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LAW ENFORCEMENT STANDARDS PROGRAM

BATTERIES USED WITH LAW ENFORCEMENT COMMUNICATIONS EQUIPMENT

COMPARISON AND PERFORMANCE CHARACTERISTICS

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

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COMPARISON AND PERFORMANCE CHARACTERISTICS

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

by

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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 is conducting research leading to the development and promulgation of national voluntary equipment 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.

Standards, user guidelines, state-of-the-art surveys, and other reports will be issued under the LESL program in such areas as the following: vehicles, security systems, weapons systems, protective equipment and clothing, communications equipment and supplies, emergency equipment, and concealed objects detectors.

This document, Batteries Used with Law Enforcement Communications Equipment: Comparison and Performance Characteristics is issued for information purposes. It describes some of the preliminary work on the preparation of a standard on battery selection and application.

Technical comments and suggestions for revision are invited from all interested parties. Suggestions should be addressed to: 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.

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COMPARISON AND PERFORMANCE CHARACTERISTICS FOR BATTERIES USED WITH LAW ENFORCEMENT COMMUNICATIONS EQUIPMENT

by

R. L. Jesch and I. S. Berry

ABSTRACT

This report is the result of an extensive literature search conducted in the field of primary and secondary batteries. It lists terms and definitions pertaining to batteries and their characteristics, reviews basic battery principles and types, and assembles performance characteristics of battery systems into chart form for comparative purposes. Considered are recommended batteries, basic precautions and references to pertinent literature.

1. INTRODUCTION

The information and data compiled in this report were obtained from publications of recognized leaders in the field of batteries and from manufacturers' battery data. This report organizes the important battery ideas and characteristics into a form that is meaningful and helpful in preparing a voluntary standard for battery selection and application by the Law Enforcement Standards Laboratory. When completed, this voluntary standard is intended to serve as a guide in assisting law enforcement agencies in the proper selection and usage of batteries with the emphasis directed toward battery-operated communications equipment.

2. DEFINITIONS

Ampere-Hour

A unit-quantity of electricity used as a measure of the amount of electrical charge that may be obtained from a storage battery before it requires recharging. One ampere-hour is equal to a current of one ampere flowing for one hour [1] p. 46.

Ampere-Hour Capacity

Of a storage battery, the number of ampere-hours which can be delivered on discharge. The ampere-hour capacity of a battery on discharge is determined by a number of factors, of which the following are the most important: Final limiting voltage; quantity of electrolyte; discharge rate; density of electrolyte; design of separators; temperature, age, and life history of battery; and number, design, and dimensions of plates [1] p. 46.

Battery

A device which transforms chemical energy into electric energy. The term is usually applied to a group of two or more electric cells connected together electrically. In common usage, the term battery is also applied to a single cell, such as a flashlight battery.

Types. There are in general two type of batteries: primary batteries, and secondary storage or accumulator batteries. Primary types, although sometimes consisting of the same active materials as secondary types, are constructed so that only one continuous or intermittent discharge can be obtained. Secondary types are constructed so that they may

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[1] Figures in brackets indicate literature references at the end of this report.

be recharged, following a partial or complete discharge, by the flow of direct current through them in a direction opposite to the current flow on discharge. By recharging after discharge, a higher state of oxidation is created at the positive plate or electrode and a lower state at the negative plate, returning the plates to approximately their original charged condition [2] Vol. 2, p. 111.

Battery Capacity

The electric output of a cell or battery on a service test delivered before the cell reaches a specified final electrical condition and may be expressed in ampere-hours, watt-hours, or similar units [1] p. 161. The capacity in watt-hours is equal to the capacity in ampere-hours multiplied by the battery voltage.

Battery Charger

A device capable of supplying electrical energy to a battery [3] p. G-2.

Battery-Charging Rate

Of a storage battery, the current expressed in amperes at which a battery is charged [1] p. 161.

Battery Voltage, final

The final voltage of a battery is the prescribed lower-limit voltage at which battery discharge is considered complete. The cutoff or final voltage is usually chosen so that the useful capacity of the battery is realized. The cutoff voltage varies with the type of battery, the rate of discharge, the temperature, and the kind of service in which the battery is used. The term "cutoff voltage" is applied more particularly to primary batteries, and "final voltage" to storage batteries [1] p. 162. <u>Syn</u>. Voltage, cutoff.

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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 [3] p. G-2.

Charge

Charge, applied to a storage battery, is the conversion of electric energy into chemical energy within the cell or battery. This restoration of the active materials is accomplished by maintaining a unidirectional current in the cell or battery in the opposite direction to that during discharge; a cell or battery which is said to be charged is understood to be fully charged [4] p. 13.

Charge, state of

Condition of a cell in terms of the capacity remaining in the cell [5] p. 19.

Charging

Process of supplying electrical energy for conversion to stored chemical energy [5] p. 19.

Constant-Current Charge

A constant-current charge of a storage battery is a charge in which the current is maintained at a constant value. For some types of lead-acid batteries this may involve two rates called the starting and finishing rates [4] p. 14.

Constant-Voltage Charge

A constant-voltage charge of a storage battery is a charge in which the voltage at the terminals of the battery is held at a constant value [4] p. 14.

Cycle

One sequence of charge and discharge. Deep cycling requires that all the energy to an end-voltage established for each system be drained from the cell or battery on each discharge. In shallow cycling, the energy is partially drained on each discharge; i.e., it may be any value up to 50 percent [6] p. D-1.

Cycle Life

For secondary rechargeable cells or batteries, the total number of charge/discharge cycles before the cell or battery becomes inoperative [6] p. D-1. In practice, end-of-life is usually considered to be reached when the cell or battery delivers about 80 percent of rated ampere-hour capacity.

Discharge

The conversion of the chemical energy of the battery into electric energy [1] p. 385.

Discharge, deep

Withdrawal of all electrical energy to the end-point voltage before the cell or battery is recharged [5] p. 19.

Discharge, high-rate

Withdrawal of large currents for short intervals of time, usually at a rate that would completely discharge a cell or battery in less than one hour [5] p. 19.

Discharge, low-rate

Withdrawal of small currents for long periods of time, usually longer than one hour [5] p. 20.

Drain

Withdrawal of current from a cell [5] p. 19.

Dry Cell

A primary cell in which the electrolyte is absorbed in a porous medium, or is otherwise restrained from flowing. Common practice limits the term dry cell to the Leclanché cell, which is the major commercial type [2] Vol. 4, p. 276.

Electrode

An electrical conductor through which an electric current enters or leaves a conducting medium, whether it be an electrolytic solution, solid, molten mass, gas, or vacuum. For electrolytic solutions, many solids, and molten masses, an electrode is an electric conductor at the surface of which a change occurs from conduction by electrons to conduction by ions. For gases and vacuum, the electrodes merely serve to conduct electricity to and from the medium [2] Vol. 4, p. 471.

