

Contents

About the Authors	ix
Preface to the First Edition	xiii
Preface to the Second Edition	xvii
Foreword	xix

PART I HISTORY AND INTRODUCTION

1 Introduction	3
Chapter Preview	3
1.1 Definitions	3
1.2 General Properties	4
1.3 Types of Ceramic and Their Applications	5
1.4 Market	5
1.5 Critical Issues for the Future	7
1.6 Relating Microstructure, Processing, and Applications	8
1.7 Safety	10
1.8 Ceramics on the Internet	10
1.9 On Units	10
Chapter Summary	13
2 Some History	17
Chapter Preview	17
2.1 Earliest Ceramics: The Stone Age	17
2.2 Ceramics in Ancient Civilizations	19
2.3 Clay	19
2.4 Types of Pottery	21
2.5 Glazes	22
2.6 Development of a Ceramics Industry	23
2.7 Plaster and Cement	24
2.8 Brief History of Glass	25
2.9 Brief History of Refractories	27
2.10 Major Landmarks of the Twentieth Century	28
2.11 Museums	30
2.12 Societies	31
2.13 Ceramic Education	31
Chapter Summary	31

PART II MATERIALS

3	Background You Need to Know	37
	Chapter Preview	37
3.1	The Atom	37
3.2	Energy Levels	38
3.3	Electron Waves	39
3.4	Quantum Numbers	40
3.5	Assigning Quantum Numbers	41
3.6	Ions	42
3.7	Electronegativity	45
3.8	Thermodynamics: The Driving Force for Change	46
3.9	Kinetics: The Speed of Change	49
	Chapter Summary	50
4	Bonds and Energy Bands	53
	Chapter Preview	53
4.1	Types of Interatomic Bond	53
4.2	Young's Modulus	53
4.3	Ionic Bonding	55
4.4	Covalent Bonding	60
4.5	Metallic Bonding in Ceramics	65
4.6	Mixed Bonding	65
4.7	Secondary Bonding	66
4.8	Electron Energy Bands	68
	Chapter Summary	71
5	Models, Crystals, and Chemistry	73
	Chapter Preview	73
5.1	Terms and Definitions	73
5.2	Symmetry and Crystallography	75
5.3	Lattice Points, Directions and Planes	76
5.4	Importance of Crystallography	78
5.5	Pauling's Rules	78
5.6	Close-Packed Arrangements: Interstitial Sites	81
5.7	Notation for Crystal Structures	83
5.8	Structure, Composition, and Temperature	83
5.9	Crystals, Glass, Solids, and Liquid	84
5.10	Defects	85
5.11	Computer Modeling	85
	Chapter Summary	86
6	Binary Compounds	89
	Chapter Preview	89
6.1	Background	89
6.2	CsCl	90
6.3	NaCl (MgO, TiC, PbS)	90
6.4	GaAs (β -SiC)	91
6.5	AlN (BeO, ZnO)	92
6.6	CaF ₂	93
6.7	FeS ₂	94
6.8	Cu ₂ O	95
6.9	CuO	95
6.10	TiO ₂	95
6.11	Al ₂ O ₃	96
6.12	MoS ₂ and CdI ₂	97
6.13	Polymorphs, Polytypes, and Polytypoids	98
	Chapter Summary	100

