SOLAR CAR CONFERENCE | MARCH 20-22, 2015 | UNIVERSITY OF MICHIGAN

BATTERY BASICS

Steve McMullen

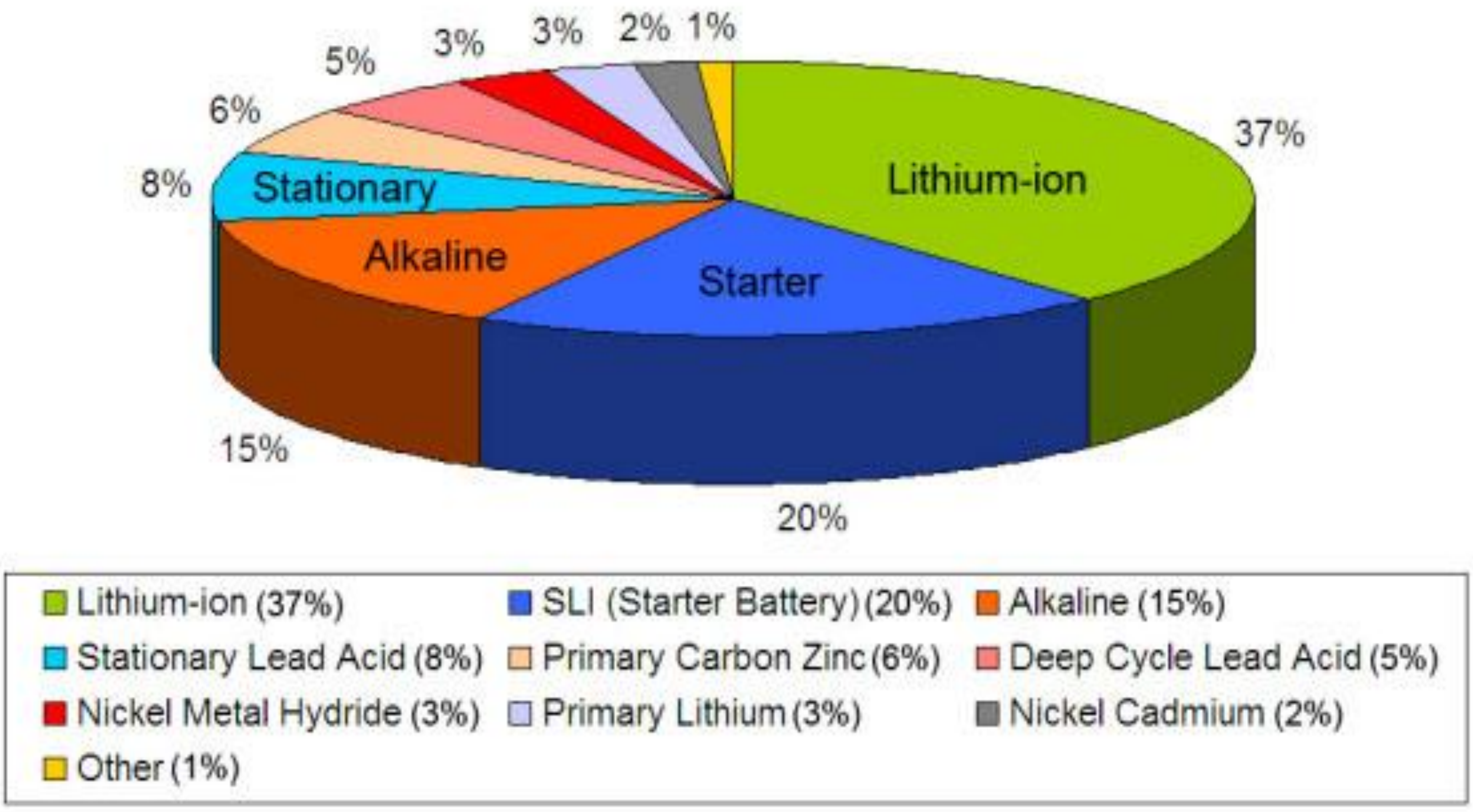
March 21, 2015

WHY ARE YOU HERE?

Because Many of Your Vehicles will be “Powered by Lithium”

