Outline

- Why is this important?
- Brief history of batteries
- Basic chemistry
- Battery types and characteristics
- Case study: ThinkPad battery technology

Motivation

- To exploit properties of batteries in low-power designs
  - Protocols (Span , MAC layer)
  - Hardware (Cricket)
  - Example: *n* cells; discharge from each cell, round-robin fashion [Chiasserini and Rao, INFOCOM 2000]

Battery (Ancient) History

1800	Voltaic pile: silver zinc
1836	Daniell cell: copper zinc
1859	Planté: rechargeable lead-acid cell
1868	Leclanché: carbon zinc wet cell
1888	Gassner: carbon zinc dry cell
1898	Commercial flashlight, D cell
1899	Junger: nickel cadmium cell

Battery History

1946	Neumann: sealed NiCd
1960s	Alkaline, rechargeable NiCd
1970s	Lithium, sealed lead acid
1990	Nickel metal hydride (NiMH)
1991	Lithium ion
1992	Rechargeable alkaline
1999	Lithium ion polymer

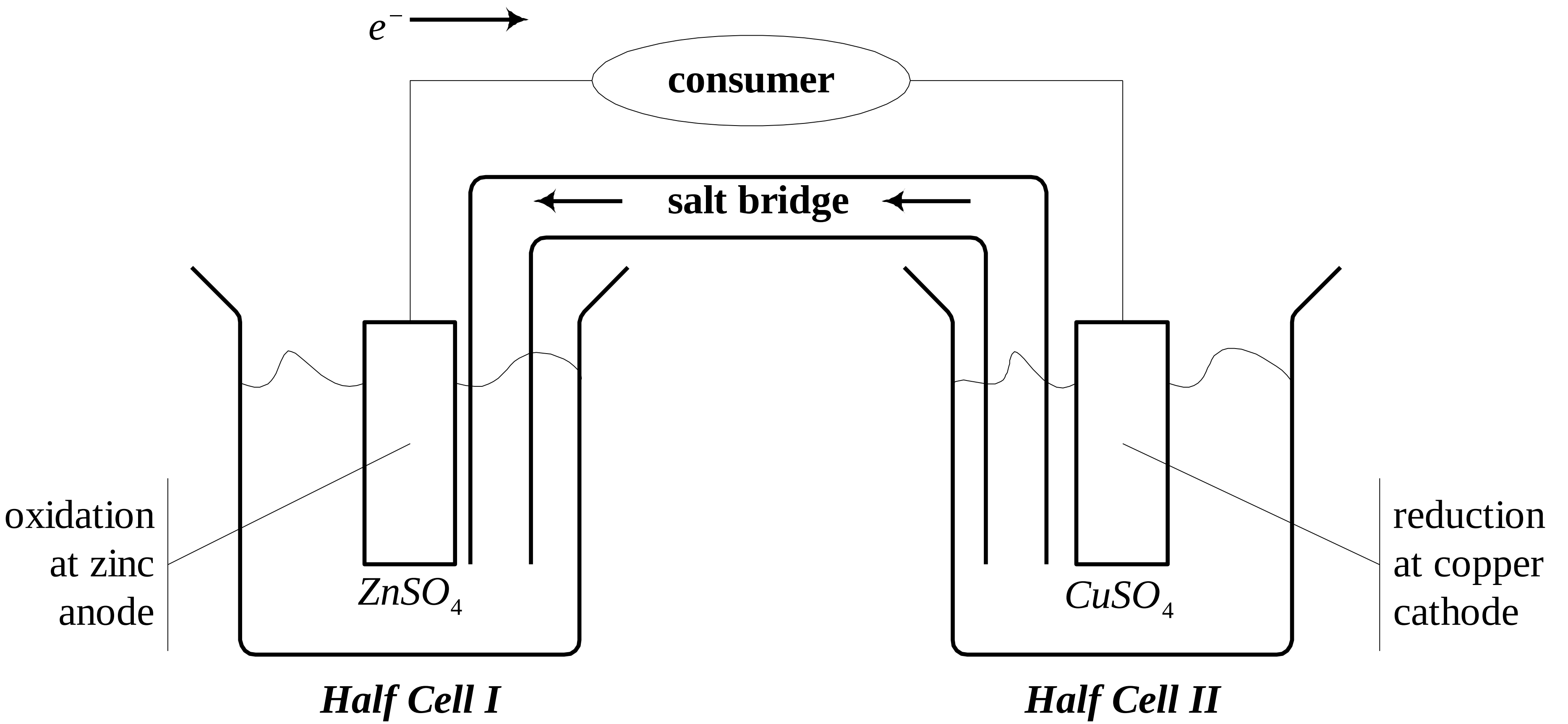
Battery Nomenclature

Duracell batteries | 9v battery | 6v dry cell

Two cells | **A real battery** | **Another battery**

More precisely

The Electrochemical Cell



The Electrochemical Cell (2)

