Lithium Ferro Phosphate (LFP) Batteries

The “Safe Lithium”

Simon Chan
Radlink Communications
Workshop agenda

• Rechargeable batteries
  – Why use rechargeable batteries?
  – Different battery chemistries
  – ‘Horses for courses’

• Lithium rechargeable batteries
  – Are they safe?
  – Different types of Lithium cells
    • Different chemistries
Workshop agenda

• Quiz time!
• Short break

• Lithium rechargeable batteries (continued)
  – Shapes and sizes
  – What cell types are best?

• What we do at Radlink
  – Case studies
Workshop agenda

• Lithium rechargeable batteries (continued)
  – LFP characteristics – Facts & figures
  – Selecting a suitable cell for your project
  – Connecting cells together
  – Charging and discharging
  – Battery management systems

• Virtual factory tour

• Wrap-up!

• Share your questions
WARNING

• This is a Workshop and \textbf{not} a lecture.

• We will be doing \textit{interactive} activities together.

• Strap your brain on and let’s go 😊

• \textit{Note:} stop me at any time if you have questions or comments.
Your presenter...

• Simon Chan

– Born in Hong Kong
– Lived in Australia since ’74
– Raised & educated in Perth
– I love R&D and creating new products
– Have worked 31 years in many awesome companies
– Now working for Australia’s largest 2-way radio integration company
– Started using Lithium batteries for our own energy storage needs
– Now creating unique Lithium battery solutions for industry

For more info about me, see: https://www.linkedin.com/in/simonskchan
Rechargeable batteries – Why?

• Why use rechargeable batteries?

  – Portable equipment

  – People want batteries which are:
    • Low cost
    • Lightweight
    • Have long battery life

  – High expectations set by smartphones & smart devices
Rechargeable batteries – Why?

• Charging rechargeable batteries

  – 10+ years ago, it was very challenging
    • Poor charger design often saw products fail early
    • Eg Cordless telephones, shavers, torches, UPS

  – Must include charger on-board

  – Design is so much easier now!
    • Batteries have also improved a great deal over the last 20 years!
Rechargeable batteries – Why?

Audience participation

• Where have you seen rechargeable batteries in use?
  – Hint: think of all the portable equipment in your life...

• What battery chemistry was used?

• How large were the batteries?
Rechargeable batteries – Lead Acid

- Different battery chemistries
  - Lead Acid

  - Readily available
  - Low cost
  - Tolerant to overcharge

1900’s
Rechargeable batteries – Lead Acid

- Different battery chemistries
  - Lead Acid

  - Lead is toxic
  - Heavy (30-50Wh/kg)
  - Easy to degrade & damage
    - Heat
    - Excessive discharge
    - Electrodes become brittle with age
    - Sulphation (not reaching full charge often enough)

  - Takes a long time to charge – cannot sustain ‘fast charge’
  - Limited cycle life
  - Bulge / crack / leak
Rechargeable batteries – NiCd

- Different battery chemistries
  - Nickel Cadmium

- Readily available
- Low cost
- Can be rapidly charged (1 to 2 hours to full charge)
- High peak discharge current
Rechargeable batteries – NiCd

- Different battery chemistries
  - Nickel Cadmium

- Cadmium is toxic

- Terrible self-discharge characteristics

- Charge – discharge memory effect

- Difficult to charge – multi-stage charging cycle

1950’s
Rechargeable batteries – NiMH

• Different battery chemistries
  – Nickel Metal Hydride

✔ Readily available
✔ Low cost
✔ Good energy to weight ratio
✔ Moderate peak discharge current
✔ No charge – discharge memory effect
✔ Low toxicity

