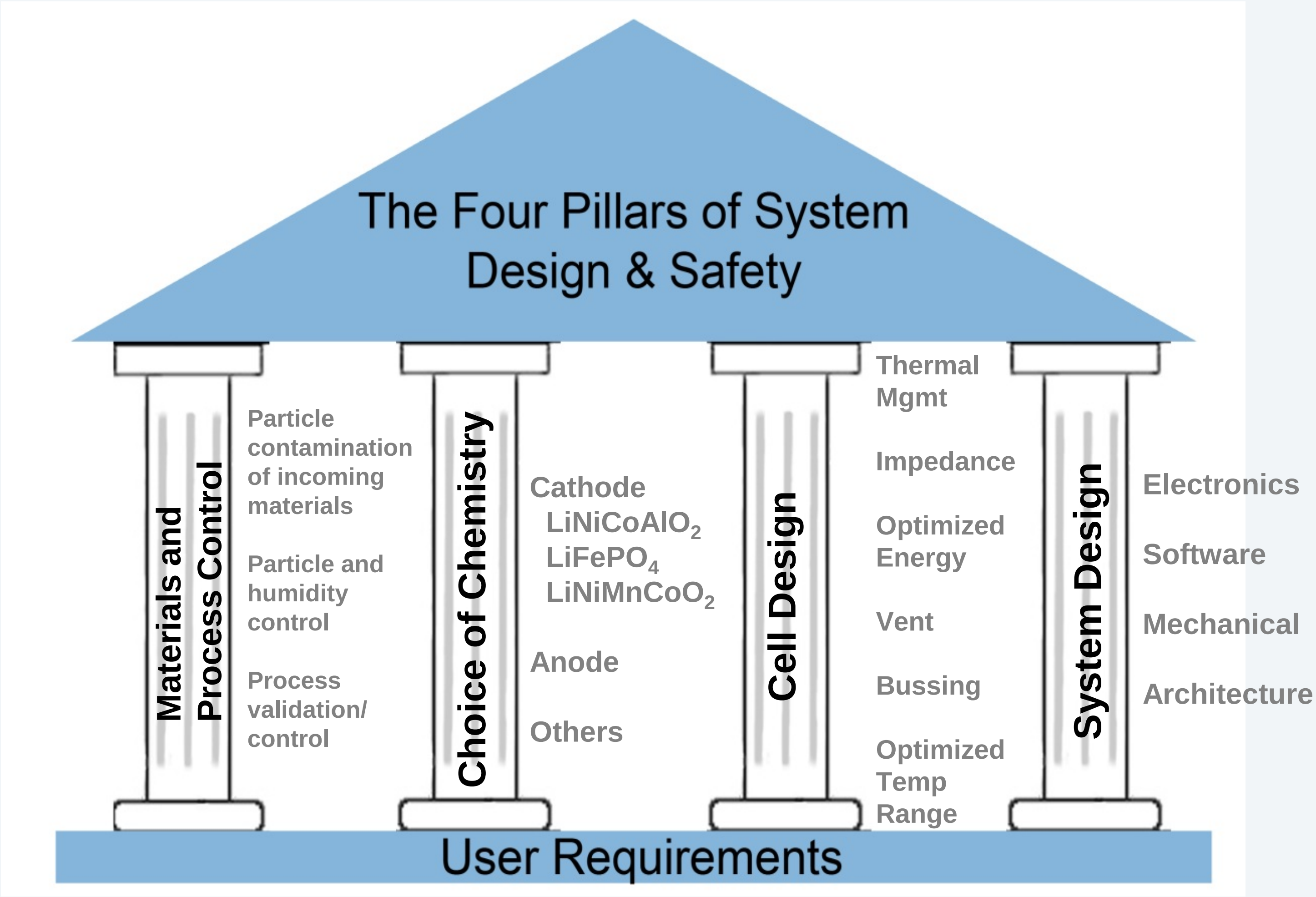
Li-Ion Safety

March 28, 2013

saft

Safety by design

- Four critical pillars of safety

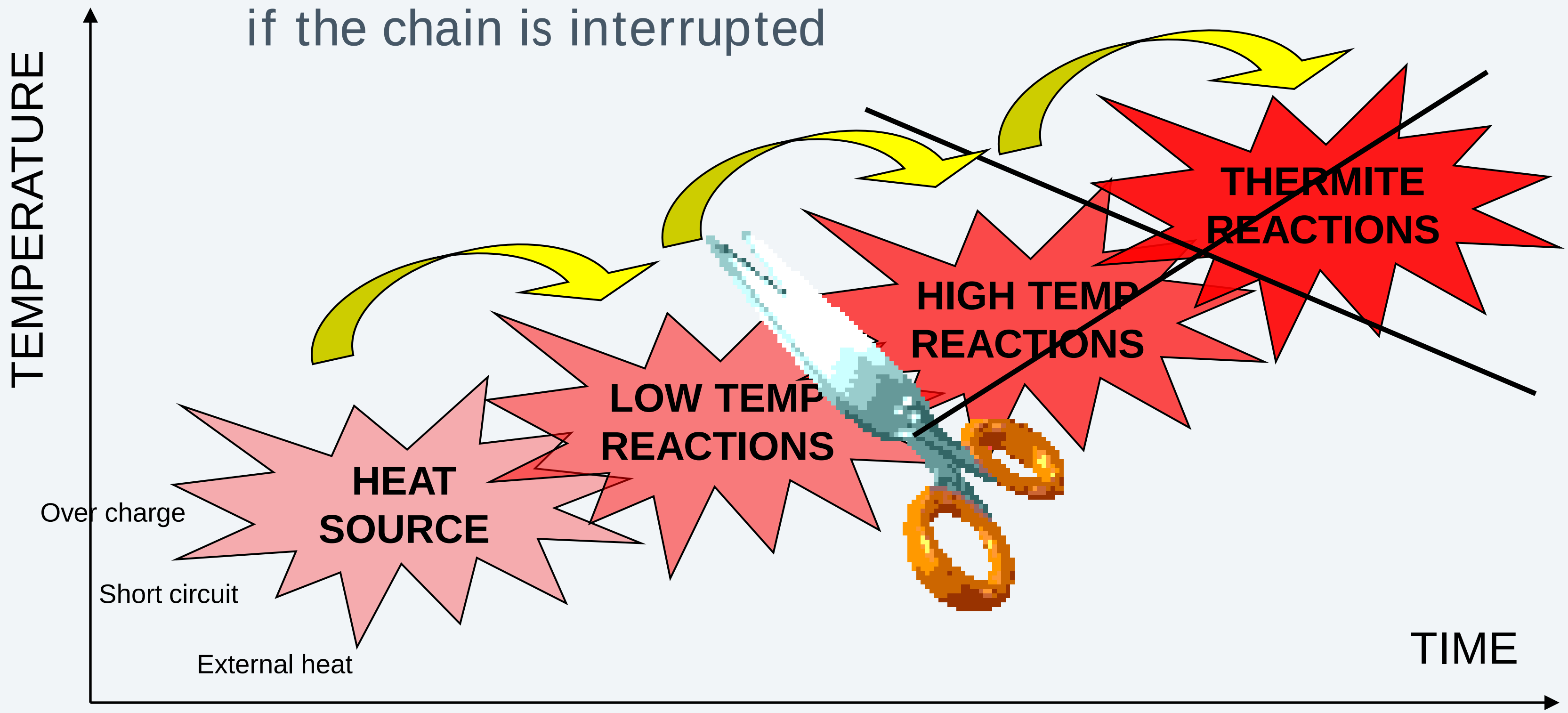


SAFETY

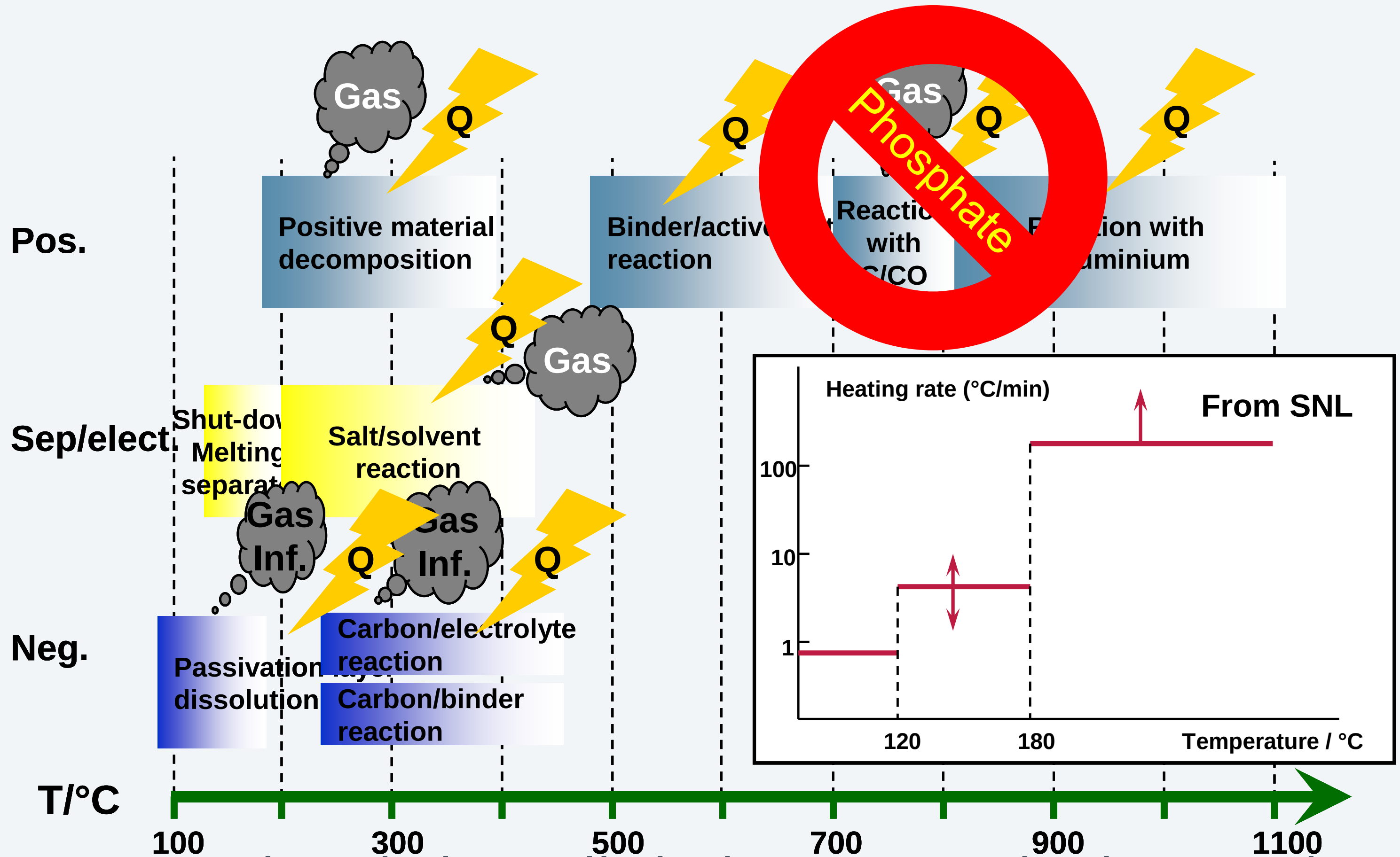
- Dangerous abuse conditions
  - **Overcharge**
  - **Crush**
  - **Overheating**
  - **Short circuit (without protection)**
- Certain conditions do not pose problems
  - Over-discharge (except at very high rate) - cell shorts via Cu dissolution in a benign way and becomes resistor in series
    - We have never had this become an issue, even if others claim it is a problem for them
  - Immersion in water – cell discharges and becomes unusable

