Lithium-ion Batteries
Safety Characteristics / Requirements

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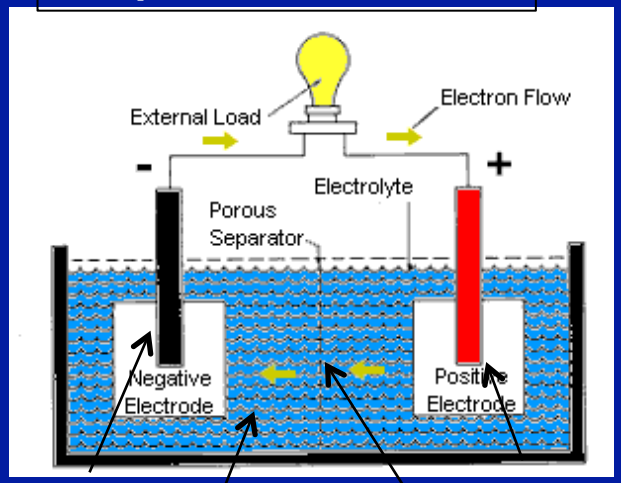
January 17 2016

Battery Tutorial

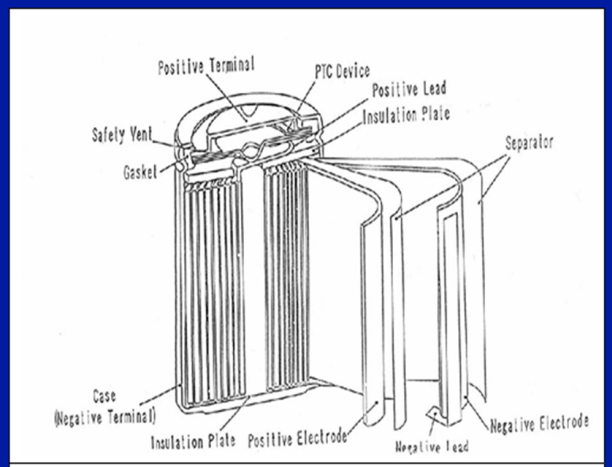
- Electrochemical cell converts chemical energy into electrical energy
- Requires combination of an anode and a cathode to allow flow of electrons through the load and provide energy.
- Anode: Provides electrons to the load during discharge (typically a metal)
- Cathode: Accepts electrons from the load 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

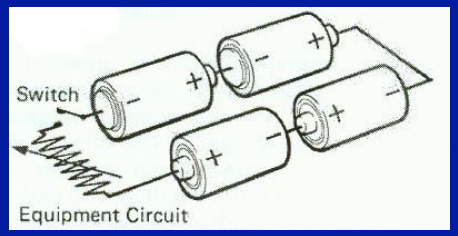
Types of Electrochemical Energy Storage

- 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

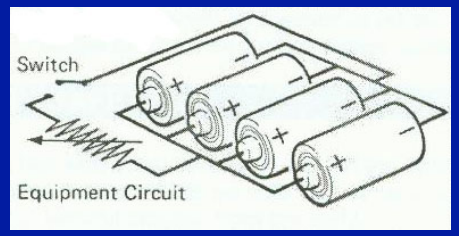
- A cell is the basic unit of a battery
- A battery is an assembly of cells
- Cell geometry is typically cylindrical or prismatic
- Cells can be arranged in series, in parallel or a combination of both:
  - Series arrangement provides higher voltages
  - Parallel arrangement provides higher capacity (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)

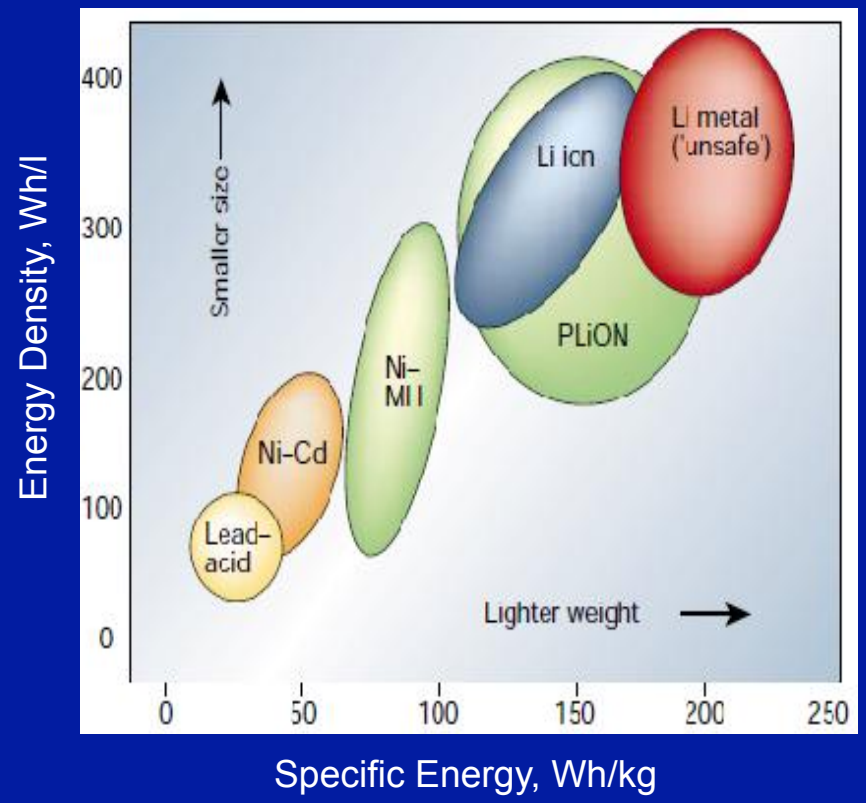


Capacity is additive, voltage is not and remains the same as for a single cell.

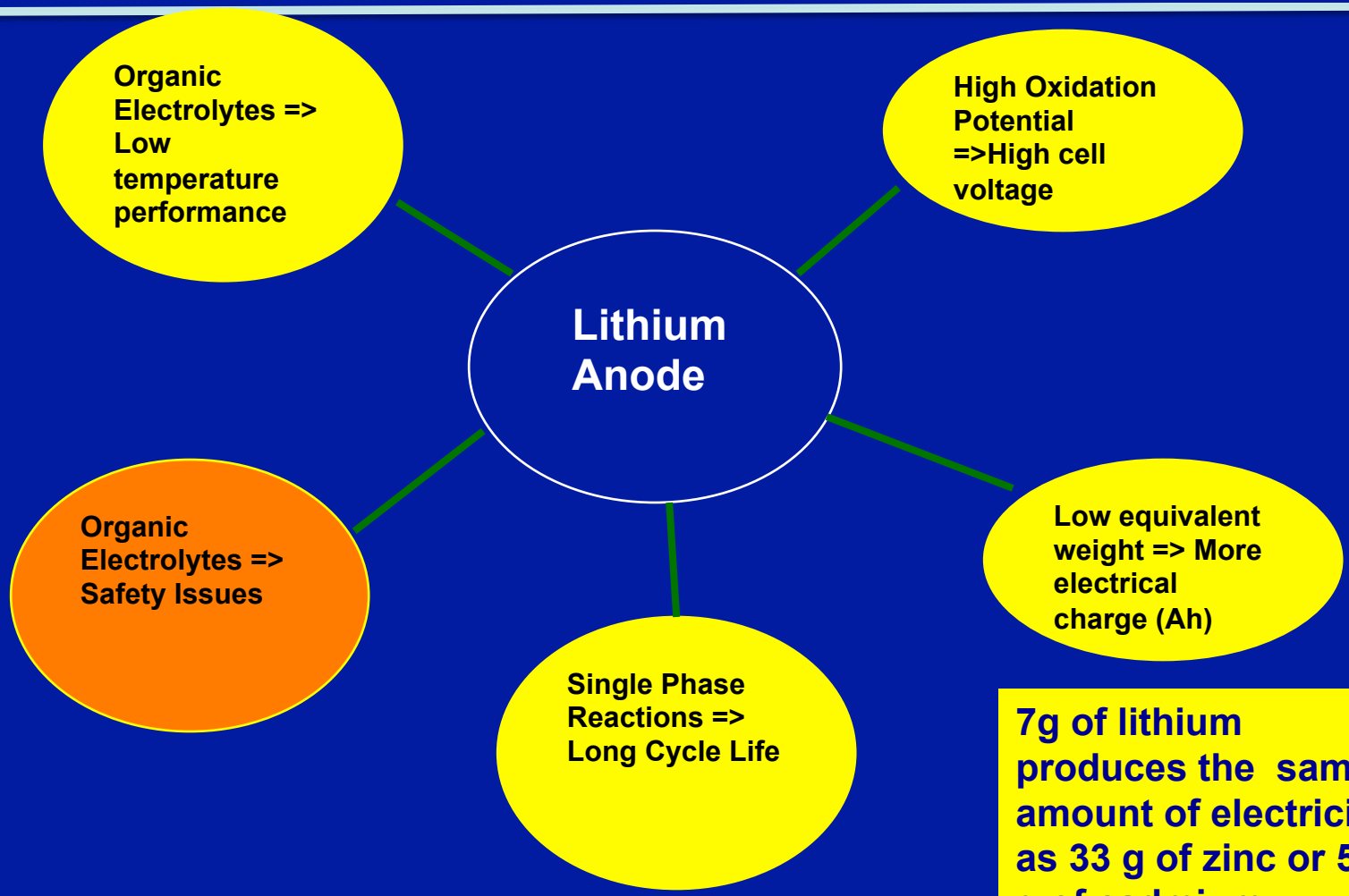
Parallel Configuration (bank)

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



Would Lithium battery be that high energy and long life system?

