LAW ENFORCEMENT STANDARDS PROGRAM

BATTERIES USED WITH LAW ENFORCEMENT COMMUNICATIONS EQUIPMENT

CHARGERS AND CHARGING TECHNIQUES

prepared for the
National Institute of Law Enforcement and Criminal Justice
Law Enforcement Assistance Administration
U. S. Department of Justice

by

W. W. Scott, Jr.

Electromagnetics Division
National Bureau of Standards
Boulder, Colorado 803002

June 1973

U.S. DEPARTMENT OF JUSTICE
Law Enforcement Assistance Administration
National Institute of Law Enforcement and Criminal Justice

ACKNOWLEDGEMENTS

This report was formulated by the Law Enforcement Standards Laboratory of the National Bureau of Standards under the direction of Marshall J. Treado, Program Manager for Communications, and Jacob J. Diamond, Chief of LESL. The technical review of this report, under the direction of H. E. Taggart, LESL Communication's Project Leader, was conducted by the staff of the NBS Electromagnetics Division.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 80 cents
Stock Number 2700-00216

TABLE OF CONTENTS

FOREWORD

In accordance with Title I, Section 402(b) of the Omnibus Crime Control and Safe Streets Act of 1968, P.L. 90-351, the National Institute of Law Enforcement and Criminal Justice (NILECJ) has established the Law Enforcement Standards Laboratory (LESL) at the National Bureau of Standards.

LESL has been established to conduct research leading to the development and promulgation of national voluntary standards that will assist law enforcement and criminal justice agencies in the selection and procurement of quality equipment. In addition to standards development, LESL is defining minimum performance levels and developing methods for measuring the required performance of equipment designated by NILECJ.

This report, LESP-RPT-0202.00, Batteries Used With Law Enforcement Communications Equipment: Chargers and Charging Techniques, was prepared by the Electromagnetics Division of the National Bureau of Standards. Additional reports, standards, user guidelines, as well as state-of-the-art surveys are planned for issuance under the LESL program in the areas of protective equipment, communications equipment, security systems, weapons, emergency equipment, concealed objects detectors, and vehicles.

NILECJ Standards are subject to continuing review. Technical comments and recommended revisions are invited from all interested parties. Suggestions should be addressed to the Program Manager for Standards, National Institute of Law Enforcement and Criminal Justice, Law Enforcement Assistance Administration, U. S. Department of Justice, Washington, D. C. 20530.

Martin B. Danziger
Assistant Administrator
National Institute of Law Enforcement and Criminal Justice

CHARGERS AND CHARGING TECHNIQUES FOR BATTERIES USED WITH LAW-ENFORCEMENT COMMUNICATIONS EQUIPMENT

by

W. W. Scott, Jr.

ABSTRACT

Proper charging techniques are extremely important if a user expects to obtain a long battery life over many discharge-charge cycles. This report discusses basic charge characteristics of sealed nickel-cadmium and sealed lead-acid batteries and cells. Methods of charging such batteries are presented along with advantages and disadvantages of different common charge systems. Fast-charge systems are also discussed with emphasis placed on ways of determining when full charge on a battery is achieved.

1. INTRODUCTION

Charging is the process of supplying electrical energy to a battery for conversion into stored chemical energy. No attempt should be made to charge primary batteries, such as most alkaline-manganese dioxide or all mercuric oxide types [1]. Such charging usually creates gas pressure within the battery with possible sudden hazardous release.

This report will emphasize charging methods for sealed secondary batteries, particularly sealed nickel-cadmium types, with some information provided on sealed lead-acid batteries.

2. BATTERY CHARGING CHARACTERISTICS

2.1. General

One of the most critical operations that can be performed on a cell, and one which most directly affects the useful life of the cell, is that of charging. One manufacturer of sealed nickel-cadmium batteries reports that multiple instances of rapid deterioration of batteries in the field was due to destructive charging techniques [2]. The manufacturer found that since nickel-cadmium batteries have very low internal resistance (lower than lead-acid batteries), a charger voltage just slightly above the battery voltage may produce a very large charging current. This large charging current, while it does no harm during the first 85% of the charge cycle, must decrease rapidly, in a non-linear manner, for the remainder of the charge cycle to avoid overheating or venting and probable damage to the battery.

A manufacturer of sealed lead-acid batteries found that the cycle life of their batteries is greatly affected by the charging method used [3]. Assuming optimum conditions, it is claimed that this type of battery can deliver over 100 charge-discharge cycles.

2.2. Sealed Nickel-Cadmium Cells and Batteries

Constant current charging is usually recommended for both pocket-plate and sintered-plate sealed nickel-cadmium cells. Charge (or discharge) current is usually expressed in terms of the nominal battery capacity rating (C) in ampere-hours divided by the charge (or discharge) time [4]. Current is often expressed in written notation as a fraction or multiple of C. For example, a current of 0.1 C is that current which in ten hours would theoretically fully charge (or discharge) an ideal battery. Other examples are shown in table I.

A general rule is that currents between about 0.05 C and 0.1 C may be applied for an indefinite period of time without serious overcharging occurring. In many cases, it is possible to charge at rates much higher than 0.1 C, but control devices to prevent high-rate overcharge are required. Rates lower than about 0.05 C are generally insufficient to charge a battery, but are used after the battery is charged to maintain the battery for months at a time where self-discharge might otherwise reduce the available capacity. To obtain optimum battery performance, it is usually recommended that a battery on trickle charge be discharged every 6 or 12 months and recharged at the normal rate. Table I relates common charging rates (in terms of a fraction of the battery nominal capacity rating) in amperes and resulting time to

TABLE I

CHARGE RATE DESCRIPTIONS

DESIGNATION	CHARGE RATE (AMPERES)	NOMINAL CHARGE TIME (HOURS)
Standby (trickle)	0.01 C to 0.03 C	100 to 33
Slow (overnight)	0.05 C to 0.1 C	20 to 10
Quick	0.2 C to 0.5 C	5 to 2
Fast	1 C and more	1 and less

NOTE

The charge rate in amperes is equal to the nominal battery capacity rating (C) in ampere-hours divided by the charge time in hours. It is assumed that the battery is to be brought from a discharged to fully charged condition and that there is 100% charging efficiency.

bring a completely discharged battery to full charge (assuming 100% charge efficiency with commonly used charge-rate designations).

Unfortunately, 100% charge efficiency in a battery does not occur so that in actuality, for constant current charging, charge time is usually extended to obtain a full charge. The amount of extended charge time cannot be exactly specified because the total charge required depends upon the specific history, environment (mainly temperature), charge rate, initial charge state, and amount of overcharge for that cell. However, most manufacturers recommend that their cells and batteries be charged at the 0.1 C rate (10-hour rate) for 14 to 16 hours. For example, a one ampere-hour cell would be charged at 100 milliamperes (mA) for 14 to 16 hours.

