Building Battery Arrays with Lithium-Ion Cells

About the Sponsor

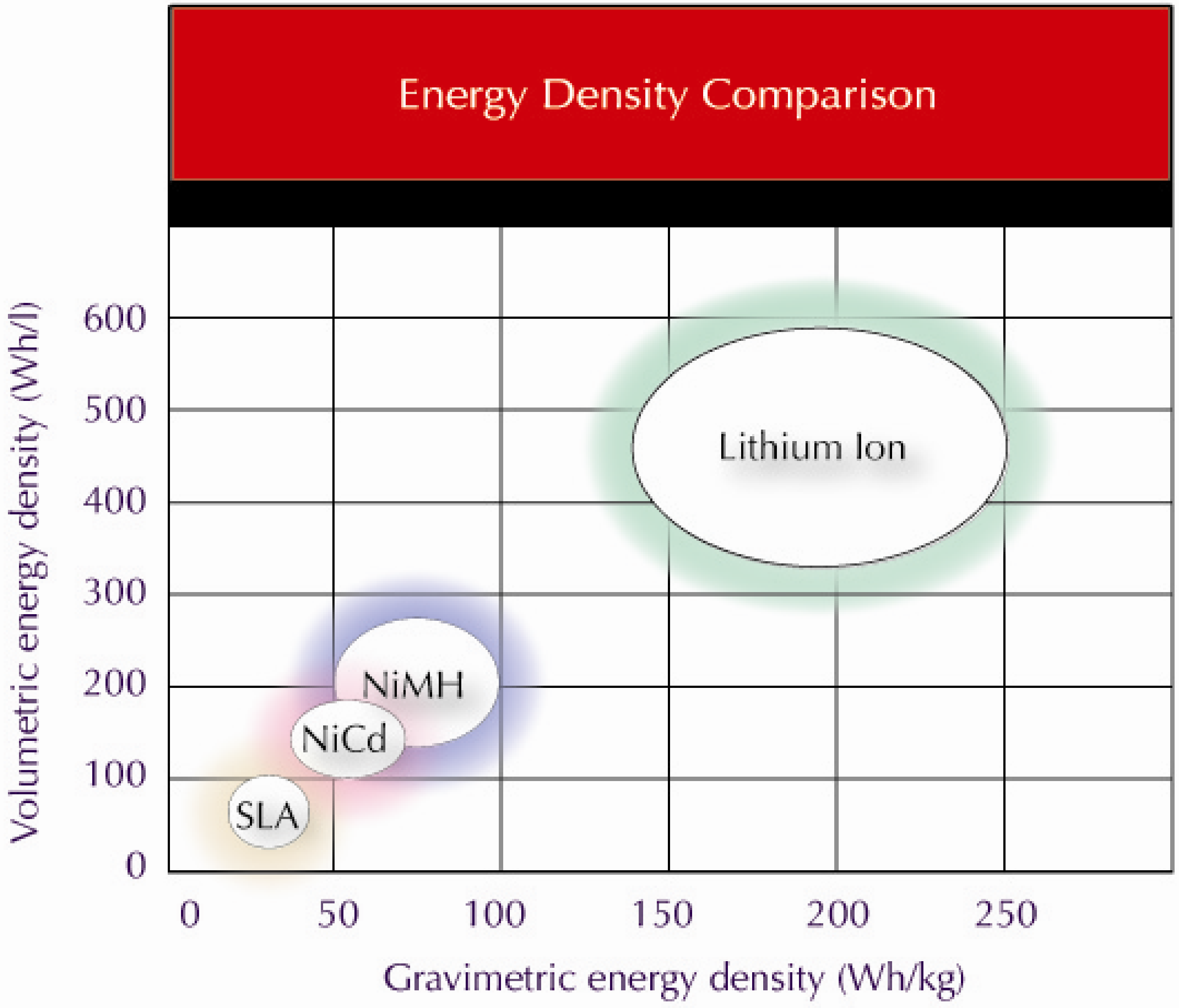
- Micro Power Electronics
  - Design and manufacture of lithium battery packs, chargers and power supplies for mission-critical applications
  - OEM Customers include leading medical, data collection, and military manufacturers of portable devices
  - 20+ years experience with over 1000 battery system designs
  - FDA Registered and ISO 9001:2000 and 13485 certified

Agenda

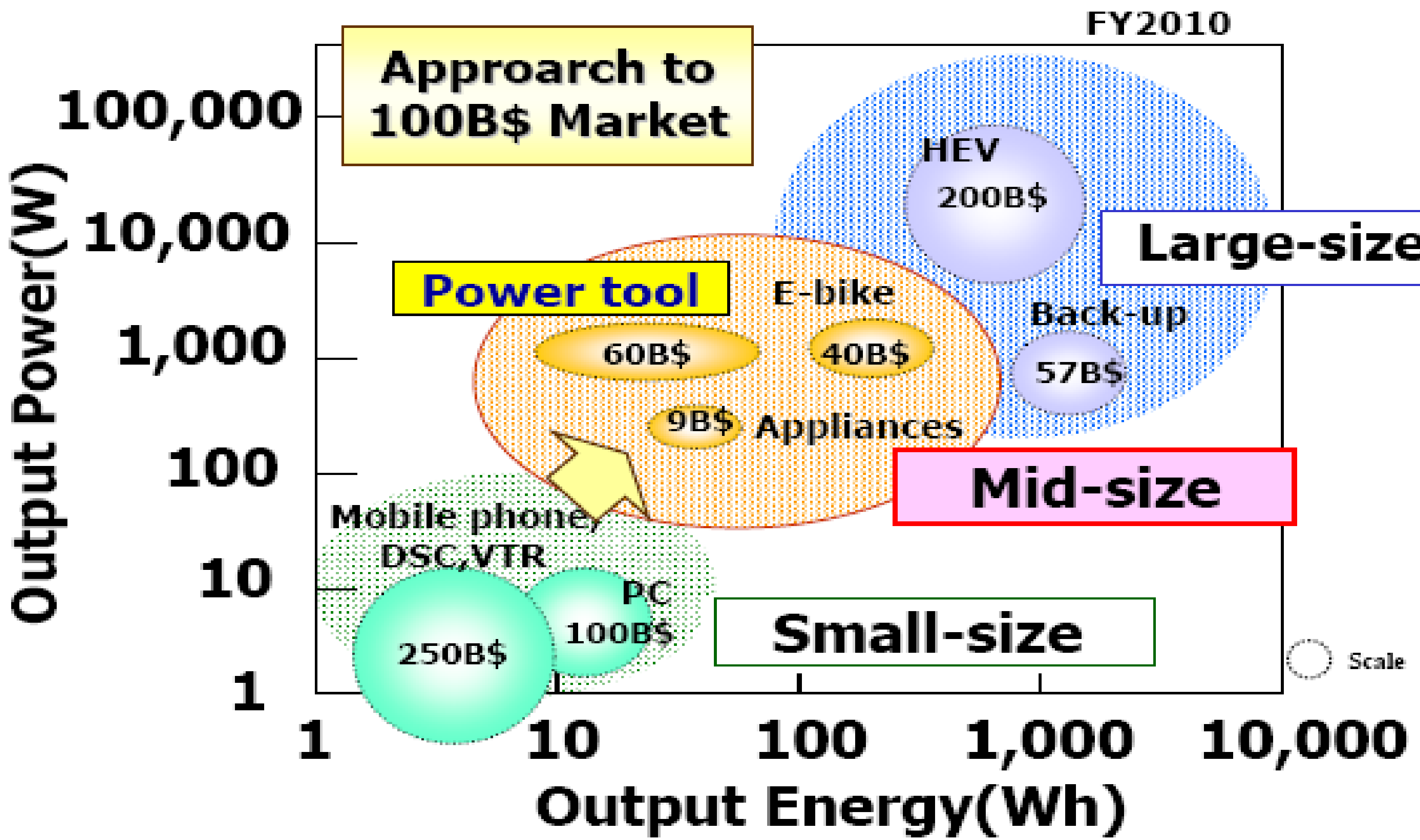
- Market drivers/applications for high-cell count battery packs
- Challenges to the designers of large arrays
- Technology solutions available
- Cell imbalance and TI’s solution
- Question and Answer

Introduction

- Li-ion desirable because of energy density and higher voltage
- Traditional applications require fewer than 12 cells
- Applications require high wattage and/or long runtime
  - High voltage (cells in series)
  - High capacity (cells in parallel)
- Issues arise in high cell count packs


Energy Density Comparison
Lithium Ion
NiMH
NiCd
SLA
Volumetric energy density (Wh/l)
0
100
200
300
400
500
600
0
50
100
150
200
250
Gravimetric energy density (Wh/kg)

