ECE 398GG – ELECTRICAL VEHICLES

4. EV Batteries and Their Management

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Battery energy and power density

- Energy stored per unit mass and per unit volume are key measures for batteries.
- Energy rate (power) per unit mass and volume or also important.
- The capacity rate (*C* rate) sets a reference point for energy and power.
- Also vital: Cycle life, cycle efficiency, self discharge, thermal capability.

Perspective

- Global battery market in 2019 was more than $100 billion. (http://www.grandviewresearch.com/industry-analysis/battery-market)
- Of this, about 30% lead acid and about 30% lithium ion.
- Familiar use for lead-acid batteries: vehicle starting, lighting, and ignition (SLI).
- Massive use: Backup and auxiliary power for telecommunications and computing.

Rechargeable types

- Rechargeable batteries (*secondary* batteries) have been around for more than 150 years.
- Lead-acid batteries date to 1859. The overall reaction involves metallic lead, lead oxide, and sulfuric acid on the one side, with lead sulfate and water on the other side.
- Nickel-iron batteries (1901) were favored by Edison and used in Detroit Electric and other electric cars.

Courtesy I. Pitel

Rechargeable types

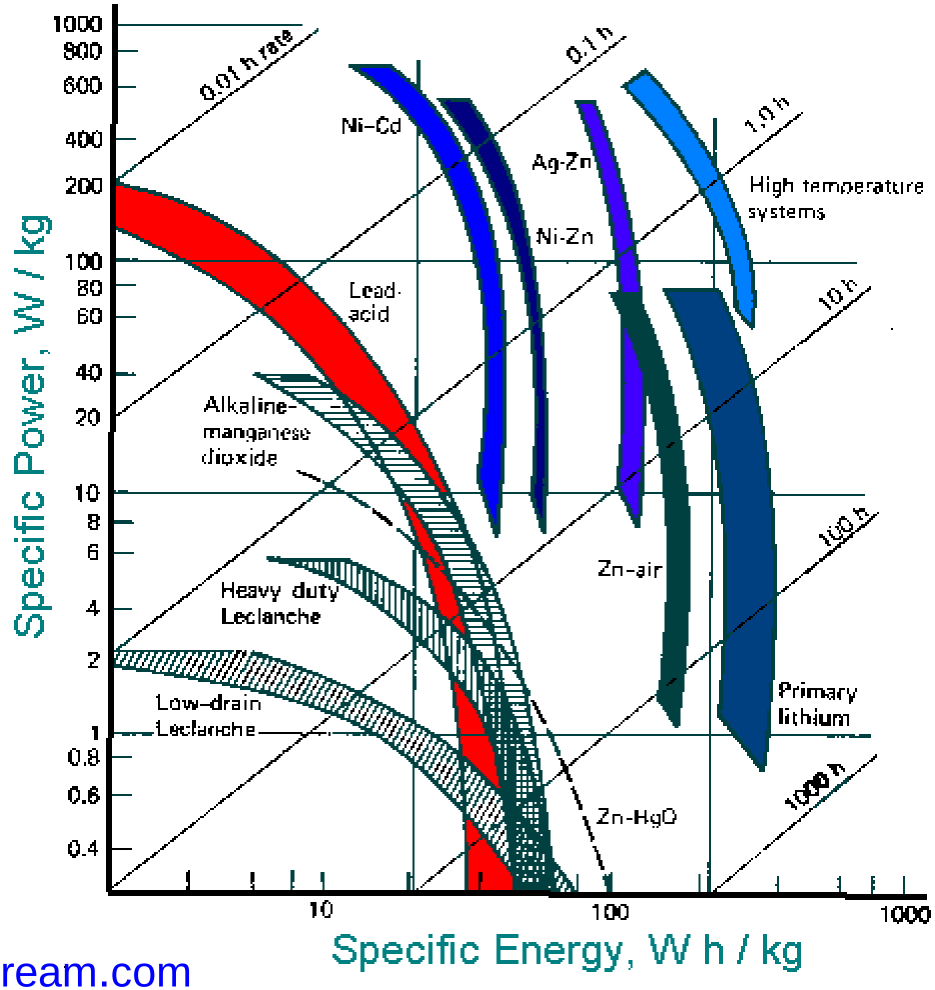
- Nickel cadmium batteries (NiCd) (1899) can have high specific power, with common commercial devices rated to 20C.
- Cadmium is extremely toxic, and NiCd batteries are phasing out.
- Nickel-metal-hydride (NiMH) batteries (1967) avoid cadmium but are near-drop-in replacements for NiCd.
- They are still common in hybrid cars because the power density can be higher than for lithium cells.

A few types (various sources, includes www.powerstream.com)

Type	Cell voltage (room temp)	Energy density	Power density	Self discharge	Charge efficiency (typical)	Cycle life
Lead acid	2.04 V	35 Wh/kg	600 W/kg	16% per month	80%	200
Nickel cadmium	1.30 V	60 Wh/kg	600 W/kg	10% per month	70%	>5000
Nickel metal hydride	1.35 V	100 Wh/kg	600 W/kg	10% per month (but 20% first day)	75%	500
Sodium sulfur	2.08 V (350°C)	110 Wh/kg	150 Wh/kg	--	85%	4500
Vanadium redox	1.41 V	20 Wh/kg	--	--	75%	>20,000
Lithium ion	Variable to 4.1 V	200 Wh/kg	300 W/kg	2% per month	90%+	2000
Lithium ion (polymer)	Variable to 4.1 V	200 Wh/kg	400 Wh/kg	5% per month	90%+	500

