

Robert A. Huggins

Advanced Batteries

Materials Science Aspects



Springer

Contents

Preface	v
1 Introduction	v
2 Applications of Electrochemical Energy Storage	vi
3 Changes That Have Taken Place in Recent Years	ix
4 Objectives of This Book	x
5 Thinking Tools	xi
6 Terminology and Conventions	xii
1 Introductory Material	1
1.1 Introduction	1
1.2 Simple Chemical and Electrochemical Reactions	1
1.3 Major Types of Reaction Mechanisms	6
1.3.1 Reconstitution Reactions	6
1.3.2 Insertion Reactions	8
1.4 Important Practical Parameters	9
1.4.1 The Operating Voltage and the Concept of Energy Quality	10
1.4.2 The Charge Capacity	12
1.4.3 The Maximum Theoretical Specific Energy (MTSE) ..	13
1.4.4 Variation of the Voltage as Batteries are Discharged and Recharged	13
1.4.5 Cycling Behavior	15
1.4.6 Self-Discharge	16
1.5 General Equivalent Circuit of an Electrochemical Cell	17
1.5.1 Influence of Impedances to the Transport of Ionic and Atomic Species within the Cell	18
1.5.2 Influence of Electronic Leakage within the Electrolyte	18
1.5.3 Transference Numbers of Individual Species in an Electrochemical Cell	19

1.5.4	Relation between the Output Voltage and the Values of the Ionic and Electronic Transference Numbers . . .	20
1.5.5	Joule Heating to Due to Self-Discharge in Electrochemical Cells	21
1.5.6	What If Current is Drawn from the Cell?	21
	References	23
2	Principles Determining the Voltages and Capacities of Electrochemical Cells	25
2.1	Introduction	25
2.2	Thermodynamic Properties of Individual Species	25
2.3	A Simple Example: The Lithium/Iodine Cell	27
2.3.1	Calculation of the Maximum Theoretical Specific Energy	29
2.3.2	The Temperature Dependence of the Cell Voltage . . .	29
2.4	The Shape of Discharge Curves and the Gibbs Phase Rule	30
2.5	The Coulometric Titration Technique	36
	References	39
3	Binary Electrodes Under Equilibrium or Near-Equilibrium Conditions	41
3.1	Introduction	41
3.2	Binary Phase Diagrams	41
3.2.1	The Lever Rule	44
3.2.2	Examples of Binary Phase Diagrams	44
3.3	A Real Example, The Lithium: Antimony System Again	46
3.4	Stability Ranges of Phases	51
3.5	Another Example, The Lithium: Bismuth System	51
3.6	Coulometric Titration Measurements on Other Binary Systems . .	53
3.7	Temperature Dependence of the Potential	53
3.8	Application to Oxides and Similar Materials	55
3.9	Ellingham Diagrams	56
3.10	Liquid Binary Electrodes	57
3.11	Comments on Mechanisms and Terminology	60
3.12	Summary	62
	References	62
4	Ternary Electrodes Under Equilibrium or Near-Equilibrium Conditions	65
4.1	Introduction	65
4.2	Ternary Phase Diagrams and Phase Stability Diagrams	65
4.3	Comments on the Influence of SubTriangle Configurations in Ternary Systems	67
4.4	An Example: The Sodium/Nickel Chloride “Zebra” System	70

4.5	A Second Example: The Lithium–Copper–Chlorine Ternary System	72
4.5.1	Calculation of the Voltages in This System	74
4.5.2	Experimental Arrangement for Lithium/Copper Chloride Cells	77
4.6	Calculation of the Maximum Theoretical Specific Energies of Li/CuCl and Li/CuCl ₂ Cells	77
4.7	Specific Capacity and Capacity Density in Ternary Systems	78
4.8	Another Group of Examples: Metal Hydride Systems Containing Magnesium	78
4.9	Further Ternary Examples: Lithium–Transition Metal Oxides	85
4.10	Ternary Systems Composed of Two Binary Metal Alloys	90
4.10.1	An Example: The Li–Cd–Sn System at Ambient Temperature	90
4.11	What About the Presence of Additional Components?	91
4.12	Summary	91
	References	91
5	Electrode Reactions That Deviate From Complete Equilibrium	93
5.1	Introduction	93
5.2	Stable and Metastable Equilibrium	93
5.3	Selective Equilibrium	95
5.4	Soft Chemistry (Chimie Douce)	96
5.5	Formation of Amorphous vs. Crystalline Structures	96
5.6	The Conversion of Crystalline to Amorphous Structures by Insertion Reactions	98
5.7	Deviations from Equilibrium for Kinetic Reasons	98
	References	99
6	Insertion Reaction Electrodes	101
6.1	Introduction	101
6.2	Examples of the Insertion of Guest Species into Layer Structures	103
6.3	Floating and Pillared Layer Structures	104
6.4	More on Terminology Related to the Insertion of Species into Solids	104
6.5	Types of Inserted Guest Species Configurations	105
6.6	Sequential Insertion Reactions	107
6.7	Coinsertion of Solvent Species	110
6.8	Insertion into Materials with Parallel Linear Tunnels	110
6.9	Changes in the Host Structure Induced by Guest Insertion or Extraction	111
6.9.1	Conversion of the Host Structure from Crystalline to Amorphous	111

