 

# ASM Handbook®

## Volume 13A
## Corrosion:
## Fundamentals, Testing, and Protection

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ASM International Handbook Committee

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# Foreword

ASM International is pleased to publish *ASM Handbook,* Volume 13A, *Corrosion: Fundamentals, Testing, and Protection,* the first book in a two-volume revision of the landmark 1987 *Metals Handbook,* 9th Edition volume on corrosion. *ASM Handbook,* Volume 13A has been completely revised and updated to address the needs of ASM International members and the global technical community for current and comprehensive information on corrosion principles, evaluation techniques, and protection methods. Advances in material science and corrosion technologies since the 1987 *Corrosion* volume was published have lessened some of the costs and degradation caused by corrosion. However, the systems that society relies on have increased in complexity during this time, so corrosion can have more far-reaching effects. Corrosion remains a multibillion-dollar problem that confronts nearly every engineer in every industry.

ASM International is indebted to the Co-Chairs and Editors of this Handbook, Stephen D. Cramer and Bernard S. Covino, Jr., who had the vision and the drive to undertake the huge effort to update and revise the 1987 *Corrosion* volume. *ASM Handbook,* Volume 13A is the first fruit of their efforts; they are also leading the project to complete *ASM Handbook,* Volume 13B, *Corrosion: Materials, Environments, and Industries,* scheduled to publish in 2005. The Editors have done an outstanding job in organizing the project, in recruiting renowned experts to oversee sections and to write or revise articles, and in reviewing every manuscript. We are pleased with their vision to recruit authors from Canada, Mexico, France, Germany, United Kingdom, Poland, Japan, India, and Australia, as well as from the United States. This diverse community of volunteers, sharing their knowledge and experience, make this Volume truly an *international* effort.

We thank the authors and reviewers of the 1987 *Corrosion* volume, which at the time was the largest, most comprehensive volume on a single topic ever published by ASM. This new edition builds upon that groundbreaking project. Thanks also go to the ASM Handbook Committee for their oversight and involvement, and to the ASM editorial staff for their tireless efforts.

We are especially grateful to the nearly 200 authors and reviewers listed in the next several pages. Their willingness to invest their time and effort and to share their knowledge and experience by writing, rewriting, and reviewing articles has made this Handbook an outstanding source of information.

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# Policy on Units of Measure

By a resolution of its Board of Trustees, ASM International has adopted the practice of publishing data in both metric and customary U.S. units of measure. In preparing this Handbook, the editors have attempted to present data in metric units based primarily on Système International d'Unités (SI), with secondary mention of the corresponding values in customary U.S. units. The decision to use SI as the primary system of units was based on the aforementioned resolution of the Board of Trustees and the widespread use of metric units throughout the world.

For the most part, numerical engineering data in the text and in tables are presented in SI-based units with the customary U.S. equivalents in parentheses (text) or adjoining columns (tables). For example, pressure, stress, and strength are shown both in SI units, which are pascals (Pa) with a suitable prefix, and in customary U.S. units, which are pounds per square inch (psi). To save space, large values of psi have been converted to kips per square inch (ksi), where 1 ksi = 1000 psi. The metric tonne ($kg \times 10^3$) has sometimes been shown in megagrams (Mg). Some strictly scientific data are presented in SI units only.

To clarify some illustrations, only one set of units is presented on artwork. References in the accompanying text to data in the illustrations are presented in both SI-based and customary U.S. units. On graphs and charts, grids corresponding to SI-based units usually appear along the left and bottom edges. Where appropriate, corresponding customary U.S. units appear along the top and right edges.

Data pertaining to a specification published by a specification-writing group may be given in only the units used in that specification or in dual units, depending on the nature of the data. For example, the typical yield strength of steel sheet made to a specification written in customary U.S. units would be presented in dual units, but the sheet thickness specified in that specification might be presented only in inches.

Data obtained according to standardized test methods for which the standard recommends a particular system of units are presented in the units of that system. Wherever feasible, equivalent units are also presented. Some statistical data may also be presented in only the original units used in the analysis.

