

ASM Handbook®

Volume 13C Corrosion: Environments and Industries

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Materials Park, Ohio 44073-0002
www.asminternational.org

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Foreword

This work, *Corrosion: Environments and Industries*, is application driven. The best practices in segments of industry with respect to materials selection, protection of materials, and monitoring of corrosion are presented. The challenges of local environments encountered within these industries, as well as large-scale environmental challenges, are documented. The choice of solutions to these challenges can be found.

Just as the environment affects materials, so also corrosion and its by-products affect the immediate environment. Nowhere is the immediate effect of more concern than in biomedical implants. We are pleased with the new information shared by experts in this field.

As we recognize the energy costs of producing new materials of construction, the creation of engineered systems that will resist corrosion takes on added importance. The importance and costs of maintenance have been discussed for many of the industrial segments—aviation, automotive, oil and gas pipeline, chemical, and pulp and paper industries, as well as the military. The consequences of material degradation are addressed as the service temperatures of materials are pushed higher for greater efficiency in energy conversion. As engineered systems are made more complex and the controlling electronics are made smaller, the tolerance for any corrosion is lessened.

ASM International is deeply indebted to the Editors, Stephen D. Cramer and Bernard S. Covino, Jr., who envisioned the revision of the landmark 1987 *Metals Handbook*, 9th edition, Volume 13. The energy they sustained throughout this project and the care they gave to every article has been huge. The resulting three Volumes contain 281 articles, nearly 3000 pages, 3000 figures, and 1500 tables—certainly impressive statistics. Our Society is as impressed and equally grateful for the way in which they recruited and encouraged a community of corrosion experts from around the world and from many professional organizations to volunteer their time and ability.

We are grateful to the 200 authors and reviewers who shared their knowledge of corrosion and materials for the good of this Volume. They are listed on the next several pages. And again, thanks to the contributors to the preceding two Volumes and the original 9th edition *Corrosion* Volume.

Thanks also go to the members of the ASM Handbook Committee for their involvement in this project and their commitment to keep the information of the *ASM Handbook* series current and relevant to the needs of our members and the technical community. Finally, thanks to the ASM editorial and production staff for the overall result.

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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 ($\text{kg} \times 10^3$) 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

Corrosion, while silent and often subtle, is probably the most significant cause of physical deterioration and degradation in man-made structures. The 2004 global direct cost of corrosion, representing costs experienced by owners and operators of manufactured equipment and systems, was estimated to be \$990 billion United States dollars (USD) annually, or 2.0% of the \$50 trillion (USD) world gross domestic product (GDP) (Ref 1). The 2004 global indirect cost of corrosion, representing costs assumed by the end user and the overall economy, was estimated to be \$940 billion (USD) annually (Ref 1). On this basis, the total cost of corrosion to the global economy in 2004 was estimated to be approximately \$1.9 trillion (USD) annually, or 3.8% of the world GDP. The largest contribution to this cost comes from the United States at 31%. The next largest contributions were Japan, 6%; Russia, 6%; and Germany, 5%.

ASM Handbook Volume 13C, *Corrosion: Environments and Industries* is the third and final volume of the three-volume update, revision, and expansion of *Metals Handbook*, 9th edition, Volume 13, *Corrosion, Testing, and Protection*—was published in 2003. The second volume—Volume 13B, *Corrosion: Materials*—was published in 2005. These three volumes together present the current state of corrosion knowledge, the efforts to mitigate corrosion’s effects on society’s structures and economies, and a perspective on future trends in corrosion prevention and mitigation. Metals remain the primary focus of the Handbook. However, nonmetallic materials occupy a more prominent position, reflecting their wide and effective use to solve problems of corrosion and their frequent use with metals in complex engineering systems. Wet (or aqueous) corrosion remains the primary environmental focus, but dry (or gaseous) corrosion is also addressed, reflecting the increased use of elevated- or high-temperature operations in engineering systems, particularly energy-related systems, where corrosion and oxidation are important considerations.

Volume 13C recognizes, as did Volumes 13A and 13B, the diverse range of materials, environments, and industries affected by corrosion, the global reach of corrosion practice, and the levels of technical activity and cooperation required to produce cost-effective, safe, and environmentally-sound solutions to materials problems. As we worked on this project, we marveled at the spread of corrosion technology into the many and diverse areas of engineering, industry, and human activity. It attests to the effectiveness of the pioneers of corrosion research and education, and of the organizations they helped to create, in communicating the principles and experience of corrosion to an ever-widening audience. Over 50% of the articles in Volume 13C are new. Looking back over the three volumes, 45% of the articles are new to the revised Handbook, reflecting changes occurring in the field of corrosion over the intervening 20 years. Authors from 14 countries contributed articles to the three Handbook volumes.

Volume 13C is organized into two major Sections addressing the performance of materials in specific classes of environments and their performance in the environments created by specific industries. These Sections recognize that materials respond to the laws of chemistry and physics and that, within the constraints of design and operating conditions, corrosion can be minimized to provide economic, environmental, and safety benefits.

The first Section is “Corrosion in Specific Environments,” addressing distinct classes of environments where knowledge of the general attributes of the environment provides a “generic” framework for understanding and solving corrosion problems. By the nature of this approach, solutions to problems of corrosion performance and corrosion protection are viewed as spanning industries. The specific environments addressed in Volume 13C are fresh water, marine (both atmospheric and aqueous), underground, and military, with an eclectic mix of other environments included under specialized environments.

The second Section is “Corrosion in Specific Industries,” addressing corrosion performance and corrosion protection in distinct environments created by specific industries. The specific industries addressed in Volume 13C are nuclear power, fossil energy and alternative fuels, petroleum and petrochemical, land transportation, commercial aviation, microelectronics, chemical processing, pulp and paper, food and beverage, pharmaceutical and medical technology, building, and mining and mineral processing. Corrosion issues in the energy sector receive considerable attention in this Section. In addition, there is substantial overlap between this Section and topics addressed in military environments in the first Section.

Supporting material is provided at the back of the Handbook. A “Corrosion Rate Conversion” includes conversions in both nomograph and tabular form. The “Metric Conversion Guide” gives conversion factors for common units and includes SI prefixes. “Abbreviations and Symbols” provides a key to common acronyms, abbreviations, and symbols used in the Handbook.

Many individuals contributed to Volume 13C. In particular, we wish to recognize the efforts of the following individuals who provided leadership in organizing subsections of the Handbook (listed in alphabetical order):

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Larry Paul	Corrosion in the Fossil and Alternative Fuel Industries
Robert L. Ruedisueli	Corrosion in Marine Environments
John E. Slater	Corrosion in the Building Industry

These knowledgeable and dedicated individuals generously devoted considerable time to the preparation of the Handbook. They were joined in this effort by more than 200 authors who contributed their expertise and creativity in a collaboration to write and revise the articles in the Handbook, and

by the many reviewers of their articles. 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 1987 edition, the contribution of the previous author is acknowledged at the end of the article. This location in no way diminishes their contribution or our gratitude. Authors 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, Diane Grubbs, and Scott Henry for their encouragement, tactful diplomacy, and many helpful discussions. We are most grateful to the National Energy Technology Laboratory (formerly the Albany Research Center), U.S. Department of Energy, for the support and flexibility in our assignments that enabled us to participate in

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Stephen D. Cramer, FNACE
Bernard S. Covino, Jr., FNACE
National Energy Technology Laboratory
U.S. Department of Energy

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