- Zinc is (much) more easily oxidized than Copper

$$Zn \longrightarrow Zn^{2+} + 2e^{-} \quad (I.)$$

$$Cu^{2+} + 2e^{-} \longrightarrow Cu \quad (II.)$$

- Maintain equilibrium electron densities
    - Add copper ions in solution to Half Cell II
- Salt bridge only carries negative ions
    - – This is the limiting factor for current flow
    - – Pick a low-resistance bridge

The Electrochemical Series

Most wants to reduce (gain electrons)

- Gold
- Mercury
- Silver
- Copper
- Lead
- Nickel
- Cadmium

But, there's a reason it's a *sodium* drop

- Iron
- Zinc
- Aluminum
- Magnesium
- Sodium
- Potassium
- ***Lithium***

Most wants to oxidize (lose electrons)

Battery Characteristics

- Size
  - Physical: button, AAA, AA, C, D, ...
  - Energy density (watts per kg or cm^3)
- Longevity
  - Capacity (Ah, for drain of C/10 at 20°C)
  - Number of recharge cycles
- Discharge characteristics (voltage drop)

Further Characteristics

- Cost
- Behavioral factors
  - Temperature range (storage, operation)
  - Self discharge
  - Memory effect
- Environmental factors
  - Leakage, gassing, toxicity
  - Shock resistance

Primary (Disposable) Batteries

- Zinc carbon (flashlights, toys)
- Heavy duty zinc chloride (radios, recorders)
- Alkaline (all of the above)
- Lithium (photoflash)
- Silver, mercury oxide (hearing aid, watches)
- Zinc air

Standard Zinc Carbon Batteries

- Chemistry

  Zinc (-), manganese dioxide (+)

  Zinc, ammonium chloride aqueous electrolyte

- Features

  + Inexpensive, widely available

  – Inefficient at high current drain

  – Poor discharge curve (sloping)

  – Poor performance at low temperatures

Heavy Duty Zinc Chloride Batteries

- Chemistry

  Zinc (-), manganese dioxide (+)

  Zinc chloride aqueous electrolyte

- Features (compared to zinc carbon)

  + Better resistance to leakage

  + Better at high current drain

  + Better performance at low temperature

Standard Alkaline Batteries

- Chemistry

  Zinc (-), manganese dioxide (+)

  Potassium hydroxide aqueous electrolyte

- Features

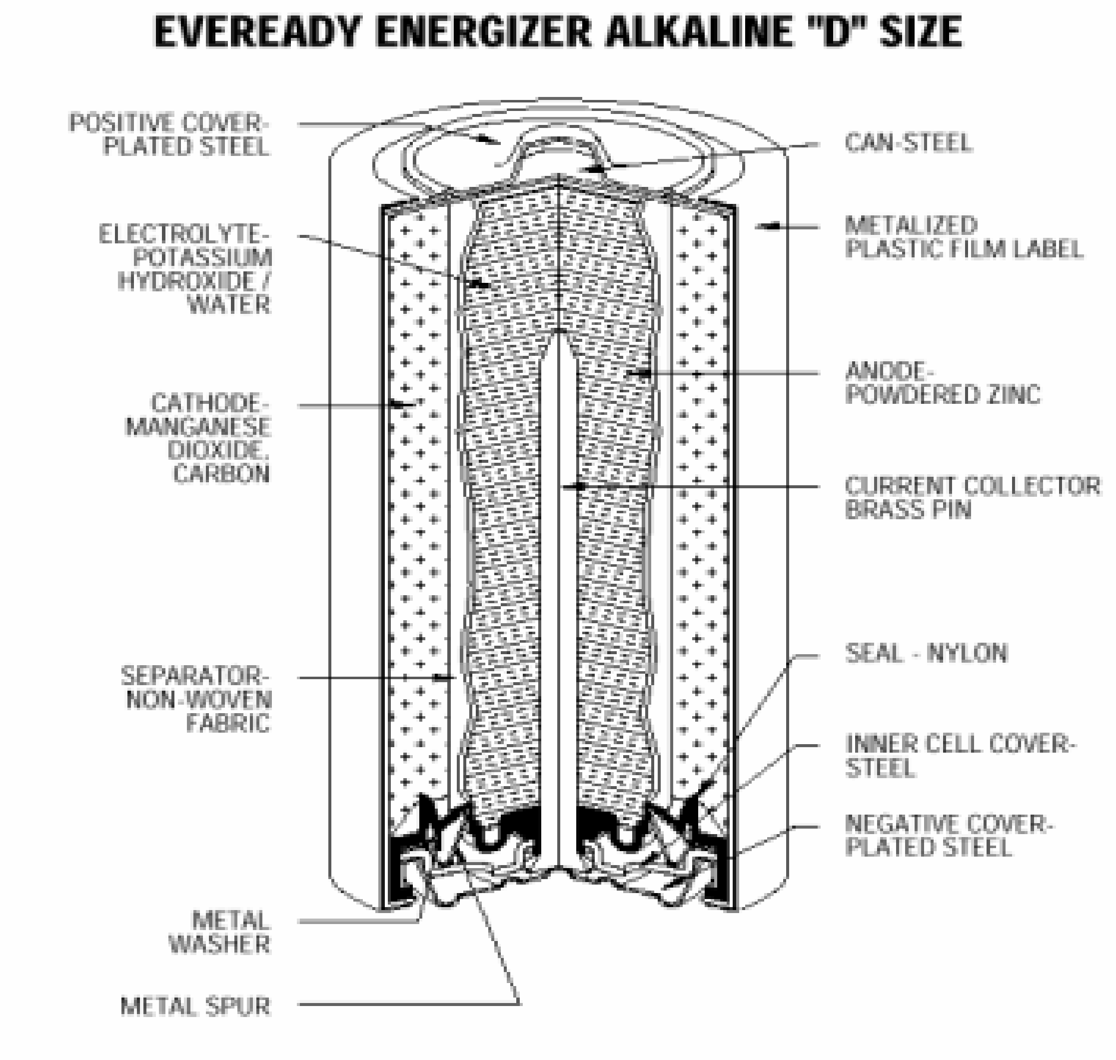
  + 50-100% more energy than carbon zinc