Simplistic view of thermal runaway mechanism

- Thermal runaway of Li-ion system is a chain reaction, with each one triggered by a source of heat and triggering the next reaction in the temperature ladder.
    - The severity of a thermal event can be limited if the chain is interrupted



Thermal run away in a charged Metal Oxide Li-ion cell



- Without appropriate design to limit the run away (such as venting, insulating layers,…), the chain of reaction leads to a violent event.

Abuse of Li-ion Cell

- Overcharge- the condition where Li-ion cell or cells is charged over the 100% state of charge – the most severe abuse condition
  - Causes
    - Charge control fails. Battery sees gross over-voltage
    - Cells are severely out of balance and while battery voltage is normal, one or two cells have much higher voltage
  - Battery protection electronics address overcharge
    - Must watch every virtual cell in a series string individually
    - Must be redundant
    - Should be able to turn of charge to string if one cell is showing over-limit voltage
- Crush – any condition where the physical integrity of a cell is disturbed
  - Causes cell to short internally typically resulting in fire and smoke
  - Crush could happen at any state of charge between 100% and 0%
  - Protection is the Mechanical Design and limited to reasonable level

Abuse of Li-ion Cell

- **Overheating** – exposure to elevated temperature
  - The separator melts and allows a direct short between the positive and negative electrode
  - Normally occurs at temperatures over $120^{o}C$
  - This is normally a secondary issue if it occurs, i.e. there is already a fire wherever the battery is…
- **Short Circuit** – exposure to a highly conductive electrical current path outside of the protected design
  - Cells may be internally protected with fuses, but only to the voltage limit of the cell fuse (<30V normally)
  - Can cause cell (s) to overheat
  - If cell design is not adequate to handle the heating, thermal runaway is possible
  - Proper cell designs can limit this, except in high voltage batteries where voltage can push currents very high
  - Battery insulation and design protect against this as well

Required Battery Safety Features

- Fully tested cells sized for the application
  - Right power level to control heating
  - Right energy level: Minimum number of parallel strings
- Full electronics protection
  - Redundant Overcharge
  - Temperature Monitoring
  - Balancing
  - Over-Current Protection
  - Dead Front connector when possible
  - Either coordinated charger control or internal charge control
  - EMI/EMC protection at the level required by the application
- Full mechanical protection
  - Physical design to survive application environment
  - Thermal design to manage either heating or cooling as needed
  - Fully tested to all required physical environments
  - EMC/EMI protection when needed

Required Cell Protection Electronic Safety Features

- Redundant Over Charge Protection
  - At least two ways to detect and stop charge in the event of a cell over-voltage
  - **MUST be able to KNOW the state of charge of all cells individually**
- Over-Current Protection
- Balancing
- Temperature sensing in enough places to protect from anomalies in discharge or charge
- Ability to cut off the flow of current into and out of battery, at the battery voltage and power level
  - This can **not** be done with cell fuses if battery voltage >30 Volts
  - PTCs do **not** work above their rated voltage (low voltage only)
  - Only discrete devices work above about 30V
- Entire power circuit must have properly rated devices for the battery voltage

Saft's View On Li Ion Battery Safety

- We've been doing this since 1996
- We make the cells and the batteries
- The failure modes are complex and unique in the battery world
- We've learned from MANY mistakes and from the UNKNOWNS
  - First cells were sometimes full of internal shorts – process control and improvement
  - First batteries had undersized components – design lessons learned – matching with the system important
  - First Customers did not realize how different the Li Ion was – better customer education and cooperative design of systems
  - Cell fusing is inadequate above a certain voltage – we now avoid them for high voltage batteries
  - Electrochemistries are not perfect for all applications – we offer the one that is best for each application
  - Battery design must be professional – it can make all the difference – heat, vib, shock, series & parallel architecture, etc…

