

Rechargeable Batteries

APPLICATIONS HANDBOOK



Technical Marketing Staff of Gates Energy Products, Inc.

Rechargeable Batteries Applications Handbook

EDN Series for Design Engineers

EDN Design Ideas on CD-ROM, 0-7506-9858-6

Simplified Design of Voltage-Frequency Converters, John D. Lenk, 0-7506-9654-0

Simplified Design of Data Converters, John D. Lenk, 0-7506-9509-9

PCB Design Using AutoCAD, Chris Schroeder, 0-7506-9834-9

Inside PC Card: CardBUS and PCMCIA Design, Faisal Haque, 0-7506-9747-4

Inside OrCAD, Chris Schroeder, 0-7506-9700-8

Simplified Design of IC Amplifiers, John D. Lenk, 0-7506-9508-0

The Art and Science of Analog Circuit Design, Edited by Jim Williams,
0-7506-9505-6

Simplified Design of Micropower and Battery Circuits, John D. Lenk, 0-7506-9510-2

Simplified Design of Switching Power Supplies, John D. Lenk, 0-7506-9821-7

Simplified Design of Linear Power Supplies, John D. Lenk, 0-7506-9820-9

EDN Designer's Companion, Edited by Ian Hickman and Bill Travis, 0-7506-1721-7

Power Supply Cookbook, Marty Brown, 0-7506-9442-4

Electronic Circuit Design Ideas, Venkataraman Lakshminarayanan, 0-7506-2047-1

Operational Amplifiers, Second Edition, Jiri Dostal, 0-7506-9317-7

Circuit Designer's Companion, T. Williams, 0-7506-1756-X

Radio Frequency Transistors: Principles and Practical Applications, Norman Dye &
Helge Granberg, 0-7506-9059-3

Rechargeable Batteries Applications Handbook, Gates Energy Products, 0-7506-9227-8

Analog Circuit Design: Art, Science, and Personalities, Edited by Jim Williams,
0-7506-9640-0

Troubleshooting Analog Circuits, Robert A. Pease, 0-7506-9499-8

Troubleshooting Analog Circuits with Electronics Workbench Circuits Disk, Robert A.
Pease, 0-7506-9949-3

Integrated Circuit and Waveform Generator Handbook, Ray Marston, 0-7506-0409-3

Electronics Circuits, Systems, and Standards, Edited by Ian Hickman, 0-7506-0068-3

Rechargeable Batteries Applications Handbook

Technical Marketing Staff
of Gates Energy Products, Inc.



Newnes

An Imprint of Elsevier

Boston Oxford Johannesburg Melbourne New Delhi Singapore

Newnes is an imprint of Elsevier

 A member of the Reed Elsevier group

Copyright © 1998 by Butterworth-Heinemann
All rights reserved.

Hardcover edition originally copyright 1992 by Butterworth-Heinemann

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher.

Permissions may be sought directly from Elsevier's Science and Technology Rights Department in Oxford, UK. Phone: (44) 1865 843830, Fax: (44) 1865 853333, e-mail: permissions@elsevier.co.uk. You may also complete your request on-line via the Elsevier homepage: <http://www.elsevier.com> by selecting "Customer Support" and then "Obtaining Permissions".



Recognizing the importance of preserving what has been written,
Butterworth-Heinemann prints its books on acid-free paper whenever possible.



Butterworth-Heinemann supports the efforts of American Forests and the
Global ReLeaf program in its campaign for the betterment of trees, forests
and our environment.

ISBN 0-7506-7006-1

The publisher offers special discounts on bulk orders of this book.

For information, please contact:

Manager of Special Sales
Butterworth-Heinemann
313 Washington Street
Newton, MA 02158-1626
Tel: 617-928-2500
Fax: 617-928-2620

For information on all electronics publications available, contact our
World Wide Web home page at: <http://www.bh.com/newnes>