  + Low self-discharge (10 year shelf life)

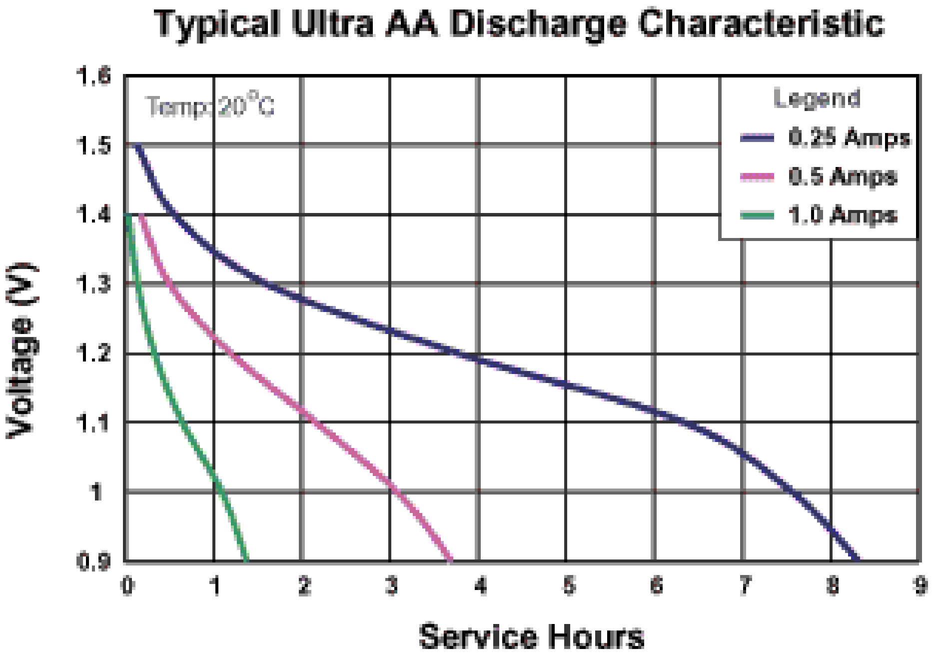
  ± Good for low current (< 400mA), long-life use

  – Poor discharge curve

Alkaline-Manganese Batteries (2)



Alkaline Battery Discharge



Lithium Manganese Dioxide

- Chemistry

  Lithium (-), manganese dioxide (+)

