“Are All Batteries Created Equal?”

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BIO - Mike Clodfelter

- Sr. Staff Application Engineer for Renesas Electronics 16bit RL78 ultra-low Power MCUs
  - Specialist in low-power, battery-operated MCU apps

Background:

- Joined NEC Electronics America in 1985 - senior FAE specializing in MCUs, LCD drive & VF displays, white goods & Industrial control/automation markets.
- Staff FAE from 1990-2006, adding segments; cable modem, digital AV, telecom equipment and automotive modules to responsibilities.
- MCU Technical marketing for K0R and RL78 from 2006-2011.
- Prior to NEC/Renesas, design engineer at Motorola Communications Group, Schaumburg IL
- BSEE from Rose-Hulman Institute of Technology
- Member of the IEEE professional association
- Active in Amateur Radio, with Extra class License
- Hobbies: hiking, biking
Renesas Technology & Solution Portfolio
Renesas Technology & Solution Portfolio

Microcontrollers
No. 1 Market Share Worldwide

Enabling the Smart Society

Advanced and Proven Technologies
System LSIs
Extensive, High-quality Portfolio
Analog & Power
Microcontroller and Microprocessor Line-up

2010

1200 DMIPS, Superscalar
- Automotive & Industrial, 65nm
- 600µA/MHz, 1µA standby

500 DMIPS, Low Power
- Automotive & Industrial, 130nm
- 190µA/MHz, 0.2µA standby

100 DMIPS, Capacitive Touch
- Industrial, 90nm
- 1mA/MHz, 100µA standby

2012

1200 DMIPS, Performance
- Automotive, 40nm
- 600µA/MHz, 1µA deep standby

500 DMIPS, FPU, DSC
- Industrial, 90nm
- 600µA/MHz, 1.5µA standby

1200 DMIPS, True Low Power
- Industrial & Automotive, 130nm
- 144µA/MHz, 0.2µA standby

1200 DMIPS, Superscalar
- Automotive & Industrial, 90nm
- 600µA/MHz, 1µA standby

8/16-Bit True Low Power
High Efficiency & Integration

- Industrial, 90nm
- 200µA/MHz, 0.3µA deep standby

- Industrial, 40nm
- 25 DMIPS, Low Power
- 0.5µA/MHz, 5µA standby

- Industrial, 40nm
- 10 DMIPS, Capacitive Touch
- 0.1mA/MHz, 10µA standby

- Automotive, 40nm
- 650µA/MHz, 5µA deep standby

- Automotive & Industrial, 130nm
- 144µA/MHz, 0.2µA standby

- Automotive & Industrial, 150nm
- 190µA/MHz, 0.3µA standby

- Automotive, 40nm
- 165 DMIPS, FPU, DSC
- 2.5µA/MHz, 0.3µA deep standby

- Automotive, 65nm
- 1200 DMIPS, Performance
- 600µA/MHz, 1µA deep standby

- Industrial, 90nm
- 10 DMIPS, Capacitive Touch
- 0.1mA/MHz, 10µA standby

- Automotive & Industrial, 130nm
- 144µA/MHz, 0.2µA standby
Challenge:
“Battery-operated, portable equipment designs are proliferating in the consumer, industrial, office, and security markets. Examples are intrusion/glass-break sensors, personal activity/health monitors, wireless utility meters, wireless household control, etc. There are many battery technologies to fit these new portable designs but not all batteries work well for a given application. The battery type must be chosen wisely to achieve performance and longevity targets.

Solution: “This class will show examples of how to choose an optimum battery for an embedded control application.”
Agenda (1)

- Quick review of Batteries & Battery technologies
  - Characteristics of ideal batteries
    (13 main attributes and issues)
  - Characteristics of real-world batteries
    (challenges a designer has to deal with!)
  - Batteries, what is a battery, really?

Examples:

Primary (disposable)
- Zinc-carbon, zinc-chloride
- Alkaline
- Lithium
- Lithium Thionyl

Secondary (rechargeable)
- Lead-Acid (& Sealed Gel-cell)
- NiCd
- NiMh
- Lithium Ion
Agenda (2)

- Choosing a battery technology to match (5) application examples, highlighting battery attributes:
  
  - For instance: voltage range, average/peak pulse current capacity, total mA-hour ratings, temp range, etc
Agenda (3)

- Maximizing battery life with low power MCUs for wireless, portable, remote operation
  - Tips:
    - Benefits of having internal low dropout voltage regulator
    - Standby/STOP mode with RAM data retained/not retained, all clocks off
    - Using Standby/STOP mode with 32KHZ/RTC operational
    - Auxiliary safety circuits used in Standby mode
    - Using Halt Mode (execution suspended) to save MCU current drain.
    - Moderating active CPU current drain

- Renesas RL78 Ultra Low Power MCU family Roadmap
An ideal battery:

- Highest mA-hour (Amp-Hour) capacity
- Widest Temp Range
- Lowest Internal Resistance
- Highest Peak current ability
- Constant Voltage

- Small size, Light Weight
- Longest Life, lowest leakage
- Readily available
- All at LOW COST!
- Easy to Design

- MCU Friendly
- No safety issues
- No disposal issues

- Lowest Internal Resistance
- Highest Peak current ability
- Constant Voltage
- Easy to Design
A real-world battery:

- Limited mA-hour (Amp-Hour) capacity
- Hot and Cold Temp Effects
- Limiting Internal Resistance
- Weak Peak current ability
- Sagging Voltage

- Large and Heavy
- Shorted lived, leaky
- Restricted Availability
- Medium to High COST!
- On-Going Replace. Costs

- Not MCU Friendly
- Safety issues
- Materials Disposal Caution
- Significant Design Trade-offs
What is a Battery?

- An Electrochemical Cell
- Invented in 1800 by an Italian Physicist – Allesandro Volta

2013 Chevy VOLT

with 16.5 kWh Lithium Ion Battery

Also sold as Opel/Vauxhall Ampera in Europe
What is a Battery?

- **Electrochemical cell reaction**
  
  (Example: Lithium/Manganese Dioxide Battery)

  The cell reaction involves the oxidation of lithium metal at the anode to produce positively charged lithium ions (Li+) and electrons (e\(^-\)), as shown.

  Li+ ions go into solution and diffuse through the electrolyte and separator to the cathode.

  Electrons travel through the external circuit and arrive at the cathode where MnO_2, Li+ ions and electrons combine.

**Battery Attributes:**
- Chemistry (anode, cathode, electrolyte)
- Cell size
- Electrode surface area
- Electrode conductivity
- Ionic conductivity

**Effects:**
- Voltage range
- Current Capacity
- Internal resistance
- Temperature characteristics
- Self-leakage/shelf life
Application Example #1: Battery-Operated Electronic Lockbox

Attributes:
- Needs timestamp with date
- 18-24 month battery life target
- Secure access
- Access logging (who, when)
- Anti-tampering security
- Temp range: -30°C (-22°F) to +60°C (140°F)
- Target battery size: medium

Energy Profile:
- Nominal voltage: 3Volts
- Long periods of standby: <1μA
- Infrequent updates thru serial: mAs
- Frequent access of lock mechanism: 100s of mAs
Application Example #1: Design Challenges and Estimated Energy Use

Design Challenges:
• Keep standby current under 1μA typ. w/ RTC
• Lock solenoids could draw 250-300mA for 0.6-1.0 seconds (needs low IR)
• Keeping batteries <50% of Lock pkg volume
• Dealing with varying battery voltage
• Wide temperature range (Anchorage & Phoenix)

Rough Current Drain Estimation:

<table>
<thead>
<tr>
<th>Activity</th>
<th>mA</th>
<th>seconds</th>
<th>times/day</th>
<th>Times # of days</th>
<th>mA-hours used in 1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solenoid actuation</td>
<td>300</td>
<td>1</td>
<td>16</td>
<td>365</td>
<td>486.67</td>
</tr>
<tr>
<td>Standby with RTC</td>
<td>0.001</td>
<td>3600</td>
<td>24</td>
<td>365</td>
<td>8.76</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>~500</td>
</tr>
</tbody>
</table>
Application Example #1: Estimated Energy Use

• Need about 500mA-Hour per year, or 1000mA-hour for 2-year application life

• Not including reduced battery capacity at Temperature extremes!

• Not including any margin for extra usage

Candidate battery type:
Use 2x AA size Primary batteries:
• LR6 Alkaline/Manganese-Dioxide (1.5V, 2200mA-HR capacity)
or
• L91-FR6 Lithium/Iron-DiSulfide (1.5V, 3000mA-HR capacity)
Appl. Example #1: Battery Discharge Voltage

Typical discharge profile of the DURACELL® Alkaline MN 1500 ("AA" size) cell.

- Alkalines have a steep voltage slope! (affects MCU operation)
Appl. Example #1: Battery Discharge Voltage @ colder temps

Akalines quickly lose their rated capacity even at 0C (32F)!
Appl. Example #1: Hot Temperature Effects (comparisons of Lithium and Alkaline)

Temperature effects on battery capacity and storage life

- **AA/LR6 Alkaline Batteries**
  - 25% loss in 4 years @ 40C

- **AA Lithium Iron Disulfide Batteries**
  - 10% loss in 4 years @ 40C
Application Example #1: Mfr Specification and Comparisons (Sanity Check)

ENERGIZER L91-FR6 Specification
Classification: "Cylindrical Lithium"
Chemical System: Lithium/Iron Disulfide (Li/FeS2)
Nominal Voltage: 1.5 Volts
Storage Temp: -40°C to 60°C
Operating Temp: -40°C to 60°C
Typical Weight: 14.5 grams (0.5 oz.)
Typical Volume: 8.0 cubic centimeters
Max Discharge: 3.0 Amps Continuous
Typical IR: 90 to 160 milliohms (depending on method)
Shelf Life: 15 years at 21°C
Application Example #1: Mfr Comparisons (Sanity Check)