Conversions and rounding have been done in accordance with IEEE/ASTM SI-10, with attention given to the number of significant digits in the original data. For example, an annealing temperature of 1570 °F contains three significant digits. In this case, the equivalent temperature would be given as 855 °C; the exact conversion to 854.44 °C would not be appropriate. For an invariant physical phenomenon that occurs at a precise temperature (such as the melting of pure silver), it would be appropriate to report the temperature as 961.93 °C or 1763.5 °F. In some instances (especially in tables and data compilations), temperature values in °C and °F are alternatives rather than conversions.

The policy of units of measure in this Handbook contains several exceptions to strict conformance to IEEE/ASTM SI-10; in each instance, the exception has been made in an effort to improve the clarity of the Handbook. The most notable exception is the use of $g/cm^3$ rather than $kg/m^3$ as the unit of measure for density (mass per unit volume).

SI practice requires that only one virgule (diagonal) appear in units formed by combination of several basic units. Therefore, all of the units preceding the virgule are in the numerator and all units following the virgule are in the denominator of the expression; no parentheses are required to prevent ambiguity.

# Preface

The direct cost of corrosion in the United States was estimated to be $276 billion annually for 1998, or 3.1% of the 1998 U.S. gross domestic product of $8.79 trillion (Ref 1). Of the industry sectors analyzed, utilities and transportation experienced the largest costs. The largest investment in corrosion control and protection strategies was in protective organic coatings. Indirect costs of corrosion, including lost productivity and corrosion-related overhead and taxes, when averaged over industry sectors, were roughly equal to or greater than the direct costs. In some cases they were substantially greater. For example, indirect corrosion costs related to the U.S. bridge infrastructure were estimated to be more than 10 times the $8.3 billion direct cost from bridge corrosion damage. Additional information is available in the article "Direct Costs of Corrosion in the United States" in this Volume.

*ASM Handbook,* Volume 13A, *Corrosion: Fundamentals, Testing, and Protection,* is the first volume in a two-volume update, revision, and expansion of *Corrosion,* Volume 13 of the ninth edition *Metals Handbook,* published in 1987. The second volume—*ASM Handbook,* Volume 13B, *Corrosion: Materials, Environments, and Industries*—is to be published in 2005. The purpose of these two volumes is to represent the current state of knowledge in the field of corrosion and to provide a perspective on future trends in the field. Metals remain the major focus of the Handbook, but nonmetallic materials occupy a more prominent position that reflects their wide and effective use to solve problems of corrosion. Wet or aqueous corrosion remains the major focus, but dry or gaseous corrosion is discussed more fully, reflecting the increased importance of processes at elevated and high temperatures.

*ASM Handbook,* Volume 13A recognizes the global nature of corrosion research and practice and the international level of corrosion activities and interactions required to provide cost-effective, safe, and environmentally sound solutions to materials problems in chemically aggressive environments. Twenty percent of the articles in Volume 13A did not appear in the 1987 Handbook. Authors from more than ten countries have contributed to Volume 13A. The table of contents has been translated into Spanish, French, Russian, Japanese, and Chinese to make the Handbook accessible to a diverse audience. Extensive references provide a road map to the corrosion literature and are augmented by Selected References that are a source of additional information.

Information technology has changed dramatically since 1987, and the most significant occurrence has been the development of the Internet as an information resource. In response, ASM International has made the contents of this Handbook and others in the *ASM Handbook* series available on the Web. This Handbook also provides a list, current at the time of publication, of significant data sources and of major national, international, academic, and government corrosion organizations and institutions that are accessible on the Web.