Printed in the United States of America
10 9 8 7 6 5 4 3 2

Contents

List of Figures xvii

List of Abbreviations xxi

Section 1 **Introduction 1**

Organization of the Handbook 1

Notice to Reader 3

Section 2 **Rechargeable Cells and Batteries 5**

2.1 Rechargeable Battery History 6

2.1.1 Early Work 6

2.1.2 Development of Lead Batteries 6

2.1.3 Development of Nickel-Cadmium Batteries 7

2.1.4 Recent Developments 8

2.2 General Battery Concepts 9

2.2.1 Primary vs. Secondary Batteries 9

2.2.2 Batteries vs. Cells 10

2.2.2.1 Cell and Battery Voltage 10

2.2.2.2 Cell and Battery Capacity 10

2.2.2.3 Connecting Cells to Form a Battery: Series vs.
Parallel 11

2.2.3 Cell Components 12

2.2.4 Classification of Application Types: Float or Cyclic 13

2.2.5 The Methods of Specifying Charge and Discharge Rates: The **C**
Rate 13

2.3 Nickel-Cadmium Cells and Batteries 15

2.3.1 Nickel-Cadmium Chemistry 15

2.3.2 Sealed Nickel-Cadmium Cells 15

2.3.2.1 Theory of Sealed-Cell Operation 16

2.3.2.2 Sealed-Cell Construction 17

2.3.3 Aerospace Cells 18

2.3.4 Other Forms of Nickel-Cadmium Batteries 19

2.4 Nickel-Hydrogen Cells 21

2.5 Sealed-Lead Cells and Batteries 23

2.5.1 Electrochemistry of the Lead Cell 23

2.5.2	Sealed-Lead Cells	23
2.5.2.1	Theory of Sealed-Cell Operation	23
2.5.2.2	Construction of Sealed-Lead Cells and Batteries	24
2.5.3	Other Forms of Lead Batteries	27
2.5.3.1	Flooded Lead-Acid	27
2.5.3.2	Gelled-Electrolyte	27
2.6	Recent Developments in Rechargeable Batteries	28
2.6.1	Enhancements in Conventional Technologies	28
2.6.2	Nickel-Metal Hydride Cells	28
2.6.2.1	Chemistry	29
2.6.2.2	Construction	29
2.6.2.3	Application Considerations	30
2.6.3	Other Advanced Couples	31
2.6.4	Environmental Issues	31
2.7	Summary	33

Section 3 Sealed Nickel-Cadmium Cells and Batteries 35

	Features and Benefits	35
	Application Examples	37
	Section Contents	37
3.1	Discharge Characteristics	39
3.1.1	General	39
3.1.1.1	Cell Discharge Performance Measures	39
3.1.1.2	Cell Capacity Defined	40
3.1.2	Cell Discharge Voltage Performance	41
3.1.2.1	Mid-Point Voltage	42
3.1.2.2	Cell Discharge Equivalent Circuit	42
3.1.2.2.1	Steady-State Performance	43
3.1.2.2.2	Dynamic Transient Response	43
3.1.2.3	Variables Influencing R_e	45
3.1.2.3.1	R_e as a function of Cell Discharge Temperature	45
3.1.2.3.2	R_e as a Function of State of Discharge	45
3.1.2.3.3	R_e as a Function of History of Use and Cell Design	46
3.1.2.3.4	Calculation and Measurement of R_e	46
3.1.2.4	Variables Influencing E_o	47
3.1.2.4.1	E_o as a Function of Cell Discharge Temperature	47
3.1.2.4.2	E_o as a Function of the State of Discharge	47
3.1.2.5	Summary of Voltage Effects	48

3.1.3	Cell Discharge Capacity Performance	49
3.1.3.1	Cell Capacity Definitions and Ratings	49
3.1.3.2	Measurement of Fully Charged Capacity	51
3.1.3.3	Actual Cell Capacity at Off-Standard Conditions	52
3.1.3.3.1	Charging Conditions	52
3.1.3.3.2	Rest Temperature and Time	53
3.1.3.3.3	Discharge Conditions	53
3.1.3.3.4	Simultaneous Multiple Off-Standard Conditions	54
3.1.3.4	Retained Capacity	55
3.1.4	Scaling the Discharge Curve	56
3.1.5	Application Performance and Other Operating Characteristics	57
3.1.5.1	Repeated Cell Polarity Reversal	58
3.1.5.2	High Overcharge Cell Temperature and Voltage Depression	59
3.1.5.3	Discharge Termination Voltage vs. Capacity	60
3.1.5.3.1	Available Cell Capacity as a Function of EODV	60
3.1.5.3.2	Discharge Cutoff Voltage	61
3.1.5.3.3	Required Application Voltage	62
3.1.5.3.4	Cell Polarity Reversal Voltage	62
3.1.6	Cell Design Factors	64
3.1.6.1	Electrode Dimensions	64
3.1.6.2	Current Collection Means	64
3.1.6.3	Separator	64
3.1.6.4	Electrolyte	65
3.1.6.5	Normalizing R_e	65
3.1.7	Summary	65
3.2	Charging	66
3.2.1	Introduction	66
3.2.2	Charging Efficiency	67
3.2.2.1	Effect of Temperature	68
3.2.2.2	Effect of Charge Rate	70
3.2.2.3	Effect of Cell Construction	70
3.2.3	Cell Pressure, Temperature and Voltage Interrelationships	70
3.2.4	Overcharge	71
3.2.4.1	Tafel Curves	72
3.2.4.2	Battery Overcharge Temperature	73
3.2.4.3	Need for Charge Control	76
3.2.5	Charging Without Feedback Control: Characteristics and Methods	76

