Battery Primer
- NiCAD/NiMH and Lead Acid

Jim Nelson
K9QF
Introduction

- Licensed in 1976 an WD9BKC
- BSEE 1981
- Lake County RACES member 1985

Major HR interests include:
- 50Mhz & higher “All Mode” & DX
- Antenna experimenting & construction
- PA’s, Batteries/charging, Power Supplies etc.
Agenda

- Focus on NiCD /NiMH and Lead Acid Batteries
  - Most commonly used in Ham Radio and back-up power
Overview

1. History
2. Concepts
   a. Primary/Secondary
   b. Cells/Batteries
   c. Components
   d. Application
   e. The “C” rate
3. Nickel-Cadmium
   a. Application
   b. Discharge
   c. Charging
   d. Battery Life
4. Sealed Lead Acid
   a. Application
   b. Discharge
   c. Charging
   d. Battery Life
5. Safety
6. Misc. circuit examples
History

- 1800 – Alessandro Volta Voltaic Pile

- 1802 – Johann Ritter Rechargeable Battery
  - Laboratory curiosity until late in the century.

- 1859 – Gaston Plante’ Wound Lead Acid Battery
  - Roll of thin lead plates and rubber sheets

- 1881 – Faure Lead Oxide Paste

- 1910 – Edison Nickel-Iron
  - Potassium Hydroxide (Alkaline) electrolyte

- 1910 – Waldmar Jungner Nickel-Cadmium
History

- 1912 – Charles Kettering “Self-Starter” for Autos
- W.W.II – Sintered-plate, Vented or Flooded NiCad
  - Exceptionally high energy density (for that time).
- 1950 – Sealed NiCad
  - Utilizes Recombined Gasses.
- 1960 – Gelled electrolyte Lead Acid
- 196? – Sealed Lead Acid
  - Utilizes Recombined Oxygen
- Recent Developments:
  - Nickel-Metal-Hydride
  - Nickel-Hydrogen
  - Lithium
Concepts

● Primary:
  – Used ONCE. Chemical reactions irreversible
  – Most common. Cheap, simple
  – $$ priority, low drain. Recharge not feasible
  – Ex. Carbon-Zinc, Alkaline

● Secondary:
  – Chemical reactions reversed when current applied.
  – Industrial, Automotive, big growth in Consumer
  – High current capable.
  – Long term economy
  – Ex. NiCad, Sealed Lead Acid (SLA)
Concepts

- Cells / Batteries
  - Cell is building block – single pair of plates.
  - Cell voltage determined by chemistry, i.e. 2.0v, 1.2v.
  - Battery is an assembly of several Cells.
  - Battery voltage must be a multiple of Cell voltage
  - Batteries and Cells may be a series or parallel combined
  - Cell/Battery capacity:
    - Determined by the amount of active material
    - Measured in Amp-Hours
Concepts

- **Components:**
  - **Negative Electrode**
    - Supplies electrons to external circuit during discharge
  - **Positive Electrode**
    - Accepts electrons from external circuit during discharge
  - **Electrolyte**
    - Completes the circuit internally
    - Alkaline supplies negative ions
    - Acid provides positive ions
  - **Separator**
    - Electrically isolates electrodes
    - Allows closer spacing without internal shorts
Concepts

- **Application Types:**
  - **Float**
    - Spends majority of life on charge
    - Battery is subject to continuous trickle charge
  - **Cyclic**
    - Discharged regularly
    - Battery recharged relatively quickly compared to discharge cycle
Concepts

- The “C” Rate:
  - C rate is the current flow rate numerically related to the cell rated capacity
  - Different cell sizes (capacities) of a family respond similarly to charges or discharges *scaled* by the cells rated capacity.
  - NiCad – 1 or 5 hour rate, SLA – 10 or 20 hour rate

✓ A 20AH SLA *may* deliver 1A for 20 hours, *But will NOT deliver 20A for 1 hour.*
Brain Break
Nickel-Cadmium

Application

Sealed NiCad cells are well suited to a wide variety of applications due to many virtues including:

- High energy density
- High rate discharge capacity
- Fast recharge
- Consistent discharge voltage
- Long operating life
- Long storage life
- Rugged construction
- Operation over a broad range of temperatures
- Operation in a wide range of environments
- Operation in any orientation
- Maintenance free use
- Continuous overcharge capability (within spec.)
Nickel-Cadmium

- **Discharge**
  - NiCad cell charge/discharge reaction does not require the transfer of material from one electrode to the other.
  - The electrodes are long lived, since the active materials in them are not consumed during operation or storage.
  - A sealed NiCad cell operates as a closed system that recycles the gasses created within the cell.
  - The discharge voltage of the sealed NiCad cell remains relatively constant until most of its capacity is discharged, then drops off sharply.
  - High discharge rates affect cell capacity because of the increasing difficulties inherent in electrolyte mass transport and electrode reactions as the current density is increased.
Nickel-Cadmium

