2018 Fall Professional Development Course

Electric-Drive Vehicle Technology

Topic 4:

Advanced Battery Systems for Hybrid and Electric Vehicles

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Advanced Battery Systems for Hybrid and Electric Vehicles

Contents

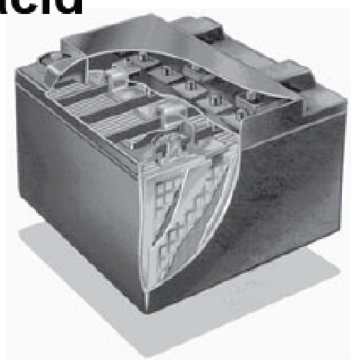
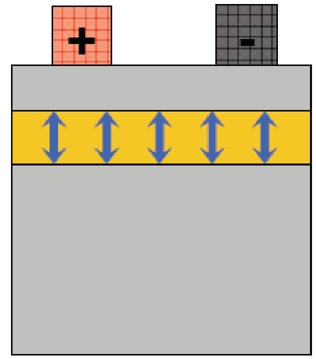
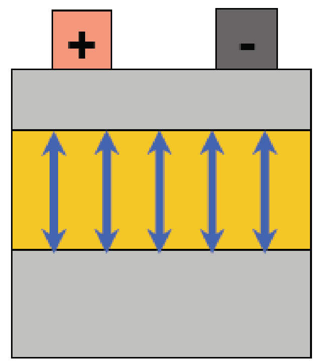
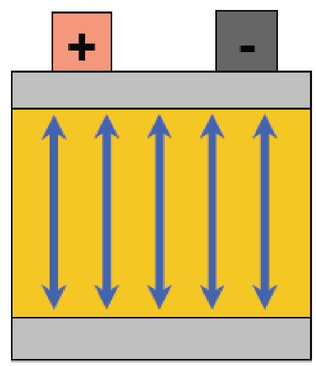
I. On-Board Energy Storage Systems for Hybrid and Electric Vehicles

Technology	Energy Carrier
Fuel (gasoline, diesel, natural gas) Tank	Petroleum
Batteries	Electrons
Hydraulic Systems	Pressure
Electrochemical Supercapacitors	Electrons
H_2 tank / Fuel Cells	Hydrogen
Fly Wheels	Inertia

Secondary Energy Storage for HEVs

The energy storage system is typically a battery and/or ultracapacitor. The system stores electricity from the generator, which helps power the motor and other auxiliary electrical devices.

- Electro-mechanical flywheels
- Mechanical flywheels
- Ultracapacitors (or Supercapacitors)
- Electro-chemical batteries
- Fluid accumulators

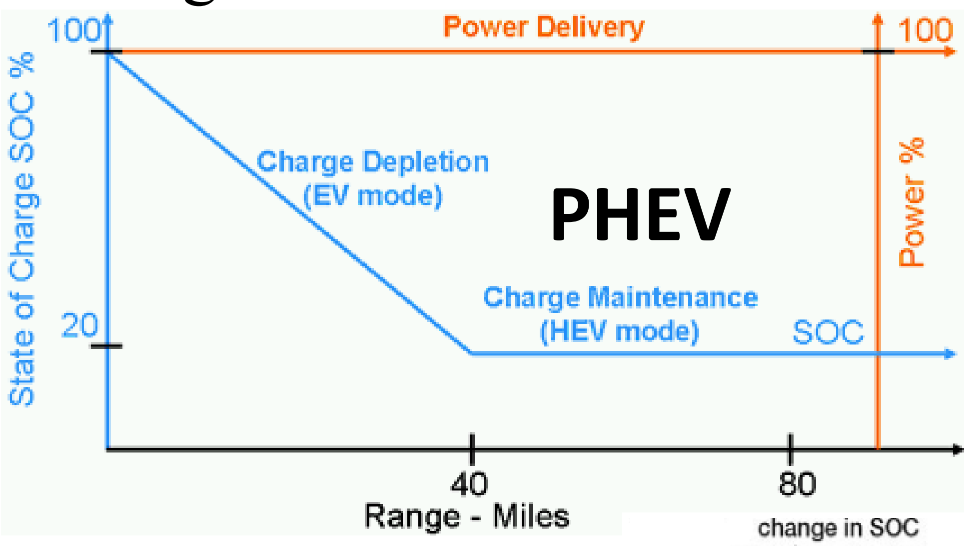
Options	Uses	Energy Utilization	Considerations
Lead acid (Pb-A) 	**Conventional car starter batteries** **Conventional, Micro HEV or Stop/Start**		• **Heavy** • **Inexpensive** • **Mature**
Nickel Metal Hydride (NiMH) 	**Current production HEV batteries**		Vs. Pb-A: • **Energy 2x** • **Power 3x** • **Cost 4x**
Lithium (Li) 	**Consumer electronics;** **PHEV, EV, and some HEV**		Vs. Pb-A: • **Energy 3x** • **Power 7x** • **Cost 6x**

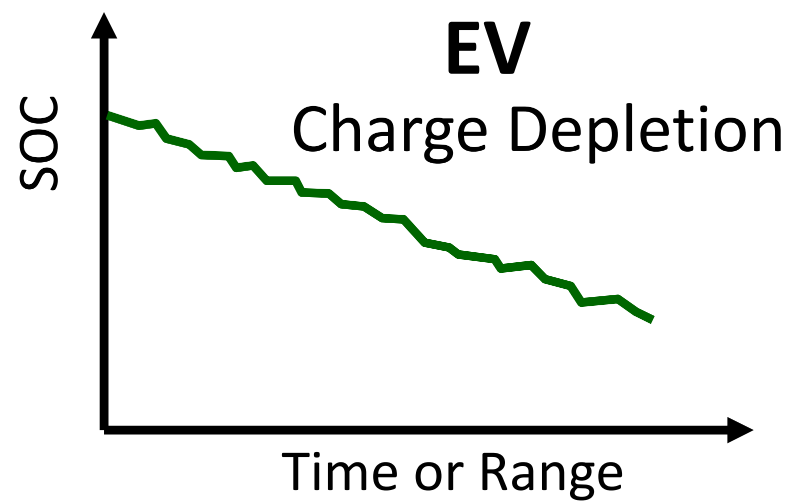
NREL National Renewable Energy Laboratory

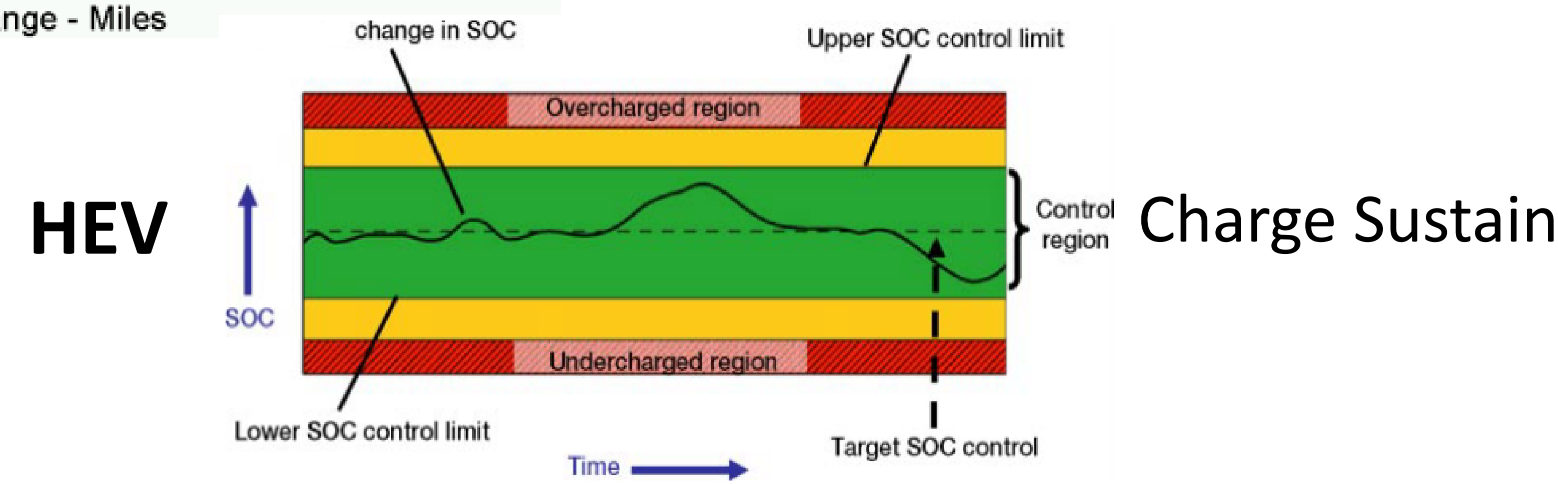
II. Battery issues for EV, PHEV, and HEV - All Electric Range (AER)

- EV's require enough batteries 30 kWh useful at 300 Wh/mi for about 100 miles.
- PHEV's require 15 kWh useful at about 250 Whr/mi for about 50 miles of AER.
- HEV's require only about 2 miles at 200 Wh/mi for about 0.4 kWh useful

- ✓ Traction batteries are usually optimized for high capacity in the case of pure electric vehicles and for high power in the case of hybrid vehicles.
- ✓ The EV battery operates down to a deep depth of discharge (DOD) for long range whereas the HEV operates at a shallow DOD for long life.







HEV Batteries Requirements

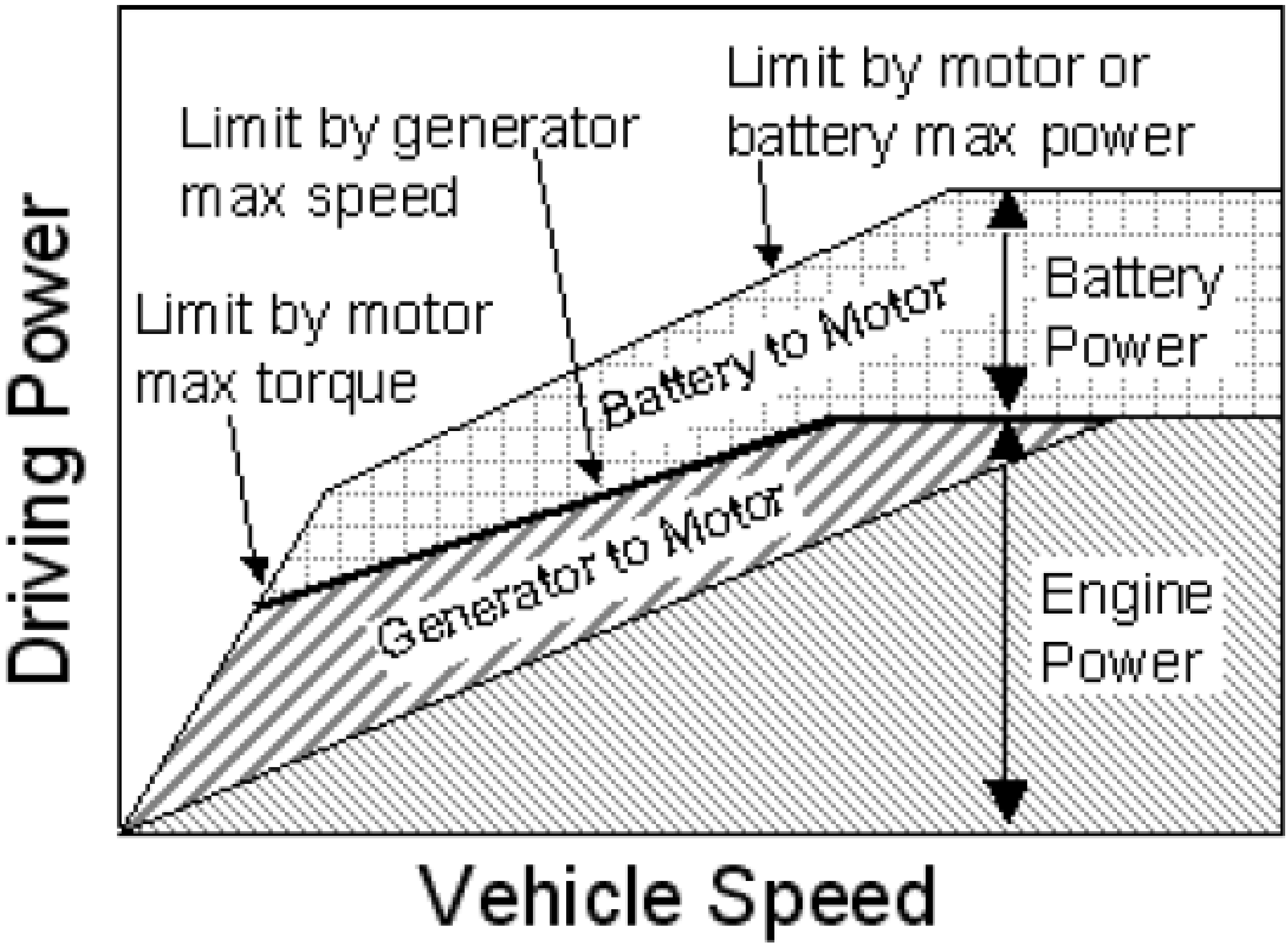
HEV applications require:
- Higher power to energy ratio than EV batteries
- Higher specific power than EV batteries
- Less specific energy than EV batteries

Mild Hybrid (Ex: Honda Civic HEV)
- 20 kW at 144 V with ~1 kWh

Full Hybrid (Ex: Toyota Prius)
- 40 kW at 300 V with ~2 kWh

Plug In Hybrid (Ex: Chevy Volt)
- 100 kW at 300V with ~20 kWh (Essentially at EV battery)

Output Characteristic of the Hybrid System



Hybrid Electric Vehicle (HEV) Battery Operating Requirements (1)

- **Series Hybrid** - The engine is used only to charge the battery. The electrical system provides a variable speed transmission and the electric motor provides the full driving power. Battery requirements similar to EV batteries but lower capacity needed since the charge is kept topped up by the engine.
- **Parallel Hybrid** - Both the engine and the electric motor provide power to the wheels. Various configurations possible to satisfy different operating conditions. The share of the load taken by the electric motor can range from zero to 100% depending on the operating conditions and the design goals. The battery capacity may be as low as 2 kWh but it must deliver short duration power boosts requiring very high currents of up to 40C for acceleration and hill climbing.

Hybrid Electric Vehicle (HEV) Battery Operating Requirements (2)

- Designed to maximize power delivered
- Must deliver high power (up to 40C) in repetitive shallow discharges and accept very high recharging rates
- Very long cycle life 1000 deep cycles and 400,000 ~ 1,000,000 shallow cycles.

GM Tahoe Hybrid

- Operating point is between 15% and 50% DOD to allow for regenerative braking.
- Never reaches full discharge. Rarely reaches full charge.

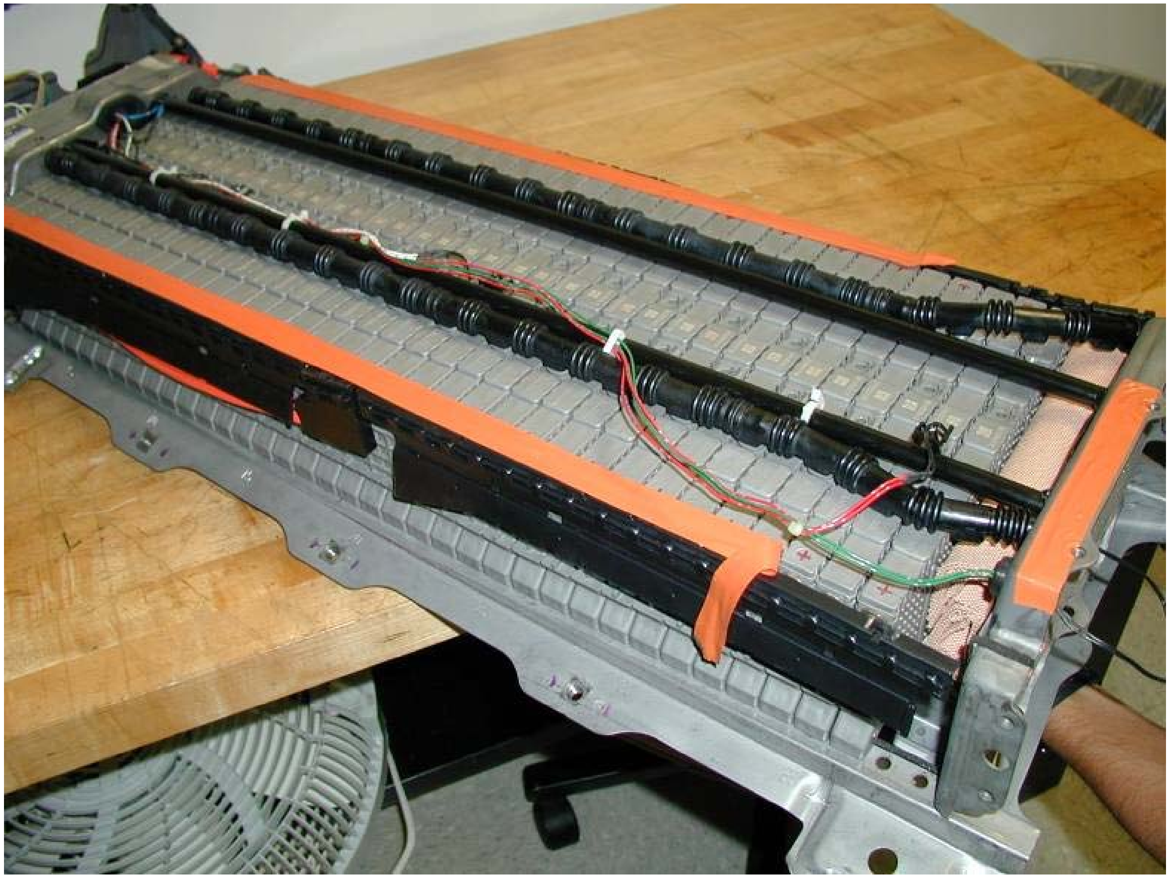
  Example: 85% ~ 60% SOC – State of Charge
  (15% DOD – Depth of Discharge)

Hybrid Electric Vehicle (HEV) Battery Operating Requirements (3)

- Needs thermal management
- Fuel-gauging and complex BMS necessary to regulate battery energy management as well as for driver instrumentation.