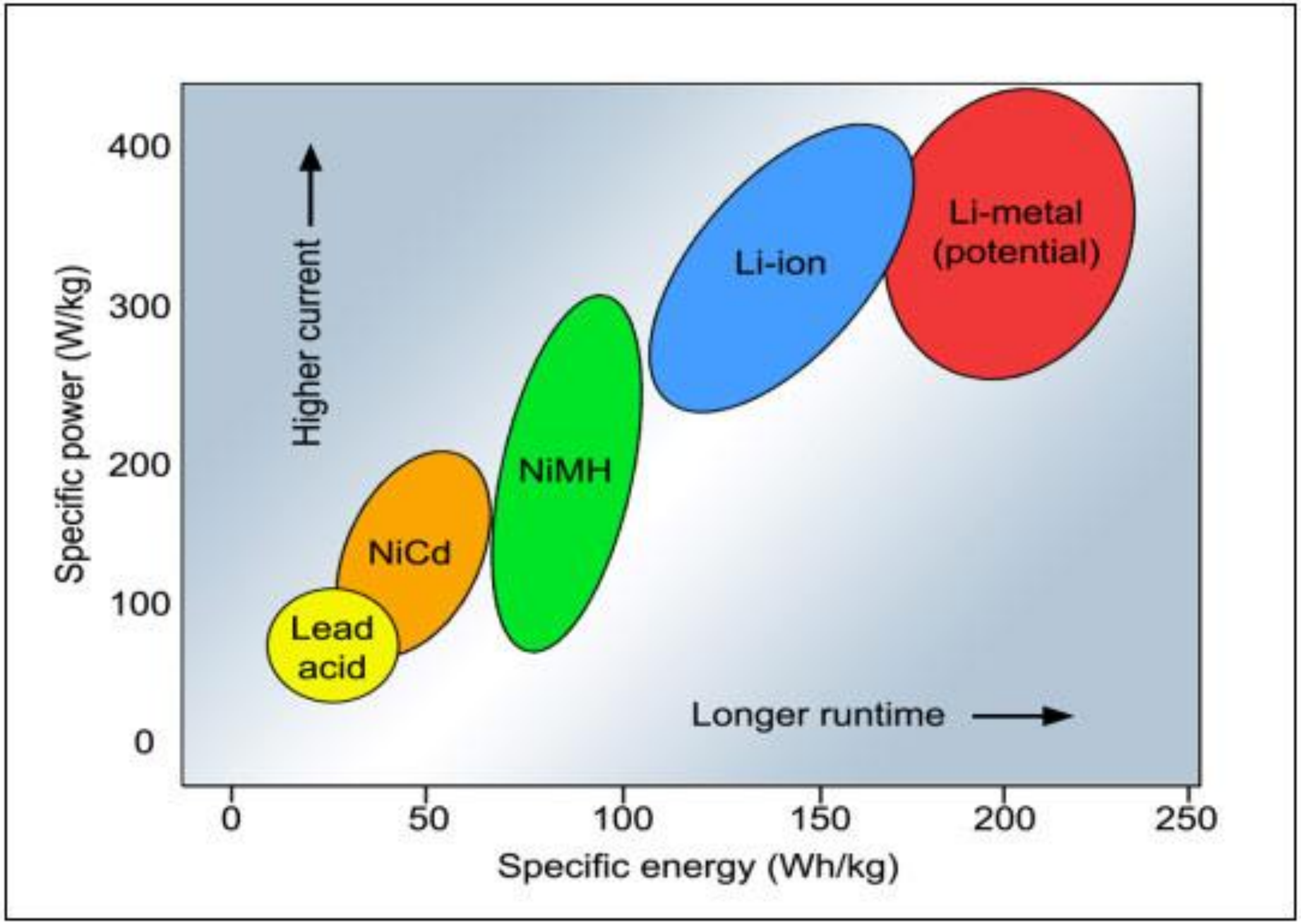
GLOBAL BATTERY MARKET

254 Manufacturers in World – 2014 (140 are rechargeable,10 in U.S.)



2009 data plot

BATTERY TECHNOLOGY



2009 data plot

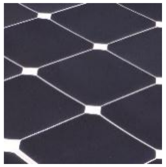
BASIC BATTERY FACTS

Batteries DO NOT store ELECTRICITY!

They store chemicals that react to
produce electricity!
Batteries are chemical storage devices!

Unlike Electrical Circuits -

Batteries CANNOT be turned ON or **OFF**,
they are always ON



BATTERY CHARACTERISTICS

Characteristics or Component	Lead-Acid	Nickel Metal Hydride	Lithium-Ion
Construction	Vented or Sealed with Pressure Relief Valve	Sealed	Sealed
Negative Active Material	Metallic Lead	Metal Alloy (AB_2 or AB_5 Class)	Lithiated Graphite
Positive Active Material	Lead Dioxide	Nickel Hydroxide	Lithium in Metal Oxide
Electrolyte	Sulfuric Acid	Potassium Hydroxide	Lithium Salt dissolved in Organic **Solvent**
Nominal Volts/Cell	2.0 V	1.2 V	3.6 V.
Operating Temp.	- 40°C to 60°C	- 30°C to 55°C	-20°C to 45°C
WEIGHT (mass)	Heavy	Medium	Lightest of all rechargeable
COST	Least expensive	Moderate cost, but rising - Nickel	More reasonable lately
Safety Concerns	Low	Medium to Low	High
Life cycle	Short	Medium to Long	Long

LITHIUM BATTERIES

Cathode (Positive)

LAYERED

- $LiCoO_2$ — Lithium Cobalt Oxide
- $LiNiO_2$ — Lithium Nickel Oxide

SPINEL

- $LiMn_2O_4$ — Lithium Manganese Oxide

OLIVINE

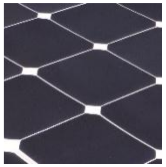
- $LiFePO_4$ — Lithium Iron Phosphate

Electrolyte

- $LiPF_6$ — Lithium Hexafluorophosphate
- EC — Ethylene Carbonate
- EMC — Ethylmethyl Carbonate
- PC — Propylene Carbonate
- DMC — Dimethyl Carbonate

Anode (Negative)

- Li (Metal)
- Graphitic Carbon **(Soft)**
- Non-Graphitic Carbon **(Hard)**
- Si-M Alloy (M = Ca, Mg, Mn, Mo, Ni, Ti)
- $Li_4Ti_5O_{12}$ — Lithium Titanium Oxide



TYPES OF CELLS

Primary

- D, C, AA, AAA and other primary disposable cells
- Typically used for non critical applications – not rechargeable
  - used in flashlights, etc…

Secondary

- Most universally accepted batteries
- Rechargeable – used in many appliances/tools

Cylindrical

Prismatic

BASICS

Voltage (Volts, mV)

Potential difference or electrical pressure between two oppositely charged bodies that causes a flow of electricity when a suitable conductive path is provided

Current (Amps, mA)

Flow of charge carriers is defined as quantity of electricity that passes through a conductor during a time of one second

Resistance (Ohms, mΩ)

Opposition of current flow, which is proportional to the collision between electrons and atoms in a conductor

Power (Watts, mW)

Amount of electrical work that is being done or consumed in a given time period

Power, $P = E/t = V \times I = V^2/R = I^2R$

Energy (Watt-hours, Joules)

Measure of electrical work, which is the movement of charge across an applied voltage Energy, $E = V \times Q$

Energy involved to move one electron across 1V is an electron-volt ($1eV = 1.613 \times 10^{-19} J$)

Capacity (Amp-hr, Coulomb)

Quantity of electricity that accumulates or passes through a conductor for a given period of time

Charge or Capacity, $\mathbf{Q} = \mathbf{I} \times \mathbf{t}$

1C is equal to the total charge carried by 6.24×10^{18} electrons

State of Charge (SOC)

Relative Amount of Energy remaining in the battery

SOLAR APPLICATION

Battery Efficiency

- Lithium - 97 to 99% IN – OUT
- Lead - 85 to 92% IN – OUT
- Nickel - 85 to 94% IN – OUT

Lithium's Low Resistance

Solar Raycing Battery - peak efficiency

But also challenging to "control"

Requires Protection System

Lithium Battery first developed in 1912 by G.N. Lewis
Not commercialized till 1970s
1991 SONY first commercialized rechargeable Lithium Battery

LITHIUM BATTERY DEVELOPMENT

Lithium Ion 18650 Cell (Sony, Panasonic, Samsung, others)

- 1994 - 1100 mAh $20
- 2001 - 1900 mAh $10
- 2014 - 3200 mAh <$2
- 2020 ?

No other formidable battery technology in the foreseeable future.

Advantages

High Specific Energy and Commendable Energy Density
Low Internal Resistance – High Coulombic Efficiency
Multiple Mechanical Packages
Long Cycle and Extend Shelf life
Low Self Discharge (<1/2 NiMH, Ni-Cad)

Limitations

Require Battery Protection for Voltage, current, Tem.
Possibility of thermal Runaway and venting if stressed
Cannot Charge at Low Temperature (0 C, 32 F)
Degrades at High Temperature when High SOC
Manufacturing variation limits Pack Designs

LITHIUM ELECTROCHEMICAL PROCESS

While Charging. . .

