NEW THIS EDITION

Price $25.00

NEW FEATURES

- Two Color Easy-to-Read Graphs
- Appendix on Quality with Incoming Inspection Procedures
- Expanded Chapter on Charging
- Revised Chapter on Discharging
- Plot Your Own Application Discharge Curve
- Three Ring "D" Binder Allows Updating
- Personal Computer Disk Pocket in Binder

NEW PRODUCTS

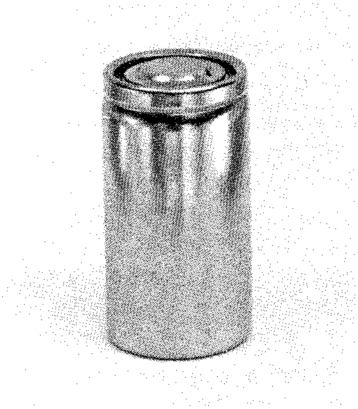
- *GE max*™ Cell
- Powerstick® Battery
- Accessory Pack II

GENERAL ELECTRIC

NEW PRODUCTS

GEmax™ SERIES

General Electric introduces the GEMAX™ Series of high performance cells ... designed to provide maximum power through high capacity and voltage capability for matching the demanding applications of tomorrow.



The new GEMAX™ Cs* cell product will provide a minimum capacity of 1.3Ah, along with a 40% decrease in internal resistance. Ideally suited for portable houseware products and power tools, the GEMAX™ Cs maximizes power and runtime performance in all cordless applications.

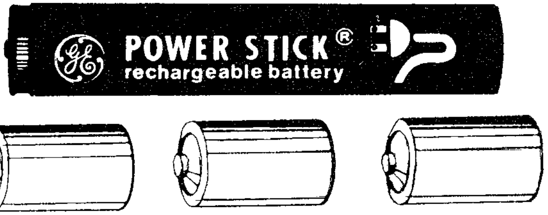
*Available December 1986.

GENERAL ELECTRIC

NEW PRODUCTS

POWER STICK®
RECHARGEABLE BATTERY

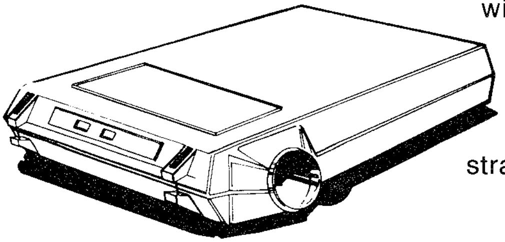
Power Stick® rechargeable batteries are designed to replace multiple throwaway C and D size batteries in AC/DC products. The patented charging ring allows Power Stick batteries to be recharged inside the product whenever it is plugged into an AC outlet.



Already designed into the portable TVs and radio cassette recorders, the Power Stick battery is ideally suited for portable typewriters, printers, computers, power tools and any other application where operation from both AC and battery power is required.

ACCESSORY PACK II

Accessory Pack II joins Accessory Pack I in offering a 12 volt portable power source to serve a host of applications including portable VCRs, power tools, and lighting products. Smaller and lighter in weight than Accessory Pack I, this 2.0Ah product comes complete with LED charge indication, belt clip and shoulder strap.



GENERAL ELECTRIC COMPANY

NICKEL-CADMIUM BATTERY
Application Handbook

Third Edition — 1986

Published by the Battery Business Department,
with assistance from
Genium Publishing Corporation
Schenectady, N.Y. 12303
Mary McLaughlin, Production Coordinator

Publication Number 211B5000AC

ISBN 0-9617205-0-6

Contributing Authors

George W. Braun
Arthur J. Catotti
John M. Evjen
Robert J. Lehnen
Ferdinand H. Mullersman
Ramesh V. Shah

Product Test and Evaluation

Nathan M. Banes

Editor
George W. Braun

Editorial Consultant
Wayne A. Losano, Ph.D.

Text Preparation
Ginger R. Yarbrough

General Electric Company
Battery Business Department
Post Office Box 861
Gainesville, FL 32602-0861 U.S.A.

GENERAL ELECTRIC

Library of Congress Catalog Card No. 86-80684

The battery devices and arrangements described in this book may be covered by patents of General Electric Company or others. Neither the disclosure of any information in this book, nor the publication or distribution of this book, grant any right or license, by implication or otherwise, under any patent owned by General Electric Company. The sale of battery devices by General Electric Company does not convey any right or license under patent claims covering combinations of battery devices with other devices or elements. In the absence of an express written agreement to the contrary, General Electric Company assumes no liability for patent infringement arising out of any use of the battery devices with other devices or elements by any purchaser of battery devices or others.

It is the responsibility of each user to assure that each battery application system is adequately designed, safe and compatible with all conditions encountered during use, and in conformance with existing standards and requirements. The circuit diagrams and other information contained herein are only illustrative of typical battery arrangements and are not intended as constructional information. Although reasonable care has been taken in their preparation to achieve technical correctness, no responsibility is assumed by the General Electric Company for any consequences of their use. Each user must ensure that each circuit is safe and otherwise completely appropriate for his application.

This handbook and its appendices contain information concerning products manufactured by General Electric Company. This information is generally descriptive only and is not intended to make or imply any representation or warranty with respect to any product. Cell and battery designs are subject to modification without notice. All product descriptions and warranties are solely as contained in formal offers to sell or quotations made by General Electric Company.

Printed in the United States of America

TABLE OF CONTENTS

CHAPTER **SECTION** **PAGE**

ILLUSTRATIONS

CHAPTER 1

Introduction

This *Nickel-Cadmium Battery Application Handbook* has been prepared for managers, engineers, designers, and others interested in rechargeable nickel-cadmium batteries. Its objective is to help the reader understand the operation and application of nickel-cadmium batteries. The *Handbook* is also designed to acquaint the reader with the versatility and features of nickel-cadmium batteries that might allow their use in previously overlooked ways. Material in the *Handbook* is based on information and data gathered for more than a quarter of a century by *General Electric* scientists, engineers, and technicians.

The *Handbook* is designed for easy use by the novice as well as by the experienced reader. The novice should read Chapter 2 and, perhaps, Chapter 6 on battery applications before reading Chapters 3, 4, and 5. The experienced reader will probably be able to skim or skip Chapter 2. The glossary at the end of the *Handbook* will define many terms used that may cause difficulty.

The *Handbook* covers nickel-cadmium rechargeable batteries of sealed wound cells. Vented and aerospace cells are described briefly in Chapter 2.

Chapter 2 is a general description of nickel-cadmium batteries, including internal chemistry. Primary and secondary systems are compared and the construction and theory of operation of sealed cells are described. Chapter 3 covers various schemes for charging the batteries, including charging efficiency, continuous and fast charging, and overcharging. Chapter 4 discusses discharge performance, application, and design-related factors affecting battery operation. Chapter 5 covers life expectancy and proper storage of nickel-cadmium batteries. Chapter 6, the application chapter, supplements the information presented in the previous chapters with information on specific uses. The last chapter is devoted to safety. Readers can use the index to locate information on a specific subject or point of interest.

The appendix includes information on quality control, standards, trouble shooting, product descriptions and specifications. A mail-in registration is provided.

Although this *Handbook* is quite comprehensive, it will not answer all questions for all readers. You are invited to request further information or application assistance by contacting the address below:

General Electric Company
Battery Business Department
Post Office Box 861
Gainesville, Florida 32602-0861
U.S.A.

Telephone 904-462-3911
Telex 810-836-8500

Chapter 2
General Description of Nickel-Cadmium Cells and Batteries

Section

2.1 GENERAL OVERVIEW

Batteries are electrochemical devices used to supply electrical energy. Chemical energy stored in a battery is converted into electric energy directly by chemical reactions when the battery is discharged. The electric energy made available is a function of the electrical potential of the active material, the efficiency of the electrochemical reactions, and the amount of dischargeable active material in a battery. Many combinations of electrochemical couples have been tried as energy storage systems with varying degrees of success. Each type of battery has physical and electrical advantages and disadvantages. This application *Handbook* focuses on the nickel-cadmium electrochemical couple, describing its strengths and potential limitations.

2.2 PRIMARY VS. SECONDARY BATTERIES

Batteries can be classified as primary or secondary. Primary batteries can be used only once because the active chemicals transformed during the discharge reaction cannot be returned to the original state. Secondary batteries, sometimes called *storage batteries* or *accumulators,* can be used repeatedly because the chemical reaction can be readily reversed by recharging the battery.

Primary batteries are widely used in products where recharging may not be practical. The most common primary batteries are the *carbon-zinc* dry cell and the *alkaline* cell. These and other primary batteries are sometimes suitable for certain low-current applications, but are often less economical than a rechargeable battery. The secondary battery, due to the reversibility of its chemical reaction, can be used repeatedly with a simple recharge following each discharge. The two most popular rechargeable, or secondary, batteries are the nickel-cadmium battery and the common lead-acid battery.

2.3 BATTERIES VS. CELLS

The term *battery* is generally used to describe a single unit comprised of one or more cells. Cells are the basic *building blocks* of a battery. A battery can be a single cell provided with terminations and insulation and considered ready for use. More frequently, a battery is an assembly of several cells connected in series and with electrical output terminals (Figure 2-1). These batteries are sometimes referred to as *multicell batteries. General Electric's* nickel-cadmium cells can be connected in series to provide a battery with voltage rated in multiples of 1.2 volts, their nominal rating.

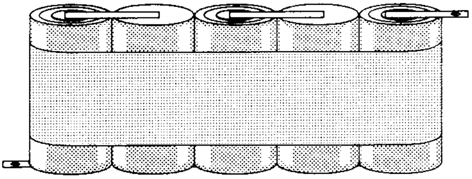
2.4 CELL COMPONENTS

The cell, the basic unit of the battery, has four main components:

1. The negative electrode (the *anode* during discharge reac-

BARE CELL
1.2 VOLTS

SINGLE CELL BATTERY
1.2 VOLTS



FIVE CELL BATTERY
6.0 VOLTS

Figure 2-1 Cells vs. Batteries

tions) supplies electrons to the external circuit when oxidized during discharge.

2. The positive electrode (the *cathode* during discharge reactions) accepts the electrons from the external circuit when reduced during discharge.
3. The electrolyte completes the circuit internally by furnishing the ions for conductance between the positive and negative electrodes.
4. A separator to hold the electrolyte in place and electrically isolate the positive and negative electrodes.

These components are then housed in a cell jar or can.

2.5 NICKEL-CADMIUM CELL CHEMISTRY

The nickel-cadmium cell has a unique set of desirable physical and electrochemical characteristics which has allowed it to become the established battery system for many applications. The nickel-cadmium cell is an electrochemical system in which the active materials contained in the electrodes change in oxidation state without any deterioration in physical state. These active materials are present as solids that are highly insoluble in the alkaline electrolyte. Unlike many other systems, the nickel-cadmium cell charge/discharge reaction does not require the transfer of material from one electrode to the other. The electrodes are long-lived, since the active materials in them are not consumed during operation or storage.

In the nickel-cadmium cell, nickel oxyhydroxide, NiOOH, is the active material in the charged positive plate. During discharge it is reduced to the lower valence state, nickel hydroxide, $Ni(OH)_2$, by accepting electrons from the external circuit:

$$2NiOOH + 2H_2O + 2e^{-} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2Ni(OH)_2 + 2OH^{-}$$

(0.490 volts)

Cadmium metal is the active material in the charged negative plate. During discharge it is oxidized to cadmium hydroxide, $Cd(OH)_2$, and releases electrons to the external circuit:

$$Cd + 2OH^{-} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} Cd(OH)_2 + 2e^{-}$$

(-0.809 volts)

These reactions are reversed during charging of the cell. The net overall reactions which occur in the potassium hydroxide (KOH) electrolyte can be expressed as follows:

$$Cd + 2HO + 2NiOOH \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2Ni(OH)_2 + Cd(OH)_2$$

(1.299Volts)

Nickel-cadmium cells are manufactured in two basic types:

sealed and vented. The sealed cell operates in a closed environment, normally allowing no escape of gas, while the vented cell permits gases to escape from the cell as part of its normal operating behavior.

2.6 SEALED NICKEL-CADMIUM CELLS

Although *General Electric* sealed cylindrical cells have a vent mechanism as a safety measure, they are still referred to as *sealed* cells. Without the safety vent, misapplication and abuse could cause an increase in internal pressure resulting from rapid generation of gases within the cell and damage the cell. The *General Electric* safety vent opens under excessive pressures and safely releases the gas to the atmosphere, then automatically recloses, allowing the cell to continue operating.

2.6.1 Theory Of Sealed Cell Operation

General Electric sealed cells are designed to operate under normal use conditions at an internal pressure well below the safety vent pressure. In order to accomplish this, three essential design criteria are adhered to:

1. The chargeable capacity of the negative electrode is sufficiently greater than that of the positive electrode for the positive electrode to achieve full charge before the negative electrode.
2. The electrolyte is uniformly distributed by the separator as a thin film across the surface of the two electrodes.
3. Oxygen gas is free to pass between the electrodes.

When a *General Electric* sealed cell is charged the positive electrode will reach a full state of charge before the negative electrode. At this stage additional charge current causes the positive electrode potential to rise to the point at which all the current is used to oxidize hydroxyl ions and generate oxygen gas at the positive electrode:

$$2OH^- \xrightarrow{\text{Overcharge}} 1/2\ O_2 + H_2O + 2e^-$$

The oxygen diffuses rapidly to the negative electrode where it is reduced back to hydroxyl ions:

$$1/2\ O_2 + H_2O + 2e^- \xrightarrow{\text{Overcharge}} 2OH^-$$

The hydroxyl ions complete the circuit by moving back to the positive electrode.

Thus, in *overcharge* all of the current generates oxygen which is subsequently recombined. The oxygen pressure initially increases but then stabilizes at a low equilibrium pressure determined by cell design, the ambient temperature, and the charge rate. Since in equilibrium all of the generated oxygen is recombined at the negative electrode, the negative electrode does not become fully charged and no hydrogen gas is generated.

The efficient recombination of oxygen enables the *General Electric* sealed cell to be continuously overcharged at the cell specification overcharge rate without developing excessive internal pressure. It can thus be kept on overcharge, maintaining the cell in a fully charged condition for long periods.

Figure 2.2 shows the electrode design of a typical sealed nickel-cadmium cell. When the cell is fully charged, the

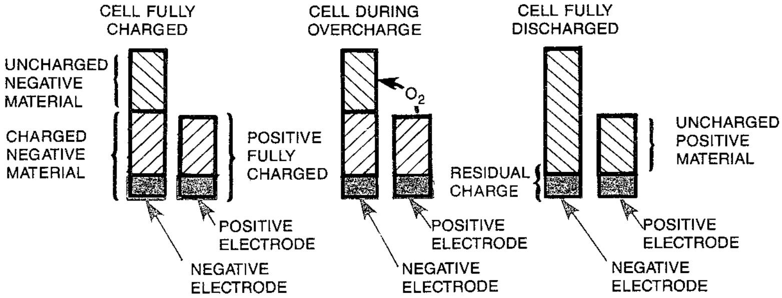


Figure 2-2 Graphic Representation of the Electrodes in a Sealed Nickel-Cadmium Cell

positive electrode active material has been converted to the high valence form, NiOOH, but the negative electrode still contains uncharged active material, $Cd(OH)_2$. In overcharge, oxygen gas is evolved from the positive—not from the negative—electrode. Each electrode in a fully discharged cell contains a small amount of charged active material called the *residual charge*. Overcharge is further discussed in Section 3.4.

2.6.2 Sealed Cell Construction

General Electric cylindrical sealed cells use a nickel plated steel can as the negative terminal and a metallic cell cover as the positive terminal. The cell cover is an assembly that includes the high pressure safety vent mechanisms shown in Figure 2-3.

Each electrode, which is a continuous conductive strip containing active material, is isolated from the other electrode by the *separator*, a nonconducting, porous, fibrous, polymeric material. The two electrodes separated by this porous separator are wound together into a *roll* configuration shown in Figure 2-4. A terminal from the positive elec-

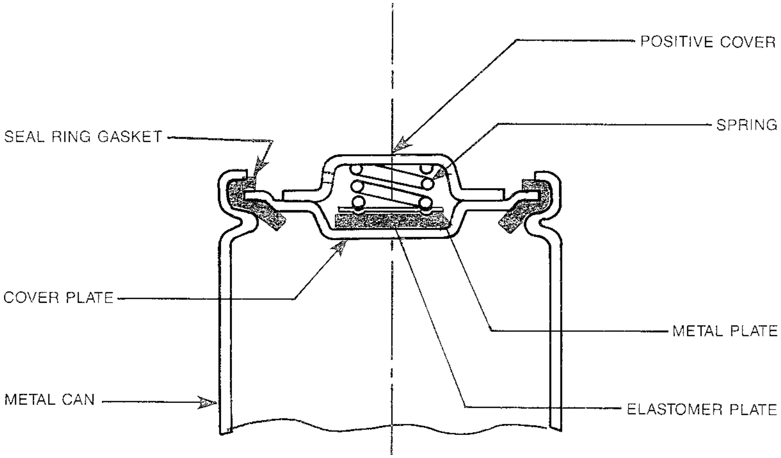


Figure 2-3 Resealable Safety Vent Mechanism

trode is connected to the cover, and the negative electrode contacts the can. An insulating seal ring isolates the positive cover from the negative can and provides a gas-tight seal for the container.

2.7 VENTED NICKEL-CADMIUM CELLS

Vented nickel-cadmium cells are designed to provide reliable high-rate discharge service in applications such as jet aircraft, diesel and turbine engine starting, and in applica-

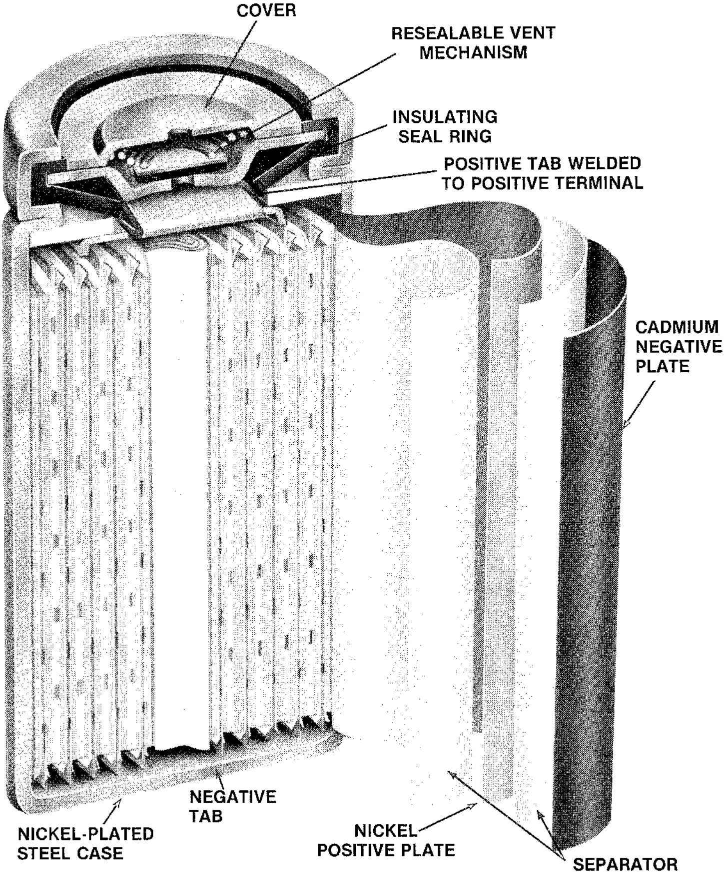


Figure 2-4 Typical Cylindrical Sealed Cell Construction

tions such as mobile X-ray and military equipment. These cells provide outstanding performance where large peaks of power, fast recharging, or many cycles are required without excessive size and weight.

The vented cell differs from the sealed cell in operating without recombining oxygen. Consequently, the cell vents gases when overcharged.

The vented cell starts with an excess amount of electrolyte. Water is consumed as a result of overcharging, requiring vented cells to be periodically inspected and replenished. The cell must typically be mounted in an upright position.

Vented cell electrodes are constructed with flat positive and negative plates, separated by non-conducting, ion-

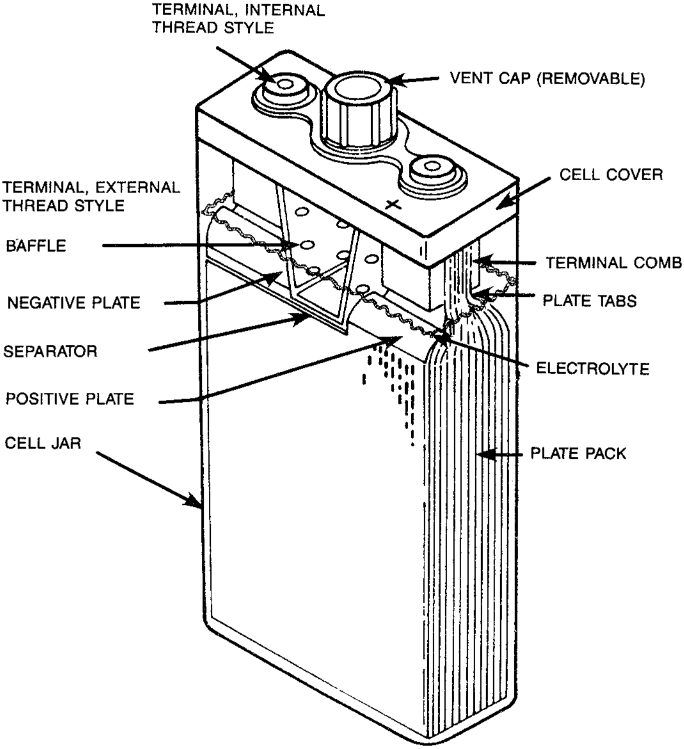


Figure 2-5 Vented Cell Construction

permeable materials that act as a gas barrier and electrical separator. The electrolyte completely covers the plates and separator, and for this reason vented cells are sometimes referred to as *flooded cells*. Figure 2-5 shows details of a vented cell.

The plates are welded to terminal posts that are extended through the cover and sealed. The terminal posts are of sufficient size to carry the high current encountered in typical applications.

The cell container, typically made of polyamide, consists of a cell jar and matching cover permanently joined during assembly. The cell container supports the various components of the cell. The vent is located in the cell cover and is typically comprised of molded polyamide plastic, with an elastomer sleeve, to provide a *bunsen* type of valve assembly. The vent cap can be removed for electrolyte leveling and acts as a valve to release gases at low internal pressure during normal operation of the cell. Except when releasing gas, the vent automatically closes the cell to prevent electrolyte spillage and entry of foreign material.

2.8 AEROSPACE CELLS

General Electric manufactures sealed nickel-cadmium cells for aerospace applications. As shown in Figure 2-6, these cells are typically rectangular, containing flat plate electrodes. Considerable research and development have gone into the design of the electrodes and the manufacturing processes for producing aerospace cells. They are designed to meet the stringent requirements necessary for operation in space vehicles. They must be lightweight, capable of many charge/discharge cycles, and, above all, highly reliable and free from defects that may affect the operating life of the space vehicle.

General Electric also manufactures lightweight nickel-hydrogen cells for space vehicles. These cells convert hydrogen gas in the discharge reaction to form water. During the charging reaction hydrogen gas is formed. To contain the

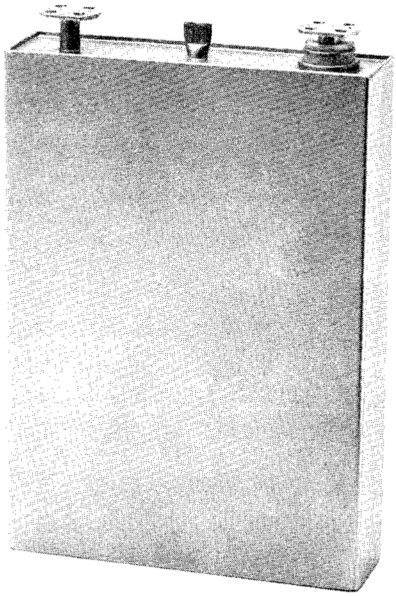


Figure 2-6 A Typical Nickel-Cadmium Aerospace Cell

hydrogen gas, a pressure vessel is employed to maintain a high pressure near 1000 psig.

General Electric's research on aerospace electrodes has contributed to a highly reliable cell with a long life. Cell life in excess of 10 years with many thousands of cycles is achievable with *General Electric* aerospace cells. Much of the knowledge gained from the extensive research on and development of these high reliability cells has been applied to the *General Electric* commercial sealed wound nickel-cadmium batteries.

2.9 SUMMARY

General Electric nickel-cadmium cells are made in both wound and flat electrode designs. The sealed cells for commercial applications have electrodes that are cylindrically wound while the sealed cells for aerospace applications have flat electrodes. The vented cells have stacked flat electrodes in rectangular plastic cases and are sometimes referred to as flooded cells. They are all available in a wide variety of battery configurations.

General Electric also manufactures nickel-hydrogen aerospace cells that are very lightweight.

The remainder of this *Handbook* will discuss only cylindrically wound sealed nickel-cadmium cells.

CHAPTER 3

Charging Characteristics and Methods

Section

3.1 INTRODUCTION

Nickel-cadmium batteries are charged by applying a direct current of proper polarity to the terminals of the battery. The charging current can be pure direct current (dc) or it may contain a significant ripple component such as half-wave or full-wave rectified current.

Throughout this chapter on charging of sealed nickel-cadmium cells and batteries, certain charging rate terms will be used. These rates will be referred to and expressed in multiples of the **C** rate. The **C** rate is defined as the rate in amperes or milliamperes numerically equal to the capacity rating of the cell, which is given in ampere-hours or milliampere-hours. For example, for a cell with a 1.2 ampere-hour capacity, the **C** rate is 1.2 amperes. This **C** rating concept, and multiples or fractions thereof, facilitates the discussion of a broad range of cell sizes and cell types, since the charging reactions within the various cell sizes and types are similar to each other at similar **C** rate charging currents. These **C** rate charging currents can also be categorized into descriptive terms, such as *Standard-Charge, Quick-Charge,* and *Fast-Charge* as shown in Table 3-1.

METHOD OF CHARGING	CHARGE RATE		RECHARGE TIME* (HOURS)	CHARGE CONTROL
	MULTIPLES OF C-RATE	FRACTION OF C-RATE		
STANDARD	0.05C 0.1C	C/20 C/10	36-48 16–20	NOT REQUIRED
QUICK	0.2C 0.25C 0.33C	C/5 C/4 C/3	7-9 5-7 4-5	NOT REQUIRED
FAST	C 2C 4C	C 2C 4C	1.2 0.6 0.3	REQUIRED
TRICKLE	0.02–0.1C	C/50–C/10	Used for maintaining charge of a fully charged battery.	

*RECHARGE TIME = STANDARD TIME TO FULLY CHARGE A COMPLETELY DISCHARGED BATTERY AT 23°C

Table 3-1 Definition of Rates for Charging

3.2 CHARGING EFFICIENCY

When a nickel-cadmium battery is being charged, not all of the charging energy is used to convert the active material to a useable (dischargeable) form. A small amount of the charging current (energy) goes into converting active material into a non-usable form, the generation of gas, or is lost in parasitic side reactions. The term *charge acceptance* is sometimes used to describe overall charging effectiveness and refers to the amount of dischargeable capacity that can be delivered as the result of a charging input.

The top curve of Figure 3-1 shows the dischargeable capacity (charge output) as a function of the charge input for a sealed cell starting from a completely discharged state. The ideal cell, with no charge acceptance losses, would display a theoretical *100 percent efficient* relationship, where all the charge delivered to the cell is obtainable on discharge. But nickel-cadmium cells typically accept and store deliverable charge at different levels of efficiency depending upon

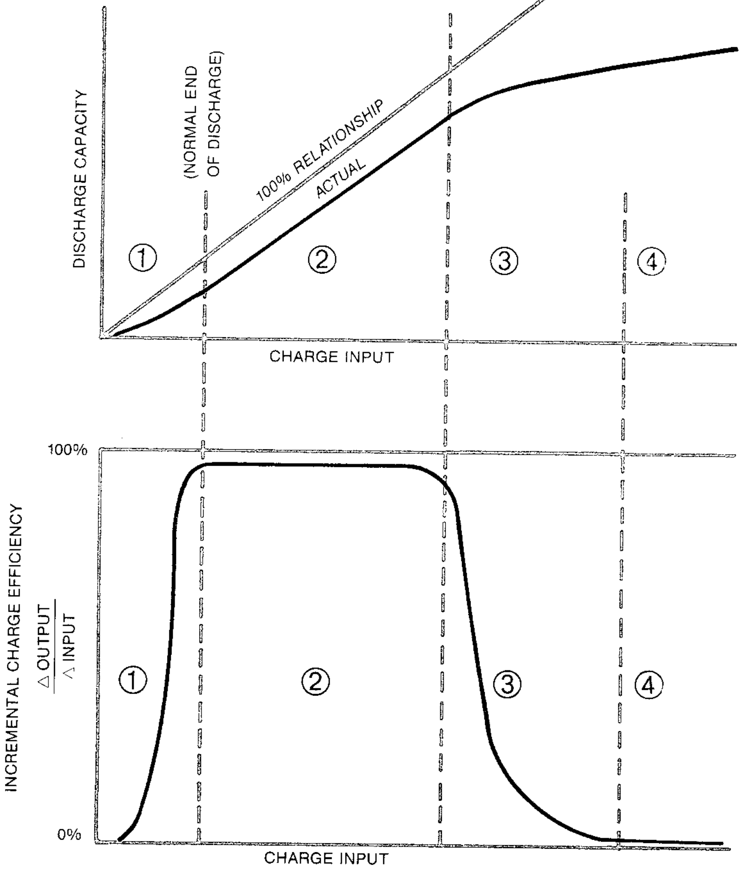


*Figure 3-1 Charge Acceptance of a Sealed Cell at 0.1**C** rate at 23°C*

the state of charge of the cell, as shown by the bottom curve of Figure 3-1. Four successive types of charging behavior—Zones ①, ②, ③ and ④ in Figure 3-1—describe this performance. Each zone reflects a distinct set of chemical mechanisms responsible for loss of charge input energy.

In Zone ① a significant portion of the charge input is used to convert some of the active material mass into a non-usable form, i.e. into charged material which is not readily accessible when the cell is discharged at medium or high rates, particularly in the first few cycles. In Zone ②, the level of incremental charge efficiency is only slightly less than 100 percent; small amounts of internal gassing and parasitic side reactions prevent the charge from being 100 percent efficient. The cell is approaching full charge in Zone ③ with a gradual shift from charging (oxidation) of positive active material to only the generation of oxygen gas in Zone ④ which will be defined as *overcharge* (overcharge is further discussed in Section 3.4). The boundaries between Zones ②, ③ and ④ are indistinct and quite variable depending upon cell temperature, cell construction, and charge rate. The level of *charge acceptance* for any given input in Zone ② is also influenced by cell temperature and charge rate.

3.2.1 Effect of Temperature

Both the incremental charge efficiency and the actual capacity of a cell charged at elevated temperatures are less than that of a cell at room temperature. Even though the charge input to a hot cell may exceed many times its rated capacity, the cell is able to accept only a portion of the charge that it would accept at room temperature.

It is characteristic of nickel-cadmium sealed cells that as the cell approaches its maximum state of charge (Zone ③), an increasing portion of the charging current goes to generating oxygen gas inside the cell and less goes to raising the cell's state of charge. At higher cell temperatures, compared to room temperature, the charging reaction causes gas generation at lower states of charge. This results in a reduction in actual capacity at elevated charge temperatures even though the cell is in overcharge (Zone ④). This is illustrated in Figure 3-2, 3-3, and 3-4. The magnitude of the effect of this phenomenon on dischargeable capacity is discussed in Section 4.3.3.1.

Figure 3-3 shows the effects of cell temperature on incremental efficiency and dischargeable capacity while maintaining the charge at a fixed 0.1**C** rate. The charge acceptance under standard conditions (23°C) is used as a reference. If the charging temperature is raised so that the cell temperature reaches 45°C or 60°C, the incremental charge efficiency is reduced and actual cell capacity is reduced. With

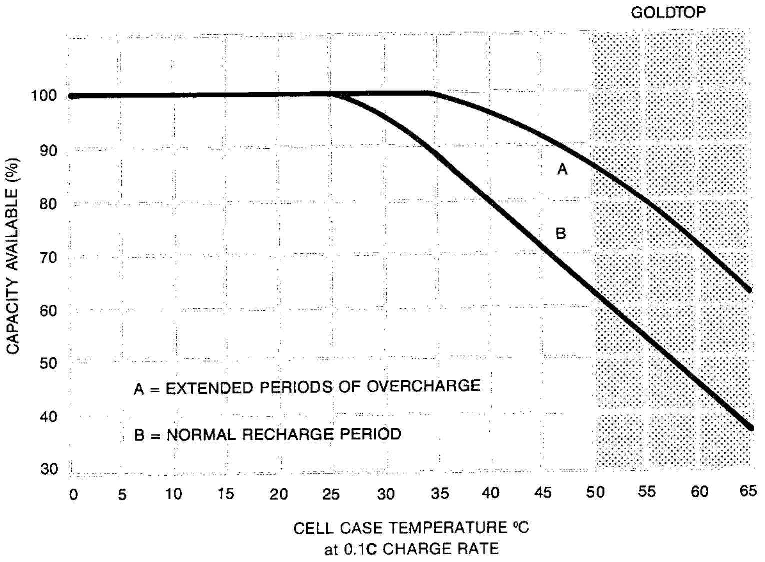


Figure 3-2 Effect of Battery Temperature During Charging Upon Available Capacity

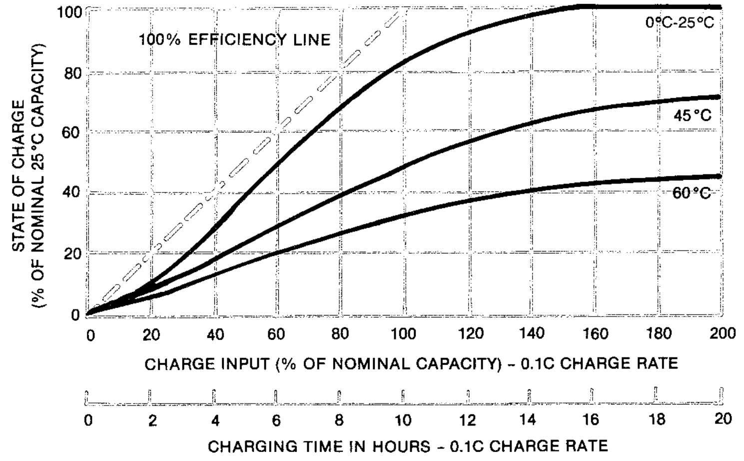


Figure 3-3 Charge Acceptance at Various Temperatures

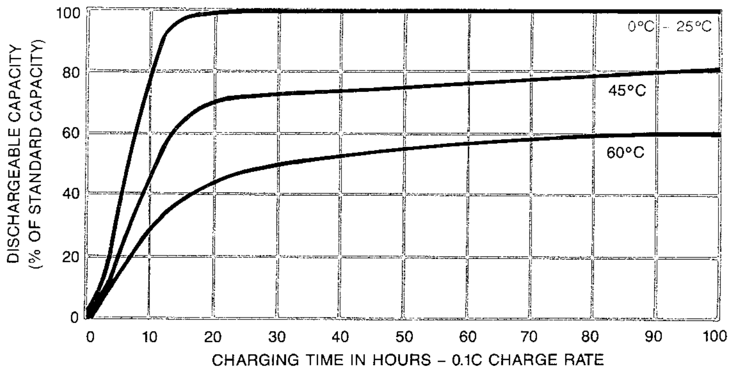


Figure 3-4 Charge Acceptance at Various Temperatures Under Extended Charge

a cell temperature of 45°C and a charge input of 200 percent of standard capacity, the actual capacity will be no more than 70 percent of standard capacity. Similarily, with a cell temperature of 60°C and a charge input of 200 percent of standard capacity, the actual capacity will be no more than 45 percent of standard capacity. However, a cell charged at 0°C to 25°C accepts charge effectively and would yield 100 percent of standard capacity with a charge input of 160 percent of its standard capacity.

The effect of these same temperatures for extended charging times at a constant 0.1**C** charge rate is shown in Figure 3-4 which continues the charge input time scale of Figure 3-3 to 100 hours. The cell charged at 23°C, being charged to 100 percent of standard capacity within 20 hours, does not increase its state of charge by charging beyond 20 hours. However, at 45°C the cell charged to only about 70 percent of standard capacity in about 20 hours will gain capacity by additional charging. Similarly, the cell charged at 60°C will increase its dischargeable capacity with increased charge input. The input requirements for reaching overcharge for a cell at 60°C may be as much as one thousand percent of standard capacity. As the active materials in a cell are converted to the charged state, the dischargeable capacity ultimately reaches the limit defined by the actual cell capacity of curve Ⓐ in Figure 3-2.

3.2.2 Effect of Charge Rate

Figure 3-5 shows the effect of charge rate on dischargeable capacity for various charge inputs. Charge rates much below .05**C** do not enable the cell to reach full capability. Charge efficiency is enhanced by charge rates higher than 0.1**C**, for cells specified as capable of charging at higher than Standard-Charge rate. For example a Fast-Charge cell charged at the 1**C** charge rate approaches standard capacity at an input of about 120 percent. However, as discussed in Section 3.7, the Fast-Charge cell cannot sustain this high rate in overcharge.

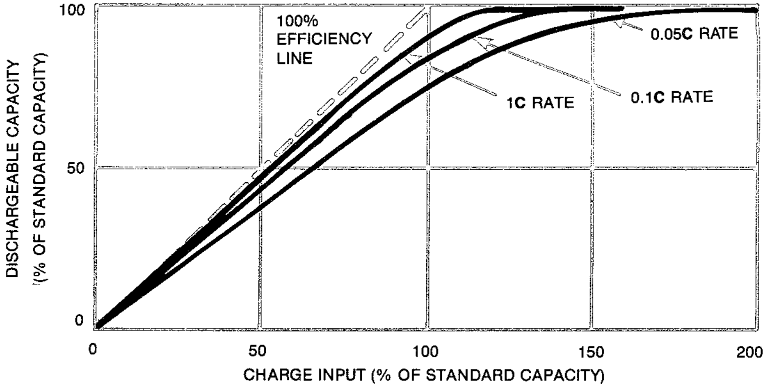


Figure 3-5 Charge Acceptance at Various Charge Rates

3.2.3 Effect of Cell Construction

The cell design and construction can have an effect on charge efficiency at elevated temperatures. The chemical composition of the electrodes and the electrolyte can be modified to improve the high temperature charge characteristics of cells having a cell specification for high temperature use. This is not done to all cells as it can also negatively impact low temperature cell capacity and fast charge capability, and raise internal resistance. The cell specification data shows actual cell capacity as a function of charge temperature for each cell type.

3.3 CELL PRESSURE, TEMPERATURE AND VOLTAGE INTERRELATIONSHIPS

The interrelationship of cell pressure, temperature, and voltage during charge and overcharge is one of fundamental importance, particularly at the faster charge rates. Figure 3-6 represents on one graph the relationship between charge input and the temperature, pressure, and voltage of a typical cell, using a fixed charge rate of 0.1**C** in a 23°C ambient.

All nickel-cadmium sealed cells can be charged continuously at their cell specification overcharge rate by a simple constant current charger, without consuming or releasing any of the materials in the cell. The cells are designed so that at the cell specification overcharge rate, the net electrochemical reaction occurring at one electrode is exactly opposite to that occurring at the other electrode, as was discussed in Section 2.6.1.

The cell pressure stays very low during most of the charge and starts to rise as the cell approaches full charge. The cell pressure is the result of oxygen being generated and remains quite low until the positive plate (electrode) begins to reach its highest state of oxidation. As the positive elec-

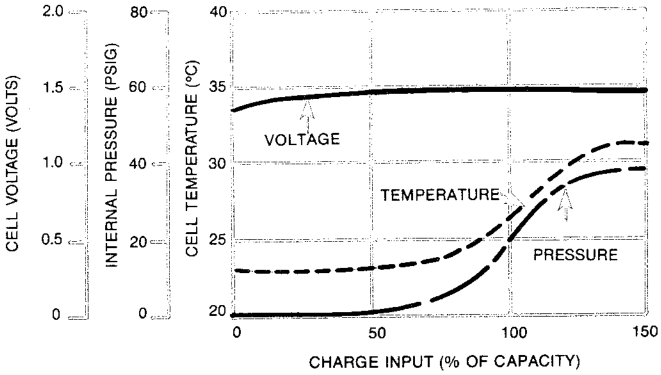


*Figure 3-6 Characteristics of Voltage, Pressure and Temperature vs. Charge Input of a Typical Sealed Cell at 0.1**C** Charge Rate in 23°C Ambient*

trode approaches full charge, more and more of the charge energy goes into generating oxygen gas until the point is reached when most or all of the charge energy is devoted to the generation of oxygen. The pressure reaches an equilibrium and ceases to rise. This is the stabilized overcharge condition where the rate of oxygen generation at the positive and the rate of recombination at the negative electrode are in balance.

The cell temperature during the major portion of the charge time increases only slightly. As the cell approaches full charge, oxygen generation increases at the positive electrode, the pressure increases, recombination of oxygen increases at the negative electrode, heat is generated, and the cell temperature rises. Eventually the cell reaches a stabilized pressure and temperature which are dependent on the heat transfer characteristics of the cell, the battery configuration, its container, the ambient temperature, and

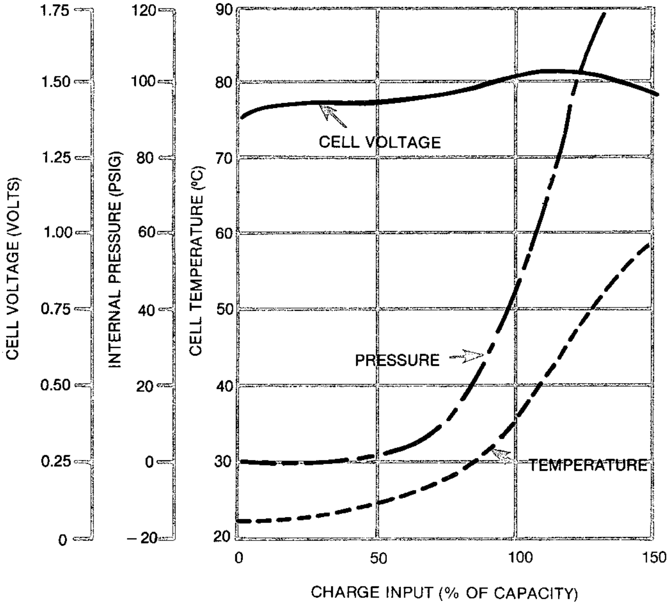


*Figure 3-7 Characteristics of Voltage, Pressure and Temperature vs. Charge Input of a Typical Sealed Cell at 1***C** *Charge Rate in 23°C Ambient*

the charge rate. The cell voltage also remains rather constant throughout most of the charging and rises slightly as the cell approaches full charge, dropping again in overcharge.

The effect of charge rate on the three parameters of cell pressure, cell temperature, and cell voltage is demonstrated dramatically by comparing Figures 3-6 and 3-7. Figure 3-6 shows the profiles of the same parameters for a 0.1**C** charge rate as Figure 3-7 shows for a 1**C** charge rate (ten times faster). An analysis of the relationship between cell pressure, cell temperature, and cell voltage will establish some of the fundamental considerations in making nickel-cadmium cell and charger application decisions.

3.4 OVERCHARGE

Overcharge is the normal continued application of charging current to a battery after the battery has reached its maximum state of charge. As discussed earlier, charging cells that are already fully charged causes a rise in oxygen pressure within the cells. The magnitude of the pressure increase depends primarily on the overcharge rate. Along with this rise of pressure comes a corresponding increase in cell temperature. Pressure, temperature, and voltage reach an equilibrium in overcharge. Cells are designed to reliably handle continuous overcharge at their cell specification rate. Hence overcharge is not to be considered an adverse condition. Overcharge is simply a term commonly used to describe the normal continuation of charge after the cell is fully charged.

Standard-Charge cells may be overcharged at rates up to 0.1**C**. Quick-Charge cells which are designed to withstand higher overcharge rates for an extended time are normally charged at rates up to 0.3**C**. Fast-Charge cells, those that are normally charged at 1**C** to 4**C** rate, require special charger systems that automatically terminate the high rate. Overcharge at rates above the cell specification rate can result in excessive temperatures and venting, and is therefore abusive to sealed nickel-cadmium cells.

The electrode design of Fast-Charge and Quick-Charge cells facilitates rapid recombination of oxygen at the negative electrode which decreases the amount of oxygen pressure in the cell at any given rate. However, fast-charge rates still generate oxygen too rapidly to continue into overcharge without venting. Therefore, the charge rate must be reduced when the cell approaches full charge.

3.4.1 Tafel Curves

When a sealed nickel-cadmium cell is in overcharge within the cell specification rate, the internal pressure, temperature, and voltage of the cell eventually reach a state of equilibrium. At this condition of equilibrium, the typical voltage/current/temperature relationship is quite predictable from cell to cell. The characteristic of cell voltage vs. overcharge current, called the *Tafel Curve*, is a function of cell temperature as shown in Figure 3-8. Some of the charger circuits described later in this Chapter use this characteristic as

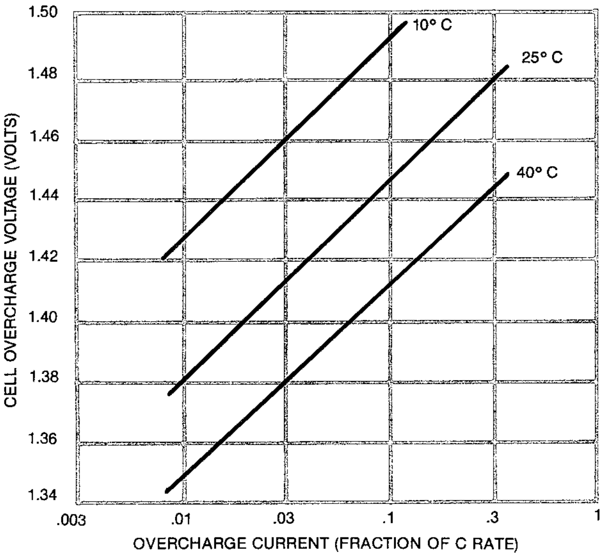


Figure 3-8 Tafel Curves for Typical Sealed Nickel-Cadmium Cells

one factor in determining temperature compensation of their voltage sensing circuit.

3.4.2 Battery Overcharge Temperature

After a sealed nickel-cadmium battery has reached overcharge, all electrical input energy is converted to heat energy. As with any other body which depends upon thermal conduction, convection, and radiation to transfer internally generated heat to the ambient, the temperature of a sealed nickel-cadmium battery in overcharge will rise above the ambient temperature by an increment related to power input. This temperature rise is sufficient to transfer the generated heat to the ambient and to establish and maintain thermal equilibrium. The temperature of a sealed nickel-cadmium battery is a major factor in determining battery life, as discussed in Chapter 5. Therefore, it is desirable to minimize battery temperature when the battery is overcharged for extended periods of time, and it is important to consider the factors which determine battery overcharge temperature.

The temperature of the nickel-cadmium battery in overcharge is influenced by:

- Ambient temperature
- Overcharge current magnitude
- The heat transfer coefficient of the battery

These factors are discussed below as they relate to battery overcharge temperature.

An ideal provision for minimizing battery overcharge temperature would utilize thermally conductive epoxy bonding of each cell to a heat sink that is maintained at a moderate temperature. This approach is seldom acceptable from the standpoint of both cost and space. Consequently, transfer of overcharge heat from a battery most often depends upon convection and radiation.

For these modes of heat transfer, the ambient temperature is typically considered to be the temperature of the air and objects surrounding the battery. In some applications, the ambient temperature may be the temperature inside equipment in which the battery is mounted. The air inside such equipment and the walls of the equipment will be heated by the battery and possibly by other sources of heat. This may cause the battery to experience an ambient temperature significantly greater than that of the room where the equipment is located. In order to estimate battery overcharge temperature, the immediate battery ambient temperature is the base temperature to which the overcharge heat generation induced temperature rise must be added.

For the convection component of heat transfer, the relationship between battery temperature rise and overcharge heat power generation is expected to be linear. Though usually considered nonlinear for radiation heat transfer, this relationship is, in reality, surprisingly linear over the relatively small range of battery temperature rise that is encountered. Consequently, for the combination of convection and radiation heat transfer, the overcharge temperature rise (ΔT) of a sealed nickel-cadmium battery can be considered proportional to the heat power that must be dissipated. This relationship is expressed below:

$$\Delta T\ (^{\circ}\mathrm{C}) = R_T \times P$$

Where: R_T = Thermal resistance, battery to ambient (°C/watt)

P = Overcharge power input (watts)

The overcharge power input is the product of battery overcharge voltage and overcharge current ($P = E_{oc} \times I_{oc}$). The overcharge voltage of the battery, within cell specification overcharge limits, is typically 1.45 volts per cell. The overcharge power input to a battery can be expressed by:

$$P\ (\mathrm{watts}) = E_{oc} \times I_{oc} = n \times 1.45 \times I_{oc}$$

Where: E_{oc} = battery overcharge voltage
I_{oc} = overcharge current (amps)
n = number of cells in battery
1.45 = typical cell overcharge voltage (volts)

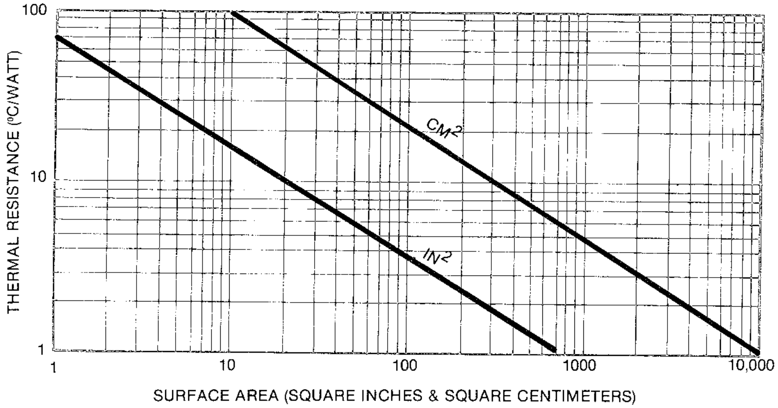


Figure 3-9 Sealed Nickel-Cadmium Battery Temperature Rise in Overcharge (Thermal Resistance as a Function of Package Surface Area)

The thermal resistance (R_T) associated with composite convection and radiation heat transfer to the surrounding ambient, from a battery enclosed by a rectangular case, can be obtained from Figure 3-9. The total surface area of the battery case is calculated in square centimeters or square inches and the corresponding value of R_T is then read from Figure 3-9. The value of R_T from this curve will be reasonably accurate for typical battery case wall materials such as metals and solid plastics of practical thickness. The thermal resistance from the inner surface to the outer surface of a typical (nonfoamed) plastic case wall is relatively small. The two major elements of thermal resistance encountered in dissipating battery generated heat are the thermal resistances from the cells to the case and from the case to the ambient.

Once the values for the overcharge power input and thermal resistance are obtained, the battery overcharge temperature rise can be calculated using the equation:

$$\triangle T(^\circ C) = R_T \times P$$

This temperature rise is added to the battery ambient temperature to obtain the calculated temperature at which the battery will operate in overcharge. This heat transfer model will typically fail to account for some characteristics peculiar to an application. Therefore, the calculated battery temperature for an encased battery should be considered a preliminary value and an actual temperature measurement should be made on a system prototype.

Several techniques, e.g. maximization of the battery surface area and elimination of the battery case, can be used to minimize overcharge temperature rise. Without the constraints of a case, maximization of effective surface area could be attained by having each cell physically separated from the others. Air would flow freely over all cells and heat would be radiated from the total surface of each cell. If a battery must be encased, and if the cells must be contiguous and they have a length-to-diameter ratio greater than one, the minimum overcharge temperature will occur with the cells connected end to end. At the other extreme, the greatest temperature rise will result when closely packed cells are foamed into a case approximating a cube. The foam impedes heat transfer from the cells to the case and the cubic battery shape results in a minimum surface area for transferring heat from the case to the ambient. A feasible design for a given application will probably lie somewhere between the extremes cited above. Nevertheless, design efforts which do succeed in minimizing the overcharge temperature of a required battery configuration will be rewarded by increased battery life.

Several general observations regarding battery overcharge temperature rise should be kept in mind when designing a battery into an application. The following points, which reflect those observations, indicate sensitivity to various parameters. Each of these effects is implicitly accounted for in the previous equation.

- The battery overcharge temperature rise is essentially proportional to overcharge current ($\Delta T = R_T \times E_{oc} \times I_{oc}$). Battery temperature remains near ambient temperature, relatively independent of charge rate, until the battery approaches full charge. The battery tempera-

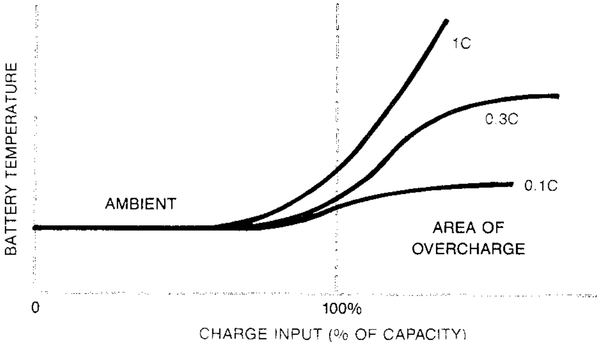


Figure 3-10 Typical Battery Temperature Response During Charge and in Overcharge

ture then transitions to the overcharge value where, for example, the temperature rise of a Quick-Charge battery overcharged at the 0.3**C** rate is three times the temperature rise of the same battery overcharged at the standard 0.1**C** rate, as shown in Figure 3-10.

- The number of contiguous cells in a battery has an effect on battery overcharge temperature rise. For example, a battery consisting of ten contiguous cells, of a given size and overcharged at the 0.1**C** rate, will have a greater temperature rise than a battery of five cells of the same size and in the same configuration which are overcharged at the same rate. This occurs because the input power in overcharge is proportional to the number of cells in the battery, but the surface area of the battery increases at a rate which is less than proportional to the number of cells. In summary, the battery with the larger number of cells has a greater overcharge input power per unit of battery surface area; consequently, it will have a greater temperature rise.
- If the same relative charge rate, such as 0.1**C**, is maintained for all cell types, an increase in cell capacity will bring about a proportionate increase in overcharge heat power but a less than proportionate increase in surface area over the range of typical cell designs.

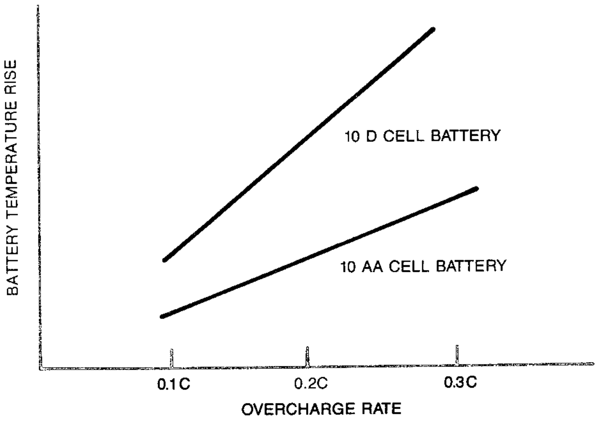


Figure 3-11 Battery Temperature Rise vs. Overcharge Rate for Two Batteries of Different Cell Sizes

The result is that battery temperature rise increases with battery capacity when the same relative charge rate, e.g. 0.1**C**, is maintained. This is shown in Figure 3-11 where the overcharge temperature rise of a battery of ten "D" cells is observed to be greater than the overcharge temperature rise of a battery of ten "AA" cells.

3.4.3 Need for Charge Control

The discussion above shows that the cell internal pressure and temperature can rise considerably, particularly when the overcharge rate is high. In many cases the charge current is low enough so that no damaging pressure or temperature effects will occur to the cell in continuous overcharge, even with years of uninterrupted overcharge. In other applications, the charge current in overcharge is too high to permit continuation into overcharge at this high rate because either the cell pressure or temperature could rise high enough to damage the cell, limiting its life. (See Chapter 5 on battery life.) In these applications, charge control is required. Overcharge control is the subject of Section 3.7.

3.5 CHARGING WITHOUT FEEDBACK CONTROL: CHARACTERISTICS AND METHODS

As mentioned above, in many applications for sealed nickel-cadmium cells and batteries the charge current is low enough and the ambient temperature surrounding the battery is such that continuing the same charge rate into overcharge is quite acceptable.

The following sections discuss charging for applications where batteries can remain in continuous overcharge, even for years, at a constant charge rate.

3.5.1 Cell Capabilities

The most frequently used and economical method for charging sealed nickel-cadmium batteries is the application of a continuous charge current which is within the cell specification overcharge capability. *General Electric* sealed nickel-cadmium cells are available in two *overcharge* capabilities:

- Standard-Charge or *overnight* charge capability
- Quick-Charge capability (rates higher than the standard charge rate)

(Fast-Charge cells have the same *overcharge* capability as Standard-Charge cells.)

3.5.1.1 Standard-Charge

The Standard-Charge capability is the 0.1**C** rate and a Standard-Charge cell is designed to be continuously charged at rates up to 0.1**C**. Normally, a cell charged at the 0.1**C** rate will become fully charged within 16 to 20 hours. In a few special instances 24 hours or more may be required for a full charge. Charge rates below the 0.05**C** rate are normally discouraged, particularly in applications at elevated temperatures or where frequent discharges are required, as the cell may not achieve full performance. This is discussed further in Chapter 4. (Fast-Charge cells may not be overcharged at the fast-charge rate; their maximum overcharge rate is shown in specification sheets but is typically set at 0.1**C** or less.)

3.5.1.2 Quick-Charge

The Quick-Charge capability permits continuous charging at rates up to 0.3**C** which will bring a discharged cell to full performance in as little as 4 to 5 hours and then continue with uninterrupted overcharge at up to the 0.3**C** charge rate. The maximum overcharge rate for a Quick-Charge cell is the 0.3**C** rate. Quick-Charge cells can be charged at lower rates, such as 0.2**C**, and these lower rates are often used to reduce overcharge temperature rise of large battery packs.

3.5.1.3 Considerations for Charging Without Feedback Control

Care must be taken to ensure that the charge rate and the cells are suited to the application's environmental requirements. If the ambient temperature is low, the cell internal pressure may rise too high in overcharge due to diminished oxygen recombination capability at the negative electrode. Figure 3-12 shows the impact of cell temperature upon sta-

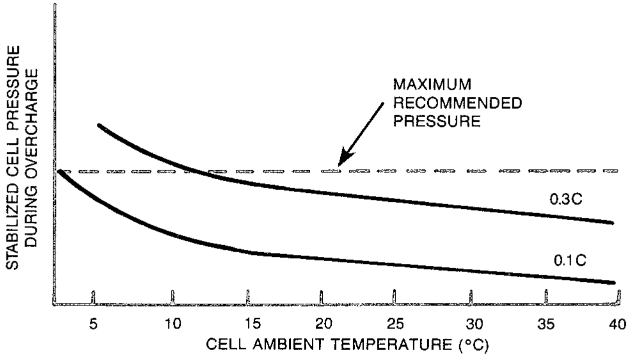


Figure 3-12 Internal Cell Pressure at Various Cell Temperatures in Overcharge

bilized internal cell pressure in overcharge. Therefore, if the battery will be exposed to low temperature environments charge control may be required. (Section 3.6.5 discusses low temperature charging.)

If the ambient temperature is high, the battery temperature in overcharge can rise significantly for large battery packs with large cells, as Section 3.4.2 showed. Continued exposure of cells to high temperature will limit the battery's life. Therefore, charge control to reduce overcharge temperature or special high temperature *Goldtop*® cells may be desired. (Battery life is discussed in Chapter 5.)

3.6 CHARGING POWER SOURCE

Sealed nickel-cadmium cells and batteries may be charged from either a direct current (dc) power source (such as another battery, a dc generator, or a photo-voltaic cell array), or they can be charged from a rectified alternating current (ac) power source. Both will be discussed below. Whichever power source is chosen, sealed nickel-cadmium cells are normally charged with a *relatively constant current.*

The *ideal* constant current source has an effective source impedance which is infinite. Approaching this ideal requires electronic regulation of charge current which is often not economically justifiable. The *constant current charger,* in practice, has a source impedance just large enough to acceptably restrict overcharge current variations resulting from anticipated source and battery voltage variations.

3.6.1 DC Power Source

A very simple method of charging utilizes a dc power source as shown in Figure 3-13. The charge current is calculated by the equation below:

$$I_{ch} = \frac{E_s - E_b}{R}$$

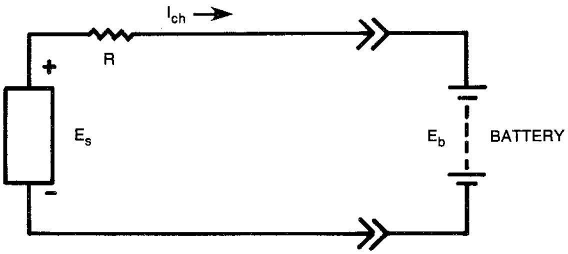


Figure 3-13 DC Charging Circuit

Where I_{ch} = Charge current
E_s = Source voltage
E_b = Battery charge voltage (1.45V/cell typical)
R = Current-limiting resistance

If the source voltage is only slightly greater than the battery charge voltage, small source or battery voltage variations result in large variations in charge current. If regulated source voltage is used, its voltage may need to be only slightly greater than the battery charge voltage. However, under this condition, temperature changes in the battery may cause enough variation of the battery electrochemical polarization to result in a significant change in the charge current. (Voltage versus temperature is shown in Tafel curves in Figure 3-8.)

3.6.2 AC Power Source

Most constant current chargers for nickel-cadmium batteries use the alternating current (ac) line as a power source. The basic requirements of common ac source chargers are like those of the dc power source, namely, the source voltage is significantly greater than the battery voltage and impedance limits the current. The impedance of an ac power source can be reactive, resistive, or a combination of these. Current limiting by reactance has an advantage in that the reactive impedance component does not contribute to heat generation. Rectification is used to convert the alternating current into direct current that flows only in the charging direction through the battery. Most chargers utilize a transformer which permits optimized matching of the source voltage to the charge voltage of the battery. Another important feature of the transformer is that it provides isolation of the charging output from the ac line, thus avoiding the hazard of electrical shock.

Several transformer circuits are conventionally used for charging from ac power. Those considered here are shown in Figures 3-14 through 3-16. In these circuits, the current limiting action is assumed to be achieved primarily by resistance. This resistance is usually accomplished by proper sizing of the wire in the transformer windings, with contribution from both the primary and secondary windings.

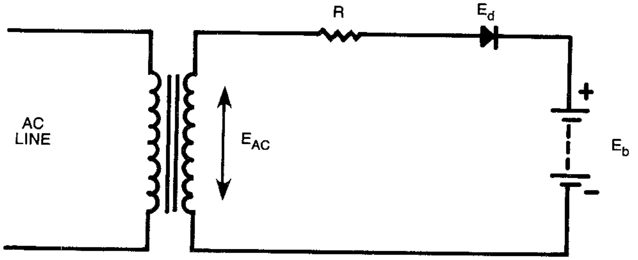


Figure 3-14 Half-Wave Charging Circuit

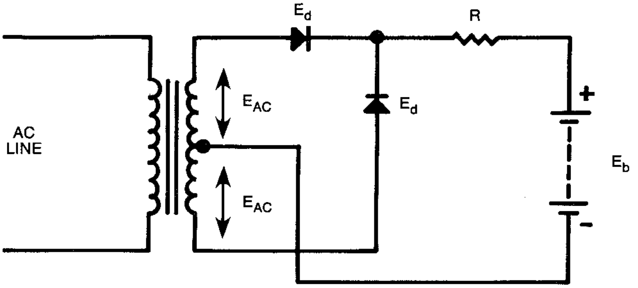


Figure 3-15 Full-Wave Center-Tap Charging Circuit

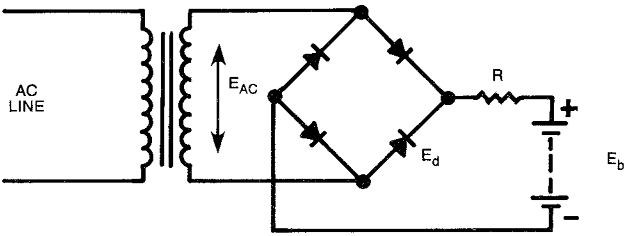


Figure 3-16   Full-Wave Bridge Charging Circuit

The nickel-cadmium battery can be charged equally well with either half-wave or full-wave current. Half-wave rectification (Figure 3-14) is the most economical where low power levels are involved, and hence is the most popular method. For higher power chargers, it is usually economically advisable to use full-wave rectification (Figures 3-15 and 3-16).

