# ASM Handbook®

## Volume 5B
## Protective Organic Coatings

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ASM International Handbook Committee

**Volume Editor**
**Kenneth B. Tator**, P.E., KTA-Tator, Inc.

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ASM International®
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# Foreword

*ASM Handbook*, Volume 5B, *Protective Organic Coatings* is a wholly new entry in the esteemed *ASM Handbook* series. Volume 5B grew out of an article, "Organic Coatings and Linings," by Kenneth B. Tator, P.E., published in 2003 in *ASM Handbook*, Volume 13A, *Corrosion: Fundamentals, Testing, and Protection*. Mr. Tator and ASM International identified a need for an entire book dedicated to industrial protective coatings, based on the engineering and economic significance of the industry. To fill the reference publications gap in the materials field, the decision was made to include the book as a Volume in the *ASM Handbook* series, industry's most comprehensive source of information on materials technology.

Volume 5B, like every Volume of the *ASM Handbook* series, was written by recognized industry experts, reviewed by groups of their peers, and edited by professionals dedicated to developing reference publications of the highest technical and editorial quality. This results in authoritative, reliable sources of information in every area of materials specialization, now including protective organic coatings.

ASM International is grateful for the hard work and dedication of its many volunteer authors and reviewers who gave of their expertise and time to make Volume 5B possible, particularly Kenneth B. Tator, P.E., KTA-Tator, Inc., Volume Editor and author of numerous articles in the Volume.

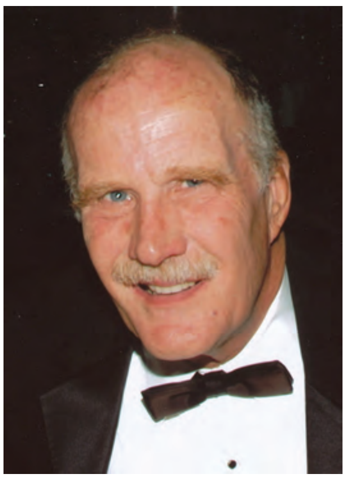
*ASM Handbook*, Volume 5B, *Protective Organic Coatings* is comprised of five divisions, which offer introductory material, an in-depth presentation of specific coating materials, practical information on surface preparation and coating application, coverage of coating use by various industries, and detailed discussion of coating analysis and evaluation methods. Volume 5B authors provided the latest information on the many industry standards that must be adhered to in the preparation, application, and testing of protective coatings.

Volume 5B includes full-color printing of all of its figures, including all photographs. ASM International thanks Kenneth B. Tator, P.E., and KTA-Tator, Inc., a corrosion and coatings consulting and inspection firm, for their generous contributions that have allowed the photographs in this book to be reproduced in color.

**Sunniva R. Collins, Ph.D.**
President
ASM International

**Terry F. Mosier**
Interim Managing Director
ASM International

# Preface



**Kenneth B. Tator, P.E.**
**Chairman of the Board,** KTA-Tator, Inc.
Pittsburgh, PA, USA

Corrosion is a phenomenon of nature involving the deterioration of a material (usually a metal) due to a chemical or electrochemical reaction with the environment.

In accord with this definition, virtually every material object around us corrodes or can be expected to corrode. Metallic corrosion is most evident, and that of steel is most familiar to even casual observers because it results in a brown-colored rust that leads to pitting and ultimate loss of structural strength. Of course, other metals deteriorate to varying degrees on exposure to certain environments, although the deterioration may not be as evident. Corrosion of nonmetals also occurs, and that of wood and concrete is also of great concern. This destructive material deterioration occurs to transportation vehicles (automobiles, trucks, railroad cars, etc.), bridges, pipelines of all types (water and wastewater, oil, gas, etc.), private homes and public buildings, even home appliances, electronic equipment, and—heaven forbid—personal computers and cell phones. Corrosion is all-pervasive in most environments in every region, country, and continent around the world!

