Classroom Photocopying Permission

Laboratory Safety

DISCLAIMER

Teaching General Chemistry: A Materials Science Companion

Arthur B. Ellis

Margret J. Geselbracht

Brian J. Johnson

George C. Lisensky

William R. Robinson

American Chemical Society, Washington, DC

1993

Library of Congress Cataloging-in-Publication Data

Teaching general chemistry: a materials science companion / Arthur B. Ellis... [et al.].
p. cm.

Includes bibliographical references and index.

ISBN 0-8412-2725-X
1. Solid state chemistry 2. Chemistry—Study and teaching (Secondary) I. Ellis, Arthur B., 1951-

QD478.T43 1993
541'.0421—dc20 93-29739
CIP

The paper used in this publication meets the minimum requirements of American National Standard for Information Sciences—Permanence of Paper for Printed Library Materials, ANSI Z39.48-1984

Cover: Magnetic spiking phenomenon observed when a cow magnet is placed beneath a Petri dish containing a ferrofluid. Chapter 2 discusses this phenomenon.

About the binding of this book: This book is bound with a lay-flat binding process. When opened, the pages will lay flat, leaving the reader's hands free.

The Authors

From left to right: Margret J. Geselbracht, Assistant Professor, Department of Chemistry, Reed College, Portland, OR; Brian J. Johnson, Associate Professor, Department of Chemistry, St. John's University, Collegeville, MN; William R. Robinson, Professor, Department of Chemistry, Purdue University, West Lafayette, IN; Arthur B. Ellis, Meloche-Bascom Professor, Department of Chemistry, University of Wisconsin–Madison, Madison, WI; and George C. Lisensky, Professor, Department of Chemistry, Beloit College, Beloit, WI. This is a composite photograph. To the best of the authors' knowledge, the five authors were never all at the same place at the same time!

Contents

Demonstrations ... xiii
Topic Matrix ... xv
Preface ... xvii
Laboratory Safety ... xxv

An Introduction to Solids

1. An Introduction to Materials Science ... 1
What Is Materials Science? ... 1
The Life Cycle of a Material ... 5
The Age of Materials ... 8
Analytical Methods: Thinking Small ... 8
Control of Interfaces ... 9
New Materials ... 10
"Smart" Materials ... 11
Some of What's Already Here ... 11

2. Atoms and Electrons ... 15
Direct Evidence for Atoms:
The Scanning Tunneling Microscope ... 15
Indirect Evidence for Atoms: Heat Capacities ... 24
Electrons in Solids ... 28
Paramagnetism ... 28
Ferromagnetism ... 30
Ferrofluids ... 36
Piezoelectric Crystals ... 42

3. Stoichiometry ... 49
Determining Stoichiometry from Unit Cells ... 50
Solid Solutions ... 59
Substitutional Stoichiometry ... 59
Variable Stoichiometry ... 63
A Caveat for Classroom Use ... 65

4. Determination of Structure Using Diffraction Data 77
Diffraction 77
Optical Transforms 81

5. Common Crystalline Structures 97
Metals 97
Packing in Three Dimensions 102
Ionic Solids 108
Cubic Holes 111
Octahedral Holes 113
Tetrahedral Holes 117
Summary of Ionic Structures 121
Covalent Solids 123
Molecular Solids 126
More Connections to Molecular Shapes: Extended Shared Polyhedra 127
Appendix 5.1. The ICE Solid-State Model Kit 139
Appendix 5.2. Solid-State Structures and MacMolecule 140
Appendix 5.3. Bubble Raft Construction 141
Appendix 5.4. Tetrahedral and Octahedral Models 142
Appendix 5.5. Crystal Habits 143
Appendix 5.6. Elements and Compounds That Exhibit the Common Structural Types 144
Appendix 5.7. Synthesis and Reactivity of $AuAl_2$ 147

6. Defects in Solids 155
Defects in Metals 156
Types of Defects 159
Work Hardening and Annealing 167
Hardening of Alloys: Steel 170
Defects in Ionic Compounds 174
F-Centers in Salts: Spectroscopy of Defects 176
Spectroscopy 180
F-Center Luminescence 182

7. Electronic Structure of Crystalline Solids 187
Bands in Metals 188
Electrical Conductivity of Metals 191
Thermal Conductivity of Metals 200
Optical Properties of Metals 204
Covalent Insulators and Semiconductors 206
Localized and Delocalized Bonding Pictures 206
Tetrahedral Solids 206
Electrical and Optical Properties of Insulators and Semiconductors Having the Diamond Structure 209
Electrical and Optical Properties of Insulators and Semiconductors Having the Zinc Blende Structure 215