Positive electrodes become more positive by releasing electrons

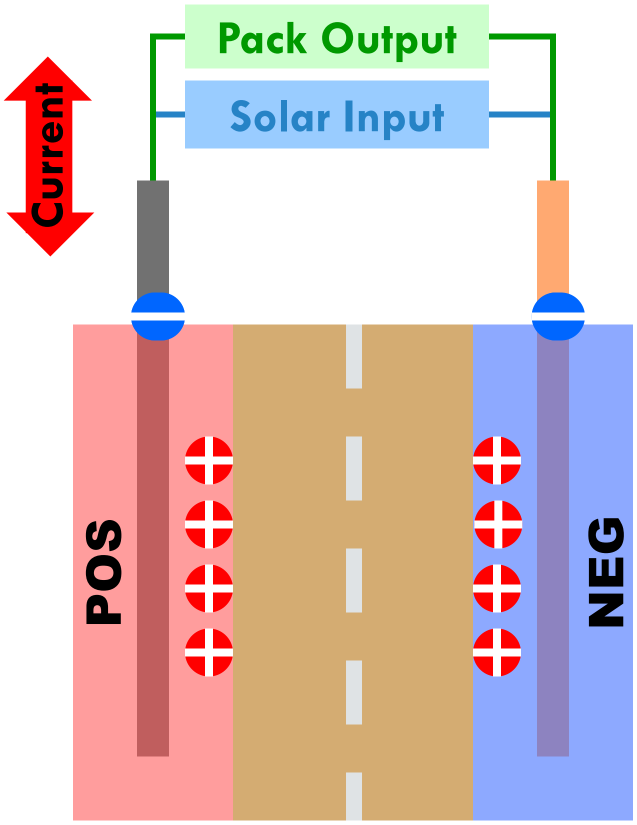
$P^{K} \rightarrow P^{K+1} + e^{-}$

(Oxidation)

Negative electrodes become more negative by accepting electrons

$N^{M} + e^{-} \rightarrow N^{M-1}$

(Reduction)



While Discharging . . .

Positive electrodes become less positive by accepting electrons

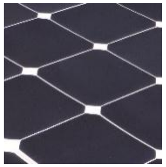
$P^{K+1} + e^{-} \rightarrow P^{K}$

(Reduction)

Negative electrodes become less negative by releasing electrons

$N^{M-1} + e^{-} \rightarrow N^{M}$

(Oxidation)



STATE OF CHARGE (SOC)

How to Measure

❖ Voltage, Amp-hr Counting, Impedance, Estimation, other

❑ Voltage – Li-Ion/poly

- Must be Open Circuit Voltage
  - Floating – no loads applied
- Temperature affects results
  - Hotter/Higher, Cooler/Lower
- Requires minimum 4 hours rest to be accurate
  - Battery must attain equilibrium
  - Battery Manufacturers recommend 24 hours
  - Most accurate after impound release

http://www.mpoweruk.com/soc.htm

Good source of understanding

- Fairly Flat curve (80% of the curve) requires
  - accurate voltage measurements
  - OCV with min 4 hours rest
- Nickel SOC can be voltage based
- LiFePO4 must consider Hysteresis
- Lead Acid – is difficult as well

❑ Coulomb Counting – Amp Hours

- Must comprehend loss of accuracy
  - Reset of battery
  - Inefficiency of transfer

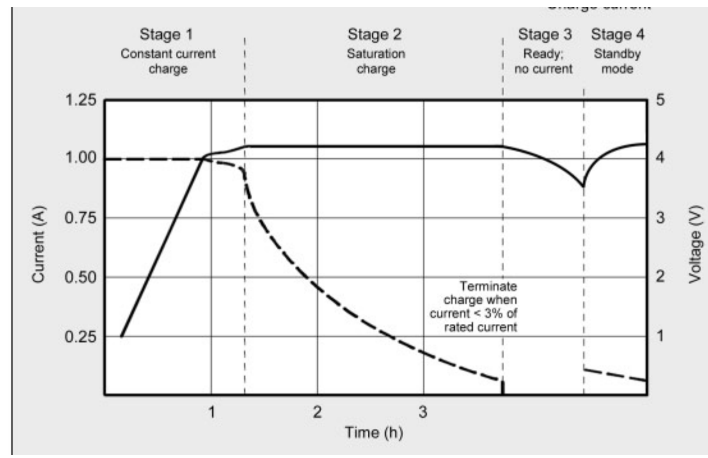
TOPPING OFF LITHIUM

Lithium are very "strict" here

- Over charge degrades capacity
  - Can lead to Stress and ultimately an Event

To Saturate, must reduce current

- Expect greater **in**efficiency after here
- End of Charge occurs at <3% of rated Charge
  - While limiting to Upper Voltage
  - Will still drift down (rubber band after extended rest) to less than Max Voltage
  - Benefit in measuring after impound
  - Top off at <3% C for full charge



Lithium prefers not being "fully" charged - Some Stress Occurs

Lithium responds rapidly to recharge - discharge

- voltage shoots up quickly – like a weight lifted by an elastic strap
- OCV Lags as does Capacity, It likewise droops back after charge is off
- This is very typical of ALL batteries – just more pronounced in Lithium

DISCHARGING LITHIUM

Cells are sensitive to the Low voltage

Cells have steep curve at Lower SOC.

Low Voltage Cut-offs are prone to overshoot (beyond Low Voltage Mfg. Limit)

Limit lower cut-off for the BPS to voltage where overshoot is considered within the Mfg limits.

Address Slow Response Time by setting cut-off voltage even higher.

Copper precipitates/plates out and creates dendritic shorts

Some burn out and capacity drops

Continued activity results in hard shorts

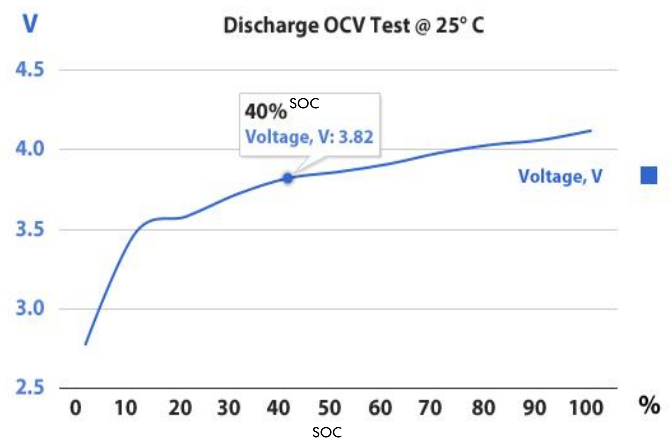
Hard Shorts generate Heat and result in venting

This sneaks up on a solar vehicle team

- An event may occur latently, at a different time from the cause.

