environmental • failure analysis & prevention • health • technology development

Lithium Ion & Lithium Polymer Batteries

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Exponent, Inc.

A leading engineering & scientific consulting firm dedicated to helping our clients solve their technical problems.

Who We Are

Exponent is a multi-disciplinary consulting firm dedicated to solving important science, engineering and regulatory issues for clients

Exponent Offices

Exponent®







Engineering Sciences

- Biomedical Engineering
- Electrical & Semiconductors
- Engineering Management Consulting
- Mechanical Engineering
- Materials & Corrosion Engineering
- Polymer Science & Materials Chemistry
- Thermal Sciences

Environmental Sciences

- Ecological & Biological Sciences
- Environmental & Earth Sciences


Health Sciences





- Chemical Registration & Food Safety
- Epidemiology, Biostatistics & Computational Biology
- Exposure Assessment & Dose Reconstruction
- Occupational Medicine & Environmental Health
- Toxicology & Mechanistic Biology

PROJECTS

Civil & Construction




- Buildings & Structures
- Civil Engineering
- Construction Consulting
- Industrial Structures

Transportation





- Biomechanics
- Human Factors
- Statistical & Data Sciences
- Vehicle Engineering
- Visual Communications

Technology Development

General Battery Hazards

- **High Instantaneous Current**
- **Voltage Dependent on Number of Cells in Series**
  - High Voltage Can Result in an Arc Explosion
    - High Voltage and Current Equals High Power
    - High Power Results in Explosive Energy Release
    - Similar to HV AC Source
      - Injuries and Death Can Occur
      - Possible Fire Ignition
  - High Voltage Can Result in Shock Injuries or Electrocution
- **Large Amount of Energy Available to a Load Fault**
  - Batteries Usually Fused to Prevent Large Fault Current
    - Example: Automotive Fuses
  - However, If Protection Fails Fire Can Occur

Battery Energy Release

- **Flammable battery electrolyte (Lithium Ion)**
- **Why are they used?**
  - Lithium Ion Energy Density
    - ~150 Wh/kg — Nominal Cell Voltage: 3.6V
    - ~200 Wh/L
  - Nickel Metal Hydride Energy Density
    - ~100 Wh/kg — Nominal Cell Voltage: 1.2V
    - ~100 Wh/L
  - Nickel Cadmium Energy Density
    - ~60 Wh/kg — Nominal Cell Voltage: 1.2V
    - ~70 Wh/L
  - Lead Acid Energy Density
    - ~40 Wh/kg — Nominal Cell Voltage: 2V
    - ~65 Wh/L

Challenges

- **Lithium Ion batteries are significantly different in every aspect compared to traditional battery chemistries**
  - Organic electrolyte
  - Strong oxidizers and reducers
  - No recombination rate ability

    … requires failsafe controls
- **Cell is manufactured at one location ...battery at another, product at another…**

  ... yet all needs to fit and work together

Lithium Battery Powered Systems

- **What are the main issues?**
  - Chemistry
  - Electrical system – Arcing/Shock and Electrocution
  - Manufacturing
  - Recalls
  - Accidents
  - Pack integration architecture - Module separation - choice of insulator solutions
  - Protection circuit and redundancy in protection systems

The Pack, Host Device and Accessories

- Critical sub-systems responsible for maintaining a suitable environment for the cells
  - Mechanical protection
    - FMEA
    - “Real World” mechanical testing
  - Environmental protection
    - Use profile temperature cycling
    - Cycling with exposure to expected (or unexpected) conditions
  - Electrical stability within operational windows
    - Safety's and limits maintained over all use and foreseeable misuse conditions

Focus needs to be on the electrical and electronic design too

- Attention to circuit design and layout – copper traces
- Sufficient protection in the design
- Independent safety protection redundancy
- Choice of components
- Effects of high voltage
- Connectivity
- Characterization of the worst case scenarios – multiple points of failure