7	Complex Crystal and Glass Structures	103
	Chapter Preview	103
7.1	Introduction	103
7.2	Spinel	104
7.3	Perovskite	105
7.4	The Silicates and Structures Based on SiO ₄	107
7.5	Silica	108
7.6	Olivine	108
7.7	Garnets	109
7.8	Ring Silicates	110
7.9	Micas and Other Layer Materials	111
7.10	Clay Minerals	111
7.11	Pyroxene	112
7.12	β-Aluminas and Related Materials	113
7.13	Calcium Aluminate and Related Materials	113
7.14	Mullite	114
7.15	Monazite	114
7.16	YBa ₂ Cu ₃ O ₇ and Related HTSCs	114
7.17	Si ₃ N ₄ , SiAlONs, and Related Materials	115
7.18	Fullerenes and Nanotubes	116
7.19	Zeolites and Microporous Compounds	117
7.20	Zachariasen's Rules for the Structure of Glass	118
7.21	Revisiting Glass Structures	119
	Chapter Summary	120
8	Equilibrium Phase Diagrams	123
	Chapter Preview	123
8.1	What's Special About Ceramics?	123
8.2	Determining Phase Diagrams	124
8.3	Phase Diagrams for Ceramists: The Books	126
8.4	Gibbs Phase Rule	127
8.5	One Component ($C = 1$)	128
8.6	Two Components ($C = 2$)	128
8.7	Three and More Components	130
8.8	Composition with Variable Oxygen Partial Pressure	131
8.9	Quaternary Diagrams and Temperature	134
8.10	Congruent and Incongruent Melting	135
8.11	Miscibility Gaps in Glass	136
	Chapter Summary	137
 PART III TOOLS		
9	Furnaces	143
	Chapter Preview	143
9.1	The Need for High Temperatures	143
9.2	Types of Furnace	143
9.3	Combustion Furnaces	144
9.4	Electrically Heated Furnaces	145
9.5	Batch or Continuous Operation	145
9.6	Indirect Heating	147
9.7	Heating Elements	148
9.8	Refractories	150
9.9	Furniture, Tubes, and Crucibles	151
9.10	Firing Process	151
9.11	Heat Transfer	152
9.12	Measuring Temperature	153
9.13	Safety	155
	Chapter Summary	156

10	Characterizing Structure, Defects, and Chemistry	159
	Chapter Preview	159
10.1	Characterizing Ceramics	159
10.2	Imaging Using Visible-Light, Infrared, and Ultraviolet Microscopy	160
10.3	Imaging Using X-rays and CT Scans	162
10.4	Imaging in the SEM	162
10.5	Imaging in the TEM	163
10.6	Scanning-Probe Microscopy	164
10.7	Scattering and Diffraction Techniques	166
10.8	Photon Scattering	167
10.9	Raman and IR Spectroscopy	167
10.10	NMR Spectroscopy and Spectrometry	170
10.11	Mössbauer Spectroscopy and Spectrometry	171
10.12	Diffraction in the EM	172
10.13	Ion Scattering (RBS)	173
10.14	X-ray Diffraction and Databases	174
10.15	Neutron Scattering	176
10.16	Mass Spectrometry	177
10.17	Spectrometry in the EM	177
10.18	Electron Spectroscopy	178
10.19	Neutron Activation Analysis	179
10.20	Thermal Analysis	180
	Chapter Summary	181

PART IV DEFECTS

11	Point Defects, Charge, and Diffusion	187
	Chapter Preview	187
11.1	Are Defects in Ceramics Different?	187
11.2	Types of Point Defects	188
11.3	What is Special for Ceramics?	189
11.4	What Type of Defects Form?	190
11.5	Equilibrium Defect Concentrations	190
11.6	Writing Equations for Point Defects	193
11.7	Solid Solutions	193
11.8	Association of Point Defects	196
11.9	Color Centers	197
11.10	Creation of Point Defects in Ceramics	198
11.11	Experimental Studies of Point Defects	198
11.12	Diffusion	199
11.13	Diffusion in Impure, or Doped, Ceramics	200
11.14	Movement of Defects	203
11.15	Diffusion and Ionic Conductivity	204
11.16	Computing	205
	Chapter Summary	206
12	Are Dislocations Unimportant?	209
	Chapter Preview	209
12.1	A Quick Review of Dislocations	210
12.2	Summary of Dislocation Properties	214
12.3	Observation of Dislocations	214
12.4	Dislocations in Ceramics	215
12.5	Structure of the Core	216
12.6	Detailed Geometry	218
12.7	Defects on Dislocations	220
12.8	Dislocations and Diffusion	222

