ECE 398GG – ELECTRICAL VEHICLES

6. Battery Hazards and Safety

Oliver Gross

Stellantis NA

OUTLINE

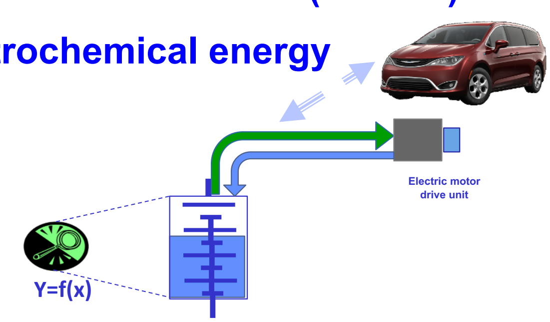
- Key hazards batteries are exposed to and key hazards batteries produce
- Electrochemical vs. chemical energy release
- Thermal propagation
- High voltage hazards
- Test and characterization methods
- Mitigation and control strategies

THE HAZARDS FOR BATTERIES AND *EV*s

- A battery is an active energy storage device:
  - its operation to perform its primary function gets it de-energized: lack of control of such an operation creates hazards
  - is unlike a fuel tank, which can be drained of fuel passively without the operation the device
- A key battery function is to isolate the electrochemical components from the environment and vice versa; the failure of this function leads to many of the hazards we associate with batteries

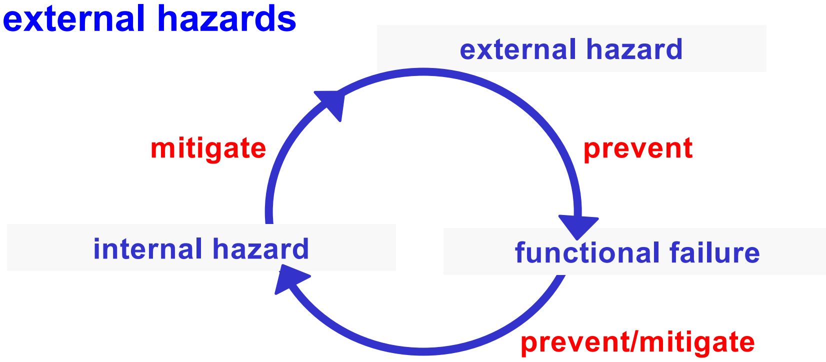
REVIEW OF THE *EV* BATTERY PRIMARY FUNCTIONS

- Provide electrical power
- Accept electrical power
- Control state of function
- Communicate with the host (vehicle)
- Store electrochemical energy



THE FUNCTION – HAZARD LOOP

- External hazards can lead to functional failures
- Functional failures can lead to internal hazards
- Internal hazards can propagate to become external hazards



LIST: HAZARDS RELATED TO *EV* BATTERIES

- Most hazards can be captured within this list:

external hazards	internal hazards
debris impact to enclosure	isolation failure
excessive heat / fire	internal short circuit
water immersion	excessive cell temperature
static load	vented gas products
external electrical short	fluid leak

EUCAR HAZARD LEVELS

EUropean Center for Automotive Research

Hazard Level		Classification Criteria, Effect
0	No effect	No effect, no loss of functionality
1	Passive Protection activated	No defect, no leakage, no venting, no fire or flame, no rupture or explosion, no exothermic reaction or thermal runaway, cell reversibly damaged, repair of protection device needed
2	Defect Damage	No leakage, no venting, no fire or flame, no rupture, no explosion, no exothermic reaction or thermal runaway, cell irreversibly damaged, repair needed.
3	Leakage ≤50%	No venting, no fire or flame, no rupture, no explosion, weight loss ≤ 50% of the electrolyte weight electrolyte - solvent + salt
4	Venting >50%	No fire or flame, no rupture, no explosion, weight loss >50% of the electrolyte weight
5	Fire or Flame	No rupture, no explosion, i.e.; no flying parts
6	Rupture	No explosion, but flying parts, ejection of parts of the active mass
7	Explosion	Disintegration of the cell

Li-ION TECHNOLOGY

- Today's predominant battery technology
- Highest rechargeable battery energy density (*Wh/l*) and specific energy (*Wh/kg*)
- Excellent cycle life and durability
- High-cell voltage (*e.g.,* 3.6 *V*) implies aqueous electrolytes cannot be used and organic solvent-based electrolytes are used instead
- Flammability concerns – particularly, when coupled with the high material energies