  Alkali metal salt in organic solvent electrolyte

- Features

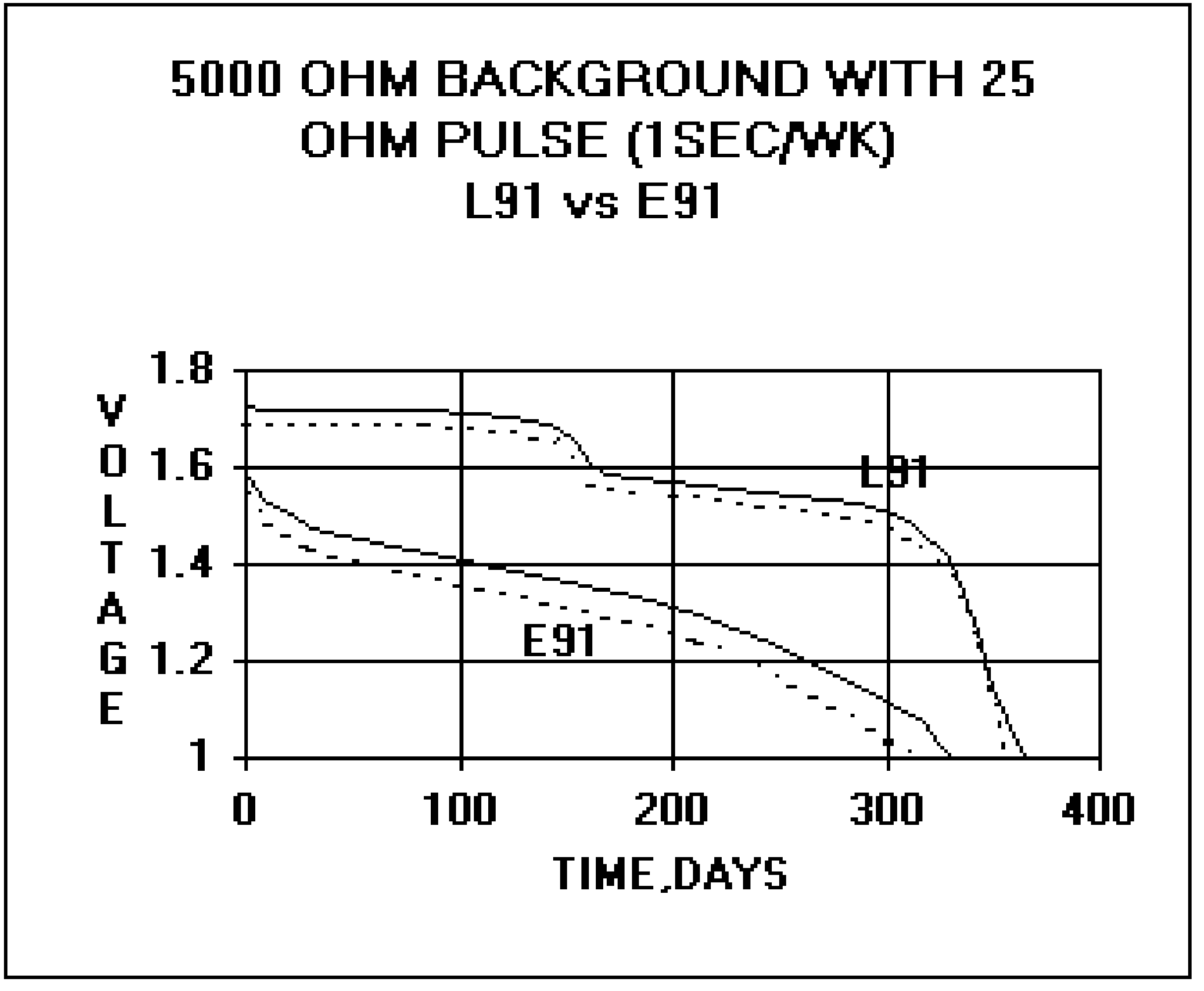
  + High energy density

  + Long shelf life (20 years at 70°C)

  + Capable of high rate discharge

  – Expensive

Lithium v Alkaline Discharge



Secondary (Rechargeable) Batteries

- Nickel cadmium
- Nickel metal hydride
- Alkaline
- Lithium ion
- Lithium ion polymer
- Lead acid

