Lithium-ion Batteries
Fundamentals and Safety Characteristics

Kumar Bugga
Jet Propulsion Laboratory
California Institute of Technology

November 11 2017

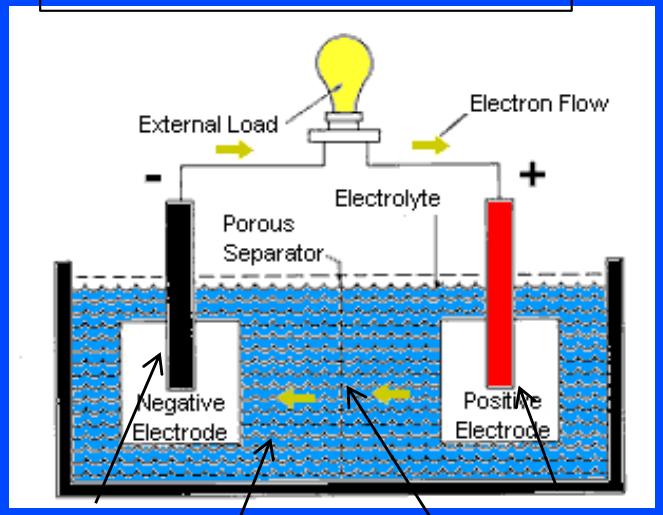
© 2017 California Institute of Technology. Government sponsorship acknowledged.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

Battery Tutorial

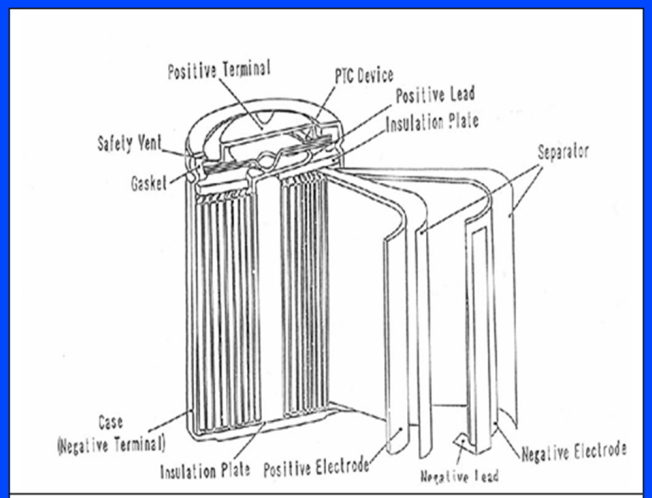
- Electrochemical cell converts chemical energy into electrical energy
- Requires combination of an anode and a cathode to allow flow of electrons through the load and provide energy.
- Anode: Provides electrons to the load during discharge (typically a metal)
- Cathode: Accepts electrons from the load during discharge (usually a metal oxide)
- Separator: Porous membrane that prevents the two electrodes from shorting but enables ions to move back and forth
- Electrolyte: Medium for conducting ions between anode and cathode during discharge

Simple Cell Schematic



Anode Electrolyte Separator Cathode

Cylindrical Cell



Internal Cell Assembly

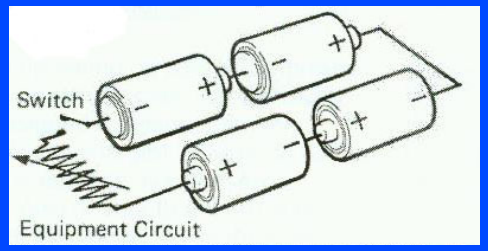
Types of Electrochemical Energy Storage

- **Primary cells: Non-rechargeable**
  - **Irreversible cell reactions**
  - **One time use**
  - **Used in Probes and Small rovers such as Huygens Probe or Sojourner Rover**
- **Secondary cells: Rechargeable *(will cover only this category)***
  - **Reversible cell reactions; Cell reaction reversed during charge**
  - **Multiple uses (Discharge and charge cycles)**
  - **Used in Orbiters and Landers such as Mars Reconnaissance Orbiter or MER**
- **Fuel cells**
  - **Non-rechargeable reactants that are replenished as they are consumed**
  - **Hydrogen- oxygen fuel cells on Gemini, Apollo and Space Shuttle**
    - **Coupled with hydrogen propellants and life support oxygen**
  - **More prominent in human exploration missions**
- **Capacitors**
  - **Charge separation across double layer or with the use of dielectric**
  - **No electrochemical reactions**
  - **Used for burst power applications (load-leveling), e.g., Cassini**

Cell vs. Battery

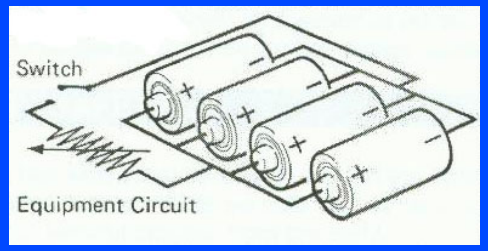
- A cell is the basic unit of a battery
- A battery is an assembly of cells
- Cell geometry is typically cylindrical or prismatic
- Cells can be arranged in series, in parallel or a combination of both:
  - Series arrangement provides higher voltages
  - Parallel arrangement provides higher capacity (more charge)
  - Terminology: 8S2P means eight cells in one series string with two such strings in parallel.

Battery Configuration



Voltage is additive, capacity is not and remains the same as for a single cell.

Series Configuration (string)

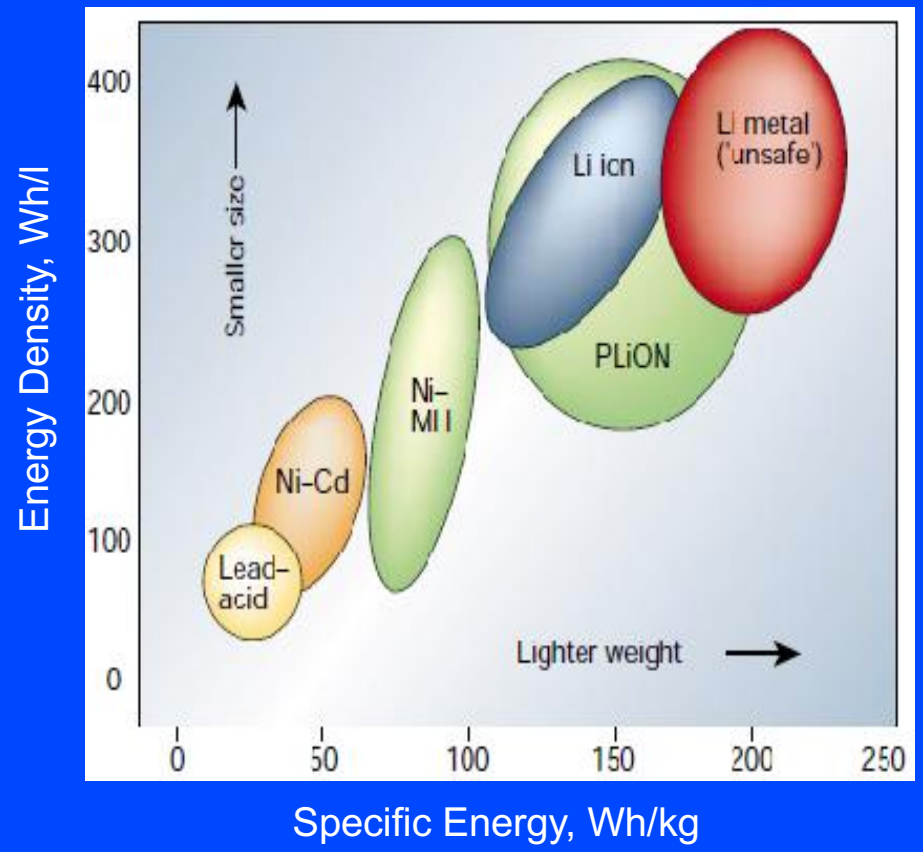


Capacity is additive, voltage is not and remains the same as for a single cell.

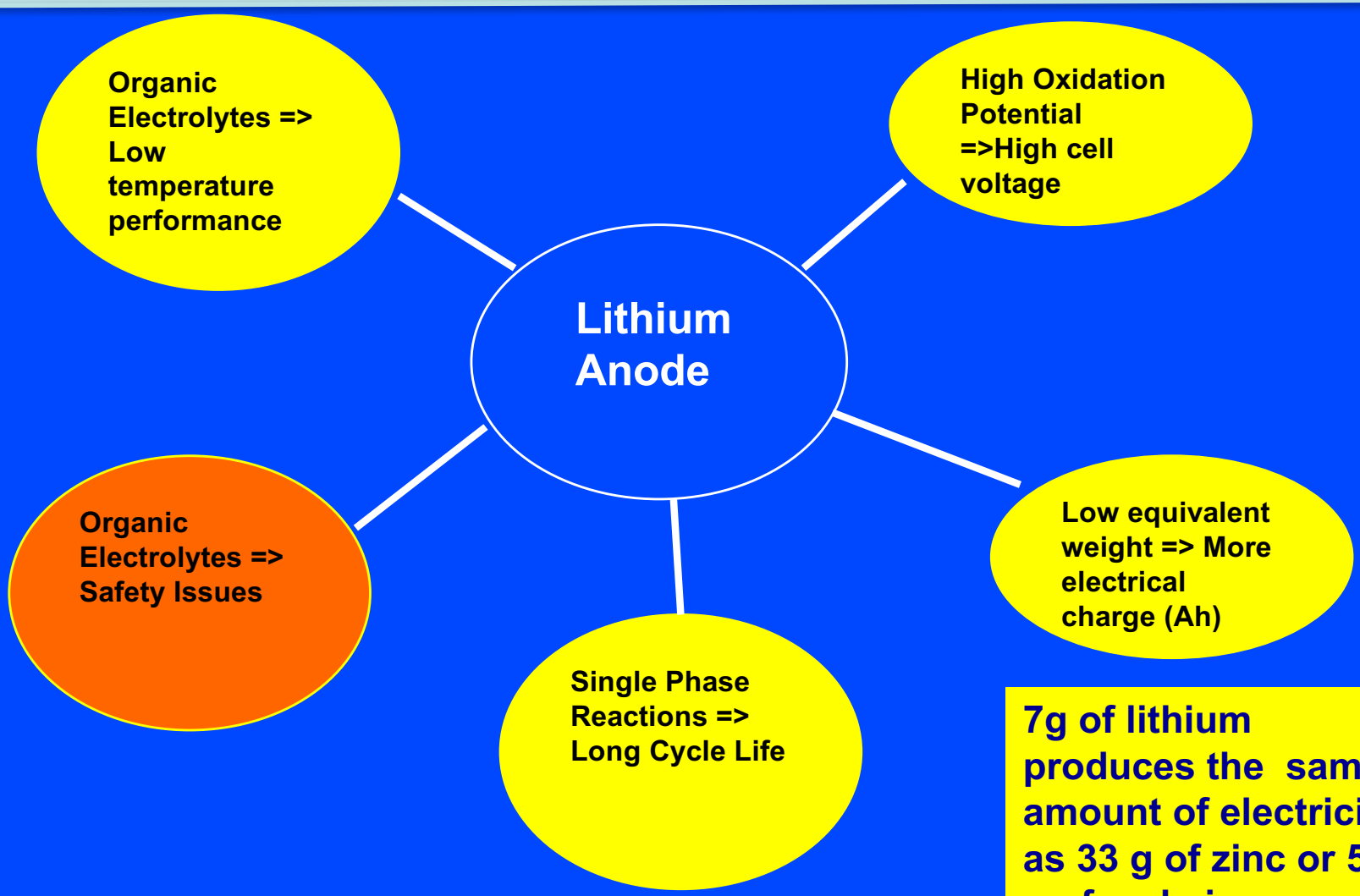
Parallel Configuration (bank)

Battery Performance Metrics

Characteristic	Definition
Cell Voltage, V	Cathode potential minus anode potential ($E_{cathode}$-E_{anode})
Capacity, Ah	Total coulombs
Cell Energy, Wh	Product of voltage and Capacity
Power , W	Product of voltage and Current
Specific energy, Wh/kg	Energy per unit mass, Wh/kg
Energy Density, Wh/l	Energy per unit volume; Wh/l
Cycle life, #	Number of charge discharge cycles till the capacity drops below 80% of the initial value
Shelf life (Calendar life), years	Duration of storage period till the capacity drops below 80% of the initial value
Depth of Discharge, %	Extent to which the battery is discharged



Why Lithium battery is the highest energy system?

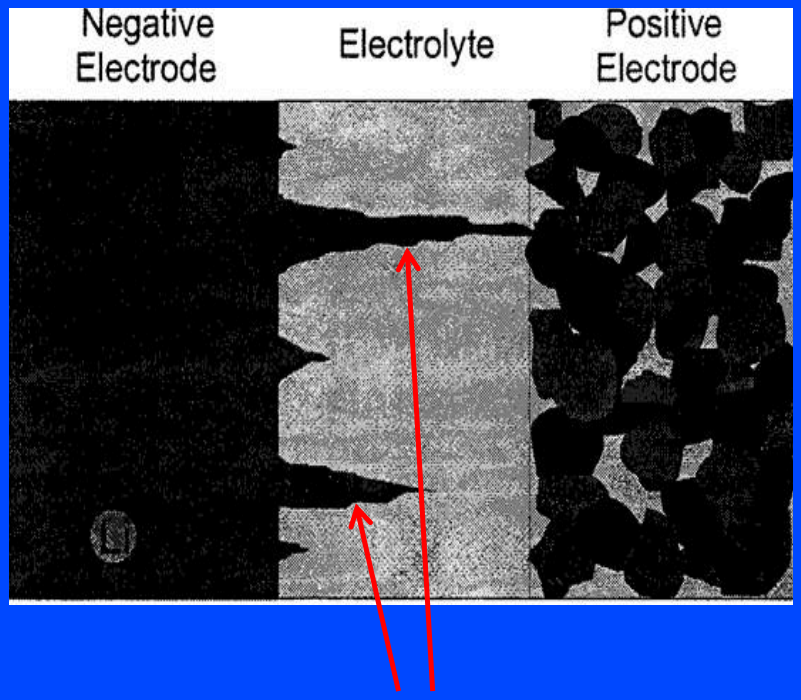


7g of lithium produces the same amount of electricity as 33 g of zinc or 56 g of cadmium

- **High specific energy, high energy density, long life and wide-operating temperature are possible with a Li battery**

Li-Based Rechargeable Batteries (Pre-Lithium Ion Era)

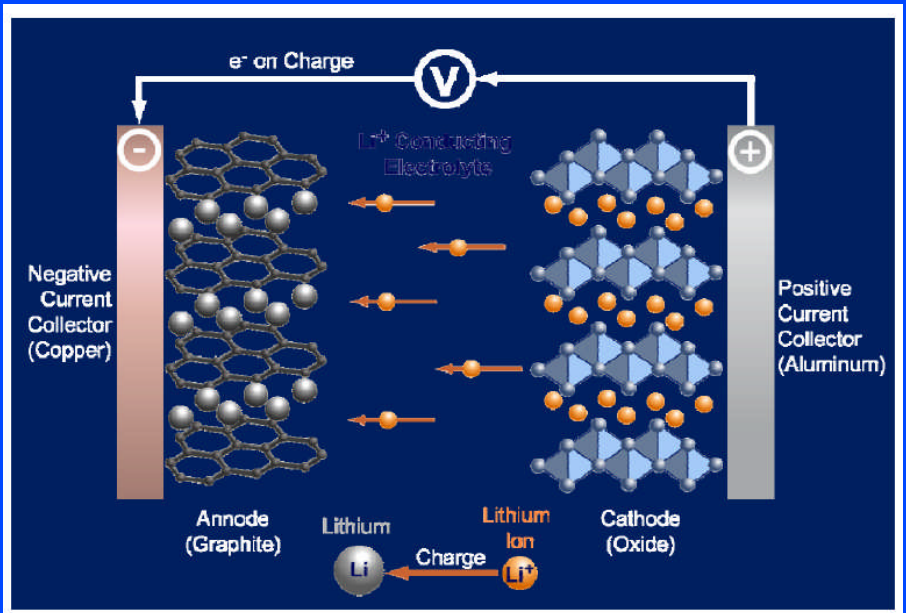
- Battery research between 1975 through 1991 focused on Li metal anode based systems, but the efforts were not as widespread as today
  - Several Li-insertion cathodes and stable electrolytes were developed at various laboratories (Bell Labs, Exxon, Honeywell, JPL)
  - Good cycle life (>500 cycles) and high specific energy (>150 Wh/kg) realized in laboratory cells, but were also accompanied by early cell failures
- <u>Safety</u> was a serious concern
  - Lithium deposits as dendrites causing internal shorts and catastrophic cell failures



Lithium dendrites during the cycling of Li cell causing shorting

The Dawn of Lithium-Ion Battery (1991)

- Sony announced the breakthrough technology of Li-ion with a carbon anode and with lithium cobalt oxide cathode.
- First Li-ion cell (~70 Wh/kg) was better than the best available aqueous system (Nickel-metal hydride) – a big boost to the portable electronics which in turn stimulated a boom in battery R&D
  - Lithium-ion shuttles from cathode to anode (during discharge) and vice versa on charge; Hence the name lithium-ion (also called rocking chair!)
  - Cells can be assembled in discharged state without handling lithium.



