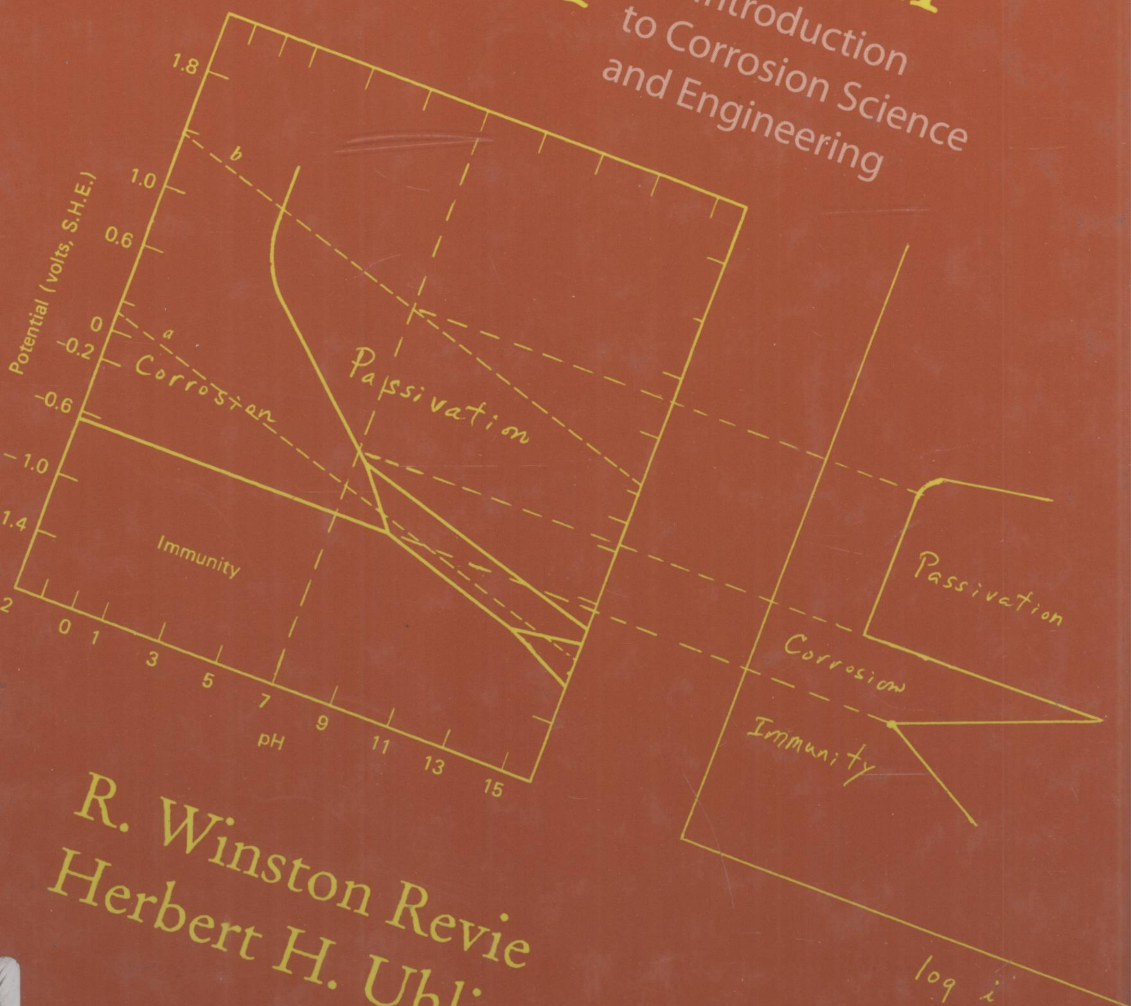
WILEY

# Corrosion and Corrosion Control

4th Edition

## An Introduction to Corrosion Science and Engineering





R. Winston Revie
Herbert H. Uhlig

# CORROSION AND CORROSION CONTROL

## An Introduction to Corrosion Science and Engineering

FOURTH EDITION

R. Winston Revie
Senior Research Scientist
CANMET Materials Technology Laboratory
Natural Resources Canada

Herbert H. Uhlig
Former Professor Emeritus
Department of Materials Science and Engineering
Massachusetts Institute of Technology