ASM International has three comprehensive volumes on corrosion in its *ASM Handbook* series: Volume 13A, *Corrosion: Fundamentals, Testing, and Protection*; Volume 13B, *Corrosion: Materials*; and Volume 13C, *Corrosion: Environments and Industries*. Corrosion carries significant costs, estimated in 2013 to be more than $450 billion annually in the United States and $2.2 trillion worldwide, according to NACE International, the global authority on corrosion.

However, by utilizing existing corrosion-prevention technologies, the cost can be drastically reduced, perhaps by one-third or more. What are those technologies? They include proper corrosion design and maintenance; the use of more resistant construction materials, such as corrosion-resistant alloys and plastics; the use of corrosion inhibitors; anodic and cathodic protection; metallic coatings; and the use of organic protective coatings. This last technology is the subject of this Volume. It is an important subject because organic protective coatings are by far the most widely used means of corrosion protection. The application and use of organic protective coatings, including zinc-rich coatings, accounted for 88.3% of all monies spent for corrosion protection in the United States, as estimated by the report "Corrosion Cost and Preventive Strategies in the United States," FHWA-RD-01-156, issued by the Federal Highway Administration in 2002. Adjusted to the 2013 estimated cost of corrosion in the United States of $450 billion utilizing the same ratios of corrosion cost to coating protection expense used in 2002, the money spent for protective coating corrosion abatement in the United States would exceed $175 billion, or over $545 for every man, woman, and child in the United States, at the end of 2014—not a trifling sum!

This printed Volume is but a snapshot in time regarding coatings. It is not all-inclusive, as there are other areas where coatings are used and some specific types of coatings that are not covered herein. Moreover, like everything else in life these days, change is constant, and the rate of technological improvement is accelerating at an ever-increasing rate. Coatings, like all materials, have benefited greatly from the advent of nanotechnology, and superior coatings are being introduced to the market on an almost daily basis. ASM International is releasing this book not only in printed form but also in a digital format, available on the ASM International website. This makes possible future updates and additional content, so our coverage keeps pace with technology. I absolutely encourage readers to assist ASM International in keeping this Volume's digital version current with updated technology.

This Volume is organized into five divisions: Introduction (consisting of four articles); Coating Materials (nineteen articles); Surface Preparation and Coating Application (seven articles); Industrial Uses (nine articles); and Coating Analysis and Evaluation (six articles). A total of 50 authors wrote the Volume's 45 articles. I am most grateful to those authors, and their employer corporations and organizations, for the contribution of the considerable time and expertise necessary to write articles for this Volume. What a remarkable group of professionals!

I'd also like to thank Patty Conti, Production Coordinator; Kate Fornadel, Senior eProduction Coordinator; Diane Whitelaw, Production Coordinator; and Madrid Tramble, Manager, Production at ASM International for publishing this first *ASM Handbook* totally in color. A color production requires a lot more attention to detail than a black-and-white production, and Patty and the ASM group have pulled it off—congratulations! Others at ASM International who deserve special thanks are Steve Lampman, Senior Content Developer; Karen Marken, Senior Managing Editor; and Scott Henry, Director, Content and Knowledge-Based Solutions.

I'm indebted to Amy Nolan, Content Developer at ASM International, for helping to obtain authors and reviewers and for nagging authors (mostly me) to get their articles written on schedule. Without her, this book could not have been written.

I would also like to thank my employer, KTA-Tator, Inc., for so graciously allowing me the time to work on this Volume, as I conducted much of my work at home—although they likely felt they were better off without me at the office.

Finally, and perhaps most importantly, I would like to thank my wife Maureen who put up with my computer rage and other frustrations while I was working at home. She is the love of my life, and, as a result of my Handbook effort, while always a beautiful woman, Maureen now has exemplary patience, resilience, and tolerance—I am truly blessed!