6.9.2	Dependence of the Product upon the Potential	113
6.9.3	Changes upon the Initial Extraction of the Mobile Species	114
6.10	The Variation of the Potential with Composition in Insertion Reaction Electrodes	114
6.10.1	Introduction	114
6.10.2	The Variation of the Electrical Potential with Composition in Simple Metallic Solid Solutions	116
6.10.3	Configurational Entropy of the Guest Ions	116
6.10.4	The Concentration Dependence of the Chemical Potential of the Electrons in a Metallic Solid Solution	117
6.10.5	Sum of the Effect of These Two Components upon the Electrical Potential of a Metallic Solid Solution	118
6.10.6	The Composition: Dependence of the Potential in the Case of Insertion Reactions that Involve a Two-Phase Reconstitution Reaction	119
6.11	Final Comments	122
	References	122
7	Negative Electrodes in Lithium Cells	123
7.1	Introduction	123
7.2	Elemental Lithium Electrodes	123
7.3	Problems with the Rechargeability of Elemental Electrodes	124
7.3.1	Deposition at Unwanted Locations	124
7.3.2	Shape Change	124
7.3.3	Dendrites	125
7.3.4	Filamentary Growth	125
7.3.5	Thermal Runaway	126
7.4	Alternatives	127
7A	Lithium–Carbon Alloys	127
7A.1	Introduction	127
7A.2	Ideal Structure of Graphite Saturated with Lithium	129
7A.3	Variations in the Structure of Graphite	130
7A.4	Structural Aspects of Lithium Insertion into Graphitic Carbons	131
7A.5	Electrochemical Behavior of Lithium in Graphite	132
7A.6	Electrochemical Behavior of Lithium in Amorphous Graphite	134
7A.7	Lithium in Hydrogen-Containing Carbons	134

7B	Metallic Lithium Alloys	136
7B.1	Introduction	136
7B.2	Equilibrium Thermodynamic Properties of Binary Lithium Alloys	136
7B.3	Experiments at Ambient Temperature	137
7B.4	Liquid Binary Alloys	138
7B.5	Mixed-Conductor Matrix Electrodes	138
7B.6	Decrepitation	143
7B.7	Modification of the Micro and Nanostructure of the Electrode	145
7B.8	Formation of Amorphous Products at Ambient Temperatures ..	147
	References	148
8	Convertible Reactant Electrodes	151
8.1	Introduction	151
8.2	Electrochemical Formation of Metals and Alloys from Oxides ..	152
8.3	Lithium–Tin Alloys at Ambient Temperature	152
8.4	The Lithium–Tin Oxide System	153
8.5	Irreversible and Reversible Capacities	155
8.6	Other Possible Convertible Oxides	157
8.7	Final Comments	158
	References	158
9	Positive Electrodes in Lithium Systems	159
9.1	Introduction	159
9.2	Insertion Reaction, Instead of Reconstitution Reaction, Electrodes	160
9.3	More than One Type of Interstitial Site or More than One Type of Redox Species	161
9.4	Cells Assembled in the Discharged State	162
9A	Solid Positive Electrodes in Lithium Systems	163
9A.1	Introduction	163
9A.2	Influence of the Crystallographic Environment on the Potential ..	166
9A.3	Oxides with Structures in Which the Oxygen Anions Are in a Face-Centered Cubic Array	167
9A.3.1	Materials with Layered Structures	167
9A.3.2	Materials with the Spinel Structure	169
9A.3.3	Lower Potential Spinel Materials with Reconstitution Reactions	174
9A.4	Materials in Which the Oxide Ions Are in a Close-Packed Hexagonal Array	175
9A.4.1	The Nasicon Structure	175
9A.4.2	Materials with the Olivine Structure	177
9A.5	Materials Containing Fluoride Ions	179