Toyota Prius

- Needs interfacing with overall vehicle energy management.
- Typical voltage > 144 Volts.
- Typical power > 40 kW
- Capacity 1 to 10 kWh depending on the application.
- The size, shape and weight distribution of the battery pack must be tailored to the vehicle.



Toyota Prius HV Battery

1.3KWH

HV Battery Pack	'04 Prius and Later	'01-'03 Prius
Battery pack voltage	201.6V	273.6V
Number of Ni-MH battery modules in the pack	28	38
Number of cells	168	228
Ni-MH battery module voltage	7.2V	←

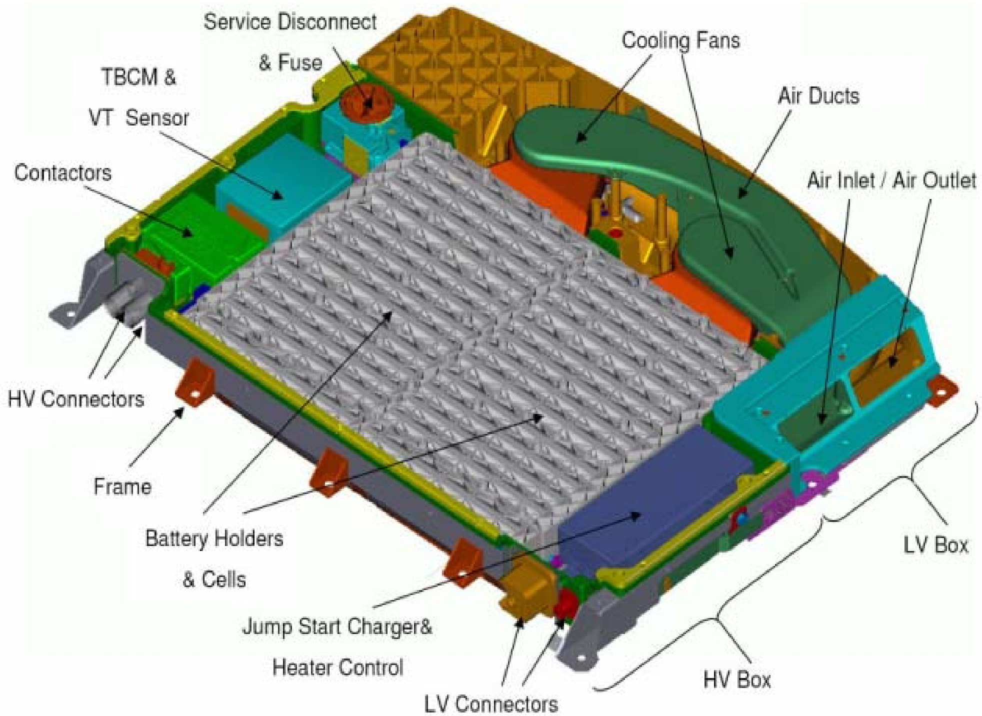
Source: autoshop101

Ford Fusion Hybrid

The Sanyo-supplied battery pack -- 270 volts and 1.4 kWh

Source:Fire Engineering.com

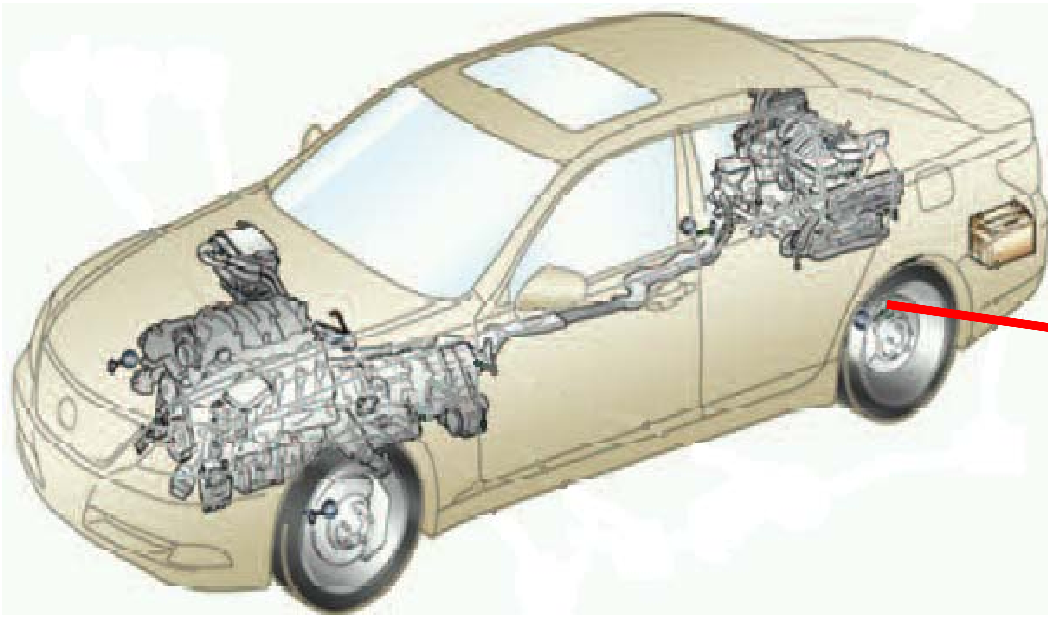
Ford Escape Hybrid
NiMH High Voltage Battery Pack



Manufacturer: Sanyo Electric Co.
Cell: nickel metal hydride (NiMH)
Number of Cell: 250, cylinderial
Weight 50 kg (110 lb)
Pack Voltage 330V, 5.5 Ah (1.8kWh)

Source: Michigan Clean Fleet Conference, May 2007

Lexus LS600h



- 288V Nickel Metal Hydride (NiMH) battery pack consisting of 20 low voltage (1.2 V/cell x 12 cell =14.4 Volt) modules connected in series.
- The hybrid battery is covered for 8 years/100,000 miles warranty.

Source: www.lexus.com

GM Chevrolet Tahoe Hybrid

1.8 kWh, 300V NiMH battery pack

Plug in Hybrid Electric Vehicle (PHEV) Battery Operating Requirements (1)

- The plug in hybrid is designed to be used both as an EV for city driving and as an HEV when the charge is depleted or for highway driving. The dual requirements for an extended all electric range, 20 ~ 40 miles, as well as maintaining high power availability at low state of charge (eg. 30% SOC), impose very stressful conditions on the battery.

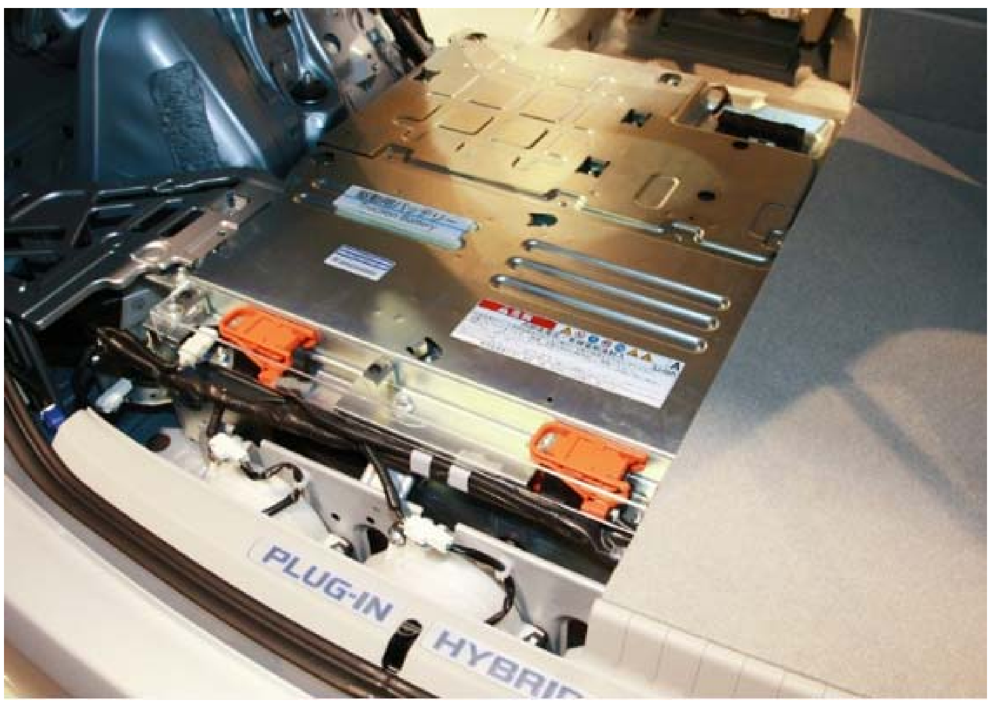
Toyota Prius Plug-in Hybrid (PHEV)

Toyota' first-generation lithium-ion battery has had more than three years of field testing in Japan, North America, and Europe. The battery is now being tested in 600 Toyota Prius plug-in hybrids in a more severe charge-depleting mode.

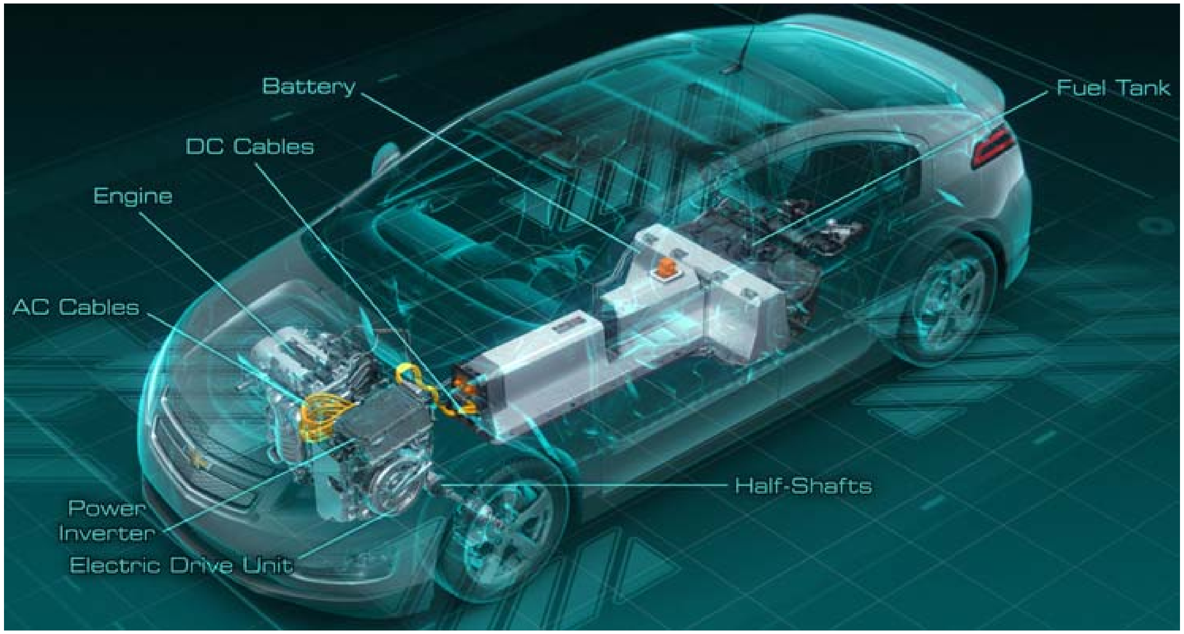
- The Prius PHEV is based on a third generation Toyota Prius outfitted with 4.4 kWh lithium-ion batteries co-developed with Panasonic
- The Prius plug-in total all-electric range is 14.3 mi (PHEV14) has a expected total range of 475 miles (764 km)
- The lithium-ion battery pack can be charged in 180 minutes at 120 volts or in 90 minutes at 240 volts.

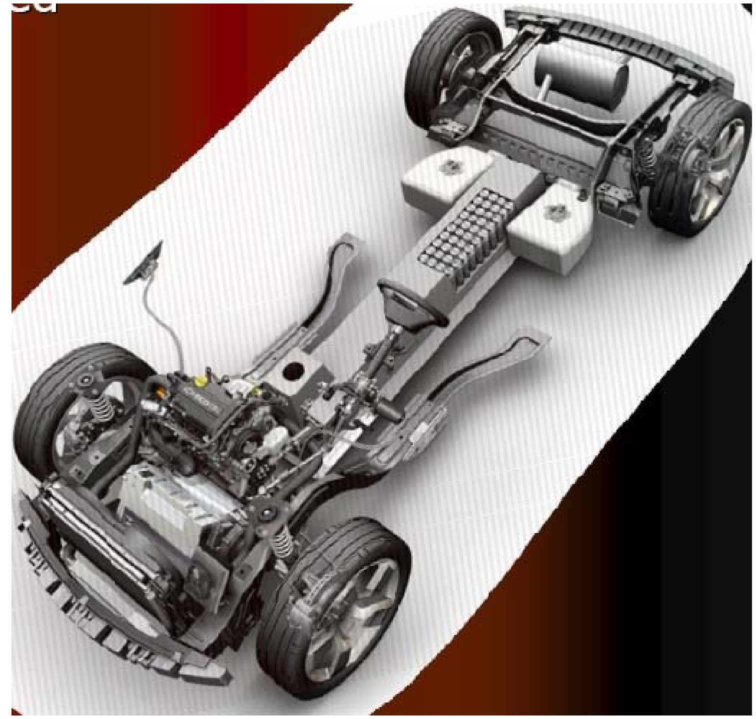
Plug-in Toyota Prius Hybrid Battery

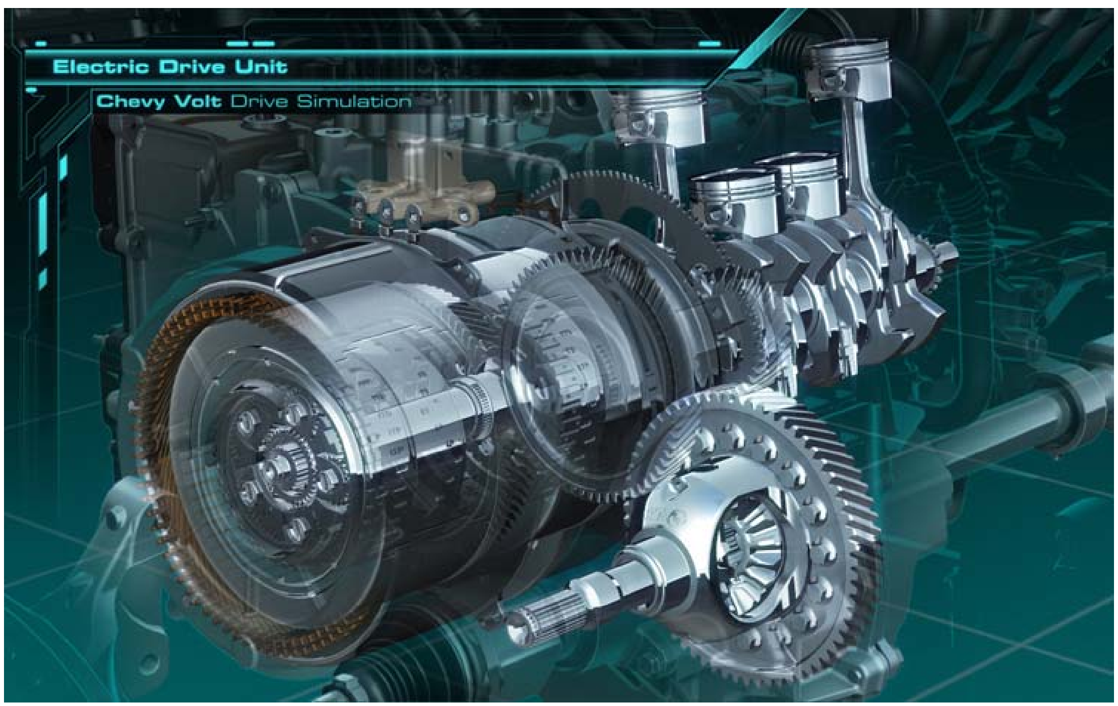
- Battery weight is 160kg (353lbs) in contrast to normal 40kg (88lbs)
- Vehicle weight is 1,490kg (3,285lbs) vs. normal 1,350kg (2,976lbs), 140kg (309lbs) difference.



Chevrolet Volt (PHEV40 – 40 miles AER)







- 400 lb Li-ion Battery Pack
- 136 kW peak power
- 16 kWh energy content
- Home plug-in charging
- Use just half of its 16 kWh capacity between 80% (upper limit) and 30% (lower limit) SOC

Electric Vehicle (EV) Battery Operating Requirements (1)

- The battery must be capable of regular deep discharge (80% DOD) operation
- It is designed to maximize energy content and deliver full power even with deep discharge to ensure long range.
- A range of capacities will be required to satisfy the needs of different sized vehicles and different usage patterns.
- Must accept very high repetitive pulsed charging currents (greater than 5C) if regenerative braking required.

GM EV1

Electric Vehicle (EV) Battery Operating Requirements (2)

- Routinely receives a full charge
- Often also reaches nearly full discharge
- Fuel-gauging critical near "empty" point
- Needs a Battery Management System (BMS)
- Needs thermal management
- Typical voltage > 300 Volts
- Typical capacity > 20 ~ 60 kWh
- Typical discharge current up to 2C rate continuous and 3C peak for short durations

Nissan Leaf EV

- 1C is often referred to as the current a battery can fully discharge in one hour. Thus a 1000mAh battery would provide 1000mA for one hour if discharged at 1C rate.