Electrolyte

A chemical compound which when fused or dissolved in certain solvents, usually water, will conduct an electric current. All electrolytes in the fused state or in solution give rise to ions which conduct the electric current [2] Vol. 4, p. 484.

End-of-Discharge Voltage

The voltage of the battery at termination of a discharge but before discharge is stopped [3] p. G-3.

Energy

Output capability; expressed as capacity times voltage, or watt-hours [5] p. 19.

Energy Density

Ratio of cell energy to weight or volume (watt-hours per pound, or watt-hours per cubic inch) [5] p. 19.

Float Charging

Method of recharging in which a secondary cell is continuously connected to a constant-voltage supply that maintains the cell in fully-charged condition [5] p. 19.

Internal Resistance

The internal resistance of a cell or battery is the resistance to the flow of an electric current within the cell or battery [4] p. 9.

Negative Terminal

The negative terminal of a battery is the terminal toward which positive electric charge flows in the external circuit from the positive terminal [4] p. 9. (See positive terminal.)

Parallel Connection

Parallel connection is the arrangement of cells in a battery made by connecting all positive terminals together and all negative terminals together, the voltage of the group being only that of one cell and the current drain through the battery being divided among the several cells [4] p. 10. (See series connection.)

Polarity

The polarity of a battery is an electrical condition determining the direction in which current tends to flow on discharge. By common usage, the discharge current is said to flow from the positive electrode through the external circuit to the negative terminal [4] p. 9.

Positive Terminal

The positive terminal of a battery is the terminal from which the positive electric charge flows through the external circuit to the negative terminal when the cell discharges [4] p. 8. (See negative terminal.)

Primary Battery

A battery made up of primary cells [1] p. 975. (See primary cell.)

Primary Cell

A cell designed to produce electric current through an electrochemical reaction which is not efficiently reversible. Hence the cell, when discharged, cannot be efficiently recharged by an electric current [1] p. 975.

Note: When the available energy drops to zero, the cell is usually discarded. Primary cells may be classified by the types of electrolyte used.

Rechargeable

Capable of being recharged; refers to secondary cells or batteries [5] p. 20.

Secondary Battery

A battery made up of secondary cells [1] p. 1156. (See storage battery; storage cell.)

Series Connection

Series connection is the arrangement of cells in a battery made by connecting the positive terminal of each successive cell to the negative terminal of the next adjacent cell so that their voltages are additive [4] p. 10. (See parallel connection.)

Shelf Life

For a dry cell, the period of time (measured from date of manufacture), at a storage temperature of 70°F, after which the cell retains a specified percentage (usually 90 percent) of its original energy content [5] p. 20.

Storage Battery

An assembly of identical cells in which the electrochemical action is reversible so that the battery may be recharged by passing a current through the cells in the opposite direction to that of discharge. While many nonstorage batteries have a reversible process, only those that are economically rechargeable are classified as storage batteries [2] Vol. 13, p. 153. Syn. Accumulator; Secondary Battery. (See secondary cell.)

Storage Cell

An electrolytic cell for the generation of electric energy in which the cell after being discharged may be restored to a charged condition by an electric current flowing in a direction opposite to the flow of current when the cell discharges [1] p. 1239. Syn. Secondary Cell. (See storage battery.)

Terminals

The terminals of a battery are the parts to which the external electric circuit is connected [4] p. 8.

Trickle Charging

Method of recharging in which a secondary cell is either continuously or intermittently connected to a constant-current supply that maintains the cell in fully charged condition [5] p. 20.

Voltage, cutoff

Voltage at the end of useful discharge [5] p. 19. (See Voltage, end-point.)

Voltage, end-point

Cell voltage below which the connected equipment will not operate or below which operation is not recommended [5] p. 19.

Voltage, nominal

Voltage of a fully-charged cell when delivering rated current [5] p. 20.

Wet Cell

A cell, the electrolyte of which is in liquid form and free to flow and move [1] p. 1400.

3. BASIC BATTERY PRINCIPLES AND TYPES

The term "battery" is usually applied to a group of two or more voltaic cells connected together electrically. In common usage, the term "battery" is often incorrectly applied to a single cell such as "flashlight battery." In any event, these cells contain a positive electrode, a negative electrode, and an electrolyte that form an electrochemical system which produces electrical energy. The electrochemical system of a battery has certain basic characteristics that are a function of the particular materials used for the electrodes and the electrolyte [7]. Different electrochemical system compositions produce different basic characteristics, such as voltage, that must be determined before a battery can be specified. Unfortunately, ideal characteristics cannot be found in any one battery, and the characteristics of one battery cannot always be compared directly with the features of another. However, the discussion of these basic characteristics will help to indicate which features of various batteries are most suitable for a particular application.

There are, in general, two groups of batteries: primary batteries and secondary or storage batteries.

3.1. Primary Batteries

Primary batteries [8], [9] are so constructed that only one continuous or intermittent discharge can be obtained. Once a completely discharged state is reached, the battery is generally discarded and replaced with a new battery [10]. Primary batteries may be categorized into six major subgroups [11] and classified by the type of electrolyte used.

1. Electromotive Force Standard Cells.
2. Solid-Electrolyte Cells.
3. Wet Cells.
4. Reserve Cells.
5. Fuel Cells.
6. Dry Cells.

3.1.1. Primary "Dry" Batteries

The dry battery is a widely known and accepted means of supplying energy to low-power devices [12]. The only primary batteries discussed in this report are of the "dry" type.

Carbon-Zinc

The carbon-zinc battery, sometimes referred to as the Leclanché cell [13], produces a nominal output of 1.5 volts per cell and is best known for its use in flashlights.

Alkaline

The alkaline battery [11] is very similar to the carbon-zinc battery except for the highly alkaline electrolyte that is used. It is best suited to high drain applications and usually lasts twice as long as the carbon-zinc battery.

Mercury

The mercury battery [5] produces a nominal output of 1.4 volts per cell and is known for its flat voltage discharge characteristics. Mercury batteries are used as reference sources in regulated power supplies, electronic computers, voltage recorders and other similar equipment. Its high energy density and long shelf life suit it to use in emergency transmitters.

Other "Dry" Batteries

Two other primary batteries of interest not compared in this report are the silver-oxide battery and the newly developed lithium battery [14]. The silver-oxide battery [5] is well known for its use in miniature power sources as in hearing aids and electric watches. The new lithium battery reportedly has a very high energy density, a shelf life of one year, and a working voltage of 2.6 volts per cell.