An additional charge circuit is shown in Figure 3-17. This circuit uses a capacitor to limit current in conjunction with a full-wave bridge rectifier. The primary advantage of this circuit is that it is essentially loss-free. With a 120V, 60 Hz source, the charge current is approximately 40 milliamperes (mA) per microfarad of capacitance. For a 220V, 50 Hz source, the charge current is approximately 60 mA per microfarad of capacitance. The capacitor must be able to withstand peak line voltage.

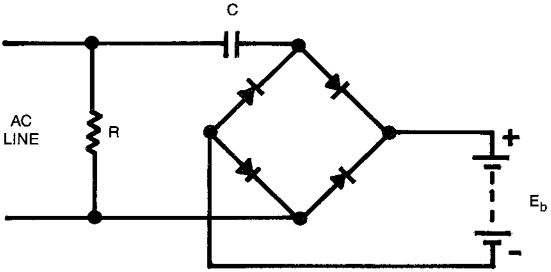


Figure 3-17   Capacitive Charging Circuit

The peak inverse voltage rating of the bridge rectifier in Figure 3-17 needs to equal only the battery charge voltage if the battery is never disconnected from the charge circuit, but must withstand line voltage if the battery is disconnected. The circuit is typically used for charging small capacity batteries. The primary disadvantage of this circuit is that it provides *no electrical isolation* from the ac line. Therefore, in a practical sense, *safety* considerations limit the application of capacitor-type chargers to devices where the charger and battery are completely enclosed. The enclosure must prevent user contact with any part of the circuit including the battery contacts. Resistor **R** in Figure 3-17 serves only to discharge the capacitor to prevent possible *electrical shock*, at the line cord plug, when the circuit is disconnected from the ac receptacle.

3.5.3 Current Regulation

The charger must provide sufficient current regulation so that the battery is not damaged when it is left in overcharge. In Section 3.4.1 the overcharge characteristic (Tafel curves, Figure 3-8) of sealed cells shows that cell charge voltage is a function of cell temperature as well as overcharge current. The nickel-cadmium charger current must be sufficiently well regulated to prevent the overcharge current from reaching unacceptable levels as a consequence of high battery temperature and high ac line voltage. The *overcharge* rate should *never* exceed the cell specification charge rate by more than 20 percent.

To achieve an acceptably well regulated *constant current* charger design, the transformer secondary voltage of an ac power source is selected so that its open circuit voltage is about 2.2 volts root mean square (rms) per cell. The voltage drop of each series rectifying diode must also be considered. The following information may be a useful guideline for the design of simple chargers.

The dc overcharge current with rectified ac source can be calculated using two equations:

Half-Wave: $I_{oc} = \frac{\sqrt{2}E_{ac}}{\pi R} \times K_1$

Full-Wave: $I_{oc} = \frac{2\sqrt{2}E_{ac}}{\pi R} \times K_1$

Where: I_{oc} = Overcharge current
E_{ac} = ac rms open circuit source (secondary) voltage (outside to center tap when center tap is used)
R = Sum of total effective transformer resistance and external resistance
K_1 = Coefficient taken from Figure 3-18
Where:
E_b = Battery voltage during overcharge
E_d = Diode voltage drop

Overcharge current I_{oc} is not a linear function of the difference between E_{ac} and $[E_b + E_d]$. This difference is accounted for in coefficient K_1 (determined from Figure 3-18). The rectifier voltage drop E_d is a nonlinear function of current, but 0.8 volt is a typical value that can be used for the silicon diode; a value of 1.6 volts must be used when calculating for a silicon bridge rectifier.

The value of voltage to be entered as E_b is typically 1.45 volts per cell at 23°C (see Tafel curve Figure 3-8) for 0.1**C** to 0.3**C** charge rates. The ratio of rms current to dc charging current is always greater than 1.0 in a rectified ac charging circuit. This ratio increases as the ratio of E_{ac} to $(E_b + E_d)$ decreases. The rms current must be calculated to determine the ratings for the transformer, diode(s), and any external resistor. This rms current can be calculated using the appropriate equation below. Coefficient K_2 is determined from Figure 3-18.

Half-Wave: $I_{rms} = \sqrt{2}\, K_2 I_{oc}$

Full-Wave: $I_{rms} = K_2 I_{oc}$

The greatest rms current will occur with high line voltage and at the start of charge where battery voltage may be

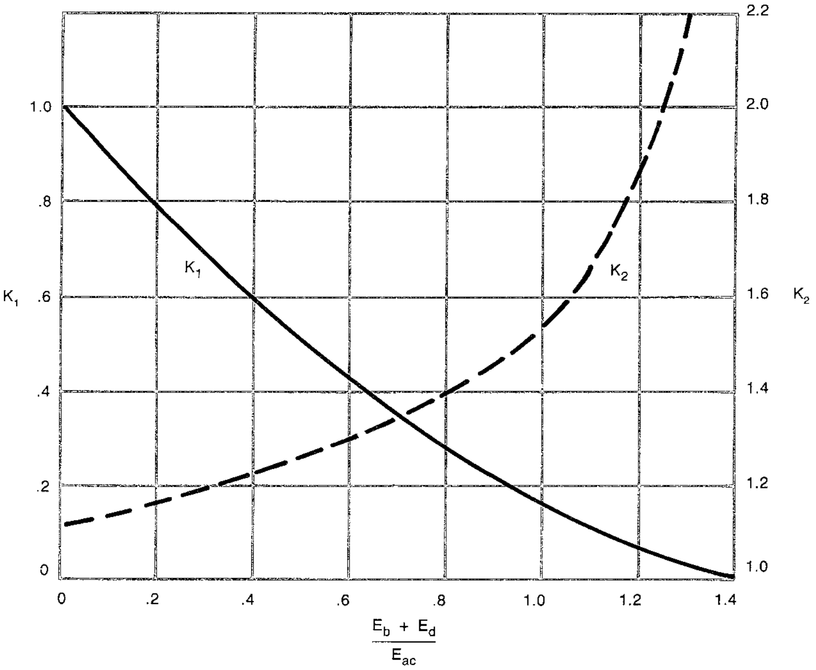


Figure 3-18 Coefficients K_1 and K_2 for Calculating Charging Circuit Currents

about 1.30 volts per cell. Charging circuit components must be rated to tolerate these conditions for a significant portion of the charge time and even more severe conditions for a brief period if a battery has been deeply discharged to zero volts.

3.6.4 Series/Parallel Charging

As discussed above, charging of sealed nickel-cadmium cells and batteries is quite simple when the batteries or cells are connected in series. *Sealed cell batteries should not be charged in parallel.* Because of the slight differences in the Tafel curve (Figure 3-8) of each cell, one battery in a parallel-connected group of batteries may accept more current in overcharge than the other battery. This one battery would heat up due to its acceptance of more current, its electrochemical polarization would decrease, and it would accept even more of the charge current. A slight imbalance in the overcharge current can increase to where one battery is overcharged at a level significantly greater than its cell specification rating.

It is possible to constant-current charge multiple nickel-cadmium sealed cell batteries from a common power source, but a current limiting resistor must be associated with each battery as indicated in Figure 3-19. If the batteries do not all have the same number of cells the source voltage must be adequate for the battery having the greatest number of cells and each resistor must be of the proper value for the number of cells and capacity in that charging branch. When an ac source is used, and all batteries have the same number of cells, a single rectifier of adequate rating can be used at point Ⓐ of Figure 3-19 in place of individual rectifiers in each charging branch.

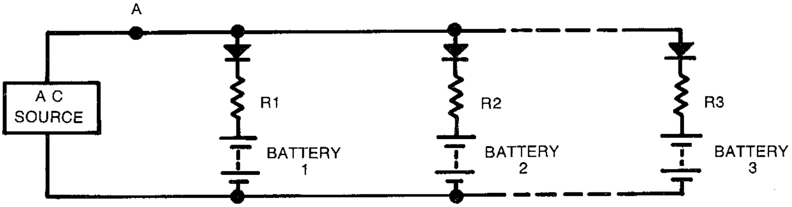


Figure 3-19 Constant-Current Charging in Parallel

For standby power applications it is sometimes desirable to have a large bank of parallel connected batteries under continuous charge. Figure 3-20 gives a typical schematic. The batteries are independently charged through their respective resistors from the rectified source and are isolated from each other by rectifiers (CR1) through (CRN). When switch (S1) is closed, all the batteries will contribute load current equally.

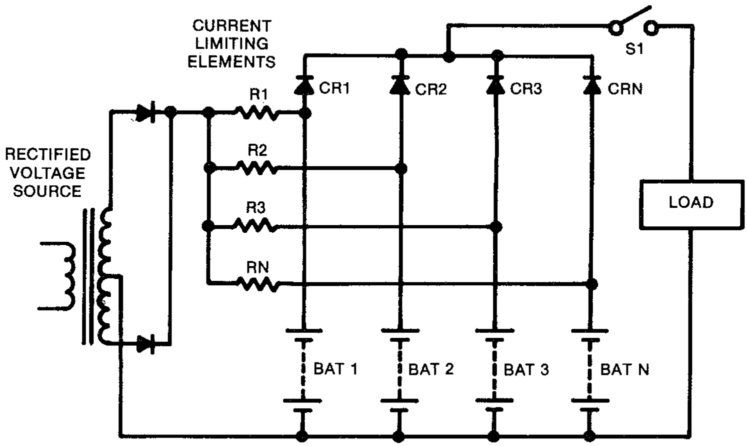


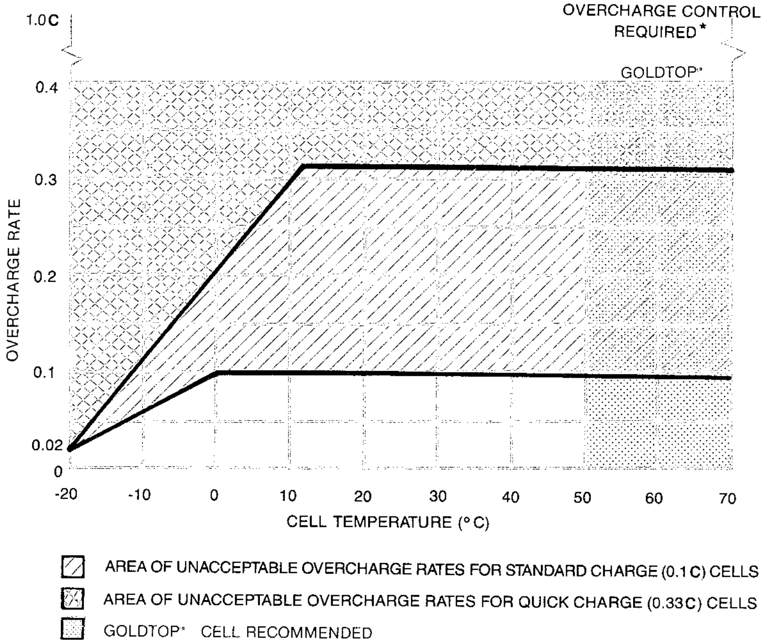
Figure 3-20 Charging in Parallel for Standby Power Applications

3.6.5 Low-Temperature Charging

Charging at low temperatures introduces a phenomenon not observed at room temperature. At low temperatures the efficiency of the oxygen recombination reaction at the negative electrode is reduced. Depending upon the temperature and the charge rate, hydrogen gas may also be generated at the negative electrode. A build-up of pressure may occur from both oxygen and hydrogen gases when charging at very low temperatures. This pressure increase could be enough to cause the high-pressure safety vent to operate.

In practice, most charging occurs at room temperature well above the temperature at which hydrogen gas generation would become a factor. In Quick-Charge applications where charging below 10°C or Standard-Charge rate applications below 0°C the charger should be designed so that the charging current is reduced as the temperature drops, as in Figure 3-21.

The charging voltage of a cold cell will rise, not only in overcharge as shown in Figure 3-8 (the Tafel Curves), but also during charging due to the reduced mobility of the electrolyte ions at lower temperatures and increased elec-



*(GOLDTOP CELLS CANNOT BE CHARGED ABOVE 0.33C
FAST CHARGE CELLS CANNOT BE OVERCHARGED AT FAST CHARGE RATES)

Figure 3-21 Maximum Recommended Overcharge Rates at Various Temperatures

trochemical polarization at the electrodes. The charging voltage of a very cold cell will rise above 1.50 volts at the 0.1**C** charge rate. The charge current which will bring the charge voltage of a cold cell to no greater than 1.50 volts is low enough to limit excessive gas generation. Accordingly, a voltage *clamp* on the charger circuit which limits charger output voltage (battery voltage) to 1.50 volts dc per cell in addition to the normal constant current regulation is a very effective method of achieving system reliability at low temperatures.

3.6.6 Elevated Temperature Charging

As discussed earlier in Section 3.2.1, the capability of a sealed nickel-cadmium cell to charge effectively is reduced at elevated temperatures. The amount of charge utilized by a hot cell depends on the charge rate and its temperature. At very low charge rates (less than .05**C** ampere rate) and cell temperature exceeding 40°C, the loss of dischargeable capacity becomes apparent. To achieve the highest level of charging effectiveness when charging above 40°C, the charge rate should be at the maximum overcharge rate within the cell specification overcharge rating.

But charging cells in an elevated-temperature environment at a higher rate introduces another problem. The cell temperature in overcharge will rise above its ambient temperature in proportion to the charge rate; a high overcharge rate will therefore bring about a correspondingly high rise in cell temperature. If the ambient temperature is already high, the cell temperature in overcharge can rise to such a level that continuous overcharge will significantly reduce cell life (discussed in Chapter 5). One way to overcome the high temperature in overcharge is to use the charge control methods discussed in Section 3.7.4.

3.6.7 Photo-Voltaic Source

Photo-voltaic cells, sometimes referred to as *solar cells,* are commonly used for charging nickel-cadmium batteries in space vehicles and in remote locations.

Figure 3-22 shows a photo-voltaic array used as a nickel-cadmium battery charger. The reverse blocking diode (CR1) assures that the battery will not discharge through the solar cells when light intensity is low.

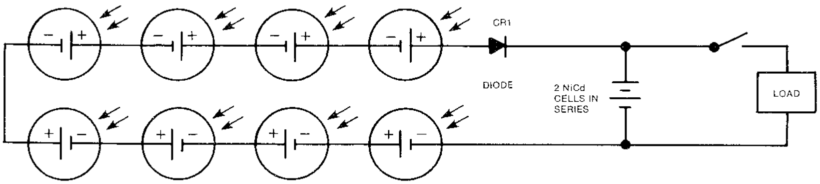


Figure 3-22 Series Array of Photo-Voltaic Cells

Silicon photo-voltaic cells are capable of delivering about 450mV when irradiated by the sun at its zenith (peak sun). There must be sufficient number of solar cells to provide an array voltage of about 1.45V per nickel-cadmium cell plus the reverse blocking diode voltage drop. Within the limits of their voltage output capability, photo-voltaic cells deliver an essentially constant current which is proportional to the incident sunlight. Therefore, no current limiting resistor is required. The photo-voltaic cell size (area) is typically selected to deliver rated nickel-cadmium charge current under peak sun conditions.

3.7 CHARGING WITH FEEDBACK CONTROL: CHARACTERISTICS AND METHODS

The term *Fast-Charge* is defined as a charging technique which permits the battery to be charged at the 1**C** rate or greater to obtain a full charge in about one hour or less. The fast-charging scheme requires that some means be provided to terminate the fast charge before the battery receives too much overcharge at the high rate. Nickel-cadmium sealed cells cannot sustain indefinite overcharge at fast-charge rates.

Many fast chargers utilize the split-rate constant-current approach. Split-rate charging is a technique in which the battery is initially charged at a fast rate. Then, at an appropriate time when the battery is fully charged or nearly fully charged, the charging rate is switched to a slow rate. The slow rate may be 0.1**C** or an even lower *trickle* rate because the battery has already reached a high state of charge.

Fast charging also has the advantage of being able to partially charge a battery in a very short time, often a matter of minutes. The fast charge method is ideal for those applications requiring a number of partial or complete charge/discharge cycles per day.

Fast charging has other limitations in addition to requiring charge control. In most charger designs, the charge control involves a sensor which adds to circuit complexity and cost. The power source must be sized to provide high charge currents which means greater cost, size, and weight relative to a standard-rate charger. There is always a possibility that a fast-charge control will fail to terminate the high-rate charge. A thermal fuse located physically in the battery and electrically in the charging path may provide added protection. The rather large increase in battery temperature, resulting from the uncontrolled and continued fast-charge current, can cause the thermal fuse to open and thus terminate the charge current. The following sections are devoted to the various schemes of charge control employed in fast-charge systems.

3.7.1 Coulometric Control

The most fundamental method of fast charging is to charge the battery such that it receives just the amount of capacity it needs to bring it to full charge and no more. This can be done by measuring, with a coulometer, the amount of charge in ampere-minutes removed from the battery during each discharge and then measuring the amount of charge returned during each subsequent recharge. The fast-charge current is then terminated when the number of ampere-minutes returned to the battery equals the amount needed to recharge the battery.

The coulometer used for charge control is a device capable of integrating current over time. It must be able to provide a signal when a predetermined charge current-time product has been reached. The coulometer and the battery are electrically connected in series. The coulometer can be a chemical or an electronic device. Figure 3-23 shows a block diagram of a coulometer charge control. If the battery is discharged through the load, the discharge current also passes through the coulometer. The coulometer integrates the discharge current-time product. During a subsequent charge, the coulometer integrates the charge current-time product. When the coulometer has integrated a charge equal to the previously integrated discharge it provides a signal to terminate the charge. A scaling factor is usually applied to account for the less than 100 percent efficiency of charging.

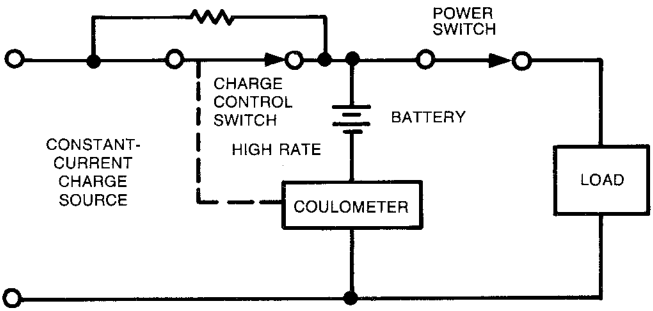


Figure 3-23 Coulometer Charge Control

Coulometer fast-charge control works best on systems in which the battery does not experience long rest periods after charging. Since the coulometer may not possess a self-discharge characteristic similar to nickel-cadmium cells, it may not provide an accurate measure of the input required to offset self-discharge so as to fully charge the battery. This can be compensated for, however, by using coulometer control of the fast-charge rate and then switching to a standard rate to ensure full charge.

3.7.2 Time Control

3.7.2.1 Simple Timed Control

It is advantageous to minimize the amount of time a battery is at elevated temperatures during overcharge because battery life is decreased with exposure to elevated temperature. This is discussed in detail in Chapter 5. A simple time-limit control can be applied to reduce the overcharge to a trickle rate and therefore decrease the temperature, when typical overcharge rates (0.1**C** for Standard-Charge or 0.3**C** for Quick-Charge cells) cause unacceptable temperature rise as discussed in Section 3.4.2. Time limit control can restrict the period of the initial charge rate to the amount of time required for a discharged battery to reach full charge, for example, 16 hours for 0.1**C** rate or 4 hours for 0.3**C** rate. Even if the battery is already near full charge when charging is initiated, the period of overcharge temperature stress established by the time-limit control may be small compared to the period of stress that would result from an uncontrolled charge time.

3.7.2.2 Dump-Timed Control

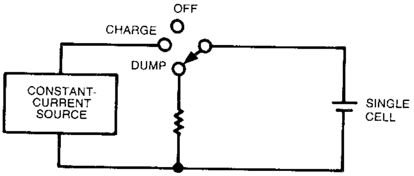
Another fundamental control method for fast charging is to charge the battery for a predetermined amount of time following each use of the battery. If the battery characteristics are known, and the state of charge of the battery is known, a timed charge of extremely high rate can be safely delivered to a sealed nickel-cadmium battery (using a cell designated for charging at that extremely high rate).

This concept of fast charging for a specific time is valid only when the state of charge of the battery is known at the instant the timed high-rate charge is applied. The concept is best suited for single-cell battery applications. Multicell battery applications require very careful analysis of the individual cell characteristics and the interaction between cells with regard to both charge and discharge. Both multi- and single-cell applications need a cell designated for the charge rate used. The following discussion about dump-timed charge (DTC) is limited to single-cell battery applications.

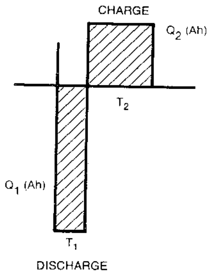
In the timed-charge approach, a constant-current charging source of appropriate output is connected to the battery through a timed switch. The timer can be mechanical, thermal, electrical, or even chemical. When charging, the timer is actuated, the fast-charge current is supplied to the battery for a predetermined time, and it is then terminated. For example, using a cell designed for DTC, a completely discharged 1.0 ampere-hour cell in a given application may be fast charged safely at its 5**C** rate (5.0 amperes) for up to 10 minutes before the timer terminates the fast-charge current. If the beginning state of charge of a cell is zero, the cell may be charged at the fast rate for a rate-time product equivalent to almost one hundred percent of the rated capacity of the cell.

One way to ensure that the cell is discharged enough to safely tolerate a timed fast charge is to apply a discharge load for the period of time that can remove the proposed charge input. The dump-timed charge method in sequence discharges the cell to a level that accommodates the charge rate-time product which immediately follows. The discharge given the cell prior to charge is normally at a rate much higher than the charge rate. Therefore, less time is required for this discharge than for the planned charge time. This fast discharge has been termed a *dump*. When it is followed by a timed charge, the term *dump-timed charge* (DTC) is used.

Figure 3-24 shows the DTC circuit elements and the relationship described in the paragraph above. The cell is discharged at a high rate in a short time, $\textcircled{T_1}$. The cell is then charged at a fast rate for a set period of time, $\textcircled{T_2}$. The product of the dump time and dump rate can be expressed in ampere-hours as $\textcircled{Q_1}$. The product of the charge time and charge rate is $\textcircled{Q_2}$. As long as $\textcircled{Q_1}$ is equal to or greater than $\textcircled{Q_2}$, the times and rates can be varied to suit the application, subject to the particular cell characteristics.



a. DUMP-TIMED CHARGE CIRCUIT



b. DTC CHARGE VS. DISCHARGE

Figure 3-24 Dump-Timed Charge

3.7.3 Pressure Sensing Control

Another possibility for controlling fast charge is to sense the internal pressure of the cell and terminate the fast-charge current when the pressure rises to a predetermined level.

In Section 3.3 it was shown that as the cells in the battery pack approach full charge, some of the charge current begins to cause oxygen gas to form at the positive electrode. Oxygen gas pressure builds up within the cell as the battery approaches full charge. At fast-charge rates oxygen formation is very rapid as full charge is approached and correspondingly the internal pressure rises rapidly. It is this rising pressure characteristic that could be used as the signal to trigger a cutoff of the fast-charge current.

The concept of using pressure as the cutoff signal, though ideal in theory, is not simple to incorporate. To measure the pressure by internal means requires a special cell with a pressure sensor or a modified common cell with the pressure sensor introduced in some way. The modification of a common cell may affect the cell performance and is *not recommended*. Attempts have been made to measure the expansion or swelling of the cell casing through the use of strain gauges as the internal pressure rises. Neither approach has been broadly adopted due to the high cost involved and the possibility of poor reliability on multicell batteries when compared with other charge-control techniques.

3.7.4 Temperature Sensing Control

Fast-Charge nickel-cadmium sealed cells and batteries may be fast charged using battery temperature as the signal to terminate the high charge current, provided that certain precautions are followed. A number of methods, each with certain attributes and limitations, are used to sense temperature and to control the fast charging. The following subsections will describe these various methods and present information to help select the proper method for the specific application being considered.

Temperature control of fast charging relies on the concept, developed in Section 3.3, that there is an increase in internal cell pressure and an increase in cell temperature as a cell approaches full charge and subsequently reaches overcharge. Both of these parameters are related to the charge rate and the temperature at which the charging is conducted.

The relationship of cell temperature and cell internal pressure to charge input is shown in Figure 3-25. The internal cell pressure begins to rise before the 100 percent charge input point is reached because some oxygen gas is generated. Consequently the charging efficiency decreases in this region (see discussion in Section 3.2). The rate of pressure rise and the level which the pressure reaches are functions of the charge rate as shown by the solid line curves in Figure 3-25. The cell temperature rise is also a function of the charge rate as shown by the dotted line curves in Figure 3-25. The temperature rise lags behind the pressure rise

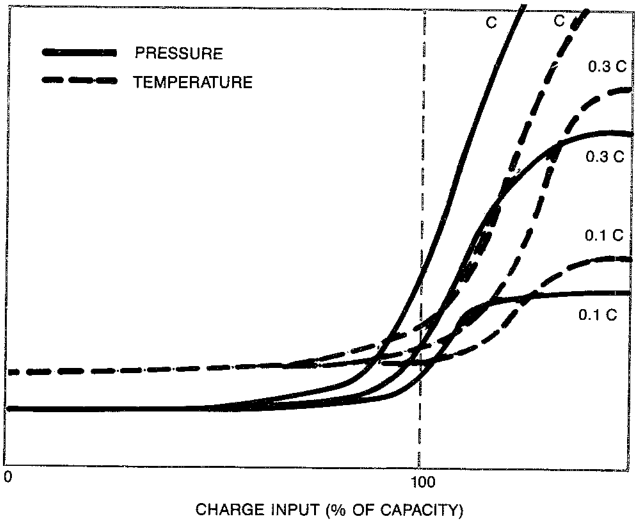


Figure 3-25 Typical Cell Temperature and Internal Pressure During Charging for Various Charge Rates

due to the thermal mass of the cell and because oxygen pressure must exist before recombination can bring about heat generation with a consequent increase in cell temperature. This temperature rise is generally detectable when the cell approaches full charge. The amount of temperature rise for any specific cell size and cell construction has a direct relationship to charge current.

The ambient temperature around the battery during charging has an effect on the cell internal pressure and the final temperature to which the battery will rise. The pressure required to achieve a given rate of oxygen reduction at the negative electrode is an inverse function of temperature. At low cell temperatures the oxygen pressure can rise rapidly and may reach the release pressure of the safety vent mechanism. At high cell temperatures the pressure rise will be substantially less than exists at normal temperatures because oxygen recombination is enhanced.

A variety of methods of using this temperature rise characteristic for controlling the fast charge current are available. In the following sections, four control methods are discussed:

- Temperature Cutoff (TCO)
- Incremental Temperature Cutoff (ΔT TCO)
- Incremental Temperature Control (ΔT Control)
- Rate of Temperature Change Control (dT/dt Control)

The following information on temperature sensors is provided as background for the use of the above temperature cutoff concepts.

Thermostat Temperature Sensing

The simplest temperature sensor for Fast-Charge rate cutoff is the *manual* reset thermostat. This device is a switch that opens when the rising cell temperature reaches the actuating temperature and that can be closed manually when the temperature falls below the temperature which permits manual reset. The thermostat is thermally coupled to a selected cell in the battery pack and can be electrically connected in series with the charging circuit (See Figure 3-26).

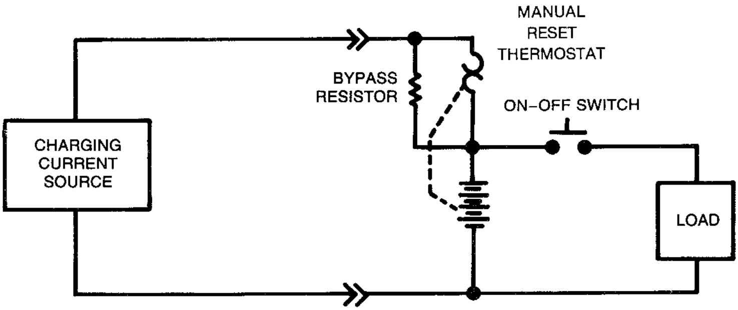


Figure 3-26 TCO Sensing Circuit-Thermostat

A bypass resistor around the thermostat drops the charging current to a trickle charge rate when the thermostat is open. The manual reset thermostat and the bypass resistor become a uniquely simple fast-charge system.

While the advantage of the manual reset thermostat is that it is a low-cost approach to the sensing of the cutoff point and switching the fast-charge current, it has an operational disadvantage. A *dead band* exists between opening and reclosing of the thermostat. Fast-Charge cannot be initiated if battery temperature is above the manual reset temperature of the thermostat, that is, above the opening temperature or in the dead band of the thermostat. This elevated temperature could exist when the battery is connected to the charger in a high temperature ambient. The battery would have to be cooled to the thermostat manual reset temperature before a fast charge could be initiated.

If an automatic reset thermostat is used in place of a manual reset thermostat, an undesirable *bouncing* condition can occur in overcharge. The thermostat, heated to its opening temperature by the battery, terminates fast charge. When the battery cools, the thermostat falls below its closing temperature, and fast charge is again initiated. This repeated on-off condition, illustrated in Figure 3-27, shortens battery life because the cells are exposed to higher average temperature and internal pressure for an extended time. (Battery life vs. temperature is described in Chapter 5.)

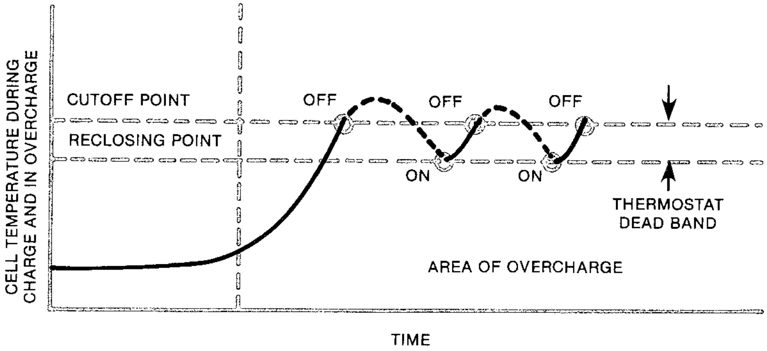


Figure 3-27 Temperature Excursions in Overcharge When Using An Automatic Reset Thermostat

Of course, the manual reset thermostat avoids this on-off bouncing. It will not reclose until it is reset by pushing its reset button, either manually or automatically by reinserting the battery into the charger. A possible method of correcting the automatic reset thermostat bouncing condition would be to thermally couple the low rate charge bypass resistor to the automatic reset thermostat so that its heat would keep the thermostat from cooling and reclosing. However, this would tend to keep the battery at an elevated temperature, especially at the location of the thermostat, until it is disconnected from the charger, thus reducing battery life; this is therefore *not recommended.* A commonly used method to avoid bouncing is to provide an electronic function in the charger which detects the opening of the automatic reset thermostat and then keeps the fast-charge current source disconnected until a positive action has taken place (such as removing the battery from the charger) which is detected by the electronic latching mechanism.

Thermistor Temperature Sensing

Thermistors are temperature sensitive resistors that can be used to sense the temperature of a cell in a battery pack. Thermistors are available with positive temperature coefficient (PTC) and negative temperature coefficients (NTC) of resistance. PTC thermistors which have a large temperature coefficient in the temperature region of interest can be obtained. Because of this large temperature coefficient in a relatively narrow temperature region, this type of PTC thermistor is referred to as a *switch type thermistor*. A Circuit responding to such PTC thermistor is less critical and generally need not include a costly potentiometer for establishing a set point. The switch type PTC thermistor is appropriate for temperature cutoff (TCO) control of fast charge (discussed in Section 3.7.4.1). However, the switch type PTC does not permit matched pairs that behave well over a wide temperature range and thus NTC thermistors are used for incremental temperature cutoff (ΔTCO) fast-charge control (discussed in Section 3.7.4.2). Switch type PTC thermistors are typically more costly than NTC thermistors.

For temperature cutoff control, the signal developed by the thermistor circuit is continuously applied to the control circuit as shown in Figure 3-28. When the temperature rises to the set point, the control circuit acts to open the fast-charge current switch, lowering the charge rate to the trickle rate. The latching function in the control circuit, which may not be reset until an action like the battery's being removed from the charger circuit, holds the current switch

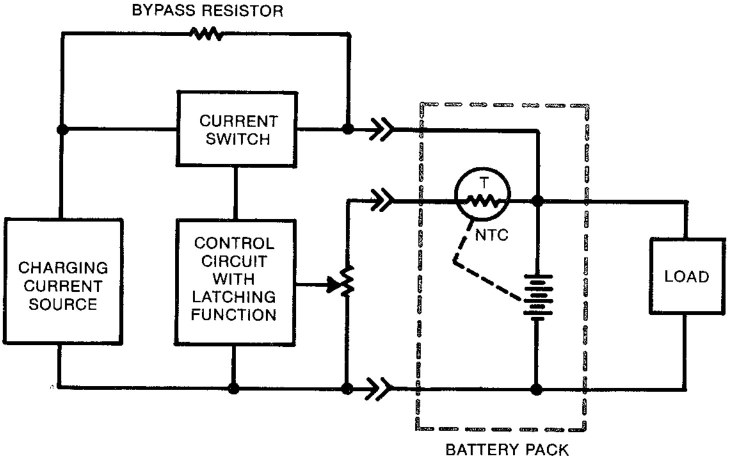


Figure 3-28 Sensing Circuit With Latching Function-Thermistor

open even when the temperature of the cell falls. Thus, bouncing back into high rate overcharge is avoided.

A thermistor is small enough to fit into almost any battery pack without increasing its size. The thermistor, with associated control circuit, has no *dead* band which means that fast-charge can be initiated whenever the cell temperature is below the cutoff setting.

3.7.4.1 Temperature Cutoff

The temperature cutoff (TCO) fast charger is the simplest of all temperature-based fast-charge control methods, particularly with a manual reset thermostat. In its most basic form it consists of a constant current dc power supply and a battery containing a thermostat. The thermostat is tightly coupled thermally to a cell in the battery. As the fast-charge rate is applied to the battery, the battery accepts charge with essentially no temperature rise until the cells approach full charge. As full charge is approached, the increasing presence of oxygen causes the recombination reaction at the negative plate to progress more rapidly, which in turn causes the cell temperature to rise sharply. The thermostat, thermally coupled to a cell casing, is set to operate at a temperature carefully chosen to provide termination of the fast-charge rate well before the cell internal pressure reaches the pressure at which the safety vent would open. Chargers are typically designed so that when the thermostat has operated the charge current is reduced and held to an acceptable trickle overcharge rate.

This sequence of events is represented in Figure 3-29. If the charge is started with cells at room temperature, the cell pressure and temperature show little increase until near full charge. The basic interactions between the rate of rise of pressure and the rate of rise of temperature and their displacement in time determine the feasibility of utilizing temperature rise as a fast-charge control.

In Figure 3-29, the temperature sensor is set to terminate the fast-charge rate when the cell temperature reaches 45°C.

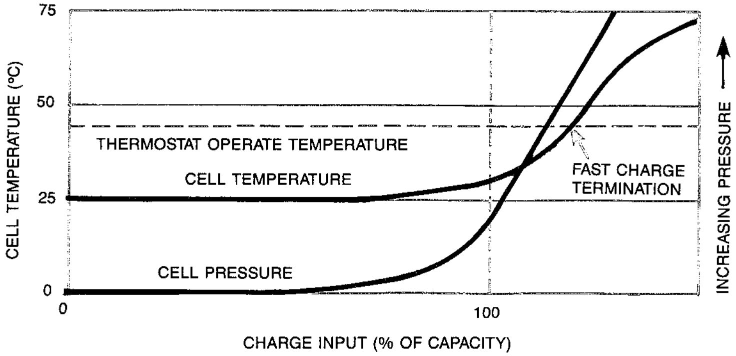


Figure 3-29 Sealed-Cell Pressure and Temperature During Charging vs. State of Charge in 23°C Ambient

At this time the gas pressure within the cell is climbing rapidly but is normally within operating limits. A fast-charge system utilizing *General Electric* Fast-Charge cells and a TCO charger will, in most circumstances, provide a perfectly viable system. However, three special situations must be considered:

1. Battery Charged In A Low Temperature Ambient—This condition presents a serious limitation to the TCO concept. When a battery is charged in a low temperature ambient, it may fail to reach the predetermined cutoff temperature, leading to uncontrolled fast charging and permanent cell damage. The two curves in Figure 3-30 illustrate the same battery at the same charge rate but charged in two different ambient temperatures. The battery charged at room temperature, Curve Ⓐ, reaches the cutoff temperature setting. The battery in the cold environment, Curve Ⓑ, fails to cutoff the fast-charge current.
2. Cold Battery Placed In The Charger—This condition is also a serious shortcoming of the fast charge TCO concept. If the battery is cold at the start of charging, even if charged in a 23°C ambient temperature, the cutoff temperature may not be attained before pressure in the cell has reached an excessive value and venting has occurred. The temperature profile would look like Curve

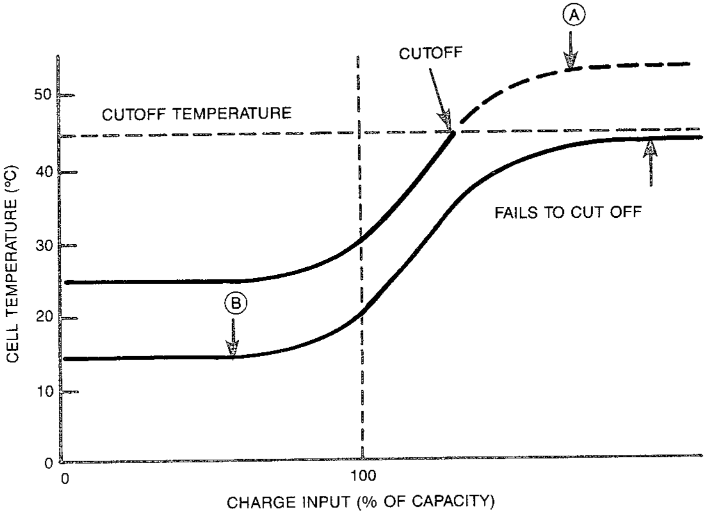


Figure 3-30 Effect of Low Ambient Temperature on Ability of System to Cutoff

Ⓔ in Figure 3-31. The time in overcharge to reach the temperature cutoff point for Curve Ⓔ is longer than that for a battery at room temperature, represented by Curve Ⓓ. Therefore, the peak pressure would be significantly higher for battery Ⓓ than Ⓔ. This is in addition to the problems covered in Section 3.6.5 on low-temperature charging.

3. Hot Battery Placed in the Charger—If the battery temperature is above the cutoff setting of the temperature sensor, the charger will deliver only the trickle charge rate to the battery. When the battery cools down to the reset point of the thermostat, the fast-charge current can be initiated.

If these three situations do not occur, the TCO concept, when used within cell specification charge rates and appropriate cutoff temperature settings, will be a very reliable charging system. If either of the two cold temperature application situations is likely to occur, one of the other temperature sensing systems should be selected.

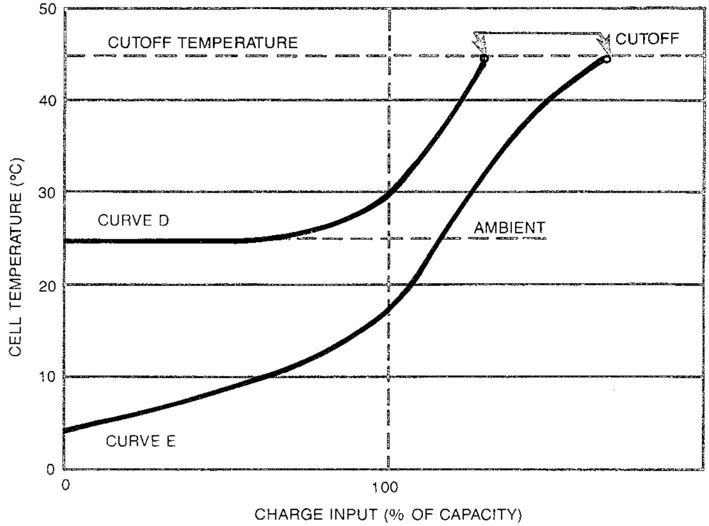


Figure 3-31 Effect of Cold Battery in Room Ambient on the Time to Reach Temperature Cutoff

3.7.4.2 Incremental Temperature Cutoff

The preceding cold ambient temperature application situation which causes the simple TCO fast-charge control concept to be unsuitable is overcome with the Incremental Temperature Cutoff (△TCO or delta TCO) concept wherein fast charge is terminated when the battery temperature has risen by a predetermined increment above the ambient temperature.

Figure 3-30 shows the effect of charging a battery in a cold ambient temperature (Curve Ⓑ) and at room temperature (Curve Ⓐ). Using the TCO concept, batteries in either ambient can typically be cutoff reliably after a 10°C rise. In both examples of Figure 3-30 the cutoff with a 10°C △TCO occurs comparatively early so that excessive charging at the fast-charge rate is avoided, resulting in greater battery life (see Chapter 5 on battery life). In the case of Curve Ⓔ in Figure 3-31 the cutoff is accomplished by the △TCO method while the normal TCO fails to terminate the fast-charge current. The sealed nickel-cadmium battery should not be fast charged in an ambient temperature below 10°C. (See Section 3.6.5 on low-temperature charging.)

Two temperature sensors are required to create the ΔTCO system. One is affixed to a selected cell in the battery pack so that it measures the skin temperature of the highest temperature cell in the pack (normally the centermost cell). The other temperature sensor is located away from the battery pack so that it is thermally isolated from battery and charger heat and so it senses the surrounding air. The charge control then terminates the fast-charge current when the battery temperature sensor rises by the selected increment above the temperature of the ambient sensor. The appropri-ate value for the amount of temperature difference (delta) for cutoff should be selected for each case, depending upon type of battery, cell size, number of cells in the pack, battery packaging, and other thermal considerations; the 10°C value is often used.

The temperature sensors are normally thermistors or thermocouples which provide a signal to a comparator circuit within the special charger as shown in Figure 3-32. When the temperature rise reaches the prescribed increment, the comparator circuit signals the fast-charge switch

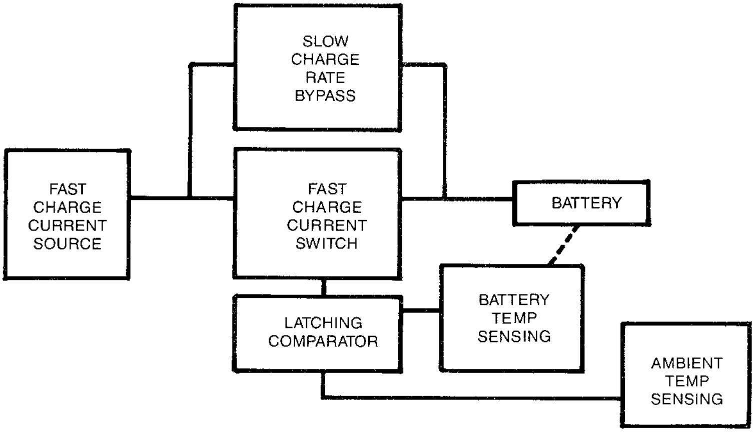


Figure 3-32 ΔTCO Control System to terminate the fast-charge current. A trickle charge current normally continues after the high-rate current is cut off.

3.7.4.3 Differential Temperature Control

Another method of fast-charge control using temperature rise to reduce the charge rate is the Differential Temperature (ΔT) Control Method. This fast-charge control is accomplished by establishing a temperature rise limit which reduces the charge current in overcharge to a rate just adequate to maintain a predetermined battery temperature rise above ambient. Figure 3-33 shows the concept. Output signals from a battery temperature sensor and an ambient temperature sensor provide inputs to a nonlatching comparator which compares the outputs of the two temperature sensors and controls the charge rate. These thermistors are chosen, or their signal outputs are conditioned, so that when the battery temperature has risen above the ambient temperature by a difference ΔT, e.g. 5°C, the comparator and charge current control will act to produce a smooth transition of current from the fast-charge rate to an overcharge rate that will just maintain the predetermined temperature rise ΔT.

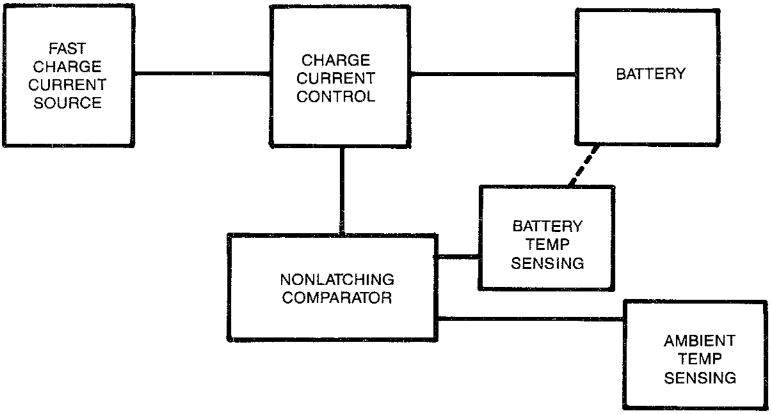


Figure 3-33 ΔT Control System

Because there is no latched cutoff condition, this control system automatically permits a battery, which was hot when placed in the charger, to receive the fast-charge rate when it cools to a temperature less than ΔT above the ambient temperature. This charge control method has a disadvantage in that design precautions must be taken to prevent cyclic rapid ambient temperature changes, caused by air conditioning and heating systems, from causing the charger to deliver pulses of fast-charge current when the battery is in overcharge. (These pulses could provide an overcharge rate greater than the cell specification rate and therefore may be abusive.) Consequently, the method requires extensive system engineering.

3.7.4.4 Rate of Temperature Change Cut-Off

The Temperature versus Time Curve for a nickel-cadmium battery in response to fast-rate overcharge has a shape as shown in Figure 3-34. This characteristic is such that the rate of temperature change (dT/dt) becomes a useful value as full charge is approached.

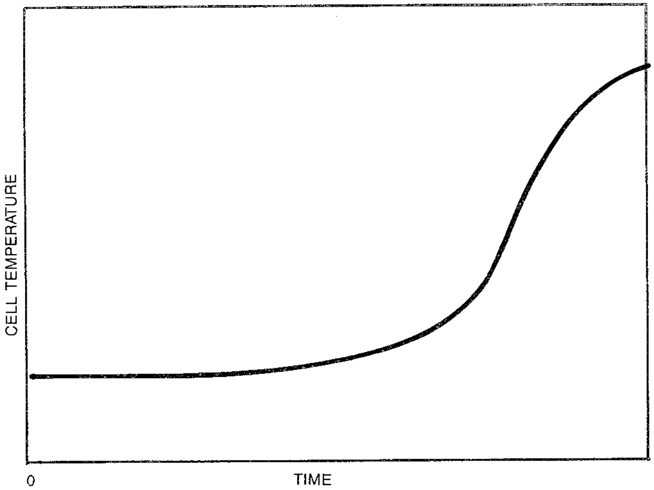


Figure 3-34 Typical Fast-Charge Temperature Profile

The signal from a temperature sensor can be electronically differentiated with respect to time in two ways. The first is to use an operational amplifier. A limitation of this method is the sensitivity of the operational amplifier to the presence of electrical noise which can readily produce extraneous outputs which result in inaccurate control.

The second and better approach is to sense a predetermined small temperature change ΔT based on the average of samples grouped around points in time separated by a time interval Δt. This is readily achievable with a microcomputer chip and becomes particularly feasible when the microcomputer chip is already present for some other purpose. The microcomputer approach requires analog-to-digital (A/D) conversion of temperature sensor signals to provide usable inputs to the microcomputer. The degree of sensitivity of dT/dt that the microcomputer can detect (and thus how early in the temperature rise fast charge can be terminated) is dependent on the resolution and accuracy of the A/D converter and, of course, noise is again a factor.

3.7.5 Voltage Sensing Control

Battery voltage can be used as a signal for controlling charge current and indeed the voltage clamp described previously in Section 3.6.5 on low temperature charging is an example of just such voltage control of charge current.

The many factors which affect nickel-cadmium cell charging voltage such as temperature, age of cell, previous history, and type of construction must be taken into account. These variables can, in many instances, have a greater effect on battery voltage than the state of charge. Therefore, voltage sensing for charge control must take into account the effects and features of the points described in the following section.

It must be recognized that a primary failure mode of nickel-cadmium cells at the end of life is internal shorting (described in Chapter 5). Any fast-charge control method which depends solely on voltage magnitude to terminate fast charge may lose control when a cell shorts. Voltage cutoff (VCO) and constant potential (CP) are examples of charge controls that are subject to this problem. Loss of fast-charge control means the battery will possibly vent a mixture of hydrogen and oxygen. (See Chapter 7 on Safety.)

The voltage of fully discharged sealed nickel-cadmium cell during charging takes on a profile similar to that shown in Figure 3-35. At room temperature a fully discharged Fast-Charge cell, when placed on charge at 1**C** rate, will rapidly rise to about 1.40 volts and then will gradually rise to about 1.45 to 1.50 volts as more of the active material is charged and the cell approaches full charge. After there is little uncharged positive plate active material remaining and oxygen is being generated at the positive plate, the cell voltage again rises somewhat more rapidly.

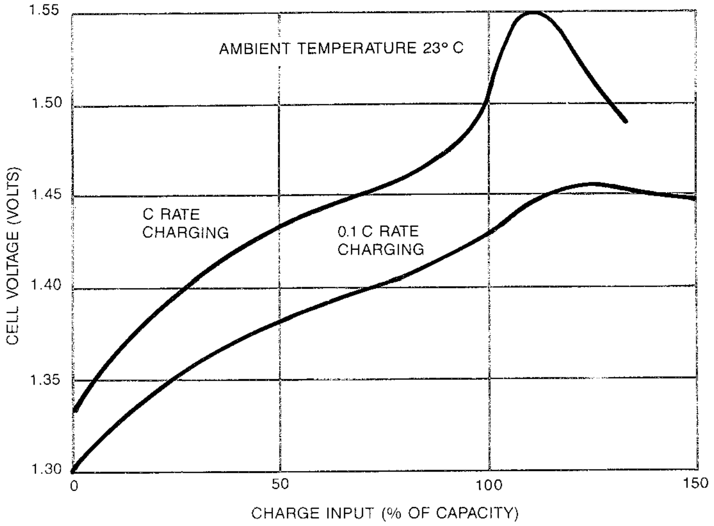


Figure 3-35 Typical Charging Voltage Profile of Sealed Nickel-Cadmium When Charged at 23°C

The level of cell voltage and the rate of rise are dependent upon the charge rate, as shown in Figure 3-36. The degree

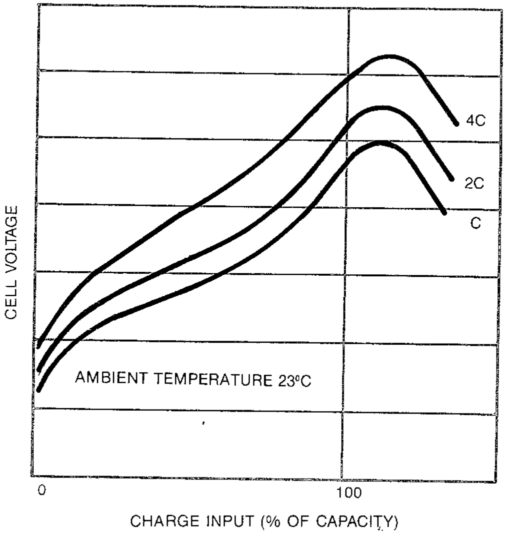


Figure 3-36 Effect of Charge Rate on Voltage Profile of a Sealed Cell Designed for Fast Charging

of the cell voltage rise upon approaching full charge is also dependent on other factors such as the cell design, age, and previous history. Some cells produce a pronounced voltage rise and other cells produce a minimal voltage rise. The curves shown in the figures are general representations of typical Fast-Charge cells.

The charge voltage of all sealed nickel-cadmium cells will also vary with the temperature of the cell. If the cell is very cold the charge voltage can rise to a high value. Conversely, the voltage of a warm cell during charging will be lower, as shown in Figure 3-37.

The typical sealed nickel-cadmium cell will exhibit a charging voltage which varies inversely with temperature by about 3 millivolts per degree Celsius. The charge voltage of sealed nickel-cadmium cells will also vary from cell type to cell type depending upon the design of the cell. These differences in design, construction, and manufacturing processing all have an impact on cell charging volt-

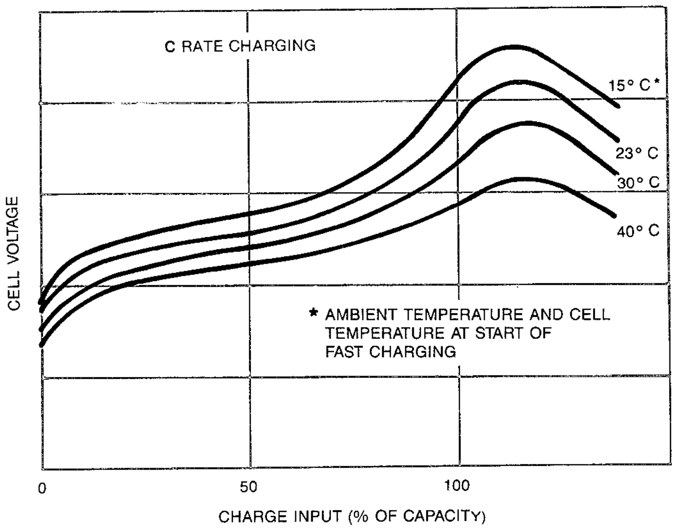


*Figure 3-37 Typical Charging Voltage Profile of Sealed Nickel-Cadmium Cells at Various Ambient Temperatures for 1***C** *Rate Charge*

age. An indication of the range of voltages is shown in Figure 3-38. The three curves shown are representative of the magnitude of charging voltage differences which can be expected from cells of different design, construction, and manufacturing process and are not specific to any actual one.

It is important to appreciate that different charging voltage characteristics will be exhibited by a battery depending upon:

- Charge rate as the battery approaches full charge
- Cell temperature during charging
- Cell design, construction, and manufacturing process

For this reason, the product designer should consult with *General Electric* when designing a fast-charge control using only voltage magnitude. The correct selection of charge rate, signal point, charger design, and degree of temperature compensation of the signal must be selected in light of the cell type. A voltage-sensing control system may lead to product field problems if battery characteristics and

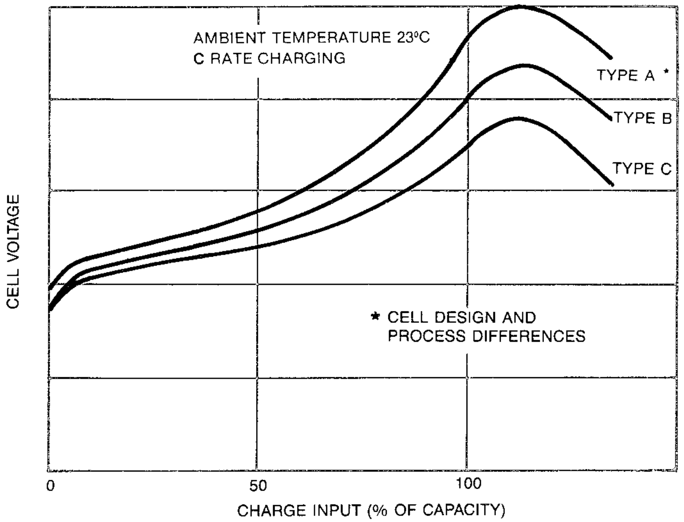


*Figure 3-38 Typical Charging Voltage Profile of Sealed Nickel-Cadmium Cells at 23°C and the 1***C** *Charge Rate*

variations are not understood and taken into consideration. Given the possible difficulties with voltage magnitude charge control, it is generally a technique not promoted by *General Electric.*

3.7.5.1 Constant Potential Source Charging

A constant-potential (CP) charging source would imply that the charger could maintain a constant voltage independent of the charge current load. During the charging operation, few CP-type battery chargers fail to encounter a current limitation. The result is a deviation from the constant-voltage mode. Consequently, this method of charging would more logically be called *voltage-limited charging*. In view of the historically established terminology, however, and to avoid confusion, the expression *constant potential (CP) charging* will be used in this discussion.

Charging from a CP source is quite common for vented nickel-cadmium and lead-acid batteries, but not for sealed nickel-cadmium batteries, because the sealed nickel-cadmium battery charging characteristic is different. Figure 3-39 illustrates this difference in terms of voltage response to a constant charge current. Vented nickel-cadmium and lead-acid batteries exhibit a pronounced voltage increase in response to an applied constant current as the battery approaches full charge. This response is caused by the onset of hydrogen generation at the negative plate. Sealed nickel cadmium produces a relatively small voltage rise. Its negative plate is depolarized by the recombination of oxygen so that no hydrogen overvoltage or gas generation occurs.

When charging from a CP source, the initial charge current supplied to a battery is typically limited only by the

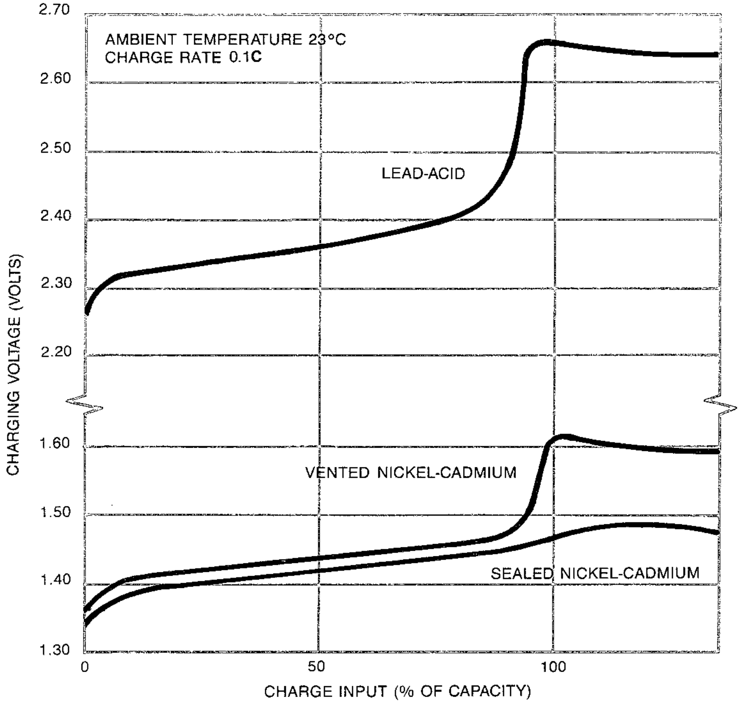


Figure 3-39 Comparison of Charging Voltage Characteristics of Different Types of Batteries

current capability of the charger. This affords an opportunity to rapidly bring the battery to full charge. The onset of hydrogen generation in vented nickel-cadmium and lead-acid batteries, as full charge is approached with a CP source, causes the charge current to decrease to a low level. The constant-potential charge control scenario for sealed nickel-cadmium batteries is not so readily accomplished.

When charged at 23°C, the voltage of a sealed nickel-cadmium battery must reach about 1.45 volts per cell in order to achieve full charge. If charging is done from a CP source of 1.45 volts, the overcharge current would be about 0.1**C** if the cell temperature remained constant.

The heat generation associated with an initial 0.1**C** overcharge current can cause a significant temperature rise for sealed nickel-cadmium batteries. The related increase in electrochemical activity reduces the electrochemical polarization. Maintaining a fixed charging voltage as the temperature rises will result in an overcharge current greater than would have occurred had the nickel-cadmium battery remained at the ambient temperature.

If heat transfer from the sealed nickel-cadmium battery is less than excellent, or if the ambient temperature should increase, overcharge current may continue to escalate with an attendant increase in battery temperature. This system instability associated with a fixed voltage charging source has been classically termed *thermal runaway*. Of course, the severity of the runaway resulting from this instability, loss of charge control, is determined by the current limit of the charger.

If a sealed nickel-cadmium battery is to be subjected to a constant voltage source (CP charging) during overcharge, rather than a current source, it is imperative that such voltage source be automatically adjusted as a function of battery temperature, not ambient temperature. The appropriate adjustment can be determined from the Tafel curves of Figure 3-8. The adjustment coefficient typically used is −3mV per degree C per cell. Even with such automatic modification of charging voltage in response to battery temperature, the designer will want to consider the following points regarding sealed nickel-cadmium CP charging systems:

1. Because of the implicit voltage limit, a CP system may, for some cell designs, be slow in providing capacity recovery after battery storage. This can be improved, however, by incorporating a provision to switch to an acceptable constant current overcharge rate at some point after initiation of charging, e.g. following a time delay.
2. The CP system voltage limit must be selected commensurate with cell design.
3. There is a tendency for sealed nickel-cadmium overcharge characteristics to shift during cell life such that CP system overcharge current increases as the cell ages. This would result in increased overcharge temperature with an associated reduction of battery life. That can be avoided by switching to a constant current overcharge as mentioned in Item 1. above.

3.7.5.2 Voltage Cutoff

The voltage cutoff (VCO) control method uses voltage as the signal to terminate the fast charge. As shown in Figure 3-40, the voltage cutoff method senses the rise in battery charging voltage as the battery approaches full charge. When the voltage rises to the predetermined voltage point, the charger circuit switches off the fast-charge current.

Normally, a trickle-charge current continues to the battery once the fast-charge current is terminated. The charger circuit to accomplish this switching is illustrated by the block diagram of Figure 3-41. The VCO level must be automatically adjusted because of the temperature dependent characteristics of the battery charge voltage.

If the cutoff point is not automatically adjusted for cell temperature, one of the following could occur:

1. Cold Cells in a Cold Ambient—The battery voltage will reach the normal cutoff voltage point quite early; if the

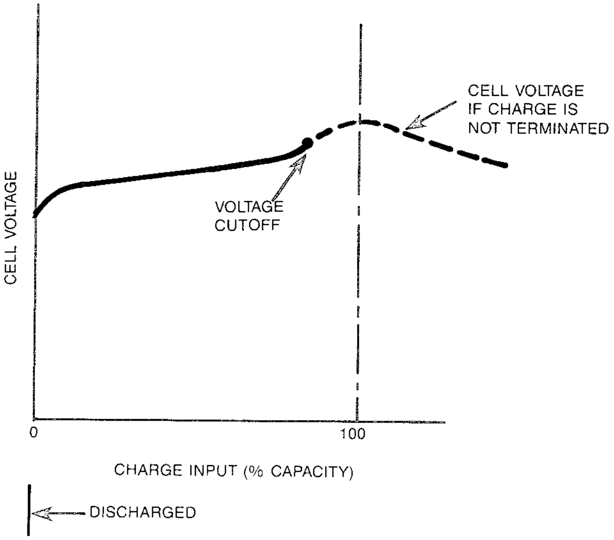


Figure 3-40   Fast Charge VCO Concept

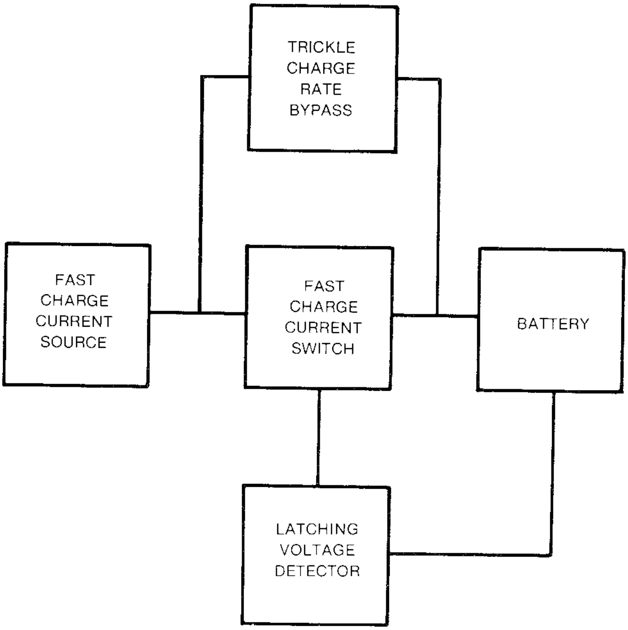


Figure 3-41   Voltage Cutoff Control

cutoff value is not automatically adjusted for cell temperature, the battery will receive only a partial charge before cutoff.

2. Warm Cells in a Warm Ambient—The battery voltage depressed by high temperature may never reach the cutoff voltage point; if the cutoff value is not adjusted for cell temperature, the battery will continue to charge at the fast-charge rate, leading to permanent cell damage and a reduction in life.