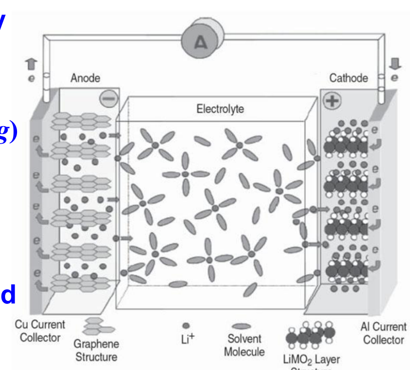
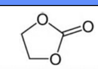
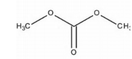
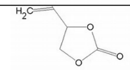
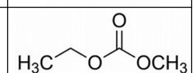
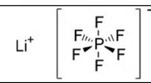
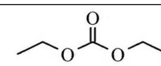


TABLE OF COMMON ELECTROLYTE MATERIALS

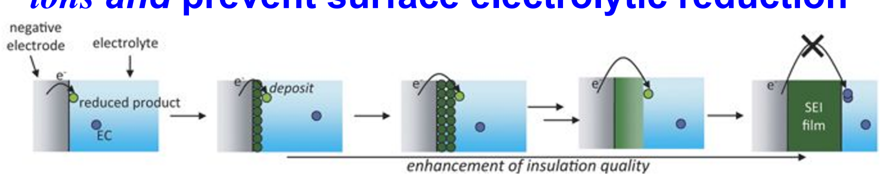
Batteries currently use *$LiPF_6$* (*lithium hexafluorophosphate*) salt in organic solution of *ethylene carbonate* (*EC*) solvent and other viscosity modifiers (*diethylcarbonate* (*DEC*), *dimethylcarbonate* (*DMC*), *ethylmethylcarbonate* (*EMC*): for example is 1.2 *M $LiPF_6$* in 3:7 *EC*:*EMC* – is considered a standard test electrolyte

material	structure	material	structure
ethylene carbonate (EC)		dimethyl carbonate (DMC)	
vinyl ethylene carbonate (VEC)		ethyl methyl carbonate (EMC)	
Lithium hexafluorophosphate		diethyl carbonate (DEC)	

9

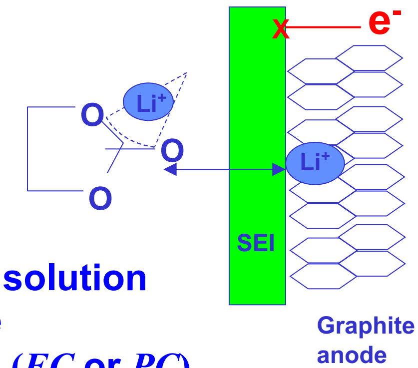
ELECTROLYTE MATERIALS

- **The *EC* is a solid at room temperature and dissolves the salt and provides the ionic transport for both the *Li^+* cations and the *PF_6^-* anions**
- **The other carbonates dissolve and dilute the *EC* to lower the electrolyte viscosity and make it more volatile**
- **Plays a large role in the development of stable *SEI* – *solid electrolyte interphase* – to allow passage of *Li-ions and* prevent surface electrolytic reduction**



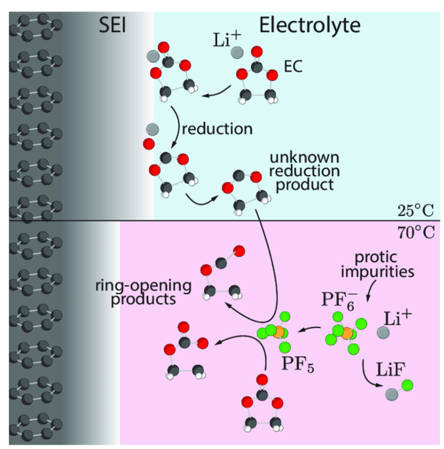
SOLID ELECTROLYTE INTERPHASE (SEI) LAYER

- *SEI* layer forms on the anode (carbon) surfaces
- Ionically conductive, electronically insulative layer
- Created during *initial charge* in the formation process
  - reduction of electrolyte solution onto the carbon surface
  - main organic carbonate (*EC* or *PC*) react with *Li* to form soluble *Li-oxide* within *organic structure*