Lithium Ion Basics

- **Positive Electrode (thicker white spiral in scan)**
  - Aluminum Current Collector
  - Coated with $LiCoO_2$ Active material
- **Negative Electrode (thinner…)**
  - Copper Current Collector
  - Coated with Graphite
- **Electrolyte**
  - Ethylene Carbonate
  - $LiPF_6$ Salt
- **"Jellyroll" is wrapped electrodes with electrolyte injected**

- CT Cross-section scan

Lithium Ion Basics

- **Copper is used as the negative electrode because if aluminum is used the aluminum participates as an ion in the charge and discharge reactions causing corrosion**
- **Reaction Equation:**

Charged — Discharged

$$Li_{1/2}CoO_2 + Li_{1/2}C_6 \leftrightarrow C_6 + LiCoO_2$$

Types of Lithium Ion Batteries

- **Cylindrical cells use nickel-plated steel cans**
  - The cell can is at the cell negative potential
- **Prismatic cells typically use aluminum cans**
  - The cell can is at the cell positive potential
  - Some larger, heavier prismatic cells use nickel-plated steel cans (can at cell negative potential)
- **Polymer cells use a polymer coated aluminum foil pouch**
  - Pouch is left electrically floating and is insulated from both the positive and negative terminals of the cell
  - More sensitive to mechanical abuse

Lithium Ion Battery Failure Analysis

- **Use a Fault Tree Analysis (FTA) approach**
  - The root causes discussed are the branches of the tree
  - Cut off branches that are not consistent with the evidence
  - Remaining branches evaluated to rank relative likelihood as root cause
- **Test electronics to determine functionality of charge and protection circuits**
- **Analyze heat and mechanical damage patterns to determine if they are external**
- **Analyze the damage to the protection circuit for evidence of an electronics failure**
- **Most often "internal cell fault" is the only branch remaining**

Manufacturing Issues

- Microparticle contamination in the active material slurries used to coat the electrodes
- Assembly line tools wear and can drop particles into the cell raw materials
- Cutter blades dull leaving burrs and tears on the current collector metals and leads connected to the foils
- Rough lead to foil connection techniques can leave sharp edges
- Nickel plating on substandard cell cans and other construction materials can flake and drop into the "jellyroll" during cell construction

Take Control While You Can

- The Cells
  - Forget the spec sheet – test to device requirements
  - Confirm quality and continue to check
  - Shop for a deal…but don't get burned

- The Pack, Host Device and Accessories
  - Don't stop with the standards and guidelines – understand the possible failure modes and design away from them
  - Simple, robust circuits based on accepted designs
  - Redundancy for critical operations
  - Respect for the limits of the cells
  - Mechanical integrity sufficient for the intended use and foreseeable environmental conditions

The Cells: Qualify, Confirm and Check

- Qualify cells for the intended application
  - Test to the specifications of the device
  - Test under normal use conditions
  - Test under reasonable abuse conditions
- Confirm you are getting what you paid for
  - Assess and record build quality and workmanship
  - Consider analytical work for custom designs
- Check your incoming material on a regular basis
  - Establish an incoming QC procedure
  - Catch problems on the inside