3.2. Secondary (Storage) Batteries

Secondary (storage) batteries [15] are so constructed that they may be recharged, following a partial or complete discharge, by applying a direct current to the battery in a direction opposite to that of the current flow on discharge. This means that this type of battery can be charged and discharged many times before battery replacement is required. Secondary batteries fall into two general classifications: lead-acid and alkaline. The lead-acid type is so classified because the electrolyte is an acid (sulfuric), and the electrodes are plates of lead. The alkaline types are so classified because the electric energy is converted from chemical action through an alkaline solution which is used in nickel-iron, nickel-cadmium and silver-zinc batteries.

Lead-Acid

The lead-acid battery is probably best known for its use in automobiles and has been the workhorse of the rechargeable battery types for many years, being able to supply large currents at a relatively high output of 2.0 volts per cell. Recent technological advancements in the field of lead-acid batteries have resulted in the development of a sealed lead-acid battery that is rechargeable, spill-resistant and portable [16], [17]. This sealed battery looks promising for applications in portable and mobile communications equipment.

Nickel-Iron

The nickel-iron battery, also known as the Edison battery, produces an average voltage on discharge of 1.2 volts per cell. These batteries have been used extensively in industrial trucks and for standby or emergency sources of power. (The characteristics of this battery were not used for comparative purposes in this report.)

Nickel-Cadmium

The nickel-cadmium battery, also known as the Jungner battery, is quite similar to the nickel-iron battery except that cadmium is used in place of iron for the negative electrode. The average voltage on discharge is 1.2 volts per cell. These batteries are noted for their use in portable devices that normally require more energy over a period of time than is ordinarily available from primary batteries. Nickel-cadmium batteries are used extensively in portable and mobile communications equipment.

Silver-Zinc

Silver-zinc batteries produce a nominal output of 1.5 volts per cell. These batteries are noted for their high watt-hour capacity per unit volume or weight and are used primarily for military applications where battery power with minimum weight is an essential consideration, as in space satellites and torpedoes.

4. BATTERY COMPARISON

Table I is the chart of Battery Comparison for Mobile and Portable Communications Equipment which is divided into two main categories: Secondary (Storage) Batteries and Primary "Dry" Batteries.

Battery types listed which are used in mobile and portable communications equipment include: the nickel-cadmium sealed type storage batteries using either sintered plates or pocket plates, the primary "dry" mercury type useful as an interim replacement for the nickel-cadmium type, and the sealed lead-acid type recently commercially available.

TABLE 1

BATTERY COMPARISON FOR MOBILE AND PORTABLE COMMUNICATIONS EQUIPMENT

++ = Much above avg.
\+ = Above avg.
Avg. = Average
– = Below avg.
— = Much below avg.

SECONDARY BATTERIES	Volts per Cell	Nominal Capacity (Amp–Hrs)	High Rate Discharge (Amps)	Internal Resistance (Ohms)	Charging Capability	Charge Retention	Operation at		Energy Density (Wh/lb Wh/in^3)	Deep Discharge (Cycles)	Estimated Total Life (Yrs)	Applications
							High Temp. >122° F	Low Temp. <32° F				
Nickel–Cadmium sealed sintered plates	1.2	0.2–160	++	–	avg.	—	+	+	–	200–2000	2–10	Mobile and portable communication equipment. Cordless home appliances and power tools.
Nickel–Cadmium sealed pocket plates	1.2	0.05–70	+	–	–	avg.	avg.	avg.	–	100–250	5	Same
Lead–Acid sealed	2.0	0.9–7.5	avg.	–	avg.	+	+	+	–	100–400	4–5	Same
Lead–Acid vented	2.0	0.1–120	avg.	–	avg.	—	+	avg.	–	200–700	3–6	Automobile starting, lighting & ignition.
Silver–Zinc	1.5	0.1–300	++	–	–	–	avg.	avg.	+	1–80	0.02–2	Torpedoes. High energy density available.
PRIMARY "DRY" BATTERIES												
Mercury	1.3	0.04–14	avg.	+		++	++	–	++		Depends on use	Can replace rechargeable batteries in portable and mobile equipment.
Alkaline	1.5	0.58–10	+	avg.		+	+	avg.	+		Depends on use	Radios and model toys.
Carbon–Zinc	1.5	1–6	—	avg.		avg.	–	–	avg.		Depends on use	Flashlights, small toys.

Several types of batteries, not ordinarily used in mobile and portable communications equipment, are also included in the chart mainly for comparative purposes. These batteries serve as references against which to compare characteristics of the battery types used in communications equipment. These types include: the lead-acid vented storage battery (such as used in automobiles, etc.), the silver-zinc battery (used in torpedoes, etc.), the carbon-zinc battery (used in flashlights, etc.), and the dry alkaline type (used in portable tape recorders, etc.).

It was necessary to obtain ample data and information on particular battery types from battery literature and manufacturers' battery data, in order to determine ratings for the performance characteristics shown in table I. The ratings were determined by arriving at an average value of each performance characteristic based on data obtained for all battery types listed in table I.

4.1. Volts Per Cell

Described here is the nominal operating voltage of each individual type of cell under actual loaded operating conditions for a battery of the type listed. This cell voltage is primarily a characteristic of the particular material used for the electrodes and the electrolyte.

Several cells are usually connected in series to construct a battery having higher voltage. For example, some of the nickel-cadmium sealed batteries used in portable and mobile communications equipment consist of twelve cells connected in series to obtain nominally 14.4 volts required for operation.

4.2. Nominal Capacity in Ampere-Hours

This column lists the ranges of battery capacities that are generally commercially available. The smallest figure shows that some small nickel-cadmium batteries are manufactured with only 0.2 ampere-hour capacity. The high figure indicates that batteries with capacities as great as 160 ampere-hours are available, but not all the batteries in this capacity range (0.2 to 160 amp-hr.) are in the physical configuration, voltage and current ranges used in mobile and portable transceivers utilized by law enforcement agencies.

Carbon-zinc dry cells are not usually rated by ampere-hour capacity, because their capacity depends largely on the "discharge" and "rest between discharge" cycle, which is usually difficult to predict or estimate.

4.3. High-Rate Discharge

High rate discharge, as applied in this report, means using batteries where currents are such that the entire capacity of the battery is expended in less than one hour. Few types of communications equipment, classed as mobile or portable, require current of more than one ampere for normal operation. Where high currents are required, the best battery among those shown in table I is the sealed nickel-cadmium with sintered plates [18]. The carbon-zinc battery is a very poor source of high current.

4.4. Internal Resistance

The internal resistance of a battery [15] increases and the nominal voltage decreases throughout its useful life.

Since internal resistance opposes the flow of electric charge within a cell, the ability to draw the required amount of current from a battery is enhanced by the battery having low internal resistance. As shown in table I, the internal resistance of secondary (storage) batteries is relatively low.