3.7.5.3 Rate-of-Voltage Change

Rate-of-voltage-change (dV/dt) charge control provides a means for limiting the amount of overcharge by terminating fast charging at some point where the voltage begins to rise prior to Point ② in Zone Ⓒ of Figure 3-42. The relatively large magnitude of dV/dt of this part of the voltage profile presents an opportunity for terminating fast charge prior to the voltage maximum. The dV/dt charge control system must be designed to ignore the relatively large dV/dt in Zone Ⓐ of the charge voltage characteristic. The system may be designed so as not to respond to a dV/dt for

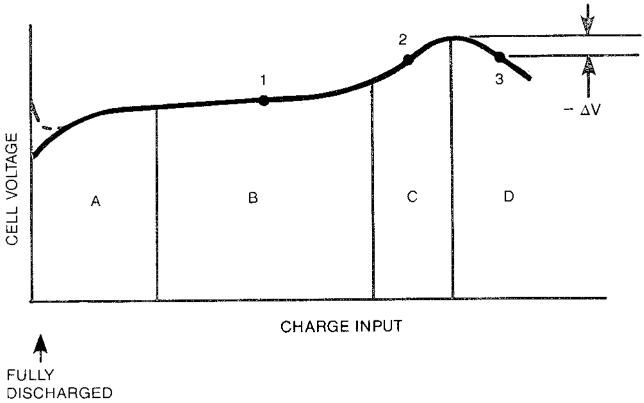


Figure 3-42 Classic Nickel-Cadmium Fast-Charge Profile

some initial period or not to respond until the battery voltage has exceeded some voltage plateau such as at Point ① in Zone Ⓑ.

The ability to terminate fast-charge current on the basis of dV/dt depends on a reliable and repeatable voltage profile. In certain circumstances the battery may not always provide the expected voltage profile and this could result in the fast-charge current not being cutoff. A backup termination method is required. A microcomputer chip is technologically the best approach to process the dV/dt signal. An analog-to-digital (A/D) converter is required to provide a usable voltage signal to the microcomputer.

3.7.5.4 Inflection Point Cutoff

There is usually an inflection point ($d^2V/dt^2 = 0$) near the midpoint of Zone Ⓒ of Figure 3-42 if the battery has been fully discharged or nearly fully discharged prior to charging. Using this feature to accomplish an inflection point cutoff (IPCO) of fast charge has appeal because that type of cutoff preceeds the voltage peak, limits the amount of fast charging as full charge is approached, and requires only two terminal connections to the battery.

At the inflection point, the second derivative of voltage is zero. Because a zero value of second derivative is rather difficult to detect as such, another approach is to sense a decreasing value of positive dV/dt ($d^2V/dt^2 < 0$) which occurs just beyond the inflection point. The profile in Zone Ⓐ of Figure 3-42 also has a decreasing slope. This complication requires a charger design that will avoid responding to the initial decreasing slope by not responding to the inflection point sensing circuit until (1) after a prescribed time delay, (2) after a predetermined voltage has been reached or (3) by following some other enabling procedure.

There are conditions where a battery may not display a characteristic that will meet the criteria established for fast-charge cutoff based upon the inflection point. Applying a fast-charge to a fully charged battery is an example. Therefore, a backup (such as −△V in Section 3.7.5.5) cutoff method is required for this type of fast-charge control.

3.7.5.5 Voltage Decrement Cutoff

As shown in Figure 3-42, a typical battery during fast charging will exhibit a voltage maximum at the transition from Zone Ⓒ to Ⓓ, followed by a voltage decrease that is a result of battery temperature rise. At moderate charging temperatures the decrease in voltage beyond the peak is well defined. It can be detected by an analog circuit or a microcomputer chip which remembers the highest voltage it has seen and responds to a voltage decrement (−△V) relative to the maximum. The voltage decrement cutoff (VDCO) charge control method requires only two terminal connections. A usable value of voltage decrement typically yields a termination of the fast-charge process at a point that is equivalent in battery stress to a △TCO of about 5° to 10°C.

At elevated battery temperatures the negative voltage slope past the charge voltage peak is reduced, causing the VDCO to be delayed relative to normal operating temperatures for a given −△V detection sensitivity.

This delay is generally not a problem unless the sensitivity of the control circuit is such as to require a −△V greater than about −30mV/cell and the charging temperature exceeds 40°C ambient.

3.7.6 Voltage and Temperature Sensing Control

One of the most reliable fast-charge concepts is the use of both voltage and temperature signals to sense when the fast charge current should be terminated. Two concepts using voltage and temperature of the battery are described below.

3.7.6.1 Voltage-Temperature Cutoff

The forgoing discussions about temperature-sensing charge controls (Section 3.7.4) and voltage sensing controls (Section 3.7.5) for fast charging nickel-cadmium batteries identified some limitations of each control system. A very reliable fast-charge system is obtained by using both the voltage and temperature of the battery in an *OR* logic form to act as indicators of approaching full charge.

The voltage-temperature cutoff (VTCO) concept provides for a means of sensing both voltage and temperature. The charger is designed to monitor battery voltage and the temperature of one or more cells in the battery. Fast-charge current is terminated when the battery voltage or temperature exceeds a predetermined level.

The voltage level sensed is typically the entire battery voltage. The temperature of the battery (or of a cell or number of cells) is sensed by a temperature sensing device. The precise values of these voltage levels and temperature levels for cutoff depends upon the type of cells in the battery, the application temperature range and the fast-charge current. With this control method, both temperature and voltage values can be set to achieve a high state of charge before the fast-charge current is terminated, without compromising battery life or reliability.

3.7.6.2 Voltage Limit Temperature Cutoff

Voltage Limit Temperature Cutoff (VLTCO) is simply a variation of VTCO. The VCO function associated with VTCO avoids hydrogen generation by preventing the battery voltage from exceeding a given level. At low temperatures VTCO can result in premature fast-charge cutoff with consequent decrease in delivered capacity. A voltage limit, as an alternative to VCO, can provide the same protection against hydrogen generation in low temperature applications without resulting in premature cutoff. The voltage limit, when charging a cold battery, causes a decrease in charge current until battery temperature increases as full charge is approached. At that time increasing cell temperature will cause an increase in charge current, driving the battery to TCO without having exceeded a critical voltage along the way. It is imperative, however, that the fast-charge current be sufficient to drive the battery temperature to the TCO level at the lowest required ambient charging temperature or the fast-charge will not be terminated.

With VLTCO control and a given combination of battery heat transfer characteristic and ambient temperature, it is possible for battery temperature to stabilize in the fast-charge mode at a temperature below TCO, even if the fast-charge current would normally drive the battery temperature to TCO. This is not a likely event, but as a precaution the design should be checked for this possibility before the VLTCO charge control method is implemented.

3.8 Summary

There are a variety of charge methods which are capable of effectively charging nickel-cadmium sealed cells. These methods all accomplish the same end: putting enough energy into the battery to provide the required amount of discharge energy. The methods differ in the time it takes to accomplish the task, the complexity of circuitry used, and the techniques utilized to provide the charging function in a safe and reliable manner.

Chapter 4
Discharging

4.1 GENERAL

The nickel-cadmium cell is used to store electrical energy. Its basic function is to make that energy available during discharge. This chapter will describe the discharge characteristics quantitatively. The electrical discharge performance characteristics of a cell performing this work are voltage and capacity (the integral of current multiplied by time). The values of these two discharge parameters are functions of a number of application-related factors and this dependence will also be described in this chapter. The general shape of the discharge curve, voltage as a function of capacity (or time), is shown in Figure 4-1. As may be noted in this figure, the discharge voltage of the nickel-cadmium cell typically remains relatively constant until most of its capacity is discharged, and then drops off rather sharply. This curve, when scaled by considering the effects of all the application variables, provides a complete description of the functional performance of a battery.

Differences in the design, internal construction, and the conditions of actual use of the cell will also affect these performance characteristics. For example, Figure 4-2 illustrates the average (typical) effect of discharge rate.

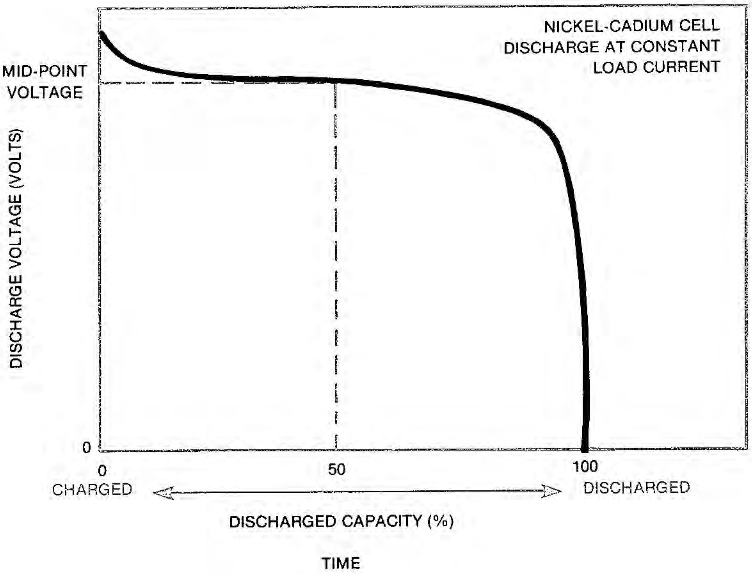


Figure 4-1 Nickel-Cadmium Cell Discharge Curve—Constant Current

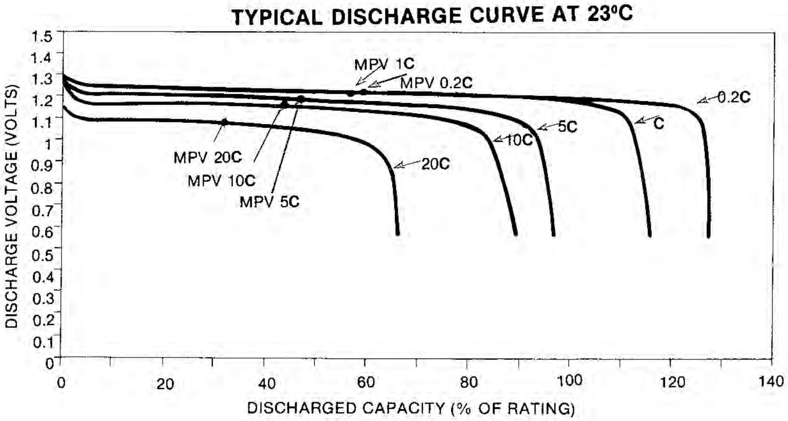


Figure 4-2 Typical Discharge Curves at 23 °C

The remainder of this chapter will define the discharge curve in terms which will facilitate the construction of a complete discharge curve (Voltage vs both Capacity and Run Time) for any cell (battery) proposed for an application, using variables and parameter values appropriate to that application.

4.1.1 Cell Discharge Performance Measures

The construction of a discharge voltage curve for any set of operating conditions requires that the curve measurement term be defined. These are developed as a geometric shape in Figure 4-3 and then related to the typical discharge voltage curve in Figure 4-4.

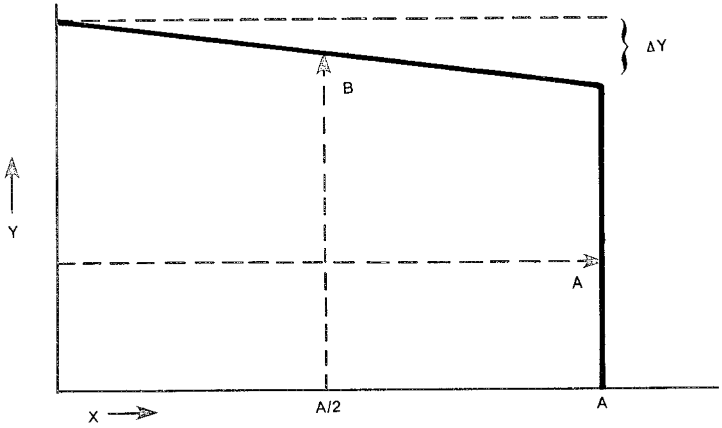


Figure 4-3 A Geometric Shape

Dimensions which may be used to describe the geometric shape in Figure 4-3 are the values of Ⓐ and Ⓑ. With the addition of a value for △Y, the figure is completely dimensioned by three values. If △Y were always a fixed value, or even some fixed percentage of Ⓑ, only the two values Ⓐ and Ⓑ would be necessary in order to convey complete dimensional information about the figure.

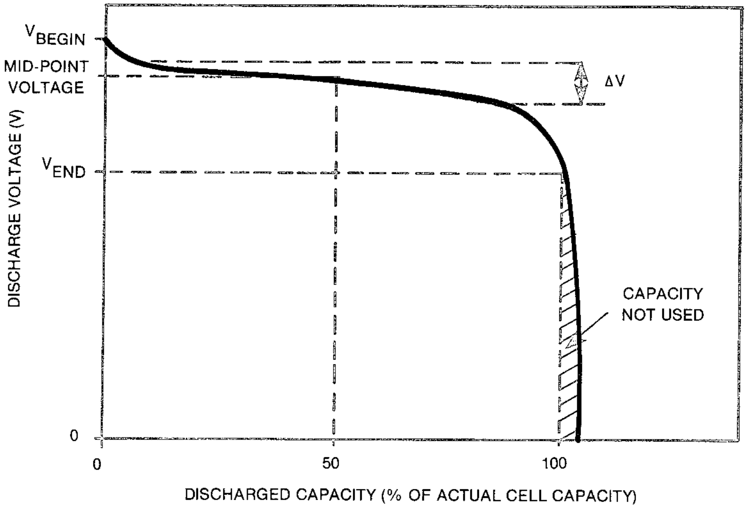


Figure 4-4 Nickel-Cadmium Discharge Curve

Next, Figure 4-4 illustrates the general shape of the nickel-cadmium discharge voltage curve. Note that it bears a strong similarity of shape to Figure 4-3. The Ⓧ axis in the previous figure becomes capacity (or time) and the Ⓨ axis becomes cell voltage.

Just as the value of Ⓑ is the average value of height of the area in Figure 4-3, the value of Mid-Point Voltage (MPV) is approximately the average value of discharge voltage for a nickel-cadmium cell. Just as Ⓐ multiplied by Ⓑ is the area of Figure 4-3, MPV multiplied by cell capacity is the approximate area (energy) of Figure 4-4. Finally, the three dimensions of MPV, cell capacity, and ΔV are all that are required to approximately dimension the entire nickel-cadmium discharge curve. By defining the relationship of these three discharge curve dimensions to each of the discharge conditions, a close approximation of the actual discharge curve may be drawn. This procedure will be described in Sections 4.2, 4.3 and 4.4.

As a matter of convenience, the values of MPV, Capacity, and ΔV, for any set of applied conditions, can be written directly on the voltage and capacity scales of Figure 4-4. This will then become the described discharge curve without the need for redrawing. It will only be necessary to place numerical values on the voltage and capacity scales.

4.1.2 Cell Capacity Defined

The basic term *Capacity* simply means an integral of current over a defined period of time.

$$\textit{Capacity} = \int_{\Delta t} i\,dt$$

The equation may be applied to either charging or discharging current.

The further definition of particular kinds of capacity is somewhat arbitrary and requires a variety of adjectives applied to the basic term. These are introduced in Table 4-1 and then discussed in Section 4.3. It may be helpful to think of *capacity* as analogous to the parameter *volume*. For ex-

Standard Conditions	=	Laboratory Conditions: charge/rest/discharge rates/voltage/temperature
Standard Capacity	=	Cell capacity measured under standard conditions.
Rated Capacity	=	The minimum standard capacity.
Actual Capacity	=	Capacity of a fully charged cell measured under non-standard conditions except standard end of discharge voltage (EODV).
Retained Capacity	=	Capacity remaining after a rest period.
Available Capacity	=	Capacity delivered prior to a non-standard EODV.
Dischargeable Capacity	=	Capacity which a cell can deliver before it becomes fully charged.

TABLE 4-1 Capacity Terminology Defined

ample, the term *volume* by itself is simply a cubic spatial measurement. *Volume* may be used to mean the cubic space within a container or it may be the amount of material placed in the container, or the amount of space left in the container remaining to be filled, or it may even mean the amount of material which can be poured out of the container (for example, a viscous or partially frozen material which can not all be poured out). The term *cell capacity* is used here in the context of the *total amount of capacity which may be discharged from the cell.*

4.2 CELL DISCHARGE VOLTAGE PERFORMANCE

4.2.1 Mid-Point Voltage

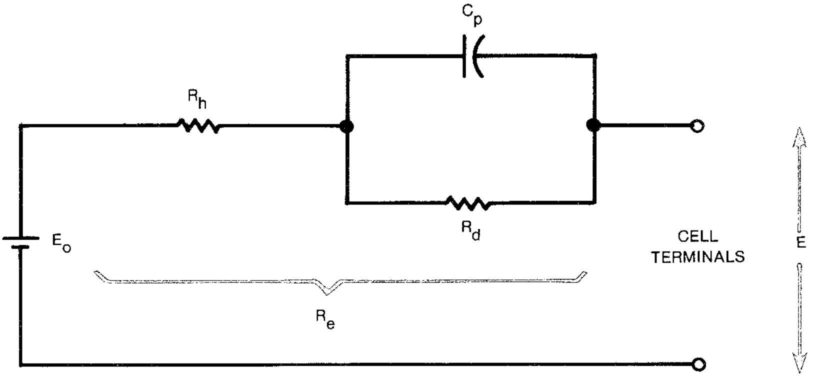
4

This section describes the voltage (vertical or Ⓨ) dimension of the discharge curve. Section 4.3 will deal with the capacity (horizontal or Ⓧ) dimension. This section also describes the application factors which influence voltage delivery. Figure 4-4 illustrates the mid-point voltage (MPV) as *that voltage delivered by the cell at the point when one half of the total actual cell capacity has been discharged*. MPV is also shown to be a reasonable approximation of the *average* voltage delivered during an entire constant current discharge. This approximation allows the discharge delivered energy to be calculated just as if the discharge curve were a rectangle (MPV multiplied by cell capacity), and the results to be determined in watt-hours or watt-minutes. Energy which is discharged chemically but which is not delivered to the external circuitry is converted to heat within the cell. This generated heat results in a temperature rise in the cell. The amount of cell temperature rise is dependent on the generation rate, the thermal mass, and the heat transfer coefficient of the cell.

The remainder of Section 4.2 will describe the methods by which MPV may be estimated for any combination of application factors.

4.2.2 Cell Discharge Equivalent Circuit

Figure 4-5 represents a thèvenin equivalent discharge circuit, which for typical applications can be used to visualize and understand the performance of the nickel-cadmium cell during discharge. The actual voltage delivered by the cell will therefore be approximated by using this analogous technique.



E_o = effective cell no-load voltage

R_e = $(R_h + R_d)$ = total effective internal resistance

R_h = effective instantaneous resistance

R_d = effective delayed resistance

C_p = effective parallel capacitance

E = cell terminal voltage

Figure 4-5 Nickel-Cadmium Cell Equivalent Discharge Circuit

The values of voltage and resistance are not constant at their standard condition values but are functions of a variety of application variables such as state of discharge, cell temperature, and cell use history. Discussions in Sections 4.2.3 and 4.2.4 will describe how these *application variables* influence the values of effective cell no-load or open circuit voltage (E_o) and effective cell internal resistance (R_e) and through them the actual discharge terminal voltage delivered by the cell.

The average cell discharge voltage, illustrated in Figure 4-4, can be defined using the discharge equivalent circuit described above. The extended term, or steady-state, discharge voltage was shown to be:

$$E = E_o - IR_e$$

At the midpoint of the discharge curve, where $E_o = MPV_o$, this equation becomes:

$$MPV = MPV_o - IR_e$$

The equivalent circuit is presented only as an aid to assist in explaining the voltage delivery behavior. The electrical values of effective no-load voltage (E_o), effective cell internal resistance (R_e), and effective capacitance (C_p) are used, not necessarily because they are physically present in the cell as lumped values but because the cell performs approximately as though they are.

4.2.2.1 Steady-State Performance

Effective *steady-state* internal cell resistance R_e is composed of two resistive components in series, R_h and R_d. During the initial few seconds of discharge, the delivered cell voltage drops rapidly from the initial level determined only by R_h to the extended time *steady-state* discharge level ($R_h + R_d$) which is the total effective internal resistance R_e, as shown in Figure 4-6. The practical result of using the equivalent circuit approach, with its values of E_o and R_e, is illustrated in Figure 4-7. On this chart the discharge terminal voltage response of a representative cell is plotted as a function of load discharge current. The equation of this load line is ($E = E_o - IR_e$) for the normal case of extended term, *steady-state*, discharge.

4.2.2.2 Dynamic Transient Response

Due to the relatively short duration of the dynamic transient response it can simply be ignored in most applica-

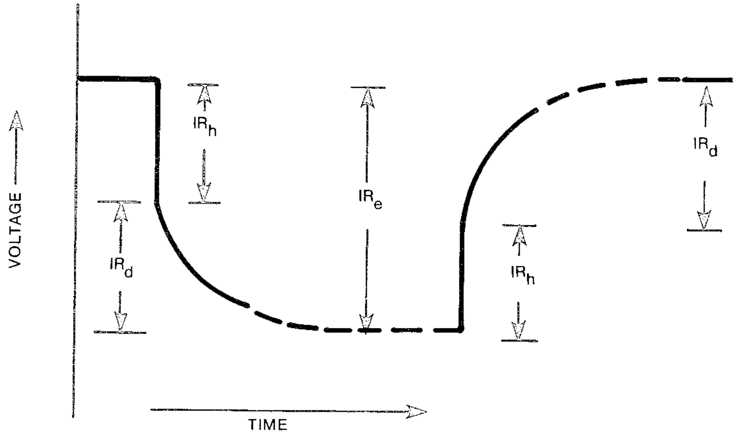


Figure 4-6 Transient Cell Discharge Voltage

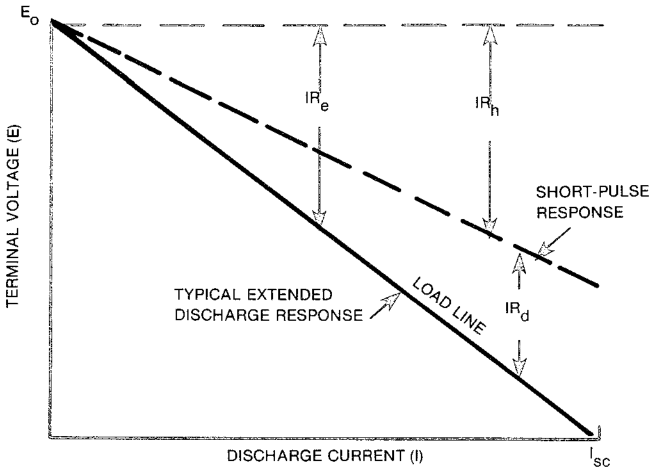


Figure 4-7 Nickel-Cadmium Discharge Load Regulation Lines

tions. When the load switch is closed the voltage response is initiated on the upper load regulation line of Figure 4-7 and then rapidly transfers exponentially (time constant = $C_p \times R_d$) to the steady-state load regulation line. This transfer occurs as the *effective* capacitor is charged. The reverse effect occurs when the load is suddenly reduced or terminated. The equation of the load line for a discharge pulse of very short duration is thus ($E = E_o - IR_h$). Typical values for R_h as a fraction of R_e range from 25 to 75 percent, depending primarily on the design of the cell.

The combination of the parallel portion of the resistance (R_d) and the effective capacitance (C_p) has a time constant of approximately one to three percent of the cell discharge time, varying somewhat with cell temperature and discharge rate. Typical values for this time constant become shorter as the discharge rate is increased and longer as the cell temperature is decreased.

For very short discharge periods (pulses), R_d C_p can almost be ignored. The effective internal resistance, considered to consist only of R_h, causes an instantaneous drop in discharge voltage when the load switch is closed and an instantaneous rise in voltage when the load switch is opened. These effects were illustrated in Figure 4-6. For repetitive discharge pulses, the amount of average voltage drop depends approximately on the steady-state resistance (R_e) multiplied by the average current. The average current may be calculated by multiplying the current during the *ON* pulses by their duty cycle. The actual voltage oscillates above and below this average value.

4.2.3 Variables Influencing R_e

The value of R_e, for any particular cell, is influenced by the value of several application variables. The most important of these are cell temperature during discharge, the amount of capacity already discharged, and the *history* (age and previous use) of the cell.

4.2.3.1 R_e as a Function of Cell Discharge Temperature

The effective internal resistance, (R_e), changes with cell temperature. The resistance is at a minimum at cell tem-

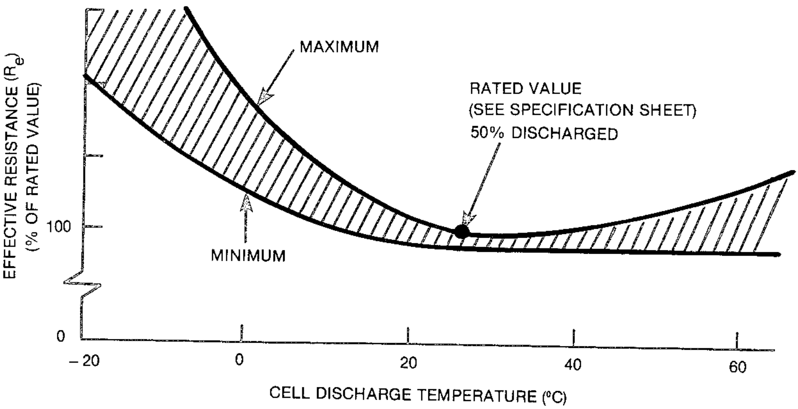


Figure 4-8 Effect of Cell Discharge Temperature on Resistance—R_e

peratures between 20° and 40°C. Below 20°C, the R_e begins to rise as shown in Figure 4-8, primarily due to the difficulty of ionic flow through the increasingly viscous electrolyte of the cell.

4.2.3.2 R_e as a Function of State of Discharge

Effective internal resistance also depends on the percentage of the capacity of the cell which remains to be discharged, as shown in Figure 4-9. The amount of capacity that has been discharged from the cell is expressed on the horizontal or ⓧ axis as a percentage of the total *actual* capacity which the cell is capable of delivering under the prevailing operating conditions and environment. As may be seen from the graph, R_e remains a rather stable value for the major portion of the total discharge period. For a short period at the beginning of the discharge, the effective resistance is quite difficult to measure accurately and thus is indicated as being somewhat variable.

Since the variations of E_o during discharge are approximately linear and also relatively small, the typical nickel-cadmium discharge voltage curve shape may be seen as

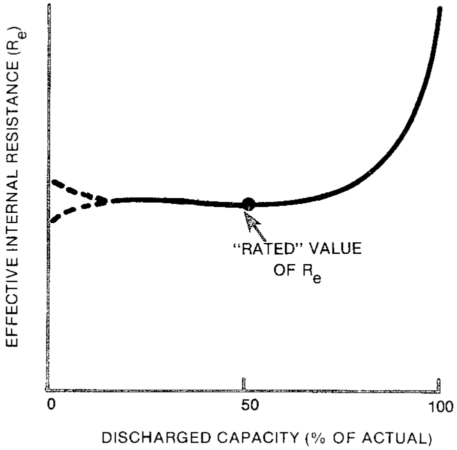


Figure 4-9 Effect of State of Discharge on Resistance—R_e

almost a mirror image of the curve of R_e as a function of discharged capacity shown in Figure 4-9. The discharge voltage of nickel-cadmium cells remains relatively flat, subject primarily to a slowly decreasing value of E_o, throughout most of the discharge period. Toward the end of discharge the significant increase in the effective internal cell resistance (R_e) is the principal cause of the steep decrease in discharge voltage. This increase in R_e is the result of having converted most of the available active material to the lower valence state, thus making the ionic conduction path to access the remaining unconverted material more and more tortuous.

The value of R_e near the midpoint, 50 percent on Figure 4-9, is relatively constant and therefore insensitive to errors in locating the midpoint. This fact is later utilized in designing the R_e measurement procedure and minimizes R_e measurement errors.

4.2.3.3 R_e as a Function of History of Use and Cell Design

Changes in the R_e characteristic of a particular cell also occur with the long-term use of the cell, its *history*. The principal effect of cell history is a very slowly increasing value of R_e as a result of both use and abuse.

The value of the effective internal resistance (R_e), considering all the other factors constant, is approximately inversely proportional to the total designed capacity of the cell. For instance, two identical cells being discharged in parallel have twice the capacity and one-half the effective internal resistance of each individual cell.

4.2.3.4 Calculation and Measurement of R_e

The effective internal resistance of a cell or battery should be considered as the relationship between steady-state current and delivered voltage at a specific relative or equivalent point in the discharge such as equal percent discharged. For example, the relationship between the two values of MPV (50 percent discharged) of two discharge curves at two different constant current discharge rates, for a specific cell, is described by the fundamental R_e equation:

$$R_e = -(MPV_2 - MPV_1) / (I_2 - I_1)$$

This relationship may be extended to:

$$R_e = -\Delta E / \Delta I$$

or:

$$R_e = -(E_2 - E_1) / (I_2 - I_1)$$

to relate the change in voltage delivered by a cell to the difference in discharge rate when the discharge rate is changed. This approximate relationship exists only for changes from one *steady state* to another, allowing time for dissipation of the transient.

4.2.4 Variables Influencing E_o

In addition to the effect of R_e and the discharge rate, certain application variables influence the discharge voltage by changing the magnitude of the effective no-load voltage E_o.

4.2.4.1 E_0 as a Function of Cell Discharge Temperature

Although the overcharge voltage of a nickel-cadmium cell has a relatively linear relationship to cell temperature during overcharge, as may be seen in Section 3.4.1, the effective no-load voltage is not influenced in the same way by the cell temperature during discharge. While E_0 at the midpoint of the discharge curve (MPV_0), at all cell temperatures above 20°C, changes only slightly, the value of MPV_0 decreases at negative temperatures as shown in Figure 4-10. The total decrease in discharge voltage at low cell temperatures therefore is the result of this change in MPV_0 in addition to significant increases in the value of R_e at low cell temperature (shown in Figure 4-8).

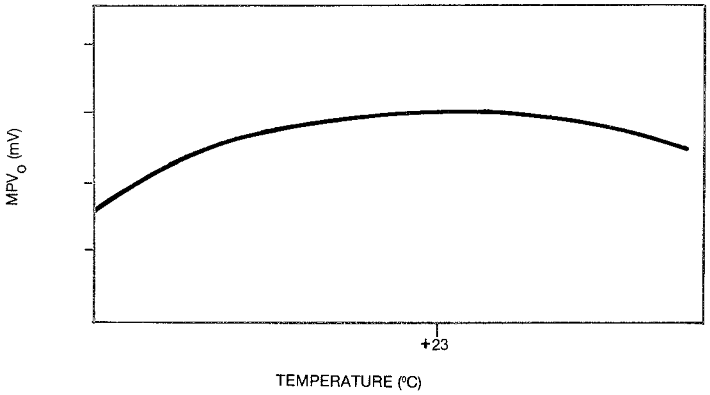


Figure 4-10 Effect of Cell Discharge Temperature on Voltage—MPV_0

4.2.4.2 E_0 as a Function of the State of Discharge

E_0, the effective open-circuit cell voltage, also varies moderately during the discharge process as a function of the state of charge of the cell.

The effect which the amount of discharge of a cell has on the value of E_0 is shown in Figure 4-11. This figure shows

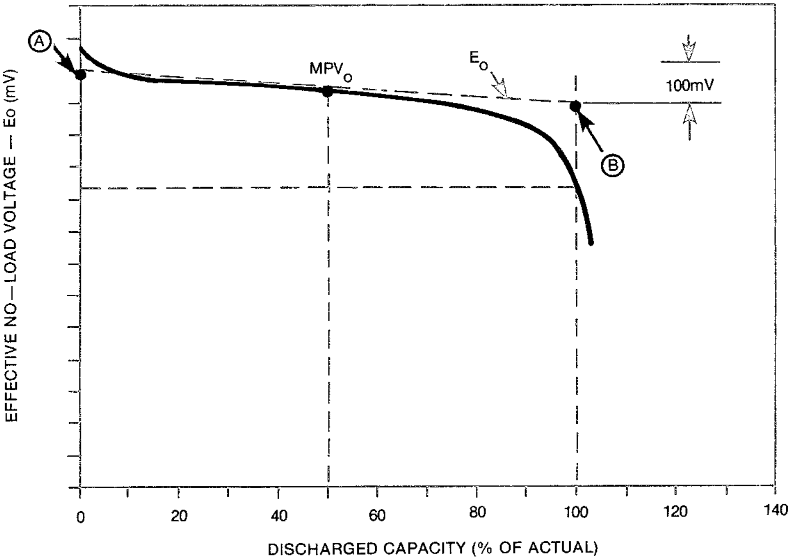


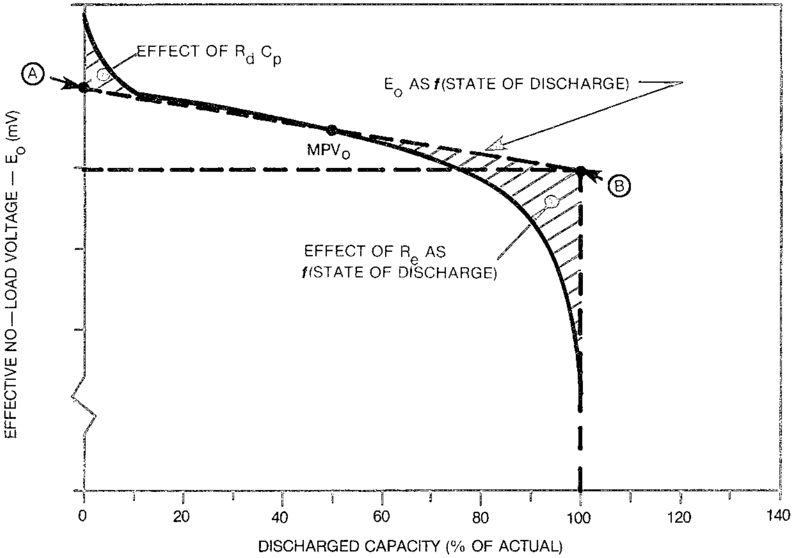
Figure 4-11 Effect of State of Discharge on Voltage—E_o

the typical *effective no-load voltage* of a sealed nickel-cadmium cell at 23°C as a function of the amount of capacity discharged from the cell. As Figure 4-11 shows, the effective open circuit voltage remains relatively flat throughout most of the discharge period, with an approximately linear 100 mV drop from fully charged to fully discharged. The dashed line Ⓐ - Ⓑ in the figure describes this gradual decrease in E_o, and is the principal ΔV effect in Figure 4-4.

These no-load voltage effects may be but a small part of the total effect on the discharge voltage. The more significant effect on discharge voltage, particularly in high rate discharge, is caused by the effective internal resistance of the cell, particularly as the end of a discharge is approached and in high discharge current applications.

4.2.5 Summary of Voltage Effects

For a review of the various terms and effects on voltage



$V = f(E_o, I, R_e)$

Where: $E_o = f(\text{Temperature; State of Discharge})$

$R_e = f(\text{Temperature; State of Discharge})$

However for midpoint only: $MPV_o = f(\text{Temperature})$

$MPR_e = f(\text{Temperature})$

Figure 4-12 Summary of Effects on Voltage

delivery, refer to the exaggerated curve of Figure 4-12 and the accompanying equations. Voltage delivered is a function of discharge current and two cell variables—the equivalent open circuit voltage (E_o) and the effective internal resistance (R_e). The curve of Figure 4-12 shows the effect of state of discharge on both E_o and R_e.

The principal *load regulation* voltage loss is a function only of discharge rate and R_e as was described in Figure 4-7. R_e is in turn dependent on cell design and cell discharge temperature, as in Figure 4-8.

The average no-load *supply* voltage MPV_o is relatively independent of operating variables except for the effect of low cell temperature which is shown in Figure 4-10. Except for the illustrated effect of cell temperature on MPV_o, E_o is dependent only on discharged capacity. That relationship is relatively independent of other operating variables. This state of discharge effect may be approximated as a nearly linear ± 50 mV relative to MPV_o over the 100 percent range of actual capacity of the cell.

The two deviations shown as shaded areas, from the straight line Ⓐ - Ⓑ of Figure 4-12, are the transient result of R_d and C_p at the beginning of the curve and the rapidly increasing R_e as a function of the depleting state of charge at the ending of the discharge curve; also contributing to the initial transient is the depletion of electrode surface charge which occurs at the beginning of discharge of a fully charged cell. Some valance shift may also be accounted for. The effect of R_d and C_p reappears of course if the load is removed and then reapplied. Other than these two deviations from the straight line, it may be seen that discharge rates and low cell discharge temperatures are the only application parameters having significant effects on the discharge voltage. Both of these effects may be conveniently calculated, as they will be in Section 4.4.

4.3 CELL DISCHARGE CAPACITY PERFORMANCE

4.3.1 Cell Capacity Definitions and Ratings

This section describes the capacity (horizontal ⓧ) dimension of the discharge curve (Figures 4-3 and 4-4) as well as the adjectives which are required in order to differentiate the variety of possible meanings of *capacity*.

The term *capacity* is used in battery technology to describe a number of different Coulombic (ampere hour) quantities. Therefore there is a need to define several kinds of capacity in order to have meaningful numerical values used in measured, specified, and calculated capacities.

Cell capacity always indicates the relative amount of energy that the fully charged cell is capable of storing and then *delivering* to the electrical load. *Cell capacity* is defined in units of ampere-hours (milliampere-hours, ampere-minutes, or other units of current multiplied by time) but can conveniently be related to volt-ampere-minutes, watt-hours, or some similar measurement of energy, by multiplying the ampere-hours by the average delivered voltage (MPV).

The description of cell capacity under a variety of applied conditions requires the use of numerical values. It is therefore necessary to outline certain specific definitions of capacity which are used to describe the effects of the various factors which influence that cell capacity.

Standard cell capacity is a measure of the total capacity capable of being stored and discharged in a relatively new production cell under a defined standard set of applied conditions. These conditions include cell temperature, rate and time of charge, rest time, and rate of discharge along with a defined end-of-discharge voltage. *Standard* cell capacity assumes that the cell is fully charged at standard cell temperature, at the *General Electric* cell specification rate, and that it is discharged at the same standard cell temperature at a

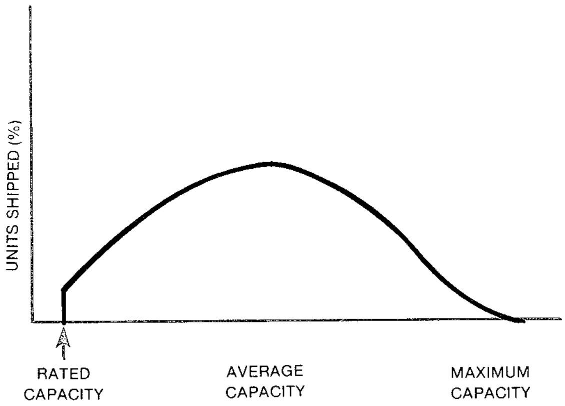


Figure 4-13 Statistical Distribution of Standard Cell Capacity

specified standard discharge rate to a specified standard end-of-discharge voltage (EODV). The value of standard cell capacity may lie anywhere within the statistical distribution of capacity as manufactured. Such a distribution is illustrated in Figure 4-13.

Unless otherwise stated, *standard* conditions are assumed in this *Handbook*.

When any of the applied conditions differ from standard, the capacity of the cell may be influenced. A new term, which is titled *actual* cell capacity (for actual conditions), is used for all nonstandard conditions which alter the amount of capacity which the fully charged new cell is capable of delivering when fully discharged to a standard EODV.

That portion of actual cell capacity which can be delivered by the fully charged new cell to some nonstandard end-of-discharge voltage is called *available* cell capacity.

Cells are rated at standard specified values of discharge rate and the other applied conditions. *Rated* cell capacity (**C**) for each *General Electric* cell type is defined as the minimum *standard capacity* to be expected from that cell. Rated cell capacity is always a single specific designated value for each cell model (type, size and design), as contrasted with the statistically distributed values for all other defined capacities. The rated value must also be accompanied by the *hour-rate* of discharge upon which the rating is based (e.g. 1 hr, 5 hr, 10 hr, 20 hr, etc). The rated capacity for each *General Electric* cell type is designated in the appendix specification section.

The *General Electric* process for the manufacture of nickel-cadmium cells produces a comparatively tight spread in the overall distribution of standard capacity. A representative distribution of capacity is shown in Figure 4-13. The distribution may be truncated if any cells with capacity less than rated have been removed from the population.

The distribution of Figure 4-13 refers to single cell capacity and NOT multicell battery capacity. The capacity of any multicell battery is always determined by the lowest capacity cell in the battery. The distribution of battery capacity, therefore, has the same minimum value as in Figure 4-13 (rated capacity), but its maximum capacity may be somewhat reduced. This reduction will depend on the number of cells in the battery and the *width* (statistical variance) of the capacity distribution of the particular population of cells from which batteries are actually constructed. For example, if batteries were constructed using only identical capacity cells within each battery, the distribution of battery capacity would be the same as the distribution of cell capacity. For further explanation of the effects of cell capacity distribution on battery capacity, see Section 4.5.

After the battery is stored for a period of time following a full charge, the reduced capacity which the new cell still retains, and which can be discharged, is called *retained capacity.* (See Section 4.3.4 for explanation and discussion of this term.)

Table 4-2 summarizes the specific conditions for each of the capacities defined above.

Conditions / Capacity Terminology	Charging			Resting		Discharging		
	Cell Temp	Rate	Amount (4)	Ambient Temp	Time	Cell Temp	Rate	EODV (3)
Standard Conditions	23°C	0.1C	20 hr Min.	23°C	Minimum	23°C	1C	0.9V
Standard Cell Capacity (1)	23°C	0.1C	20 hr Min.	23°C	Minimum	23°C	1C	0.9V
Rated Cell Capacity (2)	23°C	0.1C	20 hr Min.	23°C	Minimum	23°C	1C	0.9V
Actual Cell Capacity	@	@	Fully Charged	@	Minimum	@	@	0.75MPV (3)
Retained Cell Capacity	@	@	Fully Charged	@	@	@	@	0.75MPV (3)
Available Cell Capacity	@	@	Fully Charged	@	Minimum	@	@	@
Dischargeable Capacity	@	@	@	@	Minimum	23°C	1C	0.9V

Battery Capacity is approximately equal to the capacity of the minimum capacity cell in the battery when that cell is discharged to zero volts.

Notes: (1) · *Standard* Cell Capacity = *Actual* Capacity of a particular production cell under Standard conditions. Characteristically ranges from 100 to 130% of *Rated* Capacity.

(2) · *Rated* Cell Capacity = Minimum *Standard* Cell Capacity = **C**
See the *General Electric* Specification sheet for the value of **C** assigned to each cell design.

(3) · EODV = End of Discharge Voltage;
MPV = Mid Point Voltage

(4) · The amount of charge required for the measurement of Cell Capacity, is *Full Charge* into overcharge. (Zone 4, Figure 3-1, Paragraph 3.4).
2.0**C** Ahrs (20 hours at the 0.1**C** rate) at 23°C, is required to insure that a cell with maximum *Standard* Cell Capacity is fully charged.
2.4 C Ahrs (24 hours at 0.1C rate) at 23°C, is required on initial charge or after extended storage — (Reference Chapter 5).

(@) = Any specified value of a test condition other than a Standard value.

Table 4-2 Capacity Terms Defined

4.3.2 Measurement of Fully Charged Capacity

The capacity of a cell, or battery, is normally measured by completely discharging it while integrating the current over the period of the discharge. Variations in the capacity measurement procedure can result in data inconsistencies.

One method of measuring capacity is to discharge the cell with a constant current load. The load circuit is adjusted to maintain a constant discharge current as the cell voltage declines. Recording cell voltage on a time recorder results in the discharge curve of Figure 4-4. Calculation of discharged cell capacity is thus only a multiplication of the time needed to reach the specified EODV times the value of constant current. An added refinement is the simultaneous use of a current integrator. *General Electric* experience has shown that use of a current integrator can significantly improve the accuracy compared to manual integration. Maintaining the constant current load by introducing a series aiding power supply with automatic constant-current control is also convenient and may further enhance the measurement accuracy.

The least accurate method of measuring capacity is to place a fixed resistance load across the cell terminals and monitor the voltage as a function of time as the cell discharges. With a fixed resistance, the current decreases as the cell voltage declines. A recorder is used to record this voltage. The discharge recording of variable voltage and current is then manually integrated over time to calculate the discharged capacity. Unfortunately, the value of the rate of discharge current upon which actual cell capacity depends is not a fixed value in this method of measurement and thus the results can be quite difficult to associate with a generalized applied condition.

The value of measured cell capacity depends also on the end-of-discharge voltage (EODV) used in the measurement. An EODV of 0.9 V for 1**C** rate discharges is typically used. Although some single cell 1**C** rate applications will not necessarily function down to this voltage, higher values of

EODV, when used in measurement procedures, may increase the inaccuracy of the results. For EODV's, in the flatter portion of the curve for example, small errors in measured voltage can result in significant errors in the time (capacity) to termination of the discharge. Definitions of *standard* 1**C** rate cell capacity used in this *Handbook* are based on a discharge at a *constant current* to a cell EODV of 0.9V (0.75 × 1.2V).

Because some off-standard conditions, such as high discharge rates and/or low cell temperature, will significantly reduce the average voltage delivered by the cell, an EODV of 0.75 multiplied by MPV is used in order to permit the desired independent consideration of cell capacity and delivered voltage. This form of EODV designation defines the minimum *useful* voltage for any load in terms of the average voltage (MPV) being used by that load and for which the load device is designed. Other values of cell EODV and their effects are discussed in Section 4.5.4.1. See the discussion of battery discharge cutoff voltage in Section 4.5.4.2.

4.3.3 Actual Cell Capacity at Off-Standard Conditions

Standard cell capacity is the total actual cell capacity of a particular individual cell under standard conditions of charge, rest, and discharge. Standard cell capacity typically ranges from 100 to 130 percent of the specified *rated* value (minimum). *Actual cell capacity* is the capacity of that same individual cell when the conditions under which the cell is charged and discharged differ from *standard* conditions. The difference between *standard* and *actual* cell capacity of any particular cell results from the effects of variations from standard conditions of 1) cell temperature during charge, 2) charge rate, 3) cell temperature during discharge, and 4) discharge rate.

The effects of each of these *off-standard conditions* are defined in terms of the amount of derating of *standard* cell capacity which is required in order to arrive at a value for *actual* cell capacity. The most conservative estimate to be used for the initial value for standard capacity is the *rated* minimum capacity. Either that value or the more liberal typical or average *standard* value may be used to initiate the derating procedure for *actual* capacity.

4.3.3.1 Charging Conditions

Both cell temperature during charge and the amount of charging (capacity input) have an impact on the capacity which the cell is capable of discharging. These differences can be defined by using the following variables:

- Charge Temperature (°C)
- Charge Rate (A)
- Charge Time (hr)

Elevating the charge temperature of the cell influences the charge behavior in two ways, as discussed in Section 3.2.1. First, increasing the temperature of the cell on charge will result in requiring significantly more charge input for the cell to reach its full charge condition, and thus to achieve the maximum energy storage capability that is its actual capacity at that elevated cell temperature.

Second, in addition to the increased amount of charge input required to achieve *full* charge, the increased cell temperature reduces the actual cell capacity below the standard capacity value. This is true even though the cell is fully charged at those elevated cell temperatures—for example 72 hours or more at C/10-rate at 48°C. Assuming that the cell is fully charged for measurement purposes, the effect of cell temperature during charge on actual capacity is shown in Figure 4-14.

Although actual cell capacity is not affected by charge temperatures below 23°C, control must be exercised to decrease the charge current below the standard rated value when operating Standard and Quick-Charge cells at cell temperatures below 0 and 10°C respectively. See Figure 3-21 and the individual cell specification sheet for the allowable value of charge current, as a function of cell temperature, which will result in a cell pressure low enough to

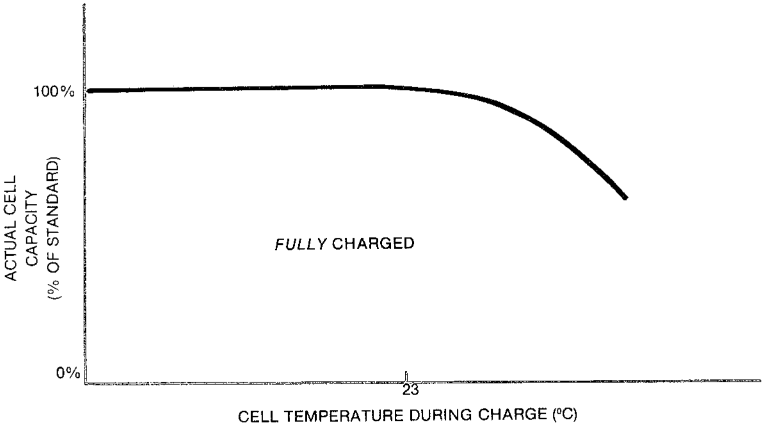


Figure 4-14 Effect of Cell Charge Temperature on Actual Capacity

prevent the cell from venting, and which may still reliably charge the cell.

4.3.3.2 Charge Rate

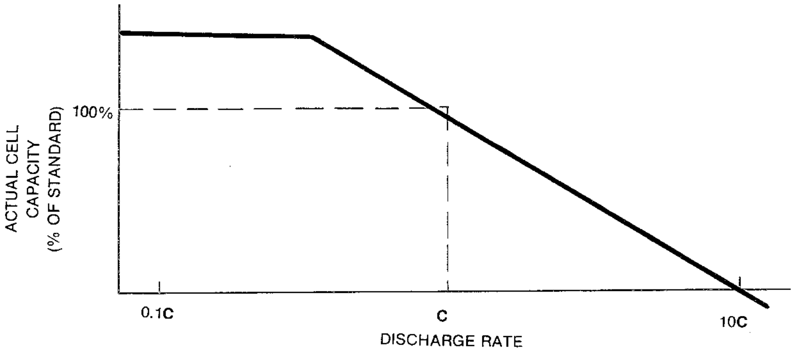
The effect of charge rate (standard and quick) on actual cell capacity is relatively negligible as long as the cell reaches overcharge and the charge rate is within the cell specifications. Values of charge rates below the minimum cell specification rate, even if the cell reaches overcharge, may result in lowering the value of actual cell capacity. On the other hand, fast charge rates, which must be terminated prior to any significant amount of overcharge to avoid cell damage, may produce actual cell capacities which are modestly greater than 100 percent of standard. (See Chapter 3 for a discussion of the effects of fast charging.)

4.3.3.3 Rest Temperature and Time

Cell temperature, during a minimal rest period between charge and discharge, has a negligible effect on the value of actual cell capacity. However, increasing the rest temperature speeds up the process of *self discharge* which, if the rest period is lengthy, results in a reduction of the capacity retained by the cell and, hence, available for discharge. This subject is discussed in detail in Section 4.3.4. See also the discussion of the effect of cell discharge temperature in Section 4.3.3.5.

4.3.3.4 Discharge Rate

The influence of discharge rate on actual cell capacity results from the increasing difficulties inherent in electrolyte mass transport and electrode reactions as the current density is increased. This influence of rate on actual cell capacity, at standard temperatures and at rates of discharge up to approximately 0.25**C**, is insignificant. The relationship between discharge rate and cell capacity at discharge rates above this value is semilogarithmic with increasing rate as shown in Figure 4-15. Increasing the discharge rate also increases the internal voltage loss of the cell and reduces the output voltage, as discussed in Section 4.2. These voltage losses are indicative of the internal dissipation of some of the stored energy. The reduced capacity at increased discharge rates, however, simply reflects a reduction in the amount of charge which is available at these increased rates. The energy represented by the capacity that is not dischargeable at those higher rates is not lost or dissipated. It simply remains in the cell where it could be discharged at lower rates.



4.3.3.5 Cell Discharge Temperature

Low cell temperature during discharge has an effect upon actual cell capacity and that relationship is shown in Figure 4-16.

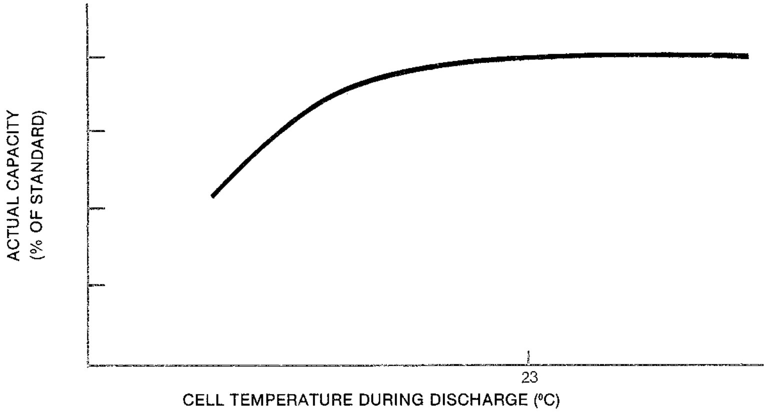


Figure 4-16 Effect of Cell Discharge Temperature on Actual Capacity

4.3.3.6 Simultaneous Multiple Off-Standard Conditions

An estimate of actual cell capacity may be made in those instances where several of the above charge and discharge conditions are *off-standard* at the same time. Since the factors are reasonably independent of each other, the estimated value of actual capacity may be arrived at by multiplying the various effects together. For example, 90 percent due to high discharge rate multiplied by 80 percent due to high charge temperature yields an estimated actual cell capacity of 72 percent of standard when both conditions are present.

For some cases, however, which are not totally independent combinations of off-standard conditions, an additional effect of compounding must be considered. For example, assume that a derating for a cell temperature of −20°C at the standard **1C** rate of discharge is 65 percent, and the derating for a 5**C** discharge at the standard cell temperature of +23°C is 84 percent. The combined effect of 5**C** and −23°C is not the linearly calculated 55 percent (65 percent multiplied by 84 percent) as might be expected, but a more likely compounded 35 percent. Application assistance should be requested early for application condition combinations significantly off standard.

4.3.4 Retained Capacity

Capacity retention is a measure of the ability of a battery to retain its stored energy during an extended open circuit rest period. The capacity retained is a function of the length of time of the rest period, the cell temperature during the rest period, and the previous *history* of the cell. Capacity retention characteristics are also influenced by the design of the cell. Nickel-cadmium cells are manufactured utilizing a variety of electrode formulation processes. Each process is unique and electrodes made from each of these processes may possess different capacity retention characteristics. Other cell design parameters such as electrode spacing, electrode surface area, and separator, also play a role in the capacity retention capability of a cell.

The term used to describe the decay of retained capacity is *self discharge*. The rate of self discharge of any particular cell design is a function of the amount of retained capacity and is dependent on cell temperature.

Figure 4-17 illustrates the typical retained capacity of a nickel-cadmium cell, as functions of storage time and cell storage temperature, in terms of a percent of the original actual capacity stored in the cell at the beginning of a rest period.

The normal process of self discharge is the result of two electrochemical mechanisms:

A) The charged nickel hydroxide oxidizes water at electrode sites having low oxygen overvoltages. The oxy-

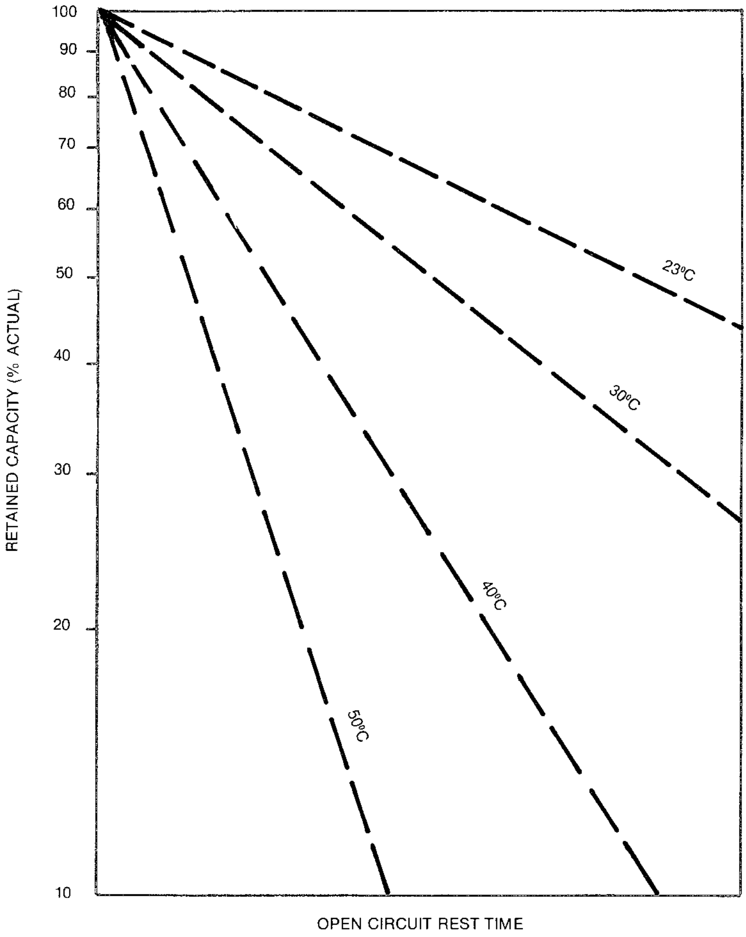


Figure 4-17 Retained Capacity

gen so generated diffuses to the cadmium electrode, where it is reduced by cadmium. The net result is a loss of charge at both electrodes.

B) The second electrochemical mechanism causing self discharge is parasitic side reactions. The best examples in sealed nickel-cadmium cells are the reactions due to the naturally occurring process nitrates. The nitrate ions

> are reduced to ammonia at the cadmium electrode. They subsequently diffuse to the positive nickel-hydroxide electrode where they are oxidized back to nitrate ions. This nitrate shuttle cycle continues until one or both electrodes are fully discharged. With the passage of time and the use of the cell, some of the ammonia is oxidized to nitrogen and the self discharge rate is reduced, thereby improving the retained capacity characteristics of the cell.

It is for this latter reason that measurement of the retained capacity performance of nickel-cadmium cells should be undertaken after the evaluation of other characteristics of importance. The resulting measurement will be more representative of the real use of the cell as well as more repeatable and accurate.

4.3.4.1 Poor Capacity Retention

In addition to the normal electrochemical mechanisms described above, poor capacity retention may also be one symptom of approaching end of life. The abnormal mechanism in this instance, however, is ohmic in form and is the result of one or more conductive paths between the current collectors of the positive and negative electrodes. This phenomenon may be visualized as a continuous resistive load on the cell and is further discussed in Section 4.3.4.2 and 5.1. The symptoms thus differ from the results of the electrochemical activities (A) and (B) above, in that the rate of self discharge is not cell temperature dependent. In addition, since it is a function only of cell voltage, not of electrochemical charge, the process will continue unabated all the way to an open circuit voltage of zero.

4.3.4.2 Retained Capacity Calculation

The rate of self discharge due to both above (A) and (B) factors of electrochemical discharge is a function of the amount of capacity (charge) remaining in the cell and therefore tends to be exponential in form. Thus, when both the charge in the cell and the self discharge rate approach zero, the rate of decay in cell voltage also approaches zero and tends to remain in the 1.0 to 1.1 volt region for an extended period of time. Since these self discharge mechanisms are the result of electrochemical reactions, they are also accelerated by increasing the temperature of the cell. This rate/cell temperature relationship is an Arrhenius function in which the logarithm of the self discharge time constant decreases linearly with the reciprocal of the increasing cell temperature, which is expressed in absolute degrees Kelvin.

The equation for the normal capacity retention function is:

$$(C_R/C_A) = \epsilon^{-t/tc}$$

Where: C_R is the retained capacity
C_A is the actual or initial capacity
tc is time constant in days (to 36.8% of C_A)
t is the open circuit rest time in days

In order to encompass the completely general case of capacity retention, a second term may be added to the exponential equation to make it:

$$(C_R/C_A) = [\,\epsilon^{-t/tc}] - [t/t_r]$$

Where: t_r is the number of days to 100 percent deplete, the charge through an existing shunt resistance

The shunt resistance may be either internal or external, such as an actual applied load. This equation is useful for calculating the capacity remaining in a very low-rate, long-term discharge.

4.4 SCALING THE DISCHARGE CURVE

Reviewing the capacity and voltage discussions in Sections 4.2 and 4.3, that information may now be applied to actually place voltage and capacity values on the curve of Figure 4-4. The redrawn curve, with voltage and capacity scales, appears in Figure 4-18.

The procedure for arriving at values for these scales for use in Figure 4-19 is as follows:

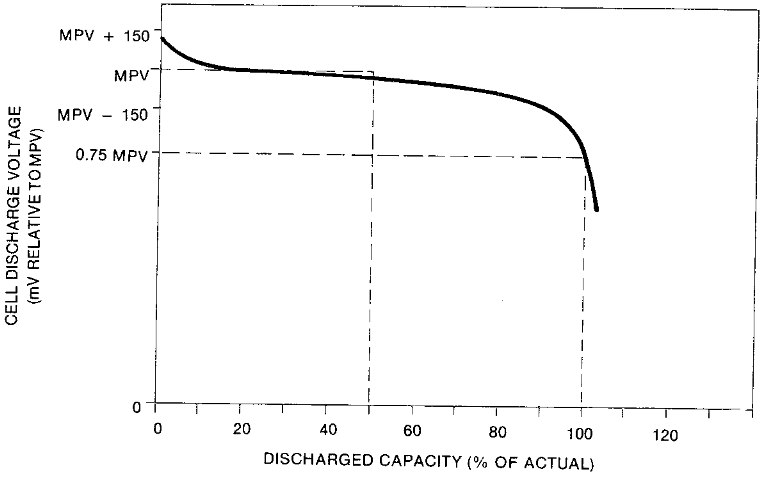


Figure 4-18 Nickel-Cadmium Cell Discharge Curve

CAPACITY

1) Record Rated Capacity **C** from the specification sheet.
2) From the specification section determine the magnitude of reductions/increases of cell capacity due to:
   a) Effect of Cell Charge Temperature on Actual Capacity (refer to Figure 4-14)
   b) Discharge Rate (refer to Figure 4-15)
   c) Cell Discharge Temperature (refer to Figure 4-16).
3) Multiply **C** by the derating factors listed in 2a, 2b, and 2c to arrive at a value $\textcircled{C_a}$ for the minimum 100 percent actual cell capacity value in ampere-hours. (See Section 4.3.3.6 for a discussion of nonlinear effects.)
4) Divide the selected value of actual capacity by the discharge rate to arrive at the corresponding 100 percent value of discharge time $\textcircled{t_a}$.
5) Because the Rated **C** value was used in Step 1 above, the values along the abscissa are representative of the minimum capacity cell from the manufacturing distribution. If a more typical or average representation is desired, the capacity and time scales may be in-

creased to represent the cell of average capacity in Figure 4-13.

6) The described capacity distribution pertains to cell capacity and not to multicell battery capacity. The distribution of battery capacity has a similar minimum but with a reduced distribution range, thus lowering the average. This effect is further described in Section 4.3.1 and 4.5.

7) If necessary, determine the retained portion of actual capacity by use of the capacity retention percentage in the retained capacity graph in the appendix specification section corresponding to Figure 4-17.

VOLTAGE

1) Determine the value of R_e from the specification sheet.

2) Using cell discharge temperature, and curves in the appendix specification section determine:
   a) Effect of Cell Discharge Temperature on Voltage—MPV_o (refer to Figure 4-10)
   b) Effect of Cell Discharge Temperature on Resistance—R_e (refer to Figure 4-8)
   c) Mid-Point R_e = Rated R_e multiplied by (b) above.

3) Calculate the cell midpoint voltage from the discharge current and the value of R_e as:

$$MPV = (MPV_0 - IR_e) \text{ millivolts per cell.}$$

4) Calculate the other values for the cell voltage scale as indicated on the graph.

5) Multiply the values on the cell voltage scale in (4) by the number of cells (N) to arrive at the values for the scale of equivalent battery voltage. Care must be observed, however, to consider also the resistance of interconnections and final terminations. If these connections are welded, their effect may well be ignored. Pressure connections, on the other hand, may cause extreme variability in voltage performance of even low rate discharges.

THE RESULT

By placing these values of actual capacity, discharge time, cell and battery voltage, in their proper position on the Universal Discharge Curve in the specification section (refer to Figure 4-19), a graph of the actual operating voltage versus discharged capacity and time will be produced. This graph will thus be a reasonable approximation of the discharge voltage curve to be expected from a relatively new (small amount of use history) battery at the set of operating conditions described.