Schematic of a lithium-Ion cell

- **Much safer than Li metal based systems, if properly operated (without overcharging)**

Lithium ion battery should not be operates as a Li battery => No Li plaiting

Li-ion Cell Reactions

- Anode: Carbon compound (graphite)
- Cathode: Lithium metal oxide such as $LiCoO_2$, $LiNi_{0.8}Co_{0.2}O_2$, $LiMn_2O_4$, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$, and several other combinations of mixed oxides as well as lithium metal phosphate.
- Electrolyte: $LiPF_6$ (has a problem with aluminum corrosion), combination of carbonates (ethylene carbonate, propylene carbonate, dimethyl carbonate, diethyl carbonate, ethylmethyl carbonate)
- The half reactions are:

  Cathode: $LiMO_2 \rightarrow Li_{1-x}MO_2 + xLi^+ + xe^-$

  Anode: $C + xLi^+ + xe^- \rightarrow Li_xC$
- The overall reaction is: $LiMO_2 + C \Leftrightarrow Li_xC + Li_{1-x}MO_2$

  where $LiMO_2$ represents the lithiated metal oxide intercalation compound.

Multiple Options for Lithium- Ion Cells

- Unlike with the aqueous systems, there are several options for Li-ion cells depending on the cathode and anode.
- Performance characteristics (energy, power, cycle life etc.) are specific to the combination of anode, cathode and electrolyte.
- Specific chemistries can be chosen for high energy, high power and wide temperature operations.

Anodes

Carbon Anodes

- Coke
- Graphite
- Hard carbon
- Mesocarbon micro-bead (MCMB);

Electrolytes

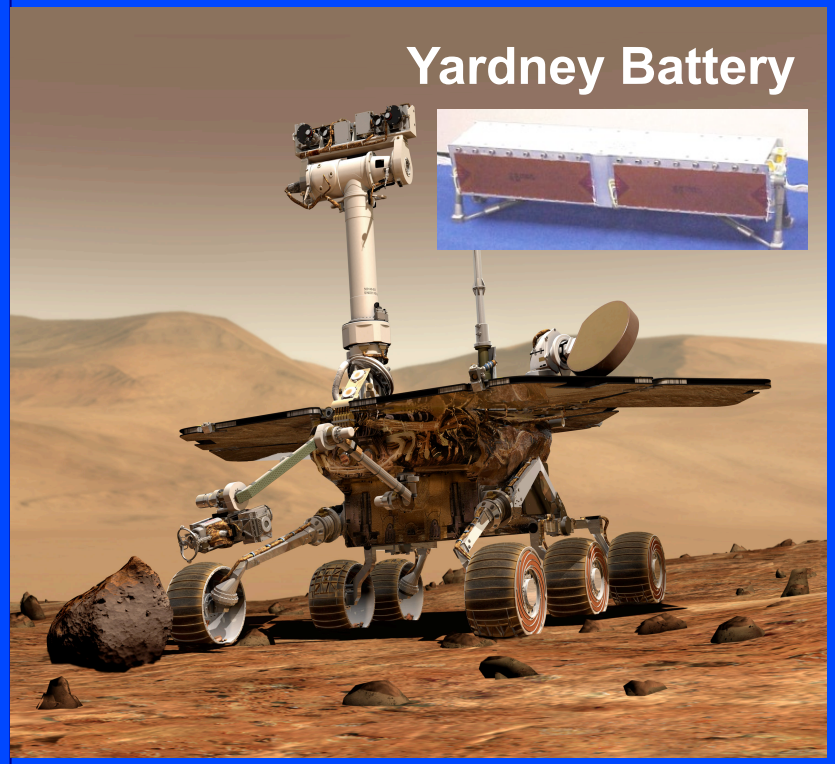
- **Organic (Liquid) Electrolytes**
- **Liquid electrolyte in polymer gels**
- **Solid State electrolytes**

Cathodes

- **Oxides (lithium cobalt oxide, nickel cobalt oxide, nickel cobalt manganese oxide)**
- **Phosphate (Lithium Iron Phosphate)**

Mars Exploration Rover- Spirit and Opportunity (2003)

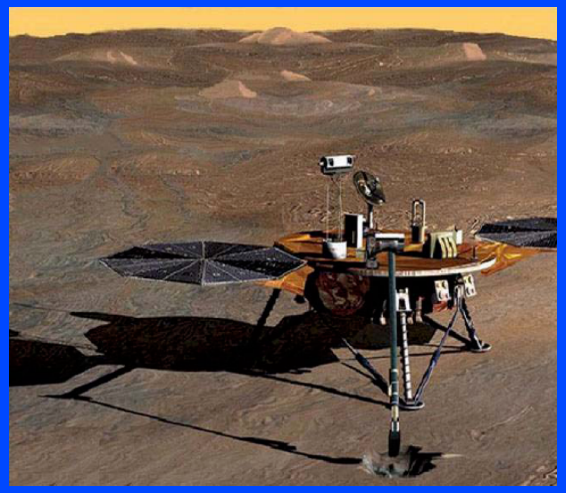
- First major NASA mission with Li-ion batteries
- Excellent performance from the Li-ion battery, both in cycle and calendar life
- Mission enabling: Alternate battery technologies were not viable
  - Silver-zinc battery would have limited the life to six months or less
  - A Ni-H_2 battery would be about four times heavier (7.5 kg vs 28 kg)
- Cell balancing methods utilized to prevent overcharge.
- Led to the use of Li-ion batteries on several missions not only within JPL but across NASA (e.g., GSFC missions)



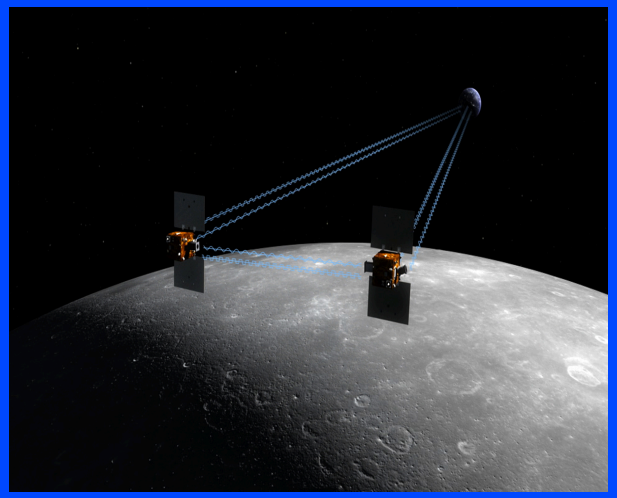
- **Spirit operated over 9 years (vs. 90 days of design life)**
- **Opportunity rover is still operational: 3975 Martian sols (11 years and 2 months) and 10 km.**
- **Battery is expected to last for few more years.**

Missions with MER-Heritage Batteries

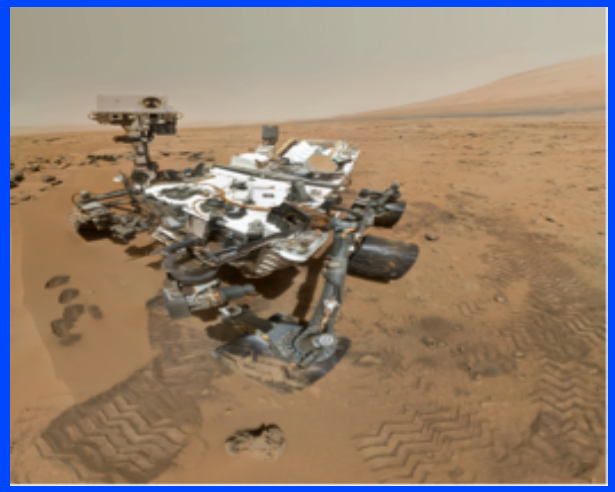
Phoenix Lander (2007)



GRAIL (2011)



Mars Curiosity (2011)



Mars Rover (2020)

- **MER Battery has had big impact across multiple JPL missions.**
- **Mars 2020 rover follows the same rover design as Curiosity but with different payload.**
- **Mars 2020 Rover will retain the battery heritage with minor changes in the battery chemistry.**

Small Commercial Cells (18650)

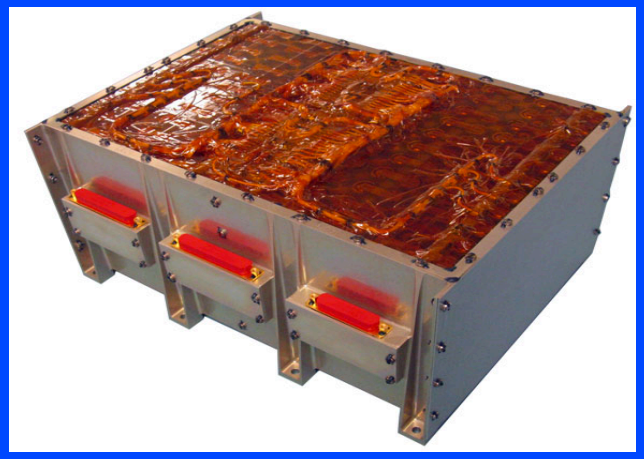
Commercial Off The Shelf (COTS)

Flight Batteries using commercial 18650 cells (ABSL)

- **Sony Hard Carbon – Lithium Cobalt Oxide**
- **Built-in protection devices: PTC (thermal fuse) CID (Current Interrupt device), vent**
- **Consistent cell fabrication by Sony**
- **Further, the cells are well matched using proprietary methods by ABSL**

•***No need for cell balancing electronics based on the cell uniformity***

•**Redundancy from multiple parallel strings.**

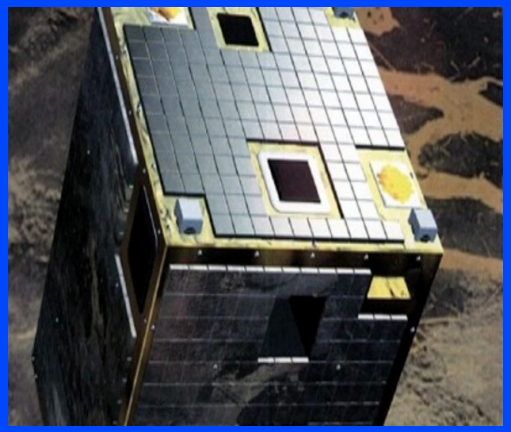


Several Battery Deigns Available (8S10P, 8S16P, 8S52P)

Analogy with TESLA battery using Panasonic cells

Missions with Commercial Cells (Sony)

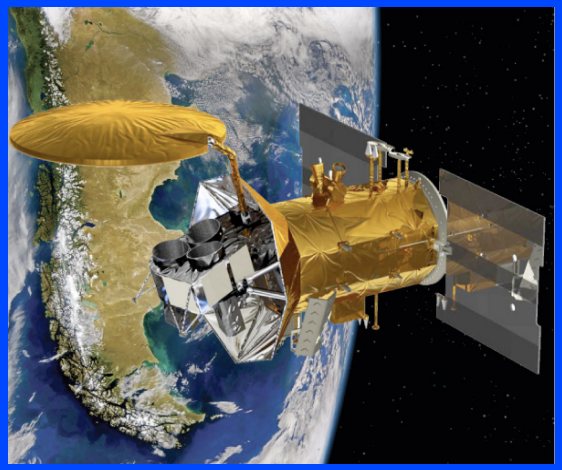
PROBA (2001)



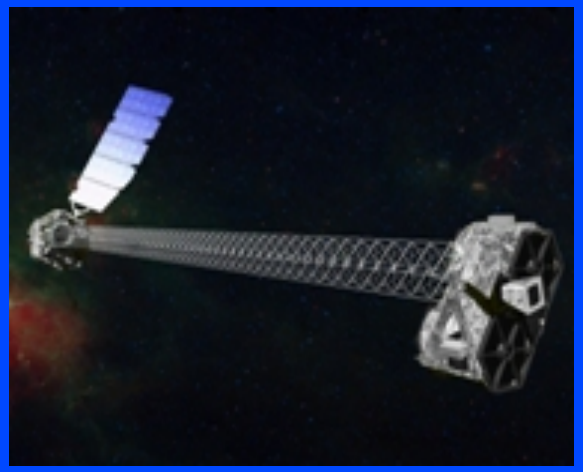
Mars Express (2003)

Kepler (2009)

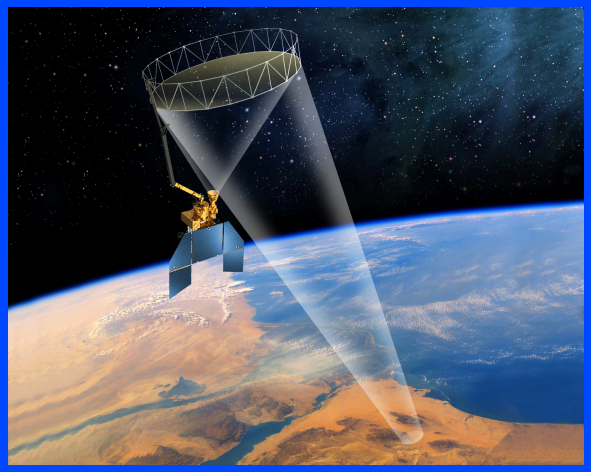
Aquarius (2011)



NuSTAR (2012)



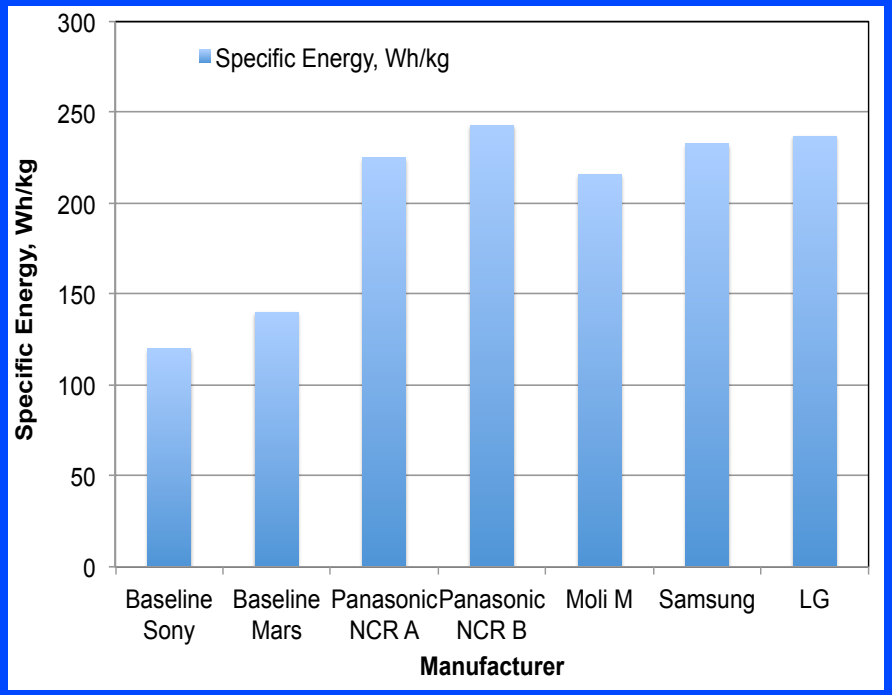
SMAP (2014)