Ragone Plot

- Specific power vs. specific energy
- Notice the log-log scales



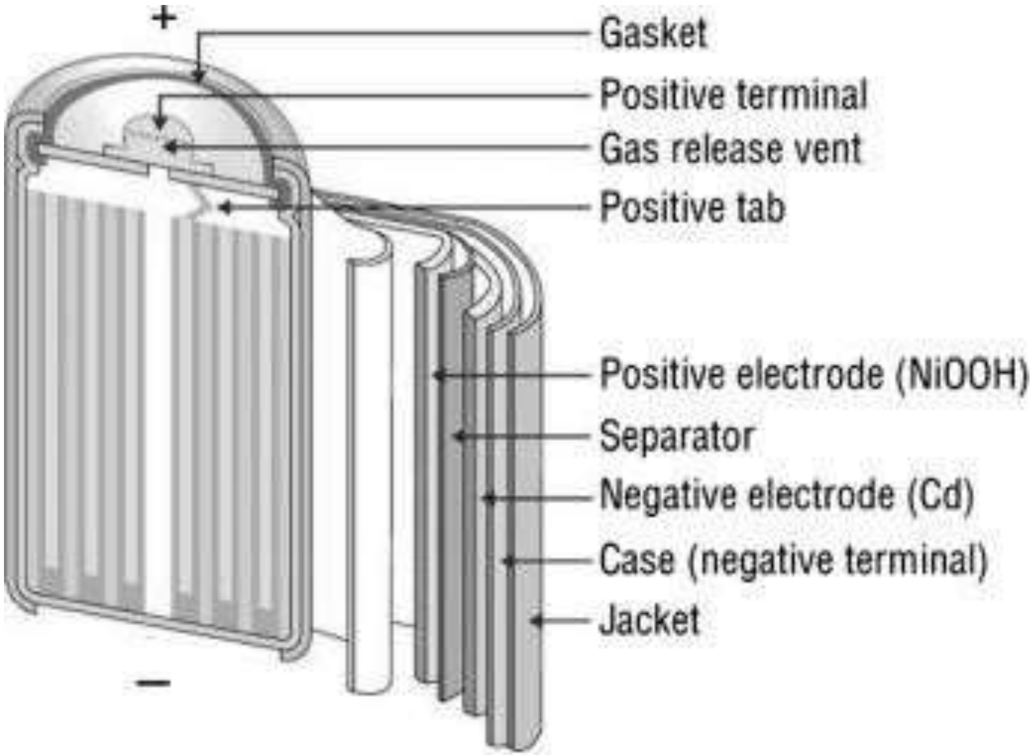
www.powerstream.com

Present, future

- Although there are many rechargeable battery chemistries, lead acid, NiMH, and lithium-ion cells are the only ones in broad commercial application.
- Lead-acid batteries for SLI, NiMH for power-dense applications, Li-ion for energy dense applications.
- Future? Dozens of chemistries in various lab stages.
  - The ultimate could be related to a combination of lithium (the most electropositive element) and fluorine (the most electronegative element. Could yield a 6 V cell.
  - Mg-ion and Na-ion cells. Both in active development.
  - Lithium-air batteries are more akin to fuel cells. As batteries, they need much improvement on reversibility, efficiency, and other challenges.

