



Congratulations, Dorothy!

# Battery Overview

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# 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**

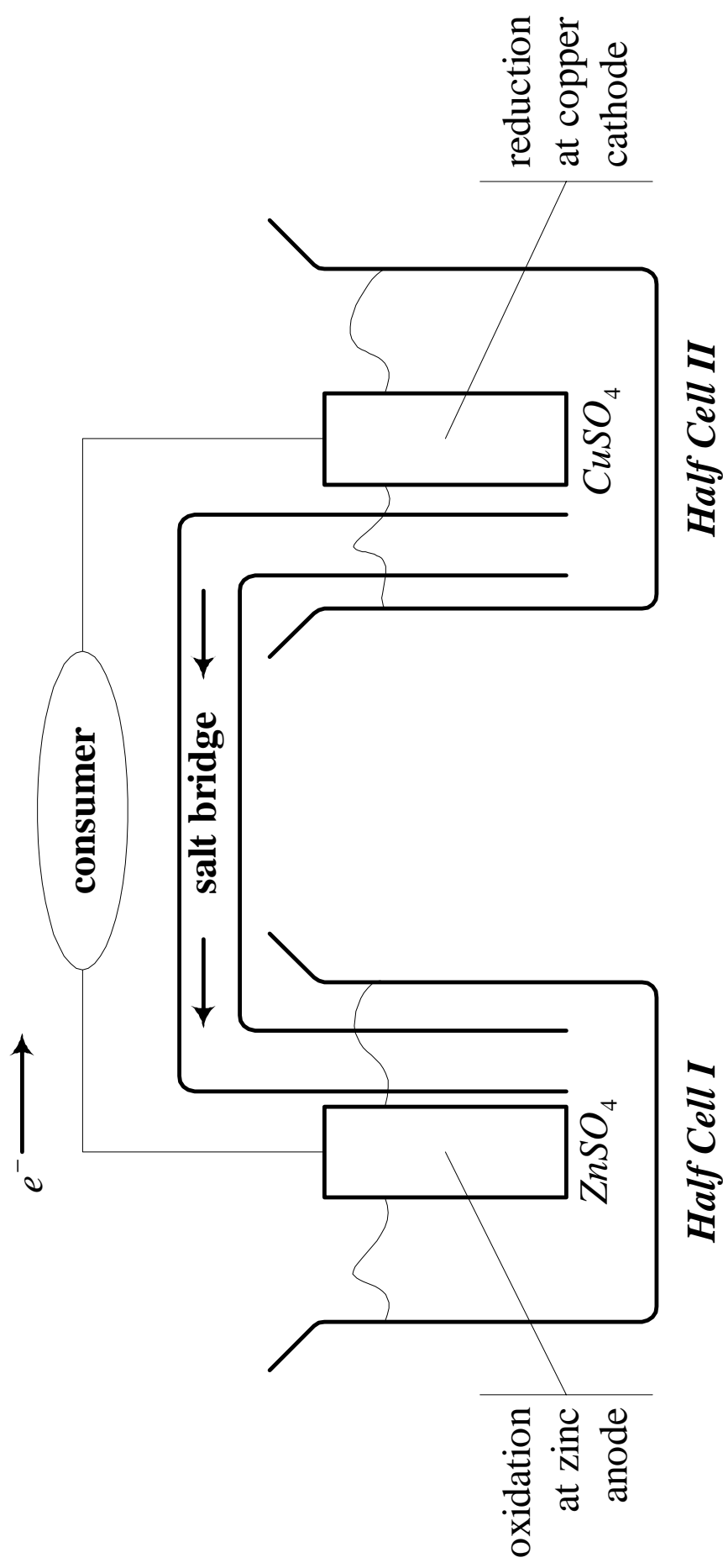
**A real battery**

**Another battery**

**More precisely**



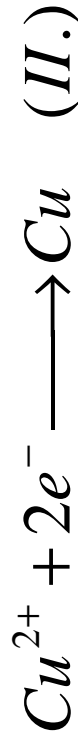
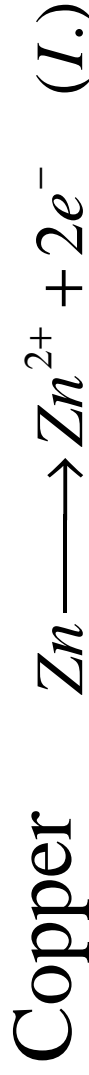
# The Electrochemical Cell