ELECTROLYTE ISSUES

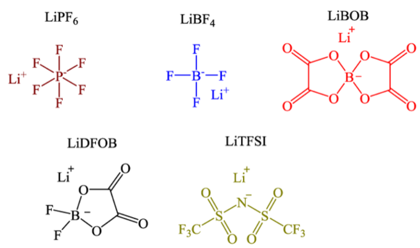
- *$LiPF_6$* is sensitive to water, decomposing to form *hydrofluoric acid* (*HF*) and *fluoro-phosphoric acid*
- High temperatures (> 55° C) will also encourage decomposition of the salt under the voltages seen within the cell
  - the acids attack the anode and cathode, leading to the destruction of the cell
  - stabilizers are added to electrolyte to mitigate these issues



Schematic summary of observed electrolyte decomposition mechanisms

ELECTROLYTE ISSUES

- $LiPF_6$ also decomposes at potentials around 4.5 *V*
- Other salts are being considered as well (*LiTFSI* and other Imides, "*LiBOB*", $LiBF_4$)
- Solvent flammability/volatility



Common Electrolyte Salt

- $LiPF_6$ - *Li hexafluorophosphate* - this salt is almost exclusively used in current *Li-ion* batteries because it provides the best mix of the required properties; con – easily reacts with water to form *HF*
- $LiAsF_6$ - *Li hexafluoroarsenate* -similar performance to *Li hexafluorophosphate* without *HF* formation;con –arsenic is highly toxic
- $LiClO_4$ – *Li perchlorate* – one of the first salts studied, bu abandoned due to explosivity
- *LiFSI* and *LiTFSI* – "imide salts" – these salts are under intensive research currently for use with the next generation materials (silicon, 5 *V* cathodes) due to the high thermal stability and stability with water

CHEMICAL *vs.* ELECTROCHEMICAL ENERGY

- *Graphite + Li*:

$$C_6 + Li = LiC_6;\ \ 4.9\ kJ/g$$

$$LiC_6 + 6\ 1/4\ O_2 = ½\ Li_2O + 6\ CO_2;\ \ 63.6\ kJ/g$$

- In the presence of *oxygen* and heat, the energy per *gram* of *lithiated graphite* anode released is 13 X that of the stored electrochemical energy
- A similar issue is faced by the decomposition of a metal oxide anode

CATHODE ELECTROCHEMICAL DECOMPOSITION

- **A classic metal oxide cathode material has this formulation:**

$$LiMO_2;\ M{=}3+$$

- **However, when charged the amount of lithium is considerably less:**

$$Li_{1\text{-}x}MO_2;\ M = (1 - x)\ 3+\ \&\ x4+$$

- **The cathode is prone to decompose to more table materials, under heat, releasing heat and oxygen:**

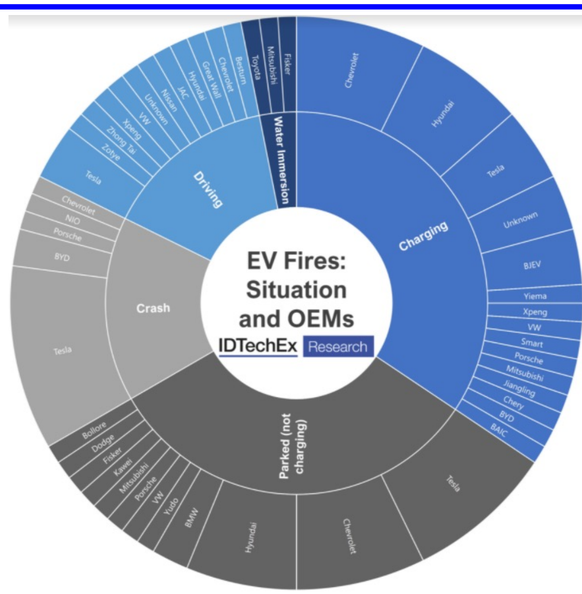
$$Li_{1\text{-}x}MO_2 \rightarrow (1\text{-}x)LiMO_2 + xO_2\ ;\ M = 3+$$

remember: the anode reaction and the fuel triangle!

DISTRIBUTION OF *EV/PHEV* FIRES

95 vehicle types:

make / model / year



CELL POWER & HEAT GENERATION

cell specifications:

capability (*C*): 25 *Ah*

nominal DC resistance (*R*): 0.5 *mohm*

V_{max}: 4.2 *V*

V_{nom}: 3.68 *V*

specific heat capacity (Q_h): 1 *kJ/kg K*

specific energy: 250 *Wh/kg*

key equations:

power (*P*) = $V_{min} * (V_{max} - V_{min}) / R$ (*W*)