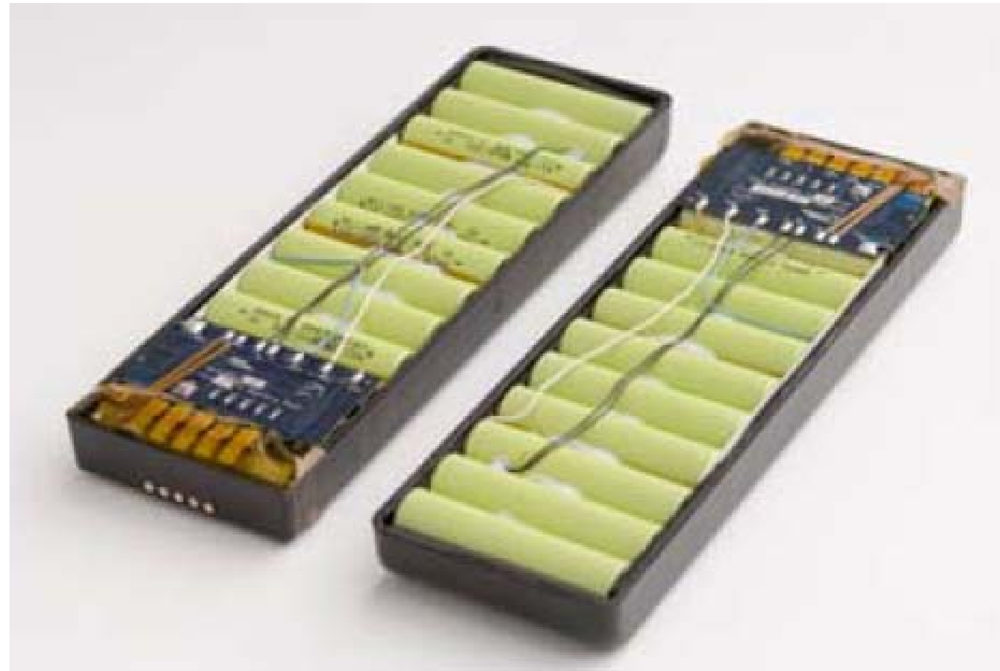
Nissan Leaf

- Type: lithium-ion battery
- Weight: 400 ponds
- Total capacity (kWh): 24
- Power output (kW): over 90
- Energy density (Wh/kg): 140
- Power density (kW/kg): 2.5
- Number of modules: 48
- Charging times: Quick charger DC 50kW (0 to 80%): < 30 min
- home-use AC200V charger: < 8 hrs
- Battery layout: Under seat & floor
- LEAF's claimed 100-mile range is based on EPA's L.A.-cycle test
- No active thermal management system, a single fan to distribute heat evenly throughout the interior of the pack.

Ford Focus Electric Vehicle (EV)

- 23 kWh liquid-cooled lithium-ion battery pack that provides an all electric range of 100 mi
- Ford has chosen an advanced active liquid-cooling and heating system to regulate the temperature of its lithium-ion battery packs, which are designed to operate under a range of ambient conditions.
- An active liquid system heats or chills a coolant before pumping it through the battery cooling system. This loop regulates temperature throughout the system against external conditions.

Tesla Roadster’s Battery Pack



This battery is microprocessor-controlled and consists of almost 7000 individual cells and weighs nearly 1000 pounds. There are 11 modules, each consisting of 9 cells in series and 69 in parallel to produce the 375V and 142Ah capacity (53.2KWh). This modular approach is common for electric vehicles.

Source: www.micro-power.com/

Tesla Roadster Battery System

450kg pack is comprised of (6,831) 3.8V cylindrical 18650 cells


Packs Location In-Vehicle

Cell Configuration
  99 cells in series
  69 parallel strings

11 Modules – each 621 cells


Rear Axle

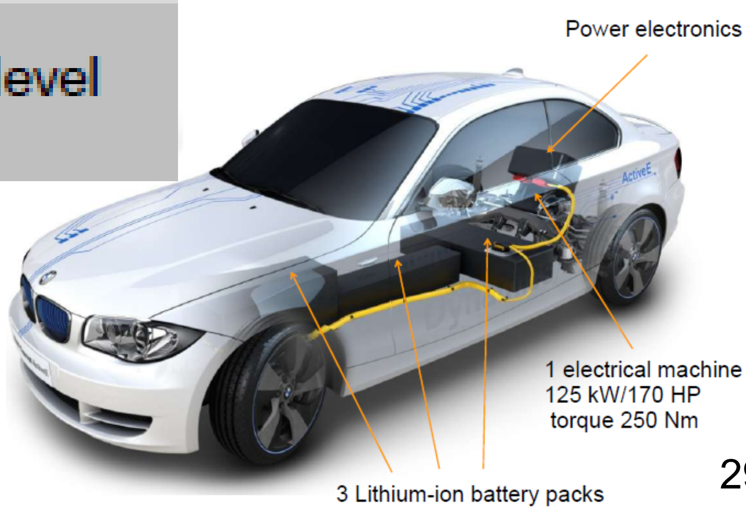

190kW Battery Pack

BMW Mini-E

Vehicle	2-seater	
Electric motor	Output	150 kW/204 hp
	Torque	220 Nm/ 162 lbft
	Top speed	90 mph
Energy storage	Lithium-Ion battery	35 kWh, 29 kWh available
	Voltage	390 V
	Number of battery cells	5,088 in 42 modules
	Cooling	Air cooled dependent on cell temperature
	Charging times (230 V: 0-100%)	3.0 hours at 50 A 4.5 hours at 32 A 24 hours at 12 A
	Weight	260 kg / 570 lbs
	Range	100 +/- miles in real world conditions

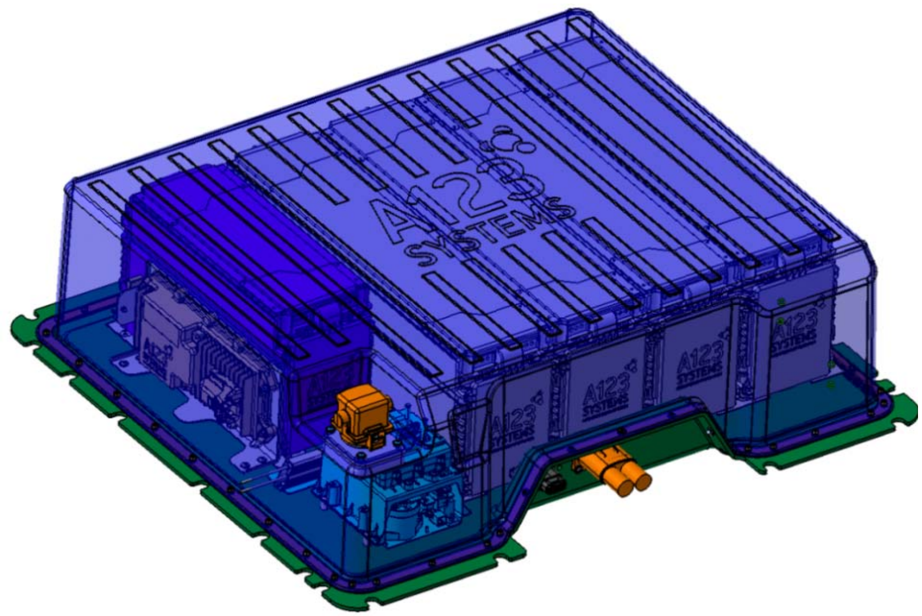
BMW Active-E Concept

Vehicle	4-seater, 200 ltr. Trunk	
Electric motor	Output	125 kW/170 hp
	Torque	250 Nm / 184 lbft
	Top speed	90 mph
Energy storage	Lithium-Ion battery	32 kWh
	# of battery modules	25 modules
	Cooling	Liquid cooling
	Charging time approximated	4 hours at 32 A 7kW - 220V
	Range	Range at level of MINI E



A123 Configurable Battery Pack – V3 (22.8 kWh)

	CHARGE		DISCHARGE	
Duration	cont	10-sec	cont	10-sec
Test Pack Power (kW)	-24	-125	68	207
Cell Min Capacity (Amp-Hr)	20.0	20.0	20.0	20.0
Cell Weight (kg)	0.48	0.48	0.48	0.48
Cell Max Voltage	3.6	3.6	3.6	3.6
Cell Nominal Voltage	3.2	3.2	3.2	3.2
Cell Min Voltage	2.5	2.5	2.5	2.5
Cell Energy (W-Hr)	64	64	64	64
Cells in parallel	3	3	3	3
Pack Modules per pack	6	6	6	6
Pack Series Elements	119	119	119	119
Pack Total cells	357	357	357	357
Pack Cell Configuration	119S3P	119S3P	119S3P	119S3P
Pack Vmax	428	428	428	428
Pack Vnom	381	381	381	381
Pack Vmin	298	298	298	298
Pack Capacity (A-Hr)	60	60	60	60
Pack Energy (kW-Hr)	22.8			
Cell Weight (kg)	171			
Pack Weight (kg, est)	235			
Test Current (A)	-60	-300	180	612
Test Temperature (DegC)	25	25	25	25
Test SOC (%)	60	60	60	60
Test C-Rating	-1.0	-5.0	3.0	10.2

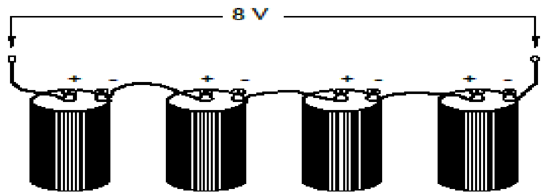


Pack Layout

- modules: 26S3P x 4, 15S3P x 1
- Cell – Prismatic
- application – BEV
- required energy – > xx kWh
- pack space available
- data location

III. Overview of Electrochemistry

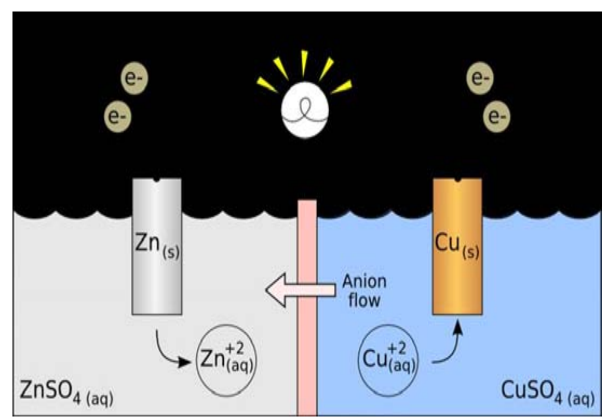
- **Battery**: A device consisting of <u>one or more cells</u> in series and/or parallel to convert chemical energy to electric energy.



- **Electrochemical** cell reaction: A chemical reaction that involves the transfer of electron from one material to another material through an electrical circuit including the internal ion transfer in the liquid or solid electrolyte solution

$A^{+} + B \Rightarrow A + B^{+}$ (example: $Cu^{+2} + Zn \rightarrow Cu + Zn^{+2}$)

$m\,A + n\,B^{m+} \rightleftharpoons n\,B + m\,A^{n+}$

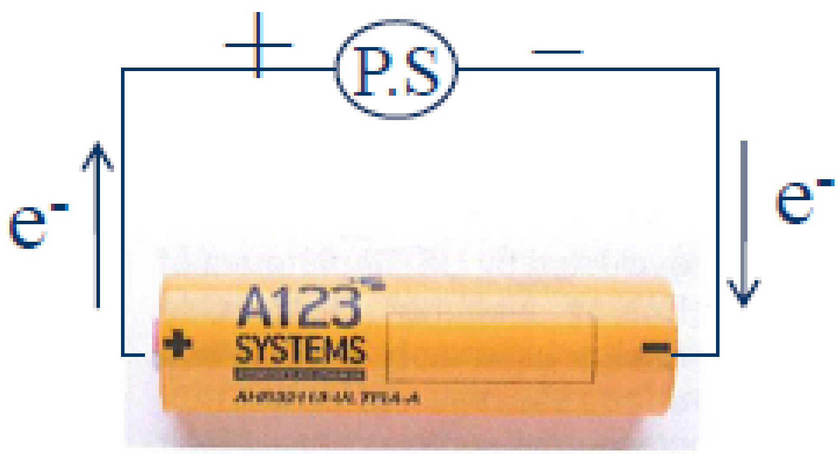


Electrochemistry

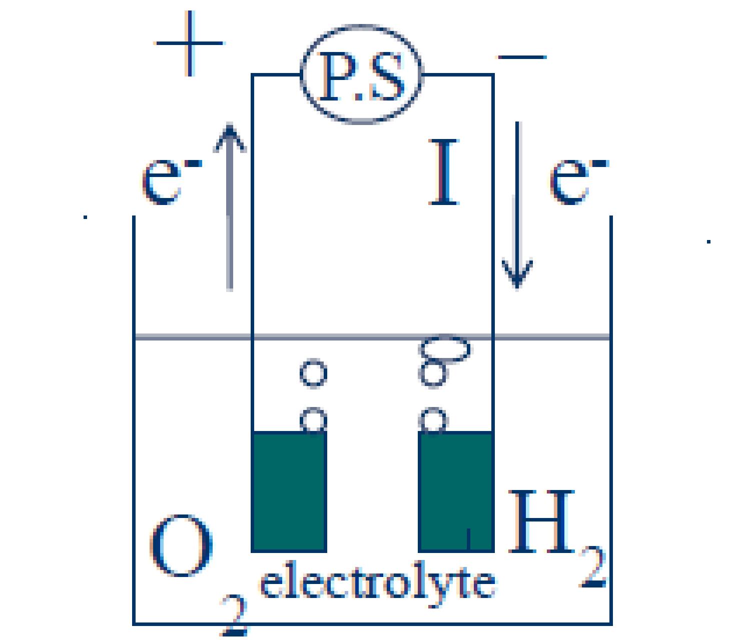
- Electrochemistry is the science that study the relation (conversion) between **Chemical Energy** and **Electrical Energy**
- Cell voltages depend on electrochemistry of electrodes
- Cell voltages measured in electrochemical cells as differences in electrode potentials
- Electrode potential of hydrogen electrode in acid defined as zero volts
- Electrode potentials given as cell voltage vs. hydrogen for reduction reaction

Examples of Conversion of Electrical Energy to Chemical Energy:

- Electrolysis
- Charging battery



A123 Systems 19650 Li Ion Cell

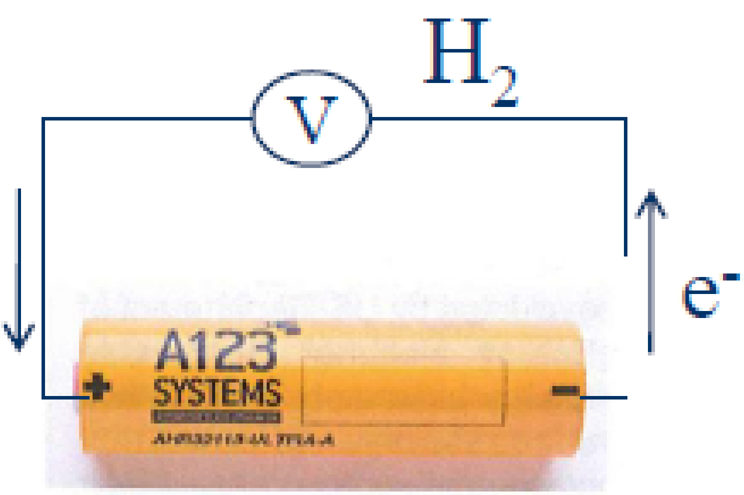


Water electrolysis

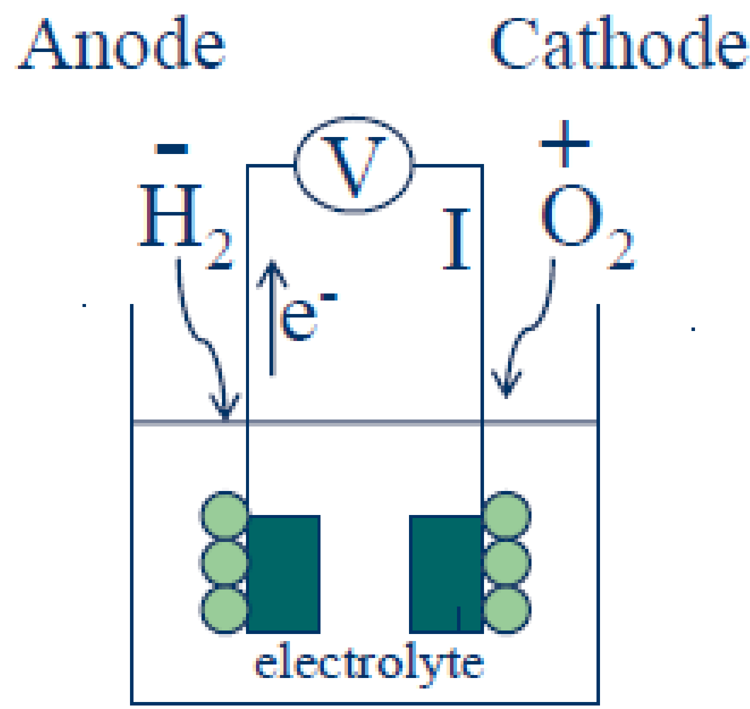
$$2H_2O \longrightarrow 2H_2 + O_2$$

Examples of Conversion of Chemical Energy to Electrical Energy:

- Batteries
- Fuel Cells



A123 Systems 19650 Li Ion Cell



Fuel Cell

$$2H_2 + O_2 \longrightarrow 2H_2O$$

Electrochemical reactions in battery cell
Battery voltage (under open circuit conditions)

- How is chemical energy converted to electrical energy in a battery?
- What are the (+) and the (-) poles of the battery?
- What is the voltage of the battery at **open circuit** conditions (maximum voltage)?