- Discharge

*Figure 3-2 Typical Discharge Curves at 23°C*
Nickel-Cadmium

- Discharge

  - Factors affecting capacity:
    - Repeated cell polarity reversal.
    - Excessive charge/overcharge rates.
    - High overcharge cell temperature.
    - Storage at elevated temperatures.
    - High discharge cutoff voltage.
    - Depth of discharge.
    - Normal cell aging.
Nickel-Cadmium

- Discharge

*Figure 3-15 Effect of Discharge Rate on Actual Capacity*
Nickel-Cadmium

- Discharge

*Figure 3-16 Effect of Cell Discharge Temperature on Actual Capacity*
Nickel-Cadmium

- Discharge

**Figure 3-70 Effect of Depth of Discharge on Cycle Life**
Brain Break

"YOU DON'T NEED ANOTHER @*! & RADIO!"

"QRZ"
Nickel-Cadmium

- Charging

*Always charge using constant current.*

- Charge rates:
  - Standard
  - Quick
  - Fast
  - Trickle
# Nickel-Cadmium

- Charging

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

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

**Table 3-3 Definition of Rates for Charging**
Nickel-Cadmium

- Charging

Figure 3-27 Charge Acceptance at Various Charge Rates
Nickel-Cadmium

● Charging

  – Charge control (termination)
    ● Coulometric
    ● Timed
    ● Temperature
    ● Voltage
Nickel-Cadmium

- Charging

*Figure 3-28 Voltage, Pressure, and Temperature Characteristics during Charge at 0.1 C and 23°C*
Nickel-Cadmium

- Charging

Figure 3-29 Voltage, Pressure, and Temperature Characteristics during Charge at 1 C and 23°C
Brain Break
Nickel-Cadmium

- Battery Life

Figure 3-20 Nickel-Cadmium Cell Polarity Reversal Voltages
Nickel-Cadmium

● Battery Life

**Dendritic shorting**
NiCd batteries, when not used regularly, tend to develop dendrites which are thin, conductive crystals which may penetrate the separator membrane between electrodes. This leads to internal short circuits and premature failure, long before the 800–1000 charge/discharge cycle life claimed by most vendors. Sometimes, applying a brief, high-current charging pulse to individual cells can clear these dendrites, but they will typically reform within a few days or even hours. Cells in this state have reached the end of their useful life and should be replaced. Many battery guides, circulating on the Internet and online auctions, promise to restore dead cells using the above principle, but achieve very short-term results at best.
Nickel-Cadmium

- Battery Life

*Figure 2-4 Electrode Performance Schematic*
Nickel-Cadmium

- Battery Life

Figure 3-47 Typical Room-Temperature Charging Voltage Profile for Sealed Nickel-Cadmium Cells
Nickel-Cadmium

• Battery Life

Memory and lazy battery effects
It is sometimes claimed that NiCd batteries suffer from a "memory effect" if they are recharged before they have been fully discharged. The apparent symptom is that the battery "remembers" the point in its charge cycle where recharging began and during subsequent use suffers a sudden drop in voltage at that point, as if the battery had been discharged. The capacity of the battery is not actually reduced substantially. Some electronics designed to be powered by NiCds are able to withstand this reduced voltage long enough for the voltage to return to normal. However, if the device is unable to operate through this period of decreased voltage, the device will be unable to get as much energy out of the battery, and for all practical purposes, the battery has a reduced capacity.
Nickel-Cadmium

- Battery Life

Memory and lazy battery effects
There is controversy about whether the memory effect actually exists, or whether it is as serious a problem as is sometimes believed. Some critics claim it is used to promote competing NiMH batteries, which apparently suffer this effect to a lesser extent. Many nickel-cadmium battery manufacturers either deny the effect exists or are silent on the matter. The memory effect story originated from orbiting satellites, where they were typically charging for twelve hours out of twenty four for several years. After this time, it was found that the capacities of the batteries had declined significantly, but were still perfectly fit for use. It is thought unlikely that this precise repetitive charging (e.g. 1000 charges / discharges with less than 2% variability) would ever be reproduced by consumers using electrical goods. An effect with similar symptoms to the memory effect is the so-called voltage depression or lazy battery effect. (Some people use this term as a synonym for "memory effect") This results from repeated overcharging; the symptom is that the battery appears to be fully charged but discharges quickly after only a brief period of operation. Sometimes, much of the lost capacity can be recovered by a few deep discharge cycles, a function often provided by automatic NiCd battery chargers. However, this process may reduce the shelf life of the battery. If treated well, a NiCd battery can last for 1000 cycles or more before its capacity drops below half its original capacity.
Nickel-Cadmium

- Battery Life

**Voltage depression due to over-charging**
A common process often ascribed to memory effect is voltage depression. In this case the peak voltage of the battery drops more quickly than normal as it is used, even though the total energy remains almost the same. In modern electronic equipment that monitors the voltage to indicate battery charge, the battery appears to be draining very quickly and therefore about to run out of energy. To the user it appears the battery is not holding its full charge, which seems similar to memory effect. This is a common problem with high-load devices such as digital cameras.