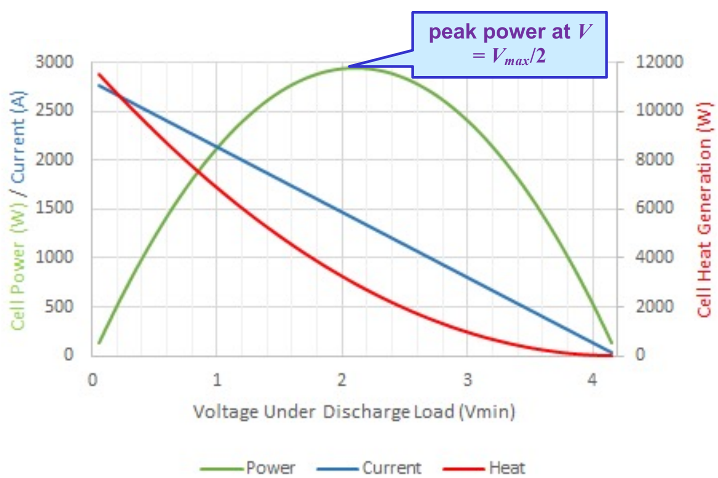
current (*I*) = P / V_{min} (*A*)

$P_{heat} = I^2 * R$ (*W*)

$Q_{heat} = P_{heat} * t$ (*J*)

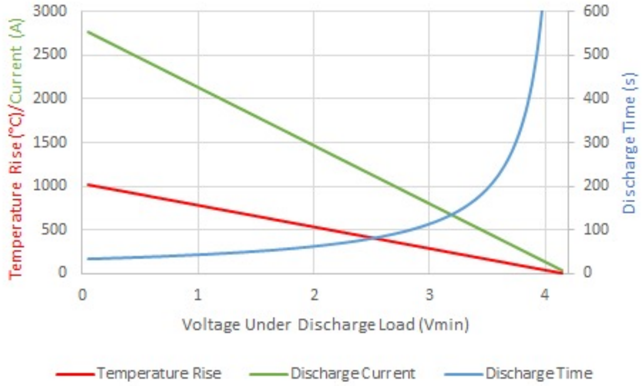
CELL UNDER UNCONSTRAINED DISCHARGE

Based on the cell specifications given in the previous slide



CELL POTENTIAL TEMPERATURE RISE

- ❑ Assumptions: adiabatic condition and the current can be maintained throughout the discharge



- ❑ The temperature rise looks incredible!

CELL POTENTIAL TEMPERATURE RISE

- ❑ Assume a 10-*s* discharge at a specified voltage $= f(V_{max})$:

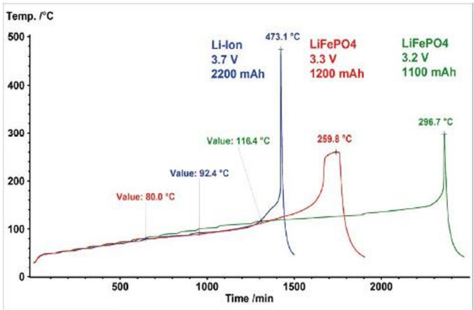
10s discharge

Vmin=f(Vmax)		I (A)	T (°C)
2Vmax/3	3 V	933	36
Vmax/2	2 V	1400	80
Vmax/3	1 V	1867	142
Vmax/4	1 V	2100	180

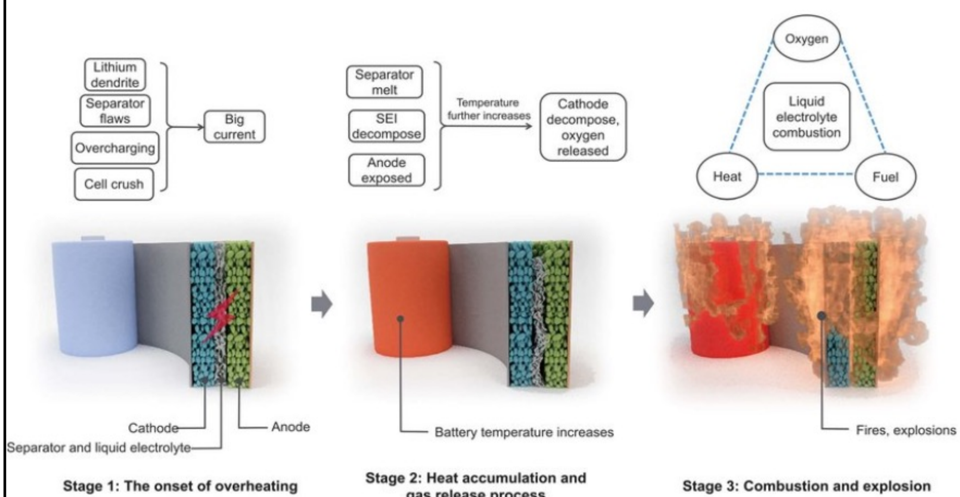
- ❑ Assume cell is adiabatic, even though there will be heat rejected into the environment
- ❑ The table shows the potential temperature rise that can be achieved inside the cell