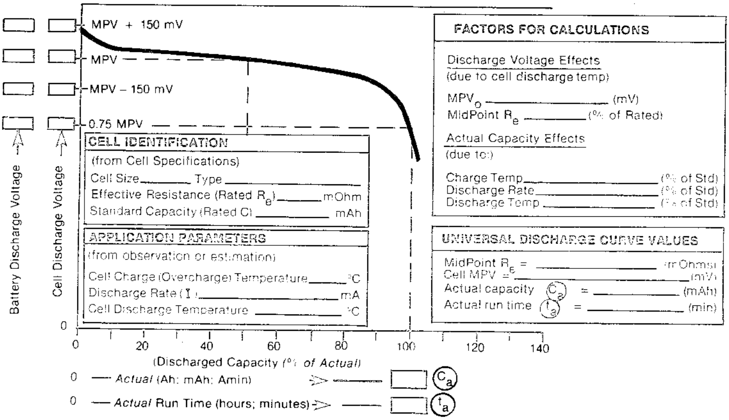


Figure 4-19 Universal Discharge Curve
Cell/Battery Voltage vs Discharge Actual Capacity & Run Time

4.5 APPLICATION PERFORMANCE AND OTHER OPERATING CHARACTERISTICS

The performance of the cell and battery is of course dependent on its state of health in addition to the immediate environment or application factors considered in Sections 4.2 and 4.3. The performance which was scaled in Section 4.4 is predicated on a cell in the *as new* condition. A number of factors associated with the design of the end-product and its actual use constitute the *environment history* of the cell. This history will perhaps change the characteristics of the cell over an extended period of time in use. These issues may all be grouped under the general heading of *cell history*—the electrical and mechanical environments which have been applied to the cell during its lifetime.

Some of the possible historical events which may produce a variety of performance degrading effects relative to Figure 4-19 are as follows:

- Repeated cell polarity reversal
- Excessive charge/overcharge rates
- High overcharge cell temperature
- High discharge cutoff voltage
- Normal cell wear out

4.5.1 Cell Discharge to Polarity Reversal

When a multicell battery is discharged completely, even small differences in the actual capacity of individual cells inherently cause one cell to reach complete discharge sooner than the rest. It is the actual capacity of this lowest capacity cell, the minimum capacity cell of the battery, which thus determines the actual battery capacity.

Continuation of the discharge after this lowest capacity cell has reached zero volts will cause reversal of the terminal voltage of that cell, because the cells of the battery are connected in series. As the cell polarity is reversed beyond a negative 0.2 volts it begins to generate gas internally. Generally, in a sealed nickel-cadmium cell the electrode which is reversed first will be the nickel electrode, in which case hydrogen will be generated. The sealed nickel-cadmium cell is capable of only very slow dissipation of hydrogen gas. It also has a very limited amount of gas storage volume. Thus, frequent and/or extensive reversal will lead to elevated cell pressure sufficient to open the resealable safety vent. This is the reason for avoiding or minimizing application conditions which lead to repetitive or extensive cell reversal. Such applications may lead to venting which, if

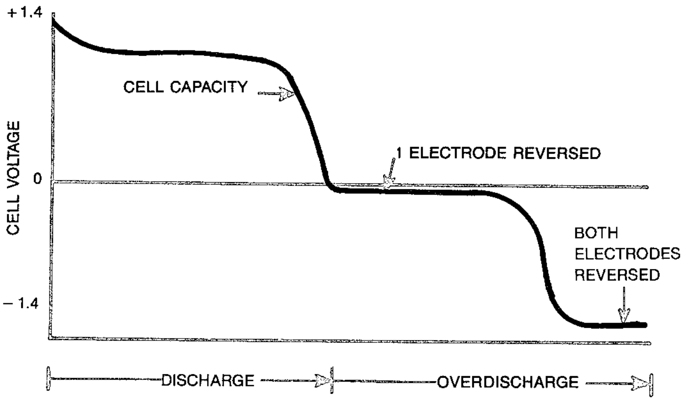


Figure 4-20 Nickel-Cadmium Cell Polarity Reversal Voltages

repeated and/or extensive, will eventually degrade the performance of the sealed cell.

The general shape of the cell voltage curve during discharge into polarity reversal is shown in Figure 4-20. The magnitude of the negative voltage appearing on the polarity reversed cell is dependent on the discharge rate as well as cell design and manufacturing process parameters.

General Electric cells are designed and manufactured to resist adverse effects of cell reversal caused by the deep discharging of a multi-cell battery. Batteries of low cell count that are fully charged between cycles normally possess insufficient capacity differences to generate any significant permanent damage resulting from extending the discharge of the battery to a low end-of-discharge voltage.

The important point, relative to the detrimental effects of cell reversal, is that these are cumulative effects. They are dependent on both the depth (Ah) in reverse and the frequency of cell reversal. The depth of reversal is in turn dependent on the EODV and the actual capacity differences between the cells in the battery. The long-range detrimental effects on voltage and capacity performance increase with both these factors.

It is also important to note that the detrimental effects of reversal are the least when the rates of discharge during the reversal are the highest. This apparent paradox results from the fact that cells which experience terminal voltage reversal during high rate discharge still have significant amounts of charge remaining in the electrodes. (See Section 4.5.4.4 for cell polarity reversal voltage)

4.5.2 Excessive Charge/Overcharge Rates

Chapter 3 dealt with acceptable charge/overcharge rates as a function of cell temperatures. The inability of the cell to recombine oxygen as effectively or as rapidly at low cell temperatures as at higher cell temperatures was discussed. A charge rate which is acceptable in an application at normal cell temperatures and use conditions may become unacceptably high if the product is then exposed to unusually low cell temperatures. Overcharge, while the cell temperature is below its specified charge temperature limit, may generate hydrogen. The long-term effects of excessive overcharge rates at low cell temperature are similar to those of cell reversal described in Section 4.5.1 and may result in venting of either hydrogen or oxygen or both. This abusive treatment results in loss of water from the electrolyte and eventual degradation of performance, both voltage and capacity. Low cell temperature charging is discussed in Section 3.6.5 and the effects of abusive charging on cell life are treated in Section 5.3.1.

4.5.3 Voltage Depression

The effects of elevated charge temperature on the immediate cycle capacity of the cell have been discussed in Section 3.2.1 and 4.3.3.1. Cells exposed to overcharge for very extended periods of time, particularly at elevated cell temperatures, may develop an additional shortcoming called *voltage depression*. This phenomenon is one in which the cell voltage is depressed approximately 150 mV below the normally expected values which were calculated on Figure 4-19. This depression affects E_0 and is independent of discharge rate.

This depression effect initially appears on the discharge voltage curve near the end of discharge. With extension of the overcharge time (non-discharge) of the cell, this depression progresses slowly toward the mid-point and beyond. Accompanying this effect of depression in the voltage dimension of the curve is an actual slight increase in the capacity dimension as illustrated in Figure 4-21. This depressed voltage effect is an electrically reversible condition and disappears when the cell is completely discharged and charged (sometimes called *conditioning*). It thus appears only on the first discharge following a very extended overcharge. It will reappear if the extended overcharge is repeated.

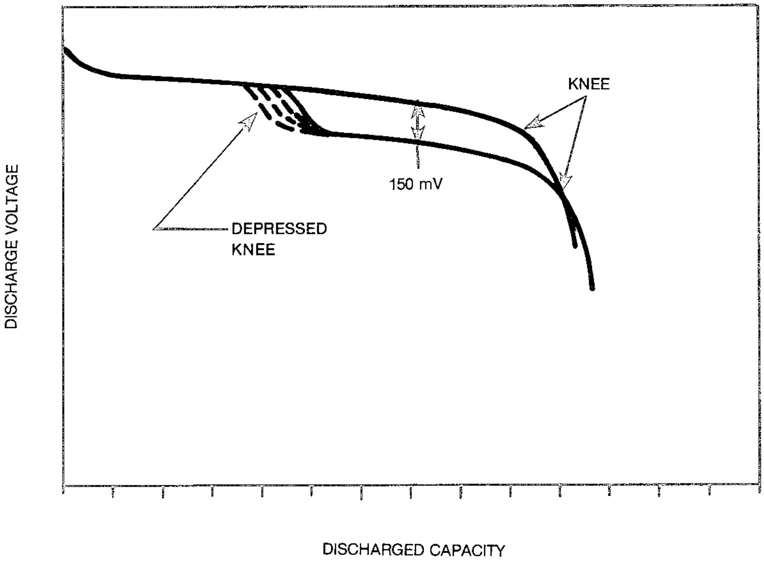


Figure 4-21 Effect of Long Term Overcharge at Elevated Temperature

The phenomenon which causes this depressed voltage is continuous overcharging of the active material of the electrode. The effect is erased by discharging and recharging that portion of the active material which has experienced the extensive overcharge. For this reason the depressed voltage effect in the discharged portion of the curve is erased by the very act of observing it, when the discharge is carried beyond the first *knee* of the depressed curve. Complete discharge, and subsequent full charge, essentially restores the curve to its normal form.

The reversibility of this effect is probably the very characteristic that gives rise to the misnomer **Memory**. When cells are subjected to continuous charge/overcharge, with only modest discharges (repetitive or otherwise), the reversibility of the effect actually prevents the voltage depression from occuring in that portion of the electrode active material which is cycled. The voltage depression phenomenon is, however, not erased from that portion of the electrode material which has been subjected to continuous overcharge but NOT discharged. In this situation, whenever the cell is discharged deeper than recent previous discharges and reaches the beginning of the previously uncycled material, the voltage may decrease 150 mV per cell. This misleads the observer into believing that the discharge is at the knee of the normal discharge curve and erroneously concluding that the cell *remembers* and, thus, delivers only the amount of capacity previously repetitively used. Instead, the phenomenon is actually related only to extended overcharging and incomplete discharging, not repetitive shallow cycling. This is because that portion of the electrode material which has experienced overcharge and not been discharged for an extended period of time slowly shifts to a more inaccessible form.

The depressed voltage effect can of course cause loss of useful capacity in those application cases where a high cutoff voltage prevents complete discharge of the minimum capacity cell in the battery. If voltage depression has occured, complete discharge requires continuation down through the depressed knee to that voltage level which keeps all the electrode material active. An end-of-discharge voltage (EODV) on the minimum cell of, for example, 75 percent of its MPV or less will accomplish that restoration with each discharge. This is further discussed in Sections 4.5.4 and 6.4.4.

4.5.4 Discharge Termination Voltage vs. Capacity

In actual use, the most frequent discharge termination which the battery encounters is not determined by voltage at all but by the time-of-use pattern of the product. The majority of applications are ones in which all the available capacity is seldom used at any one time. The discharge is typically terminated in these products when the immediate task at hand is completed—for example a 5-minute shave with a shaver battery capable of 40 minutes, or a power outage requiring 48 seconds of emergency lighting from a system with a designed capability of one and one-half hours run time. These discharge durations should be considered to be random time controlled cutoff discharges, and are not a function of battery voltage.

4.5.4.1 Available Cell Capacity as a Function of EODV

From Figure 4-4 it may be concluded that less capacity is available if the end-of-discharge voltage (EODV) is increased, and more capacity will be available if EODV is decreased. A close-up view of the knee of the discharge curve can demonstrate this effect on the available capacity of the cell, relative to the actual capacity.

Figure 4-22 illustrates this close-up view of the two extremes in the shape of the knee. This figure shows the amount of capacity available to various EODV values. Curve Ⓐ in Figure 4-22 has a relatively sharp normal knee which results in only a minor variation in available capacity with EODVs equal to or lower than 90 percent of MPV. Curve Ⓑ in Figure 4-22 represents a different curve shape resulting from some combinations of higher discharge rate, extended overcharge, higher cell temperature, history, etc. Curve Ⓑ illustrates the more significant variation of available discharge capacity which may be present in cells with that more rounded knee in their discharge voltage characteristic.

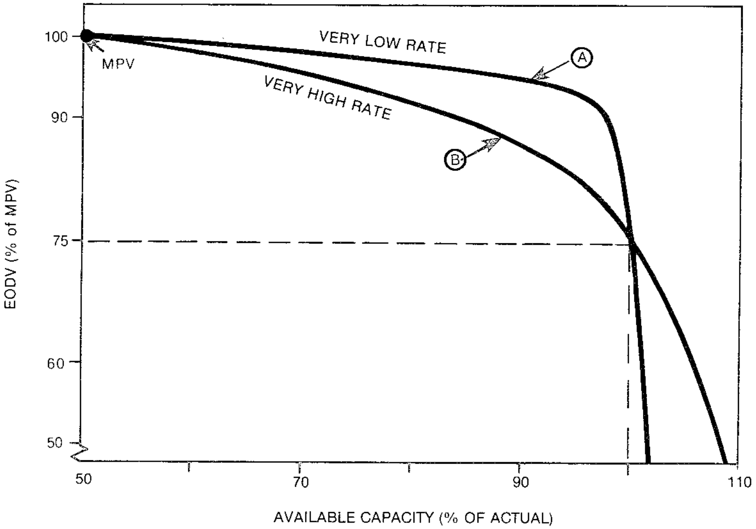


Figure 4-22 Effect of EODV on Available Capacity

4.5.4.2 Discharge Cutoff Voltage

Battery operated products may be considered in general to have more than one level or means of battery discharge load switching. First there is the primary switching means by which the battery load is normally initiated and terminated. This load switching function may be accomplished either manually (by a simple on/off or by a momentary type switch) or automatically (by electronic circuitry).

In addition some end products may contain a back-up secondary feature which acts to preempt the primary load switch-off by terminating the discharge at a predetermined value of battery voltage. These preemptive discharge termination techniques, which tend to determine the minimum EODV value (i.e., the maximum amount of discharge) in various applications, may be classified as either *hard, semi-hard* or *soft.*

The end products which have *hard* cutoff voltages contain circuitry which senses the battery voltage actually being delivered to the product and automatically terminates the further discharge of the battery by electrically switching the battery load off when battery voltage falls below a predetermined value. This prevents any further significant discharge of the battery. A hard cutoff voltage is frequently employed and designed into those products in which a low supply voltage from the battery would result in unsatisfactory load performance, the negative consequences of which might be undetectable to the user at the time. Some load circuits, particularly electronic loads, may possess such a nonlinear relationship between battery voltage and load current that they inherently display nearly hard cutoff characteristics, even without an actual battery-switch-out mechanism. Typical products which may use hard cutoffs are some video cameras, tranceivers and cordless telephones.

There is a second similar design technique used only in manually operated end products. These products might be considered to have a *semi-hard* cutoff voltage. They are characterized by battery voltage sensing circuits similar to the hard cutoff case, but which only signal the user that the battery is discharged. Further discharge is not, however, electrically prevented if the operator, for any reason, does not open the primary load demand switch. (See Section 6.4.3 on low state-of-charge sensing.)

The third category of applications inherently has a *soft* cutoff voltage. The soft cutoff case is illustrated by an application in which the user is the only judge of the amount of reduction of function, resulting from the reducing battery voltage, which will be tolerated before deciding to terminate the discharge and recharge the battery. This is the cutoff employed by all appliances in which no additional circuitry has been provided beyond the primary load demand switch. Typical products in the soft cutoff category are power tools with momentary type load switches, and flashlights with simple on/off primary load switching.

There are two principal criteria which should be used for the determination/selection of discharge cutoff voltages in the end product of any of the above described three types of discharge termination. These criteria are:

- Required Application Voltage (RAV)
- Cell-Polarity-Reversal Voltage (CPRV)

4.5.4.3 Required Application Voltage

Required Application Voltage (RAV) is the lowest battery voltage which will produce acceptable product function. Its value is dictated by the system design of the end product. This voltage is the lower limit of the operating voltage range between battery supply voltage and end product load voltage.

Products are normally specified to operate nominally at the average delivered battery voltage. The average operating voltage in the case of the battery is approximately equal to the midpoint voltage (MPV). (MPV is discussed in Section 4.2). It is therefore helpful to think of the RAV lower voltage limit as a tolerance on the minimum side of that average operating voltage (i.e., some fractional portion of the nominal operating voltage).

As a general rule the degree of utilization of the capacity of the single cell battery will be very close to 100 percent of the total battery (cell) capability when the end product is designed to function satisfactorily down to a single cell battery voltage of 75 percent of the average operating voltage (0.75 multiplied by MPV). This results in a required end-product functional voltage tolerance of +15 percent and −25 percent from the nominal MPV operating value. Since MPV may be conveniently calculated by the procedures illustrated in Section 4.4, all the effects of cell design, as well as application discharge rate and cell temperature, are thus inherently compensated for by using the 0.75 MPV cutoff rule.

In the case of multicell batteries, 100 percent utilization of the total capacity capability is achieved with even less down-side voltage tolerance requirements. This is due to the effect of the sharp drop in battery voltage which occurs when the minimum capacity cell in the battery reaches the end of its capacity and initiates the drop to EODV.

The relationship between battery voltage and product performance may be adjusted during the design of the end product by increasing or decreasing the number of cells in the battery (battery supply voltage). It may also be adjusted by increasing or decreasing the response of the end product at specific battery voltages. The battery supply voltage can also be increased in the case of high-rate, low-run time applications by the use of a low R_e design cell, or a larger cell with higher capacity which thus inherently has a lower R_e (R_e is discussed in Section 4.2).

4.5.4.4 Cell Polarity Reversal Voltage

Although it may be convenient to think of multicell battery voltage in terms of *mean voltage per cell* (battery voltage/number of cells), the mathematics of the cell polarity reversal phenomenon illustrated in Section 4.5.1 result in a fundamental difference from this convenient and simple relationship. The voltage delivered by the nickel-cadmium cell, following the knee of the curve, normally falls off with extreme rapidity. Because of this characteristic, even quite small differences in the actual capacity of the various cells in the battery will result in a low and possibly reversed voltage for the cell with the minimum capacity, before the remaining cells in the battery have even reached the knee of their particular voltage curve. Reflection on this situation will disclose that a multicell battery, in the decreasing voltage region near the end of its capacity, will quite likely have the minimum capacity cell going through zero volts, as in Figure 4-20. The limiting scenario cell-reversal situation might thus be comprised of all cells save one at or above their knee while the lowest capacity cell is at zero or even a slight negative voltage.

Polarity reversal of the minimum capacity cell can be prevented if necessary (see Section 4.5.1) in this case by limiting the multicell battery EODV to approximately:

$$\text{CPRV}_1 = (\text{MPV} - 100)(n - 1) \text{ millivolts}$$

Where: n = number of cells in battery
CPRV is minimum battery voltage which avoids cell reversal.

This equation describes the battery voltage with one cell at zero and the other (n − 1) cells at a point just prior to their voltage knee which is generally located at least 100 mV below midpoint. This equation thus provides a quite conservative estimate of the discharge termination battery voltage that would prevent driving any cell in the battery into reverse polarity.

A more generous determination of CPRV might be to allow a greater average decrement of voltage below midpoint for the (n − 1) cells, for example 150 mV each. It might also recognize that the reversed cell polarity must reverse to at least 200 mV prior to any detrimental effects. Taking both of these allowances into account, the reversal prevention voltage might then be more liberally adjusted toward:

$$\text{CPRV}_2 = [(\text{MPV} - 150)(n - 1) - 200] \text{ millivolts}$$

In addition to the above liberalization, and because any damaging effects of cell reversal are dependent on the cumulative amount (amp hour magnitudes) of capacity in reverse, and each reversal may utilize only a fraction of the total tolerance for any one cell, the minimum operating voltage selected might be further reduced by:

a) Use of cell designs with greater tolerance for reversal. The *General Electric* nickel-cadmium cell has a very high tolerance for cell polarity reversal.
b) Consideration of an end product use pattern which indicates infrequent reliance on cutoff voltage as the actual discharge termination.
c) The use of cells with tightly grouped capacity distributions for making each battery.
d) Reduced expectations of battery life in terms of the number of deep discharge reversals expected in use.
e) Consideration of the general rule that higher rate discharges have softer knees with greater decrements below their MPV, further reducing the value of CPRV and thus minimizing the possibility of cell reversal.

Only the end product designer is in a position to design / adjust / balance the value of RAV and CPRV for the various requirements of cutoff voltage. It is helpful, however, to understand that the MPV is the key voltage from which all these factors may be considered. MPV is the average voltage delivered under the actual load and therefore determines the average functional performance of the end product in addition to its relationship to minimum acceptable product performance. MPV also determines the initial discharge voltage delivered to the end product, approximately [n multiplied by (MPV + 150)] mV. MPV also fixes the maximum battery voltage at which any one cell could possibly be placed in reverse polarity.

The low voltage tolerance of the load need not be designed any lower than either 0.75 multiplied by MPV or the selected value of CPRV, whichever is higher, in order to utilize the maximum useful capacity of the battery.

4.6 CELL DESIGN FACTORS

Design related factors are those elements of a specific cell design that will have an impact on the discharge voltage and/or the actual capacity which is available for a given load under specific operating conditions. The principal elements of the cell include electrode type and dimensions, current collection means, separator, and electrolyte.

These are controlled by *General Electric* and used in a variety of arrangements which yield desirable performance characteristics to match a variety of applications.

4.6.1 Electrode Dimensions

The thickness and surface area of an electrode have a significant effect on the ability of the cell to deliver voltage at high discharge rates and/or to produce its maximum capacity. Normally, to maximize the capacity of a cell, the electrode is made rather thick and thus correspondingly shorter in coiled length. This thick electrode will provide a cell with more active material than would a thin electrode of the same total volume and, because of that additional active material, will deliver more capacity. However, the thick electrode has a high R_e and cannot deliver voltage at high discharge rates as well as the thin electrode of the same total volume and chemistry. For a specific current level, the surface current density in the thick electrode, with its smaller frontal surface area, is higher than that of the thin electrode, which has the larger surface area. Accordingly, for high-rate discharge service the electrodes are designed to be thin and have a large frontal surface area. For high capacity requirements the electrodes are designed thicker with less area.

The thickness and surface area of an electrode also have an effect upon its ability to accommodate high overcharge rates. The oxygen evolved in overcharge at the positive electrode must be effectively reduced at the negative electrode. An electrode with a large surface area will reduce the generated oxygen more readily and at a lower pressure than an electrode with a small surface area. For this reason, fast charge cells are normally designed with thin electrodes having large area.

4.6.2 Current Collection Means

To achieve good voltage regulation at very high discharge rates, all parts of the cell must be designed for low internal resistance. One way to achieve low R_e is to provide multiple parallel paths for current to flow from the electrode to the cell terminals. This is accomplished by using a current collector that contacts the electrode spiral in many places. That design technique is embodied in the *General Electric* GEmax™ cell.

4.6.3 Separator

The separator fulfills a number of functions in the operation of a cell. These include:

- Maintaining physical (electrical) separation of the electrodes.

- Wicking the electrolyte to and from the electrodes while immobilizing that portion of the electrolyte not in the electrodes.
- Providing low resistance conduction of OH^- ions from one electrode to the other through that immobilized electrolyte during charging and discharging of the cell.
- Providing permeability for the oxygen gas to migrate rapidly and easily from the positive to the negative electrode during overcharge.
- Preventing or retarding the migration of cadmium species from the negative to the positive electrode.

In performing these functions a number of separator design trade-offs affect the performance of the cell.

A thicker and less porous separator improves the life of the cell. A thin separator reduces the R_e and increases the volume for active capacity materials as well as improving the oxygen gas transfer between electrodes, thus enhancing overcharge rate capacity.

If high cell temperature operation is required, a *Goldtop*® cell with polypropylene separator is normally used along with material changes in other life-limiting components. For normal cell temperatures a polyamide material is generally specified. Polyamide material is more wettable and therefore wicks the electrolyte better than polypropylene. It thus provides higher ion conductivity, resulting in lower internal resistance and better capacity stability over the life of the cell.

4.6.4 Electrolyte

A number of different electrolyte design options have an impact upon cell life and performance. Most nickel-cadmium cells are designed with a potassium hydroxide electrolyte having a concentration ranging from 29 percent to 37 percent. The concentration used depends upon the application temperature of the battery and the trade-off between performance and life. A variety of additives may also be used in the electrolyte to enhance performance in particular types of applications.

4.6.5 Normalizing R_e

The effects of cell design, aspect ratio of the cell shape, plate manufacturing methods, etc., on the internal resistance R_e may be seen in a sharper perspective by normalizing the $R_e$value relative to cell capacity. To accomplish this, the resistance is expressed in terms of the voltage decrease for each **C** rate of increase of discharge rate (mV/**C** amperes). Thus an R_e of 30 milliohms for a 0.5 Ah cell becomes 15 mV/**C** rate (30 × 0.5). For example, a discharge current of 8**C** rate would result in a discharge voltage which was 120 mV/cell below the effective open circuit voltage E_o. Another cell design with an R_e of only 7 milliohms in a 4 Ahr cell becomes 28 mV/**C** rate (7 × 4). This 7 milliohm cell is thus almost twice as high in effective resistance as the 30 milliohm cell above when the effect of its larger capacity is normalized out of the measurement. This method of expressing R_e better illustrates the effects of cell design and is frequently convenient to use because it is a more constant value which is indicative of overall cell technology and relative power delivery capability.

4.7 SUMMARY

The discharge characteristics which describe sealed nickel-cadmium cell performance are capacity and voltage. Capacity, measured in terms of ampere-hours (or milliampere-hours), is dependent upon cell size, the cell design and construction, the effectiveness of the charge, the cell temperature of the application, the open circuit time between charge and discharge, the discharge rate, the end-of-discharge voltage, and the previous history of the cell in cycling, overcharging, or idleness.

The average discharge voltage is dependent upon the cell size and construction, the discharge rate, the cell temperature of the application, and the previous history of the cell in cycling or idleness.

These two characteristics, capacity and voltage, were discussed in detail in Sections 4.2 and 4.3. Techniques for determining and illustrating their approximate *new cell* values in any application situation were described in Section 4.4.

Chapter 5
Battery Life and Storage

Section

5.1 BATTERY LIFE

Nickel-cadmium cells and batteries are suitable for a wide range of consumer, industrial, and military applications. They provide a long-lasting, trouble-free, rechargeable source of electrical energy that in most applications provides a life expectancy of many years and/or hundreds of cycles of operation. The life of sealed nickel-cadmium batteries is influenced by actual use, the temperature, the charging and discharging parameters, and by the cell, as well as by the battery design and construction. The end of useful life is heavily dependent on the requirements of the application and upon the habits and expectations of the individual user. A capacity of less than 50 percent of cell specification capacity is used by *General Electric* as a measure of end of life.

Two types of battery operating capability loss can cause the device powered by the battery to fail to meet the user's operating expectations:

- Permanent loss of battery operating capability
- Reversible loss of operating capability

A permanent loss of capability is an irreversible failure of the battery to perform its expected function. A reversible loss of operating capability, however, can be overcome to provide additional useful life by some conditioning procedure. This reversible loss of operating capability of nickel-cadmium batteries is discussed in Chapter 4. Permanent cell failure is discussed in this chapter.

Life of sealed nickel-cadmium cells may be measured in terms of *time* or *cycles*. Some factors are time dependent while others are cycle dependent. The effects of these factors will be discussed in light of their respective concerns.

Life characteristics of nickel-cadmium batteries, like those of many electronic components, can be described by a bathtub shaped curve of failure rate vs. time as shown in Figure 5-1; this characteristic curve is called a *hazard function*.

The first of three distinct time zones is Ⓐ in Figure 5-1. It is usually identified as the infantile failure period. The typi-

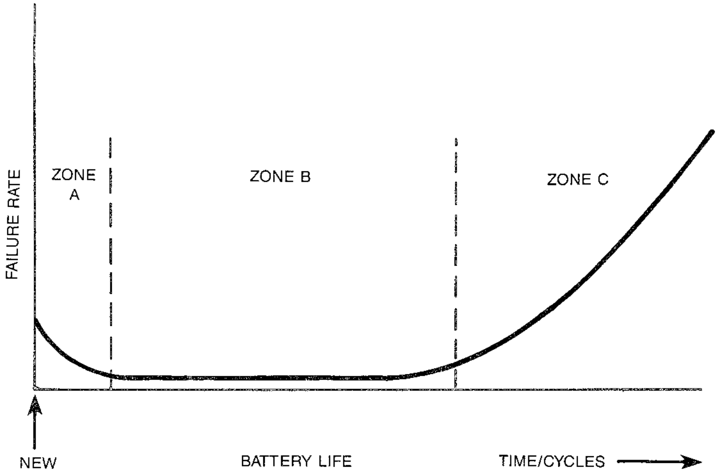


Figure 5-1 Typical Life Characteristic of Nickel-Cadmium Batteries

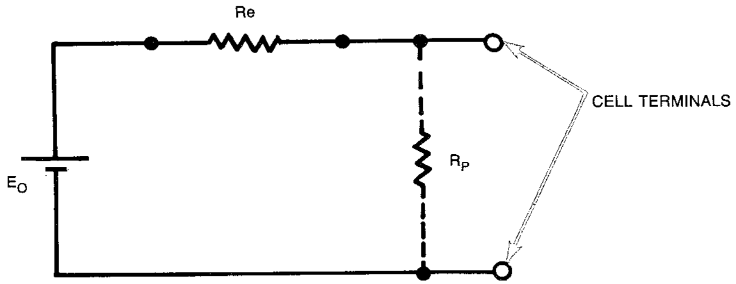
cal profile shows a small and decreasing failure rate as the early failures are weeded out. The second period, Zone Ⓑ in Figure 5-1, is the random failures period and typically shows a very low failure rate. The third, Zone Ⓒ in Figure 5-1, is identified as the wear-out period. During the wear-out period the battery failure rate increases with time. The term *wear-out* is used to describe the condition when the cumulative gradual aging effects, through oxidation or other deterioration or materials, result in eventual loss of the cell operating capability.

Battery life in any application or use, whether quantified in terms of service years or number of charge/discharge cycles, is dependent upon a combination of variables, including:

- Cell design and construction
- Charge/overcharge conditions
- Discharge conditions
- Temperature of the application
- Voltage requirement
- Number of cells in the battery

The end of service life of a battery is often defined by users as the time when the device powered by the battery will no longer meet their perception of minimum acceptable level of operation. Therefore, the end of life for a battery in any specific application depends on the expectations of the user and on the changing performance of the device itself with wear and age, in addition to the ability of the individual cells of the battery to continue to perform their basic function with acceptable effectiveness.

The nickel-cadmium cell can be represented by its equivalent electrical circuit as was discussed in Chapter 4. An equivalent circuit showing voltage source (E_o) and the series resistance (R_e) is shown again in Figure 5-2. In this diagram an additional parallel resistance (R_p) is added to schematically represent the resistance between the positive and negative electrodes, which plays a role in describing one of the failure mechanisms.



WHERE:

Re = CELL INTERNAL RESISTANCE

R_p = RESISTANCE BETWEEN ELECTRODES
MAY DECREASE WITH AGING (SHORTING THE CELL)

Figure 5-2 Equivalent Circuit of a Nickel-Cadmium Cell Showing R_p Failure Mechanism

Useful life of a nickel-cadmium cell is ended when either R_e in Figure 5-2 increases significantly or when R_p becomes relatively small. These variations in R_e and R_p are due to gradual changes in the cell's internal components (e.g. the separator, electrolyte, and electrodes) which change throughout their life. R_p is reduced and approaches zero as the cell becomes internally shorted and can no longer store energy. As R_e increases significantly, the cell can no longer be effectively discharged and ceases to function. The discussion in the next section will detail the various circumstances under which R_e increases and/or R_p decreases to the degree that useful life of the cell is terminated.

5.2 WEAR-OUT MECHANISMS

The typical nickel-cadmium cell will have a very long and useful life with little loss of performance as it typically wears out very slowly as shown in Figure 5-3. A number of wear-out phenomena (discussed in the following paragraphs) occur, affecting performance. These include:

- Deterioration of the electrolyte
- Deterioration of the separator
- Deterioration of the seal integrity

5.2.1 Electrolyte Carbonates

The typical sealed nickel-cadmium cell, as manufactured by *General Electric*, contains a very low level of carbonate. However, the cell contains organic components like separator, seals, and vents. These organic components are slowly oxidized in the presence of the electrolyte, potassium hydroxide, and oxygen, forming small amounts of carbonate. Increasing carbonate concentration changes the characteristics of the electrolyte, reducing the oxygen recombination capability of the negative electrode and the high-rate charge/discharge capability of the cell.

5.2.2 Deterioration of Separator

Sealed nickel-cadmium cells contain a porous synthetic fabric *separator*. This material provides electrical insulation and mechanical isolation between the positive and negative electrodes. A primary cause for electrical shorts in the cell (a reduction of R_p in Figure 5-2) is degradation of this separator material. Degradation is cumulative; when the

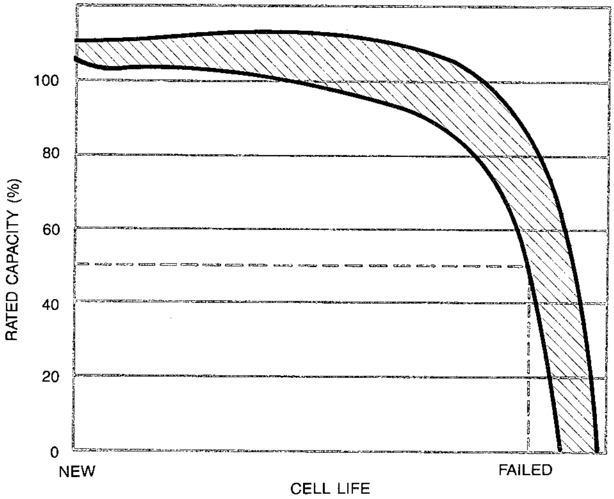


Figure 5-3 Capacity vs. Cell Life—A Typical Representation of Expected Life

degradation has caused sufficient deterioration of the separator material, the separator loses its ability to maintain isolation of the electrodes. An ohmic path is then formed and the cell becomes internally electrically shorted. The rate of separator degradation is a function of the integral of cell temperature over time.

A shorted cell may not always appear to have an electrical short. The short may have a sufficiently high resistance (R_p in Figure 5-2) to allow most of the charge current to flow to the electrodes and charge the active material but sufficiently low resistance (R_p) to self-discharge the cell rather quickly. Such a cell may perform acceptably if discharged immediately after charging but poorly on applications requiring long periods at rest (open circuit) after charging. In effect it will exhibit poor capacity retention. (See Section 4.3.4.)

When the ohmic path through the deteriorated separator has a low resistance, the charge current is partially shunted and the cell cannot be fully charged; what charge is absorbed will quickly flow through the internal short circuit path once removed from the charger, resulting in no usable capacity. The cell voltage determines the current through the internal current path (short). If the cell voltage can be increased enough by high charge currents, the shunting current is sometimes of sufficient magnitude to *burn off* or *clear* the shorted contact, providing a brief extension of life (sometimes colloquially referred to as *zapping* cells).

In some applications, with multicell batteries the device may still provide satisfactory performance, even with one or more shorted cells. In other applications a single shorted cell can degrade the voltage performance of the device to an unacceptable level, at which time the battery has reached the end of its useful life. (For additional information see Section 4.5.4.3 on the required application voltage, RAV.)

5.2.3 Deterioration of Seal Integrity

The electrolyte and the oxygen gas generated during overcharge are normally contained within the cell. *General Electric* sealed nickel-cadmium cells are designed with two sealing points. One sealing component is a plastic seal ring. This seal ring electrically isolates the cover (the positive terminal) from the can (the negative terminal). The seal is made during assembly and completes the cell closure between the can and cover. The second seal point is the safety vent. Typically this is an elastomeric material which is held with a fixed force over an orifice in the cover. Neither the plastic seal ring nor the rubber vent seal is totally immune to attack and deterioration when exposed to the internal potassium hydroxide electrolyte and oxygen. The deterioration rate of the sealing materials is a function of temperature and of the materials used in the particular cell design.

As the seal ring and the safety vent seal (shown in Figures 2-3 and 2-4) slowly deteriorate there comes a point when they no longer provide an effective gas seal. The only continuous source of gases is the water in the electrolyte. That water is lost as it is electrolyzed, resulting in hydrogen and oxygen gas escaping through the deteriorated seal. This failure is not usually observed because other failure modes typically occur first.

Sealed nickel-cadmium cells contain a carefully measured amount of electrolyte. The amount of electrolyte is selected to wet but not saturate the separator and electrodes so there is no excess. Some small loss of electrolyte can be tolerated without significant impact on the cell's performance. However, continued loss of electrolyte will eventually result in an increase of R_e (in Figure 5-2) and a commensurate drop in some cell performance parameters. The resealable safety vent will limit the loss; however, continued venting will lead to dry out and end of useful life.

5.3 USE FACTORS AFFECTING BATTERY LIFE

The preceding paragraphs discussed the wear-out mechanisms that limit the useful life of the battery. The other key factor in battery life is how the battery is used. When the battery is misapplied or misused it can fail much earlier than expected.

5.3.1 Effect of Improper Charging

Improper charging is a principle form of battery misuse. Any charging which results in cell venting may in turn cause an increase in the cell's R_e due to water lost from the electrolyte.

An acceptable continuous charge rate (overcharge rate) allows the cell to generate only oxygen in overcharge (no hydrogen) to the degree that the build-up of pressure does not exceed the setting of the safety vent. If the cell temperature is low (such as in a garage in winter), the capability of the cell to effectively reduce oxygen generated in overcharge is lessened. If the charge rate exceeds the recommended maximum at the cell temperature, the oxygen pressure when starting overcharge may exceed the safety vent pressure setting and the gas will be expelled through the vent. A moderate amount of lost oxygen can be tolerated. However, if such venting continues, or is repeated, the amount of water in the electrolyte is decreased to the point that the cell will not function properly. This is sometimes referred to as *dry-out*. Under dry-out conditions, R_e (see Figure 5-2) increases to the degree that the cell can no longer be effectively charged or discharged (the discharge voltage is low and the charge voltage is high). Proper charging is covered in Chapter 3.

5.3.2 Temperature

The most important application factor that affects normal cell wear-out life is temperature. As mentioned previously, elevated temperatures cause the separator and seal materials to degrade. As this rate of degradation is a direct function of the cell temperature (at any given time), applications exposing batteries to high ambients or overcharge temperatures will experience a reduction of life from those expected at 23°C.

Since the total amount of component deterioration is a function of the time-temperature integral, occasional brief exposures of the cell to very high temperatures of less than 100°C can be tolerated with little effect.

5.3.3 Effect of Continuous Overcharge

Although many of the applications for sealed nickel-cadmium batteries are cyclic duty, another widespread use of these batteries is in standby power or principally *on-charge* applications such as emergency lighting, alarm systems, computers and always ready-to-serve cordless applications.

The key life-limiting factor in these almost continuous overcharge duty applications is the cell temperature. In most standby duty equipment, the sealed nickel-cadmium battery is maintained in a fully charged, ready-to-serve function by applying a continuous charge to the battery. The temperature in overcharge, discussed in Section 3.4.2, can be significantly above the ambient temperature due to heat generating sources in the vicinity of the battery as well as the charging energy, converted to thermal energy in overcharge. The temperature of the cell and its internal components determines the life of the battery in these standby duty applications. Section 5.4 examines the typical relationship of life versus temperature for two cell construction types.

5.3.4 Effect of Depth of Discharge on Cycle Life

Although *General Electric* nickel-cadmium cells have inherent deep discharge protection, the cycle life of sealed nickel-cadmium cells is affected by the depth of discharge as shown in Figure 5-4. When a cell is fully exercised in every cycle the active materials in the electrodes are *worked* more, causing slight degradation to occur earlier than in the same cell undergoing less *exercise*. The band shown in Figure 5-4 indicates a rather broad range of expected results, particularly in the shallow depth-of-discharge region.

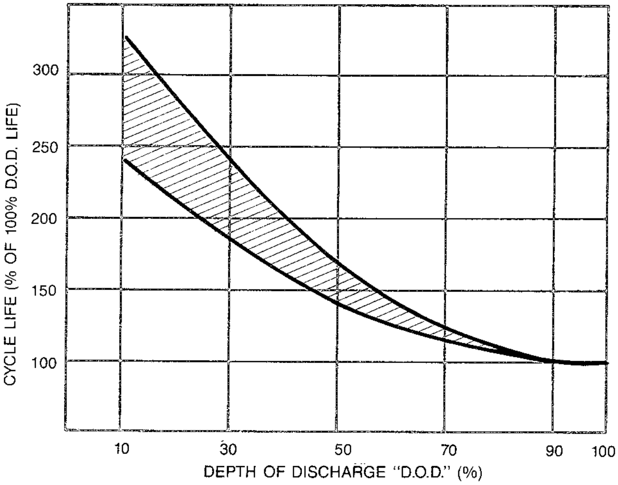


Figure 5-4 Effect of Depth of Discharge on Cycle Life

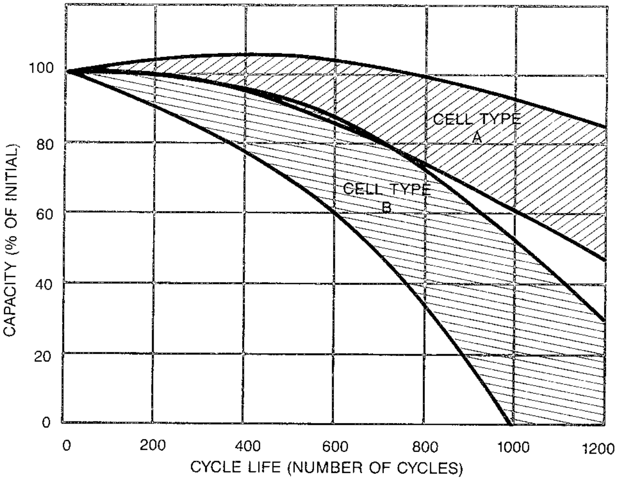


Figure 5-5 Typical Cycle Life of Nickel-Cadmium Cells at 23°C and Deep Discharge

5.3.5 Effects of Mechanical Shock and Vibration

General Electric nickel-cadmium cells have a rugged construction and can tolerate the shock and vibration of normal use. For example, *General Electric* cells have been subjected to long-term exposure to 10g excitation in the axial and transverse directions over a frequency range of 100 to 500 Hz with no loss in performance. However, severe shock and vibration can cause damage to the battery components and the cells, resulting in sudden failure due to electrical shorts or opens in the intercell connections of the battery. Under such abusive conditions the life of a battery can be abruptly terminated at any time.

5.4 EFFECT OF CELL CONSTRUCTION ON BATTERY LIFE

The life of a sealed nickel-cadmium cell depends in large measure upon its design and construction. The electrode design and method of manufacture, the separator, and the cell roll geometry have the most significant effect upon the capacity of the cell during its operating life. A typical representation of cell cycle life is shown in Figure 5-5. Cell Type Ⓐ and Cell Type Ⓑ indicate that different capacity trends can be expected from different types of electrode construction as a function of the number of cycles. The cycles in Figure 5-5 are deep discharge cycles and the average temperature is 23°C. The Type Ⓐ and Type Ⓑ curves in Figure 5-5 are not specific *General Electric* designs, but are illustrated to emphasize the fact that different designs and process techniques may have an effect on the capacity during life.

The two types of cell construction in Figure 5-6 show the time (non-cycle) life difference due to electrode construction, separator, electrolyte, and other design factors versus temperature. Cell Type Ⓓ is able to handle high temperature exposure with limited reduction in lifetime while Cell Type Ⓔ is designed primarily for applications at nominal temperature and below. Again, Type Ⓓ and Type Ⓔ curves

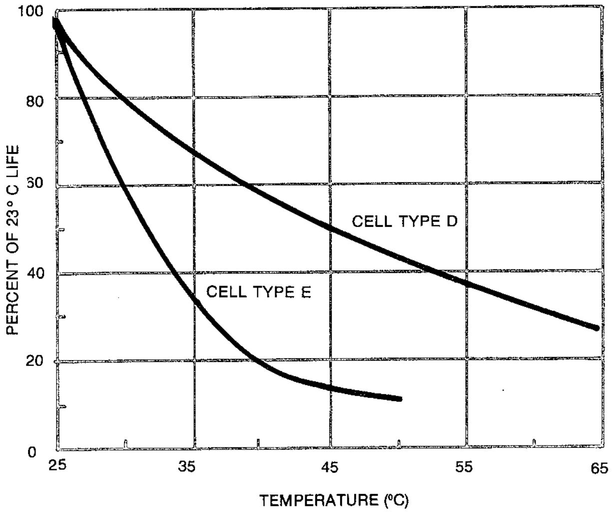


Figure 5-6 Life Derating vs. Cell Temperature

in Figure 5-6 are not specific *General Electric* designs but are shown to highlight the difference between cell design.

5.5 QUALIFICATION TESTING

Some users of batteries may perform special testing to qualify batteries for use in a specific application. This qualification testing takes the form of a series of specific tests in which the battery or cells must meet certain minimum or maximum limits for each test procedure. These qualification tests take on many forms and have various names, such as *type* and *performance* tests. A *type test* may contain not only initial performance measurement tests but also some form of *life* exposure with periodic performance measurements.

5.5.1 Performance Testing

The purpose of performance testing is to define the electrical characteristics of the battery under a variety of conditions. Since *General Electric* sealed nickel-cadmium cells may increase in capacity during the first few cycles for any specific set of conditions, it is necessary to perform stabilization cycles prior to measuring the performance to obtain realistic and repeatable data. Five cycles are usually sufficient to reach stabilization.

5.5.2 Life Testing

Qualification testing is usually conducted on an accelerated basis in one form or another to reduce the test time to a practical time limit. A qualification life test may be generalized to the degree that the test regime does not reflect the effects of normal charge-discharge activity that all particular applications will experience. This generalized life test procedure does not necessarily provide an entirely valid basis for projecting actual cyclic or calendar life for all particular applications.

A type test regime may attempt to simulate, to varying degrees, the actual expected use pattern of the device. Such regimes may compress calendar time by ignoring all intermittent use patterns and storage (idle) periods which are typical of most applications. Laboratory tests may not truly simulate the expected real time use of the product. All of the variables encountered in a typical real time use of the product would be difficult, if not impossible, to duplicate in a type test.

In most applications, the battery is exercised randomly with some shallow discharges and some deep discharges. The effect of this random usage is typically beneficial for cell performance and may extend the life beyond that found in a fixed, regimented cycle regime such as a qualification test.

With the increase in popularity of fast charging systems, which can fully charge a battery in one hour or less, cyclic life testing with many cycles per week is quite common and provides a guide to battery cycle life expectancy. Calendar time is of course not accounted for in such accelerated cycle life testing regimes. However, this test, unless used with fast-charge cells and charged by the same method as the end-use application, may be an additional nonlinear stress not seen in the real application.

It is important to recognize that the results of qualification life testing must, at best, be a compromise of the life expectancy of the battery in real time. The designer of a qualification life test procedure should consider all appropriate factors which will affect the life performance of the battery and at the same time apply a realistic and reasonable stress on the battery. Certainly some acceleration of time may be required to complete the life type test in a practical amount of time. However, in any attempt to compress test time, extreme care must be taken to avoid any nonlinear life-limiting or life-diminishing stresses on the battery which cannot be correlated with the expected real time use of the battery. Without thoughtful consideration of the significant wearout variables, a life test program may yield misleading conclusions or comparisons.

5.6 METHODS OF LIFE TESTING

General Electric tests designed to generate a data base for defining life characteristics of nickel-cadmium batteries are of two types:

- Real-time life testing
- Accelerated life testing

5.6.1 Real-Time Testing

Real-time testing, although the most representative of all testing, has a fundamental limitation. Since the life of nickel-cadmium cells is measured in years, a very long period of time is required to obtain meaningful failure data. The wide range of variables encountered in real life applications would dictate the consideration of a similar broad range of life testing regimes. For laboratory simulation of an actual application, it is usually desirable to set up conditions as close as possible to those found in the actual application. It may also be desirable to accelerate a test by imposing more difficult conditions on the battery so as to obtain information more quickly. In addition, new battery products are constantly being introduced. These and other factors thus favor reliance on accelerated life testing as the primary early means of establishing battery life expectancy data and for making cell comparison judgements for specific applications.

5.6.2 Accelerated Testing

The two major application factors for determining the appropriate method of battery life acceleration are cyclic applications and standby applications.

Cyclic dominated applications are exemplified by commercial uses of nickel-cadmium batteries in receiver/transceiver mobile communication devices, photographic equipment and power tools where cyclic experience may be as rapid as one charge/discharge per hour or as infrequent as an average of several per week.

Standby (non-cyclic) uses are typified by microprocessor memory back-up power, emergency lighting and security system standby power, and ready-to-serve household appliances such as shavers and cordless appliances on charge whenever not in use.

5.6.2.1 Cyclic Acceleration

Cyclic application accelerated life testing typically uses the accelerating factor of eliminating all idle time and most excess overcharge time. This regime utilizes:

- The maximum reasonable number of cycles per period
- Depth of discharge ranging upwards to 100 percent

Cells designed only for 0.1**C** charging can be life tested to full depth of discharge at cyclic rates no higher than about one cycle per day. This is a rather insignificant cyclic accelerating factor for producing wearout in a reasonable period of time. Cells capable of charge rates up to 0.3**C** can be tested at cyclic rates of about three cycles per day. However, time and temperature may be the limiting factor in either case just as in standby applications. Cells designed to tolerate fast-charge rates of 1**C** or greater can be exposed to accelerated cyclic rates as high as twelve cycles per day. Calendar time is not the life measurement parameter used in the high cyclic rate regimes discussed above, but rather actual cycles to failure. The objective should be to provide the optimum data in the minimum calendar time, uncompounded by unpredictable or inadvertent and unrealistic abusive stress factors.

5.6.2.2 Temperature Acceleration

It is often desirable to accelerate a life test so that results can be obtained in a shorter time than would be necessary for a standard condition test. The test parameter that is normally used for acceleration is temperature. A great deal of test data and testing experience is necessary to interpret the results of an accelerated test and use these results for predicting life under normal conditions. Plots of achieved life are normally represented in terms of *characteristic life* (that is, when 63.2 percent of the population have failed to meet predetermined minimum performance levels) as a function of the accelerating variable (i.e., temperature). These data points may be utilized to extrapolate a steadily improving estimate of real condition life, as new points become available at the lesser accelerated conditions. Without the availability of intermediate condition data, the usefulness of accelerated life tests is inherently limited to comparison between groups of batteries at the accelerated condition and these comparisons are only valid if the accelerating mechanism has the same effect on both. For example a comparison between cell types Ⓓ and Ⓔin Figure 5-6 could produce seriously misleading results for only one acceleration.

Temperature is well known as an accelerating factor in many types of life tests that result in reduction in life as temperature is increased. The amount of meaningful temperature increase must, however, be limited to the range that does not introduce new failure modes. Accelerated life tests of sealed nickel-cadmium cells at *General Electric* are conducted at temperatures of 37°C, 48°C, 60°C, 72°C and 86°C.

Non-cyclic (standby) application accelerated life testing typically uses temperature as the key time accelerating factor. The assumption is that the the occurrence of key wearout failure modes is the critical objective of such testing. The priority wearout failure modes, as discussed in Section 5.2, are shorts and electrolyte dryout. The materials of all the cell components whose design function is to insulate and/or to seal are polymeric. Such materials inherently deteriorate in time and lose their functionality. The basis of thermal acceleration testing is that the life degradation rate of these insulators and seals is temperature dependent (Arrhenius relationship). With all other factors constant, these degradation rates roughly increase by 20 to 145 percent for every 10°C rise in cell temperature. Differences in design and materials as well as temperature levels (the inverse Arrhenius factor) account for these rate differences. Therefore the protocol for thermal stress testing calls for overcharging at rates appropriate for the cell design being tested, but at a range of elevated temperatures, then extrapolating the results to the more moderate temperature of the typical application. This protocol requires periodically discharging the cells to measure the progressive degradation of cell capability as well as to simulate the anticipated infrequent discharge of such applications. The failure criterion established and used at *General Electric* is when the capacity falls below 50 percent of that capacity available at the elevated test temperature when the cell is new.

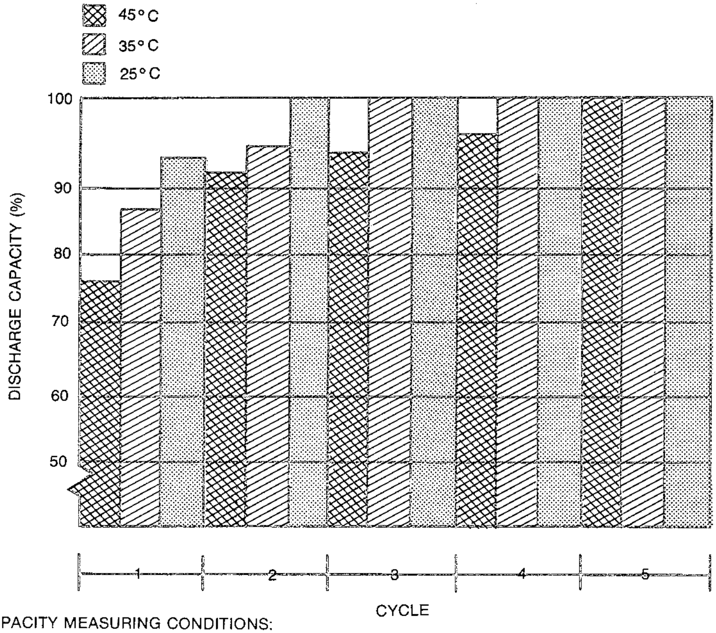
5.7 STORAGE

Nickel-cadmium cells can be stored under a wide range of temperature and humidity conditions without permanent harm to the cells. However, it is important to understand the effects of any extreme in either temperature or humidity in order to minimize any adverse effects which may accrue from uncontrolled exposure to such extremes of environment.

5.7.1 Temperature Effects During Battery Storage

General Electric nickel-cadmium batteries can be stored under a wide range of temperatures. Storage for long periods at the upper temperature extremes will cause a reduction in battery life. To ensure the maximum life capability, long exposure to extremes of the storage temperature range should be avoided. The recommended storage is 0°C to 30°C, but cells can tolerate excursions of −40 to +100°C.

Figure 5-7 depicts the number of cycles required for full capacity recovery for cells stored for one year at various temperatures. Capacity recovery cycles may increase with higher storage temperatures since the active material becomes passivated over time.



CAPACITY MEASURING CONDITIONS:
CHARGE: 0.1C × 20 HRS @ 23°C
DISCHARGE: 1C to 0.9V

Figure 5-7 Storage Temperature and Typical Capacity Recovery Characteristics

Fast-charge cells, charged at 1**C** or higher, will exhibit high charge voltage on the first cycle after prolonged storage at room temperature or if stored in warm ambients.

5.7.2 State of Charge Effects During Battery Storage

General Electric sealed nickel-cadmium batteries can be stored in either the charged or discharged state. Batteries stored in a charged state will experience self-discharge. As discussed in Chapter 4, the rate of self-discharge increases with cell temperature. However, even if a battery is stored for extended periods and becomes completely discharged, one or more charge-discharge cycles will usually place the battery in a fully operational mode. One storage concern, *loaded storage*, is explained in the following section.

5.7.3 Loaded Storage Effects During Storage

One application for nickel-cadmium batteries is to provide back-up energy for *volatile* semiconductor memories in a wide variety of electronic devices. Although the drain rate of a typical semiconductor memory and its associated circuitry is low, it is nevertheless sufficient to discharge the battery if there are long periods of storage with the load connected to the battery. The elapsed time from the time the battery is installed in the device to the powering up of the device in the field may combine with self-discharge to exceed the discharge capacity of the battery. The result in this case is that an electrical load is connected to the battery while it is in the discharged state. This is referred to as *loaded storage.*

When a nickel-cadmium battery has been completely discharged but a load continues to be applied, the battery voltage will approach zero. When the battery voltage is held at zero or close to zero, the nickel-cadmium cell will be in a *loaded storage* condition in which *creep leakage* phenomena can occur. Under these conditions there is a very small but continuing growth of an electrolyte film in the sealing surface of the positive terminal. This creep leakage, an electrochemical phenomenon, may ultimately cause small amounts of electrolyte to creep out around or through the vent seal. When this occurs small amounts of white crystals (potassium carbonate) will eventually appear on the outside surfaces of the positive terminal. This white material is minute particles of the potassium hydroxide electrolyte which have reacted with carbon dioxide in the air to form potassium carbonate. The effect of creep leakage in a single-cell *loaded storage* application is usually appearance related only. However, in cases involving batteries of two or more cells in series, the potassium hydroxide (KOH) leakage may be large enough so that other components of the device may be exposed to potential corrosion damage from electrolyte.

This effect may also occur in circuits containing electronic battery cutoff relays in which the sensing circuit remains across the battery even after the main load is switched out.

General Electric nickel-cadmium cells are designed to resist leakage but storing devices with the battery in *open circuit eliminates any possibility of loaded storage.*

5.8 SUMMARY

Battery life can be measured in terms of either usage time in years, or number of charge/discharge cycles, or both. In general the *wear-out* function of the cell is independent of cycling. Wear-out is primarily a function of cell temperature and overcharging conditions. Internal shorting failures, however, may also be dependent on the depth to which a discharge is carried. A shorting path of low current carrying capability may be able to sustain itself while shunting 0.1**C** charge current, but be unable to maintain the connection if it is suddenly required to serve as the discharge path for a partially charged cell. Some applications require that the battery be discharged only a few times a year but be maintained in a state of continual readiness. In these cases, battery life is best described by the time element. But in most applications, both time and number of cycles are of significance in the life of the product.

Chapter 6
Application

Section

6.1 INTRODUCTION

This Chapter provides information about nickel-cadmium cells and batteries as they relate to specific applications. The features of nickel-cadmium sealed cells as well as the application parameters which should be considered by the designer when the battery is being selected for a given application are highlighted.

6.2 FEATURES AND BENEFITS OF SEALED CELLS

In reviewing the features of nickel-cadmium batteries presented in earlier sections, it is clear that these batteries are particularly well suited to applications where the convenience of a self-contained, always ready power source increases the value and utility of the device or product. In applications where high power is desired a rechargeable nickel-cadmium battery is often the most economical battery type.

Sealed nickel-cadmium batteries are used in many products and applications due to their unique characteristics and capabilities. Among the most significant features of *General Electric* nickel-cadmium batteries which lead to their choice as the preferred power source are the following:

- Long operating life
- High-rate discharge capability
- Fast recharge capability (with charge control)
- Operation over a broad range of temperatures
- Long storage life
- Rugged construction
- Maintenance-free use
- Operation in a wide range of environments
- Operation in any position
- Continuous overcharge capability
- Nearly constant discharge voltage
- High energy density

An understanding and appreciation of the benefits derived from this unique combination of product features are important as they relate to a specific product or application. These special capabilities open the way to the design and manufacture of a host of products that are practical, convenient, or economical only with the nickel-cadmium battery system.

6.2.1 Long Operating Life

Nickel-cadmium batteries have a very long operating life, as measured either by number of charge/discharge cycles or by years of useful life. Whether the battery is actively used by repetitively charging and discharging, or is maintained on charge in a ready-to-serve condition, nickel-cadmium cells can offer a very long, trouble-free life. *General Electric* nickel-cadmium batteries will normally provide hundreds of charge/discharge cycles or operate for many years in a ready-to-serve standby function. A detailed discussion of battery life is presented in Chapter 5. The long operating life makes nickel-cadmium batteries an excellent value for high-frequency use.

6.2.2 High-Rate Discharge Capability

General Electric nickel-cadmium batteries can deliver energy at very rapid rates. High-rate discharge capability makes the nickel-cadmium battery ideal for use in high power devices such as power tools. In these applications a high-rate discharge capability leads to small, light and economical battery powered products. Repeated cycles with very high discharge rates are achievable. More information on discharge capabilities is presented in Chapter 4.

6.2.3 Fast-Recharge Capability

A significant feature of the nickel-cadmium battery is its ability to accept high charge rates. Although most rechargeable nickel-cadmium battery applications have traditionally used a relatively low-charge rate, which may require 16 to 20 hours to achieve a full charge, special sealed nickel-cadmium batteries that can be charged much more rapidly are available.

Quick-Charge batteries can be completely recharged at the 0.3**C** rate in four to five hours, generally without the need of charge controls. They can be overcharged at up to the 0.3**C** rate.

Fast-charge cells allow the user to recharge the battery in very short periods of time, normally within an hour. With the fast-charge capability, the use of cordless electric products is possible without advance planning or preparation. Fast charging also permits the use of the full capability of the battery several times a day, reducing the need for spares or larger batteries. As explained in Chapter 3, the fast-charge current required to obtain this short recharge time must not be continued into overcharge. This requires a special charger system with controls to terminate the high charging current.

6.2.4 Operation Over a Broad Range of Temperatures

Nickel-cadmium batteries have excellent performance characteristics over a wide range of operating temperatures. Nickel-cadmium batteries deliver usable capacity in environmental applications where temperatures may drop to −20°C or rise to 70°C. Some precautions must be taken in charging nickel-cadmium cells at extremely low temperatures. Special high temperature cells are usually required for applications in which the battery remains above 50°C.

As is the case with most components, high cell temperatures accelerate the degradation of batteries and reduce the operating life. The temperature limits stated in specification sheets represent the maximum continuous operating and storage temperatures that permit a reasonable life expectancy. The batteries may be operated or stored at higher temperatures (less than 100°C) for short periods without noticeable degradation in battery life. Whenever the application requires the battery to be subjected to continuous high temperatures, *General Electric's* high temperature *Goldtop*® battery should be used to achieve the longest useful life.

As discussed in Chapter 3, charge acceptance at higher temperatures is substantially reduced and the charge voltage is somewhat depressed. The capability of the cell to retain its charged capacity while in open circuit is also reduced at high temperatures. Low temperatures will reduce the amount of capacity that can be discharged from the battery, particularly at high discharge rates. Capacity is discussed in Chapter 4.

6.2.5 Long Storage Life

The *General Electric* nickel-cadmium cell can be stored for extended periods of time at room temperatures in either a charged or an uncharged condition with virtually no degradation in capability and, after just one or two normal charge/discharge cycles, will exhibit normal performance. This feature has considerable value in applications where the battery is used only occasionally with long periods of time at rest in the discharged state. Battery life in storage is similar to that in use although with a lower rate of degradation. Storage and life are discussed in Chapter 5.

6.2.6 Rugged Construction

The *General Electric* sealed nickel-cadmium battery is a very rugged device, both physically and electrochemically. The cells possess good resistance to shock and vibration. The nickel-cadmium battery lends itself to applications in which it may be subjected to temperature extremes, tough physical use, or other demanding applications. (See Chapter 5 for further information.)

6.2.7 Maintenance-Free Use

Nickel-cadmium sealed-cell batteries are a good choice for applications in which periodic maintenance would be difficult, impossible, or costly. Since they require no maintenance, sealed cells are often permanently wired into a product. The gases generated during normal operation are recombined within the cell. *General Electric* sealed cells perform repeatedly through normal duty cycles with no loss of active material or electrolyte.

The sealed cell is an install-and-forget power source. With the exception of periodic charging, it will perform virtually without attention throughout its life.

6.2.8 Operation in a Wide Range of Environments

Nickel-cadmium sealed cells can be operated in a full vacuum or in a positive pressure environment. They also may be operated in environments with a relative humidity range normally encountered in commercial applications, without noticeable effects on performance or degradation of life.

6.2.9 Operation in Any Orientation

Sealed cells can be mounted and operated in any position or attitude. The combination of sealed construction, absorbent separator, and highly porous electrodes holds the electrolyte so that normal ionic conduction required in the charging and discharging reactions occurs regardless of the cell orientation. This feature permits product design flexibility for portability. *General Electric* nickel-cadmium cells have even powered drills in space and on the moon!

6.2.10 Continuous Overcharge Capability

The nickel-cadmium sealed cell battery is designed to accommodate extended charging at recommended charge rates, with no noticeable effect on performance or life. Very simple and inexpensive chargers can be used when charging at Standard rates. With this simple charger the Standard battery is normally fully charged at the standard 0.1**C** rate in 16-20 hours. Where a faster charge is desired, special Quick-Charge cell designs are available which will tolerate continuous overcharge up to 0.3**C** rate and can be recharged in four to five hours with a similarly inexpensive charger. This ability of nickel-cadmium sealed cells to accept continuous overcharging using either the Standard or Quick-Charge rates has value in those applications where the product must be ready to operate upon demand. Because of the ability to handle continuous overcharge current, *General Electric* nickel-cadmium batteries are widely used in standby power applications to automatically provide temporary service to systems requiring modest amounts of energy during power outages. Examples are emergency lighting, alarms, and microprocessor memory holdup applications. (See Chapter 3 for further information on charging.)

6.2.11 Nearly Constant Discharge Voltage

Nickel-cadmium sealed cell batteries have a nearly *flat discharge voltage profile* throughout the major portion of the discharge. At the very beginning of discharge (for a fully charged cell) at the one-hour rate, the voltage will drop quickly to about 1.28 volts and then decline very slowly to about 1.20 volts after 80% of the capacity has been delivered by the cell. Then, during the final 20% of discharge, the voltage will again drop quite quickly to 0.9 volts or less.