Voltage depression is caused by repeated over-charging of a battery, which causes the formation of small crystals of electrolyte on the plates. These can clog the plates, increasing resistance and lowering the voltage of some individual cells in the battery. This results in a seemingly rapid discharge as those individual cells discharge quickly and the voltage of the battery as a whole suddenly falls. This effect is very common, as consumer trickle chargers typically overcharge.
Nickel-Cadmium

• Battery Life
  - Duracell NiMH datasheet

“Although many years of premium performance can be enjoyed from a nickel-metal hydride battery that is properly handled, the capacity delivered in each charge/discharge cycle will eventually begin to decrease. This inevitable decrease in capacity can be accelerated by overcharging, storage or usage at high temperatures, or through poor matching of cells within a pack. Often, battery users who experience short service life have incorrectly attributed capacity loss to a phenomenon called “memory effect.” The term memory effect is used synonymously with the term “voltage depression.” Voltage depression is a scientifically measurable characteristic of all batteries, however, nickel-cadmium batteries demonstrate particularly acute sensitivity. A properly designed application with nickel-metal hydride batteries will result in neither permanent performance loss nor perceivable temporary capacity decreases from this characteristic.”
Nickel-Cadmium

- Battery Life

**FIGURE 5.9.1**

Effects on Ni-MH cell capacity due to repetitive partial discharges.

[Conditions: Charge: (Cycle #1 – #21) = 1C to -ΔV = 12mV. Discharge: Cycle #1 = 1C to 1.0 V, (Cycle #2 – #18) = 1C to 1.15V, (Cycle #19 – #21) = 1C to 1.0V; Temperature: 21°C (70°F)]
Nickel-Cadmium

• Battery Life

Deep discharge
Some rechargeable batteries can be damaged by repeated deep discharge. Batteries are composed of multiple similar, but not identical, cells. Each cell has its own charge capacity. As the battery as a whole is being deeply discharged, the cell with the smallest capacity may reach zero charge and will "reverse charge" as the other cells continue to force current through it. The resulting loss of capacity is often ascribed to the memory effect.

Age and use
All rechargeable batteries have a finite lifespan and will slowly lose storage capacity as they age due to secondary chemical reactions within the battery whether it is used or not. Lithium ion batteries can lose 5%-20% of their storage capacity every year from the time of manufacture. All rechargeable batteries have a finite number of charge/discharge cycles and will lose a very small amount of storage capacity during each cycle. Typically, rechargeable batteries are rated for hundreds or thousands of cycles.
Brain Break
Sealed Lead Acid

- **Application**
  - Sealed Lead Acid cells are well suited to a wide variety of applications because of their:
    - Very high energy density
    - Very high rate discharge capacity
    - Fast recharge
    - Simple float recharge
    - Long operating life
    - Long storage life
    - Rugged construction
    - Operation over a broad range of temperatures
    - Operation in a wide range of environments
    - Operation in any orientation
    - Maintenance free use
    - Good voltage discharge consistancy
Sealed Lead Acid

- **Discharge**
  - During discharge, the active materials in the electrodes (lead dioxide +, sponge metallic lead -) react with the sulfuric acid in the electrolyte to form lead sulfate and water.
  - A Sealed Lead Acid cell operates as a closed system that recycles the gasses created and materials converted within the cell.
  - Since the sulfuric acid is “consumed” in the process, measurement of acid concentration through pH or specific gravity, provides an indication of the charge state of the cell.
  - Open circuit voltage may also provide an estimation of charge state of the cell.
Sealed Lead Acid

- Discharge

Figure 6. Open Circuit Voltage vs. State of Charge
Sealed Lead Acid

- **Discharge**
  - Discharge rate has a significant effect on capacity.

*Figure 4-3 Capacity versus Discharge Rate*
Sealed Lead Acid

- Discharge

Figure 3. Discharge Characteristic Curves: Genesis NP Batteries
Sealed Lead Acid

- Discharge
  - Pulse discharging can extend operating capacity.