12.9	Movement of Dislocations	222
12.10	Multiplication of Dislocations	223
12.11	Dislocation Interactions	225
12.12	At the Surface	225
12.13	Indentation, Scratching, and Cracks	225
12.14	Dislocations with Different Cores	226
	Chapter Summary	227
13	Surfaces, Nanoparticles, and Foams	231
	Chapter Preview	231
13.1	Background to Surfaces	231
13.2	Ceramic Surfaces	232
13.3	Surface Energy	232
13.4	Surface Structure	234
13.5	Curved Surfaces and Pressure	235
13.6	Capillarity	237
13.7	Wetting and Dewetting	238
13.8	Foams	239
13.9	Epitaxy and Film Growth	240
13.10	Film Growth in 2D: Nucleation	240
13.11	Film Growth in 2D: Mechanisms	241
13.12	Characterizing Surfaces	242
13.13	Steps	245
13.14	In Situ Condition	246
13.15	Surfaces and Nano	246
13.16	Computer Modeling	247
13.17	Introduction to Properties	249
	Chapter Summary	250
14	Interfaces in Polycrystals	253
	Chapter Preview	253
14.1	What are Grain Boundaries?	253
14.2	For Ceramics	255
14.3	GB Energy	256
14.4	Low-Angle GBs	258
14.5	High-Angle GBs	260
14.6	Twin Boundaries	262
14.7	General Boundaries	265
14.8	GB Films	265
14.9	Triple Junctions and GB Grooves	268
14.10	Characterizing GBs	269
14.11	GBs in Thin Films	271
14.12	Space Charge and Charged Boundaries	271
14.13	Modeling	272
14.14	Some Properties	272
	Chapter Summary	274
15	Phase Boundaries, Particles, and Pores	277
	Chapter Preview	277
15.1	The importance	277
15.2	Different types	278
15.3	Compare to Other Materials	278
15.4	Energy	279
15.5	The Structure of PBs	279
15.6	Particles	280
15.7	Use of Particles	281
15.8	Nucleation and growth of particles	282
15.9	Pores	284
15.10	Measuring porosity	286

15.11	Porous Ceramics	287
15.12	Glass/Crystal Phase Boundaries	288
15.13	Eutectics	289
15.14	Metal/Ceramic PBs	289
15.15	Forming PBs by Joining	290
	Chapter Summary	292

PART V MECHANICAL STRENGTH AND WEAKNESS

16	Mechanical Testing	297
	Chapter Preview	297
16.1	Philosophy	297
16.2	Types of Testing	299
16.3	Elastic Constants and Other ‘Constants’	299
16.4	Effect of Microstructure on Elastic Moduli	302
16.5	Test Temperature	302
16.6	Test Environment	303
16.7	Testing in Compression and Tension	304
16.8	Three-point and Four-point Bending	305
16.9	K_{IC} from Bend Test	306
16.10	Indentation	306
16.11	Fracture Toughness from Indentation	307
16.12	Nanoindentation	308
16.13	Ultrasonic Testing	309
16.14	Design and Statistics	309
16.15	SPT Diagrams	313
	Chapter Summary	313
17	Plasticity	317
	Chapter Preview	317
17.1	Plastic Deformation	317
17.2	Dislocation Glide	318
17.3	Slip in Alumina	319
17.4	Plastic Deformation in Single Crystals	319
17.5	Plastic Deformation in Polycrystals	322
17.6	Dislocation Velocity and Pinning	323
17.7	Creep	324
17.8	Dislocation Creep	325
17.9	Diffusion-Controlled Creep	325
17.10	Grain-Boundary Sliding	326
17.11	Tertiary Creep and Cavitation	327
17.12	Creep Deformation Maps	327
17.13	Viscous Flow	328
17.14	Superplasticity	329
	Chapter Summary	330
18	Fracturing: Brittleness	333
	Chapter Preview	333
18.1	Importance of Brittleness	333
18.2	Theoretical Strength: Orowan Equation	334
18.3	Effect of Flaws: Griffith Equation	335
18.4	Crack Tip: Inglis Equation	337
18.5	Stress Intensity Factor	337
18.6	R Curves	338
18.7	Fatigue and Stress Corrosion Cracking	339
18.8	Failure and Fractography	340
18.9	Toughening and Ceramic Matrix Composites	342