Manufacturing Defects can result in an event as well

- Test extensively before assembling your pack



LITHIUM EVENTS

Over Charge

- Cathode over oxidizes creating free Carbon Dioxide
- Gas Pressure within the cell increases
- If Current Interrupt Device (CID) is present, it opens at about 1380 kpa (200 psi)
- If not, cell membrane ruptures and gases, likely flames exit at about 3450 kpa(500 psi)
- Typically, any high pressure distorts cell structure and shorts occur internally (causes sparks)
- Cell is extremely sensitive to Current & Temperature approaching this state
- All forms of destruction are evident when Overcharge is cause of an event

LITHIUM EVENTS

Over Discharge

- Copper precipitates out within cell
- Shorts are produced
- Results in reduced capacity initially (Stress)
- Can result in Event same as Over Charge
- Extended time at reduced voltage results in added Stress
- Store at 40% SOC or more at room temp.
- If attempting to revive a cell (below the low voltage limit)
  - remove those that don’t reach normal voltage within **a minute** of boosting
  - these are damaged beyond proper recovery
  - Dispose of these cells accordingly, they will cause issues otherwise.

LITHIUM EVENTS

Over Current

- Internal temperature rise
- Thermal event will occur
- CID may protect or not

Over Temperature

- Unrealistic Voltages can cause it
- Increased Cell Pressures
- Uncontrolled venting
- An Event is eminent
- Do NOT Charge Lithium above temperature limit- this starts the thermal event.

Under Temperature

- Do Not Charge Lithium based cells below 0 C , 32 F

Apple iPhone 3GS's Lithium-ion polymer battery, which has expanded due to a overcurrent failure

LITHIUM EVENTS

Why Lithium Batteries Fail?

Any additional Stress caused by exceeding limits results in cell sensitivity to the operational environment

- Temperature, Vibration, Voltage, Current and other stress may result in failure at any time and under any circumstance.

Watch Cells for Reduced Performance

Occasionally measure Cells within Module

Sometimes cells can reverse, don't be surprised!

If cells deviate from the others, Isolate them before an Event occurs.

Paralleled Cells are most at Risk

Samsung Galaxy 3

WHY LITHIUM BATTERIES FAIL?

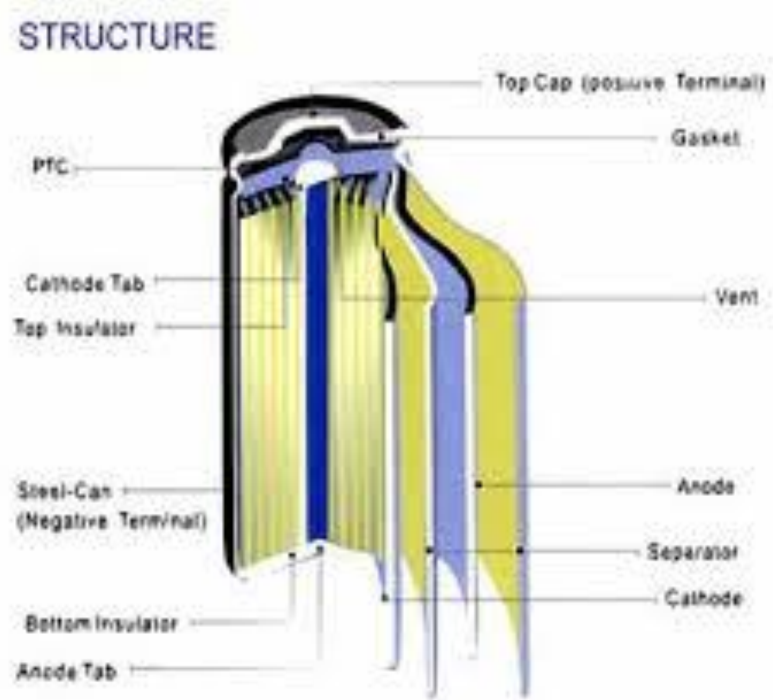
Battery failures can be classified in three main categories:

- "Infantile" failures
- Ultimate or End of Life (EOL) failures
- Abuse failures

WHY LITHIUM BATTERIES FAIL?