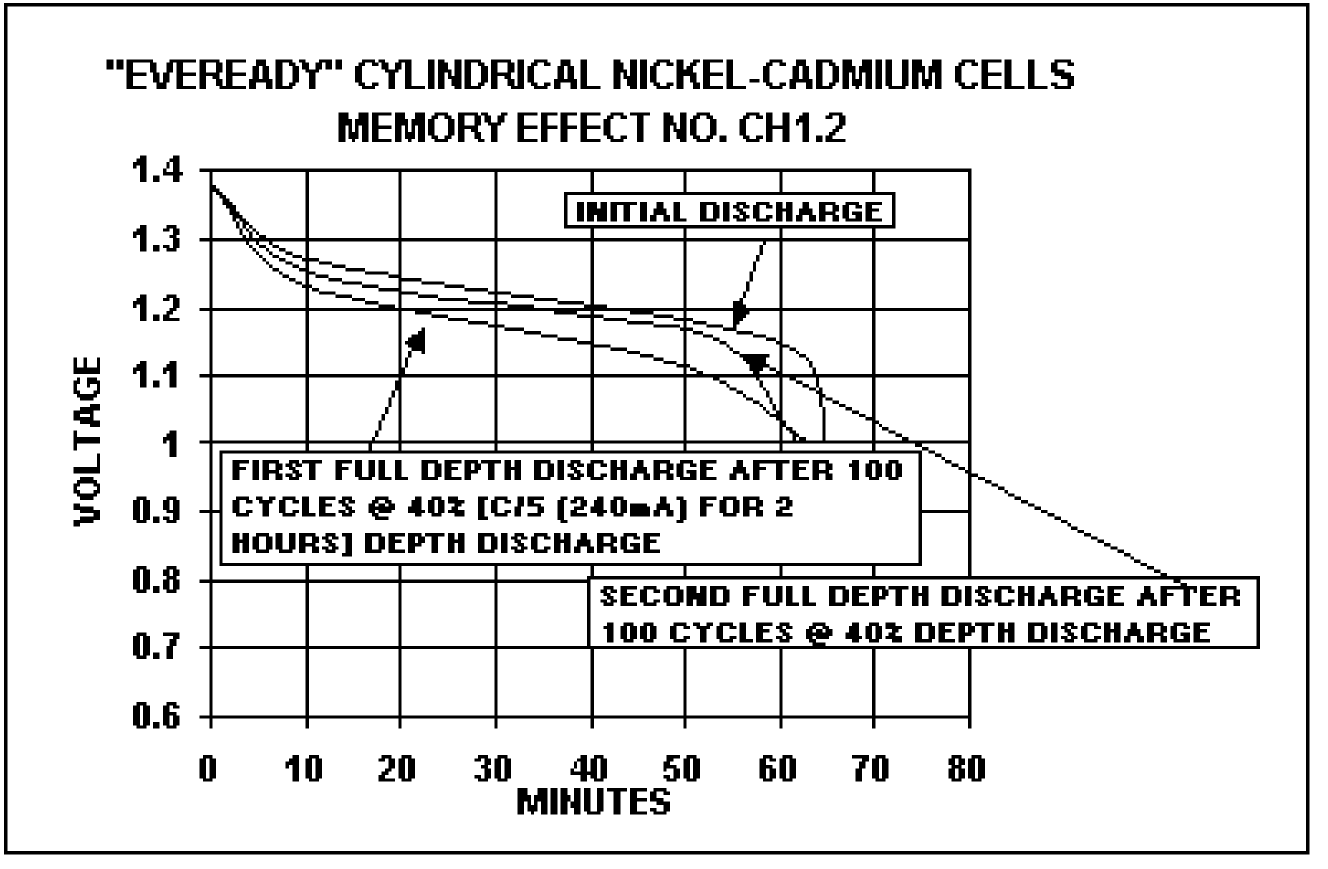
Nickel Cadmium Batteries

- Chemistry
  - Cadmium (-), nickel hydroxide (+)
  - Potassium hydroxide aqueous electrolyte
- Features
  - + Rugged, long life, economical
  - + Good high discharge rate (for power tools)
  - – Relatively low energy density
  - – Toxic

NiCd Recharging

- Over 1000 cycles (if properly maintained)
- Fast, simple charge (even after long storage)
  - C/3 to 4C with temperature monitoring
- Self discharge
  - 10% in first day, then 10%/mo
  - Trickle charge (C/16) will maintain charge
- Memory effect
  - Overcome by 60% discharges to 1.1V

NiCd Memory Effect



Nickel Metal Hydride Batteries

- Chemistry

  $LaNi_5$, $TiMn_2$, $ZrMn_2$ (-), nickel hydroxide (+)