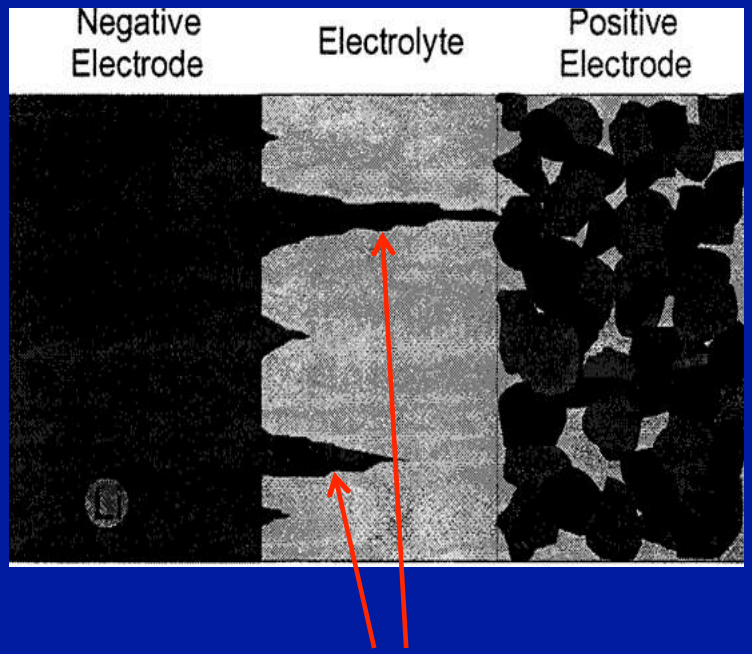


7g of lithium produces the same amount of electricity as 33 g of zinc or 56 g of cadmium

- **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)

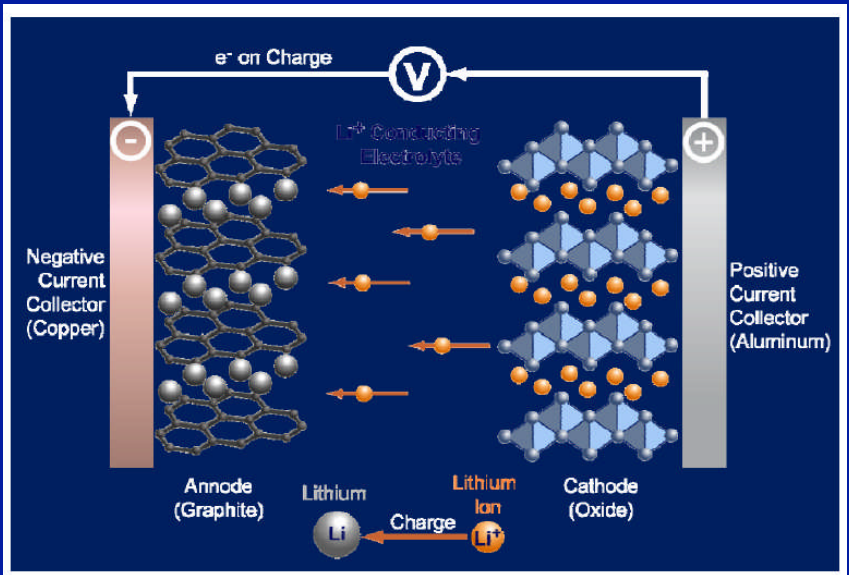
- Battery research between 1975 through 1991 focused on Li metal anode based systems, but the efforts were not as widespread as today
  - Several Li-insertion cathodes and stable electrolytes were developed at various laboratories (Bell Labs, Exxon, Honeywell, JPL)
  - Good cycle life (>500 cycles) and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

Introduction 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)**

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

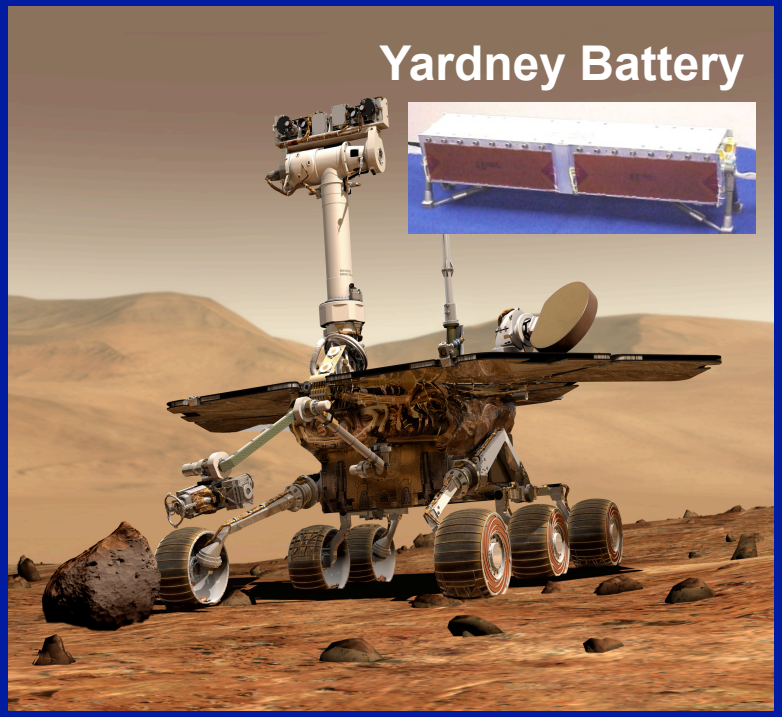
- **Organic (Liquid) Electrolytes**
- **Liquid electrolyte in polymer gels**
- **Solid State electrolytes**

Cathodes

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

Mars Exploration Rover- Spirit and Opportunity (2003)

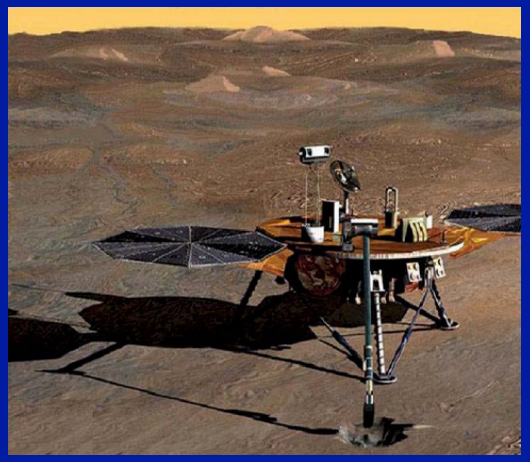
- First major NASA mission with Li-ion batteries
- Excellent performance from the Li-ion battery, both in cycle and calendar life
- Mission enabling: Alternate battery technologies were not viable
  - Silver-zinc battery would have limited the life to six months or less
  - A Ni-H_2 battery would be 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)



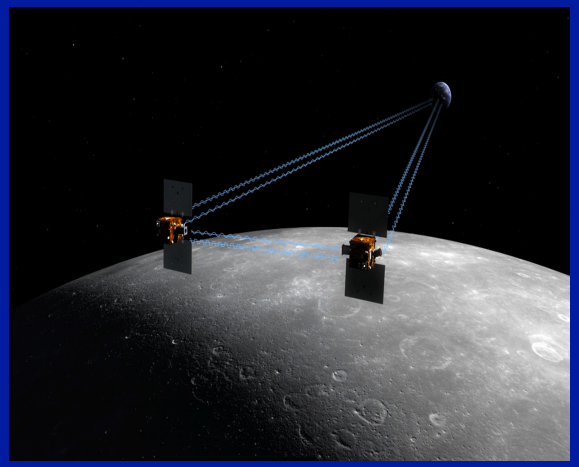
- **Spirit operated over 9 years (vs. 90 days of design life)**
- **Opportunity rover is still operational: 3975 Martian sols (11 years and 2 months) and 10 km.**
- **Battery is expected to last for few more years.**

Missions with MER-Heritage Batteries

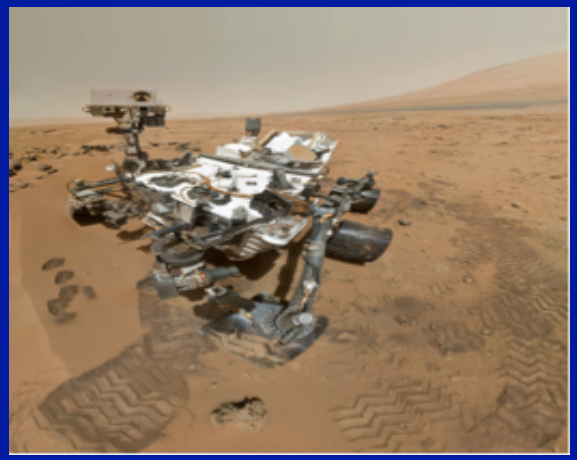
Phoenix Lander (2007)



GRAIL (2011)



Mars Curiosity (2011)



Mars Rover (2020)

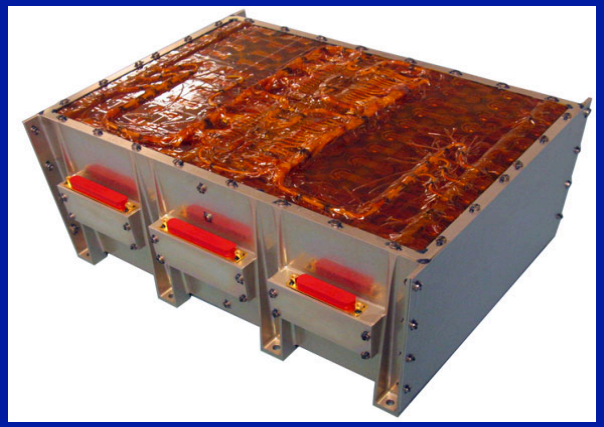
- **MER Battery has had big impact across multiple JPL missions.**
- **Mars 2020 rover follows the same rover design as Curiosity but with different payload.**
- **Mars 2020 Rover will retain the battery heritage with minor changes in the battery chemistry.**