The mercury type primary "dry" battery has above average internal resistance. This limits its use to applications requiring only average or lower current discharge under operating conditions.

4.5. Charging Capability

Charging of batteries should be carried out strictly in accordance with the manufacturers' instructions. For example, the constant-current method is normally used for charging sealed nickel-cadmium batteries because constant-potential charging increases the risk of thermal runaway [6], [18]. This is a condition in which the charging current for a fully-charged nickel-cadmium battery rises out of all proportion to the impressed voltage. Runaway occurs after the battery is fully charged and the excess charging current is dissipated as heat as shown in figure 1. This can permanently damage batteries which are constructed without a resealing safety vent.

4.6. Charge Retention

As indicated in table I, the charge retention of batteries stored at room temperature varies considerably among the different types of batteries. Means are available for improving the charge retention for some types of batteries. For example, the sintered-plate type sealed nickel-cadmium

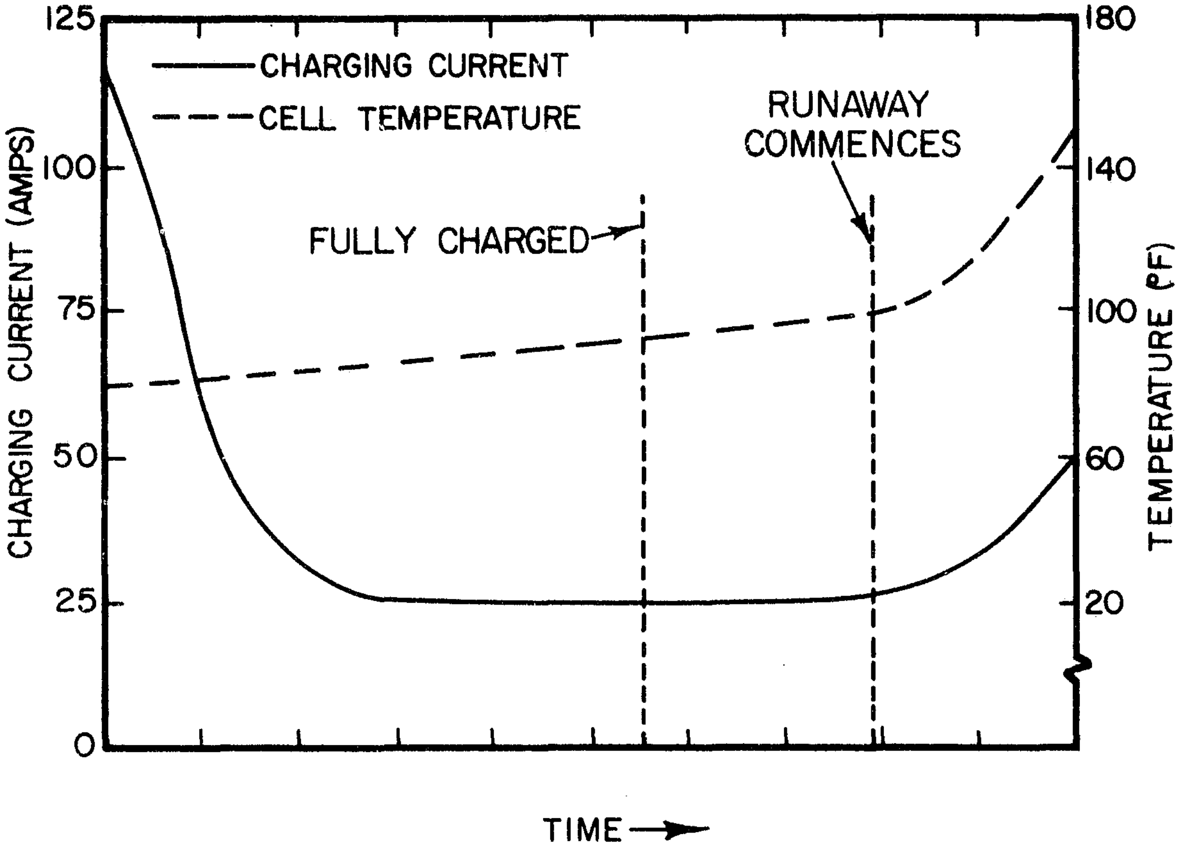

Figure 1. Thermal runaway in a sealed nickel-cadmium battery caused by constant-potential charging [6].

battery has a much shorter charge retention if improperly stored. Most of its usable charge will be spent within the range indicated in figure 2 after six months of storage at room temperature. However, if these batteries are stored at 32°F, nearly all of the charge is still available even after six months of storage.

The pocket-plate type sealed nickel-cadmium battery retains most of its charge during six months of storage at room temperature, but more of its charge is retained when stored at lower temperatures. The ability of a secondary battery to remain charged while stored may not be a problem, in some cases, if the battery is discharged and recharged regularly.

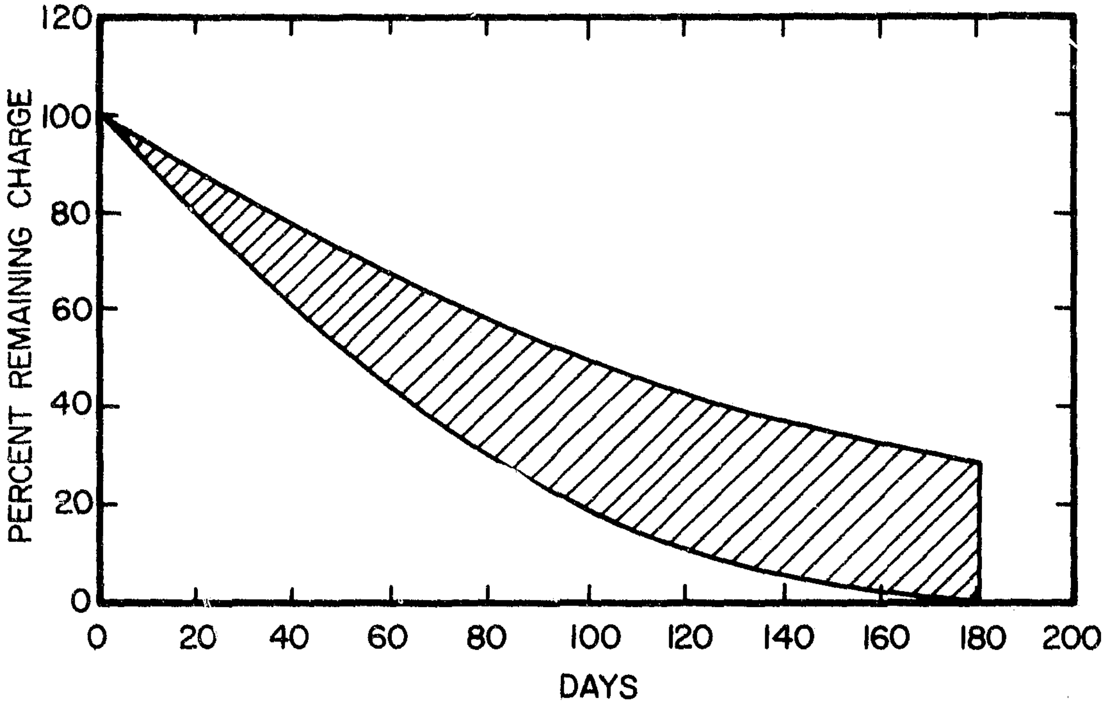

Figure 2. Charge retention of sealed nickel-cadmium sintered cells at room temperature [18].