Generally speaking, charging efficiency is lower for damaged cells, lower charge rates, higher initial charge states, and higher cell temperatures. Also, certain characteristics can significantly affect cell charge acceptance. For example, a cell charged at a temperature of 50° Celsius (50°C), even when charged to a time-current product equal to 160% or more of rated capacity, will produce no more than

75% of its rated capacity when discharged. At a temperature of 25°C, the same cell would produce 100% of rated capacity for an input charge of 160%. See figure 1.

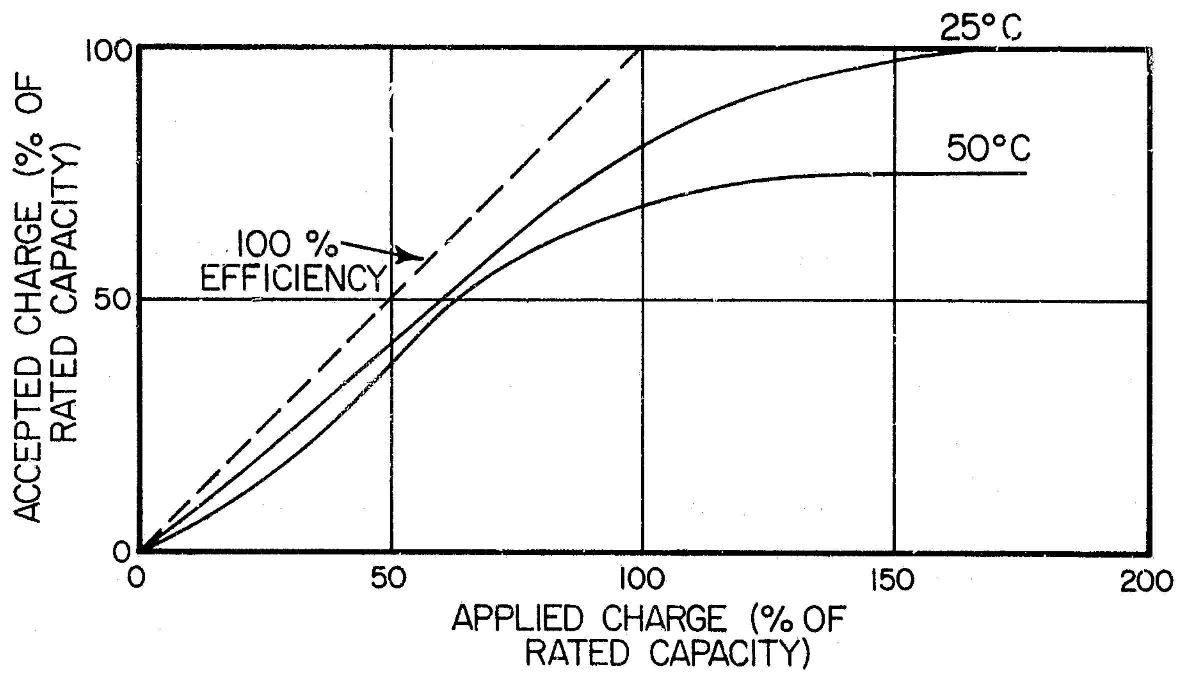

Figure 1. Charging efficiency at temperatures of 25°C and 50°C for charge rate 0.1 C.
Adapted from copyrighted material used by permission of the General Electric Company (see acknowledgment).

Another characteristic greatly affecting charging efficiency is charge rate. Figure 2 shows that a charging

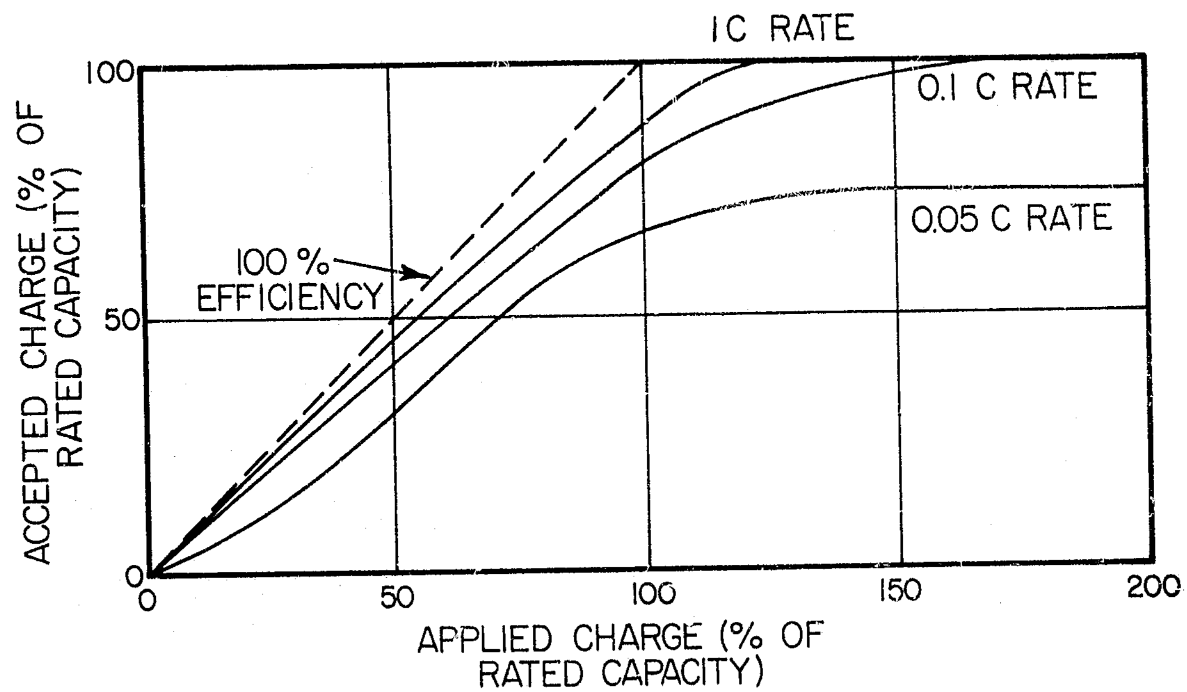

Figure 2. Charging efficiency for different charge rates at an ambient temperature of 25°C.
Adapted from copyrighted material used by permission of the General Electric Company (see acknowledgment).

rate of 0.05 C produces only about 75% of nominal capacity, even after a charge input of 140%. However, charging at the 0.1 C rate will produce 100% nominal capacity available after about a charge input of 160%. Charging at the 1 C rate produces better efficiency and might be preferred except that, as is shown in figure 3, the pressure and temperature of the cell becomes destructively high near full charge.