Defense programs

Improved Target Acquisition System (ITAS)

- Improved Target Acquisition System for the Army's TOW Missile
- Delivered more than 3,000 ITAS batteries; currently in the field
- Qualified to TOW Missile Level Spec and tested to NAVSEA 9310
- Replacement for former Ag-Zn battery, resulting in several improvements:
  - Charging time < 6 hours
  - Operating time > 16 hours
  - Total life > 10 years

Raytheon

Tripod-mounted ITAS system with battery connected

Military HEV experience

- Saft has supplied Li-ion HEV batteries for several military demonstrator vehicles, including:
  - BAE System's Manned Ground Vehicles for the US Army's Future Combat Systems program
  - General Dynamics Land Systems' RSTV, 8x8 AHED and AGMV
  - Carnegie Mellon University's National Robotics Engineering Center's Crusher unmanned vehicle
  - US Army TACOM / DRS Technologies' HMMWV

RSTV

AHED 8x8

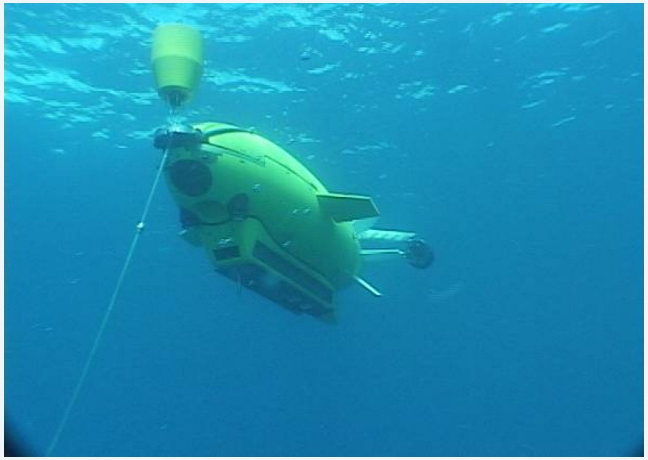
Crusher

HMMWV

NLOS-C

Underwater experience: Marlin

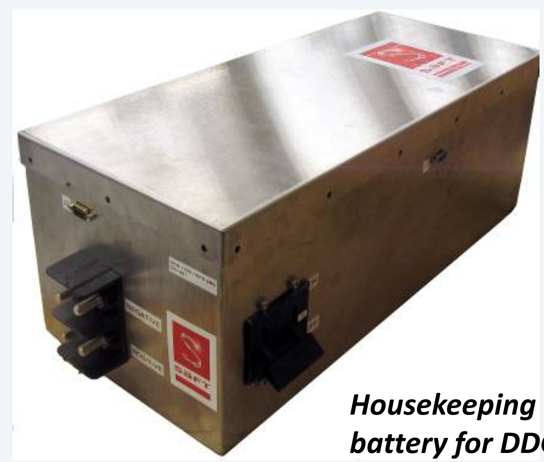
- Providing batteries to Lockheed Martin for this Autonomous Underwater Vehicle
- Used in offshore oil and gas, science and oceanography, and other military and civilian applications
- Two batteries, using VL 52E cells:
  - 100 V battery - utility (or propulsion) power
  - 25 V battery - powers the instrumentation (or electronics)



Combined 100 V and 25 V battery system for Marlin

Naval experience: DDG-1000

- Providing two types of Li-ion batteries for DRS Technologies' power system
  - Load center battery: Shuts down the ships' breakers electronically
  - Housekeeping power supply: back-up power for the ships' loads
- Batteries capable of operating at high temperatures (70° C)
- Using VL 34P cells
- Have been NAVSEA Note 9310 tested