THERMAL RUNAWAY ISSUES

- An issue for ALL Batteries.
- Of particular interest for Li-ion, due to high energy density AND the use of flammable electrolytes
- Both cathode and anode materials will exothermically decompose, at elevated temperatures.
- The energy levels are exacerbated with higher *state of charge* (*s.o.c.*)



THE 3 STAGES OF CELL THERMAL RUNAWAY



Source: K. Liu, Y. Liu, D. Lin, A Pei, Y Cui; Materials for Li-Ion Battery Safety, http://advances.sciencemag.org/June 22, 2018

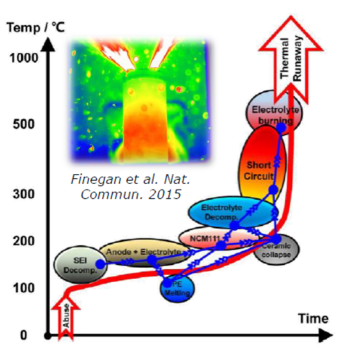
SOME SALIENT *Li-ION* CELL TEMPERATURES

Some temperature-based events:

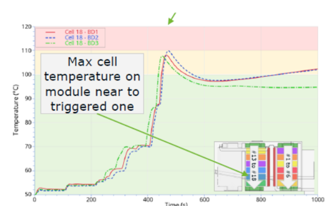
T (°C)	Event
-46	Most electrolytes precipitate salt or freeze
-40 to +55	Operating range
+65	Electrolyte salt instability against graphite
+85	SEI layer begins to dissolve, allowing electrolyte reaction with anode
+115	Earliest onset of metal-oxide cathode decomposition
+130	Melting Point of Polyethylene (separator)
+140	Flashpoint of some electrolyte solvents
+150	Melting Point of Polypropylene (separator)
+180	Melting Point of Li metal
+210	Metal Phosphate Decomposition
+680	Melting Point of Al metal

MORE ON CELL PROPAGATION

GTR No.20 proposes notification of thermal event to occupant and provides at least 5 minutes to egress vehicle, before propagation between cells leads to enclosure breach.



Feng et al. Energy Storage Materials, 10, 2018 NMC/graphite chemistry



VOLTAGE RANGES

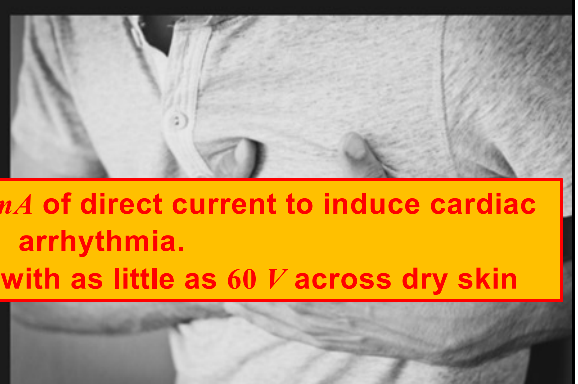
- A single cell is, typically, operating between $2.8\ V$ and $4.2\ V$, with $3.7\ V$ nominal value
- Cells are connected in series, in order to deliver more power
  - *EV*s will often have ~100 cells in series – $400\ V$ systems
  - more recent systems have around 200 cells in series – $800\ V$ systems

ELECTRIC SHOCK

Electric Shock

Electrical current passing through the human body can cause:

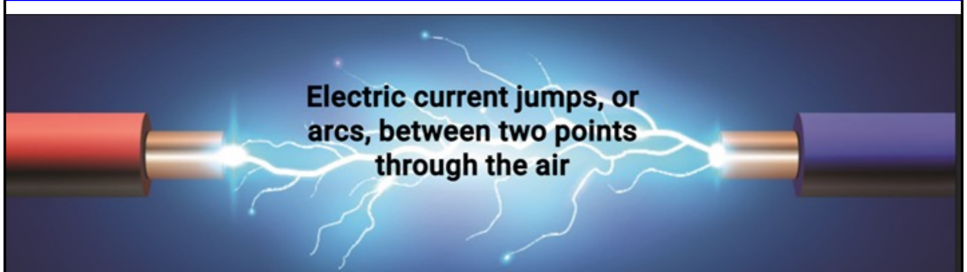
- Cardiac arrhythmia (heart beats irregularly) or cardiac arrest (heart stops beating)
- Skin and tissue burns
- Nerve damage
- Amputation
- Blindness
- Possible death