Estimated Market Scale in Japan (FY2010)



Tesla Electric Vehicle Battery

Comparison of “Large Size” and Mid Size”

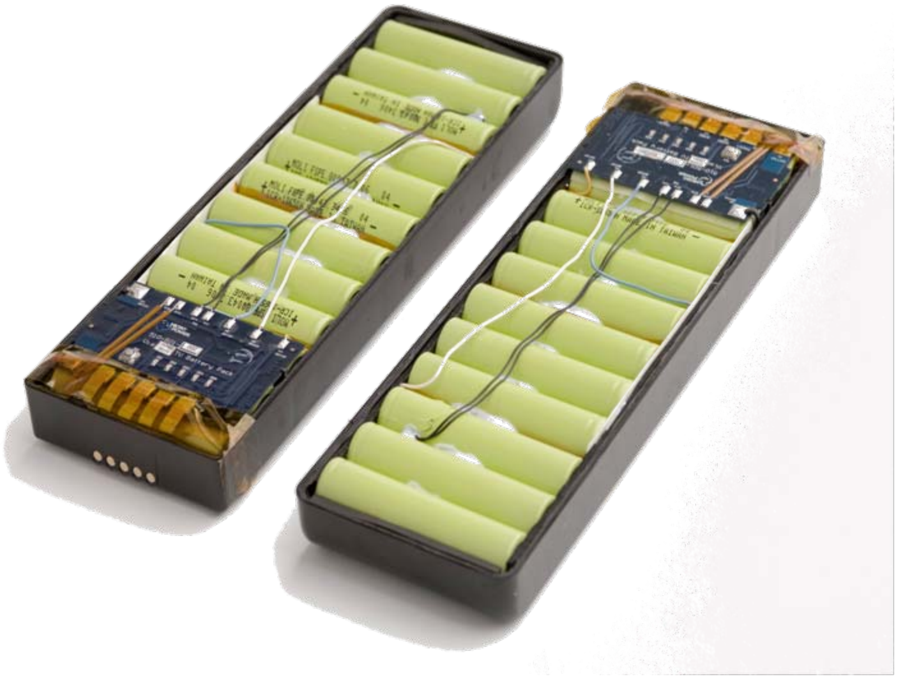
	Large: Electric Vehicle	Mid: Remote Monitor
Operating Voltage	375V	21.6V
Stored energy	53kWh 142Ah	0.33kWh 15.4Ah
Pack mass	450kg	~2kg
# 18650 cells used	6800	42
Topology	9s69p X11 modules	6s7p

Market Demand for Large and Mid Size Batteries with Li-ion

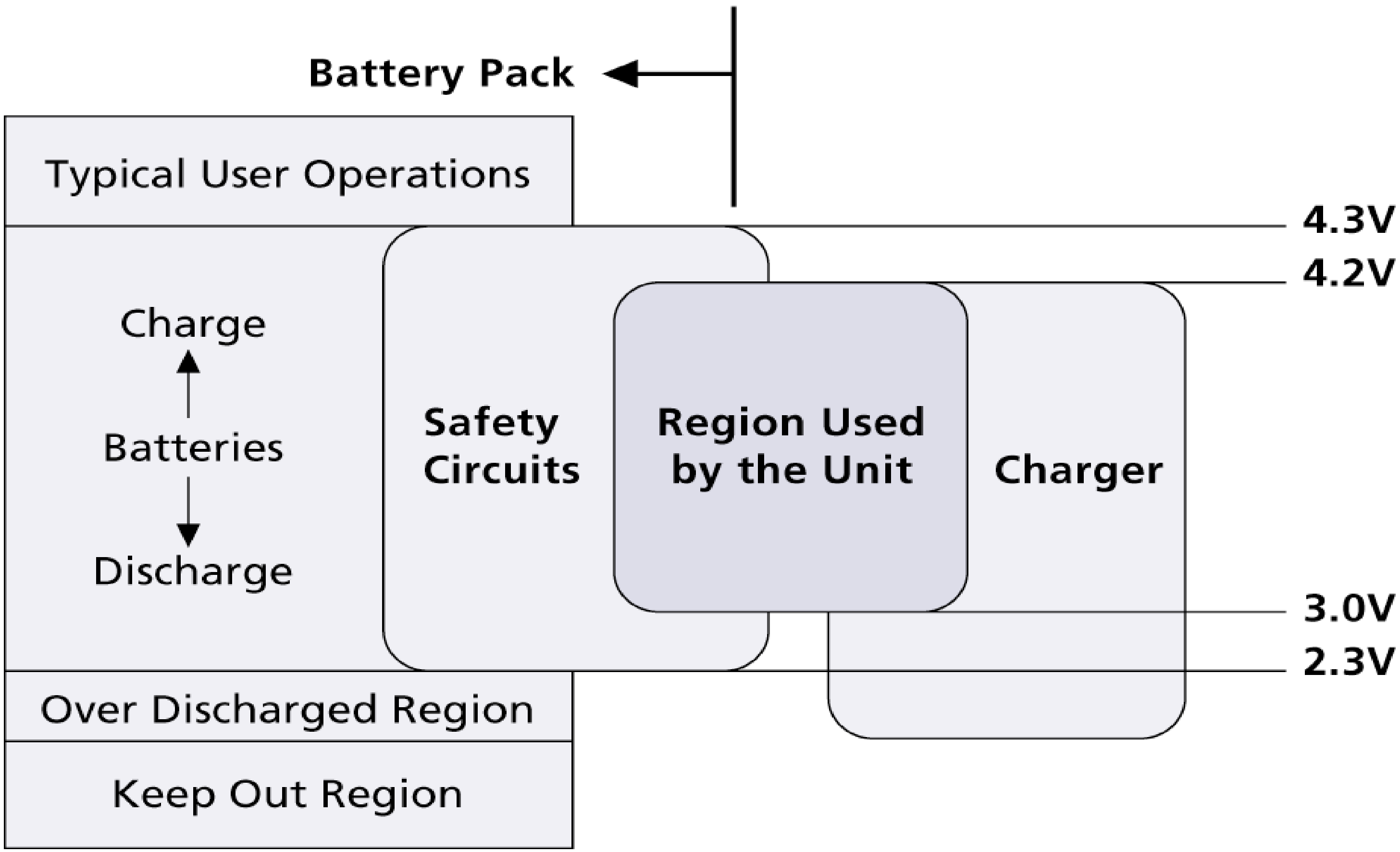
- Electric Vehicles
- Bikes
- UAV
- Powertools
- Lawn and garden equipment
- UPS
- Telecom backup
- Oil and gas exploration
- Automated CPR
- Ventilators
- Wheelchairs
- Oxygen concentrators
- Ventricular assist devices
- Intra Aortic Balloon Pump

Anatomy of a Portable Battery System

- Cells
- Circuit board
  - protection circuitry
  - fuel gauge
  - communications bus
- Insulation
- External contacts
- Vent holes
- Plastic enclosure



Safety Circuits for Lithium-Ion Batteries



Large Scale Battery Management: Challenges for high capacity

- Vendor Support
- Balancing
  - High current circuit design
  - Diodes- odd number of cells
- Fuel gauge limitations
- Shipping regulations

- Solutions:
  - Bigger cells
  - Modules
  - Heat sinks
  - Active cooling
  - Large ICs

Large Scale Battery Management: Challenges for high voltage

- Shipping
- Thermal management
- Cell matching
- Pack reliability
- Fuel gauging
- Cycle life
- Cell balancing

✓ For a given wattage high series is more effective than high parallel cell count

- Solutions for cell balancing and fuel gauging are new on market
- High voltage chemistries far off