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.**

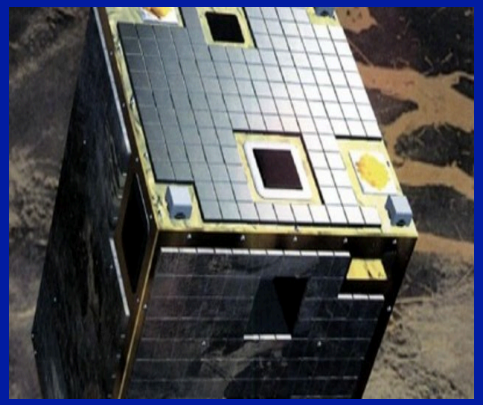


Several Battery Deigns Available (8S10P, 8S16P, 8S52P)

Analogy with TESLA battery using Panasonic cells

Missions with Commercial Cells (Sony)

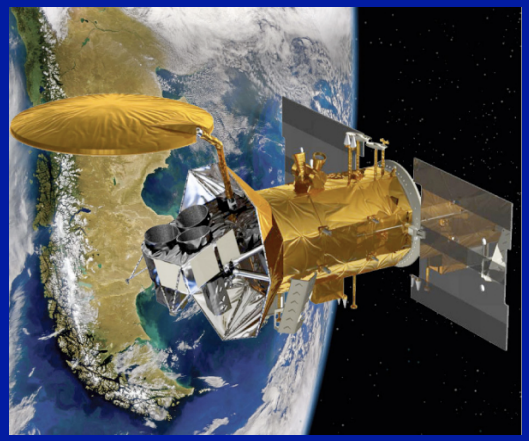
PROBA (2001)



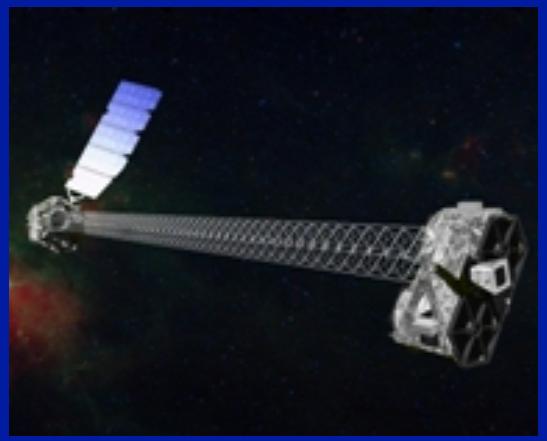
Mars Express (2003)

Kepler (2009)

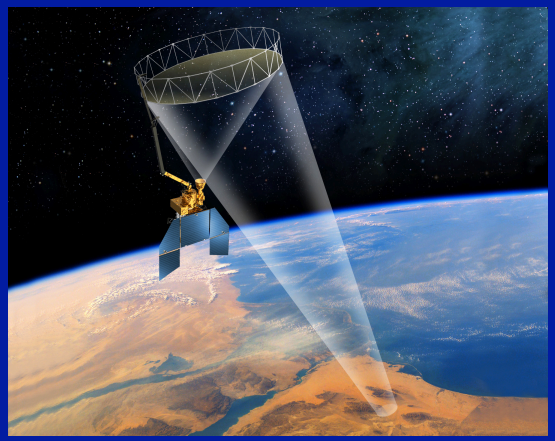
Aquarius (2011)



NuSTAR (2012)



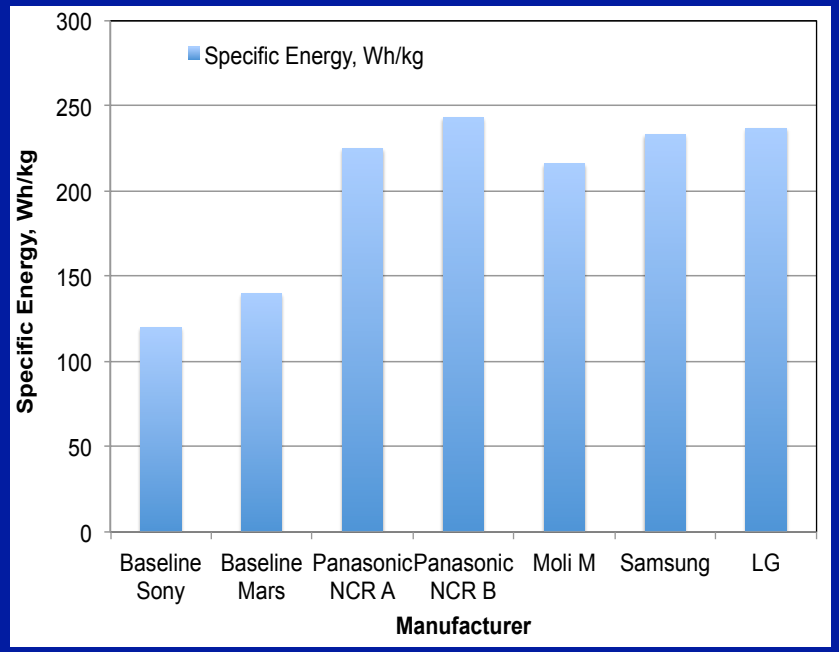
SMAP (2014)



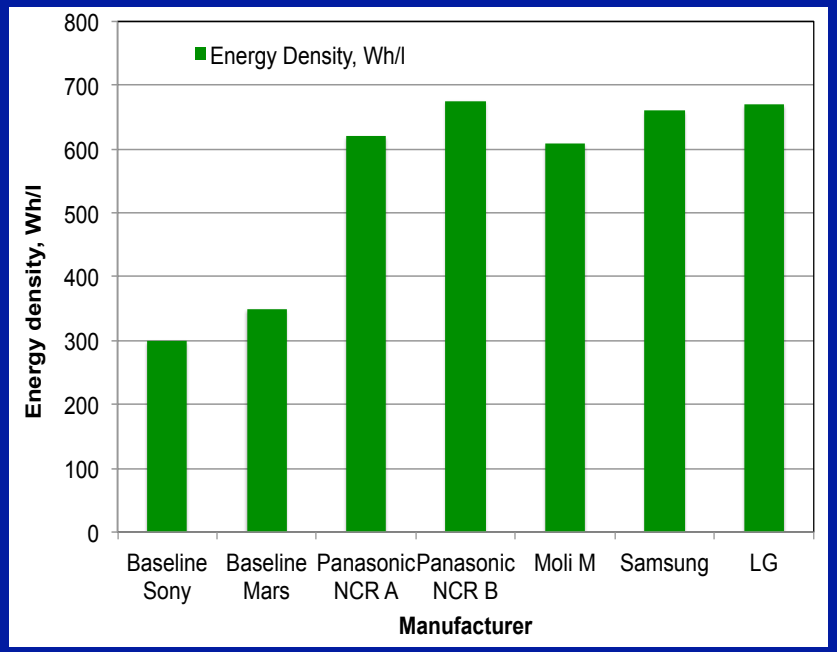
Commercial Cells are Continuing to Get Better

- 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



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 he 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 batteries are discharge below 2.0 V per cell.
    - 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.

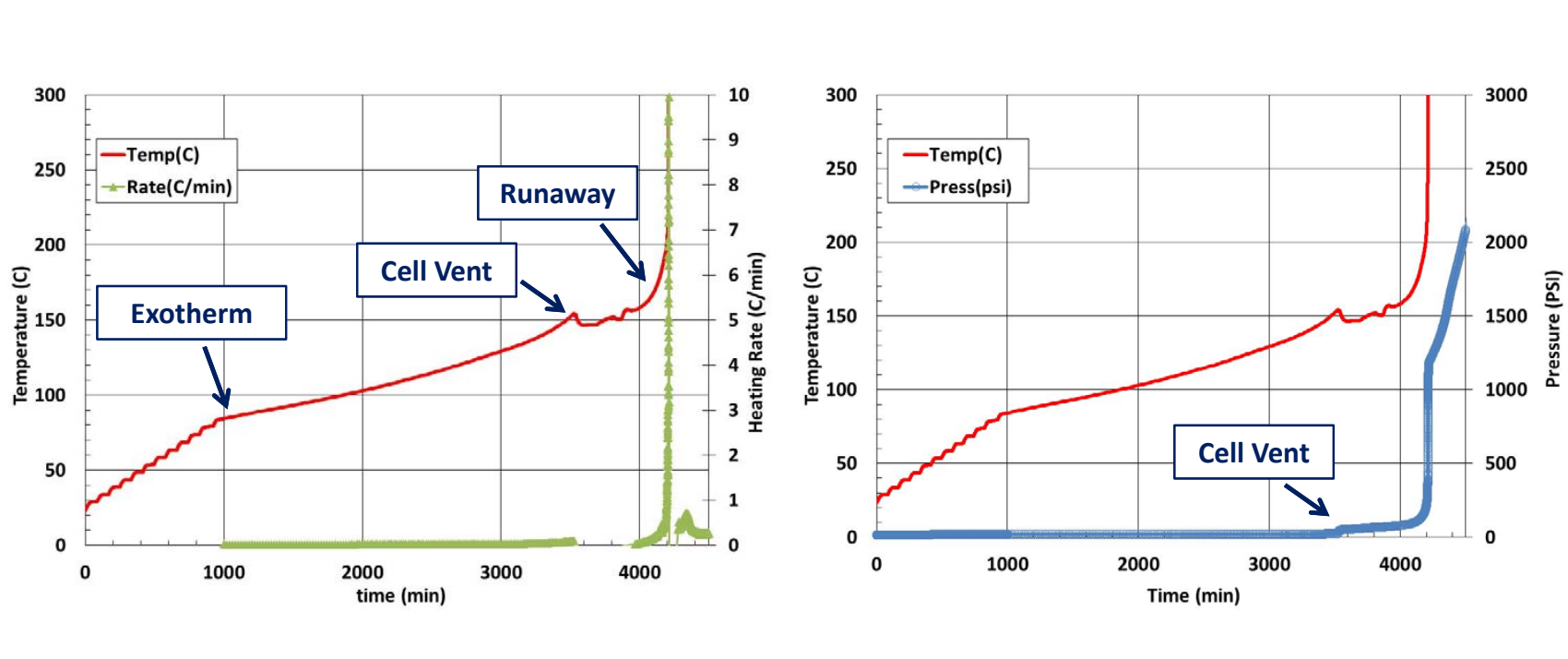
Risk of High pressure Gas release

- 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.