  Potassium hydroxide aqueous electrolyte

- Features

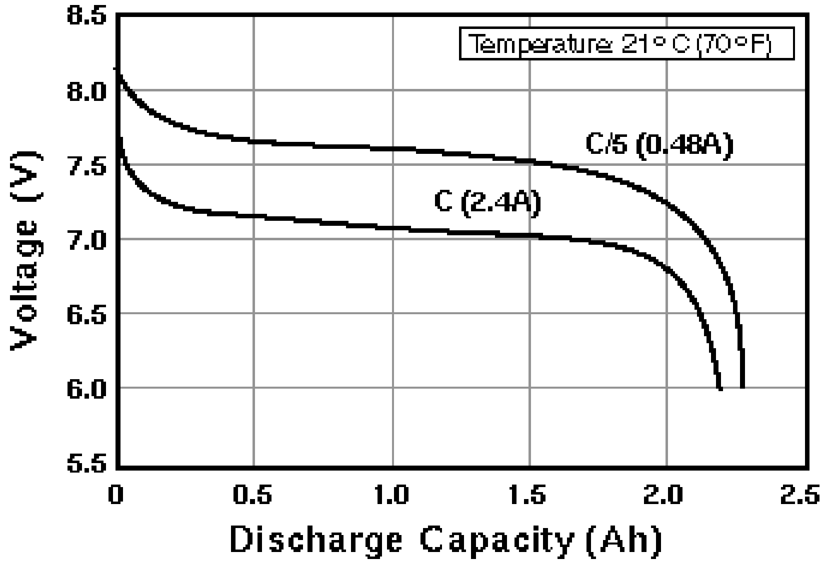
  + Higher energy density (40%) than NiCd

  + Nontoxic

  – Reduced life, discharge rate (0.2-0.5C)

  – More expensive (20%) than NiCd

NiMH Battery Discharge

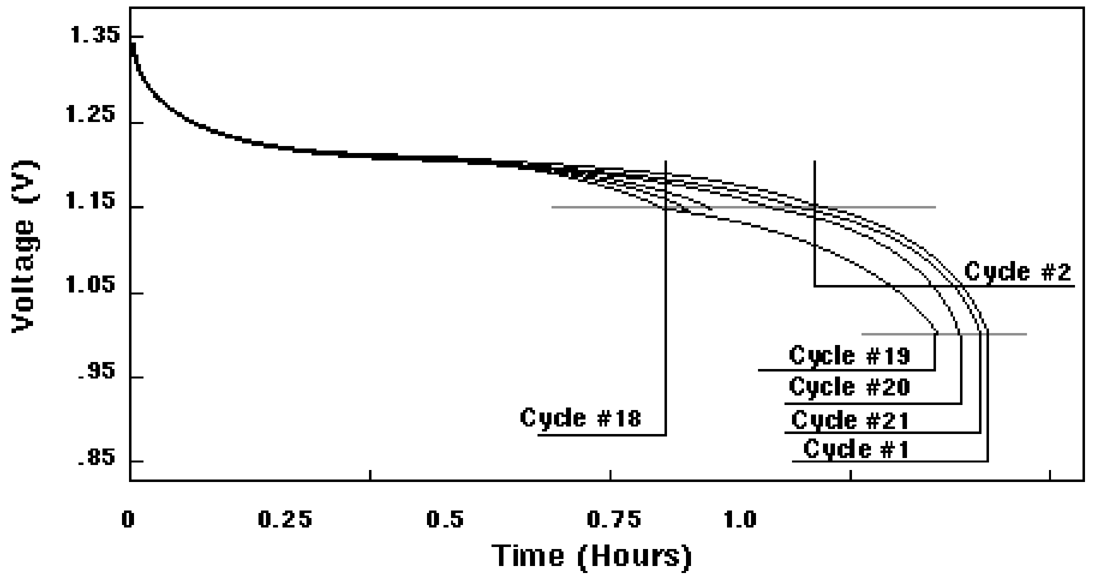


Voltage and capacity of DURACELL DR30 Ni-MH batteries at various discharge temperatures and rates.
[Conditions: Charge: 1C to -ΔV = 60mV @ 21°C (70°F)]

NiMH Recharging

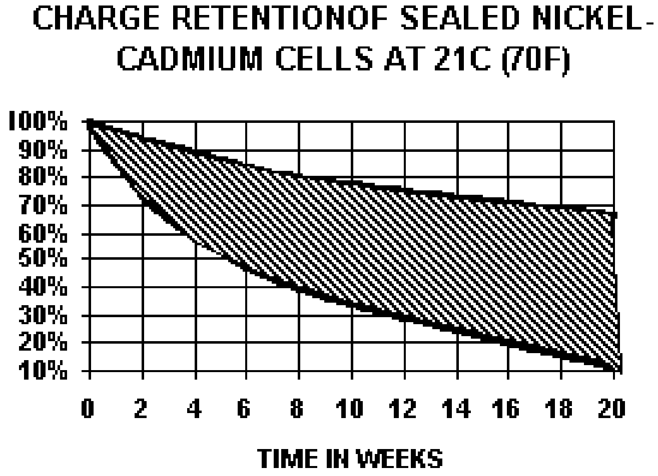
- Less prone to memory than NiCd
- Shallow discharge better than deep
  - Degrades after 200-300 deep cycles
  - Need regular full discharge to avoid crystals
- Self discharge 1.5-2.0 more than NiCd
- Longer charge time than for NiCd
  - To avoid overheating