3.2.5.1	Cell Capabilities	77
3.2.5.1.1	Standard Cells	77
3.2.5.1.2	Quick-Charge and Fast-Charge Cells	77
3.2.5.2	Considerations for Charging Without Feedback Control	77
3.2.6	Charging with Feedback Control: Characteristics and Methods	78
3.2.6.1	Coulometric Control	79
3.2.6.2	Time Control	79
3.2.6.2.1	Simple Timed Control	79
3.2.6.2.2	Dump-Timed Control	80
3.2.6.3	Temperature Sensing Control	80
3.2.6.3.1	Temperature Sensing Methods	82
3.2.6.3.2	Temperature Cutoff	84
3.2.6.3.3	Incremental Temperature Cutoff	86
3.2.6.3.4	Differential Temperature Control	87
3.2.6.3.5	Rate of Temperature Change Control (dT/dt Control)	88
3.2.6.4	Voltage Sensing Control	89
3.2.6.4.1	Constant-Potential Charging	91
3.2.6.4.2	Voltage Cutoff	92
3.2.6.4.3	Rate-of-Voltage Change	94
3.2.6.4.4	Inflection Point Cutoff	94
3.2.6.4.5	Voltage-Decrement Cutoff	95
3.2.6.5	Voltage and Temperature Sensing Control	95
3.2.6.5.1	Voltage-Temperature Cutoff	95
3.2.6.5.2	Voltage Limit Temperature Cutoff	96
3.2.7	Charging Power Sources	96
3.2.7.1	DC Power Source	96
3.2.7.2	AC Power Source	97
3.2.7.3	Current Regulation	99
3.2.7.4	Series/Parallel Charging	101
3.2.7.5	Low-Temperature Charging	101
3.2.7.6	Elevated Temperature Charging	102
3.2.7.7	Photovoltaic Sources	102
3.2.8	Summary	104
3.3	Storage	105
3.3.1	Short-Term Storage Effects (Self-Discharge)	105
3.3.1.1	Self-Discharge Mechanisms	105
3.3.1.2	Retained Capacity Calculation	106
3.3.1.3	Temperature Effects on Self-Discharge	106
3.3.2	Long-Term Storage Effects	106

3.3.2.1	Temperature Effects During Battery Storage	107
3.3.2.2	Loaded-Storage Effects	107
3.3.3	Summary	108
3.4	Battery Life	109
3.4.1	Wear-out Mechanisms	111
3.4.1.1	Electrolyte Deterioration	111
3.4.1.2	Separator Deterioration	112
3.4.1.3	Deterioration of Seal or Vent Integrity	112
3.4.2	Use Factors Affecting Battery Life	113
3.4.2.1	Effect of Improper Charging	113
3.4.2.2	Effect of Elevated Temperature	113
3.4.2.3	Effect of Continuous Overcharge	113
3.4.2.4	Effect of Depth of Discharge on Cycle Life	114
3.4.2.5	Effects of Mechanical Shock and Vibration	114
3.4.3	Effect of Cell Construction on Battery Life	114
3.4.4	Summary	116
3.5	Application Information	117
3.5.1	Features and Benefits of Sealed Cells	117
3.5.1.1	High Energy Density	117
3.5.1.2	High-Rate Discharge Capability	118
3.5.1.3	Fast-Recharge Capability	118
3.5.1.4	Long Operating Life	118
3.5.1.5	Long Storage Life	118
3.5.1.6	Rugged Construction	118
3.5.1.7	Operation Over a Broad Range of Temperatures	118
3.5.1.8	Operation in a Wide Range of Environments	119
3.5.1.9	Operation in Any Orientation	119
3.5.1.10	Maintenance-Free Use	119
3.5.1.11	Continuous Overcharge Capability	119
3.5.1.12	Consistent Discharge Voltage	119
3.5.2	Economic Considerations	119
3.5.2.1	Battery Duty Cycle	120
3.5.2.2	Voltage vs. Watt-Hour	121
3.5.2.3	Life-Cycle vs. First Cost	121
3.5.2.3.1	Cost per Watt-Hour	121
3.5.2.3.2	Cost per Watt-Hour Per Cycle or Per Year	122
3.5.3	Electrical Considerations	122
3.5.3.1	Cell Voltage—General Overview	122
3.5.3.2	Designing for the High-Rate Capability of Nickel-Cadmium Batteries	123
3.5.3.3	Low State of Charge Indicator	124
3.5.3.4	Proper Voltage Selection	124