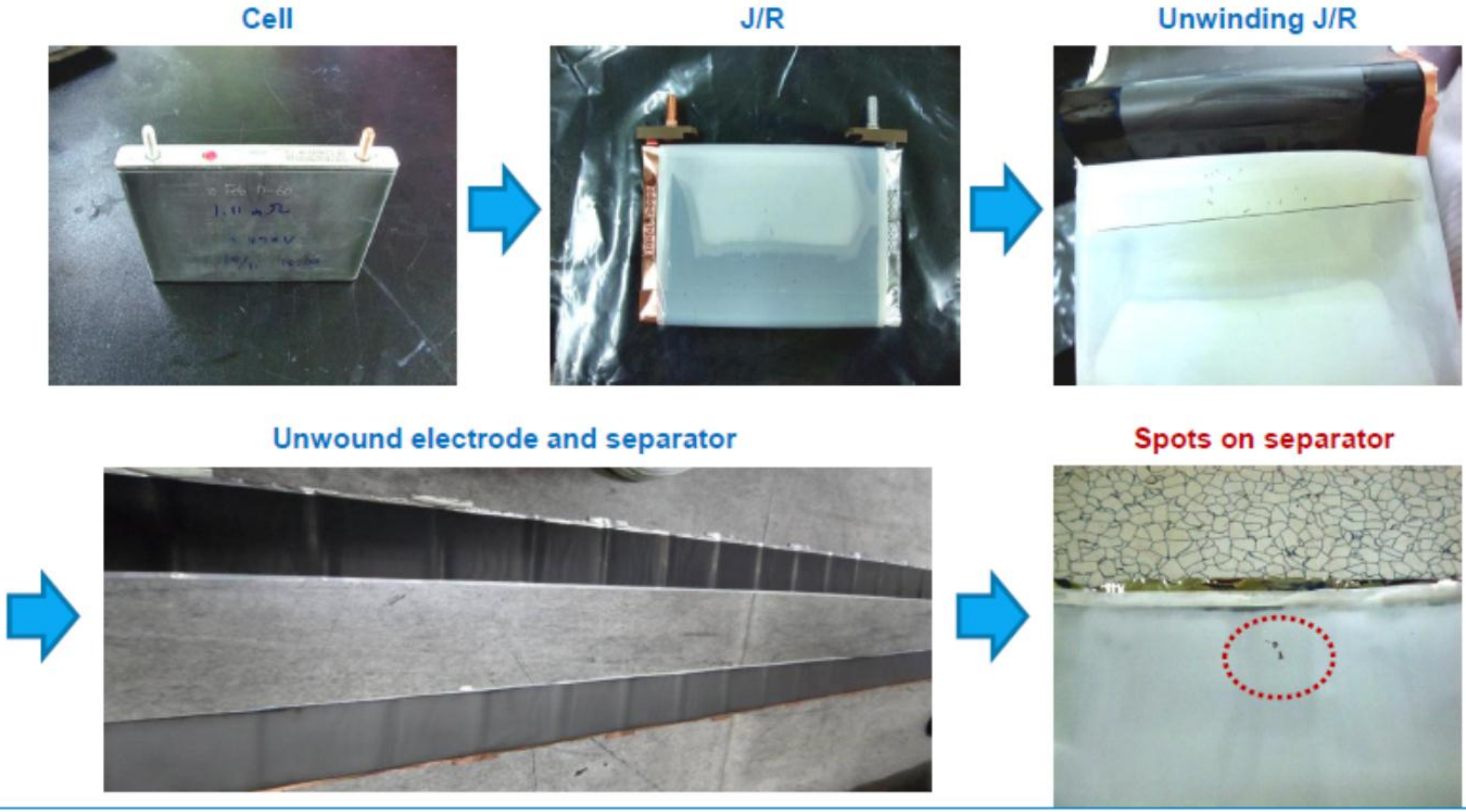
"Infantile" Failures

- Typically associated with manufacturing defects
- Presently 0.1- 0.2 PPM failure from the mfg.
- Possible contamination: water, oxygen or other foreign materials in the raw materials
- Internal short circuit due to:
  - ✓Chemical breakdown of separator
  - ✓Presence of (metallic or other) particles
  - ✓Mechanical movement of components leading to separator failure due to vibration or impact
  - ✓Mechanical mishandling
- Cell Variation –Pack Imbalance
  - ✓Pack is only as good as weakest cell



WHY LITHIUM BATTERIES FAIL?

Infantile Failure



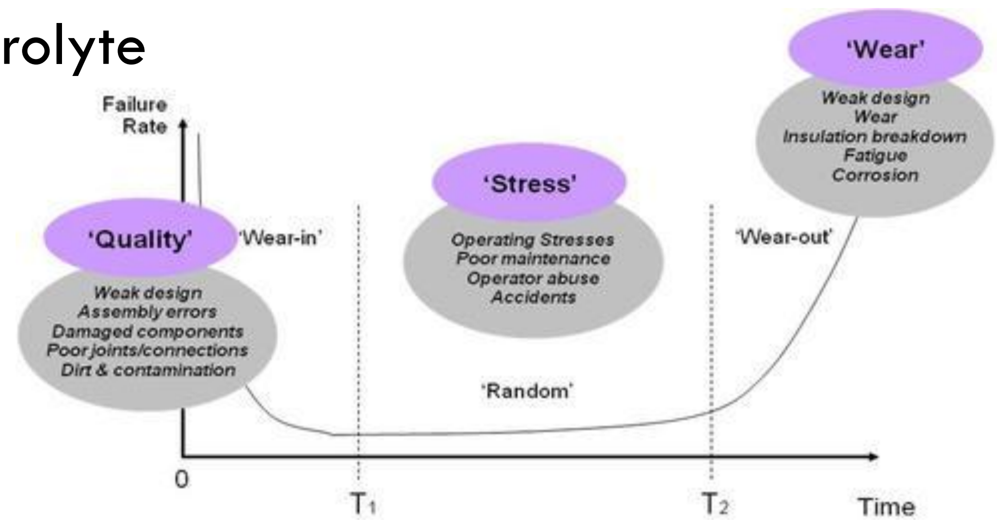
WHY LITHIUM BATTERIES FAIL?

Ultimate of End of Life (EOL) Failures

- Disintegration and/or dissolution of active material structure
- De-lamination or shedding of active material from current collector substrate
- Micro-structural degradation
- Decomposition of electrolyte

All lead to a

Reduction in Capacity!



WHY LITHIUM BATTERIES FAIL

- Abuse Failures
  - Mechanical
    - ✓ Excessive Mechanical shock or vibration may fracture current carrying tabs, terminals or inter-cell connections
    - ✓ Puncture or crush leading to short circuit
    - ✓ Applying loads to terminals of cells
  - Electrical
    - ✓ Overcharge, over discharge or external short circuit
    - ✓ Rapid charging or discharging, Excessive Current
  - Thermal
    - ✓ Radiant heat – above threshold temperature may lead to spontaneous combustion or explosion
    - ✓ High or low-temperature storage
    - ✓ Thermal shock
    - ✓ Conductive heat from Direct Soldering degrades performance

WHY LITHIUM BATTERIES FAIL?

Proper Handling

- Avoid applying excessive force to insert or remove cell from packaging, battery holder or housing, which may:
  - Deform battery cells leading to internal short circuit
  - Crush terminal cap/tabs twisted/bent
  - Damage seal resulting in a cell venting
- If inspecting cells
  - Return the cells to their original container
  - Or keep them separated and secured in place
  - Do not stack or scatter cells

- All dented cells, individual or within module/pack, should be disposed regardless of electrolyte leakage
  - Denting of sides or ends increases the likelihood of developing an internal short circuit and reduction in capacity and should be discarded
- Cells should be transported in non-conductive carrying trays to reduce the chances of cells being dropped, causing shorting or other physical damages
- DO NOT Solder Directly on Cell – Internal damage will Occur

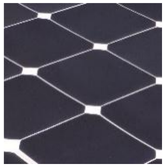
WHY LITHIUM BATTERIES FAIL?

Abuse Failures (cont.)