9A.6	Hybrid Ion Cells	180
9A.7	Amorphization	180
9A.8	The Oxygen Evolution Problem	180
9A.9	Closing Comments	186
9B	Liquid Positive Electrode Reactants	186
9B.1	Introduction	186
9B.2	The Li/SO ₂ System	186
9B.3	The Li/SOCl ₂ System	188
9C	Hydrogen and Water in Positive Electrode Materials	188
9C.1	Introduction	188
9C.2	Ion Exchange	189
9C.3	Simple Addition Methods	190
9C.4	Thermodynamics of the Lithium–Hydrogen–Oxygen System	190
9C.5	Examples of Phases Containing Lithium That are Stable in Water	191
9C.6	Materials That Have Potentials Above the Stability Window of Water	192
9C.7	Absorption of Protons from Water Vapor in the Atmosphere	192
9C.8	Extraction of Lithium from Aqueous Solutions	193
	References	193
10	Negative Electrodes in Aqueous Systems	197
10.1	Introduction	197
10A	The Zinc Electrode in Aqueous Systems	197
10A.1	Introduction	197
10A.2	Thermodynamic Relationships in the H–Zn–O System	198
10A.3	Problems with the Zinc Electrode	199
10B	The “Cadmium” Electrode	199
10B.1	Introduction	199
10B.2	Thermodynamic Relationships in the H–Cd–O System	200
10B.3	Comments on the Mechanism of Operation of the Cadmium Electrode	201
10C	Metal Hydride Electrodes	202
10C.1	Introduction	202
10C.2	Comments on the Development of Commercial Metal Hydride Electrode Batteries	203
10C.3	Hydride Materials Currently Being Used	203
10C.4	Disproportionation and Activation	204
10C.5	Pressure–Composition Relation	205
10C.6	The Influence of Temperature	206

10C.7	AB ₂ Alloys	208
10C.8	General Comparison of These Two Structural Types	209
10C.9	Other Alloys That Have Not Been Used in Commercial Batteries	210
10C.10	Microencapsulation of Hydride Particles	210
10C.11	Other Binders	211
10C.12	Inclusion of a Solid Electrolyte in the Negative Electrode of Hydride Cells	211
10C.13	Maximum Theoretical Capacities of Various Metal Hydrides	211
	References	212
11	Positive Electrodes in Aqueous Systems	213
11.1	Introduction	213
	↓	
11A	Manganese Dioxide Electrodes in Aqueous Systems	214
11A.1	Introduction	214
11A.2	The Open Circuit Potential	215
11A.3	Variation of the Potential During Discharge	216
	↓	
11B	The “Nickel” Electrode	216
11B.1	Introduction	216
11B.2	Structural Aspects of the Ni(OH) ₂ and NiOOH Phases	217
11B.3	Mechanism of Operation	218
11B.4	Relations Between Electrochemical and Structural Features ...	220
11B.5	Self-discharge	221
11B.6	Overcharge	223
11B.7	Relation to Thermodynamic Information	223
	↓	
11C	Cause of the Memory Effect in “Nickel” Electrodes	226
11C.1	Introduction	226
11C.2	Mechanistic Features of the Operation of the “Nickel” Electrode	228
11C.3	Overcharging Phenomena	230
11C.4	Conclusions	232
	References	233
12	Other Topics Related to Electrodes	235
12.1	Introduction	235
	↓	
12A	Mixed-Conducting Host Structures into Which Either Cations or Anions Can Be Inserted	235
12A.1	Introduction	235
12A.2	Insertion of Species into Materials with Transition Metal Oxide Bronze Structures	236