Primary mercury types have excellent shelf life and lose very little of their capacity during storage at room temperature even after several years [8].

4.7. High-Temperature Operation

Most of the batteries compared operate reasonably well at temperatures up to approximately 120°F. The sealed nickel-cadmium batteries usually operate best at temperatures from approximately 68°F to 86°F; their capacities decrease at temperatures outside this range. Most sintered-plate batteries operate satisfactorily at temperatures as high as 140°F; whereas the pocket-plate type can operate only up to about 110°F, as shown in figure 3.

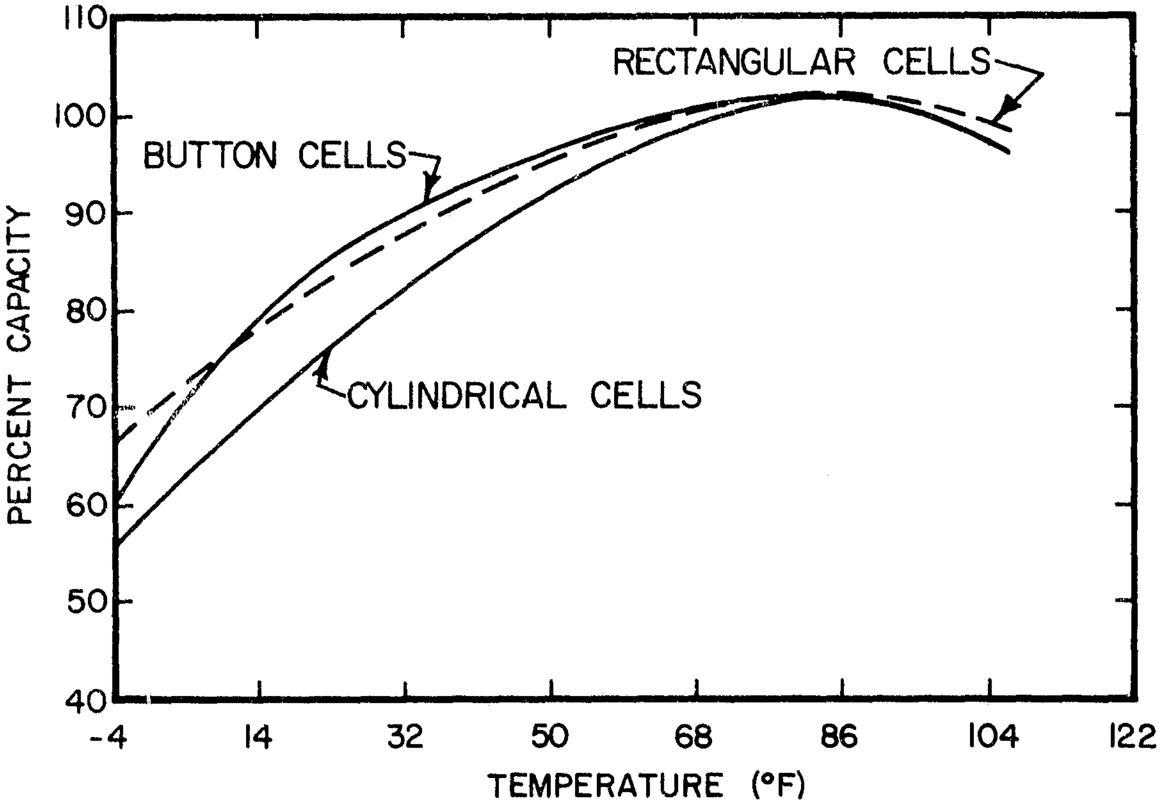

Figure 3. Effect of temperature on capacity of sealed pocket-type nickel-cadmium batteries [18].

Mercury batteries operate best above approximately 50°F as shown in figure 4, and are ideal for use during summer seasons and in hot climates. Only about half of the mercury battery capacity is available at 40°F, which reinforces its use primarily at the higher temperatures.

4.8. Low-Temperature Operation

Some types of batteries are specifically designed for low-temperature operation below 32°F. The sintered-plate type sealed nickel-cadmium battery can operate down to about -40°F and the pocket-plate type to approximately -5°F.

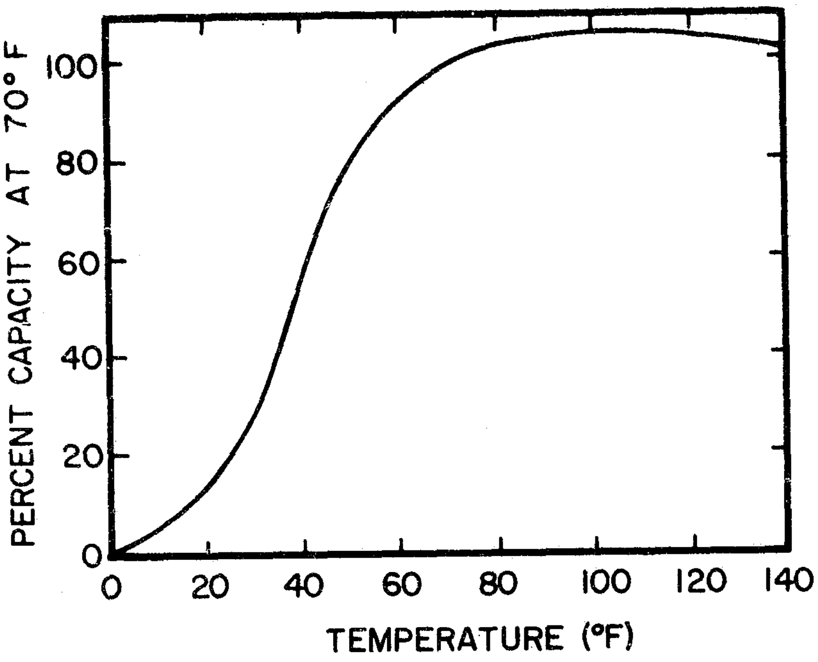

Figure 4. Effect of temperature on capacity of mercury cells [8].