1990’s
Rechargeable batteries – NiMH

• Different battery chemistries
  – Nickel Metal Hydride

  ❌ Terrible self-discharge characteristics

  ❌ Limited cycle life

  ❌ Double charge time of NiCd
**Useful Summary Slide**

With thanks to Battery University

http://batteryuniversity.com/learn/article/secondary_batteries

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Lead Acid</th>
<th>NiCd</th>
<th>NiMH</th>
<th>Li-ion&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Cobalt</th>
<th>Manganese</th>
<th>Phosphate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific energy (Wh/kg)</td>
<td>30–50</td>
<td>45–80</td>
<td>60–120</td>
<td>150–250</td>
<td>100–150</td>
<td>90–120</td>
<td></td>
</tr>
<tr>
<td>Internal resistance</td>
<td>Very Low</td>
<td>Very low</td>
<td>Low</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Cycle life&lt;sup&gt;2&lt;/sup&gt; (80% DoD)</td>
<td>200–300</td>
<td>1,000&lt;sup&gt;3&lt;/sup&gt;</td>
<td>300–500&lt;sup&gt;3&lt;/sup&gt;</td>
<td>500–1,000</td>
<td>500–1,000</td>
<td>1,000–2,000</td>
<td></td>
</tr>
<tr>
<td>Charge time&lt;sup&gt;4&lt;/sup&gt;</td>
<td>8–16 h</td>
<td>1–2 h</td>
<td>2–4 h</td>
<td>2–4 h</td>
<td>1–2 h</td>
<td>1–2 h</td>
<td></td>
</tr>
<tr>
<td>Overcharge tolerance</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
<td>Low. No trickle charge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self-discharge/month (room temp)</td>
<td>5%</td>
<td>20%&lt;sup&gt;5&lt;/sup&gt;</td>
<td>30%&lt;sup&gt;5&lt;/sup&gt;</td>
<td>&lt;5%</td>
<td>Protection circuit consumes 3% per month</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell voltage (nominal)</td>
<td>2V</td>
<td>1.2V&lt;sup&gt;6&lt;/sup&gt;</td>
<td>1.2V&lt;sup&gt;6&lt;/sup&gt;</td>
<td>3.6V&lt;sup&gt;7&lt;/sup&gt;</td>
<td>3.7V&lt;sup&gt;7&lt;/sup&gt;</td>
<td>3.2–3.3V&lt;sup&gt;7&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Charge cutoff voltage (V/cell)</td>
<td>2.40 Float 2.25</td>
<td>Full charge detection by voltage signature</td>
<td>4.20 typical Some go to higher V</td>
<td>3.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discharge cutoff voltage (V/cell, 1C)</td>
<td>1.75V</td>
<td>1.00V</td>
<td>2.50–3.00V</td>
<td>2.50V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak load current</td>
<td>5C&lt;sup&gt;8&lt;/sup&gt; 0.2C</td>
<td>20C</td>
<td>5C</td>
<td>2C &lt;1C</td>
<td>&gt;30C</td>
<td>&gt;30C</td>
<td></td>
</tr>
<tr>
<td>Best result</td>
<td>5C 0.2C</td>
<td>20C 1C</td>
<td>5C 0.5C</td>
<td>2C &lt;1C</td>
<td>&gt;30C</td>
<td>&gt;30C</td>
<td></td>
</tr>
<tr>
<td>Charge temperature</td>
<td>–20 to 50°C (–4 to 122°F)</td>
<td>0 to 45°C (32 to 113°F)</td>
<td>0 to 45°C&lt;sup&gt;9&lt;/sup&gt; (32 to 113°F)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discharge temperature</td>
<td>–20 to 50°C (–4 to °F)</td>
<td>–20 to 65°C (–4 to 49°F)</td>
<td>–20 to 60°C (–4 to 140°F)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance requirement</td>
<td>3–6 months&lt;sup&gt;10&lt;/sup&gt; (topping chg.)</td>
<td>Full discharge every 90 days when in full use</td>
<td>Maintenance-free</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety requirements</td>
<td>Thermally stable</td>
<td>Thermally stable, fuse protection</td>
<td>Protection circuit mandatory&lt;sup&gt;11&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In use since</td>
<td>Late 1800s</td>
<td>1960</td>
<td>1990</td>
<td>1991</td>
<td>1996</td>
<td>1999</td>
<td></td>
</tr>
<tr>
<td>Toxicity</td>
<td>Very high</td>
<td>Very high</td>
<td>Low</td>
<td>Low</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coulombic efficiency&lt;sup&gt;12&lt;/sup&gt;</td>
<td>~90%</td>
<td>~70% slow charge</td>
<td>~90% fast charge</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Moderate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>1</sup> Protection circuit mandatory

<sup>2</sup> Cycle life is dependent on the depth of discharge (DoD) and the rate of discharge.

<sup>3</sup> Note that NiMH batteries are often rated for a capacity of 500–1,000 mAh for a 10-hour discharge.

<sup>4</sup> Charge time is typically given as a guideline and may vary depending on the specific battery and charger.

<sup>5</sup> Some NiCd batteries have a self-discharge rate of 1% per month.