Solid Solutions Having the Zinc Blende Structure: Tunable Band Gaps........ 218
Ionic Insulators and Semiconductors........ 226
Appendix 7.1. Assembly of LED Reference Strip........ 229

8. Chemical Equilibrium: Acid-Base and Redox Analogies in Solids........ 237
Electrons and Holes........ 237
The Autoionization Analogy........ 241
Doping with Electron Donors and Acceptors........ 245

The Hydrogen Atom Model for Estimating Dopant Ionization Energies........ 246
Dopants for Compound Semiconductors........ 250
The Semiconductor as an Acid–Base System........ 251
Effect of Doping on Conductivity........ 251
Analogies to Weak Acids and Bases........ 252
The Fermi Level and Its Analogy to pH........ 253
Extent of Ionization........ 254
Neutralization Reactions and Buffers........ 255
The p–n Junction: A Solid-State Concentration Cell........ 257
Biasing the p–n Junction........ 267
Ionic Concentration Cells........ 269
Oxygen Sensors........ 269
The Fluoride-Selective Electrode........ 271

9. Applications of Thermodynamics: Phase Changes........ 277
Effects of Temperature and Pressure on Equilibria: Illustrations of Le Chatelier's Principle with Solids........ 278
Nickel–Titanium Memory Metal........ 281
The Structural Cycle of Shape Memory........ 282
Changing the "Memorized" Shape of NiTi........ 289
Acoustic Properties of NiTi Phases........ 294
Hysteresis........ 296
Chemical Composition........ 297
Applications........ 298
The 1-2-3 Superconductor........ 301
Physical Properties of Superconductors........ 303
The Mechanism of Superconductivity........ 309
Chemical Properties of a High-T_C Superconductor........ 310
Other Superconductors........ 312
Applications........ 313
Ionically Conducting Copper Mercury Iodide........ 315
Structure and Phase Change........ 315
Conductivity Mechanism........ 315
Appendix 9.1. Prediction of Shifts in Equilibria........ 319
Appendix 9.2. Construction of the Projector Mirror........ 322

10. Synthesis of Materials 329
Solid-Phase Techniques 330
Diffusion and "Heat-and-Beat" Methods 330
Precursor Techniques 334
Reactions in Liquids 336
Solvents 336
Melts (Fluxes) 338
Gas-Phase Synthesis 338
Chemical Vapor Transport 338
Preparation of Thin Films 340
Chemical Vapor Deposition (CVD) and Molecular Beam Epitaxy (MBE) 340
Optical Fibers 342
Chemie Douce or Soft Chemistry 345
Preparation of Large, Pure Crystals 347
Zone Refining 348
Czochralski Crystal Growth 349

Laboratory Experiments

1. **Heat Capacities of Materials** 353
2. **Solid-State Structure and Properties** 361
3. **Solid Solutions with the Alum Structure** 369
4. **Optical Diffraction Experiments** 377
5. **X-Ray Analysis of a Solid** 385
6. **Radon Testing** 395
7. **Periodic Properties and Light-Emitting Diodes** 401
8. **Hydrogen Insertion into WO_3** 413
9. **Absorption of Light** 419
10. **A Shape Memory Alloy, NiTi** 423
11. **A High-Temperature Superconductor, $YBa_2Cu_3O_{7-x}$** 429
12. **A Solid Electrolyte, Cu_2HgI_4** 439
13. **Diffusion in Solids, Liquids, and Gases** 447
14. **Magnetic Garnets, $Y_xGd_{3-x}Fe_5O_{12}$** 455
15. **The Sol-Gel Preparation of Silica Gel Sensors** 463

Appendices

1. **Glossary** 473
2. **Supplier Information** 487
3. ***Journal of Chemical Education* Review** 497
4. **Answers to Selected Problems** 505
5. **Index** 541