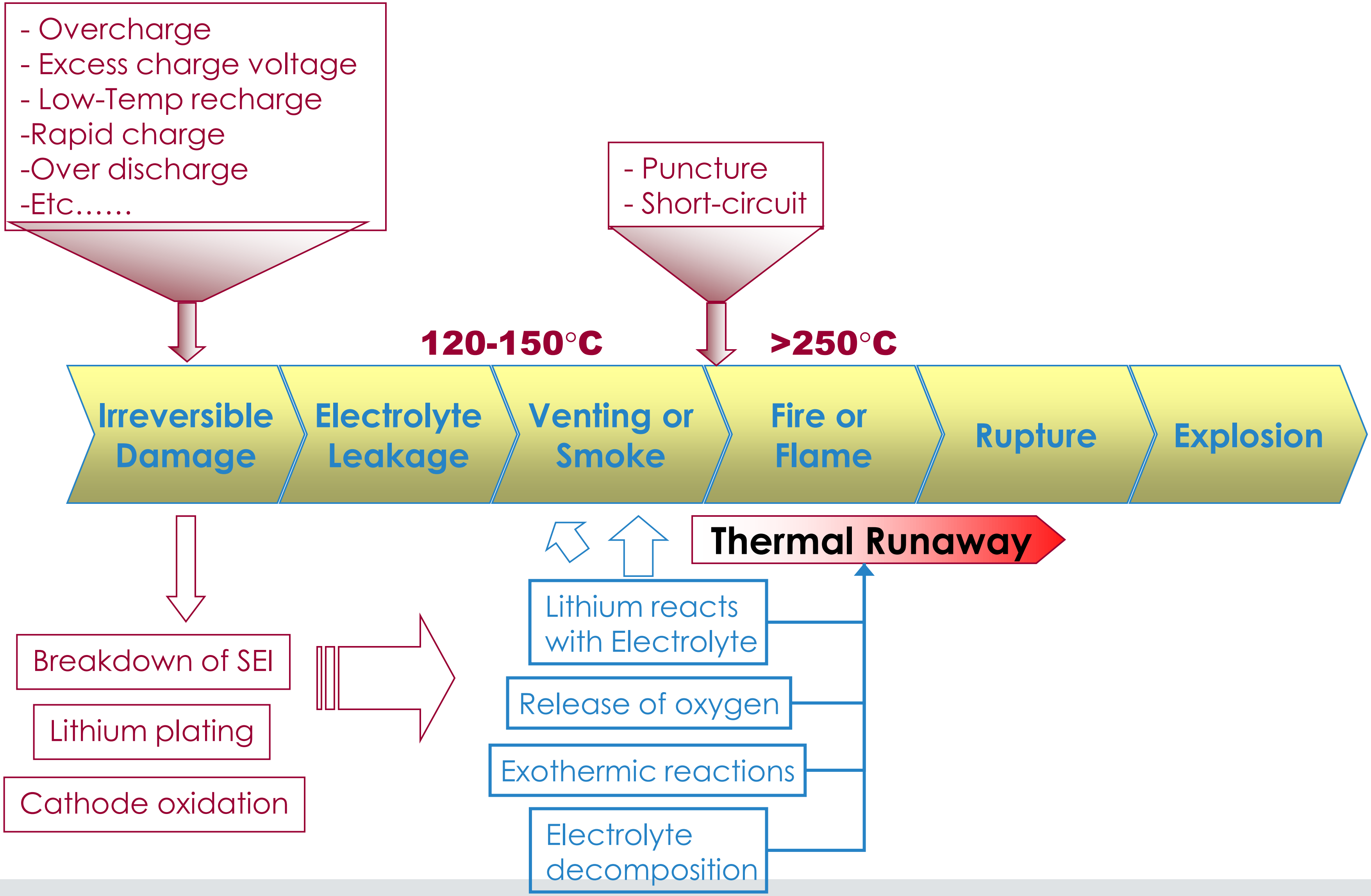
- While at ASC Event
  - Solar Vehicle crashes (battery containment compromised)
  - Defective protection system – BPS
  - Bypasses any required switches
  - Incorrect service on pack - shorting
- While not at ASC Event
  - By-passing critical safety controls - BPS
    - Improper charging or discharging
    - Thermal abuses
    - Short-circuit
    - Improper Storage

Always check cells at start

Tesla Impact Failure



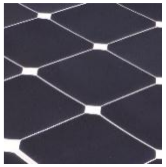
FAILURE MECHANISM



WHY LITHIUM BATTERIES FAIL?

ASC has had ~~1~~ ~~2~~ 3 incidents …

It is critical that we prevent these accidents from happening.



MAKING BAD CELL - SAFE

All “questionable” cells should be fully discharged (0 v)

Use conductive bath to short cell to discharge

Expect heat to be generated, use a metal container

Use10 times volume of cell or more of salt water 10% to 50% concentration of salt (1/4 cup to a gallon works)

Drop into solution away from anyone as gases are poisonous and may erupt from the container (open field or vented hood is fine)

After 2 or 3 hours, check the voltage and verify before disposing the cell

Follow your University's rules to dispose these cells. They are recyclable at this state

BALANCING OR NOT

Balancing is a Challenging activity!!!!!

- It is based on either Voltage or SOC or ?
- If measurement is questionable, how to properly balance?

Balancing generally reduces capacity on those cells that are higher by dumping energy to heat

- Resistive loads are applied by FET's to align cells.

Other methods are available but much more difficult to establish

Strongly suggest teams do better job of matching

- Balance becomes not important
- Balance failure modes and losses then are not
- Design pack for "easy" cell exchange would be better time spent

MATCHING

Cells going into packs have variation that reduce pack capacity

Ability of BPS to detect prevents pack thermal events

If too difficult for BPS to detect, Event may and has Occurred

Better to MATCH so BPS can do job with monitoring all cells

Talk to Manufacturer and confirm process of cell shipment

- Are cells charged to common state?
- Are cells held to common temperature during charge ?
- Do they have a common voltage upon shipment and what is it?

Buy all cells at one time!!

- Reduced chance of variation which causes problems above

Put pack together with like cells to provide least risk

Consider having Manufacturer "matching" Modules worth of cells and providing team the data. It will be worth much.

BREAKOUT SESSION

If you have Electrical & Battery discussion questions, we can address them in the Electrical Breakout B session at 3:00 later today

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ELECTRICAL BASICS

Steve McMullen

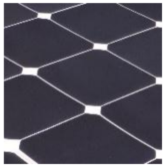
March 21, 2015

ELECTRICAL

Solar Vehicles are ELECTRIC VEHICLES with Solar Panels

MOTOR

- Typically AC high efficiency >97%
  - Permanent Magnet - Magnetic Poles on stator – Permanent Magnet Rotor
    - Axial or Radial Design
    - New Gen is Axial Design
  - Switched Reluctance
    - No Magnets
    - More complex Switching
- DC – A little less efficient – 85 to 93%
- Motor Integrated into Wheel Hub



ELECTRICAL

INVERTER – Smart bi-directional converter

- That box is "**where the smoke hides**"
- Allows Regen and Motoring, Forward and Reverse
- Can be Sensitive to In-Rush Current
  - Must have "Pre-Charge" circuit on Motor Power On Switch
  - Consists of Lower Power Switch to temporarily engage power around main motor switch and a resistive load to prevent inrush. Once Capacitors are charge (Time Delay) Main Motor Switch can be engaged to restart drive.
- Sensitive to Pole Position – Encoders/Sensors must be "aligned"
- Sensitive to Moisture/Humidity/Heat
- Sensitive to Vibration
- Should be close to the Motor and Power Sources to reduce losses
- Can be sensitive to Noise – Electromagnetic
- Is typically a producer of EMI

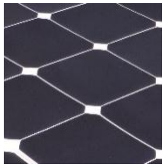
ELECTRICAL

BATTERY PACK

- Must encompass Main Power Relays/Switches
- Is limited to two boxes to contain the battery cells
- Each parallel string must contain a Main Fuse
- Should contain DC/DC Converter
- Must Contain Battery Protection Equipment
- Should contain Supplemental Battery
- Box interior must be Non-Conductive/Compatible with Electrolyte
- Cells must be retained
- Cell should spaced for cooling air flow
- Cell case most likely is Negative Cell voltage

- Entire System should be cycled many times to "characterize" the performance
- Package to right is fastest way to get pack together.