Milliamp-Hours Capacity
Constant Current Discharge to 0.9 Volts at 21°C

Application Example #2: AA Lithium Iron Disulfide Batteries
Temperature Performance / Continuous Discharge to 0.9 Volts
Application Example #1: (Conclusion)

My Pick: FR6 Lithium/Iron-DiSulfide (2x AA)

Reasons:
• Good mA-hour capacity (3000mA-Hr)
• Very wide operating temp range (-40C to +60C)
• Good/stable voltage (<0.3 Volt drop) for >95% life
• Low internal resistance

Conclusions:
• Large current drains generally require larger batteries.
• Wide temp range may require specialized batteries
• Operational and FEP* voltage effects on MCU should be considered

FEP* = Function End Point
Application Example #2: Wireless RF Sensor (e.g.: Glass Break/Intrusion Sensor, etc)

**Attributes:**
- Needs time-stamp with date
- 1-4 year battery life target (prefer 4yrs)
- Periodic wakeup
- Data logging
- Temp range: -20°C (-4°F) to +50°C (+122°F)
- Battery target: small 3V single cell

**Note*: ANT+, BlueTooth low-energy, Zigbee/802.15.4, WiFi

**Energy Profile:**
- Periods of standby – <1μA
- Periodic temp measurement – mAs
- Random wakeup; event analysis – mAs
- Receive coordination from base – 10s of mAs
- Transmit alarm event/Status to base – 10s of mAs

<table>
<thead>
<tr>
<th>Wireless Type</th>
<th>Avg. Current</th>
<th>Peak Current</th>
<th>Use Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>WiFi</td>
<td>25-50mA</td>
<td>150mA</td>
<td>Medium</td>
</tr>
<tr>
<td>Zigbee, Bluetooth</td>
<td>5-20mA</td>
<td>50mA</td>
<td>Medium</td>
</tr>
<tr>
<td>ANT+, Bluetooth LE</td>
<td>1-5mA</td>
<td>10mA</td>
<td>High</td>
</tr>
<tr>
<td>ANT+, Bluetooth LE</td>
<td>&lt;1mA</td>
<td>10mA</td>
<td>Low/Medium</td>
</tr>
</tbody>
</table>
Application Example #2: Wireless Sensor

- Target: single 3V primary battery
- Example:
  - CR2032 (220-240 mA-Hr) or CR2450 (610 mA-Hr) Lithium Coin cell
  - CR123 (1500 mA-Hr) Cylindrical Lithium

<table>
<thead>
<tr>
<th>Wireless Type/use profile</th>
<th>Avg. Current (mA)</th>
<th>Consumption (mA-Hr per year)</th>
<th>Lithium Coin Cell</th>
<th>Cylindrical Lithium</th>
</tr>
</thead>
<tbody>
<tr>
<td>WiFi/ medium</td>
<td>25</td>
<td>219000</td>
<td>NG</td>
<td>NG</td>
</tr>
<tr>
<td>Zigbee, Bluetooth/ med.</td>
<td>5</td>
<td>43800</td>
<td>NG</td>
<td>NG</td>
</tr>
<tr>
<td>ANT+, Bluetooth LE, Proprietary/ high</td>
<td>1</td>
<td>8760</td>
<td>NG</td>
<td>NG</td>
</tr>
<tr>
<td>ANT+, Bluetooth LE, Proprietary/ low</td>
<td>0.050</td>
<td>438</td>
<td>1.4yrs (CR2450)</td>
<td>~3.4 yrs?</td>
</tr>
<tr>
<td>ANT+, Bluetooth LE, Proprietary/ very low</td>
<td>0.025</td>
<td>219</td>
<td>~1.1-2.8 years?</td>
<td>~3.4-6.8 yrs?</td>
</tr>
</tbody>
</table>

NG: No Good

- Hard to maintain adequate battery power for Wireless sensors
CR2032 Capacity versus Constant & Pulse Loading

CR2032 coin cell continuous discharge curves

- Reduced Capacity
- F.E.P.: Function End Point

Initial, Continued Voltage Droop from Load
Slow recovery to previous O.C.V.
CR2032 Capacity versus Constant & Pulse Loading

Decreased Loaded Voltage as IR increases
CR2032 Capacity versus Pulse Loading

Effects of Pulse duty cycle on Capacity

A. 30mA (1mSEC On / 74mSEC Off)
   100uA background

B. 30mA (1mSEC On / 9mSEC Off)
   100uA background
CR2032 Capacity versus Pulse Loading

Effects of Pulse magnitude on Capacity

C. 10mA Pulse load
100uA background

D. 30mA Pulse load
100uA background
Battery Construction Attributes and Tradeoffs

Microlithium™ coin (button) cell.