The carbon-zinc battery does not operate satisfactorily at lower temperatures. Most of the other types of batteries listed exhibit average or better characteristics at lower temperatures. Operation is enhanced when they are used at temperatures above 32°F.

4.9. Energy Density

The primary mercury battery is outstanding and alkaline batteries have above average energy densities, while the carbon-zinc type is average in this respect.

Most of the secondary (storage) batteries are below average in energy density (watthours per pound and watthours per cubic inch), with the silver-zinc type being above average.

4.10. Deep Discharge

The "Deep Discharge" column in table I indicates the number of times each type of battery can have 70% of its capacity removed by discharging and can then be recharged to its full capacity.

The number of times each type of battery can be "deeply discharged" varies considerably; for instance, the sintered-plate sealed nickel-cadmium type can be recycled several hundred times while the silver-zinc type indicates a maximum of 80 recycles [18]. The other types fall between these two.

4.11. Estimated Total Lifetime

The sealed sintered-plate nickel-cadmium battery has an estimated lifetime of up to 10 years, while the silver-zinc battery has a possible total lifetime of only 2 years.

Possible lifetime for the other types of secondary batteries varies from 5 to 6 years [18]. For the primary dry batteries, lifetime depends largely on the discharge and rest between discharge cycle. Consequently, no lifetime in years can be meaningfully stated.

5. RECOMMENDED BATTERIES

From the previous sections it is apparent why the sintered-plate sealed nickel-cadmium type battery is recommended for use in mobile and portable communications equipment--especially for law enforcement agencies. Next best is the pocket-plate sealed nickel-cadmium type battery.

The sealed lead-acid type battery also looks promising for use in mobile and portable communications equipment. Information on this type of battery is very limited. An objective examination of the manufacturers' published performance characteristics and experimental measurements to verify these characteristics, should be performed. Results of this investigation could verify or change the comparative ratings of the sealed lead-acid type battery as listed in table I. Presently available manufacturers' specifications do not list a sealed lead-acid battery which is physically the right size with the required voltage and capacity to be immediately usable in mobile or portable transceivers. When sealed lead-acid batteries of the correct configuration become available, field tests will be helpful in determining whether this type of battery is suitable for this application by law enforcement agencies. The high cost of the silver-zinc battery limits the use of this system mainly to areas where cost is of minor importance, such as in military and space applications.

Advantages of the sealed nickel-cadmium sintered-plate batteries include: (1) better high and low temperature operation than the pocket-plate type, (2) the capability of more deep discharge cycles than either the pocket-plate nickel-cadmium or sealed lead-acid types, (3) longer probable lifetime and (4) lower overall cost when prorated over the entire lifetime.

Disadvantages of the sintered-plate sealed nickel-cadmium type batteries include: (1) initial cost is about 20% higher than the pocket-plate nickel-cadmium type and (2) poor charge retention during storage for six months at room temperature. Refer to section 4.6 on Charge Retention.

Most of the other characteristics listed in table I show that the sealed sintered-plate nickel-cadmium batteries are approximately equivalent to those of the pocket-plate and sealed lead-acid batteries.

6. PRECAUTIONS IN USING RECHARGEABLE BATTERIES

6.1. Memory Effect

Sealed nickel-cadmium cells given a repetitive shallow discharge under certain cycling conditions may exhibit an apparent temporary loss of capacity; this is sometimes called "memory." Referring to figure 5, if the cell experiences a repeated series of partial charge and discharge cycles of similar magnitudes, it may become conditioned to deliver only slightly more capacity than has been required of it during these preceding repetitive cycles. This effect may also occur when sealed nickel-cadmium cells are overcharged for long periods of time. Thus, especially if the discharge cycles are short, the cell capacity may be temporarily shortened. This "memory effect" of decreased capacity can be essentially erased by deeply discharging and then recharging the cell for a few cycles; nearly all of the original cell capacity can be regained by using this procedure [3]. However, care must be taken when deeply discharging a multi-cell battery where the individual cell is inaccessible. A battery can be permanently damaged by trying repeatedly to reduce its stored energy to zero. (See section 6.3 on Discharging.)

6.2. Safety Vents

All sealed-cell batteries should have adequate safety vents. Resealable vents are preferred. Vents are necessary to keep the cells and batteries from exploding if excessive internal pressure builds up when they are charged or discharged too rapidly. Rupturing of cells located inside electronic equipment can sometimes damage an expensive piece of equipment beyond repair.

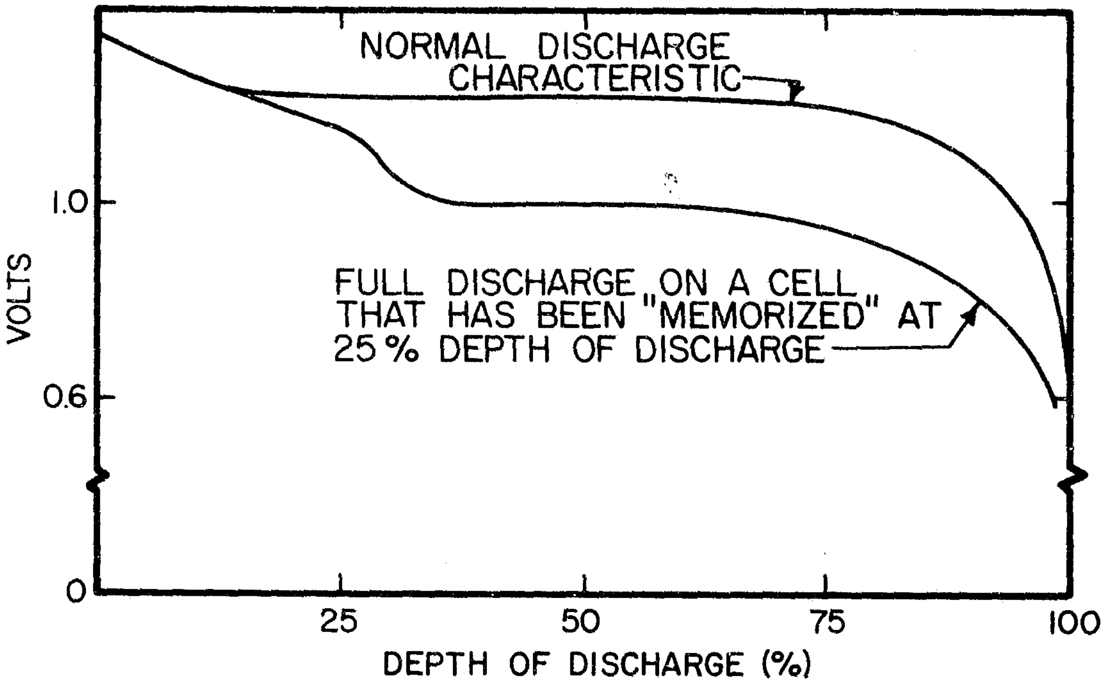

Figure 5. Temporary memory effects of nickel-cadmium batteries resulting from repetitive charge/discharge cycling [3].