WILEY-INTERSCIENCE
A JOHN WILEY & SONS, INC., PUBLICATION

Published by John Wiley & Sons, Inc., Hoboken New Jersey
Published simultaneously in Canada



***Library of Congress Cataloging-in-Publication Data:***

Uhlig, Herbert Henry, 1907–
Corrosion and corrosion control : an introduction to corrosion science and engineering / Herbert H. Uhlig, R. Winston Revie.—4th ed.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-471-73279-2 (cloth)
1. Corrosion and anti-corrosives. I. Revie, R. Winston (Robert Winston), 1944– II. Title.
TA462.U39 2008
620.1′1223–dc22

2007041578

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

# CORROSION AND CORROSION CONTROL

# PREFACE

The three main global challenges for the twenty-first century are energy, water, and air—that is, sufficient energy to ensure a reasonable standard of living, clean water to drink, and clean air to breathe. The ability to manage corrosion is a central part of using materials effectively and efficiently to meet these challenges. For example, oil and natural gas are transmitted across continents using high-pressure steel pipelines that must operate for decades without failure, so that neither the groundwater nor the air is unnecessarily polluted. In design, operation, and maintenance of nuclear power plants, management of corrosion is critical. The reliability of materials used in nuclear waste disposal must be sufficient so that that the safety of future generations is not compromised.

Materials reliability is becoming ever more important in our society, particularly in view of the liability issues that develop when reliability is not assured, safety is compromised, and failure occurs. Notwithstanding the many years over which university, college, and continuing education courses in corrosion have been available, high-profile corrosion failures continue to take place. Although the teaching of corrosion should not be regarded as a dismal failure, it has certainly not been a stellar success providing all engineers and technologists a basic minimum "literacy level" in corrosion that would be sufficient to ensure reliability and prevent failures.

Senior management of some organizations has adopted a policy of "zero failures" or "no failures." In translating this management policy into reality, so that "zero" really does mean "zero" and "no" means "no," engineers and others manage corrosion using a combination of well-established strategies, innovative approaches, and, when necessary, experimental trials.

One objective of preparing the fourth edition of this book is to present to students an updated overview of the essential aspects of corrosion science and engineering that underpin the tools that are available and the technologies that are used for managing corrosion and preventing failures. A second objective is to engage students, so that they are active participants in understanding corrosion and solving problems, rather than passively observing the smorgasbord of information presented. The main emphasis is on quantitative presentation, explanation, and analysis wherever possible; for example, in this new edition, the galvanic series in seawater is presented with the potential range of each material, rather than only as a qualitative list. Considering the potential ranges that can be involved, the student can see how anodic/cathodic effects can develop, not only when different materials form a couple, but also when materials that are nominally the same are coupled. In this edition, some new numerical problems have been added, and the problems are integrated into the book by presenting them at the ends of the chapters.

Since the third edition of this book was published, there have been many advances in corrosion, including advances in knowledge, advances in alloys for application in aggressive environments, and advances of industry in response to public demand. For example, consumer demand for corrosion protection of automobiles has led to a revolution of materials usage in the automotive industry. For this reason, and also because many students have a fascination with cars, numerous examples throughout this book illustrate advances that have been made in corrosion engineering of automobiles. Advances in protecting cars and trucks from corrosion must also be viewed in the context of reducing vehicle weight by using magnesium, aluminum, and other lightweight materials in order to decrease energy usage (increase the miles per gallon, or kilometers per liter, of gasoline) and reduce greenhouse gas emissions.

Although the basic organization of the book is unchanged from the previous edition, there is in this edition a separate chapter on Pourbaix diagrams, very useful tools that indicate the thermodynamic potential–pH domains of corrosion, passivity, and immunity to corrosion. A consideration of the relevant Pourbaix diagrams can be a useful starting point in many corrosion studies and investigations. As always in corrosion, as well as in this book, there is the dual importance of thermodynamics (In which direction does the reaction go? Chapters 3 and 4) and kinetics (How fast does it go? Chapter 5).