Battery Energy

- What is the capacity (charge) of a battery cell
- What is the energy of a battery
- How capacity and energy change with the current that flow in the battery

Half-Cell Electrochemical Potential of Zn^{2+}

(1) $Zn^{2+} + 2e^- \rightleftharpoons Zn$ -0.76V

(2) $2H^+ + 2e^- \leftrightharpoons H_2$ 0.00V

$Zn + 2H^+ \rightleftharpoons Zn^{2+} + H_2$

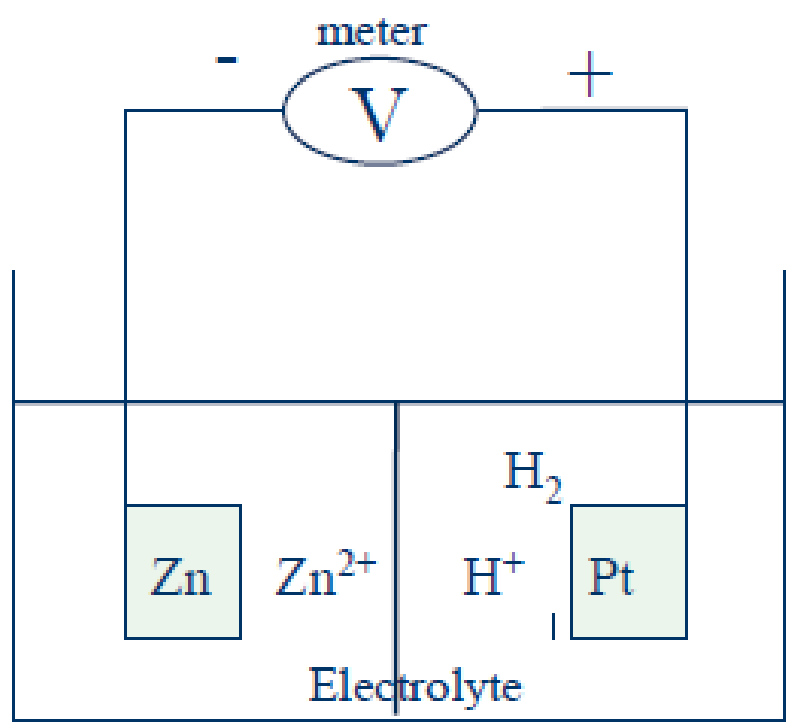
$E^o = -0.76\ V$

Standard conditions mean activities of all species are 1

$[Zn^{2+}] = [H^+] = 1M$

$P(H_2) = 1$ atm

$Zn^{2+} + 2e^- \rightleftharpoons Zn$



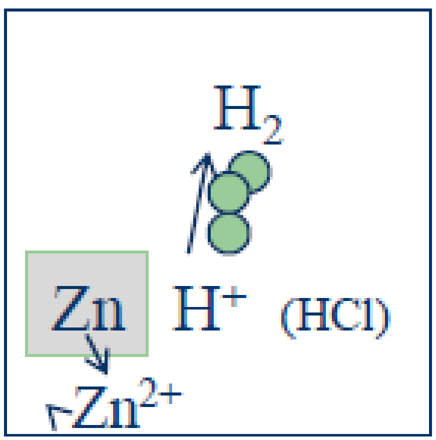
$2H^+ + 2e^- \rightleftharpoons H_2$

Half-Cell Electrochemical Potential of Zn

$$(1)\quad Zn \longrightarrow Zn^{2+} + 2e^- \qquad 0.76V$$
$$(2)\quad 2H^+ + 2e^- \longrightarrow H_2 \qquad 0.00V$$
$$Zn + 2H^+ \longrightarrow Zn^{2+} + H_2$$

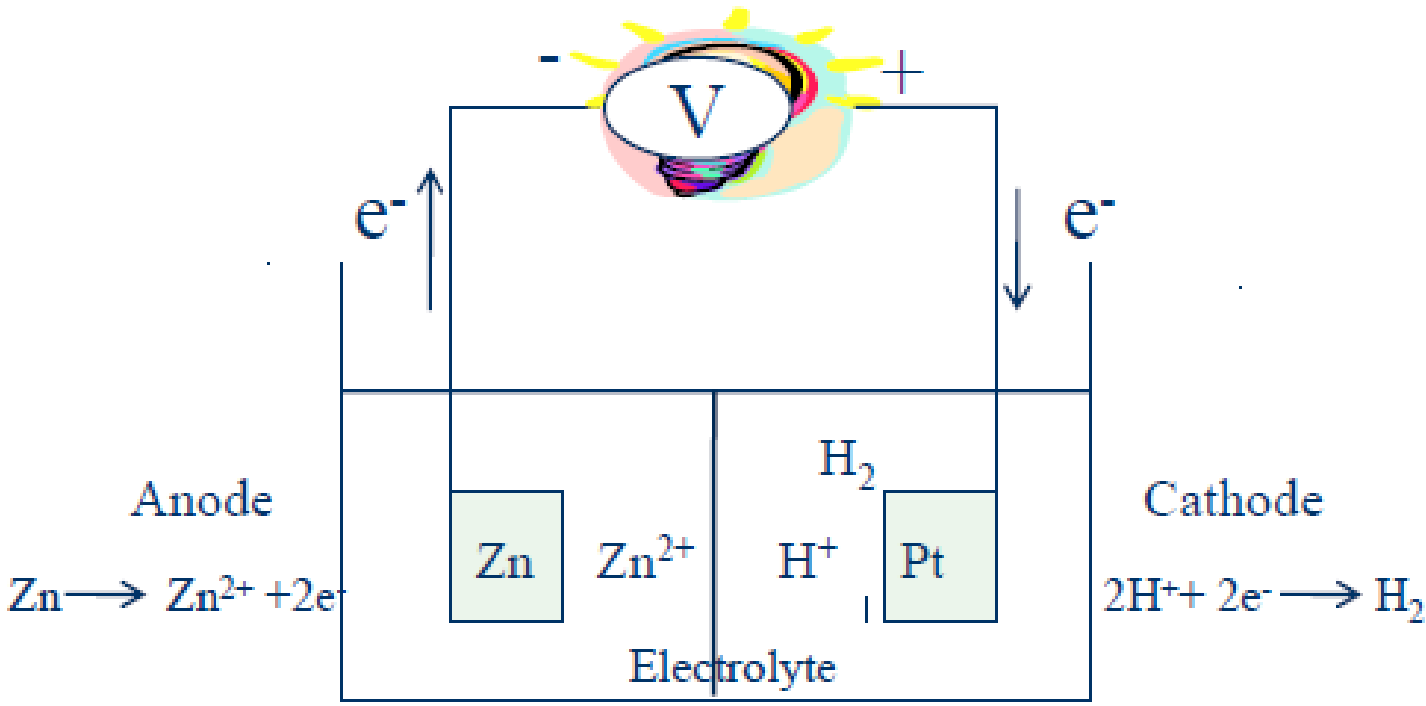
$E^o = 0.76$

chemical



$\Delta G^o = -nFE^o$

Gibbs free energy



Half-Cell Electrochemical Potential of Cu^{2+}

(1) $Cu^{2+} + 2e^- \rightleftharpoons Cu$ $\quad +0.34V$

(2) $2H^+ + 2e^- \leftrightharpoons H_2$ $\quad 0.00V$

$Cu + 2H^+ \rightleftharpoons Cu^{2+} + H_2$

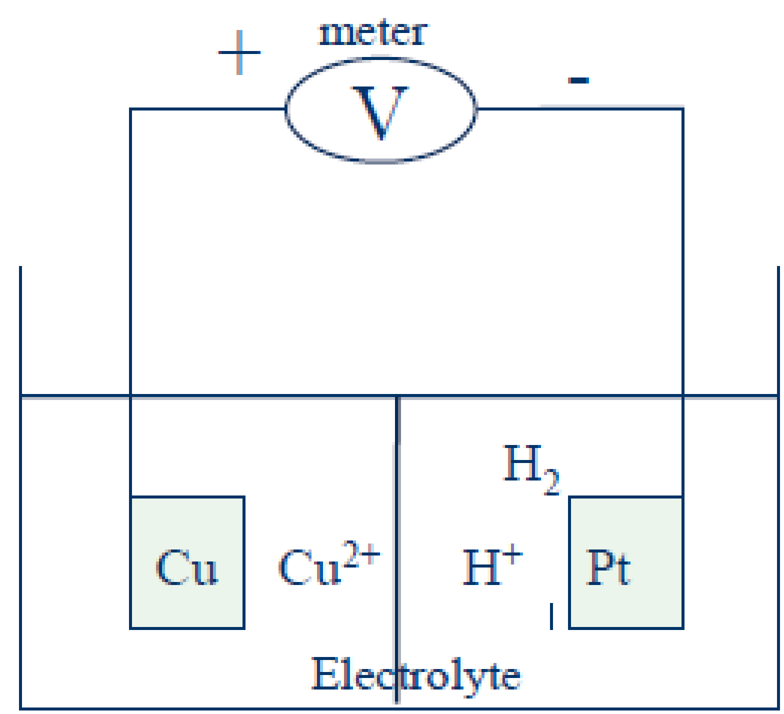
$E^o = +0.34\ V$

Standard conditions mean activities of all species are 1

$[Cu^{2+}] = [H^+] = 1M$

$P(H_2) = 1\ atm$

$Cu^{2+} + 2e^- \rightleftharpoons Cu$



$2H^+ + 2e^- \rightleftharpoons H_2$

Half-Cell Electrochemical Potential of Cu^{2+}

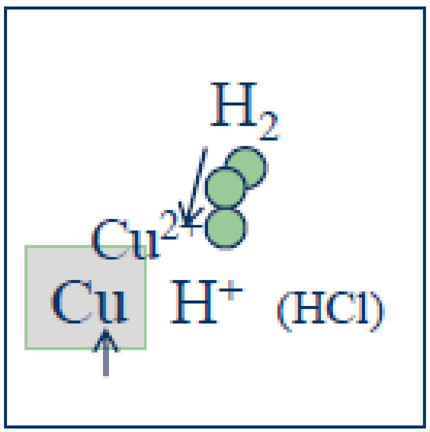
$$(1)\quad Cu^{2+} + 2e^- \longrightarrow Cu \qquad +0.34V$$

$$(2)\quad H_2 \longrightarrow 2H^+ + 2e^- \qquad 0.00V$$

$$Cu^{2+} + H_2 \longrightarrow Cu + 2H^+$$

$$E^o = +0.34$$

chemical

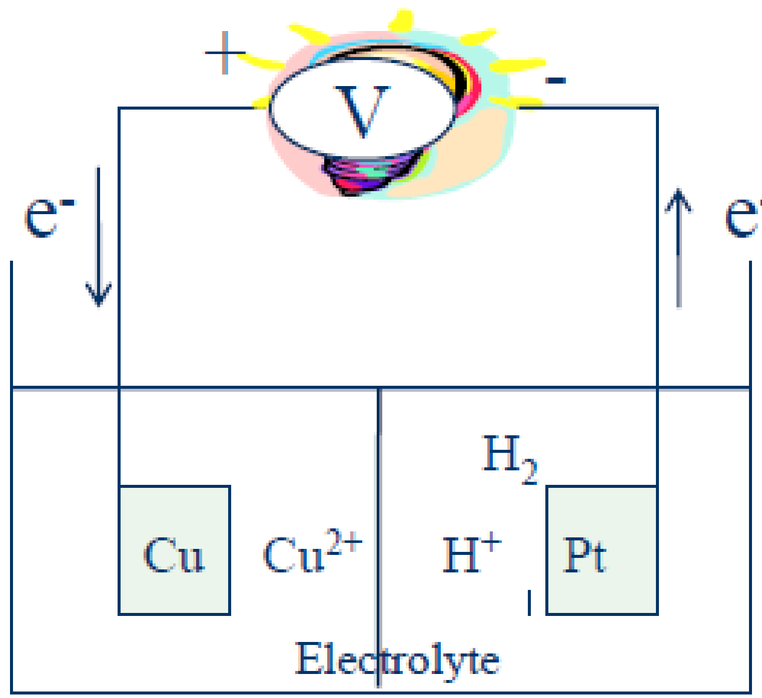


$$\Delta G^o = -nFE^o$$

Gibbs free energy

Cathode

$Cu^{2+} + 2e^- \longrightarrow Cu$



Anode

$H_2 \longrightarrow 2H^+ + 2e^-$

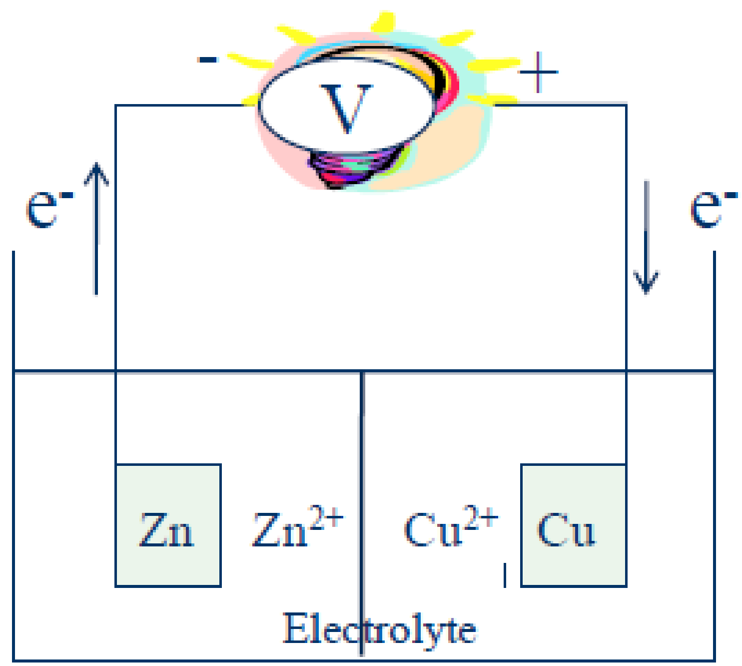
Full Cell Electrochemical of $Zn\text{-}Cu^{2+}$

- **Electrochemical Reaction:** Oxidation-reduction reaction in which the two half of the reaction are separated via electrodes and electrical connection

$Zn \longrightarrow Zn^{2+} + 2e^-$ Redox couple

$Cu^{2+} + 2e^- \longrightarrow Cu$ Redox couple

$Zn + Cu^{2+} \longrightarrow Zn^{2+} + Cu$



Anode

$Zn \longrightarrow Zn^{2+} + 2e^-$

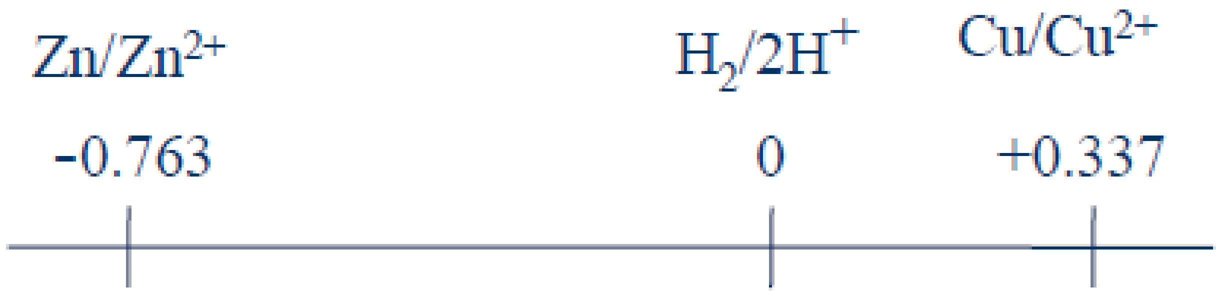
Anodic half cell reaction

Cathode

$Cu^{2+} + 2e^- \longrightarrow Cu$

cathodic half cell reaction

Full Cell Electrochemical Potential of Zn-Cu^{2+}



Step 1

$$Zn^{2+} + 2e^- \rightleftharpoons Zn \quad -0.763 \text{ anode}$$

$$Cu^{2+} + 2e^- \rightleftharpoons Cu \quad +0.34 \text{ cathode}$$

Step 2 (reverse the sign of the more negative reaction)

$$Zn \longrightarrow Zn^{2+} + \cancel{2e^-} \qquad +0.763V$$

$$Cu^{2+} + \cancel{2e^-} \longrightarrow Cu \qquad +0.34\ V$$

$$Zn + Cu^{2+} \longrightarrow Zn^{2+} + Cu \qquad +1.103\ V$$

- When get +V, Galvanic cell (spontanous)

$$E^o = E^o_{cath} - E^o_{anod} = 0.34 - (-0.763) = 1.103$$

- **Oxidation:** removing electrons from atom or molecule

$$Zn \longrightarrow Zn^{2+} + 2e^-$$

- **Reduction:** Addition of electrons to atom or molecule

$$Cu^{2+} + 2e^- \longrightarrow Cu$$

- **Oxidation – Reduction Reaction:** Chemical Reaction in which electrons move from one species(which is oxidized) to another (which is reduced)

$$Zn + Cu^{2+} \longrightarrow Zn^{2+} + Cu$$

Redux couple: Zn and Cu^{2+}

Primary (Non Rechargeable) Batteries

- Primary batteries are used once, then discarded. They have the advantage of convenience and cost less per battery, with the down side of costing more over the long term. Generally, primary batteries have a higher capacity and initial voltage than rechargeable batteries, and a sloping discharge curve
- **Advantages:** High energy density since no design compromises necessary to accommodate recharging. Best alternative for low cost, low drain applications such as watches or hearing aids. The obvious choice for single use applications such as guided missiles and military ordnance. Low initial cost, Convenient. Wide availability of standard products
- **Shortcomings:** Not suitable for high drain applications due to short life time and the cost of continuous replacement.
- **Applications:** Consumer batteries used in Toys, Flashlights, Watches, Clocks
- **Typical Battery Chemistries**, Leclanché Cells (dry cell), Alkaline, Lithium, Silver Oxide, Zinc Air

Secondary Batteries - Rechargeable
Lead Acid Batteries

- Lead acid batteries were invented in 1859 by Gaston Planté and first demonstrated to the French Academy of Sciences in 1860. They remain the technology of choice for automotive SLI (Starting, Lighting and Ignition) applications because they are robust, tolerant to abuse, tried and tested and because of their low cost.
- Lead-acid batteries are composed of a Lead-dioxide cathode, a sponge metallic Lead anode and a Sulphuric acid solution electrolyte. This heavy metal element makes them toxic and improper disposal can be hazardous to the environment.
- The cell voltage is 2 Volts
- During discharge, the lead dioxide (positive plate) and lead (negative plate) react with the electrolyte of sulfuric acid to create lead sulfate, water and energy.
- During charging, the cycle is reversed: the lead sulfate and water are electro-chemically converted to lead, lead oxide and sulfuric acid by an external electrical charging source.