Demonstrations

1.1. Re-entrant Foam 4
2.1. Specific Heat and Molar Heat Capacity 26
2.2. Paramagnetism 29
2.3. A Comparison of Paramagnetism and Ferromagnetism 32
2.4. The Curie Point of Nickel 34
2.5. The Curie Point of Iron 34
2.6. Ferrofluids 37
2.7. The Ferrofluidics Bottle Cell 38
2.8. The Piezoelectric Effect 45
3.1. Corner-Shared Atoms in a Simple Cubic Unit Cell 55
3.2. The fcc Structure Videotape 58
3.3. Disordered Binary Solid Solutions 60
4.1. The Optical Transform Slide 85
4.2. Individualized Use of Optical Transform Slides 86
5.1. Demonstrations of Close Packing: Bubble Rafts, BB Trays, and Bubble Wrap 100
5.2. Interstices in Close-Packed Structures 105
5.3. Models of Cubes, Octahedra, and Tetrahedra 110
5.4. Octahedral, Cubic, and Tetrahedral Crystals 110
5.5. Removal of Graphite and Molybdenum Sulfide Layers 126
6.1. Ductility and Fracturing 159
6.2. Dislocations and Other Defects 165
6.3. Hearing Atoms Move: Breaking the Sound Barrier 166
6.4. Work Hardening 169
6.5. Annealing, Hardening, and Tempering of Bobby Pins 172
6.6. Annealing, Hardening, and Tempering of Piano Wire 173
6.7. F-Centers 178
6.8. Thermoluminescence from F-Centers 182
7.1. Electron Flow in a Band 193
7.2. Oxidative Intercalation of Graphite 194
7.3. Electrical Resistance 198
7.4. Temperature Dependence of Resistance in a Metal 199
7.5. Thermal Conductivity in the Classroom 200
7.6. A More Quantitative Measure of Thermal Conductivity 201
7.7. Metallic Reflectivity 205
7.8. The Hardness of Diamond 214
7.9. Photoconductivity of CdS 214
7.10. Tunable Band Gaps Based on Solid Solutions 221
7.11. The Effect of Temperature on LED Emission 223
8.1. Hole Energies and Conductivity 240
8.2. A Classroom Model of Hole Conductivity 241
8.3. Biasing and Dissection of an LED 263
8.4. Counting Photons Using a Solar Cell 266

9.1. The Effect of Pressure on the Melting Point of Ice........................ 279
9.2. The Shape-Memory Property of Memory Metal............................ 282
9.3. The Annealing of NiTi into a New Shape....................................... 289
9.4. The Mechanical Properties of Two NiTi Phases............................ 292
9.5. Superelasticity.. 293
9.6. Acoustic Properties of Two NiTi Phases.. 295
9.7. Levitation.. 308
9.8. The Order-Disorder Phase Change in
Copper(I) Mercury(II) Iodide.. 317
9.9. Conductivity Changes in Cu_2HgI_4.. 318
10.1 Synthesis of NiAl and CoAl... 332
10.2. Solvent Influence on Reactivity... 336

Topic Matrix

Topic					*Chapter*						*Experiment*
Atoms	1	2									1
Acids and Bases								8			15
Bands							7	8			7, 8
Batteries		2	3					8			
Bohr model for hydrogen atom								8			
Bonding			3		5	6	7				2
Conductivity, thermal and electrical							7				8, 11, 12
Coordination numbers/geometry					5						2
Crystal structure		2	3		5		7		9		2, 4, 5
Defects						6		8	9		6
Diffusion										10	13
Dipoles		2									
Electrochemistry								8			
Electromagnetic radiation				4		6	7	8			4,9
Electronegativity							7				7
Electrons		2					7	8			7,8
Entropy								8	9		
Equilibrium								8	9		
Free energy								8	9		
Heat capacity		2									1
Intermolecular forces		2									2
Ionic solids					5						2
Ionization								8			
Kinetics						6				10	
Lasers				4				8			4,9
Le Chatelier's principle									9		10
Magnetism		2							9		11, 14
Metals			3		5	6	7				2,10
Molecular orbital theory							7				
Nuclear chemistry						6					6
pH								8			15
Periodic properties			3			6	7				7
Phase changes						6			9		10, 11, 12
Quantum mechanics						6		8			
Redox		2							9	10	8,11
Semiconductors			3		5		7	8			2, 7, 9
Smart materials	1	2							9		10
Solid solutions			3			6	7		9	10	3, 7, 14
Spectroscopy - Beer's Law							7	8			7, 9
Stoichiometry			3		5				9	10	2, 11
Structures of solids			3		5	6	7		9		2, 5, 10
Superconductivity	1								9		11
Thermochemistry		2							9		
Thermodynamics						6			9	10	
Transition metals		2								10	3,10,11,12
VSEPR				4	5						2
X-ray diffraction				4							4, 5

Preface

The Spirit of the Companion

With the arrival of the 90s, it is an appropriate time to update and broaden the career advice Dustin Hoffman received in the 1967 movie, "The Graduate." Instead of urging readers to work with plastics, the intent of this book is to show, more generally, that materials are both a source of great opportunities for chemists in the coming decade and a natural vehicle for introducing chemical principles. Whether the solids are semiconductors, metals, superconductors, polymers, or composites, our society is increasingly dependent on advanced materials and devices that deliver performance within the constraints set by our limited energy and environmental resources. The introductory chemistry course can provide a firm foundation for understanding the burgeoning field of materials chemistry.

