Battery Technology & Applications Overview

Upal Sengupta
Staff Applications Engineer
Power / Battery Management Solutions

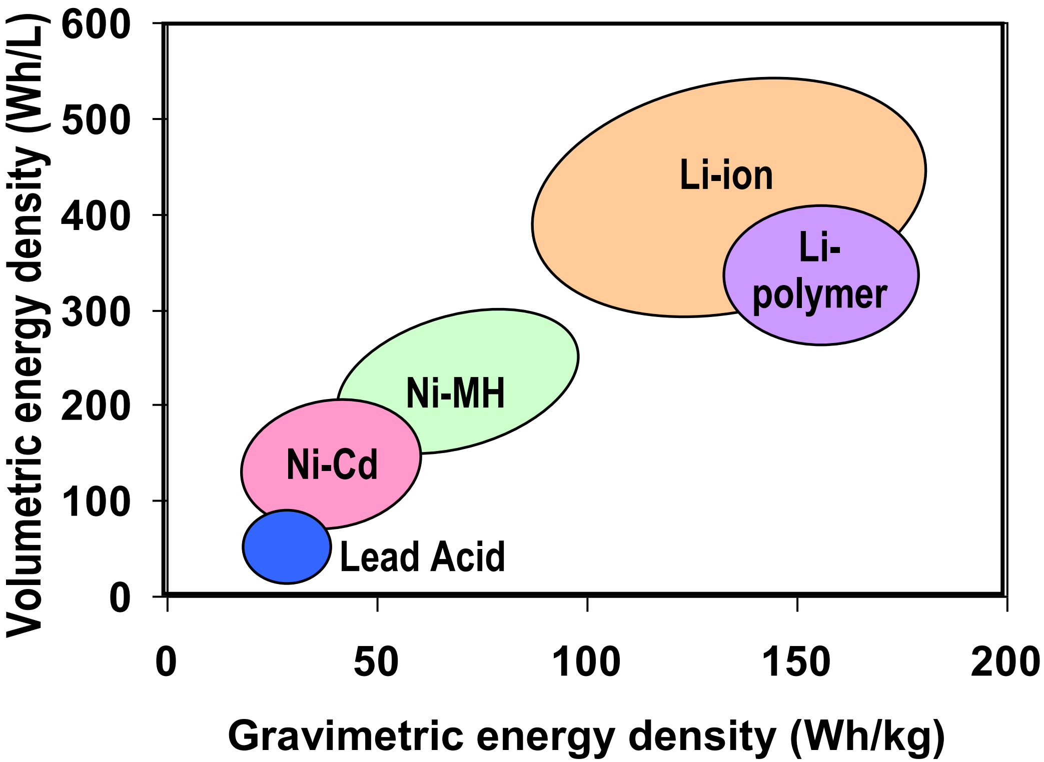
Battery Technology & Applications Overview

- Battery Technology
  - NiCd/NiMH/Lead/**Li+**
  - Optimizing Performance for different applications
- Li-Ion Battery Charging
- Battery Capacity Monitoring / Fuel Gauging
- Wireless Power

BATTERY TECHNOLOGY

Rechargeable Battery Options

- **Lead Acid**
  - ↑ 100 years of fine service!
  - ↓ Heavy, low energy density, toxic materials

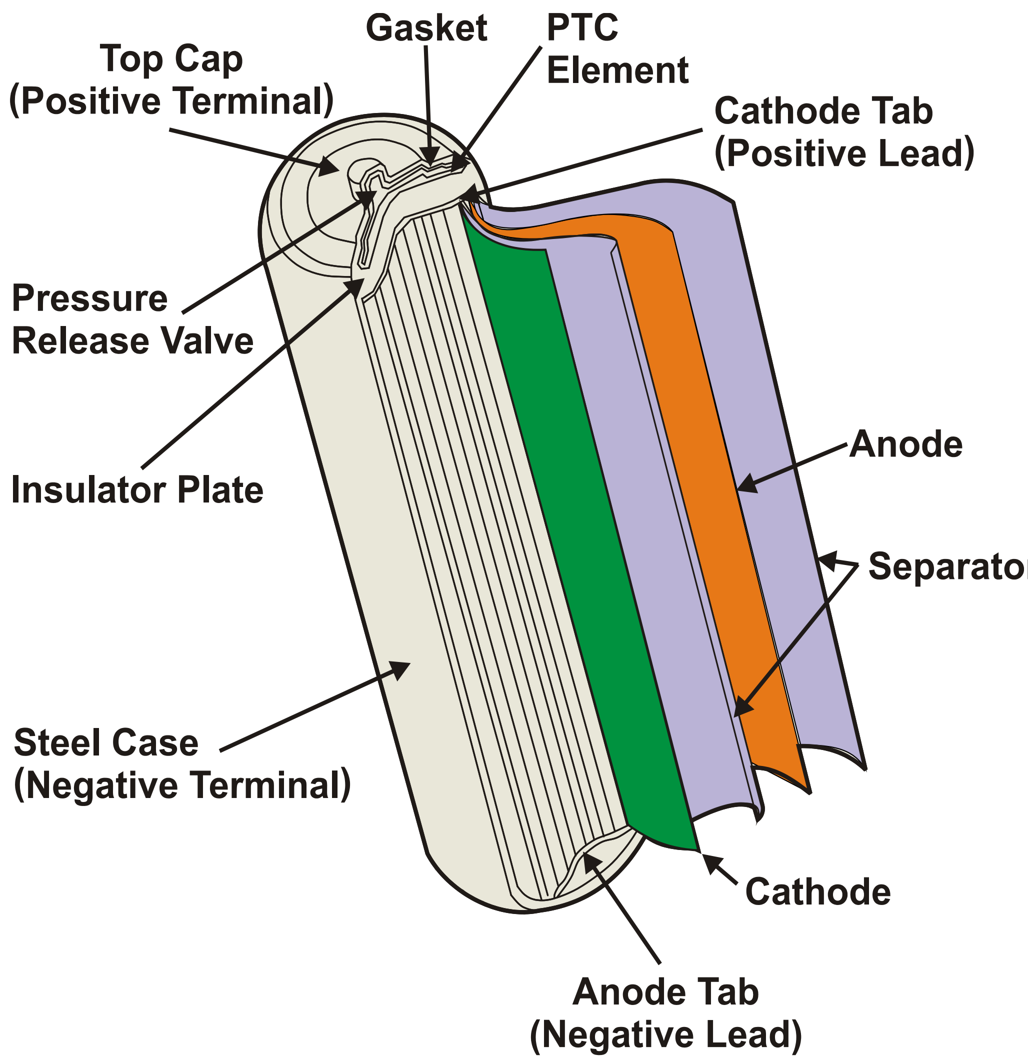


- **NiCd**
  - ↑ High cycle count, low cost
  - ↓ Toxic heavy metal, low energy density
- **NiMH**
  - ↑ Improvement in capacity over NiCd
  - ↓ High self-discharge
- **Lithium Ion / Polymer**
  - ↑ High Energy density, low self-discharge
  - ↓ Cost, external electronics required for battery management

Cell Construction and Safety

Safety Elements

- Aluminum or steel case
- Pressure relief valve
- PTC element
- Polyolefin separator
  - Low melting point (135 to 165°C)
  - Porosity is lost as melting point is approached
  - Stops Li-Ion flow and shuts down the cell
- Recent incidents traced to metal particles that pollute the cells and create micro-shorts

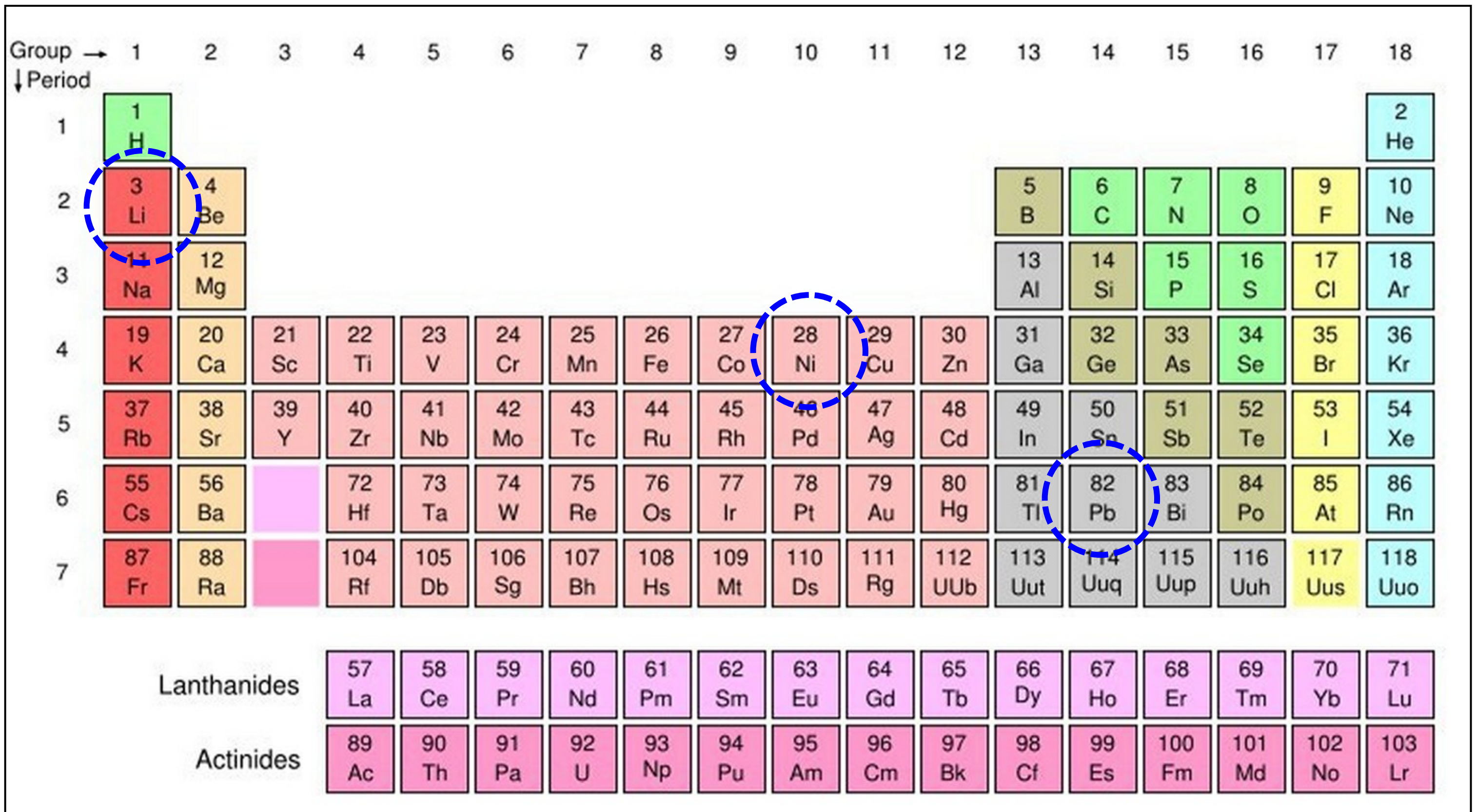


“What’s Important” in various applications

- Vehicle Starter Application:
  - Extremely high surge current → **need very low cell internal resistance**
  - **Must work at all extremes of temperature**
  - Battery discharge is very brief – spend > 99% of time being recharged
  - Battery is rarely (ideally, “never”) fully discharged → cycle life is not important
- Power Tool Application:
  - Frequent, fast discharge use → **need low resistance and fast recharge**
  - Rugged, durable cells are desirable
  - “Green” trend replaces NiCd with Li-Ion → **DIFFERENT TYPE OF LI-ION** than in phone & notebook PC applications, optimized for high current usage
  - requires different type of charging & monitoring circuits!
- Small Handheld Devices:
  - Light weight and small size are critical
  - High energy capacity for longest possible run time
  - <u>Accurate capacity monitoring is important</u> – especially for smartphones

Why is Li-Ion popular?

- A high performance battery for high performance devices!
  - *Gravimetric energy density → High Capacity, Light weight battery*
  - *Volumetric density energy → High Capacity, Thin battery*
  - *Low self-discharge → Stays charged when not in use*



All Li-Ion Packs need electronic battery management!

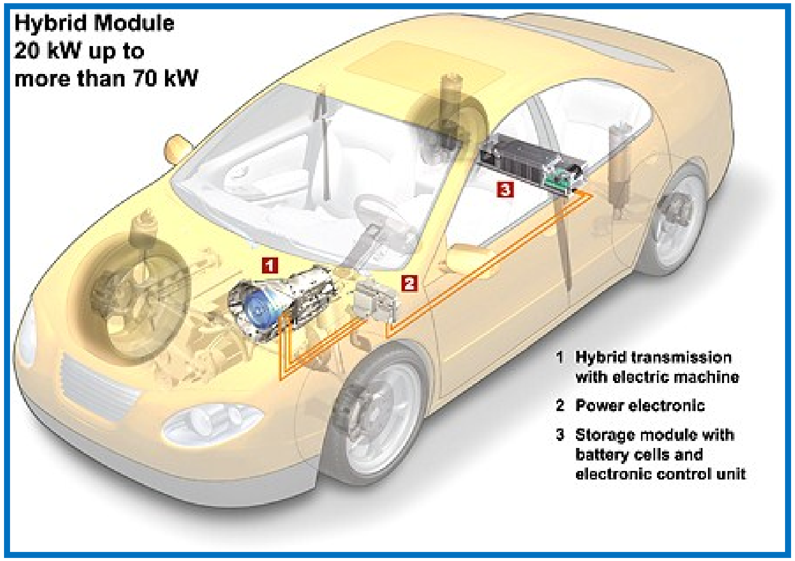
- **Li-Ion performance enables numerous applications that would not be as desirable or even practical with older technologies like NiCd or Lead-Acid**

- **But there is no free lunch! Lithium-Ion batteries offer high performance, but are not as "rugged" or abuse-tolerant as other technologies**

- **Every Li-Ion battery needs to have an electronic battery management circuit to ensure safe, reliable, and long-lasting use of the battery**

The <u>basic</u> functions of all pack monitoring circuits are the same…

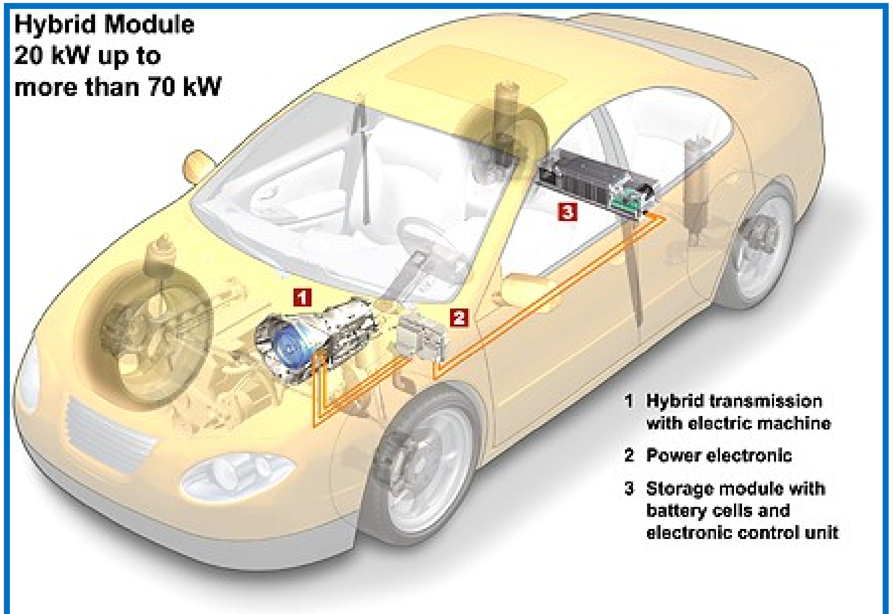
- Maintain safe operation of the battery pack under all conditions
- Extend / maintain service life of the battery as long as possible
- Ensure complete charging and utilization of the pack on each usage cycle



Complexity varies greatly, based on application needs

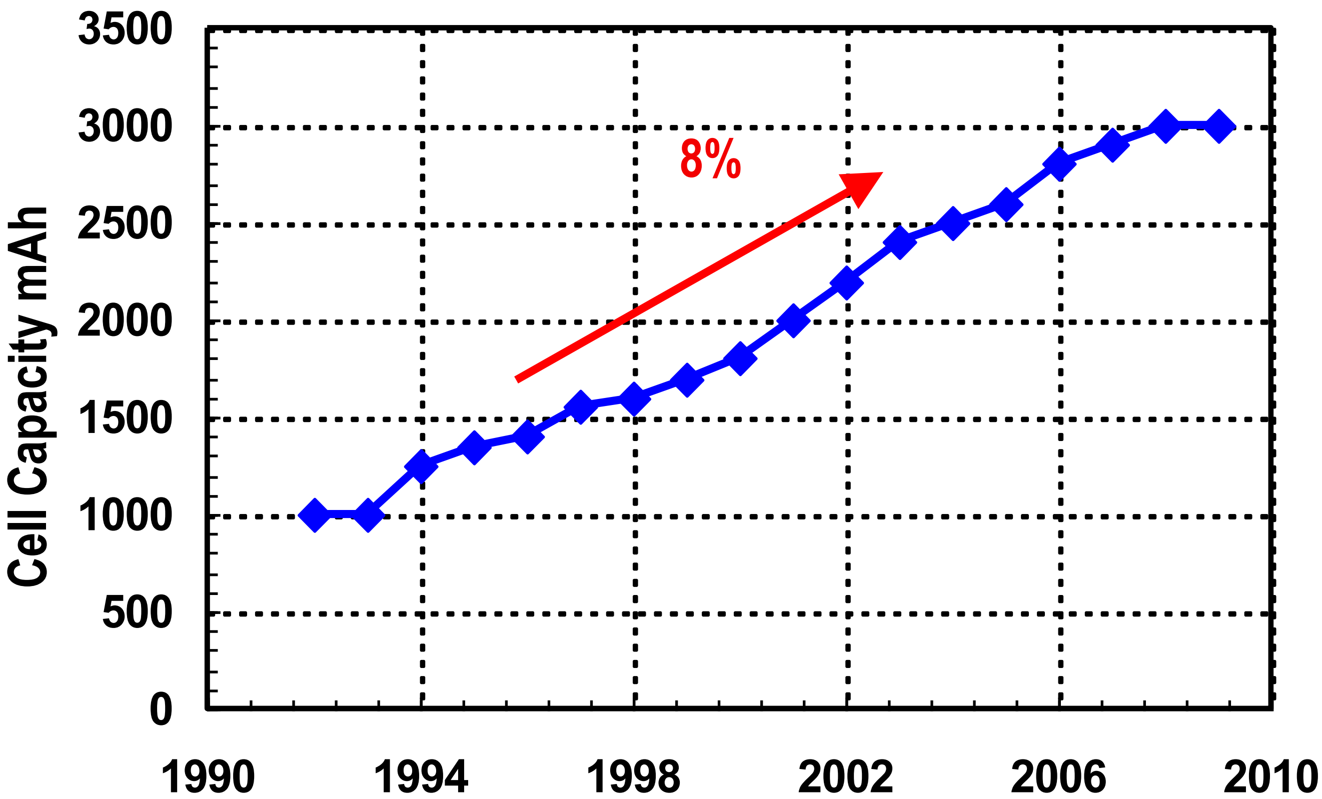
Low current (< 1A) charging; simple battery level indication, basic safety monitoring