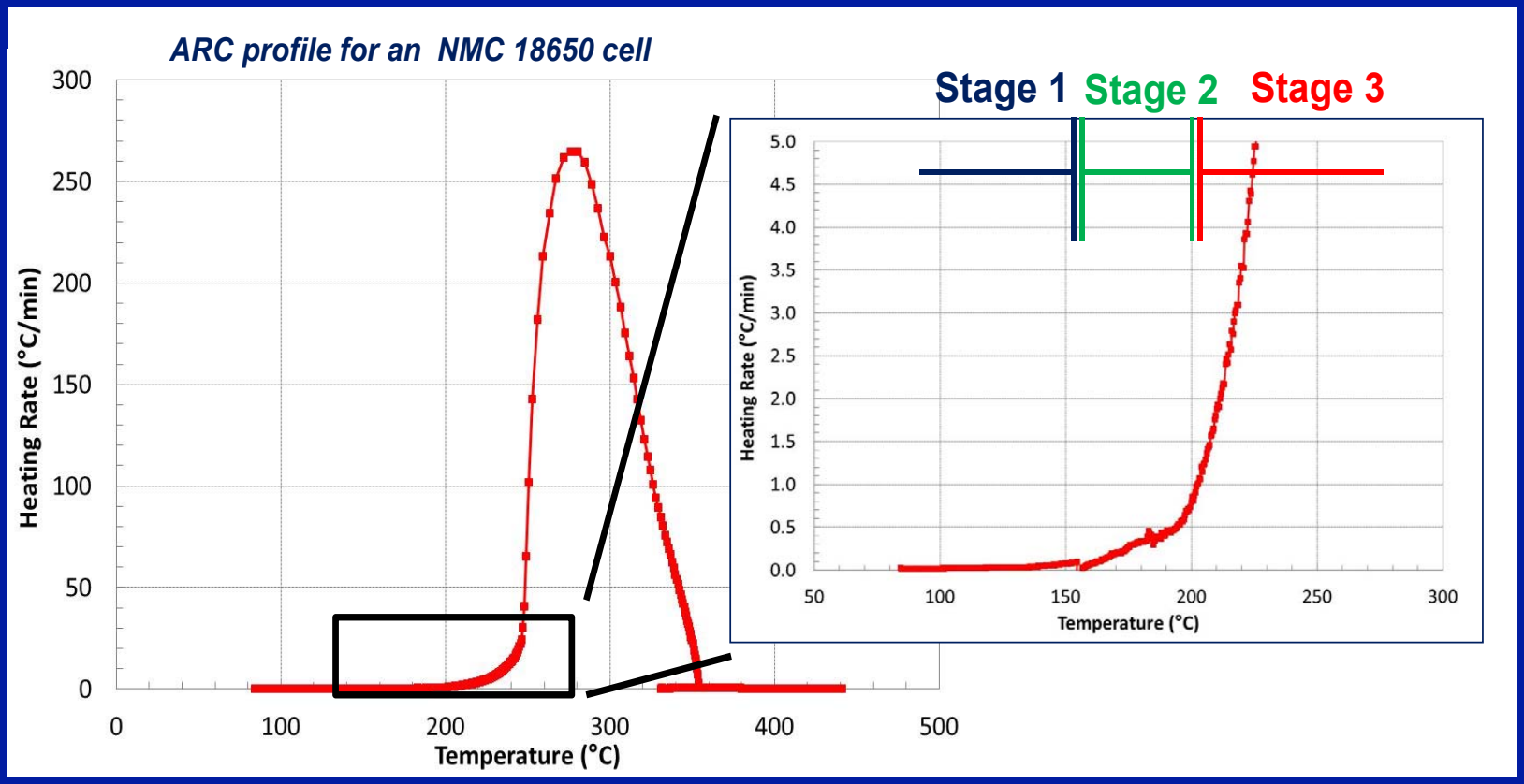
Toxicity and Hazardous Materials Release

- 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)



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

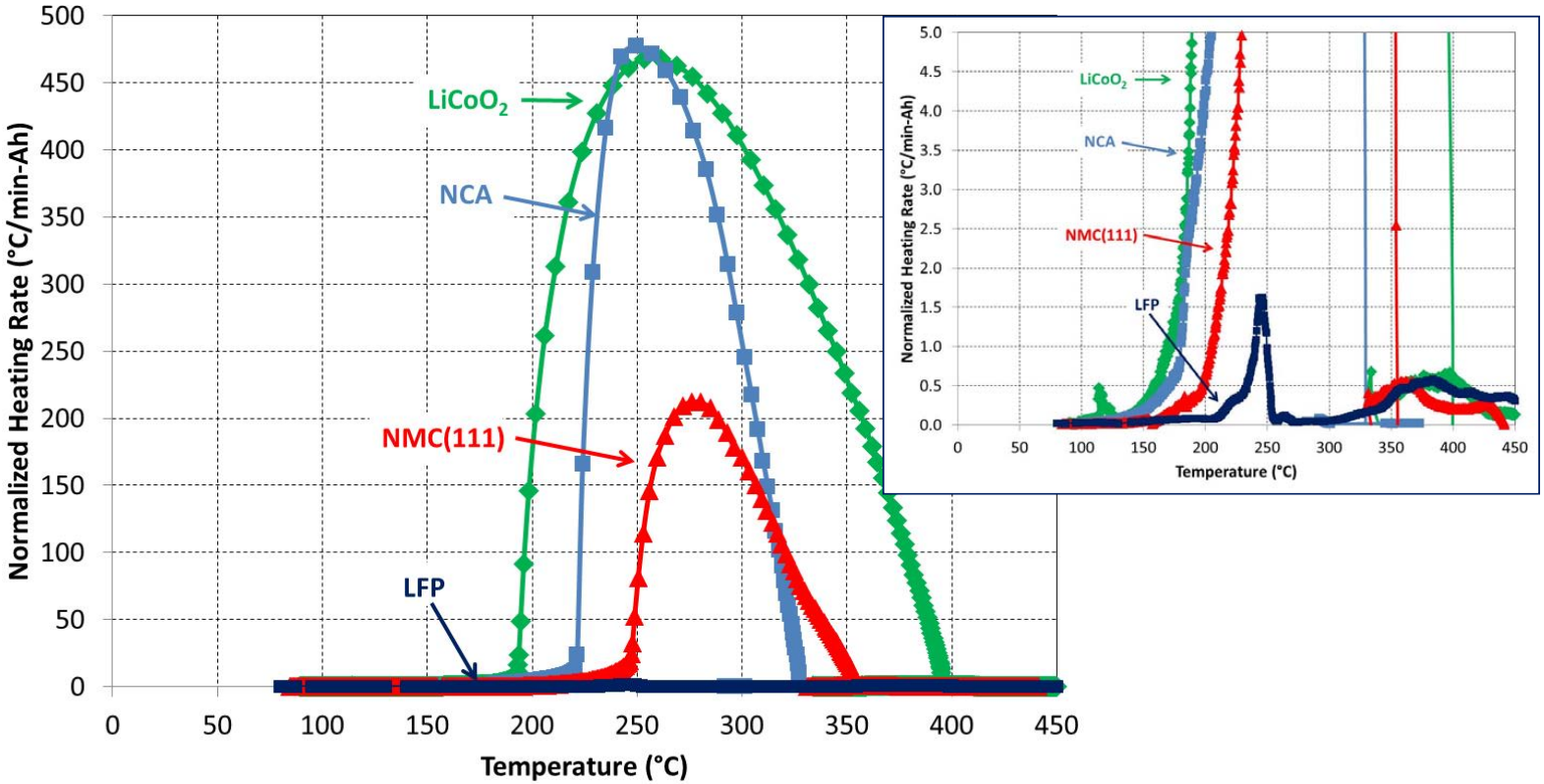
Stage 2: 160°C - 200°C – Acceleration (cell vent, accelerated anode and electrolyte degradation, onset of cathode decomposition)