12A.3	Materials with Cubic Structures Related to Rhenium Trioxide . . .	237
12A.4	Hexacyanometallates	237
12A.5	Electrochemical Behavior of Prussian Blue	241
12A.6	Various Cations Can Occupy the A Sites in the Prussian Blue Structure	244
12A.7	The Substitution of Other Species for the Fe^{3+} and the Fe^{2+} in the P and R Positions in the Prussian Blue Structure	245
12A.8	Other Materials with $x = 2$ That Have the Perovskite Structure	246
12A.9	The Electronic Properties of Members of the Prussian Blue Family	246
12A.10	Batteries with Members of the Prussian Blue Family on Both Sides	247
12A.11	Catalytic Behavior	247
12A.12	Electrochromic Behavior	248
12A.13	Insertion of Species into Graphite	249
12A.14	Insertion of Guest Species into Polymers	251
12A.15	Summary	252
12B	Cells with Liquid Electrodes: Flow Batteries	252
12B.1	Introduction	252
12B.2	Redox Reactions in the Vanadium/Vanadium System	255
12B.3	Resultant Electrical Output	255
12B.4	Further Comments on the Vanadium/Vanadium Redox System	255
12C	Reactions in Fine Particle Electrodes	257
12C.1	Introduction	257
12C.2	Translation of Two-Phase Interface by Chemical Diffusion	257
12C.3	Alternative Mechanism for the Translation of Poly-Phase Interfaces	258
12C.4	Reactions in Electrodes Containing Many Small Particles	260
12C.5	Mechanism Involved in Changing the Composition of Lithium-Carbons	260
	References	261
13	Potentials	263
13.1	Introduction	263
13A	Potentials in and Near Solids	264
13A.1	Introduction	264
13A.2	Potential Scales	265
13A.3	Electrical, Chemical, and Electrochemical Potentials in Metals	265
13A.4	Relation to the Band Model of Electrons in Solids	271
13A.5	Potentials in Semiconductors	272
13A.6	Interactions Between Different Materials	273

13A.7	Junctions Between Two Metals	273
13A.8	Junctions Between Metals and Semiconductors	275
13A.9	Selective Equilibrium	276
13B	Reference Electrodes	276
13B.1	Introduction	276
13B.2	Reference Electrodes in Nonaqueous Lithium Systems	277
	13B.2.1 Use of Elemental Lithium	277
	13B.2.2 Use of Two-phase Lithium Alloys	277
13B.3	Reference Electrodes in Elevated Temperature Oxide-Based Systems	278
	13B.3.1 Gas Electrodes	278
	13B.3.2 Polyphase Solid Reference Electrodes	279
	13B.3.3 Metal Hydride Systems	280
13B.4	Relations Between Binary Potential Scales	280
13B.5	Potentials in the Ternary Lithium–Hydrogen–Oxygen System ..	280
	13B.5.1 Lithium Cells in Aqueous Electrolytes	282
13B.6	Significance of Electrically Neutral Species	282
13B.7	Reference Electrodes in Aqueous Electrochemical Systems ...	283
13B.8	Historical Classification of Different Types of Electrodes in Aqueous Systems	284
	13B.8.1 Electrodes of the First Kind	284
	13B.8.2 Electrodes of the Second Kind	285
13B.9	The Gibbs Phase Rule	287
13B.10	Application of the Gibbs Phase Rule to Reference Electrodes ..	288
	13B.10.1 Nonaqueous Systems	288
	13B.10.2 Aqueous Systems	288
13B.11	Systems Used to Measure the pH of Aqueous Electrolytes	291
13B.12	Electrodes with Mixed-Conducting Matrices	292
13B.13	Closing Comments	293
13C	Potentials of Chemical Reactions	293
13C.1	Introduction	293
13C.2	Relation Between Chemical Redox Equilibria and the Potential and Composition of Insertion Reaction Materials	294
13C.3	Other Examples	295
13C.4	Summary	297
13D	Potential and Composition Distributions Within Components of Electrochemical Cells	297
13D.1	Introduction	297
13D.2	Relevant Energy Quantities	297
13D.3	What Is Different About the Interior of Solids?	298

