PERRY'S CHEMICAL ENGINEERS' HANDBOOK SEVENTH EDITION

McGraw-Hill

New York
San Francisco
Washington, D.C.
Auckland
Bogotá
Caracas
Lisbon
London
Madrid
Mexico City
Milan
Montreal

New Delhi

San Juan Singapore Sydney Tokyo

Toronto

Prepared by a staff of specialists under the editorial direction of

Late Editor
Robert H. Perry

Editor

Don W. Green

Deane E. Ackers Professor of Chemical and Petroleum Engineering, University of Kansas

Associate Editor **James O. Maloney**Professor Emeritus of Chemical Engineering,

University of Kansas

Library of Congress Cataloging-in-Publication Data

Perry's chemical engineers' handbook. — 7th ed. / prepared by a staff of specialists under the editorial direction of late editor Robert H. Perry: editor, Don W. Green: associate editor, James O'Hara Maloney.

p. cm.
Includes index.
ISBN 0-07-049841-5 (alk. paper)
1. Chemical engineering—Handbooks, manuals, etc. I. Perry, Robert H., date. II. Green, Don W. III. Maloney, James O. TP151.P45 1997
660—dc21 96-51648

McGraw-Hill



CIP

A Division of The McGraw-Hill Companies

Copyright © 1997, 1984, 1973, 1963, 1950, 1941, 1934 by The McGraw-Hill Companies, Inc. Copyright renewed 1962, 1969 by Robert H. Perry. All rights reserved.

Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher

1 2 3 4 5 6 7 8 9 0 DOW/DOW 9 0 2 1 0 9 8 7

ISBN 0-07-049841-5

INTERNATIONAL EDITION

Copyright © 1997. Exclusive rights by The McGraw-Hill Companies, Inc., for manufacture and export. This book cannot be re-exported from the country to which it is consigned by McGraw-Hill. The International Edition is not available in North America.

When ordering this title, use ISBN 0-07-115448-5.

The sponsoring editors for this book were Zoe Foundotos and Robert Esposito, the editing supervisor was Marc Campbell, and the production supervisor was Pamela A. Pelton. It was set in Caledonia by North Market Street Graphics.

Printed and bound by R. R. Donnelley & Sons Company.

This book was printed on acid-free paper.

Information contained in this work has been obtained by The McGraw-Hill Companies, Inc. ("McGraw-Hill") from sources believed to be reliable. However, neither McGraw-Hill nor its authors guarantee the accuracy or completeness of any information published herein, and neither McGraw-Hill nor its authors shall be responsible for any errors, omissions, or damages arising out of use of this information. This work is published with the understanding that McGraw-Hill and its authors are supplying information but are not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought.

Dedicated to Robert H. Perry

ABOUT THE EDITORS

The late **Robert H. Perry** served as chairman of the Department of Chemical Engineering at the University of Oklahoma and program director for graduate research facilities at the National Science Research Foundation. He was a consultant to various United Nations and other international organizations. From 1973 until his death in 1978 Dr. Perry devoted his time to a study of the cross impact of technologies within the next half century. The subjects under his investigation on a global basis were energy, minerals and metals, transportation and communications, medicine, food production, and the environment.

Don W. Green is Chair and the Deane E. Ackers distinguished professor of chemical and petroleum engineering and codirector of the Tertiary Oil Recovery Project at the University of Kansas in Lawrence, Kansas, where he has taught since 1964. He received his doctorate in chemical engineering in 1963 from the University of Oklahoma, where he was Dr. Perry's first doctoral student. Dr. Green has won several teaching awards at the University of Kansas, and he is a fellow of the AIChE and a distinguished member of the Society of Petroleum Engineers. He is the author of numerous articles in technical journals.

James O. Maloney is Professor Emeritus of the Department of Chemical and Petroleum Engineering, University of Kansas. He holds a Ph.D. degree in chemical engineering from Pennsylvania State University. In 1941 he began his professional career at the DuPont de Nemours Company, before joining the University of Kansas in 1945, where he taught for 40 years. He served as department chairman for nineteen years. He is a fellow of the AIChE.