Tyva Energie



ELECTRICAL

Battery Pack Development

- Test Cells to understand variation.
  - Assemble Modules based on Cell **Variation**
  - Characterize Modules
- Test Modules to understand variation
  - Assemble Pack based on Module **Variation**
  - Characterize Pack
- Test Pack
  - Repeats full discharge and charge cycles, **Characterize**

Impedance, OCV, Weight, Voltage

Make sure measurements are accurate and calibrated

How many cells will it take to assemble a BALANCED PACK?

ELECTRICAL

How does one assemble a Pack of Cells

Cell to cell, for a module, hopefully difference will not cause inrush of current to occur. If it does, you haven't matched parallel cells going into modules.

Module to module

- Modules will likely have small differences that require team to consider resistive load between modules when first connecting
- This will equalize voltage between so they can be connected.

Safety preference is to have no cells in parallel or minimize and monitor cells in parallel and also monitor modules that are in series. This approach one has one terminal connection to HV Loads, fuse.

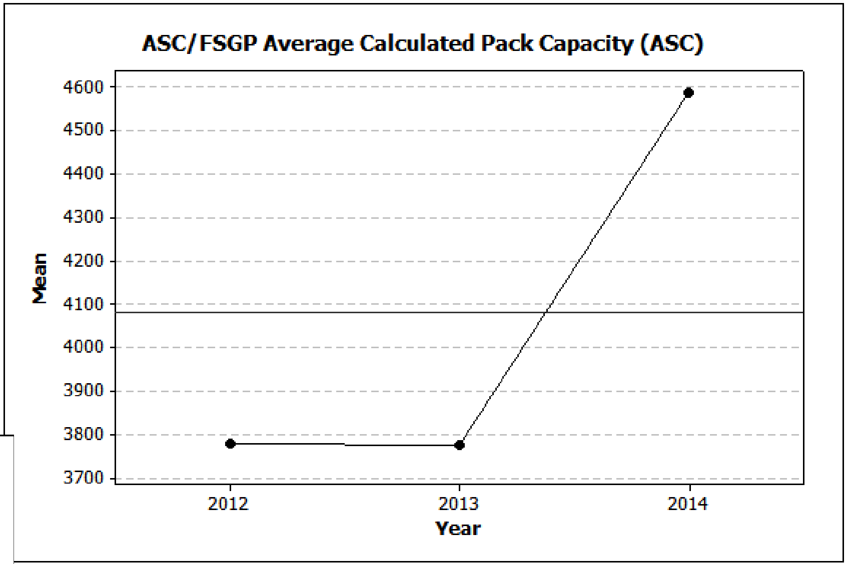
Parallel strings are not preferred as they require multiple fuses

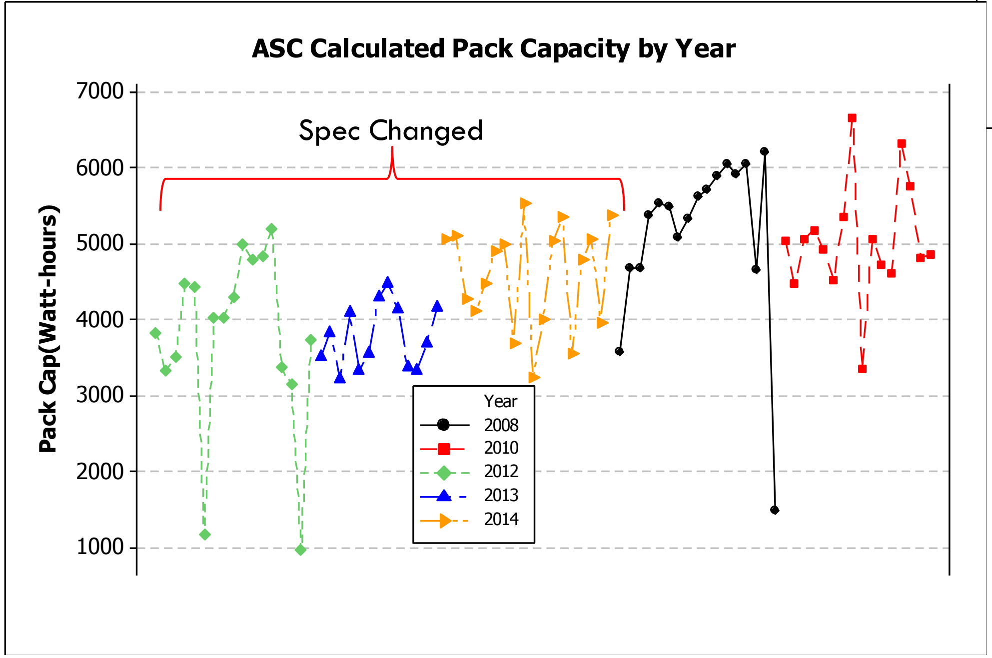
Again a module is a Parallel set of cells, A String is a series'd set of Modules or Cells

ELECTRICAL

Calculated Capacity 2014

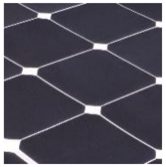
- LiFePO4 Up to 40kg from 30kg
- NiMH up to 60 kg from 45kg
- No Lead Acid (125 kg)





Same Weight Limits
for 2016

7 Cell Models Packs exceeded
200 Watt-hours/kilogram
(Li-Ion and Li-Poly)



ELECTRICAL

FUSES – DC voltage and current rated

- The fuse rating must not exceed 200% of the maximum expected current draw or 75% of the rated wire current capacity

  Main – Must be first connection on Positive pole of Main Battery and be of the Fast Blow rated to protect the Main Power Switch as well.

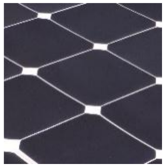
  Supplemental – Same should be same as the Main w/less V.