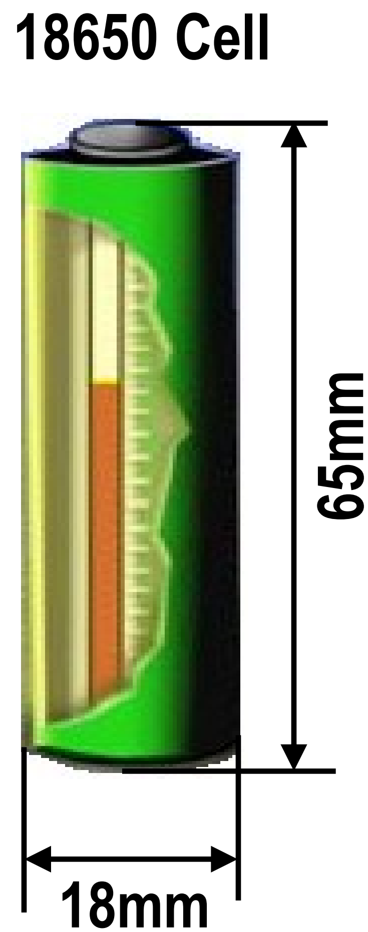
Accurate capacity and remaining run-time estimation; Fast Charging (2 – 10A); redundant safety



High precision cell monitoring, capacity reporting, and cell balancing; high current charge and discharge; multi-point temperature monitoring; highly redundant safety monitoring and control

18650 Li-Ion Cell Capacity Development Trend

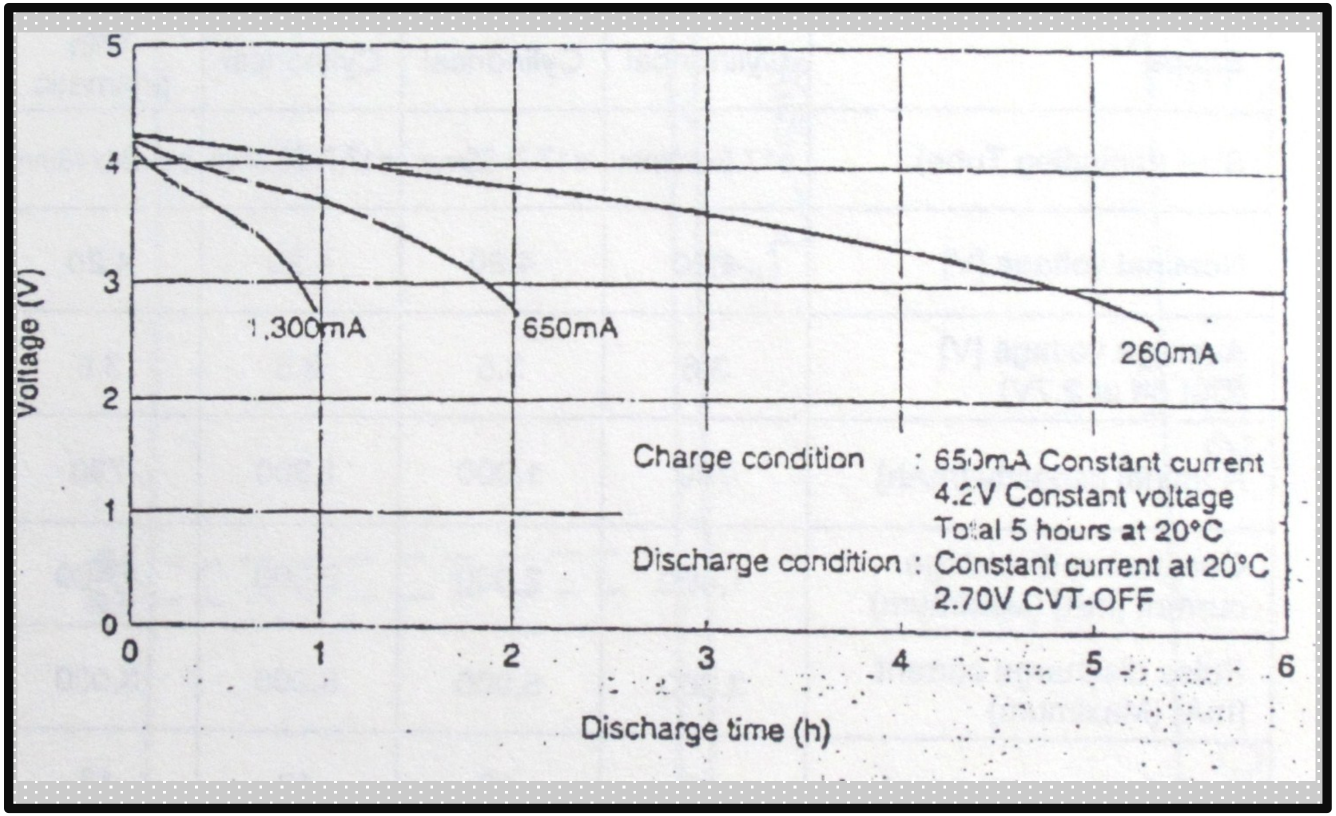




- 18650: Cylindrical, 65mm length, 18mm diameter
- 8% yearly capacity increase over last 15 years

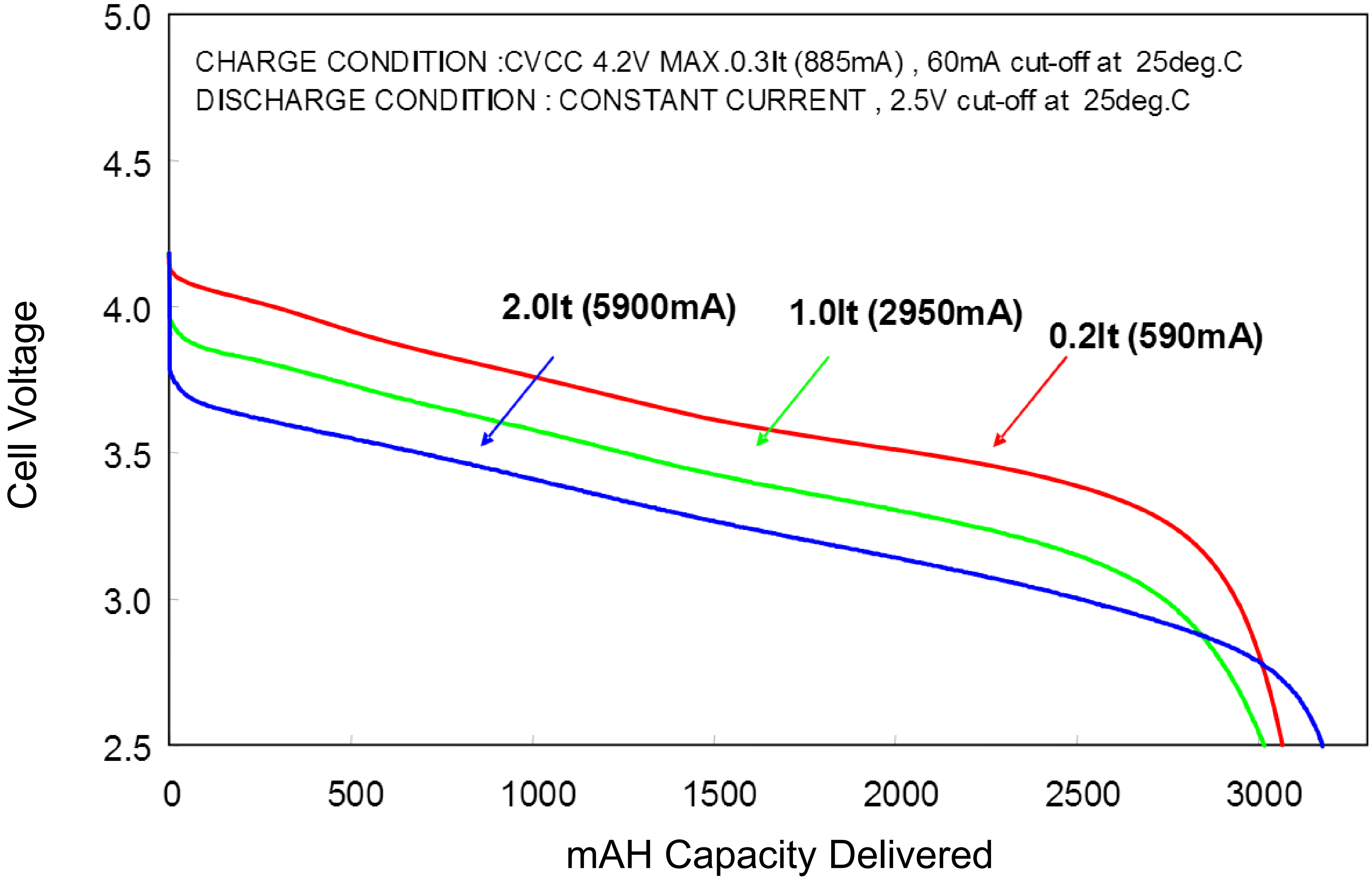
- *Li-Ion Battery Tutorial, Florida battery seminar*

"Classic" Lithium-Ion (Cobalt) 18650 Cell Performance, ca. 1993.



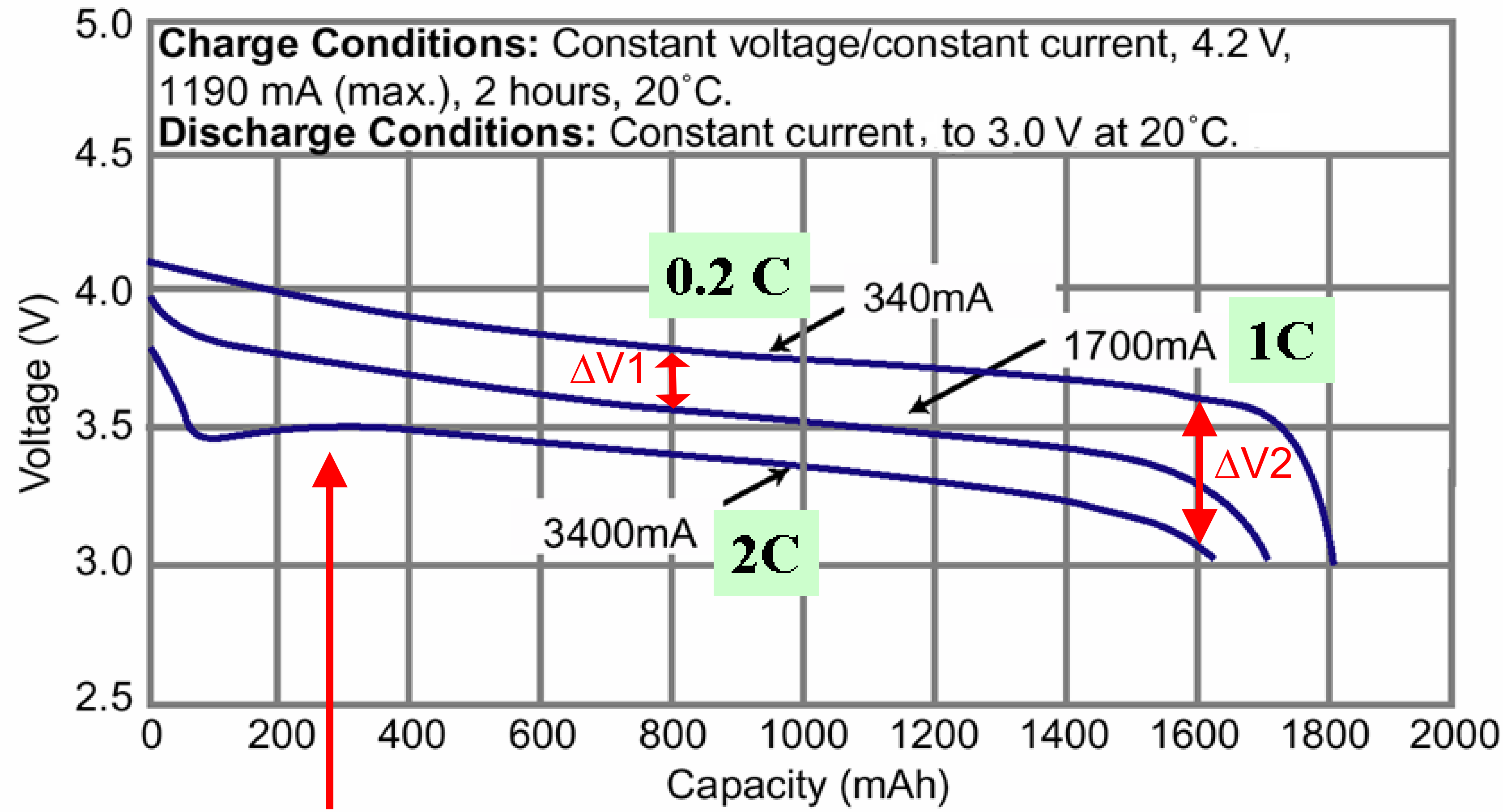
- *1300mAH nominal capacity, max discharge rate 1C or less*
- *A comparably sized "Energy Cell" today would have approximately 2 – 3X the capacity and/or rate capability.*

Panasonic NCR18650 Cell (2012)



http://industrial.panasonic.com/www-data/pdf2/ACA4000/ACA4000CE254.pdf

Li-Ion 18650 Discharge at Various Rates

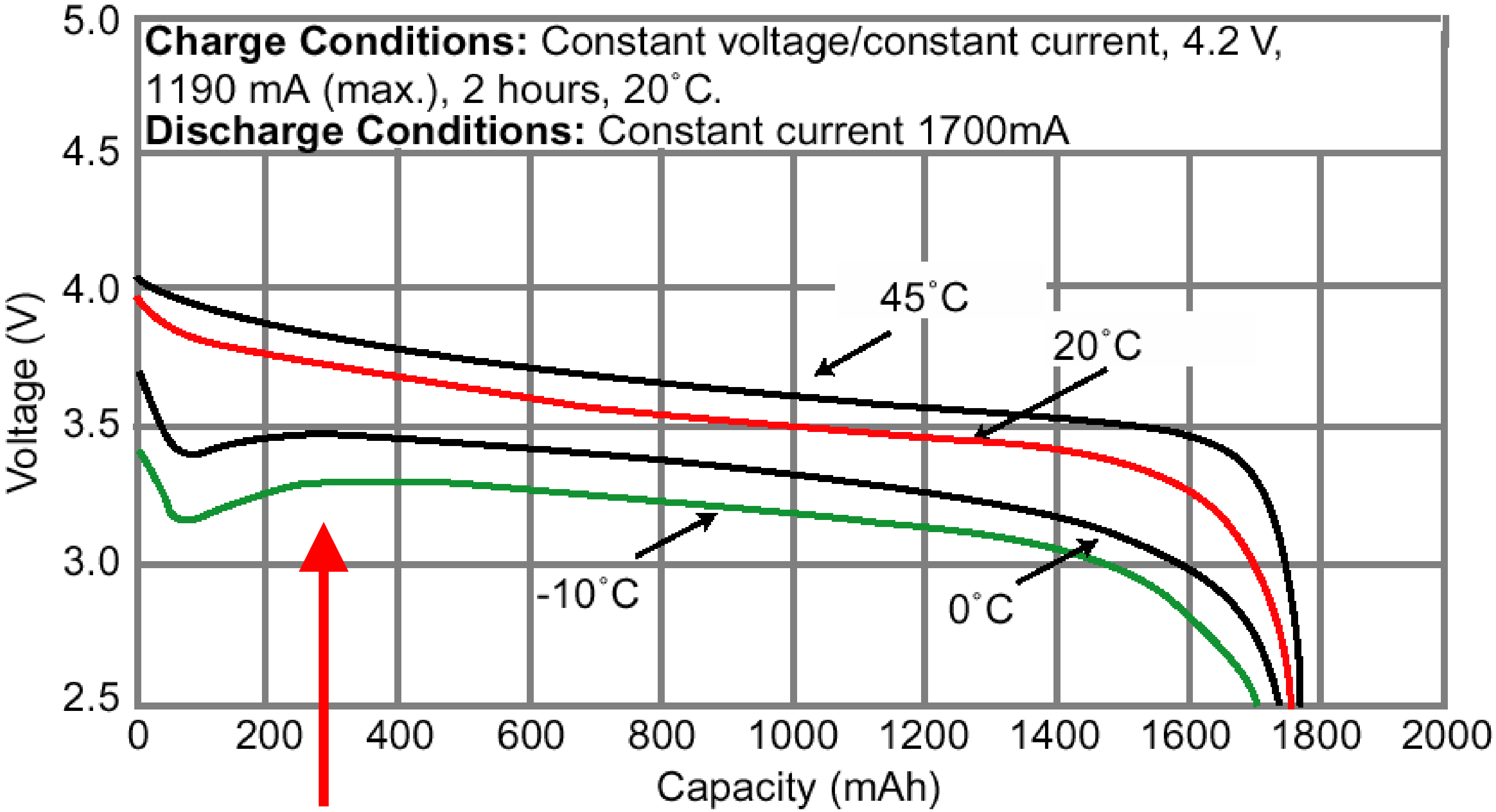


Self-heating Effect Lowers the Internal Impedance

$$\Delta V = \Delta I \times R_{BAT}$$

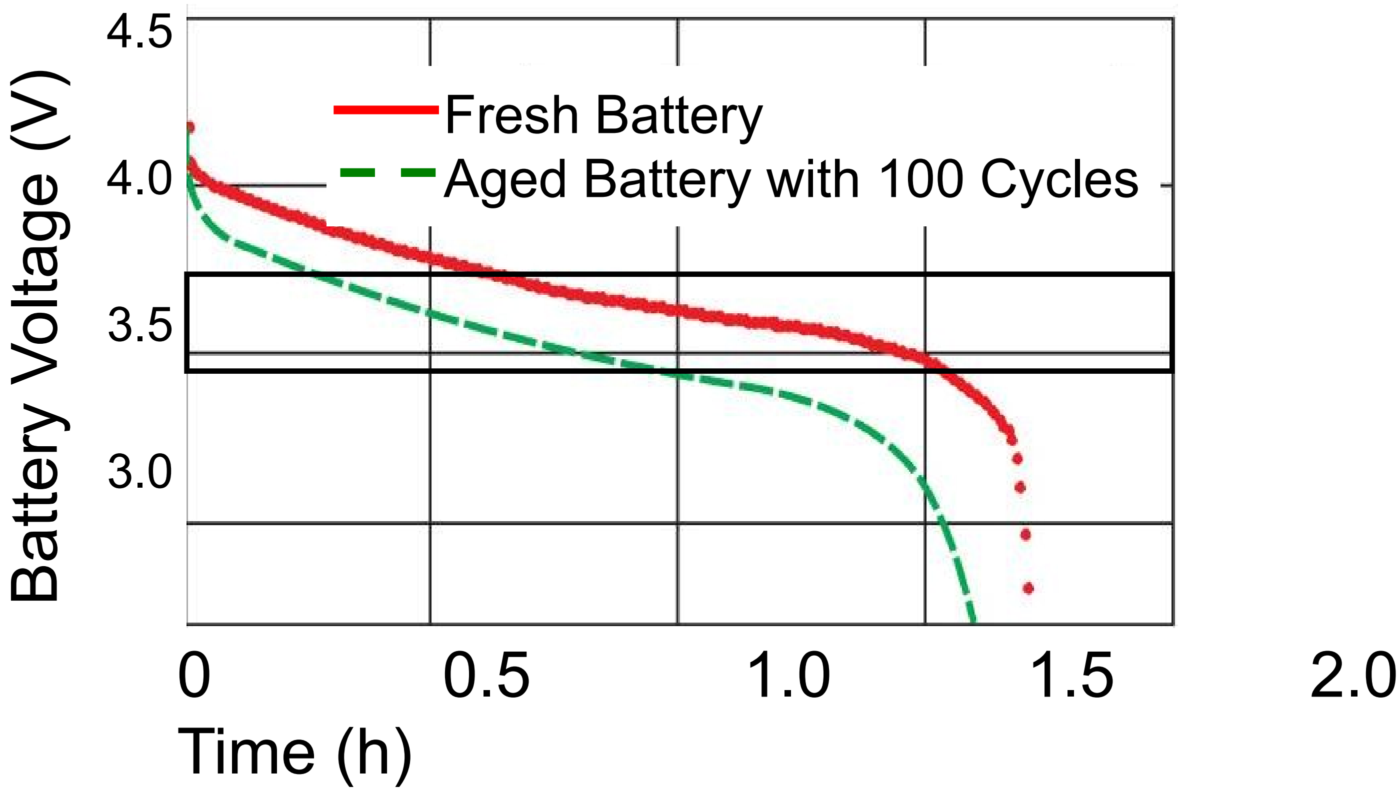
Li-Ion 18650 Discharge vs. Temperature

- Organic electrolyte makes internal resistance of Li-Ion battery more temperature dependent than other batteries