**Coin cell:**
- Smallest volume
- Highest IR
- Lowest peak current

**Bobbin cell:**
- Medium volume
- Medium IR
- Medium peak current
- Highest energy density (more efficient)

**Spiral-Wound cell:**
- Medium volume
- Low IR
- High peak current
- Good energy density (less than bobbin)

DURACELL® MicroLithium™ bobbin cell.

DURACELL® high rate spiral-wound cell.
Internal Impedance/Resistance – varies with age, loading

At battery end-of-life, IR (Internal Resistance), ESR (Equivalent Series Resistance) increases dramatically (10x-100x of initial)

Recommended: using an MCU with low-battery detect!

Case A:
\[ V_{\text{drop}} = 0.1V \]
\[ R_{\text{ESR}} = 10 \text{ Ohms} \]
\[ V_{\text{load}} = 3.0V \]
\[ R_{\text{Load}} = 300 \text{ Ohms} \]
\[ +3.1V \text{ load} \]

Case B:
\[ V_{\text{drop}} = 0.6V \]
\[ R_{\text{ESR}} = 100 \text{ Ohms} \]
\[ V_{\text{load}} = 100 \text{ Ohms} \]
\[ +2.4V \text{ load} \]

Case C:
\[ V_{\text{drop}} = 1.0V \]
\[ R_{\text{ESR}} = 10 \text{ Ohms} \]
\[ V_{\text{load}} = 300 \text{ Ohms} \]
\[ +2.4V \text{ load} \]

Note: IR is more dynamic, complex than simple resistance
Conclusions from Example #2 Analysis:

Consider a larger Lithium Coin Cell? – CR2450

Conclusions on CR2032 Coin cell performance:

- Max rated battery capacity is at low drain (<<1mA)

- Conditions degrading Coin Cell Capacity:
  - Continuous > 500uA drain
  - Pulsed current drains > few mAs
  - High duty cycle
  - Low temp <20C

- All actual use conditions must be considered

Capacity still too low!
Application Example #2: Wireless Sensor

Sanity check:

**Energizer 123 (EL123AP) Specification**

- Chemical System: Lithium/Manganese Dioxide (Li/MnO2)
- Designation: ANSI-5018LC, IEC-CR17345
- Nominal Voltage: 3.0 Volts
- Storage Temp: -40°C to 60°C (-40°F to 140°F)
- Operating Temp: -40°C to 60°C (-40°F to 140°F)
- Typical Capacity: 1500 mAh (to 2.0 volts)
  (Rated at 100 ohms at 21°C)
- Typical Weight: 16.5 grams (0.58 oz.)
- Typical Volume: 7.0 cubic centimeters (0.4 cubic inch)
- Max Discharge: 1500 mA continuous (3500 mA pulse)

Higher voltage over full battery life
Application Example #2: Wireless Sensor

Conclusion:

My Pick: CR123 Cylindrical Lithium

Reasons:
• Good mA-hour capacity (1500mA-Hr)
• Very wide operating temp range (-40C to +60C)
• Good/stable discharge voltage (<0.15 Volt drop) for >90% life

Conclusions:
• Coin cell batteries have many issues for pulsed current apps
• Wide temp range may require specialized batteries
Application Example #2: Wireless Sensor

- Target a 1500mA-Hour battery and work backwards!

- **Battery capacity:**
  1500mA-Hr/ 4 years (8766 hours/year)
  = 1500mA-Hr/ 35064 hours
  = 42.8uA average for 4 years

- **Wireless usage:**
  20mA active current for 100mSEC every 1 minute:
  = 20mA * 0.1 sec / 60 sec
  = 33.3uA average

- Add in 1uA standby mode:
  34.3uA average total

- 42.8uA/34.3uA → 125% capacity
Application Example #3: Blood Glucose Meter

Attributes:
• Needs timestamp with date
• 18-24 month battery life target
• Several samples per day
• Low battery alert
• Data recording
• Temp range: +5C to +45C
• Size: small

Energy Profile:
• Long periods of standby – <1uA
• Unscheduled wakeup for data analysis – mAs
• Infrequent data downloads via USB port – 10s of mAs (via PC HOST USB cable!)
**Application Example #3: Blood Glucose Meter**  
(with Segmented STN LCD Panel)

**System Activity and current draw**

1. **STOP/Standby mode**
2. **System initialization**
3. **Wait for blood test strip insertion**
4. **A/D conversion and calculate Glucose level**
5. **Display result**
6. **No further button activity, back to STOP/standby**

**Time**

- **MCU wakes up with button press**
- **Total current** = $1\text{mA-SEC} + 20\text{mA-SEC} + 24\text{mA-SEC} + 126\text{mA-SEC} = 171\text{ mA-SEC}$
  (average per reading)

**Target:** 6 readings per day, 1026 mA-SEC per day

**Assuming 1uA in standby, daily** = $(85,370\text{ sec} \times 1\text{ua}) + (1026\text{ mA-SEC}) = 1035\text{ mA-SEC}$

**Approximate life** = $(220\text{mA-hr} \times 3600\text{ sec/hr}) / 1111\text{ mA-SEC/day} = 713\text{ days (~2 years)}$
Add 1.5mA to total On-Time

System Activity and current draw

1. STOP/Standby mode
   - 1 sec @2.5mA
2. 40 sec @2.0mA
3. 3 sec @9.5mA
4. 120 sec @2.2mA
5. Display result
   - MCU wakes up w/ button press
6. No further button activity, back to STOP/standby

Assume current drains is now double previous value!