Ken Tator
Editor

# 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 may 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.

# List of Contributors and Reviewers


**Thomas N. Ackerson**
Curtiss-Wright IMR Test Labs

**Cory Allen**
Vulcan Painters, Inc.

**Mike Ames**
SAE Inc.

**Joshua Armstrong**
Tesla Nanocoatings Inc.

**Pete Ault**
Elzly Technology Corporation

**D. Bennett**
Corrosion Probe, Inc.

**Mike Bentkjaer**
Sherwin-Williams

**Kristen Blankenship**
AGC Chemicals Americas, Inc.

**Kevin J. Brown**
KTA-Tator, Inc.

**Liza A. Capino**
Sherwin-Williams Company

**Jon R. Cavallo**
UESI, Inc.

**Kimmer Cline**
KTA-Tator, Inc.

**William D. Corbett**
KTA-Tator, Inc.

**Marvin Dettloff**
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Consultant

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Stonhard/Epoplex

**Denis Grimshaw**
Jotun Powder Coatings

**Bill Hannemann**
Retired

**Todd Hawkins**
Tesla Nanocoatings Inc.

**Jayson L. Helsel**
KTA-Tator, Inc.

**J. Bruce Henley**
The Brock Group

**Rick Huntley**
KTA-Tator, Inc.

**Robert A. Iezzi**
RAI Technical Solutions, Inc.

**Alison B. Kaelin**
ABKaelin, LLC

**J. Alan Kehr**
Alan Kehr Anti-Corrosion

**Charles Kennedy**
Trenton Corporation

**Kevin D. Knight**
Retro-Specs, Ltd.

**Michael G. Koehler**
Professional Analysis and Consulting, Inc.

**James Lane**
Professional Analysis and Consulting, Inc.

**Gary Larson**
AkzoNobel Coatings

**Barry Law**
Master Painters Institute (MPI)

**Chi Lee**
Sherwin-Williams Company

**Stanford T. Liang**
AM Health and Safety, Inc.

**Scott Lillard**
University of Akron

**James Machen**
KTA-Tator, Inc.

**Timothy McDonough**
Sherwin-Williams Company

**Carly McGee**
KTA-Tator, Inc.

**Donald Miller**
Tnemec Company

**Jim Molnar**
UTLX

**Douglas P. Moore**
Carboline Company

**R. A. Nixon**
Corrosion Probe, Inc.

**David Norman**
Retired Corrosion Control Engineer

**Ahren Olson**
Bayer Material Science LLC

**Cindy O'Malley**
KTA-Tator, Inc.

**Dan O'Malley**
KTA-Tator, Inc.

**Robert Parker**
AGC Chemicals Americas, Inc.

**Trevor Parry**
Consultant

**Hap Peters**
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VersaFlex Inc.

**Leo J. Procopio**
The Dow Chemical Company

**Frank Rampton**
Trenton Corporation

**Douglas Reardon**
KTA-Tator, Inc.

**Michael P. Reina**
KTA-Tator, Inc.

**Steven Reinstadtler**
Bayer MaterialScience LLC

**Greg Richards**
KTA-Tator, Inc.

**Cheryl Roberts**
KTA-Tator, Inc.

**Stuart J. Rowan**
Case Western Reserve University

**Don Sampson**
API USA

**Tim Schaffer**
Watco Companies

**Mark Schultz**
Sherwin-Williams Company

**E. Bud Senkowski**
KTA-Tator, Inc.

**Valerie Sherbondy**
KTA-Tator, Inc.

**Charles Simpson**
Tesla Nanocoatings Inc.

**William R. Slama**
AkzoNobel

**Bruce K. Snyder**
Sherwin-Williams Company

**Edward P. Squiller**
Bayer Material Science LLC

**Chrissy Stewart**
KTA-Tator, Inc.

**Heather Stiner**
SSPC: The Society for Protective Coatings

**Kenneth B. Tator**
KTA-Tator, Inc.

**Kenneth A. Trimber**
KTA-Tator, Inc.

**Jorma Virtanen**
Tesla Nanocoatings Inc.

**Lucian Williams**
Denso NA

**Todd Williams**
Bayer Material Science LLC

**Gerald L. Witucki**
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