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

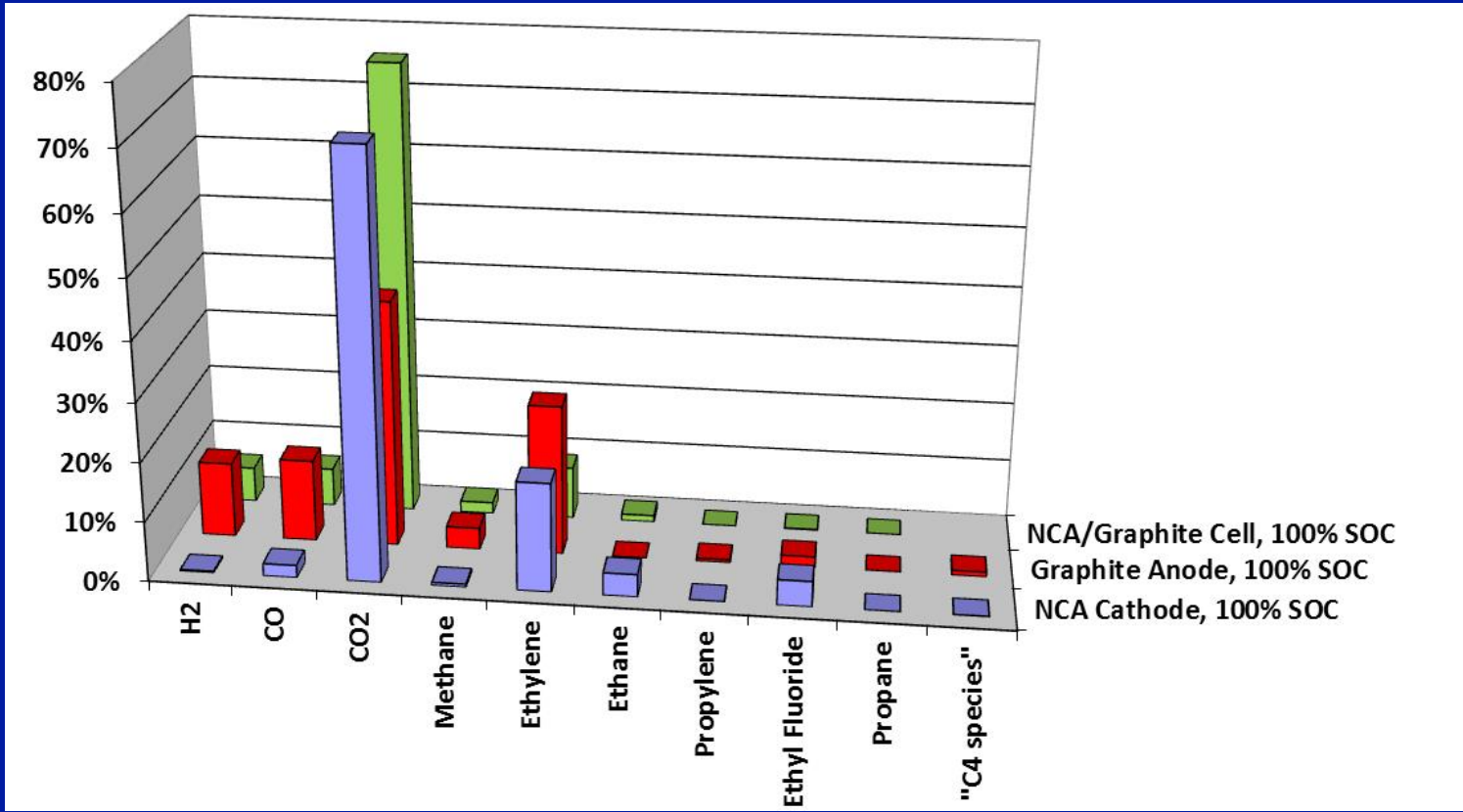
Accelerating rate calorimetry (ARC) of 18650 cells with different cathode materials



- ***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)

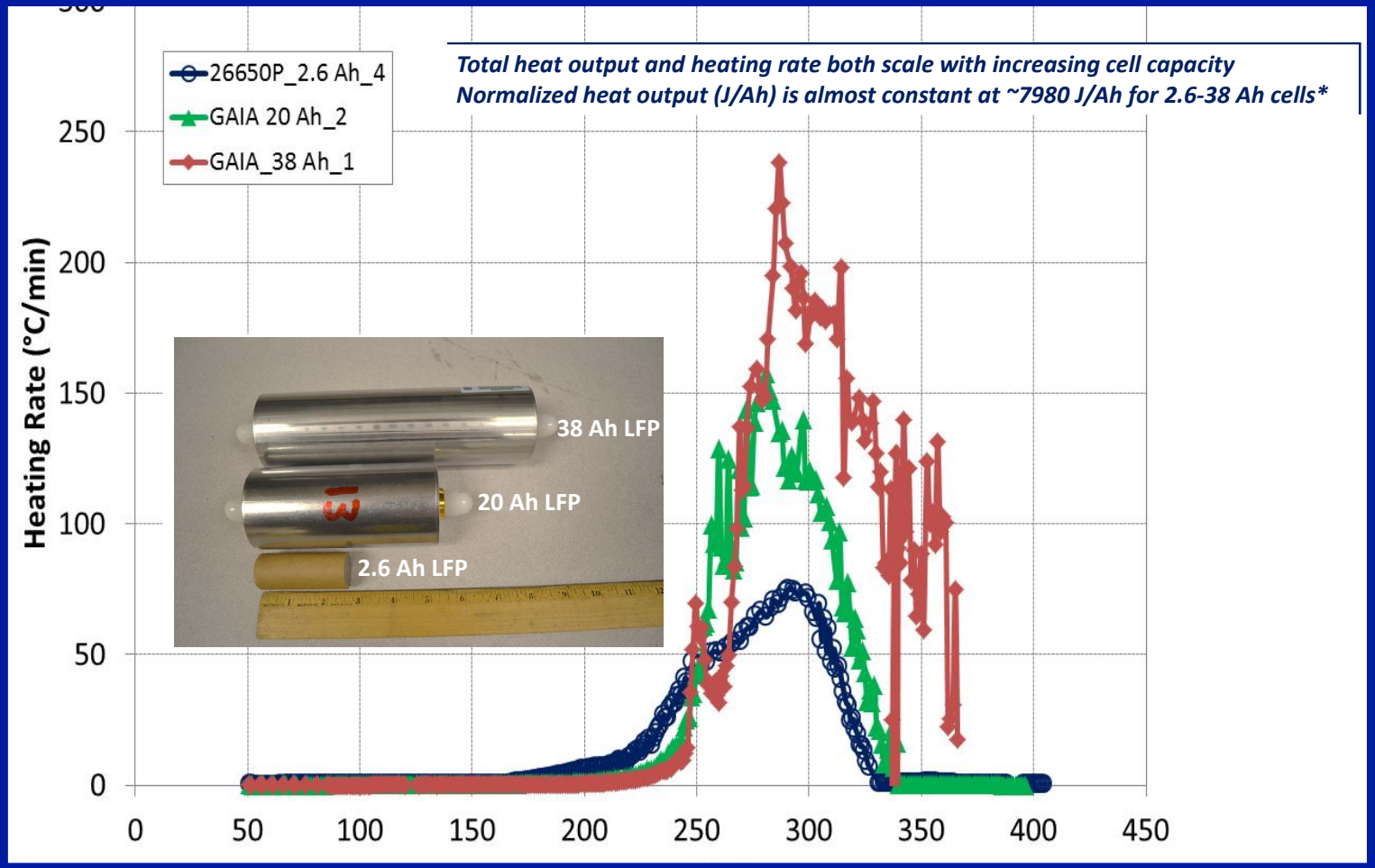
Vent Gas Analysis from ARC



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



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

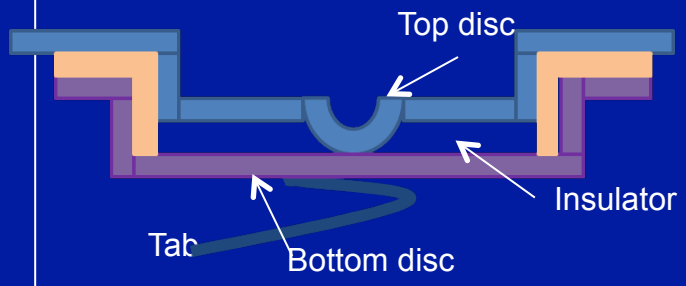
Data from Sandia National Lab (Courtesy Chris Orendoff)

Examples of Cell Protective Devices

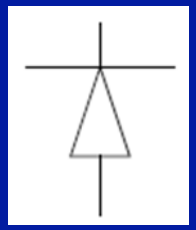
- Lithium-ion cells, whether cylindrical, prismatic, etc. irrespective of size, have different forms of internal protective devices
  - PTC
  - CID
  - Tab/lead meltdown (fusible link type)
  - Bimetallic disconnects

- 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.

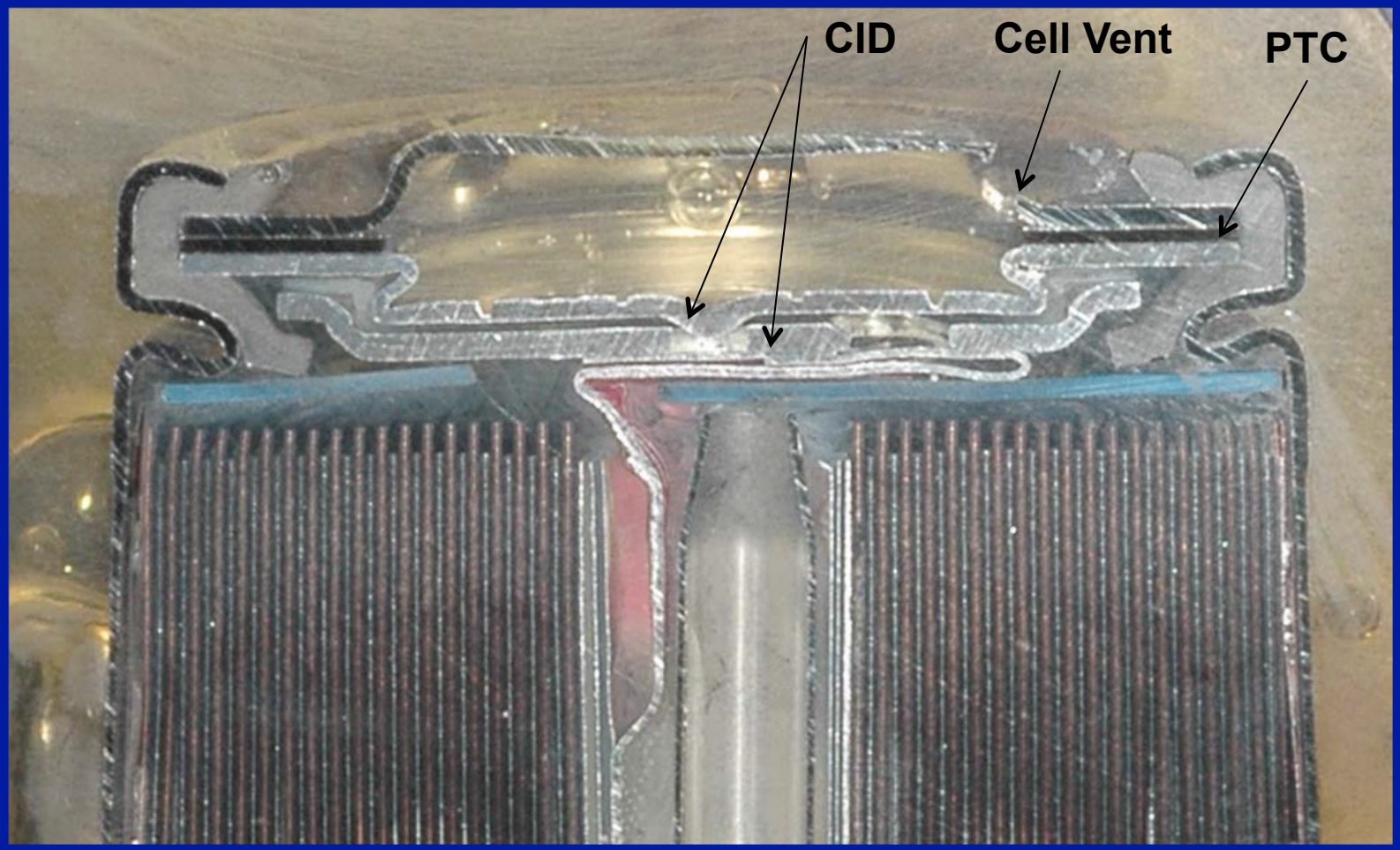
CID



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)