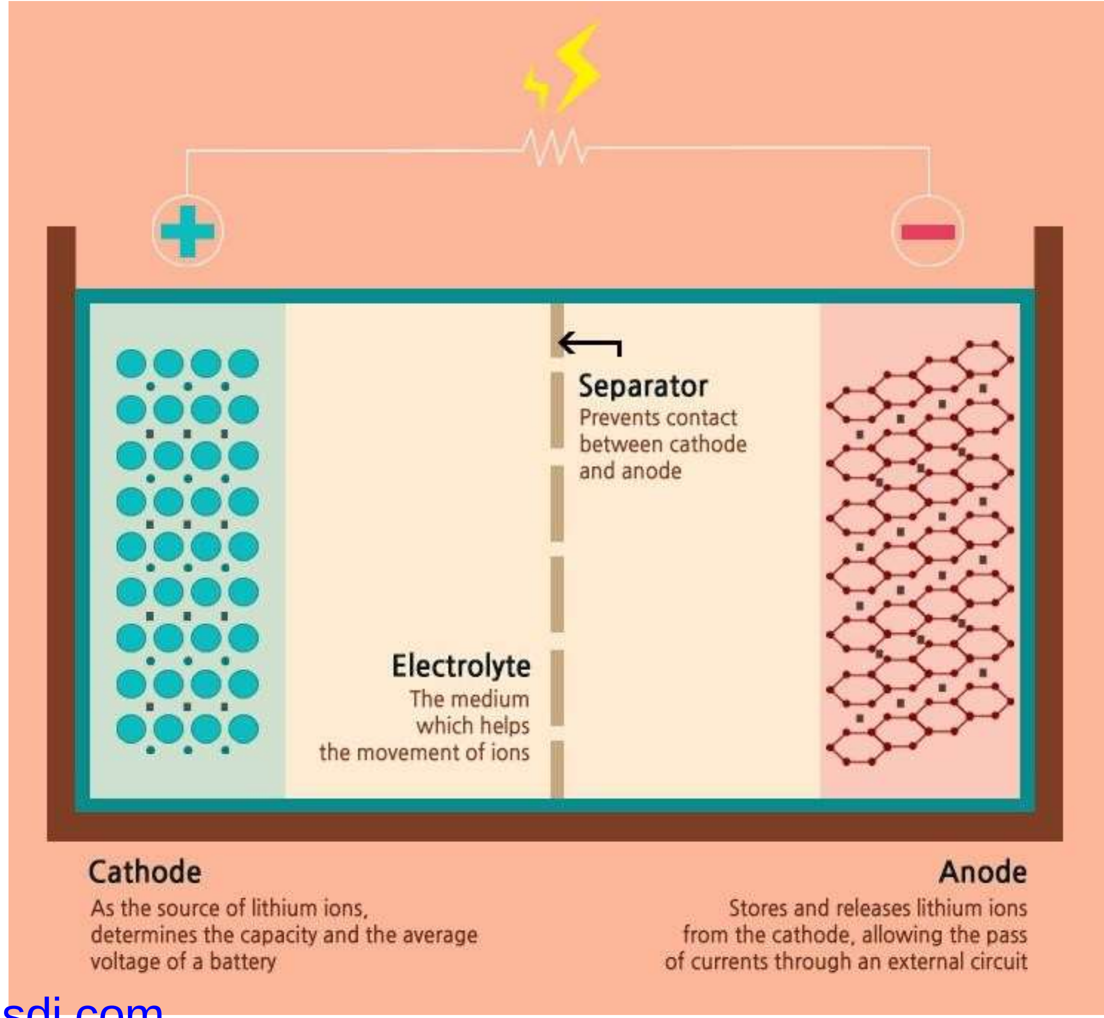
Cylindrical battery construction

- NiCd example



S. Revankar, *Chemical Energy Storage*, Elsevier, 2019

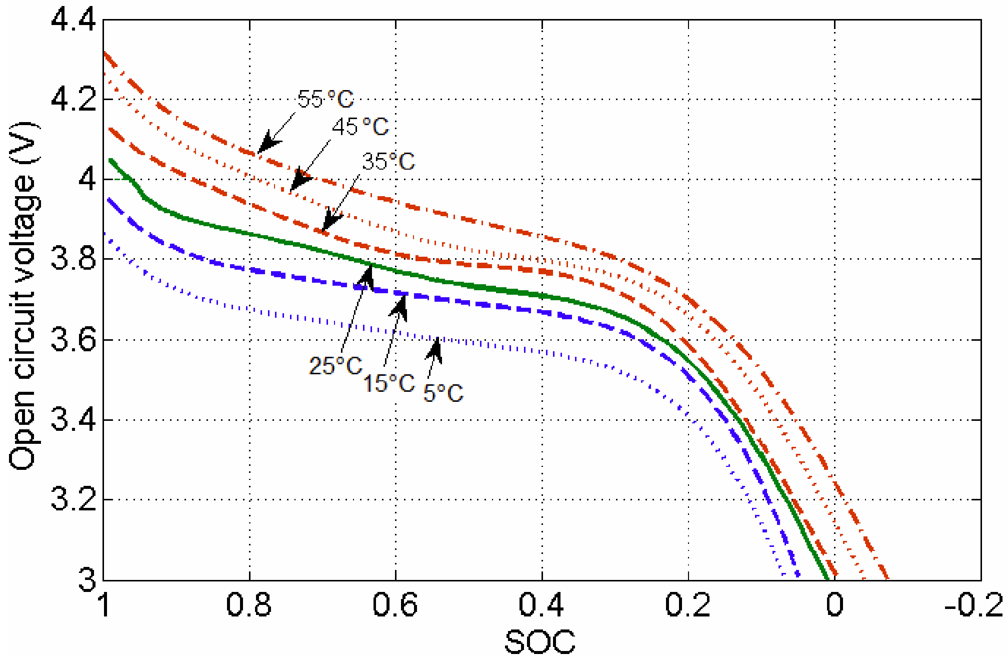
Li-ion configuration



www.samsungsdi.com

General issues

- Any electrochemical reaction follows an Arrhenius relation, in which the rate is proportional to $e^{-E_a/kT}$ where E_a is an activation energy, k is Boltzmann's constant, and T is temperature.
- The effect is roughly a doubling of reaction rate for each 10°C rise.
- Impacts on battery performance are fundamental.



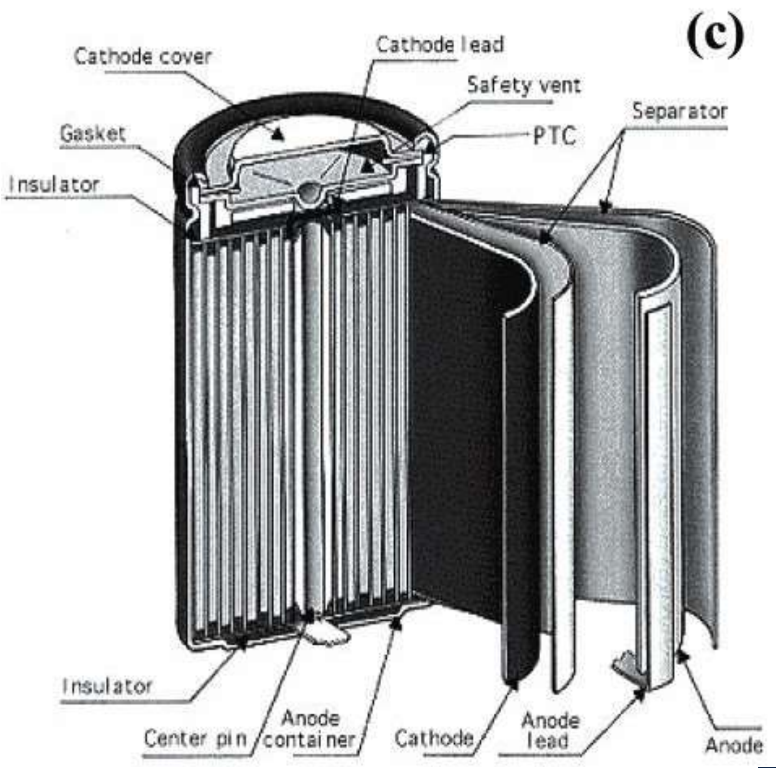
Li-ion challenges

- The high cell voltage (up to 4.1 V) rules out water-based electrolytes.
  - Lead acid: sulfuric acid
  - Nickel cells: potassium hydroxide solution
  - Li-ion: organic liquids, usually with dissolved lithium salts
- Thermal runaway: If a local hotspot gets above a certain point, it can start an exothermic reaction with the electrolyte degrading.
- Local damage or fire can follow.
- Case penetration can initiate this, https://www.youtube.com/watch?v=hCDkjOak3E0

Li-ion challenges

- Recycling infrastructure really is not in place.
- There might need to be economic or regulatory incentives for recycling.
- In the U.S., about 99% of lead-acid batteries are recycled.
- Lead recycling is more profitable than lead mining

Li-ion configuration



- The key in Li-ion cells is that lithium is bound in an ionic state rather than available as a pure metal.

  Graphite is typical as the anode (negative electrode).

  The cathode is a lithium compound.
  - Lithium cobalt oxide
  - Lithium iron phosphate
  - Lithium manganese oxide
  - Others

  Electrolyte: a lithium salt in ethylene carbonate or dimethyl carbonate.

P. Arora, Z. Zhang, “Battery separators,” *Chem. Rev*., vol. 104, 2004.

Battery arrangement

- In any battery (or fuel cell), ions or protons diffuse through the electrolyte and electrons are directed through the external circuit.
- This works if the external circuit requires less voltage than the inherent open-circuit electrochemical potential.
- Electrolytes in general can be liquid (water based on carbonate based) or solid (polymers or some ceramics).
- Ionic conductivity limits current rate capabilities.

Mechanical stresses

- It is typical for mass densities to differ between the two sets of end products in a secondary battery.
- Usually this means that a cell expands during charging.
- The change produces cyclic mechanical stress.
- It also produces pressure in the package.
- Vital to manage this for packaging, mounting, and physical management.
- If charging produces gases (e.g. hydrogen), internal pressure is an important issue.

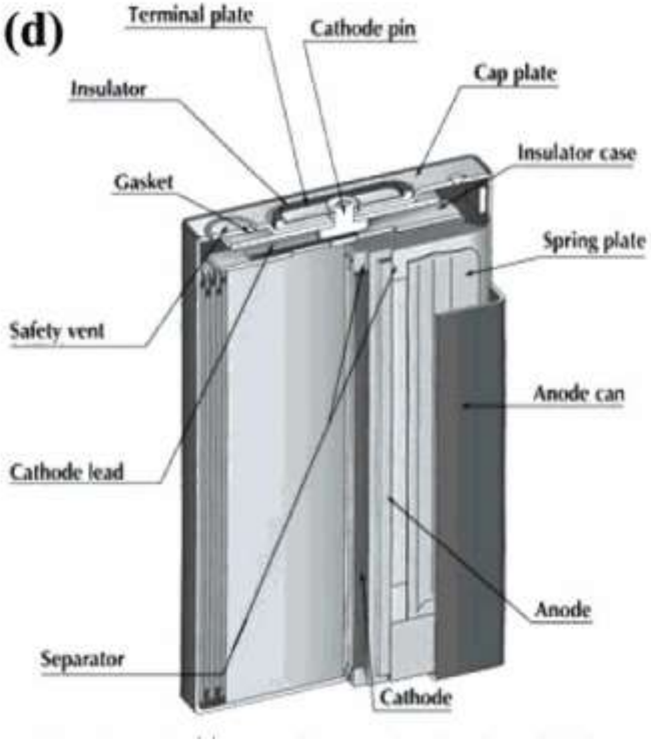
Li-ion cells

- Good consumer-grade Li-ion cells will include internal thermal cutouts, fuses, and extra space for expansion.
- Although the maximum voltage is about 4.1 V, usually 3.6 V is taken as the nominal value. A 3 Ah cell therefore has nominal capacity of 10.8 Wh.
- Almost all practical uses involve series and parallel connection of cells. The typical notation is nSmP, e.g. 99S60P for an early Tesla pack.