It takes as little as $100\ mA$ of direct current to induce cardiac arrhythmia.
This can be achieved with as little as $60\ V$ across dry skin

DEFINITION OF HIGH VOLTAGE

ARC FLASH



***EV*s have hundreds of *volts* in their propulsion system, providing opportunity for arc flashes**

An arc flash can cause blindness, severe burns and tissue damage

TYPICAL *HV*-RELATED *EV* LABELS

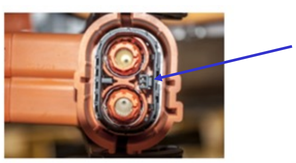
Shock Warning Label

Lithium-Ion Battery Warning Labels

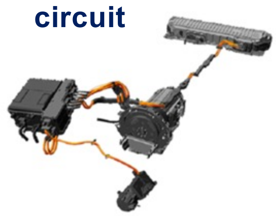
First Responder Label


First Responder Cable Cut Label

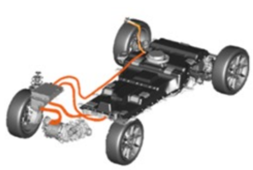
THE PARTS OF AN *HV* PROPULSION SYSTEM


High Voltage Connectors

HVIL
circuit

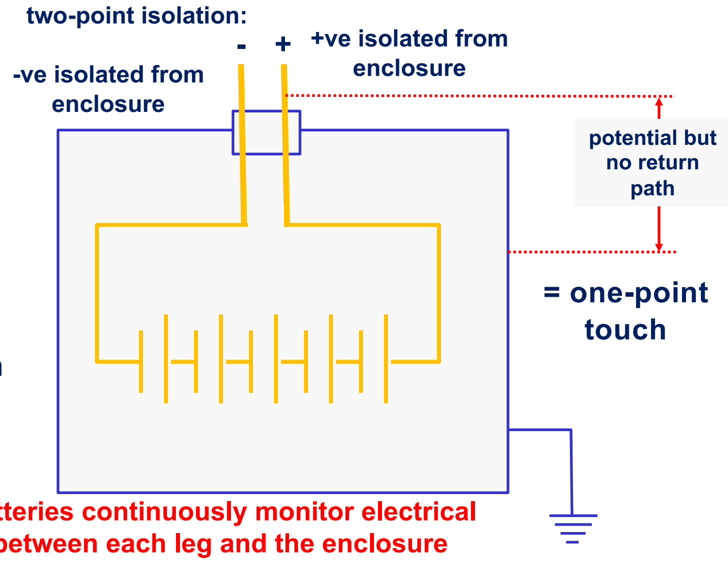

High Voltage Wiring


Battery Pack Internal Cables


High Voltage Wiring


Power Inverter Module (PIM)

TWO–POINT ISOLATION / ONE–POINT TOUCH

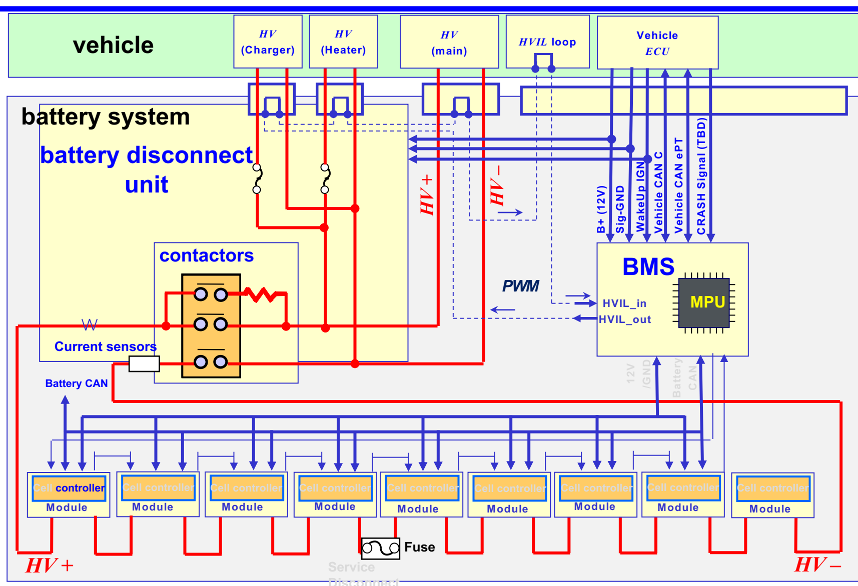


- *500 Ω/V*
- 1,000 V_{DC}

design min

most *HV* batteries continuously monitor electrical isolation between each leg and the enclosure