# The Electrochemical Cell (2)

- Zinc is (much) more easily oxidized than



- 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<sup>+</sup>
- Potassium
- *Lithium*

Most wants to oxidize  
(lose electrons)

# Battery Characteristics

- **Size**
  - Physical: button, AAA, AA, C, D, ...
  - Energy density (watts per kg or cm<sup>3</sup>)
- **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

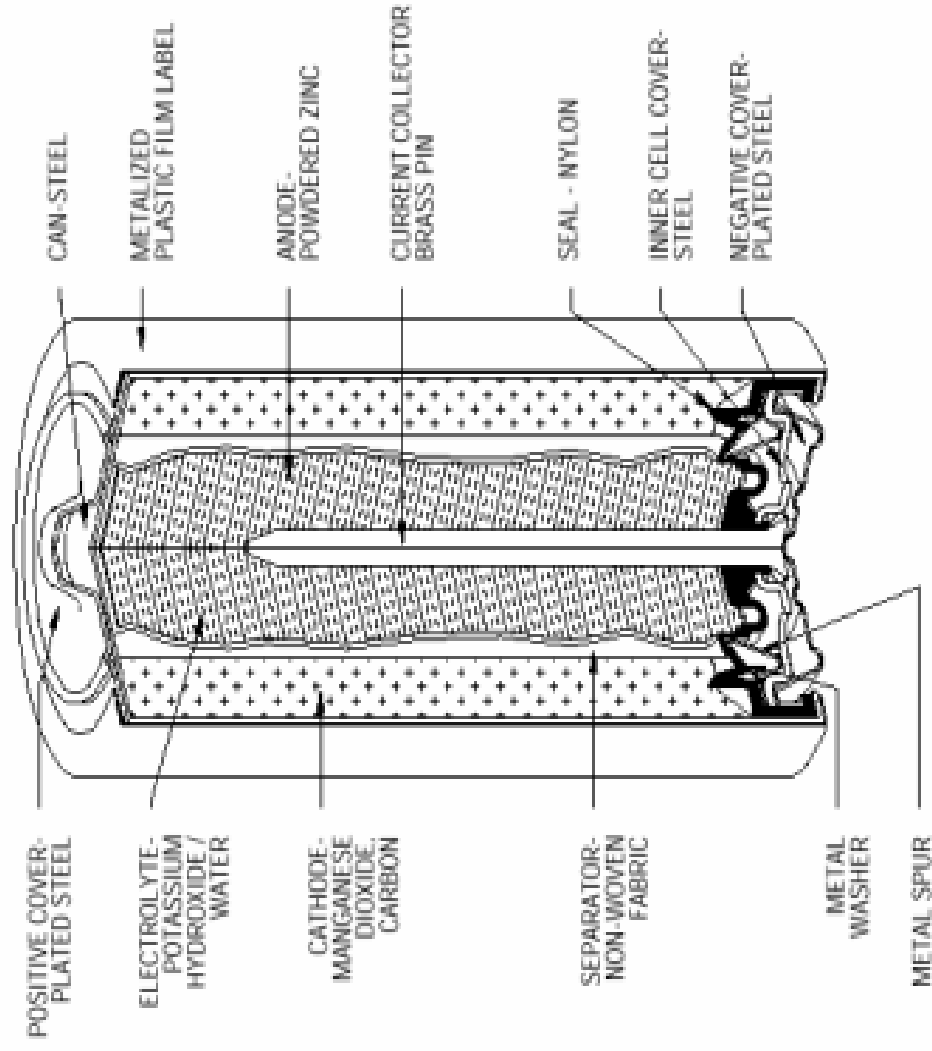
# Standard Alkaline Batteries

- 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

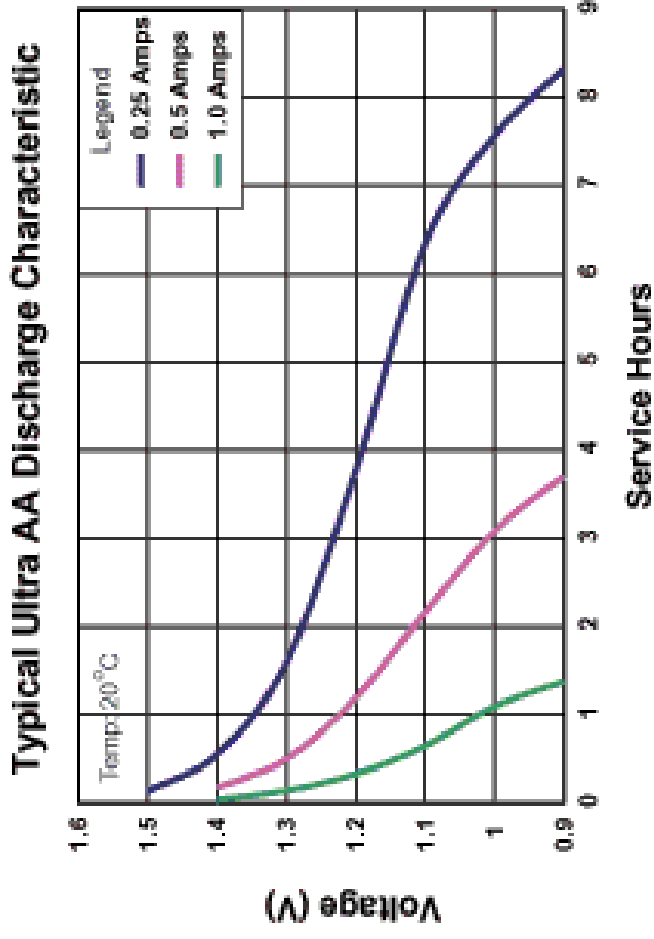