3.5.3.5	Maximum Power Discharge	124
3.5.3.6	Parallel Discharge	126
3.5.4	Physical Considerations	126
3.5.4.1	Proper Location of the Battery with Respect to the Charger	126
3.5.4.2	Battery Enclosures and Form Factor	127
3.5.4.3	Battery Assemblies	127
3.5.4.4	Cell Interconnection	128
3.5.4.4.1	Welded Interconnections	128
3.5.4.4.2	Pressure Contacts	128
3.5.5	Environmental Considerations	128
3.5.5.1	Temperature	128
3.5.6	Other Considerations	129
3.5.6.1	Handling Batteries in the Charged State	129
3.5.6.2	Inventory	129
3.5.6.3	Agency Listing of Chargers	129
3.5.6.4	Detachable Chargers	130
3.5.7	Typical Applications for Sealed Nickel-Cadmium Batteries	130
3.5.7.1	Standby Power	130
3.5.7.2	Emergency Lighting and Alarms	130
3.5.7.3	Electronic Loads	131
3.5.7.4	Intermittent Surge Power	132
3.5.7.5	Motor Loads	133
3.5.7.5.1	Heavy Motor Loads	136
3.5.7.5.2	Light Motor Loads	137
3.5.7.6	Consumer Devices/Products	137
3.5.7.7	Hobby Uses	137
3.5.7.8	Toys	138
3.5.7.9	Portable Audio/Video	138
3.5.7.10	Military	138
3.5.8	Summary	138
3.6	Battery Testing, Quality Control, and Specification	140
3.6.1	Qualification Testing	140
3.6.1.1	Performance Testing	140
3.6.1.2	Life Testing	141
3.6.1.2.1	Real-Time Testing	141
3.6.1.2.2	Accelerated Testing	142
3.6.2	Product Verification Tests	144
3.6.3	Battery Troubleshooting	144
3.6.4	Standards/Regulatory Agencies	144
3.6.4.1	Standards for Sealed Nickel Cadmium Batteries	146
3.6.5	Summary	148

3.7 Safety	149
3.7.1 General	149
3.7.2 Potential Battery Hazards	149
3.7.2.1 Chemical Burns from the Electrolyte	149
3.7.2.2 Ingestion of Very Small Sealed Cells	149
3.7.2.3 Burns or Excessive Heat from High-Rate Discharge	149
3.7.2.4 Electric Shock	150
3.7.2.5 Proper Disposal	150
3.7.2.6 Venting	152
3.7.3 Integration with the Product	151
3.7.4 Detachable Charger	151
3.7.5 Summary	151

Section 4 Sealed-Lead Cells and Batteries 153

Features and Benefits	153
Application Examples	155
Section Contents	155
Note to the Reader	155
4.1 Discharge Characteristics	157
4.1.1 General	157
4.1.1.1 Discharge Types	157
4.1.1.1.1 High-Rate Discharges	157
4.1.1.1.2 Medium-Rate Discharges	157
4.1.1.1.3 Low-Rate Discharges	158
4.1.1.2 Design for Discharge Performance	158
4.1.2 Measures of Discharge Performance	158
4.1.2.1 Capacity Stabilization	159
4.1.3 Battery Capacity	159
4.1.3.1 Battery Capacity Definitions and Ratings	160
4.1.3.2 Measurement of Fully Charged Capacity	162
4.1.3.3 Capacity as a Function of Discharge Rate	163
4.1.3.4 Capacity as a Function of Battery Temperature	163
4.1.3.5 Capacity During Battery Life	164
4.1.3.6 Effect of Pulsed Discharge on Capacity	164
4.1.3.7 Battery Capacity Ratings vs. Discharge Rate	165
4.1.4 Cell Equivalent Discharge Circuit	166
4.1.4.1 Effective No-Load Cell Voltage, E_o	169
4.1.4.2 Effective Internal Resistance, R_e	167
4.1.4.2.1 R_e as a Function of State of Charge	168
4.1.4.2.2 R_e as a Function of Temperature	168