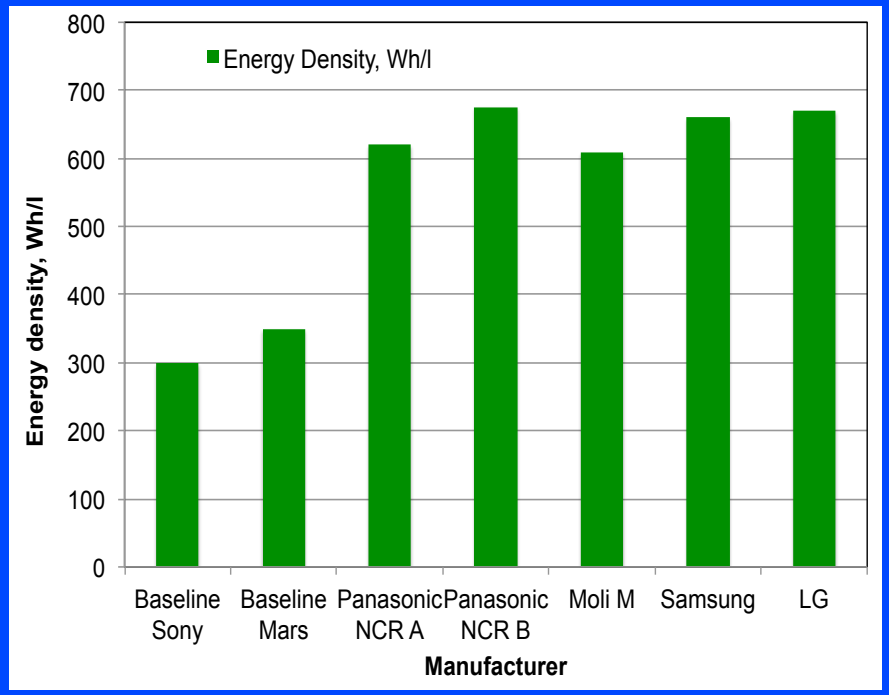
Commercial Cells are Continuing to Get Better

- Commercial manufacturers have traditionally focused on small cells (cylindrical 18650 cells and pouch cells).
- Considerable incentive to make the batteries lighter and smaller.
- With improved cell designs (dense electrodes, thin separators), many commercial manufacturers have achieved significant energy improvements

Specific Energy

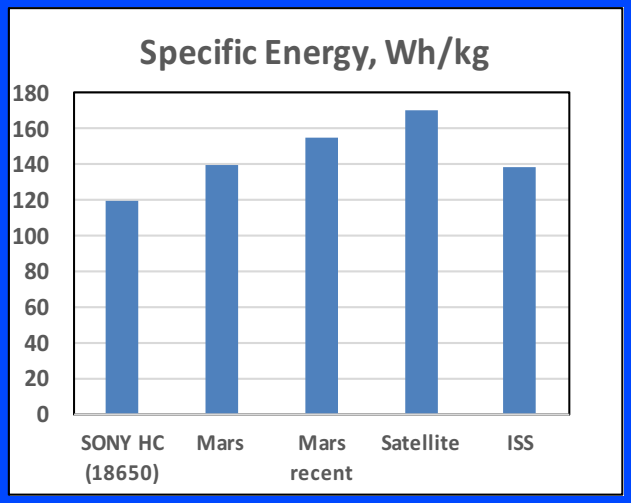


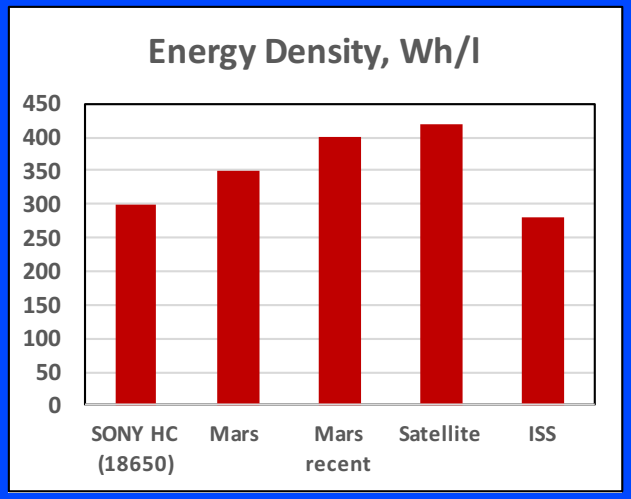
Energy Density



State of Art / State of Practice

State of Practice

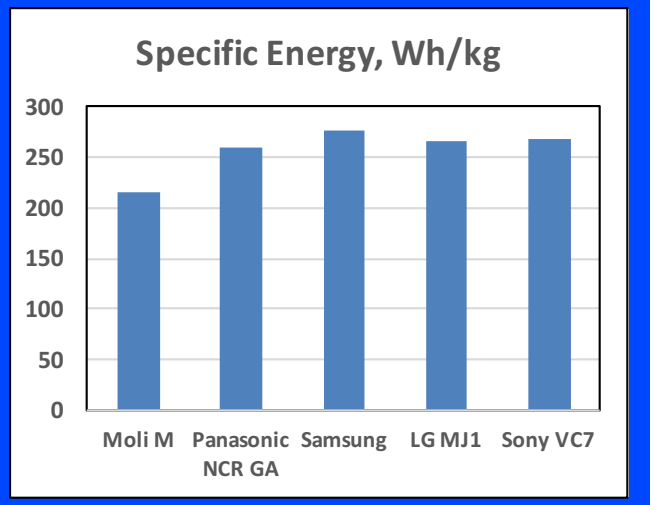


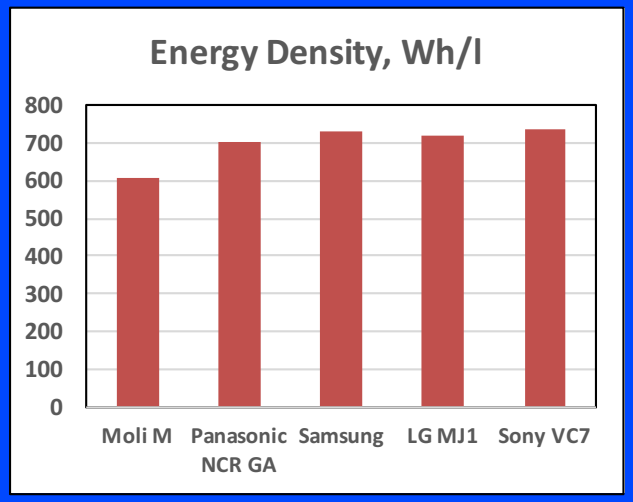


Chemistry of SOA cells

Cathode	$LiCoO_2$ (LCO)	160-200 mAh/fg
	$LiNi_{0.8}Co_{0.2}O_2$ (NCO)	
	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCO)	
	$Li(NiCoMn)O_2$	
Anode	MCMB	280-350 mAh/g
	Hard Carbon	
	Graphite	
	Small amount of Si?	
Electrolyte	Organic Liquids (carbonate blends, ester co-solvents, additives)	
Cell Configuration	Large format Prismatic or Cylindrical cells	Cell Balancing
	Small 18650 cells	No Cell Balancing

State of Art
Ready for Implementation





Li-ion Batteries in Electric Vehicles

Electric vehicle	Battery	Range (advertised)	Range (real world)
BMW Mini E	35kWh, air cooled; 18650 cells; NMC 355V, 96S53P, E-One Moli	156 miles	96 miles; and 70 miles below freezing
Chevy Volt	16kWh, liquid cooled Li-manganese cells from LG Chem (181kg)	40 miles	28 miles;
Toyota plug-in Prius	3 Li-ion packs, one for hybrid; two for EV (Matsushita Electric)	13 miles	
Mitsubishi iMiEV	16kWh; 88 cells, 4-cell modules; Li-ion; 109Wh/kg; GS Yuasa	80 miles	55 miles;
Nissan LEAF	24kWh; Li-manganese, 192 cells; 80Wh/kg, air cooled; 272kg, NEC	100 miles	62 miles
Tesla Roadster	56kWh, 6,831 Li-cobalt computer cells; liquid cooled, Panasonic	220 miles	140 miles;
Think City	24.5kW, Li-ion Enerdel	100 miles	N/A
Smart Fortwo ED	16.5kWh; cylindrical Li-ion (computer cells), made by Tesla Motors	85 miles	Less than predicted

- **Current Li-ion technologies provide inadequate range for all EVs**
- **Cells of different chemistries and configurations (pouch, small cylindrical or wound-prismatic) are being used.**
- **Tesla is planning to use the high energy Panasonic cells (Giga factory)**
- **More and more commercial cells will flood the market**

(Poor) Abuse Tolerance of Li-Ion Cells

Common Hazards

- Li-ion batteries present unique safety risks primarily due to their flammable electrolyte, cathode reactivity, ability to form internal short circuits during some charging conditions, and high energy density. The electrolyte in the Li-ion cells contains flammable organic solvents.
- Under high voltage conditions, they undergo exothermic electrochemical decomposition, leading to the formation of gases including hydrogen, carbon monoxide, carbon dioxide, and hydrocarbons. The formation of gaseous products, in conjunction with rising internal temperature due to the exothermic decomposition, lead to over-pressure conditions inside the cell resulting in venting and smoke, fire and thermal runaway.
- Typical causes for catastrophic failures encountered in Li-ion cells/ batteries are
  - Overcharge/overvoltage
  - External shorts
  - Repeated overdischarge; overdischarge with subsequent charge
  - High thermal environments
  - Internal Shorts

Shorting

- Shorting can occur in two ways.
  - External shorts on Li-ion cells through low impedance loads can also result in a rise in the cell's internal temperature followed by venting, fire and thermal runaway.
- Internal shorts can be formed in two ways.
  - Due to manufacturing defects, i.e., metal particles and fragments trapped during the manufacturing process, dislodged pieces of active material, and even wrinkles in electrodes or separators.
  - Can be caused by misuse such as stressing the cells and batteries beyond the manufacturer-specified current, voltage and temperature limits.
    - Lithium dendrites during overcharge and copper deposition during deep discharge
- Cell imbalance may also lead to over-charging and over-discharging if cell-level charge and discharge controls are not used.
  - Suitable Battery Management System (BMS) is essential

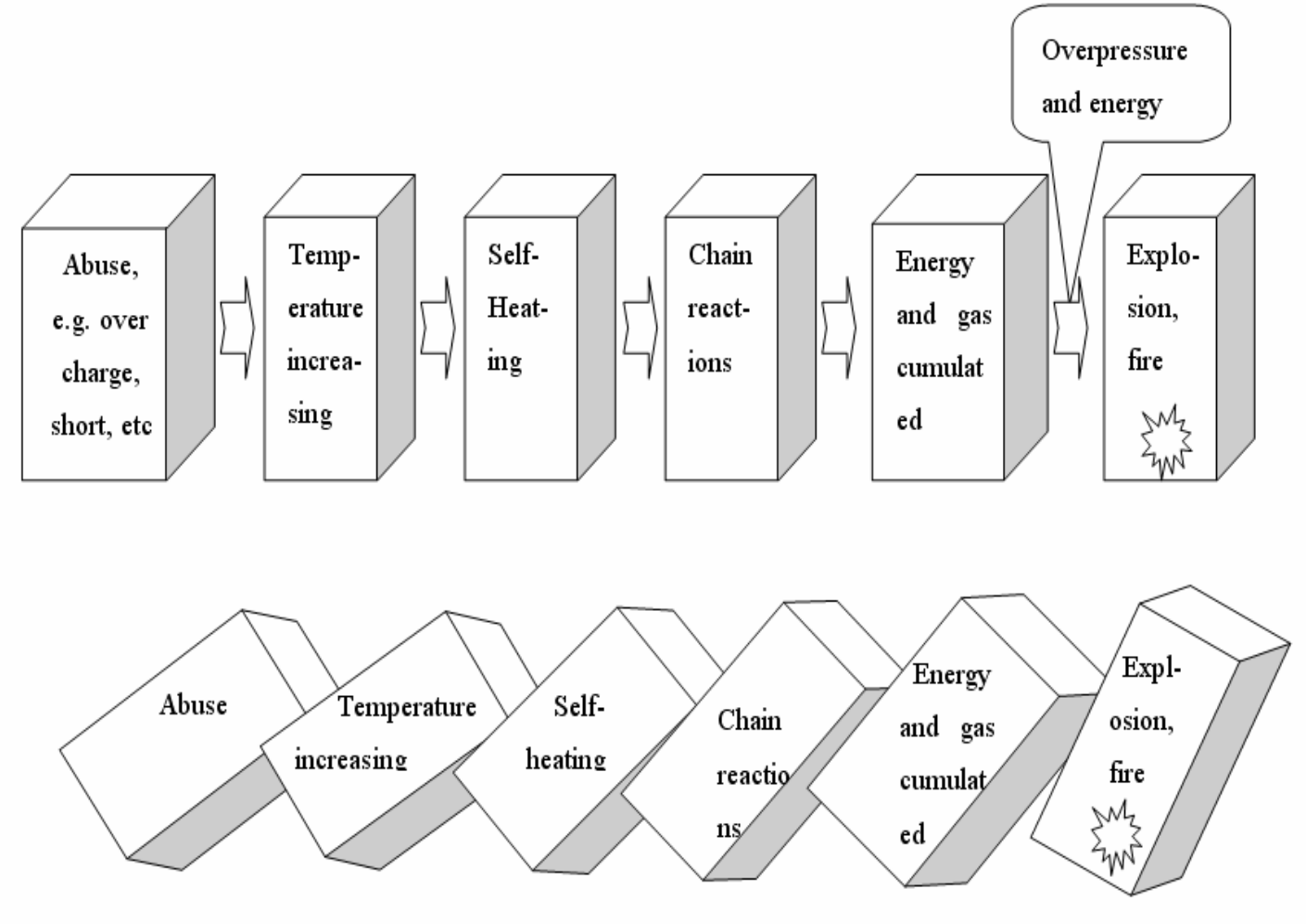
Overcharge and Over-discharge

- Charging at voltages beyond the specified limit causes lithium plating on the anode, oxygen release from the cathode, electrolyte decomposition forming gaseous products leading to cell venting and even fire.
- Essential to monitor and control the cell voltage if the cells in the multi-cell strings are not consistent within a few mV.
    - Commercial cells do not have the cell level control with the assumption that cell voltages do not diverge during use (in the course of storage or cycling).
- Over-discharge is generally a performance issue. Poor performance has been reported in instances where the cells were discharge below 2.0 V
    - Over-discharging can cause the deposition of copper from the copper current collector onto the cathode, anode and separator, which in turn, may result in two shorting failure modes.
        - Growth of lithium dendrites at the deposited copper nuclei during subsequent charging and
        - Changes in the affected cell's internal resistance that forces the remaining normal cells in the string to go into an overcharge condition more easily.

Thermal runaway

- Thermal runaway is the most deleterious form of abuse event. While it is most often caused by over-charging or short circuits (external or internal), it generally occurs whenever the heat generation in a cell exceeds the heat dissipation rate, typically when the cell's internal temperature exceeds190°C (374°F).
- Thermal runaway is a cascading process consisting of the following steps:
  - Loss of the protective SEI layer at 120ºC brings the bare carbon surface in direct contact with the organic solvent, triggering an exothermic chemical reaction between the two, raising the T_{int} above 120ºC.
  - Solvent degradation, also an exothermal process, occurring above 250 ºC, further raises the temperature.
  - Finally, exothermal decomposition of the cathode, raises the T_{int} far above 250ºC, possibly melting the aluminum current collector (melting point ~660ºC) on the cathode and in rare cases, the copper current collector (melting point ~1085ºC) on the anode.
  - Depending upon whether these cascading reactions are localized or widespread, the time-interval between the steps might coalesce therefore separating one step from another during post-thermal runaway forensic analysis might not always discern each step.
- Protective devices may help prevent thermal runaway: PTC against the pressure increase due to a decomposing solvent; and a vent against explosion. However, if T_{int} increases faster than the response time of the protective devices, thermal runaway may still occur.