18.10	Machinable Glass-Ceramics	345
18.11	Wear	346
18.12	Grinding and polishing	347
	Chapter Summary	348

PART VI PROCESSING

19	Raw Materials	353
	Chapter Preview	353
19.1	Geology, Minerals, and Ores	353
19.2	Mineral Formation	354
19.3	Beneficiation	355
19.4	Weights and Measures	356
19.5	Silica	356
19.6	Silicates	356
19.7	Oxides	359
19.8	Nonoxides	363
	Chapter Summary	366
20	Powders, Fibers, Platelets, and Composites	369
	Chapter Preview	369
20.1	Making Powders	369
20.2	Types of powders	270
20.3	Mechanical Milling	270
20.4	Spray Drying	372
20.5	Powders by Sol-gel Processing	373
20.6	Powders by Precipitation	373
20.7	Chemical Routes to Nonoxide Powders	374
20.8	Platelets	375
20.9	Nanopowders by Vapor-Phase Reactions	375
20.10	Characterizing Powders	375
20.11	Characterizing Powders by Microscopy	376
20.12	Sieving	376
20.13	Sedimentation	377
20.14	Coulter Counter	378
20.15	Characterizing Powders by Light Scattering	378
20.16	Characterizing Powders by X-ray Diffraction	379
20.17	Measuring Surface Area (BET Method)	379
20.18	Determining Particle Composition and Purity	380
20.19	Making Fibers and Whiskers	381
20.20	Oxide and Carbide Fibers	381
20.21	Whiskers	382
20.22	Glass Fibers	382
20.23	Coating Fibers	383
20.24	Making CMCS	384
20.25	CMCs from Powders and Slurries	385
20.26	CMCs By Infiltration	385
20.27	In Situ Processes	386
	Chapter Summary	386
21	Glass and Glass-Ceramics	389
	Chapter Preview	389
21.1	Definitions	389
21.2	History	390
21.3	Viscosity, η	392
21.4	Glass: A Summary of Its Properties, or Not	394
21.5	Defects in Glass	395

21.6	Heterogeneous Glass	395
21.7	YA Glass	396
21.8	Coloring Glass	396
21.9	Glass Laser	397
21.10	Precipitates in Glass	397
21.11	Crystallizing Glass	398
21.12	Glass as Glaze and Enamel	399
21.13	Corrosion of Glass and Glaze	402
21.14	Types of Ceramic Glasses	402
21.15	Natural Glass	404
21.16	Physics of Glass	405
	Chapter Summary	406
22	Sols, Gels, and Organic Chemistry	411
	Chapter Preview	411
22.1	Sol–gel Processing	411
22.2	Structure and Synthesis of Alkoxides	412
22.3	Properties of Alkoxides	413
22.4	Sol–gel Process using Metal Alkoxides	414
22.5	Characterization of the Sol–gel Process	418
22.6	Powders, Coatings, Fibers, Crystalline, or Glass?	418
	Chapter Summary	421
23	Shaping and Forming	423
	Chapter Preview	423
23.1	The Words	423
23.2	Binders and Plasticizers	424
23.3	Slip and Slurry	424
23.4	Dry Pressing	425
23.5	Hot Pressing	425
23.6	Cold Isostatic Pressing	426
23.7	Hot Isostatic Pressing	427
23.8	Slip Casting	428
23.9	Extrusion	429
23.10	Injection Molding	430
23.11	Rapid Prototyping	431
23.12	Green Machining	431
23.13	Binder Burnout	432
23.14	Final Machining	432
23.15	Making Porous Ceramics	433
23.16	Shaping Pottery	433
23.17	Shaping Glass	434
	Chapter Summary	435
24	Sintering and Grain Growth	439
	Chapter Preview	439
24.1	Sintering Process	439
24.2	Terminology of Sintering	440
24.3	Capillary Forces and Surface Forces	441
24.4	Sintering Spheres and Wires	441
24.5	Grain Growth	443
24.6	Sintering and Diffusion	443
24.7	Liquid-Phase Sintering	445
24.8	Hot Pressing	446
24.9	Pinning Grain Boundaries	446
24.10	Grain Growth	447
24.11	Grain Boundaries, Surfaces, and Sintering	449
24.12	Exaggerated Grain Growth	449