List of Contributors

Michael M. Abbott, Ph.D., Howard P. Isermann Department of Chemical Engineering, Rensselaer Polytechnic Institute; Member, American Institute of Chemical Engineers (Section 4, Thermodynamics)

Terry Allen, Ph.D., Senior Research Associate (retired), DuPont Central Research and Development (Section 20, Size Reduction and Size Enlargement)

John D. Bacha, Ph.D., Consulting Scientist, Chevron Products Company; Member, ASTM (American Society for Testing and Materials), Committee D02 on Petroleum Products and Lubricants; American Chemical Society; International Association for Stability and Handling of Liquid Fuels, Steering Committee (Section 27, Energy Resources, Conversion, and Utilization)

Glenn W. Baldwin, M.S., P.E., Staff Engineer, Union Carbide Corporation; Member, American Institute of Chemical Engineers (Section 12, Psychrometry, Evaporative Cooling, and Solids Drying)

Scott D. Barnicki, Ph.D., Senior Research Chemical Engineer, Eastman Chemical Company (Section 13, Distillation)

Kenneth J. Bell, Ph.D., P.E., Regents Professor Emeritus, School of Chemical Engineering, Oklahoma State University; Member, American Institute of Chemical Engineers (Section 11, Heat-Transfer Equipment)

Richard C. Bennett, B.S., Ch.E., Registered Professional Engineer, Illinois; Member, American Institute of Chemical Engineers (AIChE); President of Crystallization Technology, Inc.; Former President of Swenson Process Equipment, Inc. (Section 18, Liquid-Solid Operations and Equipment)

Charles E. Benson, M.Eng., M.E., Director, Combustion Technology, Arthur D. Little, Inc.; Member, American Society of Mechanical Engineers, Combustion Institute (Section 27, Energy Resources, Conversion, and Utilization)

Patrick M. Bernhagen, P.E., B.S.M.E., Senior Mechanical Engineer, Foster Wheeler USA Corporation, American Society of Mechanical Engineers (Section 11, Heat-Transfer Equipment)

- Heinz P. Bloch, P.E., B.S.M.E., M.S.M.E., Consulting Engineer, Process Machinery Consulting; American Society of Mechanical Engineers, Vibration Institute; Registered Professional Engineer (New Jersey, Texas) (Section 29, Process Machinery Drives)
- Frank T. Bodurtha, Sc.D., E.I. DuPont de Nemours and Co., Inc. (retired), Wilmington, Delaware (retired); Consultant, Frank T. Bodurtha, Inc. (Section 26, Process Safety)
- Meherwan P. Boyce, P.E., Ph.D., President, Boyce Engineering International; ASME Fellow; Registered Professional Engineer (Texas, Oklahoma) (Section 10, Transport and Storage of Fluids; Section 29, Process Machinery Drives)
- Laurence G. Britton, Ph.D., Research Scientist, Union Carbide Corporation (Section 26, Process Safety)
- Evan Buck, M.S.Ch.E., Manager, Thermophysical Property Skill Center, Central Technology, Union Carbide Corporation (Section 2, Physical and Chemical Data)
- Henry R. Bungay, P.E., Ph.D., Professor of Chemical and Environmental Engineering, Rensselaer Polytechnic Institute; Member, American Institute of Chemical Engineers, American Chemical Society, American Society for Microbiology, American Society for Engineering Education, Society for General Microbiology (Section 24, Biochemical Engineering)
- Anthony J. Buonicore, M.Ch.E., P.E., Diplomate AAEE, CEO, Environmental Data Resources, Inc.; Member, American Institute of Chemical Engineers, Air and Waste Management Association (Section 25, Waste Management)
- Michael M. Calistrat, B.S.M.E., M.S.M.E., Owner, Michael Calistrat and Associates; Member, American Society of Mechanical Engineers (Section 29, Process Machinery Drives)
- Giorgio Carta, Ph.D., Professor, Department of Chemical Engineering, University of Virginia; Member, American Institute of Chemical Engineers, American Chemical Society, International Adsorption Society (Section 16, Adsorption and Ion Exchange)
- Vincent Conrad, Ph.D., Group Leader, Technical Services Development Laboratory, CONSOL, Inc.; Member, Spectroscopy Society of Pittsburgh, Society for Analytical Chemistry of Pittsburgh, Society for Applied Spectroscopy (Section 27, Energy Resources, Conversion, and Utilization)
- Harrison Cooper, Ph.D., Harrison R. Cooper Systems, Inc., Salt Lake City, Utah (Section 19, Solid-Solid Operations and Equipment)
- B. B. Crocker, S.M., P.E., Consulting Chemical Engineer; Fellow, American Institute of Chemical Engineers; Member, Air Pollution Control Association (Section 14, Gas Absorption and Gas-Liquid System Design)
- Daniel A. Crowl, Ph.D., Professor of Chemical Engineering, Chemical Engineering Department, Michigan Technological University; Member, American Institute of Chemical Engineers, American Chemical Society (Section 26, Process Safety)
- Roger W. Cusack, Vice President, Glitsch Process Systems, Inc.; Member, American Institute of Chemical Engineers (Section 15, Liquid-Liquid Extraction Operations and Equipment)
- Donald A. Dahlstrom, Ph.D., Research Professor, Chemical and Fuels Engineering Department and Metallurgical Engineering Department, University of Utah; Member, National Academy of Engineering, American Institute of Chemical Engineers (AIChE), American Chemical Society (ACS), Society of Mining, Metallurgic Exploration (SME) of the American Institute of Mining, Metallurgical and Petroleum Engineers (AIME), American Society of Engineering Education (Section 18, Liquid-Solid Operations and Equipment)
- Thomas E. Daubert, Ph.D., Professor, Department of Chemical Engineering, The Pennsylvania State University (Section 2, Physical and Chemical Data)
- R. H. Daugherty, Ph.D., Consulting Engineer, Research Center, Reliance Electric Company; Member, Institute of Electrical and Electronics Engineers (Section 29, Process Machinery Drives)

