

Table of Contents

Preface	xv
Acknowledgments	xvii
Introduction	xix
PART 1. UNIVERSAL CHARACTERISTICS OF BATTERIES	1
Chapter 1. Definitions and Methods of Measurement	3
1.1. Introduction	3
1.2. Terminology	3
1.2.1. Accumulators	4
1.2.2. Cells, elementary cells and electrolyte	4
1.2.3. Electrodes and half-cells	4
1.2.4. Oxidation, reduction, anode and cathode	5
1.2.5. Active material	6
1.2.6. Voltage	6
1.2.7. Battery series, monoblocs, packs and BMS	6
1.3. Definitions of characteristics	7
1.3.1. Nominal voltage	7
1.3.2. Capacities	8
1.3.2.1. General definition	8
1.3.2.2. Theoretical capacity	9
1.3.2.3. Faraday's law	9
1.3.2.4. Effective capacity	11
1.3.2.5. Initial capacity	12
1.3.2.6. Assigned capacity	13

1.3.2.7. Nominal capacity	13
1.3.2.8. Aging, residual capacity, end-of-life criteria and lifetime	15
1.3.2.9. Calendar aging	18
1.3.2.10. Cycle endurance	18
1.3.2.11. Quantity of electricity discharged	19
1.3.2.12. Quantity of electricity remaining	19
1.4. Battery states	20
1.4.1. Depth of discharge	20
1.4.2. State of charge	20
1.4.3. State of energy	21
1.4.4. State of health	21
1.4.5. State of function	22
1.4.6. Theoretical gravimetric capacity	22
1.4.7. Practical gravimetric capacity	22
1.4.8. Volumetric capacity	23
1.4.9. Specific capacity	23
1.4.10. Constant internal resistance and short-circuit current	23
1.4.11. Alternating internal resistance	25
1.4.12. Impedance, impedance analysis and impedance spectroscopy	26
1.4.13. Stored energy and retrievable energy	28
1.4.14. Gravimetric energy density	29
1.4.15. Volumetric energy density	30
1.4.16. Specific energy	30
1.4.17. Footprint	30
1.4.18. Gravimetric power and volumetric power	31
1.5. Faradic efficiency	32
1.6. Charge coefficient	34
1.7. Overcharge coefficient	34
1.8. Energy efficiency	34
1.9. Self-discharge	36
1.10. Acceptance current	37
1.11. Conclusion	37
1.12. Appendix: Nernst's law	38
1.12.1. Redox potential of an electrode	38
1.12.2. Electromotive force of an electrochemical cell	39
1.12.3. Nernst's law	39
1.12.4. Activity of chemical species	41
1.12.5. Example of the application of Nernst's law to a lead-acid battery	42

1.12.6. Example of the application of Nernst's law to a NiCd battery	46
1.13. Solutions to exercises	48
PART 2. LEAD-ACID BATTERIES	55
Chapter 2. The Operation of Lead-Acid Batteries	59
2.1. Principles of operation	59
2.1.1. Electrochemical reactions	60
2.1.2. Behavior of sulfuric acid in water	61
2.1.3. Principal electrochemical reactions	62
2.1.3.1. Charge-discharge reactions at the positive electrode	62
2.1.3.2. Charge-discharge reactions at the negative electrode	63
2.1.3.3. Model of the charge-discharge processes (double sulfation reaction)	64
2.1.3.4. Degrees of oxidation of lead	67
2.1.3.5. Electrolyte: sulfuric acid solution in water	68
2.1.4. Secondary electrochemical reactions	70
2.1.4.1. Water electrolysis reactions and overcharging	70
2.1.4.2. Corrosion	73
2.1.4.3. Self-discharge reaction	78
2.2. Properties due to electrochemical reactions	80
2.2.1. State of active material in relation to the charge state	80
2.2.2. Discharge of an element in a lead-acid battery and determination of capacity	81
2.2.3. Peukert's law	84
2.2.4. Capacity retrieval after rest periods	86
2.2.5. Consequences of variations in sulfuric acid concentration in the electrolyte and stratification of the electrolyte	87
2.2.5.1. Destratification of the electrolyte	89
2.2.5.2. Open-circuit voltage and evaluation of the charge state of an element	90
2.2.5.3. Frost resistance	91
2.2.6. Quantity of material transformed	92
2.2.6.1. Atomic molar mass of the active material	92
2.2.6.2. Quantity of active material transformed	92
2.2.7. Theoretical and practical gravimetric energy	93
2.2.8. Levels of use of active material	95