Housekeeping Li-ion battery for DDG-1000

Aviation: Joint Strike Fighter (JSF) F-35

- 270 V battery: Start-up & emergency fill-in power for flight control actuators
  - > Energy: 1750 Wh
  - > Power: >36 kW @ -26C; 8.9kW @ -40C
  - > 90 pounds

- 28 V battery: Power for aircraft loads, start-up & in-flight emergency fill-in
  - > Energy: 900 Wh
  - > Capacity: 32 Ah
  - > Power: 5.0 kW @ -26C; 1.5 kW @ -40 C
  - > 29 pounds

270 V battery

28 V battery

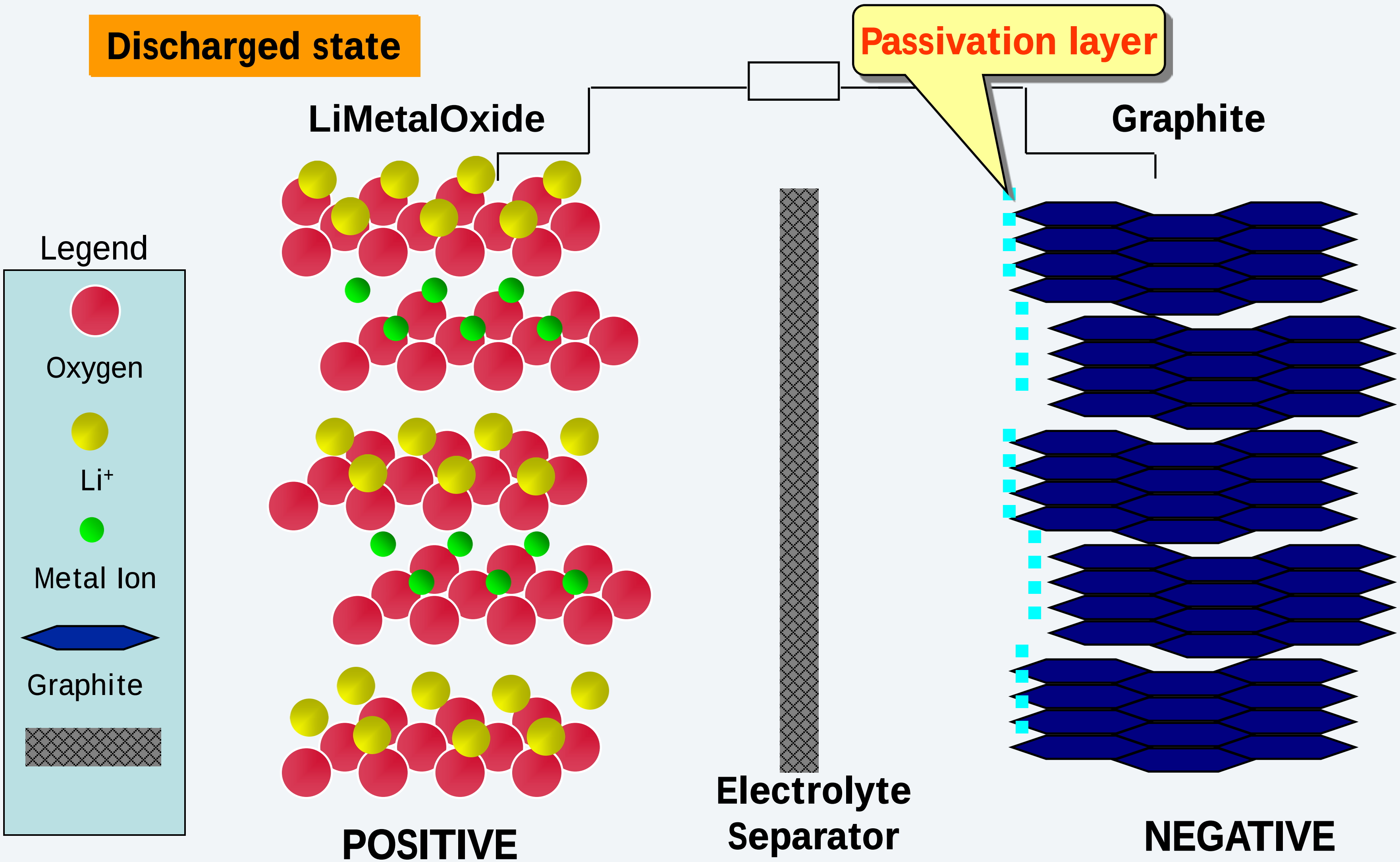
- Both Saft 270 V and 28 V Li-ion batteries are flying daily on the aircraft
- Module Electronics by Saft
- Battery Management by GE