24.13	Fabricating Complex Shapes	450
24.14	Pottery	451
24.15	Pores and Porous Ceramics	451
24.16	Sintering with Two and Three Phases	452
24.17	Examples of Sintering in Action	453
24.18	Computer Modeling	453
	Chapter Summary	454
25	Solid-State Phase Transformations and Reactions	457
	Chapter Preview	457
25.1	Transformations and Reactions: The Link	457
25.2	Terminology	458
25.3	Technology	458
25.4	Phase Transformations Without Changing Chemistry	460
25.5	Phase Transformations Changing Chemistry	461
25.6	Methods for Studying Kinetics	462
25.7	Diffusion Through a Layer: Slip Casting	463
25.8	Diffusion Through a Layer: Solid-State Reactions	464
25.9	Spinel-Forming Reaction	464
25.10	Inert Markers and Reaction Barriers	465
25.11	Simplified Darken Equation	466
25.12	Incubation Period	466
25.13	Particle Growth and the Effect of Misfit	467
25.14	Thin-Film Reactions	468
25.15	Reactions in an Electric Field	470
25.16	Phase Transformations Involving Glass	471
25.17	Pottery	472
25.18	Cement	472
25.19	Reactions Involving a Gas Phase	473
25.20	Curved Interfaces	474
	Chapter Summary	474
26	Processing Glass and Glass-Ceramics	477
	Chapter Preview	477
26.1	Market for Glass and Glass Products	477
26.2	Processing Bulk Glasses	477
26.3	Bubbles	480
26.4	Flat Glass	482
26.5	Float-Glass	483
26.6	Glass Blowing	484
26.7	Coating Glass	485
26.8	Safety Glass	486
26.9	Foam Glass	487
26.10	Sealing Glass	487
26.11	Enamel	487
26.12	Photochromic Glass	488
26.13	Ceramming: Changing Glass to Glass-Ceramics	488
26.14	Glass for Art and Sculpture	490
26.15	Glass for Science and Engineering	492
	Chapter Summary	493
27	Coatings and Thick Films	495
	Chapter Preview	495
27.1	Defining Thick Film	495
27.2	Tape Casting	495
27.3	Dip Coating	497
27.4	Spin Coating	498
27.5	Spraying	498

27.6	Electrophoretic Deposition	500
27.7	Thick Film Circuits	502
	Chapter Summary	506
28	Thin Films and Vapor Deposition	509
	Chapter Preview	509
28.1	Difference Between Thin Films and Thick Films	509
28.2	Acronyms, Adjectives, and Hyphens	509
28.3	Requirements for Thin Ceramic Films	510
28.4	Chemical Vapor Deposition	510
28.5	Thermodynamics of CVD	512
28.6	CVD of Ceramic Films for Semiconductor Devices	513
28.7	Types of CVD	514
28.8	CVD Safety	515
28.9	Evaporation	515
28.10	Sputtering	516
28.11	Molecular-Beam Epitaxy	517
28.12	Pulsed-Laser Deposition	518
28.13	Ion-Beam-Assisted Deposition	519
28.14	Substrates	519
	Chapter Summary	520
29	Growing Single Crystals	523
	Chapter Preview	523
29.1	Why Single Crystals?	523
29.2	Brief History of Growing Ceramic Single Crystals	523
29.3	Methods for Growing Single Crystals of Ceramics	524
29.4	Melt Technique: Verneuil (Flame-Fusion)	525
29.5	Melt Technique: Arc-Image Growth	527
29.6	Melt Technique: Czochralski	527
29.7	Melt Technique: Skull Melting	530
29.8	Melt Technique: Bridgman-Stockbarger	531
29.9	Melt Technique: HEM	532
29.10	Applying Phase Diagrams to Single-Crystal Growth	532
29.11	Solution Technique: Hydrothermal	533
29.12	Solution Technique: Hydrothermal Growth at Low Temperature	535
29.13	Solution Technique: Flux Growth	535
29.14	Solution Technique: Growing Diamonds	537
29.15	Vapor Technique: VLS	537
29.16	Vapor Technique: Sublimation	538
29.17	Preparing Substrates for Thin-Film Applications	538
29.18	Growing Nanowires and Nanotubes by VLS and Not	538
	Chapter Summary	539