Cell configurations

- Cylindrical cells (common)
  - – Typical size 18650, 18 mm diameter, 65 mm long.
  - – AA battery is size 14500, for example
- Prismatic cells (rectangular shape)
- Typical polymer pouch

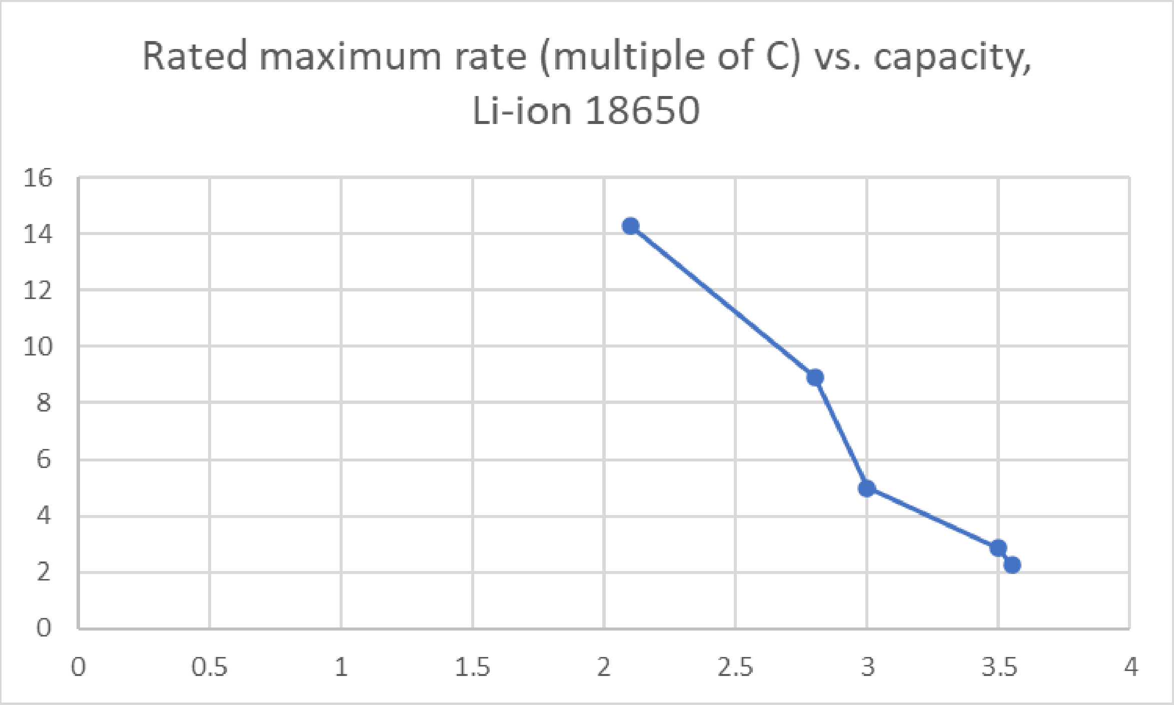
www.batteryspace.com



P. Arora, Z. Zhang, “Battery separators,” *Chem. Rev.*, vol. 104, 2004.

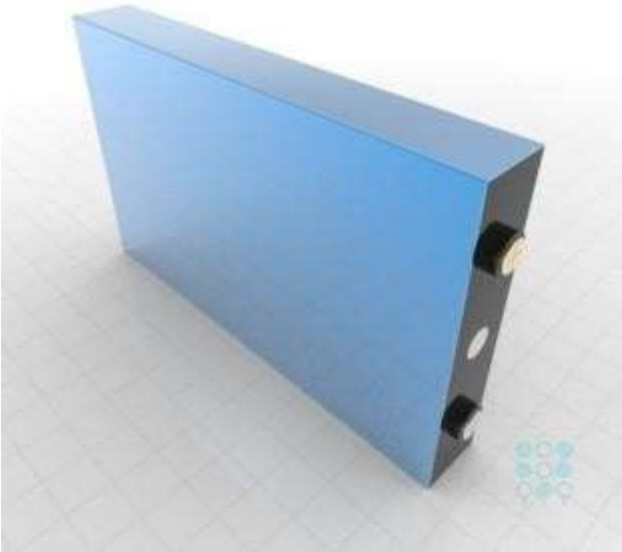
Comparing power and energy cell ratings

- All are for name-brand 18650 Li-ion cells (45-51 g).



Others

- Tesla making 21700 cylinders.
- New 46800 cells, some reporting 25 Ah capacity.
- Typical large-format prismatic cell, 72 Ah, 31 mm x 136 mm x 222 mm, 1.78 kg. Rated to 2C.



voltaplex.com

Modules

- A group of cells packaged together with a single output terminal set comprises a module.
- Most familiar: 12 V lead-acid battery, a module with 6 series cells, nominal 12 V.
- Sometimes used alone, or assembled into a complete battery pack.

www.onesourcebatteries.com

Multi-cell modules, self contained

2S2P Leaf module

evbatterycenter.com

- Modules can be from cylindrical or prismatic cells.
- Often provide coolant channels and sensors.

7S20P module

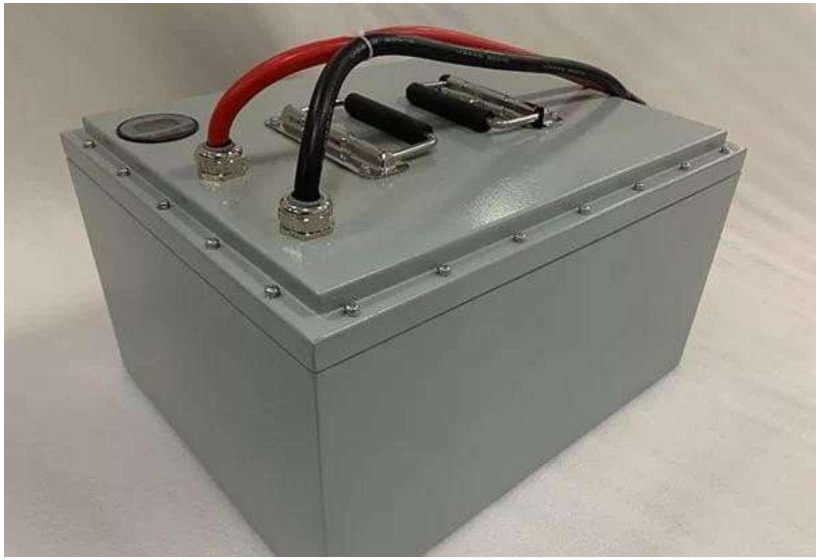
Phys.org (10/1/2009)