Typical Safety Circuits

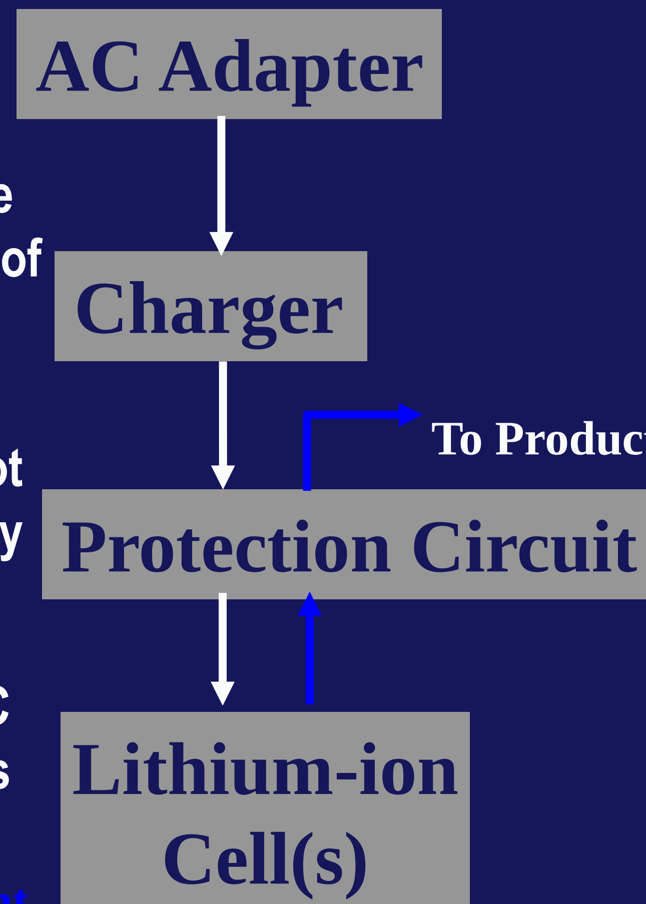
- **Consumer Electronics Applications Lithium-Ion Energy Storage System**

Converts AC voltage from outlet to a DC voltage

Conditions the DC voltage from adapter to appropriate voltage and current for the battery and controls state of charge

Provides protection to the cell to ensure that it does not operate outside its specifications. Redundancy ensures that multiple protection levels are provided

Stores the electrical energy which is used when the AC adapter is not connected. Passive protection devices provide additional protection to cells



Charge Current

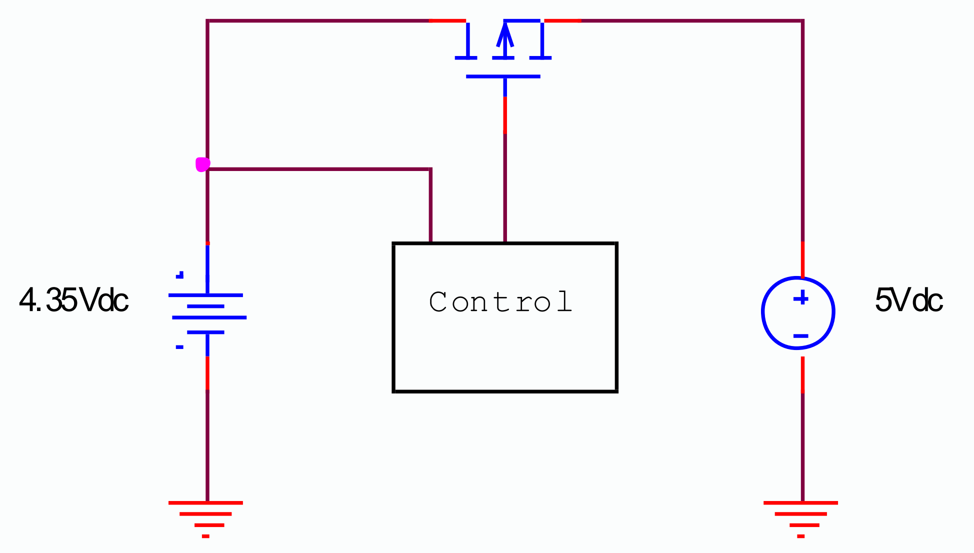
Discharge Current

Overcharge Protection

- **Multiple Cell Application: 4 Independent Levels**
  1. Charger Output Voltage
  2. Battery Protective Switch
  3. Electronically Controlled Fuse
  4. 18650 Cell Current Interrupt Device (CID)
     - Prismatic and Polymer Designs Use Thermal Cutoffs (TCO)
- **Single Cell Application: 2 Independent Levels**
  1. Charger Output Voltage
  2. Battery Protective Switch

