POLYMER HANDBOOK

FOURTH EDITION

Editors

J. BRANDRUP, E. H. IMMERGUT, and E. A. GRULKE

Associate Editors

A. ABE
D. R. BLOCH

A WILEY-INTERSCIENCE PUBLICATION

JOHN WILEY & SONS, INC.

New York • Chichester • Weinheim • Brisbane • Singapore • Toronto

This book is printed on acid-free paper. ♾

Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data:

Polymer Handbook / Editors: J. Brandrup, E. H. Immergut, and E. A. Grulke;
Associate Editors, A. Abe, D. R. Bloch. – 4th ed.
p. cm.
"A Wiley-Interscience Publication."
Includes index.
ISBN 0-471-16628-6 (cloth : alk. paper)
1. Polymers—Tables. 2. Polymerization—Tables. I. Brandrup, J. II. Immergut, E. H. III. Grulke, Eric A.
QD388.P65 1999
547.7–dc21 98-37261

Printed in the United States of America.

10 9 8 7 6 5 4 3 2

Contributors

Abe, A.
Tokyo Institute of Polytechnics, Atsugi, Japan

Allegra, G.
Dipartimento di Chimica del Politecnico, Milano, Italy

Andreeva, L. N.
Institute of High Molecular Weight Compounds, Russian Academy of Sciences, St. Petersburg, Russian Federation

Andrews, R. J.
Chemical and Materials Engineering Department, University of Kentucky, Lexington, Kentucky, USA

Bai, F.
The Maurice Morton Institute of Polymer Science, Univeristy of Akron, Akron, USA

Bareiss, R. E.
Editorial Office, Macromolecular Chemistry and Physics, Mainz, FR Germany

Barrales-Rienda, J. M.
Instituto de Ciencia y Tecnología de Polímeros, Madrid, Spain

Bello, A.
Instituto de Ciencia y Tecnología de Polímeros, Madrid, Spain

Bello, P.
Instituto de Ciencia y Tecnología de Polímeros, Madrid, Spain

Bloch, D. R.
Lakeshore Research, Racine, Wisconsin, USA

Brandrup, J.
Wiesbaden, FR Germany

Calhoun, B. H.
The Maurice Morton Institute of Polymers Science, University of Akron, Akron USA

Casassa, E. F.
Department of Chemistry, Carneagíe–Mellon University, Pittsburgh, Pennsylvania, USA

Cheng, S. Z. D.
The Maurice Morton Institute of Polymer Science, University of Akron, Akron, Ohio, USA

Chiu, F.-C.
The Maurice Morton Institute of Polymer Science, University of Akron, Akron, Ohio, USA

Cho, J.
Polymer Science and Engineering Department, Dankook University, Seoul, South Korea

Collins, E. A.
Avon Lake, Ohio, USA

Daniels, C. A.
The Geon Company, Avon Lake, Ohio, USA

DeLassus, P. T.
The Dow Chemical Company, Freeport, Texas, USA

Dixon, K. W.
Akzo Nobel Chemicals, Inc., Dobbs Ferry, New York, USA

Elias, H.-G.
Michigan Molecular Institute, Midland, Michigan, USA

Fink, G.
Max-Planck-Institut für Kohlenforschung, Mülheim an der Ruhr, FR Germany

Fink, H.-P.
Fraunhofer Institut für angewandte Polymerforschung, Teltow-Seehof, FR Germany

Fouassier, J. P.
Laboratoire de Photochimie Générale, Ecole Nationale Supérieure de Chimie, Mulhouse, France

Fu, Q.
The Maurice Morton Institute and Department of Polymer Science, University of Akron, Akron, Ohio, USA

Furuta, I.
Japan Synthetic Rubber Company Ltd., Yokkaichi, Mie, Japan

Ganster, J.
Fraunhofer Institute for Applied Polymer Research, Teltow-Seehof, Germany

Greenley, R. Z.
Monsanto Corporation (retired), St. Louis, Missouri, USA

Grulke, E. A.
Chemical and Materials Engineering, University of Kentucky, Lexington, Kentucky, USA

Goh, S. H.
Department of Chemistry, National University of Singapore, Singapore

Guzmán G. M.
Instituto de Ciencia y Tecnología de Polímeros, Madrid, Spain

Hill, D. J. T.
Department of Chemistry, University of Queensland, St. Lucia, Australia

Hiltner, A.
Department of Macromolecular Science, School of Engineering Case Western University, Cleveland, Ohio, USA

Inomata, K.
Department of Polymer Chemistry, Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo, Japan

Iwama, M.
Japan Synthetic Rubber Company Ltd., Yokkaichi, Mie, Japan

Jenkins, A. D.
School of Chemistry, Physics and Environmental Science, University of Sussex, Brighton, Sussex, UK