# Alkaline-Manganese Batteries (2)

## EVEREADY ENERGIZER ALKALINE "D" SIZE



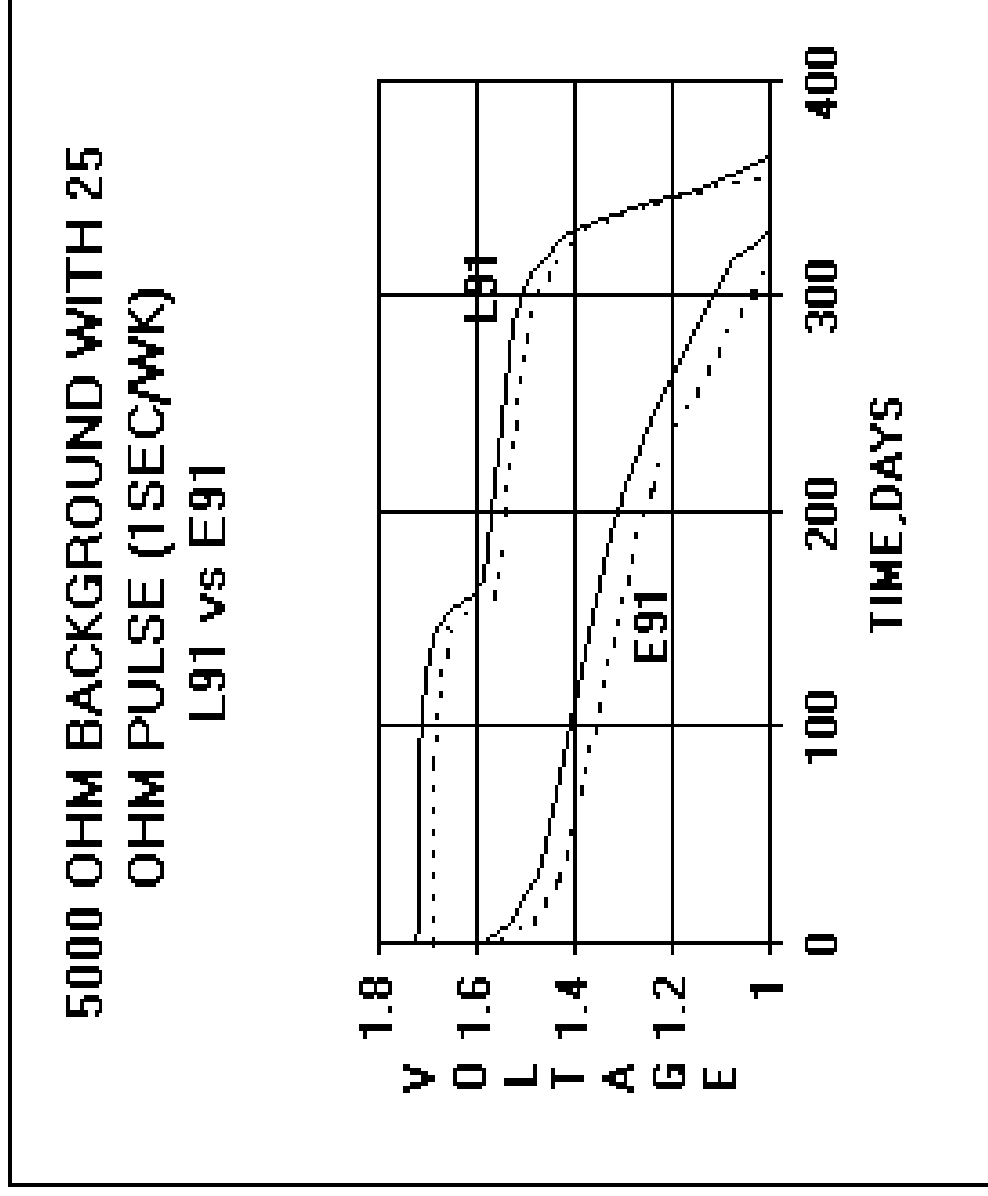
# Alkaline Battery Discharge



# 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

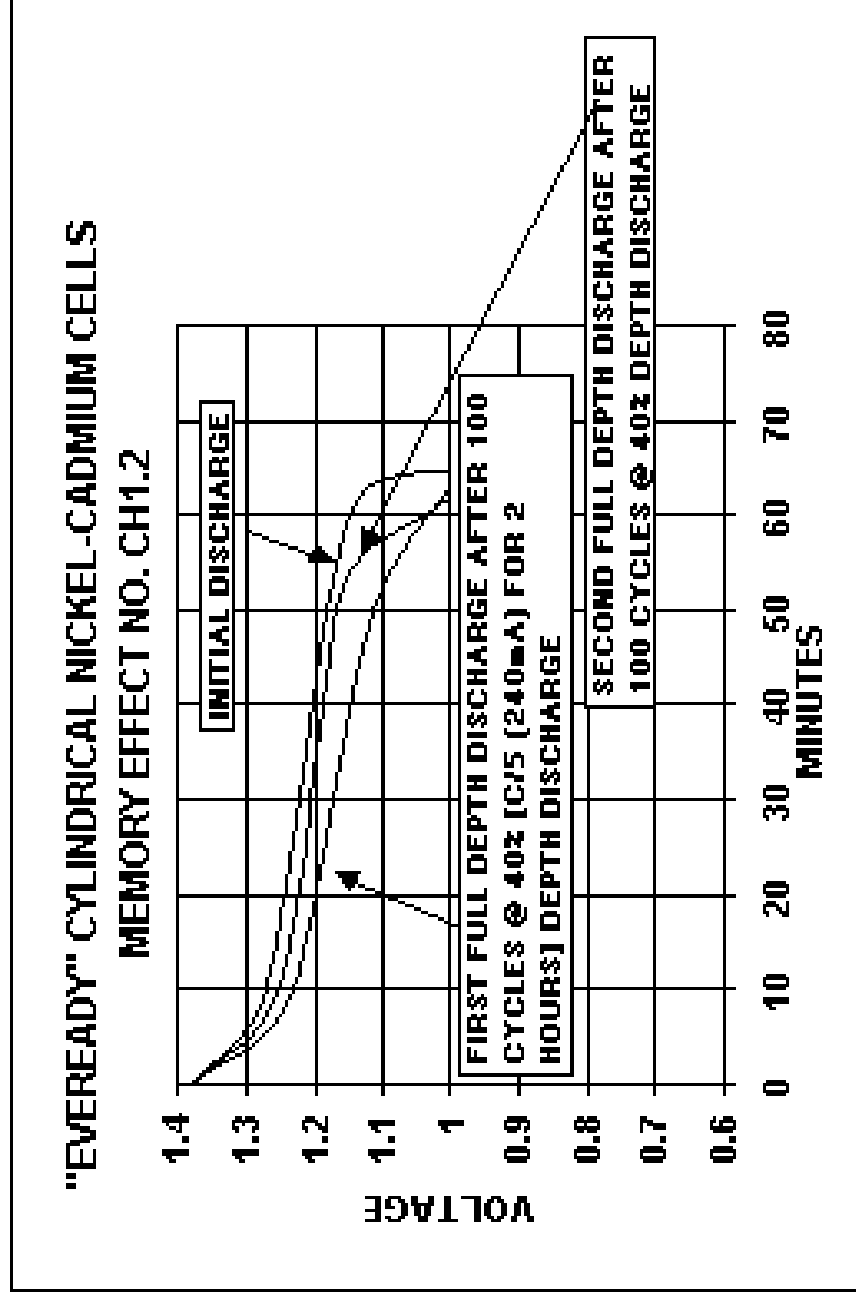