13D.4	Relations Between Inside and Outside Quantities	299
13D.5	Basic Flux Relations Inside Phases	299
13D.6	Two Simple Limiting Cases	300
13D.7	Three Configurations	300
13D.8	Variation of the Composition with Potential	300
13D.9	Calculation of the Concentrations of the Relevant Defects in a Binary Solid MX That Is Predominantly an Ionic Conductor	301
13D.10	Defect Equilibrium Diagrams	303
13D.11	Approximations Relevant in Specific Ranges of Composition or Activity	304
13D.12	Situation in Which an Electrical Potential Difference Is Applied Across a Solid Electrolyte Using Electrodes That Block the Entry and Exit of Ionic Species	305
13D.13	The Use of External Sensors to Evaluate Internal Quantities in Solids	307
13D.14	Another Case, a Mixed Conductor in Which the Transport of Electronic Species Is Blocked	308
13D.15	Further Comments on Composite Electrochemical Cells Containing a Mixed Conductor in Series with a Solid Electrolyte	309
13D.16	Transference Numbers of Particular Species	311
	References	312
14	Liquid Electrolytes	315
14.1	Introduction	315
14.2	General Considerations Regarding the Stability of Electrolytes Vs. Alkali Metals	315
14A	Elevated Temperature Electrolytes for Alkali Metals	317
14A.1	Introduction	317
14A.2	Lithium-Conducting Inorganic Molten Salts	318
14A.3	Lower Temperature Alkali Halide Molten Salts	318
14A.4	Other Modest Temperature Molten (and Solid) Salts	318
14A.5	Relation Between the Potential and the Oxygen Pressure in Lithium Systems	319
14A.6	Implications for the Safety of Lithium Cells	320
14B	Ambient Temperature Electrolytes for Lithium	321
14B.1	Introduction	321
14B.2	Organic Solvent Liquid Electrolytes	321
14B.3	Lithium Salts	322
14B.4	Ionic Liquids	323

14C	Aqueous Electrolytes for Hydrogen	324
14C.1	Introduction	324
14C.2	Nafion	325
14C.3	Other Considerations Relating to Nafion	327
14C.4	Alternatives to Nafion	328
14D	Nonaqueous Electrolytes for Hydrogen	328
14D.1	Introduction	328
14D.2	Methods Typically Used to Study Materials for Hydrogen Storage	329
14D.3	Potential Advantages of Electrochemical Methods	330
14D.4	The Amphoteric Behavior of Hydrogen	330
14D.5	Relationships Between the Potential and the Stability of Phases in Molten Salts	331
14D.6	Alkali Halide Molten Salts Containing Hydride Ions	332
14D.7	Solution of Hydrogen in Vanadium	334
14D.8	The Titanium–Hydrogen System	334
14D.9	Use of Low Temperature Organic-Anion Molten Salt to Study Hydrogen in Binary Magnesium Alloys	335
14D.10	Summary	336
	References	337
15	Solid Electrolytes	339
15.1	Introduction	339
15A	Solid Electrolytes: Introduction	340
15A.1	Introduction	340
15A.2	Structural Defects in Nonmetallic Solids	341
15A.3	Various Types of Notation That May Be Used to Describe Imperfections	343
15A.4	Types of Disorder	345
15B	Mechanism and Structural Dependence of Ionic Conduction in Solid Electrolytes	347
15B.1	Introduction	347
15B.2	Characteristic Properties	347
15B.3	Simple Hopping Model of Defect Transport	350
15B.4	Interstitial Motion in Body-Centered Cubic Structures	352
15B.5	Rapid Ionic Motion in Other Crystal Structures	354
15B.6	Simple Structure-Dependent Model for the Rapid Transport of Mobile Ions	356
15B.7	Interstitial Motion in the Rutile Structure	358
15B.8	Other Materials with Unidirectional Tunnels	361
15B.9	Materials with the Fluorite and Antifluorite Structures	362
15B.10	Materials with Layer Structures	364

15B.11	Materials with Three-Dimensional Arrays of Tunnels	367
15B.12	Structures with Isolated Tetrahedra	367
15C	Lithium Ion Conductors	368
15C.1	Introduction	368
15C.2	Materials with the Perovskite Structure	368
15C.3	Materials with the Garnet Structure	370
	References	371
16	Electrolyte Stability Windows and Their Extension	375
16.1	Introduction	375
16.2	Binary Electrolyte Phases	376
16.3	Ternary Electrolyte Phases	377
	16.3.1 Stability Limits Relative to Lithium	378
	16.3.2 Stability Limits Relative to Oxygen	379
16.4	Summary	380
16A	Composite Structures That Combine Stability Regimes	380
16A.1	Introduction	380
16A.2	Two Solid Electrolytes in Series	381
16A.3	Solid Electrolyte in Series with Aqueous Electrolyte	381
16A.4	Solid Electrolyte in Series with Molten Salt	382
16A.5	Formation of a Second Electrolyte by Topotactic Reaction Between a Liquid and a Solid Mixed Conductor Electrode	382
16A.6	Formation of a Protective Reaction Product Layer Between the Negative Electrode and the Organic Solvent Electrolyte in Lithium Cells	382
16B	The SEI in Organic Solvent Systems	383
16B.1	Introduction	383
16B.2	Interaction of Organic Solvent Electrolytes with Graphite	383
16B.3	Electrolyte Additives	387
16C	Combination of a Solid Electrolyte and a Molten Salt Electrolyte	388
16C.1	Introduction	388
16C.2	The Lithium–Nitrogen–Oxygen System	388
16C.3	Extension of the Effective Potential Range by the Formation of a Second Electrolyte In Situ	389
16C.4	A Primary Lithium/Carbon Cell	390
16C.5	Problems with This Concept	391
	References	391