<sup>6</sup> Cell voltages are nominal values and can vary slightly between different batteries.

<sup>7</sup> Li-ion batteries typically have a higher open circuit voltage (OCV) than other types of batteries.

<sup>8</sup> Peak load current is the maximum current a battery can deliver for a short period of time.

<sup>9</sup> Maximum allowable temperature for safe operation.

<sup>10</sup> Maintenance intervals can vary depending on the specific battery and its application.

<sup>11</sup> Protection circuit is a safety feature that limits the charging voltage and current to prevent damage or hazards.

<sup>12</sup> Coulombic efficiency is a measure of how efficiently a battery stores and releases energy.

<sup>13</sup> Cost varies widely depending on factors such as size, capacity, and application.
Rechargeable batteries in general

• Different battery chemistries
  – A case of ‘Horses for courses’
  – For a long time, not a lot of choice
    • Lead acid for heavy duty products
    • NiMH for portable equipment
  – Has been the status quo for a long time
  – Early generation ‘Brick’ mobiles & laptops
    • Not strictly ‘portable’ – more like ‘luggable’
Rechargeable batteries in general

• Biggest challenge: not enough stored energy when you need it most
  – Eg UPS fails to deliver power when needed!

• In the end, designers created over-engineered solutions to overcome inherent weaknesses
  – Think about lead acid systems that only reach 20% DoD (Depth of Discharge)
  – Think about how your older portable electronics used to leave you in the lurch?
Rechargeable batteries in general

But... science and technology have been improving by leaps and bounds!
Lithium batteries – Safe?

- Are Lithium batteries safe?
  - First question everyone asks!
  - Yes and no

Apple & Sony – 2008
Mac laptop fire lawsuit

Morphing Li-Po battery

Exploding Tesla Model S

Flaming Hoverboards
Lithium batteries – Safe?

• Under what conditions are Lithium batteries considered unsafe?
  – Early generations of Lithium ion batteries were really difficult to charge
    • Lots of heat being generated leading to fires
  – When lots of discharge current is flowing...
    • Heat leads to fires
  – Shock / impact / compression / piercing
    • Short circuits lead to high currents which lead to fires

1990's
Lithium batteries – Safe?

• High energy and power density means one small fault leads to a big mess
  – Lead acid: 30-50Wh/kg
  – Lithium Cobalt Oxide: 150-250Wh/kg

• Earlier lithium chemistries had thermal runaway problems...

1990’s

5x - 8x
More energy per kg
Lithium batteries – Safe?

One Lithium cell experiences thermal runaway, which then ruptures...
This then set off other cells into thermal runaway state. Kiss goodbye to laptop...

https://www.youtube.com/watch?v=UaCMvegaiA
Lithium batteries – Safe?

Bottom line
Stick to design guidelines = Safe!

1990’s
Lithium chemistries – LiCoO₂

• Lithium Cobalt Oxide – LiCoO₂
  – Nominal voltage: 3.6V
  – Capacity: 150-250 Wh/kg
  – CC/CV charging
  – Eg 18650 cell: 3.6V 2400mAh
    • Charge up to 1C (2.4A) up to 4.2V
    • Discharge up to 1C (2.4A) – no lower than 2.5V
  – 500-1000 cycles
  – Good for smartphones, tablets, laptops, cameras
  – Beware of thermal runaway at 150°C due to overcurrent
  – Toxicity issues with Cobalt
Lithium chemistries – LiMn$_2$O$_4$

• Lithium Manganese Oxide – LiMn$_2$O$_4$
  – Nominal voltage: 3.7V
  – Capacity: **100-150** Wh/kg
  – CC/CV charging
    • Charge up to **3C** up to 4.2V
    • Discharge up to **10C** – no lower than 2.5V
  – **300-700 cycles**

– Inside power tools, medical devices, electric cars
– Beware of thermal runaway at 250°C
Lithium chemistries – LiNiMnCoO$_2$

- Lithium Nickel Manganese Cobalt Oxide – LiNiMnCoO$_2$ (NMC)
  - Nominal voltage: 3.7V
  - Capacity: 150-250 Wh/kg
  - CC/CV charging
    - Charge up to 1C up to 4.2V
    - Discharge up to 2C – no lower than 2.5V
  - 1000-2000 cycles
  - Inside E-bikes, electric cars
  - Beware of thermal runaway at 210°C
Lithium chemistries – LiFePO$_4$