Tesla 6S74P Model S module

www.greentecauto.com

Packs

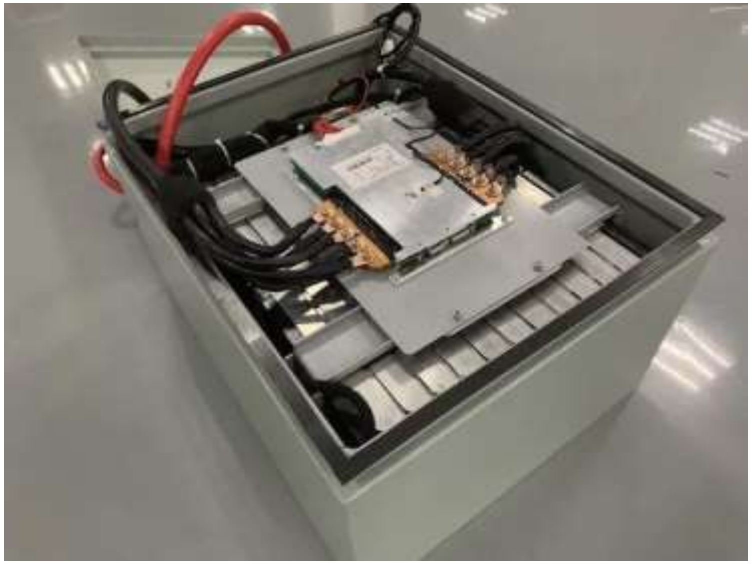
- For lead-acid cells, most common: 12 V modules, 24 V packs (called 28 V in the industry), 48 V packs.
- For Li-ion, no standards, but 20 V packs (5S) and 48 V packs (12S), are increasingly common.



www.bestgobattery.com

Packs

- A pack will include complete sensing and management electronics.



www.bestgobattery.com

Packs

- Car packs need full moisture seals and comprehensive structural integration.

www.greenoptimistic.com

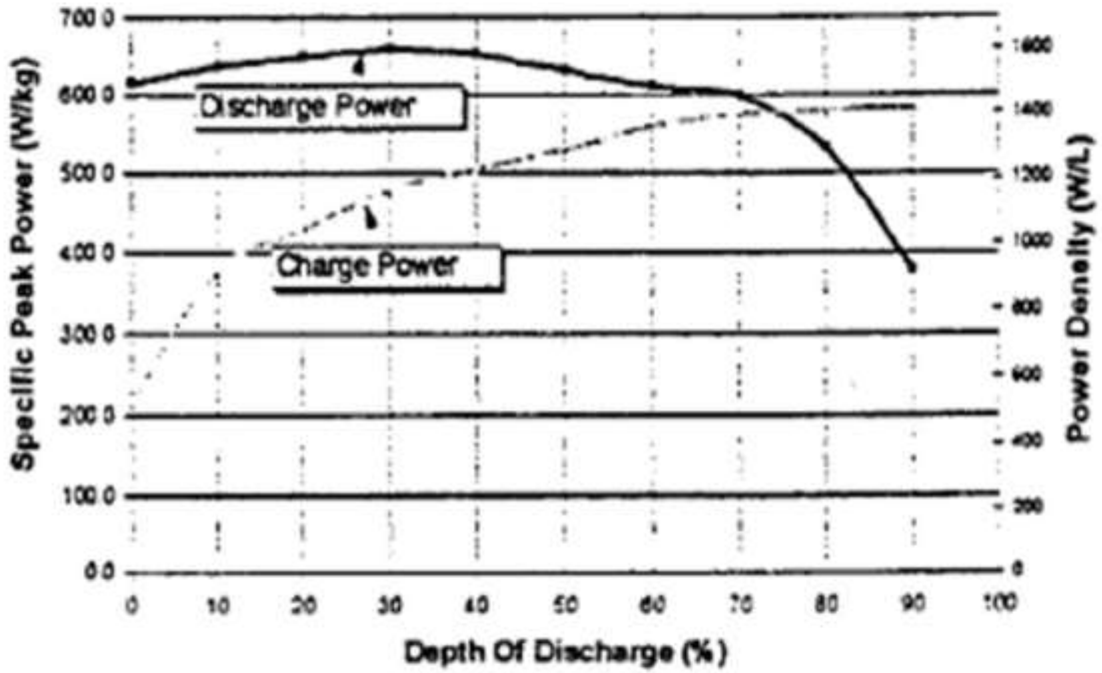
Battery operating phases

- Charge
- Discharge
- Idle
- Trickle (not used for Li-ion)

- Charge and discharge might not be symmetric.

Battery operating phases

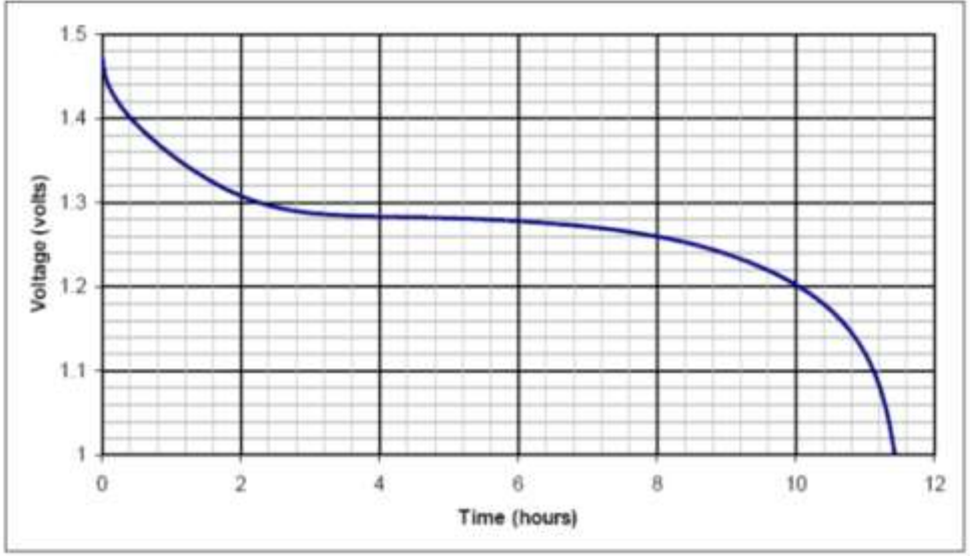
- NiMH example



From Menjak, Gow, Corrigan, Venkatesan, Dhar, Stempel, Ovshinsky, "Advanced Ovonic high-power nickel-metal hydride batteries for hybrid electric vehicle applications," in Ann. Battery Conf. Appl. Advances, 1998, pp. 13-18.

Battery operating phases

- Reduction in charge power density at the high end limits regeneration: energy acceptance drops above 60% SOC.
- Active balancing required 20% and 40% SOC, and between 60% and 80% SOC.
- Braking strategy must limit charge power at the high end.