- James F. Davis, Ph.D., Professor of Chemical Engineering, Ohio State University (Section 3, Mathematics)
- James B. Dunson, B.S., Principal Consultant, E. I. duPont de Nemours & Co.; Member American Institute of Chemical Engineers; Registered Professional Engineer (Delaware) (Section 17, Gas-Solid Operation and Equipment)
- **Thomas F. Edgar, Ph.D.,** Professor of Chemical Engineering, University of Texas, Austin, Texas (Section 8, Process Control)
- Robert C. Emmet, Jr., B.S., Ch.E., Senior Process Consultant, EIMCO Process Equipment Co.; Member, American Institute of Chemical Engineers (AIChE), American Institute of Mining, Metallurgical and Petroleum Engineers (AIME), Society of Mining, Metallurgical and Exploration Engineers (SME) (Section 18, Liquid-Solid Operations and Equipment)
- Stanley M. Englund, M.S., Ch.E., Fellow, American Institute of Chemical Engineers; Process Consultant, The Dow Chemical Company (retired) (Section 26, Process Safety)
- Bryan J. Ennis, Ph.D., President, E&G Associates, and Adjunct Professor of Chemical Engineering, Vanderbilt University; Member and Chair of Powder Technology Programming Group of the Particle Technology Forum, American Institute of Chemical Engineers (Section 20, Size Reduction and Size Enlargement)
- William Eykamp, Ph.D., Adjunct Professor of Chemical Engineering, Tufts University; Formerly President, Koch Membrane Systems; Member, American Institute of Chemical Engineers, American Chemical Society, American Association for the Advancement of Science, North American Membrane Society, European Society of Membrane Science and Technology (Section 22, Alternative Separation Processes)
- James R. Fair, Ph.D., P.E., Professor of Chemical Engineering, University of Texas; National Academy of Engineering; Fellow, American Institute of Chemical Engineers; Member, American Chemical Society, American Society for Engineering Education, National Society of Professional Engineers (Section 14, Gas Absorption and Gas-Liquid System Design)
- **Bruce A. Finlayson, Ph.D.,** Rehnberg Professor and Chair, Department of Chemical Engineering, University of Washington; Member, National Academy of Engineering (Section 3, Mathematics)
- Thomas M. Flynn, Ph.D., P.E., Cryogenic Engineer, President CRYOCO, Louisville, Colorado; Member, American Institute of Chemical Engineers (Section 11, Heat-Transfer Equipment)
- Anthony G. Fonseca, Ph.D., Director, Coal Utilization, CONSOL, Inc.; Member, American Chemical Society, Society for Mining, Metallurgy, and Extraction (Section 27, Energy Resources, Conversion, and Utilization)
- **D. G. Friend,** National Institutes of Standards and Technology, Boulder, Colorado (Section 2, Physical and Chemical Data)
- George W. Gassman, B.S.M.E., Senior Research Specialist, Final Control Systems, Fisher Controls International, Inc., Marshalltown, Iowa (Section 8, Process Control)
- Fred K. Geitner, P.Eng., B.S.M.E., M.S.M.E., Consulting Engineer, Registered Professional Engineer (Ontario, Canada) (Section 29, Process Machinery Drives)
- Victor M. Goldschmidt, Ph.D., P.E., Professor of Mechanical Engineering, Purdue University, West Lafayette, Indiana (Section 11, Heat-Transfer Equipment)
- Stanley Grossel, President, Process Safety & Design, Inc.; Fellow, American Institute of Chemical Engineers; Member, American Chemical Society; Member, The Combustion Institute; Member, Explosion Protection Systems Committee of NFPA (Section 26, Process Safety)
- Peter Harriott, Ph.D., Professor, School of Chemical Engineering, Cornell University; Member, American Institute of Chemical Engineering, American Chemical Society (ACS) (Section 18, Liquid-Solid Operations and Equipment)