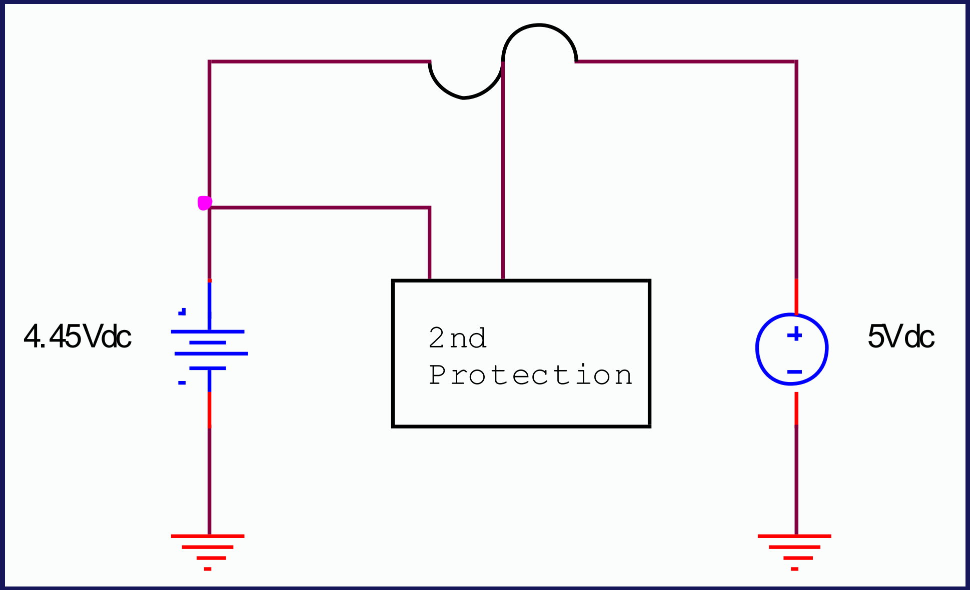
Overchage Protection

- Battery Protective Switch
- Microcontroller controlled transistor switch
- In multiple cell applications each cell is individually monitored for overcharge by the microcontroller



Overcharge Protection

- Independent IC: Secondary Protection
- Each cell is individually monitored for overcharge
- Electronically controlled fuse is opened if overcharge is detected