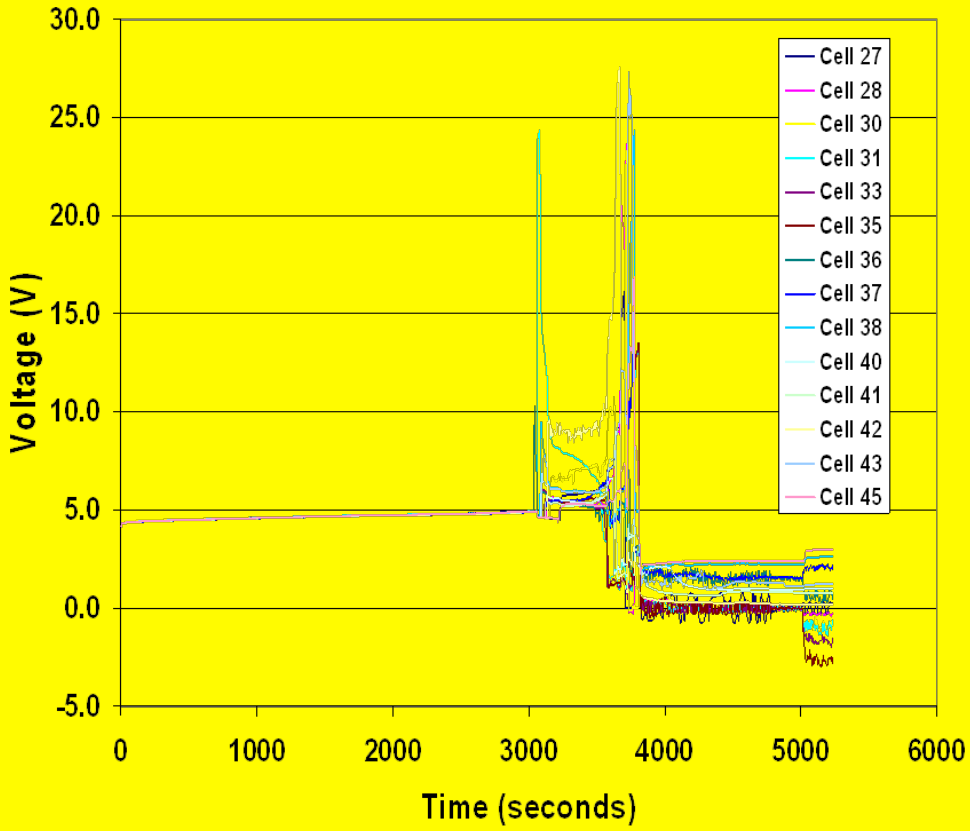
Stringent Monitoring and Control of
*Cell and battery voltage
*Battery current
*Temperature

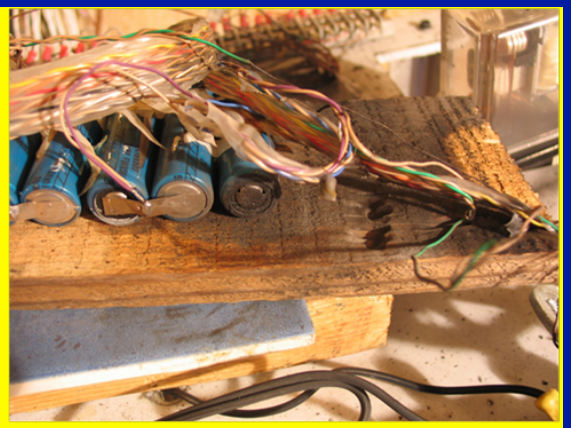
Cell Balancing designed into a majority of applications

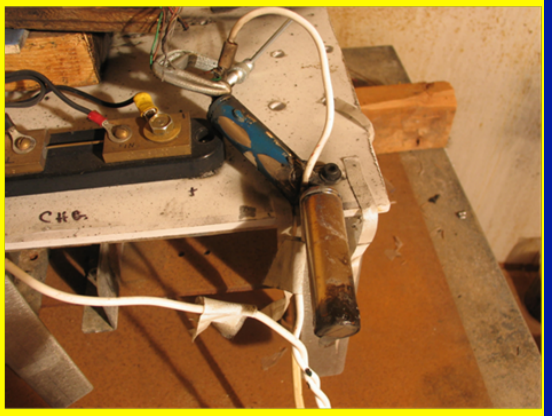
Concerns with Scaling & Testing: Cell to Module to Battery Level