- T. Alan Hatton, Ph.D., Ralph Landau Professor and Director of the David H. Koch School of Chemical Engineering Practice, Massachusetts Institute of Technology; Founding Fellow, American Institute of Medical and Biological Engineering; Member, American Institute of Chemical Engineers, American Chemical Society, International Association of Colloid and Interface Scientists, American Association for the Advancement of Science, Neutron Scattering Society of America (Section 22, Alternative Separation Processes)
- Joseph D. Henry, Jr., Ph.D., P.E., Senior Fellow, Department of Engineering and Public Policy, Carnegie Mellon University; Member, American Institute of Chemical Engineers, American Society for Engineering Education (Section 22, Alternative Separation Processes)
- W. G. High, C.Eng., B.Sc., F.I.Mech.E., Burgoyne Consultants Ltd., W. Yorks, England (Section 26, Process Safety)
- Richard Hogg, Ph.D., Professor, Department of Mineral Engineering, The Pennsylvania State University, University Park, PA (Section 19, Solid-Solid Operations and Equipment)
- **F. A. Holland, D.Sc., Ph.D.,** Consultant in Heat Energy Recycling; Research Professor, University of Salford, England; Fellow, Institution of Chemical Engineers, London (Section 9, Process Economics)
- Hoyt C. Hottel, S.M., Professor Emeritus of Chemical Engineering, Massachusetts Institute of Technology; Member, National Academy of Sciences, American Academy of Arts and Sciences, American Institute of Chemical Engineers, American Chemical Society, Combustion Institute (Section 5, Heat and Mass Transfer)
- Colin S. Howat, Ph.D., P.E., John E. & Winfred E. Sharp Professor, Department of Chemical and Petroleum Engineering, University of Kansas; Member, American Institute of Chemical Engineers; Member, American Society of Engineering Education (Section 30, Analysis of Plant Performance)
- Predrag S. Hrnjak, Ph.D., V.Res., Assistant Professor, University of Illinois at Urbana Champaign and Principal Investigator—U. of I. Air Conditioning and Refrigeration Center, Assistant Professor, University of Belgrade; Member, International Institute of Refrigeration, American Society of Heating, Refrigeration and Air Conditioning (Section 11, Heat-Transfer Equipment)
- Arthur E. Humphrey, Ph.D., Retired, Professor of Chemical Engineering, Pennsylvania State University; Member, U.S. National Academy of Engineering, American Institute of Chemical Engineers, American Chemical Society, American Society for Microbiology (Section 24, Biochemical Engineering)
- Eric Jenett, M.S.Ch.E., Manager, Process Engineering, Brown & Root, Inc.; Associate Member, AIChE, Project Management Institute; Registered Professional Engineer (Texas) (Section 29, Process Machinery Drives)
- John S. Jeris, Sc.D., P.E., Professor of Environmental Engineering, Manhattan College; Environmental Consultant; Member, American Water Works Association, Water Environment Federation Section Director (Section 25, Waste Management)
- T. L. P. Jespen, M.S., Min. Proc., Metallurgical Engineer, Basic, Inc., Gabbs, Nevada (Section 19, Solid-Solid Operations and Equipment)
- Keith P. Johnston, Ph.D., P.E., Professor of Chemical Engineering, University of Texas (Austin); Member, American Institute of Chemical Engineers, American Chemical Society, University of Texas Separations Research Program (Section 22, Alternative Separation Processes)
- Trevor A. Kletz, D.Sc., Senior Visiting Research Fellow, Department of Chemical Engineering, Loughborough University, U.K.; Fellow, American Institute of Chemical Engineers, Royal Academy of Engineers (U.K.), Institution of Chemical Engineers (U.K.), and Royal Society of Chemistry (U.K.) (Section 26, Process Safety)
- **Edgar B. Klunder, Ph.D.,** Project Manager, Energy Technology Center (Pittsburgh), U.S. Department of Energy (Section 27, Energy Resources, Conversion, and Utilization)