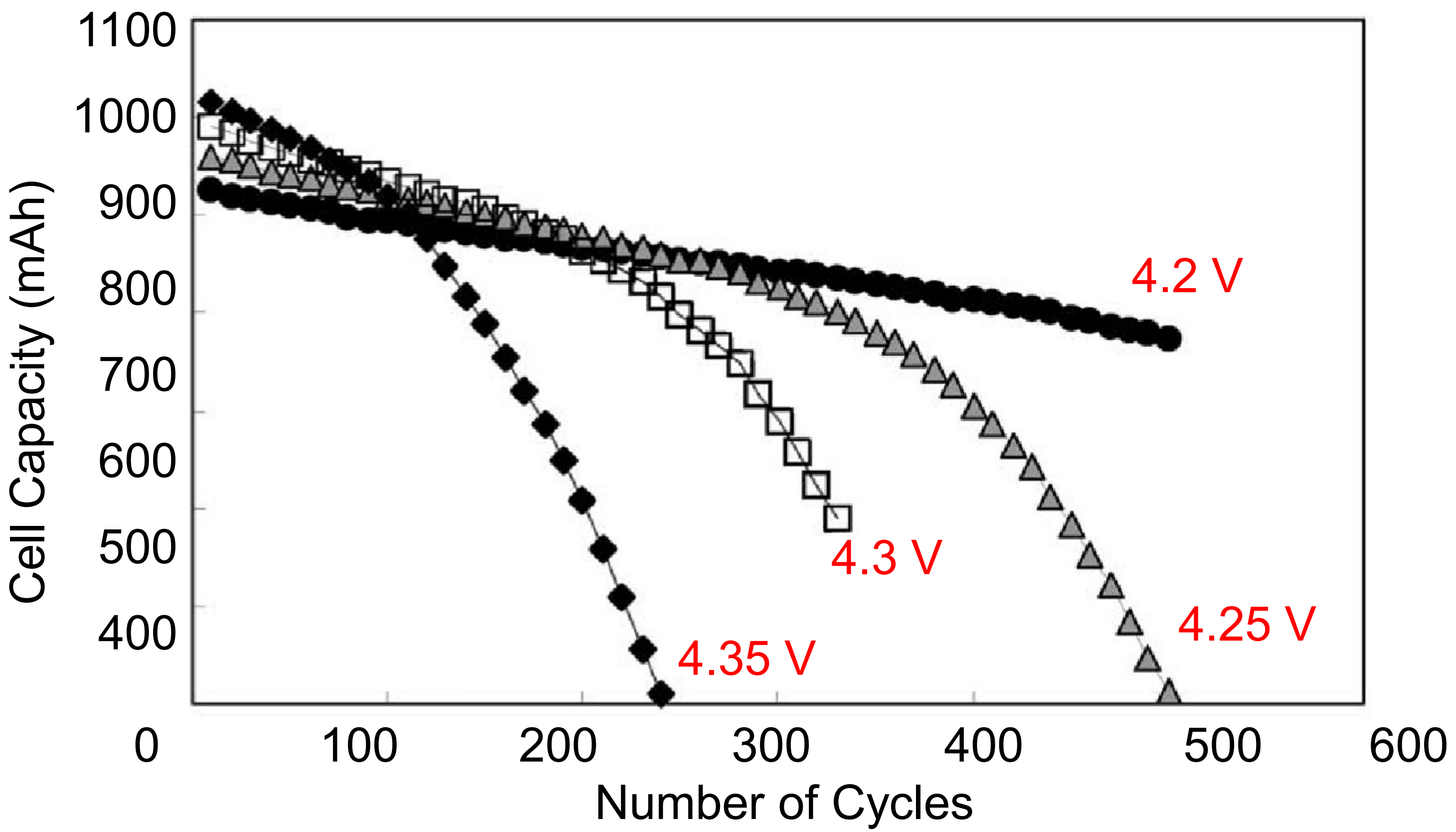
Self-heating Effect Lowers the Internal Impedance

Effect of Impedance Increase on Runtime



- Change of no-load capacity during 100 cycles < 1%
- Also, after 100 cycles, impedance doubles
- Double impedance results in 7% decrease in runtime

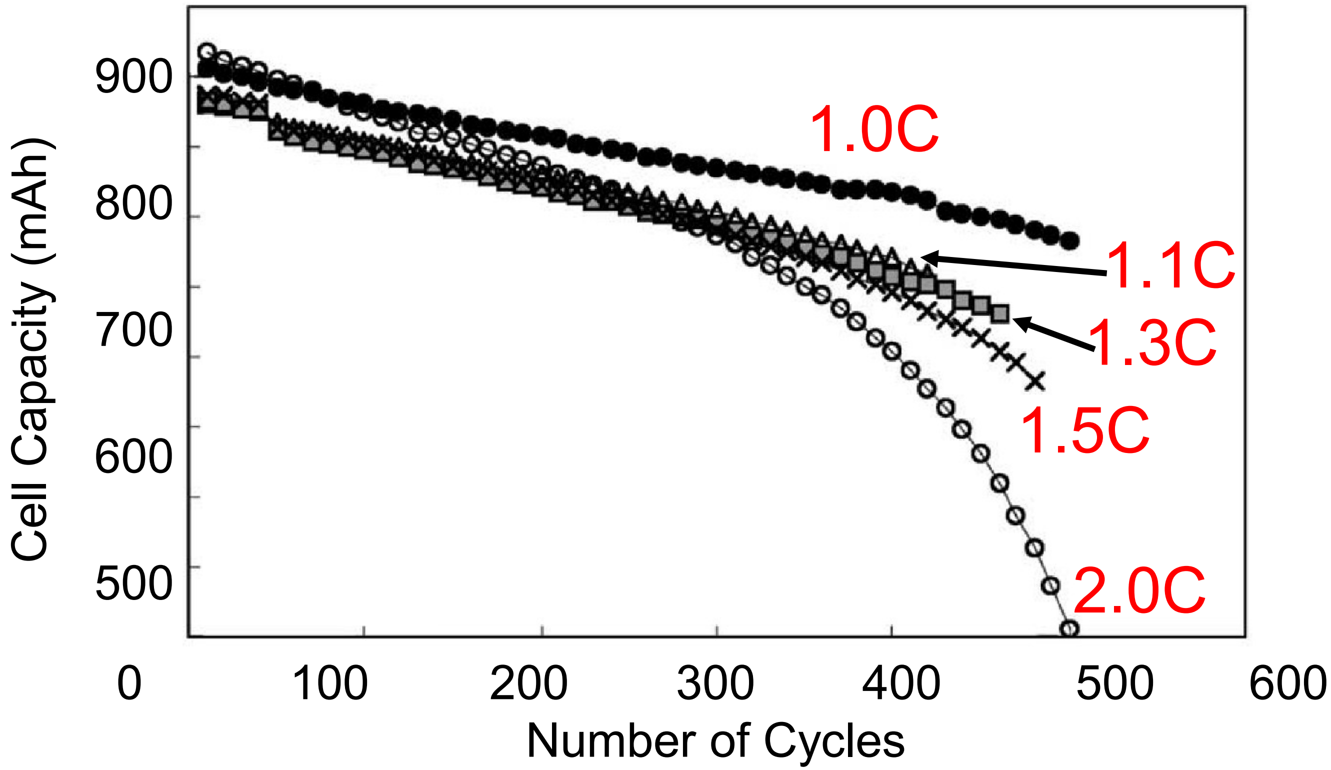
Charge Voltage Affects Battery Service Life



- The higher the voltage, the higher the initial capacity
- Overcharging shortens battery cycle life

Source: "Factors that affect cycle-life and possible degradation mechanisms of a Li-Ion cell based on $LiCoO_2$," Journal of Power Sources 111 (2002) 130-136

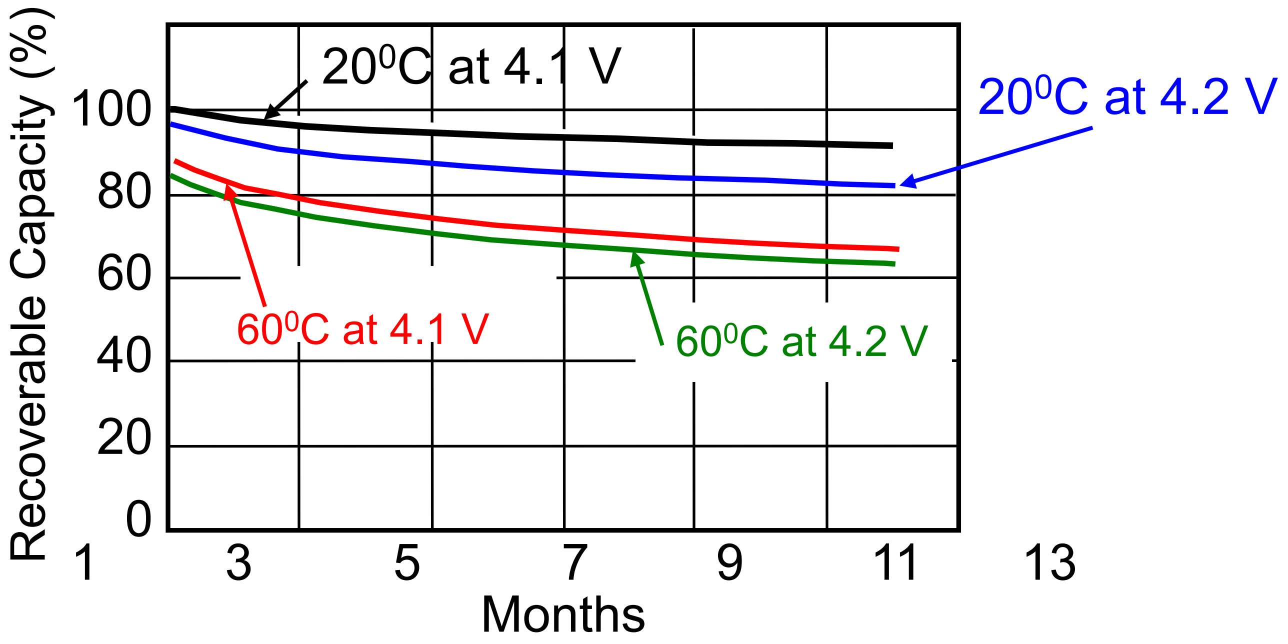
Charge Current versus Battery Degradation



- Charge Current: Limited to 1C rate to prevent overheating that can accelerate degradation
- Some new cells can handle higher-rate

Source: "Factors that affect cycle-life and possible degradation mechanisms of a Li-Ion cell based on $LiCoO_2$," Journal of Power Sources 111 (2002) 130-136

Shelf-life, Degradation without Cycling



- If battery sits on the shelf too long, capacity will decrease
- Degradation accelerates at higher temperatures and voltages
- Depending on chemistry, there are specific recommendations for best storage conditions

Source: M. Broussely et al at Journal of Power Sources 97-98 (2001)

There are many variations of "Li-Ion" Batteries!

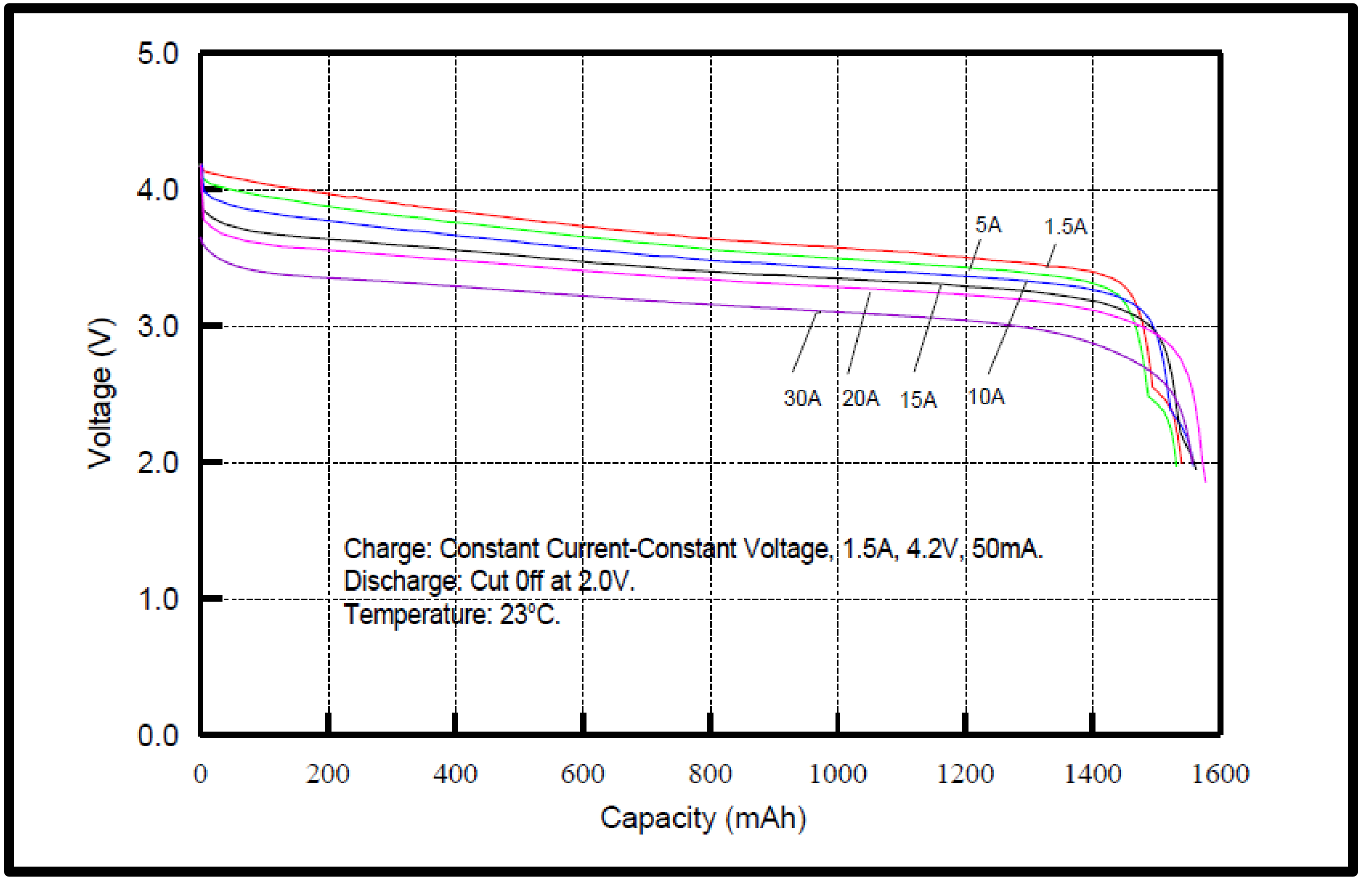
Cathode Material (Li+)	Li - CoO_2	Li - MnO	Li - $FePO_4$	Li - NMC	Li - NCA	Li - CoO_2 - NMC	Li - MnO - NMC	Li - CoO_2	Li -CoO_2
Anode Material	Graphite							Hard Carbon	LTO *("Titanate")*
V_{max}	**4.20**	4.20	**3.60**	4.20	4.20	**4.35**	4.20	4.20	2.70
V_{mid}	**3.60**	3.80	**3.30**	3.65	3.60	**3.70**	3.75	3.75	2.20
V_{min}	**3.00**	2.50	**2.00**	2.50	2.50	**3.00**	2.00	2.50	1.50

Typical Anode and Cathode Materials used for Li-Ion Cells

- *All the above cells are considered "Li-Ion"*
- *In addition to the different voltage ranges shown, they will also have different capacity, cycle life, and charge/discharge rate performance (not shown)*
- *Specific performance parameters can be optimized based on chemistry and physical design of a cell – the "important" parameters depend on the application*

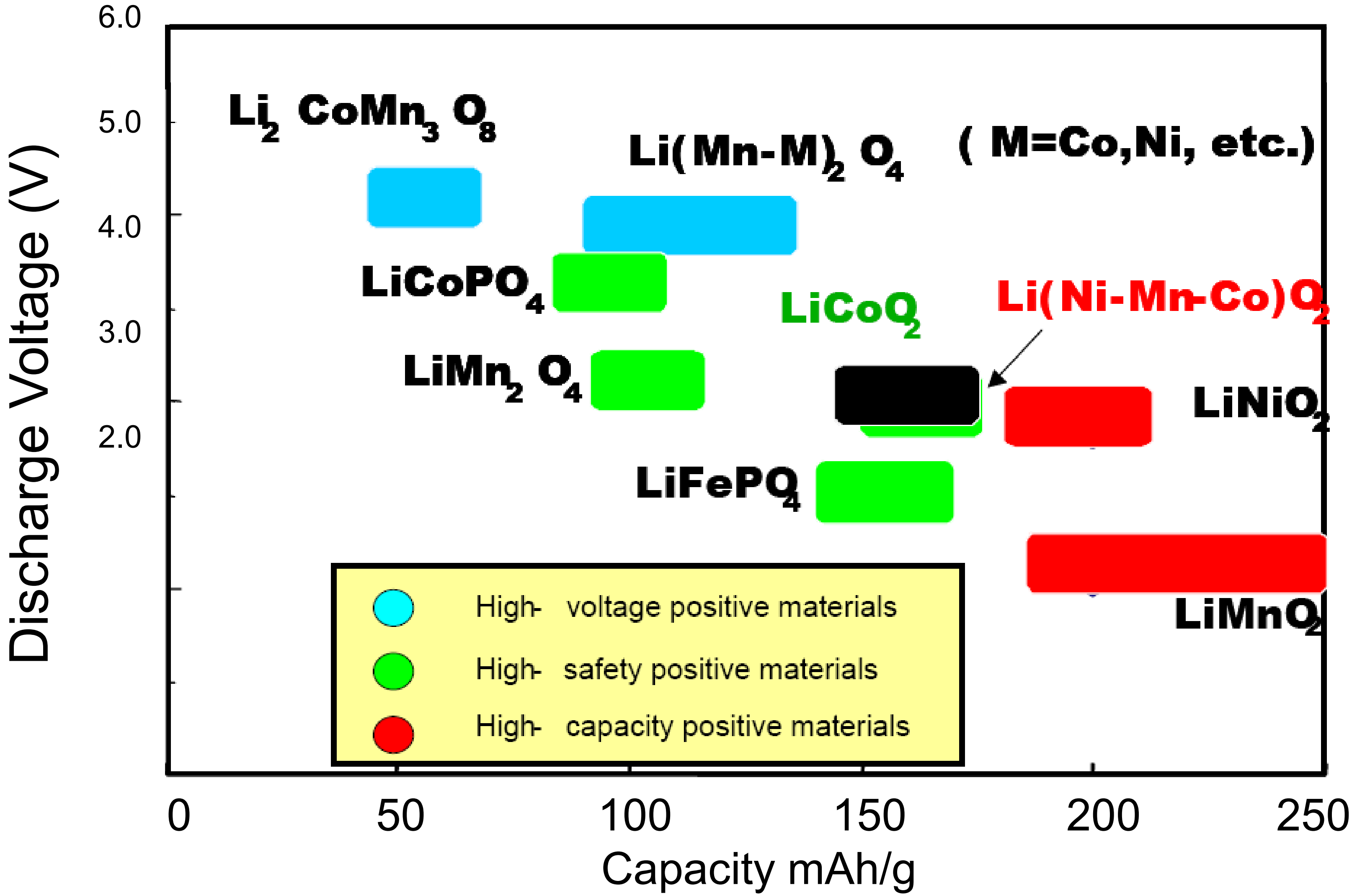
Energy Cells, Power Cells, and “Mid-Rate” Cells are designed for different applications…

Lithium-Ion IBR18650BC (Mn-NMC Blend) Power Cell Performance



- *While capacity (~1500mAH) is only slightly higher than the "classical" LiCoO2 cell, this version of Li-Ion cell can be discharged at very high currents, up to **20C** rates, and recharged in **minutes.***
- *Data provided courtesy of E-One Moli Energy (Canada), Ltd.*