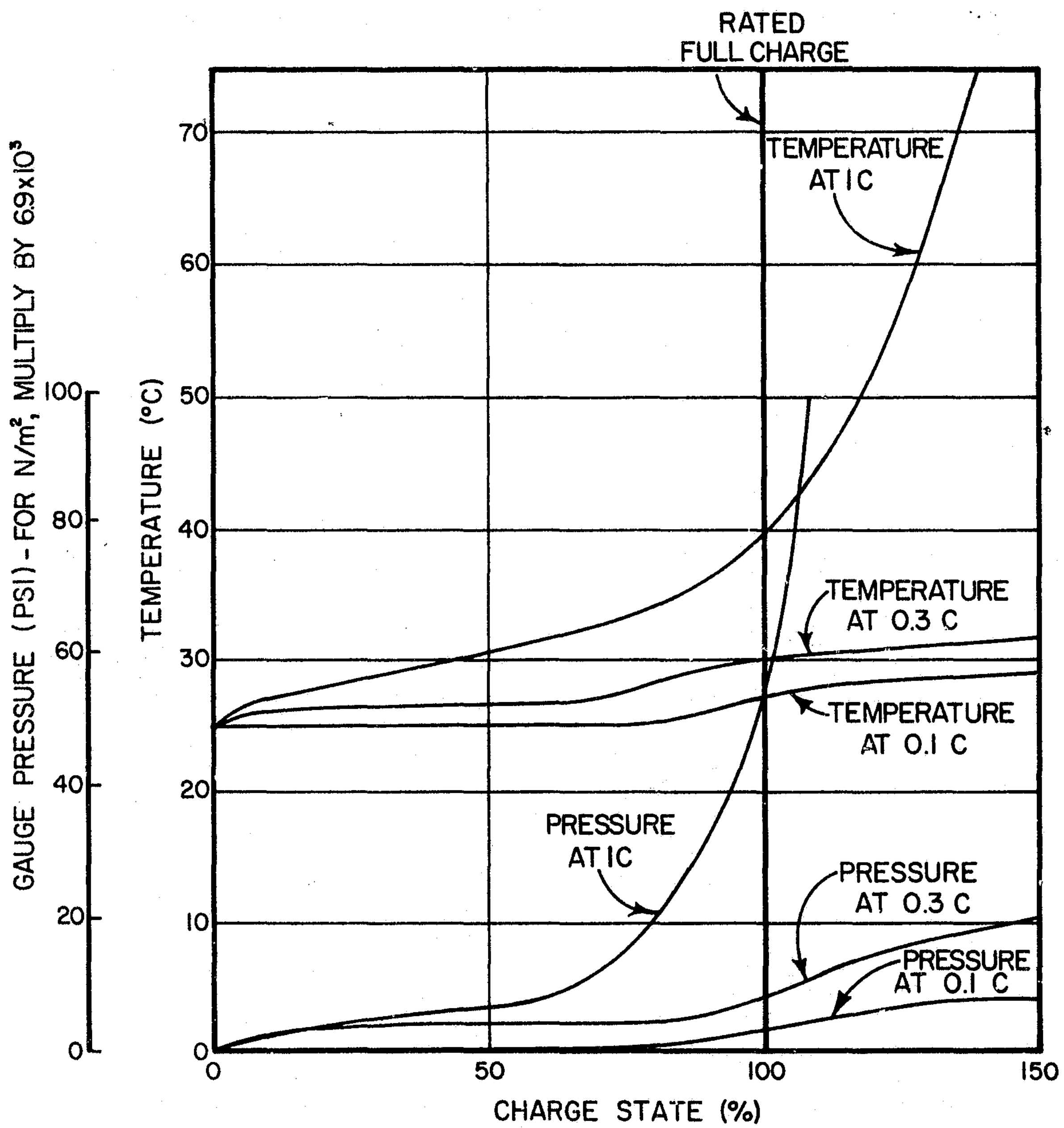

Figure 3. Pressure and temperature of a sealed nickel-cadmium cell at 25°C ambient as a function of charge state for charge rates of 0.1 C, 0.3 C and 1 C. Adapted from copyrighted material used by permission of the General Electric Company (see acknowledgment).

Exposure to high temperatures (above 50°C) will tend to degrade the insulation (often nylon) which separates the positive and negative plates. The degradation is cumulative and while brief excursions to elevated temperatures may cause no noticeable harm, repeated exposures will affect the life of the cell.

Many sealed cells of the cylindrical type have safety vents to release excessive pressure, typically 150 to 300 psi (10 to 21×10^5 N/m²). However, each time the safety vent opens, water in the electrolyte is lost, and cell capacity and life are reduced. Users of sealed nickel-cadmium batteries can sometimes relate instances of case swelling or even violent explosion during charging or shortly thereafter [5] [6]. From figure 3, it is apparent that this problem may arise at continued high charge rates after full charge is attained. One instance was related to the author where a communications battery from one manufacturer was ruined when placed in a charger built by another manufacturer for another communications system. In addition, should a cell be reverse charged for any reason, similar symptoms may occur [7].

Batteries commonly used in communications are designed for 0.1 C rate charging where gas pressures are typically about 20 psi (14×10^4 N/m²). Special constructions are available that are claimed to safely withstand the 30 to 60 psi (21 to 41×10^4 N/m²) pressures usually generated after 0.3 C charging [3]. One might correctly deduce from figure 3 that high rate charging (even up to a charge rate of 10 C or more) is possible when the cell is nearly discharged. The problem arises when the cell is nearly charged and a high charge rate is continued. Charging circuits have been designed to sense battery charge state and to automatically reduce the effective charge rate. These charging circuits will be discussed in section 3.

In summary, it is important to keep nickel-cadmium batteries cool to achieve full charge capacity and optimum battery life. Also, it is important that charge rates be within certain limits, if constant-current charging is used.

2.3. Sealed Lead-Acid Cells and Batteries

Constant potential charging with current limiting is usually recommended for sealed lead-acid cells. Unlike nickel-cadmium batteries, the voltage of a lead-acid cell is a more reliable indicator of its state of charge. The voltage to the charger should be carefully regulated because AC line voltage variations, of greatest effect when the battery approaches full charge, may produce a large change in charging current unless some means of limiting the current is provided. Current limiting may be accomplished through use of a current-limiting resistor (see section 3.2). Large charging currents in a battery near a state of full charge can produce high temperatures and a significant amount of gas. This factor alone may greatly affect the life of a sealed lead-acid battery.

Other factors known to shorten the life of these batteries are excessive discharge rates and repeated deep discharges. Excessive charge rates, overcharging, high charge or discharge temperatures, and long storage periods without activity are also known to adversely affect battery life.

In applying the constant-potential-with-current-limit charging procedure, the voltage selected for sealed lead-acid batteries should be 2.35 or 2.40 volts per cell. Initial current should be limited to about 0.15 C or 0.20 C amperes. As charging proceeds and battery voltage approaches that voltage set into the charger, the current will decrease. Using this procedure, the battery usually will be charged in about 14 to 16 hours.

Charging efficiencies with these batteries are such that it is necessary to apply about 125% to 130% of the energy removed during discharge to return the battery to full charge condition. As more experience is developed with sealed lead-acid batteries, charging recommendations will no doubt be advanced that will greatly shorten the charging time. However, it will always be necessary to avoid conditions where excessive gas is created that may cause undesired venting of the battery.