- **Kent S. Knaebel, Ph.D.,** President, Adsorption Research, Inc.; Member, American Institute of Chemical Engineers, American Chemical Society, International Adsorption Society. Professional Engineer (Ohio) (Section 5, Heat and Mass Transfer)
- **Frank Knoll, M.S., Min. Proc.,** President, Carpco, Inc., Jacksonville, Florida (Section 19, Solid-Solid Operations and Equipment)
- **James G. Knudsen, Ph.D.,** Professor Emeritus of Chemical Engineering, Oregon State University; Member, American Institute of Chemical Engineers, American Chemical Society; Registered Professional Engineer (Oregon) (Section 5, Heat and Mass Transfer)
- Michael Krumpelt, Ph.D., Manager, Fuel Cell Technology, Argonne National Laboratory; Member, American Institute of Chemical Engineers, American Chemical Society, Electrochemical Society (Section 27, Energy Resources, Conversion, and Utilization)
- **Irwin J. Kugelman, Sc.D.,** Professor of Civil Engineering, Lehigh University; Member, American Society of Civil Engineering, Water Environmental Federation (Section 25, Waste Management)
- **Tim Laros, M.S. Mineral Processing,** Senior Process Consultant, EIMCO Process Equipment Co.; Member, Society of Mining, Metallurgy and Exploration (SME of AIME) (Section 18, Liquid-Solid Operations and Equipment)
- **Richard M. Lemert, Ph.D., P.E.,** Assistant Professor of Chemical Engineering, University of Toledo; Member, American Institute of Chemical Engineers, American Chemical Society, Society of Mining Engineers, American Society for Engineering Education (Section 22, Alternative Separation Processes)
- Robert Lemlich, Ph.D., P.E., Professor of Chemical Engineering Emeritus, University of Cincinnati; Fellow, American Institute of Chemical Engineers; Member, American Chemical Society, American Society for Engineering Education, American Chemical Society (Section 22, Alternative Separation Processes)
- Wallace Leung, Sc.D., Director, Process Technology, Bird Machine Company; Member, American Filtration and Separation Society (Director) (Section 18, Liquid-Solid Operations and Equipment)
- M. Douglas LeVan, Ph.D., Professor, Department of Chemical Engineering, University of Virginia; Member, American Institute of Chemical Engineers, American Chemical Society, International Adsorption Society (Section 16, Adsorption and Ion Exchange)
- **Peter E. Liley, Ph.D., D.I.C.,** School of Mechanical Engineering, Purdue University (Section 2, Physical and Chemical Data)
- **James D. Litster, Ph.D.,** Associate Professor, Department of Chemical Engineering, University of Queensland; Member, Institute of Chemical Engineers—Australia (Section 20, Size Reduction and Size Enlargement)
- **Peter J. Loftus, D. Phil.,** Arthur D. Little, Inc.; Member, American Society of Mechanical Engineers (Section 27, Energy Resources, Conversion, and Utilization)
- **Hsue-peng Loh, Ph.D., P.E.,** Federal Energy Technology Center (Morgantown), U.S. Department of Energy; Member, American Institute of Chemical Engineers, American Society of Information Sciences (Section 27, Energy Resources, Conversion, and Utilization)
- **Douglas E. Lowenhaupt, M.S.,** Group Leader, Coke Laboratory, CONSOL, Inc.; Member, American Society for Testing and Materials, Iron and Steel Making Society, International Committee for Coal Petrology (Section 27, Energy Resources, Conversion, and Utilization)
- James O. Maloney, Ph.D., P.E., Emeritus Professor of Chemical Engineering, University of Kansas; Fellow, American Institute of Chemical Engineering; Fellow, American Association for the Advancement of Science; Member, American Chemical Society, American Society for Engineering Education (Section 1, Conversion Factors and Mathematical Symbols)

LIST OF CONTRIBUTORS

- **Thomas J. McAvoy, Ph.D.,** Professor of Chemical Engineering, University of Maryland, College Park, Maryland (Section 8, Process Control)
- Chad McCleary, EIMCO Process Equipment Company, Process Consultant (Section 18, Liquid-Solid Operations and Equipment)
- **Thomas F. McGowan, P.E.,** Senior Consultant, RMT/Four Nines; Member, American Institute of Chemical Engineers, American Society of Mechanical Engineers, Air and Waste Management Association (Section 25, Waste Management)
- Howard G. McIlvried, III, Ph.D., Senior Engineer, Burns and Roe Services Corporation, Federal Energy Technology Center (Pittsburgh), Member, American Chemical Society, American Institute of Chemical Engineers (Section 27, Energy Resources, Conversion, and Utilization)
- John D. McKenna, Ph.D., President and Chairman, ETS International, Inc., Member, American Institute of Chemical Engineers, Air and Waste Management Association (Section 25, Waste Management)
- Shelby A. Miller, Ph.D., P.E., Resident Retired Senior Engineer, Argonne National Laboratory; American Association for the Advancement of Science (Fellow), American Chemical Society, American Institute of Chemical Engineers (Fellow), American Institutes of Chemists (Fellow), Filtration Society, New York Academy of Sciences, Society of Chemical Industry (Section 18, Liquid-Solid Operations and Equipment; Section 27, Energy Resources, Conversion, and Utilization)
- **Booker Morey, Ph.D.,** Senior Consultant, SRI International; Member, Society of Mining, Metallurgy and Exploration (SME of AIME), The Filtration Society, Air and Waste Management Association; Registered Professional Engineer (California and Massachusetts) (Section 18, Liquid-Solid Operations and Equipment)
- Charles G. Moyers, Ph.D., P.E., Principal Engineer, Union Carbide Corporation; Fellow, American Institute of Chemical Engineers (Section 12, Psychrometry, Evaporative Cooling, and Solids Drying; Section 22, Alternative Separation Processes)
- **John Newman, Ph.D.,** Professor of Chemical Engineering, University of California, Berkeley; Principle Investigator, Inorganic Materials Research Division, Lawrence Berkeley Laboratory (Section 22, Alternative Separation Processes)
- James Y. Oldshue, Ph.D., President, Oldshue Technologies International, Inc.; Member, National Academy of Engineering; Adjunct Professor of Chemical Engineering at Beijing Institute of Chemical Technology, Beijing, China; Member, American Chemical Society (ACE), American Institute of Chemical Engineering (AIChE), Traveler Century Club, Executive Committee on the Transfer of Appropriate Technology for the World Federation of Engineering Organizations (Section 18, Liquid-Solid Operations and Equipment)
- Robert W. Ormsby, M.S., Ch.E. P.E., Manager of Safety, Chemical Group, Air Products and Chemicals, Inc.; Air Products Corp.; Fellow, American Institute of Chemical Engineers (Section 26, Process Safety)
- John E. Owens, B.E.E., Electrostatic Consultant, Condux, Inc.; Member, Institute of Electrical and Electronics Engineers, Electrostatics Society of America (Section 26, Process Safety)
- **Bhupendra Parekh, Ph.D.,** Associate Director, Center for Applied Energy Research, University of Kentucky, Lexington, Kentucky (Section 19, Solid-Solid Operations and Equipment)
- Mel Pell, Ph.D., Senior Consultant, E. I. duPont de Nemours & Co.; Fellow, American Institute of Chemical Engineers; Registered Professional Engineer (Delaware) (Section 17, Gas-Solid Operations and Equipment)
- W. R. Penney, Ph.D., P.E., Professor of Chemical Engineering, University of Arkansas; Member, American Institute of Chemical Engineers (Section 14, Gas Absorption and Gas-Liquid System Design)