Despite the key role that chemistry plays in what is often called "materials science," there has been relatively little materials chemistry in introductory chemistry courses. In fact, a 1989 National Science Foundation *(1)* report concluded that "the historic bias of chemistry curricula toward small molecule chemistry, generally in the gaseous and liquid states, is out of touch with current opportunities for chemists in research, education, and technology." Furthermore, the report notes that "the attractiveness of chemistry and physics for undergraduate majors could be enhanced by greater emphasis on materials-related topics which would help students better relate their studies to the 'real world'."

Our experience has been, however, that many chemistry teachers are uncomfortable teaching materials chemistry, which has a strongly interdisciplinary flavor: Teachers may be less confident describing solid-state synthesis, processing, structure and bonding, and those physical and chemical properties of solids which have a language that is largely rooted in physics, engineering, and materials science. The extended, three-dimensional structures of solids, which are often hard to visualize, may represent another formidable obstacle.

The goal of this volume, *Teaching General Chemistry: A Materials Science Companion*, and its supporting instructional materials, is to demystify materials chemistry so that its essence—the interrelationship of synthesis, processing, structure, bonding, and physicochemical properties—can be readily brought into introductory chemistry courses.

A second goal of the Companion is to refresh and enliven general chemistry. The topics presented here enable instructors to put a new spin on the material that is traditionally covered in general chemistry. The examples from cutting-edge research, as well as everyday life, will serve to maintain student interest while illustrating the basic ideas that are important to an understanding of chemistry.

The Ad Hoc Committee

An ad hoc committee was formed in 1990, in recognition of the fact that both the interdisciplinary nature of materials chemistry and a lack of appropriate instructional tools were preventing many teachers from discussing the subject. The committee's composition reflects both technical and pedagogical expertise: Research areas spanning much of the breadth of modern materials chemistry are represented, as is skill at bringing chemical concepts into the classroom and laboratory *(2)*. The Ad Hoc Committee for Solid-State Instructional Materials comprises Aaron Bertrand, Georgia Institute of Technology; Abraham Clearfield, Texas A&M University; Denice Denton, University of Wisconsin-Madison; John Droske, University of Wisconsin-Stevens Point; Arthur B. Ellis, University of Wisconsin—Madison (Chair); Paul Gaus, The College of Wooster; Margret Geselbracht, Reed College; Martha Greenblatt, Rutgers University; Roald Hoffmann, Cornell University; Allan Jacobson, University of Houston; Brian Johnson, St. John's University; David Johnson, University of Oregon; Edward Kostiner, University of Connecticut; Nathan S. Lewis, California Institute of Technology; George Lisensky, Beloit College; Thomas E. Mallouk, University of Texas at Austin; Robert E. McCarley, Iowa State University; Ludwig Mayer, San Jose State University; Joel Miller, University of Utah; Donald W. Murphy, AT&T Bell Laboratories; William R. Robinson, Purdue University; Don Showalter, University of Wisconsin—Stevens Point; Duward F. Shriver, Northwestern University; Albert N. Thompson, Jr., Spelman College; M. Stanley Whittingham, SUNY at Binghamton; Gary Wnek, Rensselaer Polytechnic Institute; and Aaron Wold, Brown University.

Objectives

The principal objectives of the Ad Hoc Committee in producing the Companion are to revitalize the introductory chemistry course for all students and to increase the number and diversity of technically able students who will pursue careers as chemists, chemistry teachers, scientists, and engineers. To accomplish these objectives, the committee collected and created instructional materials and developed pedagogical strategies for the introduction of these materials into the curriculum.

The philosophy underpinning the committee's effort to mainstream materials chemistry into the curriculum is that *virtually every topic typically discussed in a general chemistry course can be illustrated with examples from materials chemistry.* The Companion is intended to collect, in one place, a critical mass of text, demonstrations, laboratory experiments, and leads to supporting instructional materials (software and kits, for example) that illustrate how materials chemistry fits into the traditional introductory chemistry course. At the same time, the Companion needs to be sufficiently flexible that it can accommodate, and even help to define, new introductory course structures.