Corrosion is described by well-known laws of thermodynamics, kinetics, and electrochemistry. The many variables that influence the behavior of a material in its environment can lead to a wide and complex range of performance, from the benign to the catastrophic. Understanding and avoiding detrimental corrosion is an interdisciplinary effort requiring knowledge of chemistry, electrochemistry, materials, engineering, and structures. All applications of engineered materials pivot on the fulcrum between environmental degradation, of which corrosion is a major element, and service or service life, with cost determining the point of balance. Costs are determined not in the spare confines of a material and its environment but in a complex landscape defined by technical, economic, social, environmental, health, safety, legal, and consumer constraints. This is illustrated by the experience of a Portland, OR Water Bureau engineer working to make way for a new light rail line along city streets (Ref 2):

> . . . Construction conflicts are anticipated . . . , but day-to-day construction also alters the original design and corrosion control scheme of existing installations. As development occurs and utilities weave and cross, coatings are damaged, pipes are shorted, wires are cut, and test stations always seem to disappear . . . Work had to be sequenced and paced to minimize traffic interference . . . Environmental regulators were classifying the pavement as an engineered cap for brownfield and other contaminated areas . . . Utilities responded by characterizing the roadway as a constantly opening and closing zipper because we continually construct there . . . Corrosion control methods for urban areas must be designed for installation and operation in a congested environment that is constantly changing.

This Handbook is organized into six major sections addressing corrosion fundamentals, testing, and protection.

The first Section, "Fundamentals of Corrosion," covers the theory of aqueous and gaseous corrosion from the thermodynamic and kinetic perspectives. It presents the principles of electrochemistry, the mechanisms of corrosion processes, and the methods for measuring corrosion rates in aqueous, molten salt, liquid metals, and gaseous environments. It introduces geochemical modeling as a means for characterizing and understanding corrosion in complex environments. While corrosion is usually associated with the environmental degradation of a material, this Section also describes ways in which corrosion is used for constructive or beneficial purposes.

The second Section, "Forms of Corrosion," describes how to recognize the different types of corrosion and the forces that influence them. It addresses uniform corrosion, localized corrosion, metallurgically influenced corrosion, mechanically assisted corrosion, environmentally induced cracking, and microbiologically influenced corrosion. The Section introduces the complex processes of wear-corrosion interactions that accelerate material deterioration at rates greater than those resulting from wear processes or corrosion processes alone.

The third Section, "Corrosion Testing and Evaluation," describes the planning of corrosion tests, evaluation of test results, laboratory corrosion testing, simulated service testing, and in-service techniques for damage detection and monitoring. It concludes by describing standard methods and practices for evaluating the various forms of corrosion.

The fourth Section, "Methods of Corrosion Protection," begins by discussing as a baseline the corrosion resistance of bulk materials. The Section continues with methods of corrosion protection, including surface treatments and conversion coatings, ceramic, glass and oxide coatings, metal coatings, coatings and linings, electrochemical corrosion control methods, and corrosion inhibitors.

The fifth Section, "Designing for Corrosion Control and Prevention," continues the theme of the fourth Section from the perspective of materials selection and equipment design. Corrosion control is an economic process as well as a technical process, and this Section discusses corrosion economic calculations, predictive modeling for structure service life, and a review of corrosion costs in the United States.

The sixth Section, "Tools for the Corrosionist," covers topics that are complementary to corrosion fundamentals, testing, and protection. It is a new addition to the Handbook. The topics include conventions and definitions in corrosion and oxidation, applications of modern analytical instruments in corrosion, materials science, statistics, and information sources and databases.

Other useful Handbook contents include the "Glossary of Terms," containing definitions of corrosion, electrochemistry, and materials terms common to corrosion and defined in the literature of ISO, ASTM, and NACE International. The "Corrosion Rate Conversion" Section includes conversions in both nomograph and tabular form. The metric conversion guide features conversion factors for common units and includes SI prefixes. Finally, "Abbreviations and Symbols" provides a key to common acronyms, abbreviations, and symbols.

The six Sections in the Handbook are divided into several subsections. These subsections were organized and written under the leadership of the following individuals (listed in alphabetical order):