Double the current drain to 2222 mA-SEC/day
Approximate life = (220mA-hr x 3600 sec/hr)/2222 mA-SEC/day = 356 days (~1year)
Application Example #3: Blood Glucose Meter (with COG Graphics STN LCD Panel)

**Conclusion:**

- **2x CR2032**
  - Capacity: ~220mA-Hr (each)
  - **Recommendation:** User should replace both used batteries with new

- **1x CR2450**
  - Capacity: ~610mA-Hr
  - **CR2450 not as commonly available?**

**Choices:** *(1x or 2x)* CR2032 or CR2450

**Reasons:**
- CR2032 coin cells; readily available, inexpensive
- Good fit for temp range (+5C to +60C)
- Compact size

**Conclusions:**
- Coin cell batteries are fine for apps with light pulse loading
- Wide temp range may require specialized batteries
Application Example #4:

Attributes:
- Needs elapsed time
- 20 year battery life target
- Periodic transmission of RF data
- Anti-tampering security
- Temp range: -40°C to +85°C
- Target battery size: medium

Energy Profile:
- Long periods of standby – <0.6μA
- Random wakeup to count water/gas units used – 100s of uAs (low duty cycle)
- Less frequent RF transmission of serial number, unit status – 10s of mAs

Application Example 4: Water/Gas Meter
Battery Self-Leakage

- Battery self-leakage increases with temperature

![Lithium Manganese Battery Self-discharge graph]

- Internal Leakage Increases Exponentially At Elevated Temps!
Specialized Battery for Long Life

**Battery System/IEC Nomenclature**

<table>
<thead>
<tr>
<th>Battery System/IEC Nomenclature</th>
<th>Class</th>
<th>Cathode Material</th>
<th>Cathode Properties</th>
<th>Electrolyte Salt Properties</th>
<th>Electrolyte Salt Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium Carbon-Monofluoride Li/(CF)x BR</td>
<td>Solid Cathode</td>
<td>Poly-Carbon Monofluoride</td>
<td>Solid Stable</td>
<td>Lithium Tetra Fluoroborate LiBF4</td>
<td>Stable</td>
</tr>
<tr>
<td>Lithium Manganese Dioxide Li/Mn02 CR</td>
<td>Solid Cathode</td>
<td>Manganese Dioxide</td>
<td>Solid Stable</td>
<td>Lithium Perchlorate LiCl04</td>
<td>Explosive</td>
</tr>
<tr>
<td>Lithium Thionyl Chloride LiS0CI2</td>
<td>Solid Cathode</td>
<td>Lithium Thionyl Chloride</td>
<td>Liquid Toxic</td>
<td>Lithium Tetra Choroaluminate LiAlCl4</td>
<td>Corrosive</td>
</tr>
</tbody>
</table>

**Attribute**

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Lithium Carbon-Monofluoride</th>
<th>Lithium Thionyl Chloride</th>
<th>Attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Nominal Voltage</td>
<td>3.0V</td>
<td>3.6V</td>
<td>Rated Nominal Voltage</td>
</tr>
<tr>
<td>Rated Nominal Capacity (mAh)</td>
<td>50-300 mAh</td>
<td>790-3650 mAh</td>
<td>Rated Nominal Capacity (mAh)</td>
</tr>
<tr>
<td>Nominal Pulse Capability (mA)</td>
<td>5-10 mA</td>
<td>35-125uA</td>
<td>Nominal Discharge Current (mA)</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-40° C to +85° C</td>
<td>-55° C to +85° C</td>
<td>Temperature Range</td>
</tr>
</tbody>
</table>
Application Example #4: Water/Gas Meter w/ Wireless Communication

Calculate mA-Hr battery capacity

- Standby:
  0.5uA x 20years (8766 hours/year)
  = 87.7mA-hr total after 20 years

- Metering:
  1mA active current for 2 sec every hour:
  = 1mA * 2 sec / 3600 sec (/hour) * 8766hrs * 20 years
  = 97.4mA-hr total after 20 years

- Wireless communication:
  20mA for 100mSEC every 5 minutes
  = 20mA * 1.2 sec /3600 (/hour) * 8766hrs * 20 years
  = 1169mA-Hr total after 20 years