The resealable safety vent allows internal gas to escape before the pressure can damage the cell and helps to provide essentially normal operation after resealing--provided the electrolyte does not escape or the vent fails to reseal [3].

6.3. Discharging

The number of times multi-cell batteries are deeply discharged should be kept to a minimum. When cells are assembled into batteries, the cells are usually grouped by placing those with similar capacities in one battery. Cell capacities are not identical and, because of slight differences in capacity, one or more cells will expend their stored energy before the others during discharge. When the lowest capacity cell reaches zero voltage before the other cells, it starts into reverse charge because the rest are still discharging through it. Reverse charging builds up internal pressure due to the generation of gas during charging. This usually results in the opening of the safety vent which, when repeated several times, can adversely affect battery performance. A multi-cell rechargeable battery can be permanently damaged by trying repeatedly to reduce its stored energy to zero during very deep discharge before recharging it.

It is recommended that the discharge be stopped when the battery voltage reaches the following minimum value [3]:

$$V_m = V_c (N - 1) - 0.2$$

where: V_m is minimum voltage for battery operation,

V_c is nominal cell voltage,

N is the number of cells in the battery.

Multi-cell batteries are sometimes tapped to give two or more voltage levels. Preferably, rechargeable batteries should not be tapped because the cells providing energy to both voltage level circuits will be drained at a faster rate than the other cells. This can lead to reverse charging of some cells while the others are being discharged.

Series discharging of multi-cell rechargeable batteries is permissible if the batteries are of the same capacity and are not discharged too deeply.

Parallel discharging of rechargeable batteries is acceptable provided that the voltage ratings are the same or that reverse current protection is provided.

6.4. Charging

A term frequently used in discussing secondary batteries is the battery capacity, "C," expressed in ampere-hours. (See section 2, Definitions.) The C concept is a convenient means of describing discharging and charging systems without reference to the absolute battery capacity. The battery capacity, "C," is a quantity of charge which a fully-charged battery is capable of delivering. This quantity will generally depend upon the rate at which the charge is withdrawn, the temperature, and the end-of-discharge voltage. The rate of discharge, that is the discharge current, is often normalized to the battery capacity and expressed as a fraction of C. Thus, a battery with a C of 10 ampere-hours discharged at a 2 ampere rate would be said to have a discharge rate of 0.2 C. The normalized current is sometimes referred to as the "C" rate.

When charging most sealed nickel-cadmium batteries, the charge current should not exceed 0.1 C. However, for some specially designed quick-charge cells, the maximum charge current can sometimes be as high as 0.3 C.

If the overcharge capability of the cell is exceeded, gas at high pressure will develop and the safety vent will relieve the excess pressure. If the excess charge current is not terminated, the resealable safety vent will continue to open until the cell is dried out, and the cell will then fail prematurely.

Sealed cells should not be charged from a constant-voltage source that is set at too high a voltage, due to the risks of thermal runaway and consequent venting. Sealed cells should not be charged in parallel for the same reason.

6.5. Storing

Sealed-cell batteries should be in an open-circuit condition when stored. Storage with a short-circuit or a load across the terminals may damage some sealed-cell batteries [3].

It is preferable to store sealed sintered-plate nickel-cadmium cells and batteries at temperatures below normal room temperature. Storing them in a refrigerator or home freezer is an easy way to preserve most of the charge during storage for several months.

6.6. Additives

The addition of compounds and mixtures to the electrolyte of lead-acid batteries [19] to improve performance is not required or recommended.

6.7. "Do's and Do Not's" for Batteries

Do

1. Do discharge and recharge sealed nickel-cadmium batteries a few cycles to erase the "memory" effect of below-normal capacity. Deep discharge battery cell by cell or by equation. (See section 6.1 on Memory Effect.)
2. Do use sealed cells having resealable safety vents.
3. Do limit the number of times multi-cell batteries are deeply discharged, in order to prolong battery life.
4. Do establish a minimum voltage limit (see section 6.3) to operate multi-cell batteries; don't discharge them below this minimum voltage, in order to prolong battery life.

5. Do charge sealed nickel-cadmium cells and batteries using a constant-current source. A constant-voltage source may be used only when provided with a special circuit to prevent damage to the cells and batteries.
6. Do store sealed-cell batteries with no load and with no short-circuit across the terminals. Store them in a refrigerator or home freezer to help maintain charged capacity.

Do Not

1. Do not dispose of batteries in a fire [3].
2. Do not try to solder directly to a sealed cell because the seal or safety vent can be damaged by too much heat.
3. Do not attempt to replace one defective cell in a multi-cell battery of matched cells unless you have equipment to grade the cells and properly match the replacement cell to the capacity of the other cells in the battery.
4. Do not place an uninsulated sealed multi-cell battery assembly on a metal bench or other metal surface because this may place a short circuit across the cells.
5. Do not use uninsulated metal tools when working near the connections of a battery. Severe arcing may result when a current path is made between cell terminals.
6. Do not wear rings without wearing gloves when handling charged cells. Severe burns can result from short-circuiting a charged cell. Metal watch bands, jewelry and identification bracelets are also dangerous when working near charged cells.
7. Do not put a charged cell in your pocket. If you have a coin or other metal object in your pocket, the cell may short circuit and produce extreme heat or even explode.

8. Do not get electrolyte on your skin. If you do, wash quickly. Also, neutralize alkaline electrolyte with a mild acid such as vinegar; neutralize acid electrolyte with baking soda and water.

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7. REFERENCES

[1] R. I. Sarbacher, Ed., Encylopedic Dictionary of Electronics and Nuclear Engineering. Englewood Cliffs, N.J.: Prentice-Hall, 1959.

[2] McGraw-Hill Encyclopedia of Science and Technology. New York: McGraw-Hill, 1966.

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

[4] Definitions of Electrical Terms; Group 60 Electrochemistry and Electrometallurgy, ASA C42.60-1957, American Standards Association, Oct. 10, 1956.

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

[6] Handbook Service and Maintenance Instructions; Naval Aircraft Storage Batteries, Publication No. 926-01-1-1001, ARINC Research Corp., prepared for Bureau of Naval Weapons, Dept. of the Navy, under Contract N600(19)61786, Jan. 1965 (Rev. Sept. 1969).