Space heritage

- Supplied the first U.S. – made Li-ion battery to go into space on the space shuttle EVA mission in 1999
- Over 85 satellites in orbit using Saft Li-ion batteries
- Selected by NASA to develop the next-generation Li-ion space technology

BACK UP INFORMATION

Structure of a Li-ion Cell



Electrochemical cell

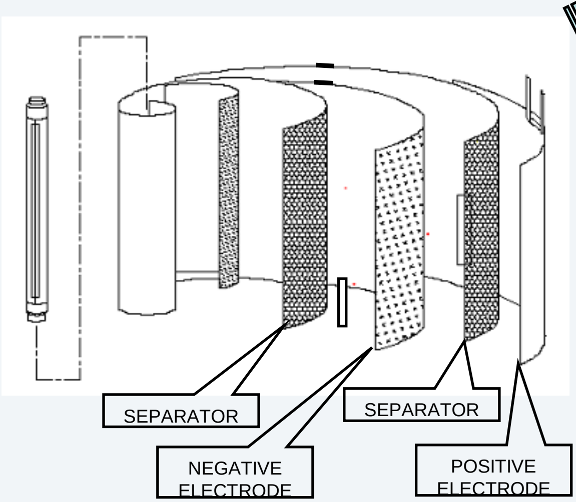
Structure in a nutshell

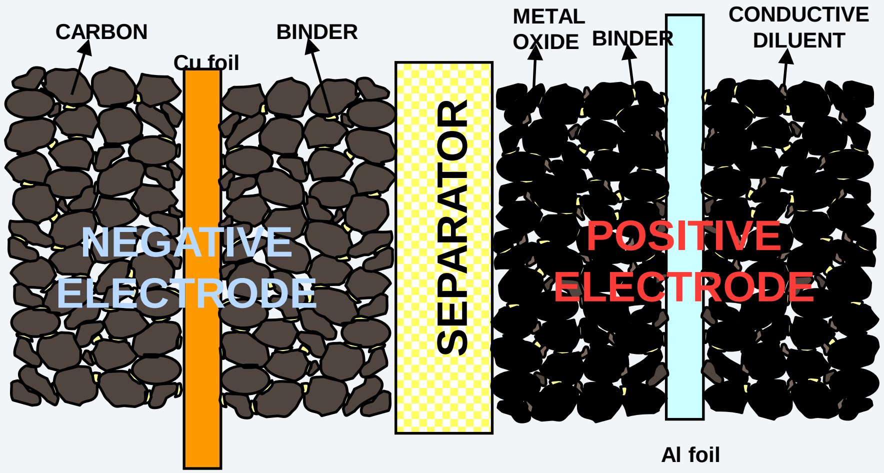
Li-Ion Architecture

-Cell assembly with electrodes

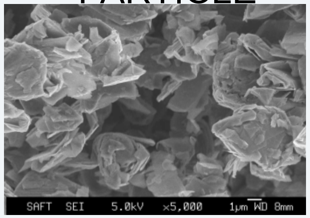
-Porous electrode

-Particle morphology

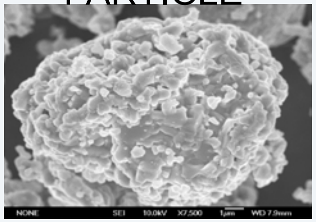




NEGATIVE PARTICLE



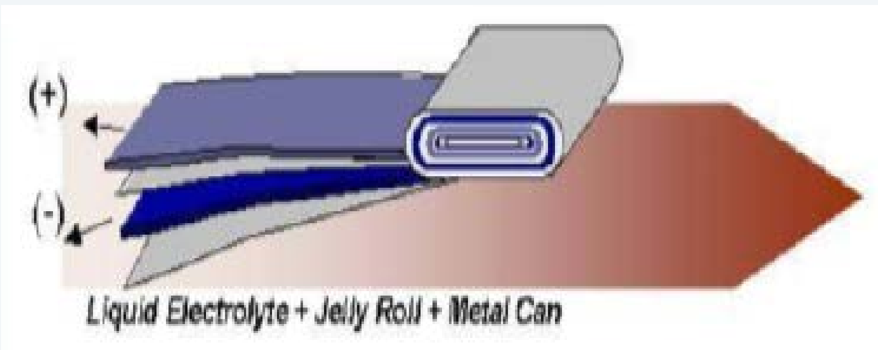
