidays in coatings also develop in