After establishing the essential basics of corrosion in the first five chapters, the next 23 chapters expand upon the fundamentals in specific systems and applications and discuss strategies for protection. There are separate chapters on aluminum (Chapter 21), magnesium (Chapter 22), and titanium (Chapter 25) to provide more information on these metals and their alloys than in the previous editions. Throughout this book, environmental concerns and regulations are presented in the context of their impact on corrosion and its control—for example, the EPA Lead and Copper rule enacted in the United States in 1991. The industrial developments in response to the Clean Air Act, enacted in 1970, have reduced air pollution in the United States, with some effect on atmospheric corrosion (Chapter 9). To meet the requirements of environmental regulations and reduce the use of organic solvents, compliant coatings have been developed (Chapter 16).

This is primarily a textbook for students and others who need a basic understanding of corrosion. The book is also a reference and starting point for engineers, researchers, and technologists requiring specific information. The book includes discussion of the main materials that are available, including alloys both old and new. For consistency with current practice in metallurgical and engineering literature, alloys are identified with their UNS numbers as well as with their commonly used identifiers. To answer the question from students about why so many alloys have been developed and are commercially available, the contributions of individual elements to endow alloys with unique properties that are valuable for specific applications are discussed. Throughout the book, there are numerous references to further sources of information, including handbooks, other books, reviews, and papers in journals. At the end of each chapter, there is a list of "General References" pertinent to that chapter, and most of these were published in 2000 and later.

This edition includes introductory discussions of risk (Chapter 1), AC impedance measurements (Chapter 5), Ellingham diagrams (Chapter 11), and, throughout the book, discussions of new alloys that have been developed to meet demands for increasing reliability notwithstanding the increased structural lifetimes that are being required in corrosive environments of ever-increasing severity. Perhaps nowhere are the demands for reliability more challenging than in nuclear reactors, discussed in Chapters 8 and 26. In the discussion of stainless steels (Chapter 19), the concept of critical pitting temperature (CPT) is introduced, as well as the information on critical pitting potential (CPP). The important problem of corrosion of rebar (reinforced steel in concrete) is discussed in Chapter 7 on iron and steel.

In addition to new technologies and new materials for managing corrosion, new tools for presenting books have become available; hence, this book is being published as an electronic book, as well as in the traditional print format. An instructor's manual is also being prepared.

Experience has been invaluable in using the book in a corrosion course in the Department of Mechanical and Aerospace Engineering at Carleton University in Ottawa, which Glenn McRae and I developed along with other members of the Canadian National Capital Section of NACE International.

It would be a delight for me to hear from readers of this book, with their suggestions and ideas for future editions.

I would like to acknowledge my many friends and colleagues at the CANMET Materials Technology Laboratory, with whom it has been my privilege to work for the past nearly 30 years. I would also like to thank the many organizations and individuals who have granted permission to use copyright material; acknowledgments for specific material are provided throughout the book. In addition, I would like to thank Bob Esposito and his staff at John Wiley & Sons, Inc. for their encouragement with this book and also with the Wiley Series in Corrosion.

I would like to thank the Uhlig family for their generosity and hospitality during five decades, beginning when I was a student in the M.I.T. Corrosion Laboratory in the 1960s and 1970s. In particular, I would like to acknowledge Mrs. Greta Uhlig, who continues to encourage initiatives in corrosion education in memory of the late Professor Herbert H. Uhlig (1907–1993).

Lastly, I would like to quote from the Preface of the first edition of this book:

> If this book stimulates young minds to accept the challenge of continuing corrosion problems, and to help reduce the huge economic losses and dismaying wastage of

> natural resources caused by metal deterioration, it will have fulfilled the author's major objective.

Indeed, this remains the main objective today.

Ottawa, Canada
September 2007

R. WINSTON REVIE

# CONTENTS