This nearly flat discharge voltage characteristic of nickel-cadmium sealed cell batteries is valuable in applications that require a high voltage to operate efficiently, such as a dc motor driven product, or where constancy of electrical power output is important, for example in cordless drills, tape players, portable televisions and shavers. A complete discussion of the discharge voltage is given in Chapter 4.

6.2.12 High Energy Density

The watt-hours per kilogram provided by the nickel-cadmium battery are among the highest for a rechargeable system. A lead-acid system capable of delivering the same amount of energy would weigh considerably more and require more space than the equivalent nickel-cadmium battery. Thus, nickel-cadmium allows the design of small, lightweight devices such as instruments, photo flashes, video cameras and shavers.

6.3 ECONOMIC CONSIDERATIONS

It is important for the designer to have a working knowledge of the cost of nickel-cadmium batteries and how duty cycles, use patterns, and application variations may affect the economics of the battery system. The following discussion treats the economic considerations of using nickel-cadmium batteries.

6.3.1 General

The use pattern of the battery-powered product, the peak and average power levels required, the total amount of energy required, the duty cycle to which it is subjected, and the recharge time allowable will all affect the economics of a battery system. The designer will have to consider not only the first cost (procurement cost) of the battery, but the operating cost (battery cost over the life of the product) as well. The first cost of the battery is often incidental to the value of the product and service rendered by that product. In these products a *General Electric* nickel-cadmium battery with a long, reliable operating life requiring no special attention is usually chosen.

6.3.2 Battery Duty Cycle

In earlier chapters the various discharge characteristics and recharging rates which are part of a nickel-cadmium cell's normal duty cycle are discussed in detail. Three rates of charge are categorized as (a) Standard-Charge at a rate which requires *overnight* recharging time; (b) Quick-Charge, a moderately rapid rate which recharges cells in several hours; and (c) Fast-Charge, which uses the high-current capability of nickel-cadmium sealed cells by recharging them in about one hour or less.

For a rechargeable battery system, the duty cycle or use pattern will have a significant impact on the required battery rating, hence size and cost. In Figure 6-1, three different duty cycles are displayed. Each duty cycle requires the same amount of energy from the battery in a 24-hour period.

A. The constant energy required in Cycle Ⓐ in Figure 6-1 for an eight-hour period suggests a battery capacity equal to the total capacity required, say 2.0 ampere-hours, for the eight-hour period (250mA × 8 hours = 2.0 ampere-hours). This means that the battery capacity required to satisfy the Duty Cycle Ⓐ in Figure 6-1 needs to be at least 2.0 ampere-hours at an eight-hour drain rate. The battery would be recharged during the 16-hour *off* period at the 0.1**C** rate (200mA) so that it would be fully charged for the next discharge period. This duty cycle is an example of a standard-charge rate application.

B. The energy required for the duty cycle presented in Cycle Ⓑ of Figure 6-1 is also 2.0 ampere-hours over the

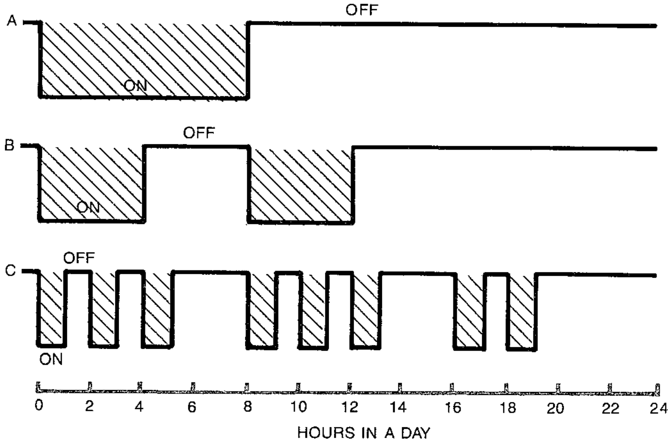


Figure 6-1 Possible Duty Cycles of Nickel-Cadmium Battery System

24-hour period, but it is split into two four-hour periods of 1.0 ampere-hour each. The drain rate of 250mA is the same. In this case, a smaller battery with a quick recharge capability could be chosen. A 1.0 ampere-hour battery with a 0.3**C** ampere recharge rate capability of 300mA could be used, and this would significantly reduce the battery size, weight, and cost. The battery, after a four-hour discharge, would be recharged during the next four hours and be ready for the next discharge. This would be a quick-charge application.

C. In Cycle Ⓒ of Figure 6-1, the same energy and drain rate (2.0 ampere-hours at 250mA) is delivered to the load, but with at least a one hour *off* period between each one-hour discharge period. A battery charger system capable of one-hour recharge would help reduce the battery ampere-hour rating required. The battery would have to deliver 250mA for one hour about every other hour. A 250mAh battery (dramatically decreasing the size of the battery) along with a special charger with means of terminating the fast-charge current of about 250mA (1**C**) could meet this need. The fast-charge system cost would be higher, so the higher charger cost would offset some or all of the lower battery cost.

As these three examples show, the duty cycle with a fast or quick recharge capability can reduce battery cost, size, and/ or weight. The charger cost, however, increases with higher power requirements and these trade-offs should be evaluated.

6.3.3 Voltage vs. Watt-Hour

In many applications the battery cost can be minimized by optimizing the voltage-versus-watt-hour relationship. Using a small number (lower voltage) of large capacity cells is an alternative to using a greater number (higher voltage) of smaller capacity cells. The larger capacity cells could also offer higher reliability by having fewer cells per battery.

6.3.4 Cost Per Watt-Hour

The first cost (or replacement cost) of a battery is frequently evaluated in terms of cost per watt-hour. When the battery cost is determined in these terms only, the nickel-cadmium battery may be the more costly battery system. However, evaluated over the operating life of the product to be powered it very often becomes the most economical choice, particularly when the maintenance and special care in storage required by other battery systems are considered. To determine the operating cost of the nickel-cadmium battery, one can start by establishing the cost per watt-hour as a basis.

The nickel-cadmium cell is rated 1.2 volts dc. Hence, 1.2 volts times the ampere-hour capacity of the cell gives the watt-hour rating of the cell. This product, multiplied by the number of cells in the battery, yields the battery watt hour rating as shown in the equation below. The cost of the battery can then be reduced to a common denominator of cost per watt-hour:

$$\text{Watt-hours} = 1.2 \times N \times \mathbf{C}$$

Where: 1.2 = Cell Voltage
N = Number of Cells in Series
C = Capacity of Each Cell (Amp Hours)

6.3.5 Cost Per Watt-Hour Per Cycle or Per Year

As stated earlier, the true cost of a rechargeable battery is the cost over the life of the battery. *General Electric* nickel-cadmium batteries are designed so that in most applications they will often deliver hundreds of charge/discharge cycles over many years. Tests have been performed on batteries that demonstrate a life of generally well over 500 cycles. The long operating life should be evaluated when determining the true lifetime cost of the system.

6.4 ELECTRICAL CONSIDERATIONS

6.4.1 Cell Voltage—General Overview

The general cell-voltage response during a typical cycle is shown in Figure 6-2. In this representation a fully discharged cell is charged at the 0.1**C** rate in a 23°C ambient into the overcharge state, rested, discharged, and then rested again.

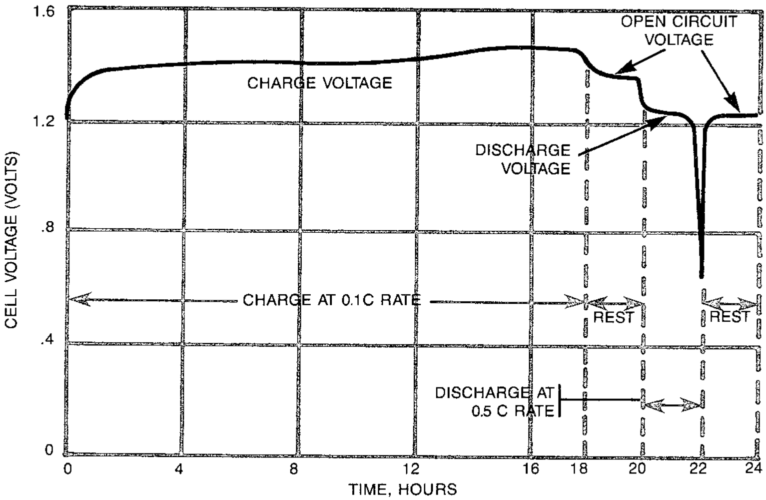


Figure 6-2 Typical Cell Voltage Response During Typical Duty Cycle @ 23°C

Figure 6-2 shows the voltages for each phase of this typical cycle. The voltage of a nickel-cadmium cell can vary from about 0.6 volts per cell up to about 1.5 volts depending upon the cell's state of charge and whether it is being discharged, charged, or is at rest. The useful discharge voltage range is normally 1.3 volts to 0.9 volts in typical applications. The normal standard (0.1**C**) rate charging voltage range is 1.3 volts per cell up to 1.5 volts. Occasional deviations from these limits may be observed in extreme temperature environments, at high charge or discharge rates, when the cell is new, or when the cell has been stored for an extended period. (See Chapter 3 on charging.)

The discharge characteristics of a nickel-cadmium battery are quite different from the ordinary dry-cell battery. Figure 6-3 presents the voltage characteristics under discharge of an ordinary carbon-zinc and alkaline cell with the rechargeable nickel-cadmium cell. The comparison shown is for a discharge current of 800mA where both primary cells are "D" size. The voltage of the carbon zinc cell falls quite rapidly as it is discharged, while the nickel-cadmium cell discharge voltage is nearly constant for most of the discharge. (See Chapter 4 on discharging.)

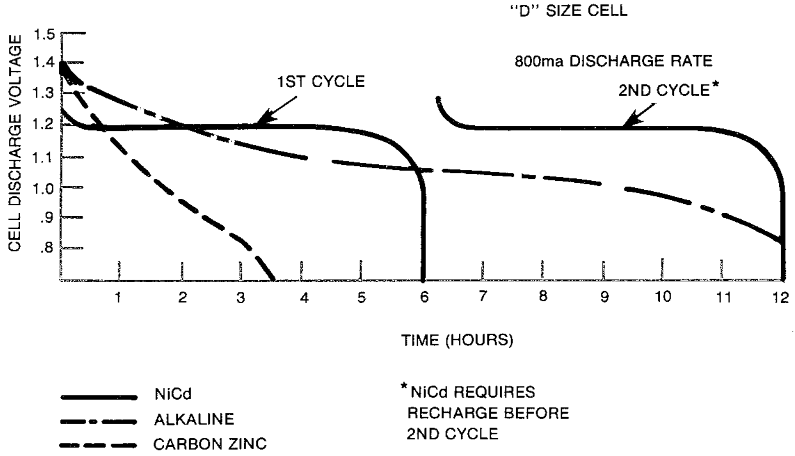


Figure 6-3 Discharge Characteristics of Ordinary Dry "D" Size Cells and Nickel-Cadmium Batteries

6.4.2 Designing for the High Rate Capability of Nickel Cadmium Batteries

Since nickel-cadmium batteries are capable of very high rate discharge, care must be taken in the design of the product so that neither the battery nor the conductors will overheat. A short circuit across a fully charged nickel-cadmium battery can cause currents up to 100 **C**. The heat generated from such large current can cause temperatures to rise quickly with the possibility of a *safety* hazard.

The designer should be aware of this possibility and design the circuitry and/or physical barriers to minimize the possibility of short circuits and to minimize the consequences should a short circuit occur.

6.4.3 Low State of Charge Indicator

As stated in earlier chapters, the voltage and internal resistance of nickel-cadmium batteries varies only slightly with state of discharge so it is difficult to use these parameters to determine state of charge. It is possible to determine when a nickel-cadmium battery is fully charged or when it is fully discharged. Between these extremes, variation of the battery voltage and internal resistance parameters with temperature, battery history and other environmental factors usually make them poor indicators of state of charge.

Figure 6-4 shows an example of how voltage sensing might be used to attempt detecting low state of charge. The signal voltage at level Ⓐ will correctly indicate a low state of charge for a battery in history/temperature condition C_1. However, if the battery condition becomes C_2, the low battery signal will be premature. If low state of charge detection were at level Ⓑ, this problem would be avoided. (See Section 4.5).

One way to obtain a state of continuous charge indication is to use integrators or coulometers that monitor the amount of energy taken out of the system and work very much like coulometers used in charging (See Section 3.7.1).

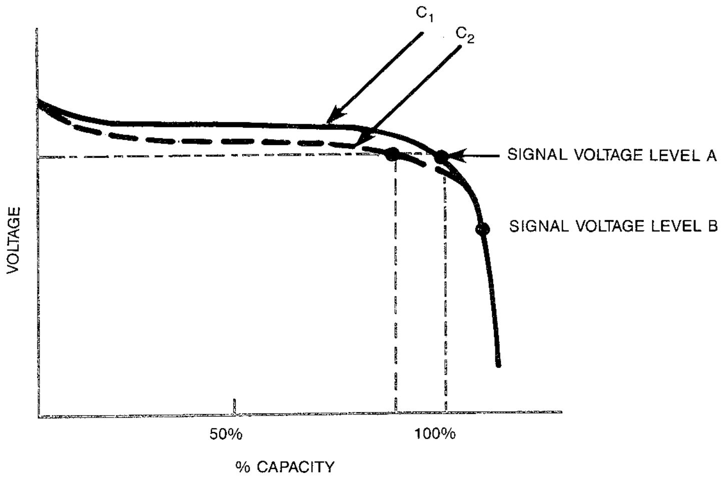


Figure 6-4 Signal Voltage vs. Capacity

Such an integrator normally ignores self-discharge. When reset to 100% at the end of each full charge, it will provide only short-term accuracy.

6.4.4 Proper Voltage Selection

Nickel-cadmium batteries can, in certain applications, fail to meet performance expectations due to improper selection of the number of cells in the battery pack. In certain use patterns and application environments the battery discharge voltage may be depressed. This is caused by previous history, temperature, rest time, and time on charge. (See Section 4.5.) However, these voltage variations need not be of concern if they are accounted for during initial design. In the case of a 5-cell pack, for example, full capacity will be achieved with 1**C** rate discharge to a voltage of 4.5 volts (0.9 volts per cell or 0.75 MPV). If 5.4 volts were required as the minimum operational voltage for the end product, the battery would fail to deliver its full capacity, in some circumstances (such as low temperature), since this would represent 1.08 volts per cell, or 87% of MPV. Accordingly, a battery with 6 cells is correct in this example to achieve full capacity utilization under all environmental conditions for the minimum required voltage (RAV) of 5.4 volts.

Proper design ($RAV \leq 0.75 \times MPV$) also will avoid possible voltage depression (sometimes called *memory*) without the need for conditioning cycles.

In general, the higher the drain rate the lower the cutoff voltage to be used. The formula provided in Section 4.5 gives the voltage which nickel-cadmium battery products should accommodate to permit full utilization of battery capacity.

6.4.5 Maximum Power Discharge

When discharged at relatively low rates (2**C** rate and less), the maximum amount of electrochemical energy that is converted inside the cell is delivered to the external circuit. These low rates are typical of energy type discharges. However, as the discharge rate is increased, more and more voltage is dissipated by the effective internal resistance of the cell. A smaller and smaller portion of the converted energy, therefore, is delivered to the external circuit. The actual power delivered to the external circuit, however, increases.

The linear effect of discharge rate on deliverable voltage is shown on the conventional delivered power curve for power sources of Figure 6-5. This curve demonstrates that for maximum power delivery from a given size cell, the discharge rate should be approximately one-half the short-circuit current. This is the conventional matched impedance operating point, where load resistance equals source resistance, for maximum power transfer.

At the maximum power operating point (P_{max}) approximately one-half of the converted power is actually delivered to the external circuit, while the other half is dissipated internally in the cell as heat. The P_{max} point occurs at a maximum power current (I_{mp}) discharge rate. I_{mp} is the discharge current at which the cell delivers maximum power to the external circuit. I_{mp} for a source with a linear load

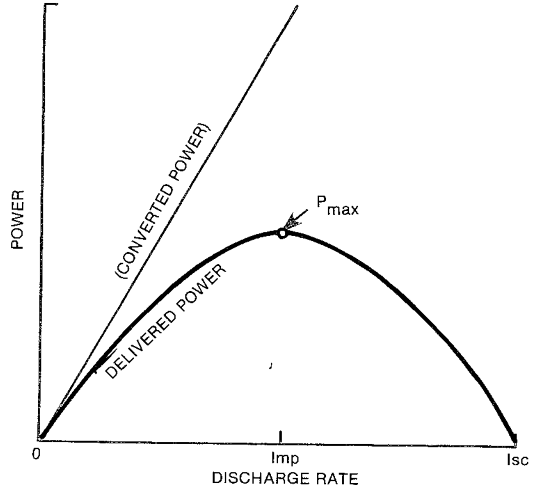


Figure 6-5 Battery Power Output

regulation line is one-half the short-circuit current (I_{sc}) and coincides with a delivered voltage which is one-half E_o, the effective cell no-load voltage. Operation of the cell in the I_{mp} condition, therefore, produces the maximum deliverable power and an equivalent amount of internal heating. It also has a delivered capacity which is less than its **C** rate capacity because it is operating at a relatively high discharge rate. In addition, each unit of discharge capacity is delivering only one-half of the amount contained in a maximum energy discharge. The use of this operating point, however, does permit the use of the minimum sized cell required to provide a particular amount of power.

A note of caution should be provided relative to operation at maximum power rates. Since approximately one-half of the converted energy ends up in the form of internal battery heat, the temperature rise of the cell could be excessive if all of its energy were consumed on one discharge without allowing time for cooling between partial discharges. A total discharge at the I_{mp} rate, without cooling, could raise internal temperatures by more than 50°C. For this reason, the application engineer may have to consider special heat sinks or forced air cooling to dissipate the heat.

I_{mp} and R_e are related by:

$$I_{mp} = \frac{E_o/2}{R_e}$$

In fact, I_{mp} has some advantages over R_e in its ease of use in design calculations. First, I_{mp} is a property of the basic cell which, unlike R_e remains constant for any battery made from that cell, independent of the number of cells connected in series. R_e for a battery is approximately equal to N times R_e of the individual cell. Second, both the capacity and the weight of a cell are approximately proportional to its I_{mp} value, but inversely proportional to its R_e value. When cells are placed in parallel, capacity, weight and I_{mp} are all the sum of the individual values, while R_e is the inverse of the sum of the individual cell values. Third, the maximum deliverable power from a cell is proportional to its I_{mp} capability so that an I_{mp} rating for a given cell directly indicates its maximum power capability.

6.4.6 Parallel Discharge

Nickel-cadmium sealed cells are generally connected in series to achieve a desired voltage. The capacity available for discharge is then governed by the cell size (amp-hour) selected. However, batteries may be connected in parallel during discharge to obtain greater capacity.

Connecting two nickel-cadmium batteries of equal or unequal capacities (cell size) in parallel results in the combined effect shown in Table 6-1.

Since the terminal voltage of both batteries must be equal, no instabilities exist when sharing the discharge load current.

DISCHARGE OF CELL A AND CELL B IN PARALLEL	COMBINED EFFECT
NO LOAD VOLTAGE	SAME AS EITHER CELL
CAPACITY	SUM OF CAPACITIES OF CELL A AND CELL B
I_{mp}	SUM OF I_{mp} (CELL A) and I_{mp} (CELL B)
R_e	$\frac{R_e \text{ (cell A)} \times R_e \text{ (cell B)}}{R_e \text{ (cell A)} + R_e \text{ (cell B)}}$

Table 6-1 Parallel Discharge

A problem with parallel connected batteries arises in charging. Parallel charging could result in improper sharing of charge current, resulting in battery damage. It is necessary to have a series/parallel switch or electronic system to allow only discharging in parallel. (See Section 3.6.4). *Do not charge sealed nickel-cadmium batteries in parallel.*

6.5 PHYSICAL CONSIDERATIONS

6.5.1 Proper Location of the Battery with Respect to the Charger

A primary consideration in properly locating the charger relative to the battery is charger heat. Transformer/rectifier type chargers, covered in Chapter 3, generally produce a significant amount of heat. If this heat is allowed to be transferred to the battery the increased battery temperature can shorten battery life (see Chapter 5). Therefore, it is usually best to locate the transformer at a distance from the battery, such as a remote wall outlet supported charger, or thermally insulate it from the battery.

Capacitive chargers produce less heat than equivalent transformer chargers and may be a solution if it is important to mount the charger close to the battery. Capacitive charging is discussed in Section 3.6.2 and a typical circuit is shown in Figure 3-17.

6.5.2 Battery Enclosures and Form Factor

The battery enclosure may have a significant adverse impact upon battery life if not designed properly to prevent the cell's temperature from rising significantly in overcharge. The most common battery enclosures are made from plastic materials that are resistant to alkaline solutions and have a high impact strength. Metal housings are sometimes used, but metal requires careful design and assembly to avoid shorting of the cells in the battery pack. Aluminum is not recommended for enclosures because in the event that any leakage did occur the electrolyte from the battery would react with the aluminum.

A good battery form factor allows for air movement around cells to help reduce temperature rise in overcharge. For example, a four-cell "AA" *stick* (cells connected end-to-end) would have a greater surface area for heat dissipation and therefore lower overcharge temperature than would four "AA" cells in a square configuration.

6.5.3 Battery Assembly

Welded interconnects are usually preferred to the pressure contact holders common with primary (throw-away) cells. Frequently replacing the primaries gives some wiping action to the contacts but even then they may offer a high resistance charge/discharge path. The *General Electric* nickel-cadmium rechargeable battery will usually give years of service before needing replacement; thus, a wiping action would seldom occur to the pressure contacts. Complete battery assemblies in overall plastic shrink wrap, vacuum-formed or injection-molded plastic cases, with wire leads and connectors, are more suited to rechargeable devices.

In older packs, replacement of individual cells as they wear out is usually not practical as all the cells have a similar life. Also individual cell replacement may result in mixing cells of different internal construction into one pack. For these reasons, batteries should normally be replaced as entire packs.

Never solder directly to the nickel-cadmium cells, only to solder tabs or wire leads. A hot soldering iron placed directly on the cell is likely to cause seal ring and vent seal damage as well as damage to the separator systems.

6.6 ENVIRONMENTAL CONSIDERATIONS

6.6.1 Temperature

High and low temperature applications will require some special considerations. Incremental charge acceptance is reduced at elevated temperatures. Charging time will therefore need to be extended to gain maximum advantage of available capacity. However, even with extended charge time the battery may not be capable of storing as much capacity as if charged at room temperature. (See Chapter 3 on high temperature charging.) Low cell temperature will also reduce the actual cell capacity as discussed in Chapter 4. Two high temperature alternatives are available. One is to charge at room temperature and discharge at the high temperature. The other is to oversize the battery to allow for the reduced available capacity at the operating temperature as shown in the applicable specification sheet. In both cases a high-temperature *Goldtop*® cell can give the longest service life. The discharge voltage can also be altered by low temperature and this should be taken into account during product design. High temperature environments will also increase the rate of self-discharge, as discussed in Chapter 4.

Another consideration for high temperature use is its effect on reducing battery life, discussed in Chapter 5.

Ventilation of the battery pack is important to minimize the adverse effects of high temperatures that may develop from the self-generated heat of a large battery when continuously overcharged. See Figure 3-9 for calculating an estimate of heat rise of a battery in overcharge. (Also see Chapter 7 on *safety* requirements of ventilation.)

Charging at low temperature requires special control that will reduce the rate of charge as the temperature becomes lower and which will allow little or no charging below −20°C. The charge current values for low temperature charging are described in Section 3.6.5. Low temperature discharging is acceptable but battery capacity must be derated from room temperature capacity; therefore run time is reduced. Delivered voltage may be reduced by the increase in R_e, particularly at high discharge rates (see Section 4.2.3). Again, proper design should eliminate voltage problems during use.

At low temperatures the discharge rate has a great effect on deliverable capacity. Both the midpoint voltage and available capacity will be significantly reduced as discharge rate is increased. (See Section 4.2.4.) Self discharge is reduced at low temperatures.

6.7 OTHER CONSIDERATIONS

6.7.1 Using Batteries in Charged State

Nickel-cadmium batteries are typically shipped in a discharged state. Charged batteries can present a handling as well as *safety* problem because of their ability to deliver large amounts of current that can, when shorted, cause burns. *General Electric* does provide charged batteries for special customer requirements, but this requires special precautions by the OEM who specifies charged batteries. If an inspection process is designed around using charged batteries, inventories must be accurately controlled to avoid in-process problems of no charge resulting from self discharge. Also special handling procedures are mandatory for charged cells. (See Chapter 7 on safety.)

In-process charging is the common solution when charged batteries are required, allowing ease in handling and flexible inventory control. The device may be tested from console power while at the same time slightly charging the battery.

In this case, battery power is then only used to verify that the battery is in the circuit and to check parameters such as correct polarity wiring by observing motor rotation.

6.7.2 Inventory

Batteries should be used on a first-in, first-out (FIFO) system. Battery life degradation, as covered in Chapter 5, is a function of time, even if the battery is never used. As temperature increases, the degradation rate of the battery increases, making it desirable to keep inventory between 0°C and 30°C when practical. Storage is covered in detail in Chapter 5.

6.7.3 Agency Listing of Chargers

Charging from a wall outlet type electrical source usually means there will be a desire for agency *safety* evaluation or listing of the charger. One advantage of the remote charger is that agency listing can, for many charger types, be obtained separately from the product containing the battery. In many instances this eliminates any need for the battery powered device to be evaluated by the agency, as it is not directly connected to ac line voltage. Charger manufacturers frequently offer agency listed standard charger types.

6.7.4 Detachable Chargers

When a detachable charger is disconnected from a battery, or device, the terminals of the battery may be exposed and could be shorted by pencil tips, paper clips, coins, etc., resulting in rapid high discharged energy. Methods of preventing unwanted rapid discharge include (1) placing the rectifying element (diode) within the battery rather than the charger, (2) placing a current limiting device (fuse or resistor) between one cell within the battery and the charging terminal, and (3) appropriate design of the polarized connector which obviates the possibility of simultaneous contact of the battery power terminals.

6.8 TYPICAL APPLICATIONS FOR SEALED NICKEL-CADMIUM BATTERIES

6.8.1 Standby Power

Batteries are the power backup source for uninterruptable power supplies used to provide emergency power for alarms, lighting systems, and computers in case of a power failure. Nickel-cadmium batteries are ideal for these applications as they are capable of continuous overcharging and can tolerate a wide range of temperatures. Figure 6-6 shows a battery as an integral part of the power supply. The battery acts not only as an alternate or portable power source, but it may also provide sufficient filtering, replacing the common electrolytic filter capacitor.

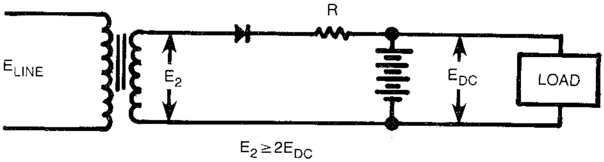


Figure 6-6 Power Supply for Battery Power Source

6.8.2 Emergency Lighting and Alarms

Applications using nickel-cadmium batteries in room temperature environments (0°C to 35°C) need little special consideration other than the heat generated by continuous overcharge current.

Systems that are mounted in exterior environments where very low temperatures occur will require charge control. (See Section 3.6.5 and Figure 3-21.)

High temperature environments create special problems. Cell life is reduced by high temperatures. This must be considered when designing for battery locations, e.g. near a fluorescent ballast or in an enclosure having poor heat transfer. In addition to a potential reduction in operating life at high temperatures, the charge acceptance is less. In a lighting fixture where the battery is continuously held at a high temperature (40°C to 60°C) due to lamp/ballast heat, the battery may not attain a capacity as high as the 23°C cell specification rating (see Figure 3-2, Section 3.2.1.). When charged at high temperatures the battery will deliver only a portion of its room temperature capacity. If the battery continues to receive charge current after the lamp/ballast is turned off, thereby allowing the battery temperature to drop to room temperature at some point in the day, full capacity may be achieved. The chemistry used in cell manufacture influences high temperature charging so the cell product specification for charge acceptance vs. temperature should be examined. High temperature charging is discussed in Section 3.6.6.

Figure 6-7 shows a simplified circuit for emergency lighting which provides power to the lamp when ac line power is interrupted. The system includes a charging circuit to keep the battery charged when ac line voltage is present. Relay contact (K1) is open when line power is on but closes when the relay coil is de-energized due to a power outage. When the relay contacts close, the battery supplies current to the emergency lamp. When ac power returns to the circuit, relay contact (K1) opens and the lamp is turned off. The battery is again charged, giving a simple and completely automatic emergency lighting system.

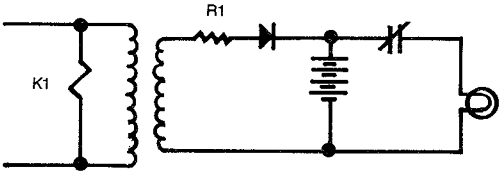


Figure 6-7 Simplified Circuit for Emergency Lighting

6.8.3 Electronic Loads

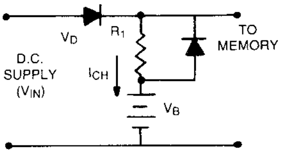
Batteries are frequently mounted directly on printed circuit (pc) boards as a local source of uninterruptable power for electronic memory. Some special charging circuits have been developed to serve these applications, with some examples shown in Figure 6-8.

One special precaution that should be followed for these applications is avoiding storage of the battery while it is connected to a load. Nickel-cadmium batteries should be stored in an open-circuit condition. Even the very small current drain of a micro-chip can have an adverse effect on the battery in storage. Once the battery is completely discharged and the battery voltage is held near zero, this *loaded storage* condition can induce leakage of electrolyte from the cell. It is therefore preferable to design the load circuit so the battery may be placed in open circuit during long-term storage in warehouses, retail stores, or other situations of long-term idleness. Many times this is accomplished by making the battery circuit incomplete until the pc board is inserted into the device or insulating the battery with a non-conductive material that is removed when the device is placed in operation. Since this is not practical in all applications, special cells have been developed that are highly resistive to the adverse effects of *loaded storage*. (See Section 5.7.3.)

An example of the nickel-cadmium battery used for standby power is a small computer which uses MOS semiconductor memory. Power input to the memory must be maintained above a certain voltage to avoid loss of data. If voltage to the memory is reduced below a critical level, the entire contents of the memory would need to be retrieved and read back into the memory once normal power service was resumed. The battery provides proper memory support power. The block diagram in Figure 6-9 illustrates this application.

One method of accomplishing the instantaneous transfer to the battery power is shown in Figure 6-10. The battery is

DIODE COUPLED CIRCUIT



$$R1 = \frac{V_{IN} - V_D - V_B}{I_{CH}}$$

WHERE: I_{CH} = 0.1C (CHARGING CURRENT WHEN V_{IN} IS PRESENT)

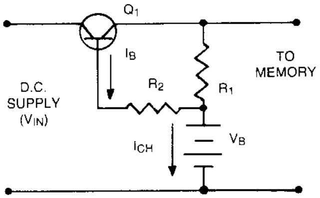
V_D = 0.7V (VOLTAGE DROP OF DIODE)

V_B = 1.45V/CELL (BATTERY OVERCHARGE VOLTAGE)

C = RATED BATTERY CAPACITY IN AMPERE HOURS

ADVANTAGE IS LOWER COST IF DIODE VOLTAGE DROP CAN BE TOLERATED

SINGLE TRANSISTOR CIRCUIT



$$R1 = \frac{V_{IN} - V_{CE} - V_B}{I_{CH} - I_B}$$

$$R2 = \frac{V_{IN} - V_{BE} - V_B}{I_B}$$

WHERE: I_{CH} = 0.1C (CHARGING CURRENT WHEN V_{IN} IS PRESENT)

I_B = TRANSISTOR BASE CURRENT

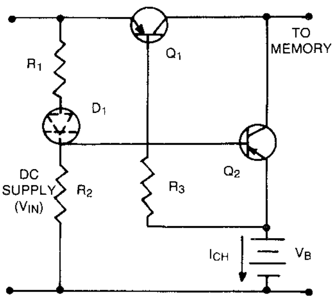
V_{BE} = VOLTAGE DROP OF BASE-EMITTER

V_{CE} = VOLTAGE DROP ACROSS SATURATED Q_1

V_B = 1.45V/CELL (BATTERY OVERCHARGE VOLTAGE)

ADVANTAGE IS LOW TRANSISTOR VOLTAGE DROP. DISADVANTAGE IS VOLTAGE DROP ACROSS R_1 DURING HIGH CURRENT DISCHARGE.

DUAL TRANSISTOR CIRCUIT



ASSUME BASE CURRENT OF TRANSISTOR Q_2 IS TO BE 10% OF $I_{(Load)}$

$$R2 = \frac{V_B - V_{BE}(Q_2)}{0.1 \times I_{Load}}$$

$$R1 < \left[\frac{V_{IN}}{V_B - V_{BE}(Q_2)'} - 1\right] R_2$$

$$R3 = \frac{V_{IN} - V_B - V_{BE}(Q_1)}{I_{CH}}$$

WHERE: I_{CH} = 0.1C (CHARGING CURRENT WHEN V_{IN} IS PRESENT)

$V_{BE}(Q_1)$ = BASE-EMITTER VOLTAGE DROP OF TRANSISTOR Q_1 WHEN BASE CURRENT EQUALS I_{CH}

$V_{BE}(Q_2)$ = BASE-EMITTER VOLTAGE DROP OF TRANSISTOR Q_2 FOR COLLECTOR-EMITTER SATURATION

$V_{BE}(Q_2)'$ = BASE-EMITTER VOLTAGE DROP OF TRANSISTOR Q_2 AT COLLECTOR CURRENT THRESHOLD.

V_B = 1.45V/CELL (BATTERY OVERCHARGE VOLTAGE)

D_1 CAN BE ADDED TO ELIMINATE BATTERY DISCHARGE THRU BASE-EMITTER OF Q_2 & R_1 CALCULATIONS WOULD NEED MODIFICATION IF DIODE IS ADDED.

ADVANTAGE IS LOW SERIES VOLTAGE DROPS, BUT AT HIGHER COST.

Figure 6-8 Some Special Charging Circuits for Batteries Providing Standby Power to Electronic Circuits

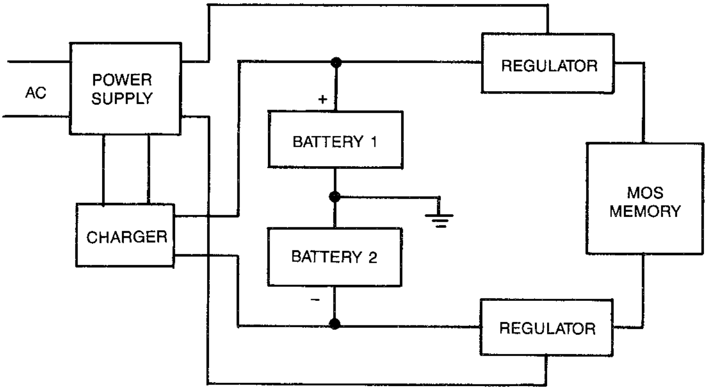


Figure 6-9 *Diagram of Nickel-Cadmium Battery Used as Standby Power in Small Computer*

selected so that the battery charge voltage minus the threshold voltage of the rectifier is slightly below the normal dc voltage level, E_2, of the power supply when normal ac power is on. Rectifier CR_1 isolates the battery from the equipment when the ac power is on. When the power is interrupted, E_2 begins to drop, but because the battery power is available, E_2 drops only to E_1 minus the voltage across CR_1, and the circuit continues to function. In this type of circuit, the load must be able to operate adequately on that slightly lower voltage.

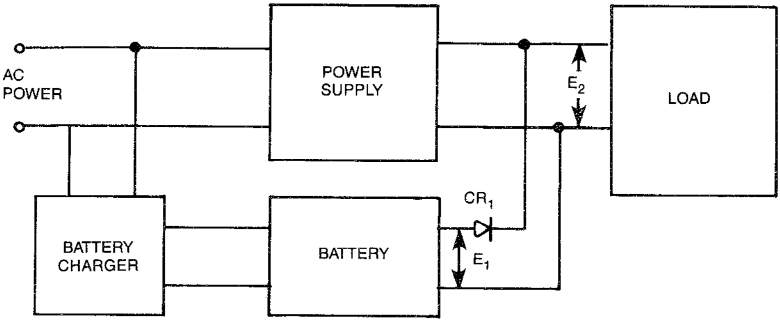


Figure 6-10 *One Method of Instantaneous Transfer to Battery Power*

6.8.4 Intermittent Surge Power

The high-rate discharge capability of nickel-cadmium batteries permits their use in applications requiring short-time, intermittent surge power. In such applications the battery is under constant charge. When the periodic need arises for a relatively large amount of power beyond the capability of the power supply, the battery delivers that energy. This is similar to a capacitor energy storage/discharge function, but differs in that the battery is capable of much longer periods of discharge time at higher power levels.

An example of this application is the telephone line carrier equipment that allows a second private line of communications in a location where only one set of telephone lines is available. The communication signal is modulated at the telephone central switching station, transmitted on the one set of lines available, and demodulated at the phone receiver location. The battery is continually charged at low rates over the telephone lines. When the telephone is called, the battery supplies the energy required to ring the bell and sometimes even the energy required for the voice communication.

6.8.5 Motor Loads

General Electric nickel-cadmium batteries are used in a variety of motor driven devices, for example, electric toothbrushes, shavers, garden tools, power tools, starter motors, tape recorders, and radio-controlled hobby cars. Battery selection requires a thorough understanding of the motor characteristics as well as the gear trains, fans, blades or other power train components. Motor design and battery selection go hand in hand and are discussed in this section.

Trade-offs in battery selection, as in other applications, must include size, weight, run time, performance and economics. The battery voltage regulation is a major consideration for motor design. It is shown in Figure 6-11. E_0 is the effective open circuit voltage, and the slope of the line is a result of the effective internal dc resistance (R_e) of the battery (See Section 4.2).

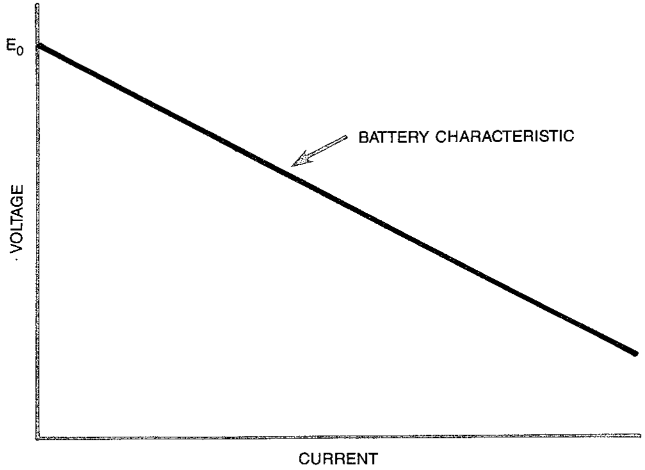


Figure 6-11 Typical Battery Voltage-Current Characteristic

Battery discharge characteristics depend upon both the number of cells and the type and size of cells. In general, effective internal resistance is in approximately inverse proportion to cell capacity (size). However it can also vary within a cell size depending upon cell design.

When the cells are connected in series the individual resistances will combine to yield the effect shown in Figure 6-12. The battery characteristics also vary depending on the state of charge. Figure 6-13 shows this variation for residual capacities from 100 percent to 20 percent.

Figure 6-14 adds the motor stall line characteristic to the battery supply characteristic of Figure 6-12. By adding constant torque curves the full family of characteristics is shown in Figure 6-15. The relationship between torque and speed may now be observed over 80 percent of the battery capacity and interpreted at any point between the limits.

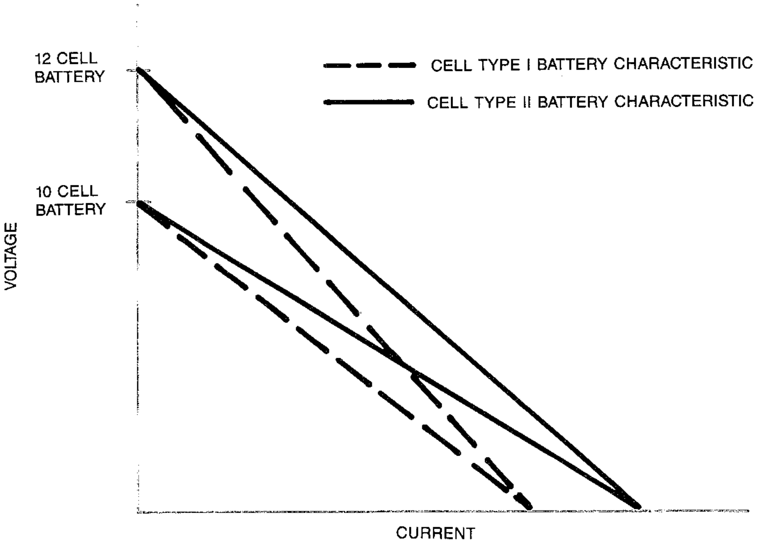


Figure 6-12 *Characteristics of 10-Cell and 12-Cell Batteries for Two Cell Types*

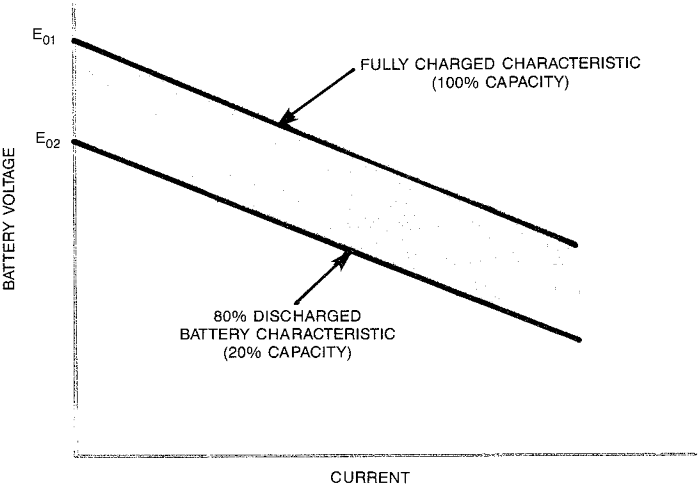


Figure 6-13 *Battery Characteristic at Different States of Charge (Percent Capacity Remaining)*

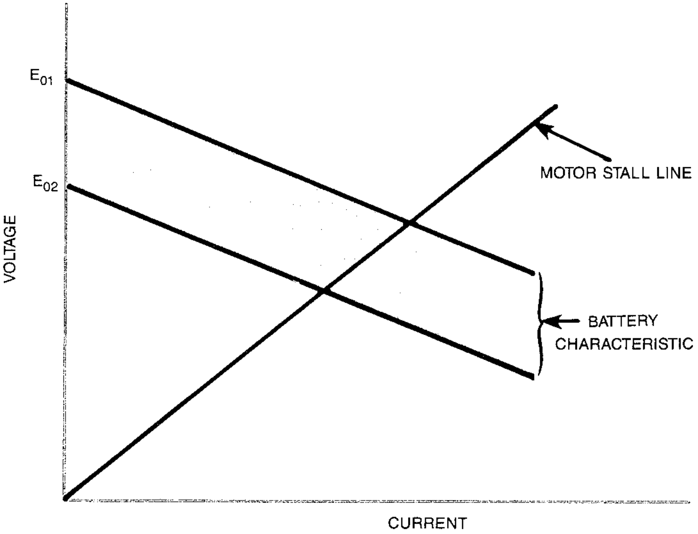
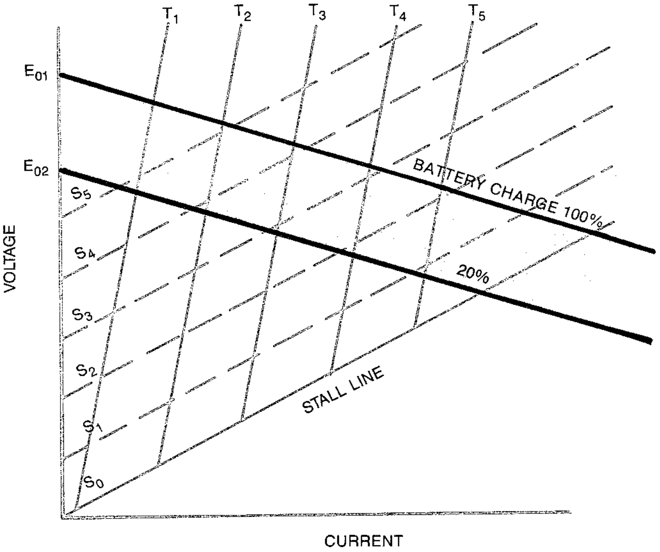


Figure 6-14 Stall Line of Motor and Battery Characteristics



S = SPEED — CONSTANT SPEED LINES
T = TORQUE — CONSTANT TORQUE LINES

Figure 6-15 Motor Speed-Torque, and Battery Characteristic

Trade-offs between operating battery/motor power transfer and the total system run time may need to be considered during the process of matching the battery/motor/load components in a specific system. The characteristics of the motor and any load device may be conveniently combined in the form of input-output diagrams. For example voltage vs. current input characteristics of a motor may be overlaid by torque vs. speed output. The characteristics of a load device, such as for example the pressure vs. volume output of a blower or pump, may be substituted directly for torque/speed scales in the case of an additional system element on the output of the motor. The characteristics of a battery under consideration may then be plotted directly on the voltage/current scales to determine system output performance and allow calculation of system run time from the battery capacity at the discharge rate selected. Adjustments in the characteristics of any individual element may then be made and the effects observed in terms of total system performance.

Figure 6-16 illustrates the E vs. I operating points required by a motor in order to extract equal amounts of power from three different battery selections. This curve could be used

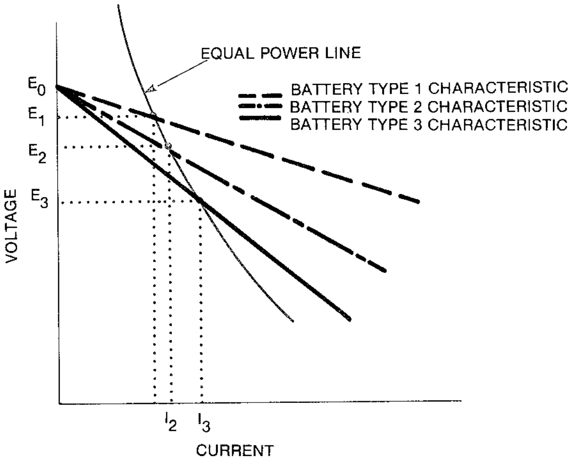


Figure 6-16 Equal Power for Three Battery Types

to match three different motor designs to produce equivalent output torque/speed under the assumption that all three motors are designed to operate at the same efficiency over this range. Calculation of the run time available from each of the three combinations, as a result of the three different battery drain rates and probably three different battery capacities at those rates, will then permit selection of the battery/motor combination providing the longest runtime under otherwise equivalent system performance.

6.8.5.1 Heavy Motor Loads

General Electric nickel-cadmium batteries are well suited for the heavy motor load applications found in power tools, such as drills. These tools require high levels of power combined with a lightweight battery. The *General Electric* nickel-cadmium battery is capable of handling very heavy drain rates for a moderate period of time while maintaining high voltage so that a maximum amount of power is delivered to the load.

Applications with normal operation drain rates of 5**C** to 20**C** are common with some power tools requiring as much as 30**C** for short periods of heavy load that approach motor stall.

The ability of *General Electric* nickel-cadmium batteries to withstand shock and vibration, to be quickly recharged, and to be stored in any state of charge, makes the *General Electric* nickel-cadmium batteries the ideal power source for cordless power tools and appliances.

6.8.5.2 Light Motor Loads

General Electric nickel-cadmium batteries are widely used in household products that have operating loads of 1 to 10**C** rate such as cordless vacuums, toothbrushes, shavers and mixers. Here the battery provides a small lightweight power source that is kept always ready by maintaining it on charge. The high energy density and ability to withstand continuous overcharge make the *General Electric* nickel-cadmium batteries ideal for these cordless appliances.

6.9 CONSUMER DEVICES/PRODUCTS

6.9.1 General

Nickel-cadmium batteries are used to power many consumer devices. Mixers, telephones, flashlights, camera flashes, and portable computers are a few examples.

As most consumer devices are not provided with special low-temperature charge control, the operating instructions should advise the customers not to leave the unit on charge where temperatures may be below freezing, such as in garages and tool sheds during winter. Low temperature charging is covered in Section 3.6.5.

The consumer should not expect the device to operate before the battery is charged and should be instructed to fully charge the battery prior to use. In some cases this instruction is printed on tape placed over the operating switch where the customer cannot miss it, thus eliminating unnecessary returns of devices perceived as inoperable.

Another potential misunderstanding results when a charger is plugged into an outlet controlled by a switch that is *off* and the battery does not get charged. This situation can be avoided by incorporating a charging indicator, such as a Light Emitting Diode (LED), to positively indicate that the battery is receiving charge current.

6.9.2 Computer Controlled Charging

Portable computers offer unique charge and discharge possibilities as the computational ability may be tapped to control fast charging. It can also integrate discharge current and self-discharge to give a measure of capacity. Computer controlled charging must always be fail-safe. The computer program should evaluate battery status and *turn on* high-rate charging. Using one of the fast-charge control methods from Chapter 3, the computer switches to trickle rate when the battery reaches full charge. Any program interruption, signal interference, or programming error must result in low-rate charging.

6.9.3 Hobby Uses

Radio controlled (RC) cars, boats, and planes are in wide-spread use both as adult hobbies and children's toys.

The transmitter and receiver batteries usually require no special knowledge as they are typically charged and discharged at standard rates. However, in RC hobby cars where the nickel-cadmium battery provides the power for racing, battery knowledge can provide the winning edge. These race car batteries are typically fast-charged and high-rate discharged.

A full charge is essential to finishing the race. As excessive battery temperature reduces charging efficiency, actual cell capacity and voltage, fast-charge control schemes that minimize battery heating while ensuring full charge are best. Therefore TCO or negative dV/dt systems, possibly with some low-rate topping charge, may provide the best capacity input. Batteries should be allowed to cool after discharge between races before attempting recharge. When not in use, batteries should be stored in a cool environment (15-25°C).

As motor speed is typically directly proportional to battery voltage, a low internal resistance (R_e) GE$^{\underline{max}\text{TM}}$ cell should be chosen to deliver the highest battery voltage at high discharge currents. The R_e of the battery will be the total of all the cells plus the interconnections and lead assemblies. A battery of series-connected cells can only yield the capacity of the lowest capacity cell in the pack.

For maximum performance the time between charging and use should be minimized to lessen the effects of self-discharge.

The serious hobbiest should be familiar with previous sections on fast-charging, high temperature charge acceptance, R_e/voltage, and battery/motor matching. Knowledge, experimentation, and selection of *General Electric* fast-charge GE$^{\underline{max}}$™ cells with low R_e will yield the highest voltage and capacity.

6.9.4 Toys

Nickel-cadmium rechargeable batteries used in toys eliminate the constant incremental cost of new primary batteries, thereby reducing the lifetime cost of the toy.

A second advantage of nickel-cadmium batteries is the nearly constant discharge voltage, resulting in a uniform performance level. This is unlike primary batteries whose voltage decreases as capacity is used, resulting in decreasing performance. The toy using *General Electric* rechargeable nickel-cadmium batteries will not experience a gradual performance decrease. When the device no longer runs a simple recharge will place it back in service, extending play without battery procurement problems.

Two sets of batteries, one in the toy and one on charge, may ensure that play is not interrupted waiting for batteries to recharge and will essentially allow continued use of the toy.

6.9.5 Portable Audio/Video

Nickel-cadmium batteries are an ideal choice for portable audio/visual devices as they have the desired features of high energy density, long cycle life, and can be stored in any state of charge, as well as on charge. However, care should be taken that batteries left on overcharge do not experience high temperatures which limit their life.

6.10 MILITARY

General Electric sealed nickel-cadmium cells are used in many military applications including submarines, avionics, missiles, portable infantry communications, detectors, instruments, emergency lights, remote targets, laser designators, as well as common flashlights.

Generally these applications require the ability to operate in environmental extremes, the strength of construction to withstand shock and vibration, and the assurance of excellent quality and reliability.

General Electric sealed nickel-cadmium cells are manufactured to meet the sometimes stringent military requirements of the battery, including first article testing and ongoing piece part inspections. Typically they are shipped with certificates of conformance.

Due to the specialized nature of these applications, performance requirements should be discussed with *General Electric* application engineers at the feasibility study stage.

6.11 SUMMARY

The preceding discussion illustrates the benefits, cost effectiveness, and usefulness of the *General Electric* nickel-cadmium sealed-cell battery. Highlighted strengths of these batteries are their long operating life, high-rate discharge capability, simple storage, ruggedness, ability to operate in a broad range of environments and positions, and continuous overcharge capability. Careful attention to circuit design and matching the battery to the load will help the designer realize the full potential of *General Electric* nickel-cadmium batteries.

This chapter has also emphasized the economic advantages of using the *General Electric* nickel-cadmium battery. The long service life of the battery and simplicity of the charger should be major considerations in determining the true cost of a system.

A range of uses, including standby power for alarms, lighting systems, and computers; power for heavy load applications such as in power tools; and light-weight power for consumer devices such as shavers and portable computers, as well as military uses, makes the *General Electric* nickel-cadmium battery an attractive choice.

Chapter 7

Safety

Section

7.1 GENERAL

DO NOT PUT IN FIRE OR MUTILATE; MAY BURST OR RELEASE TOXIC MATERIALS.

DO NOT SHORT CIRCUIT; MAY CAUSE BURNS.

Potential hazards may arise from the improper use of sealed nickel-cadmium rechargeable batteries. Manufacturers and assemblers of battery-using products or systems should ensure that the systems are properly designed and that adequate battery handling procedures are in place. Where appropriate, the end-use consumer should be made aware of these potential hazards and ways to avoid them.

7.2 POTENTIAL BATTERY HAZARDS

In the following sections potential hazards from the improper use of batteries are discussed individually along with the principles for avoidance.

7.2.1 Chemical Burn—Electrolyte

The electrolyte used in most nickel-cadmium cells is a mixture of potassium hydroxide (KOH) and water to a concentration of approximately 30%. This material is a strong caustic, is classified as corrosive, and can cause significant chemical burns if it touches human tissue. In the event that a sealed cell should leak, protective gloves should be worn when handling the cell. Never rub your eyes if electrolyte gets on hands or fingers. First aid treatment requires that the caustic material be diluted with copious amounts of clean water. Medical attention should then be sought if a significant amount of KOH was involved or if the caustic material touched the eyes.

7.2.2 Ingestion—Very Small Sealed Cells

Most cells are too large to be swallowed but cells of any size should never be placed in the mouth, nose, or ears. Damage to tissue may result from chemical and/or electrical burning. A physician's care should be sought in all cases of ingestion or where the cell becomes lodged in the nose or ears. In all cases of ingestion, the progress of the cell through the body should be carefully monitored and surgical intervention is usually indicated if the progress is stopped. Cells lodged in the nose or ears should be immediately removed by the physician.

7.2.3 Burns or Excessive Heat from High-Rate Discharge

The nickel-cadmium cell can deliver power at high rates. Typical maximum discharge rates for nickel-cadmium can cause short circuit currents as high as 100**C**. Accordingly, the rate of power delivery should be adequately controlled by the end product using this power source. Furthermore, care must be exercised in the handling of the cell and in its application to avoid external shorts. Accidental short circuiting may be caused by a number of conditions: a) placing an uninsulated multi-cell battery on a metal shelf or bench; b) using uninsulated tools when working in the vicinity of the battery; c) wearing rings, metal watch bands, I.D. bracelets, and other jewelry without suitable insulating protection; or d) carrying coins or keys in your pocket with a battery. Due consideration must also be given to the capability of large battery assemblies of many cells in series to arc along paths which have become contaminated. This arcing can result in a carbonized path, eventually resulting in the equivalent of a short. The very high rate short circuit current that may flow into an external short or along a carbonized path can cause significant heating with terminals or wires becoming very hot. The heat could then potentially ignite adjacent flammable materials. The safety design of end products should consider this power rate delivery capability. For example, a discharge current limiting device such as a fuse, resistor, diode, or circuit breaker, may be used in the circuit to prevent flow to external causes of short-circuit currents.

7.2.4 Electric Shock

Battery assemblies of more than 30 cells in series present voltages greater than 43.5 volts when on charge. This voltage is generally considered the threshhold of electrical shock capability. Appropriate design measures should therefore be taken, warning labels should be provided, and the battery assemblies should be handled carefully.

7.2.5 Proper Disposal

Do not mutilate batteries, as corrosive electrolyte can be released (see 7.2.1). Do not dispose of sealed nickel-cadmium cells in a fire, as they may burst explosively or release toxic fumes. Disposal of cells in a charged condition is not recommended for the reasons set forth in 7.2.3. In disposing of a single lot of a large number of batteries give appropriate consideration to the total amount of toxic materials in the lot.

Dispose of in accordance with Local, State and Federal environmental regulations.

7.2.6 Venting

Nickel-cadmium cells can produce hydrogen and oxygen which under some conditions may be vented from the cell. A mixture of hydrogen and oxygen or hydrogen and air will explode if ignited. Mixtures from approximately 5 percent hydrogen to over 90 percent hydrogen are *explosive*. Maximum explosion pressure multipliers of approximately 9 times may be realized with the most explosive mixture (stoichiometric) of 66 percent hydrogen and 33 percent oxygen. Pressure multipliers decrease as the hydrogen content is diluted or enriched from that value. Approximately 0.3cc of H_2O will electrolyze to gas per ampere-hour of electrolysis input and yield about 415cc of H_2 and 207cc of O_2 at one atmosphere. Cells have roughly 2cc of water per ampere hour of rated capacity. As with automobile batteries, potential ignition sources should not be allowed in the vicinity of batteries in overcharge.

Most sealed nickel-cadmium cells will not vent sufficient amounts of gases to develop an explosive environment but precautions must be taken to provide ventilation holes to diffuse the atmosphere inside the compartment (such as a plastic case) which encloses the battery. Completely sealed battery compartments are not acceptable; *ventilation of some sort must be provided*. This is particularly true for Fast-Charge applications where failure to terminate the fast-charge current would cause rapid venting of the cell.

In the highly unlikely event that the safety vent of a sealed cell becomes inoperative while subjected to abuse, under some conditions the internal pressure could become sufficient to separate the cover from the can. The remote possibility of such an occurrence is further reduced by minimizing the occurrence of abusive situations which could damage the vent mechanism or generate excessive gases.

7.3 INTEGRATION WITH THE PRODUCT

Batteries are used in many products designed for use in emergency situations where reliability of the product is very important. The product designer should use great care in integrating the battery into the product and in selecting the appropriate size and type of battery. The designer must also consider the inherent characteristics and performance of the battery. Thorough instructions on proper use, storage, and charging practices should be provided to the user. A periodic test procedure is advisable as well as a warning that will unmistakably indicate that the battery is no longer functional or that its condition or performance is no longer adequate for the application.

7.4 DETACHABLE CHARGERS

When a detachable charger is disconnected from a battery, or device, the terminals of the battery may be exposed and could be shorted by pencil tips, paper clips, coins, etc., resulting in rapid high discharged energy (see 7.2.3). Methods of preventing unwanted rapid discharge are described in Section 6.7.4.

7.5 SUMMARY

Improper use, handling, or disposal of nickel-cadmium cells can pose hazards. Batteries should not be put in a fire nor mutilated or abused, especially in ways that would release their contents. In handling batteries or applying them to devices, care should be taken to avoid any short circuit and to otherwise limit any high-rate discharge.

WARNINGS

The WARNINGS set forth below should generally be communicated to each ultimate user of nickel-cadmium batteries (cells). They should appear in an appropriate and effective location for each end product.

7.5.1 DO NOT incinerate or mutilate; may burst or release toxic materials.

7.5.2 DO NOT short circuit; may cause burns.

7.6 NOTICE TO READER

It is the responsibility of each user to ensure that each battery application system is adequately designed, safe and compatible with all conditions encountered during use, and in conformance with existing standards and requirements. The circuits contained herein are illustrative only and each user must ensure that each circuit is safe and otherwise completely appropriate for the desired application.

This *Handbook* and its appendices contain information concerning products manufactured by *General Electric Company*. This information is generally descriptive only and is not intended to make or imply any representation or warranty with respect to any product. Cell and battery designs are subject to modification without notice. All product descriptions and warranties are solely as contained in formal offers to sell or quotations made by *General Electric Company.*

LIST OF ABBREVIATIONS

Abbreviation	Description
A/D	analog to digital
ac	alternating current
A	ampere
Ah	ampere-hour
°C	degree Celsius
C	rate as a function of capacity
cm	centimeter
CP	constant potential
CPRV	cell polarity reversal voltage
cm^3	cubic centimeter
DTC	dump timed-charge
ΔT	(delta T) incremental temperature
ΔTCO	(delta TCO) incremental temp. cutoff
ΔV	(delta V) incremental voltage
dia.	diameter
dc	direct current
dT/dt	rate of temperature change
dV/dt	rate of voltage change
E_o	no load voltage
EODV	end of discharge voltage
EMF	electromotive force
°F	degree Fahrenheit
F	farad
GE	General Electric
g	gram
Hz	hertz
h	hour
I	current
IPCO	inflection point cutoff
in	inch
in^2	square inch
kg	kilogram
KOH	potassium hydroxide
LED	light emitting diode
log	logarithm
m^2	square meter
MPV	mid-point voltage

Abbreviation	Description
μA	microampere
μF	microfarad
mA	milliampere
mAh	milliampere-hour
mg	milligram
mm	millimeter
mV	millivolt
mW	milliwatt
Ni-Cd	nickel-cadmium
OEM	original equipment manufacturer
P	pressure
PTC	positive temperature coefficient
R_T	thermal resistance
RAV	required application voltage
R_e	internal resistance
s	second (time)
TCO	temperature cutoff
VCO	voltage cutoff
VDCO	voltage decrement cutoff
VLTCO	voltage limit temperature cutoff
V	volt
VA	voltampere
W	watt
Wh	watthour

GLOSSARY

The following definitions are not intended to be all-inclusive, but rather to guide the reader in understanding special meanings of common terms as used in relation to *General Electric* nickel-cadmium battery products.

-A-

A.N.S.I. American National Standards Institute.

ACCUMULATOR An electrochemical system capable of storing electrical energy by conversion into chemical energy and which can give it back again by reconversion. These conversions take place due to the passage of current in one direction or the other. See Secondary Battery.

ACTIVE MATERIAL Chemically reactive material which is used to generate electric current in the battery. In the nickel-cadmium cell, nickel hydroxide and cadmium hydroxide are used as active materials at the positive and negative electrodes, respectively.

ALKALINE PRIMARY BATTERY A primary battery which employs alkaline aqueous solution for its electrolyte.

AMPERE-HOURS Product of current in amperes multiplied by the time current is flowing. Capacity of a cell or battery is usually expressed in ampere-hours.

ANODE An electrode at which an oxidation reaction (loss of electrons) occurs. In secondary cells, either electrode may become the anode, depending upon direction of current flow.

ASSEMBLED BATTERY Any battery composed of multiple cells.

AVAILABLE CAPACITY See Capacity.

-B-

BATTERY One or more cells connected to form one unit and having provisions for external connections.

BATTERY CASE Battery box or enclosure which contains cells, associated connectors, and hardware.

BOUNCING Repeated cycling of a battery/charger system in overcharge between fast-charge rate and trickle charge rate. Caused by using an automatic reset thermostat or other switch that does not latch when terminating the fast-charge current.

-C-

C designates the declared rated capacity of the cell (battery). All cell charge/discharge current is specified in terms of a multiple of **C**. (For example the 0.1**C** current for a 1.2 amp-hour rated cell is 120mA.)

C_p Effective parallel capacitance.

C-RATE Charge or discharge current in amperes; numerically equal to the rated capacity of a cell in ampere-hours.

CADMIUM ELECTRODE See Negative Plate.

CADMIUM HYDROXIDE Active material used at the negative electrode of the nickel-cadmium cell.

CAN See Container.

CAPACITY, CELL (Battery) Measured in Ahrs.

> **Actual Capacity** Cell capacity of a fully charged cell when measured under non-standard conditions except using a standard end of discharge voltage.
>
> **Available Capacity** The capacity of a fully charged cell delivered under non-standard conditions including non-standard end of discharge voltage.
>
> **Deliverable Capacity** See Available Capacity.
>
> **Dischargeable Capacity** The capacity which a cell can deliver before it becomes fully charged or the amount of capacity that can be withdrawn after a limited input.
>
> **Nameplate Capacity** See Rated Capacity.

Nominal Capacity The capacity, typically delivered under standard conditions, a value greater than rated capacity which is a minimum value.