2.2.9. Water consumption	95
2.3. Polarity inversion	96
2.4. Effects of temperature, aging and thermal runaway	97
2.5. Failure modes	100
2.5.1. Shedding	100
2.5.2. Hardening	105
2.5.3. Corrosion of the positive collector	105
2.5.4. Expansion of the negative plate	106
2.6. Appendices	107
2.6.1. Correction factor for densities in relation to temperature in $^{\circ}\text{C}^{-1}$	107
2.6.2. <i>Coups de fouet</i>	107
2.7. Solutions to exercises	110
Chapter 3. Internal Composition and Types of Lead–Acid Batteries	115
3.1. Composition of lead–acid batteries	115
3.1.1. Grid alloys	116
3.1.2. Positive electrode	119
3.1.2.1. Flat plates	119
3.1.2.2. Tubular plates	120
3.1.3. Negative plates	123
3.1.4. Porosity and lifetime	124
3.1.5. Separators	124
3.1.6. Electrolyte	125
3.1.6.1. Liquid electrolyte (flooded batteries)	126
3.1.6.2. Gel electrolyte and absorbed electrolyte (“immobilized” electrolyte)	126
3.1.7. Container	126
3.2. Families of lead–acid batteries	126
3.2.1. Flooded batteries	127
3.2.1.1. Classic flooded batteries	127
3.2.1.2. Maintenance-free flooded batteries	128
3.2.2. Recombinant gas batteries	129
3.2.2.1. Gel batteries	130
3.2.2.2. AGM batteries	130
3.2.2.3. Spiral wound batteries	131
3.3. Other battery types and future prospects	132

Chapter 4. Lead Batteries: Main Characteristics	135
4.1. Introduction	135
4.2. Electrical characteristics	135
4.2.1. Voltage of a cell	135
4.2.2. Nominal capacities available	135
4.2.3. Practical mass energy	137
4.2.4. Practical energy density	139
4.2.5. Acceptable depth of discharge	139
4.2.6. Power-to-weight ratio	140
4.2.7. Self-discharge	140
4.2.8. Charge acceptance	140
4.2.9. Faradic efficiency, charge coefficient, and overcharge coefficient	144
4.2.10. Dependency of energetic and Faradic efficiencies on SOC	146
4.3. Charge of lead batteries	149
4.3.1. Charge of a battery cell used in floating	150
4.3.2. Charge of a battery cell used in cycling	150
4.3.3. Charging a battery	152
4.3.4. Summary of charge voltages	153
4.3.5. The particular case of photovoltaic applications	153
4.3.6. Charge in pulsed currents	155
4.4. Energy management	155
4.5. SOC indicator	156
4.6. Conditions of use	162
4.6.1. Operating temperature	162
4.6.2. Storage conditions	162
4.6.3. Lifetime, endurance in cycles	164
4.6.4. MultiBatt concept	169
4.6.5. Internal failure	170
4.6.6. Risks of accidents	170
4.7. Economic considerations	171
4.7.1. Buying cost	171
4.7.2. Energy cost on lifecycle	171
4.7.3. Cost of restored kWh	172
4.7.4. Some suppliers/manufacturers	173
4.7.5. Main markets	174
4.7.6. Recycling	174
4.8. Applicable standards	174
4.9. Future developments	175

4.10. To find out more	176
4.11. Solutions to exercises	176
Chapter 5. Manufacturing Starting, Lighting and Ignition Batteries	181
5.1. Introduction	181
5.2. Manufacturing an SLI battery	182
5.3. Raw materials	184
5.3.1. Lead for making the active material	186
5.3.2. Production of lead oxide	186
5.3.3. Lead for making the grids	188
5.4. Different ways of manufacturing lead SLI batteries	189
5.4.1. Expanded metal	189
5.4.2. Continuous casting	195
5.4.3. Molding	198
5.5. Composition of the paste	201
5.6. Pasting the grids	204
5.7. Curing of the plates	204
5.8. Assembly	209
5.9. Formation of the battery	218
5.9.1. Jar formation	218
5.9.2. Tank formation	224
5.10. Final test and dispatch	225
5.11. Solutions to exercises	225
PART 3. INTRODUCTION TO NICKEL-BASED BATTERIES	227
Chapter 6. Nickel–Cadmium Batteries	229
6.1. Introduction	229
6.2. Operating principle	230
6.2.1. Main reactions at the electrodes	230
6.2.1.1. Positive electrode	230
6.2.1.2. Negative electrode	230
6.2.1.3. Chemical equation	230
6.2.2. Secondary reactions	231
6.2.2.1. Open cells	232
6.2.2.2. Sealed cells	233
6.2.3. Role of the electrolyte	235
6.3. Main characteristics	236
6.3.1. Voltage of a cell	236