The Companion is presented in a ready-to-use format that will enable teachers to integrate materials chemistry into their courses with minimal effort. Instructors will then have solid-state examples to complement molecular examples. By presenting both, the interconnectedness and universality of scientific thinking can be emphasized.

The Companion assumes essentially no background in materials chemistry but builds on a foundation of molecular chemistry shared by many college and pre-college chemistry teachers. Because the Companion is written for teachers, extra depth is sometimes included beyond the level one might present in an introductory chemistry course; most teachers are more comfortable when they have extra material available for support. The Companion contains enough information in the text, footnotes, and leading references to permit more quantitative and sophisticated treatments for upper-level undergraduate and even graduate courses.

As will be evident throughout the Companion, materials chemistry is intimately connected to other traditional disciplines like physics and engineering. Many colleagues in related scientific and engineering disciplines, who recognize the role of chemistry as a foundation course for students pursuing technical careers, have graciously contributed their expertise to this project *(3)*. Some of the Companion's contents will also be useful in their courses, which span the undergraduate science and engineering curriculum.

We encourage our readers to use and adapt materials from the Companion and to send us constructive comments that can be passed on to other users.

The authors' royalties from the book are being donated to the Institute for Chemical Education (ICE) to assist with dissemination of solid-state instructional materials.

Selection Criteria for Inclusion of Topics

In developing the Companion, we have omitted a great deal of information that would have provided a more comprehensive view of materials chemistry in favor of a more focused, less daunting offering. Furthermore, with a few exceptions, polymers are conspicuously absent from the Companion. This omission is deliberate: A related project, headed by John Droske and also funded by the National Science Foundation (*see* reference 4), will soon be releasing instructional materials describing how polymers can be integrated into the curriculum. John has graciously shared his group's work with us so that we could best complement rather than duplicate one another's efforts.

Key criteria for including materials in the Companion were that they be thought-provoking, illustrative of core chemical concepts, and easily incorporated into existing course structures. We particularly sought to include high-tech materials and advanced devices that have or will become an important part of our environment. Student recognition that these advanced materials and devices derive from chemical principles is a major pedagogical objective. We feel, too, that the incorporation of state-of-the-art examples from materials chemistry will provide a strong sense of relevance that will help revitalize the introductory chemistry course for all students, whether or not they pursue technical careers.

Two other criteria were cost and safety considerations. Most of the demonstration and laboratory experiments described herein require relatively little time or money to set up and dismantle, and instructions for doing so safely are provided throughout the Companion. In field tests of these instructional materials, we have found that the ease with which many of the solids can be safely handled and transported and the ability to use them repeatedly, minimizing expense and waste disposal, are particularly appealing to teachers.

How the Companion is Organized

An Introduction to Solids

The first ten chapters of the Companion represent a general introduction to solids that can either be read sequentially, for an overview; or topically, if particular kinds of solid-state illustrations are sought. The first chapter is meant to provide a context for this volume: the chapter describes materials chemistry, provides examples of cutting-edge research and applications that illustrate why materials chemistry is expected to be one of the most rapidly moving scientific and technological frontiers in the next decade, and highlights the role that chemists are playing in advancing this field.

To facilitate integration into the existing course structure at many institutions, the remainder of the first part of the Companion is organized under traditional general chemistry textbook chapter headings, such as “Stoichiometry” and “Equilibrium.” Teachers will recognize some of the Companion’s content as being simply a new twist on well-established and widely used material. In other cases, we believe that teachers will discover, as we have, exciting new approaches to the presentation of fundamental chemical concepts.

Demonstrations are an integral part of the Companion and are listed at the front of the Companion for ease of location. In field tests and workshops we have found demonstrations to be a particularly effective means for stimulating interest in materials chemistry.

Lists of additional reading materials have been included at the end of each chapter. More advanced texts that can be drawn upon are A.R. West's *Basic Solid State Chemistry* (Wiley, NY, 1988), P. A. Cox's *The Electronic Structure and Chemistry of Solids* (Oxford University Press, Oxford, 1987), and L. Smart and E. Moore's *Solid State Chemistry* (Chapman and Hall, London, 1992). *The Materials Research Society Bulletin* (MRS Bull.), published monthly (Pittsburgh, PA), is recommended as a source of current information on all aspects of materials chemistry. Appendix 3 lists articles relevant to materials chemistry that have appeared in the *Journal of Chemical Education* since 1982, arranged according to topic.