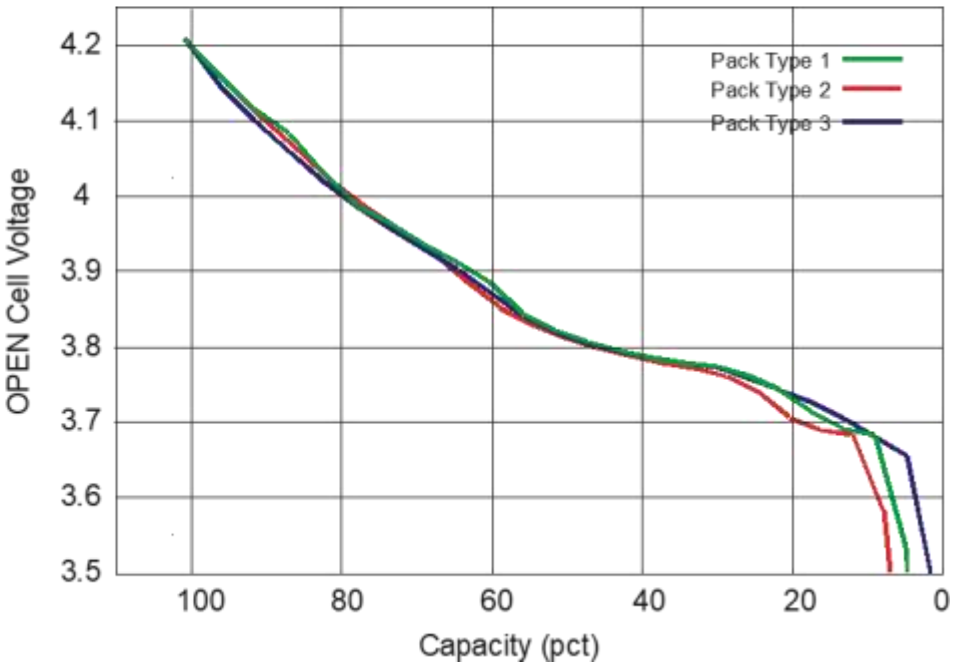
“Harding Handbook for Quest Batteries,” Fig. 3.7.2, available http://www.hardingenergy.com/pdfs/NiMH.pdf

Monitoring

- Notice the wide section of flat voltage.
- Voltage measurements alone cannot estimate SOC.
- Voltage is more favorable for lead acid and Li-ion cells.

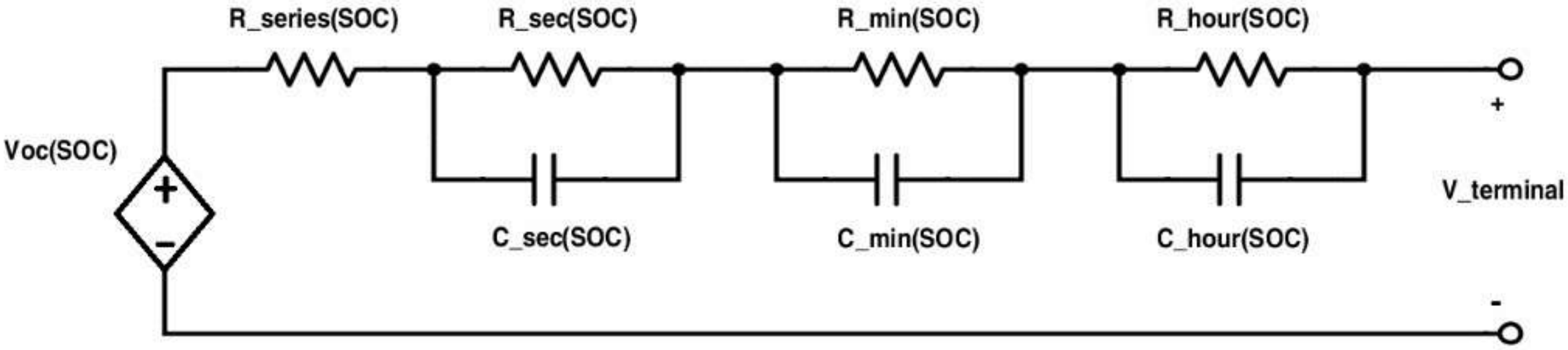
Monitoring

- Li-ion cells have almost linear open-circuit voltage above 20% SOC.
- Can we measure open circuit voltage?



Drawbacks

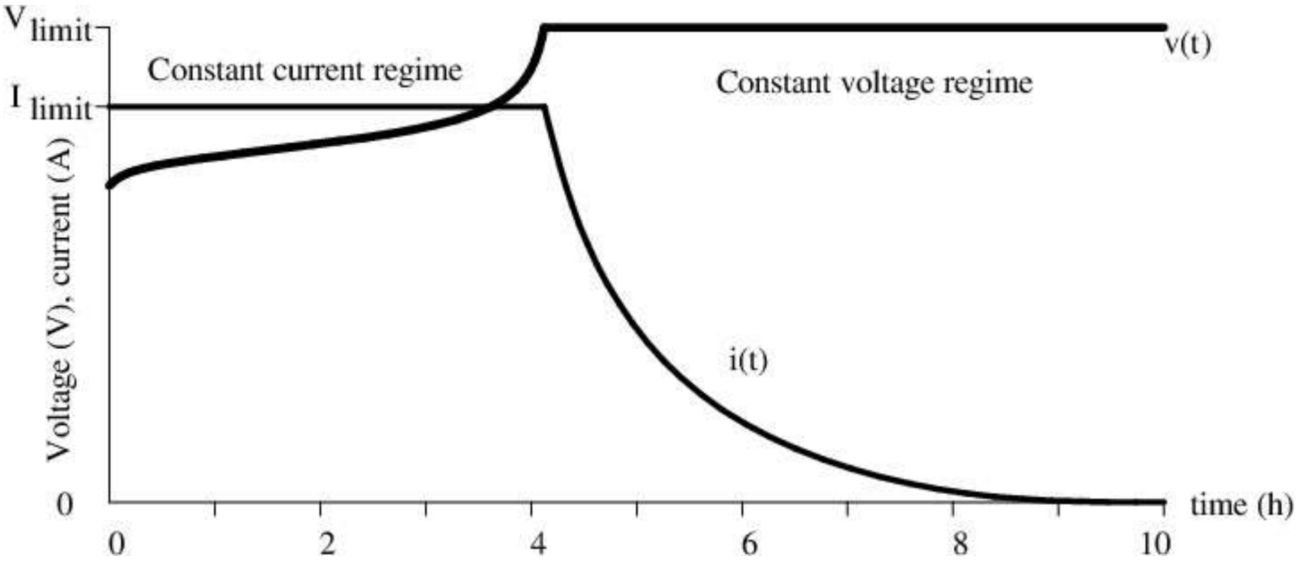
- Li-ion cells are intolerant of overcharge.
- Extremely important to stop at 4.1 V – for *any* cell.
- Temperature compensation is vital: It is 4.1 V at 25°C.
- Open circuit voltage takes time to settle down. Do we have the ability to turn a pack on and off to check SOC?



Typical cell electrical model

Charge sequence

- Best charging practice is “CCCV sequence.”
- This means charge at constant current until a voltage limit is reached, and then continue to charge at reduced current, maintaining this voltage.



Charge sequence

- For lead-acid batteries, the constant voltage interval can continue indefinitely.
- Lead-acid final voltage might be adjusted based on the specific cell type and strategy (always temperature).
- For Li-ion, charging stops when current gets below a certain value (such as $C/100$).