4.1.4.2.3	R_e as a Function of Cell Life	168
4.1.5	Cell Voltage—General Overview	169
4.1.5.1	Mid-point Voltage	170
4.1.5.2	Battery Discharge Voltage as a Function of Discharge Rate	170
4.1.5.3	Battery Discharge Voltage as a Function of Cell Temperature	171
4.1.6	High-Rate Discharges	173
4.1.7	Discharge Limits	173
4.1.7.1	Cell and Battery Discharge Limits	175
4.1.7.2	Disconnect Circuits	176
4.1.8	Discharging Cells and Batteries in Parallel	176
4.1.9	Summary	177
4.2	Charging	178
4.2.1	Importance of Adequate Charging	178
4.2.2	Sealed-Lead Charging Characteristics	178
4.2.2.1	Cell Pressure, Temperature, Voltage, and Current Interrelationships During Charging	179
4.2.3	Charge Acceptance	181
4.2.3.1	Effect of State of Charge on Charge Acceptance	181
4.2.3.2	Effect of Temperature on Charge Acceptance	181
4.2.3.3	Effect of Charging on Charge Acceptance	181
4.2.3.4	Other Factors Affecting Charge Acceptance	182
4.2.4	Overcharging	183
4.2.4.1	Oxygen Recombination Reaction	183
4.2.4.2	Oxidation Effects of Overcharge	184
4.2.4.3	Overcharge Characteristics—The Tafel Curves	184
4.2.5	Types of Charging	185
4.2.6	Constant-Voltage (Constant Potential) Charging	186
4.2.6.1	Uses of Constant-Voltage Charging	186
4.2.6.1.1	Cycling Down and Charge Time	187
4.2.6.2	Approaches to Constant-Voltage Charging	187
4.2.6.2.1	Single-Potential Charging	187
4.2.6.2.2	Dual-Potential Constant-Voltage Charging	189
4.2.6.3	Charging Parameters	189
4.2.6.3.1	Float Voltage	190
4.2.6.3.2	Current Limits	190
4.2.6.4	Temperature Compensation of Constant-Voltage Charging	190
4.2.6.5	Tradeoffs in Constant-Voltage Charger Design	191
4.2.7	Constant-Current Charging	191

4.2.7.1	Single-Rate Constant-Current Charging	192
4.2.7.1.1	Charge Rate Selection	193
4.2.7.2	Split-Rate Constant-Current Charging	194
4.2.7.2.1	Advantages of Split-Rate Chargers	194
4.2.8	Taper Charging	196
4.2.9	Special Charging Situations	197
4.2.9.1	High-Voltage Batteries	197
4.2.9.1.1	Personnel Safety	197
4.2.9.1.2	Charge Balancing	197
4.2.9.2	Series/Parallel Charging	198
4.2.9.3	Low-Temperature Charging	199
4.2.9.4	Elevated Temperature Charging	199
4.2.10	Charging Power Sources	199
4.2.10.1	DC Power Sources	199
4.2.10.1.1	Charging from Vehicles	199
4.2.10.2	AC Power Sources	200
4.2.10.3	Photovoltaic Sources	200
4.2.11	Summary	200
4.3	Storage	202
4.3.1	Self-Discharge	202
4.3.2	State-of-Charge Indication	202
4.3.3	Capacity Retention During Storage	203
4.3.4	Charge Retention During Storage	203
4.3.4.1	Effect of Temperature on Charge Retention	205
4.3.5	Storage Conditions	205
4.3.5.1	Storage Limits	205
4.3.5.2	Recovery After Storage	206
4.3.6	Summary	206
4.4	Battery Life	207
4.4.1	Application Distinctions	207
4.4.1.1	End-of-Life Definition	207
4.4.2	Aging Mechanisms	208
4.4.2.1	Plate Morphology	209
4.4.2.2	Grid Oxidation	209
4.4.2.3	Mechanical Deterioration	209
4.4.3	Float Life	209
4.4.3.1	Life Definition	210
4.4.3.2	Factors Affecting Float Life	210
4.4.3.2.1	Charge Current/Voltage	210
4.4.3.2.2	Battery Temperature	210
4.4.3.2.3	Discharge Parameters	211
4.4.4	Cycle Life	211