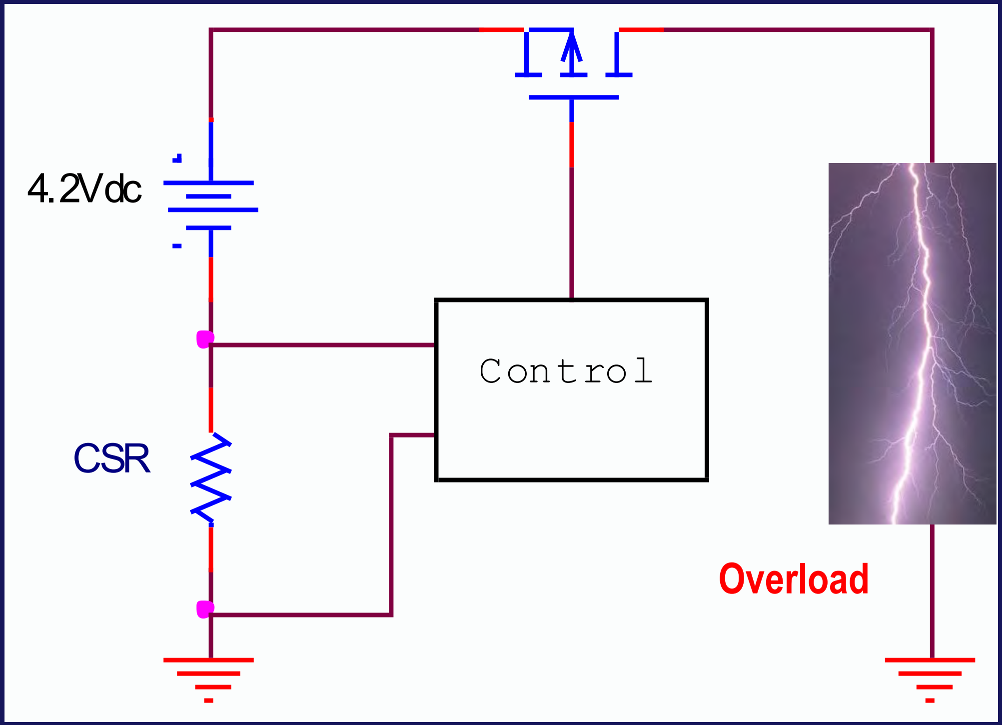


Overcurrent Protection

- **Multiple Cell Application:**
  - 4 Independent Levels for Charge Current
  - 3 Independent Levels for Discharge Current
    1. Charger Current Limit (Charger Only)
    2. Battery Protective Switch
    3. Standard Current Fuse
    4. Positive Temperature Coefficient Device (PTC)
       - Prismatic and Polymer Designs Integrate PTCs external to the cells
- **Single Cell Application:**
  - 3 Independent Levels for Charge Current
  - 2 Independent Levels for Discharge Current
    1. Charger Current Limit (Charger Only)
    2. Battery Protective Switch
    3. PTC external to cell

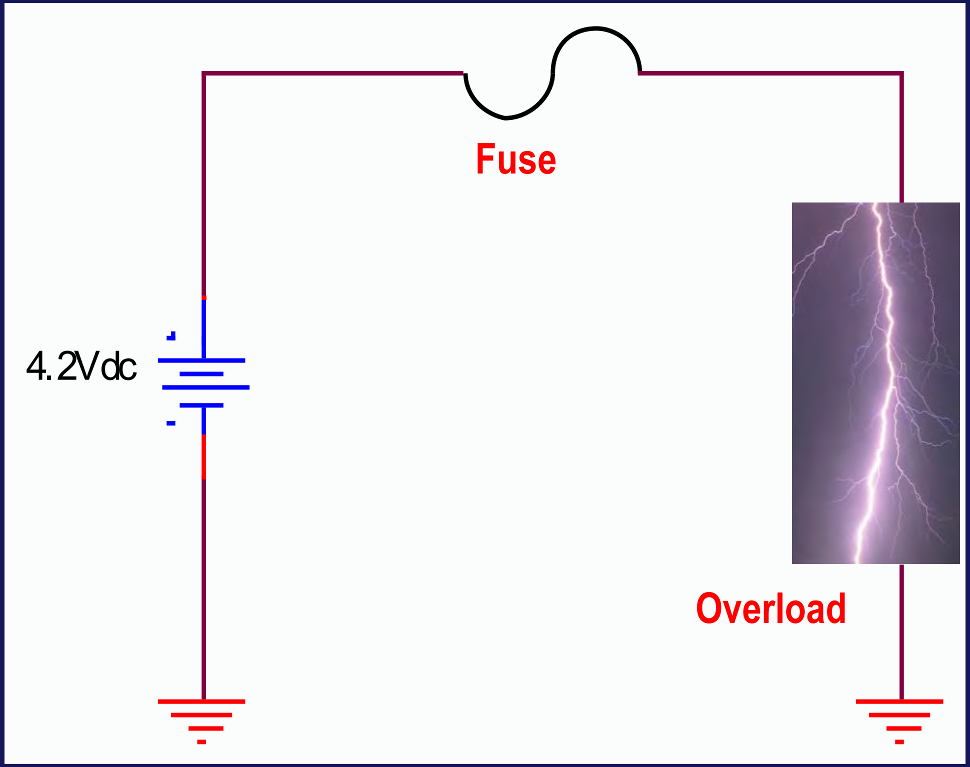
Overcurrent Protection

- **Battery Protective Switch**
  - Microcontroller monitors charge and discharge current using a Current Sense Resistor (CSR)
    - Or FET On-Resistance
  - If overcurrent detected
    - Protective Switch Opens