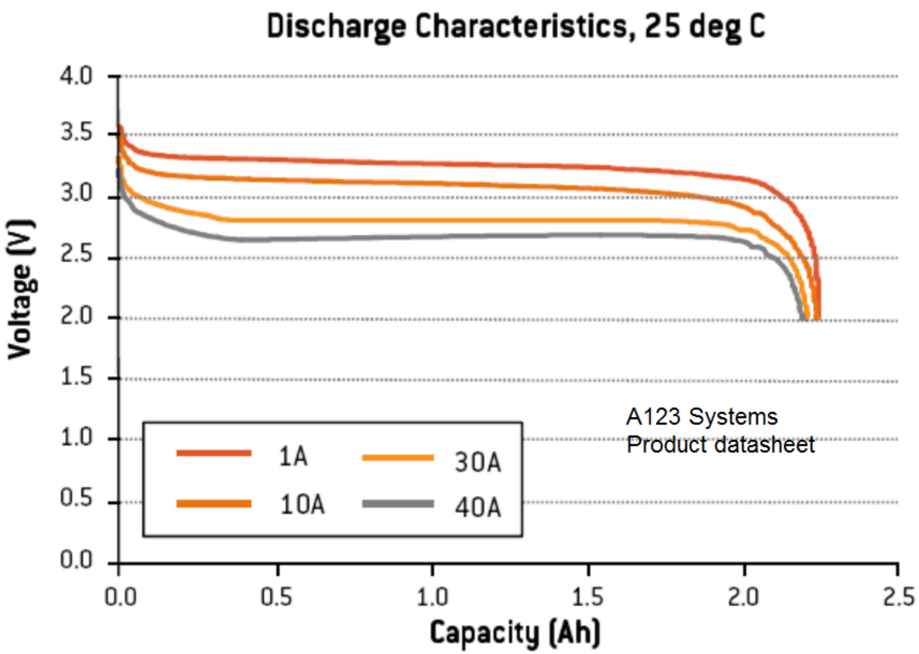
Choices in materials to increase voltage

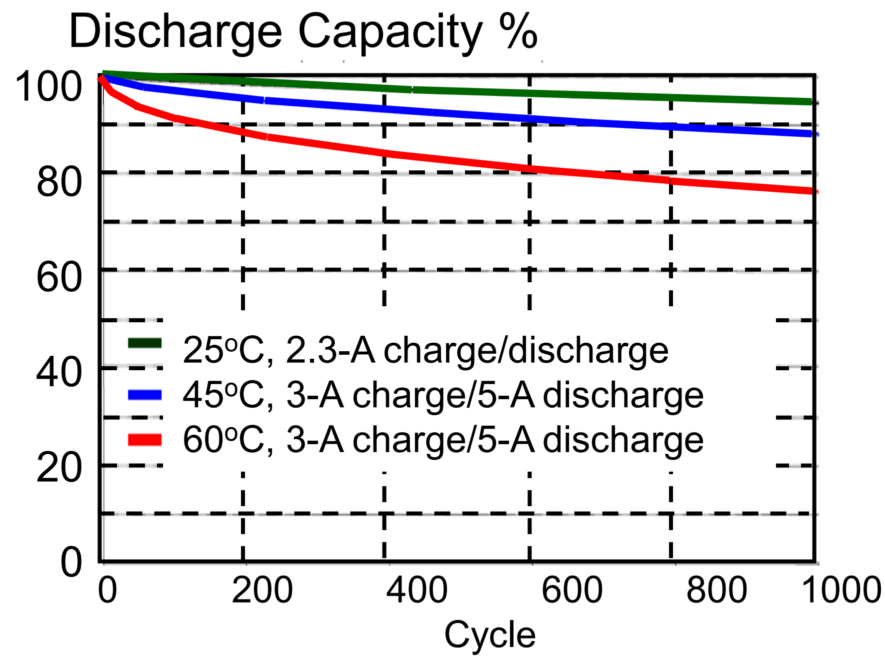


Source: Ali Madani, "An overview of the European Li-Ion battery R&D" Florida Battery seminar 2007

High Current / High Safety Battery

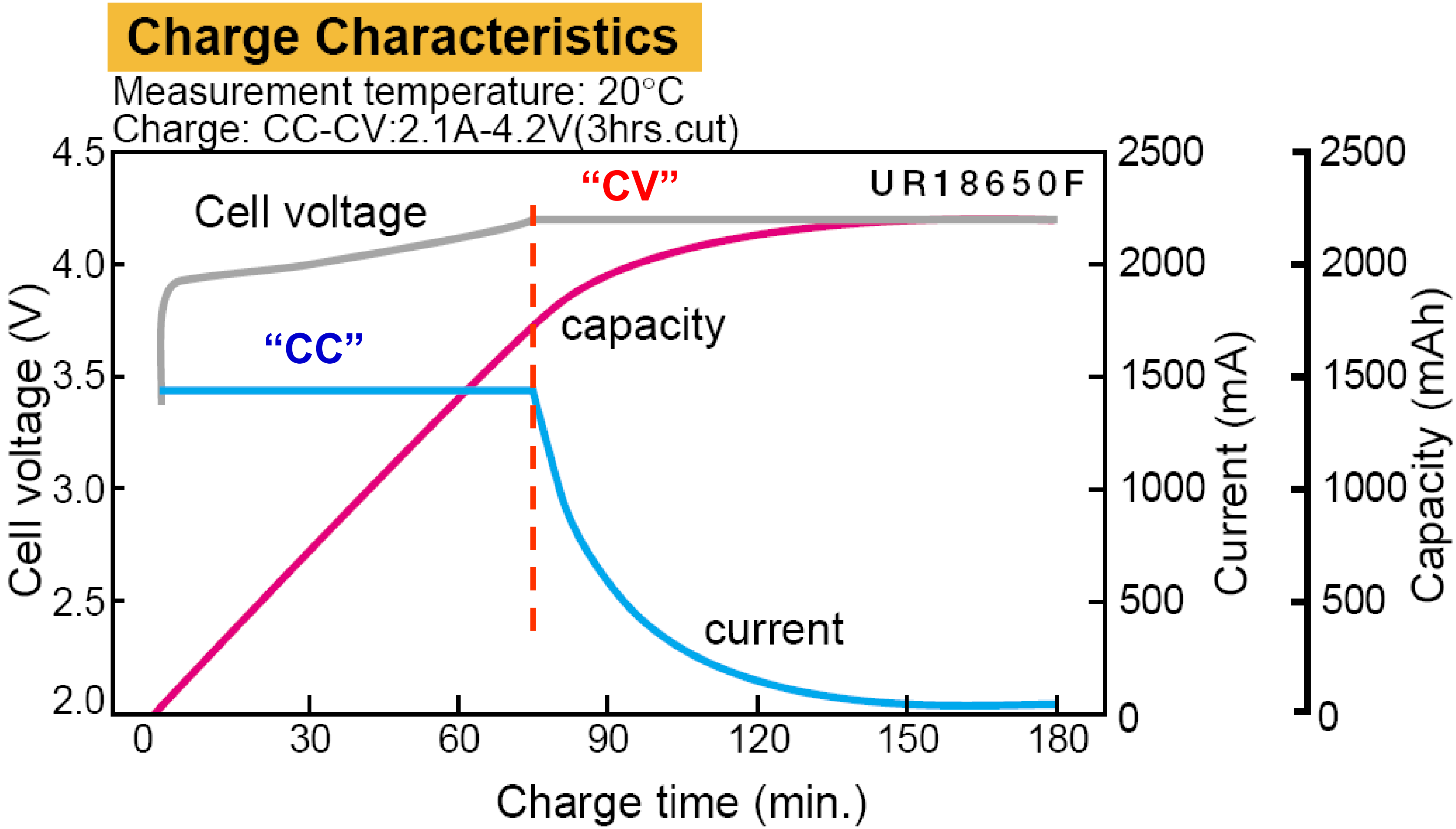
- Cell manufacturer can fine-tune the cell for either high discharge rate or high capacity. 10C rate discharge is possible with Ni/Mn/Co hybrid cathodes
- High Current Chemistry Example: A123 Systems company: 26650A $LiFePO_4$,
  - **Safety: 350°C Thermal Runaway**
  - **10 mΩ at 1 Hz**



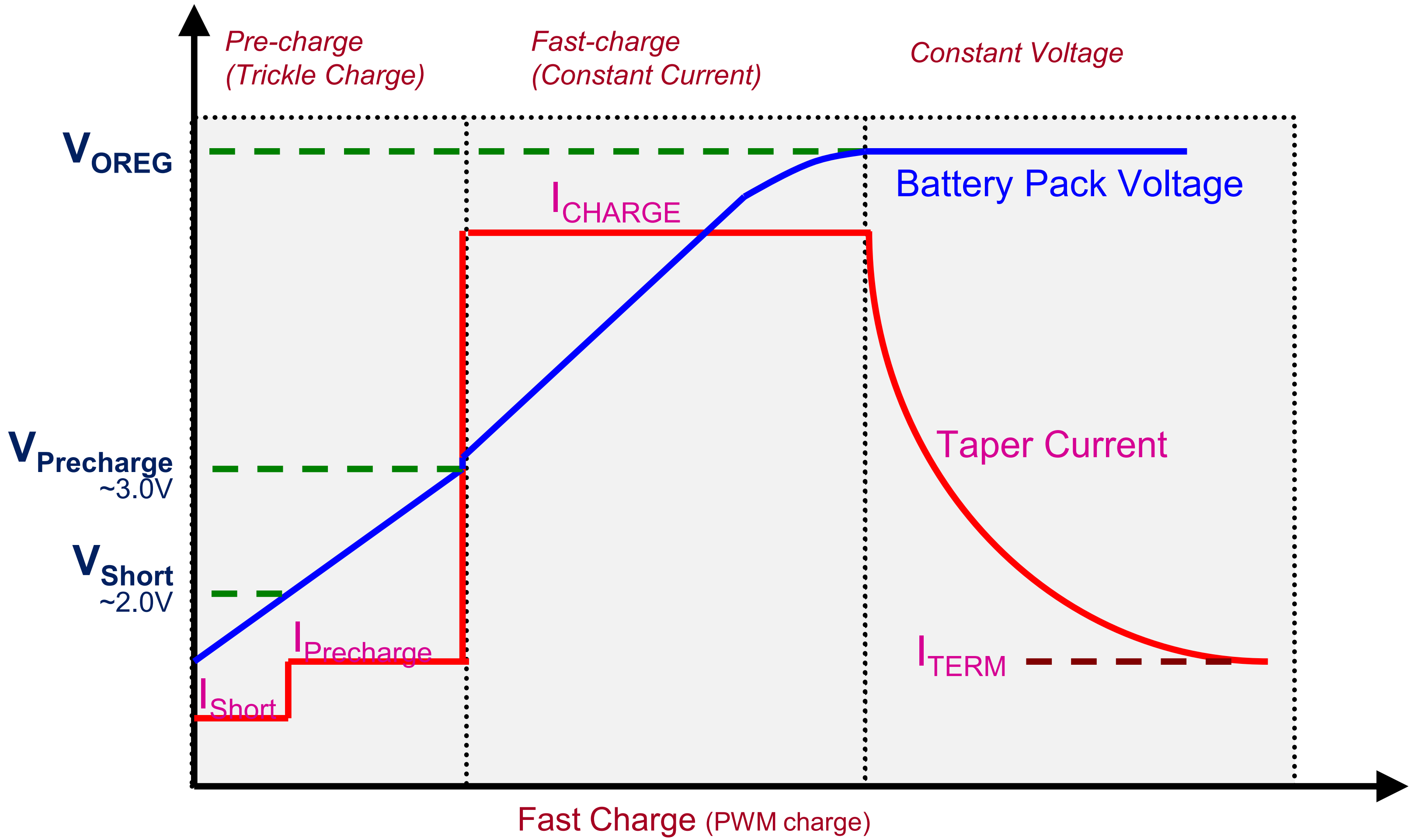


LI-ION CHARGING CONSIDERATIONS

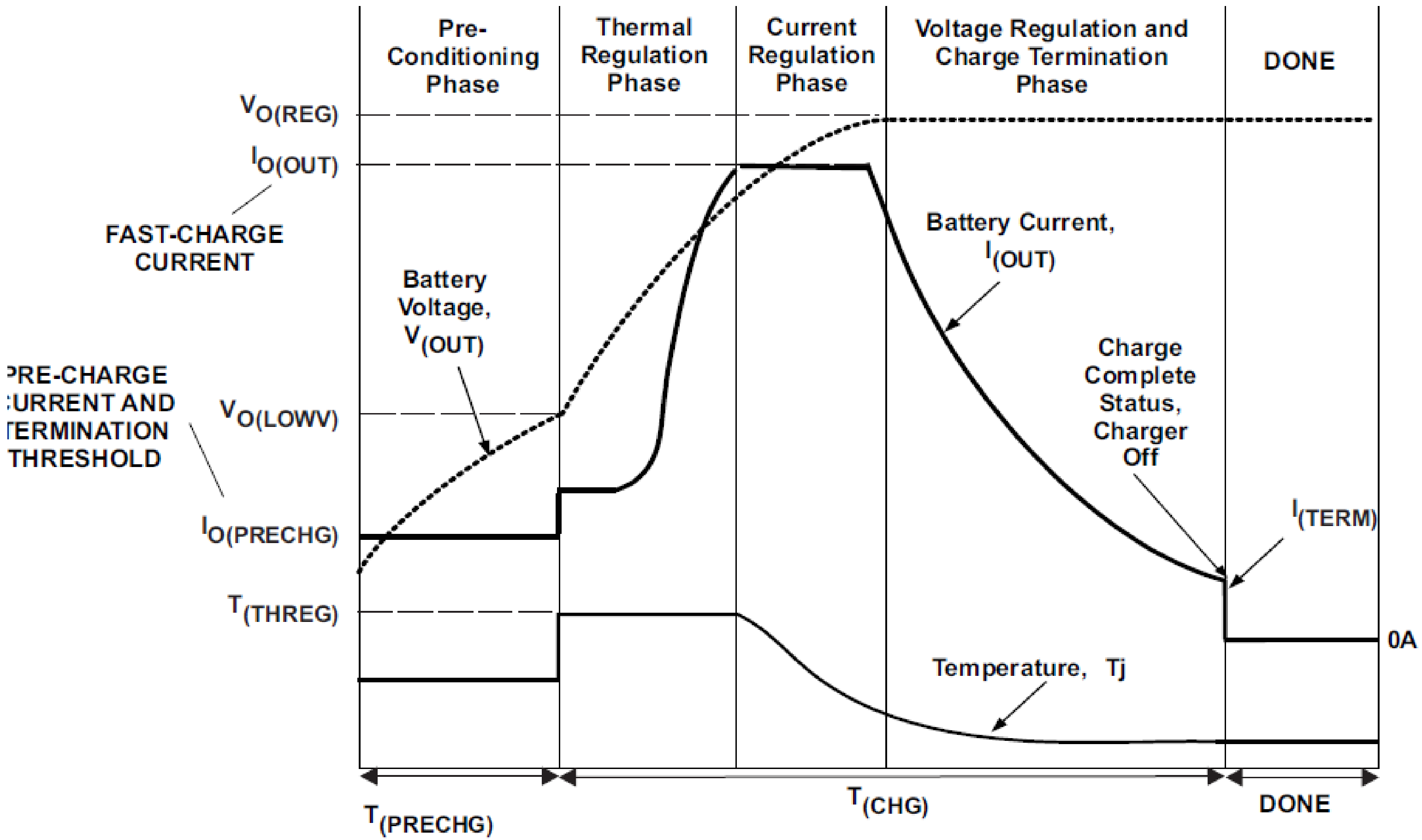
"Ideal" Li-Ion CC-CV Charge Curve



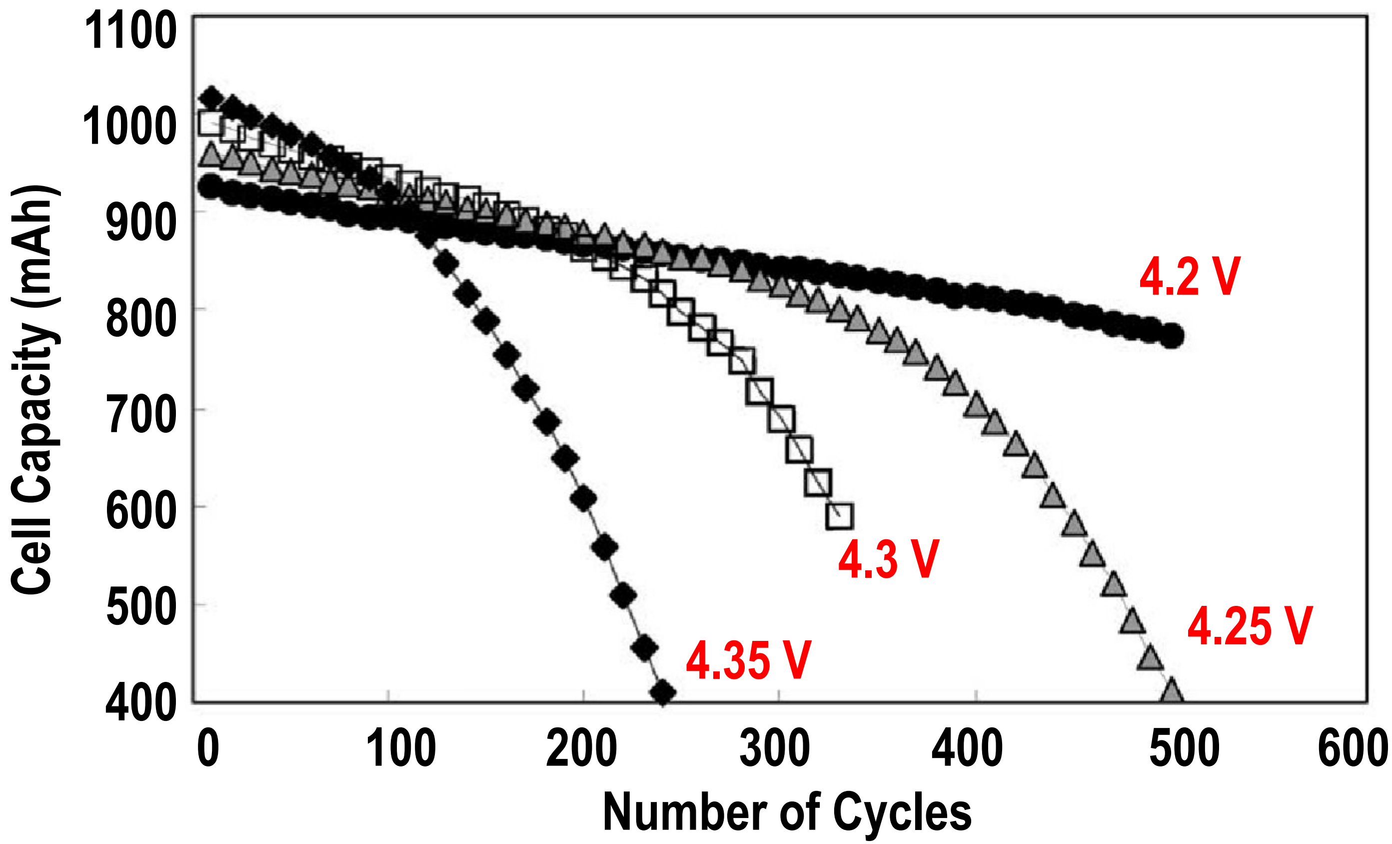
Practical "CC-CV" allows for fault conditions