Domino effect of lithium ion battery fire and explosion



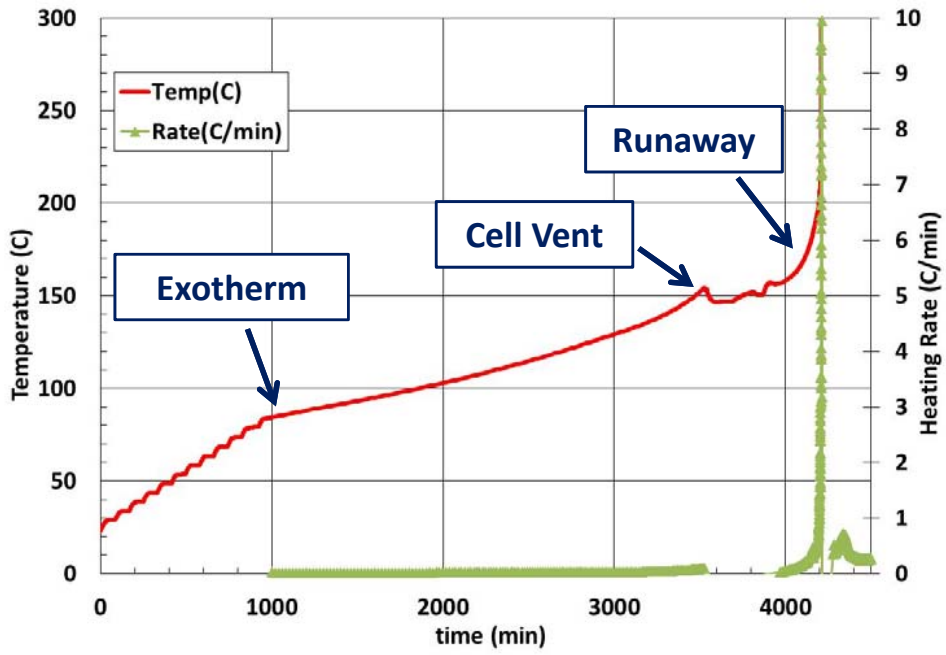
Risk of High pressure Gas release

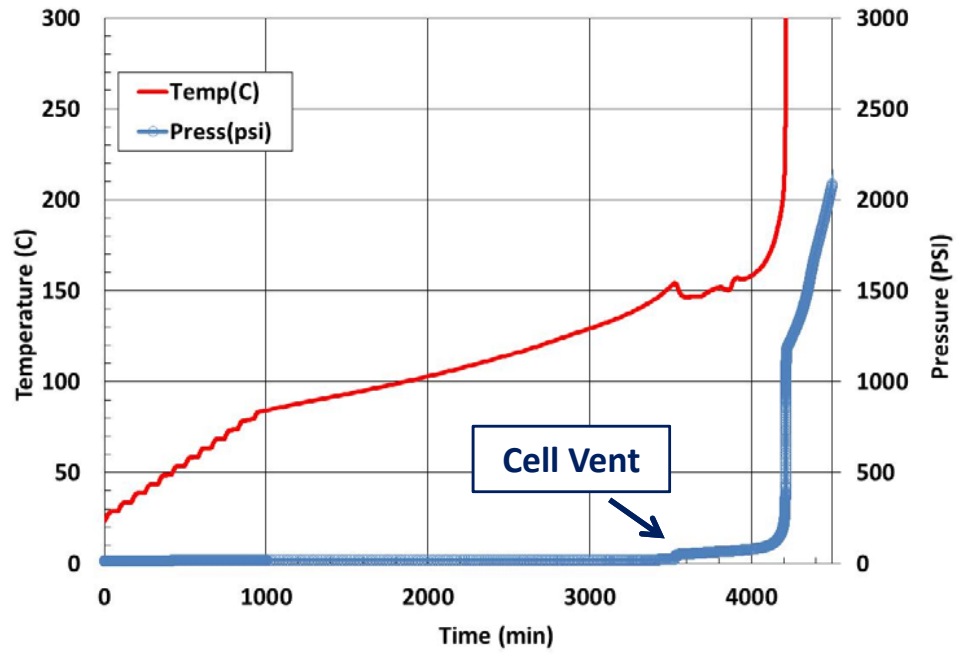
- The hazard posed by the gases vented by a Li-ion battery must be evaluated for its intended application and storage area. In a confined space, the solvents vented from a battery have the potential of mixing with the ambient air and forming an explosive mixture.
- Rapid generation of high internal pressures during abuse situations such as thermal runaway due to the breakdown of the electrolyte solvent.
- The cell (battery) can explode or otherwise generate shrapnel during an abuse situation, which is concern particularly for human-rated applications.

Toxicity and Hazardous Materials Release

- Lithium-ion cells contain both hazardous and flammable materials. Under abusive conditions such as overcharge, heating, or external shorting or internal cell shorting, additional hazardous materials, many in the gas phase, may be generated and react with the ambient moisture to produce additional toxic compounds. Hazardous emitted gases may include, but are not limited to:
  - Carbonates: Ethylene carbonate ($C_3H_4O_3$), Dimethyl carbonate ($C_3H_6O_3$), Ethyl-methyl carbonate ($C_4H_8O_3$), Propylene carbonate ($C_4H_6O_3$), and Diethyl carbonate ($C_5H_{10}O_3$),
  - Gases: Carbon dioxide (CO_2), Carbon monoxide (CO), Hydrogen (H_2), Oxygen (O_2)
  - Hydrocarbons: Methane (CH_4), Ethane (C_2H_6), Ethylene (C_2H_4), Propane (C_3H_8), Propylene (C_3H_6), and Butane (C_4H_{10}),
  - Fluorides: Ethyl fluoride (C_2H_5F) and Hydrogen fluoride (HF)
- $LiPF_6$ salt reacts with ambient moisture to form HF when released from the cell. HF can be in the gaseous as well as in the dissolved state. In either form, HF tends to react quickly with its surrounding therefore may be difficult to detect.

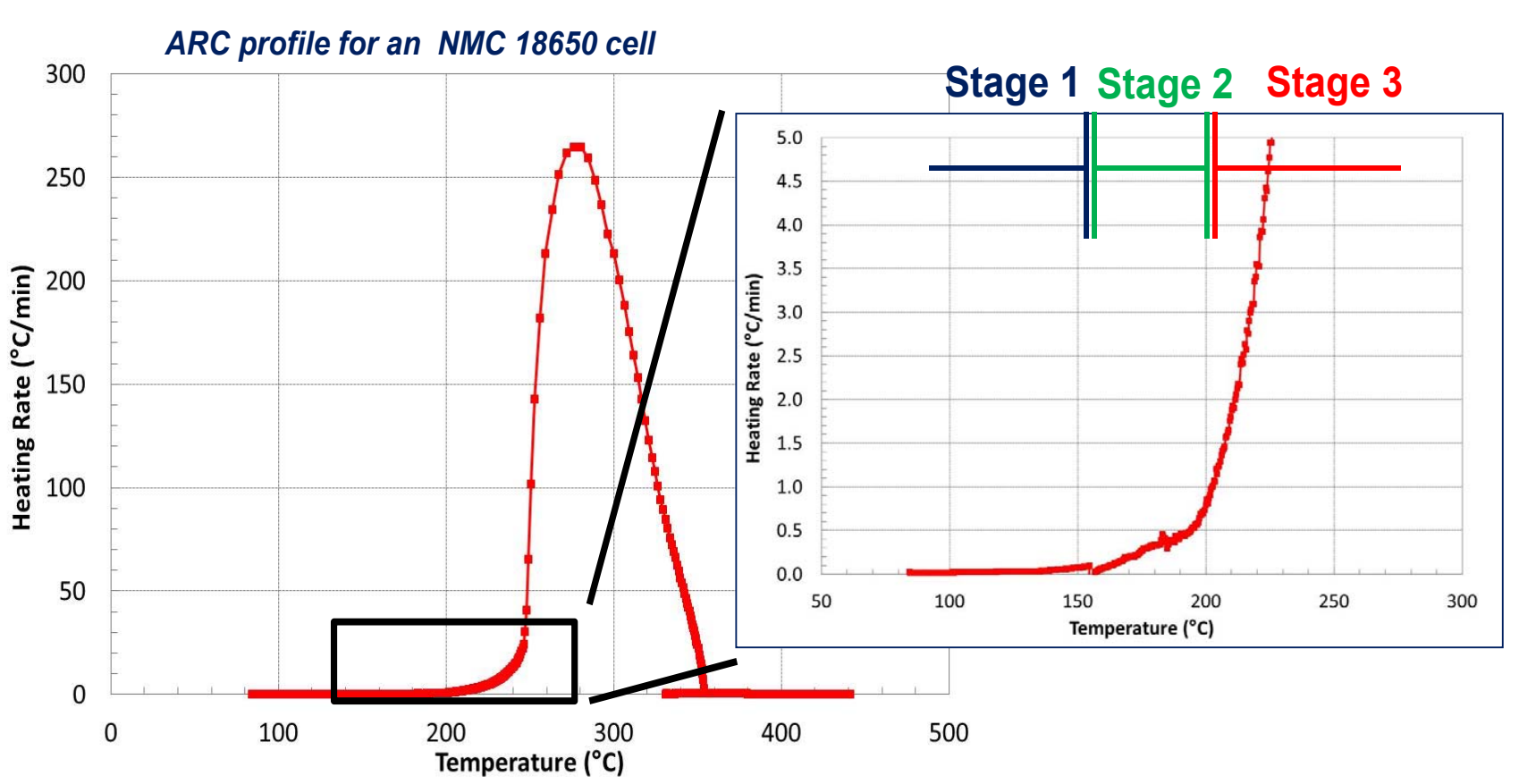
Accelerated Rate Calorimetry of a Li-Ion cell





Data from Sandia National Lab (Courtesy Chris Orendoff)

Accelarated Rate Calorimeter (ARC) Testing



Stage 1: < 160°C – Onset (SEI layer breakdown, electrolyte degradation, etc.)

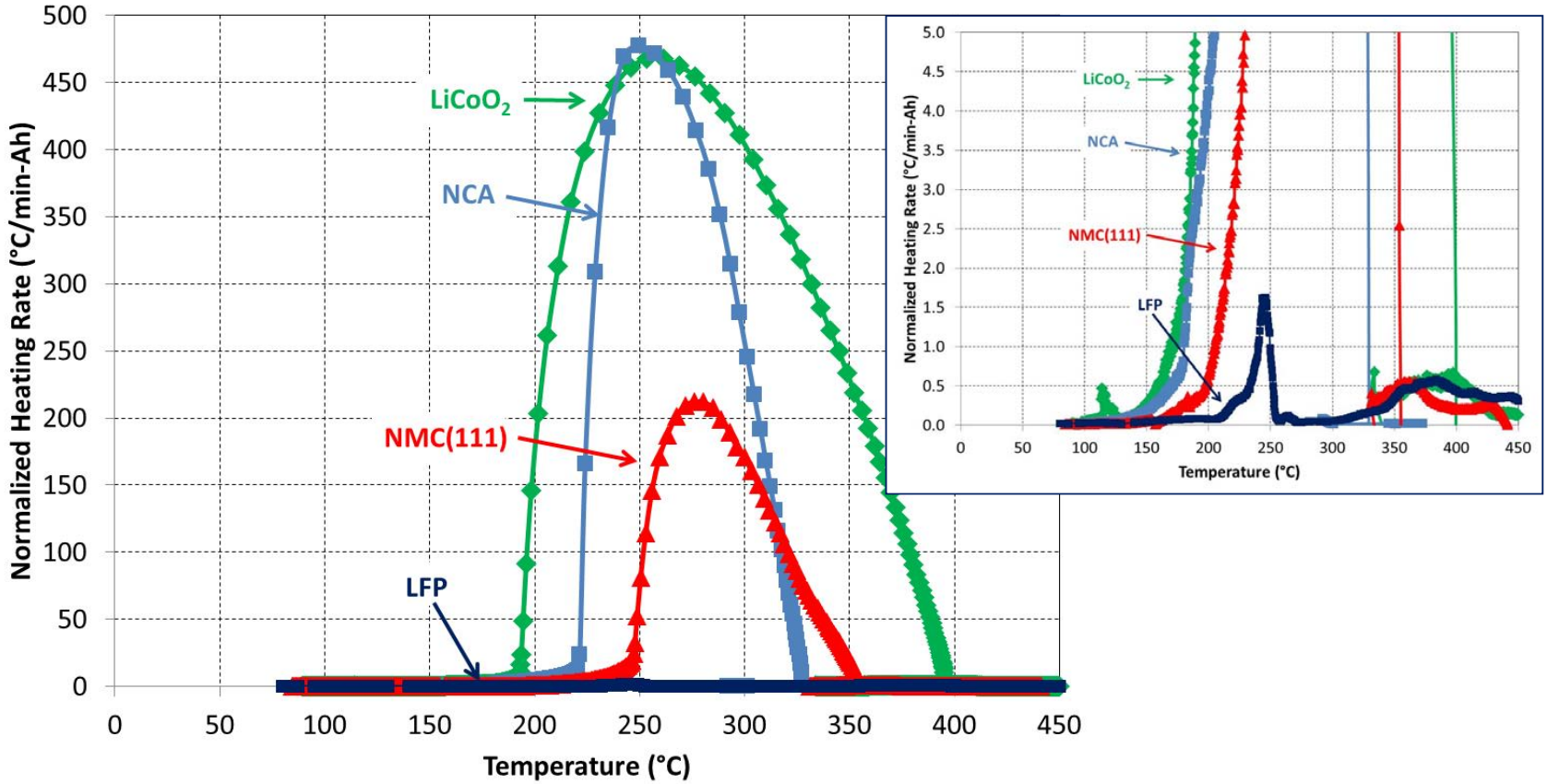
Stage 2: 160°C - 200°C – Acceleration (cell vent, accelerated anode and electrolyte degradation, onset of cathode decomposition)

Stage 3: > 200°C – Runaway (full cell materials degradation, energetic release and uncontrolled rapid disassembly)

Data from Sandia National Lab (Courtesy Chris Orendoff)

Impact of cell chemistry

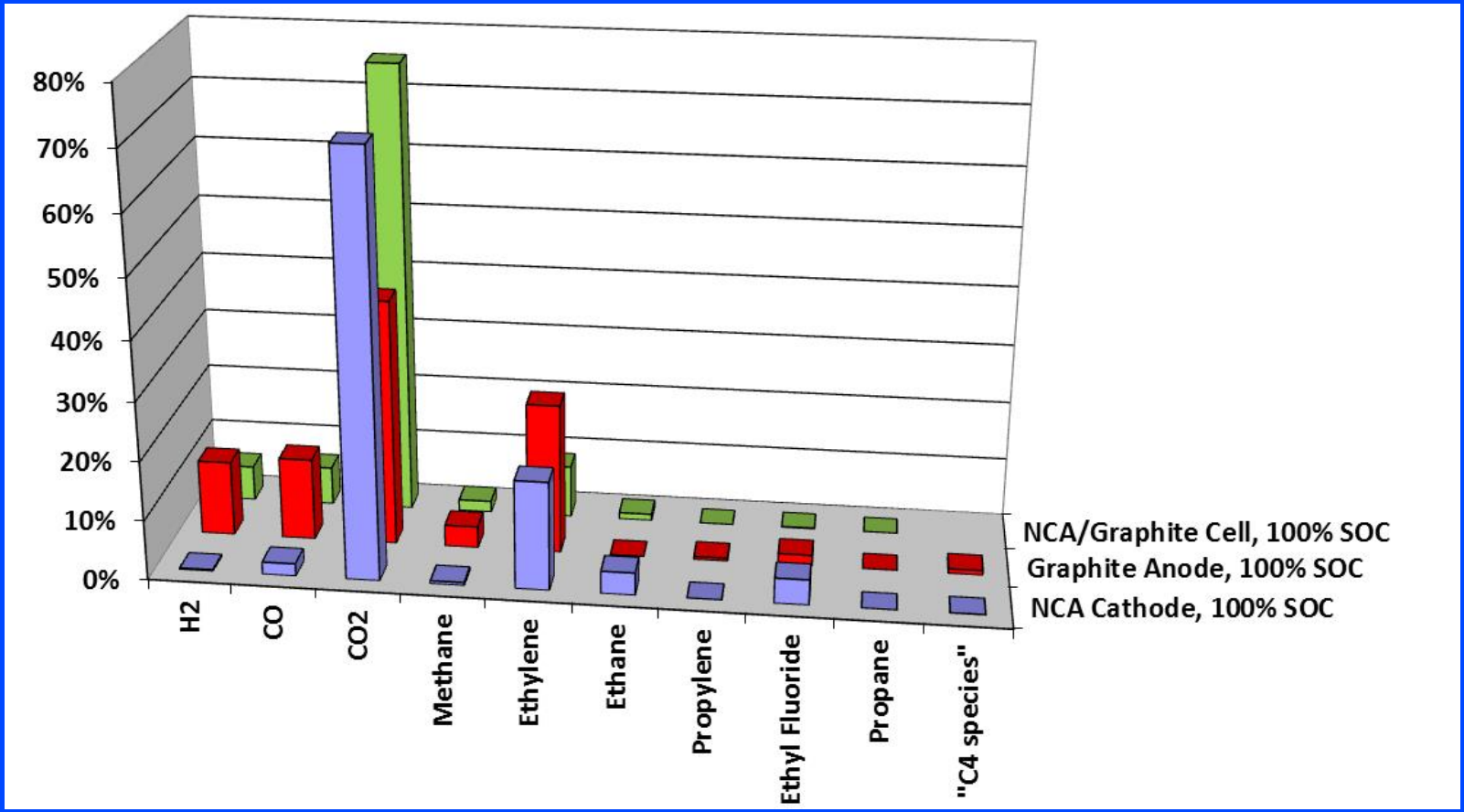
Accelerating rate calorimetry (ARC) of 18650 cells with different cathode materials