PART VII PROPERTIES AND APPLICATIONS

30	Conducting Charge or Not	545
	Chapter Preview	545
30.1	Ceramics as Electrical Conductors	545
30.2	Conduction Mechanisms in Ceramics	547
30.3	Number of Conduction Electrons	548
30.4	Electron Mobility	549
30.5	Effect of Temperature	549
30.6	Ceramics with Metal-Like Conductivity	550
30.7	Applications for High- σ Ceramics	551
30.8	Semiconducting Ceramics	553
30.9	Examples of Extrinsic Semiconductors	554

30.10	Varistors	556
30.11	Thermistors	557
30.12	Wide-Band-Gap Semiconductors	558
30.13	Ion Conduction	558
30.14	Fast Ion Conductors	559
30.15	Batteries	559
30.16	Fuel Cells	560
30.17	Ceramic Insulators	562
30.18	Substrates and Packages for Integrated Circuits	564
30.19	Insulating Layers in Integrated Circuits	565
30.20	Superconductivity	566
30.21	Ceramic Superconductors	567
	Chapter Summary	569
31	Locally Redistributing Charge	573
	Chapter Preview	573
31.1	Background on Dielectrics	573
31.2	Ferroelectricity	578
31.3	BaTiO ₃ : The Prototypical Ferroelectric	579
31.4	Solid Solutions with BaTiO ₃	582
31.5	Other Ferroelectric Ceramics	582
31.6	Relaxor Dielectrics	583
31.7	Ceramic Capacitors	583
31.8	Ceramic Ferroelectrics for Memory Applications	586
31.9	Piezoelectricity	586
31.10	Lead Zirconate-Lead Titanate Solid Solutions	588
31.11	Applications for Piezoelectric Ceramics	589
31.12	Piezoelectric Materials for MEMS	589
31.13	Pyroelectricity	590
31.14	Applications for Pyroelectric Ceramics	590
	Chapter Summary	591
32	Interacting with and Generating Light	593
	Chapter Preview	593
32.1	Some Background for Optical Ceramics	593
32.2	Transparency	595
32.3	Refractive Index	596
32.4	Reflection from Ceramic Surfaces	597
32.5	Color in Ceramics	598
32.6	Coloring Glass and Glazes	599
32.7	Ceramic Pigments and Stains	600
32.8	Translucent Ceramics	601
32.9	Lamp Envelopes	602
32.10	Fluorescence	603
32.11	Basics of Optical Fibers	604
32.12	Phosphors and Emitters	607
32.13	Solid-State Lasers	607
32.14	Electro-Optic Ceramics for Optical Devices	608
32.15	Reacting to Other Parts of the Spectrum	612
32.16	Optical Ceramics in Nature	613
32.17	Quantum Dots and Size Effects	614
	Chapter Summary	614
33	Using Magnetic Fields and Storing Data	617
	Chapter Preview	617
33.1	Brief History of Magnetic Ceramics	617
33.2	Magnetic Dipoles	618
33.3	Basic Equations, Words, and Units	618