- Walter F. Podolski, Ph.D., Chemical Engineer, Electrochemical Technology Program, Argonne National Laboratory; Member, American Institute of Chemical Engineers (Section 27, Energy Resources, Conversion, and Utilization)
- **Herbert A. Pohl, Ph.D.** (deceased), Professor of Physics, Oklahoma State University (Section 22, Alternative Separation Processes)
- **Kent Pollock, Ph.D.,** Member of Technical Staff, Group 91, Space Surveillance Techniques, MIT Lincoln Laboratory (Section 22, Alternative Separation Processes)
- George Priday, B.S., Ch.E., EIMCO Process Equipment Company; Member, American Institute of Chemical Engineering (AIChE), Instrument Society of America (ISA) (Section 18, Liquid-Solid Operations and Equipment)
- Michael E. Prudich, Ph.D., Professor and Chair of Chemical Engineering, Ohio University; Member, American Institute of Chemical Engineers, American Chemical Society, Society of Mining Engineers, American Society for Engineering Education (Section 22, Alternative Separation Processes)
- Raj K. Rajamani, Ph.D., Professor, Department of Metallurgy and Metallurgical Engineering, University of Utah, Salt Lake City, Utah (Section 19, Solid-Solid Operations and Equipment)
- Lawrence K. Rath, B.S., P.E., Federal Energy Technology Center (Morgantown), U.S. Department of Energy; Member, American Institute of Chemical Engineers (Section 27, Energy Resources, Conversion, and Utilization)
- Grantges J. Raymus, M.E., M.S., President, Raymus Associates, Incorporated, Packaging Consultants; Adjunct Professor and Program Coordinator, Center for Packaging Science and Engineering, College of Engineering, Rutgers, The State University of New Jersey; formerly Manager of Packaging Engineering, Union Carbide Corporation; Registered Professional Engineer, California; Member, Institute of Packaging Professionals, ASME (Section 21, Handling of Bulk Solids and Packaging of Solids and Liquids)
- Lanny A. Robbins, Ph.D., Research Fellow, Dow Chemical Company; Member, American Institute of Chemical Engineers (Section 15, Liquid-Liquid Extraction Operations and Equipment)
- **Joseph J. Santoleri, P.E.,** Senior Consultant, RMT/Four Nines; Member, American Institute of Chemical Engineers, American Society of Mechanical Engineers, Air and Waste Management Association (Section 25, Waste Management)
- Adel F. Sarofim, Sc.D., Lammot DuPont Professor of Chemical Engineering and Assistant Director, Fuels Research Laboratory, Massachusetts Institute of Technology; Member, American Institute of Chemical Engineers, American Chemical Society, Combustion Institute (Section 5, Heat and Mass Transfer)
- Kalanadh V. S. Sastry, Ph.D., Professor, Department of Materials Science and Mineral Engineering, University of California, Berkeley, CA; Member, American Institute of Chemical Engineers, Society for Mining, Metallurgy and Exploration (Section 19, Solid-Solid Operations and Equipment)
- Paul J. Schafbuch, Ph.D., Senior Research Specialist, Final Control Systems, Fisher Controls International, Inc., Marshalltown, Iowa (Section 8, Process Control)
- Carl A. Schiappa, B.S., Ch.E., Process Engineering Associate, Michigan Division Engineering, The Dow Chemical Company; Member, AIChE and CCPS (Section 26, Process Safety)
- **David K. Schmalzer, Ph.D., P.E.,** Fossil Energy Program Manager, Argonne National Laboratory; Member, American Chemical Society, American Institute of Chemical Engineers (Section 27, Energy Resources, Conversion, and Utilization)
- J. D. Seader, Ph.D., Professor of Chemical Engineering, University of Utah, Salt Lake City, Utah; Fellow, American Institute of Chemical Engineers; Member, American Chemical Society; Member. American Society for Engineering Education (Section 13, Distillation)