CCCV - From an actual data sheet…



Charge Voltage Affects Battery Service Life



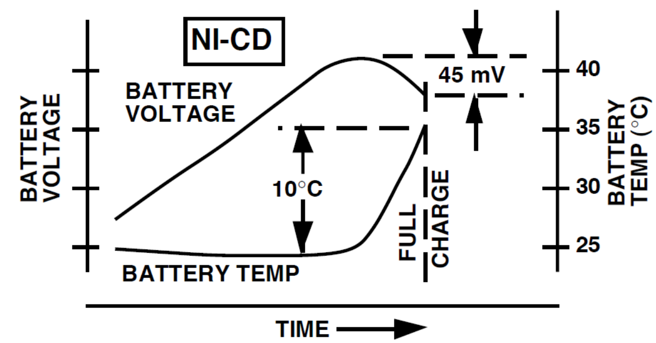
- The higher the voltage, the higher the initial capacity
- Overcharging shortens battery cycle life

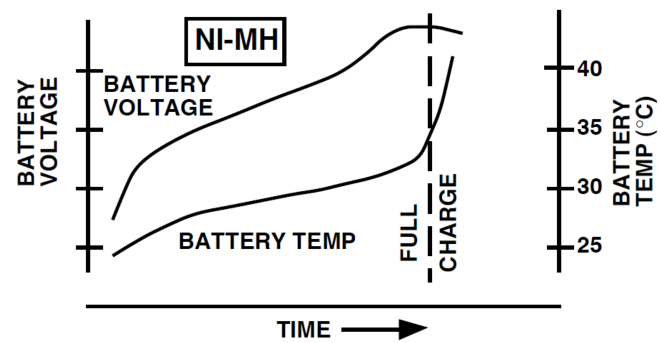
Source: "Factors that affect cycle-life and possible degradation mechanisms of a Li-Ion cell based on $LiCoO_2$," Journal of Power Sources 111 (2002) 130-136

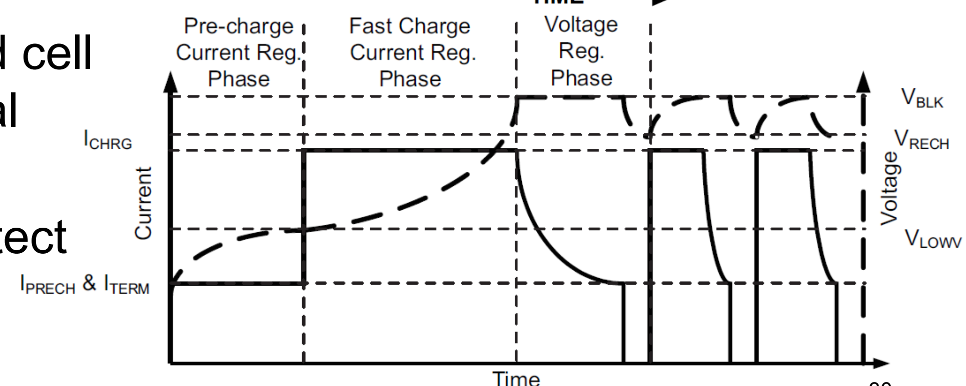
Other Chemical Systems (NiCd/NiMH/$PbSO_4$)

- Charging *algorithm* (control sequence for applying power to the cells) must be appropriate for the chemistry
- NiCd, NiMH, and $PbSO_4$ systems – unlike Li-Ion – can all tolerate slight overcharge
  - Simple low current "trickle charge" can be used (10 – 24 hours to full!)
- But - they cannot tolerate significant overcharge!
  - So… to ensure long term pack service life, a quality fast charging system should monitor voltage, current, and cell (pack) temperature for ALL chemical battery types
  - Charger uses this information to detect that the pack is full and reduce or terminate the charge current

REF: TI APPNOTE SNVA557







Texas Instruments

Introduction to / Selection of Battery Monitoring Circuits

BATTERY GAUGING

Battery Monitoring / Gauging

What is Fuel Gauging Technology?

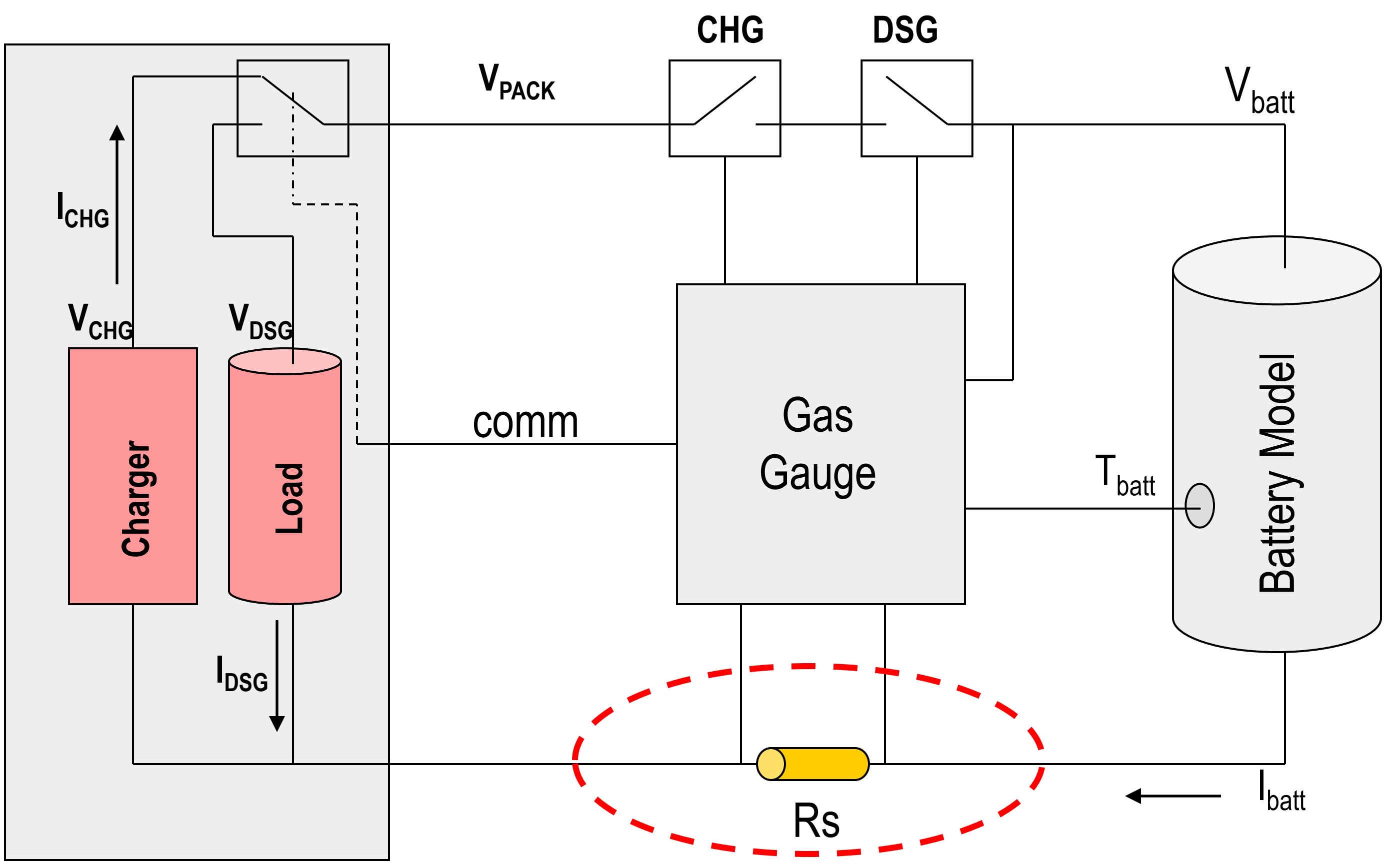
Fuel Gauging = technology to report battery operational status and predict battery capacity under all system active and inactive conditions.

Key benefits are providing extended RUN TIME and LIFE TIME!

The Gas Gauge function autonomously reports and calculates:

- Voltage
- Charging or Discharging Current
- Temperature
- Remaining **battery capacity** information
  - *Capacity percentage*
  - *Run time to empty/full*
  - *Talk time, idle time, etc.*
- Battery **State of Health**
- Battery **safety** diagnostics

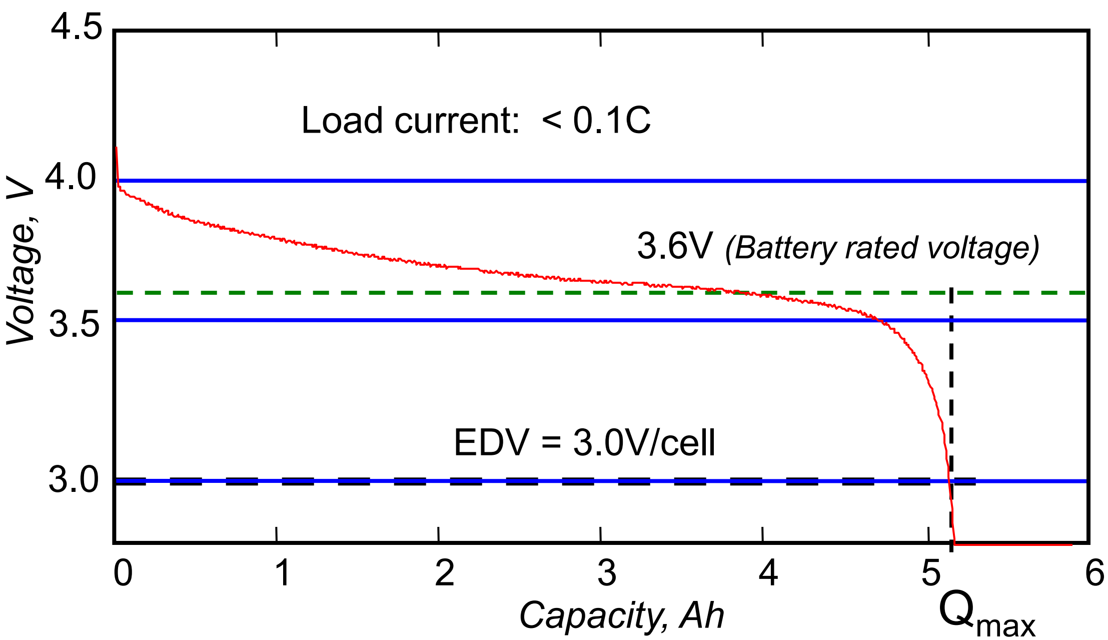
Basic Smart Battery System



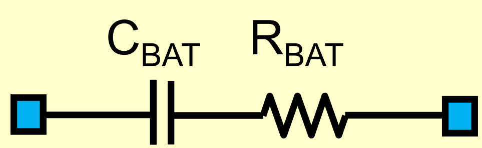
$$q_k = q_0 + \Delta t \cdot \sum_k I_k$$

Gauging: *Battery Chemical Capacity (Qmax)*

Li-Ion Discharge Profile



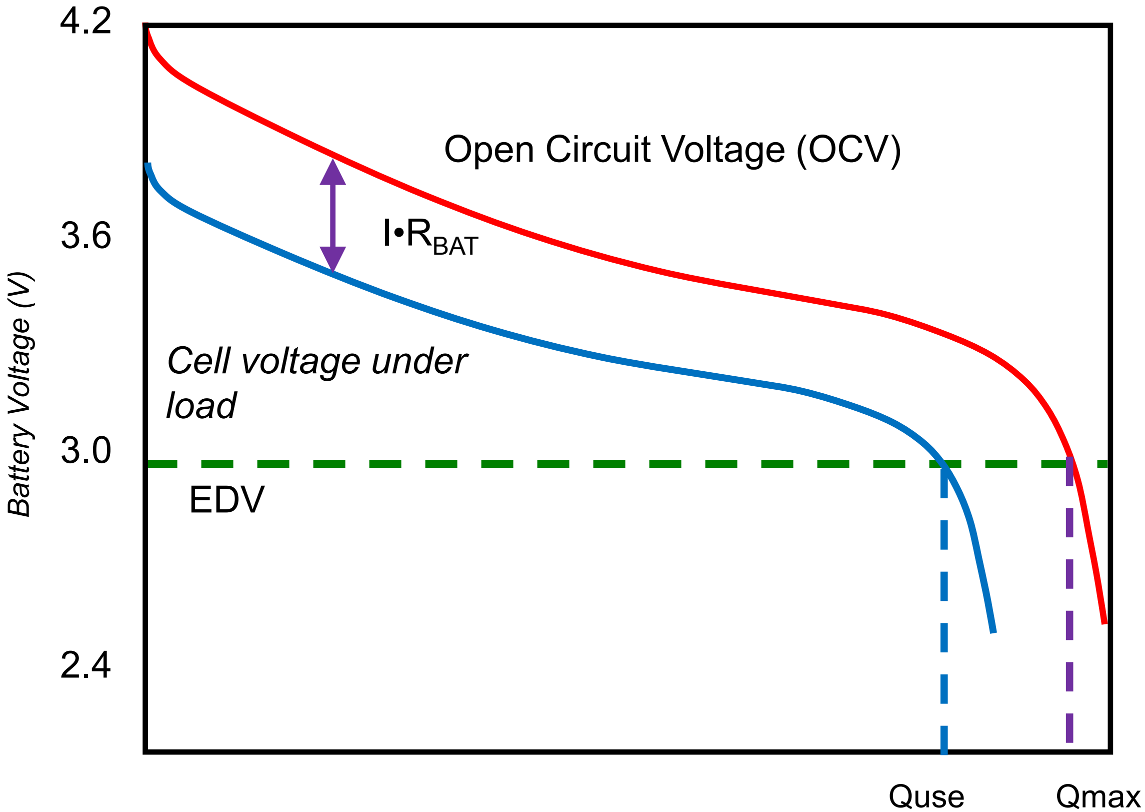
Battery Model

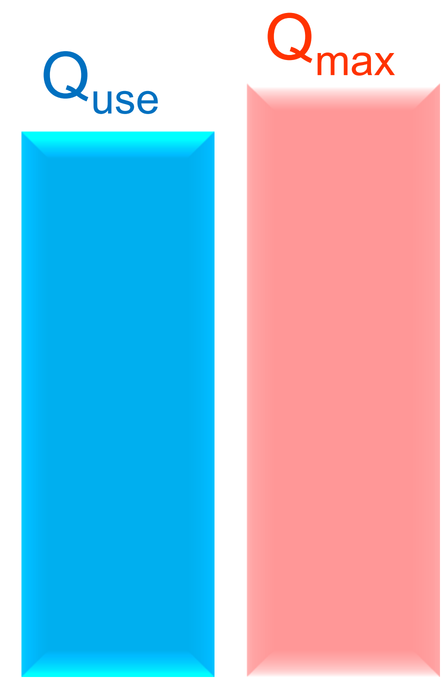


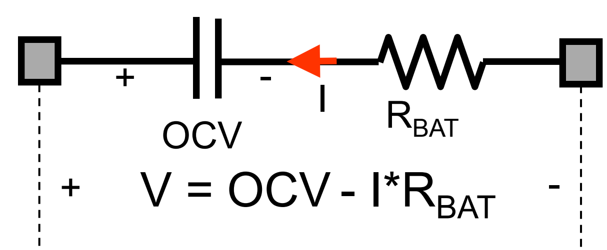
Definitions:

- **Battery Capacity = *"1C"***
  1C Discharge rate is *current to completely discharge a battery in one hour*
  Example:
  - *2200mAh battery*
  - *1C discharge rate = 2200mA @ 1 hr*
  - *0.5C rate: 1100mA @ 2hrs*
- **Battery Capacity (Qmax):** Amount of charge can be extracted from the fully charged cell to the end of discharge voltage (EDV).
- **EDV** *(End of Discharge Voltage)*: Minimum battery voltage acceptable for application or for battery chemistry

Gauging: *Usable Capacity "Q_{USE}"*







- *EDV will be reached earlier for higher discharge current.*
- *Useable capacity $Q_{use} < Q_{max}$*

Gauging: *Types of Gauging Algorithms…*

Cell Voltage Measurement

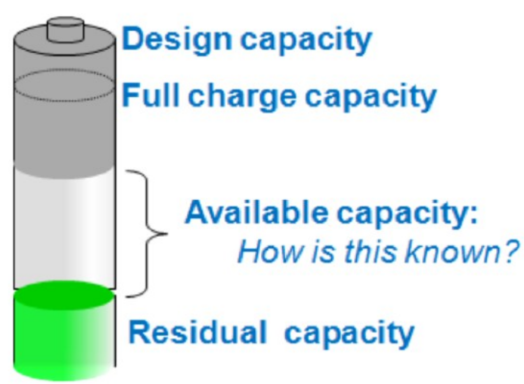
- Measures cell voltage
- Advantage: Simple
- Not accurate over load conditions

Coulomb Counting

- Measures and integrates current over time
- Affected by cell impedance
- Affected by cell self discharge
- Standby current
- Cell Aging
- Must have *full to empty* learning cycles
- Must develop cell models that will vary with cell maker
- Can count the charge leaving the battery, but won't know remaining charge without complex models
- Models will become less accurate with age

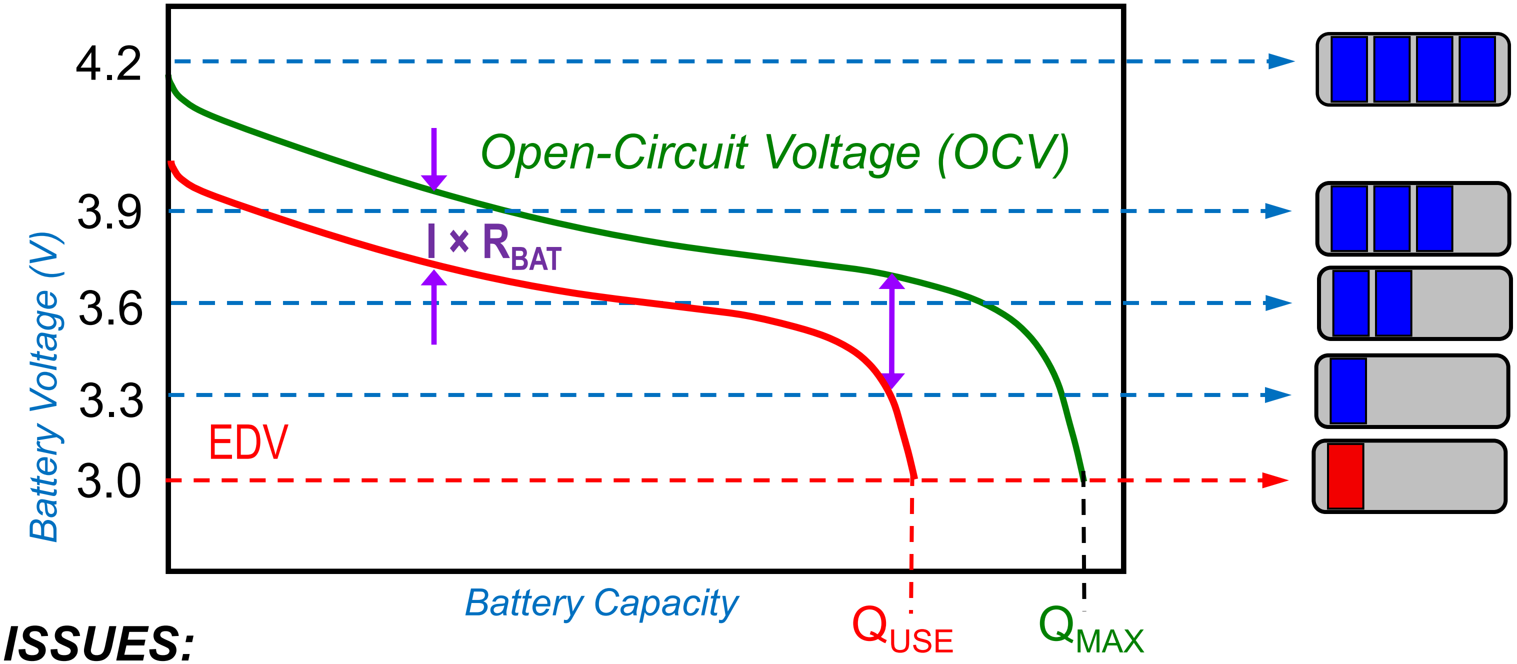
Impedance Track™

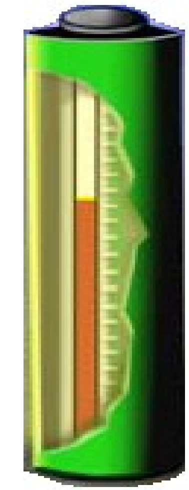
- Directly measures effect of discharge rate, temp, age and other factors by learning cell impedance
- Calculates effect on remaining capacity and full charge capacity
- No learning cycles needed
- No host algorithms or calculations