# Nickel Cadmium Batteries

- **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

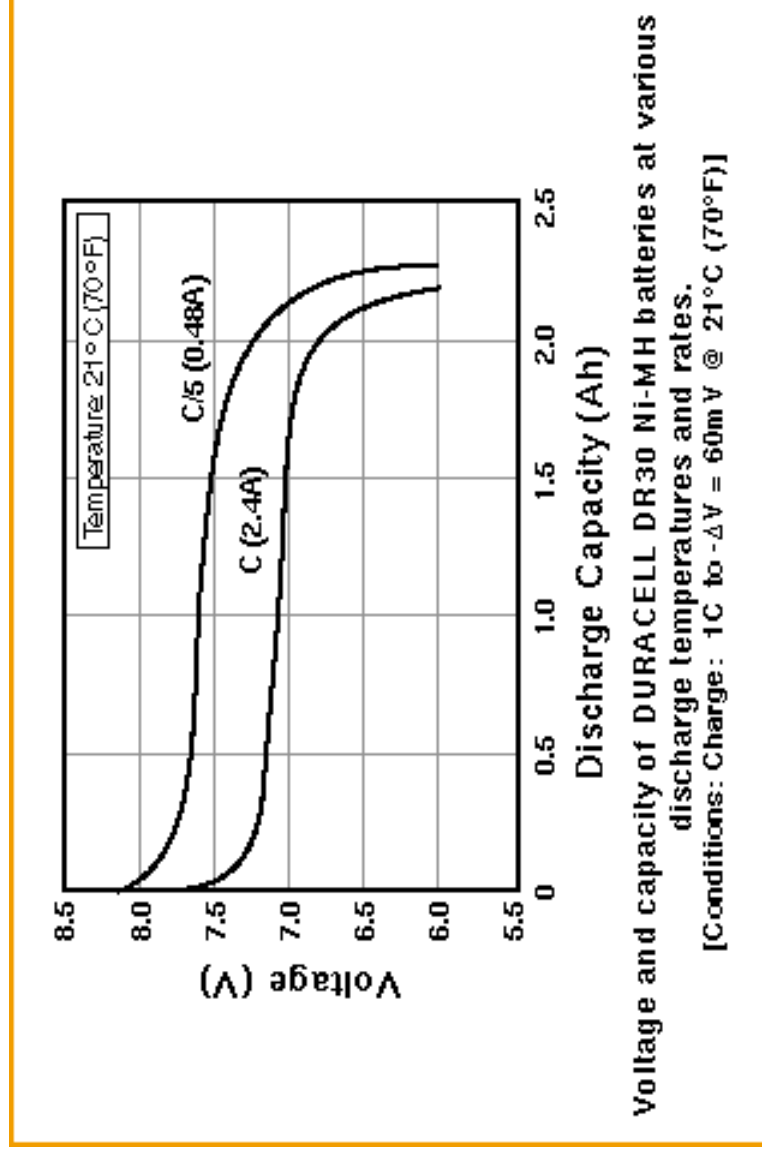




# Nickel Metal Hydride Batteries

- Chemistry
  - LaNi<sub>5</sub>, TiMn<sub>2</sub>, ZrMn<sub>2</sub> (-), 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