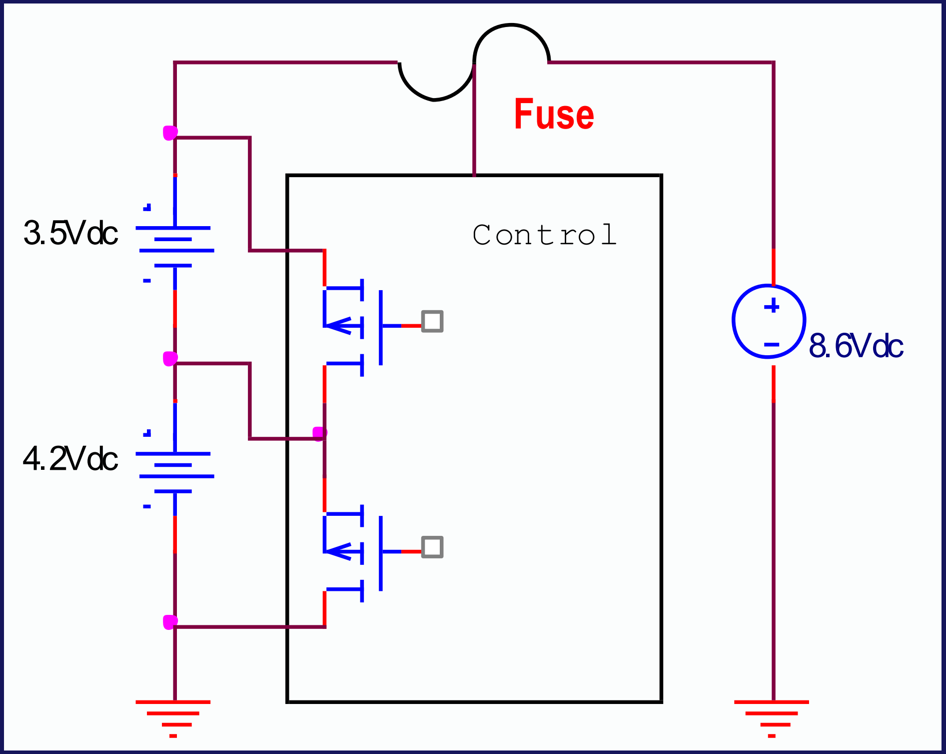
Overcurrent Protection

- **Standard Current Fuse**
  - Overcurrent will cause the fuse to open



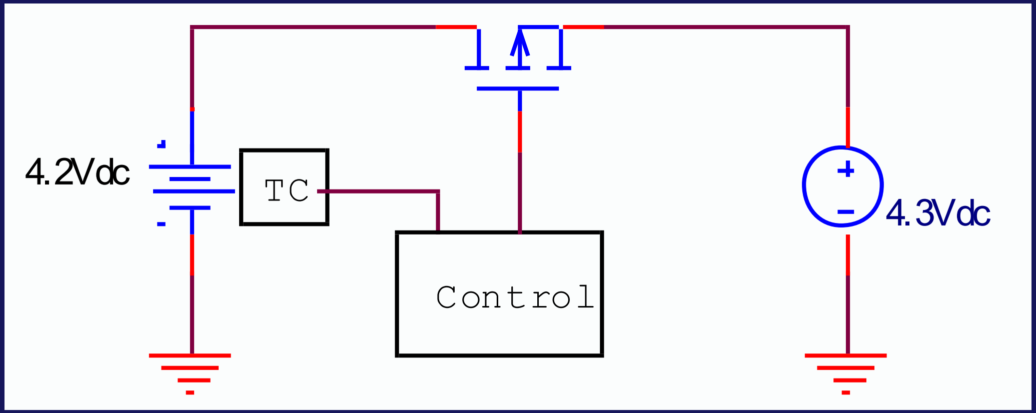
Imbalance Protection

- **Series connected cells require imbalance protection**
  - Microcontroller monitors individual cell voltages
  - Methods of protection include:
    - Rebalancing by diverting charge current from higher voltage cells
    - If imbalance is severe, electronically controlled fuse can be opened