- ***All measurements at 100% SOC and for cells with 1.2 M $LiPF_6$ in EC:EMC (3:7)***
- ***Differences in runaway profiles are related to oxygen release and combustion at different cathodes***

Data from Sandia National Lab (Courtesy Chris Orendoff)

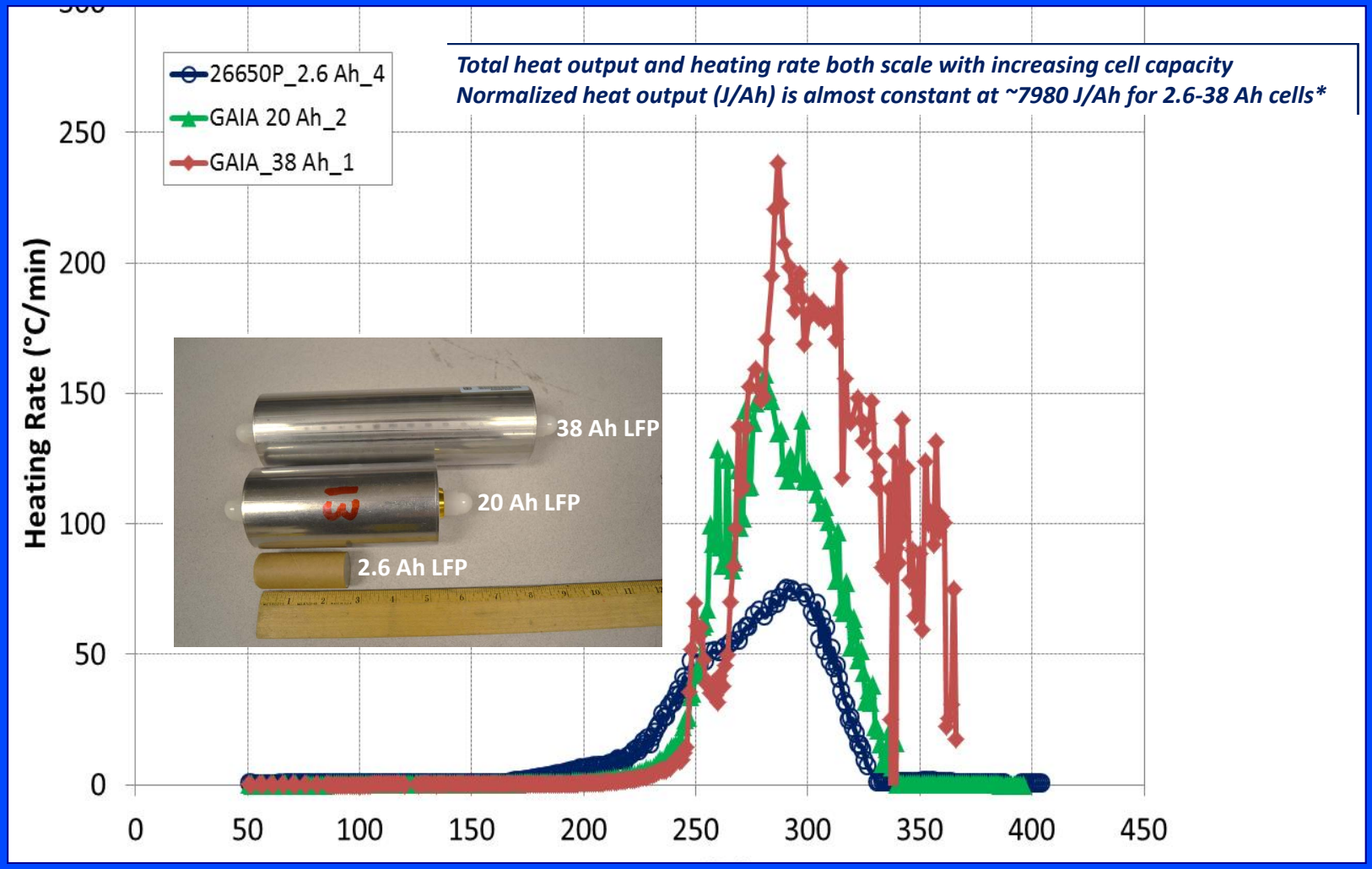
Vent Gas Analysis from ARC



18650 cell electrodes separated from a cell at 100% SOC and repackaged in 18650 cans
Grab samples collected during an ARC experiment and analyzed
Analysis show significantly more H_2 and CO generation at the anode interface

Data from Sandia National Lab (Courtesy Chris Orendoff)

Impact of cell Size on Runaway



Total heat output and heating rate both scale with increasing cell capacity
Normalized heat output (J/Ah) is almost constant at ~7980 J/Ah for 2.6-38 Ah cells*

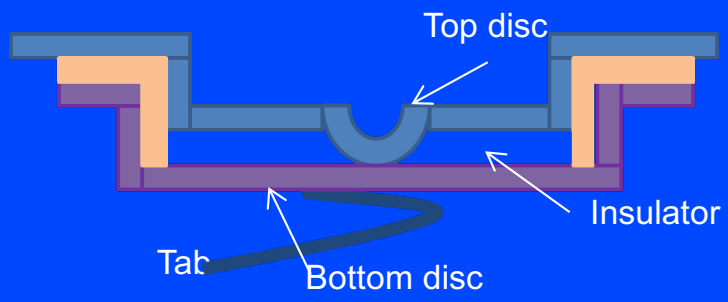
As measured, the LFP cells show the expected trends where larger capacity cells show larger heating rates and larger temperature rise during thermal runaway

Data from Sandia National Lab (Courtesy Chris Orendoff)

Examples of Cell Protective Devices

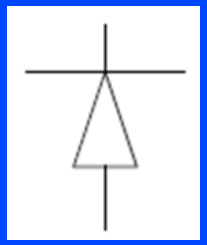
- Lithium-ion cells, whether cylindrical, prismatic, etc. irrespective of size, have different forms of internal protective devices
  - PTC
  - CID
  - Tab/lead meltdown (fusible link type)
  - Bimetallic disconnects

CID

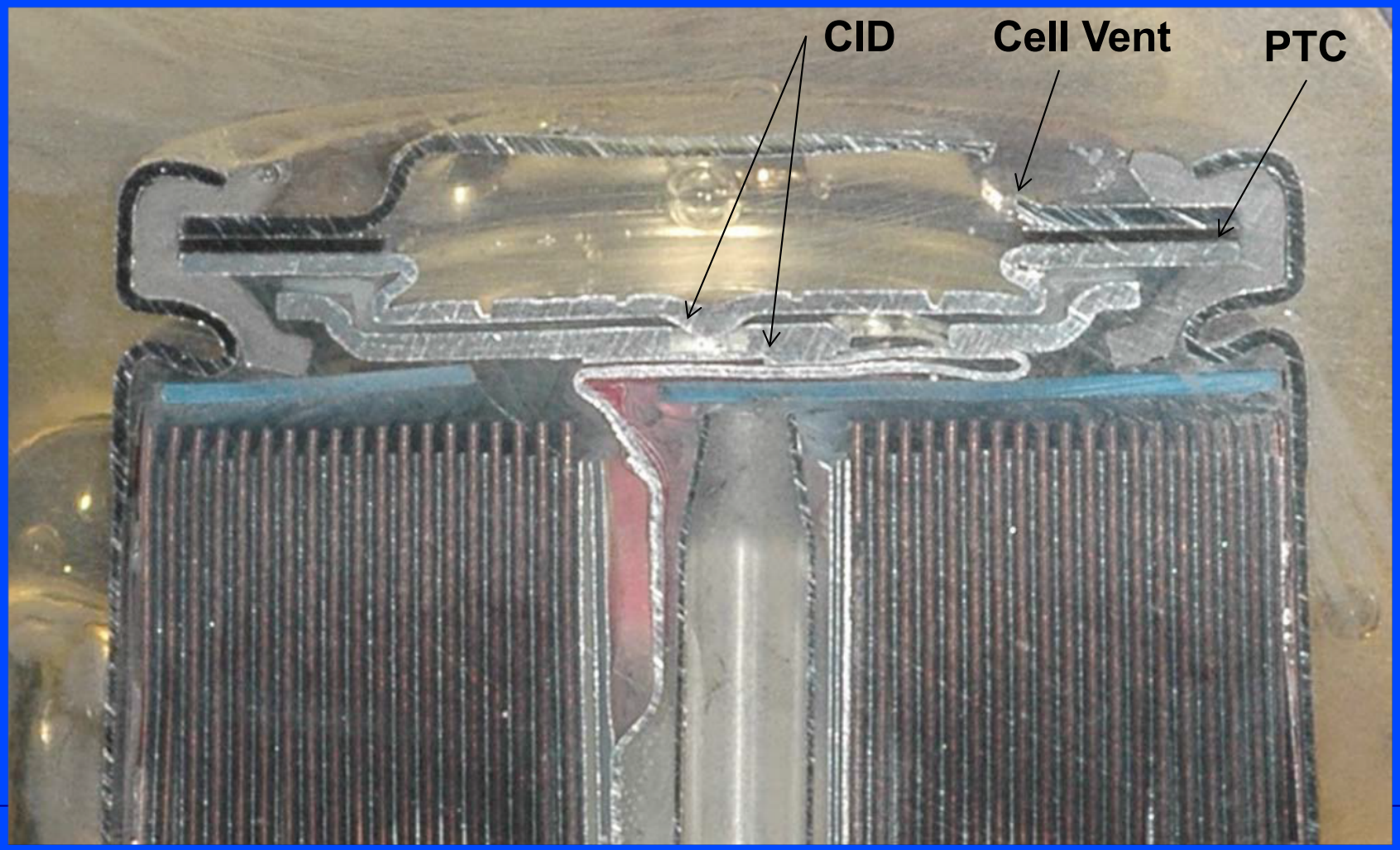


- External protective devices used in lithium-ion battery designs are
  - Diodes
  - PTC/polyswitch/contactors
  - Thermal fuses (hard blow or resettable)
  - Circuit boards with specialized wire traces
- Although cell level protective devices protect cells and low voltage /low capacity batteries (less than 12 V and 60 Wh), extensive testing at NASA-JSC has shown that cell level protective devices do not always protect when the cells are used in batteries of high voltage and high capacity.

Diode



Li-ion 18650 Cell Cross-Section



Failure Modes & Controls or Mitigation Measures for Li-Ion Batteries

Overcharge
Min. 3 controls
Verified by test
*Manuf. spec

Repeated Overdischarge/ Overdischarge followed by charge
Min. 3 controls verified by test
*Manuf. Spec.

High temperatures/High Thermal Environments
*Thermal analysis leading to appropriate thermal sensing; 3 Controls; Verified by test
Design qualified to extreme temps *Manuf. Spec.

External Shorts
High and Low Impedance
Controls and Design for Minimum Risk
Verified by test;
*heat dissipation

Internal Short
Design for Minimum Risk
Stringent testing and screening of flight cells; manuf. facility audits
•Impeccable cell quality, cell uniformity; Usage within manufac.spec. (latent defects, field failures)

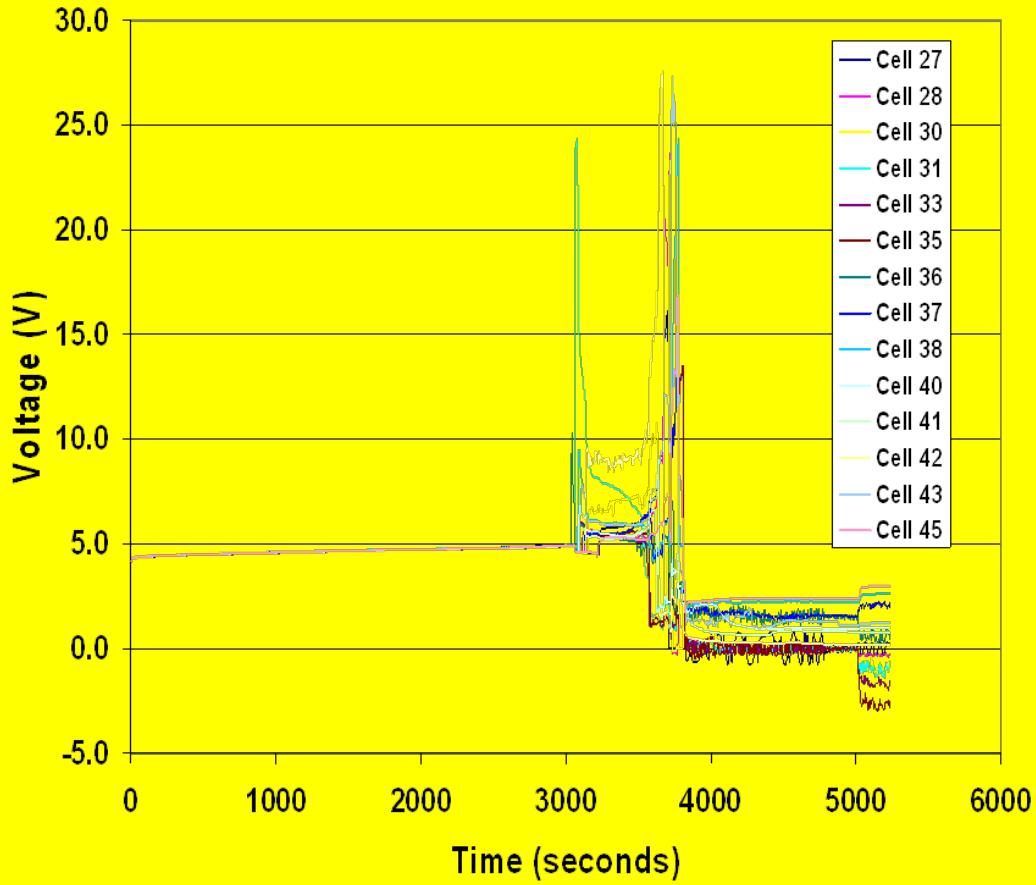
Stringent Monitoring and Control of
*Cell and battery voltage
*Battery current
*Temperature

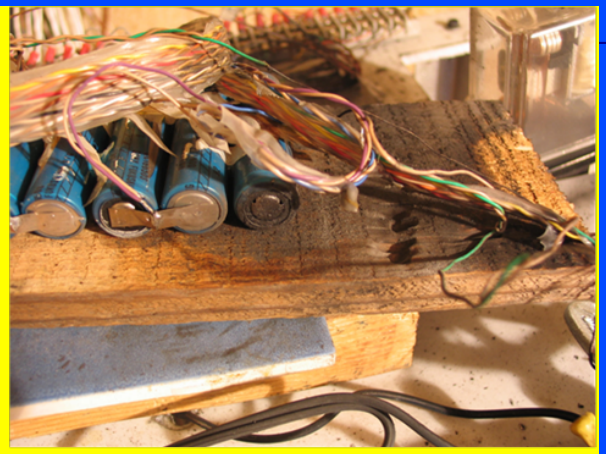
Cell Balancing designed into a majority of applications

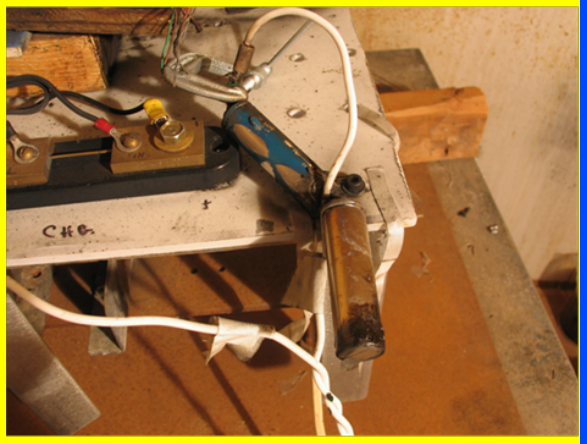
Concerns with Scaling & Testing: Cell to Module to Battery Level

- Cell level controls do not necessarily translate to module or battery level controls
- All safety controls need to be verified by testing at the appropriate level and in the relevant environment
  - Hazards such as overcharge and external short have opposite outcomes in pressurized versus non-pressurized environments due to the difference in heat dissipation
- Li-ion battery designs should have high fidelity thermal analysis to show that the battery design is safe under worst case environments (temperatures and pressures) and under all nominal and off-nominal conditions.
  - Results of thermal analysis should provide guidance on safe designs with very good heat dissipation paths; increases safety and life of the battery
- Li-ion battery management electronics should be robust
  - strike a balance in monitoring and control;
  - extensive testing of control electronics should be carried out on ground
  - For human-rated safety critical applications insight into telemetry should be appropriate for trouble-shooting off-nominal events.