3. CHARGING TECHNIQUES AND CIRCUITS

Rechargeable batteries of the types discussed have the capability of being charged from a hundred to a thousand times. However, as was pointed out earlier, the selection of a charging system is very important in order to obtain an effective charge without significantly damaging the battery. This section will discuss several frequently used methods of charging such batteries.

3.1. Constant Voltage Charging

All chargers have a voltage higher than that of the battery in order for a charging current to flow. Figure 4 illustrates the principle involved for a Constant-Voltage Charger.

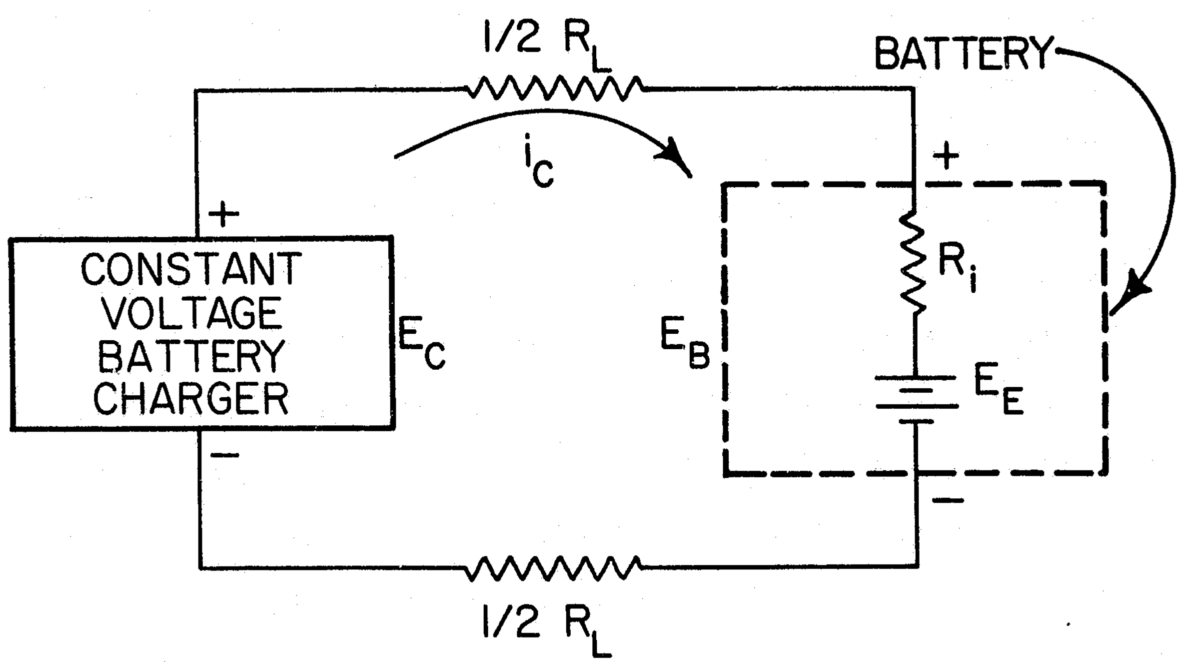

Figure 4. Constant-voltage charger.

$$E_C = i_C(R_i + R_L) + E_E, \quad (3.1)$$

or

$$i_C = \frac{E_C - E_E}{R_i + R_L} \quad (3.2)$$

where E_C = charger voltage in volts,

E_B = battery voltage across terminals under current loading, in volts,*

E_E = battery voltage across terminals under no current load in volts,

i_C = charging current in amperes,

R_i = internal battery resistance in ohms, and

R_L = lead resistance in ohms.

Unfortunately, battery voltage E_B for a nickel-cadmium battery is dependent upon many variables such as state-of-charge, temperature, charge rate, load rate, etc. and cannot be precisely predicted. Voltage drops due to lead resistance R_L are often insignificant unless high charging currents, long lead lengths, small diameter leads, or poor contacts are present. The internal battery resistance R_i is usually very low (several milliohms). In order to keep the charging current i_C at a reasonably low value, especially near overcharge conditions, the voltage difference E_C-E_E must be accurately maintained at a low level. Because this is relatively difficult to accomplish, manufacturers usually do not

*$E_B = E_E + i_C R_i$.

recommend the constant voltage method for charging sealed batteries of any type. However, nickel-cadmium batteries of the vented type may be safely charged by this method since overcharge and attendent gas generation have little adverse effect on this type of battery. Also the low cost of the charger is an advantage.

3.2. Constant-Current Charging

Constant-Current chargers use simple construction and therefore are the least expensive of the chargers recommended for sealed batteries. One simple way of obtaining essentially a constant-current charger is to greatly increase the charger voltage E_C so that it is much larger than the battery voltage E_B, and to add in series a large current-limiting resistor, R_S. The circuit equation then becomes:

$$E_C = i_C(R_S + R_L + R_i) + E_E \tag{3.3}$$

but as

$$R_S >> R_i + R_L,$$

then

$$E_C \simeq i_C R_S + E_E \tag{3.4}$$

or

$$i_C \approx \frac{E_C - E_E}{R_S}. \tag{3.5}$$

Since E_C is large compared to E_E, the charging current is largely determined by the value of R_S. It is readily seen that small variations in E_E do not grossly affect i_C. One manufacturer uses a miniature incandenscent lamp as the series current-limiting resistor, thereby providing a visual indication of whether charging current is being accepted by the battery or not. In modern practice, current limiting can be easily accomplished by silicon-controlled rectifiers and other solid-state series regulators for about the same cost as the series resistor, but without wasting supply power and creating heat.

As discussed in section 3.2, sealed nickel-cadmium batteries are usually charged at the 0.1 C rate for 14 to 16 hours to bring the battery to a fully charged condition. The charge rate of 0.1 C has the advantage of allowing use of low cost cells without the hazard of battery failure because of high pressures and temperatures such as may happen at higher charge rates. Another advantage is that smaller and more reliable and economical chargers can be used at this lower charge rate. Perhaps the major advantage to the user is that in general, sealed nickel-cadmium cells may be charged at the 0.1 C rate indefinitely without damage or serious performance deterioration. One manufacturer reported that cylindrical cells charged at 0.1 C for as long as two years showed no loss in capability [8]. However, it was cautioned that button cell batteries are more critical, and excessive overcharge at the 0.1 C rate should be avoided. Another manufacturer reported their cells had functioned successfully for more than four years at a 0.1 C charge rate. The cells were essentially on continuous overcharge since very little capacity was removed on each cycle. However, it is reported that some engineers, seeking to reduce stress, design their systems for continuous charging at the 0.05 C rate as an extra safety margin against battery failure [9].