Overtemperature Protection

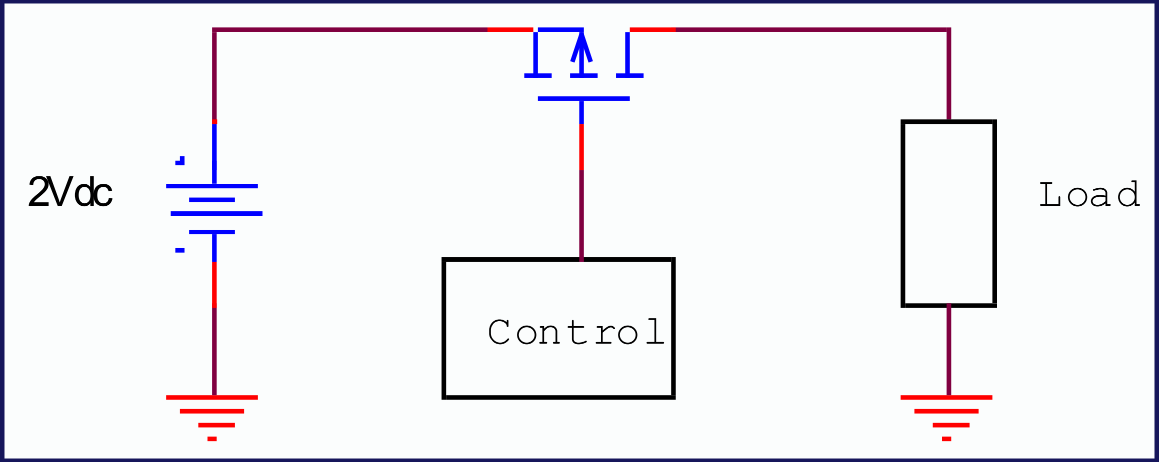
- Microcontroller senses cell temperature using a thermocouple (TC) and terminates charge or discharge current using a switch based on the following typical criteria:
  - Charge initiation allowed within 0°C and 50°C range
  - Charge continuation allowed within 0°C and 60°C range
  - Discharge allowed within 0°C and 70°C range



Overdischarge Protection

- **Microcontroller monitors cell voltages**
  - Opens switch when the capacity of the battery is drained
  - Drained battery will be drained further by protection electronic loading
  - Protection electronics will shut down when the cell voltages drop below 2V

- **Drained pack can be reenabled with low "pre-charge" current to bring the cells back into normal range**



Large Battery Systems

- Cell designs that assist in the distribution of heat
- Ceramic separators to improve thermal stability
- Positive electrode material with greater thermal stability
- Case designs to improve heat transfer (fins etc.)
- Forced convection mechanisms for heat transfer
- Soft packages for cells to provide larger aspect ratios to aid in better heat transfer

Large Battery Systems

- **Electrical Shock Hazard**
  - HEV Li-ion battery systems have substantially higher operating voltages
  - Typically 160 V or higher
  - UL defines a voltage in excess of 42.4 Vac or 60 Vdc as hazardous
- **Arcing**
  - An arcing fault can result in extremely high temperatures on the order of 10,000° C or higher.
  - These high temperatures can generate hot gases and molten metal which can result in serious burns and cause clothing to ignite

Test standards

Lithium-Ion Abuse Standards

- **Underwriters Laboratories**
  - UL 1642: Lithium Batteries
  - UL 1973 (Proposed): Batteries for use in Light Electric Rail (LER) Applications and Stationary Applications
  - UL 2054: Household and Commercial Batteries
  - UL 2271: Batteries for use in light electric vehicle applications
  - UL 2580: Batteries for use in electric vehicles
- **Institute of Electrical and Electronics Engineers (IEEE)**
  - IEEE 1625: Rechargeable Batteries for Multi-Cell Mobile Computing Devices
  - IEEE 1725: Rechargeable Batteries for Cellular Telephones
- **American National Standard (ANSI)**
  - C18.2M Part2: Portable Rechargeable Cells and Batteries – Safety Standard
- **Society of Automotive Engineers (SAE)**
  - J2464: Electric and Hybrid Electric Vehicle Rechargeable Energy Storage Systems (RESS), Safety and Abuse Testing
  - J2929: Electric and hybrid vehicle propulsion battery system safety standard – lithium based rechargeable cells