Charge sequence

- The ideal current might be $C/5$ or even less.

- Within the most linear part of the range, higher current might be feasible.
- Example: $3C$ when SOC is between 20% and 80%.
- You can imagine the hype: “Can recharge to 80% in less than 20 minutes.”
- Fast charging always implies extra I^2R loss, more heat, and life reduction.

Charge acceptance

- A situation with recharge from a source other than a charger, such as regenerative braking or downhill driving is called *charge acceptance*.
- This is an important limiting factor: Can a fully charged car immediately accept regeneration energy?
- Generic answer is “no.” Coming downhill in a parking structure after fully charging can be a problem.
- Alternatives:
  - Disable regeneration above a certain battery voltage.
  - Include a resistive braking unit to avoid brake thermal stress.

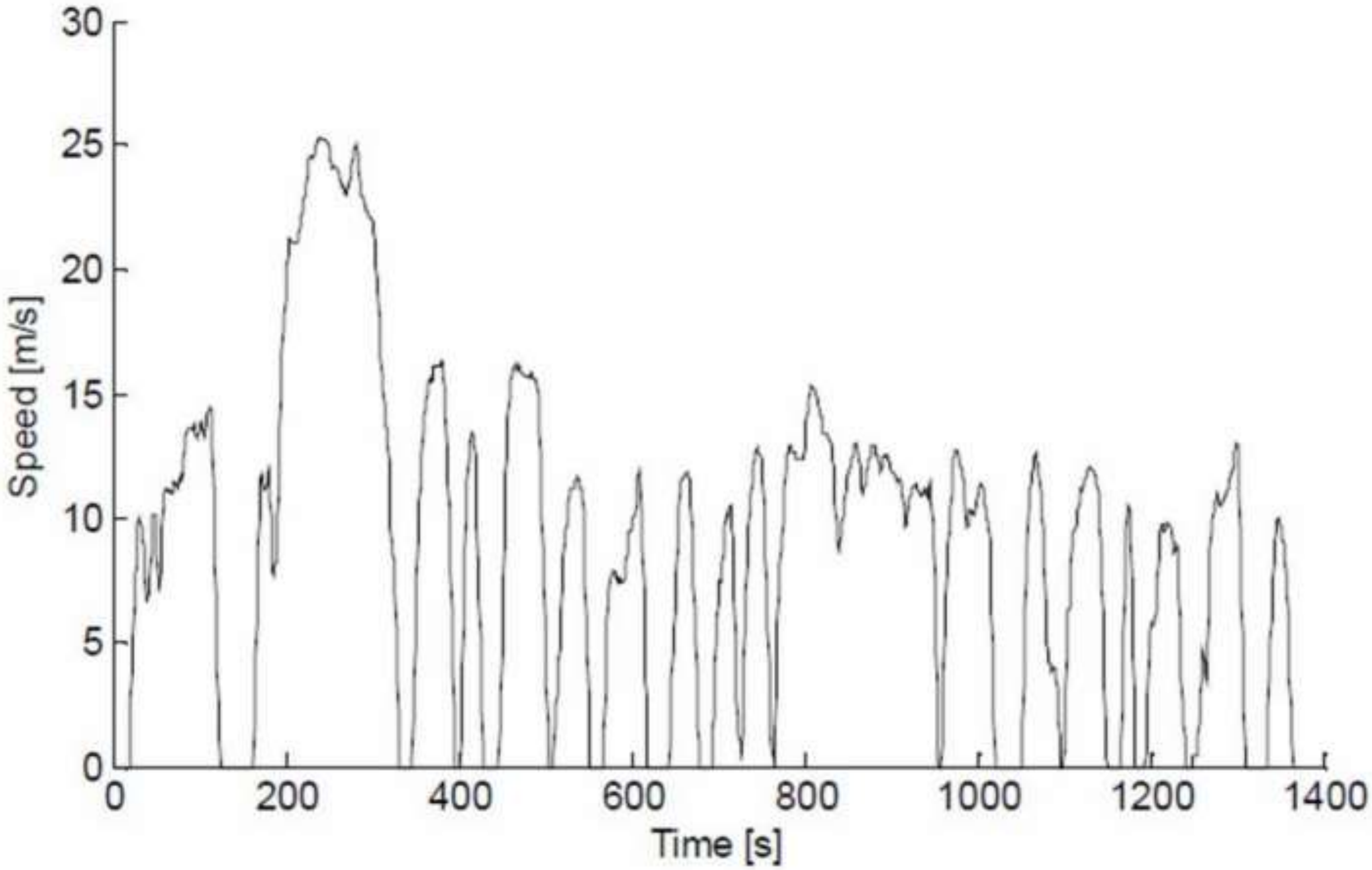
Idle

- Are there “key off” loads that will discharge a battery over time?
- Self-discharge is also important.
- Rule of thumb in the industry: Three weeks parked at the airport with no risk of not starting up.
- For an all-electric car, what storage reduction might be acceptable over three weeks?
- For Li-ion cells, key off loads are almost always more important than self discharge.
  - Security systems
  - Sensors and computers
  - Communications

Discharge

- In passenger cars, the discharge details are essentially impossible to predict.
- About all we know is that it will be rare for a driver to push toward power limits.
- Drive cycles are about all we can hope for in terms of testing out discharge.

Discharge



Discharge and life

- Cycle life is usually based on “100% depth of discharge” complete discharge cycles.
- In transportation, these are rare.
- The effect is nonlinear, but a very rough guide is the notion of “total lifetime discharge.”
- What does this mean? If a battery can manage 1000 cycles at 100% DoD, it is providing 1000*Q*, when *Q* is the rated charge capacity for 100% discharge.
- We might expect 10,000 cycles at 10% DoD based on this total lifetime discharge.
- Actual results seem to be better than this.

Optimum range

- NiMH batteries work best (most efficient, longest cycle life) when maintained close to 50% DoD.
- A NiMH pack managed to 50% ± 10% can perform for hundreds of thousands of miles.
- Li-ion packs have some similarity.
- Roughly speaking, managing a Li-ion pack to 55% ± 35% seems to give excellent results.
- Notice the implied derating:
  - The NiMH pack performs best when only 20% of the capacity is used.
  - An Li-ion pack performs well over about 70% of the capacity range.

Balancing

- Consider a large pack, such as 99S60P in a Tesla.
- For both charge and discharge, how do we ensure even energy flows and balanced use of cells?
- For parallel cells, the voltages will match but perhaps not the current.
- For series cells, the currents will match but perhaps not the voltages.
- Does it matter?