Large Module Solutions

Thermal & Packaging Properties

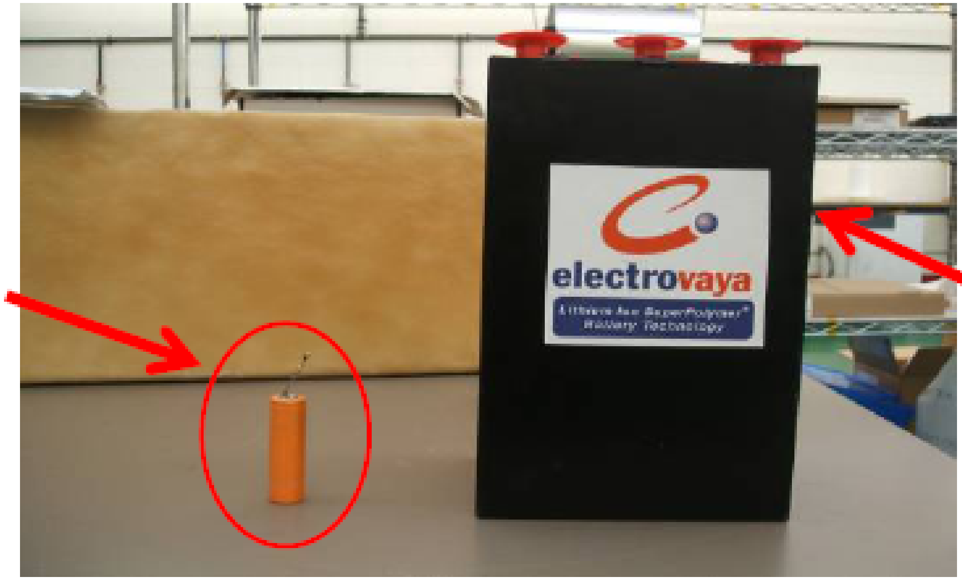
Cylindrical Wound Cells

- Hot spots
- Heat removal
- Metal Casing
  - Any pressure inside could cause a shrapnel explosion

Pouched, Prismatic Cell/Module

- Excellent Thermal Properties
- Key Safety Advantages

Scale-up Ease: 1.5 kWh Battery Module with Large Format cells



- The same 1.5kWh module
  - 166 (cobalt commercial)18650 cells
  - 356 (phosphate) 18650 cells.
- A 25KWh system would require
  - 2768 (cobalt commercial) 18650 cells
  - 5932(commercial phosphate) 18650 cells.

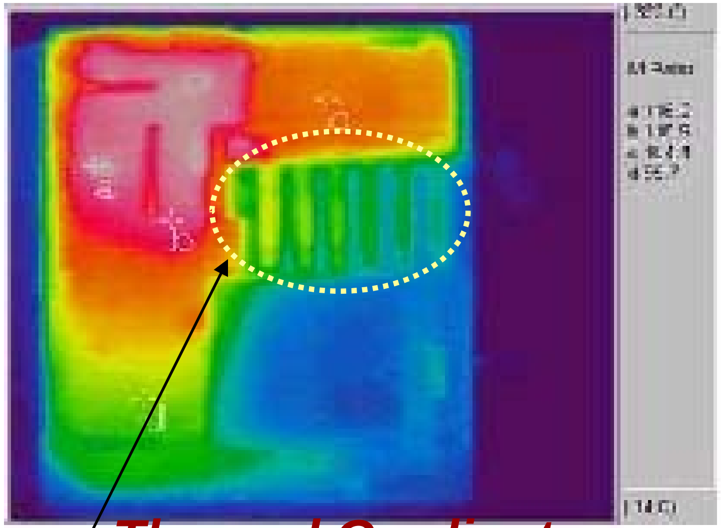
Cathode Materials on the horizon

Material	Nominal Voltage vs. Li	Specific Capacity mAh/g
$LiCoO_2$	3.7-3.8	~190 (Practical)
Li(NiCoMn)O2	3.7-3.8	>160
LiMn2O4	~3.8	~120
$LiFePO_4$	3.45	130-150
$LiFe_{1-x}M_xPO_4$	3.45	130-160
$Li_3V_2(PO_4)_3$	3.6-4.7	197
$LiVPO_4F$	4.2	155
$LiVPO_4.OH$	4.1	158
$LiVP_2O_7$	4.1	116
Li_2MPO_4F	4.7	143
Na_2MPO_4F	4.7	122
$Li_4V_2(SiO_4)(PO_4)_2$	3.6-4.7	260
$Li_3V_{1.5}Al_{0.5}(PO_4)_3$	3.6-4.7	203
β-$LiVOPO_4$	4.0	159
$NaVPO_4F$	3.7	143
$Na_3V_2(PO_4)_2F_3$	3.7	192

✓ **Electrolyte window is fundamental limitation**

Causes of Cell Imbalance

- Poor Cell Capacity Matching
- Impedance Variations
- Heat – Self discharge doubles for each 10º C rise
- Non-Uniform Thermal Stress
- Non-Uniform Electrical Loading of Pack
- Chemical Efficiency Variations
- High discharge rates



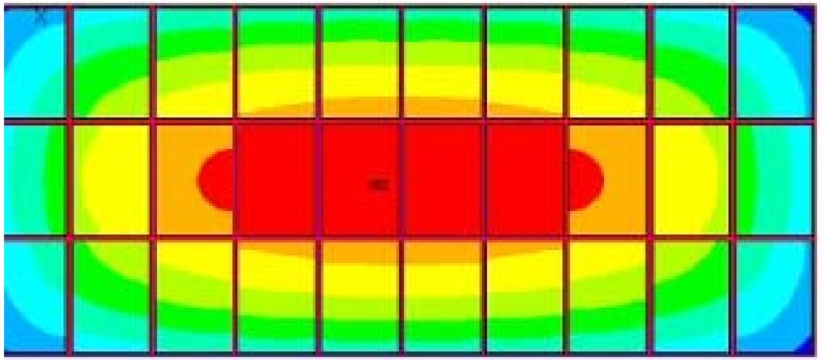
Thermal Gradients

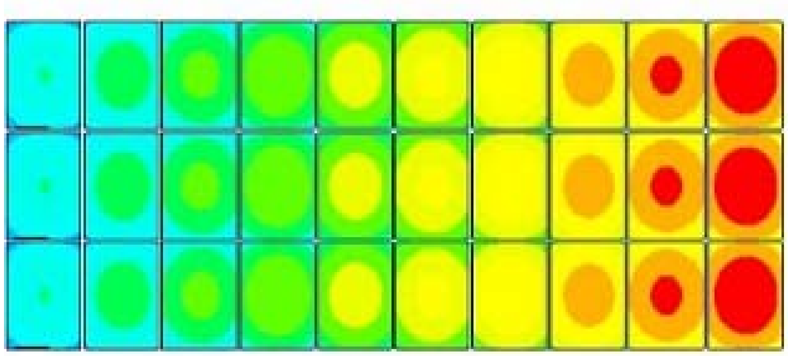
Pack Imbalance

This IBM ThinkPad™ 600 shows peak base temperatures of 116.6°F (pink/grey), & significant areas above 100°F (orange).

High-Cell Count Imbalance

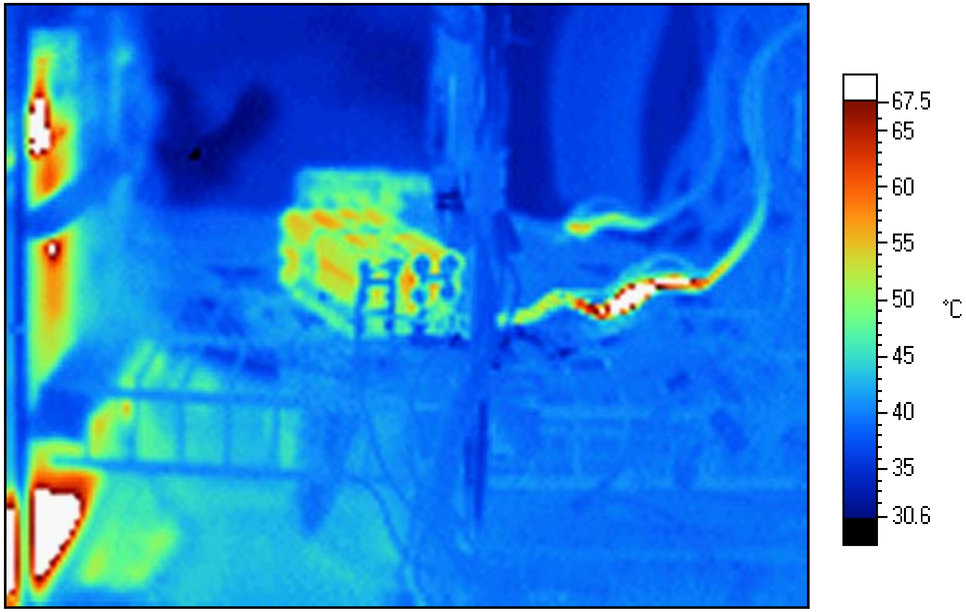
- Temperature Becomes a Greater Factor:
  - Gradients Are Larger
  - Physical Cell Arrangement Can Influence Temperature
  - High Rate Charge/Discharge