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Lithium-Ion Abuse Standards

- **International Electrotechnical Commission**
  - IEC 62133: Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications
  - IEC 62281: Safety of Primary and Secondary Lithium cells and batteries during transport
- **United Nations (UN)**
  - Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, Part III, Section 38.3
- **Japanese Standards Association**
  - JIS C8714: Safety tests for portable Lithium-ion secondary cells and batteries for use in portable electronic applications
- **Battery Safety Organization (BSO)**
  - Proposed: Manual for the evaluation of energy systems for light electric vehicle (LEV) – secondary lithium batteries.

Battery Systems Support Overview

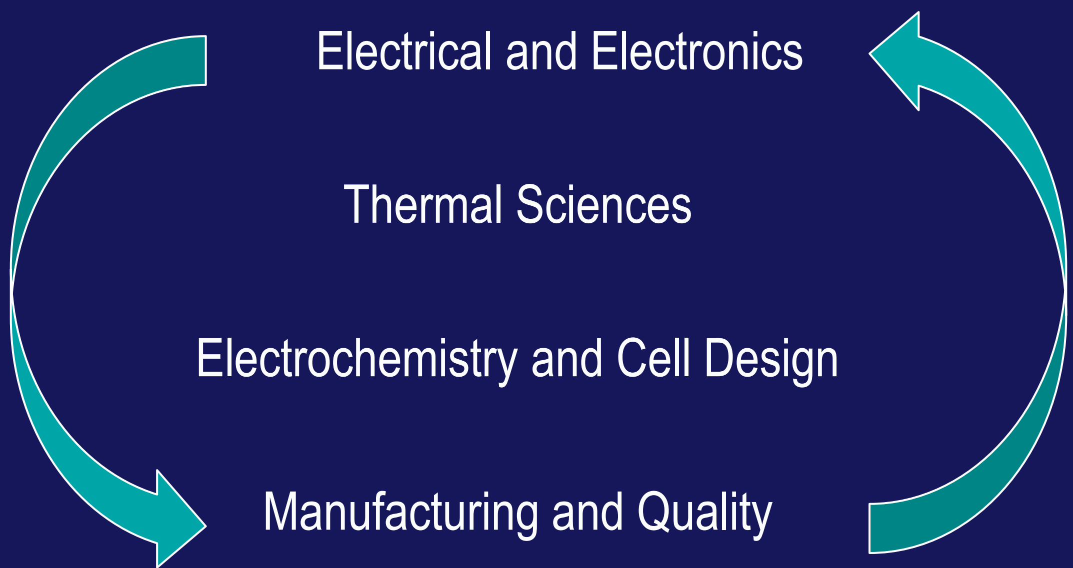
- Failure analysis and root cause determination
  - Litigation
  - Field Incidents
  - Recall support
- Design evaluation and review
- Standard and customized testing abuse/misuse testing
- Battery Accelerated aging and predictive life modeling
- System integration support

Vehicle → Electrical System → Battery Pack → Electrochemical Cells

Multidisciplinary Approach

By forming a multidisciplinary team we have experience with:

- Cells
- Power management
- Electrical system
- Risk analysis
- Auditing of component factories



Equipment and Capabilities: Phoenix

- Pack, System and Vehicle Level Support:
  - circuit design and layout
  - protection and redundancy in the design
  - choice of components
  - effects of high voltage
  - environmental impact on performance (water, temperature, humidity, etc...)
  - connectivity
  - characterization and testing of the worst case scenarios
- Equipment and Facilities:
  - Environmental chambers (-25 °C to 100 °C)
  - Shock table
  - Vibration table
  - Thermal imaging camera
  - Vacuum chambers
  - High speed video capability (up to 2000 frames/second)
  - Maccor cell cyclers
  - Complete vehicle testing center