Battery balancing

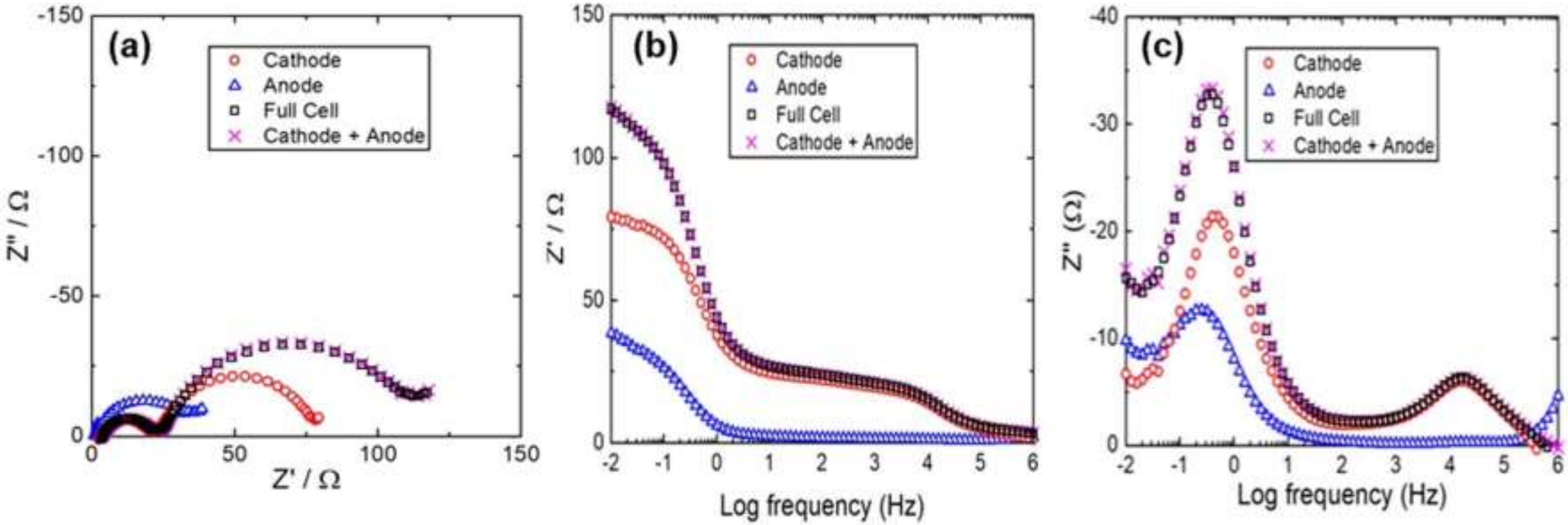
- In the end, we need cells to be matched in terms of state of charge.
- Why?
  - Charge voltage is limited to 4.1 V for *any* cell.
  - We need to shift to CV charging when even *one* cell hits the limit.
  - If any cell is low, how can it be recharged? Over time, will it drag down the others?
- For parallel connections, this is a modest issue:
  - Voltage is linear in SOC.
  - Matched voltage implies matched SOC.

Battery balancing

- For series connections, there is a problem.
- A weak cell that hits the voltage limit early will slow down charging for an entire pack.
- In Li-ion applications, external circuit management is essential to deal with this.

Battery testing

- What about testing? Voltage, current, temperature, SOC monitoring, what else?
- Gold standard is *impedance spectroscopy* (EIS), the complex impedance over a frequency range.



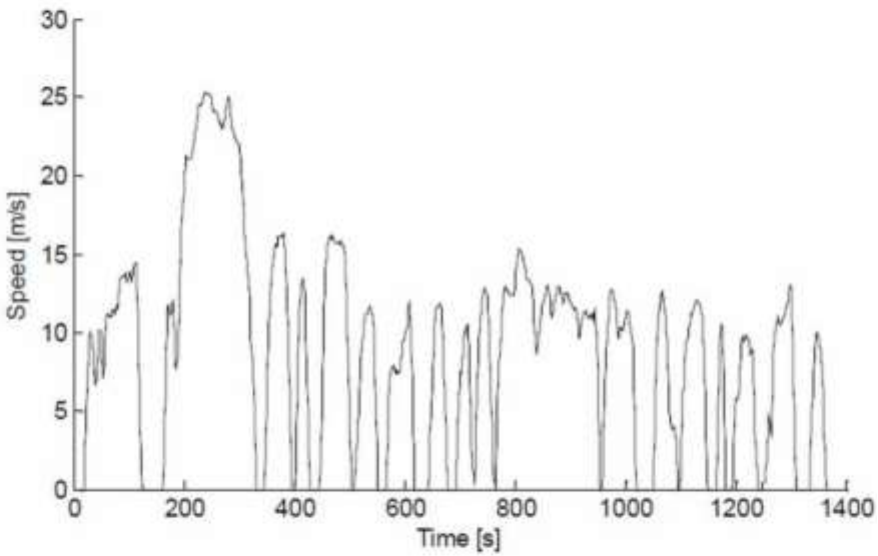
L. Middlemiss, A. Rennie, R. Sayers, A. West, “Characterisation of batteries by electrochemical impedance spectroscopy,” *Energy Reports*, vol. 6, May 2020.

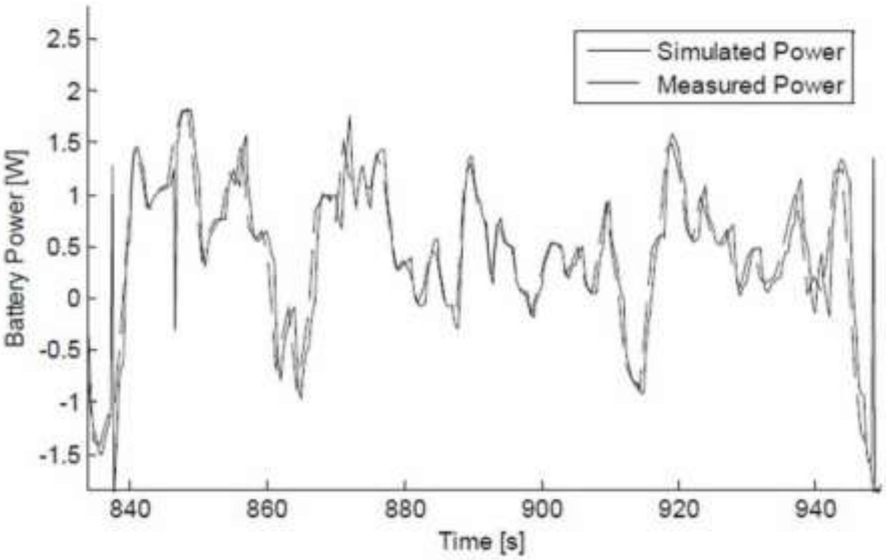
More about EIS

- Notice the range: 0.01 Hz (100 s) to 100 kHz.
- This is a slow measurement that takes tens of minutes.
- It provides a lot of information, but is really not possible for real-time testing and monitoring of EV batteries.
- It is very hard to interpret at the pack level.

Battery models

- Remember that in EV applications, we have pretty accurate energy analysis, and can predict what a vehicle will use.
- With good battery models, we can analyze how the power and energy in a drive cycle will affect batteries.





Battery models

- That is correct – We can estimate quite accurately the currents, voltages, stresses, and SOC on a battery pack given a drive cycle.
- This sort of analysis provides opportunities for control optimization.