- 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





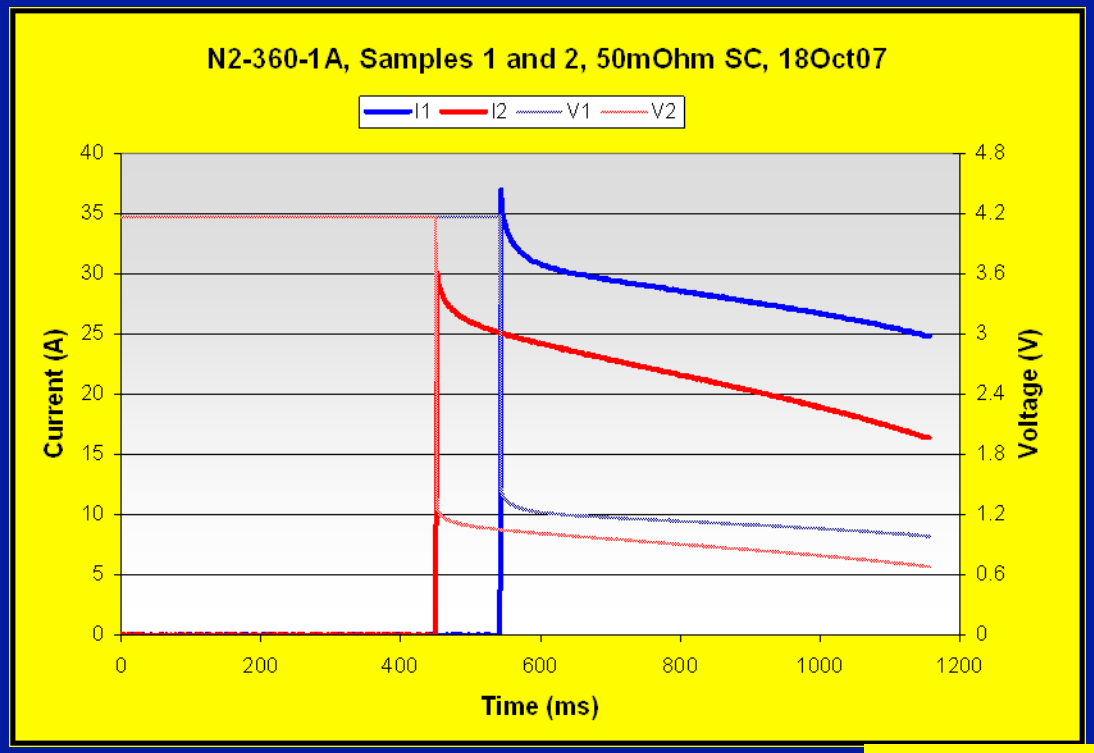


Missing : 27, 28, 30 and 31

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

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

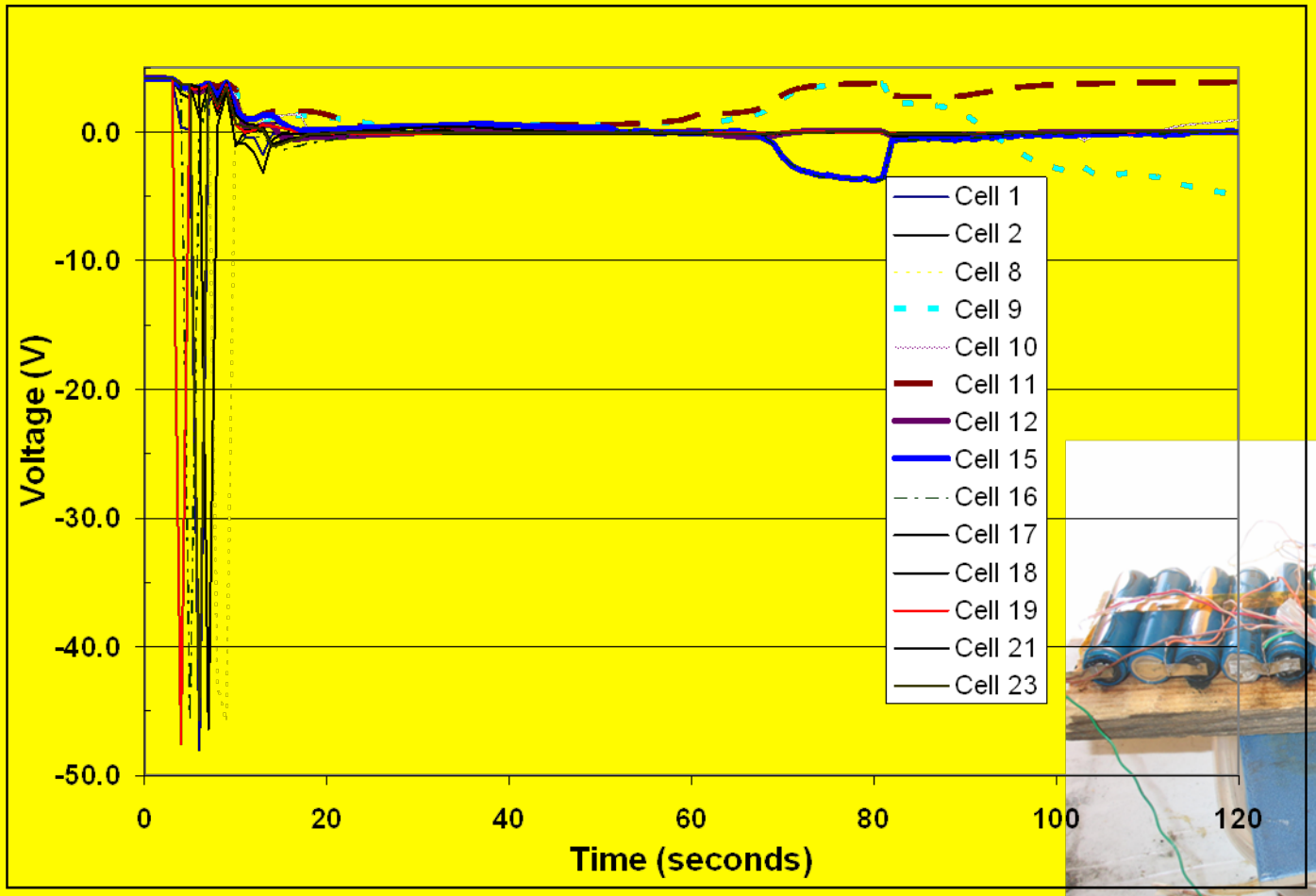
50mOhm Short Circuit, Single Cell



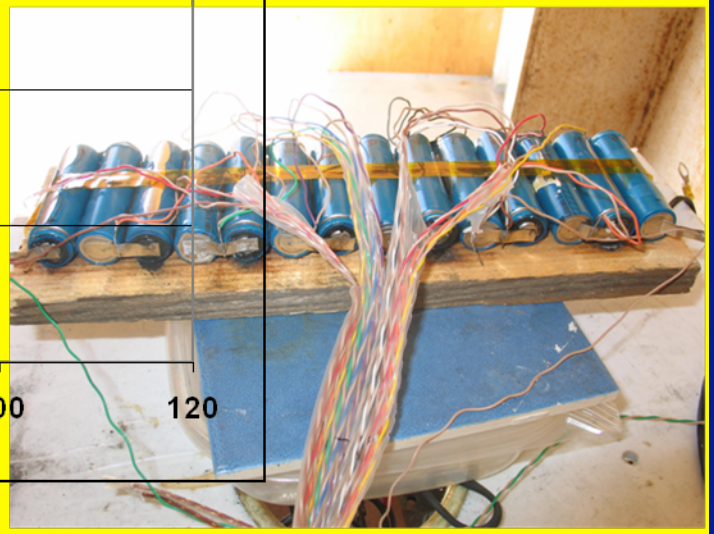
	Peak Current (A)	Peak Temp (°C)	Peak Temp Time (minutes)
N2-360-1A-1	37	78	43
N2-360-1A-2	30	82	49

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

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



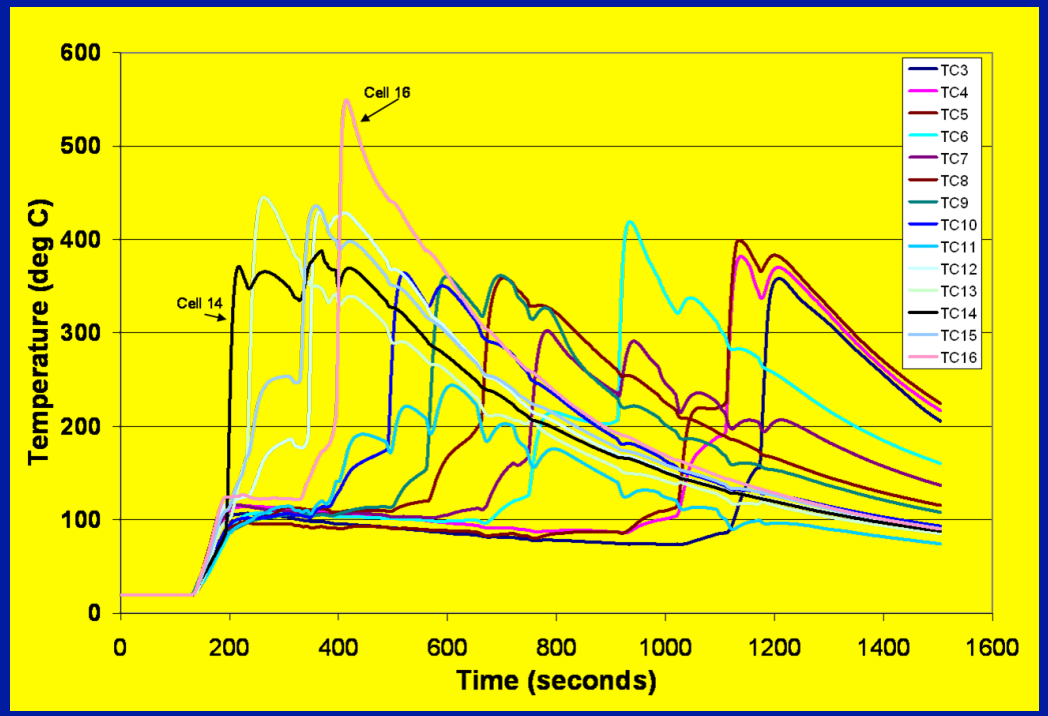
Only venting observed, no fire
Cell Voltages in bold – No visible signs of Venting or damage, but no voltage;
All others vented with Obvious leakage or discoloration



Rapid cell venting within the first 10 seconds

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

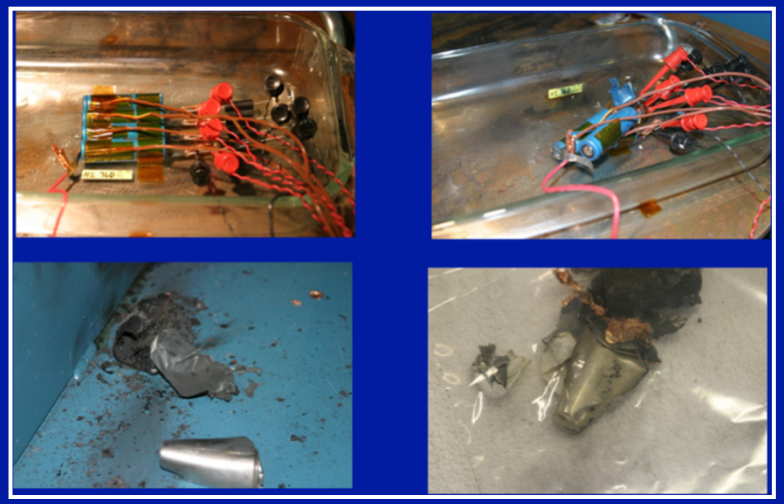
External Short Test on 14S Under Vacuum Conditions



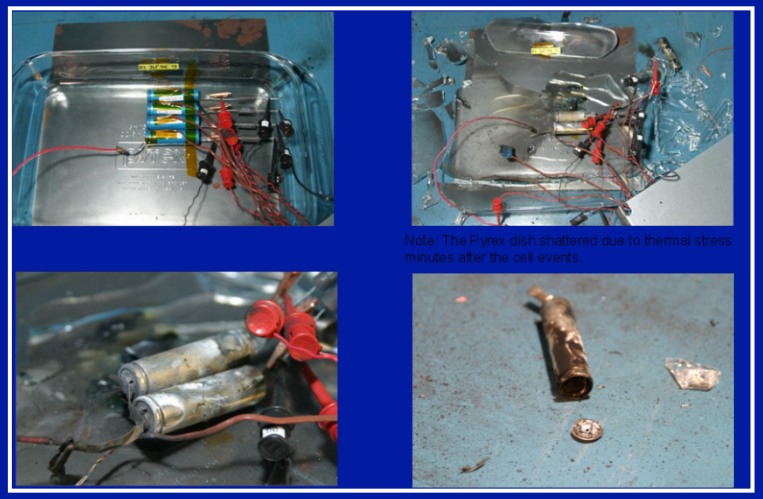
Data from NASA/Johnson Space Center (Courtesy Judy Jeevarajan)

Examples Showing Cell Limitations in Multi-cell Batteries

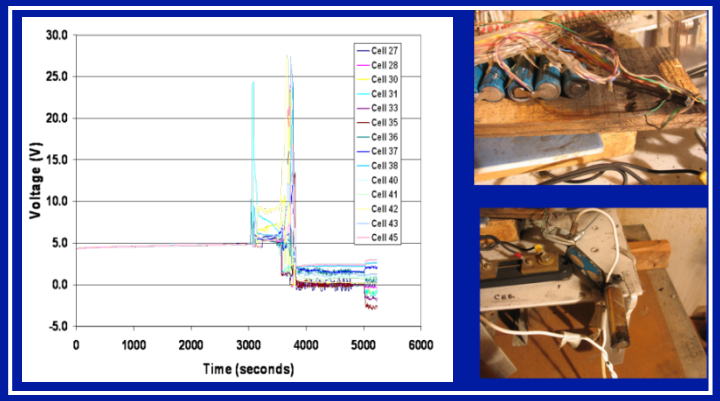
48V 6A Overcharge on 4P Battery



12V 6A Overcharge on 4P Battery



Photos show the limitations of 18650 size cells;
These cells are only test vehicles; protective devices, Internal and external to the cells, irrespective of cell size, should be fully characterized at all appropriate levels if used within the first three levels of safety control.