POSITIVE PARTICLE

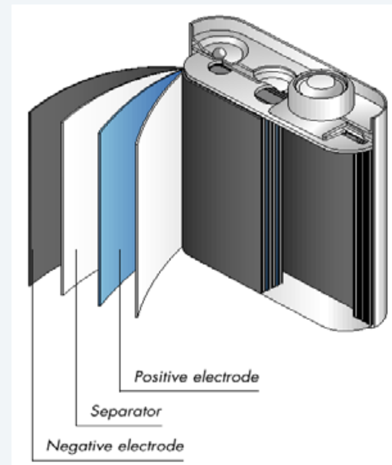


Geometrical Surface Area (Measured electrode area) **+** **True (Fractal) Surface Area** (Materials specific surface area)

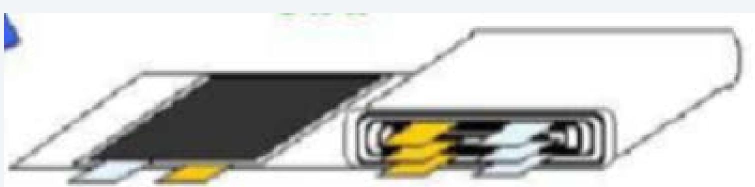
Prismatic Cells

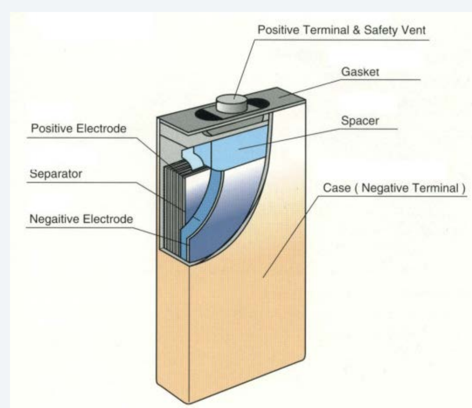
WOUND CELL DESIGN





STACKED CELL DESIGN





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Current Chemistries

- Currently Used Cathodes
  - $LiCoO_2$ (LCO)
  - $LiNiCoAlO_2$ (NCA)
  - $LiNiMnCoO_2$ (NMC)
  - $LiMn_2O_4$ (LMO)
  - $LiFePO_4$ (LFP)
- Currently Used Anode
  - Carbon/Graphite
- Emerging (???) anodes
  - $Li_4Ti_5O_{12}$
  - Amorphous (Co-Sn-C) high capacity anodes