A more recent report on sealed nickel-cadmium batteries used in portable transceivers cautioned that there was difficulty with the 16-hour recharging schedule [10]. Although some radios would be heavily used, depleting the battery in 8 hours, most probably would not. In these cases, most of the 16 hours would be spent in overcharging the battery. The author argued that while continuous charging at this rate is not usually considered detrimental to individual cells, packaging the cells into batteries for use in portable transceivers presents unusual problems. First, cells are usually packed into a plastic battery housing (which is a thermal insulator) allowing temperature buildup during overcharge. Second, batteries in portable transceiver service are subjected to a very wide range of ambient temperatures both in normal use and recharge. He argued that for long battery life, temperatures during recharging should be

reduced, but not at the expense of increasing the 16 hour recharge time. He suggested a different type of charger, one that charges at higher than 0.1 C rate for a major part of the battery capacity, and then switches to a lower current before full charge is attained.

3.3. Charge Sensors and Fast Charge Systems

Additional types of chargers are available for charging at rates higher than 0.1 C, but these all use some means of sensing when the battery is fully charged, and they all involve some means of limiting the charge current to a safe value. This section will discuss various methods of determining full-charge conditions in a battery.

As a sealed nickel-cadmium cell is charged, the internal pressure, cell case temperature, and cell voltage all increase at a low rate. However, as the cell approaches full charge and proceeds into overcharge, the three parameters begin changing at a much greater rate. This rate-of-change increase, as the cell approaches full charge, is the key to most fast-charge control methods. With appropriate sensors, these parameters can signal when fast charge must be terminated.

3.3.1. Voltage-Controlled Fast Charger

A voltage-controlled charger prevents applied charging voltage from exceeding a preset voltage level related to the peak cell voltage. However, the peak attainable cell voltage is dependent upon many variables, including charge rate, cell design, manufacturing process, and cell temperature. These variables make it difficult for any one voltage-controlled charger to charge all types and sizes of sealed nickel-cadmium cells. However, for a given cell, most of these variables can be fixed within the charger design. Unfortunately, cells may have a temperature coefficient of voltage of up to -4 millivolts per degree Celsius, thereby requiring temperature compensation of the voltage cut-off point. Otherwise high temperature conditions may occur where the fast charge rate continues into overcharge. Reliable voltage-controlled chargers probably should have one or more temperature sensors attached to the battery.

3.3.2. Temperature-Controlled Fast Charger

Temperature-controlled chargers basically consist of a constant-current power supply and a thermal switch attached to the battery to be charged. The switch is set to open the charging circuit when the battery reaches a certain temperature. The temperature is chosen to terminate the charge before the internal cell pressure exceeds a safe level.

Temperature changes as high as 5°C per minute can be obtained when charging at the 1 C rate.

The reliability of any temperature-controlled fast charge system depends upon accurate design information on battery characteristics, thermal switch accuracy and repeatability, and heat transfer characteristics of the cells and battery case. Battery characteristics are perhaps the most important factor because the pressure of a sealed nickel-cadmium cell is temperature-dependent when in overcharge. The colder the cell, the higher the overcharge pressure. Therefore, if this charging system is to be used to charge batteries in cold ambient conditions (such as after a cold winter night patrol), the pressure-temperature relationship for the type of cell used should be known to allow safe charging. Most manufacturers recommend that these cells be charged within ambient limits of about 5°C and 40°C to avoid battery life deterioration.

3.3.3. Pressure-Controlled Fast Charger

Pressure-controlled chargers make use of a pressure switch attached to one or more cells of a battery. As a nickel-cadmium cell approaches full charge, pressure increases rapidly, as shown in figure 3. During overcharge conditions, almost all the charging current goes into gas production. In fact, the pressure can increase at the rate of 3 psi (2×10^4 N/m^2)

per minute at the 1 C charging rate. This type of charging control is feasible and has been successfully applied to satellite systems for several years. However, pressure-controlled charging systems can be relatively expensive since special cell construction is required in order to include a pressure sensor and still insure that the cell is compatible with other cells in the battery. As mentioned previously, if cells within a battery are not well-matched, the lowest capacity cell will be driven into a reverse-charge situation during near discharge conditions, thereby seriously affecting the life of the battery. The special cell is unusual in that it has a third, and sometimes a fourth, electrode built into it. The third electrode is usually connected to the negative electrode through a resistor providing a voltage indicative of the cell pressure. Fully discharged sealed batteries have been repeatedly recharged to 80% of capacity in less than 20 minutes by this method, without evidence of immediate or cumulative adverse effects.

3.3.4. Coulometer Sensor

Another method makes use of a chemical coulometer connected in series with the battery at all times including discharge and charge. The coulometer consists essentially of two cadmium (negative) plates, one of which is completely charged and the other discharged. When current is passed

through the coulometer, a very low voltage is developed which rises rapidly after the battery has reached about 80% rated charge condition. The coulometer has the advantage that it determines the charge-time product. Thus the same charge level would be obtained and indicated if a heavy charge current for a given short period of time, or a small charge current for a proportionately longer period of time were passed through the coulometer into the battery. The voltage signal can be used to terminate the fast charge. Disadvantages include high cost, leakage rate characteristics that may be different than the battery, and difficulties in getting the coulometer and cells to track across the temperature range of the charge cycle.

3.3.5. Time Charge Method

All of the charge systems just discussed assume that the batteries can be placed on charge at any state of discharge. In other words, cells with an unknown charge-state can be safely charged at a fast rate using the previously discussed systems. However, if it is known with certainty that a battery is essentially discharged, there is one additional fast-charge system that could be used. It makes use of the fact that sealed nickel-cadmium batteries can safely accept very high charge rates providing the battery is not forced into an overcharge condition. Charge rates as high as 20 C amperes or more can be successfully applied.

This method makes use of a high-rate constant current supply and a timer to cut off the current at a predetermined time. For example, a 500 milliampere-hour (mAh) battery which is essentially discharged may be fast charged at the 5 C rate (2.5 amperes) for a timed interval of about 10 to 12 minutes. It should be remembered that the charge acceptance efficiency of nickel-cadmium batteries improves at the higher charge rates.

It is cautioned that the timed-charge method can be very dangerous as there is no margin for error should the battery actually have a smaller time-charge capacity than expected.

3.3.6. Dumped Time-Charge Method

A modification of the timed-charge method is sometimes utilized in an effort to gain knowledge of the cell state-of-charge. For example, the existing charge (if any) may be "dumped" through no less than a 0.1 ohm resistor to quickly bring the cell down to a fully discharged condition. The cell can then be charged with a timed-charge. Alternatively, a known amount of charge may be "dumped" through a known resistance for a specified time interval. In either case, a known timed-charge (up to the amount dumped) may be safely applied without danger of harming the cell. However, as

already emphasized, such a method may be successfully applied only to individual cells and not to batteries. Individual cells within a battery must not be discharged below about 1.0 volts per cell. If this occurs, one or more cells may be reverse charged with probable damage to those cells.

3.3.7. Pulsed Charge-Discharge Method

There has long been much interest in rapid-charge systems for sealed cells and batteries. A successful rapid-charge system would be of great use in the portable communications industry as well as in the growing medical electronics field, where it is recognized that electronic equipment interactions due to leakage currents can be minimized if certain equipment (such as surgeons' saws, etc.) have their own battery power source. Consumer products, such as golf carts, toothbrushes, portable power saws and drills, could also provide a large market for rapid-charged sealed batteries.