Jenkins, J.
School of Chemistry, Physics and Environmental Science, University of Sussex, Brighton, Sussex, UK

Johnson, M.
Chemistry/Physics Library, University of Kentucky, Lexington, Kentucky, USA

Kamachi, M.
Department of Applied Physics and Chemistry, Fukui University of Technology, Gakuen, Fukui, Japan

Kerbow, D. L.
DuPont Fluoroproducts, Wilmington, Delaware, USA

Kimura, S.-I.
Japan Synthetic Rubber Company Ltd., Yokkaichi, Mie, Japan

Korte, S.
Zentrale Ferschung, Bayer AG, Leverkunsen, FR Germany

Krause, S.
Department of Chemistry, Rensselaer Polytechnic Institute, Troy, New York, USA

Kurata, M.
Institute for Chemical Research, Kyoto University, Uji, Kyoto, Japan

Lechner, M. D.
Physikalische Chemie, Universität Osnabrück, Osnabrück, FR Germany

Leonard, J.
Department de Chimie and CERSIM, Université Laval, Quebec, Canada

Li, F.
The Maurice Morton Institute of Polymer Science, University of Akron, Akron, Ohio, USA

Liggat, J.
Department of Pure and Applied Chemistry, University of Strathclyde, Glasgow, Scotland

Lindemann, M.
Greenville, South Carolina, USA

Luft, G.
Institut für Chemische Technologie, Technische Hochschule, Darmstadt, FR Germany

Magill, J. H.
School of Engineering, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

McKenna, T. F.
Centre Nationale de la Recherche Scientifique, Laboratoire de Chimie et Procédés de Polymerisation/Departement Genie des Procédés, Villeurbanne, France

Mehta, R. H.
Dupont Nylon, Chattanooga, Tennessee, USA

Meille, S. V.
Dipartimento di Chimica del Politecnico, Milano, Italy

Metanomski, W. V.
Chemical Abstracts Service, Columbus, Ohio, USA

Michielsen, S.
School of Textile and Fiber Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA

Miller, R. L.
Michigan Molecular Institute, Midland, Michigan, USA

Morita, Y.
Japan Atomic Energy Research Institute, Takasaki, Gunma-ken, Japan

Mück, K.-F.
Ticona GmbH, Kelsterbach, FR Germany

Nagai, S.
Plastics Technical Association, Osaka, Japan

Nordmeier, E.
Physikalische Chemie, Universität Osnabrück, Osnabrück FR Germany

Ogo, Y.
Research Institute for Solvothermal Technology, Hayashi, Takamatsu, Kagawa, Japan

Orwoll, R. A.
College of William and Mary, Williamsburg, Virginia, USA

Pauly, S.
Fachlaboratorium für Permeationsprüfung, Wiesbaden, FR Germany

Peebles, L. H., Jr.
Chemistry Division, Naval Research Laboratory, Washington, DC, USA

Perera, M. C. S.
Magnetic Resonance Facility, School of Science, Griffith University, Nathan, Australia

Porzio, W.
Instituto di Chimica delle Macromolecole del C.N.R., Milano, Italy

Pyda, M.
Department of Chemistry, University of Tennessee, Knoxville, Tennessee, USA

Quirk, R. P.
The Maurice Morton Institute of Polymer Science, University of Akron, Akron, Ohio, USA

Riande, E.
Instituto de Ciencia y Tecnología de Polímeros, Madrid, Spain

Richter, W. J.
Max-Planck-Institut für Kohlenforschung, Mülheim an der Ruhr, FR Germany

Rothe, M.
University of Ulm, Ulm, FR Germany

Rule, M.
Coca Cola Company, Atlanta, Georgia, USA

Salort, J. F.
Madrid, Spain

Salom, C.
Escuela Técnica Superior de Ingenieros Aeronáuticos, Universidad Politécnica, Madrid, Spain

Sanchez, I. C.
Chemical Engineering Department, University of Texas at Austin, Austin, Texas, USA

Santos, A. M.
Faculdade de Engenharia Quimica de Lorena - FAENQUIL, Lorena, Sao Paulo, Brazil

Schoff, C. K.
PPG Industries, Allison Park, Pennsylvania, USA

Schuld, N.
Institut fur Physikalische Chemie, Universität Mainz, Mainz, FR Germany

Seferis, J. C.
Chemical Engineering Department, University of Washington, Seattle, Washington, USA

Seguchi, T.
Japan Atomic Energy Research Institute, Takasaki, Gunma-ken, Japan

Schrader, D.
The Dow Chemical Company, Midland, Michigan, USA

Sperati, C. A.
Chemical Engineering Department, Ohio University, Athens, Ohio, USA

Steinmeier, D. G.
Physikalische Chemie, Universität Osnabrück, Osnabrück, FR Germany