- Lithium Iron Phosphate – LiFePO$_4$ (aka Lithium Ferro Phosphate or LFP)
  - Nominal voltage: 3.2V
    - $4 \times 3.2V = 12.8V$ – simple retrofitting of 12V lead acid systems
    - $8 \times 3.2V = 25.6V$ (think 24V) and $16 \times 3.2V = 51.2V$ (think 48V)

- Capacity: 90-120 Wh/kg (1/3rd weight of lead acid)

- CC/CV charging
  - Charge up to 2C up to 3.65V (*specially designed cells for rapid charging*)
  - Discharge up to 5C – no lower than 2.5V
Lithium chemistries – LiFePO$_4$

- Lithium Iron Phosphate – LiFePO$_4$ (continued)
  - **1000-6000** cycles (*dependent on DoD = Depth of discharge*)
  - Good for high load currents and endurance
  - Low risk of thermal runaway (trigger at >270°C)
  - Can tolerate over-charging without damage
  - The ‘Safe Lithium battery’
  - Good for Australian conditions & my favourite battery chemistry!

With thanks to Battery University

http://batteryuniversity.com/learn/article/types_of_lithium_ion
Useful Summary Slide

Figure 15: Typical specific energy of lead-, nickel- and lithium-based batteries.

With thanks to Battery University

http://batteryuniversity.com/learn/article/types_of_lithium_ion
Useful summary slide

12V 22Ah = 260Wh

Lithium Cobalt Oxide
Weight: 1.65kg
Volume: 0.86L

Lithium Ferro Phosphate
Weight: 2.63kg
Volume: 1.48L

Lead Acid
Weight: 7.01kg
Volume: 2.32L
### Useful Summary Slide

With thanks to Battery University

http://batteryuniversity.com/learn/article/secondary_batteries

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Lead Acid</th>
<th>NiCd</th>
<th>NiMH</th>
<th>Li-ion¹</th>
<th>Cobalt</th>
<th>Manganese</th>
<th>Phosphate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific energy (Wh/kg)</td>
<td>30–50</td>
<td>45–80</td>
<td>60–120</td>
<td>150–250</td>
<td>100–150</td>
<td>90–120</td>
<td></td>
</tr>
<tr>
<td>Internal resistance</td>
<td>Very Low</td>
<td>Very low</td>
<td>Low</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Cycle life² (80% DoD)</td>
<td>200–300</td>
<td>1,000⁵</td>
<td>300–500⁵</td>
<td>500–1,000</td>
<td>500–1,000</td>
<td>1,000–2,000</td>
<td></td>
</tr>
<tr>
<td>Charge time³</td>
<td>8–16h</td>
<td>1–2h</td>
<td>2–4h</td>
<td>2–4h</td>
<td>1–2h</td>
<td>1–2h</td>
<td></td>
</tr>
<tr>
<td>Overcharge tolerance</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Low. No trickle charge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self-discharge/month (room temp)</td>
<td>5%</td>
<td>20%⁵</td>
<td>30%⁵</td>
<td>&lt;5%</td>
<td>Protection circuit consumes 3%/month</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell voltage (nominal)</td>
<td>2V</td>
<td>1.2V⁴</td>
<td>1.2V⁴</td>
<td>3.6V⁷</td>
<td>3.7V⁷</td>
<td>3.2–3.3V</td>
<td></td>
</tr>
<tr>
<td>Charge cutoff voltage (V/cell)</td>
<td>2.40 Float 2.25</td>
<td>Full charge detection by voltage signature</td>
<td>4.20 typical Some go to higher V</td>
<td>3.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discharge cutoff voltage (V/cell, 1C)</td>
<td>1.75V</td>
<td>1.00V</td>
<td>2.50–3.00V</td>
<td>2.50V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak load current</td>
<td>5C⁸ 0.2C</td>
<td>20C 1C</td>
<td>5C 0.5C</td>
<td>2C &lt;1C</td>
<td>&gt;30C &lt;10C</td>
<td>&gt;30C &lt;10C</td>
<td></td>
</tr>
<tr>
<td>Charge temperature</td>
<td>–20 to 50°C (-4 to 122°F)</td>
<td>0 to 45°C (32 to 113°F)</td>
<td>0 to 45°C⁹ (32 to 113°F)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discharge temperature</td>
<td>–20 to 50°C (-4 to °F)</td>
<td>–20 to 60°C (-4 to 48°F)</td>
<td>–20 to 60°C (-4 to 140°F)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance requirement</td>
<td>3–6 months¹⁰ (topping chg.)</td>
<td>Full discharge every 90 days when in full use</td>
<td>Maintenance-free</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety requirements</td>
<td>Thermally stable</td>
<td>Thermally stable, fuse protection</td>
<td>Protection circuit mandatory¹¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In use since</td>
<td>Late 1800s</td>
<td>1960</td>
<td>1990</td>
<td>1991</td>
<td>1996</td>
<td>1999</td>
<td></td>
</tr>
<tr>
<td>Toxicity</td>
<td>Very high</td>
<td>Very high</td>
<td>Low</td>
<td>Low</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coulombic efficiency¹²</td>
<td>~90%</td>
<td>~70% slow charge</td>
<td>~90% fast charge</td>
<td>99%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Moderate</td>
<td>High¹³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Quiz time!