Grand total = Standby + Metering + Wireless comm.
= 1354mA-Hr total after 20 years
(7.7uA average current over 20 years)
Application Example #4: Water/Gas Meter w/ Wireless Communication

- Double-Check Lithium Thionyl Chloride battery: Maxell ER17/50 (2750mAh)

- Slight acceleration in self leakage due to 60C temps
- Even Lithium Thionyl has significant self leakage @20C
- So use extra mA-Hr capacity to attain 20 year life
Application Example #4: Water/Gas Utility Meter w/ Wireless communication

Conclusion:

My Pick: Lithium Thionyl Chloride

Reasons:
• Lithium Carbon-Monofluoride and Lithium Manganese Oxide - relatively low mA-Hr capacity
• Thionyl has Wide operating temp range (-40C to +85C)
• Thionyl has low self-leakage due to elevated temps

Conclusions:
• Some batteries have corrosive or dangerous properties if mishandled
• For industrial/commercial applications, Lithium Thionyl Chloride Dangerous properties can be managed
Application Example #5: Energy Harvesting

Solar Panel → Boost/Buck Convertor, Charger → Over-Current, Low/High Voltage, Temp Protect → Li-ion Battery Pack

Charging Status → Sensor 1 → Sensor n → Low Power MCU → Zigbee (802.15.4) RF Transceiver

Application Example #5: Energy Harvesting w/ Solar power, etc for recharging Li-ion Battery. (e.g.: Remote Sensor for Temp, Pressure or Intrusion Alarm)

Attributes:
• Needs elapsed time
• Battery life target - NA
• Periodic reporting of Temp/status
• Temp range: -40C to +75C
• Size: may/may not be critical

Energy Profile:
• Standby not critical – several uAs OK
• Frequent wakeup report status – 10s of mAs
• Less frequent RF transmission to report an event – 10s of mAs
Energy Densities for Rechargeable Batteries

Typical energy densities of lead, nickel- and lithium-based batteries

<table>
<thead>
<tr>
<th>ANODE MATERIAL</th>
<th>ATOMIC WEIGHT</th>
<th>AMPERE HOUR CAPACITY PER GRAM (Ah /g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb</td>
<td>207.19</td>
<td>0.26</td>
</tr>
<tr>
<td>Zn</td>
<td>65.37</td>
<td>0.82</td>
</tr>
<tr>
<td>Fe</td>
<td>55.85</td>
<td>0.96</td>
</tr>
<tr>
<td>Li</td>
<td>6.94</td>
<td>3.86</td>
</tr>
</tbody>
</table>

Li-Ion batteries advantages:
- Highest Energy Density
- Lightest weight

Downsides:
- Complex charging, Safety circuitry
- Most versions have disposal, handling issues
<table>
<thead>
<tr>
<th>Common name</th>
<th>Electrode material</th>
<th>Average potential difference</th>
<th>Specific capacity (mA·h/g)</th>
<th>Specific energy (W-h/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium Cobalt Oxide</td>
<td>LiCoO₂</td>
<td>3.7 V</td>
<td>140</td>
<td>518</td>
</tr>
<tr>
<td>Lithium Manganese Oxide</td>
<td>LiMn₂O₄</td>
<td>4.0 V</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>Lithium Iron Oxide</td>
<td>LiNiO₂</td>
<td>3.5 V</td>
<td>180</td>
<td>630</td>
</tr>
<tr>
<td>Lithium Iron Phosphate</td>
<td>LiFePO₄</td>
<td>3.3 V</td>
<td>150</td>
<td>495</td>
</tr>
<tr>
<td>Lithium Iron Fluorophosphate</td>
<td>Li₂FePO₄F</td>
<td>3.6 V</td>
<td>115</td>
<td>414</td>
</tr>
<tr>
<td>Lithium nickel manganese cobalt 3.6V</td>
<td>LiCo₁/₃Ni₁/₃Mn₁/₃O₂</td>
<td>3.6 V</td>
<td>160</td>
<td>576</td>
</tr>
<tr>
<td>Lithium nickel manganese cobalt 4.2V</td>
<td>Li (Li₈NiₓMn₇Co₂)O₂</td>
<td>4.2 V</td>
<td>220</td>
<td>920</td>
</tr>
</tbody>
</table>

Li-Ion battery chemistries:
- Wide range of voltages to choose from (match to MCU supply?)
- Some chemistries have toxic content
- All have safety issues (short circuit, and overtemp)
Application Example #5: Solar Panel
Safety issues for Lithium Ion batteries

Li-Ion battery packs require:
- Temperature monitoring
- Temperature fuse
- Overcurrent protection

Note: from Battery University
Lithium Ion Charge Profile
Application Example #5: Solar panel

Conclusion

Many Choices: Lithium Ion, NiMH, NiCad, Lead Acid

Tradeoffs:
• Lithium Ion battery voltages good match w/ MCU and wireless HW voltages.
• Lithium Ion batteries have the highest energy density
• Lithium Ion also has most safety issues
• Lead Acid is lowest cost but lowest energy density