Lead Acid (PbA) Battery Half-Cell Potentials

Electrode reaction	E^0, V
$Li^+ + e \rightleftharpoons Li$	−3.01
$Rb^+ + e \rightleftharpoons Rb$	−2.98
$Cs^+ + e \rightleftharpoons Cs$	−2.92
$K^+ + e \rightleftharpoons K$	−2.92
$Ba^{2+} + 2e \rightleftharpoons Ba$	−2.92
$Sr^{2+} + 2e \rightleftharpoons Sr$	−2.89
$Ca^{2+} + 2e \rightleftharpoons Ca$	−2.84
$Na^+ + e \rightleftharpoons Na$	−2.71
$Mg(OH)_2 + 2e \rightleftharpoons Mg + 2OH^-$	−2.69
$Mg^{2+} + 2e \rightleftharpoons Mg$	−2.38
$Al(OH)_3 + 3e \rightleftharpoons Al + 3OH^-$	−2.34
$Ti^{2+} + 2e \rightleftharpoons Ti$	−1.75
$Cd(OH)_2 + 2e \rightleftharpoons Cd + 2OH^-$	−0.81
$Zn^{2+} + 2e \rightleftharpoons Zn$	−0.76
$Ni(OH)_2 + 2e \rightarrow Ni + 2OH^-$	−0.72
$Ga^{3+} + 3e \rightleftharpoons Ga$	−0.52
$S + 2e \rightarrow S^{2-}$	−0.48
$Fe^{2+} + 2e \rightleftharpoons Fe$	−0.44
$Cd^{2+} + 2e \rightleftharpoons Cd$	−0.40
Pb → $PbSO_4 + 2e \rightleftharpoons Pb + SO_4^-$	−0.36
$In^{3+} + 3e \rightleftharpoons In$	−0.34
$Tl^+ + e \rightleftharpoons Tl$	−0.34
$Co^{2+} + 2e \rightleftharpoons Co$	−0.27
$Ni^{2+} + 2e \rightleftharpoons Ni$	−0.23

PbO_2 + Pb + 2 H_2SO_4 → 2 $PbSO_4$ + 2 H_20

PbA Cell Voltage:

$E^o = 1.69 - (-0.36) = 2.05$ V

Electrode reaction	E^0, V
$Sn^{2+} + 2e \rightleftharpoons Sn$	−0.14
$Pb^{2+} + 2e \rightleftharpoons Pb$	−0.13
$O_2 + H_2O + 2e \rightleftharpoons HO_2^- + OH^-$	−0.08
$D^+ + e \rightleftharpoons \frac{1}{2}D_2$	−0.003
$H^+ + e \rightleftharpoons \frac{1}{2}H_2$	0.000
$HgO + H_2O + 2e \rightleftharpoons Hg + 2OH^-$	0.10
$CuCl + e \rightleftharpoons Cu + Cl^-$	0.14
$AgCl + e \rightleftharpoons Ag + Cl^-$	0.22
γ-$MnO_2 + H_2O + e \rightleftharpoons \alpha$-$MnOOH + OH^-$	0.30
$Cu^{2+} + 2e \rightleftharpoons Cu$	0.34
$Ag_2O + H_2O + 2e \rightleftharpoons 2Ag + 2OH^-$	0.35
γ-$MnO_2 + H_2O + e \rightleftharpoons \gamma$-$MnOOH + OH^-$	0.36
$\frac{1}{2}O_2 + H_2O + 2e \rightleftharpoons 2OH^-$	0.40
$NiOOH + H_2O + e \rightleftharpoons Ni(OH)_2 + OH^-$	0.45
$Cu^+ + e \rightleftharpoons Cu$	0.52
$I_2 + 2e \rightleftharpoons 2I^-$	0.54
$2AgO + H_2O + 2e \rightleftharpoons Ag_2O + 2OH^-$	0.57
$Hg^{2+} + 2e \rightleftharpoons 2Hg$	0.80
$Ag^+ + e \rightleftharpoons Ag$	0.80
$Pd^{2+} + 2e \rightleftharpoons Pd$	0.83
$Ir^{3+} + 3e \rightleftharpoons Ir$	1.00
$Br_2 + 2e \rightleftharpoons 2Br^-$	1.07
$O_2 + 4H^+ + 4e \rightleftharpoons 2H_2O$	1.23
$MnO_2 + 4H^+ + 2e \rightleftharpoons Mn^{2+} + 2H_2O$	1.23
$Cl_2 + 2e \rightleftharpoons 2Cl^-$	1.36
$PbO_2 + 4H^+ + 2e \rightleftharpoons Pb^{2+} + 2H_2O$	1.46
$PbO_2 + SO_4^{2-} + 4H^- + 2e \rightleftharpoons PbSO_4 + 2H_2O$	1.69 ← PbO_2
$F_2 + 2e \rightleftharpoons 2F^-$	2.87

H_2O stability window in acid

Discharge mode:

(-) Anode: $Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e-$ $E^o = 0.36V$

(+) Cathode: $PbO_2 + 4H^+ + SO_4^{2-} + 2e- \rightarrow PbSO_4 + 2H_2O$ $E^o = 1.69V$

Overall: $PbO_2 + Pb + 4H^+ + 2SO_4^{2-} \rightarrow 2PbSO_4 + 2H_2O$ $E^o = 2.05V$

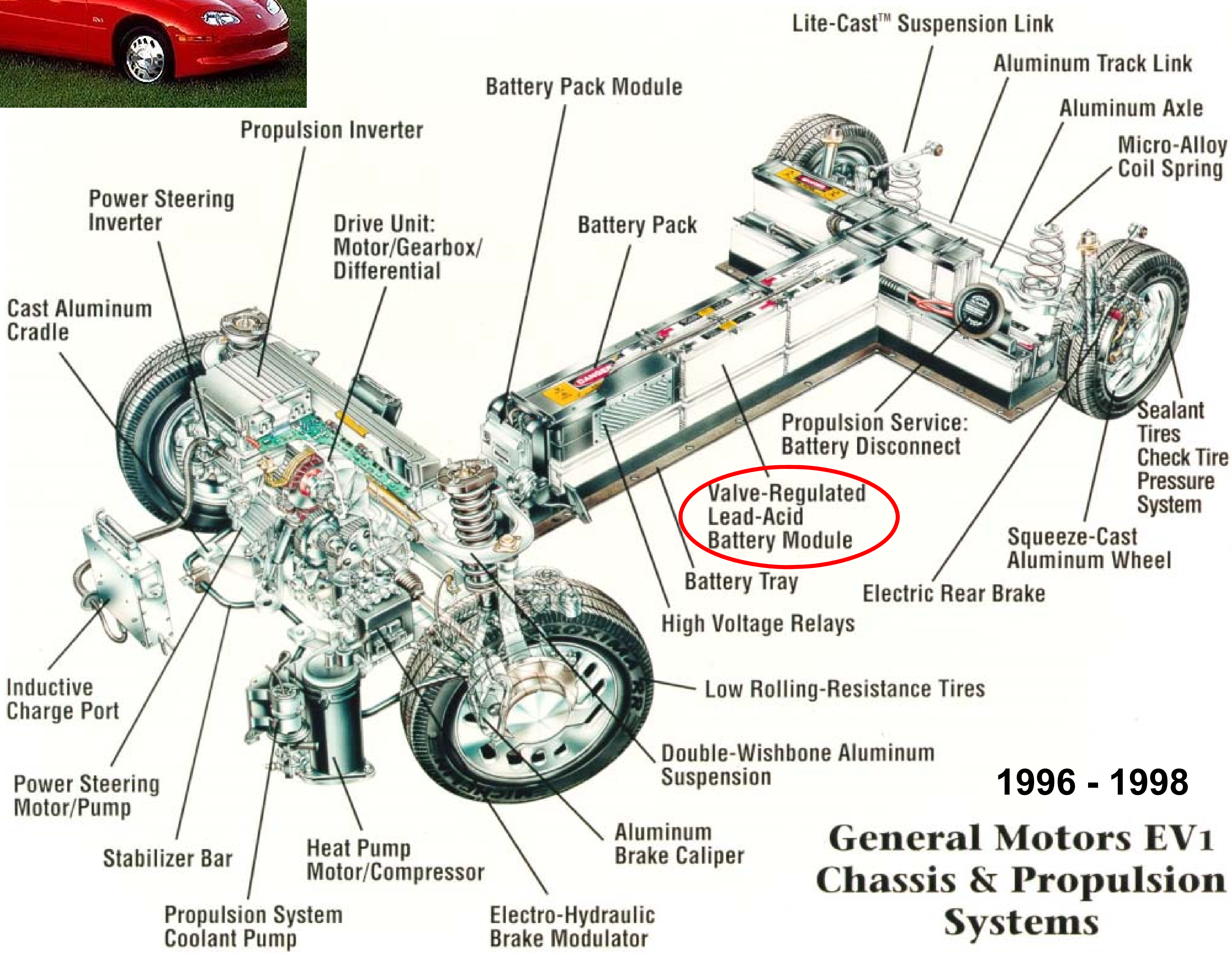
Recharge mode:

(-) Cathode: $PbSO_4 + 2e- \rightarrow Pb + SO_4^{2-}$ $E^o = - 0.36V$

(+) Anode: $PbSO_4 + 2H_2O \rightarrow PbO_2 + 4H^+ + SO_4^{2-} + 2e-$ $E^o = -1.69V$

Overall: $2PbSO_4 + 2H_2O \rightarrow Pb + PbO_2 + 4H^+ + 2SO_4^{2-}$ $E^o = - 2.05V$

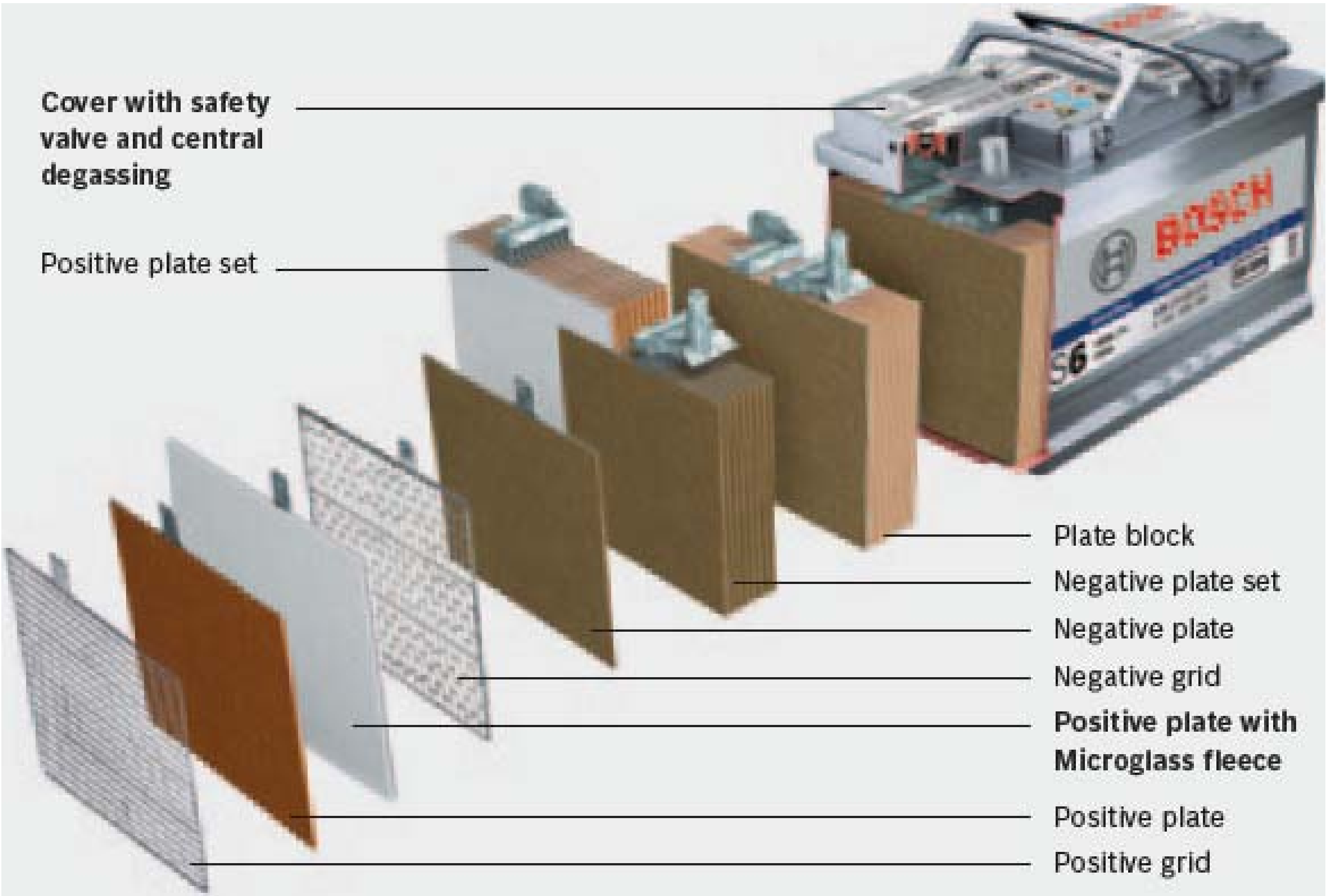
Positive plates	:	$PbO_2 + 4H^+ + SO_4^{2-} + 2e \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} PbSO_4 + 2H_2O$
Negative plates	:	$Pb + SO_4^{2-} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} PbSO_4 + 2e^-$
Over all reaction	:	$PbO_2 + Pb + 2H_2SO_4 \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2PbSO_4 + 2H_2O$



1996 - 1998

General Motors EV1 Chassis & Propulsion Systems

Absorbent Glass Mat (AGM) Battery



Micro-glass fiber mats are located tightly between the lead plates and bind in all of the electrolyte

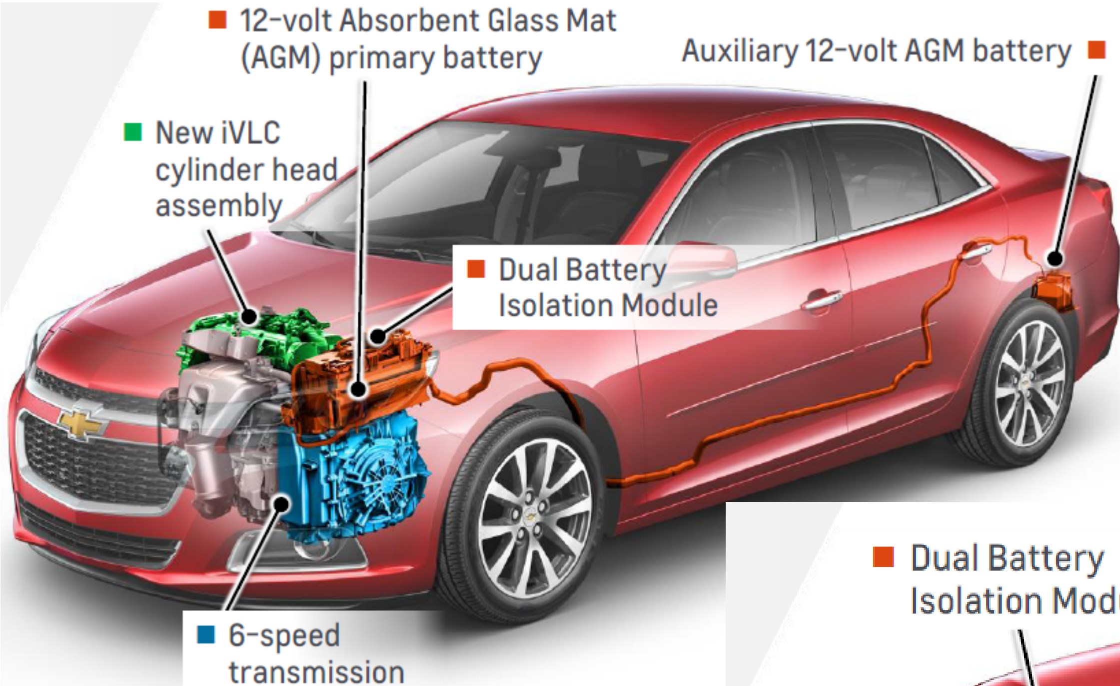
- High pressure minimizes loss of the active material
- Low internal resistance
- Faster reaction between the acid and plate material
- Higher amounts of energy pass through in demanding situations