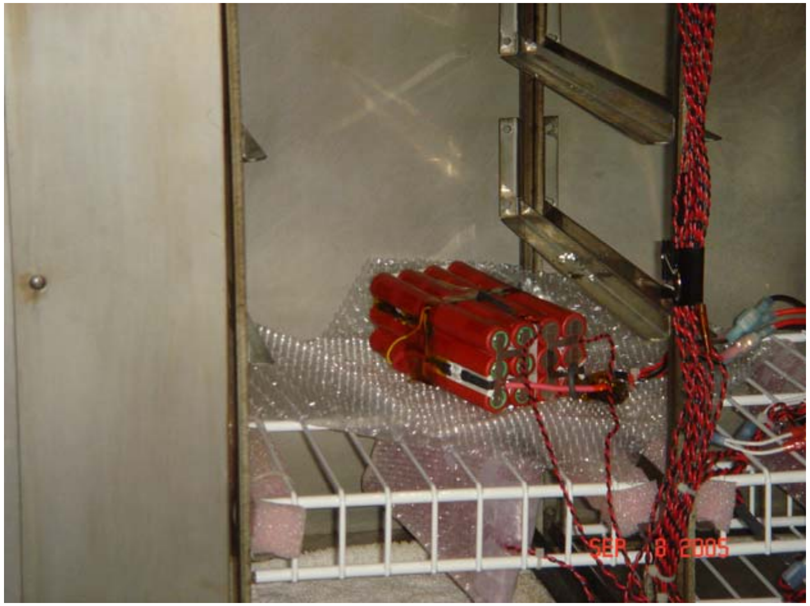




Prismatic HEV Cell Array
Top: Cooling Fan Failure
Bottom: Left to Right Low Flow Cooling
(Images copyright/courtesy NREL)

Real Thermal image 4s6p 2.4Ah



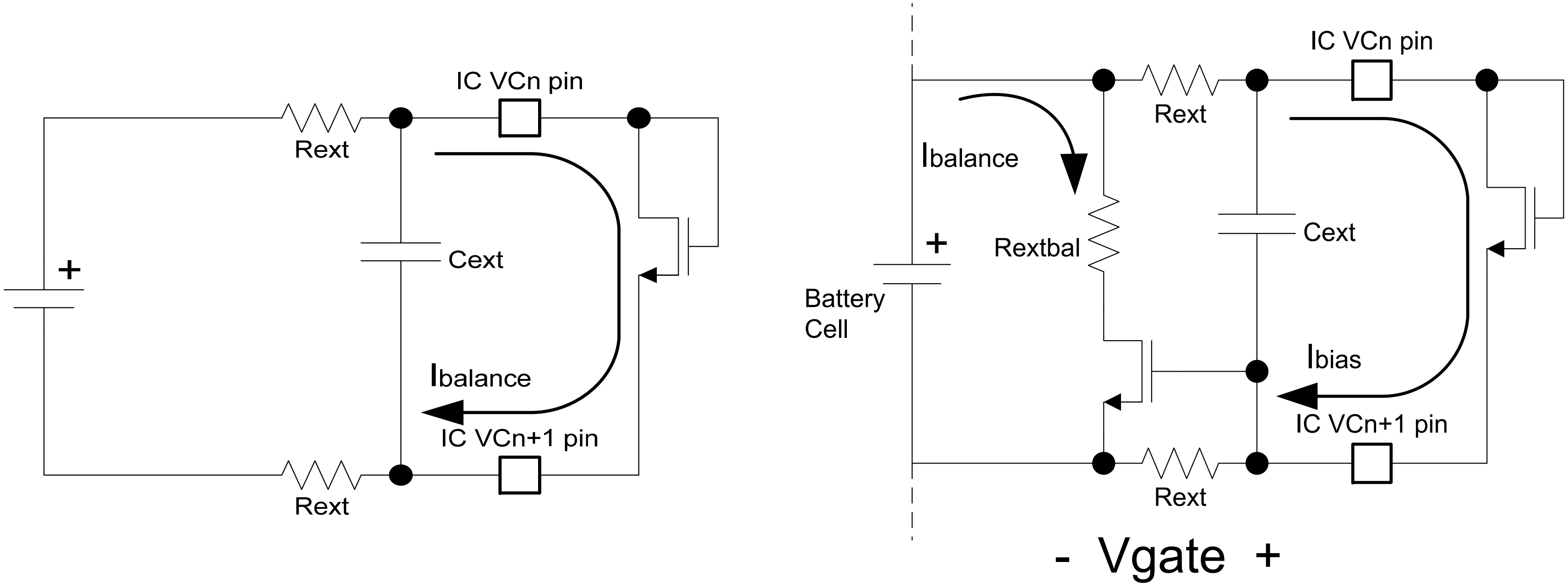


Texas Instruments
Cell Balancing Strategies

Cell Balancing Techniques

- Purpose
  - Deliver as much energy during discharge as possible.
  - Extend cycle life of battery pack
- Two Techniques
  - Bleed or Bypass : providing alternative current path to a cell that is out of balance to other cells in series
  - Active or Charge Redistribution : moving charge from higher charged cells to lower charged cells in series