Conclusions:
Solar panel battery selection mainly depends on:
• Desired end-product size
• Desired system voltage range
• Total ma-Hr current capacity needed
Battery-operated MCU design ideas
MCU/CPU Operational Definitions

CPU Operation/Active Mode
- Instructions executed,
- All peripherals available

CPU Halt/Idle Mode
- Instruction execution suspended,
- Main System clock running
- All peripherals available

CPU STOP/Standby 32KHZ/RTC Mode
- Instructions execution STOP,
- Main system clock STOP
- A few peripherals available

CPU STOP/Standby Mode (No Clocks)
- Instructions execution STOP,
- Main system clock stopped
- 32KHZ/RTC stopped
- RAM data is retained
Managing Peripherals

Peripheral functions
- Digital (Primarily AC Drain)
- Analog (Primarily DC Drain)
- Other:

Legend:
- MCU Analog Blocks
- CPU/ SW
- MCU Digital Blocks

- CPU Active Mode (all resources)
  Vs.
  - CPU Halt/Idle Mode (all Peripherals)
  Vs.
  - CPU STOP Mode

20% x Active Current
<0.01% x Active Current

Digital processing (CPU/ SW)

Serial Ports
Timers/ Counter
Real Time Clock
DMA
Watch Dog Timer
Low Voltage Detect

Comparators
Op-amps (Amplify, filter)
Digitize (12-bit ADC)
Digital processing (CPU/ SW)

LCD controller/ driver with boost
Convert To analog (DAC)

Display results
- Analog voltages (AC and DC)
- Voice/tones

Stable, accurate VREF
DC Voltage Level

Analog, Transducer Signals

MCU

CPU/ SW

MCU
Digital Blocks

Op-amps (Amplify, filter)

• DC current in standby?
• AC current when operating?
• Can clocks be gated/scaled?
• What should be left on in standby mode?
Use Internal Voltage Regulator to Minimize Current Drain

Internal voltage regulator

- Internal core LDO voltage regulator
  - Keeps CPU and core function current drains constant

Functions attached to I/O pins
- Current drains rise proportionally to supply voltage

MCUs with No Internal Voltage Reg; Current Drain Increases with Supply Voltage!

MCUs with an Internal Voltage Reg; Current Drain Constant Over Supply Voltage!

Supply Current, CPU and Core Peripherals

Supply Voltage

1.8V  2.4V  3.0V  3.6V  4.2V  4.8V  5.5V
5 Key Factors Enable Low Power Consumption

RTC, Interval timer, WDT or LVD current consumption: key factors as well as STOP mode current

![Graph showing average current calculation](image)

Average Current = \( \frac{(\text{Active current} \times \text{Active time}) + (\text{Standby current} \times \text{Standby time})}{\text{Total time}} \)

- Keys to achieve low power consumption
  - Low active power
  - Low standby power (STOP/Halt, LVD, WDT, Interval timer)
  - Fast wake up
  - High processing speed
  - Long standby interval
Low Power Comparison

- Outstanding Overall Performance

Operating Mode (uA/MHz)

- Halt Mode: RTC + LVD
  - A: 213
  - B: 150
  - C: 363
  - D: 380
  - RL78

- Stop Mode: WDT + LVD
  - A: 14.3
  - B: 10.3
  - C: 5.1
  - D: 0.54

Halt Mode: RTC + LVD

- A: 5.6
- B: 3.6
- C: 10.6
- D: 0.54

Stop Mode: WDT + LVD

Note: (RL78G13)
1: At 32MHz
2: 0.45 uA (RTC only)
3: 0.23 uA (all stopped, RAM retained)
RL78 Roadmap

Application Specific

RL78 Core

General Purpose

LCD (Segment)

G12
Basic

G13
Standard

G14
High Performance

G1A
12-bit ADC

G1A
(USB)
32-64 pin

G1C
(Next –USB)
32-80 pin

G1x
(Entry)
Sub 20 pins

L1A
Lighting
20-38 pin

L12
32-64 pin

L13
64-80 pin

L1C
USB+12bit ADC
80-100 pin

BTLE

I1A

Production

Sampling

1H’11
2H’11
1H’12
Beyond

FY
<table>
<thead>
<tr>
<th>G12</th>
<th>Pin Count</th>
<th>Flash</th>
<th>WS</th>
<th>ES</th>
<th>MP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 to 30-pin</td>
<td>16 KB</td>
<td>-</td>
<td>-</td>
<td>Today</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>G13</th>
<th>Pin Count¹</th>
<th>Flash</th>
<th>WS</th>
<th>ES</th>
<th>MP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 to 128-pin</td>
<td>Up to 512 KB</td>
<td>-</td>
<td>-</td>
<td>Today</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>G14</th>
<th>Pin Count²</th>
<th>Flash</th>
<th>WS</th>
<th>ES</th>
<th>MP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 to 100-pin</td>
<td>Up to 256 KB</td>
<td>-</td>
<td>-</td>
<td>Today</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I1A</th>
<th>Pin Count³</th>
<th>Flash</th>
<th>WS</th>
<th>ES</th>
<th>MP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 to 38-pin</td>
<td>Up to 64 KB</td>
<td>-</td>
<td>-</td>
<td>Today (105C) 2012/9 (125C)</td>
</tr>
</tbody>
</table>