Mercedes-Benz ECO Stop/Start

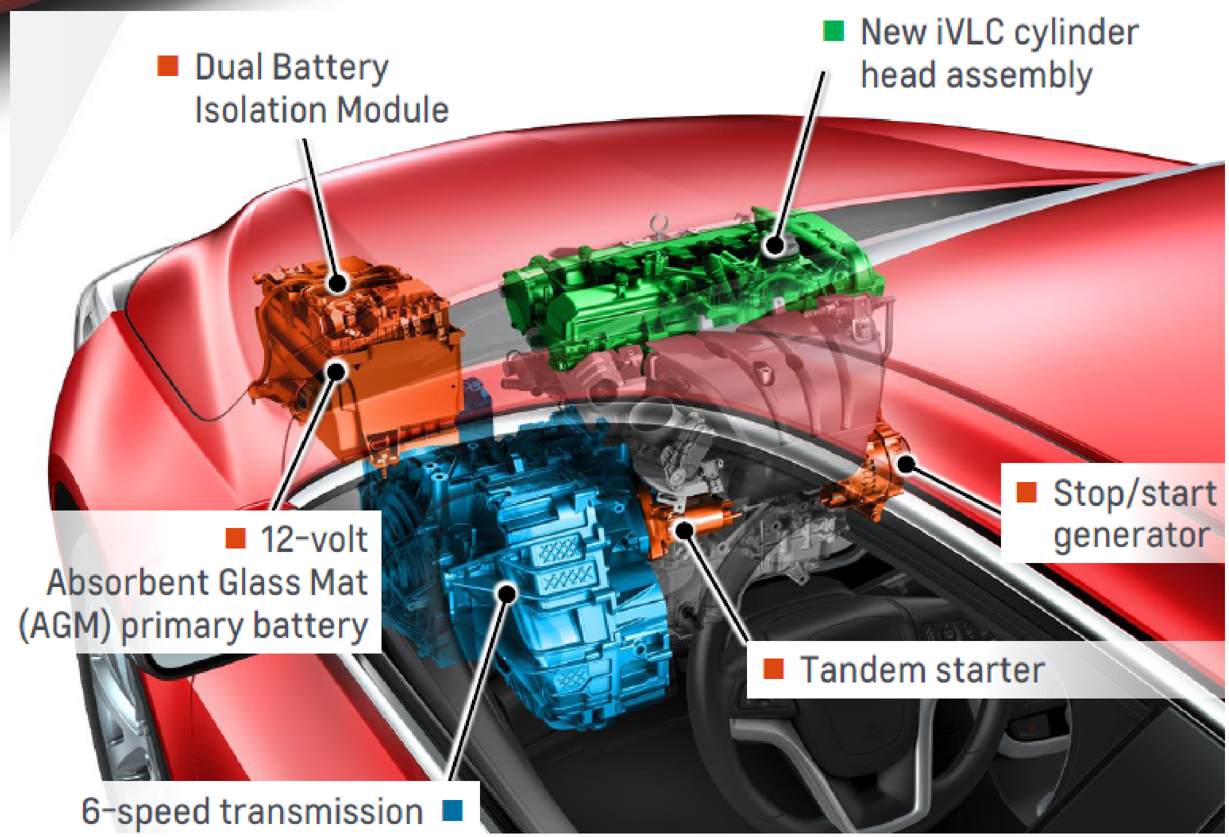
CLA class

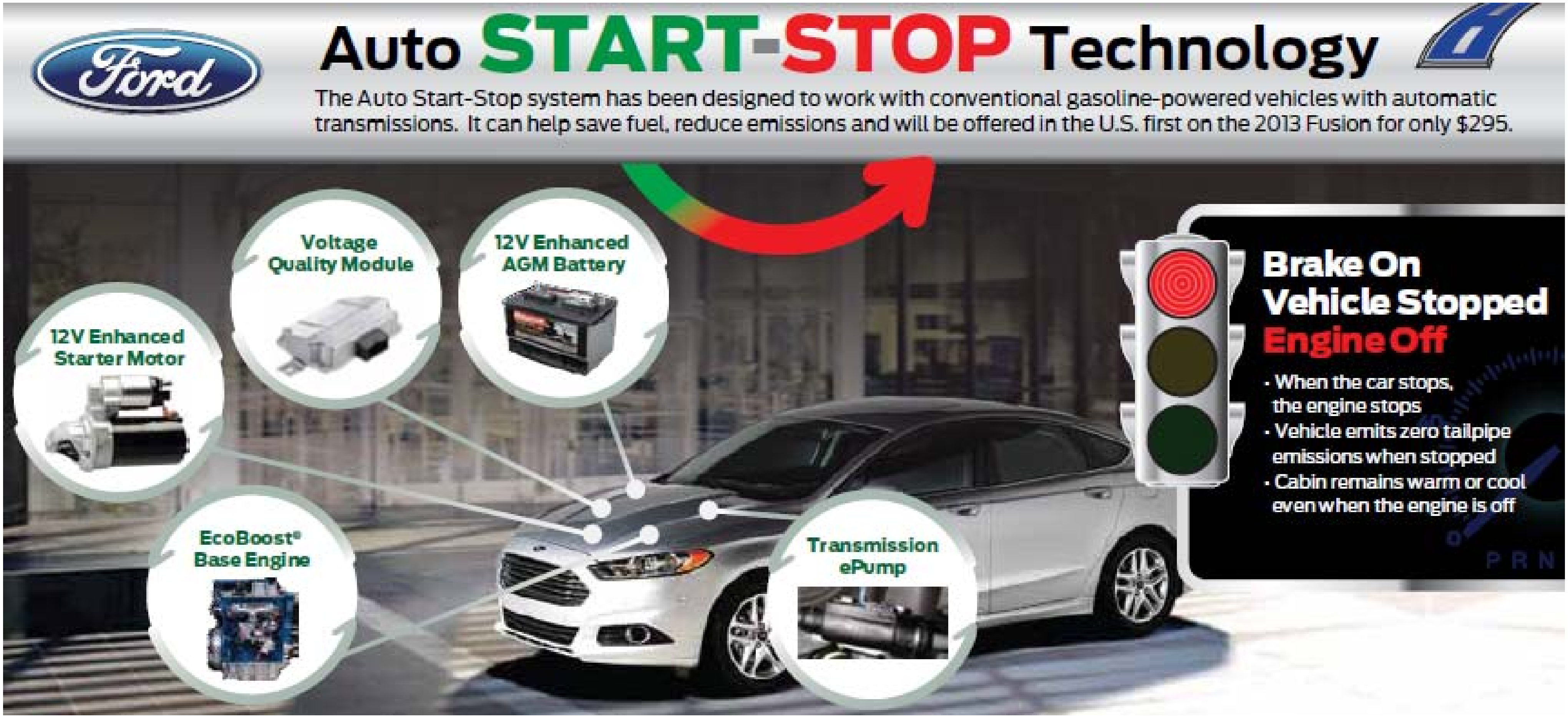
- ECO Start/Stop system automatically shuts off the engine at stoplights and other idle situations.
- As soon as the driver lifts off the brake, the engine instantly restarts, for immediate acceleration response.
- The ECO Start/Stop system can also be shut off by the driver at any time.

Chevrolet Malibu Stop/Start

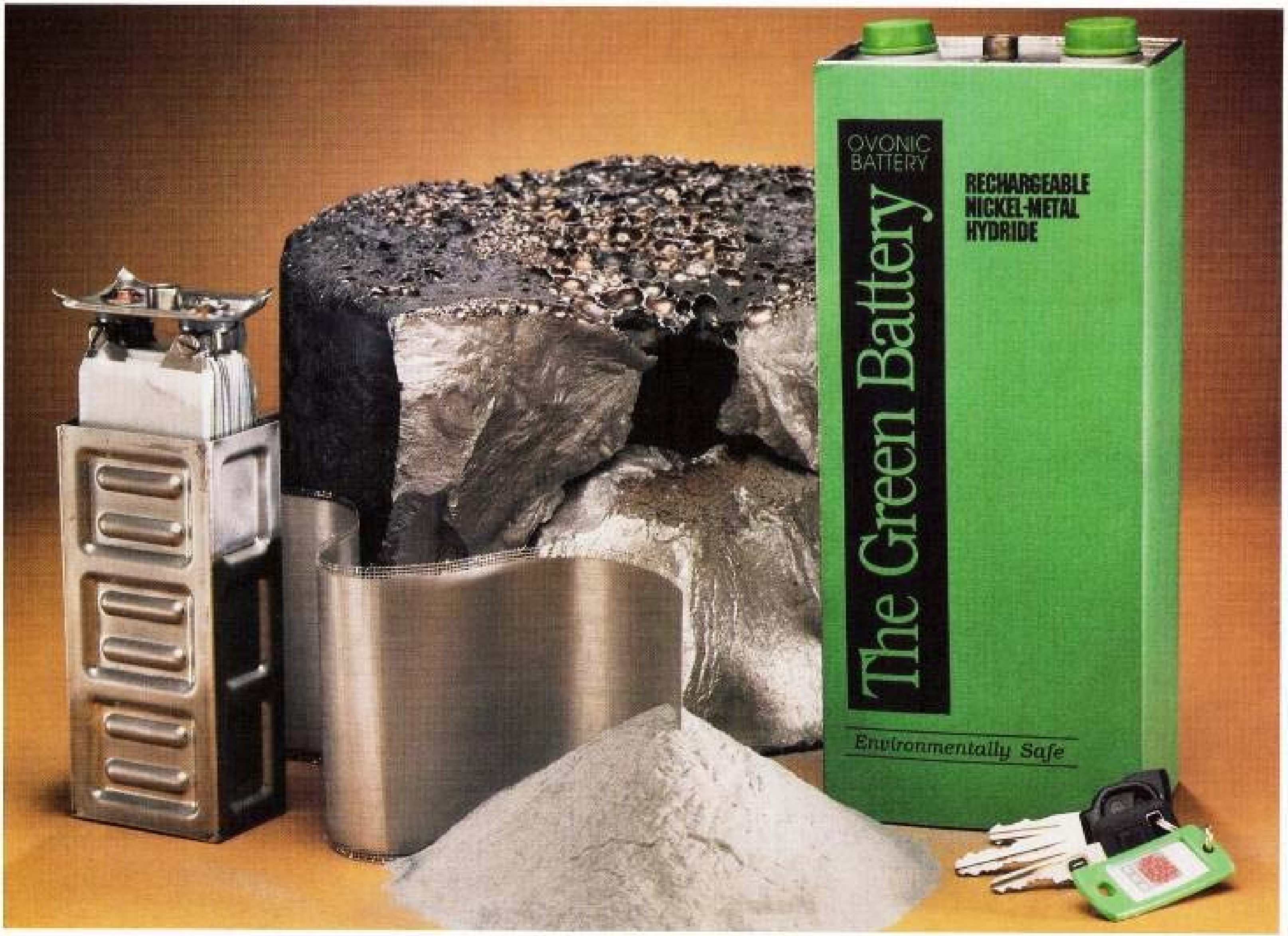


- ✓ Ecotec 2.5L with iVLC
- ✓ Enhanced 6T45 transmission
- ✓ Stop/start
- ✓ 25 MPG city/36 MPG hwy




Ford
Auto START-STOP Technology
The Auto Start-Stop system has been designed to work with conventional gasoline-powered vehicles with automatic transmissions. It can help save fuel, reduce emissions and will be offered in the U.S. first on the 2013 Fusion for only $295.
Voltage Quality Module
12V Enhanced AGM Battery
12V Enhanced Starter Motor
EcoBoost® Base Engine
Transmission ePump
Brake On
Vehicle Stopped
Engine Off
· When the car stops, the engine stops
· Vehicle emits zero tailpipe emissions when stopped
· Cabin remains warm or cool even when the engine is off

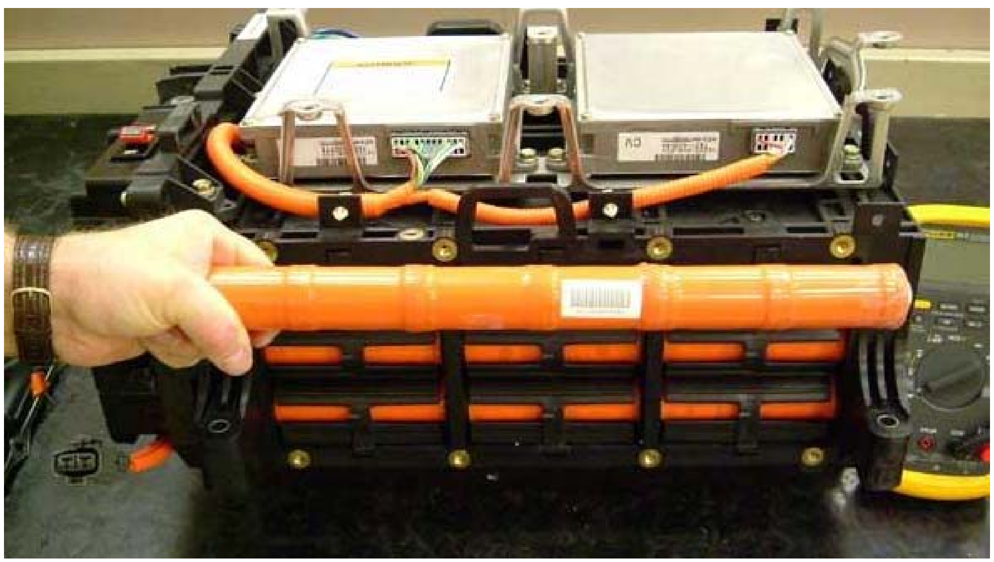
Nickel-Metal Hydride Batteries



Environmentally safe Ovonic battery with metal-hydride materials in ingot, powder and electrode form.

Nickel Hydrogen battery for satellite

NiMH batteries for consumer products



Honda HEV battery pack

NiMH Battery Half-Cell Potentials

$NiOOH + MH \rightarrow Ni(OH)_2 + M$

NiMH Cell Voltage:

$E^o = 0.45 - (-0.83) = 1.28$ V

Electrode reaction	E^0, V
$Li^+ + e \rightleftharpoons Li$	−3.01
$Rb^+ + e \rightleftharpoons Rb$	−2.98
$Cs^+ + e \rightleftharpoons Cs$	−2.92
$K^+ + e \rightleftharpoons K$	−2.92
$Ba^{2+} + 2e \rightleftharpoons Ba$	−2.92
$Sr^{2+} + 2e \rightleftharpoons Sr$	−2.89
[illegible]	−2.84
[illegible]	−2.71
[illegible]	−2.69
[illegible]	−2.38
[illegible]	−2.34
$Ti^{2+} + 2e \rightleftharpoons Ti$	−1.75
$Be^{2+} + 2e \rightleftharpoons Be$	−1.70
$Al^{3+} + 3e \rightleftharpoons Al$	−1.66
$Zn(OH)_2 + 2e \rightleftharpoons Zn + 2OH^-$	−1.25
$Mn^{2+} + 2e \rightleftharpoons Mn$	−1.05
$Fe(OH)_2 + 2e \rightleftharpoons Fe + 2OH^-$	−0.88
$2H_2O + 2e \rightleftharpoons H_2 + 2OH^-$	−0.83
$Cd(OH)_2 + 2e \rightleftharpoons Cd + 2OH^-$	−0.81
$Zn^{2+} + 2e \rightleftharpoons Zn$	−0.76
$Ni(OH)_2 + 2e \rightarrow Ni + 2OH^-$	−0.72
$Ga^{3+} + 3e \rightleftharpoons Ga$	−0.52
$S + 2e \rightarrow S^{2-}$	−0.48
$Fe^{2+} + 2e \rightleftharpoons Fe$	−0.44
$Cd^{2+} + 2e \rightleftharpoons Cd$	−0.40
$PbSO_4 + 2e \rightleftharpoons Pb + SO_4^{2-}$	−0.36
$In^{3+} + 3e \rightleftharpoons In$	−0.34
$Tl^+ + e \rightleftharpoons Tl$	−0.34
$Co^{2+} + 2e \rightleftharpoons Co$	−0.27
$Ni^{2+} + 2e \rightleftharpoons Ni$	−0.23

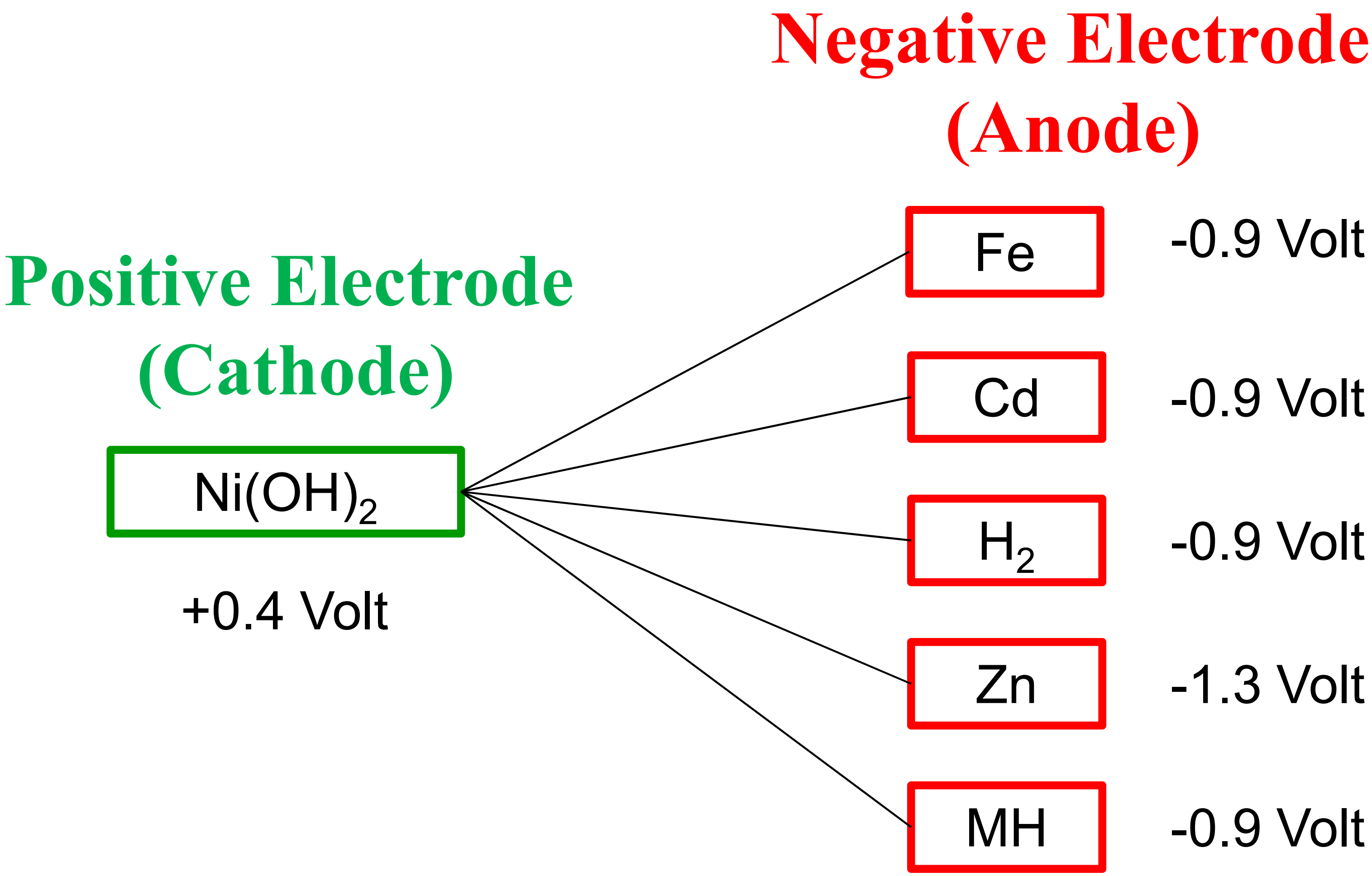
MH

Electrode reaction	E^0, V
$Sn^{2+} + 2e \rightleftharpoons Sn$	−0.14
$Pb^{2+} + 2e \rightleftharpoons Pb$	−0.13
$O_2 + H_2O + 2e \rightleftharpoons HO_2^- + OH^-$	−0.08
$D^+ + e \rightleftharpoons \frac{1}{2}D_2$	−0.003
$H^+ + e \rightleftharpoons \frac{1}{2}H_2$	0.000
$HgO + H_2O + 2e \rightleftharpoons Hg + 2OH^-$	0.10
$CuCl + e \rightleftharpoons Cu + Cl^-$	0.14
$AgCl + e \rightleftharpoons Ag + Cl^-$	0.22
$\gamma\text{-}MnO_2 + H_2O + e \rightleftharpoons \alpha\text{-}MnOOH + OH^-$	0.30
$Cu^{2+} + 2e \rightleftharpoons Cu$	0.34
$Ag_2O + H_2O + 2e \rightleftharpoons 2Ag + 2OH^-$	0.35
$\gamma\text{-}MnO_2 + H_2O + e \rightleftharpoons \gamma\text{-}MnOOH + OH^-$	0.36
$\frac{1}{2}O_2 + H_2O + 2e \rightleftharpoons 2OH^-$	0.40
$NiOOH + H_2O + e \rightleftharpoons Ni(OH)_2 + OH^-$	0.45
$Cu^+ + e \rightleftharpoons Cu$	0.52
$I_2 + 2e \rightleftharpoons 2I^-$	0.54
$2AgO + H_2O + 2e \rightleftharpoons Ag_2O + 2OH^-$	0.57
$Hg^{2+} + 2e \rightleftharpoons 2Hg$	0.80
$Ag^+ + e \rightleftharpoons Ag$	0.80
$Pd^{2+} + 2e \rightleftharpoons Pd$	0.83
$Ir^{3+} + 3e \rightleftharpoons Ir$	1.00
$Br_2 + 2e \rightleftharpoons 2Br^-$	1.07
$O_2 + 4H^+ + 4e \rightleftharpoons 2H_2O$	1.23
$MnO_2 + 4H^+ + 2e \rightleftharpoons Mn^{2+} + 2H_2O$	1.23
$Cl_2 + 2e \rightleftharpoons 2Cl^-$	1.36
$PbO_2 + 4H^+ + 2e \rightleftharpoons Pb^{2+} + 2H_2O$	1.46
$PbO_2 + SO_4^{2-} + 4H^+ + 2e \rightleftharpoons PbSO_4 + 2H_2O$	1.69
$F_2 + 2e \rightleftharpoons 2F^-$	2.87