[7] M. Barak, "Batteries and fuel cells," Proc. Inst. Elec. Eng. (GB), pp, 1561-1585, vol. 17, Aug. 1970.

[8] George Wood Vinal, Primary Batteries. New York: Wiley, 1950.

[9] George W. Heise and N. C. Cahoon, Ed., The Primary Battery, Vol. 1, New York: Wiley, 1971, sponsored by The Electrochemical Society, Inc.

[10] "Home flashlight battery chargers: Are they practical? Are they dangerous?," Media Bulletin No. 2006, National Better Business Bureau, Inc., Nov. 1969.

[11] RCA Battery Manual, Radio Corporation of America, Electron Tube Div., 17 pp., (undated).

[12] "D-cell batteries," Consumer Reports, pp. 718-722, Nov. 1971.

[13] Walter J. Hamer, "Evaluation procedures and annual performance data for Leclanché cells," Electrochemical Technology, pp. 490-498, Nov.-Dec. 1967.

[14] "Long-life lithium battery on horizon," p. 16, EDN/EEE, Nov. 1, 1971.

[15] George Wood Vinal, Storage Batteries, New York: Wiley, 1955.

[16] "Gel/Cell Rechargeable Batteries," Globe Battery Div., Globe-Union, Inc., Publication 41-1322, 9 pp. (undated).

[17] "Battery touts highest watt-hours per dollar," EDN, p. 54, Apr. 1, 1971.

[18] S. Uno Falk and Alvin J. Salkind, Alkaline Storage Batteries. New York: Wiley, 1969, sponsored by The Electrochemical Society, Inc.

[19] *Report of the Committee on Battery Additives of the National Academy of Sciences*, National Academy of Sciences--National Research Council, Oct. 30, 1953.

References Not Cited in This Report

[20] E. F. Lindsley, "Everything you always wanted to know about all those little batteries," Popular Science, pp. 46-48 & 116, Jan. 1971.

[21] *Burgess Engineering Manual; Complete Battery Data for the Design Engineer*, Gould, Inc., Burgess Battery Div., Form No. 1418, 146 pp., 1971, Library of Congress Cat. Card No. 58-12558.

[22] "Characteristics and Uses of Nickel-Cadmium Batteries," The International Nickel Co., Inc., 26 pp., 1966.

[23] *Battery Engineering Information*, ESB, Inc., Ray-O-Vac Div., 24 pp., (undated).

[24] C. L. Mantell, *Batteries and Energy Systems*, New York: McGraw-Hill, 1970.

[25] Raymond Jasinski, *High-Energy Batteries*, New York: Plenum Press, 1967.

[26] Saul Padwo, "Batteries for cordless, portable appliances," *The Battery Man*, vol. 6, Apr. 1964.

[27] Robert F. Chase, "Power for portables," *IEEE Trans. Vehicular Technol.*, pp. 248-251, vol. VT-19, Nov. 1970.

[28] Louis Belove, "Applications for sealed nickel-cadmium batteries," Appliance Engineer, vol. 3, Mar. 1969.

[29] James J. Craven, Jr., "The nickel-cadmium cell; its characteristics and applications," QST, pp. 82-84, July 1965.

[30] P. Bauer, "Characteristics of three-electrode, sealed nickel-cadmium cells," IEEE Trans. Aerospace, pp. 784-788, vol. AS-2, Apr. 1964.

[31] P. J. Rappaport, "Performance ratings of secondary batteries," Electronics, pp. 60-62, vol. 33, Feb. 19, 1960.

[32] F. Albrecht, "Problems in the selection and testing of nickel-cadmium batteries for satellites," AIEE Trans. Appl. Ind., pp. 84-92, vol. 81, May 1962.

[33] A. S. Cherdak and R. C. Shair, "Determination of state of charge of nickel-cadmium batteries," Proc. Ann. Power Sources Conf., pp. 59-63, 1961.

[34] T. J. Hennigan and K. O. Sizemore, "Charge control of Ag-Cd cells and Ag-Zn cells," Proc. Ann. Power Sources Conf., 1967.

[35] F. Alliegro and B. Mundel, "High-capacity sealed nickel-cadmium batteries," Proc. Ann. Power Sources Conf., pp. 67-69, 1961.

[36] H. Henshall, "Batteries for high altitude applications," IRE Can. Convention Rec., pp. 23-26, 1958.

[37] N. Rhita, "How live is your nickel-cadmium battery?," *Radio-Electronics*, p. 38, vol. 31, Oct. 1960.

[38] A. Fleischer, R. E. Rockey, and G. B. Ellis, "Design factors for nickel-cadmium batteries," *Electrochem. Soc.; Extended Abstracts of Papers Presented at the Sessions of the Battery Division*, abstract no. 1Q, Fall Meeting 1957.

[39] F. Alliegro, Louis Belove, and P. Voyentzie, "High-capacity sealed nickel-cadmium batteries," *Proc. Ann. Power Sources Conf.*, pp. 99-101, 1962, N63-14152.

[40] H. T. Francis, *Space batteries* (handbook), IIT Research Inst., 60 pp., 1964, NASA-SP-5004, N64-18052.

[41] D. C. Bomberger and L. F. Moose, "Nickel-cadmium cells for the spacecraft battery," *Telestar*, pp. 1687-1702, vol. 3, Jan 1963, NASA-SP-32, N64-11082.

[42] E. Kantner, et. al., "Investigation of hermetically sealed maintenance-free, high rate, nickel-cadmium batteries for aircraft applications," *Quart. Tech. Prog. Rept. No. 3*, 39 pp., Nov. 1965, Gulton Industries, Inc., contract AF33-615-2087, AD-463855.

[43] W. W. Clark, et. al., "Alkaline battery evaluation," *Final Report for 30 June 1960-15 Mar. 1964*, 542 pp., June 1964, Inland Testing Labs., contract AF33(616)7529, APL-TDR64-76, AD-602676.

[44] Performance Forecast of Selected Static Energy Devices, NATO Advisory Group for Aeronautical Research and Development, meeting of Propulsion and Energetics Panel, June 12-16, 1967.

[45] J. Wartell and H. N. Seiger, "Investigation of methods leading to the determination of the state of charge of nickel-cadmium batteries," Final Rept. No. 4, 1 Jan. - 30 Dec. 1963, 96 pp., contract DA-36-039AMC00109(E), AD-435989, N64-20345.

[46] P. F. Grieger, "Auxiliary electrode for charge control of sealed nickel-cadmium batteries," Quart. Prog. Rept. No. 4, 15 Mar. - 14 June 1965, 64 pp., Thomas A. Edison Industries, contract DA-28-043-AMC00152E, AD-469278.

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