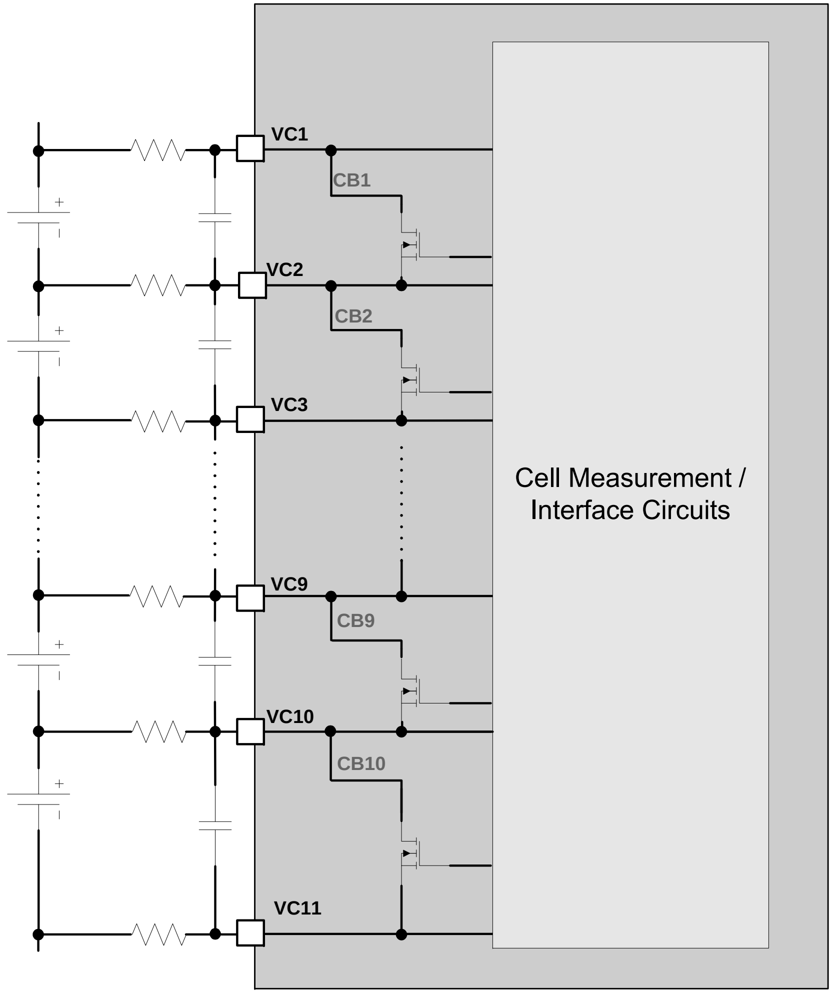
Internal Cell Balancing – Charge Cycle



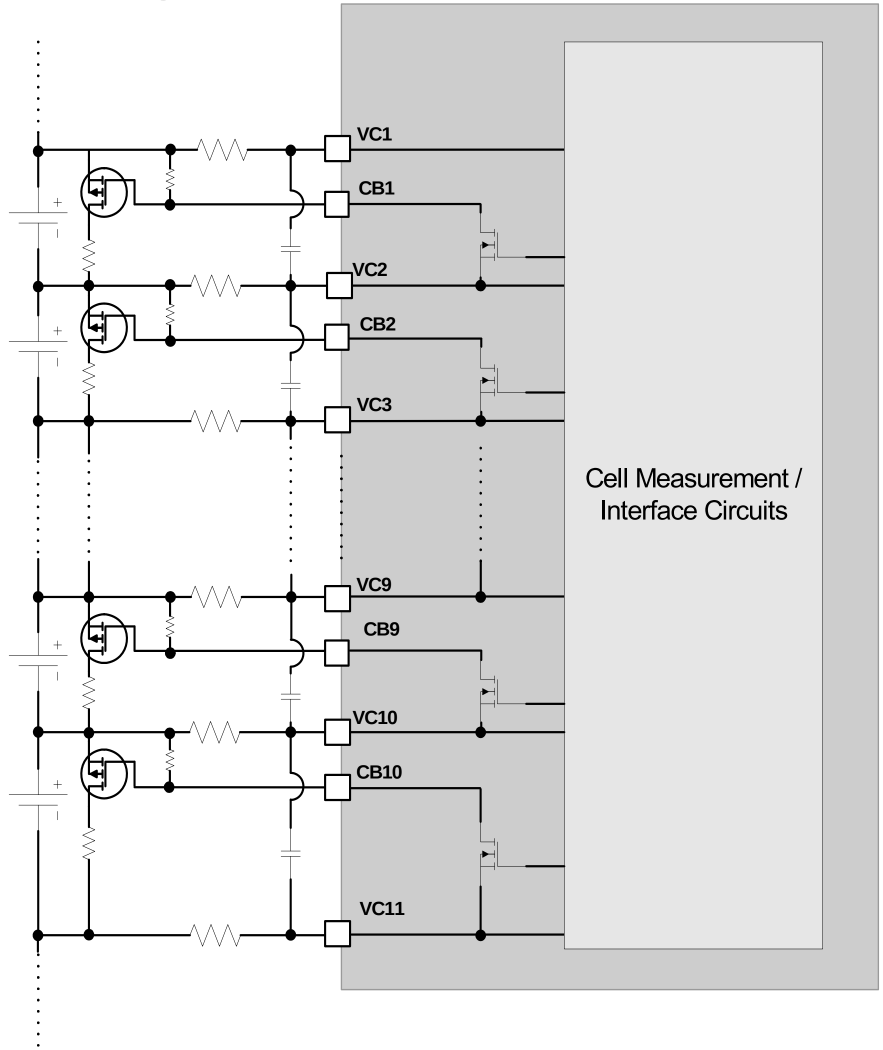
- **Limit to internal FET capacity**
- **10 - 200 mA per datasheet**
- **Real value based on thermals**

- External MOSFET can be controlled by the state of the integrated FET
- Higher bypassing current is achieved due to low Rdson of the external FETs
- Gate voltage is limited by resistance across the “lower” Rext (Rvcx)

10 Series System 50mA



10 Series System 200mA



Bypass Balance Review

- Ends of OCV curve makes largest difference
  - Recommended to balance during charge cycle
- Duty cycle limitations
- Amount of energy moved is limited to by time, temperature and current
- Cost of high current resistors & low ohm FETs
- Energy conservation vs energy stored/delivered
- Thermally challenging at high temp portions of pack life

Charge Redistribution Cell Balancing

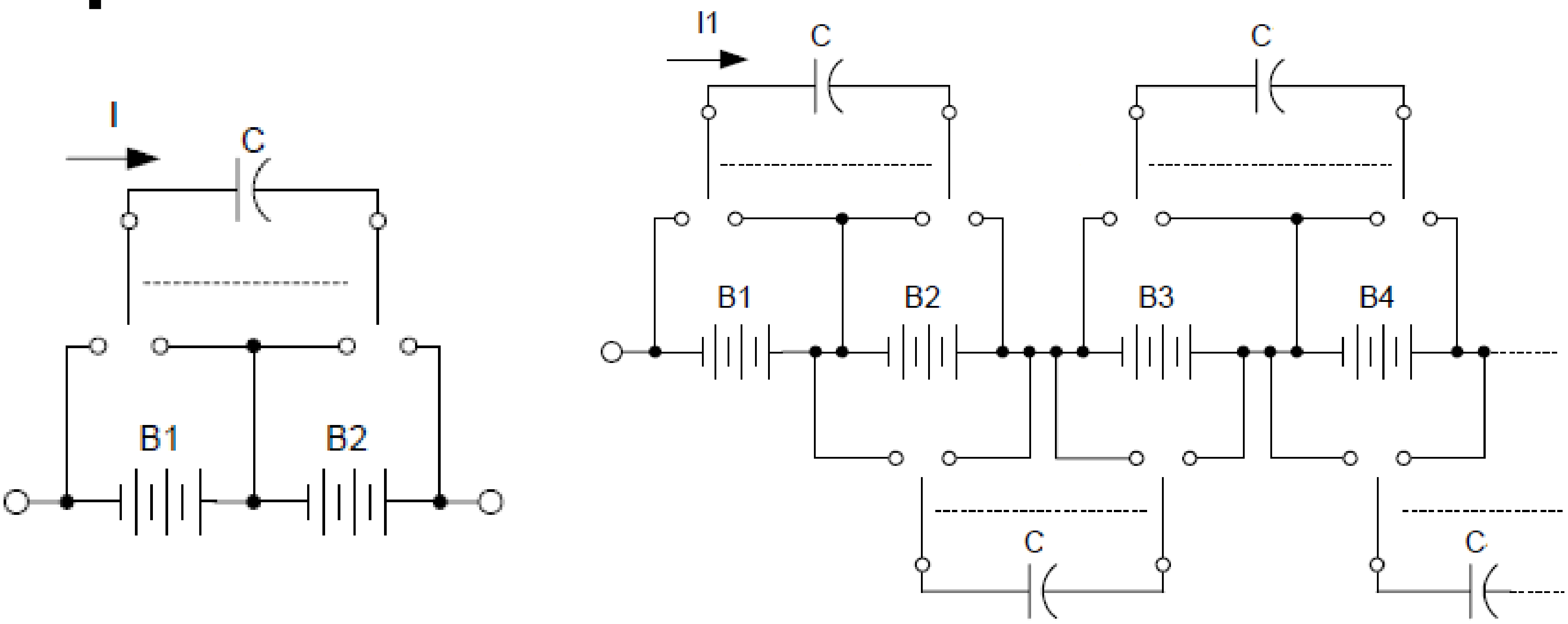
Basics

- Energy transfer between adjacent cells
- Move energy where and when its needed to minimize global imbalance
- Current path is outside of charge / discharge path
- Can be implemented during charge, idle and discharge periods

Topology Choices

- Capacitive – switch capacitor across higher cell to lower cell
- Inductive – store energy from higher cell before delivering it to lower cell

Capacitive Redistribution

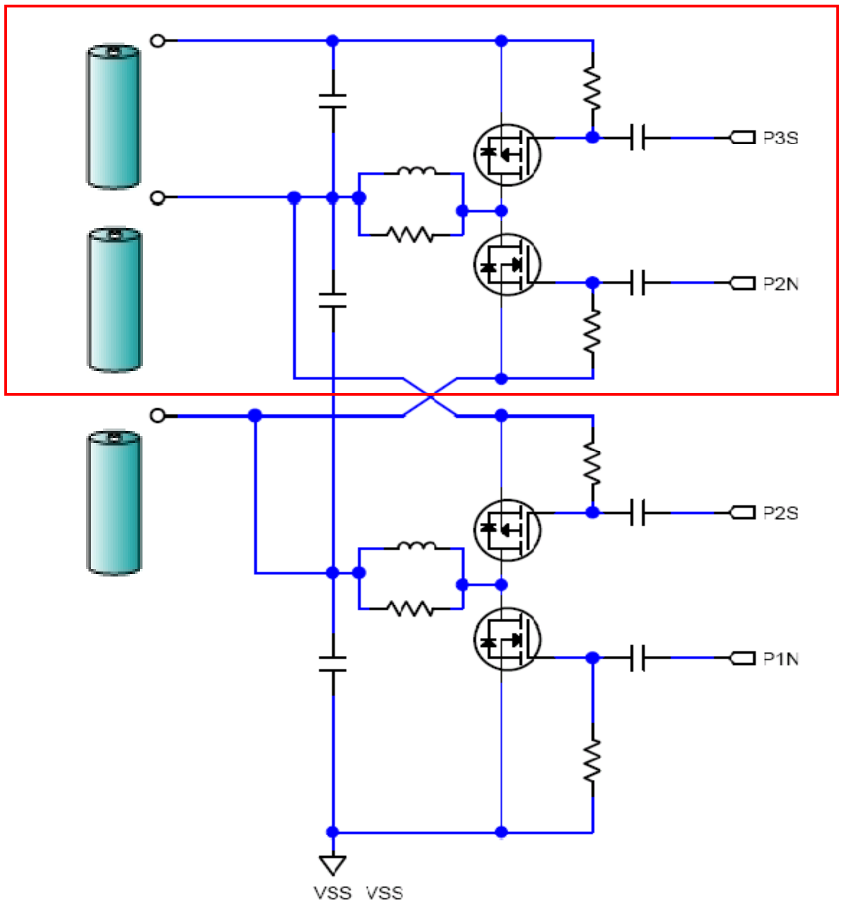


- Simple higher voltage to lower voltage measurements and shuttle
- Maximum 50% efficiency
- High voltage differences only happens at ends of cycle
- Bidirectional energy movement