6.3.2. Most common forms	238
6.3.3. Available capacities	238
6.3.4. Mass and volume energies	238
6.3.5. Acceptable depth of discharge	240
6.3.6. Faradic and energetic efficiencies in a charge-discharge cycle	240
6.3.7. Operating temperature	242
6.3.8. Self-discharge	242
6.3.9. Memory effect	243
6.3.10. Lifetime in cycling	245
6.3.11. Charge operating mode	246
6.3.12. Maintenance	248
6.3.13. Cost	248
6.3.14. Manufacturers	249
Chapter 7. Nickel–Metal Hydride Batteries	251
7.1. Introduction	251
7.2. Operating principle	252
7.2.1. Main reactions at the electrodes	252
7.2.1.1. Positive electrode	253
7.2.1.2. Negative electrode	253
7.2.1.3. Chemical equation	253
7.2.1.4. Metal hydriding	253
7.2.2. Secondary reactions	254
7.3. Main characteristics	256
7.3.1. Voltage of a cell	256
7.3.2. Most common forms	256
7.3.3. Available capacities	257
7.3.4. Mass and volume energy	258
7.3.5. Gravimetric and volumetric powers	260
7.3.6. Faradic and energetic efficiencies in a charge-discharge cycle	260
7.3.7. Self-discharge	261
7.3.8. Memory effect	262
7.3.9. Operating temperature	262
7.3.10. Storage conditions	262
7.3.11. Lifetime in cycling	263
7.3.12. Calendar lifetime and prolonged storage	264
7.3.13. Charge operating mode	264
7.3.14. State of charge indicator	268
7.3.15. Internal failure	268

7.3.16. Cost to the general public	269
7.3.17. Main usages	269
7.3.18. Some manufacturers, suppliers, brands and designers	270
7.4. Solution to exercise	271
Chapter 8. Other Nickel-Based Batteries	273
8.1. Introduction	273
8.2. Nickel–iron batteries	273
8.2.1. Operating principle	273
8.2.1.1. Positive electrode	274
8.2.1.2. Negative electrode	274
8.2.1.3. Chemical equation	274
8.2.1.4. Electrolyte	275
8.2.2. Main characteristics	275
8.2.2.1. Voltage of a cell	275
8.2.2.2. Charging procedure	275
8.2.2.3. Mass energy	275
8.2.2.4. Power	275
8.2.2.5. Effect of temperature	276
8.2.2.6. Self-discharge	276
8.2.2.7. Lifetime in cycling and calendar lifetime	276
8.2.2.8. Resistance to extreme conditions	276
8.2.3. NiFe batteries today	276
8.3. Nickel–zinc batteries	277
8.3.1. Operating principle	277
8.3.1.1. Main reactions at the electrodes	277
8.3.1.2. Positive electrode	278
8.3.1.3. Negative electrode	278
8.3.1.4. Chemical equations	278
8.3.1.5. Secondary reactions	279
8.3.1.6. Electrolyte	279
8.3.2. Main characteristics	281
8.3.2.1. Voltage of a cell	281
8.3.2.2. Available capacities	281
8.3.2.3. Most common forms	283
8.3.2.4. Specific energies	283
8.3.2.5. Mass power	283
8.3.2.6. Operating temperature	283
8.3.2.7. Self-discharge	283
8.3.2.8. Lifetime	284

8.3.2.9. Charging mode	284
8.3.2.10. Charge–discharge efficiency	284
8.3.2.11. Cost.	285
8.3.2.12. Maximum temperatures	285
8.3.2.13. Safety.	285
8.3.2.14. Maintenance.	285
8.3.2.15. Applications.	285
8.3.2.16. Recycling	285
8.4. More information on nickel-based batteries	286
8.4.1. Resources and properties of nickel	286
8.4.2. Recycling channels for nickel-based batteries.	286
8.4.3. Bibliography	287
Conclusion	289
Index	291