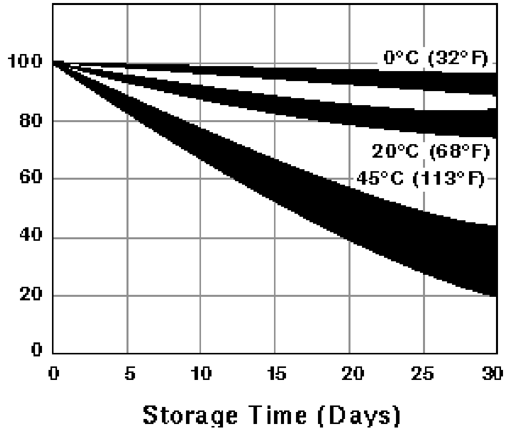
NiMH Memory Effect



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)]

NiCd v NiMH Self-Discharge

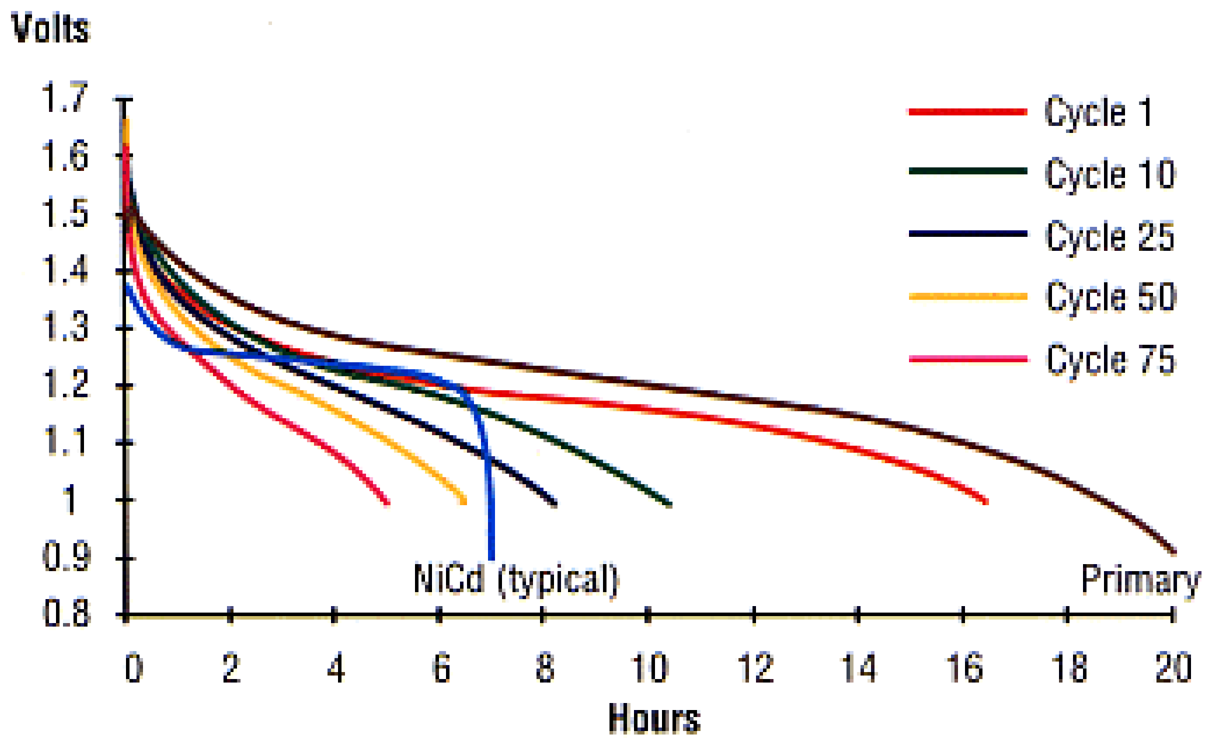




Secondary Alkaline Batteries

- Features
  - 50 cycles at 50% discharge
  - No memory effect
  - Shallow discharge better than deeper

NiCd v Alkaline Discharge



Lead Acid Batteries

- Chemistry

  Lead

  Sulfuric acid electrolyte
- Features

  + Least expensive

  + Durable

  – Low energy density

  – Toxic

Lead Acid Recharging

- Low self-discharge
  - 40% in one year (three months for NiCd)
- No memory
- Cannot be stored when discharged
- Limited number of full discharges
- Danger of overheating during charging

Lead Acid Batteries

- Ratings
  - CCA: cold cranking amps (0F for 30 sec)
  - RC: reserve capacity (minutes at 10.5v, 25amp)
- Deep discharge batteries
  - Used in golf carts, solar power systems
  - 2-3x RC, 0.5-0.75 CCA of car batteries
  - Several hundred cycles