H_2O stability Window In acid

NiOOH

Happy Family



* All voltages are referred to Hg/HgO reference electrode

NiMH Battery Charging

Positive electrode: (Anode / Oxidation)	$Ni(OH)_2 + OH^- \rightarrow NiOOH + H_2O + e^-$	$E_o = -0.45V$
Negative electrode: (Cathode / Reduction)	$M + H_2O + e^- \rightarrow MH + OH^-$	$E_o \sim -0.83V$
	$MH_y + xH_2O + xe^- \rightarrow MH_{x+y} + xOH^-$	
Over all cell reaction:	$Ni(OH)_2 + M \rightarrow NiOOH + MH$	$E_o \sim -1.28V$

Note:

(1) There is no change in KOH concentration and no water consumption.
Overcharge (positive limited cells):
(+) $2OH^- \rightarrow H_2O + \frac{1}{2}O_2 + 2e^-$
(-) $MH_{x+y} + 2H_2O + 2e^- \rightarrow MH_{x+y+2} + 2OH^-$
$MH_{x+y+2} + \frac{1}{2} O_2 \rightarrow MH_{x+y} + H_2O$

(2) No change in KOH concentration and no water consumption during overcharge.

(3) In the whole cell reaction, it is “H” atom movement between electrodes. In this charging process, “H” atom moves out from positive $Ni(OH)_2$ matrix and enter into negative hydrogen storage alloy matrix (lattices).

NiMH Battery Discharging

Positive electrode: (Cathode / Reduction) $NiOOH + H_2O + e^- \rightarrow Ni(OH)_2 + OH^-$ $E_o = 0.45V$

Negative electrode: (Anode / Oxidation) $MH + OH^- \rightarrow M + H_2O + e^-$ $E_o \sim 0.83V$

$MH_{x+y} + xOH^- \rightarrow M_y + xH_2O + xe^-$

Over all cell reaction: $NiOOH + MH \rightarrow Ni(OH)_2 + M$ $E_o \sim 1.28V$

$xNiOOH + MH_{x+y} \rightarrow xNi(OH)_2 + MH_y$

Note:

(1) There is no change in KOH concentration and no water consumption.
Overdischarge (positive limited cells):

(+) $H_2O + \frac{1}{2} O_2 + 2e^- \rightarrow 2OH^-$

(-) $MH_{y+2} + 2OH^- \rightarrow MH_x + 2H_2O + 2e^-$

$MH_y + \frac{1}{2} O_2 \rightarrow MH_{y-2} + H_2O$

(2) There is no change in KOH concentration and no water consumption during overcharge.

Anode vs. Cathode

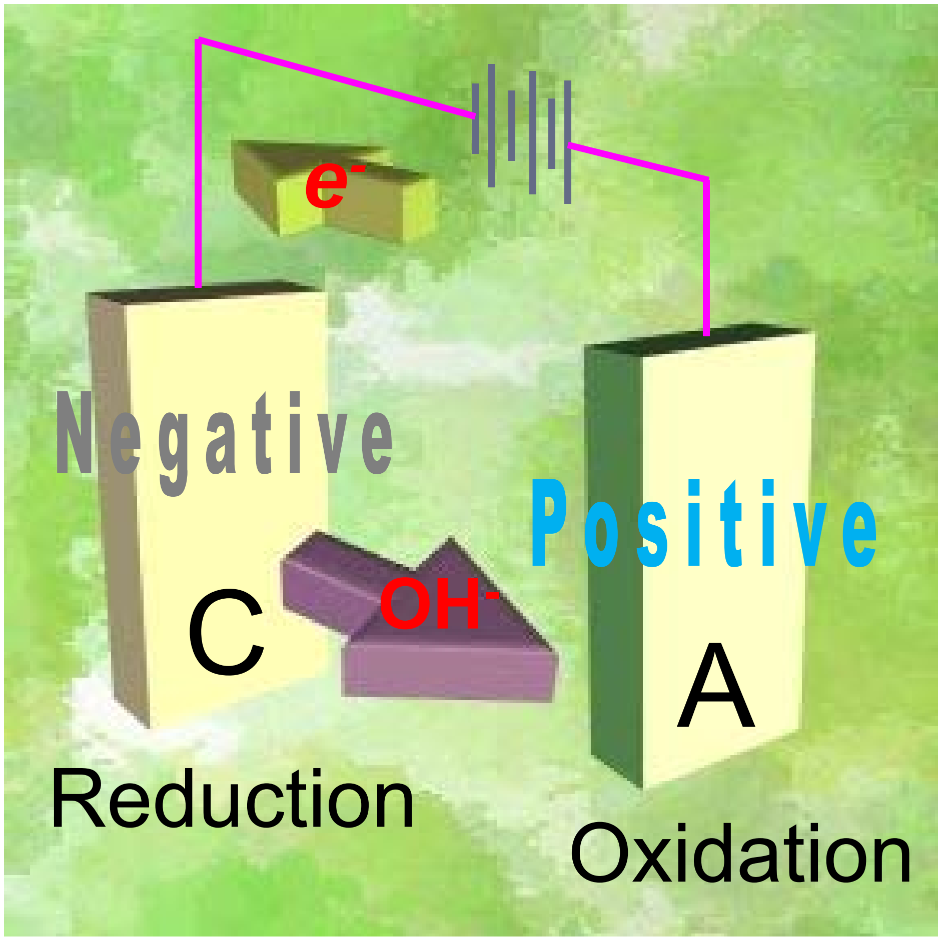
- Anode
  - where oxidation happens

- Cathode
  - where reduction happens

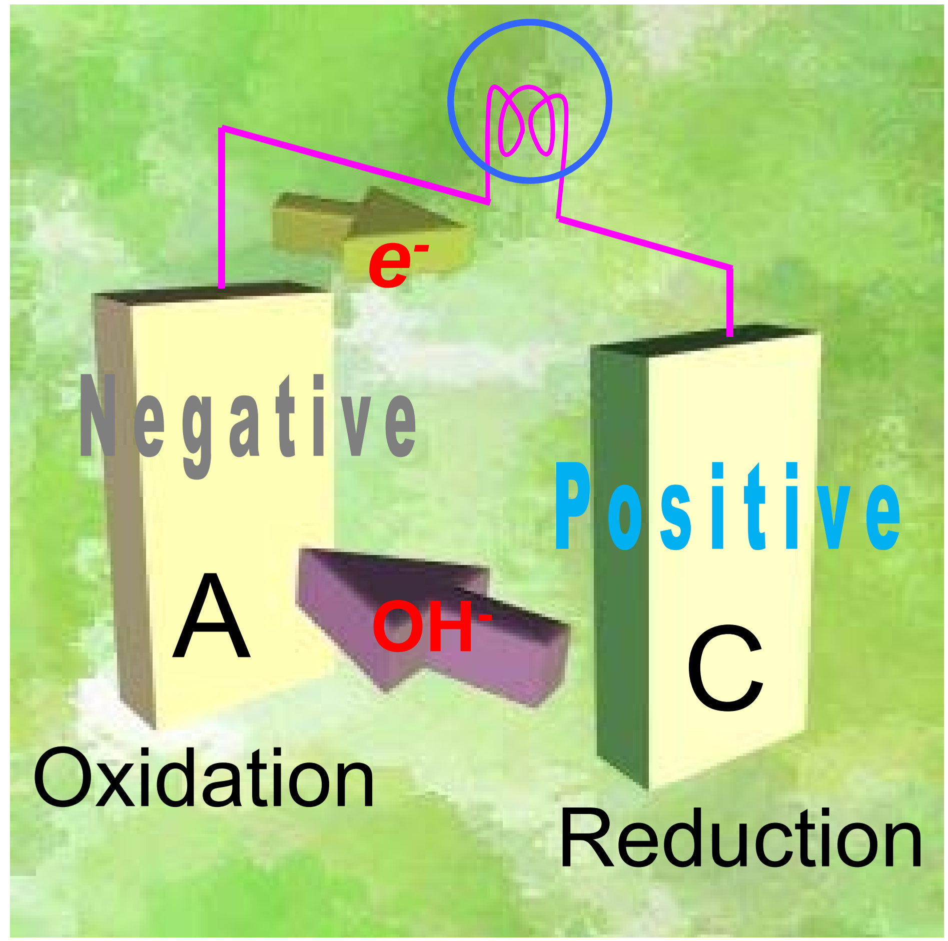
- Rule of thumb
  - CCC Cd-Charge-Cathode ($Cd^{2+} \rightarrow Cd^{0}$)
  - CDA Cd-Discharge-Anode
  - NCA Ni-Charge-Anode ($Ni^{2+} \rightarrow Ni^{3+}$)
  - NDC Ni-Discharge-Cathode