At present, devices that make use of sealed nickel-cadmium batteries are normally charged at the 0.1 C or 16-hour rate. By means of a recently patented rapid charge system, such batteries are claimed to be charged in about 20 minutes [11, 12, 13]. This rapid charge system charges initially at the 5 C rate until the voltage of the battery reaches 1.50 volts per cell (at room temperature, 23°C) at which time the battery is switched from the charger to a low-resistance load and discharged for a timed 3 seconds at the 20 C rate. This apparently depolarizes the electrodes and electrolyte and removes gases formed during charging, thereby allowing charging at a faster rate than otherwise would be possible. The battery is then again charged until the voltage reaches 1.5 volts per cell. The process of discharging and charging continues, each cycle becoming shorter in time interval until about 20 minutes after initiating battery charging, the battery is essentially charged to full capacity.

Unfortunately, the difficulty with the use of voltage sensing for charging control is that the voltage of a sealed nickel-cadmium cell tends to change with repetitive cycling and usually varies with temperature and charge rate. To account for the effect of different ambient temperatures on the battery voltage, an ambient temperature sensor is used to prevent possible damage when in overcharge. The sensor automatically compensates the decision voltage at which the battery is switched from charge to discharge. For example, it is claimed that the decision voltage for an ambient temperature of 0°C should be 1.54 volts per cell while for an ambient temperature of 40°C, 1.47 volts is a typical decision voltage.

In general, field experience has indicated that while most rapid-charge systems are effective in charging most nickel-cadmium batteries, catastrophic failures do occur. These failures usually occur through pressure buildups in continued rapid-charge when one or more cells in a battery are completely charged. Unfortunately, it appears that there is a large variation of electrical characteristics among cells of the same type produced by even the same manufacturer. These electrical variations may be due in part to variations in purity of materials, presence of contaminants, and different amounts of electrode materials. Until quality control is improved, failures from this cause will continue.

Many cells of the button type, such as are used in law enforcement communications equipment, are imported by several well-known battery companies in the United States. While several manufacturers protect their cylindical cells from rupture by a pressure relief vent, the button cells have no such provision. As button cells are hermetically sealed in steel cases, internal pressures can become very high before failure. It is recommended that button-cells be not substantially overcharged, even at the relatively "safe" 0.1 C charge rate.

3.3.8. Diode Protection

One protection for batteries constructed from button cells is to place a zener diode of appropriate current handling capability across each cell. The zener diode should have a voltage breakdown below the charged cell voltage normally associated with excessive cell gassing. A germanium diode, capable of handling reasonable charging currents, is also connected across the cell but with opposite polarity to that of the battery. This greatly reduces reverse charging current through a discharged cell when the battery is forced into deep discharge. However, use of such semiconductors to provide cell protection may also substantially increase the rate of self discharge of the battery.

One manufacturer of equipment that uses nickel-cadmium batteries recharges batteries at a 3-hour rate. However, to prevent the battery from being overcharged, both temperature and voltage sensing is employed. An appropriate signal from either one shuts off the charging current and, reportedly, greatly reduces incidents of failure.

4. GENERAL COMMENTS AND CAUTIONS

This section will discuss certain topics of particular interest to users of portable communications equipment.

Figure 5 illustrates an internal arrangement of nickel-cadmium cells for a battery used in law-enforcement communications equipment. Twelve button cells are spot-welded or strapped together in series with negative and positive plate-type terminals located at the right side of the battery.

Figure 6 is an exploded view of a button cell. From left to right is shown the cell cup (positive pole), positive plate, negative and positive plate paired together, negative plate, contact spring and cell cover (negative pole). The two positive (or negative) plates are electrically interconnected but insulated from the two negative (or positive) plates by a thin separator. The cell cup rim is crimped over the cell cover rim while a plastic washer between them insulates the two poles from each other. The crimp is shown in the assembled cell.

4.1. Determining Loss of Capacity in Battery Packs

A typical battery pack used in portable communications equipment may consist of 12 sealed nickel-cadmium cells connected in series to provide a nominal 14.4 volts (1.2 volts per cell) with a 500 mAh capacity. When the battery is discharged to 12 volts (1.0 volt per cell), essentially all of the stored capacity has been used.

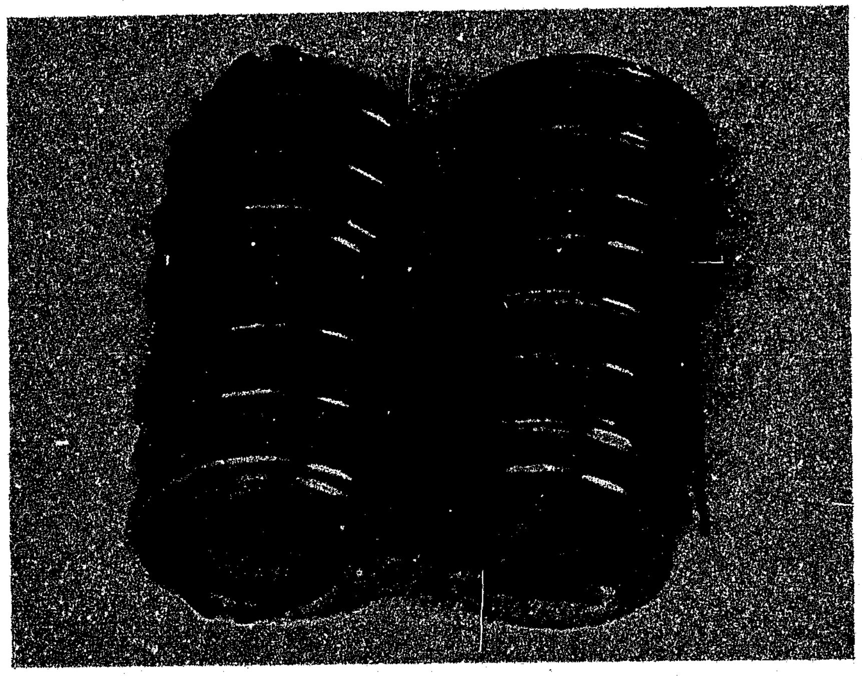

Figure 5. Internal arrangement of nickel-cadmium cells for a battery used in law-enforcement communications equipment.

Figure 6. Exploded view of a button cell.

One problem, known to all users of such battery packs, is how to determine when one or more cells have failed. A cell may fail by internal shorting, such as may occur through interplate insulation breakdown. Such a failure means that the contribution of that cell to increasing the voltage of the battery is lost, although little hinderance to current flow is usually found. It also means that for the battery under discussion, only about 11/12 or 92% of the original battery power capability is available. If two cells fail through shorting, then 10/12 or 83% of the original battery power capability remains.