Let’s review what we have learnt so far today

5 questions – 5 minutes

Tick... Tock...

Tick... Tock...
Quiz time!

Question 1

Before Lithium batteries came along, what rechargeable battery chemistries were available to a design engineer or product developer?
Quiz time!

Question 2

List 2 things why Lead Acid batteries are still a viable option for some energy storage systems
Quiz time!

Question 3

Name at least one reason NiMH batteries have fallen out of favour for use in portable equipment?
Of the Lithium battery chemistries discussed so far, which one has the highest energy density?
Quiz time!

Question 5

What are some of the key benefits of using LFP batteries?
Quiz time!

Please feel free to discuss among yourselves then share your answers with everyone

5 questions – 5 minutes

Tick... Tock...
Tick... Tock...
Quiz time!

Question 1
Before Lithium batteries came along, what rechargeable battery chemistries were available to a design engineer or product developer?
Quiz time!

Answer

• Lead Acid

• Nickel Cadmium

• Nickel Metal Hydride
Quiz time!

**Question 2**

List 2 things why Lead Acid batteries are still a viable option for some energy storage systems
Quiz time!

Answer

Lead acid batteries are:

- Readily available
- Low cost
- Tolerant to overcharge
Quiz time!

Question 3

Name at least one reason NiMH batteries have fallen out of favour for use in portable equipment?
Quiz time!

Answer

NiMH batteries have:

- Terrible self-discharge characteristics
- Limited cycle life
- Slow charge time
Quiz time!

Question 4

Of the Lithium battery chemistries discussed so far, which one has the highest energy density?
Quiz time!

Answer

Both LiCoO$_2$ (LCO) and LiNiMnCoO$_2$ (NMC) are able to achieve an Energy Density of 150-250Wh/kg

12V 22Ah = 260Wh

Lithium Cobalt Oxide
Weight: 1.65kg  Volume: 0.86L
(This could be even smaller and lighter)
Quiz time!

Question 5

What are some of the key benefits of using LFP batteries?
Quiz time!

Answer

- LFPs charge at up to 2C and discharge at up to 5C
- 1000-6000 cycles (dependent on DoD = Depth of discharge)
- Good for high load currents and endurance
- Low risk of thermal runaway (trigger at >270°C)
- Can tolerate some over-charging without damage
- Good for Australian conditions – zero maintenance and high ambient temperatures
Lithium battery shapes and sizes

• 18650
  – 18mm diameter
  – 65mm long

• 26650
  – 26mm diameter
  – 65mm long

• 32650
  – 32mm diameter
  – 65mm long

Note: Photos not to scale!
Lithium battery shapes and sizes

• Prismatic cells

• Pouch cells
Lithium battery shapes and sizes

• What cell type works best? Prismatic cells:
  – Encased in aluminium or steel for stability
  – Jelly-rolled or stacked
  – Cell is space-efficient
  – Costlier to manufacture

  – Modern prismatic cells are used in the electric powertrain and energy storage systems

With thanks to Battery University

http://batteryuniversity.com/learn/article/types_of_battery_cells
Lithium battery shapes and sizes

• What cell type works best? Pouch cells:
  – Latest technology
  – Lightweight
  – Cost-effective
  – Exposure to humidity shortens life
  – Exposure to high temperature shortens life
  – Swelling of 8–10 percent over 500 cycles must be considered in mechanical design

– The pouch cell is growing in popularity and serves similar applications to the prismatic cell.