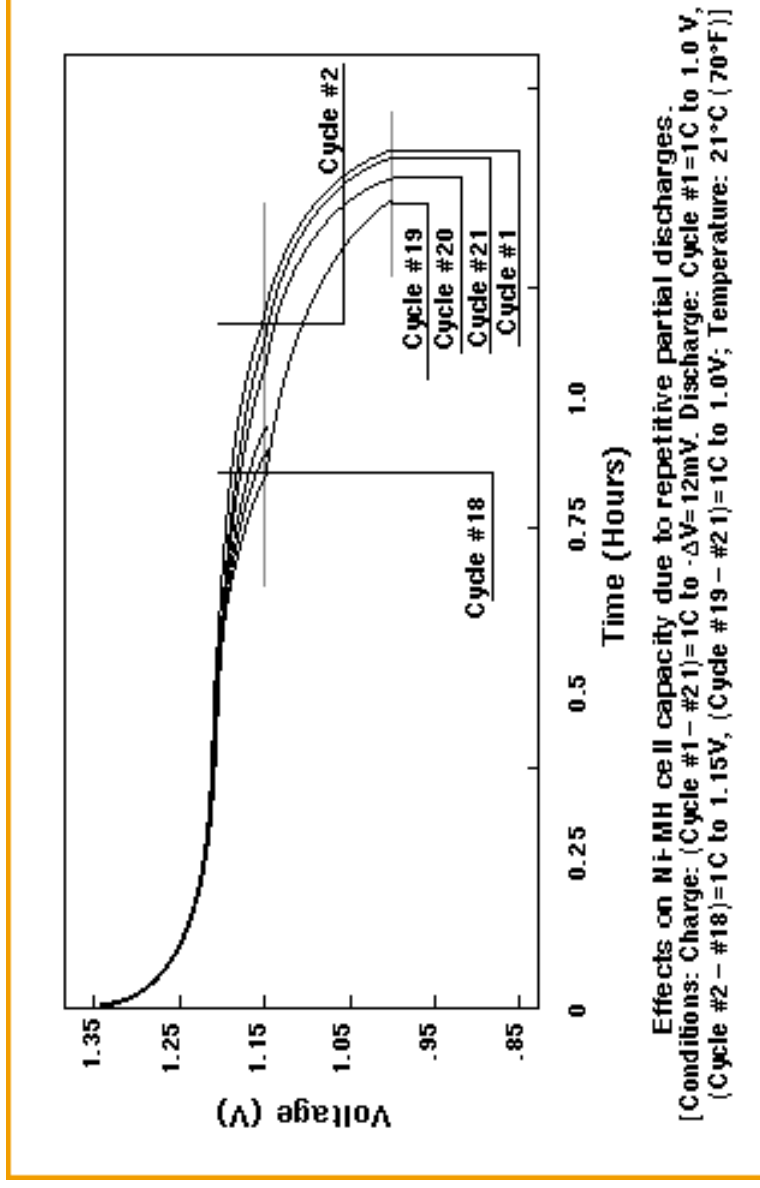
# NiMH Battery Discharge



# NiMH Recharging

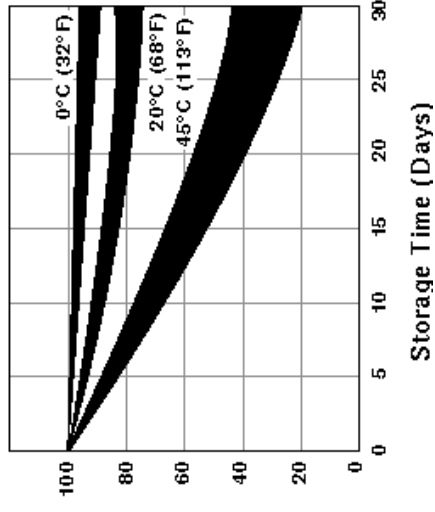
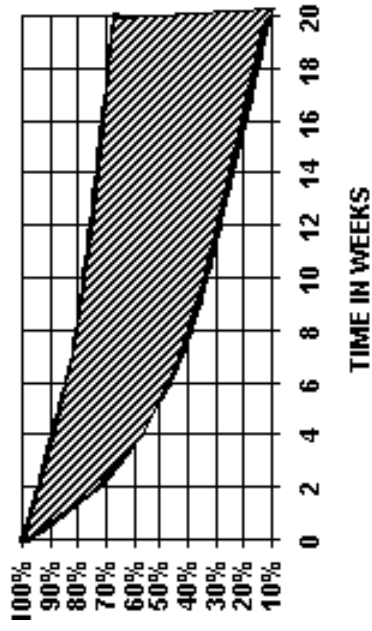
- Less prone to memory than NiCd
- Shallow discharge better than deep
  - Degrades after 200-300 deep cycles
  - Need regular full discharge to avoid crystals
- Self discharge 1.5-2.0 more than NiCd
- Longer charge time than for NiCd
  - To avoid overheating