Another problem is that individual cell current capacity may decrease due to venting and resulting loss of electrolyte. This type of performance degradation would not necessarily affect the charged cell voltage. Hence, a voltage check of the battery immediately after charging would not necessarily reveal its usefulness as an energy source. Occasionally, a cell fails through internal open circuit, whereupon the battery is obviously dead and no voltage or current is available from it.

The problem therefore is mainly one of measuring battery capacity to ascertain if a given battery is useful for communications service. One manufacturer of portable communications equipment recommends that such batteries be replaced if they fail to deliver 80% or more of their original rated capacity. Below about 80%, batteries are usually found to deteriorate quickly.

The method often recommended by manufacturers to determine battery capacity is one of timed-dump. As an example, the 14.4 volt battery will be used in the following calculations. Initially, the battery is fully charged and then discharged several times to about 9 to 12 volts to eliminate any "memory" effects. (Special care should be taken not to reverse one or more cell polarities when discharging to 9 volts.) Then after the battery is again charged, a resistance of appropriate power capacity is selected to simulate current drain used by the communications equipment in the transmit mode of operation. For the example chosen, the current drain is about 390 milliamperes at 14.4 volts and the 37 ohm resistor should be rated for ten watts (or higher).

$$R_b = \frac{E}{I} = \frac{14.4}{0.39} = 37 \text{ ohms.} \qquad (4.1)$$

The value 14.4 volts is used as an average because the battery voltage decreases slowly and linearly from about 15.4 volts to about 13.4 volts for most of the effective battery capacity and then decreases rapidly to 12 volts. Therefore, the average current is directly related to the average voltage.

The time interval for battery discharge to 12 volts should be recorded and multiplied by the average current to determine the measured battery capacity, C_m. For the example, say the time interval was one hour.

$$C_m = IT = (390)(1) = 390 \text{ mAh}, \qquad (4.2)$$

but the battery was rated nominally at 500 mAh, so the measured capacity (C_m) was determined to be 78% of nominal capacity (C_n).

$$C(\%) = 100 \frac{C_m}{C_n} = (100) \frac{390}{500} = 78\% \qquad (4.3)$$

For the example and guideline given, if a battery of this type discharged to 12 volts in less than an hour, it would be discarded. Unfortunately this method, although convenient to apply, does not really test the battery under the varying load-time conditions that these batteries experience in use.

4.2. Determining Actual Capacity Required of Battery Packs

One way of determining battery capacity requirements is to measure the battery drain of the communications equipment under conditions of standby, receive, and transmit. The Electronic Industries Association (EIA) standards for portable land mobile communications equipment (RS-316) state in EIA section 2.3.1. that the standard duty cycle for equipment containing a transmitter and receiver is defined as 6 seconds

(10%) receive at rated audio power output, 6 seconds (10%) transmit at rated RF power output, and 48 seconds (80%) standby [14]. It also provides that the standard duty-cycle shall be performed 8 hours each day followed by 16 hours rest. The minimum battery life standard (EIA section 3.1.2.) for any given battery complement shall exceed 1 day.

The communications equipment usually used with the battery chosen as an example, normally has the following current drains in the coded squelch configuration:

Standby -- 10 mA

Receive -- 62 mA

Transmit -- 325 mA

Using this data and the 10% transmit, 10% receive, and 80% standby, standard duty cycle with the minimum battery life standard of 8 hours, the minimum battery capacity requirement can be determined.

$$C_r = 8(0.1X + 0.1R + 0.8S) \qquad (4.4)$$

where C_r is the minimum required battery capacity in mAh,

X is the transmit mode battery drain in mA,

R is the receive mode battery drain in mA, and

S is the standby mode battery drain in mA.

Calculation yields for the example, 374 mAh, as the minimum battery capacity requirement. From Eq. 4.3., this corresponds to 75% of the rated battery capacity of 500 mAh.

The conclusion can be drawn that as the minimum battery capacity requirements for the equipment is less than the usual guideline for replacing a battery (when the battery fails to deliver 80% of rated capacity), then the guideline is reasonable.

4.3. Battery Capacity as Determined from Constant Load and Switching Load Tests

The American National Standards Institute (ANSI) specifications for batteries give guidelines for capacity tests [15]. In general, the test that best represents any particular service is that which most nearly duplicates the power output of the battery when in actual use. Intermittent tests are preferred to continuous tests and should be used whenever possible because they usually simulate service conditions more closely.

A question then arises, "Should the intermittent tests recommended by ANSI and EIA be strictly adhered to when making battery capacity tests, or is the simple continuous load test recommended by many equipment and battery manufacturers satisfactory?" The constant load test is described and illustrated by example in section 4.1 while the intermittent or switching load test is similarly described in section 4.2. Comparisons between the intermittent and continuous load tests were made using six 14.4 volt, 500 mAh sealed nickel-cadmium batteries. The results are shown in table II.

TABLE II

COMPARISON OF TWO BATTERY CAPACITY TESTS FOR DISCHARGE TO 1.0 VOLT PER CELL

BATTERY DESIGNATION	CONSTANT LOAD TEST MINUTES	SWITCHING LOAD TEST HOURS + MINUTES
A	64	12 + 11
B	79	10 + 21
C	64	9 + 37
D	76	9 + 2
E	68	8 + 36
F	60	8 + 35

The batteries listed in table II were each charged under constant current conditions at the 0.06 C charge rate for 30 hours or more before each test. The batteries were then removed from the charger and allowed to rest for one to two hours before being tested.

From table II, it is apparent that for the constant load tests, results are similar and close to 60 minutes, except for batteries B and D. This suggests that there is very little difference between the batteries. However, the switching load tests, which simulate conditions under use, indicates there is considerable difference between batteries. Battery A shows nearly 50% more capacity than several other batteries (E and F) by the switching load test, yet the results obtained from the constant load test do not correlate at all. The ability for a battery to recover itself between heavy current drains (transmit mode) cannot be made apparent through a constant load test.

The batteries tested in each case have more capacity than the EIA minimum life standard of 8 hours. Additional tests should be made on batteries that have had considerable field use (rather than the new ones tested for this report.) Two batteries were acquired of the type tested above, that had been rejected from field use because "they would not hold a charge through the working shift." Laboratory testing indicated that although they would accept charging current normally, and apparently charge to a normal voltage, within several hours of removal from the charger, their voltage decreased rapidly under no load conditions and was considerably below 12 volts. Apparently most of the cells had high internal leakage. Information should be obtained on the relative merits between the two test methods for batteries that have degraded performance. For example, a battery with significant internal leakage may appear fair during a one hour test and prove poor in the longer tests recommended by ANSI and EIA.

4.4. Internal Load Resistance Effects on Battery Performance

The internal resistance of nickel-cadmium cells is usually very low. However, for the battery under discussion, which consists of 12 cells connected in series, the total internal resistance may be significant under certain conditions. It was found that the internal resistance was remarkably low and constant until the battery was almost discharged, at which time the internal resistance became significantly large. For example, battery F, which seemed typical of the batteries tested, had an internal resistance of 1.4 ohms when fully charged, 3.3 ohms after 8 hours of the switching load test, and 22.8 ohms at the conclusion of the test (after 35 minutes of the second day). At the

conclusion of the test, it was calculated that under transmit conditions, where a load of 44 ohms was connected across the battery, about 1/2 of the battery power was being wasted as internal heat in the battery.