4.4.4.1	Life Definition	211
4.4.4.2	Factors Affecting Life	211
4.4.4.2.1	Depth of Discharge	212
4.4.4.2.2	Cycle Time	212
4.4.4.2.3	Charging Parameters	213
4.4.4.2.4	Battery Temperature	213
4.4.5	Tradeoffs	213
4.4.5.1	Reliability vs. Life	214
4.4.5.2	Charger Cost vs. Life-Cycle Savings	214
4.4.5.3	Product Life vs. Battery Life	214
4.4.6	Summary	215
4.5	Application Information	215
4.5.1	Economic Considerations	215
4.5.1.1	Economic Features of Cyclic Applications	215
4.5.1.2	Standby Power Applications	216
4.5.2	Choice of Single-Cell vs. Monobloc Batteries	217
4.5.3	Physical Considerations	217
4.5.3.1	Battery Packaging	217
4.5.3.1.1	Battery Form Factor and Configurations	217
4.5.3.1.2	Cases	218
4.5.3.1.3	Interconnections and Terminations	218
4.5.3.2	Mounting the Battery	218
4.5.3.2.1	Where to Mount the Battery	218
4.5.3.2.2	How to Mount the Battery	219
4.5.3.2.3	Safety in Mounting the Battery	219
4.5.3.2.4	Heat Transfer in Mounting the Battery	219
4.5.4	Operating Environment Considerations	220
4.5.4.1	Operating Temperatures	220
4.5.4.2	Relative Humidity	220
4.5.4.3	Vacuum or Pressure	220
4.5.4.4	Corrosive Atmosphere	220
4.5.4.5	Shock and Vibration	220
4.5.5	Transporting Starved-Electrolyte Sealed-Lead Cells and Batteries	221
4.5.6	Functional Applications for Sealed-Lead Batteries	221
4.5.6.1	Standby Battery Power	221
4.5.6.2	Engine Starting	222
4.5.6.3	Portable Power	223
4.5.6.4	Alternate Power Sources	223
4.5.7	Summary	223
4.6	Battery Testing	224
4.6.1	Characterization Test Procedures	224

4.6.1.1	Preparation for Testing	225
4.6.1.2	Discharge and Charge Acceptance Tests	225
4.6.1.3	Life Tests	225
4.6.1.3.1	Float Life	226
4.6.1.3.2	Cycle Life	226
4.6.1.4	Storage Life	227
4.6.1.5	Overdischarge Recovery	227
4.6.1.6	Effective Internal Resistance, R_e , Testing	228
4.6.1.7	Mechanical and Environmental Tests	228
4.6.2	Product Verification Tests	228
4.6.3	Testing Logistics	229
4.6.4	Testing Precautions	231
4.6.5	Battery Troubleshooting	231
4.6.6	Summary	231
4.7	Safety	232
4.7.1	Cell Contents	232
4.7.2	Shorting Precautions	232
4.7.2.1	Handling Cells and Batteries	233
4.7.2.2	Shipping and Storage	233
4.7.3	Venting Precautions	234
4.7.4	Overcharge Protection	234
4.7.5	Disposing of Batteries	234
4.7.6	Summary	234
Appendix A Product Line Data, Sealed Nickel-Cadmium Cells		237
Appendix B Product Line Data, Sealed-Lead Cells and Batteries		257
Glossary		271
Index		283