Overcharge Test on a 14-Cell String Showing Cell Voltages for the Sony Li-ion Cells





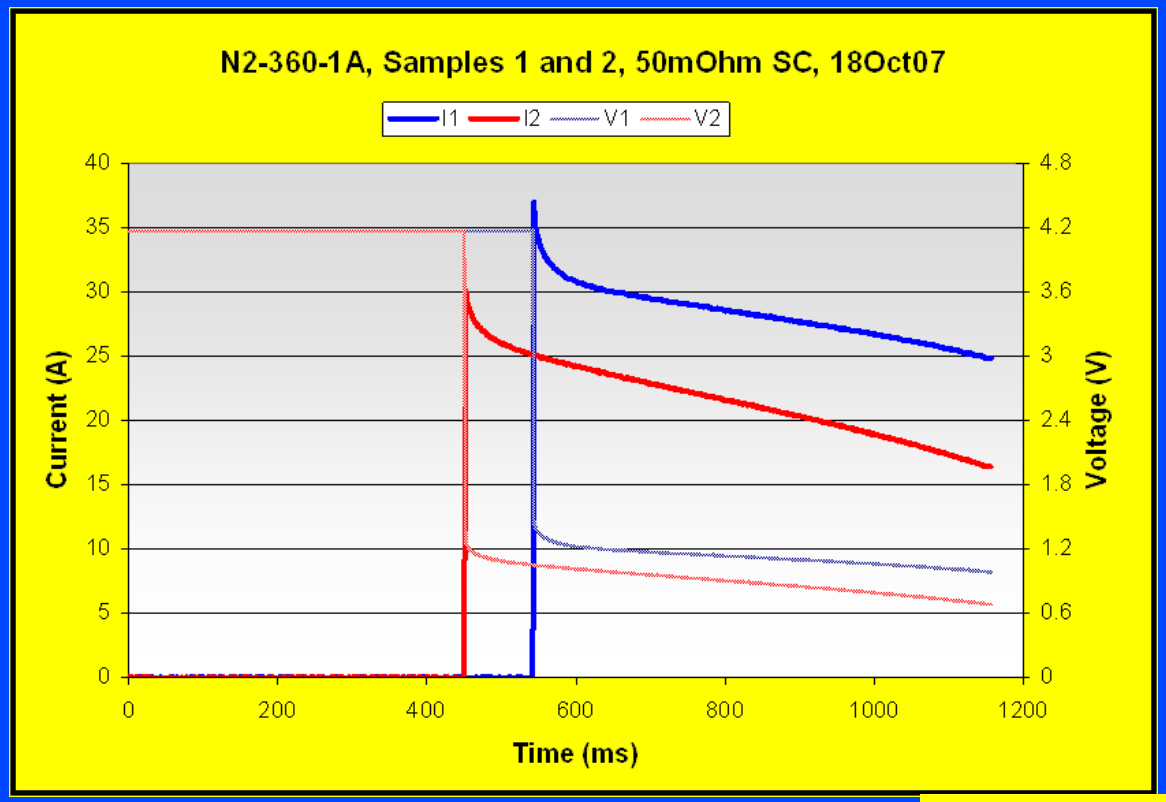


Missing : 27, 28, 30 and 31

Cells 37, 38 and 45 showed no visible Signs of venting

Data from NASA/Johnson Space Center (Courtesy Judy Jeevarajan)

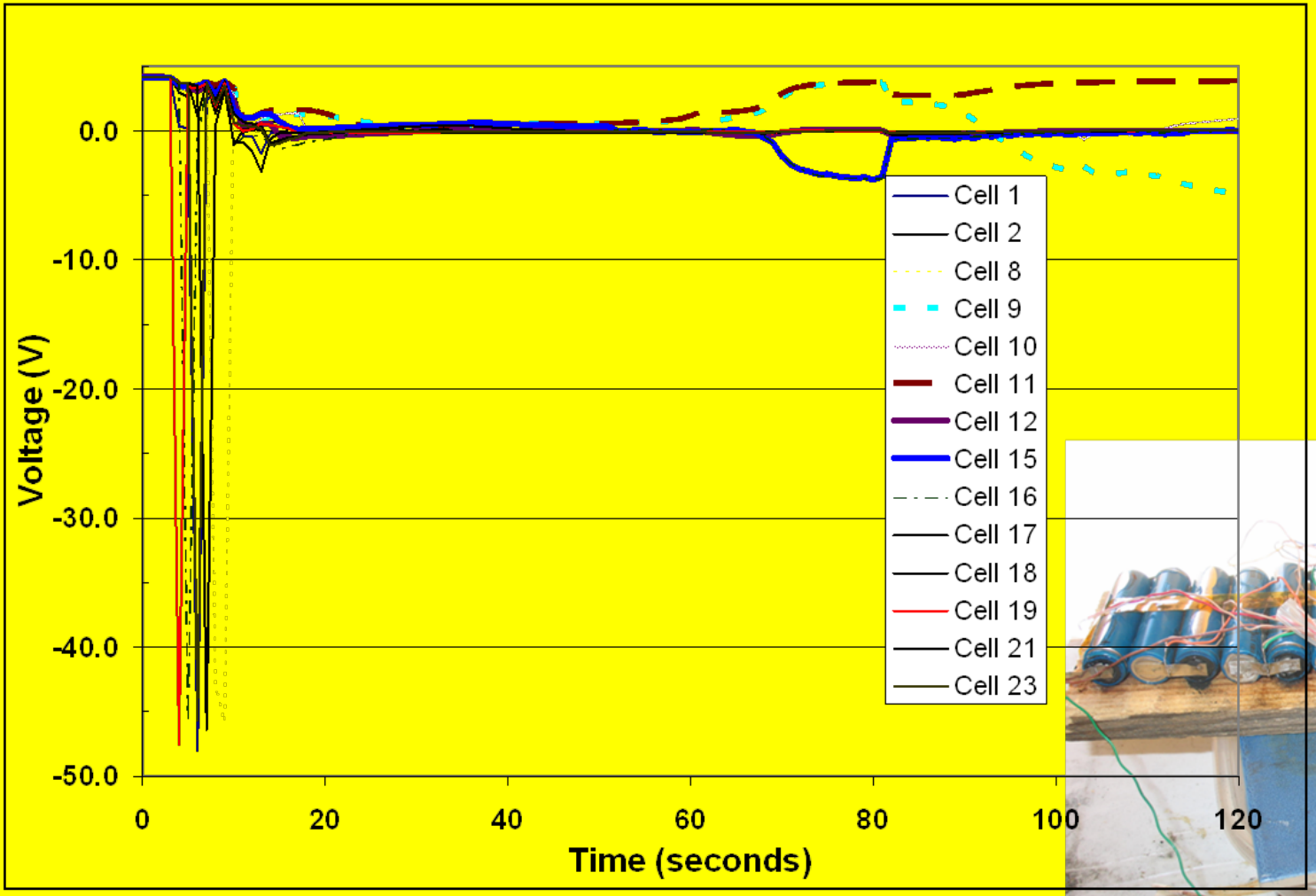
50mOhm Short Circuit, Single Cell



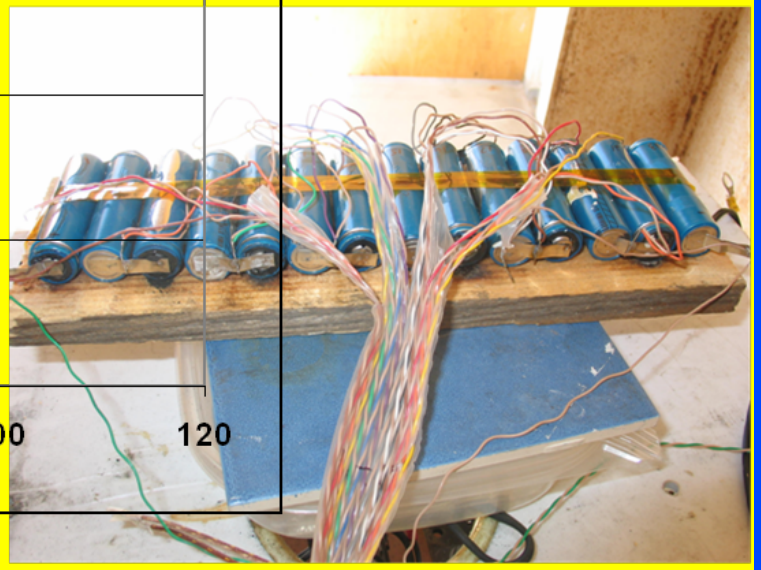
	Peak Current (A)	Peak Temp (°C)	Peak Temp Time (minutes)
N2-360-1A-1	37	78	43
N2-360-1A-2	30	82	49

Data from NASA/Johnson Space Center (Courtesy Judy Jeevarajan)

14-Cell String Short Circuit Test on Sony Li-ion Cells



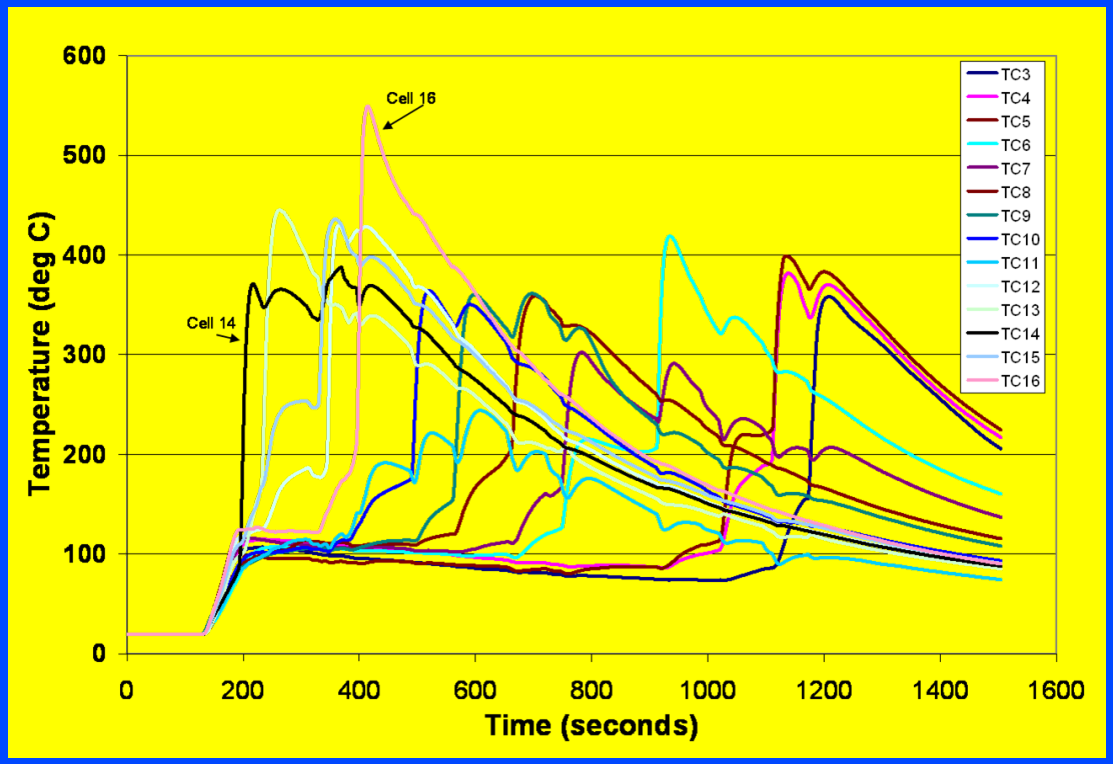
Only venting observed, no fire
Cell Voltages in bold – No visible signs of Venting or damage, but no voltage;
All others vented with Obvious leakage or discoloration



Rapid cell venting within the first 10 seconds

Data from NASA/Johnson Space Center (Courtesy Judy Jeevarajan)

External Short Test on 14S Under Vacuum Conditions

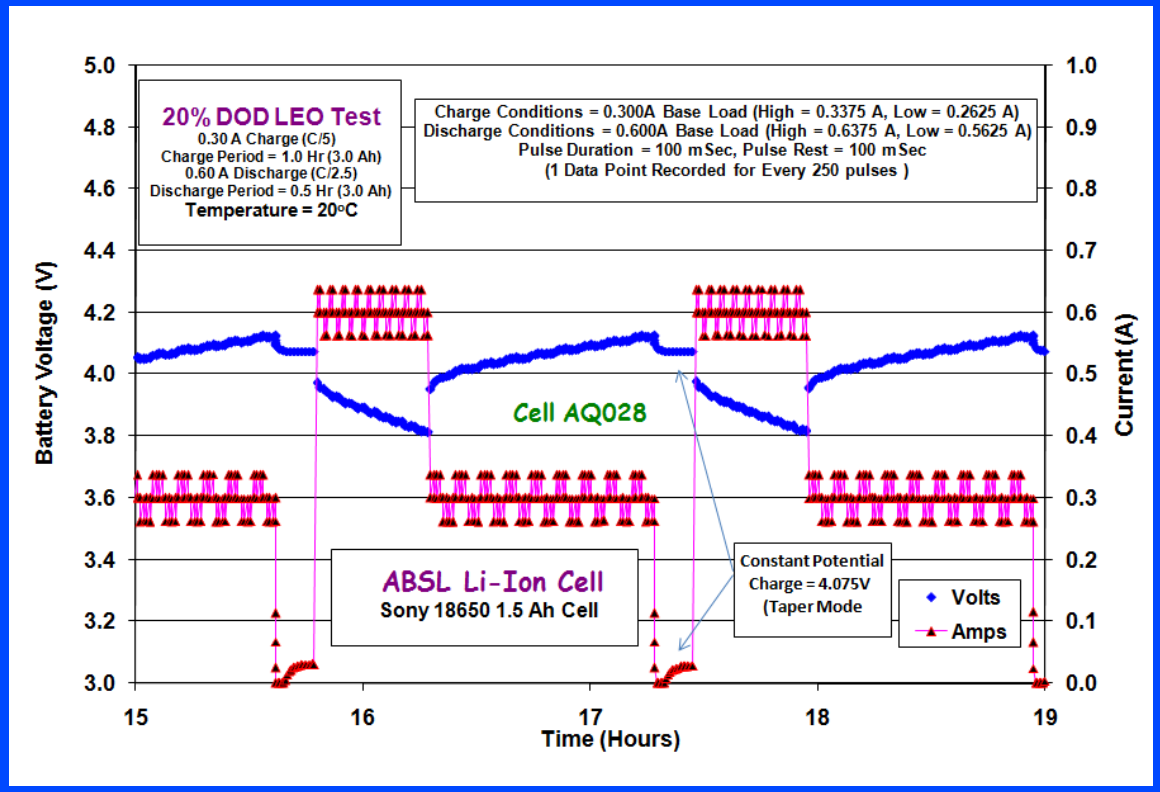


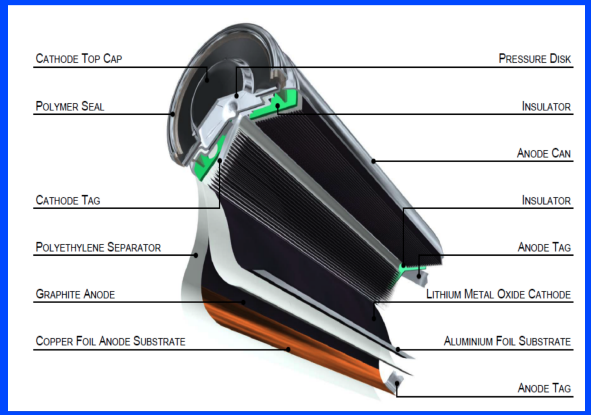
Data from NASA/Johnson Space Center (Courtesy Judy Jeevarajan)

Examples

Example 1: ABSL Lithium-Ion Battery On Power Bus with Ripples

LEO Cycling-Low Frequency Ripple





Battery Incident During Testing at JPL

- Oct 20, 2009, a ABSL 30V, 15Ah Li Ion battery being tested under pulse cycling mode became overheated, caught fire and released smoke and toxic fumes
  - Smoke detector did trigger fire alarm
- No personnel injuries resulted
- Li Ion cell materials including organic electrolytes, PVDF binder, lithiated metal oxides, carbonaceous anode and miscellaneous plastics were released into the room, exhausted to the outside, and vented into laboratory

Description and Consequences of event

- Fire was contained and limited to a steel locker
- Remains of destroyed battery were dislodged from the locker, segregated from intact test articles in adjacent lockers
- Hardware damage limited to the test articles Li Ion battery (cells) in the incident locker and adjacent locker
- Flight hardware (spare MER flight thermal batteries) were in the adjacent B26 room, no damage occurred
- The laboratory was inaccessible for about 7 days.