Gauging

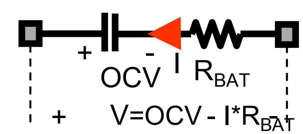
Simple Measured Cell Voltage - Effect of IR drop





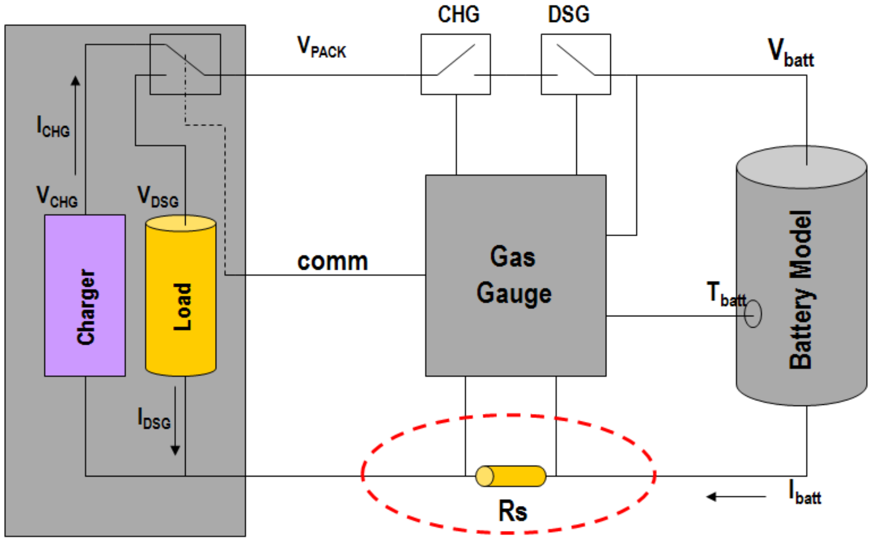
ISSUES:

- *25% granularity*
- *First bar lasts many times longer then subsequent bars*
- *No compensation for cell age*
- *Less run time*
- *Two bars represents over 50% capacity between 3.8 and 3.4 V*
- *Pulsating load varies capacity bar up and down*
- *Accurate ONLY at very low current*



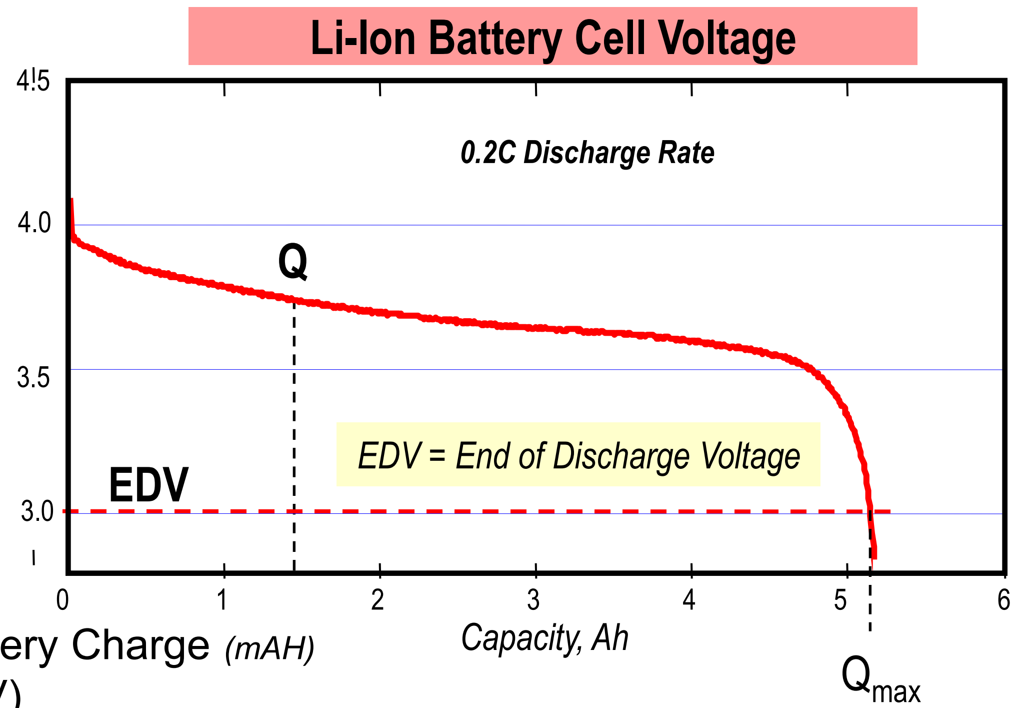
$$V = V_{OCV} - I \times R_{BAT}?$$

Gauging - *Coulomb Counting*



$$q_k = q_0 + \Delta t \cdot \sum_k I_k$$

- Measure and Integrates Charge
- Current sensed w/ resistive shunt



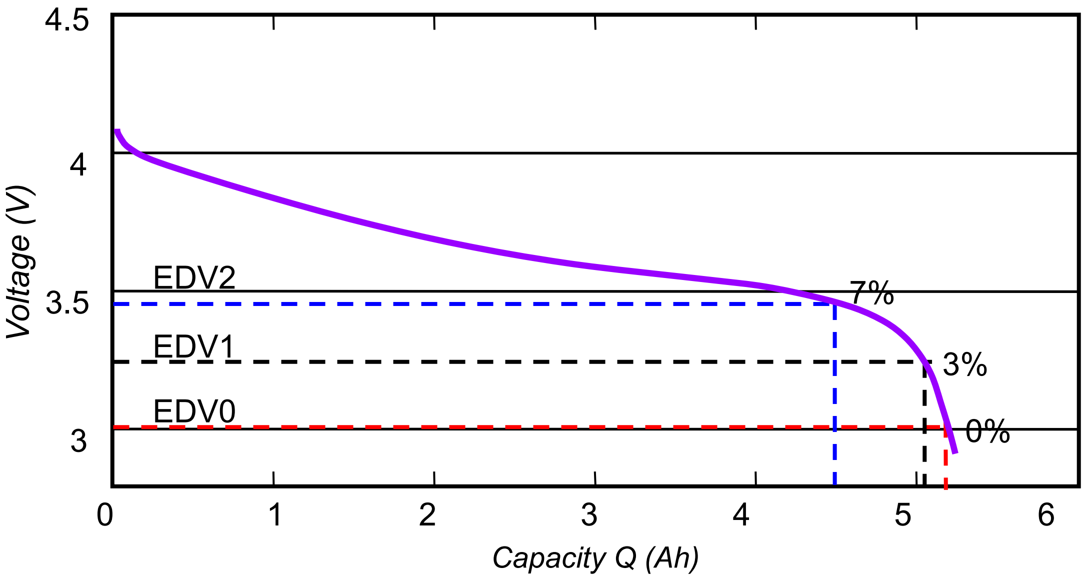
- Use this combined with OCV to relate battery Charge *(mAH)* to battery DOD (%) and battery Voltage (V)

ISSUE: Internal battery resistance is variable - cell impedance changes with…

- *Current*
- *Voltage*
- *Time*
- *Temperature*

Gauging

Coulomb Counting - *Learning before Fully Discharged*



ISSUES:

- Too late to learn when 0% capacity is reached
- How to learn if EDV thresholds aren't reached?
- A set voltage threshold for given percentage of remaining capacity
- True voltage at 7%, 3% EDV
  - *Remaining capacity depends on current, temperature, and impedance*

DISADVANTAGES:

- New full capacity must be learned over time *(full chg/dsg cycle)*
- Learning cycle needed to update Qmax
  - Battery capacity degradation with aging (Qmax Reduction: 3 – 5% with 100 cycles)
  - Gauging error increases 1% for every 10 cycle without learning
- End of discharge points not compensated
- Counting capacity out of battery doesn't tell how much the battery can still deliver under all conditions, needs capacity learning.
- Not suitable for high variable load current
- Uses processor resources for gauging computations

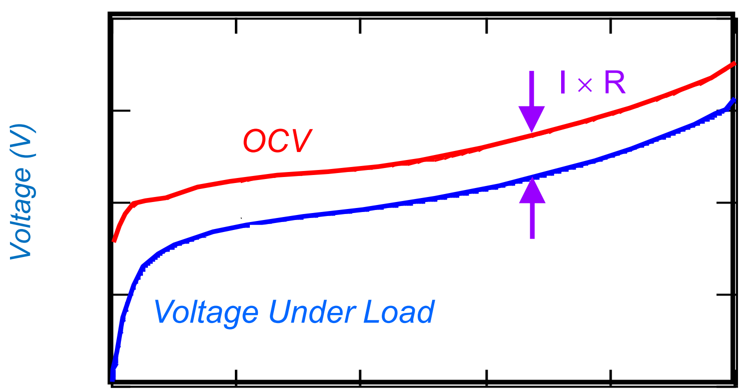
Gauging: *Impedance Track™ gas gauge*

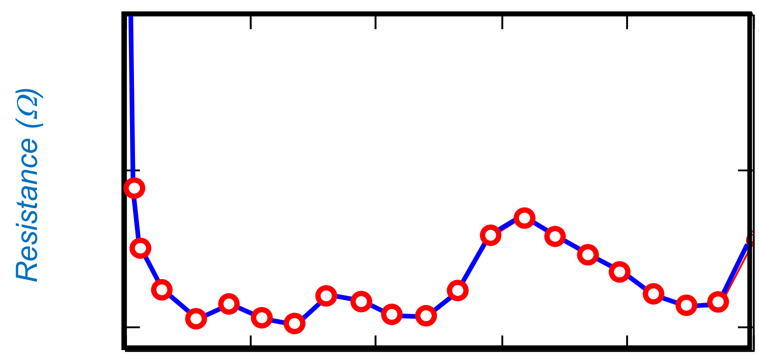
- Incorporates
  - *Voltage-based gauge: Accurate gauging under no load*
  - *Coulomb counting: Accurate gauging under load*
  - *Real-time impedance update*
  - *Remaining run-time calculation*
  - *Safety and State of Health*
- Updates impedance at every cycle

$$R_{BAT} = \frac{OCV - V_{BAT}}{I_{AVG}}$$

- Uses impedance, discharge rate, and temperature information to calculate rate/temperature adjusted FCC *(Full Charge Capacity)*

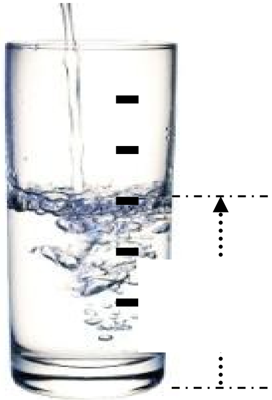
$$V = OCV(SOC, T) - I \times R_{BAT}(SOC, T)$$



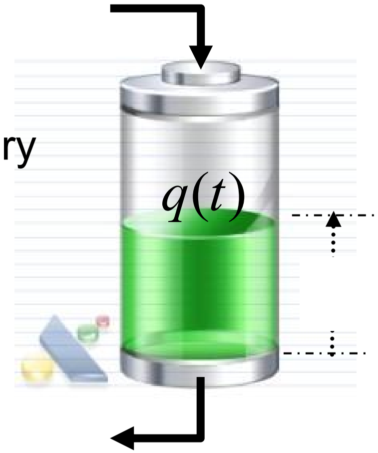


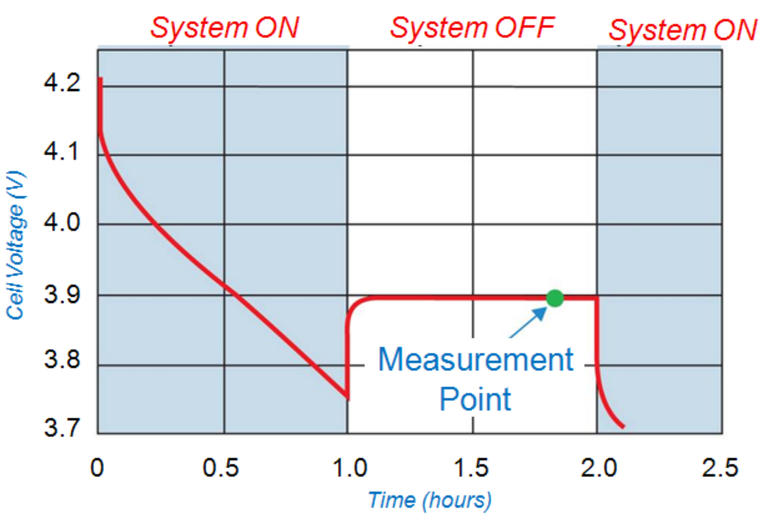
SOC (%)

Gauging: *OCV - Voltage lookup*



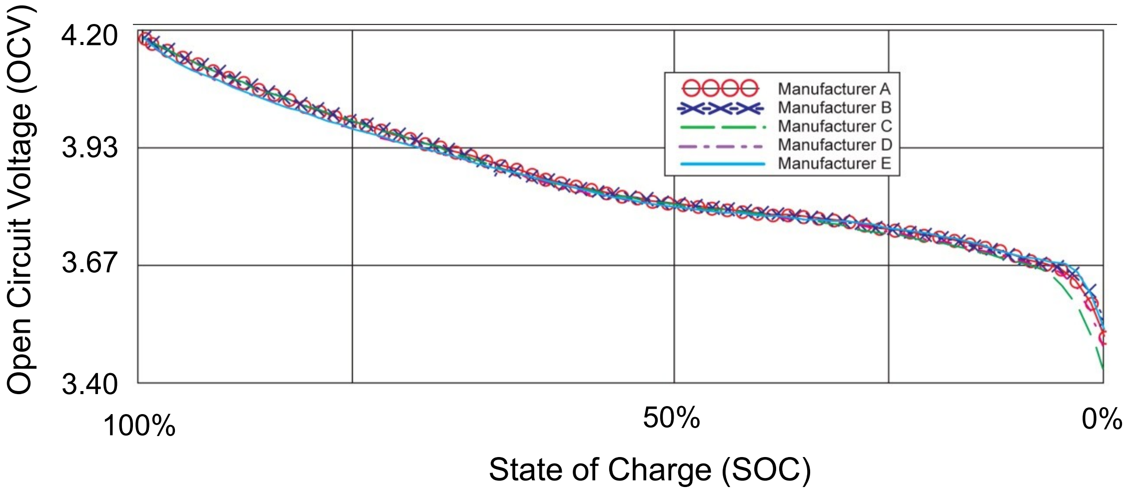
- One can tell how much water is in a glass by reading the water level
  - Accurate water level reading should only be made *after the water settles* *(no ripple, etc)*
- One can tell how much charge is in a battery by reading *well-rested* cell voltage
  - Accurate voltage should *only be made **after*** the battery is well rested *(stops charging or discharging)*

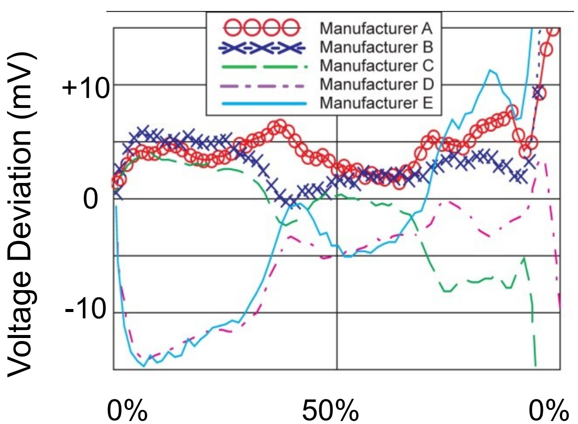


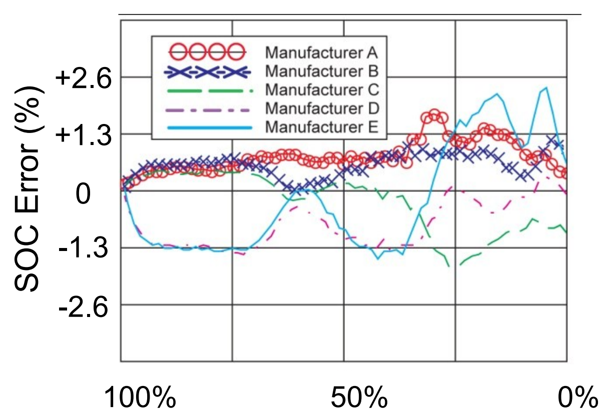


- OCV measurement allows SOC estimation
- Relaxation time varies depending on:
  - SOC,
  - Prior load rate
  - Temperature

Comparison of OCV Profiles for 5 Manufacturers

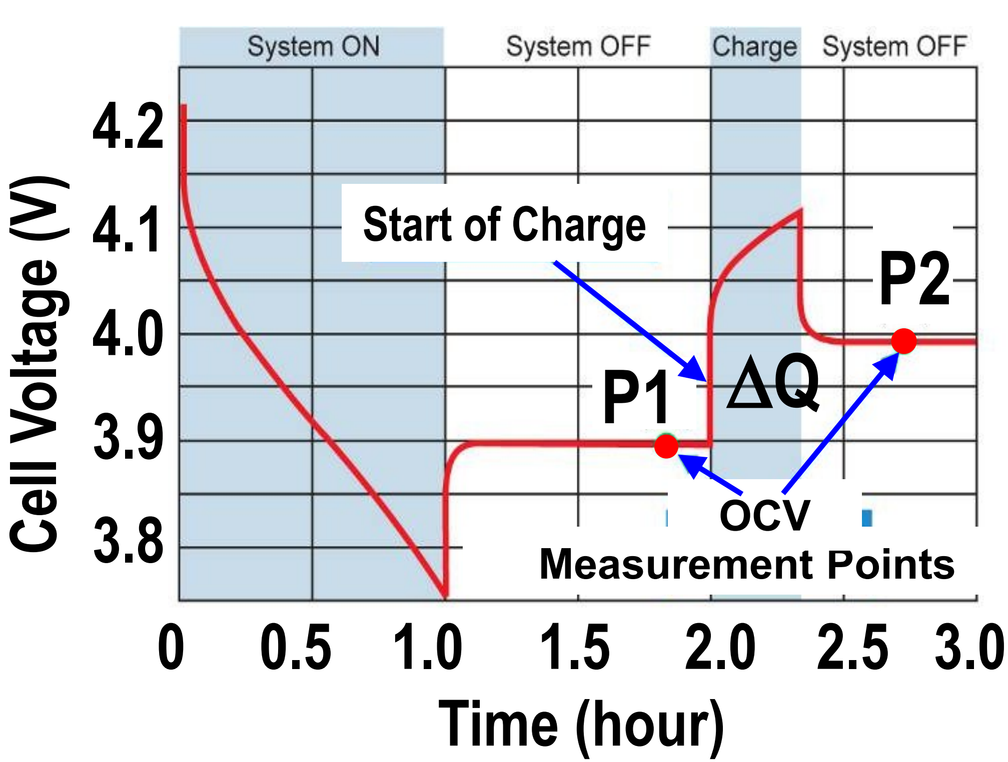


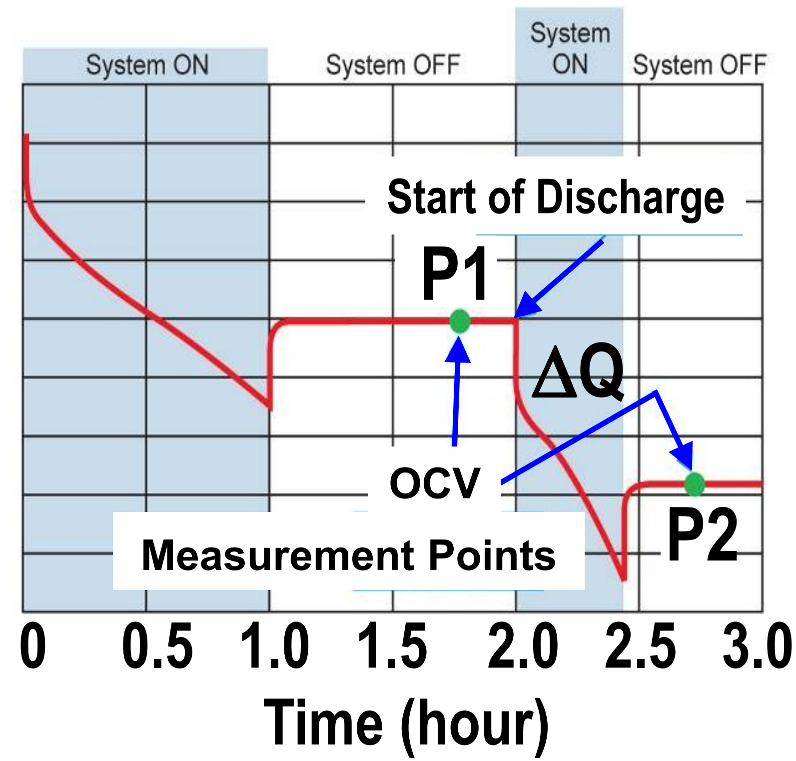




- OCV profiles similar for all tested manufacturers, <u>using same chemistry</u>
- Average SOC prediction error based on OCV – SOC correlation is about 1%
- Same database can be used with batteries produced by different manufacturers as long as cell chemistry is the same
- TI maintains OCV profile data for many different cell types (“Chemical ID” table)