A variety of representative exercises of varying levels of difficulty have been included, along with answers.

Laboratory Experiments

The second part of the Companion consists of laboratory experiments provided by members of the Ad Hoc Committee, whose authorship is noted thereon. Most of these experiments have been field-tested in introductory college chemistry courses.

Topic Matrix and Glossary

For much of the material in the Companion, a topic, demonstration experiment, or laboratory experiment could be used under any of several traditional chapter headings, and an arbitrary choice was made. Other possible choices, intended to give teachers maximum flexibility, are identified by using the matrix that follows the table of contents. A glossary has been included (Appendix 1) for quickly identifying definitions of key terms used in the Companion.

Supporting Instructional Materials

Sources of materials needed for demonstration and laboratory experiments are given in the Supplier Information, Appendix 2. A current list of suppliers will be maintained by ICE and can be obtained by writing ICE at the Department of Chemistry, University of Wisconsin—Madison, Madison, WI 53706. If you find alternate suppliers, please send us this information to add to the list.

Among the supporting instructional materials, the ICE Solid-State Model Kit (SSMK) is particularly noteworthy. Because of the periodic three-dimensional nature of many of the solids discussed in the Companion, it is critical that teachers and students have a good model with which to view such structures. The ICE SSMK has been designed to permit ready assembly and viewing of common structures in conjunction with the Companion.

Electronic mail can be used to obtain answers to questions that may arise from the use and adaptation of materials from the Companion. Questions submitted to ellis@chem.wisc.edu (INTERNET) will be answered as expeditiously as possible.

We hope there aren't any errors. However, given the breadth of material covered and our efforts to make this volume available to the community quickly, there may well be some errors, for which we apologize in advance. Please contact the authors to inform us of any mistakes.

The "Big Picture"

At the start of this project, one of the Ad Hoc Committee members, Joel Miller, noted that our objective should be to try to make it possible for solids to be used for at least ten percent of the examples in general chemistry courses. The Companion makes it possible, at the teacher's discretion, for solids to comprise as much as fifty percent of the examples. Lisensky and Ellis have incorporated solids for several consecutive semesters in small (25 students) and large (250 to 350 students) introductory chemistry courses at Beloit College and UW—Madison, respectively. Their findings, based on subsequent course performance and exit surveys, is that the solids-enriched course provides equivalent preparation for further study and gives students, particularly nonmajors, a perspective on chemistry that the students themselves describe as broad and relevant.

James Trefil notes in several of his books that science is like an interconnected web of ideas that can be entered from virtually any point *(5)*. The matrix linking topics in the Companion with traditional chemical concepts and the connections noted throughout with other disciplines is an illustration of this philosophy. What we hope to have shown with the Companion is that materials chemistry is an excellent launching point for exploring the web of chemically based ideas.

At the same time, we would be disappointed if this volume were treated as an end point. The cutting-edge examples presented herein show that chemistry, and science in general for that matter, is a living discipline. Like our research enterprise, the introductory course should be treated as a "moving target" with many opportunities for innovation. The Companion is intended to show that there is a natural synergism between research and teaching that can be used to suffuse introductory chemistry courses with relevance and vitality.

Acknowledgments

Many individuals and organizations contributed to the Companion. It is a pleasure to acknowledge ACS Books staff, Cheryl Shanks, Joan Comstock, Janet Dodd, and the production team, who handled the publication of this volume. We thank Sylvia Ware and Glenn Crosby, of the ACS Society Committee on Education, and the Committee, which provided seed money for our efforts; Patricia Daniels, Susan Hixson, James Harris, David Nelson, Robert Reynik, Curtis Sears, Robert Watson, and Gene Wubbels of the National Science Foundation, which provided major funding for this project through grants from the Education Directorate (USE-9150464) and from the Division of Materials Research; Robert Lichter of the Camille and Henry Dreyfus Foundation and the Foundation, which provided support for two Dreyfus Conferences that were crucial for planning this effort; Frank Di Salvo and Lynn Schneemeyer, who hosted our second Dreyfus Conference in conjunction with the 1992 Solid-State Gordon Research Conference; Robert Nowak, Tom Kennedy, Ted Tabor, and Warren Knox of Dow Chemical Company and the Dow Chemical Company Foundation, and Pat Takemoto of the UW—Madison Office of Outreach Development, which provided seed money for the ICE Solid-State Model Kit.