This Page Intentionally Left Blank

List of Figures

Figure 2-1	Voltaic Pile	7
Figure 2-2	Examples of Cells and Batteries	11
Figure 2-3	Cell Essentials	12
Figure 2-4	Electrode Performance Schematic	17
Figure 2-5	Resealable Safety Vent Mechanism	18
Figure 2-6	Roll Consisting of Plates and Separator	18
Figure 2-7	Cutaway of Typical Cell	19
Figure 2-8	A Typical Nickel-Cadmium Aerospace Cell	19
Figure 2-9	Typical Nickel-Hydrogen Aerospace Cell	22
Figure 2-10	Wound Element for Sealed-Lead Cell	25
Figure 2-11	Sealed-Lead Single Cells	25
Figure 2-12	Sealed-Lead Monoblocs	26
Figure 2-13	Single Cell Assembly	26
Figure 2-14	Monobloc Assembly	27
Figure 3-1	Nickel-Cadmium Cell Discharge Curve—Constant Current	40
Figure 3-2	Typical Discharge Curves at 23°C	40
Figure 3-3	A Geometric Shape	41
Figure 3-4	Nickel-Cadmium Cell Discharge Curve	42
Figure 3-5	Nickel-Cadmium Cell Equivalent Discharge Circuit	43
Figure 3-6	Transient Cell Discharge Voltage	44
Figure 3-7	Nickel-Cadmium Cell Discharge Load Regulation Lines	44
Figure 3-8	Effect of Cell Discharge Temperature on Resistance— R_e	45
Figure 3-9	Effect of State of Discharge on Resistance— R_e	45
Figure 3-10	Effect of Cell Discharge Temperature on Voltage E_o	47
Figure 3-11	Effect of State of Discharge on Voltage E_o	48
Figure 3-12	Summary of Effects on Voltage	48
Figure 3-13	Statistical Distribution of Standard Cell Capacity	50
Figure 3-14	Effect of Cell Temperature on Actual Capacity	53
Figure 3-15	Effect of Discharge Rate on Actual Capacity	54
Figure 3-16	Effect of Cell Discharge Temperature on Actual Capacity	54
Figure 3-17	Retained Capacity	55
Figure 3-18	Nickel-Cadmium Cell Discharge Curve	56
Figure 3-19	Universal Discharge Curve	57
Figure 3-20	Nickel-Cadmium Cell Polarity Reversal Voltages	58
Figure 3-21	Effect of Long-Term Overcharge at Elevated Temperature	60
Figure 3-22	Effect of EODV on Available Capacity	61
Figure 3-23	Charge Acceptance of a Sealed Cell at 0.1C and 23°C	67
Figure 3-24	Effect of Battery Temperature During Charging on Available Capacity	68
Figure 3-25	Charge Acceptance at Various Temperatures	69
Figure 3-26	Charge Acceptance at Various Temperatures Under Extended Charge	69
Figure 3-27	Charge Acceptance at Various Charge Rates	70
Figure 3-28	Voltage, Pressure, and Temperature Characteristics during Charge at 0.1C and 23°C	71

- Figure 3-29 Voltage, Pressure, and Temperature Characteristics during Charge at 1C and 23°C 72
- Figure 3-30 Tafel Curves for Typical Sealed Nickel-Cadmium Cells 73
- Figure 3-31 Sealed Nickel-Cadmium Battery Temperature Rise in Overcharge 75
- Figure 3-32 Typical Battery Temperature Response during Charge and in Overcharge 76
- Figure 3-33 Battery Thermal Response for Different Cell Sizes 76
- Figure 3-34 Internal Cell Pressure Response to Temperature in Overcharge 78
- Figure 3-35 Coulometer Charge Control 79
- Figure 3-36 Dump-Timed Charge 81
- Figure 3-37 Cell Temperature and Pressure During Charging 81
- Figure 3-38 TCO Sensing Circuit with Thermostat 83
- Figure 3-39 Temperature Excursions in Overcharge with an Automatic-Reset Thermostat 83
- Figure 3-40 Sensing Circuit with Latching Function and Thermistor 84
- Figure 3-41 Pressure and Temperature During Charging 85
- Figure 3-42 Effect of Low Ambient Temperature on Charger Cutoff 85
- Figure 3-43 Cold Battery Effects on Time to Temperature Cutoff 86
- Figure 3-44 Δ TCO Control System 87
- Figure 3-45 Δ T Control System 88
- Figure 3-46 Typical Fast-Charge Temperature Profile 88
- Figure 3-47 Typical Room-Temperature Charging Voltage Profile for Sealed Nickel-Cadmium Cells 89
- Figure 3-48 Effect of Charge Rate on Voltage Profile 90
- Figure 3-49 Effect of Charge Temperature on Voltage Profile 91
- Figure 3-50 Effect of Cell Design Differences on Voltage Profile 91
- Figure 3-51 Charge Voltage Profiles for Different Battery Types 92
- Figure 3-52 Fast-Charge VCO Concept 93
- Figure 3-53 Voltage Cutoff Control 93
- Figure 3-54 Classic Nickel-Cadmium Fast-Charge Profile 95
- Figure 3-55 DC Charging Circuit 97
- Figure 3-56 Half-Wave Charging Circuit 98
- Figure 3-57 Full-Wave Center-Tap Charging Circuit 98
- Figure 3-58 Full-Wave Bridge Charging Circuit 98
- Figure 3-59 Capacitive Charging Circuit 99
- Figure 3-60 Coefficients for Calculating Charging Circuit Currents 100
- Figure 3-61 Constant-Current Charging with In-Line Resistors 101
- Figure 3-62 Charging for Standby Power Applications 102
- Figure 3-63 Maximum Recommended Overcharge Rates at Various Temperatures 103
- Figure 3-64 Series Array of Photovoltaic Cells 103
- Figure 3-65 Decay of Retained Capacity Over Time 107
- Figure 3-66 Capacity Recovery After Storage at Various Temperatures 108
- Figure 3-67 Typical Life Characteristics for Sealed Nickel-Cadmium Cells and Batteries (Hazard Function) 110
- Figure 3-68 Equivalent Circuit for a Sealed Nickel-Cadmium Cell including the Interplate Resistance (R_p) 110
- Figure 3-69 Capacity Decrease Through Cell Life 111
- Figure 3-70 Effect of Depth of Discharge on Cycle Life 114