*Figure 4-7 Typical Pulsed Discharge Curve*
Sealed Lead Acid

- Discharge
  - Stabilization occurs early in a cell's life due to the completion of *Formation*.
Sealed Lead Acid

- Discharge
  - Additional factors affecting capacity are:
    - Overdischarging
    - Overcharging
    - Temperature
    - High discharge cut-off voltage
Brain Break
Sealed Lead Acid

- Charging
  - Charge current converts lead sulphate to metallic lead at the negative and lead dioxide at the positive electrode.
  - In starved electrolyte (sealed) cells, the positive electrode reaches full charge before the negative. If charging continues, Oxygen generated is recombined at the negative plate, discharging it slightly, so it can accommodate overcharge.
Sealed Lead Acid

- **Charging**
  - **Charge control:**
    - **Constant Voltage**
      - Simplest to implement
      - Reliable
      - Safe
    - **Constant current**
      - More complex
      - Higher risk
      - Can return charge faster
    - **Taper**
      - Cheap
      - Abusive to battery
    - **Two step**
      - Charges faster than CV
      - Safe
      - Not much added complexity
Sealed Lead Acid

- Charging
  - Voltage / Current

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Voltage</td>
<td>2.30 - 2.35 volts/cell</td>
<td>2.35 - 2.40 volts/cell</td>
<td>2.35 - 2.40 volts/cell</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Continuous (C/500)</td>
<td>- Continuous (C/14 with charge</td>
<td>- Continuous (C/50)</td>
<td>- Continuous (C/10 to C/20 with</td>
</tr>
<tr>
<td></td>
<td></td>
<td>termination)</td>
<td></td>
<td>charge termination)</td>
</tr>
</tbody>
</table>
Sealed Lead Acid

- Charging
  - CI vs. CV
Sealed Lead Acid

- Charging
  - Voltage vs. Temperature

Figure 12. Relationship Between Charging Voltage and Temperature
Sealed Lead Acid

- Charging
  - CV charging profile

Figure 11. CHARGING CHARACTERISTICS

2.3V/CELL CONSTANT VOLTAGE CHARGING
0.25C MAX CURRENT

CHARGE VOLUME

CHARGE VOLTAGE

CHARGING CURRENT

CHARGING TIME (HOURS)
Sealed Lead Acid

- Charging
  - Two Stage
Sealed Lead Acid

- Battery Life
  - Battery life is affected by many factors including:
    - Depth of Discharge
    - Self discharge / storage conditions
    - Operating temperature
    - Deterioration
      - Aging
      - Grid Oxidation
      - Plate morphology
      - Mechanical deterioration
Sealed Lead Acid

- Battery Life
  - Service life

Figure 17. Float Service Life
Sealed Lead Acid

- Battery Life
  - Depth of discharge

Figure 16: Cyclic Service Life in Relation to Depth of Discharge
Genisis NP Series
Sealed Lead Acid

- Battery Life
  - Self discharge

Figure 5. Self Discharge Characteristics
Sealed Lead Acid

- Battery Life
  - Sulfation

In general, when lead acid batteries of any type are stored in a discharged condition for extended periods of time, lead sulfate is formed on the negative plates of the batteries. This phenomenon is referred to as “sulfation”. Since the lead sulfate acts as an insulator, it has a direct detrimental effect on charge acceptance. The more advanced the sulfation, the lower the charge acceptance.

<table>
<thead>
<tr>
<th>Battery Age</th>
<th>Refresh Charging Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within 6 months after manufacture</td>
<td>4 to 6 hours at constant current of 0.1CA, or 15 to 20 hours at constant voltage of 2.40 volts per cell.</td>
</tr>
<tr>
<td>Within 12 months after manufacture</td>
<td>8 to 10 hours at constant current of 0.1CA, or 20 to 24 hours at constant voltage of 2.40 volts per cell.</td>
</tr>
</tbody>
</table>
Sealed Lead Acid

- Battery Life
  - Plate morphology
    - A Fundamental change in the structure of the active material on the positive plate. Gradual loss of surface area converted to an amorphous structure which is chemically less active. Accounts for the bulk of capacity loss of aging.
  - Grid Oxidation
    - The other major culprit in cell aging. Primarily a function of the degree of overcharge experienced by the cell.
Brain Break
Safety

● Potential Hazards:
  – Electrolyte
  – Venting
  – Shock
  – Weight
  – Burns & excessive heat:
    ● Shorted terminals
    ● Failed charge control
Safety

- Potential Hazards
Safety

- Potential Hazards
Safety

- Potential Hazards
Safety

- Potential Hazards
Safety

- Disposal
  - Hazardous Materials
  - Regulations (RoHS etc.)
  - Reclamation $
Misc. Circuit Examples

- RACES Porta-packet boxes
  - 3 hour operation at 30%Tx high power (45W)
  - Internal P.S. % Charger
Misc. Circuit Examples

- MAX712
Misc. Circuit Examples

- MAX712
Misc. Circuit Examples

- Linear regulator protection

![Diagram](image)

**FIGURE 3.** Regulator with Protection Diodes
Where to Get More Information

- Rechargeable Batteries Applications Handbook
  ISBN 0750692278