We thank John and Betty Moore and their co-workers, who helped develop supporting instructional materials through the Institute for Chemical Education and Project Seraphim; Joe Casey of Milwaukee Area Technical College, who served as a consultant for the Model Kit; other colleagues in the UW—Madison Department of Chemistry and College of Engineering's Materials Science Program: Audrey Aylesworth, Jill Banfield, Kevin Bray, Judith Burstyn, Reid Cooper, Fleming Crim, Larry Dahl, Art Dodd, Mark Ediger, Bob Hamers, Eric Hellstrom, Tom Kelly, Dan Klingenberg, Tom Kuech, Max Lagally, Clark Landis, David Larbalestier, Rich Mayti, Leon McCaughan, Gil Nathanson, John Perepezko, Jeroen Rietveld, Jim Skinner, Don Stone, Ned Tabatabaie, Worth Vaughan, Frank Weinhold, Jim Weisshaar, Frank Worzala, and Hyuk Yu have contributed their expertise to this project; Deans John Bollinger, Phil Certain, Greg Moses, and John Wiley; individuals associated with the UW—Madison General Chemistry program: Diana Duff, Gery Essenmacher, Don Gaines, John Harriman, Fred Juergens, Lynn Hunsberger, John Moore, Janice Parker, Bassam Shakhashiri, Mary Kay Sorenson, and Paul Treichel, and our graduate student teaching assistants; and students and colleagues at Beloit College: Laura Parmentier, Brock Spencer, Rona Penn, Jill Covert, Megan Reich, and Pete Allen, who have helped us develop and test these instructional materials. We thank David Boyd of the University of St. Thomas and Todd Trout of Mercyhurst College for developing solutions to the exercises. We also thank our many colleagues around the country who have field-tested materials in the Companion.

Constructive reviews of the Companion by Wayne Gladfelter, Hans-Conrad zur Loye, Mary Castellian, Andy Bocarsly, Allen Adler, Francis Galasso, Norman Craig, and several anonymous reviewers are deeply appreciated.

Finally, on a personal note as chair of the committee, I would like to acknowledge my family, colleagues, and students, who have been the inspiration for this project. I am grateful to my wife, Susan Trebach, to our children, Joshua and Margot, and to our families for their advice and support. I thank my colleagues on the Ad Hoc Committee and in the Department of Chemistry and the Materials Science Program at UW—Madison for their contributions and support. My student research co-workers during the period of this project, Melissa Baumann, Bob Brainard, Ann Cappellari, Kathy Gisser, Pat James, Glen Kowach, Dale Moore, Kris Moore, Don Neu, Joel Olson, Dean Philipp, Ed Winder, and John Zhang, and my general chemistry students are thanked for their help and feedback, which, I believe, has greatly improved the final product.

All of us connected with the project hope that succeeding generations of students and teachers will be the beneficiaries of introductory chemistry courses that more effectively engage, prepare, and inspire. As Robert Browning wrote, "our reach should exceed our grasp. Or what's a heaven for?" *(6)*.

Arthur B. Ellis
Chair, Ad Hoc Committee for Solid-State Instructional Materials
University of Wisconsin—Madison, Wisconsin, 53706
August 1993

References

1. "Report on the National Science Foundation Undergraduate Curriculum Development Workshop in Materials," October 11–13, 1989. Pub. April 1990.
2. The development of this project has been summarized in an article, "Symposium Session on Educational Issues," In *Materials Chemistry: An Emerging Subdiscipline*; Interrante, L. V.; Ellis, A. B.; Casper, L., Eds. Advances in Chemistry Series; ACS, submitted. A sketch of the project has also been published: Ellis, A. B.; Geselbracht, M. J.; Greenblatt, M.; Johnson, B. J.; Lisensky, G. C.; Robinson, W. R.; Whittingham, M. S.; *J. Chem. Educ.* **1992**, 69**,** 1015.
3. Ellis, A. B. *Proceedings of the 1992 Frontiers in Education Conference*, Nashville, TN, p 638.
4. Droske, J. *J. Chem. Educ.* **1992**, *69*, 1014.
5. See for example, Trefil, J. *Meditations at 10,000 Feet*; Scribners: New York, 1986.
6. From *Andrea Del Sarto*. I thank David Pennington of Baylor University and the staff at the Armstrong Browning Library in Waco, TX, for identifying the source of this quotation.