| Chairperson | Subsection Title |
|---|---|
| Vinod S. Agarwala | In-Service Techniques for Damage Detection and Monitoring |
| Rudolph G. Buchheit | Surface Treatments and Conversion Coatings |
| Bernard S. Covino, Jr. | Laboratory Corrosion Testing |
| Bruce D. Craig | Environmentally Induced Cracking |
| Stephen D. Cramer | Simulated Service Testing |
| | Metal Coatings |
| | Corrosion Inhibitors |
| | Tools for the Corrosionist |
| Marek Danielewski | Fundamentals of Gaseous Corrosion |
| Stephen C. Dexter | Microbiologically Influenced Corrosion |
| Peter Elliott | Designing for Corrosion Control and Protection |
| Gerald Frankel | Metallurgically Influenced Corrosion |
| William A. Glaeser | Mechanically Assisted Degradation |
| Russell D. Kane | Uniform Corrosion |
| Carl E. Locke, Jr. | Electrochemical Corrosion Control Methods |
| Philippe Marcus | Fundamentals of Corrosion Thermodynamics |
| Paul M. Natishan | Corrosion Resistance of Bulk Materials |
| Bopinder S. Phull | Evaluating Forms of Corrosion |
| Vilupanur A. Ravi | Ceramic, Glass, and Oxide Coatings |
| Pierre R. Roberge | Planning Corrosion Tests and Evaluating Results |
| John R. Scully | Fundamentals of Aqueous Corrosion Kinetics |
| Susan Smialowska | Localized Corrosion |
| Kenneth B. Tator | Coatings and Linings |
| Peter F. Tortorelli | Fundamentals Applied to Specific Environments |
| Ian Wright | Mechanically Assisted Degradation |
| Margaret Ziomek-Moroz | Fundamentals of Corrosion for Constructive Purposes |

These talented and dedicated individuals generously devoted considerable time to the preparation of this Handbook. They were joined in this effort by more than 120 authors who contributed their expertise and creativity in a collaborative venture to write or revise the articles and by more than 200 reviewers and 5 translators. These volunteers built on the contributions of earlier Handbook authors and reviewers who provided the solid foundation on which the present Handbook rests.

For articles revised from the previous edition, the contribution of these authors is acknowledged at the end of articles. This location in no way diminishes their contribution or our gratitude. Those responsible for the current revision are named after the title. The variation in the amount of revision is broad. The many completely new articles presented no challenge for attribution, but assigning fair credit for revised articles was more problematic. The choice of presenting authors' names without comment or with the qualifier "Revised by" is solely the responsibility of the ASM staff.

We thank ASM International and the ASM staff for their skilled support and valued expertise in the production of this Handbook. In particular, we thank Charles Moosbrugger, Gayle Anton, and Scott Henry for their encouragement, tactful diplomacy, and many discussions, plus, we should add, their wistful forbearance as deadlines came and went. The Albany Research Center, U.S. Department of Energy, gave us support and flexibility in our assignments to participate in this project and we are most grateful. In particular, we thank our supervisors Jeffrey A. Hawk and Cynthia P. Doğan, who were most gracious and generous with their encouragement throughout the project.

We close with these thoughtful words from T.R.B. (Tom) Watson, president of NACE International, 1964–65, author of *Why Metals Corrode,* and corrosion leader (Ref 3):

Mighty ships upon the ocean, suffer from severe corrosion.
Even those that stay at dockside, are rapidly becoming oxide.

Alas, that piling in the sea is mostly $Fe_2O_3$.
And where the ocean meets the shore, you'll find there's $Fe_3O_4$.
'Cause when the wind is salt and gusty, things are getting awfully rusty.

We can measure it, we can test it, we can halt it or arrest it;
We can scrape it and weigh it; we can coat it or spray it;
We can examine and dissect it; we can cathodically protect it.
We can pick it up and drop it, but heaven knows we'll never stop it.

So here's to rust, no doubt about it; most of us would starve without it.

That said, given the thermodynamic, kinetic, and economic principles at work in our world, corrosion will not stop. This Handbook helps show us how to live with it.

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2. Stu Greenberger, Underground Water Utilities – Crowded and Complex, *Mater. Perform.,* Vol. 41, No. 7, July 2002, p. 8.
3. "Rust's a Must," by T.R.B. Watson, poem reprinted by permission of Jean Watson; also reprinted in *The Boatowner's Guide to Corrosion*, by Everett Collier, Ragged Mountain Press, Camden ME, 2001. One line of the poem was modified for the purposes of this publication.

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***Coatings and Linings***



***Electrochemical and Corrosion Control Methods***



***Corrosion Inhibitors***

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