Permanent Loss of Capacity Reduction in cell capacity from "as new" value, under standard rating conditions, not recoverable by reconditioning. See also Reconditioning and Failure.

Rated Capacity The capacity value shown in the specification sheet. The minimum expected capacity when a new cell is measured under standard conditions.

Recoverable Capacity See Temporary Loss of Capacity.

Residual Capacity Capacity remaining after an undefined discharge at any set of operating conditions, usually including a partial discharge or long rest.

Retained Capacity The amount of capacity remaining in a cell after an open circuit rest period. The result of self-discharge.

Standard Capacity Cell capacity measured under standard conditions. See Standard Conditions.

Temporary Loss of Capacity Reduction in cell capacity that is recovered when cell is subjected to several reconditioning cycles of full charge and discharge under standard conditions. See also Failure.

Useful Capacity See Available Capacity.

CAPACITY RECONDITIONING See Reconditioning.

CARBON-ZINC BATTERY A primary battery having a zinc anode and a manganese-dioxide cathode with an ammonium chloride and zinc chloride aqueous electrolyte.

CATHODE An electrode at which a reduction reaction (gain of electrons) occurs. In secondary cells, either electrode may become the cathode, depending upon direction of current flow.

CELL Electrochemical device, composed of positive and negative plates, separator, and electrolyte, which is capable of storing electrical energy. When encased in a container and fitted with terminals, it is the basic "building block" of a battery.

CELL CASE See Container.

CELL JAR See Container.

CELL HISTORY See History.

CELL REVERSAL Reversing of polarity of terminals of a cell in a multicell battery due to overdischarging.

CHARGE Return of electrical energy to a battery.

Charge Acceptance See Charge Efficiency.

Charge Efficiency The value which can be obtained when the dischargeable capacity of the battery is divided by the charged capacity. It indicates the degree of ease with which the battery can be charged.

Charge Retention Capacity after a period of storage of a fully charged battery.

Fast-Charge A charge rate of 1**C** or greater applied to a battery with a cell specification for that charge rate. *Can not* be used as an overcharge rate.

Quick-Charge A charge rate of 0.33**C**. See Overcharge.

Standard-Charge A charge rate of 0.1**C**.

Trickle-Charge A charge rate of 0.02**C** to 0.05**C**. *Can not* be used to fully charge a battery.

CHARGER Device capable of supplying electrical energy to a battery.

CONDITIONING See Reconditioning.

CONNECTOR Electrical conductor which joins individual cells together in a battery.

CONSTANT CURRENT Charging method in which current does not change appreciably in magnitude, regardless of battery voltage or temperature.

CONSTANT POTENTIAL Charging method which applies a fixed voltage to a cell. Often abbreviated CP.

CONTAINER Cell enclosure in which plates, separator, and electrolyte are held. It is made up of the cell jar and cover that are permanently joined.

CONTAMINANT Undesirable element, usually in the electrolyte, which reduces the capacity of the cell. In vented cells, contaminants can be introduced by use of tap water or operation without vent cap.

COULOMETER Electrochemical or electronic device, capable of integrating current-time, used for charge control or measurement.

CPRV Cell Polarity Reversal Voltage.

CUTOFF VOLTAGE Voltage at which a discharge or charge is terminated.

CYCLE In a secondary storage battery, a cycle consists of a charge followed by a discharge.

CYCLE LIFE In a secondary storage battery, the number of cycles the battery may experience before its capability falls to a point considered a failure. See Failure.

CYCLIC See Cycle.

CYLINDRICAL CELL A cylinder-shaped sealed wound cell containing a high-pressure safety vent.

-D-

DEAD BAND The range of temperatures between the point at which the thermostat opens and the point where it recloses (resets). If the temperature first exceeds the point at which the switch opens and then drops below this point, the switch remains open within the "dead band" until the temperature falls below the reset point.

DEEP CYCLING A charge/discharge cycle where perhaps 100 percent of the available capacity is withdrawn. See Reconditioning.

DEEP DISCHARGE The condition where a cell is discharged to 0.6 volts or less, at low rate.

DEPTH OF DISCHARGE Capacity removed from a battery compared to its actual capacity. It is expressed as a percentage.

DISCHARGE RATE See Rate.

DISCHARGING The withdrawing of electrical energy from a battery.

DRY CELL BATTERY Sometimes used to describe a Leclanché cell.

DUMP-TIMED CHARGE (DTC) A charging method in which the cell is first discharged at a rate-time combination equal to or greater than a charge-rate-time combination which immediately follows.

DUTY CYCLE The condition and usage to which a battery is subjected during operation, consisting of charge, overcharge, rest and discharge.

-E-

E_o See Equivalent No-load Voltage.

EFFECTIVE INTERNAL RESISTANCE, R_e The apparent opposition to current flow within a battery that manifests itself as a drop in battery voltage proportional to the discharge current. Its value is dependent upon battery design, state of charge, temperature, and age.

ELECTRODE Conducting body and the active materials in which the electrochemical reaction occurs.

ELECTROLYTE Fluid used in a cell as a medium for movement of ions. Nickel-cadmium cells contain an alkaline electrolyte, usually potassium hydroxide solution.

END-OF-CHARGE VOLTAGE The voltage of the battery at termination of a charge but before the charge is stopped.

END-OF-DISCHARGE VOLTAGE (EODV) The voltage of the battery at termination of a discharge but while still under load.

ENERGY DENSITY The stored energy as a function of the weight or volume (watt-hours per pound or watt-hours per cubic inch). Rate dependent.

ENTRAINMENT Process whereby gases generated in the cell carry electrolyte out through the vent cap.

ENVIRONMENTAL CONDITIONS External circumstances to which a cell or battery may be subjected, such as ambient temperature, humidity, shock, vibration and altitude.

EODV End Of Discharge Voltage.

EQUIVALENT CIRCUIT A circuit presented to simulate the electrical behavior of a cell.

EQUIVALENT INTERNAL RESISTANCE See Effective Internal Resistance, R_e.

EQUIVALENT NO-LOAD VOLTAGE, E_o The numerical value of the source voltage in the equivalent circuit.

-F-

FADING The long-range loss of capability with use.

FAILURE The condition in which a battery is unable to perform satisfactorily.

> **Function Failure** Condition in which the battery has caused the end-use device to fail to function at the performance level expected.
>
> **Permanent Failure** A condition which does not permit a cell or battery to be reconditioned or restored to 50% performance level.
>
> **Reversible Failure** Failure condition which may be corrected through the application of certain electrical procedures or reconditioning.

FAST-CHARGE BATTERY A nickel-cadmium battery which can be charged at the fast-charge rate and which gives a suitable signal which can be used to terminate the fast-charge current without damage to the battery.

FAST CHARGING Rapid return of energy to a battery at the rate or greater.

FLOAT The use condition of a storage battery wherein charge is maintained by a continuous, long-term constant-potential charge.

FLOODED CELL See Vented Cell.

FLOODING Filling of pores of a porous electrode with electrolyte solution, thereby minimizing access of gases to electrode surface.

FORM FACTOR Battery configurations which may be created by interconnecting cells in various arrangements.

FUNCTION FAILURE See Failure.

-G-

GAS RECOMBINATION The method of suppressing hydrogen generation by recombining oxygen gas on the negative electrode, and making the negative electrode chemically discharged when oxygen gas is generated at the positive electrode in an overcharge condition.

GE^{max}™ BATTERY The *General Electric* trademark for high performance cells.

GOLDTOP™ BATTERY The *General Electric* trademark for high temperature nickel-cadmium sealed cells that are capable of continuous exposure at temperatures up to 70°C.

-H-

HIGH-RATE CHARGE A rate greater or equal to 1**C**.

HIGH-RATE DISCHARGE A rate greater than 5**C**.

HIGH RESISTANCE SHORT See Short.

HISTORY The electrical and mechanical environments which have been applied to a cell including age, previous use, temperature exposure, charge and discharge.

-I-

I.E.C. International Electrochemical Commission

I_{mp} Current at maximum power.

IMPEDANCE An ac circuit's apparent opposition to current; consists of reactance and ohmic resistance. For the equivalent phenomenon in a dc battery.

INTERMITTENT SHORT See Short.

INTERNAL RESISTANCE The apparent resistance value of the cell voltage difference between high rate and low rate discharge. See Effective Internal Resistance, R_e.

-K-

KOH Chemical symbol for potassium hydroxide.

-L-

LECLANCHÉ See Carbon-Zinc.

LIFE The duration of satisfactory performance, measured as usage in years or as the number of charge/discharge cycles.

LOADED STORAGE The harmful condition of storing a battery under load, a non-open circuit storage condition.

LOW-RATE CHARGE 0.05**C** to 0.1**C**.

LOW-RATE DISCHARGE Less than 1**C**.

LOW RESISTANCE SHORT See Short.

-M-

MAINTENANCE-FREE BATTERY A sealed cell that does not require addition of water.

MAXIMUM-POWER DISCHARGE CURRENT, I_{mp} The discharge rate at which the terminal voltage is equal to one half of E_o and at which maximum power (energy rate) is transferred to the external load.

MEMORY Capacity that can be recovered by conditioning, a misnomer for voltage depression.

MIDPOINT VOLTAGE The battery voltage at the half-way point in the discharge between the fully charged state and the fully discharged state of a cell.

-N-

NEGATIVE ELECTRODE See Negative Plate.

NEGATIVE PLATE The plate which has an electrical potential below that of the other plate during normal cell operation. The plate impregnated with cadmium salts is the negative plate which undergoes chemical oxidation when a nickel-cadmium cell is discharged.

NET CHARGE ACCEPTANCE Sometimes used to describe charging efficiency and refers to the amount of discharge capacity that can be delivered as the result of a charging input.

Ni Nickel

Ni-Cd Nickel-Cadmium

NICKEL ELECTRODE See Positive Plate.

NICKEL HYDROXIDE Active material used at the positive electrode of nickel-cadmium cell.

NOMINAL CAPACITY The typical capacity which is greater than the rated capacity which is a minimum value.

NOMINAL VOLTAGE The midpoint voltage observed across battery during discharge at a selected rate, usually at the 0.2**C** or 0.1**C** rate.

-O-

OPEN-CIRCUIT VOLTAGE Voltage of a battery with no load.

OPERATING VOLTAGE Voltage between the two terminals when a battery is subjected to a load. Usually it is expressed by the voltage of the battery at the 50 percent discharge point.

OVERCHARGE The normal application of charge current after the battery has reached full charge.

OVERCHARGE CURRENT The charging current flowing to the battery after all the active material has been converted into a dischargeable state. Sealed nickel-cadmium batteries are capable of accepting continuous overcharge current at cell specification rates.

OVERCHARGING Continuous charge after battery has accepted its maximum amount of charge. In a sealed cell, a result will be increased cell temperature.

OXIDATION The release of electrons by the cell's active material to the external circuit. During discharge, cadmium at the negative electrode is oxidized.

OXYGEN EVOLUTION Oxygen gas evolves due to the electrolysis of water in the battery being charged, when it reaches a certain potential. This is called the potential of oxygen evolution.

OXYGEN RECOMBINATION The electrochemical process in which oxygen generated at the positive plate during overcharge is reacted (reduced) with water at the negative plate at the same rate, generating heat.

-P-

PARALLEL Electrical term used to describe the interconnection of batteries in which all the like terminals are connected together.

PERMANENT FAILURE See Failure.

PLATES Common term for electrodes.

POLARITY Electrical term used to denote the relative voltage relationship between two electrodes.

POLARITY REVERSAL See Cell Reversal.

POSITIVE ELECTRODE See Positive Plate.

POSITIVE PLATE The plate which has an electrical potential higher than that of the other plate during normal cell operation. The plate impregnated with nickel salts is the positive plate which undergoes chemical reduction during discharge of a nickel-cadmium cell.

POTASSIUM HYDROXIDE A chemical compound which, mixed with pure water in the correct proportions, is the electrolyte solution used in nickel-cadmium cells.

PRIMARY CELL A cell designed to be used only once, then discarded. It is not capable of being returned to its original charged state by the application of current.

PSIA Pounds per square inch measured relative to vacuum; i.e., absolute pressure.

PSIG Pounds per square inch measured relative to atmospheric pressures; i.e., relative pressure.

-Q-

QUICK CHARGE 0.33**C** charging rate.

QUICK-CHARGE BATTERY A nickel-cadmium battery that can be charged fully in 3 to 5 hours in a simple, constant-current charger and is capable of continuous overcharge at this quick-charge rate.

-R-

R_e See Effective Internal Resistance.

RAV Required Application Voltage

RATE Amount of current, either charge or discharge current, frequently expressed as a fraction or multiple of the one hour rate, **C**.

RATED CAPACITY See Capacity.

RATING See Capacity.

RECHARGE Return of electrical energy to a battery.

RECOMBINATION The chemical reaction of gases at the electrodes to form a non-gaseous product.

RECONDITIONING A charge/discharge cycle to eliminate voltage depression.

REDUCTION The gain of electrons; in a cell, refers to the inward flow of electrons to the active material. During discharge, nickel hydroxide at the positive plate is reduced to a lower oxidation state.

RESEALABLE In a cell, pertains to a safety vent which is capable of closing after each pressure release, in contrast to the non-resealable "one-shot" vent.

RESIDUAL CHARGE See Capacity.

RESISTANCE See Effective Internal Resistance, R_e.

REVERSAL See Cell Reversal.

REVERSIBLE FAILURE See Failure.

REVERSIBLE REACTION A chemical change which takes place in either direction, as in the reversible reaction for charging or discharging a secondary battery.

-S-

SAFETY VENT Resealable vent which operates to release abnormal gas pressure due to abusive conditions.

SEALED CELL A cell that is free from routine maintenance and can be operated without regard to position. All reactants are retained within the container. See Accumulator.

SECONDARY BATTERY A system which is capable of repeated use by employing chemical reactions that are reversible; i.e., the discharge energy may be restored by supplying electrical current to recharge the cell.

SELF-DISCHARGE The spontaneous decomposition of battery materials from charged to discharge state.

SEPARATOR Material which provides separation and electrolyte storage between plates of opposite polarity.

SERIES Electrical term used to describe the interconnection of cells or batteries in such a manner that the positive terminal of an individual cell is connected to the negative terminal of the next cell.

SHORT The condition in a battery where two plates of opposite polarity make electrical contact with each other.

> **Intermittent Short** A condition where the open circuit voltage of a battery is unstable when mechanically shocked. An intermittent short can be either low or high resistance.

SPLIT RATE CHARGE A charging method in which the battery is charged at a high rate and then automatically reduced to a lower charge rate as the battery approaches full charge.

STANDARD CHARGE Overnight return of energy to a battery at 0.1**C** rate.

STANDARD CONDITIONS Laboratory conditions of rates, voltages, and temperatures during charge, rest and discharge.

STANDBY The non-cyclic use of a battery used as back-up power.

STARVED CELL A cell containing little or no free fluid electrolyte solution; this enables gases to reach electrode surfaces readily, and permits relatively high rates of gas recombination. See Sealed Cell.

STATE OF CHARGE Residual capacity expressed in terms of fully-charged capacity.

STORAGE BATTERY See Accumulator.

-T-

TAB A battery terminal, often containing a hole for wire connection.

TAFEL CURVE Voltage temperature relationship.

TEMPERATURE

> **Ambient Temperature** The average temperature of the battery's surroundings.
>
> **Cell Temperature** The average temperature of the battery's components.

TEMPERATURE CUTOFF (TCO) A method of switching the charge current flowing to a battery from fast charge to topping charge by a control circuit in the charger that is activated by battery temperature.

TEMPORARY FAILURE See Failure.

THERMAL RUNAWAY A condition whereby a battery on constant potential charge at elevated temperature may deteriorate limiting life through internal heat generation which is caused by high overcharge currents in constant-potential charging.

TOPPING CHARGE A reduced rate charge that completes (tops) the charge on a cell and can be continued in overcharge with out damaging the cell.

TRICKLE CHARGE Charge rate below 0.05**C** used to keep battery fully charged after charging at higher rate.

-V-

VENT A normally-sealed mechanism which allows the controlled escape of gases from within a cell.

VENTED CELL A heavy-duty cell design in which the vent operates at low pressures during the normal duty cycle to expel gases generated in overcharge. A vented cell plate pack contains flat plates, separated by a gas barrier and woven nylon separator, completely immersed in electrolyte. Often called “flooded” cell.

VOLTAGE CUTOFF (VCO) A method of switching the charge current flowing to a battery from fast charge to topping charge by a control circuit in the charger that is activated by battery voltage.

VOLTAGE DEPRESSION A reduction in voltage due to long term overcharge.

VOLTAGE LIMIT In a charge-controlled battery, limit beyond which battery potential is not permitted to rise.

VOLTAGE-TEMPERATURE CUTOFF (VTCO) A method of switching the charge current flowing to a battery from fast charge to topping charge rate by means of a control circuit in the charger that is activated by either battery voltage or temperature.

-W-

WEAR OUT The loss of capacity due to normal use.

WOUND The interior cell construction in which plates are coiled into a spiral.

-Z-

ZAPPING A common term for burning away internal shorts.

INDEX

Page Number (Section Number)

Page Number (Section Number)

Page Number (Section Number)

Page Number (Section Number)

Page Number (Section Number)

Page Number (Section Number)

Page Number (Section Number)

Page Number (Section Number)

Page Number (Section Number)

Appendix
TABLE OF CONTENTS

Tables

Appendix III

Appendix IV

Appendix V

Appendix I
Quality

A1.1 Battery Quality Definition

Quality is the customer's perception of the relative excellence of the composite of all battery attributes in fulfilling his or her need and the reasonable expectations of those the product serves, when compared to available technology. It encompasses many performance and non-performance related battery attributes, such as product's ability to accept application charge and discharge rate, environmental constraints, life, reliability, appearance, aesthetics, uniformity, and other customer expectations.

A1.2 Quality Policy

It is the policy of the Battery Business Department of *General Electric Company* to design, manufacture, and market products of high quality and inherent customer value in every market segment it serves. It is the policy of *General Electric* to pursue and deserve a reputation for quality leadership that merits customer trust because full value has been received. *General Electric Company* has recognized the need to offer products of excellent quality as one of the most important requisites to current and future business success.

A1.3 Quality at Inception

The definition of quality starts with marketing, where marketing engineers evaluate the customer expectations in relation to technology and cost. Engineering converts these customer expectations into designs and specifications. Manufacturing then procures material, designs process and equipment, manufactures and delivers the product, and ensures conformance to specifications through a quality plan encompassing all functions.

A1.4 Quality Plan

Quality plan defines responsibility of all the functions in achieving the goal of being a quality leader. It includes review of marketing appraisal of customer wants, weighs them against the department's ability to fulfill them, adds needed controls to meet these wants, reviews design to ensure translation of customer requirements, and has total manufacturing control to ensure manufacture and delivery of a quality product at a minimum cost by building quality in.

Quality plan is a set of integrated multifunctional operating instructions designed to provide procedures to achieve quality. Quality plan is designed to meet Mil-Q-9858 and Mil-I-45208 systems requirements per Department of Defense (DOD) guidelines. It includes various control procedures such as design reviews, Alteration Notice (AN) procedure, Material Review Board (MRB) procedure, and Inspection Report (IR) procedure. It also includes various control measures such as incoming, inprocess, and final inspection plans. These plans are supported by documents such as Quality Test Instructions (QTI's), Quality Process Instructions (QPI's), Station Controls (SC's) and Manufacturing Process Instructions (MPI's). These documents define quality characteristics, classify categories, assign AQL's, prescribe inspection tools, and provide clear accept/reject criteria. The process quality assurance activities are carried out at various process steps, both on 100% production basis as well as sampling basis. The Mil-Std.-105D sampling plans are used to ensure that quality conformance to prescribed levels. A table for single-sample normal acceptance plan has been included in this handbook for easy reference. (Table A1-2) This table can be used by incoming inspection for battery acceptance.

A1.5 Incoming Inspection

Manufacturing cells or batteries of a high quality standard is not an accident. Quality must be built into the product. The process starts with the quality of material going into building the product. All components, chemicals, and materials used in cell and battery manufacturing operations are inspected at incoming inspection by our incoming inspection staff for their conformance to design requirements. Non-conforming material is rejected and held for MRB action. Based on criticality of deviation, the lot is sorted, reworked, scrapped, or returned to the vendor. Material may be used if the Material Review Board considers the defect as "minor", which does not affect the final product's form, fit, or function. The incoming inspection area is equipped with mechanical, chemical, electrical, electronic, and microprocessor based test equipment to measure various characteristics. Incoming inspection area maintains an up-to-date file of drawings, material specifications, incoming inspection plans, and vendor quality performance history to be effective in releasing only quality components to the production operation.

A1.6 Inprocess Quality

In-process controls of all inputs such as material, machinery, and human factors ensure that quality components will yeild quality products. Each process step, both input and output, is monitored to ensure conformance to design. In the chemical processing area a Chemical Analysis Laboratory aids inspectors and quality engineers in determining compositions and strengths of various chemicals used in manufacturing. The Process Laboratory is equipped with modern computer controlled analysis tools to provide quick response in this mass-production environment. This computer-controlled test procedure allows uploading of data to a database to facilitate trend analysis and corrective actions. In the assembly area modern measurement tools are provided to quality inspectors, in order for them to be effective in ensuring product quality. A central computer monitors quality of output of each assembly machine on a real-time basis and provides alarm when it notices shift from normality. A staff of quality engineers and production engineers reviews these changes and takes necessary action.

A1.7 Our Quality Team

At *General Electric* quality is a team effort. All employees, regardless of their functional and organizational attachments, work toward a "better than the best" quality goal. This unified approach is a result of multifunctional awareness programs such as *Quality Circles* and *Station Controls*.

A1.8 Quality Circles

The production operators are the backbone of continual quality improvement efforts. Their combined hands-on experience exceeds 10,000 man years. Quality Circles were established to utilize this tremendous knowledge pool. Quality Circles provide the opportunity for production operators to give productivity and quality improvement ideas to management from a hands-on point of view. These groups meet on a regular basis to identify problems through brainstorming and to select specific problems to work on. With the use of charts, cause-and-effect analysis, fishbone diagrams, etc., the Quality Circle groups propose solutions to the problems and present them to management. A large percentage of all problem solving ideas generated by Quality Circle groups have been implemented in the manufacturing area.

A1.9 Station Controls

Station Control is another tool used to help the manufacturing personnel become part of the quality team. Station controls are based on the fact that if the inputs to a process (station) are controlled the output is also controlled. This concept controls the processes by controlling the five *M's* (material, machine, manpower, method and measurements). Station Controls provide definition of defects and corrective action guidelines for problems before they develop. It is a team effort. The team is made up of production operators, maintenance personnel, process engineers, quality engineers, and shop management. This provides needed checks and balances to achieve optimum quality level.

A1.10 Final Inspection

Every shipment of cells and batteries from *General Electric* is inspected by a Quality Control inspector. This inspection includes electrical, mechanical, chemical, and visual checks of the product based on the final inspection outlined in quality plan. These plans are designed by Quality Control engineers in consultation with Marketing and Engineering experts to meet customer requirements. A computerized database of quality requirements is maintained and is available on-line for product testing. This allows quick response to varying customer needs and avoids the communication gaps of manual systems. Product history is maintained at final inspection to support a continuous quality improvement program.

A1.11 Recommended Incoming Inspection Procedure for Customers

Product behavior varies with the design of a battery as well as with prior electrical tests. To accomodate these variables and to provide protection against defective batteries, we recommend customers use a product acceptance procedure as outlined on Table A1-1 of this manual. Customized incoming inspection procedures may be developed based on battery type and your application. The Technical Marketing Engineer can also help the customer to ensure suitability of these procedures.

A1.12 Quality Commitment

The Battery Business Department has directed its resources to achieve zero defects. Business plans include new products, processes, equipment, and systems to attain this goal. Outgoing product quality is monitored via parts per million (PPM) measurement techniques. It identifies minor trend changes in a very low defect rate environment. PPM trends provide management check points to ensure product excellence.

Nickel-Cadmium Battery
Quality Control Reference Guide

The following are recommended incoming test procedures for customers of GE. They provide the quality checks and frequency of checks we recommend if requested by our customers. Any quality performance standards beyond the suggested customer limits must be approved by Technical Marketing and Quality Control.

Characteristic to be Checked	AQL Suggested for Customer	Reason for Test	Equipment Required	Inspection Limit (At Standard Temperature)	Failure Disposition
OCV	1-3 Cell Battery 0.65 4-9 Cell Battery 1.00 10-19 Cell Battery 2.50 20+ Cell Battery requires negotiation	Open or shorted cells and broken welds	Voltmeter	For single cell batteries: OCV = 0.5V minimum For each additional cell, increase the minimum OCV by 1.2 volts. Example: 8 cell battery $0.5 + 7(1.2) = 8.9$	If OCV is lower than limit, measure individual cell voltages; accept battery if all cells have 0.5 minimum. If cells are not accessible or are less than 0.5 V, apply low voltage test below. Cells may exhibit low OCV if they are accidentally externally shorted or have experienced long shelf life.
Capacity	2.5	Sufficient run time	Power supply and test fixtures	Per specification requirements at specified temperature	Perform one additional retest to assure proper connections, etc.
Battery dimensions	Functional: 1.0 Non-functional: 4.0	To insure fit	Calipers, micrometers, ht. gage, etc.	Per drawing dimensions	You must insure fit.
Weld strength	2.5	Weld integrity	Tensile tester	Per specification	Reject
Marking, nameplates, date codes	4.0	Identification and warranty	Visual inspection	Per specification	Reject
Visual workmanship	4.0	Appearance	Visual inspection	Per standard requirements	Reject

Standard Low Voltage Test:

1. Charge the battery at the 0.1C rate for 30 minutes.
2. Rest the cell/battery 90 minutes in open circuit condition.
3. Measure the open circuit voltage. If the OCV is equal to or greater than 1.2 volt/cell, the battery is good.

SINGLE SAMPLING PLANS FOR NORMAL INSPECTION
(MIL-STD-105D, TABLE II-A)*

LOT SIZE	AQL 0.25%		AQL 0.65%		AQL 1.00%		AQL 2.5%		AQL 4.0%		AQL 6.5%	
	Sample Size	**Reject**	**Sample Size**	**Reject**	**Sample Size**	**Reject**	**Sample Size**	**Reject**	**Sample Size**	**Reject**	**Sample Size**	**Reject**
A. 2–8	100%	1	100%	1	100%	1	5+	1	3+	1	2	1
B. 9–15	100%	1	100%	1	13+	1	5	1	3	1	2	1
C. 16–25	100%	1	20+	1	13	1	5	1	3	1	8	2
D. 26–50	100%	1	20	1	13	1	5	1	13	2	8	2
E. 51–90	50	1	20	1	13	1	20	2	13	2	13	3
F. 91–150	50	1	20	1	13	1	20	2	20	3	20	4
G. 151-280	50	1	20	1	50	2	32	3	32	4	32	6
H. 281-500	50	1	80	2	50	2	50	4	50	6	50	8
J. 501-1,200	50	1	80	2	80	3	80	6	80	8	80	11
K. 1,201-3,200	200	2	125	3	125	4	125	8	125	11	125	15
L. 3,201–10,000	200	2	200	4	200	6	200	11	200	15	200	22
M. 10,001–35,000	315	3	315	6	315	8	315	15	315	22	200	22
N. 35,001–150,000	500	4	500	8	500	11	500	22	315	22	200	22
P. 150,001–500,000	800	6	800	11	800	15	500	22	315	22	200	22
Q. 500,001 and over	1250	8	1250	15	1250	22	500	22	315	22	200	22

* EXTRACTED FROM "MIL-STD-105D"

"SAMPLE PROCEDURES AND TABLES FOR INSPECTION BY ATTRIBUTES"

\+ IF SAMPLE SIZE EQUALS OR EXCEEDS, LOT SIZE, DO 100% INSPECTION

TABLE A1-2

SINGLE SAMPLING PLANS FOR REDUCED INSPECTION (MIL-STD-105D. TABLE II-C)*

LOT SIZE	AQL 0.25% CRITICAL		AQL 0.65% CRITICAL		AQL 1.00% MAJOR		AQL 2.5% MINOR		AQL 4.0% INCIDENTAL		AQL 6.5% INCIDENTAL	
	Sample Size	Reject	Sample Size	Reject	Sample Size	Reject	Sample Size	Reject	Sample Size	Reject	Sample Size	Reject
A. 2–8	100%	1	100%	1	5$^+$	1	2$^+$	1	2$^+$	1	2$^+$	1
B. 9–15	100%	1	8	1	5	1	2	1	2	1	2	1
C. 16–25	20$^+$	1	8	1	5	1	2	1	2	1	3	2
D. 26–50	20	1	8	1	5	1	2	1	5	2	3	2
E. 51–90	20	1	8	1	5	1	8	2	5	2	5	3
F. 91–150	20	1	8	1	5	1	8	2	8	3	8	4
G. 151–280	20	1	8	1	20	2	13	3	13	4	13	5
H. 281–500	20	1	32	2	20	2	20	4	20	5	20	6
J. 501–1,200	20	1	32	2	32	3	32	5	32	6	32	8
K. 1,201–3,200	80	2	50	3	50	4	50	6	50	8	50	10
L. 3,201–10,000	80	2	80	4	80	5	80	8	80	10	80	13
M. 10,001–35,000	125	3	125	5	125	6	125	10	125	13	80	13
N. 35,001–150,000	200	4	200	6	200	8	200	13	125	13	80	13
P. 150,001–500,000	315	5	315	8	315	10	200	13	125	13	80	13
Q. 500,001 and over	500	6	500	10	500	13	200	13	125	13	80	13

* Extracted from "MIL-STD-105D" "Sampling Procedures and Tables for Inspection by Attributes"

$^+$ If Sample Size equals, or exceeds, Lot Size, do 100% inspection

TABLE A1-3

Appendix II

Standards/Regulatory Agencies

A2.1 General

A number of organizations and agencies are involved with the specification and/or assessment of the performance capabilities of nickel-cadmium cells and batteries. The area of interest of some of these agencies is the product functional performance in specific applications. Other agencies concern themselves with the safety of the product during manufacturing operations, during transportation, during original equipment manufacturer (OEM) assembly, and/or during its use in the end product.

Conformance to the standards of some of these agencies is completely voluntary while others are compulsory, backed by a broad range of governmental authority. Some agencies are concerned only with local issues while others are involved in national and/or international commerce.

The *General Electric Company* supports and endorses the standards of all agencies which aid in the safe and effective use of battery products. These standards can provide a means to communicate from the battery manufacturer to the OEM designer and finally to the product user the performance capabilities of the battery and the cautions to be observed. Some examples of these agencies are *ANSI, SAE, IEC, UL, CSA, DOT, Factory Mutual, NFPA, OSHA, and Mil Specs.*

A2.2 Standards for Sealed Nickel-Cadmium Batteries

The principal American standard which specifies the performance characteristics of sealed nickel-cadmium batteries is the American National Standards Institute, (ANSI), document C18.2—*Specifications for Sealed Rechargeable Nickel-Cadmium Cylindrical Bare Cells*. This document provides the standardized definitions of designated electrical, mechanical, and dimensional specifications, the numerical values of which are declared by the battery manufacturer. It also contains the test and/or measurement procedures by which the actual performance of the batteries may be confirmed relative to those declared specifications.

Dimensions of the nickel-cadmium consumer type batteries, designed by *General Electric* to replace ordinary dry cells, are covered in ANSI C18.1—*Specifications for Dry Cells and Batteries*.

Underwriters Laboratories, Inc. (UL), with the assistance of Industry Advisory Councils, develops Standards for Safety for the safe operation of products which might otherwise present the possibility of a hazard of electrical shock, fire, chemical, casualty, or other nature. Some of these Standards deal directly with the safety of the battery charger, such as:

UL 1236 —Electric Battery Chargers
UL 1310 —Direct Plug-In Transformer Units (Chargers)

Other Standards for safety deal with batteries as only one of several components in the overall safety of battery powered products such as:

UL 45 —Portable Garden Tools
UL 82 —Electric Garden Appliances
UL 478 —Electronic Data Processing Units/Systems
UL 1270—Radio Receivers, Audio Systems, Accessories

A third area of UL concern lies in specifying the minimium functional performance of battery powered products, where those products are used to provide safety against the hazards of fire, burglary, explosion, etc. Typical of these Standards, which generally involve battery back-up power, are:

UL 924 —Emergency Lighting and Power Equipment
UL 1023—Household Burglar Alarm System Units

UL provides for continual review and updating of their Standards to keep pace with experience and product developments. They also provide testing and periodic reexamination services to ensure that the products as manufactured will meet the specifications called for in the standards. Products which do meet these minimum criteria are privileged to bear the UL Listing mark or the Component Recognition mark.

The Canadian Standards Association (CSA) provides services in Canada which are similar to those of the UL in the United States. The CSA listing mark, however, is obligatory for commercial sale in Canada, compared to the voluntary employment of UL Standards and services. The CSA Standards require product characteristics which are, for the most part, completely comparable to UL requirements. Two of the CSA Standards are:

CSA-C22.2 No. 107 Rectifying Equipment (All Chargers)
CSA-C22.2 No. 141 Unit Equipment for Emergency Lighting

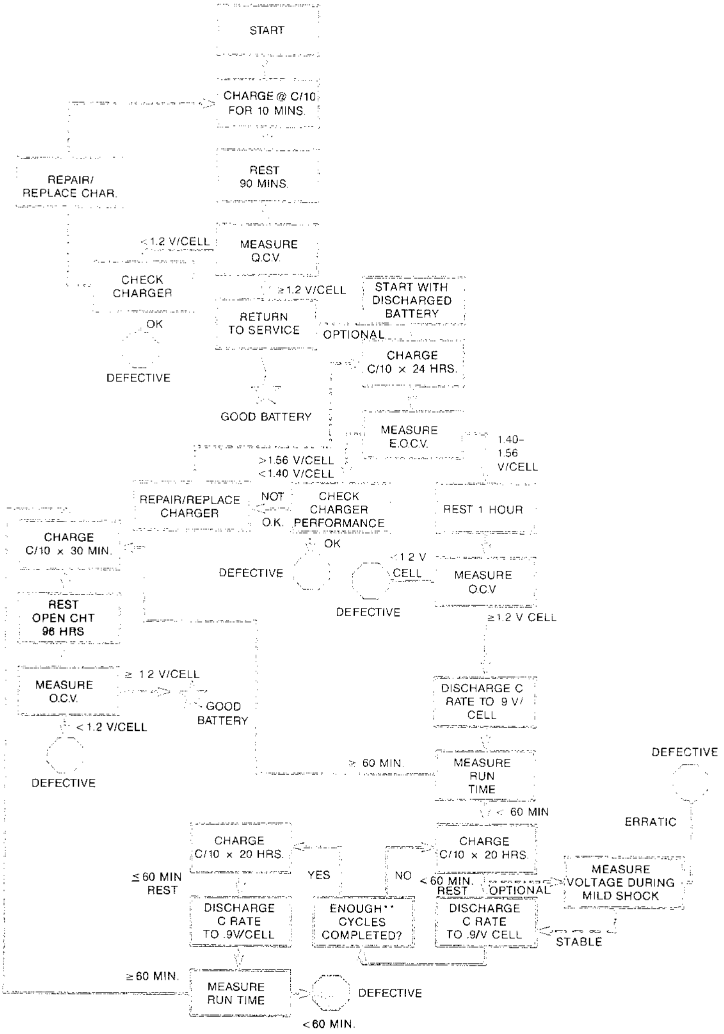
Factory Mutual serves a function for industrial products which is similar to the one which UL serves for other products. The National Fire Protection Association (NFPA) publishes the *National Electrical Code* (NEC), a standard used extensively to judge construction materials, components and methods. NEC—Article 700—*Emergency Systems* specifies the overall performance requirements for emergency lighting systems which is one of the principal bases upon which UL specifies and examines emergency lighting luminaires and the batteries which operate them.

The International Electrochemical Commission (IEC) publishes IEC—285—1983—*Sealed Nickel-Cadmium Cylindrical Rechargeable Single Cells*. This document is similar to ANSI C18.2 in its coverage of characteristics.

An important Standards Association in Europe is VDE.

Appendix III

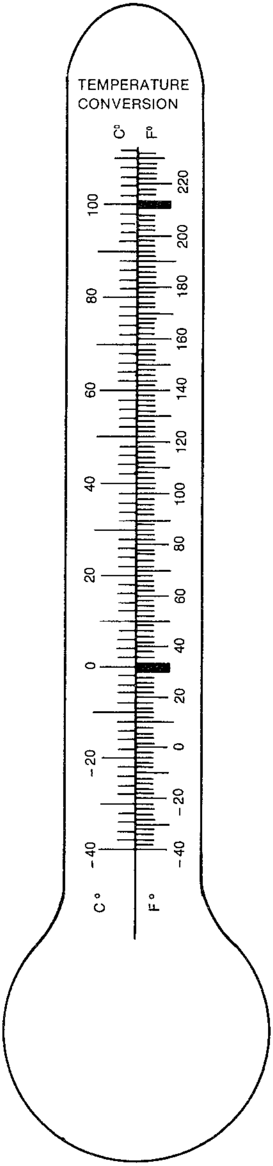
Nickel-Cadmium Battery Trouble-Shooting



GENERAL ELECTRIC

Appendix IV

Measure Conversions



LINEAR EQUIVALENTS

2.54 cm = 1 in

1.0 cm = 0.394 in

WEIGHT EQUIVALENTS

28.35 gm = 1 oz

1.0 gm = 0.0353 oz

PRESSURE EQUIVALENTS

0.07 kg/cm^2 = 1 lb/in^2

1 kg/cm^2 = 14.22 lbs/in^2

Appendix V

MATERIAL SAFETY DATA SHEET

Form Approved
OMB No. 44-R1387

U.S. DEPARTMENT OF LABOR
Occupational Safety and Health Administration

MATERIAL SAFETY DATA SHEET

Required under USDL Safety and Health Regulations for Ship Repairing, Shipbuilding, and Shipbreaking (29 CFR 1915, 1916, 1917)

SECTION I

MANUFACTURER'S NAME General Electric Company	**EMERGENCY TELEPHONE NO.** (904) 462-3911
ADDRESS ***(Number, Street, City, State, and Zip Code)*** Post Office Box 114, Gainesville, Florida 32602	
CHEMICAL NAME AND SYNONYMS Nickel Cadmium Battery (closed cylindrical)	**TRADE NAME AND SYNONYMS**
CHEMICAL FAMILY	**FORMULA**

SECTION II - HAZARDOUS INGREDIENTS N/A

PAINTS, PRESERVATIVES, & SOLVENTS	%	TLV (Units)	ALLOYS AND METALLIC COATINGS	%	TLV (Units)
PIGMENTS			BASE METAL		
CATALYST			ALLOYS		
VEHICLE			METALLIC COATINGS		
SOLVENTS			FILLER METAL PLUS COATING OR CORE FLUX		
ADDITIVES			OTHERS		
OTHERS					

HAZARDOUS MIXTURES OF OTHER LIQUIDS, SOLIDS, OR GASES		%	TLV (Units)
Each cell is a sealed container	Nickel & Nickel Hydroxide 20-30% as Ni		1mg/m^3
enclosing a nickel electrode, a	Cadmium & Cadmium Hydroxide 13-15% as Cd		0.2mg/m^3
cadmium electrode and potassium	Cobalt & Cobalt Hydroxide 1-2% as Co		0.1mg/m^3
hydroxide electrolyte.	Potassium Hydroxide 2-4% as dry KOH		2mg/m^3

SECTION III - PHYSICAL DATA N/A

BOILING POINT (°F.)		SPECIFIC GRAVITY ($H_2O = 1$)	
VAPOR PRESSURE (mm Hg.)		PERCENT, VOLATILE BY VOLUME (%)	
VAPOR DENSITY (AIR = 1)		EVAPORATION RATE (= 1)	
SOLUBILITY IN WATER			
APPEARANCE AND ODOR			

SECTION IV - FIRE AND EXPLOSION HAZARD DATA N/A

FLASH POINT (Method used)	FLAMMABLE LIMITS	Lel	Uel
EXTINGUISHING MEDIA			
SPECIAL FIRE FIGHTING PROCEDURES			
UNUSUAL FIRE AND EXPLOSION HAZARDS Cadmium fumes may be released during burning.			

PAGE (1)

(Continued on reverse side)

Form OSHA-20
Rev. May 72

GENERAL ELECTRIC

SECTION V - HEALTH HAZARD DATA

THRESHOLD LIMIT VALUE N/A

EFFECTS OF OVEREXPOSURE N/A

EMERGENCY AND FIRST AID PROCEDURES Electrolyte is caustic. DO NOT allow skin or eye contact.

Eyes: Flush with water for 15 minutes, follow-up medical attention absolute necessity. If gotten on skin vinegar or other mild acid may be used for neutralization.

SECTION VI - REACTIVITY DATA N/A

STABILITY	**UNSTABLE**		**CONDITIONS TO AVOID** Burning, rupturing.
	STABLE		

INCOMPATABILITY ***(Materials to avoid)***

HAZARDOUS DECOMPOSITION PRODUCTS

HAZARDOUS POLYMERIZATION	**MAY OCCUR**		**CONDITIONS TO AVOID**
	WILL NOT OCCUR		

SECTION VII - SPILL OR LEAK PROCEDURES

STEPS TO BE TAKEN IN CASE MATERIAL IS RELEASED OR SPILLED

Flush electrolyte spills with water.

WASTE DISPOSAL METHOD

In accordance with local, state and federal regulations.

SECTION VIII - SPECIAL PROTECTION INFORMATION N/A

RESPIRATORY PROTECTION ***(Specify type)***

VENTILATION	**LOCAL EXHAUST**	**SPECIAL**
	MECHANICAL ***(General)***	**OTHER**

PROTECTIVE GLOVES	**EYE PROTECTION**

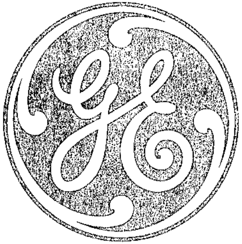
OTHER PROTECTIVE EQUIPMENT

SECTION IX - SPECIAL PRECAUTIONS

PRECAUTIONS TO BE TAKEN IN HANDLING AND STORING Electrolyte is caustic; DO NOT allow skin or eye contact; flush with water if accidentally exposed. DO NOT incinerate or mutilate; may burst or release toxic materials. DO NOT short circuit; may cause burns.

OTHER PRECAUTIONS

General Electric
PRODUCT LINE APPENDIX
LISTING



PRODUCT SPECIFICATIONS

GENERAL ELECTRIC

CELL PRODUCT LINE OVERVIEW

(See Product Specification Sheets for Actual Values)

Product Type	Description	Temperature	Charge Capability
Standard	For use in most applications	Up to 50°C Continuous	Up to **C**/3 Maximum
Goldtop®	For use in high temperature applications	Up to 70°C Continuous	Up to **C**/3 Maximum
XP60	For fast charge applications (with charge termination controls)	Up to 50°C Continuous	Up to 1.2**C** Maximum
***GE*max**™	New maximum power product for high capacity and high drain rate applications	Up to 50°C Continuous	Up to **C**/3 Maximum

	Capacity		Discharge Rate		Charge Rate			Temperature	
	Standard	High	Standard	High	Standard	Quick	Fast	Standard	High
Standard	✓		✓		✓	✓		✓	
Goldtop®	✓		✓		✓	✓			✓
XP60	✓		✓	✓			✓	✓	
***GE*max**™		✓		✓	✓	✓		✓	

NOTE: — For special needs and application capabilities consult General Electric Company

CELL SELECTOR GUIDE

(Discharge current vs. discharge time for each cell size)

(A) This typical data is based on the standard cell. Although it is similar for special types, reference should be made to individual data sheets for additional detail.

(B) Cell Selection:

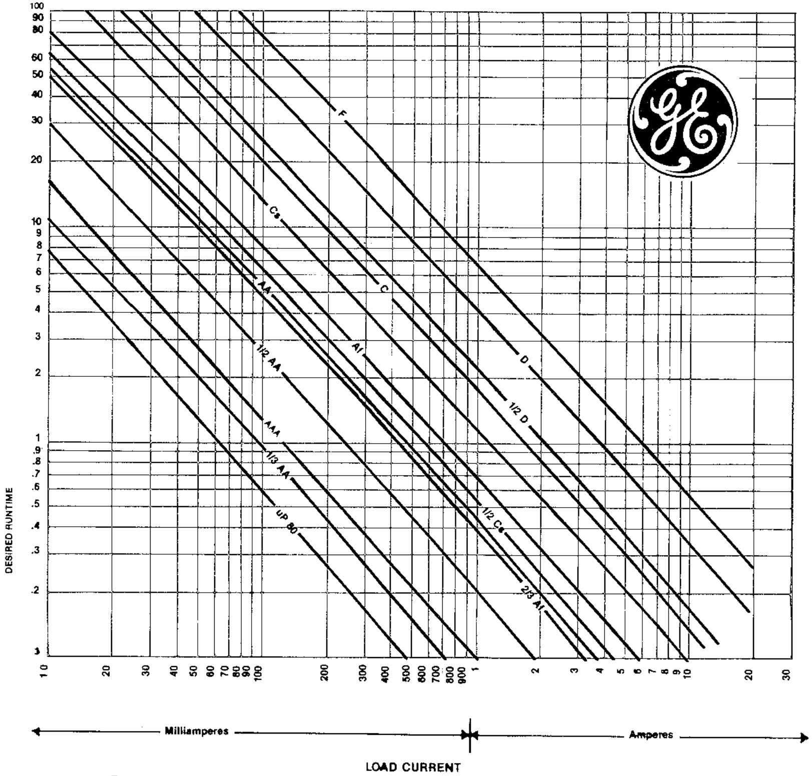
- Determine desired run time and operating current.
- Cell closest to the intersection of load and time on selector chart is preliminary choice.
- See individual data section on that cell size and product line.

Use of Cell Selector Guide

1. Locate discharge current of your application of the horizontal axis.
2. Choose the desired run time on the vertical axis.
3. The intersection of discharge current and time defines the necessary capacity. The diagonal lines represent the cell sizes that most closely match your need.

Example: Discharge current of 200 mA for 3 hours.

Solution: The cells of closest capacity are the 500mAh AA and the 600mAh ½Cs. The ½Cs will match the requirements. Use of the AA would limit run-time to 2.6 hours.



GENERAL ELECTRIC

CELL SPECIFICATIONS

				Capacity		Temperature Range						Charge Rate		Overcharge Rate		Max. Discharge		
Cell Size	Product Line (Cell)	Charge Capability	Rated *(1) Capacity (Minimum)	(mAh) *(2) **C**Rate Nominal	**C**/5 Nominal	Storage Min.	Storage Max.	(°C) Discharge Min.	Discharge Max.	Charge *(3) Min.	Charge Max.	(mA) Min.	Max.	(mA) Min.	Max.	Amp *(4) Cont.	Mo-ment.	Typical Re (mΩ)
μP80	Standard	Standard	65 @	0.1**C** rate		-40	50	-20	50	0	50	3	7	1	7	4	8	140
	Standard	Quick	65 @	0.1**C** rate		-40	50	-20	50	10	50	3	22	1	22	4	8	140
	Goldtop®	Standard	65 @	0.1**C** rate		-40	70	-20	70	0	70	3	7	1	7	4	8	150
	Goldtop®	Quick	65 @	0.1**C** rate		-40	70	-20	70	10	70	3	22	1	22	4	8	150
1/3 AA	Goldtop®	Standard	100	116	125	-40	70	-20	70	0	70	5	10	2	10	8	15	80
	Goldtop®	Quick	100	116	125	-40	70	-20	70	10	70	5	33	2	33	8	15	80
AAA	Standard	Standard	160	180	220	-20	45	-20	45	0	45	6	18	4	18	1	2	.65
	Standard	Quick	160	180	220	-20	45	-20	45	10	45	6	60	4	60	1	2	.65
1/2 AA	Standard	Standard	250	290	310	-40	50	-20	50	0	50	13	25	5	25	9	19	64
	Standard	Quick	250	290	310	-40	50	-20	50	10	50	13	80	5	80	9	19	64
	Goldtop®	Standard	250 @	0.1**C** rate		-40	70	-20	70	0	70	13	25	5	25	5	10	64
	Goldtop®	Quick	250 @	0.1**C** rate		-40	70	-20	70	10	70	13	80	5	80	5	10	64
2/3 Af	Standard	Standard	450	520	550	-40	50	-20	50	0	50	25	50	9	50	9	19	42
	Standard	Quick	450	520	550	-40	50	-20	50	10	50	25	150	9	150	9	19	42
	XP60	Fast	450	520	550	-40	45	-20	45	15	45	25	540	9	150	9	19	42
AA	Standard	Standard	500	575	625	-40	50	-20	50	0	50	25	50	10	50	9	19	36
	Standard	Quick	500	575	625	-40	50	-20	50	10	50	25	170	10	170	9	19	36
	XP60	Fast	500	575	625	-40	45	-20	45	15	45	25	600	10	50	9	19	36
	Goldtop®	Standard	500	575	625	-40	70	-20	70	0	70	25	50	10	50	9	19	36
	Goldtop®	Quick	500	575	625	-40	70	-20	70	10	70	25	170	10	170	9	19	36
1/2 Cs	Standard	Standard	600	675	750	-40	50	-20	50	0	50	27	60	12	60	29	58	28
	Standard	Quick	600	675	750	-40	50	-20	50	10	50	27	200	12	200	29	58	28

CELL SPECIFICATIONS

				Capacity		Temperature Range						Charge Rate		Overcharge Rate		Max. Discharge		
				(mAh) *(2)		(°C)						(mA)		(mA)		Amp *(4)		
Cell Size	Product Line (Cell)	Charge Capability	Rated *(1) Capacity (Minimum)	CRate Nominal	C/5 Nominal	Storage Min.	Storage Max.	Discharge Min.	Discharge Max.	Charge (3) Min.	Charge (3) Max.	Min.	Max.	Min.	Max.	Cont.	Moment.	Typical Re (mΩ)
Af	Standard	Standard	750	870	935	-40	50	-20	50	0	50	35	75	15	75	10	19	27
	Standard	Quick	750	870	935	-40	50	-20	50	10	50	35	250	15	250	10	19	27
	XP60	Fast	750	870	935	-40	45	-20	45	15	45	35	900	15	75	10	19	27
Cs	Standard	Standard	1200	1350	1400	-40	50	-20	50	0	50	60	120	25	120	29	58	21
	Standard	Quick	1200	1350	1400	-40	50	-20	50	10	50	60	400	25	400	29	58	21
	XP60	Fast	1100	1200	1200	-40	45	-20	45	15	45	1000	1500	25	110	29	58	10
	GEmax™	Standard	1300	1500	1625	-40	50	-20	50	0	50	65	130	25	130	29	58	12
	GEmax™	Quick	1300	1500	1625	-40	50	-20	50	10	50	65	430	25	430	29	58	12
	Goldtop®	Standard	1200	1350	1400	-40	70	-20	70	0	70	60	120	25	120	29	58	25
	Goldtop®	Quick	1200	1350	1400	-40	70	-20	70	10	70	60	400	25	400	29	58	25
C	Standard	Standard	1800	2000	2200	-40	50	-20	50	0	50	90	180	25	180	29	58	12
	Standard	Quick	1800	2000	2200	-40	50	-20	50	10	50	90	600	25	600	29	58	12
1/2 D	Standard	Standard	2200	2500	2700	-40	50	-20	50	0	50	110	220	25	220	58	116	10
	XP60	Fast	2100	2300	2300	-40	50	-20	45	15	45	2000	2500	25	210	58	116	8
	Goldtop®	Standard	2200	2500	2700	-40	70	-20	70	0	70	110	220	25	220	58	116	10
	Goldtop®	Quick	2000	2300	2400	-40	70	-20	70	10	70	100	650	25	650	58	116	8
D	Standard	Standard	4000	4500	4700	-40	50	-20	50	0	50	200	400	50	400	58	116	5
	XP60	Fast	4000	4400	4400	-40	50	-20	45	15	45	4000	4800	50	400	58	116	4
	Goldtop®	Standard	4000	4500	4700	-40	70	-20	70	0	70	200	400	50	400	58	116	5
	Goldtop®	Quick	3500	4000	4200	-40	70	-20	70	10	70	175	1050	50	1050	58	116	4
F	Standard	Standard	6200	7000	7100	-40	50	-20	50	0	50	310	700	70	700	58	116	8
	Goldtop®	Standard	5600	6200	6400	-40	70	-20	70	0	70	280	700	70	700	58	116	5

GENERAL ELECTRIC

CELL SPECIFICATIONS AND PERFORMANCE CURVES

			Standard Capacity			Actual Capacity			Voltage Effects		Retained Capacity
Cell Size	Product Line (Cell)	Charge Capability	Rated (1) (Minimum)	(mAh) C Rate Nominal	(2) C/5 Nominal	Charge Temp Fig. S4-14	Discharge Rate Fig. S4-15	Discharge Temp Fig. S4-16	Volt vs Cell Temp Re Fig. S4-8	MPVo Fig. S4-10	Storage Temperature Fig. S4-17
µP8O	Standard	Standard	65	@0.1**C** rate		CT1	DR4	DT1	Re1	Vo1	RC1
	Standard	Quick	65	@0.1**C** rate		CT1	DR4	DT1	Re1	Vo1	RC1
	Goldtop®	Standard	65	@0.1**C** rate		CT2	DR4	DT1	Re1	Vo1	RC1
	Goldtop®	Quick	65	@0.1**C** rate		CT2	DR4	DT1	Re1	Vo1	RC1
1/3AA	Goldtop®	Standard	100	116	125	CT2	DR1	DT1	Re1	Vo1	RC2
	Goldtop®	Quick	100	116	125	CT2	DR1	DT1	Re1	Vo1	RC2
AAA	Standard	Standard	160	180	220	CT1	DR1	DT1	Re1	Vo1	RC1
	Standard	Quick	160	180	220	CT1	DR1	DT1	Re1	Vo1	RC1
1/2 AA	Standard	Standard	250	290	310	CT1	DR1	DT1	Re1	Vo1	RC2
	Standard	Quick	250	290	310	CT1	DR1	DT1	Re1	Vo1	RC2
	Goldtop®	Standard	250	@0.1**C** rate		CT2	DR4	DT1	Re1	Vo1	RC1
	Goldtop®	Quick	250	@0.1**C** rate		CT2	DR4	DT1	Re1	Vo1	RC1
2/3 Af	Standard	Standard	450	520	550	CT1	DR1	DT1	Re1	Vo1	RC2
	Standard	Quick	450	520	550	CT1	DR1	DT1	Re1	Vo1	RC2
	XP60	Fast	450	520	550	-NA-	DR1	DT1	Re1	Vo1	RC2
AA	Standard	Standard	500	575	625	CT1	DR1	DT1	Re1	Vo1	RC2
	Standard	Quick	500	575	625	CT1	DR1	DT1	Re1	Vo1	RC2
	XP60	Fast	500	575	625	-NA-	DR1	DT1	Re1	Vo1	RC2
	Goldtop®	Standard	500	575	625	CT2	DR1	DT1	Re1	Vo1	RC2
	Goldtop®	Quick	500	575	625	CT2	DR1	DT1	Re1	Vo1	RC2
1/2 Cs	Standard	Standard	600	675	750	CT1	DR1	DT1	Re1	Vo1	RC2
	Standard	Quick	600	675	750	CT1	DR1	DT1	Re1	Vo1	RC2

NOTES:

*(1) Rating Philosophy—*General Electric* cells are rated functionally with respect to minimum capacity, usually at a **C** rate discharge. Conditions for this rating are:

Charge—0.1 **C** amps for 20 hours
Rest—2 to 4 hours
Discharge—1 **C** amps to 0.9 volts
Test Temperature—23°C
Run time will equal or exceed 1 hour.

Special cells may require different conditions, such as fast charge for XP60 cells.

The *General Electric* rating system, based upon the minimum **C** rate capacity, yields a conservative estimate of the total energy available from *General Electric* cells.

*(2) **C** is numerically equal to the rated ampere hour capacity of the cell. For example, for a 450 mAh cell, **C** = 0.450A.

C rate is a charge or discharge current (amperes), numerically equal to **C.** For example, for **C** = 0.450, then the 2**C** rate = 0.900A and a 2**C** discharge would be performed using a 900 milliampere discharge current.

CELL SPECIFICATIONS AND PERFORMANCE CURVES

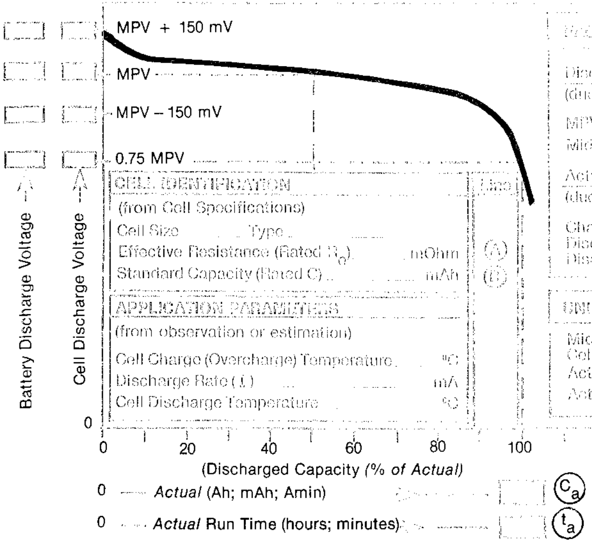
			Standard Capacity			Actual Capacity			Voltage Effects		Retained Capacity
Cell Size	Product Line (Cell)	Charge Capability	Rated *(1) (Minimum)	(mAh) C Rate Nominal	*(2) C/5 Nominal	Charge Temp Fig. S4-14	Discharge Rate Fig. S4-15	Discharge Temp Fig. S4-16	Volt vs Cell Temp Re Fig. S4-8	MPVo Fig. S4-10	Storage Temperature Fig. S4-17
Af	Standard	Standard	750	870	935	CT1	DR1	DT1	Re1	Vo1	RC2
	Standard	Quick	750	870	935	CT1	DR1	DT1	Re1	Vo1	RC2
	XP60	Fast	750	870	935	-NA-	DR1	DT1	Re1	Vo1	RC2
Cs	Standard	Standard	1200	1350	1400	CT1	DR1	DT1	Re1	Vo1	RC2
	Standard	Quick	1200	1350	1400	CT1	DR1	DT1	Re1	Vo1	RC2
	XP60	Fast	1100	1200	1200	-NA-	DR2	DT2	Re2	Vo2	RC2
	GEmax™	Standard	1300	1500	1625	CT1	DR3	DT1	Re1	Vo1	RC2
	GEmax™	Quick	1300	1500	1625	CT1	DR3	DT1	Re1	Vo1	RC2
	Goldtop®	Standard	1200	1350	1400	CT2	DR1	DT1	Re1	Vo1	RC2
	Goldtop®	Quick	1200	1350	1400	CT2	DR1	DT1	Re1	Vo1	RC2
C	Standard	Standard	1800	2000	2200	CT1	DR1	DT1	Re1	Vo1	RC2
	Standard	Quick	1800	2000	2200	CT1	DR1	DT1	Re1	Vo1	RC2
1/2 D	Standard	Standard	2200	2500	2700	CT1	DR1	DT1	Re1	Vo1	RC2
	XP60	Fast	2100	2300	2300	-NA-	DR2	DT2	Re2	Vo2	RC2
	Goldtop®	Standard	2200	2500	2700	CT2	DR1	DT1	Re1	Vo1	RC2
	Goldtop®	Quick	2000	2300	2400	CT2	DR1	DT1	Re1	Vo1	RC2
D	Standard	Standard	4000	4500	4700	CT1	DR1	DT1	Re1	Vo1	RC2
	XP60	Fast	4000	4400	4400	-NA-	DR2	DT2	Re2	Vo2	RC2
	Goldtop®	Standard	4000	4500	4700	CT2	DR1	DT1	Re1	Vo1	RC2
	Goldtop®	Quick	3500	4000	4200	CT2	DR1	DT1	Re1	Vo1	RC2
F	Standard	Standard	6200	7000	7100	CT1	DR1	DT1	Re1	Vo1	RC2
	Goldtop®	Standard	5600	6200	6400	CT2	DR1	DT1	Re1	Vo1	RC2

*(3) Cell case temperatures shown are for continuous exposure, brief excursions outside these limits can be tolerated.

Cells may be operated at higher temperatures but reduced battery life will result.

Cells may be charged below the temperature shown when rate is temperature controlled. Exceeding the low temperature specifications may result in rapid cell failure.

*(4) Maximum continuous discharge current may be further limited due to cell temperature rise and the associated impact on battery life. Temperature rise is dependent on discharge current, duration of discharge, discharge duty cycle and the thermal characteristics of multicell battery designs.