Figure 3-71	Differences in Cycle Life Caused by Differences in Cell Construction	115
Figure 3-72	Effect of Cell Construction on Life at High Temperatures	115
Figure 3-73	Possible Duty Cycles for a Nickel-Cadmium Battery Systems	121
Figure 3-74	Typical Cell Voltage Response	123
Figure 3-75	Discharge Comparison of Primary vs. Sealed Nickel-Cadmium Cells	123
Figure 3-76	Battery Power Output	125
Figure 3-77	Surface Area Differences for Battery Configurations	127
Figure 3-78	Power Supply for Battery Power Source	130
Figure 3-79	Simplified Circuit for Emergency Lighting	131
Figure 3-80	Some Special Charging Circuits for Batteries Providing Standby Power to Electronic Circuits	132
Figure 3-81	Diagram of Nickel-Cadmium Battery Used as Standby Power in Small Computer	133
Figure 3-82	One Method of Instantaneous Transfer to Battery Power	133
Figure 3-83	Typical Battery Voltage-Current Characteristic	134
Figure 3-84	Characteristics of 10-Cell and 12-Cell Batteries for Two Cell Types	134
Figure 3-85	Battery Characteristic at Different States of Charge	135
Figure 3-86	Stall Line of Motor and Battery Characteristics	135
Figure 3-87	Motor-Speed-Torque and Battery Characteristic	136
Figure 3-88	Equal Power for Three Battery Types	137
Figure 3-89	Cell Materials Degradation as a Function of Temperature	143
Figure 3-90	Use of Elevated Temperature Tests to Predict Life	143
Figure 3-91	Cell Performance Comparison as a Function of Temperature	144
Figure 3-92	Recommended Flow Chart for Battery Troubleshooting	146
Figure 4-1	Nominal Discharge Performance for Sealed-Lead Cells	159
Figure 4-2	Statistical Distribution of Standard Cell Capacity	161
Figure 4-3	Capacity vs. Discharge Rate	162
Figure 4-4	Typical Discharge Times for 2.5 Ah Sealed-Lead Cell	163
Figure 4-5	Typical Discharge Capacity as a Function of Cell Temperature	164
Figure 4-6	Typical Cell Capacity During Its Life	165
Figure 4-7	Typical Pulsed Discharge Curve	165
Figure 4-8	Equivalent Circuit Diagram of a Cell	166
Figure 4-9	Effective No-Load Cell Voltage vs. State of Charge	167
Figure 4-10	Effective Internal Resistance, R_e , vs. State of Charge	168
Figure 4-11	Effective Internal Resistance, R_e , vs. Cell Temperature	169
Figure 4-12	Effective Internal Resistance vs. Cell Life	169
Figure 4-13	Cell Voltage Before, During and After a Nominal Discharge	170
Figure 4-14	Illustration of Mid-Point Voltage	171
Figure 4-15	Cell Discharge Voltage vs. Time	171
Figure 4-16	Cell Discharge Voltage vs. Temperature	172
Figure 4-17	Typical Discharge Profiles for Various Temperatures	172
Figure 4-18	High-Rate Voltage/Current Plots	173
Figure 4-19	High-Rate Instantaneous Power Plots	174
Figure 4-20	Typical Voltage Profile for a High-Rate Discharge	174
Figure 4-21	Recommended Average Discharge Cut-Off Voltage/Cell	175
Figure 4-22	Battery Discharge Characteristics	175