THE BATTERY *HV* SYSTEM



HIGH VOLTAGE INTER – LOCK (*HVIL*)

- A low voltage (5-12 *V*) circuit within the battery and other *HV* components within the propulsion system, routing through all *HV* connections and access panels (through which *HV* can be accessed)
- Often sourced by the battery manufacturer as part of the *Battery Management System*
- The signal is normally a *pulse wave modulated* (*PWM*) signal, under 10 *mA*
- The return of the signal is sensed within the battery and at least at one additional point in the propulsion system
- Loss of the signal indicates attempted access to *HV*, allowing effective response, *i.e.*, battery command contactors open

TEST AND CHARACTERIZATION METHODS

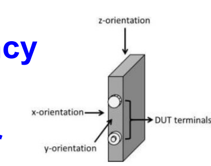
- Batteries can be tested for their behavior under, and response to, abusive conditions
- Conditions can be electrical, mechanical, thermal, environmental or functional
- Many standardized test methods exist; test choice usually depends, typically, on the purpose of the specific characteristic investigated

ELECTRICAL ISSUES

- External short circuit – a sustained electrical discharge, usually targeting the same resistance as the cell, but often at varying levels
- Over-charge – charging a cell to a voltage and capacity above 100 % *s.o.c.* setpoint; tests vary but a common characterization test – *USABC* – charges the device to 200 % rated capacity, limited to 125 % maximum voltage
- Over-discharge – discharging a cell into reversal, by attempting to remove from full charge 200 % of its rated energy capacity

MECHANICAL TESTS

- Overall tests seek to either induce an internal electrical short or a mechanical failure
- Crush – deform a device along each of its axes
- Shock – provide an impulse to the device under each of its major axes
- Vibration – similar to a shock, but signal is smaller amplitude and varied over a frequency range
- Drop/impact – drop device onto a surface or impact the device with a projectile
- Penetration – drive a penetrating object into the device



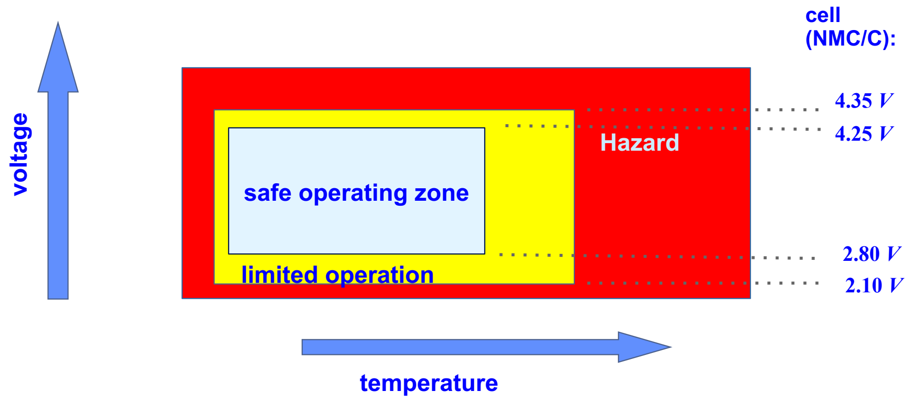
THERMAL/ENVIRONMENTAL FEATURES

- ❑ Heating – raise the temperature of the device and determine the onset point of thermal runaway and characterize the observed results
- ❑ Thermal Shock – repeatedly expose device to alternate thermal extremes
- ❑ Water Immersion – submerge the device in water – usually saline
- ❑ Humidity – expose device to higher temperatures and non-condensing humidity