With thanks to Battery University

http://batteryuniversity.com/learn/article/types_of_battery_cells
Lithium battery shapes and sizes

• What cell type works best? Cylindrical cells:
  – High specific energy
  – Good mechanical stability
  – Easy to automate manufacturing.
  – Cycles well
  – Offers long calendar life
  – Low cost
  – **Less than ideal packaging density**

– The cylindrical cell is commonly used for portable applications

With thanks to Battery University

http://batteryuniversity.com/learn/article/types_of_battery_cells
Time for a stretch!

Please be back in 10 mins
It is a case of ‘Horses for courses’

• Depending on your specific requirements, you need to weigh up the Pros and Cons before selecting a particular Lithium battery form factor
For us at Radlink...

- While we offer ‘off-the-shelf’ LFP products, we are VERY selective about what we sell to customers:
  - Mining
  - Telecommunications
  - Utilities
  - Agriculture
  - Healthcare
  - Transport
  - Etc
For us at Radlink...

- ‘Mission critical’ systems
- Must ask: “Is it fit for purpose?”
- We are not ‘white box shifters’...!
For us at Radlink...

- So we design our own energy storage solutions using 26650 Cylindrical form factor:
  - Temperature tolerance (*must work whether hot or cold*)
  - Mechanical stability (*must work on mobile equipment*)
  - Lower cost (*price sensitive market*)
  - Long life (*lower $/kWh/cycle*)
  - Simpler design (*time to market*)
  - Re-usable design (*time to market*)
  - Low maintenance (*no warranty claims due to poor design*)
  - Proprietary design optimises packaging density (*maximise space usage of cabinets*)
Case study: AAA

- Replace Lead Acid – 23kg
  - Lightweight – 7.5kg
- Improved longevity
  - 2000+ cycles
- Rapid fitment
  - IP67 connector
- High capacity
  - 12.8V 50Ah = 640Wh
- Vermin proof
  - Aluminium case with handle
Case study: Water Corporation

- Aging Lead Acid batteries
  - Due for replacement
- Trial installation
- 3 x 12.8V 50Ah in parallel
- Monitored system
- Rapid fitment
- Lightweight
- Zero maintenance
Case study: 19-inch rack mounted

- High power output
- High density storage
- Modular
- Scalable
- Lightweight
- Hot swappable
- Smart BMS
- Standard form factor
Lithium Ferro Phosphate
Facts and Figures
## LFP cell technical data

### Major Technical Parameters

<table>
<thead>
<tr>
<th>No.</th>
<th>Item</th>
<th>Standard</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Standard Capacity</td>
<td>3200mAh</td>
<td>0.5C (current value of 3200mA at 1C)</td>
</tr>
<tr>
<td>2</td>
<td>Capacity Range</td>
<td>3100~3300mAh</td>
<td>0.5C</td>
</tr>
<tr>
<td>3</td>
<td>Standard Voltage</td>
<td>3.2 V</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Alternating Internal Resistance</td>
<td>≤30mΩ</td>
<td>with PTC</td>
</tr>
<tr>
<td>5</td>
<td>Charge Conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cut-off Voltage</td>
<td>3.65±0.05V</td>
<td>Constant current charge to 3.65V at 0.5C, constant voltage charge to stop until 0.01C mA</td>
</tr>
<tr>
<td></td>
<td>Cut-off Current</td>
<td>0.01C mA</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Discharge Cut-off Voltage</td>
<td>2.5V</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Cycle Characteristic</td>
<td>2000 times</td>
<td>100% DOD, the residual capacity is no less than 80% of rated capacity at 1C rate.</td>
</tr>
<tr>
<td>8</td>
<td>Max. Continuous Discharge Current</td>
<td>9.6A</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Pulse Discharge Current</td>
<td>15A, 5s</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Working Temperature</td>
<td>Charge: 0°C~55°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Discharge: -20°C~60°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Storage Temperature</td>
<td>-20°C ~ 45°C</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Battery Weight</td>
<td>86 g (Approx.)</td>
<td></td>
</tr>
</tbody>
</table>
LFP cell technical data

Single cell charge–discharge characteristics taken from manufacturer’s data sheet

CC = Constant Current charge @ 1.6A (0.5C)
CV = Constant Voltage charge @ 3.65V (32mA = 0.01C)
The following information is sourced from our supplier’s latest QA/QC data and reports.
LFP discharge characteristics