- Dale E. Seborg, Ph.D., Professor of Chemical Engineering, University of California, Santa Barbara, California (Section 8, Process Control)
- Richard L. Shilling, P.E., B.S.M., B.E.M.E., Manager of Engineering Development, Brown Fintube Company—a Koch Engineering Company; Member, American Society of Mechanical Engineers (Section 11, Heat-Transfer Equipment)
- F. Greg Shinskey, B.S.Ch.E., Consultant (retired from Foxboro Co.), North Sandwich, New Hampshire (Section 8, Process Control)
- Oliver W. Siebert, P.E., B.S.M.E., Washington University, Graduate Metallurgical Engineering, Sever Institute of Technology; Professor, Department of Chemical Engineering, Washington University, St. Louis, Missouri; President, Siebert Materials Engineering, Inc., St. Louis, Missouri; Senior Engineering Fellow (retired), Monsanto Co.; Mechanical Designer, Sverdrup Corp.; Metallurgist, Carondelet Foundry; United Nations Consultant to the People's Republic of China; Fellow, American Institute of Chemical Engineers; Life Fellow, American Society of Mechanical Engineers; Past Elected Director and Fellow, National Association of Corrosion Engineers, Int'l; American Society for Metals, Int'l; American Welding Society; Pi Tau Sigma, Sigma Xi, and Tau Beta Pi (Section 28, Materials of Construction)
- Jeffrey J. Siirola, Ph.D., Research Fellow, Eastman Chemical Company; Member, National Academy of Engineering; Fellow, American Institute of Chemical Engineers, American Chemical Society, American Association for Artificial Intelligence, American Society for Engineering Education (Section 13, Distillation)
- Charles E. Silverblatt, M.S., Ch.E., Peregrine International Associates, Inc.; Consultant to WesTech Engineering, Inc., American Institute of Mining, Metallurgical and Petroleum Engines (AIME) (Section 18, Liquid-Solid Operations and Equipment)
- Richard Siwek, M.S., Explosion Protection Manager, Corporate Unit Safety and Environment, Ciba-Geigy Ltd., Basel, Switzerland (Section 26, Process Safety)
- J. Stephen Slottee, M.S., Ch.E., Manager, Technology and Development, EIMCO Process Equipment Co.; Member, American Institute of Chemical Engineers (AIChE) (Section 18, Liquid-Solid Operations and Equipment)
- Cecil L. Smith, Ph.D., Principal, Cecil L. Smith Inc., Baton Rouge, Louisiana (Section 8, Process Control)
- Julian C. Smith, B. Chem., Ch.E., Professor Emeritus Chemical Engineering, Cornell University; Member, American Chemical Society (ACS), American Institute of Chemical Engineers (AIChE) (Section 18, Liquid-Solid Operations and Equipment)
- Richard H. Snow, Ph.D., Engineering Advisor, IIT Research Institute; Member, American Chemical Society, Sigma Xi; Fellow, American Institute of Chemical Engineers (Section 20, Size Reduction and Size Enlargement)
- Thomas Sorenson, M.B.A., Min. Eng., President, Galigher Ash (Canada) Ltd. (Section 19, Solid-Solid Operations and Equipment)
- Rameshwar D. Srivastava, Ph.D., Fuels Group Manager, Burns and Roe Services Corporation, Federal Energy Technology Center (Pittsburgh) (Section 27, Energy Resources, Conversion, and Utilization)
- F. C. Standiford, M.S., P.E., Member, American Institute of Chemical Engineers, American Chemical Society (Section 11, Heat-Transfer Equipment)
- **D. E. Steinmeyer, M.A., M.S., P.E.,** Distinguished Fellow, Monsanto Company; Fellow, American Institute of Chemical Engineers; Member, American Chemical Society (Section 14, Gas Absorption and Gas-Liquid System Design)
- Gary J. Stiegel, M.S., P.E., Program Coordinator, Federal Energy Technology Center (Pittsburgh), U.S. Department of Energy (Section 27, Energy Resources, Conversion, and Utilization)