Inductive Redistribution

- FET Capacitor and inductor used to create a mini dc/dc boost converter
- Bi-directional transfers energy efficiently between adjacent cells
- “Bucket brigade” allows redistribution anywhere in pack
- Move energy where and when it is needed to minimize global imbalance
- Not as efficiency challenged at mid charge / capacity levels

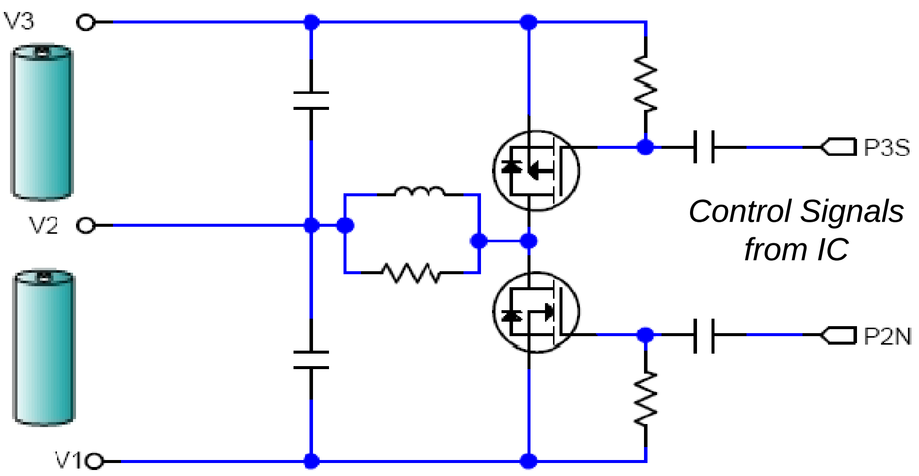
Inductive Redistribution

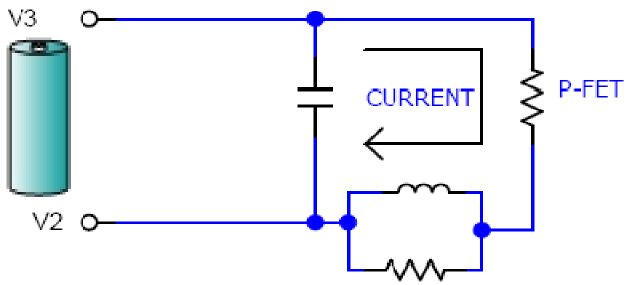


Imbalance example:

- Cell 2 is a lower voltage or capacitance
- Move energy from Cell 1 and Cell 2

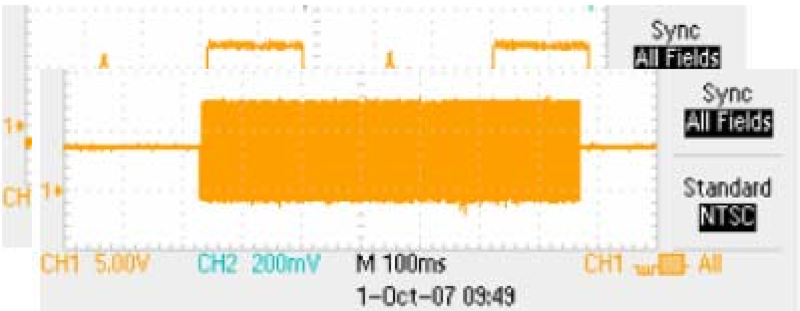
PowerPump™ Operation

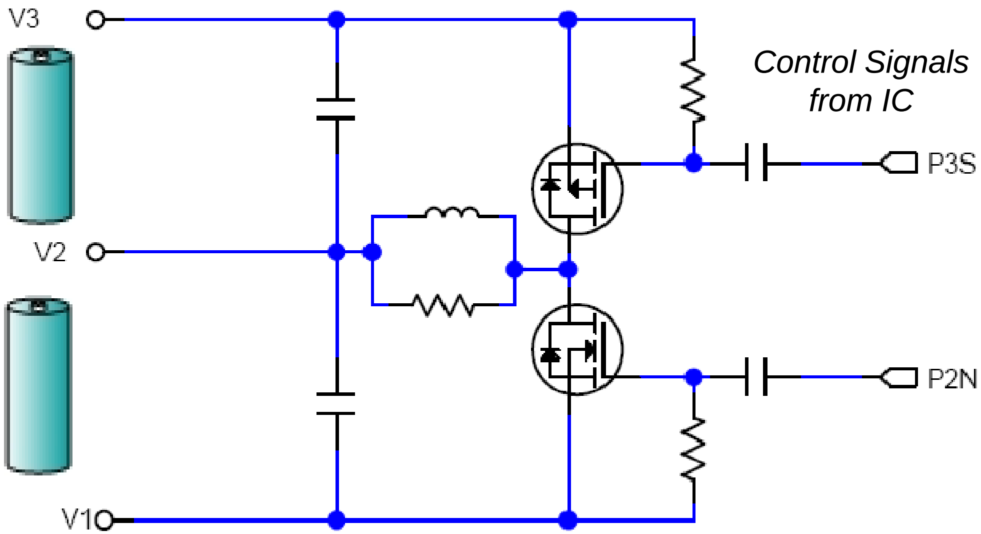


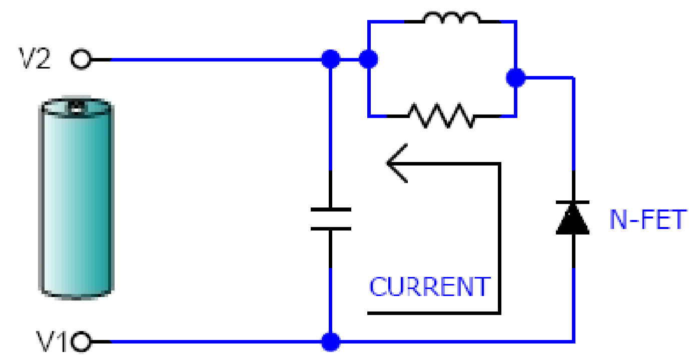


- Example: Pumping from Cell 3 →Cell 2
  - P3S frequency is 200 kHz, 33% positive Duty Cycle
  - P3S Turns PFET ON
  - $\Delta I/\Delta T = V/L$: Energy in Inductor builds

PowerPump™ Operation







- Example: Pumping from Cell 3 →Cell 2
  - P3S Turns FET Off
  - Current continues through NFET (body diode)
  - Energy transfers to Cell 2
  - Time average Balancing current is 40 to 50 mA
  - HF AC Currents confined to PCB