Additional tests indicated that, in general, these batteries have fair recovery capabilities near a discharged state, providing that additional heavy current demands are not made of them. For example, battery D was discharged to the 12 volt cutoff point during the switching load test. The test was then continued under a 10% receive (62 mA drain), 90% standby (10 mA drain) cycle. It took 1 hour, 56 minutes before the battery voltage had again decreased to 12 volts. In practice, this would indicate that although the user could not transmit, he could still use the receiver for about two hours using a coded squelch configuration. It would seem appropriate to specify in such communications equipment, a transmit mode cutoff switch set to operate at the 12 volt point to prevent battery damage through deep discharge, and also to assure a continuing receiving capability.

5. GOOD PRACTICES AND RECOMMENDATIONS WITH SEALED NICKEL-CADMIUM BATTERIES

Do

1. Do recall that the method of rating battery capacity differs among manufacturers and that usable battery capacity is decreased at the higher discharge rates.
2. Do remember that a temporary reduction in available capacity occurs below about - 5°C and that batteries should not be discharged below about - 20° C or above + 40°C.
3. Do remember that with care, battery life may approach 1000 charge-discharge cycles.
4. Do recall that good practice suggests a ten percent greater battery capacity than expected load requirements to discourage deep battery discharge.
5. Do remember that self-discharge does not adversely affect battery life.
6. Do remember that very high current values are possible during shorting conditions due to the extremely low internal resistance.
7. Do remember that battery life may be extended to as much as 5000 cycles if discharge depth does not exceed 25% of rated capacity.

8. Do remember that cells sometimes fail in a dead shorted condition, although more generally the failure is an apparent high internal leakage (i.e., a partial short) which prevents a battery from holding charge for more than a few hours.

Do Not

1. Do not discharge batteries below 1.0 volts per cell.
2. Do not charge batteries at temperatures below +5°C or above + 40°C.
3. Do not charge batteries with a constant-current source at a rate greater than 0.1 C without special precautions to limit overcharge.
4. Do not create conditions where individual cells in a battery may be reverse charged such as through deep discharge of the battery. To do so is a sure way to drastically decrease the life of a battery.
5. Do not overcharge button-cells as they are particularly sensitive to overcharging and are dangerous in that there is no provision for safety venting in the steel housing.
6. Do not attempt to charge batteries in parallel with a charger designed for one battery.
7. Do not be concerned about long idle periods in either the charged or uncharged states.
8. Do not exceed the 1 C discharge rate if battery life is not to be reduced.

6. ACKNOWLEDGMENT

The author gratefully acknowledges the General Electric Company for permission to use portions of several copyrighted figures in reference 8 as source material for figures 1, 2, and 3 prepared for this guide.

7. REFERENCES

[1] "Home Flashlite Battery Chargers: Are They Practical? Are They Dangerous?," Media Bulletin No. 2006, National Better Business Bureau, Inc., Nov. 1969.

[2] B. Gladstone and B. Newman, "Demand Pulse Charging for Nickel-Cadmium Batteries," Proc. 23rd Annual Power Sources Conference, pp. 56-59, May 20-22, 1969.

[3] "Eveready" Battery Applications and Engineering Data. New York: Union Carbide, 1971.

[4] R. L. Jesch and I. S. Berry, "Comparison and Performance Characteristics for Batteries Used with Law Enforcement Communications Equipment," unpublished[1] NBS Report (National Bureau of Standards, Boulder, Colorado 80302).[2]

[5] J. Bacher and D. Rusta, "The Analysis of Voltage-Limited Battery Charging Systems," IEEE Trans. Aerospace and Electronic Systems, pp. 792-798, vol. AES-4, no. 5, Sept. 1968.

[6] J. Ball, "There's No Overcharge for Fast-Charged Batteries," Electronics, pp. 97-100, January 22, 1968.

[1]These documents are in the public domain since they were issued as official Government writing. However, they are considered unpublished since they were not printed for wide public distribution.

[2]More information on these documents can be obtained from their authors at this address.

[7] P. Bauer, "Characteristics of Three-Electrode, Sealed Nickel-Cadmium Cells," IEEE Trans. Aerospace, pp. 784-788, vol. AS-2, April 1964.

[8] R. L. Falzone, Ed., Nickel-Cadmium Battery Application Engineering Handbook, General Electric Co., 189 pp., 1971, Library of Congress Cat. Card No. 71-152881.

[9] L. Belove, "Applications for Sealed Nickel-Cadmium Batteries," Appliance Engineer, vol. 3, March 1969.

[10] R. F. Chase, "Power for Portables," IEEE Trans. Vehicular Technol., pp. 248-251, vol. VT-19, Nov. 1970.

[11] W. B. Burkett and R. V. Jackson, "Rapid Charging of Batteries", Jan. 1967, U. S. Patent 3,517,293.

[12] W. B. Burkett and R. V. Jackson, "Termination of Rapid Charging of Batteries", Sept. 1971, U. S. Patent 3,609,503.

[13] W. B. Burkett and R. V. Jackson, "Rapid Charging of Batteries," Oct. 1971, U. S. Patent 3,614,583.

[14] Minimum Standards for Portable/Personal Land Mobile Communications FM or PM Equipment 25-470 MC, Electronic Industries Association, EIA Standard RS-316, July 1965.

[15] American National Standard Specifications for Dry Cells and Batteries, American National Standards Institutes, Inc., ANSI C18.1-1969, 1970.

☆ U.S. GOVERNMENT PRINTING OFFICE : 1973 O—519-706

USCOMM - ERL

OTHER PUBLICATIONS OF THE LAW ENFORCEMENT STANDARDS PROGRAM *

Standards

NILECJ-STD-0101.00, March 1972, "Ballistic Resistance of Police Body Armor" (Stock No. 2700-0155; Price 25 cents).

NILECJ-STD-0102.00, March 1973, "Hearing Protectors for Use on Firing Ranges" (Stock No. 2700-00182; Price 40 cents, domestic postpaid; 30 cents, GPO Bookstore).

Reports

LESP-RPT-0201.00, May 1972, "Batteries Used with Law Enforcement Communications Equipment - Comparison and Performance Characteristics" (Stock No. 2700-0156; Price 50 cents).

LESP-RPT-0501.00, May 1972, "Emergency Vehicle Warning Devices - Interim Review of the State-of-the-Art Relative to Performance Standards."

* Please order publications for which a price is indicated by title and stock number, and enclose remittance payable to the Superintendent of Documents, Government Printing Office, Washington, D. C. 20402. Single copies may be obtained from the National Criminal Justice Reference Service, Law Enforcement Assistance Administration, U. S. Department of Justice, Washington, D. C. 20530.

END