33.4	Five Classes of Magnetic Material	621
33.5	Diamagnetic Ceramics	621
33.6	Superconducting Magnets	622
33.7	Paramagnetic Ceramics	623
33.8	Measuring χ	623
33.9	Ferromagnetism	624
33.10	Antiferromagnetism and Colossal Magnetoresistance	625
33.11	Ferrimagnetism	626
33.12	Estimating the Magnetization of Ferrimagnets	629
33.13	Magnetic Domains and Bloch Walls	629
33.14	Imaging Magnetic Domains	630
33.15	Motion of Domain Walls and Hysteresis Loops	631
33.16	Hard and Soft Ferrites	632
33.17	Microwave Ferrites	634
33.18	Data Storage and Recording	634
33.19	Magnetic Nanoparticles	636
	Chapter Summary	636
34	Responding to Temperature Changes	641
	Chapter Preview	641
34.1	Summary of Terms and Units	641
34.2	Absorption and Heat Capacity	641
34.3	Melting	643
34.4	Vaporization	645
34.5	Thermal Conductivity	645
34.6	Measuring Thermal Conductivity	648
34.7	Microstructure and Thermal Conductivity	648
34.8	Using High Thermal Conductivity	649
34.9	Thermal Expansion	651
34.10	Effect of Crystal Structure on α	651
34.11	Thermal Expansion Measurement	652
34.12	Importance of Matching α s	653
34.13	Applications for Low- α	655
34.14	Thermal Shock	655
	Chapter Summary	656
35	Ceramics in Biology and Medicine	659
	Chapter Preview	659
35.1	What are Bioceramics?	659
35.2	Advantages and Disadvantages of Ceramics	660
35.3	Ceramic Implants and the Structure of Bone	661
35.4	Alumina and Zirconia	663
35.5	Bioactive Glasses	664
35.6	Bioactive Glass-Ceramics	665
35.7	Hydroxyapatite	665
35.8	Bioceramics in Composites	667
35.9	Bioceramic Coatings	668
35.10	Radiotherapy Glasses	669
35.11	Pyrolytic Carbon Heart Valves	670
35.12	Nanobioceramics	670
35.13	Dental Ceramics	671
35.14	Biomimetics	672
	Chapter Summary	673
36	Minerals and Gems	677
	Chapter Preview	677
36.1	Minerals	677
36.2	What is a gem?	678

36.3	In the Rough	678
36.4	Cutting and Polishing	680
36.5	Light and Optics in Gemology	681
36.6	Color in Gems and Minerals	683
36.7	Optical Effects	686
36.8	Identifying Minerals and Gems	686
36.9	Chemical Stability (Durability)	688
36.10	Diamonds, Sapphires, Rubies, and Emeralds	688
36.11	Opal	690
36.12	Other Gems	691
36.13	Minerals with Inclusions	694
36.14	Treatment of Gems	694
36.15	The Mineral and Gem Trade	696
	Chapter Summary	697
37	Energy Production and Storage	699
	Chapter Preview	699
37.1	Some Reminders	699
37.2	Nuclear Fuel and Waste Disposal	699
37.3	Solid Oxide Fuel Cells	701
37.4	Photovoltaic Solar Cells	702
37.5	Dye-Sensitized Solar Cells	703
37.6	Ceramics in Batteries	703
37.7	Lithium-Ion Batteries	704
37.8	Ultracapacitors	706
37.9	Producing and Storing Hydrogen	706
37.10	Energy Harvesting	708
37.11	Catalysts and Catalyst Supports	708
	Chapter Summary	710
38	Industry and the Environment	713
	Chapter Preview	713
38.1	Beginning of the Modern Ceramics Industry	713
38.2	Growth and Globalization	714
38.3	Types of Market	715
38.4	Case Studies	715
38.5	Emerging Areas	718
38.6	Mining	721
38.7	Recycling	722
38.8	As Green Materials	724
	Chapter Summary	726
	Index	729
	Details for Figures and Tables	745