Multiple Balancing Control Options

Balance on Cell Terminal Voltage

- Easiest to understand – provides the basis for more complex control

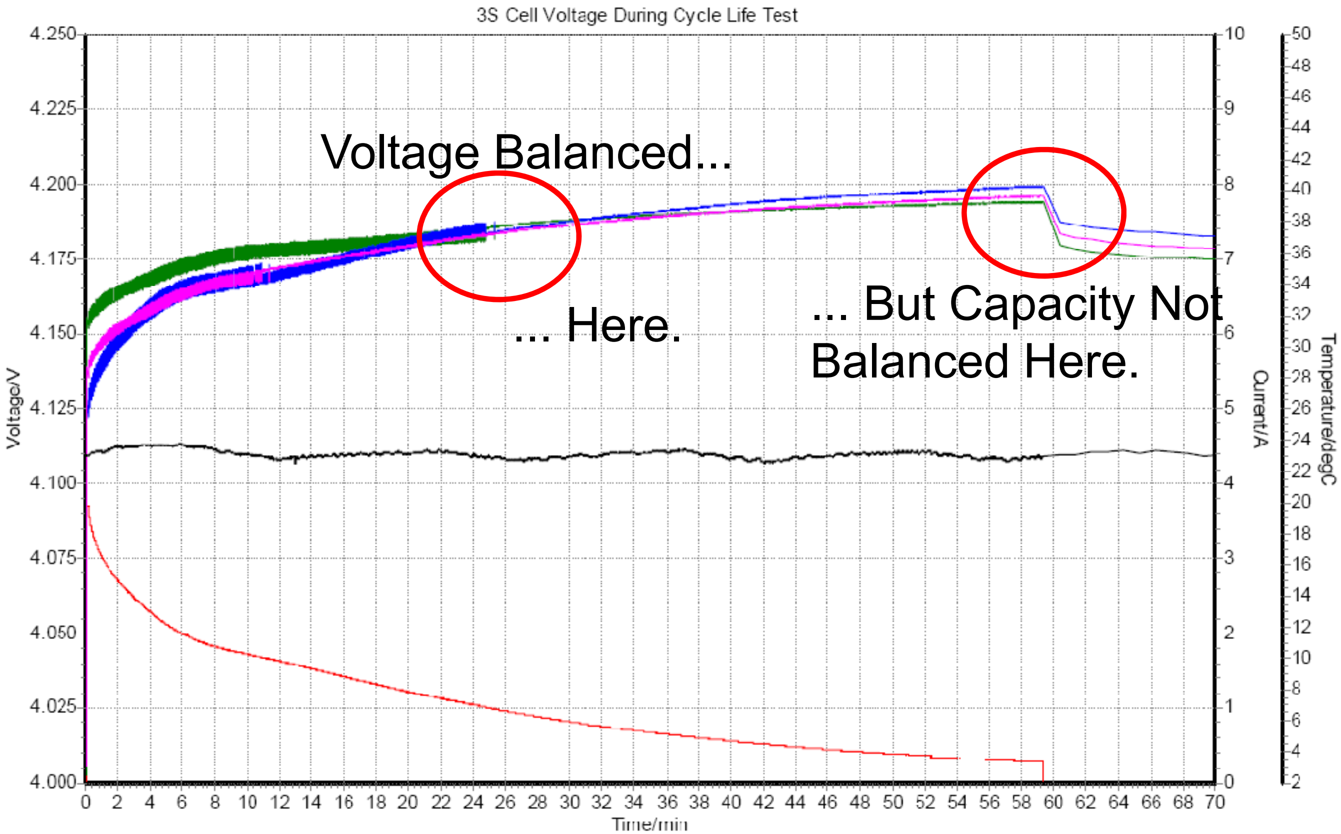
Balance on Cell OCV Estimates

- Based on Pack current and Cell Impedance measurements
- Compensates for impedance differences

Balance for SOC at 100% (or 0%)

- Based on how far each cell is from Full Charge Capacity
- Compensates for capacity divergence and OCV differences

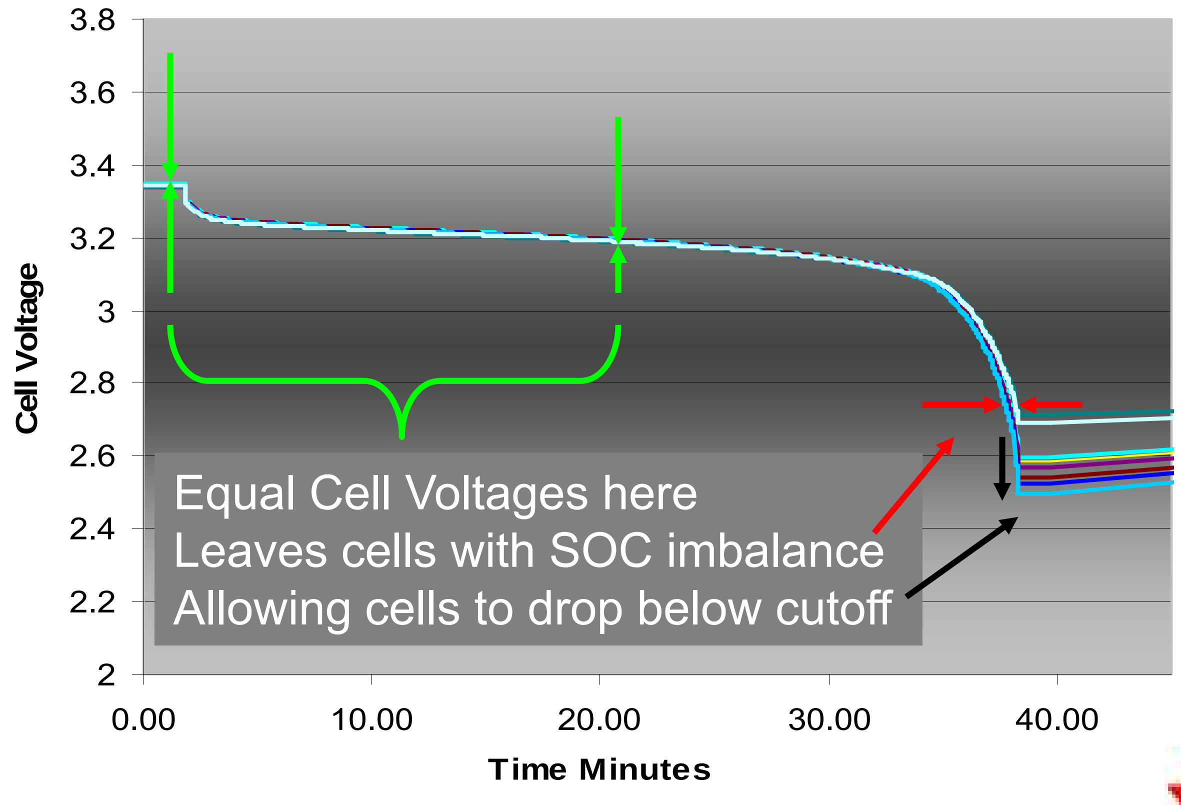
Balancing Strategy



Voltage Balancing Does NOT Always Insure Balance is Maintained Through the Cycle...