CELL IDENTIFICATION — Line

(from Cell Specifications)

		Line
Cell Size ______ Type ______		
Effective Resistance (Rated R_e) ______	mOhm	Ⓐ
Standard Capacity (Rated C) ______	mAh	Ⓑ

APPLICATION PARAMETERS

(from observation or estimation)

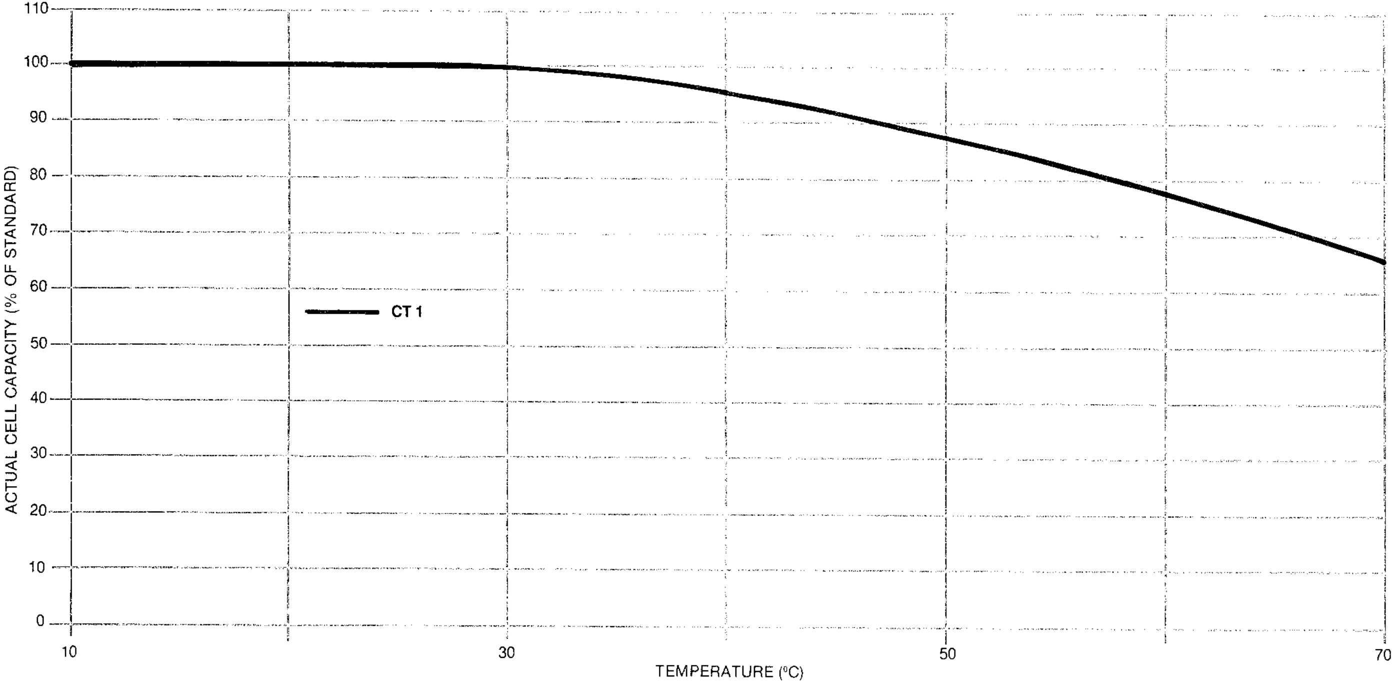
Cell Charge (Overcharge) Temperature ______	°C
Discharge Rate (I) ______	mA
Cell Discharge Temperature ______	°C

FACTORS FOR CALCULATIONS		Line	Fig. ref.
Discharge Voltage Effects (due to cell discharge temp)			
MPV_o ______	(mV)	MPV_o	S 4-10
MidPoint R_e ______	(% of Rated)	Ⓓ	S 4-8
Actual Capacity Effects (due to:)			
Charge Temp ______	(% of Std)	Ⓔ	S 4-14
Discharge Rate ______	(% of Std)	Ⓕ	S 4-15
Discharge Temp ______	(% of Std)	Ⓖ	S 4-16

UNIVERSAL DISCHARGE CURVE VALUES		CALCULATIONS
MidPoint R_e = ______	(mOhms)	Ⓐ × Ⓓ
Cell MPV = ______	(mV)	MPV_o – (I × R_e)
Actual capacity (Ⓒa) = ______	(mAh)	Ⓑ × Ⓔ × Ⓕ × Ⓖ
Actual run time (ⓣa) = ______	(min)	(60 × Ⓒa ÷ I)

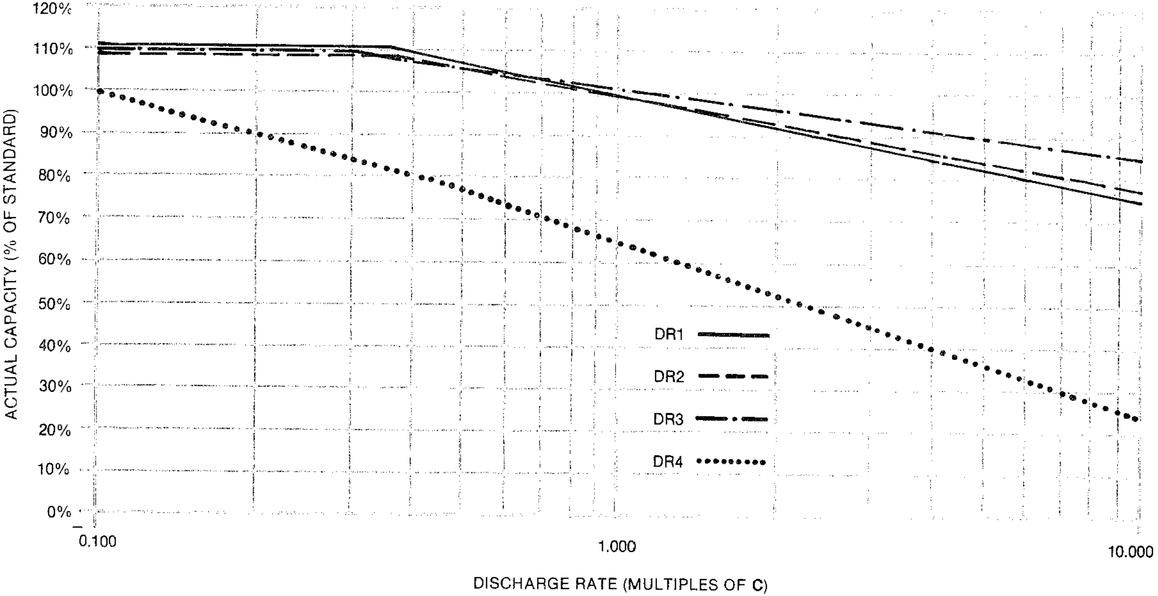
UNIVERSAL DISCHARGE CURVE

FIGURE S4-19



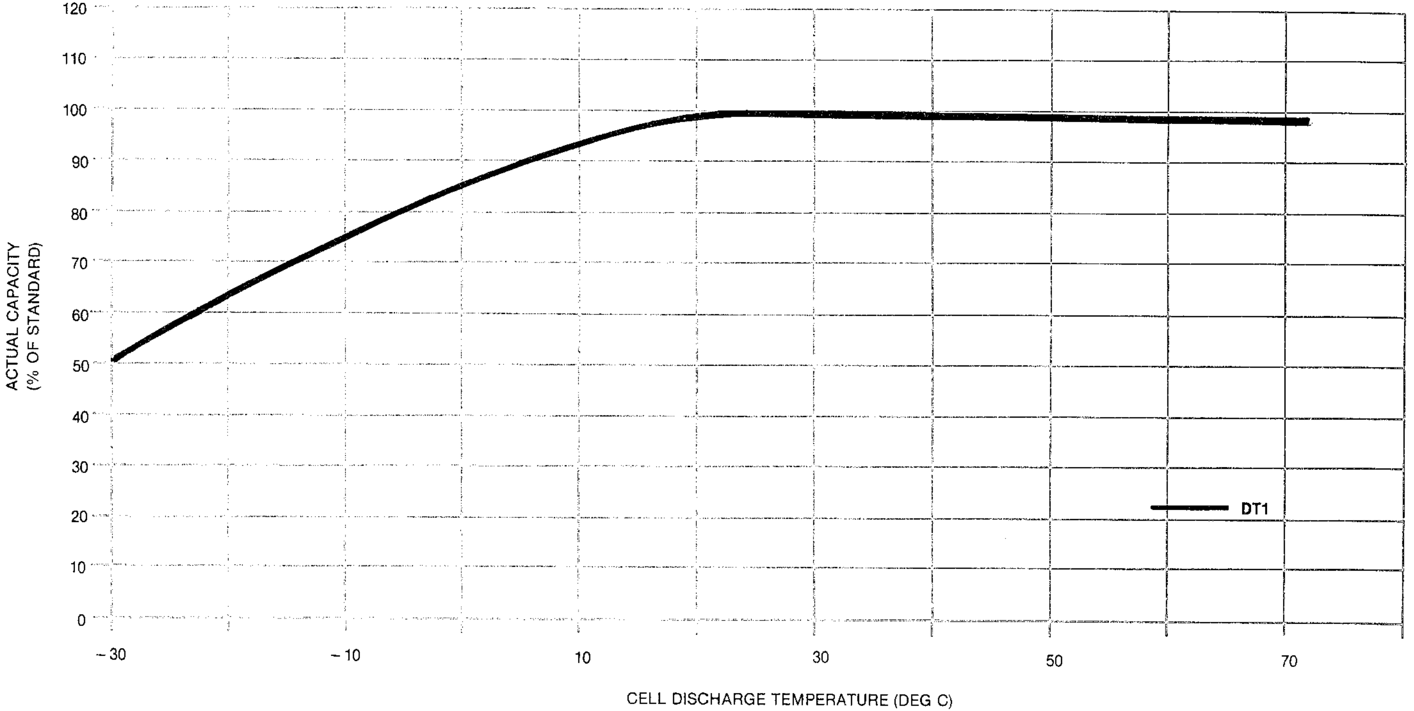
EFFECT OF CELL CHARGE TEMPERATURE
ON ACTUAL CAPACITY

FIGURE S4-14



EFFECT OF DISCHARGE RATE
ON ACTUAL CAPACITY

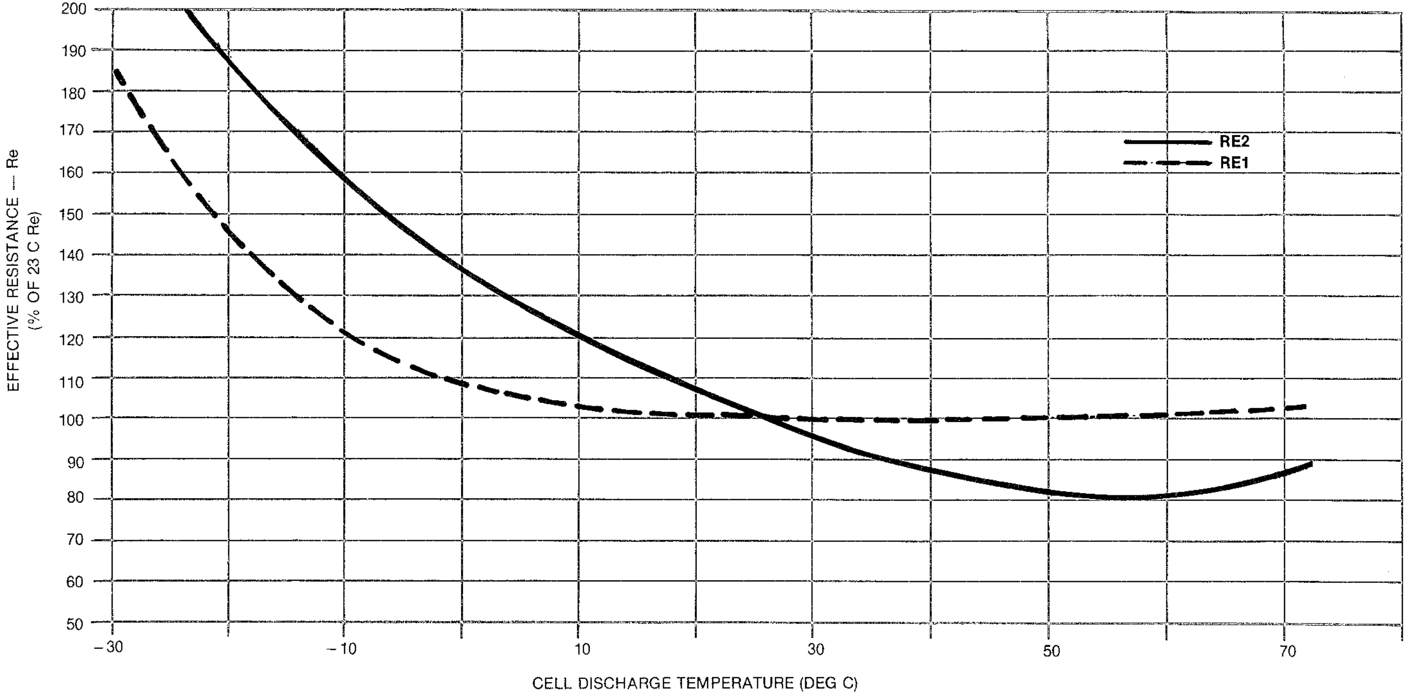
Figure S4-15



EFFECT OF CELL DISCHARGE TEMPERATURE
ON ACTUAL CAPACITY

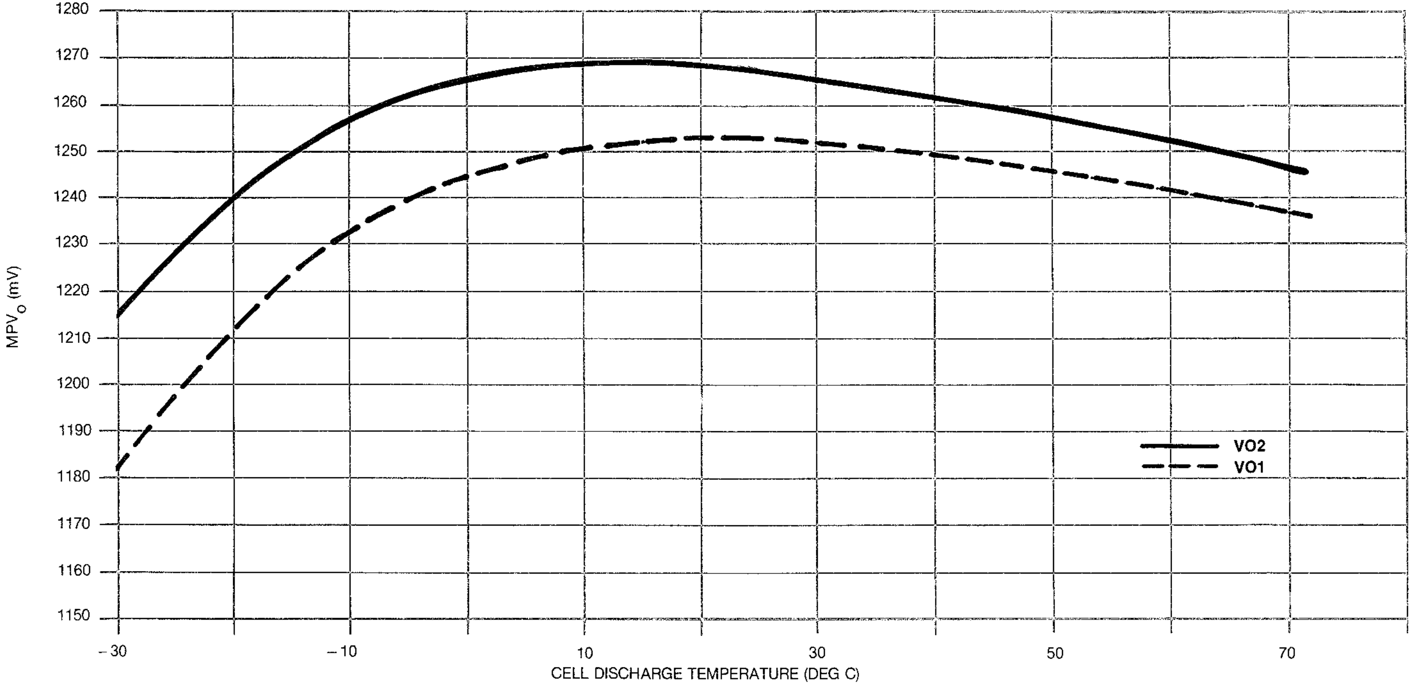
FIGURE S4-16

GENERAL ELECTRIC



EFFECT OF CELL DISCHARGE TEMPERATURE
ON RESISTANCE — R_e

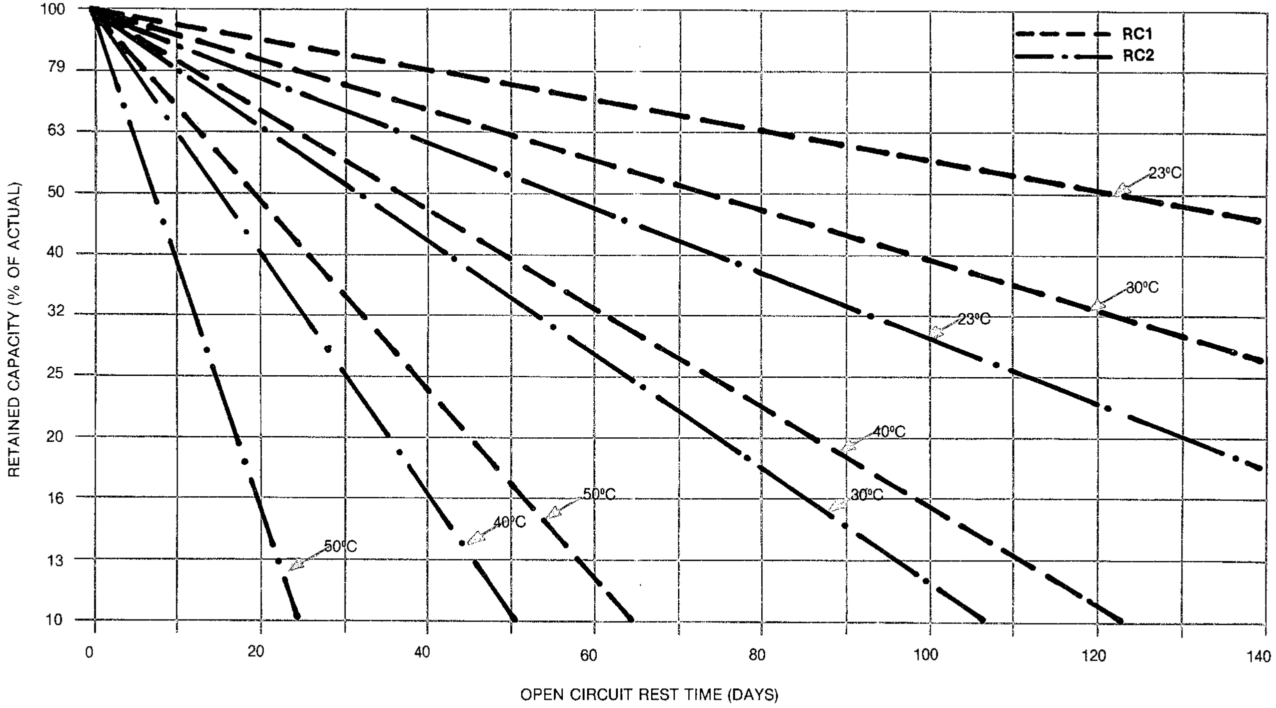
FIGURE S4-8



EFFECT OF CELL DISCHARGE TEMPERATURE
ON VOLTAGE — MPV$_O$

FIGURE S4-10

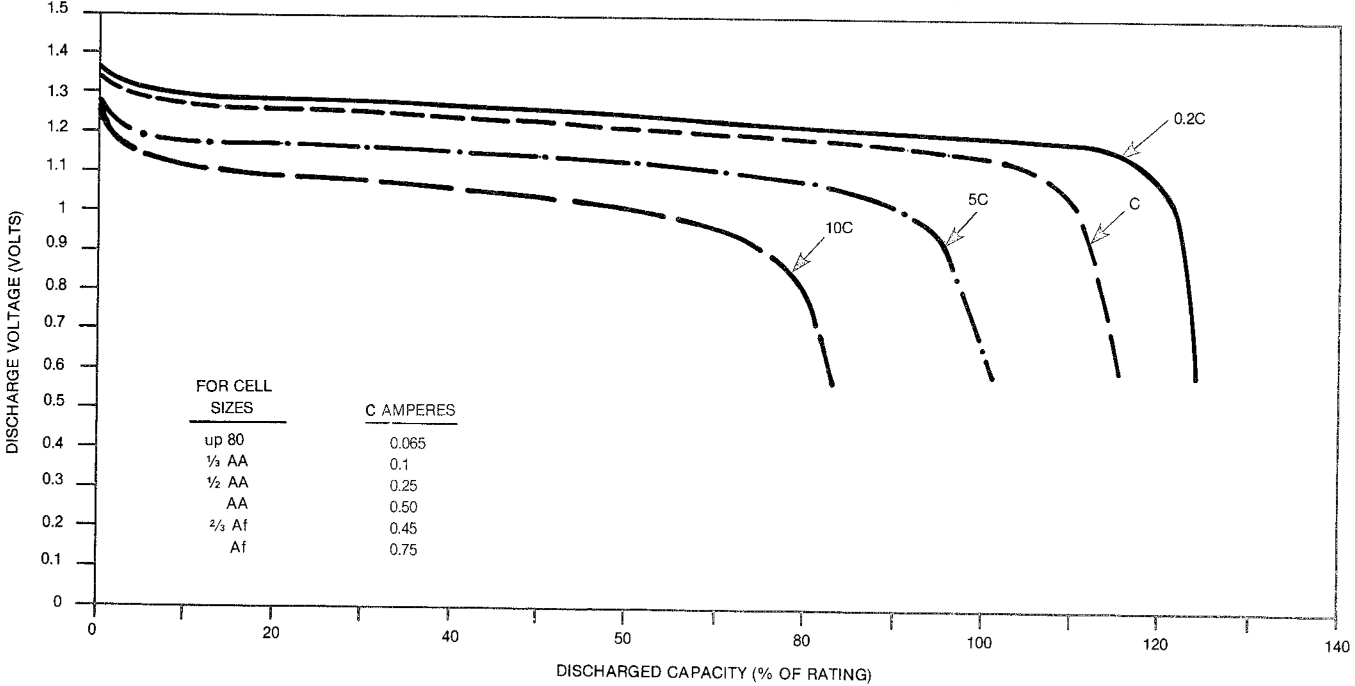
GENERAL ELECTRIC



RETAINED CAPACITY

FIGURE S4-17

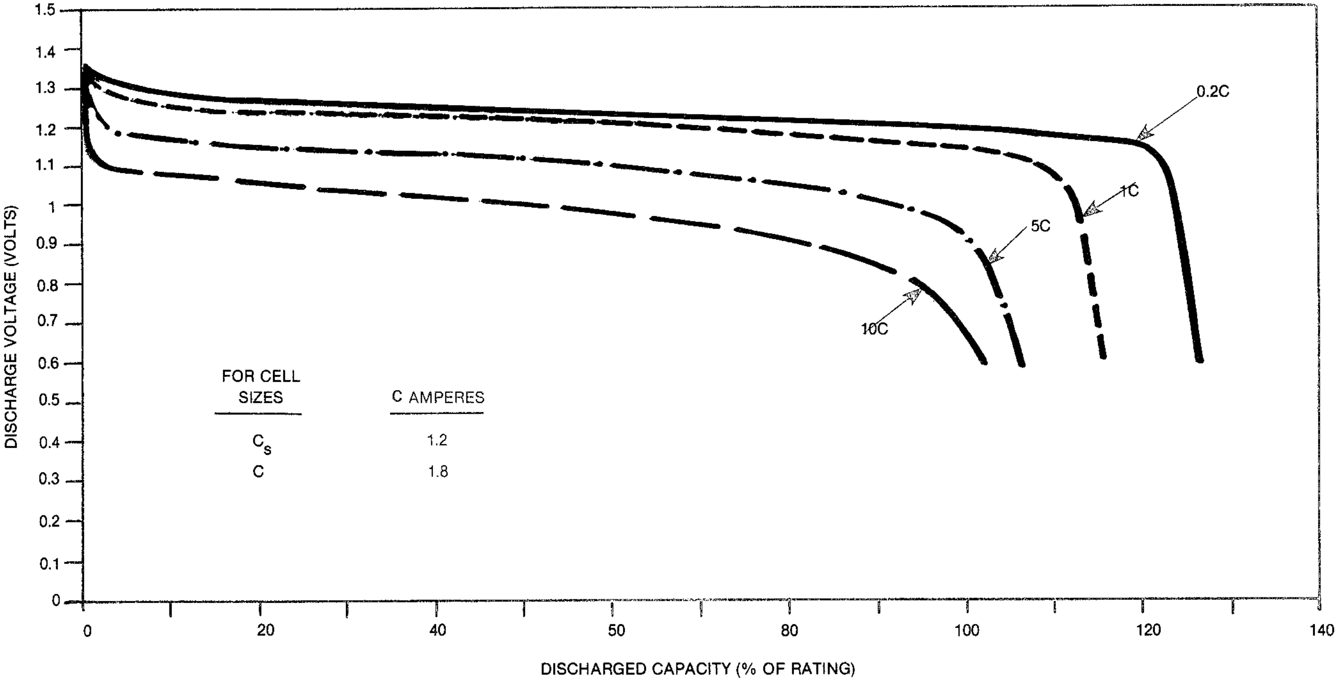
STANDARD
TYPICAL DISCHARGE CURVE AT 23C



FOR CELL SIZES	C AMPERES
up 80	0.065
⅓ AA	0.1
½ AA	0.25
AA	0.50
⅔ Af	0.45
Af	0.75

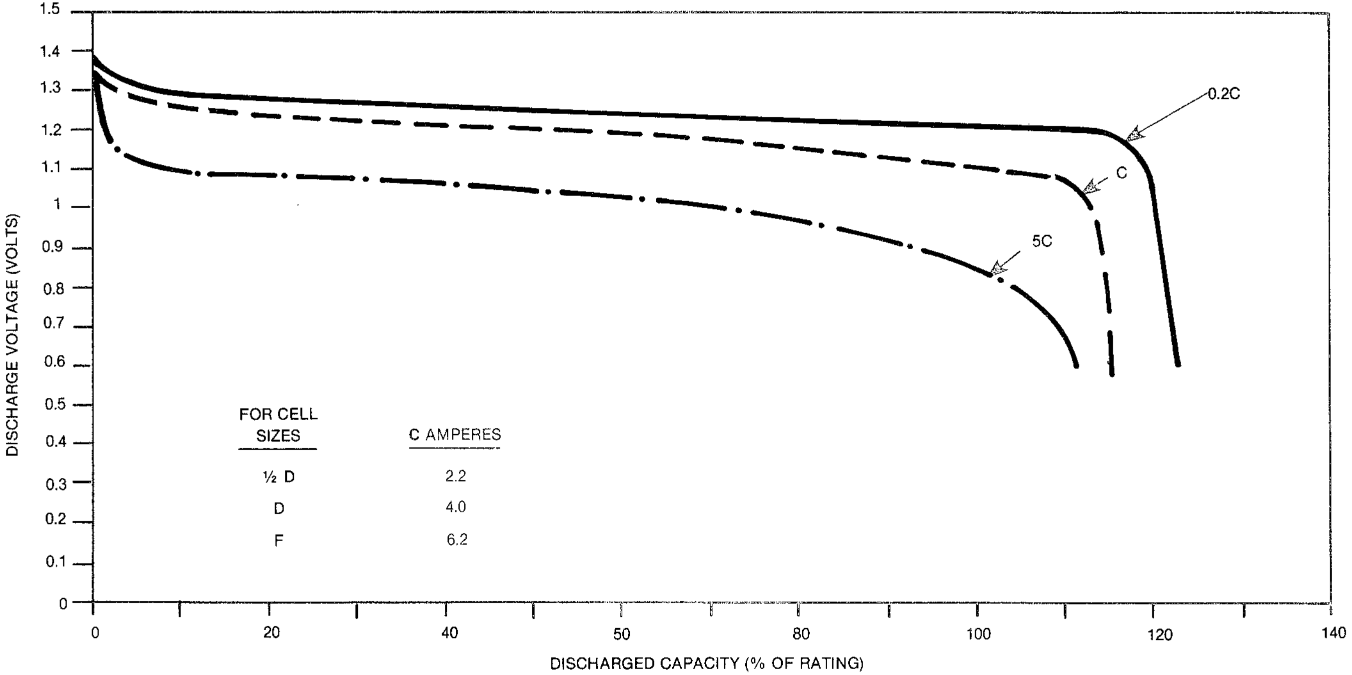
GENERAL ELECTRIC

STANDARD
TYPICAL DISCHARGE CURVE AT 23C



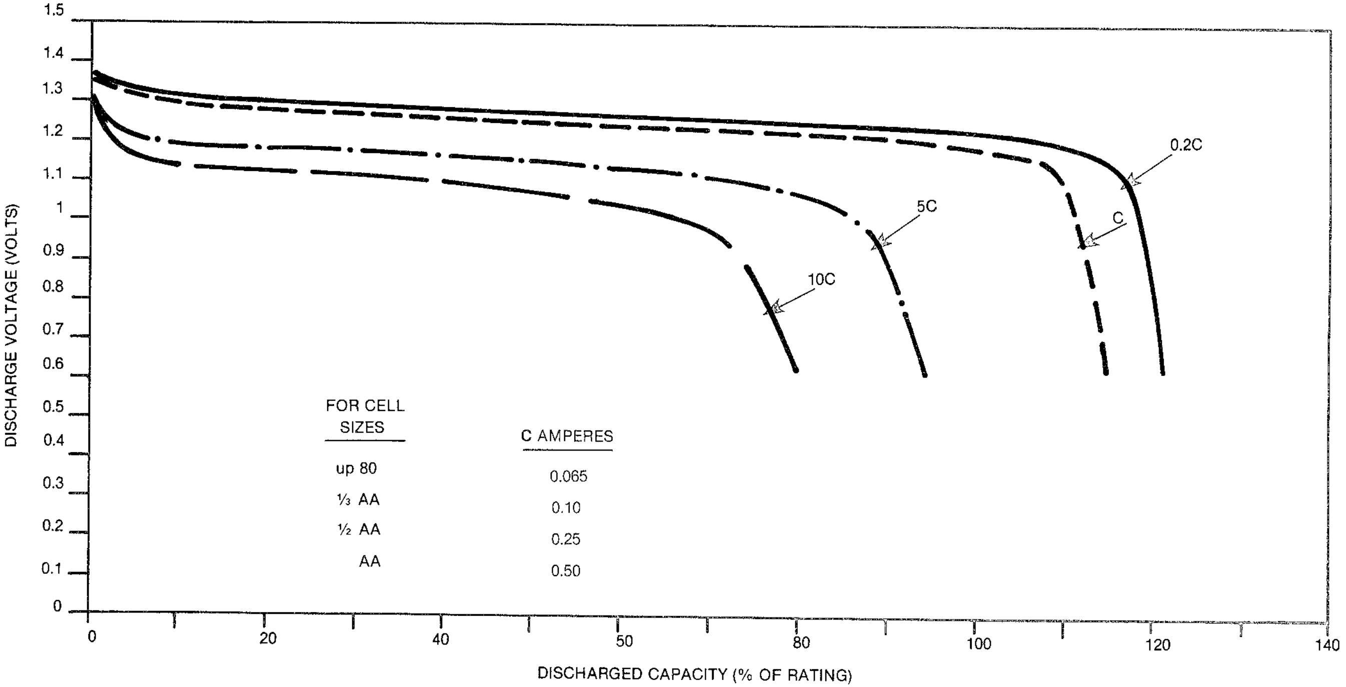
GENERAL ELECTRIC

STANDARD
TYPICAL DISCHARGE CURVE AT 23C



GENERAL ELECTRIC

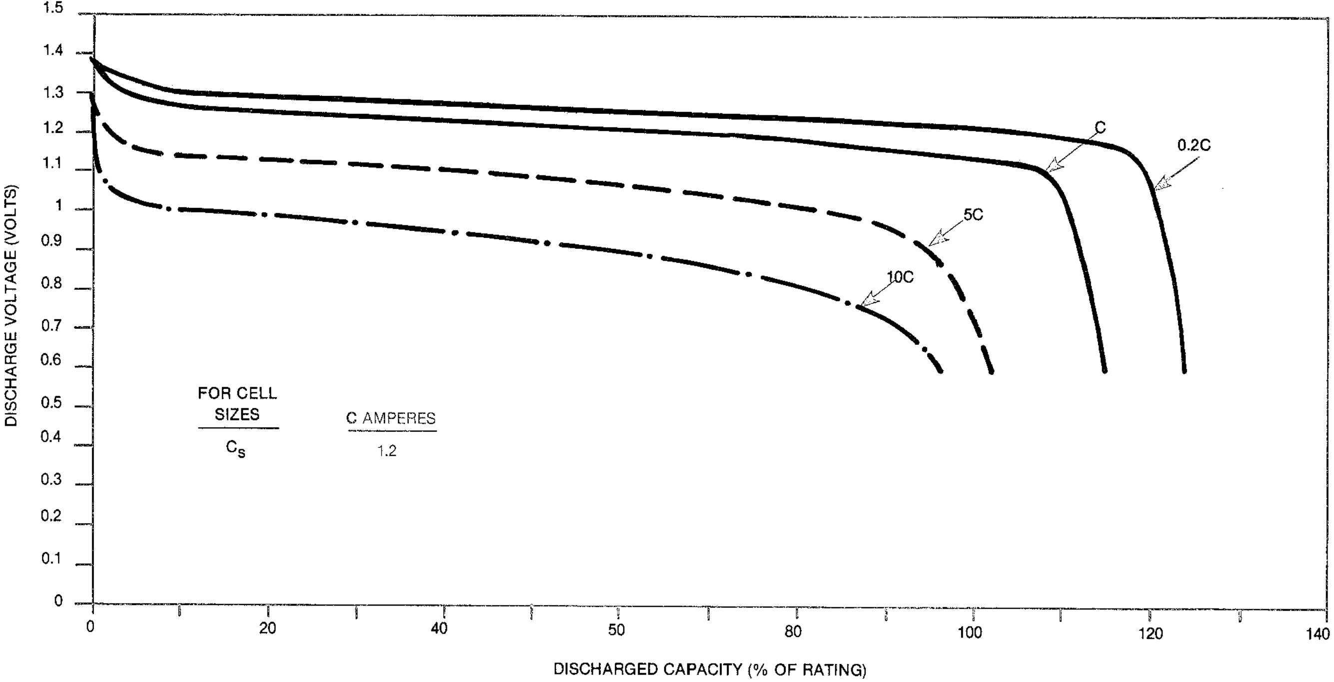
GOLDTOP®
TYPICAL DISCHARGE CURVE AT 23C



FOR CELL SIZES	C AMPERES
up 80	0.065
⅓ AA	0.10
½ AA	0.25
AA	0.50

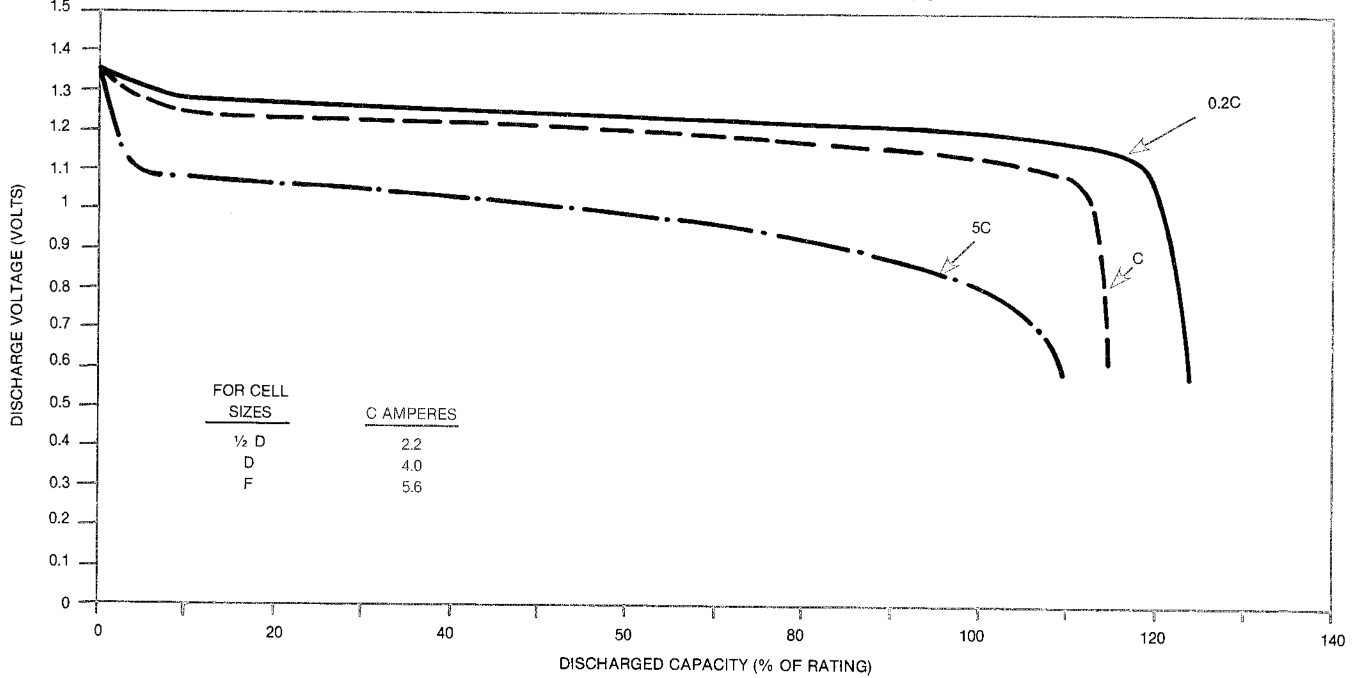
GENERAL ELECTRIC

GOLDTOP®
TYPICAL DISCHARGE CURVE AT 23C



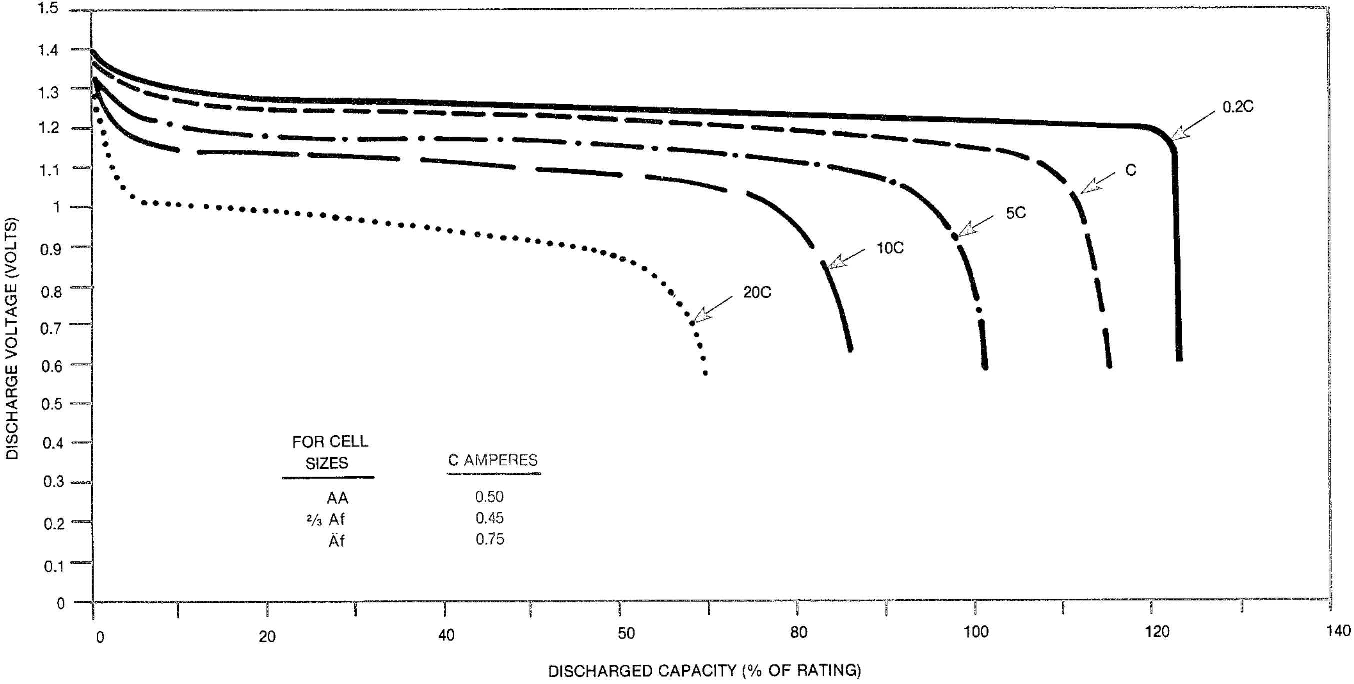
GENERAL ELECTRIC

GOLDTOP®
TYPICAL DISCHARGE CURVE AT 23C



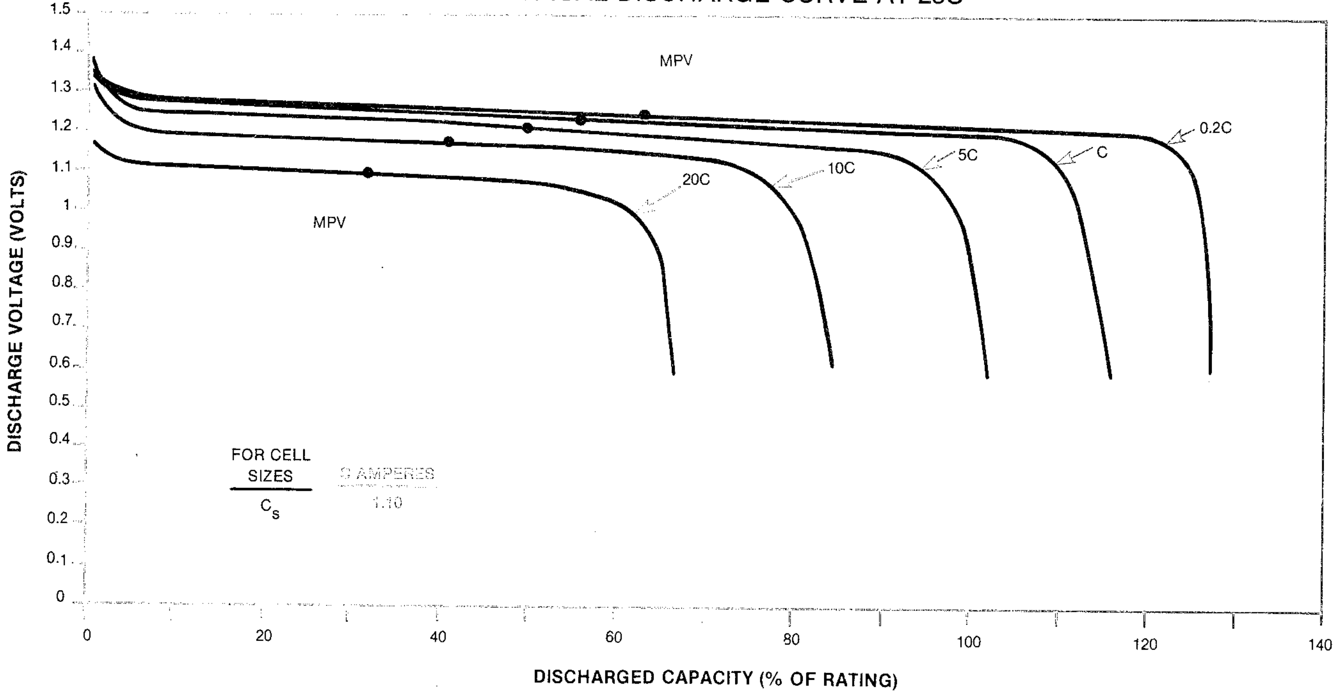
GENERAL ELECTRIC

XP60
TYPICAL DISCHARGE CURVE AT 23C



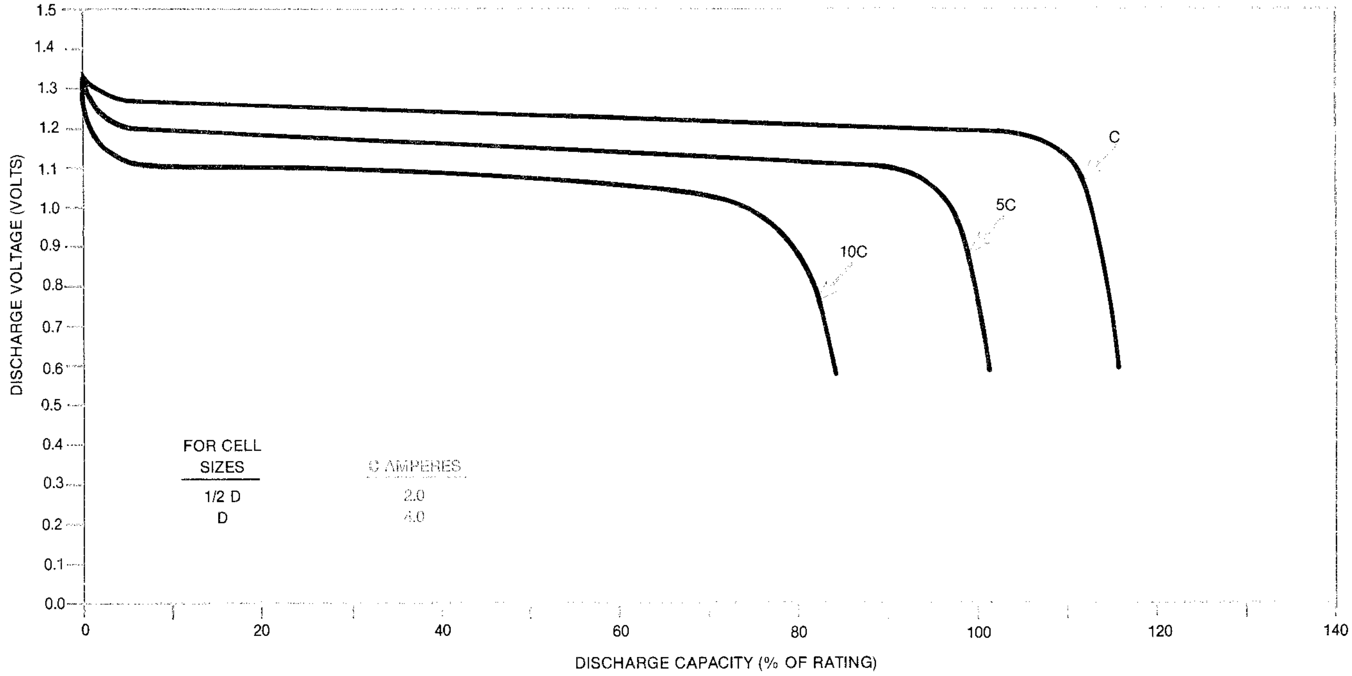
GENERAL ELECTRIC

XP60
TYPICAL DISCHARGE CURVE AT 23C



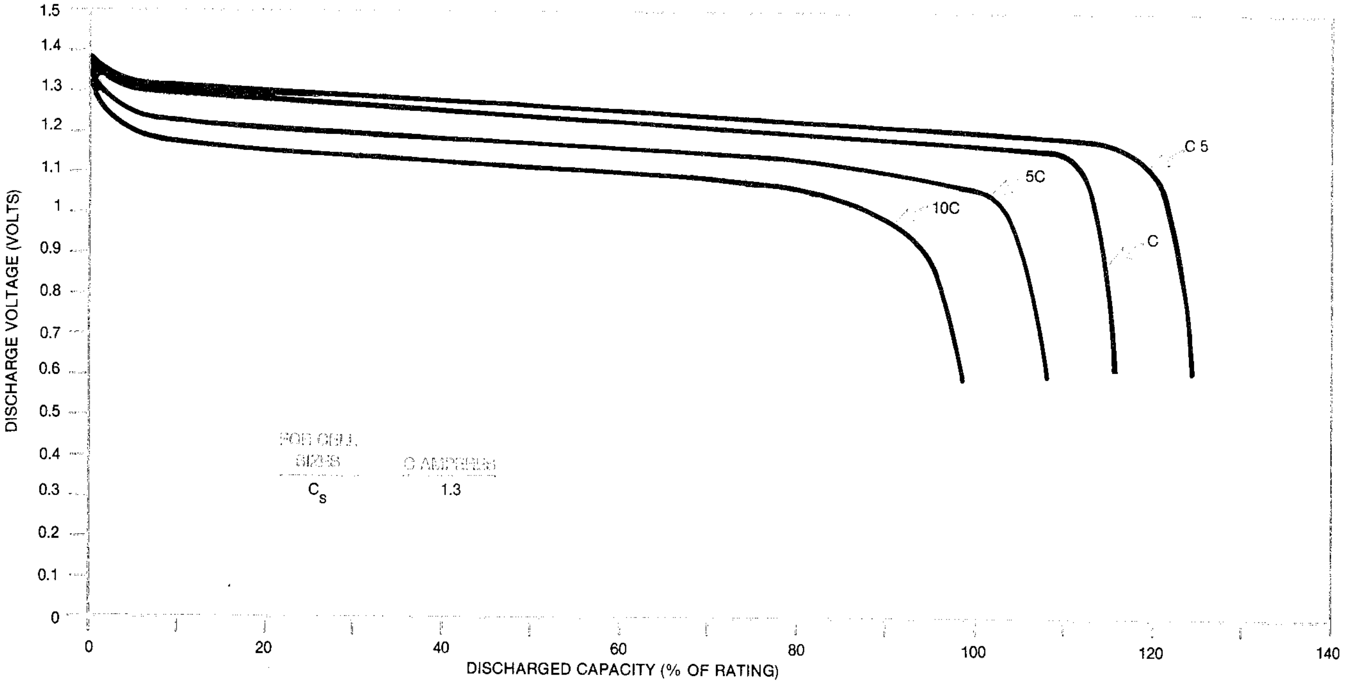
FOR CELL SIZES	C AMPERES
C_s	1.10

XP60
TYPICAL DISCHARGE CURVE AT 23ºC

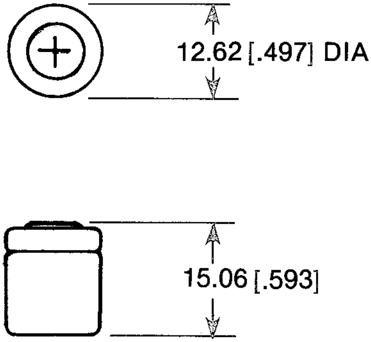


GEmax™

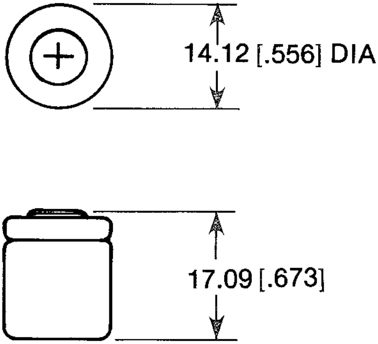
TYPICAL DISCHARGE CURVE AT 23°C



CELL OUTLINES



MP80

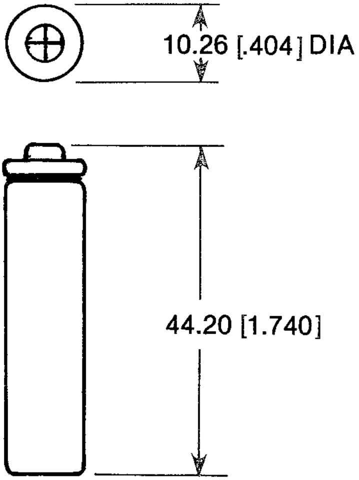


1/3 AA

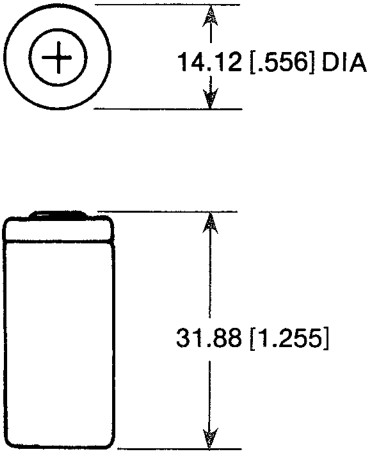
NOTES:

1. DIMENSIONS ARE IN MILLIMETERS (INCHES)
2. ALL DIMENSIONS ARE MAXIMUM

CELL OUTLINES



AAA



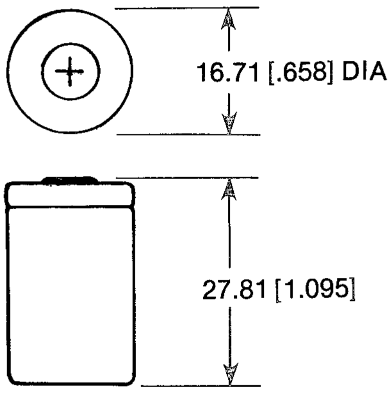
1/2 AA

NOTES:

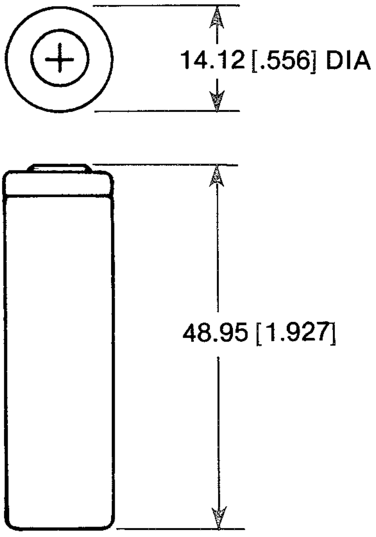
1. DIMENSIONS ARE IN MILLIMETERS (INCHES)
2. ALL DIMENSIONS ARE MAXIMUM

GENERAL ELECTRIC

CELL OUTLINES



2/3 A_f

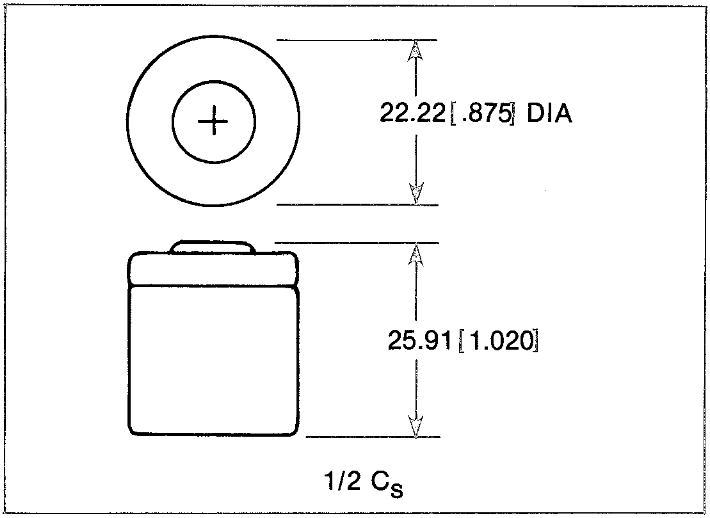


AA

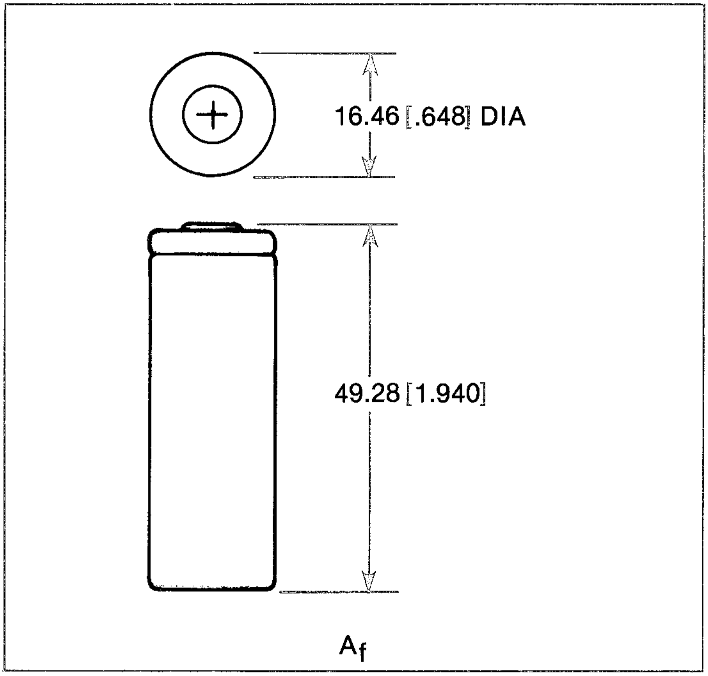
NOTES:

1. DIMENSIONS ARE IN MILLIMETERS (INCHES)
2. ALL DIMENSIONS ARE MAXIMUM

CELL OUTLINES



1/2 C_S

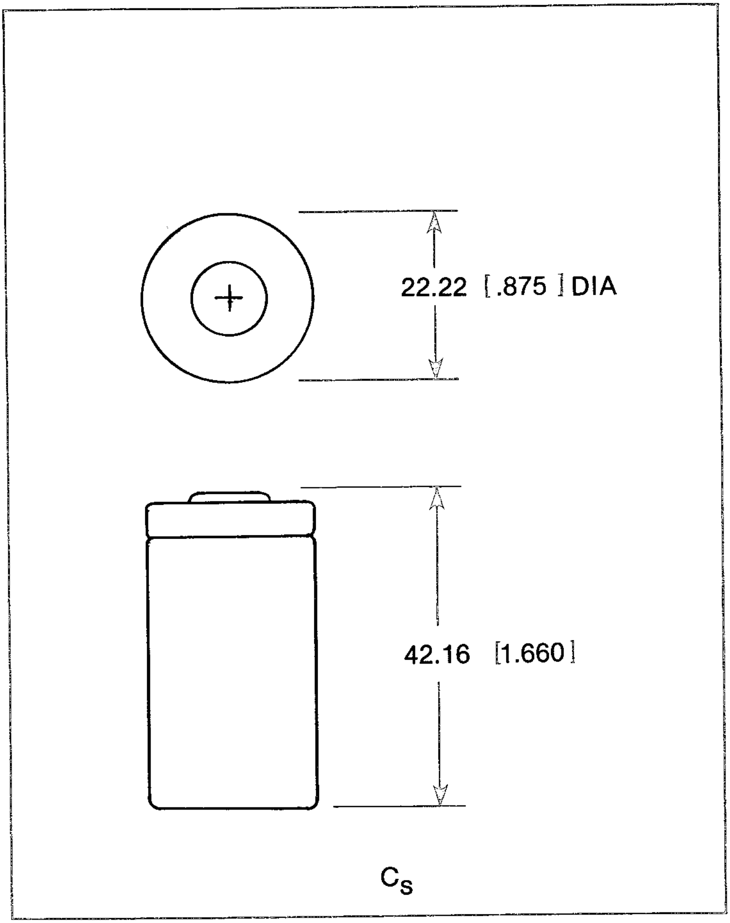


A_f

NOTES:

1. DIMENSIONS ARE IN MILLIMETERS (INCHES)
2. ALL DIMENSIONS ARE MAXIMUM

CELL OUTLINE

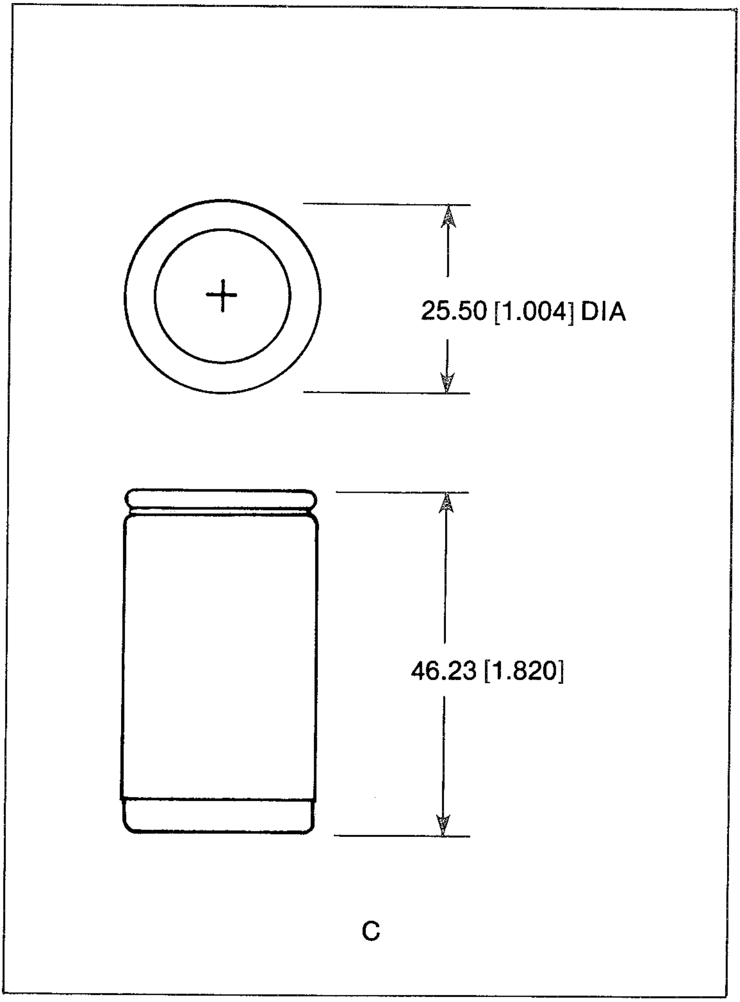


C_S

GENERAL ELECTRIC

NOTES:
1. DIMENSIONS ARE IN MILLIMETERS (INCHES)
2. ALL DIMENSIONS ARE MAXIMUM

CELL OUTLINE

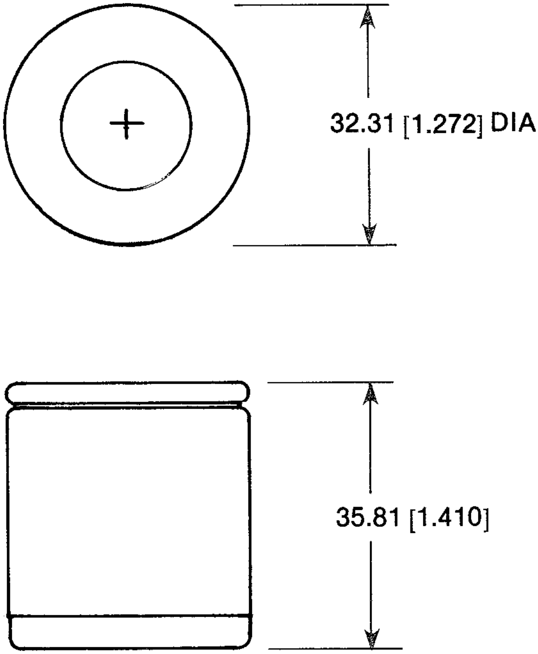


NOTES:

1. DIMENSIONS ARE IN MILLIMETERS (INCHES)
2. ALL DIMENSIONS ARE MAXIMUM

GENERAL ELECTRIC

CELL OUTLINE



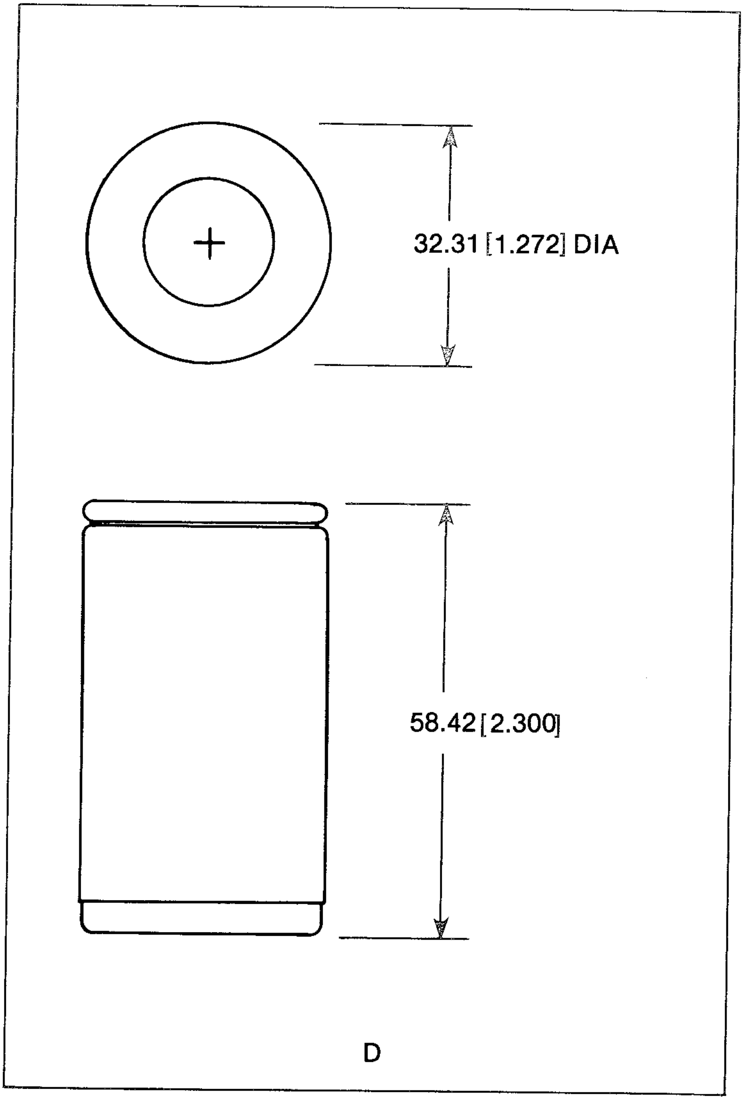
1/2 D

NOTES:

1. DIMENSIONS ARE IN MILLIMETERS (INCHES)
2. ALL DIMENSIONS ARE MAXIMUM

GENERAL ELECTRIC

CELL OUTLINE

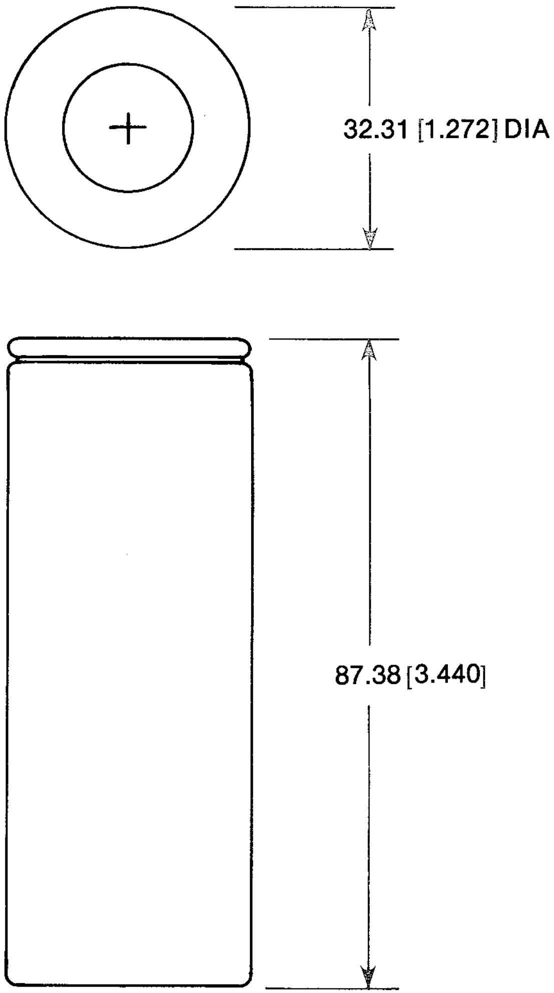


NOTES:

1. DIMENSIONS ARE IN MILLIMETERS (INCHES)
2. ALL DIMENSIONS ARE MAXIMUM

GENERAL ELECTRIC

CELL OUTLINE



F

NOTES:
1. DIMENSIONS ARE IN MILLIMETERS (INCHES)
2. ALL DIMENSIONS ARE MAXIMUM

GENERAL ELECTRIC

BATTERY PRODUCT LINE OVERVIEW

BATTERY TYPE	DESCRIPTION
STANDARD ASSEMBLED BATTERIES	
KwiKits	Single and multi cell designs readily available from General Electric with short lead times and no design cycle time.
MP^2	Batteries for microprocessor memory back-up.
TRB 80	"9V" size battery consisting of six MP80 cells in a plastic case with "9V" snap connectors.
Accessory Pack I II	12V battery in plastic case with belt clip and shoulder strap. "C" cell pack "D" cell pack
Powerstick^R Batteries	Replace multiple throwaway "C" and "D" size batteries in AC/DC products.
CONSUMER BATTERIES	AAA, 9V, AA, C & D size batteries and chargers sold at retail by General Electric.
CUSTOM ASSEMBLED BATTERIES	Any design of cells offered by General Electric in any configuration with many available options such as wire leads, plastic cases.