Learning Q_{max} without Full Discharge





- Change in capacity (mAH) is determined by exact coulomb counting
- Relative SOC1 and SOC2 are correlated with OCV after rest period
- Method works for both charge or discharge

$$Q_{max} = \frac{\Delta Q}{SOC1 - SOC2}$$

Texas Instruments

WIRELESS POWER

Wireless Power Consortium (WPC)

Proprietary Solutions

Interoperability key to adoption

WPC

- Industry wide standard for delivering wireless power up to 5W
- Aimed to enable interoperability between various charging pads and portable devices
- Standard continues to gain traction with increasing list of members (105+)
- Compatible devices will be marked with a Qi logo

Power For A Wireless

Broad Industry Support

BEST BUY
BELKIN
COMPAL
Continental
DENSO
Energizer
Ever Win International Corp.
Haier
Johnson Controls
LG
MOTOROLA
NEC
NOKIA Connecting People
orange
Panasonic
PHILIPS
PRIMAX
RRC
SAMSUNG
SoftBank
Sony Ericsson
StanleyBlack&Decker
Texas Instruments
verizon wireless

and more…

Multiple Standards for wireless power…

- www.wirelesspowerconsortium.com
- http://www.powermatters.org
- www.a4wp.org

High Level Comparison

	WPC / Qi	PMA	A4WP
Coupling	Tightly Coupled	Tightly Coupled with magnet	Loosely Coupled
Operating Frequency	100 – 200 KHz	250 – 370 KHz	6.78 MHz
Communication Path	In-Band (signaling over the power path)	In-Band	BLE / out-of-band
System level Efficiency	> 70%	> 70%	TBD
Spatial Freedom	Medium	Lowest	Highest

47

Texas Instruments

Wireless power… why?

- **<u>Convenience</u> – end-users can charge multiple devices (camera, phone, tablet, headset, other accessories) on a common charging pad or table without carrying cables or adapters**

- **Users will not need to carry chargers while traveling!**

- **<u>Infrastructure</u> (charging stations) is needed in public places, offices, hotels, vehicles, to drive growth**
  - Compare to the growth of wireless LAN ~ 10 years ago

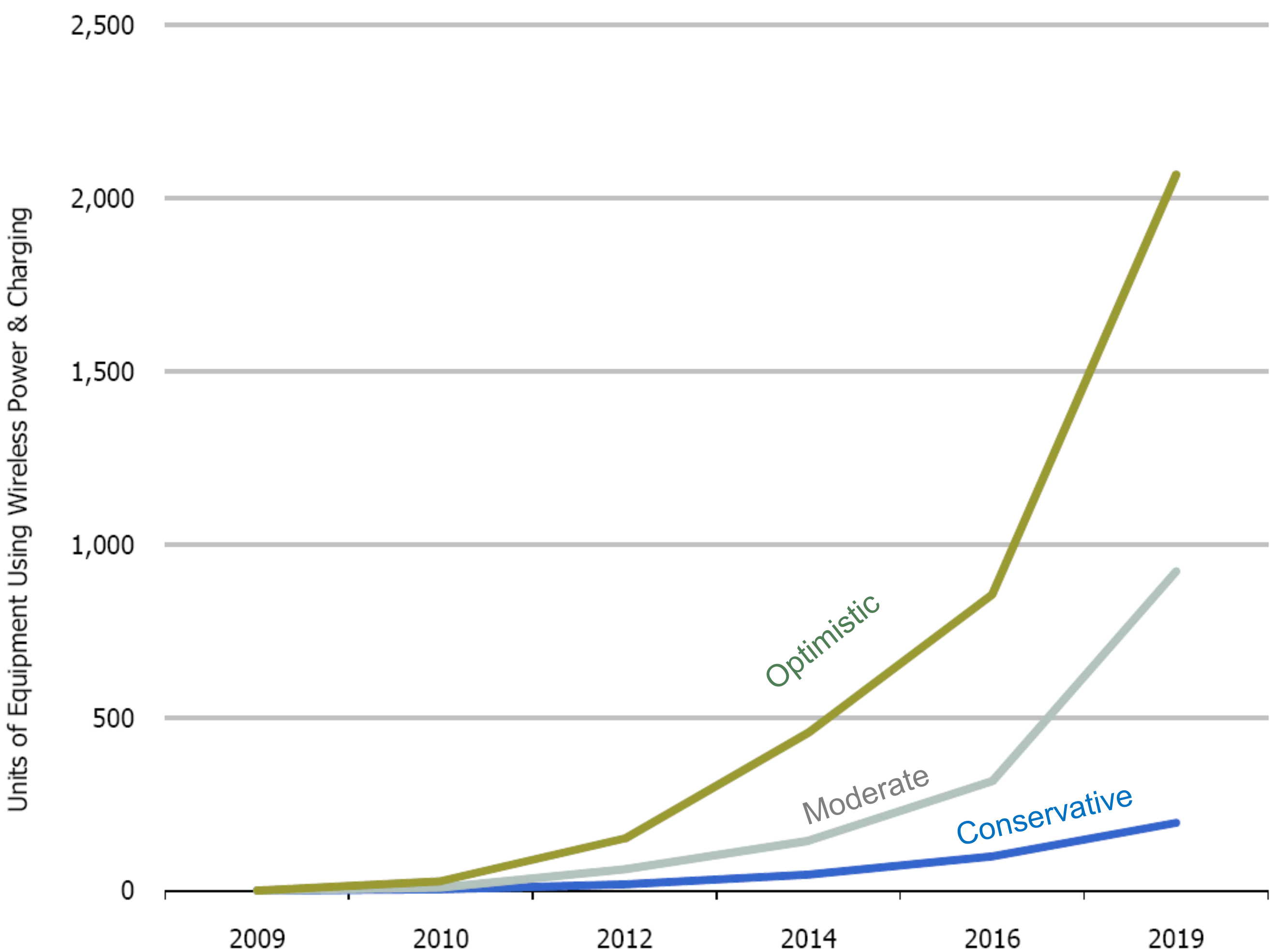
- **Longer term, wireless charging enables portability in other applications e.g. medical, wearable, that need to be sealed / waterproof**

48

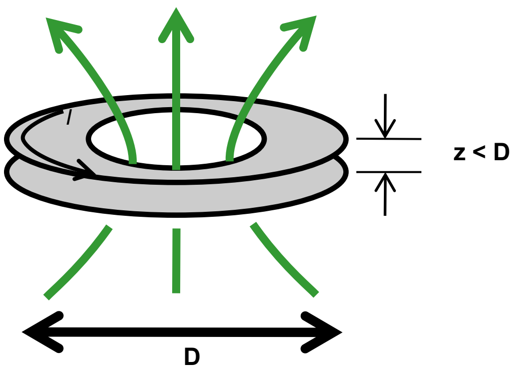
Market Forecast from 2010…

The World Market For Wireless Power & Charging

(Unit Shipments of Equipment Using Wireless Power & Charging - Millions)

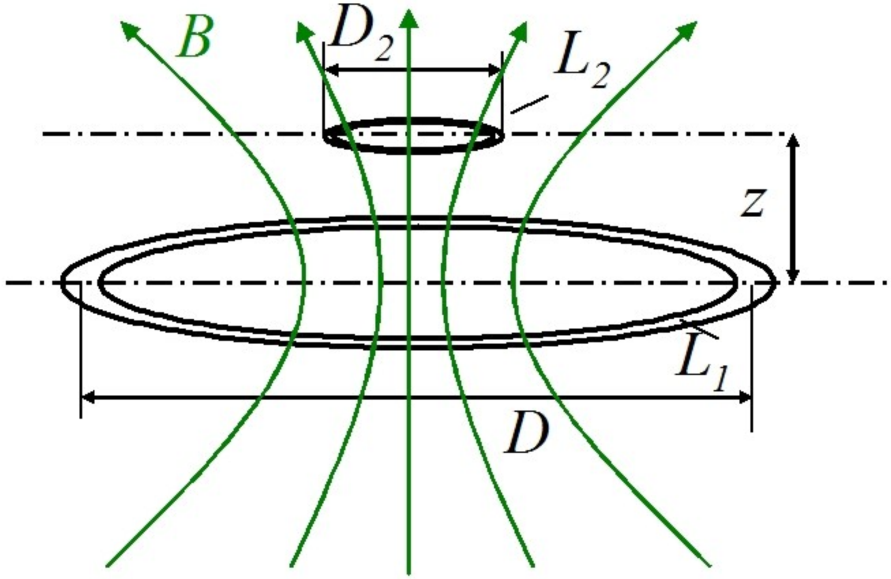


Qi: Intelligent Control of Inductively Coupled Power Transfer



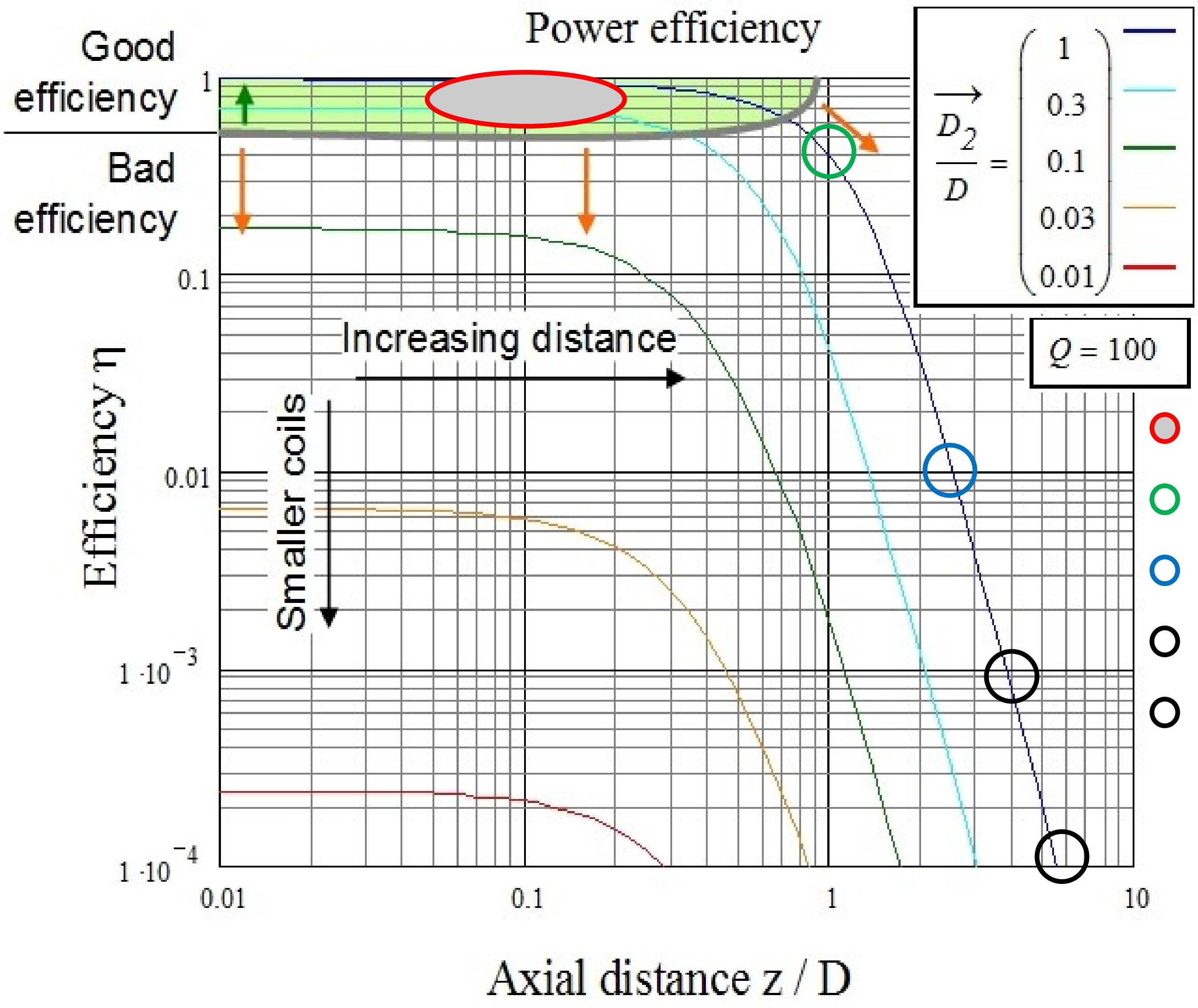
- **Power transmitted through shared magnetic field**
  - Transmit coil creates magnetic field
  - Magnetic field induces current in receiver coil
  - Shielding material below TX and above RX coils
- **Power transferred only when needed**
  - Transmitter waits until its field has been perturbed
  - Transmitter sends seek energy and waits for a digital response
  - If response is valid, power transfer begins
- **Power transferred only at level needed**
  - Receiver constantly monitors power received and delivered
  - Transmitter adjusts power sent based on receiver feedback
  - If feedback is lost, power transfer stops

Factors Affecting Coupling Efficiency



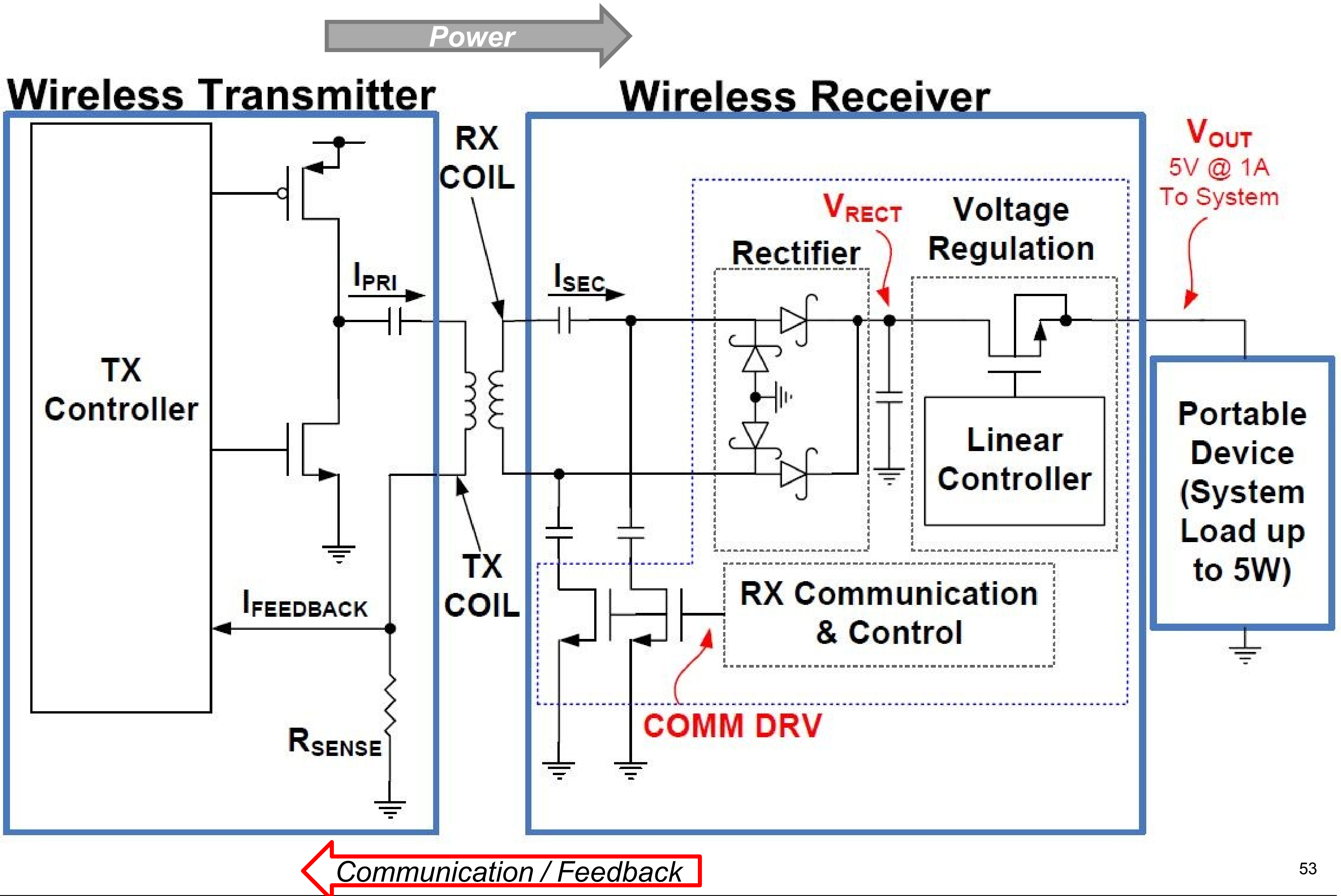
- **Coil Geometry**
  - Distance (z) between coils
  - Ratio of diameters (D_2 / D) of the two coils → *ideally D2 = D*
  - Physical orientation
- **Quality factor**
  - Ratio of inductance to resistance
  - Geometric mean of two Q factors
- **Near field allows TX to "see" RX**
- ***Good Efficiency when coils displacement is less than coil diameter (z << D)***