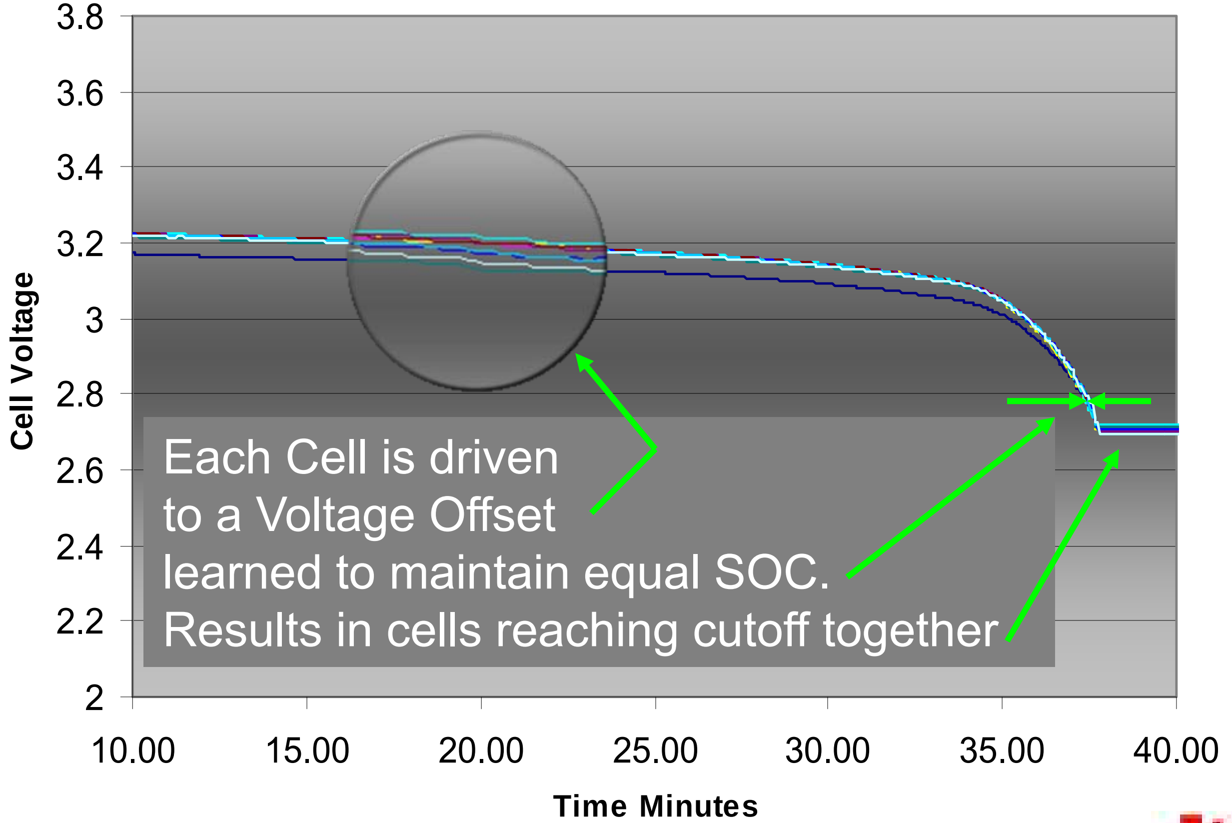
Challenges with New Chemistries

Voltage Balance but Capacity Imbalance ... *At End-of-Discharge*



Challenges with New Chemistries

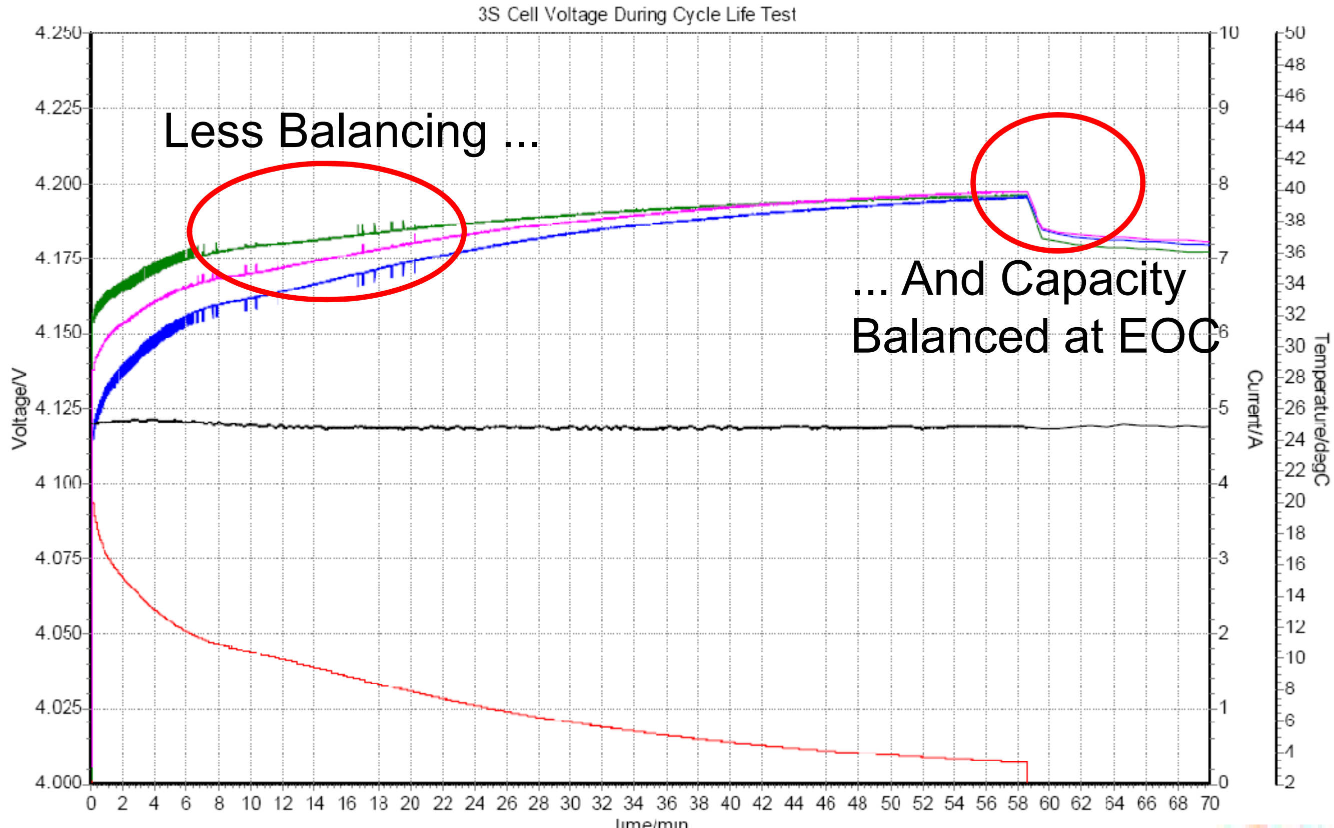
Predictive Balancing Maintains EOD Balance



Choice of Balancing Strategy

Predictive Balancing for Capacity Match at End Points

Added Benefit: Minimizes Overall Balancing Activity



Example Schematic

PowerPump™ Balancing

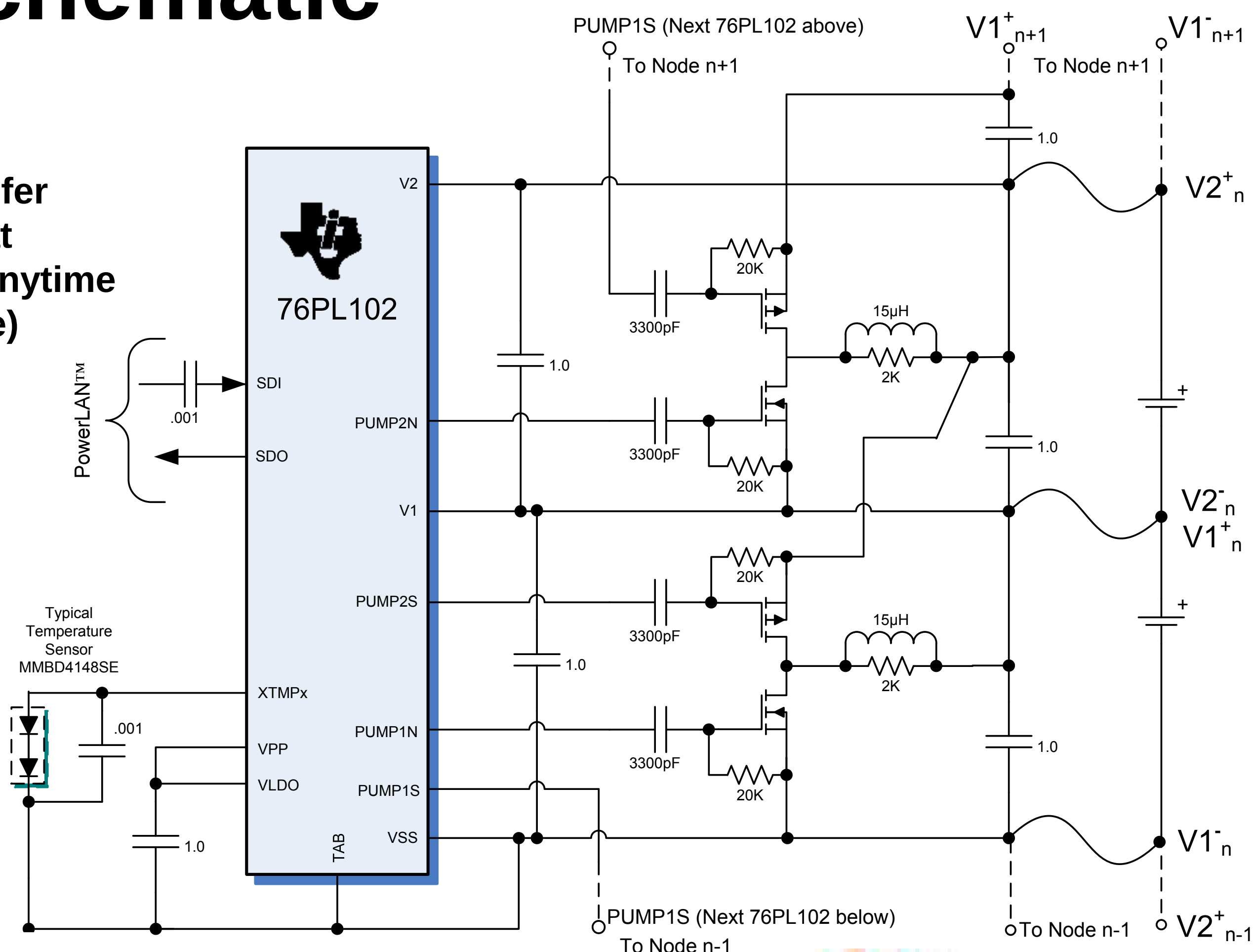
- **Cell-to-Cell Energy Transfer**
  - **Efficient - No Heat**
  - **Can be enabled anytime**

  (Charge, Idle, Discharge)

- <u>**Balance Current Sized Externally**</u>

  Inductor and Dual FETs

Example 2-cell circuit shown. ICs available for up to 6 series cells.



Cell Balancing Comparison

Bypass

- Simplest and least expensive for low currents
- High currents bring higher costs and thermal constraints
- Limited to ends of charge and discharge cycle

Redistribution

- Complex control algorithms
- Inductive has higher part counts and cost
- Able to be implemented at any time in pack life

Question and Answer