Laboratory Safety

DISCLAIMER

Safety information is included in each chapter as a precaution to the readers. Although the materials, safety information, and procedures contained in this book are believed to be reliable, they should serve only as a starting point for laboratory practices. They do not purport to specify minimal legal standards or to represent the policy of the American Chemical Society. No warranty, guarantee, or representation is made by the American Chemical Society, the authors, or the editors as to the accuracy or specificity of the information contained herein, and the American Chemical Society, the authors, and the editors assume no responsibility in connection therewith. The added safety information is intended to provide basic guidelines for safe practices. Therefore, it cannot be assumed that necessary warnings or additional information and measures may not be required. Users of this book and the procedures contained herein should consult the primary literature and other sources of safe laboratory practices for more exhaustive information. As a starting point, a partial list of sources follows.

General Information on Chemicals

A Comprehensive Guide to the Hazardous Properties of Chemical Substances by Pradyot Patniak. Van Nostrand Reinhold: New York, 1992. This guide classifies chemicals by functional groups, structures, or general use, and the introductions to these chapters discuss the general hazards. Cross-indexed by name-CAS number and CAS number-name.

Catalog of Teratogenic Agents by Thomas H. Shepard. 6th ed. Johns Hopkins University Press: Baltimore, MD, 1989. Among books on this subject, this is perhaps the most thoughtful source list.

Handbook of Reactive Chemical Hazards by Leslie Bretherick. 4th ed. Butterworths: Stoneham, MA, 1990. This book is a “must” for chemistry researchers or for anyone “experimenting” in the laboratory. It has a very useful format for determining the possible explosive consequences of mixing chemicals.

Fire Protection Guide to Hazardous Materials. 10th ed. National Fire Protection Association, 1991. Laboratory personnel are not the primary audience of NFPA publications, but this document has clear, concise, and easily accessed information on most commercial chemicals and a number of laboratory chemicals.

Safe Storage of Laboratory Chemicals edited by David A. Pipitone. 2nd ed. John Wiley and Sons: New York, 1991. The scope of this book is far broader than the title suggests. Techniques for the proper dispensing of flammable solvents and spill procedures are discussed.

Cryogens

Standard on Fire Protection for Laboratories Using Chemicals (NFPA 45). National Fire Protection Association, 1991. Especially relevant is Chapter 8, Section 8-3, “Cryogenic Fluids”.

Handbook of Compressed Gases by the Compressed Gas Association. 3rd Ed. Van Nostrand Reinhold: New York, 1990.

“Cryogenic Fluids in the Laboratory” Data Sheet I-688-Rev. 86. National Safety Council, 1986.

Improving Safety in the Chemical Laboratory: A Practical Guide edited by Jay A. Young. 2nd ed. John Wiley and Sons: New York, 1991. Section 11.11, “Low Temperature and Cryogenic Systems”, pp 192–195.

Lasers

American National Standard for the Safe Use of Lasers. ANSI Z136.1—1986. American National Standards Institute: New York, 1986. Provides guidance for the safe use of lasers and laser systems.

Light, Lasers, and Synchrotron Radiation edited by M. Grandolfo et al. Plenum Press: New York, 1990. The chapter titled “Laser Safety Standards: Historical Development and Rationale” puts ANSI Z136.1—1986 in perspective.

“Lasers—The Nonbeam Hazards” by R. James Rockwell, Jr. In *Lasers and Optronics*, August 1989, p 25.

Improving Safety in the Chemical Laboratory: A Practical Guide edited by Jay A. Young. 2nd ed. John Wiley and Sons: New York, 1991. Section 11.3.5.1, “Laser Radiation”, pp 177–178.

High Voltage

"Electrical Hazards in the High Energy Laboratory" by Lloyd B. Gordon. In *IEEE Transactions on Education,* Vol. 34, No. 3, August 1991, pp 231–242. This article contains primarily physics laboratory safety; it gives excellent information on electrical hazards. Highly recommended.

Improving Safety in the Chemical Laboratory: A Practical Guide edited by Jay A. Young. 2nd ed. John Wiley and Sons: New York, 1991. Section 11.5, "Electric Currents and Magnetic Fields", pp 181–182.

Vacuum Techniques

The Laboratory Handbook of Materials, Equipment, and Technique by Gary S. Coyne. Prentice Hall: New York, 1992. Chapter 7, "Vacuum Systems", pp 275–408.

Improving Safety in the Chemical Laboratory: A Practical Guide edited by Jay A. Young. 2nd ed. John Wiley & Sons, 1991. Section 11.7, "Vacuum and Dewar Flasks", p 183.

Compiled by Maureen Matkovich, American Chemical Society.