- John G. Stoecker II, B.S.M.E., University of Missouri School of Mines and Metallurgy; Principal Consultant, Stoecker & Associates, St. Louis, Missouri; Principal Materials Engineering Specialist (retired), Monsanto Co.; High-Temperature Design/Application Engineer, Abex Corporation; Member, NACE International, ASM International (Section 27, Energy Resources, Conversion, and Utilization)
- **Judson S. Swearingen, Ph.D.,** Retired President, Rotoflow Corporation (Section 29, Process Machinery Drives)
- Louis Theodore, Sc.D., Professor of Chemical Engineering, Manhattan College; Member, Air and Waste Management Association (Section 25, Waste Management)
- Michael P. Thien, Sc.D., Senior Research Fellow, Merck & Co., Inc.; Member, American Institute of Chemical Engineers, American Chemical Society, International Society for Pharmaceutical Engineers (Section 22, Alternative Separation Processes)
- George H. Thomson, AIChE Design Institute for Physical Property Data (Section 2, Physical and Chemical Data)
- James N. Tilton, Ph.D., P.E., Senior Consultant, Process Engineering, E. I. duPont de Nemours & Co.; Member, American Institute of Chemical Engineers; Registered Professional Engineer (Delaware) (Section 6, Fluid and Particle Dynamics)
- Klaus D. Timmerhaus, Ph.D., P.E., Professor and President's Teaching Scholar, University of Colorado, Boulder, Colorado; Fellow, American Institute of Chemical Engineers, American Society for Engineering Education, American Association for the Advancement of Science; Member, American Astronautical Society, National Academy of Engineering, Austrian Academy of Science, International Institute of Refrigeration, American Society of Heating, Refrigerating and Air Conditioning Engineers, American Society of Environmental Engineers, Engineering Society for Advancing Mobility on Land, Sea, Air, and Space, Sigma Xi, The Research Society (Section 11, Heat-Transfer Equipment)
- David B. Todd, Ph.D., President, Todd Engineering; Member, American Association for the Advancement of Science (AAAS), American Chemical Society (ACS), American Institute of Chemical Engineering (AIChE), American Oil Chemists Society (AOCS), Society of Plastics Engineers (SPE), and Society of the Plastics Industry (SPI); Registered Professional Engineer, Michigan (Section 18, Liquid-Solid Operations and Equipment)
- George T. Tsao, Ph.D., Director, Laboratory for Renewable Resource Engineering, Purdue University; Member, American Institute of Chemical Engineers, American Chemical Society, American Society for Microbiology (Section 24, Biochemical Engineering)
- Hendrick C. Van Ness, D.Eng., Howard P. Isermann Department of Chemical Engineering, Rensselaer Polytechnic Institute; Fellow, American Institute of Chemical Engineers; Member, American Chemical Society (Section 4, Thermodynamics)
- **Stanley M. Walas, Ph.D.,** Professor Emeritus, Department of Chemical and Petroleum Engineering, University of Kansas; Fellow, American Institute of Chemical Engineers (Section 7, Reaction Kinetics; Section 23, Chemical Reactors)
- Phillip C. Wankat, Ph.D., Professor of Chemical Engineering, Purdue University; Member, American Institute of Chemical Engineers, American Chemical Society, International Adsorption Society (Section 5, Heat and Mass Transfer)
- Ionel Wechsler, M.S., Min. and Met., Vice President, Sala Magnetics, Inc., Cambridge, Massachusetts (Section 19, Solid-Solid Operations and Equipment)
- Arthur W. Westerberg, Ph.D., Swearingen University Professor of Chemical Engineering, Carnegie Mellon University; Member, National Academy of Engineering (Section 3, Mathematics)
- John M. Wheeldon, Ph.D., Electric Power Research Institute (Section 27, Energy Resources, Conversion, and Utilization)

xviii LIST OF CONTRIBUTORS

Robert E. White, Ph.D., Principal Engineer, Chemistry and Chemical Engineering Division, Southwest Research Institute (Section 26, Process Safety)

J. K. Wilkinson, M.Sc., Consultant Chemical Engineer; Fellow, Institution of Chemical Engineers, London (Section 9, Process Economics)

David Winegarder, **Ph.D.**, Engineering Associate, Michigan Division Engineering, The Dow Chemical Company; Member AIChE and CCPS (Section 26, Process Safety)

John L. Woodward, Ph.D., Principal, DNV Technica, Inc. (Section 26, Process Safety)

Yoshiyuki Yamashita, Ph.D., Associate Professor of Chemical Engineering, Tohoku University, Sendai, Japan (Section 3, Mathematics)

Carmen M. Yon, M.S., Development Associate, UOP, Des Plaines, Illinois; Member, American Institute of Chemical Engineers (Section 16, Adsorption and Ion Exchange)