17	Experimental Methods to Evaluate the Critical Properties of Electrodes and Electrolytes	393
17.1	Introduction	393
17A	Use of DC Methods to Determine the Electronic and Ionic Components of the Conductivity in Mixed Conductors	393
17A.1	Introduction	393
17A.2	Transference Numbers of Individual Species	394
17A.3	The Tubandt Method	395
17A.4	The DC Assymmetric Polarization Method	395
17A.5	Interpretation of Hebb–Wagner Asymmetric Polarization Measurements in Terms of a General Defect Equilibrium Diagram	396
17A.6	DC Open Circuit Potential Method	405
17B	Experimental Determination of the Critical Properties of Potential Electrode Materials	406
17B.1	Introduction	406
17B.2	The GITT Method	408
17B.3	The PITT Method	408
17B.4	The FITT Method	409
17B.5	The WITT Method	411
17C	Use of AC Methods to Determine the Electronic and Ionic Components of the Conductivity in Solid Electrolytes and Mixed Conductors	414
17C.1	Introduction	414
17C.2	Representation of the Properties of Simple Circuit Elements on the Complex Impedance Plane	416
17C.3	The Influence of Electronic Leakage Through an Ionic Conductor	422
17C.4	Case in Which Both Ionic and Electronic Transport Are Significant	423
17C.5	Influence of an Additional Impedance Due to Transverse Internal Interfaces	425
17C.6	Behavior When There Is Internal Transverse Interface Impedance as well as Partial Electronic Conduction	426
17C.7	An Example	429
17C.8	Summary	430
	References	430
18	Use of Polymeric Materials As Battery Components	433
18.1	Introduction	433

18A	Polymer Electrolytes	434
18A.1	Introduction	434
18A.2	High Molecular Weight Polymers Containing Salts	434
18A.3	Particle-Enhanced Conductivity	436
18A.4	Ionic Rubbers	437
18A.5	Hybrid Electrolytes Containing an Ionically Conducting Plasticizer	437
18A.6	Gel Electrolytes	437
	References	439
19	Transient Behavior of Electrochemical Systems	441
19.1	Introduction	441
19A	Transient Behavior Under Pulse Demand Conditions	442
19A.1	Introduction	442
19A.2	Electrochemical Charge Storage Mechanisms	445
19A.2.1	Electrostatic Energy Storage in the Electrical Double Layer in the Vicinity of the Electrolyte/Electrode Interface	445
19A.2.2	Underpotential Faradaic Two-Dimensional Adsorption on the Surface of a Solid Electrode	447
19A.2.3	Faradaic Deposition That Results in the Three-Dimensional Absorption of the Electroactive Species into the Bulk Solid Electrode Material by an Insertion Reaction	447
19A.2.4	Faradaically Driven Reconstitution Reactions	450
19A.3	Comparative Magnitudes of Energy Storage	450
19A.4	Importance of the Quality of the Stored Energy	452
19B	Modeling Transient Behavior of Electrochemical Systems Using Laplace Transforms	453
19B.1	Introduction	453
19B.2	Use of Laplace Transform Techniques	453
19B.3	Simple Examples	455
	References	456
20	Closing Comments	459
20.1	Introduction	459
20.2	Terminology	459
20.3	Major Attention Is Given to the Driving Forces and Mechanisms That Determine the Potentials, Kinetic Properties, and Capacities of Electrodes	460
20.4	Thinking Tools	461
20.5	Major Players in This Area	461
20.6	The Future	462
	Index	463