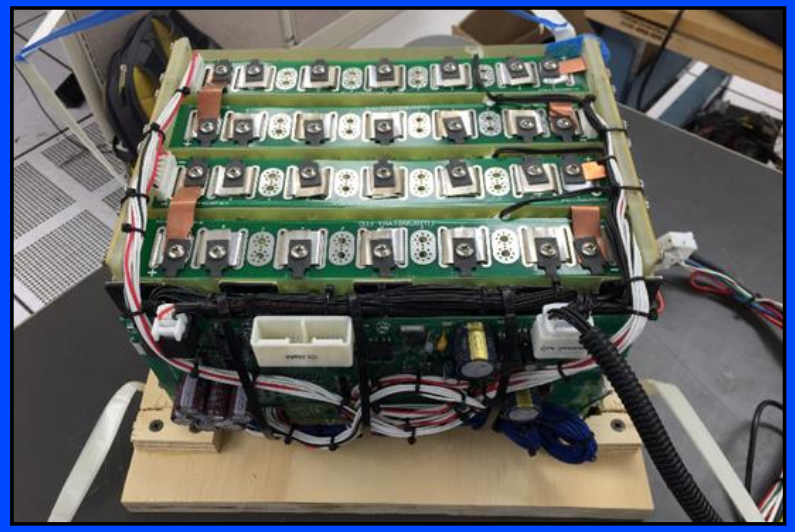
Inspection of Li-Ion Battery remains

Lessons Learned

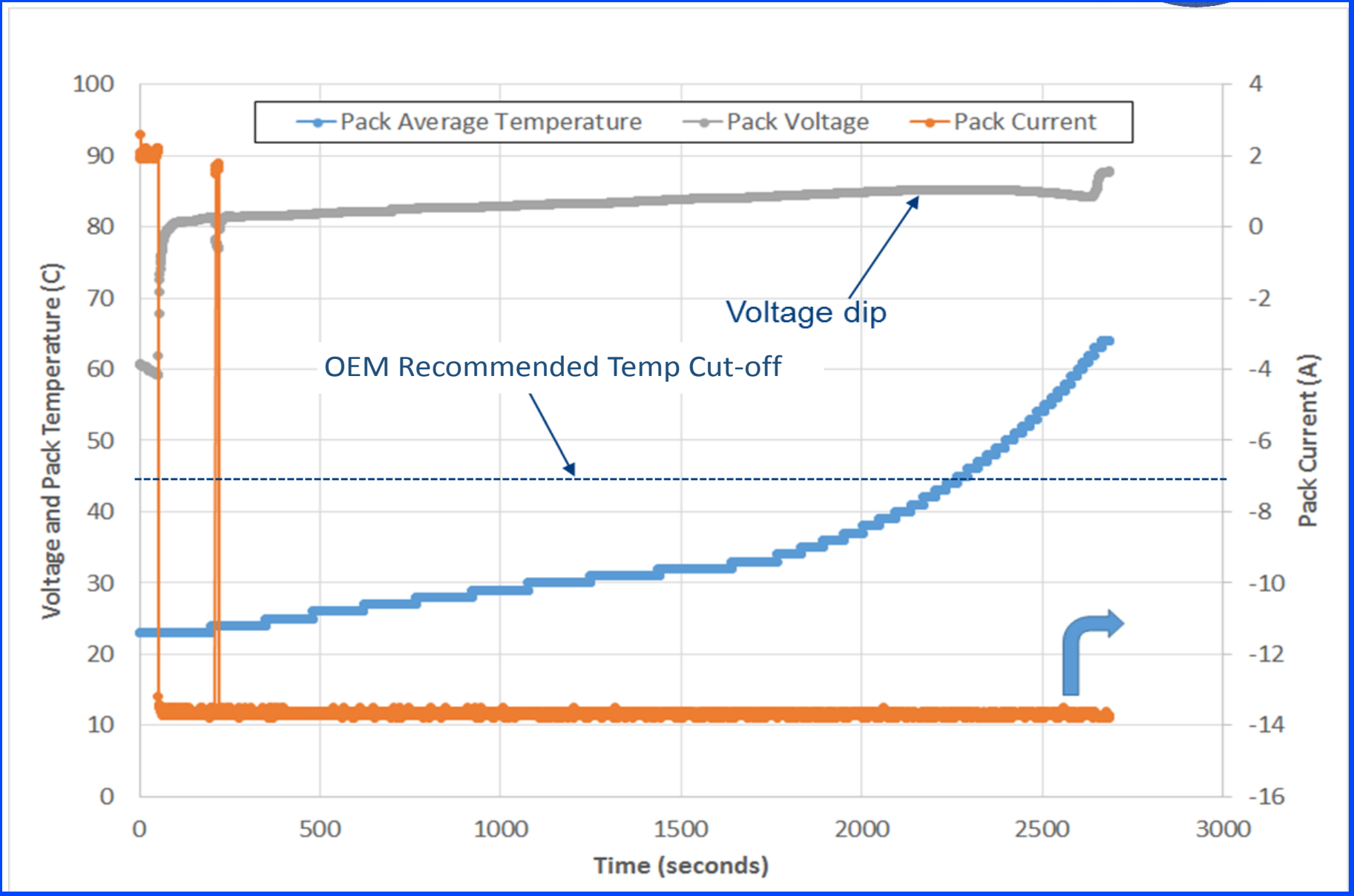
- Maccor (Cycler) may not be used in the pulse mode for long-term testing, since it compromises with the safety control
  - Maccor has independent software limits (on current, voltage and temperature) on each channel, which operate independent of the schedule.
- Sustained overcharge (of ~ 100%) is not permissible even at low rates without adequate thermal environment for heat dissipation.
  - ABSL specifies a maximum charge rate of C/5. This is, however, valid only under conditions where the cells do not warm up rapidly.
- Redundancy in the voltage sense leads recommended
- What we do not know:
  - Did the CIDs (and PTCs) function as desired in the battery?
  - Why didn't cell vent before (instead of) rupturing in the battery?
  - In the cell test, why did the CID activate a few minutes after the pressure reached maximum (and decreased).
  - What is the adequate thermal management? Should that be capable of handling heat generated during normal operating regime or any abnormalities?

Example 2: Battery on a Robot

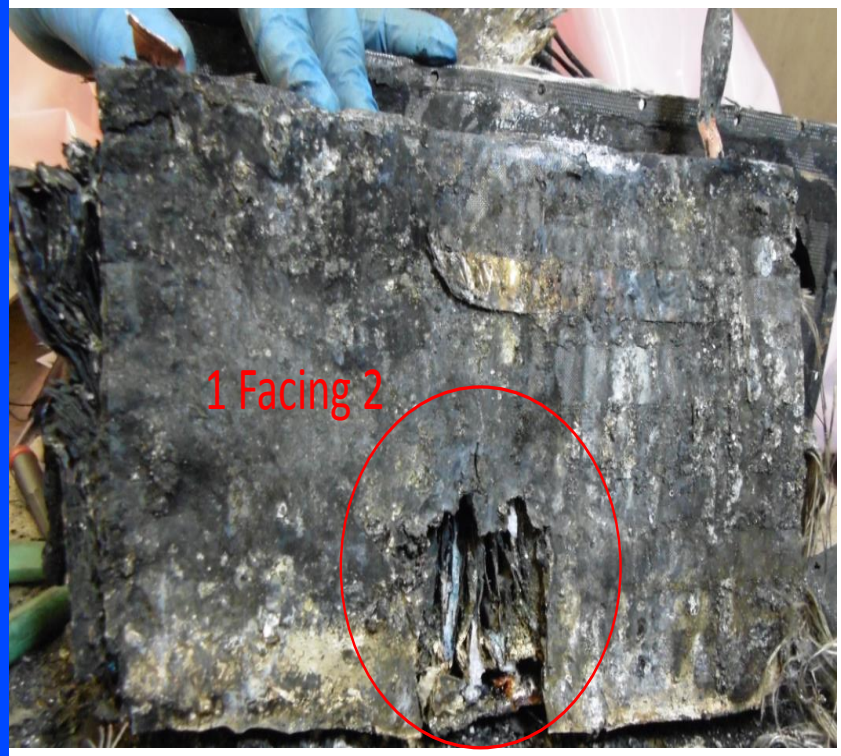
- Three (3) batteries were produced by LithiumStart
- All three batteries had the same configuration
  - 96 cells total (3.7V, 5.4Ah)
  - Two banks of 48 cells 2P24S arranged in parallel
  - Pouch Cell: PF9744128SScLP from Batterist LLC Korea
  - BMS: Orion BMS by Ewert Energy Systems
  - Integrated into custom JPL assembly

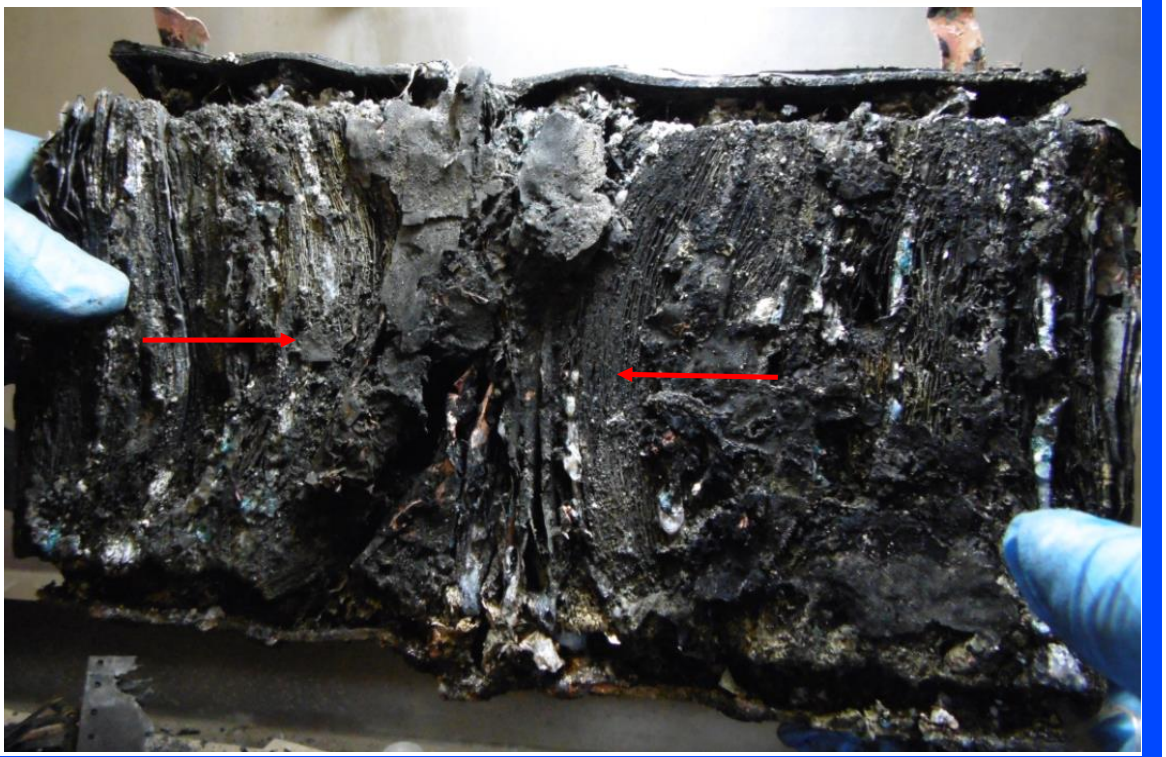


Telemetry Collected during the Event



DPA of the Battery





- String 1 had the separating material between 1 and 2 melted to the side of 1
- The separating material between other strings was easily removed
- Collapsing of the outer cells indicates the first cells to fail where in the middle of string 1
- The other units had cell bowing outward because they failed due to the heat
- Fire suppression used likely limited the damaged of the other strings even though it appears all cells went into thermal runaway

Causes for Battery Failure

- Cells had unusually low cell voltages in the battery pack before charge.
- Cells (pouch cells) had no internal/cell level safety devices
- BMS bypassed during ‘trickle’ charge. With the low battery voltages the charge currents could be up to 13 A.
- Battery management system (BMS) is inadequate with lack of over temperature auto-cutoffs (battery temperature increased >30ºC) and lack of overvoltage cut-offs
- Individual cells tested at JSC seemed to OK, but in a pack the cells showed considerable divergence.
- Imbalanced cell strings in the final battery pack.