Note 1: 32-pin VQFN 32KB 105C&125C (Jan’13)
# RL78 Roadmap Details

<table>
<thead>
<tr>
<th>RL78 Series</th>
<th>Pin Count</th>
<th>Flash (KB)</th>
<th>RAM (KB)</th>
<th>Operating Voltage (V)</th>
<th>Key Features</th>
<th>Availability</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1A</td>
<td>25 to 64</td>
<td>Up to 64</td>
<td>Up to 4</td>
<td>1.6 to 3.6</td>
<td>12-bit ADC</td>
<td>MP: 2012/Nov</td>
<td>ES: Now</td>
</tr>
<tr>
<td>G10</td>
<td>10</td>
<td>1 to 4</td>
<td>0.128 to 0.5</td>
<td>2 to 5.5</td>
<td>Low pin count</td>
<td>ES: 2012/Nov</td>
<td>20 MHz max.</td>
</tr>
<tr>
<td>G1C-1</td>
<td>32, 48</td>
<td>Up to 32</td>
<td>Up to 5.5</td>
<td>2.4-5.5V</td>
<td>USB (Host &amp; Peripheral)</td>
<td>ES: 2012/Q4</td>
<td>24MHz max.</td>
</tr>
<tr>
<td>G1C-2</td>
<td>48 to 64</td>
<td>Up to 128</td>
<td>Up to 8</td>
<td>2.4-5.5V</td>
<td>USB (Host &amp; Peripheral), OTG</td>
<td>ES: 2013/Q4</td>
<td>24MHz max.</td>
</tr>
<tr>
<td>L12</td>
<td>32 to 64</td>
<td>Up to 32</td>
<td>Up to 1.5</td>
<td>1.6 to 5.5</td>
<td>LCD, 35x8 segments</td>
<td>MP: 2012/Dec</td>
<td>24 MHz max.</td>
</tr>
<tr>
<td>L13</td>
<td>64, 80</td>
<td>Up to 128</td>
<td>Up to 8</td>
<td>1.6 to 5.5</td>
<td>LCD booster and up to 8 COM, comparator</td>
<td>ES: 2012/Dec</td>
<td>24MHz max.</td>
</tr>
<tr>
<td>L1C</td>
<td>80, 100</td>
<td>Up to 256</td>
<td>Up to 10</td>
<td>1.6 to 3.6</td>
<td>12-bit A/D, L13 features plus: USB</td>
<td>ES: End 2013/Q1</td>
<td>24MHz max.</td>
</tr>
</tbody>
</table>
Questions?
‘Enabling The Smart Society’ in Review...

- **Challenge:**
  “Battery-operated, portable equipment designs are proliferating in the consumer, industrial, office, and security markets. Examples are intrusion/glass-break sensors, personal activity/health monitors, wireless utility meters, wireless household control, etc. There are many battery technologies to fit these new portable designs but not all batteries work well for a given application. The battery type must be chosen wisely to achieve performance and longevity targets.

- **Solution:** “This class will show examples of how to choose an optimum battery for an embedded control application.”

- Do you agree that we accomplished the above statement?
Please Provide Your Feedback...

- Please utilize the ‘Guidebook’ application to leave feedback

- Ask me for the paper feedback form for you to use...
Appendix
Battery Info Websites

Battery Transportation Rules

Battery Information and Technology Resources
- www.mobilepowersolutions.com
- www.smbus.org
- www.prba.org
- www.rbrc.org
- www.batteryuniversity.com

Battery Manufacturers
- www.duracell.com
- www.rayovac.com
- www.maxell.com
- www.energizer.com
- http://www.molicel.com

Regulatory agencies and industry approvals:
- www.ul.com
- www.fcc.gov
- www.dot.gov
- www.iata.org
- ec.europa.eu/index_en.htm
- www.iec.ch
- www.rohs.eu
- www.iso.org
- www.un.org
Battery Education

http://www.allaboutbatteries.com
http://batteryuniversity.com/learn
http://en.wikipedia.org/wiki/Battery_(electricity)
Battery coding – example CR2032

- The "C" denotes a lithium-manganese dioxide chemistry. The "R" means it's a round (cylindrical) cell.
- LR = Alkaline Manganese Dioxide round cell
- FR = Lithium-iron disulfide
- HR = NiMH
- SR = Zinc-silver Oxide
- ER = Lithium Thionyl Chloride