  DC/DC - Fuse Input and all Outputs

  BPS – Fusible links are acceptable

Relays/Switches

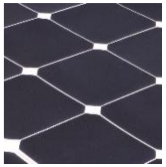
- Must be Normally open and capable to break fault currents
- Actuation device must be clearly labeled (10mm)



ELECTRICAL

Wiring

- Rated for Current
- Adequately sized for low loss
- HV Colored
  - Black - **Ground**
  - Red/Orange - **Hot**
- All wiring should be Labeled for service
- All wiring should be restrained to prevent Chaffing
- Drip Loops should be considered
- Layout vehicle for Short Wiring Runs



ELECTRICAL

Labels

- On Battery Pack
  - Technology
  - HV Label
  - Flammable
- On Junction Boxes
  - Where HV exist
  - With HV Label
- 10 mm size or larger
- Power Switch
  - Where visible to driver/ passer by
  - 10 mm or larger labels
  - Explicit instructions

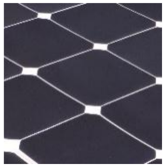
ELECTRICAL

Battery Ventilation

- Must be on whenever Main Battery is connected
- Must provide adequate ventilation (280 lpm)
- Must exhaust to EXTERIOR of Vehicle (not into Fairings/Skirts)
- Exhaust must not be able to reach driver
- Battery Box must be NEGATIVE pressure (All fans “sucking” on battery box)

Impound Box

- Must be large enough for Pack and have a lockable hasp
- Must be secure – no exposed screws that can be removed to gain access



ELECTRICAL

Isolation

- Vehicle must be isolated from all voltages
- > 500 MΩ from Positive or Neg Main Battery Terminal to any conductive surfaces on the vehicle
- Done when vehicle is all ON - System Voltage
- Typical failure locations are chaffed wires, and designed grounds.
- Failing this earns RED

Control

- All Vehicle functions must be in control of the driver
- Telemetry is unidirectional (Download from Solar Only)

ELECTRICAL

Accelerator

- Free to move
- Return to Zero position automatically when released
- If Cruise exists – Brake or vehicle off must auto re-zero accelerator along with driver change.

Umbilical

- Must be carried within the vehicle

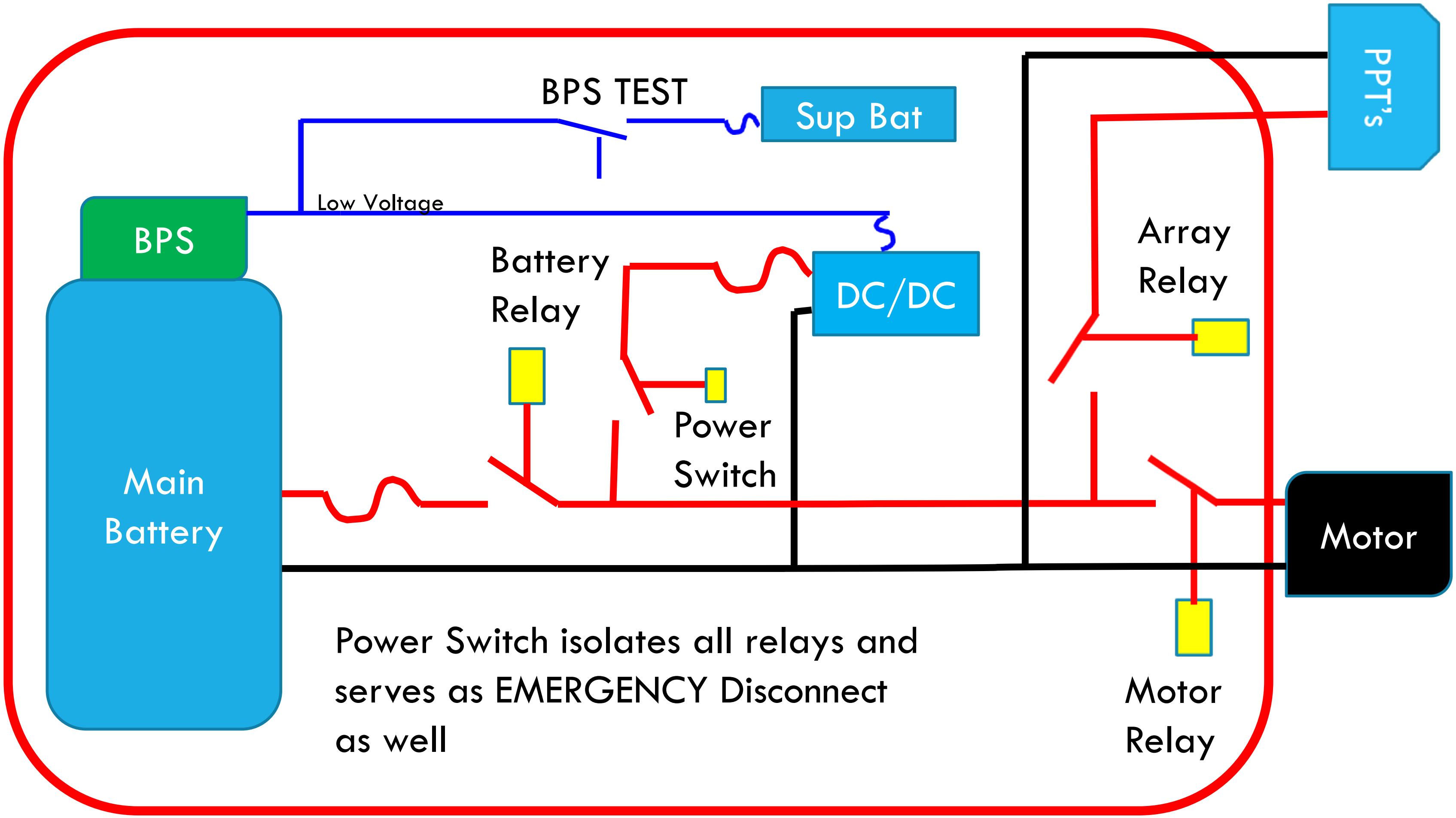
ELECTRICAL SUBMISSION EXPECTATIONS

"Battery Approval" Form Complete

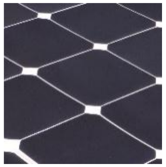
Schematic/Block Diagram/Electrical Representation

- Expect to see all HV Components
- Fuses, Shunts, Switches, Source or Sink Devices,
- Expect to see outline of Battery Box on Schematic
  - So I can detect what is in it vs what is outside of it
- Expect to see both positive and negative HV circuits.
- Benefit to team is to show **more**, less risk at Scrutineering
- Ratings of Fuses/Switches/Relays is also of interest
- I also Expect to see a "write-up" of how the System will be RESET after a BPS trip.

REPRESENTATION OF A SCHEMATIC



This is AN Approach to provide "SAFE" Impound



Q&A

Questions?