HOW TO USE THE TABLE

1. Select the battery voltage and configuration from the top row.
2. Select the desired capacity and model from the far left column.
3. If the battery dimensions are printed at the intersection, then that style is available.
4. Obtain the catalog number and dimensions as shown below.

MODEL KEY

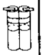
SD1	Standard temperature, C/10 charge
SD3	Standard temperature, C/3 charge
GT1	High temperature, C/10 charge
2GT1	High temperature, C/10 charge, high capacity
GT3	High temperature, C/3 charge
2GT3	High temperature, C/3 charge, high capacity
XP60	Standard temperature, C rate charge
MX3	Standard temperature, C/3 charge, high energy

NAMEPLATES

Although the exact content of the nameplate varies according to the battery size, all nameplates include a manufacturing datacode and an abbreviation of the catalog number for the battery.

KWIKIT BATTERY SPECIFICATIONS (CON'T)

EXAMPLE: For a 4.8V, 1.2Ah "box" configuration
K04C 111CS 2GT3

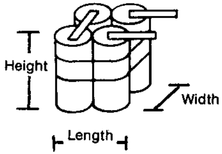
VOLTAGE CONFIGURATION			1.2V				2.4V		3.6V		4.8V				6.0V		7.2V	9.6V	12.0V	TAB TYPE
			BARE	HI-HAT	SLEEVE	TAB	1x1x2	2x1x1	1x1x3	3x1x1	1x1x4	4x1x1	2x2x1	2x1x2	1x1x5	5x1x1	2x1x3	4x2x1	5x2x1	
																				
CELL	CAT#		K01X	K01H	K01S	K01A	K02A	K02B	K03A	K03B	K04A	K04B	K04C	K04D	K05A	K05B	K06A	K08A	K10A	
CS	111CS	L	22.4 (0.88)		23.6 (0.93)	23.6 (0.93)		46.7 (1.84)		69.3 (2.73)		92.2 (3.63)	46.7 (1.84)	46.7 (1.84)		114.8 (4.52)		92.2 (3.63)	114.8 (4.52)	E
		W	22.4 (0.88)		23.6 (0.93)	23.6 (0.93)		24.1 (0.95)		24.1 (0.95)		24.1 (0.95)	47.0 (1.85)	24.1 (0.95)		24.1 (0.95)		47.0 (1.85)	47.0 (1.85)	
Standard Cs		H	41.2 (1.62)		41.7 (1.64)	42.2 (1.66)		42.2 (1.66)		42.2 (1.66)		42.2 (1.66)	42.2 (1.66)	83.3 (3.28)		42.3 (1.66)		42.2 (1.66)	42.2 (1.66)	
1.200Ah	SD3		SD3		SD3	SD3		SD3		SD3		SD3		SD3		SD3		SD3	SD3	
1.100Ah	XP60		XP60		XP60	XP60				XP60				XP60		XP60				
1.200Ah	2GT3		2GT3		2GT3	2GT3		2GT3		2GT3		2GT3	2GT3	2GT3		2GT3			2GT3	

Dimensions are:

L = 46.7mm (1.84")

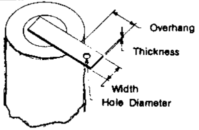
W = 47.0mm (1.85")

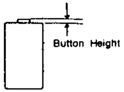
H = 42.2mm (1.66")



TAB DIMENSIONS mm (In.)

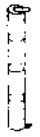
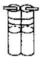
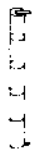
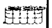
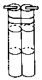
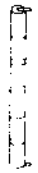
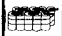
Tab Type	A	B	C	D	E	Button Height	
Overhang	5.08mm (0.20)in	3.81mm (0.15)in	6.35mm (0.25)in	0.00mm (0.00)in	0.00mm (0.00)in	AA	0.71mm (0.028)in
Width	3.18 (0.125)	3.18 (0.125)	3.18 (0.125)	6.35 (0.25)	11.6 (0.456)	C	1.50 (0.059)
Thickness	0.13 (0.005)	0.13 (0.005)	0.13 (0.005)	0.13 (0.005)	0.13 (0.005)	D	1.50 (0.059)
Hole Diameter	1.52 (0.060)	1.52 (0.060)	1.52 (0.060)	2.39 (0.094)	3.18 (0.125)		





GENERAL ELECTRIC

KWIKIT BATTERY DESIGNS

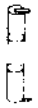
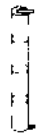
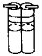
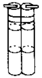
VOLTAGE CONFIGURATION			1.2V				2.4V		3.6V		4.8V				6.0V		7.2V		9.6V	12.0V	TAB TYPE
			BARE	HI-HAT	SLEEVE	TAB	1x1x2	2x1x1	1x1x3	3x1x1	1x1x4	4x1x1	2x2x1	2x1x2	1x1x5	5x1x1	2x1x3	1x1x6	4x2x1	5x2x1	
																					
CELL	CAT#		K01X	K01H	K01S	K01A	K02A	K02B	K03A	K03B	K04A	K04B	K04C	K04D	K05A	K05B	K06A	K06B	K08A	K10A	
MP80	111MP	L	12.6 (0.50)		13.7 (0.54)	13.7 (0.54)	14.2 (0.56)		14.2 (0.56)		14.2 (0.56)				14.2 (0.56)		28.7 (1.13)	14.2 (0.56)			A
		W	12.6 (0.50)		13.7 (0.54)	13.7 (0.54)	14.2 (0.56)		14.2 (0.56)		14.2 (0.56)				14.2 (0.56)		15.0 (0.59)	14.2 (0.56)			
		H	15.0 (0.59)		15.7 (0.60)	15.8 (0.62)	31.2 (1.23)		46.2 (1.82)		61.5 (2.42)				76.7 (3.02)		46.5 (1.83)	91.7 (3.61)			
0.065Ah	GT3		GT3		GT3	GT3	GT3		GT3		GT3				GT3		GT3	GT3			
			See MP2 spec sheet for Microprocessor Batteries such as Data Sentry																		
AAA	111AAA	L	10.3 (0.40)	10.5 (0.41)	10.5 (0.41)	10.5 (.41)															B
		W	10.3 (0.40)	10.5 (0.41)	10.5 (0.41)	10.5 (.41)															
		H	44.2 (1.74)	44.2 (1.74)	44.2 (1.74)	44.5 (1.75)															
0.180Ah	SD3		SD3	SD3	SD3	SD3															
1/3AA	113AA	L	14.2 (0.56)		15.2 (0.60)	15.2 (0.60)	15.8 (0.62)		15.8 (0.62)		15.8 (0.62)			31.5 (1.24)	15.8 (0.62)		31.5 (1.24)				B
		W	14.2 (0.56)		15.2 (0.60)	15.2 (0.60)	15.8 (0.62)		15.8 (0.62)		15.8 (0.62)			16.5 (0.65)	15.8 (0.62)		16.5 (0.65)				
		H	17.0 (0.67)		17.5 (0.69)	18.0 (0.71)	35.3 (1.39)		52.3 (2.06)		69.6 (2.74)			35.3 (1.39)	86.9 (3.42)		52.6 (2.07)				
0.100Ah	GT3		GT3		GT3	GT3	GT3		GT3		GT3			GT3	GT3		GT3				

GENERAL ELECTRIC

KWIKIT BATTERY DESIGNS (CON'T)

1/2AA	**112AA**	**L**	14.2 (0.56)		15.2 (0.60)	15.2 (0.60)								73.4 (2.89)			73.4 (2.89)	B
		W	14.2 (0.56)		15.2 (0.60)	15.2 (0.60)								15.8 (0.62)			30.2 (1.19)	
		H	32.0 (1.26)		32.3 (1.27)	32.5 (1.28)								32.8 (1.29)			32.8 (1.29)	
0.250Ah	SD3		SD3		SD3	SD3								SD3			SD3	
0.250Ah	GT3		GT3		GT3	GT3											GT3	
AA	**111AA**	**L**	14.2 (0.56)	15.2 (0.60)	15.2 (0.60)	15.2 (0.60)		30.5 (1.20)		44.5 (1.75)	58.9 (2.32)	30.5 (1.20)		73.4 (2.89)			73.4 (2.89)	Tab B or Button
		W	14.2 (0.56)	15.2 (0.60)	15.2 (0.60)	15.2 (0.60)		15.8 (0.62)		15.8 (0.62)	15.8 (0.62)	30.2 (1.19)		15.7 (0.62)			30.2 (1.19)	
		H	49.0 (1.93)	50.0 (1.97)	49.3 (1.94)	49.8 (1.96)		49.8 (1.96)		49.8 (1.96)	49.8 (1.96)	49.8 (1.96)		49.8 (1.96)			49.8 (1.96)	
0.500Ah	SD3		SD3	SD3	SD3	SD3		SD3		SD3	SD3	SD3		SD3			SD3	
0.500Ah	2GT3		2GT3	2GT3	2GT3	2GT3		2GT3		2GT3	2GT3	2GT3		2GT3			2GT3	
2/3Af	**213Af**	**L**	16.8 (0.66)		17.8 (0.70)	17.8 (0.70)	18.3 (0.72)		18.3 (0.72)				36.6 (1.44)				87.4 (3.44)	C
		W	16.8 (0.66)		17.8 (0.70)	17.8 (0.70)	18.3 (0.72)		18.3 (0.72)				18.8 (0.74)				36.6 (1.44)	
		H	27.9 (1.10)		28.2 (1.11)	28.7 (1.13)	56.6 (2.33)		84.6 (3.33)				56.6 (2.23)				28.7 (1.13)	
0.450Ah	SD3		SD3		SD3	SD3	SD3		SD3				SD3				SD3	
Af	**111Af**	**L**	16.5 (0.65).		17.8 (0.70)	17.8 (0.70)		35.6 (1.40)		52.1 (2.05)				86.1 (3.39)				C
		W	16.5 (0.65)		17.8 (0.70)	17.8 (0.70)		18.3 (0.72)		18.3 (0.72)				18.3 (0.72)				
		H	49.3 (1.94)		49.8 (1.96)	50.3 (1.98)		50.3 (1.98)		50.3 (1.98)				50.3 (1.98)				
0.750Ah	SD3		SD3		SD3	SD3		SD3		SD3				SD3				

KWIKIT BATTERY DESIGNS (CON'T)

VOLTAGE CONFIGURATION			1.2V				2.4V		3.6V		4.8V				6.0V		7.2V	9.6V	12.0V	TAB TYPE
			BARE	HI-HAT	SLEEVE	TAB	1x1x2	2x1x1	1x1x3	3x1x1	1x1x4	4x1x1	2x2x1	2x1x2	1x1x5	5x1x1	2x1x3	4x2x1	5x2x1	
																				
CELL	CAT#		K01X	K01H	K01S	K01A	K02A	K02B	K03A	K03B	K04A	K04B	K04C	K04D	K05A	K05B	K06A	K08A	K10A	
1/2CS	112CS	L	22.4 (0.88)		23.6 (0.93)	23.6 (0.93)														D
		W	22.4 (0.88)		23.6 (0.93)	23.6 (0.93)														
		H	25.9 (1.02)		26.4 (1.04)	26.9 (1.06)														
0.600Ah	SD3		SD3		SD3	SD3														
CS	111CS	L	22.4 (0.88)		23.6 (0.93)	23.6 (0.93)		46.7 (1.84)		69.3 (2.73)		92.2 (3.63)	46.7 (1.84)	46.7 (1.84)		114.8 (4.52)		92.2 (3.63)	114.8 (4.52)	D
		W	22.4 (0.88)		23.6 (0.93)	23.6 (0.93)		24.1 (0.95)		24.1 (0.95)		24.1 (0.95)	47.0 (1.85)	24.1 (0.95)		24.1 (0.95)		47.0 (1.85)	47.0 (1.85)	
Standard Cs		H	41.2 (1.62)		41.7 (1.64)	42.2 (1.66)		42.2 (1.66)		42.2 (1.66)		42.2 (1.66)	42.2 (1.66)	83.3 (3.28)		42.3 (1.66)		42.2 (1.66)	42.2 (1.66)	
1.200Ah	SD3		SD3		SD3	SD3		SD3		SD3		SD3		SD3		SD3		SD3	SD3	
1.100Ah	XP60		XP60		XP60	XP60				XP60				XP60		XP60				
1.200Ah	2GT3		2GT3		2GT3	2GT3		2GT3		2GT3		2GT3	2GT3	2GT3		2GT3			2GT3	
GEMAX*	Cs	H	42.2 (1.66)		42.7 (1.68)	43.2 (1.70)		43.2 (1.70)		43.2 (1.70)		43.2 (1.70)	43.2 (1.70)	85.3 (3.36)		43.2 (1.70)		43.2 (1.70)	43.2 (1.70)	
1.300Ah	MX3		MX3		MX3	MX3		MX3		MX3		MX3	MX3	MX3		MX3		MX3	MX3	
C	111C	L	25.5 (1.00)	26.2 (1.03)	26.9 (1.06)	26.9 (1.06)		53.1 (2.09)		79.3 (3.12)		105.2 (4.14)				131.3 (5.17)			131.3 (5.17)	Tab D or Button
		W	25.5 (1.00)	26.2 (1.03)	26.9 (1.06)	26.9 (1.06)		27.4 (1.08)		27.4 (1.08)		27.4 (1.08)				27.4 (1.08)			53.3 (2.10)	
		H	46.2 (1.82)	50.0 (1.97)	46.7 (1.84)	47.2 (1.86)		47.8 (1.88)		47.8 (1.88)		47.8 (1.88)				47.8 (1.88)			47.8 (1.88)	
1.800Ah	SD3		SD3	SD3	SD3	SD3		SD3		SD3		SD1				SD1			SD1	

GENER ELECTRIC

KWIKIT BATTERY DESIGNS (CON'T)

1/2D	**112D**	**L**	32.3 (1.27)		33.8 (1.33)	33.8 (1.33)			33.8 (1.33)		33.8 (1.33)		165.4 (6.51)			165.4 (6.51)	D
		W	32.3 (1.27)		33.8 (1.33)	33.8 (1.33)			33.8 (1.33)		33.8 (1.33)		34.3 (1.35)			67.1 (2.64)	
		H	35.8 (1.41)		36.3 (1.43)	36.8 (1.45)			109.5 (4.31)		145.5 (5.73)		37.3 (1.47)			37.3 (1.47)	
2.200Ah	SD1		SD1		SD1	SD1			SD1		SD1		SD1			SD1	
2.100Ah	XP60		XP60		XP60	XP60											
2.200Ah	2GT1		2GT1		2GT1	2GT1					2GT1		2GT1			2GT1	
D	**111D**	**L**	32.3 (1.27)	34.0 (1.34)	33.8 (1.33)	33.8 (1.33)	33.8 (1.33)	66.8 (2.63)	33.8 (1.33)	99.6 (3.92)		132.3 (5.21)	165.4 (6.51)		132.3 (5.21)	165.4 (6.51)	Tab D or Button
		W	32.3 (1.27)	34.0 (1.34)	33.8 (1.33)	33.8 (1.33)	33.8 (1.33)	34.3 (1.35)	33.8 (1.33)	34.3 (1.35)		34.3 (1.35)	34.3 (1.35)		67.1 (2.64)	67.1 (2.64)	
		H	58.4 (2.30)	61.2 (2.41)	58.9 (2.32)	59.4 (2.34)	118.4 (4.66)	59.9 (2.36)	177.3 (6.98)	59.9 (2.36)		59.9 (2.36)	59.9 (2.36)		59.9 (2.36)	59.9 (2.36)	
4.000Ah	SD1		SD1	SD1	SD1	SD1		SD1	SD1	SD1		SD1	SD1		SD1	SD1	
4.000Ah	XP60		XP60	XP60	XP60	XP60											
4.000Ah	2GT1		2GT1	2GT1	2GT1	2GT1	2GT1	2GT1	2GT1				2GT1		2GT1	2GT1	
F	**111F**	**L**	32.3 (1.27)		33.8 (1.33)	33.8 (1.33)						132.3 (5.21)	165.4 (6.51)				E
		W	32.3 (1.27)		33.8 (1.33)	33.8 (1.33)						34.3 (1.35)	34.3 (1.35)				
		H	87.4 (3.44)		87.9 (3.46)	88.4 (3.48)						88.9 (3.50)	88.9 (3.50)				
6.200Ah	SD1		SD1		SD1	SD1							SD1				
5.600Ah	GT1		GT1		GT1	GT1						GT1					

*Available December 1986

MEMORY PRESERVATION PRODUCT LINE

RECHARGEABLE
NICKEL-CADMIUM BATTERIES

MP²

SPECIFICATION SHEET

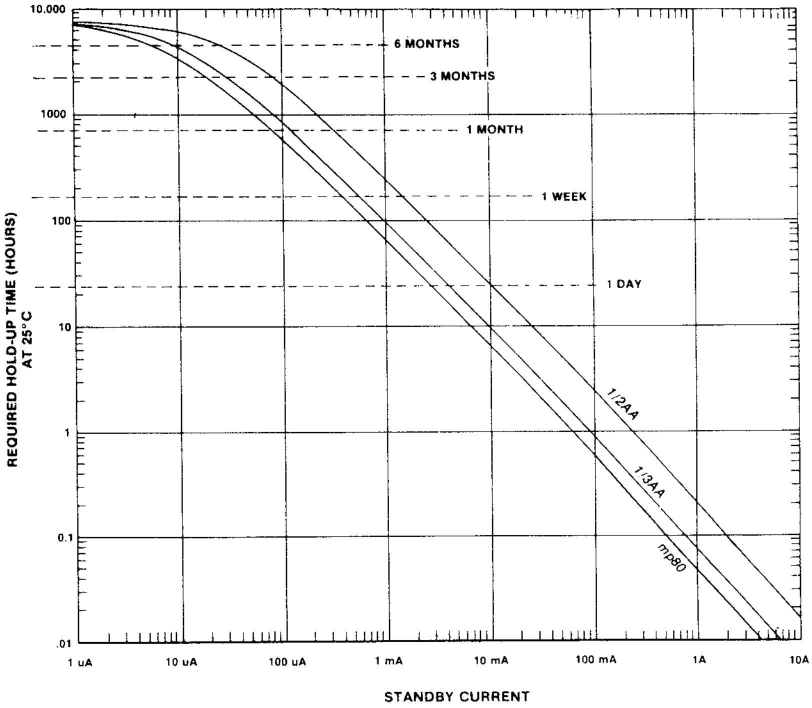
Board Mountable Standby Power for:
Computer Systems, Volatile Rams,
Microprocessor Controls, Real Time Clocks

Battery Temperature Limits (°C)	
Storage	− 40° to + 70°
Cell under discharge	− 20° to + 70°
Cell under charge	C/10 0° to + 70° C/20 − 10° to + 70°

General Electric Memory Preservation Products are capable of continous operation at 70°C. (Cells will operate reliably at higher temperatures but a reduction in performance and battery life will result. Consult factory for details of cell performance below − 40°C and above 70°C.)

GENERAL ELECTRIC

MEMORY PRESERVATION PRODUCT SELECTOR GUIDE



GENERAL ELECTRIC

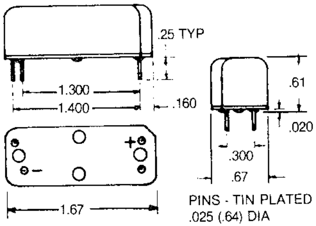
MP^2 Product Line List

BATTERY SIZE	No. Cells	Battery Voltage		BATTERY DESIGNS		Reference Battery Configuration	Capacity (mA hrs) 10 hr Rate-C/10	Charge Current (mA)		Discharge Current		DIMENSIONS IN (mm)				WT OZ (gr)
		Min on Discharge	Max on Charge	With Tabs 0.125 (3.18) x 0.005 (0.13)	With Pins 0.042 (1.07) x 0.01 (0.25)			Min	Max	Recommended Continuous Max (mA)	Momentary Max. (A)	W	H	L	C	
DATA SENTRY (mp80)	2	1.2	2.92	41B013AC00601		1A	65	4	7	13	8	See Configuration 1A				0.65 (18.4)
	3	2.4	4.38	41B013AD01401		1B	65	4	7	13	8	See Configuration 1B				0.92 (26.1)
mp80	2	1.2	2.92	41B013AC00201	41B013AC00801	2	65	4	7	13	8		0.55 (14.0)	1.22 (31.0)		0.4 (11.3)
	3	2.4	4.38	41B013AD00401	41B013AD01601	2	65	4	7	13	8		0.55 (14.0)	1.82 (46.2)		0.6 (17.0)
	4	3.6	5.84	41B013AE00201	41B013AE00401	2	65	4	7	13	8		0.55 (14.0)	2.42 (61.5)		0.8 (22.7)
	5	4.8	7.30	41B013AF00101	41B013AF00201	2	65	4	7	13	8		0.55 (14.01)	3.02 (76.7)		1.0 (28.3)
	6	6.0	8.76	41B013AG00301	41B013AG01401	2	65	4	7	13	8		0.55 (14.0)	3.61 (91.7)		1.2 (34.0)
1/3AA	2	1.2	2.92	41B017AC01001	41B017AC01101	2	100	5	10	20	15		0.60 (15.2)	1.38 (35.1)		0.5 (12.8)
	3	2.4	4.38	41B017AD02601	41B017AD02701	2	100	5	10	20	15		0.60 (15.2)	2.06 (52.3)		0.7 (19.3)
	4	3.6	5.84	41B017AE01301	41B017AE01401	2	100	5	10	20	15		0.6 (15.2)	2.74 (69.6)		0.9 (25.5)
	5	4.8	7.30	41B017AF01001	41B017AF01101	2	100	5	10	20	15		0.60 (15.2)	3.42 (86.9)		1.1 (31.2)
	6	6.0	8.76	41B017AG00601	41B017AG00701	3	100	5	10	20	15	1.17 (29.7)	0.60 (15.2)	2.06 (52.3)	0.58 (14.7)	1.4 (39.7)
1/2AA	2	1.2	2.92	41B019AC00501	41B019AC00601	2	250	12	25	50	19		0.60 (15.2)	2.54 (64.5)		1.2 (34.0)
	3	2.4	4.38	41B019AD00701	41B019AD00801	4	250	12	25	50	19	1.73 (4.39)	0.61 (15.5)	1.26 (32.5)	1.12 (28.5)	1.8 (51.0)
	4	3.6	5.84	41B019AE01201	41B019AE01301	3	250	12	25	50	19	1.20 (30.5)	0.61 (15.5)	2.54 (64.5)	0.58 (14.7)	2.4 (68.0)
	5	4.8	7.30	41B019AF00501	41B019AF00601	5	250	12	25	50	19	2.86 (72.6)	0.61 (15.5)	1.28 (32.5)	2.24 (56.9)	3.0 (85.0)
	6	6.0	8.76	41B019AG00101	41B019AG00201	4	250	12	25	50	19	1.79 (45.5)	0.61 (15.5)	2.54 (64.5)	1.17 (29.7)	3.6 (102.0)

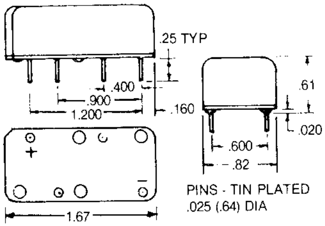
GENERAL ELECTRIC

MP^{2} PRODUCT LINE (BATTERY OUTLINE)

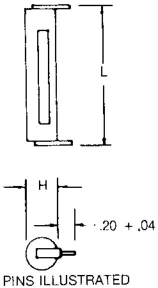
CONFIGURATION 1A



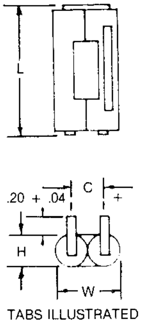
CONFIGURATION 1B



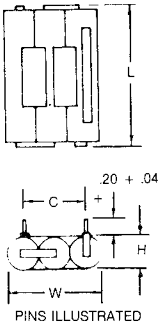
CONFIGURATION 2



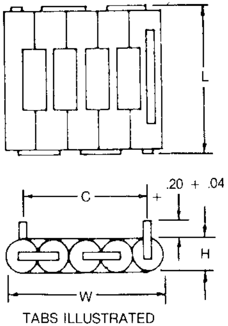
CONFIGURATION 3

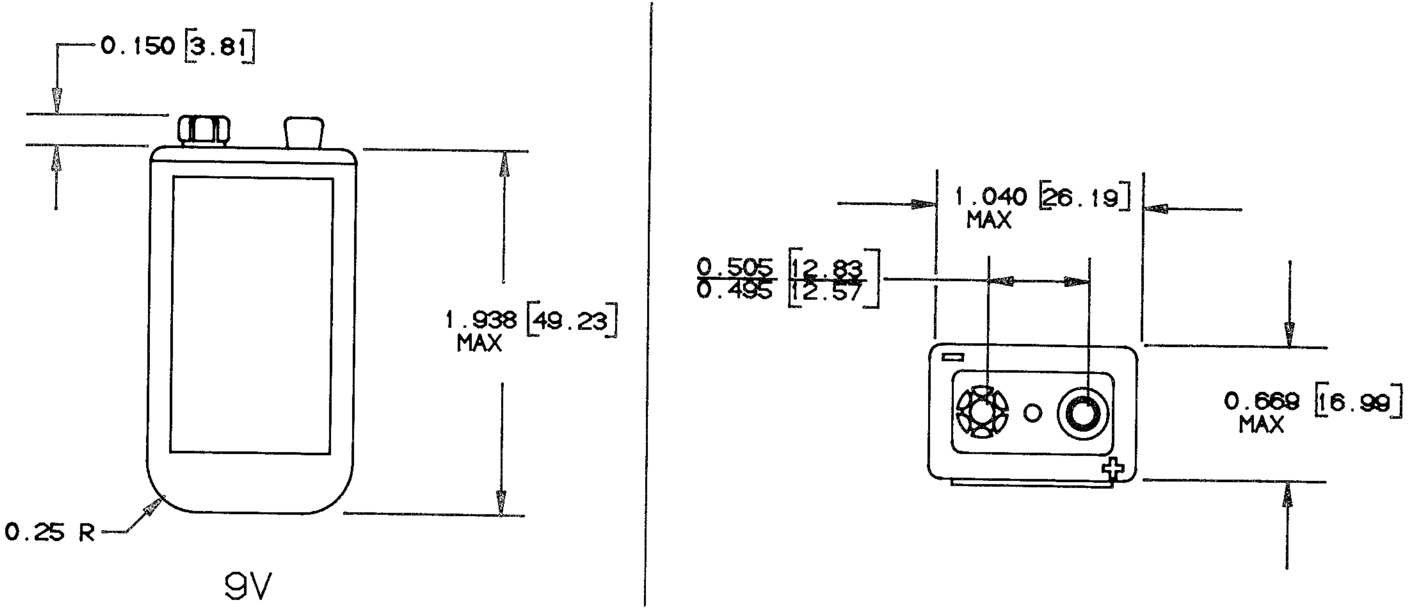


CONFIGURATION 4



CONFIGURATION 5



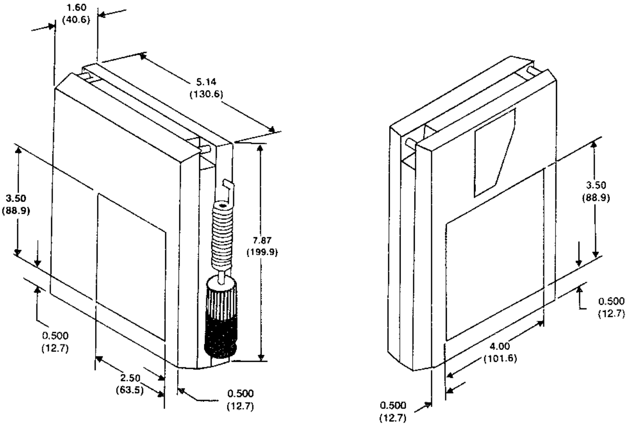


SIDE VIEW

TRB80 (9V TYPE BATTERY)

TOP VIEW

ACCESSORY BATTERY PACK I

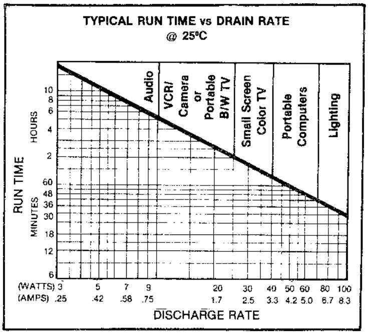


SPECIFICATIONS

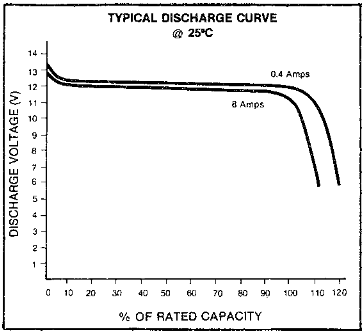
Voltage	*12.0 volts*	*Weight*	*3.8 lbs. (1724 g)*
Capacity	*4.5 Ah (nom.), 54 Wh*	*Case material*	*High impact, flame retardant plastic*
Charge time	*16 hrs.*		
Charge rate	*400 mA*	*Protection device*	*Self-resetting 18 amp circuit breaker*

PERFORMANCE

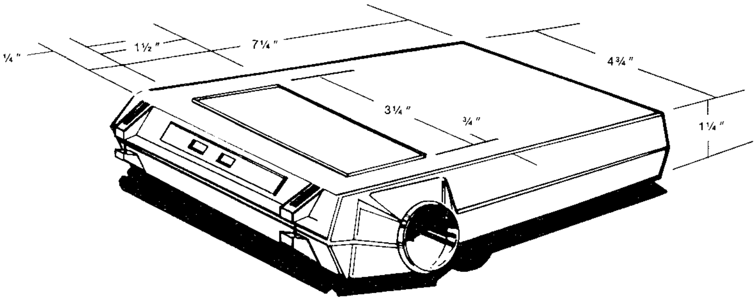
TYPICAL RUN TIME vs DRAIN RATE @ 25°C



TYPICAL DISCHARGE CURVE @ 25°C



ACCESSORY BATTERY PACK II

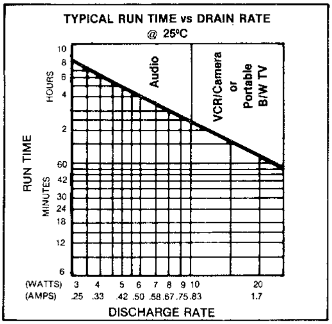


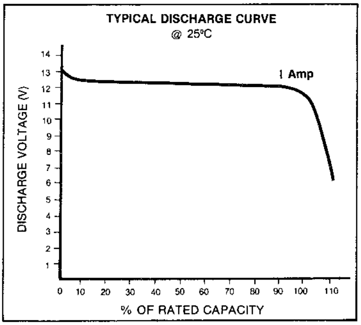
PLEASE NOTE: Dimensions are preliminary and are subject to change without notice.

SPECIFICATIONS

Voltage	*12.0 volts*	*Weight*	*1.8 lbs. (.83 kg)*
Capacity	*2.0 Ah (nom.), 23 Wh*	*Case material*	*High impact, flame retardant plastic*
Charge time	*16 hrs.*		
Charge rate	*200 mA*	*Protection device*	*Self-resetting 3 amp circuit breaker*

PERFORMANCE

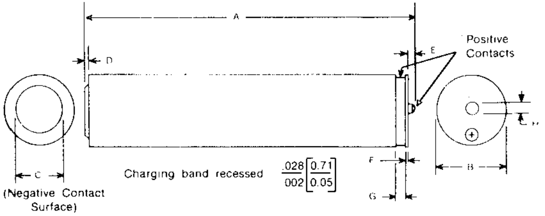

TYPICAL RUN TIME vs DRAIN RATE @ 25°C


TYPICAL DISCHARGE CURVE @ 25°C

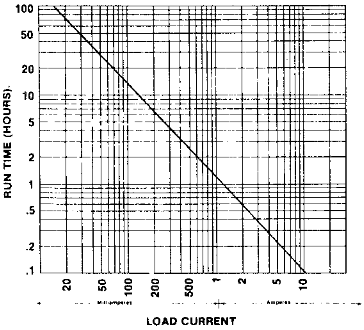
GENERAL ELECTRIC

POWER STICK® BATTERY SPECIFICATIONS

CATALOG NO.	VOLTAGE	DIMENSIONS [ ] mm A	B	C	D	E	F	G	H
41B030AD01401 Replaces 3 C cells	3.6	5.827 [148.00] 5.703 [144.86]	1.036 [26.31] .990 [25.15]	.475 [12.07] .430 [10.92]	.066 [1.68] .016 [0.41]	.110 [2.79] .090 [2.29]	.062 [1.57] .052 [1.32]	.260 [6.60] .240 [6.10]	.265 [6.73] .235 [5.97]
41B030AD02401 Replaces 3 D cells	3.6	7.12 [180.80] 7.04 [178.80]	1.332 [33.83] 1.292 [32.82]	.875 [22.23] .862 [21.89]	.056 [1.43] .006 [0.15]	.118 [3.00] .082 [2.09]	.062 [1.57] .052 [1.32]	.265 [6.73] .245 [6.22]	.260 [6.60] .240 [6.09]
41B030AE03001 Replaces 4 C cells	4.8	7.750 [196.85] 7.626 [193.70]	1.036 [26.31] .990 [25.15]	.475 [12.07] .430 [10.92]	.066 [1.68] .016 [0.41]	.110 [2.79] .090 [2.29]	.062 [1.57] .052 [1.32]	.260 [6.60] .240 [6.10]	.265 [6.73] .235 [5.97]
41B030AE02801 Replaces 4 D cells	4.8	9.48 [240.20] 9.36 [237.70]	1.332 [33.83] 1.292 [32.82]	.875 [22.23] .862 [21.89]	.056 [1.43] .006 [0.15]	.118 [3.00] .082 [2.09]	.062 [1.57] .052 [1.32]	.265 [6.73] .245 [6.22]	.260 [6.60] .240 [6.09]



LOAD CURRENT vs. RUN TIME



GENERAL INFORMATION

Capacity (C rate min.) .... 1.2 Ah
Charge rate (mA) at 25°C
Maximum in overcharge 120
Minimum charge rate 60
Temperature limits (°C)
Storage .... -40° to +50°
Under discharge .... -20° to +50°
Under charge at 120 mA .... 0° to +50°
Case material .... High impact ABS plastic

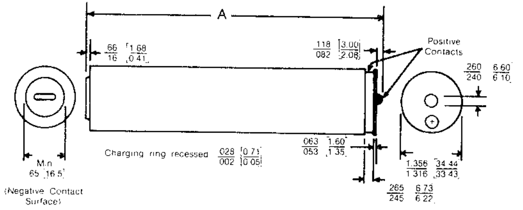
211B5000AA

GENERAL ELECTRIC

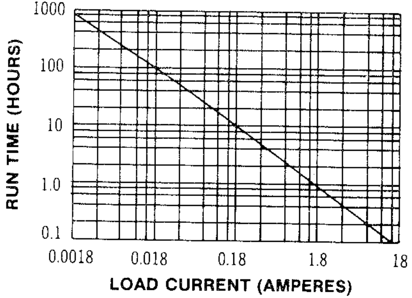
POWER STICK® *PLUS* BATTERY SPECIFICATIONS

CATALOG NO.	VOLTAGE	LENGTH (A)	
41B035AC01001 Replaces 2 D cells	2.4	4.76 4.68	[120.90 118.87]
41B035AD00601 Replaces 3 D cells	3.6	7.12 7.04	[180.80 178.80]
41B035AE01601 Replaces 4 D cells	4.8	9.48 9.36	[240.20 237.70]

DIMENSIONS Inches [mm]



LOAD CURRENT vs. RUN TIME at 25° C



GENERAL INFORMATION

Capacity (C rate min.) .... 1.8 Ah

Charge rate (mA) at 25° C
  Maximum in overcharge 180
  Minimum charge rate 90

Temperature limits (°C)
  Storage .... -40° to +50°
  Under discharge .... -20° to +50°
  Under charge at 180 mA .... 0° to +50°

Case material .... High impact plastic

GENERAL ELECTRIC

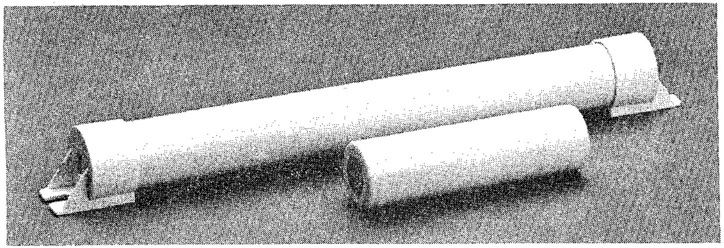
CUSTOM BATTERY DESIGNS

Our design and engineering departments can produce custom built battery assemblies to meet your specific technical requirements.

Detailed dimensions, weights and characteristics are available upon request.

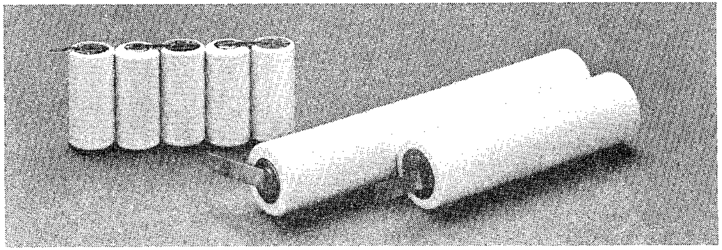
Stick Assembly

Simple cost effective designs in all cell types from 2 to 10 cells. Also available with end caps to enable simple mounting.



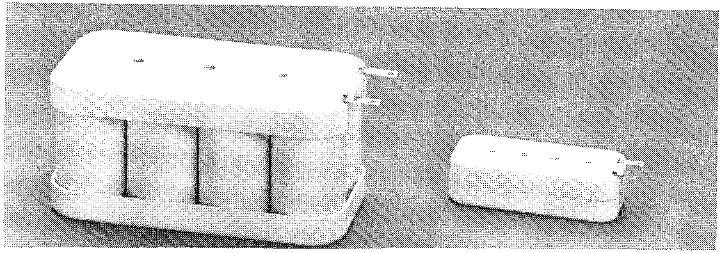
Side By Side Assembly

Assembled using high impact adhesive and/or reinforcing tape dependent upon mechanical/vibration constraints. Used with single cells and sticks.



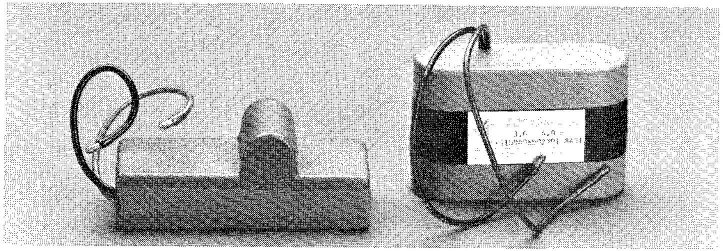
Injection Moulded Cases

These cases offer excellent mechanical and electrical insulation characteristics together with ease of fixation.



Vacuum Formed Cases

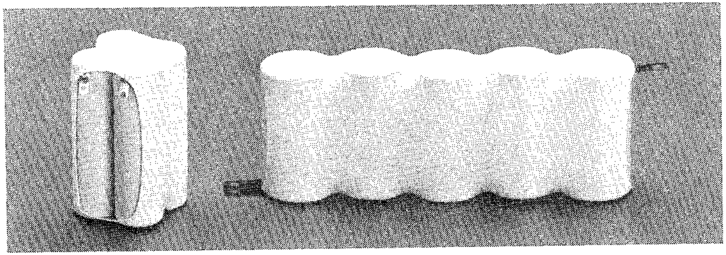
These are available in many configurations to suit special requirements and are specially suited to small/medium size production runs or where the application demands a fully enclosed battery.



CUSTOM BATTERY DESIGNS (con't)

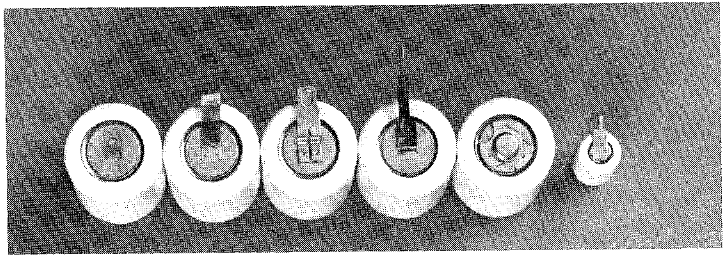
Plastic Heatshrink

The most versatile assembly system offering mechanical rigidity and extra electrical insulation.

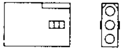


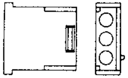
Terminations

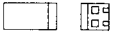
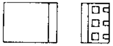
Standard terminals include short and long solder tabs, button contacts, printed circuit pins, wire leads (with or without connectors) and snap-on spade terminals. Batteries can be supplied with wire leads and connectors upon request.



STANDARD CONNECTORS FOR CUSTOM BATTERY DESIGNS

	DESCRIPTION	MFR PART NO	FEATURES
	MOLEX 2-CIRCUIT PLASTIC HOUSING	03-06-1023	ACCEPTS 062" CRIMP TERMINALS
	MOLEX 3-CIRCUIT PLASTIC HOUSING	03-06-1032	ACCEPTS 062" CRIMP TERMINALS
	MOLEX SOCKET TERMINAL 062" DIA TIN PLATED BRASS	02-06-1103	24-18 AWG WIRE

	DESCRIPTION	MFR. PART NO.	FEATURES
	AMP 2-CIRCUIT PLASTIC HOUSING	1-480318-0	ACCEPTS MATE-N-LOCK CRIMP TERMINALS
	AMP 3-CIRCUIT PLASTIC HOUSING	1-480303-0	ACCEPTS MATE-N-LOCK CRIMP TERMINALS
	AMP SOCKET TERMINAL TIN PLATED BRASS	61117-1	20-14 AWG WIRE

	DESCRIPTION	MFR. PART NO	FEATURES
	MOLEX 2-CIRCUIT PLASTIC HOUSING	09-50-3021	ACCEPTS DOUBLE CANTILEVER CRIMP TERMINALS
	MOLEX 3-CIRCUIT PLASTIC HOUSING	09-50-3031	ACCEPTS DOUBLE CANTILEVER CRIMP TERMINALS
	MOLEX TERMINAL TIN PLATED PHOSPHOR BRONZE	08-50-0108	26-22 AWG WIRE

GENERAL ELECTRIC

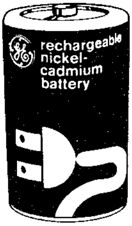
CONSUMER BATTERIES

RECHARGEABLE BATTERIES

AAA

AA

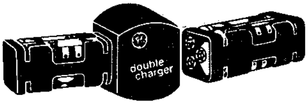
C



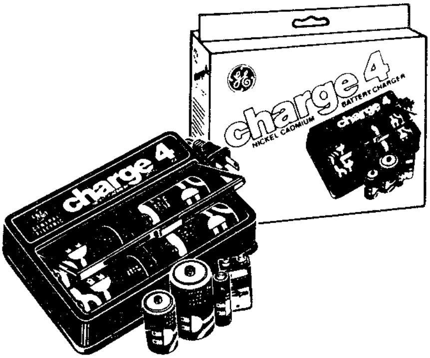
D

9-volt

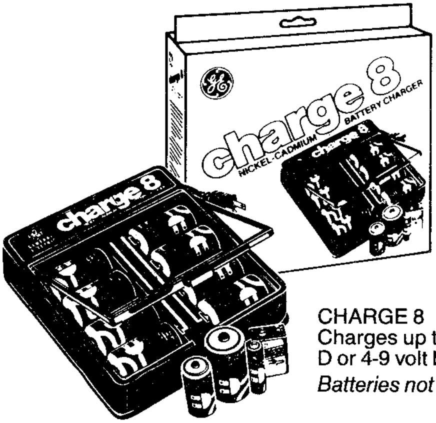
CHARGERS



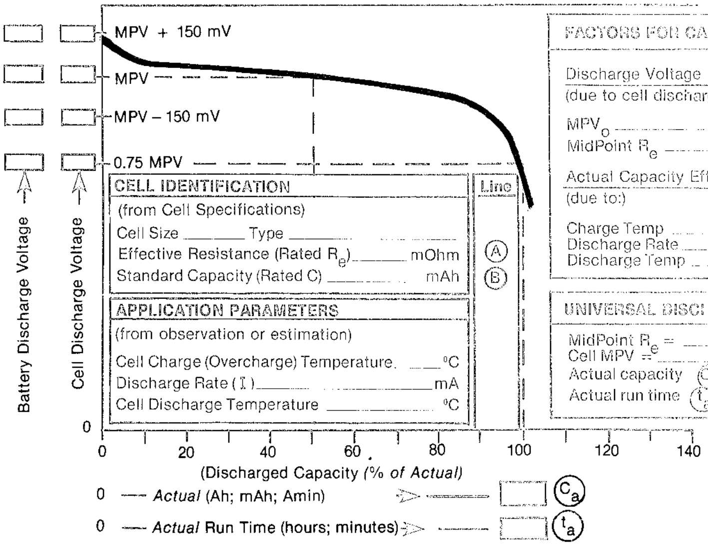
BC-2
Recharges up to 4 AAA, 4 AA,
2 C or D and 1-9 volt batteries



CHARGE 4
Charges up to 4 AA, C,
D or 2-9 volt batteries
Batteries not included



CHARGE 8
Charges up to 8 AA, C,
D or 4-9 volt batteries
Batteries not included



CELL IDENTIFICATION

(from Cell Specifications)

Cell Size ________ Type ____________

Effective Resistance (Rated R_e) ______ mOhm — Line Ⓐ

Standard Capacity (Rated C) ________ mAh — Line Ⓑ

APPLICATION PARAMETERS

(from observation or estimation)

Cell Charge (Overcharge) Temperature. ____ °C

Discharge Rate (I) ________________ mA

Cell Discharge Temperature __________ °C

FACTORS FOR CALCULATIONS

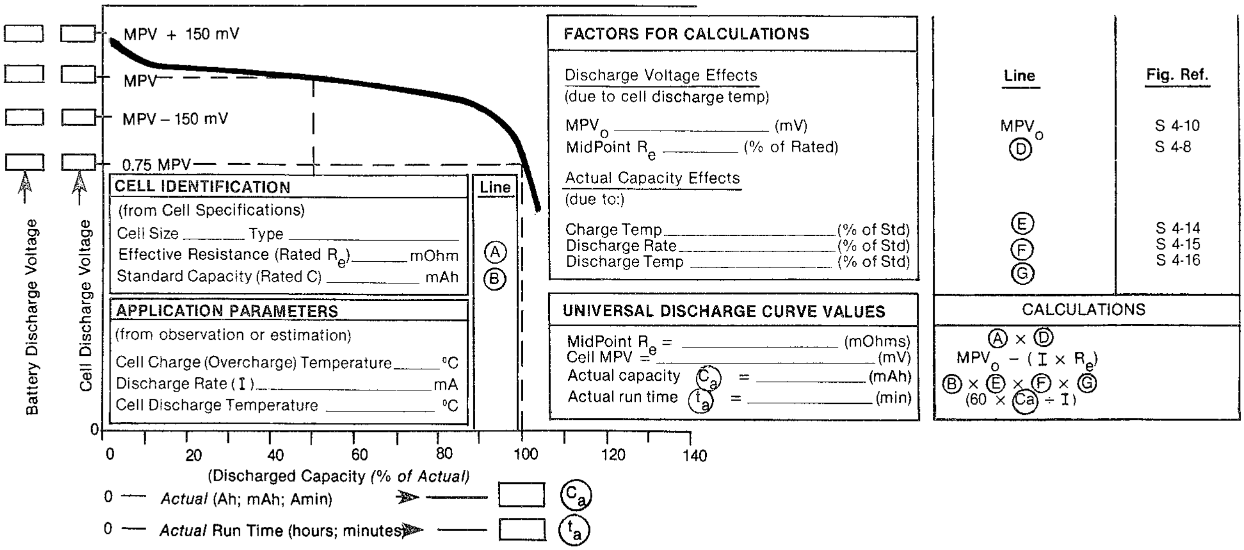
	Line	Fig. Ref.
Discharge Voltage Effects (due to cell discharge temp)		
MPV_o ________ (mV)	MPV_o	S 4-10
MidPoint R_e ______ (% of Rated)	Ⓓ	S 4-8
Actual Capacity Effects (due to:)		
Charge Temp ____________ (% of Std)	Ⓔ	S 4-14
Discharge Rate ____________ (% of Std)	Ⓕ	S 4-15
Discharge Temp ____________ (% of Std)	Ⓖ	S 4-16

UNIVERSAL DISCHARGE CURVE VALUES

	CALCULATIONS
MidPoint R_e = ____________ (mOhms)	Ⓐ × Ⓓ
Cell MPV = ____________ (mV)	MPV_o − (I × R_e)
Actual capacity (C_a) = ____________ (mAh)	Ⓑ × Ⓔ × Ⓕ × Ⓖ
Actual run time (t_a) = ____________ (min)	(60 × (C_a) ÷ I)

UNIVERSAL DISCHARGE CURVE

FIGURE S4-19



CELL IDENTIFICATION

(from Cell Specifications)

Cell Size ________ Type ________

Effective Resistance (Rated R_e) ________ mOhm

Standard Capacity (Rated C) ________ mAh

Line
Ⓐ
Ⓑ

APPLICATION PARAMETERS

(from observation or estimation)

Cell Charge (Overcharge) Temperature ________ °C

Discharge Rate (I) ________ mA

Cell Discharge Temperature ________ °C

FACTORS FOR CALCULATIONS

Discharge Voltage Effects

(due to cell discharge temp)

MPV_o ________ (mV)

MidPoint R_e ________ (% of Rated)

Actual Capacity Effects

(due to:)

Charge Temp ________ (% of Std)

Discharge Rate ________ (% of Std)

Discharge Temp ________ (% of Std)

Line	Fig. Ref.
MPV_o	S 4-10
Ⓓ	S 4-8
Ⓔ	S 4-14
Ⓕ	S 4-15
Ⓖ	S 4-16

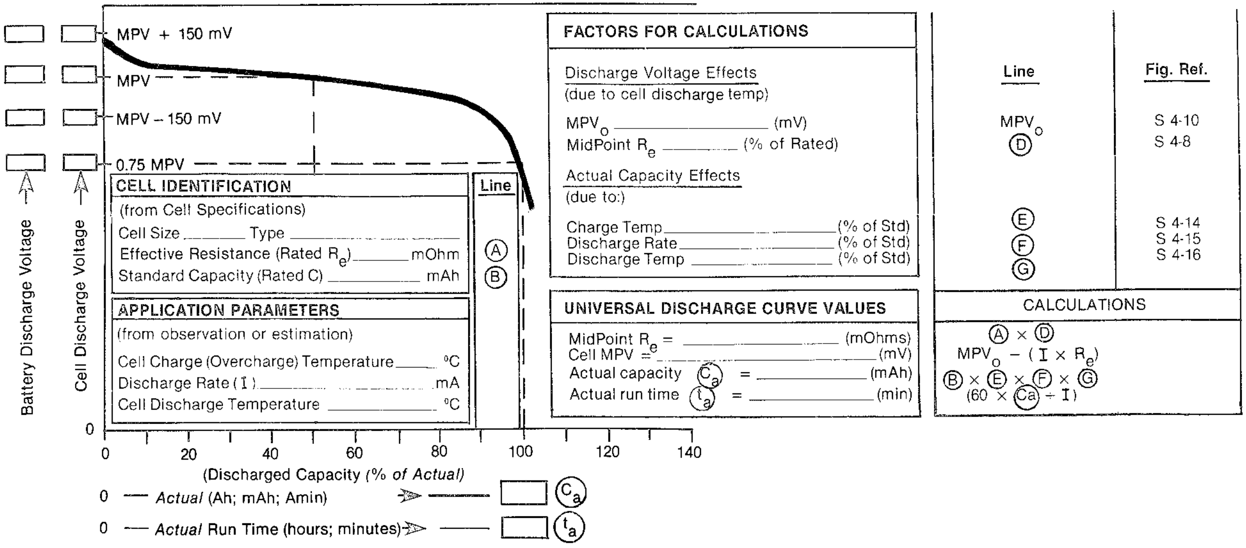
UNIVERSAL DISCHARGE CURVE VALUES

	CALCULATIONS
MidPoint R_e = ________ (mOhms)	Ⓐ × Ⓓ
Cell MPV = ________ (mV)	$MPV_o - (I \times R_e)$
Actual capacity C_a = ________ (mAh)	Ⓑ × Ⓔ × Ⓕ × Ⓖ
Actual run time t_a = ________ (min)	(60 × C_a ÷ I)

UNIVERSAL DISCHARGE CURVE

FIGURE S4-19

GENERAL ELECTRIC



CELL IDENTIFICATION

(from Cell Specifications)

	Line
Cell Size ________ Type ________	
Effective Resistance (Rated R_e) ________ mOhm	Ⓐ
Standard Capacity (Rated C) ________ mAh	Ⓑ

APPLICATION PARAMETERS

(from observation or estimation)

Cell Charge (Overcharge) Temperature ________ °C

Discharge Rate (I) ________ mA

Cell Discharge Temperature ________ °C

FACTORS FOR CALCULATIONS

	Line	Fig. Ref.
Discharge Voltage Effects (due to cell discharge temp)		
MPV_o ________ (mV)	MPV_o	S 4-10
MidPoint R_e ________ (% of Rated)	Ⓓ	S 4-8
Actual Capacity Effects (due to:)		
Charge Temp ________ (% of Std)	Ⓔ	S 4-14
Discharge Rate ________ (% of Std)	Ⓕ	S 4-15
Discharge Temp ________ (% of Std)	Ⓖ	S 4-16

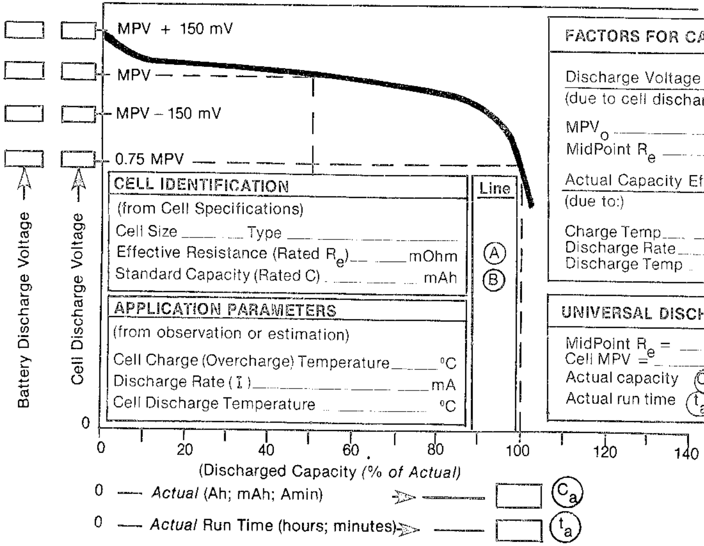
UNIVERSAL DISCHARGE CURVE VALUES

	CALCULATIONS
MidPoint R_e = ________ (mOhms)	Ⓐ × Ⓓ
Cell MPV = ________ (mV)	MPV_o – (I × R_e)
Actual capacity (C_a) = ________ (mAh)	Ⓑ × Ⓔ × Ⓕ × Ⓖ
Actual run time (t_a) = ________ (min)	(60 × (C_a) ÷ I)

UNIVERSAL DISCHARGE CURVE

FIGURE S4-19

GENERAL ELECTRIC



CELL IDENTIFICATION

(from Cell Specifications)

Cell Size ____ Type ____

Effective Resistance (Rated R_e) ____ mOhm — Line Ⓐ

Standard Capacity (Rated C) ____ mAh — Line Ⓑ

APPLICATION PARAMETERS

(from observation or estimation)

Cell Charge (Overcharge) Temperature ____ °C

Discharge Rate (I) ____ mA

Cell Discharge Temperature ____ °C

FACTORS FOR CALCULATIONS

Discharge Voltage Effects
(due to cell discharge temp)

	Line	Fig. Ref.
MPV_o ____ (mV)	MPV_o	S 4-10
MidPoint R_e ____ (% of Rated)	Ⓓ	S 4-8

Actual Capacity Effects
(due to:)

	Line	Fig. Ref.
Charge Temp ____ (% of Std)	Ⓔ	S 4-14
Discharge Rate ____ (% of Std)	Ⓕ	S 4-15
Discharge Temp ____ (% of Std)	Ⓖ	S 4-16

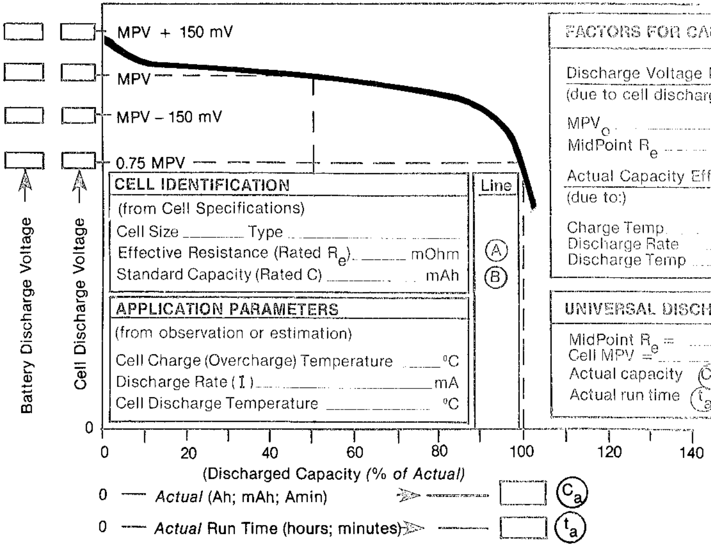
UNIVERSAL DISCHARGE CURVE VALUES

	CALCULATIONS
MidPoint R_e = ____ (mOhms)	Ⓐ × Ⓓ
Cell MPV = ____ (mV)	MPV_o − (I × R_e)
Actual capacity Ⓒa = ____ (mAh)	Ⓑ × Ⓔ × Ⓕ × Ⓖ
Actual run time ⓣa = ____ (min)	(60 × Ⓒa ÷ I)

UNIVERSAL DISCHARGE CURVE

FIGURE S4-19

GENERAL ELECTRIC



CELL IDENTIFICATION

(from Cell Specifications)

Cell Size ________ Type ____________

Effective Resistance (Rated R_e) ______ mOhm

Standard Capacity (Rated C) ________ mAh

APPLICATION PARAMETERS

(from observation or estimation)

Cell Charge (Overcharge) Temperature ______ °C

Discharge Rate (I) ______________ mA

Cell Discharge Temperature __________ °C

FACTORS FOR CALCULATIONS

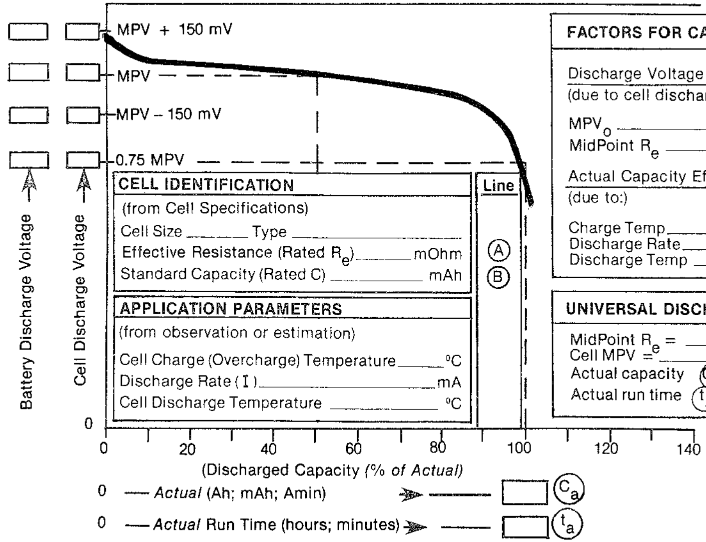
	Line	Fig. Ref.
Discharge Voltage Effects (due to cell discharge temp)		
MPV_o ____________ (mV)	MPV_o	S 4-10
MidPoint R_e ______ (% of Rated)	Ⓓ	S 4-8
Actual Capacity Effects (due to:)		
Charge Temp ____________ (% of Std)	Ⓔ	S 4-14
Discharge Rate ____________ (% of Std)	Ⓕ	S 4-15
Discharge Temp ____________ (% of Std)	Ⓖ	S 4-16

UNIVERSAL DISCHARGE CURVE VALUES	CALCULATIONS
MidPoint R_e = ____________ (mOhms)	Ⓐ × Ⓓ
Cell MPV = ____________ (mV)	MPV_o − (I × R_e)
Actual capacity Ⓒa = ____________ (mAh)	Ⓑ × Ⓔ × Ⓕ × Ⓖ
Actual run time ⓣa = ____________ (min)	(60 × Ⓒa ÷ I)

UNIVERSAL DISCHARGE CURVE

GENERAL ELECTRIC

FIGURE S4-19



CELL IDENTIFICATION

(from Cell Specifications)

Cell Size ______ Type ______

Effective Resistance (Rated R_e) ______ mOhm — Line Ⓐ

Standard Capacity (Rated C) ______ mAh — Line Ⓑ

APPLICATION PARAMETERS

(from observation or estimation)

Cell Charge (Overcharge) Temperature ______ °C

Discharge Rate (I) ______ mA

Cell Discharge Temperature ______ °C

FACTORS FOR CALCULATIONS

Discharge Voltage Effects
(due to cell discharge temp)

MPV_o ______ (mV)

MidPoint R_e ______ (% of Rated)

Actual Capacity Effects
(due to:)

Charge Temp ______ (% of Std)

Discharge Rate ______ (% of Std)

Discharge Temp ______ (% of Std)

Line	Fig. Ref.
MPV_o	S 4-10
Ⓓ	S 4-8
Ⓔ	S 4-14
Ⓕ	S 4-15
Ⓖ	S 4-16

UNIVERSAL DISCHARGE CURVE VALUES

MidPoint R_e = ______ (mOhms)

Cell MPV = ______ (mV)

Actual capacity Ⓒa = ______ (mAh)

Actual run time Ⓣa = ______ (min)

CALCULATIONS

Ⓐ × Ⓓ

$MPV_o - (I \times R_e)$

Ⓑ × Ⓔ × Ⓕ × Ⓖ

(60 × Ⓒa ÷ I)

UNIVERSAL DISCHARGE CURVE

FIGURE S4-19

GENERAL ELECTRIC

NOTES

NOTES

GENERAL ELECTRIC

Nickel-Cadmium Battery Application Handbook

Registration/Information Form

Please mail in this form to receive updated literature for your handbook.

TITLE FIRST NAME M.I. LAST NAME

DEPARTMENT / JOB TITLE / MAIL CODE

COMPANY NAME

STREET ADDRESS OR POST OFFICE BOX NUMBER

CITY STATE ZIP CODE

COUNTRY

☐ Please contact me to discuss my application.
My telephone number is:

AREA OR INTERNATIONAL CODE NUMBER EXTENSION

Please complete the following information.

Type of Business
- ☐ O.E.M.
- ☐ Distributor
- ☐ Battery Assembler
- ☐ Retailer
- ☐ Consultant
- ☐ Academic
- ☐ End User (Consumer)
- ☐ Other ____________

Type of Products
- ☐ Computer/P.O.S./EDP
- ☐ Communications
- ☐ Power Tools
- ☐ Housewares/Personal Care
- ☐ Military
- ☐ Medical
- ☐ Consumer Electronics & Appliances
- ☐ Toys/Hobby
- ☐ Instruments & Controls
- ☐ Lighting
  - ☐ portable
  - ☐ emergency
- ☐ Other ____________

Product(s) manufactured ____
____

Remove entire sheet from Manual, fold in half with address showing, add stamp and mail.

Battery Usage

Currently use Batteries ☐ Yes ☐ No

If yes, what type?

- ☐ Primary (throwaway)
  - ☐ Lithium
  - ☐ Carbon Zinc/Alkaline
  - ☐ Other ________
  - ☐ Mercury
  - ☐ Silver
- ☐ Secondary (rechargeable)
  - ☐ Nickel-Cadmium
    - ☐ sealed
    - ☐ flooded
    - ☐ pocket plate
  - ☐ Other ________
  - ☐ Lead Acid
    - ☐ sealed
    - ☐ gelled
    - ☐ standard (automotive)
    - ☐ Other ________

FOLD HERE

PLACE
STAMP
HERE

General Electric Company
Battery Business Department
Attn: Technical Marketing
P.O. Box 861
Gainesville, FL 32602-0861

Remove entire sheet from Manual, fold in half with address showing, add stamp and mail.