FUNCTIONAL TESTS

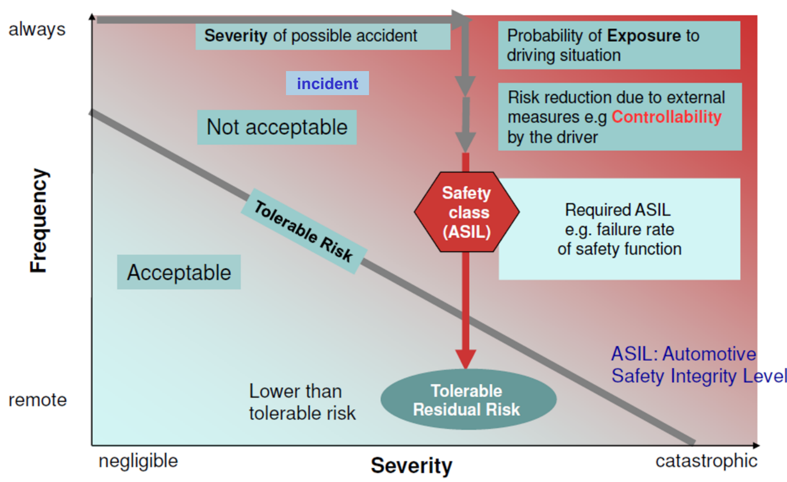
- ❑ Verify the device's response to all-type hazards
- ❑ Thermal – isolation of battery from host under extreme thermal conditions
- ❑ Electrical – verification that the active and passive devices correctly intervene operation on overcurrent, over-voltage and under-voltage
- ❑ Mechanical – monitor primary and secondary effects, and intervene on function

BATTERY & ENVIRONMENT: HAZARD & RISK (OPERATIONAL SAFETY) EXAMPLES



39

RISK EVALUATION



Functional safety related to control systems, their algorithms and software. Please refer to ISO26262

TYPICAL FUNCTIONAL SAFETY REQUIREMENTS FOR 48-*V Li-ion* BATTERY

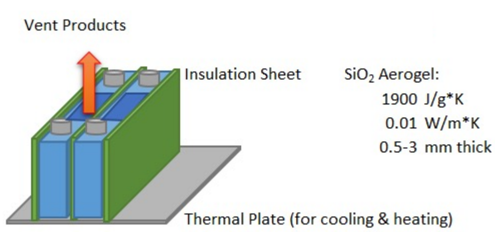
Item	ID	Hazard	ASIL	Safety Goal	Safe State
BMS	1	The specified maximum cell voltage limit is exceeded without safe reaction.	C	Maximum cell voltage violation shall lead to the safe state.	Contactor open
	2	The specified maximum cell temperature limit is exceeded without safe reaction.	C	Maximum cell temperature violation shall lead to the safe state.	Contactor open
	3	The specified maximum cell current limit is exceeded without safe reaction.	C	Maximum battery current violation shall lead to the safe state.	Contactor open
	4	The specified minimum cell voltage limit is exceeded without safe reaction.	C	Every minimum cell voltage violation shall lead to the safe state.	Contactor open

similar efforts are applied to the powertrain controller

41

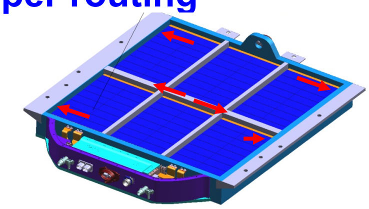
PROPAGATION MITIGATION STRATEGIES

- ❑ **Controls: prevent operations that leads to cascading failures**
- ❑ **Electrochemistry: construct thermally stable solutions via deployment of active materials/electrolytes**
- ❑ **Mechanical design: direct energy release/venting**
- ❑ **Thermal design: insulate between cells and within pack; in the future, introduce immersion**



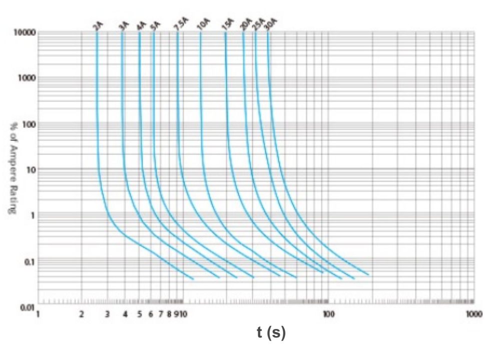
VENT GAS MANAGEMENT

- A *Li-ion* cell can produce ~ *5 l gas/Ah* in the process of complete decomposition; a cell, typically, produces about half this volume
- Gas must be managed within the battery and off-board of the vehicle
- Gas pressure, gas flow and gas temperature management through proper routing



HIGH CURRENT MANAGEMENT

- Contactors rated to voltage and peak current
- Thermal fuses
- "Smart" fuses/pyrofuses/breaker-style switches
- Redundant current measurement



example: current *vs.* time plot for a thermal fuse