Lithium Ion Batteries

- Chemistry
  - Graphite (-), cobalt or manganese (+)
  - Nonaqueous electrolyte
- Features
  - + 40% more capacity than NiCd
  - + Flat discharge (like NiCd)
  - + Self-discharge 50% less than NiCd
  - – Expensive

Lithium Ion Recharging

- 300 cycles
- 50% capacity at 500 cycles

Lithium Ion Polymer Batteries

- Chemistry

  Graphite (-), cobalt or manganese (+)

  Nonaqueous electrolyte

- Features

  + Slim geometry, flexible shape, light weight

  + Potentially lower cost (but currently expensive)

  – Lower energy density, fewer cycles than Li-ion

Battery Capacity

Type	Capacity (mAh)	Density (Wh/kg)
Alkaline AA	2850	124
Rechargeable	1600	80
NiCd AA	750	41
NiMH AA	1100	51
Lithium ion	1200	100
Lead acid	2000	30

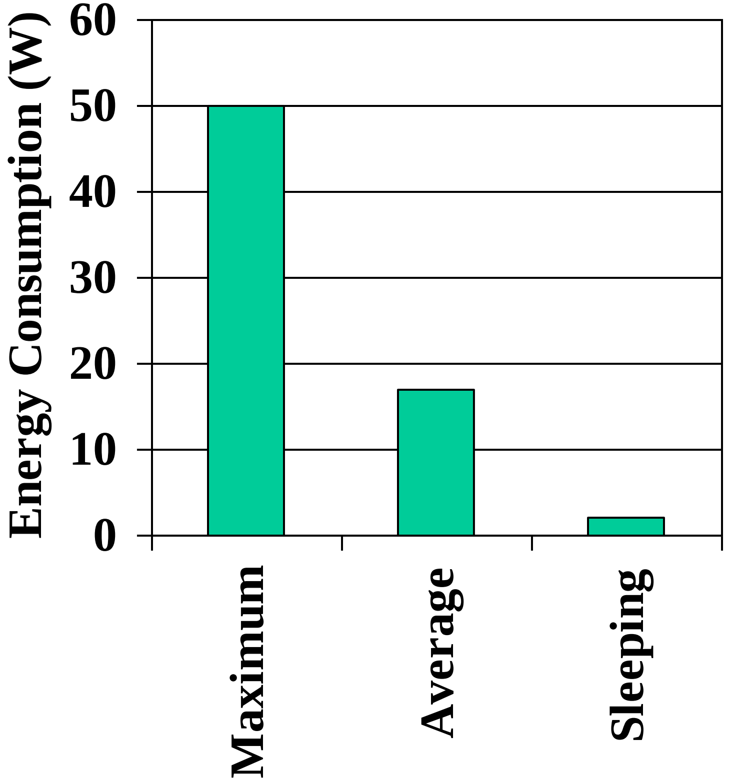
Discharge Rates

Type	Voltage	Peak Drain	Optimal Drain
Alkaline	1.5	0.5C	< 0.2C
NiCd	1.25	20C	1C
Nickel metal	1.25	5C	< 0.5C
Lead acid	2	5C	0.2C
Lithium ion	3.6	2C	< 1C

Recharging

Type	Cycles (to 80%)	Charge time	Discharge per month	Cost per kWh
Alkaline	50 (50%)	3-10h	0.3%	$95.00
NiCd	1500	1h	20%	$7.50
NiMH	300-500	2-4h	30%	$18.50
Li-ion	500-1000	2-4h	10%	$24.00
Polymer	300-500	2-4h	10%	
Lead acid	200-2000	8-16h	5%	$8.50

Example: IBM ThinkPad T21 Model 2647



- Source: IBM datasheet
- Relatively-constant discharge

Lithium-ion Batteries in Notebooks

- Lithium: greatest electrochemical potential, lightest weight of all metals
  - But, Lithium metal is explosive
  - So, use Lithium-{cobalt, manganese, nickel} dioxide
- Overcharging would convert lithium-*x* dioxide to metallic lithium, with risk of explosion

IBM ThinkPad Backup Battery

- Panasonic CR2032 coin-type lithium-magnesium dioxide primary battery
  - Application: CMOS memory backup
  - Constant discharge, ~0.1 mA
  - Weight: 3.1g
  - 220 mA-h capacity

IBM ThinkPad T21 Main Battery

- Lithium-ion secondary battery
- 3.6 A-h capacity at 10.8V
- Back-of-the-envelope calculations from workload shown earlier:
  - Maximum: 47 minutes
  - Average: 2 hours, 17 minutes
  - Sleep: 19 hours?

References

- Manufacturers

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