26650-3200mAh-3.2V Voltages at different discharge rates

Data sourced from supplier’s latest QA/QC reports
LFP discharge characteristics

2RU 3kWh 51.2V battery discharged at 57.6A (1C)

Data sourced from supplier’s latest QA/QC reports
LFP discharge characteristics

26650-3200mAh-3.2V Cell capacity after numerous charge/discharge cycles

Note: Charge/discharge at 1C = 3.2A

Data sourced from supplier’s latest QA/QC reports
LFP discharge characteristics

26650-3200mAh-3.2V Discharge at different temperatures

Note: Charge/discharge at 0.5C = 1.6A

Data sourced from supplier’s latest QA/QC reports
LFP discharge characteristics

Self Discharge Characteristics (25°C)

Data sourced from supplier’s latest QA/QC reports
LFP discharge characteristics

This is the question we get asked the most!

Data sourced from supplier’s latest QA/QC reports
Selecting the right cell for the job

Moving from data sheets to an actual design example
Selecting the right cell for the job

• How will you connect the cells together?

  – What is your nominal operating voltage?
    • Divide that by 3.2V to get number of cells in SERIES

  – What is your required Amp-hour capacity?
    • Divide that by cell capacity to give cells in PARALLEL
Selecting the right cell for the job

• Example: we need 36V 90Ah for a scooter

• Nominal operating voltage: 36V
  – Divide 36V by 3.2V = 11.25 cells
  – Can circuit operate at higher or lower voltage?
  – Higher => 12 cells in series
  – Lower => 11 cells in series
  – Since it is a motor, go higher voltage = 12 cells
Selecting the right cell for the job

• Example: we need 36V 90Ah for a scooter
• Require 90Ah
  – 18650 cells come in 1400, 1500 and 1600mAh
  – 26650 cells come in 3000, 3200 and 3300mAh
  – 32650 cells come in 5000mAh only (at this time)
  – Is there a size restriction?
    • No, then select largest cell available = 32650
  – Larger size = higher charging and discharging rate
  – 90Ah divided by 5Ah = 18 cells in parallel
Selecting the right cell for the job

- Example: we need 36V 90Ah for a scooter

- 12 cells in series = 38.4V nominal
  - 12 x 2.5V = 30V minimum (100% DoD)
  - 12 x 3.65V = 43.8V maximum (just charged)

- 18 cells in parallel = 90Ah

- “12S18P 32650 3.2V 5000mAh” battery pack
Selecting the right cell for the job

- Example: we need 36V 90Ah for a scooter

![Single cell charge–discharge characteristics graph](image)
Selecting the right cell for the job
Selecting the right cell for the job

• Example: we need 36V 90Ah for a scooter

• What charging current?
  – 32650 cells can be charged at up to 2C
  – Recommended charge rate C/3 for just over 3 hours
  – 90Ah => CC Charge at 30A for 3.5 hours
    • Or slower at 10A for 10 hours
  – CC/CV => Maximum CV voltage = 43.8V
Selecting the right cell for the job

• Example: we need 36V 90Ah for a scooter

• What working current?
  – 32650 cells can be discharged at up to 5C peak
  – 90Ah => 450A starting current
  – Up to 1C operating current => up to 90A for one hour

• Make sure connectors are ‘fit for purpose’!!
Selecting the right cell for the job

- Remember $I^2R$ losses generate a lot of heat!
  - Interconnections between cells
  - Cables to the load
  - Connector pin sizes

- Make sure there is enough space for heat to escape...
Battery Management System (BMS)

• Insurance policy... protects against misuse and abuse:
  – Over-voltage (ie over-charging)
  – Under-voltage (ie over-discharging)
  – Over-current (ie excessive continuous current)
  – Short-circuit (ie fault generated over-current)
  – Over-temperature (eg incorrect usage)

• Monitors each parallel bank of cells continuously for fault conditions
Virtual factory tour

Please come to the Radlink display table to go for a virtual tour of an LFP factory
Wrap-up…

• Although Lithium batteries have been around for nearly 20 years, the rate of adoption only took off after smartphones became a commodity

• Proliferation of EV and Solar PV systems are driving new requirements and opportunities

• The demand for lightweight, long life and low cost energy storage solutions is going ‘gangbustes’

• I personally believe smart, networked and managed LFP based battery solutions will have a bright future

• Coupled with correct energy harvesting, conversion and distribution systems, energy storage will change the world
Q & A

It’s your turn again!