Preliminary Lessons Learned

- Use only proven cell designs/chemistries
  - Work with user community to develop reference battery designs for various classes of robots, to avoid proliferation of unsafe battery designs across multiple user platforms
  - Develop and communicate guidelines for safe use and procurement of Li-ion batteries across the laboratory
- Adopt robust battery designs without any parasitic loads.
- Ensure proper functioning of the battery management systems and do not bypass the BMS.
- Follow manufacturer's operational guidelines (within the prescribed voltages ranges, current limits and storage temperatures)
- Establish procedures across the laboratory for proper handling of Li-ion batteries and understanding the associated hazards

Requirements and Test Process

NASA Standards & Certifications

"Human-Rating Requirements for Space Systems" NPR 8705.2B (2009)

Human-Rated:

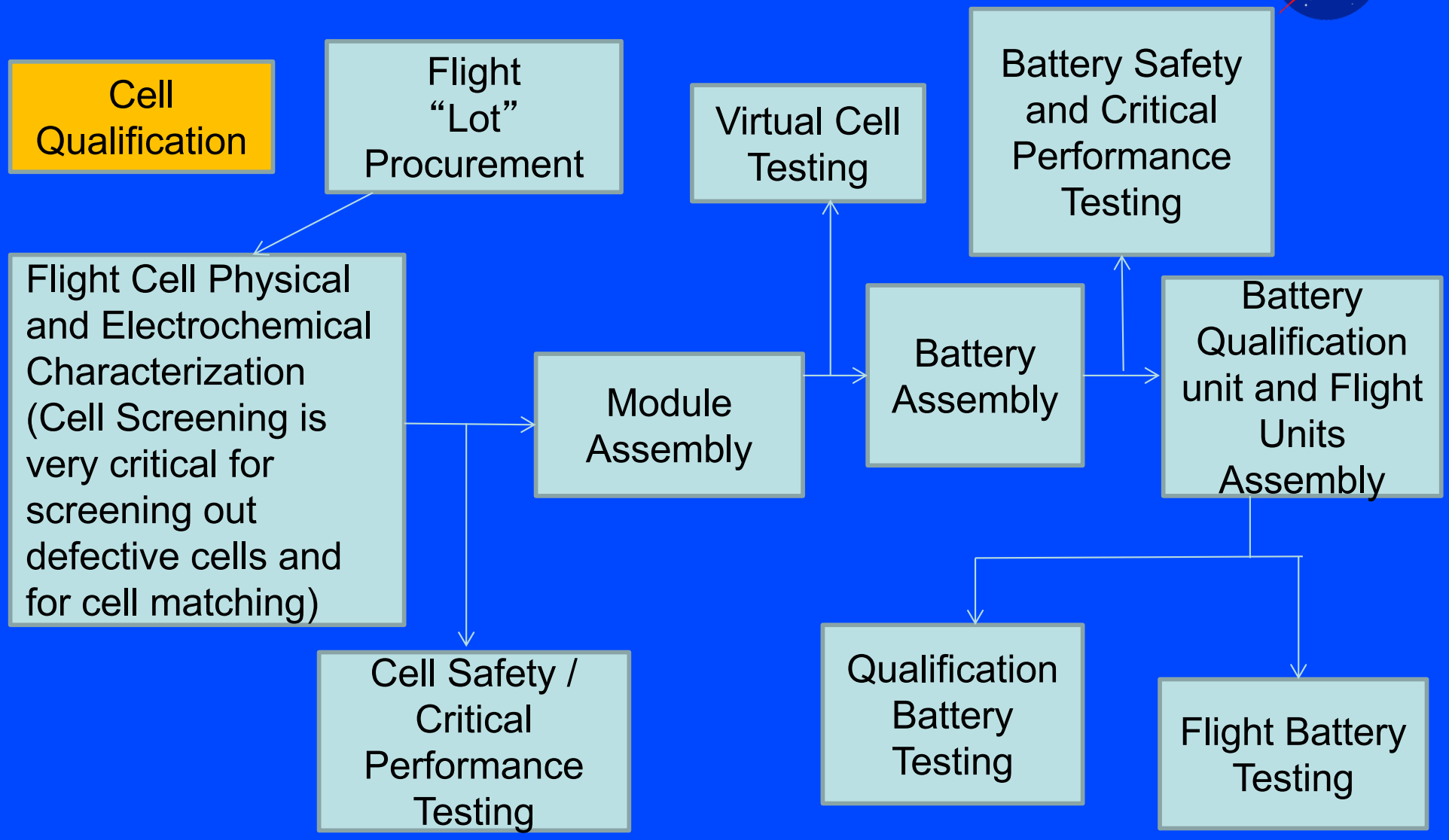
Crewed Space Vehicle Battery Safety Requirements, JSC 20793

- Manned Space Vehicle Battery Safety Handbook (since 1982) converted to Crewed Space Vehicle Battery Safety Requirements, current is Rev B. April 2006; working on Rev C now; in parallel AIAA battery safety document in preparation.
- Battery Processing, JWI 8705.3 and Battery Evaluation Forms (required for all batteries from button cells to large li-ion)

Li-Ion Battery Project & Safety Review Life Cycle

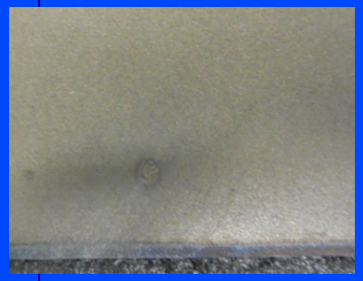
- **Systems Requirements Review (SRR)**
  - Project or Product Technical Requirements Specification (PTRS)
    - Outlines battery specifications, mission requirements for performance and safety, interfaces (mechanical, electrical, data, pressure, etc.) and unique requirements such as pressure variations, thermal extremes, vibration, shock, impact, water proofing, humidity, salt fog, etc.
- **Preliminary Design Review (PDR)**
  - Cell and Battery Design chosen at this point) (Phase 0/1 Safety Review)
- **Critical Design Review (CDR)**
  - Confirmed cell and battery design (Phase II Safety Review)
- **Manufacturing Readiness Review (MRR)**
  - Before start of cell manufacturing and/or battery manufacturing
- **Flight Readiness Review (FRR)**
  - Includes approved safety data packages (Phase III safety review and final approval)

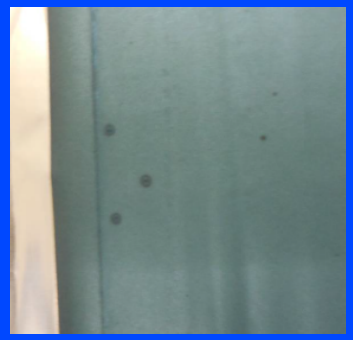
Flow Chart for Custom Li-Ion Battery Build and Acceptance (Sample)



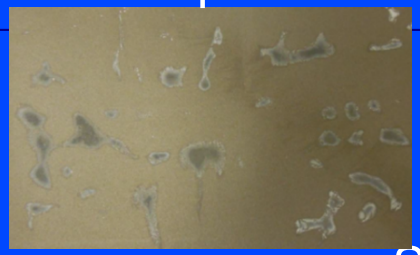
Nature of Defects Observed with Li-ion Cells

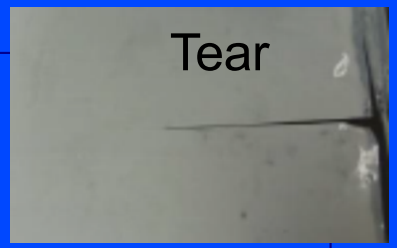
Request Chemical Analysis of Defects



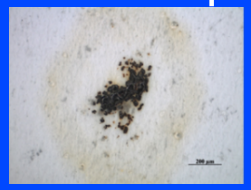


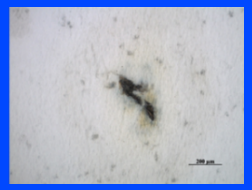
Salt Deposits ?



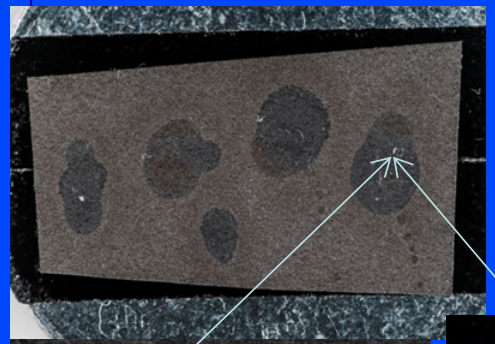


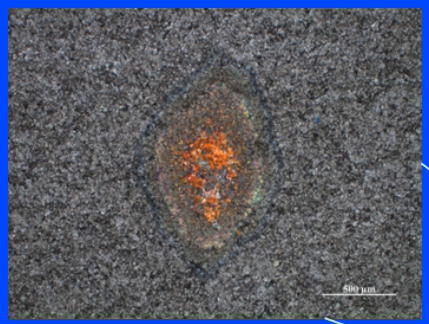
Separator

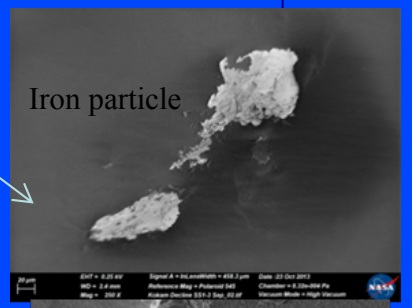




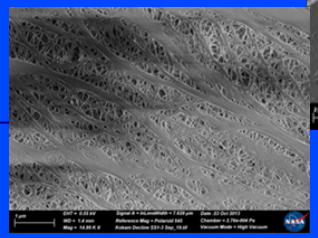
Pristine electrode







Separator away
From defect
Showing porosity



Hazards and Controls

- Fire/explosion, chemical exposure, & extreme temperatures
  - Electrical abuse
    - Controls for preventing overcharging Li-Ion
      - Constant current followed by constant voltage is desired.
        - » Preclude charging at too low or too high temperatures or too fast
        - » Use cell bank voltage sensing controls (or midstring voltage sensing)
        - » Redundant cell bank or midstring voltage sensing with software and/or hardware controls
        - » Last resort, limit the output current and output voltage of charger to the battery to levels that are safe indefinitely
        - » For custom batteries with catastrophic failure modes, in cases where software-based controls are not enveloped by hardware controls, the software is safety critical and its development shall include conventional software assurance processes and confidence not based solely on integrated testing.

Hazards and Controls

- Controls for preventing over discharging / reversal
  - Li-ion – reversal causes soft internal shorts that are rarely hazardous, but catastrophic failures can result upon recharge of overdischarged or reversed cell
    - » Capacity and DC Re matching
    - » Low voltage cut-off and/or OCV window criteria to disallow subsequent charging

Hazards and Controls

- Electrical abuse
  - Controls for preventing short circuiting
    - Secure electrical connections (*most common cause*)
      - » Loose connections create high resistance hot spots
    - Insulating barriers between cell and battery conductive components
      - » Wiring used within the flight battery shall adhere to Electrical Wire and Cable Acceptance Tests
    - Current limiters (electrical or thermal fuse or switch)
      - » at cell level
      - » in negative leg of battery
    - Electrically bond metal battery enclosure components to ensure single point ground path works

From Eric Darcy's Battery Course at NASA/JSC

Hazards and Controls (Cont.)

– Mechanical abuse

- Structural controls includes
  - Complying with safety factors for structural stress for battery enclosure against internal and external forces
  - Battery enclosure and cells shall prevent excessive pressure buildup due to gas accumulation.
  - Design of the hardware shall limit accumulation of hydrogen in enclosed spaces containing oxygen to less than 2 percent of the total free-space volume.
  - Relief valves and vents used as controls for the accumulation of excessive pressure shall be tested.
  - If the battery cell enclosure failure mode is demonstrated to be leak-before-burst, then the ratio of failure pressure to vent pressure shall be a minimum of 1.5 to 1.
  - All other cell enclosures shall demonstrate a minimum ratio of failure pressure to vent pressure of 2.5 to 1.

Hazards and Controls (Cont.)

- Fire/explosion, chemical exposure, & touch temperatures
  - Thermal abuse controls
    - Battery thermal extremes shall be controlled during all mission phases to ensure that the crew is protected from extreme touch temperatures.
    - Battery thermal extremes shall be controlled and verified via test at worst-case mission environments to ensure that all cell temperatures remain within safe operating ranges specified by the manufacturer or verified by tests.
    - External short circuits shall be controlled for the cells and battery assembly to prevent heat generation resulting from high rates of discharge.
    - Validated thermal analysis and testing shall be performed to confirm that the battery cells will not be exposed to temperatures below the manufacturer's rating or the limit established by qualification tests.
    - Battery heaters shall be designed with appropriate levels of failure tolerance to prevent excessive heating of the battery and/or cells.

Li-ion cell driven into thermal runaway by circumferential heater

Hazards and Controls (Cont.)

- Fire/explosion, chemical exposure, & touch temperatures
  - Causes - Inadequate Design and/or Workmanship leading to
    - Cell internal short – DFMR mitigation approach
      - Cells used in COTS batteries or cells selected for a custom battery shall be evaluated to ascertain the severity of an internal short circuit event.
        - » Use cell designs whose performance and safety have been sufficiently characterized
        - » Batteries should be designed to perform well within the manufacturer's specifications for the cells used to build the battery.
          - » If not, then extensive testing with margin to predicted environments should be carried out to confirm that the battery design will not be driven into a catastrophic safety hazard.
        - » Battery designs should have the required FT to prevent the cells from being subjected to off-nominal conditions that result in the formation of internal shorts.
        - » Cells or batteries used in space applications should not have any records of Consumer Product Safety Commission (CPSC) recalls.

Hazards and Controls (Cont.)

- *Fire/explosion, chemical exposure, & touch temperatures*
  - *Causes - Inadequate Design and/or Workmanship leading to*
    - *Cell internal short – DFMR mitigation approach*
      - *Cells used in COTS batteries or cells selected for a custom battery shall be evaluated to ascertain the severity of an internal short circuit event.*
      - *Measures shall be taken to reduce the likelihood of an internal short circuit event to a level acceptable to the program/project.*
        - » ***<u>Test mitigation measures</u>***
          - » *Rigorous 100-percent cell acceptance testing should be carried out, including charge retention (soft shorts), performance uniformity. Poor OCV stability, poor coulombic efficiency (Ah out/ Ah in), internal resistance fluctuations, and high self-discharge (poor voltage retention) are indicators of internal cell defects that could result in an internal short circuit.*
          - » *During cell design selection, examined by DPA and nondestructive evaluation (NDE) techniques (CT scans or high-resolution X-rays) to look for defects that could develop into latent internal short circuits.*
          - » *All anomalous observations in a DPA should be chemically analyzed and discussed with the cell manufacturer to determine whether they will lead to a catastrophic latent defect through the life of the cell.*
          - » *For lithium-ion and primary lithium systems, the vibration test levels shall be significantly higher than those typically imposed for*

Hazards and Controls (Cont.)

- Fire/explosion, chemical exposure, & touch temperatures
  - Causes - Inadequate Design and/or Workmanship leading to
    - Cell internal short – DFMR mitigation approach
      - Cells used in COTS batteries or cells selected for a custom battery shall be evaluated to ascertain the severity of an internal short circuit event.
      - Measures shall be taken to reduce the likelihood of an internal short circuit event to a level acceptable to the program/project.
- **<u>Operational mitigation measures</u>**
      - Operate battery with positive margins in operating voltage, current, temperature, and cycle life versus the manufacturer's limits for the cell design.
      - If not, perform relevant testing to confirm that no failures will develop due to this type of usage during the life of the battery.
        - » In addition, samples from each new lot should be tested to confirm that this tolerance and safe performance capability exists on subsequent productions.

Hazards and Controls (Cont.)

Fire/explosion, chemical exposure, & touch temperatures

- Causes - Inadequate Design and/or Workmanship leading to
  - Cell internal short – DFMR mitigation approach
    - Cells used in COTS batteries or cells selected for a custom battery shall be evaluated to ascertain the severity of an internal short circuit event.
    - Measures shall be taken **to reduce the severity** of an internal short circuit event to a level acceptable to the program/project.
      - » For battery designs > 80-Wh, employing high specific energy cells (> 80 Wh/kg, for example, lithium-ion chemistries) with catastrophic failure modes, the battery shall be evaluated to ascertain the severity of a worst-case single-cell thermal runaway event and the propensity of the design to demonstrate cell-to-cell propagation in the intended application and environment.
      - » The evaluation shall include all necessary analysis and test to quantify the severity (consequence) of the event in the intended application and environment *as well as to identify design modifications to the battery or the system that could appreciably reduce that severity.*

Hazards and Controls (cont.)

- Electrical Shock, Corona, and Arc-Flash
  - Causes
    - Personnel exposure to battery power terminals and/or sensor terminals.
    - Failure of battery case, exposing high voltages.
    - Failure of internal wiring, exposing high voltages to the case.
    - Bridging of battery terminals, resulting in an arc-flash.
    - Bridging of high voltage battery terminals with sharp edges, in a partial vacuum environment, resulting in a corona event.
  - Controls
    - Batteries shall protect against electrical shock as specified in NASA-STD-3001.
      - Dead facing connectors with internal contactors and/or arming plugs for high voltage (>50V)
      - Scoop-proof connectors
      - Chassis isolation > 1 Mohm
    - Batteries exceeding 100 Vdc shall be assessed for arc-flash hazards.
      - In battery designs where analysis shows an arc-flash risk, arc flash and shock personal protective equipment shall be employed when working in or around the battery (reference NFPA 70E)
    - External shorts shall be controlled as documented in Section 5.1.3.
    - Corona mitigation designs shall be incorporated as stated in JSC 29129 for high-voltage batteries used in a vacuum environment.

Summary of Safety Guidelines

- Operate the battery within the manufacturer's specified limits of temperature, current (charge and discharge) and voltage.
- Avoid thermal electrical and mechanical abuse. Avoid the following:
  - Overcharge
  - Overdischarge
  - High Temperature Exposure
  - Low temperature and/or high rate charge
- Test the battery with a BMS utilizing adequate voltage and temperature cut-offs and current limits
- Look for the integrity of the battery (any physical damage, vents etc.)
- Test the battery in ventilated area with oxygen sensors
- Handle the battery with gloves and suitable PPE (lab-coat, goggles)
- Avoid External short: No metals around
- Keep a buddy system, while testing the battery
- Use proper tools while carrying the battery from place to place