# NiMH Memory Effect



# NiCd v NiMH Self-Discharge

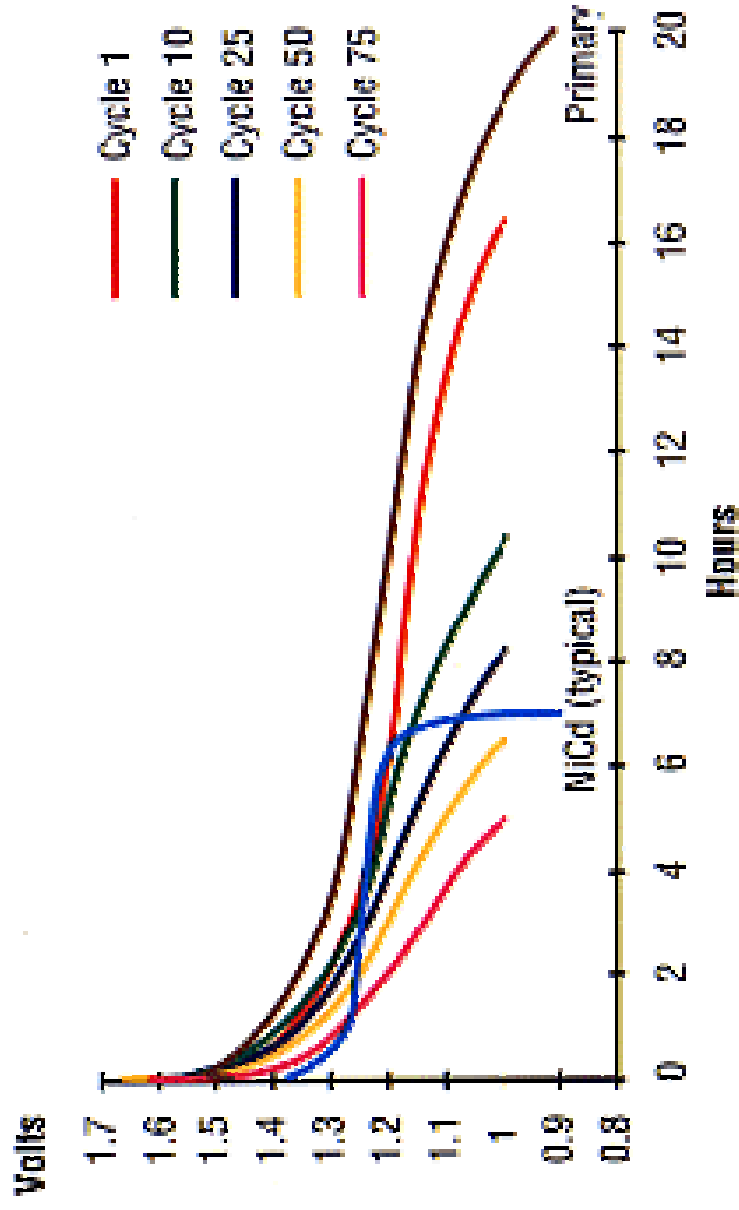
CHARGE RETENTION OF SEALED NICKEL-CADMIUM CELLS AT 21°C (70°F)



# 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

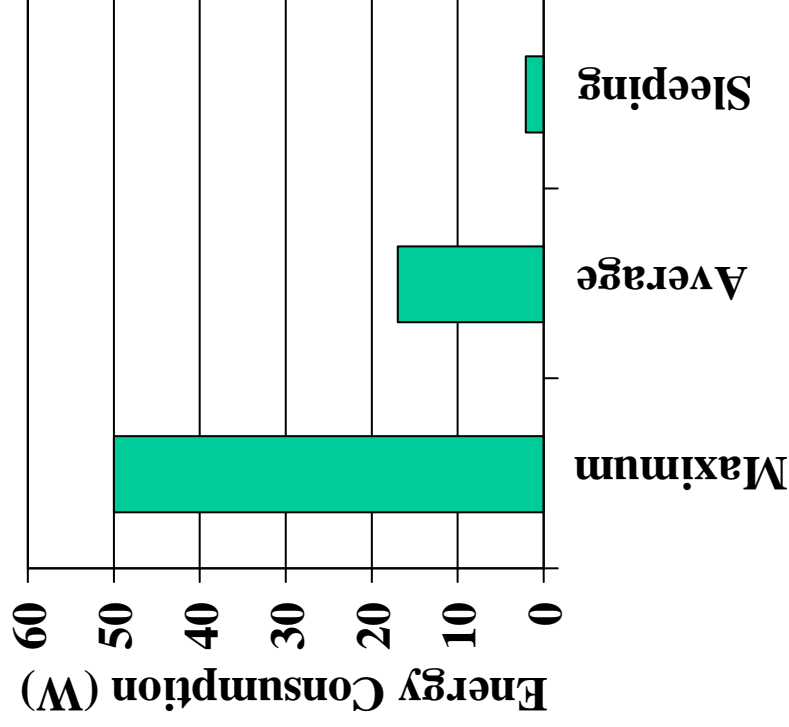
# Recharging

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,  $\sim 0.1$  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

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  - [www.duracell.com/OEM](http://www.duracell.com/OEM)
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