Tsunashima, Y.
Institute for Chemical Research, Kyoto University, Uji, Kyoto, Japan

Tsvetkov, N. V.
Institute of High Molecular Weight Compounds, Russian Academy of Science, St. Petersburg, Russian Federation

Tsvetkov, V. N.
Institute of High Molecular Weight Compounds, Russian Academy of Science, St. Petersburg, Russian Federation

Ueda, A.
Osaka Municipal Technical Research Institute, Morinomiya, Joto-ku, Osaka, Japan

Wagener, K. B.
Department of Chemistry and Center for Macromolecular Science and Engineering, University of Florida, Gainesville, Florida, USA

Whiteman, N. F.
The Dow Chemical Company, Freeport, Texas, USA

Witenhafer, D. E.
Dublin, Ohio, USA

Wolf, B. A.
Institut für Physikalische Chemie, Universität Mainz, Mainz, FR Germany

Wu, S.
E. I. DuPont de Nemours, Central Research and Development Department, Experimental Station, Wilmington, Delaware

Wunderlich, B.
Department of Chemistry, University of Tennessee, Knoxville, Tennessee, USA

Wunderlich, W.
RÖHM GmbH, Darmstadt, FR Germany

Yamada, B.
Department of Applied Chemistry, Faculty of Technology, Osaka City University, Sumiyoshi, Osaka, Japan

Zhu, L.
The Maurice Morton Institute of Polymer Science, University of Akron, Akron, Ohio, USA

Preface

The purpose of the *Polymer Handbook* is to bring together the data and constants needed in theoretical and experimental polymer research. All polymer researchers have experienced the frustration of searching for data in the ever-expanding polymer literature and know the difficulties involved in trying to locate a particular constant that is buried in a long journal article. The contributors to this Handbook have taken on the arduous task of searching the literature and compiling the data and constants that polymer chemists, polymer physicists, and polymer engineers are likely to need.

The 520 and odd tables in this Handbook are divided into eight sections. The first lists the IUPAC nomenclature rules for polymers and the International System of Units. Although several naming conventions exist in the technical literature, IUPAC names permit a consistent listing of all polymers. Section II contains data and constants needed for polymer synthesis, kinetic mechanisms, and thermodynamic studies of polymerization and depolymerization reactions. Sections III and IV contain physical constants of monomers, solvents, and oligomers. Section V lists the physical constants of many important commercial polymers. Section VI and VII cover the solid state properties of polymers and the properties of polymer solutions. Section VIII of the Handbook lists the commonly used abbreviations or acronyms for polymers and Chemical Abstract Registry Numbers, and gives suggestions for electronic data searching for polymer information. This section should also be consulted in the few cases where contributors have not used IUPAC nomenclature.

As in the previous editions, the *Polymer Handbook* concentrates on synthetic polymers, poly(saccharides) and derivatives, and oligomers. Few data on biopolymers are included. Spectroscopic data as well as data needed by engineers and designers, such as mechanical and rheological data, are minimized, since many excellent compilations exist elsewhere. Only fundamental constants and parameters that refer to the polymer molecule, that describe the solid state of polymer molecules, or that describe polymer solutions, were compiled. Constants that depend on processing conditions or on sample history were not emphasized, as they can be found in existing plastics handbooks and encyclopedias.

A critical evaluation of the values published in the literature was not attempted, since such a task would have required an inordinate amount of time and a sizable staff. Therefore, the users of this Handbook should consult the original literature for details when in doubt about the validity of any data. (The authors of the individual tables were nevertheless requested to eliminate obviously erroneous data from otherwise complete compilations.)

The Fourth Edition revisions have focused on data generated in the ten years since the publication of the Third Edition. Therefore, a completely revised *Polymer Handbook* has been prepared. We have added new tables and incorporated a large amount of new data into existing tables. As a result, the Fourth Edition contains approximately twenty-five percent more data, and the number of pages has increased from about 1850 in the Third Edition to about 2250.

We hope that this new edition will be as useful to the polymer research community as the three earlier editions and that many of the *Polymer Handbook*'s previous users will also obtain the Fourth Edition for their laboratory and library.

The publisher plans a CD-ROM for the *Polymer Handbook* in the near future. We would be grateful if our contributors and users send us any new data they accumulate in the course of their research, and any errors, misprints, omissions and other flaws. We will pass on such data to the publisher, for the polymer database, and for future editions of this Handbook.

We would like to thank all of the contributors to the *Polymer Handbook* for their help and continued patience. The staff at John Wiley, especially Carla Fjerstad, Shirley Thomas, and Jacqueline Kroschwitz, have provided excellent help and support in getting all the work done. We hope that the outstanding efforts of all these people will find due appreciation among the users of this Handbook.

July, 1998

J. Brandrup
E. H. Immergut
E. A. Grulke
A. Abe
D. R. Bloch