Overcharge Test on a 14-Cell String

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

External Short on 8S5P Matrix Pack

Requirements and Test Process

NASA Standards & Certifications

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

Human-Rated:

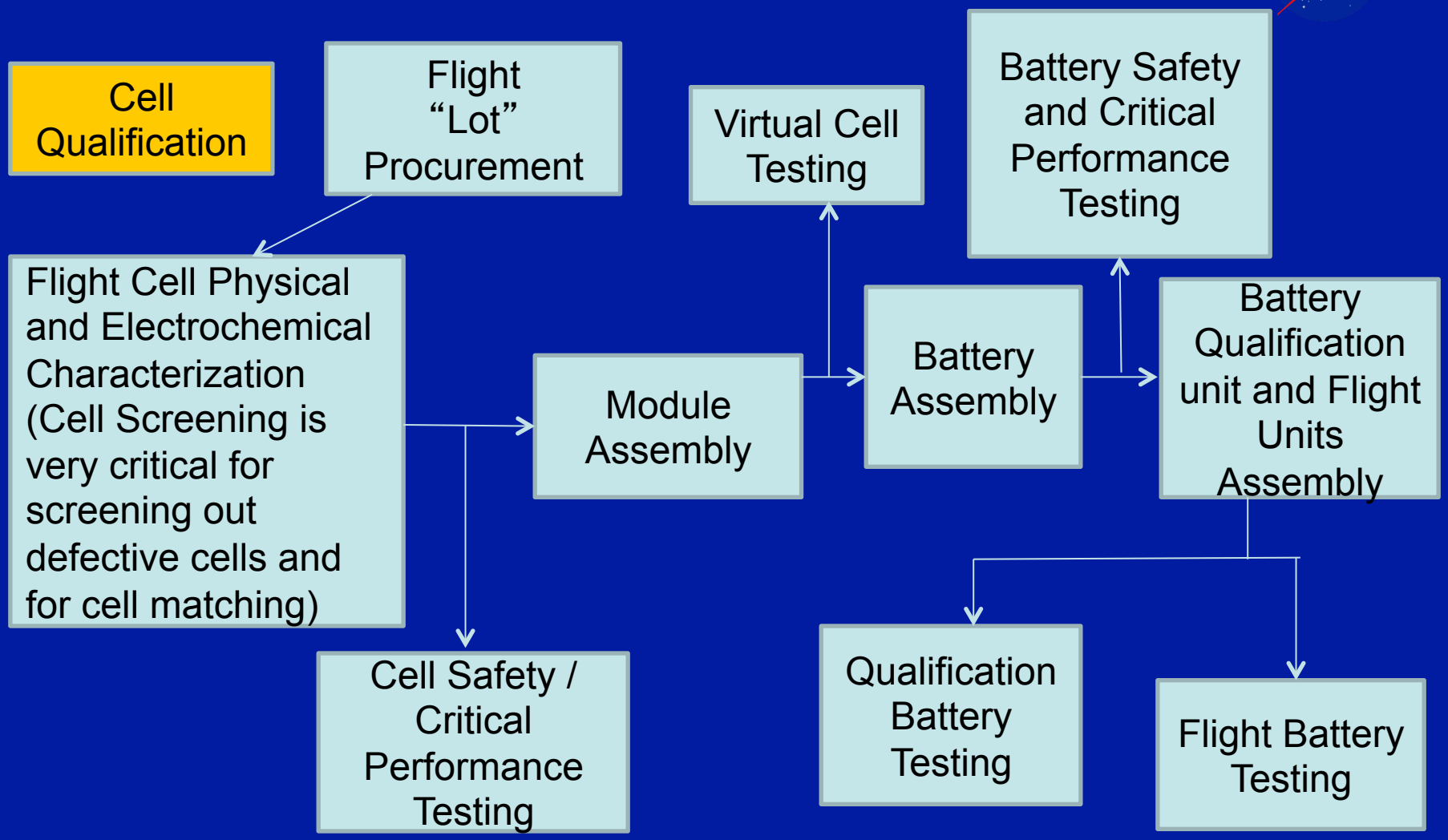
Crewed Space Vehicle Battery Safety Requirements, JSC 20793

- 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

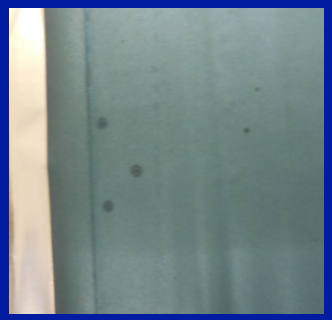
- **Systems Requirements Review (SRR)**
  - Project or Product Technical Requirements Specification (PTRS)
    - Outlines battery specifications, mission requirements for performance and safety, interfaces (mechanical, electrical, data, pressure, etc.) and unique requirements such as pressure variations, 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)



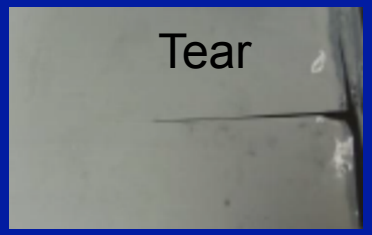
Nature of Defects Observed with Li-ion Cells

Request Chemical Analysis of Defects

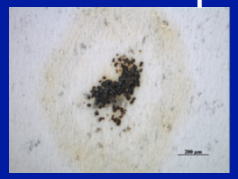


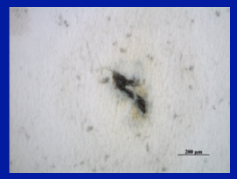
Delamination

Salt Deposits ?

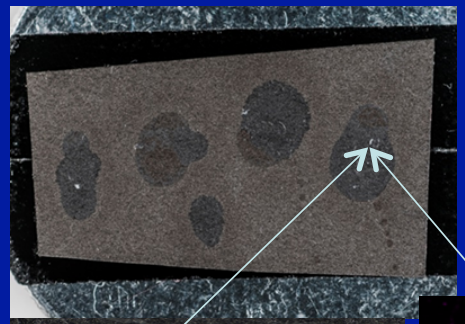


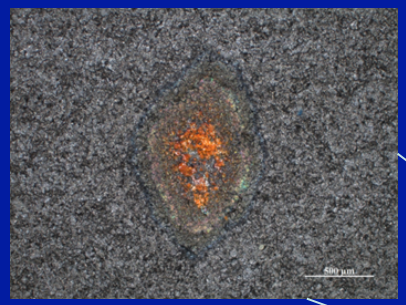
Separator

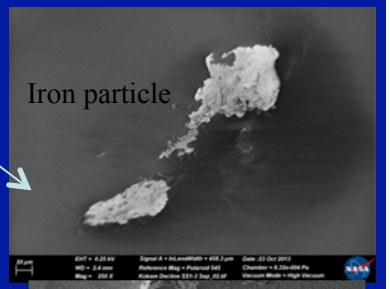




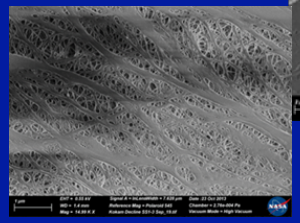
Pristine electrode







Separator away
From defect
Showing porosity



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
- 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

Back up

NASA Non-Human-Rated Li-ion Battery Applications

Deep Space Missions:

First Mission in 2002 (Maj. 20-70 Ah; One at 120 Ah**)**

Current:

•Mars Exploration Rover (Spirit and Opportunity)
•Mars Phoenix Lander
•Juno (Jupiter Obiter)
•Kepler
•NuStar
•GRAIL
•Aquarius
•Mars Science Laboratory
•SMAP (On-going) and

Future:

•Europa Orbiter
•Mars 2020 Rover
•Mars Insight (Lander)

Satellite Applications:

First Mission in 2006 (6 Ah to 134 Ah)

Current:

- Lunar Reconnaissance Orbiter (LRO)
- Solar Dynamics Observatory (SDO)
- Van Allen Probes (formerly RBSP Radiation Belt Storm Probes)
- Interstellar Boundary Explorer (IBEX)
- ST-5 (mission completed)

Future:

- **Global Precipitation Measurement (GPM) spacecraft**
- **Magnetospheric Multiscale (MMS) spacecrafts**
- **Mars Atmosphere and Volatile EvolutioN (MAVEN)**
- **DSCOVR (Triana) spacecraft**
- **James Webb Space Telescope (JWST)**
- **Joint Polar Satellite System-1 (JPSS-1)**
- **Solar Probe Plus**
- **Ice, Cloud and Land Elevation Satellite -2 (ICESAT-2)**
- **GeoStationary Operational Environmental Satellite (GOES-R)**

NASA Human-Rated Li-ion Battery Applications

Current: Flying Li-ion since 1999

- Government furnished equipment ~ 20 types (< 20V/ 10 Ah)
- Experiments/Payloads (55 to 60 types) up to 270 V (high energy, high power, capacity 2 to 20 Ah
- Crew suit (main power) 20 V/ 40 Ah
- Space vehicles and Space Launch Systems
  - HTV (32 V / 174 and 100 Ah), SpaceX (28 V/ 200 Ah and 28 V/16.5 Ah)

Future (and in work):

- ISS Main Power (120 V / 134 Ah)
- Robonaut (106 V / 60 Ah)
- New Tools (18 V to 28 V / 8Ah)
- New Vehicles (Orion 120V/ 30Ah; Orion LAS 140V 10Ah, 28V 1Ah;
  Orbital, 28 V/190 Ah; Boeing, SNC, Blue Origin)
- Surface mobility systems (270 V / 60 Ah high power)
- Lunar Lander Platforms (varying); Habitats (≥ 28 V)

Uniqueness:

- Space, confined volume and human-rated with zero tolerance to fire
- pressurized and unpressurized environments