Factors Affecting Coupling Efficiency



- Optimal operating distance
- 40% at 1 diameter
- 1% at 2.5 diameters
- 0.1% at 4 diameters
- 0.01% at 6 diameters

bq50k + bq51K: Qi-Compliant Solution

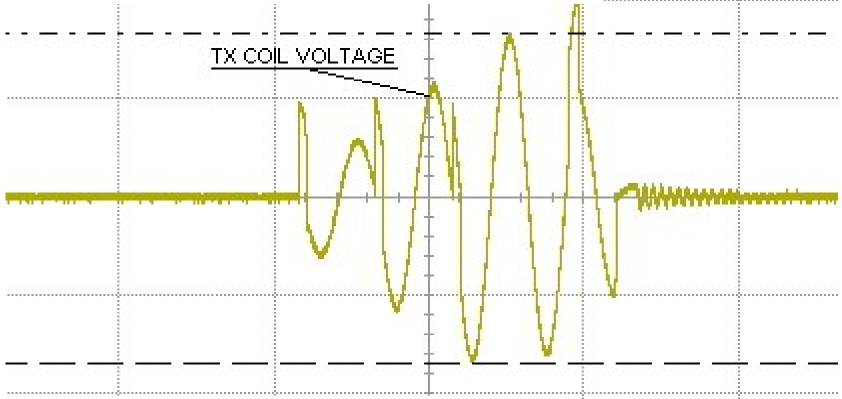


WPC Standard Communication - Basics

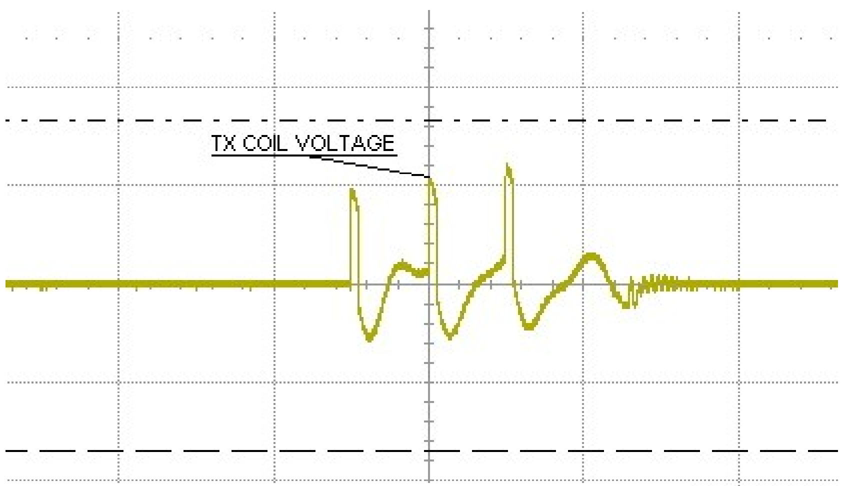
- **Primary side controller must detect that an object is placed on the charging pad.**
  - When a load is placed on the pad, the primary coil effective impedance changes.
  - "Analog ping" occurs to detect the device.
- **After an object is detected, must validate that it is WPC-compatible receiver device.**
  - "Digital Ping" – transmitter sends a longer packet which powers up the RX side controller.
  - RX side controller responds with signal strength indicator packet.
  - TX controller will send multiple digital pings corresponding to each possible primary coil to identify best positioning of the RX device.
- **After object is detected and validated, Power Transfer phase begins.**
  - RX will send Control Error Packets to increase or decrease power level
- **WPC Compliant protocol ensures interoperability.**

Analog Ping with and without object on pad

Vertical Scale: 20V/div
Horizontal Scale: 20 uS/div

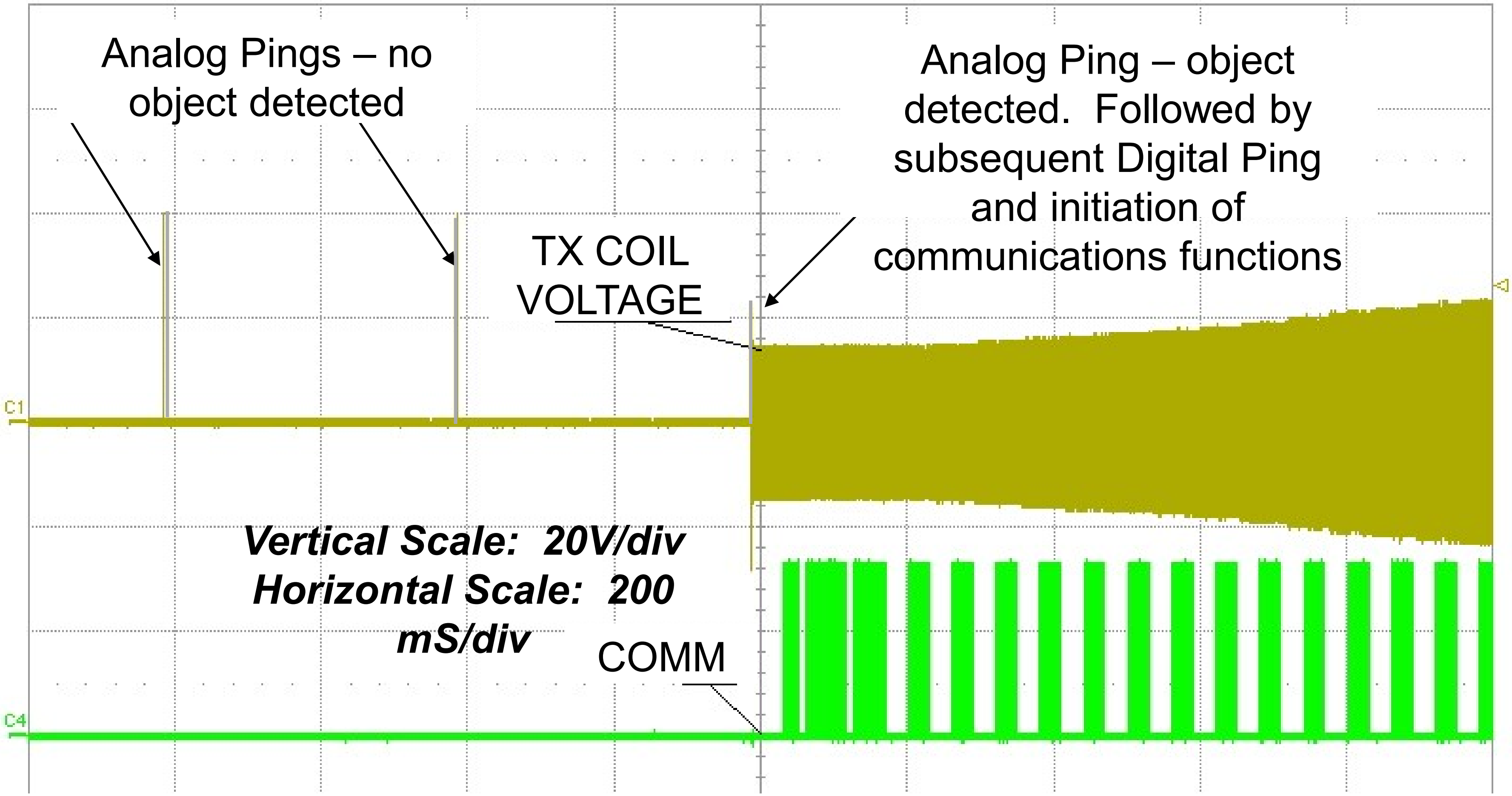


(a) No object on pad

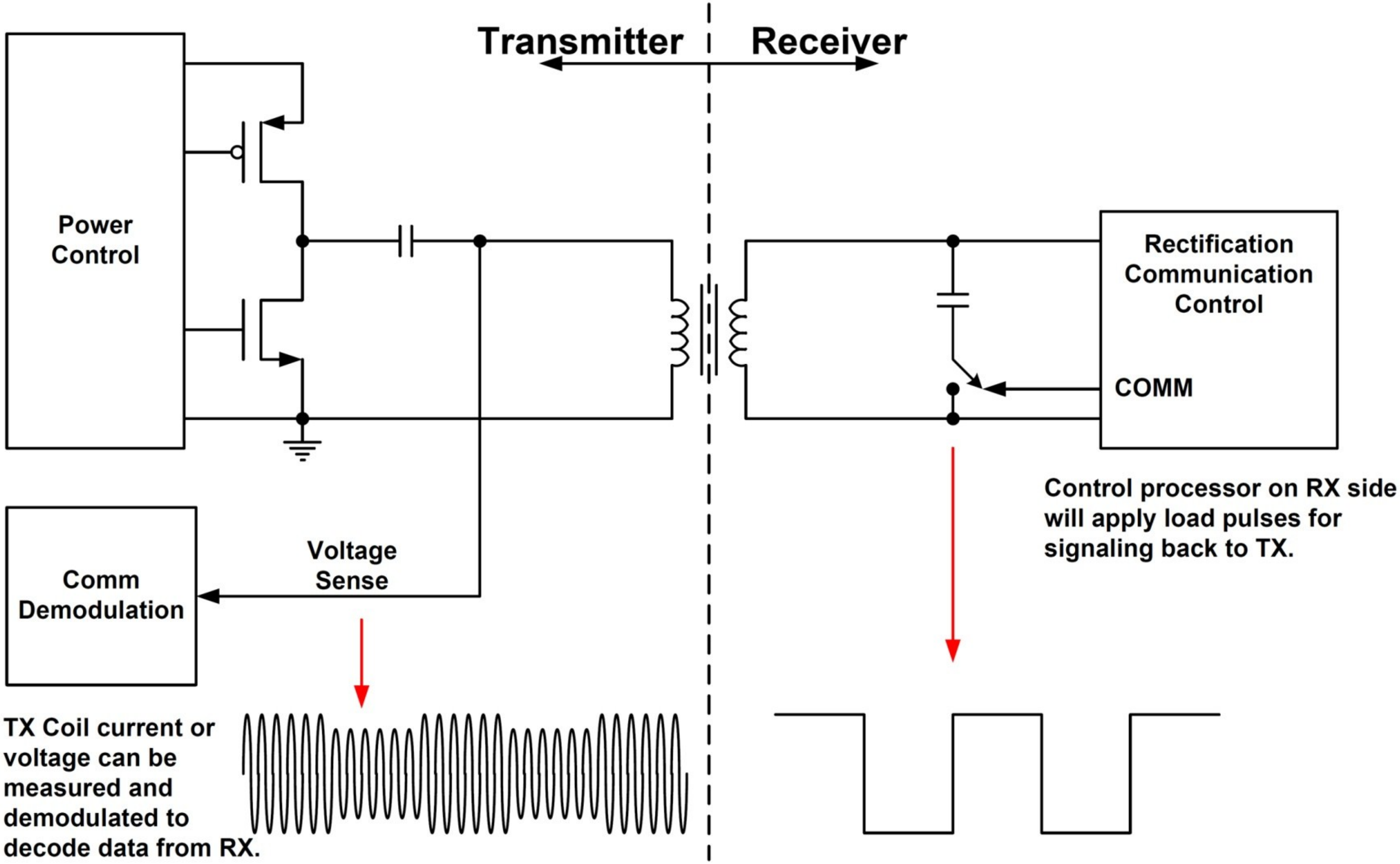


(b) RX Device placed on pad

Analog Ping / Digital Ping / Startup



Communication – How it works…

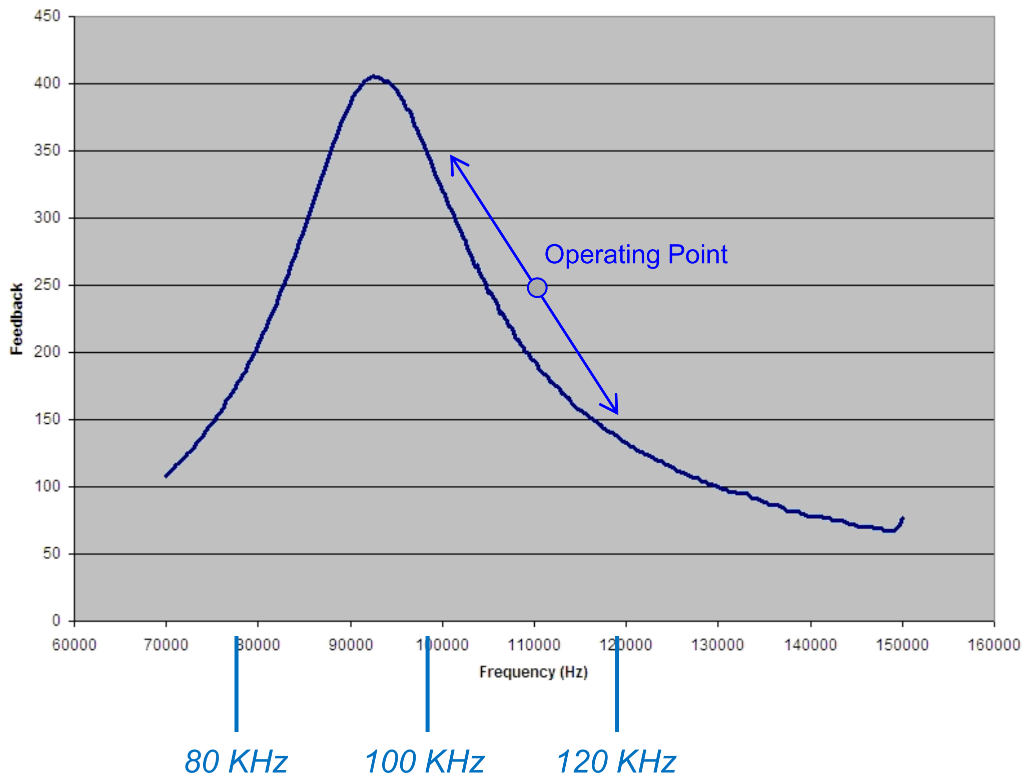


Control processor on RX side will apply load pulses for signaling back to TX.

TX Coil current or voltage can be measured and demodulated to decode data from RX.

Switching Frequency Variation

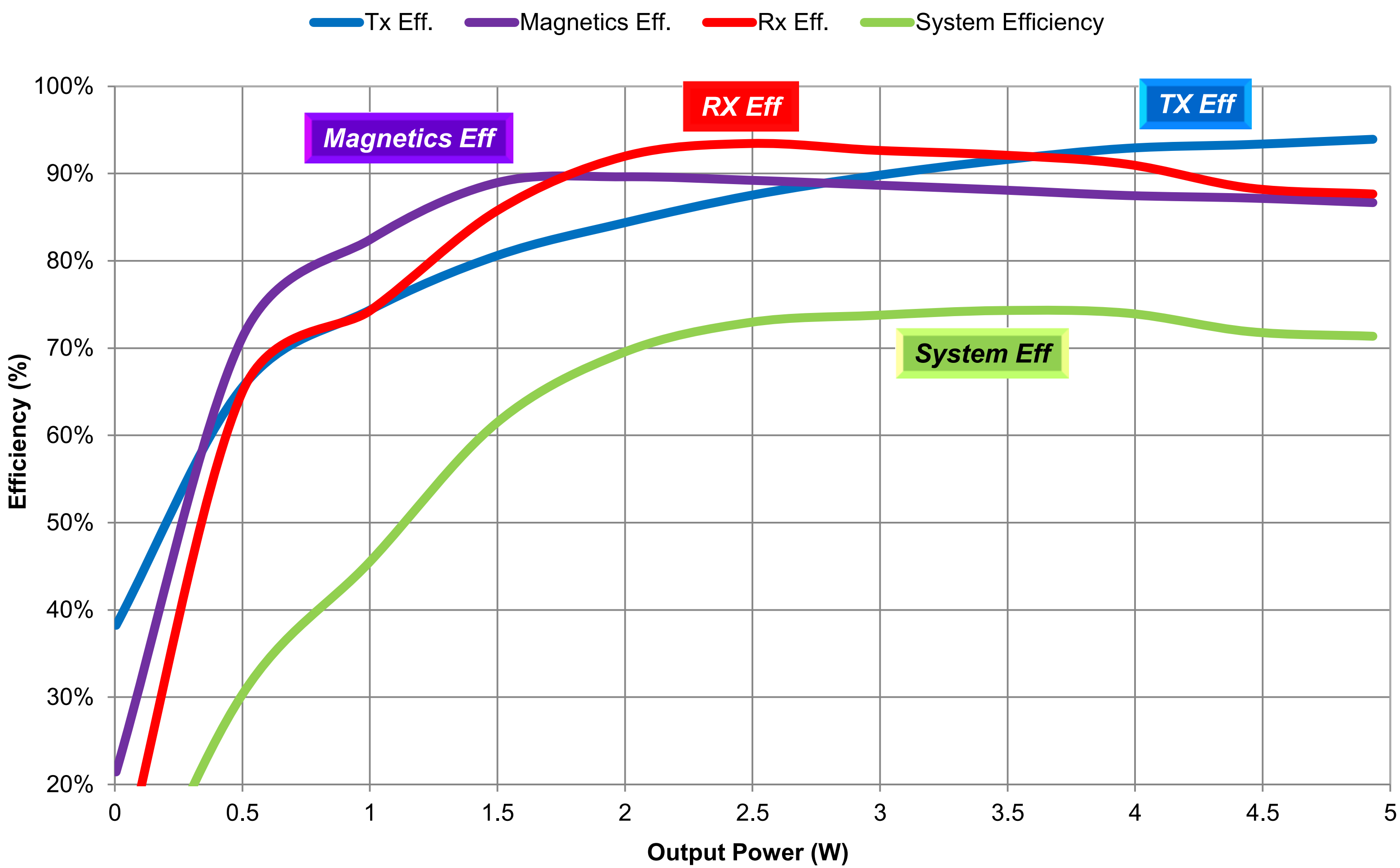
- System operates near resonance for improved efficiency.
- Power control by changing the frequency, moving along the resonance curve.
- Modulation using the power transfer coils establishes the communications.
- Feedback is transferred to the primary as error.



TEXAS INSTRUMENTS

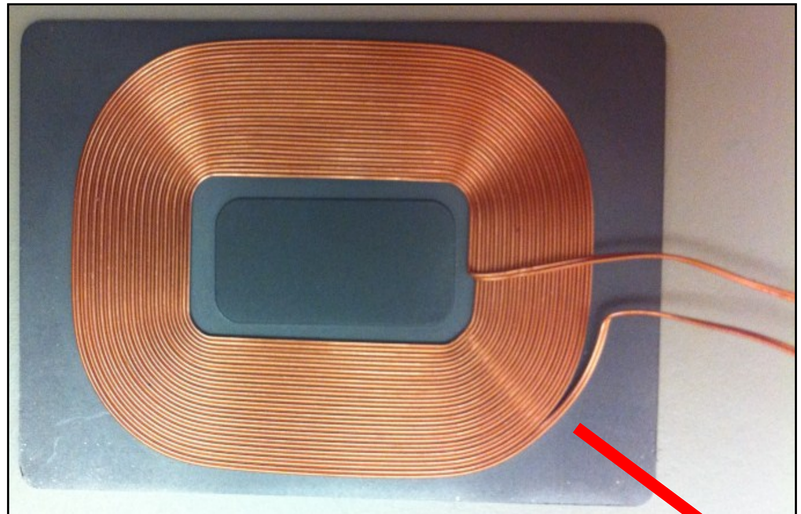
bqTesla System Efficiency Breakdown

Measured from DC input of Transmitter to DC output of Receiver



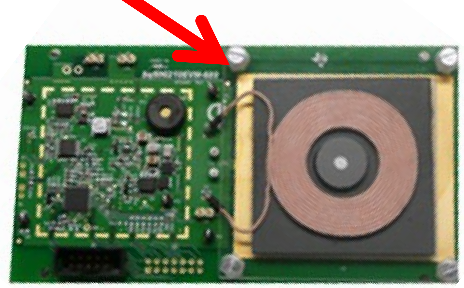
Qi-compliant coil used w/ EVM kit

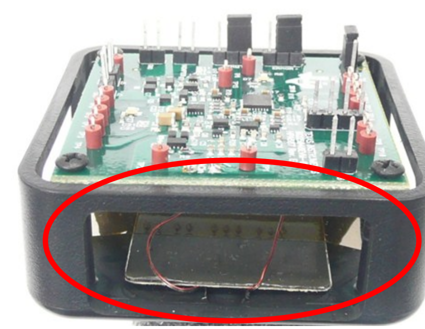
WPC Compliant Transmitter Coil

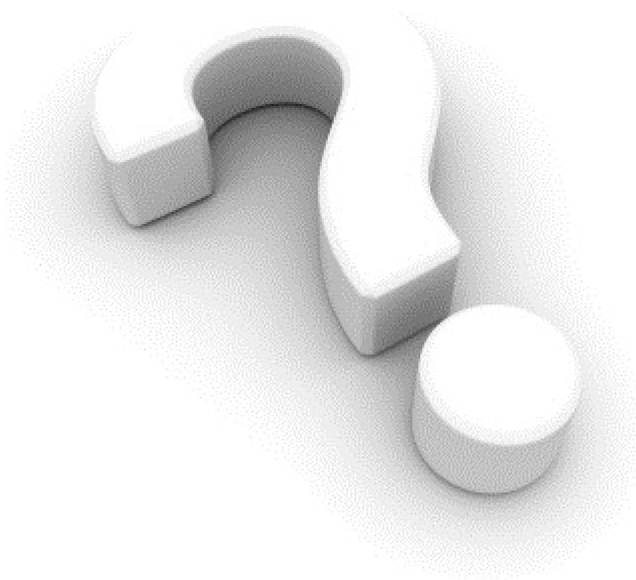


40-mm x 30-mm x 0.75-mm

WPC Compliant Receiver Coil







Questions