NiMH Electrochemistry

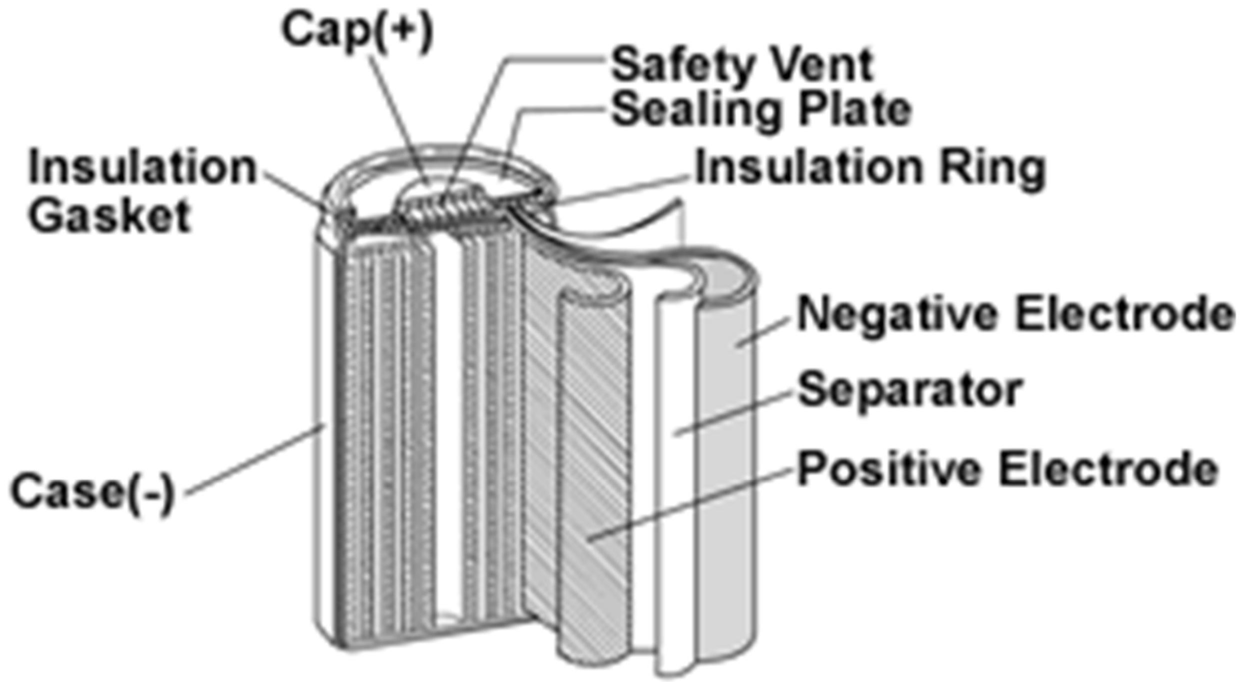
During Charge



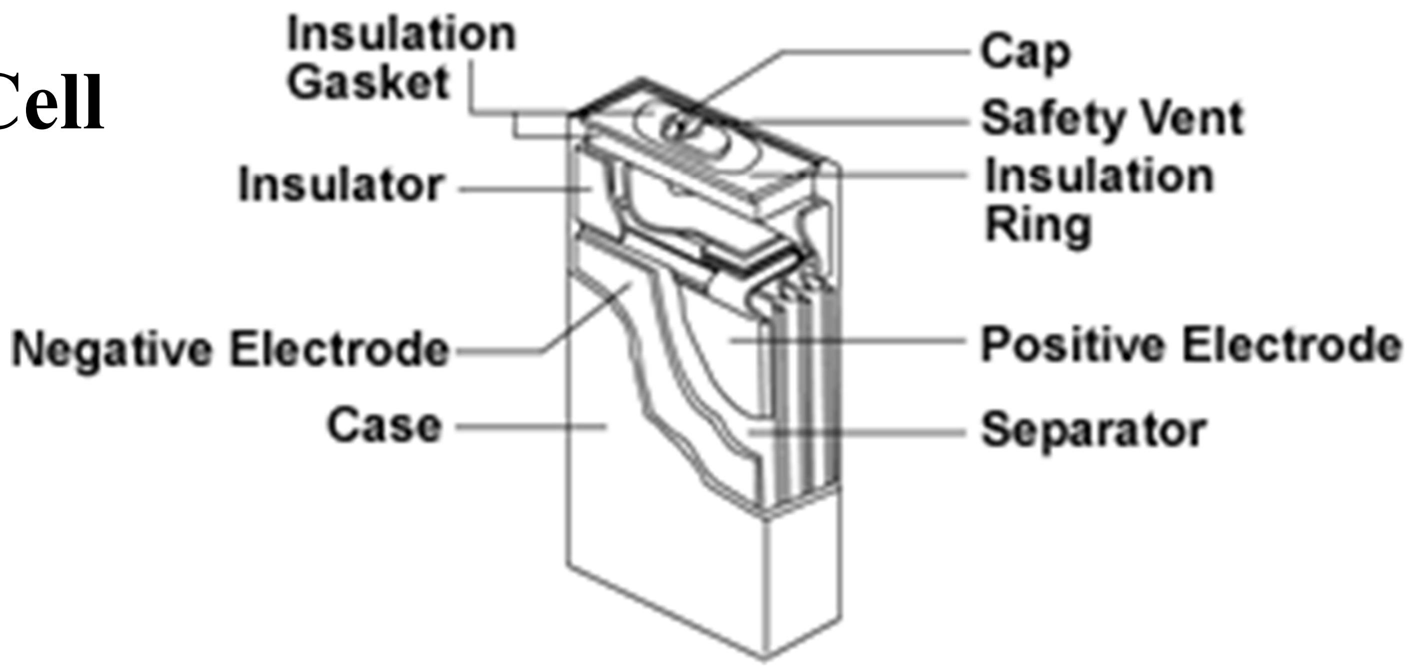
During Discharge



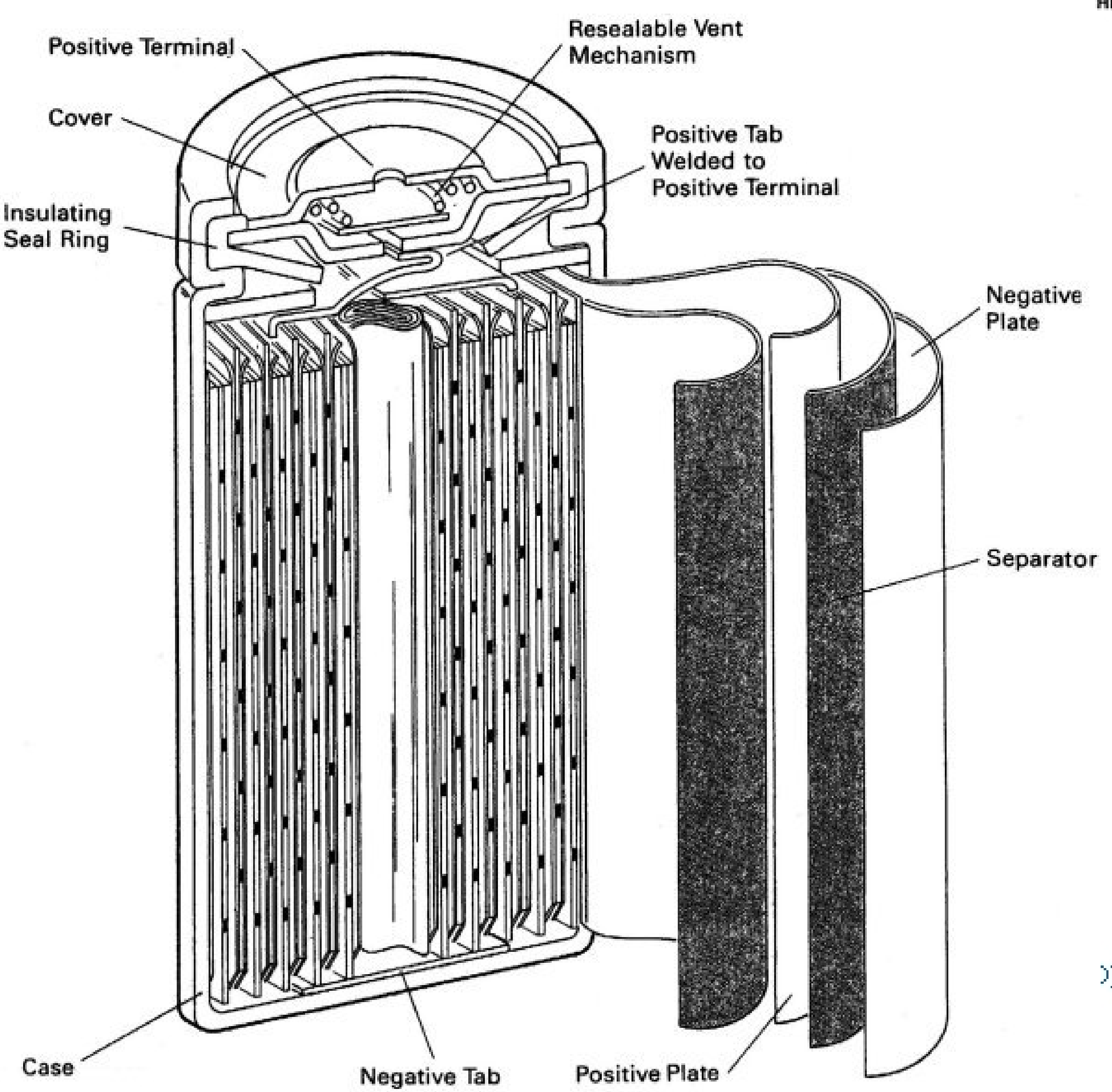
Cylindrical Cell



Prismatic Cell



Jelly Roll Construction of Ni-MH Battery



Ni-H_2

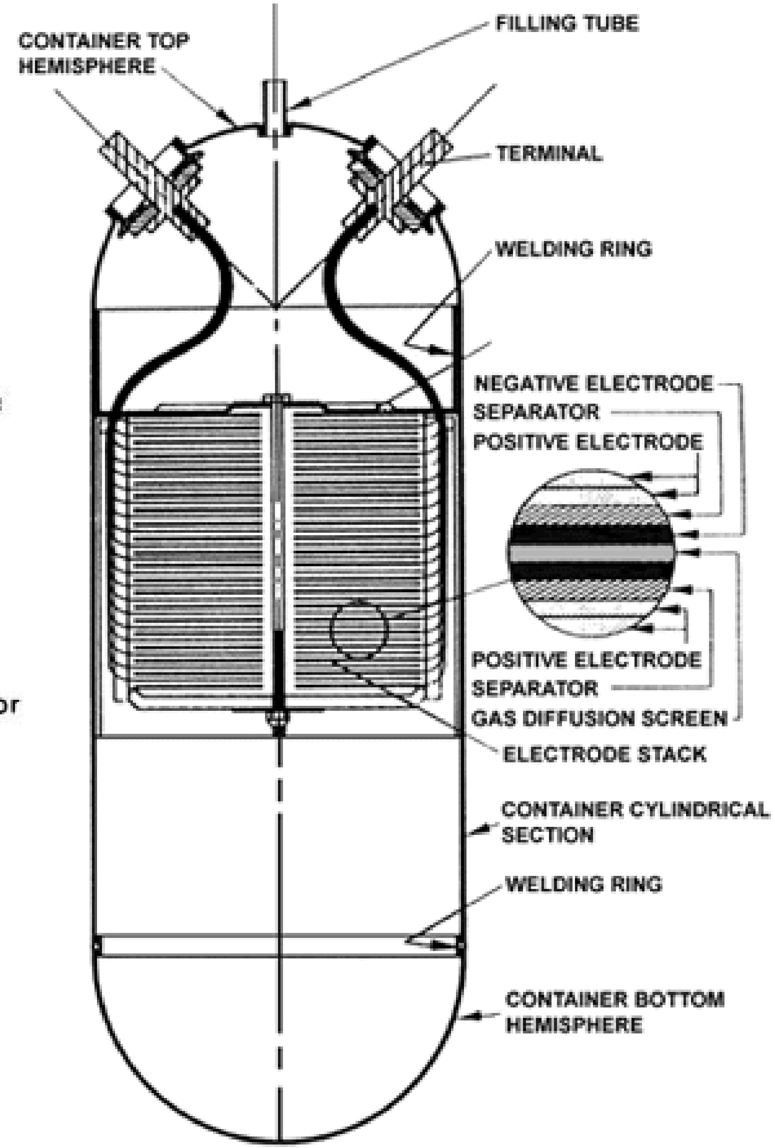


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Figure 1. NiH2 CPV Positioned Vertically (only the upper of two stack sets is shown)

Why Lithium?

- Lithium can provide both high voltage and high storage capacity.
- High Voltage:

  Li is the strongest metal reducing agent. Therefore a Li anode generates a large potential difference between anode and cathode (large energy output).
- Light Metal:

  Since Li is very light it provides a very high theoretical gravimetric capacity (storable charge per unit weight) of 3.86 Ah/g.

Battery Alternatives for PHEV, HEV or EV

	Lead-Acid	NiMH	Li-Ion
Specific Energy (Wh/kg)	25	60 ~ 80	75 ~ 150
Energy Density (Wh/L)	90	110 ~ 220	120 ~ 190
Life (years)	4 ~ 7	10 ~ 20	??
Cost ($/kWh)	150 ~ 200	300 ~ 800 2X Lead Acid	1300 ~ 2500 2X NiMH
Maturity	Industry standard in telecom, UPS and emergency backup	Large format proven for 10 years in HEV and EV	Mature in consumer, large format unproven
Concerns	Maintenance, battery replacement cost	Stationary applications unproven	Safety, life, high temperature stability

Lithium-ion Batteries: The Emerging EV and PHEV Battery

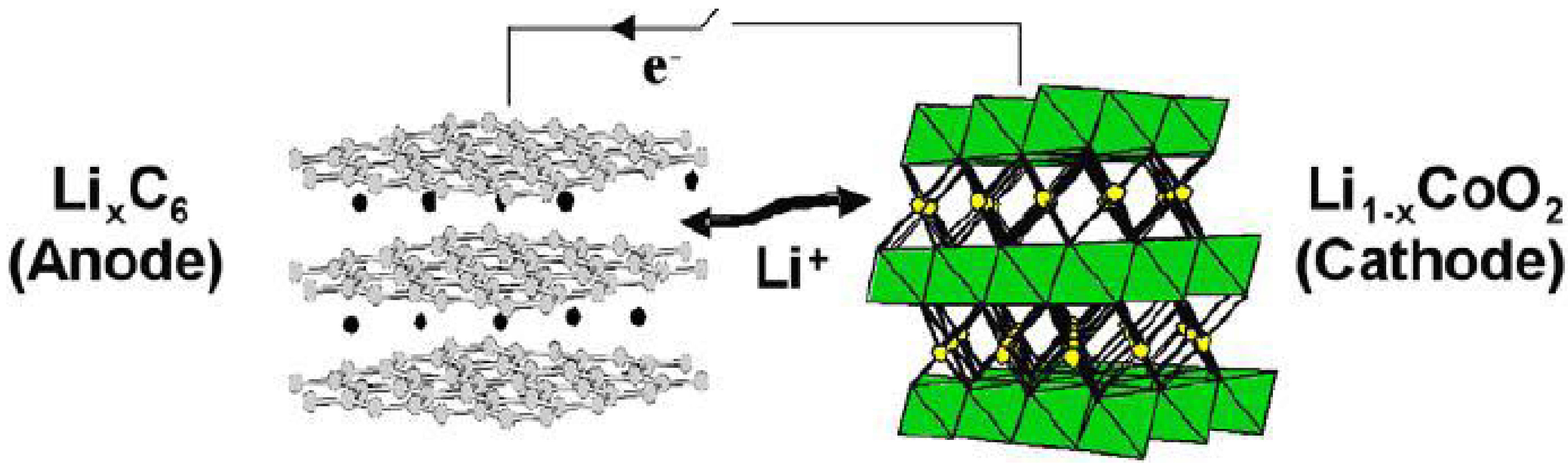
Reaction: $Li\text{-}C_6 + CoO_2 \rightarrow LiCoO_2 + C_6$ $E^o = 3.6$ V

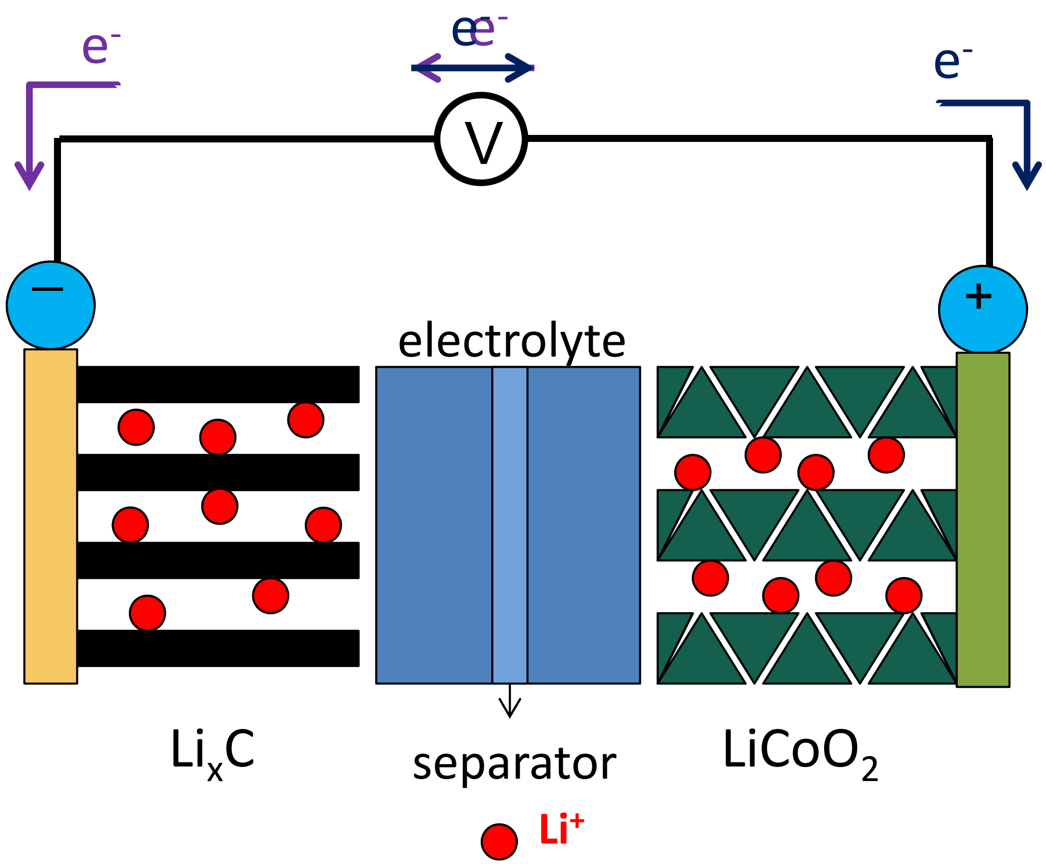
- Origins in R&D at University of Texas ~1982
- Cobalt oxide Li-Ion battery commercialized by Sony 1991
- Originally high energy, low power with cost & safety issues
- Rapid growth in portable electronics to $7B industry today
- Early EV and HEV prototypes had safety issues
- New Li-Ion chemistries developed
- Safer materials and battery constructions
- Very high power and energy now available
- Less expensive materials, high system costs remain

The layered anode structure can be combine with a layered cathode structure

During charge and discharge:

1. Li moves in and out of a layered compound
2. The host structure does not change chemical state





Principle of operation in a commercialized LIB

- **Components**
  - Current collector: copper, aluminum
  - Liquid electrolyte: $LiPF_6$ dissolved in a mixture of propylene carbonate and diethyl carbonate
  - Separator
  - Negative electrode (anode)
    $$C + xLi^+ + xe^- \leftrightarrow Li_xC$$
  - Positive electrode (cathode)
    $$LiCoO_2 \leftrightarrow xLi^+ + Li_{(1-x)}CoO_2 + xe^-$$

"Ionic" current density: "ions" have to move in the electrolyte, electrodes, including rate of ion transfer across the electrode/electrolyte interface → *Slow*

"Electronic" current density: "electrons" move in a conductor → *Fast*

To maintain charge neutrality in the electrodes:
ionic current density = electronic current density

↓

The electrodes and electrolyte need to have a large surface area and small thickness

Lithium Battery Half-Cell Potentials

Li

Electrode reaction	E^0, V
$Li^+ + e \rightleftharpoons Li$	−3.01
$Rb^+ + e \rightleftharpoons Rb$	−2.98
$Cs^+ + e \rightleftharpoons Cs$	−2.92
$K^+ + e \rightleftharpoons K$	−2.92
$Ba^{2+} + 2e \rightleftharpoons Ba$	−2.92
$Sr^{2+} + 2e \rightleftharpoons Sr$	−2.89
$Ca^{2+} + 2e \rightleftharpoons Ca$	−2.84
$Na^+ + e \rightleftharpoons Na$	−2.71
$Mg(OH)_2 + 2e \rightleftharpoons Mg + 2OH^-$	−2.69
$Mg^{2+} + 2e \rightleftharpoons Mg$	−2.38
$Al(OH)_3 + 3e \rightleftharpoons Al + 3OH^-$	−2.34
$Mn^{2+} + 2e \rightleftharpoons Mn$	−1.05
$Fe(OH)_2 + 2e \rightleftharpoons Fe + 2OH^-$	−0.88
$2H_2O + 2e \rightleftharpoons H_2 + 2OH^-$	−0.83
$Cd(OH)_2 + 2e \rightleftharpoons Cd + 2OH^-$	−0.81
$Zn^{2+} + 2e \rightleftharpoons Zn$	−0.76
$Ni(OH)_2 + 2e \rightarrow Ni + 2OH^-$	−0.72
$Ga^{3+} + 3e \rightleftharpoons Ga$	−0.52
$S + 2e \rightarrow S^{2-}$	−0.48
$Fe^{2+} + 2e \rightleftharpoons Fe$	−0.44
$Cd^{2+} + 2e \rightleftharpoons Cd$	−0.40
$PbSO_4 + 2e \rightleftharpoons Pb + SO_4^{-}$	−0.36
$In^{3+} + 3e \rightleftharpoons In$	−0.34
$Tl^+ + e \rightleftharpoons Tl$	−0.34
$Co^{2+} + 2e \rightleftharpoons Co$	−0.27
$Ni^{2+} + 2e \rightleftharpoons Ni$	−0.23

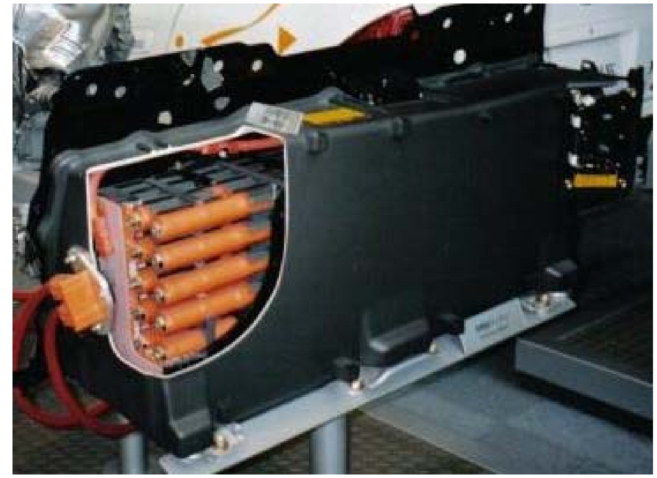
Lithium Battery Cell Voltage:

$E^o = 1 - (-3) \approx 4$ V

Electrode reaction	E^0, V
$Sn^{2+} + 2e \rightleftharpoons Sn$	−0.14
$Pb^{2+} + 2e \rightleftharpoons Pb$	−0.13
$O_2 + H_2O + 2e \rightleftharpoons HO_2^- + OH^-$	−0.08
$D^+ + e \rightleftharpoons \frac{1}{2}D_2$	−0.003
$H^+ + e \rightleftharpoons \frac{1}{2}H_2$	0.000
$HgO + H_2O + 2e \rightleftharpoons Hg + 2OH^-$	0.10
$CuCl + e \rightleftharpoons Cu + Cl^-$	0.14
$AgCl + e \rightleftharpoons Ag + Cl^-$	0.22
$\gamma\text{-}MnO_2 + H_2O + e \rightleftharpoons \alpha\text{-}MnOOH + OH^-$	0.30
$Cu^{2+} + 2e \rightleftharpoons Cu$	0.34
$Ag_2O + H_2O + 2e \rightleftharpoons 2Ag + 2OH^-$	0.35
$\gamma\text{-}MnO_2 + H_2O + e \rightleftharpoons \gamma\text{-}MnOOH + OH^-$	0.36
$\frac{1}{2}O_2 + H_2O + 2e \rightleftharpoons 2OH^-$	0.40
$NiOOH + H_2O + e \rightleftharpoons Ni(OH)_2 + OH^-$	0.45
$Cu^+ + e \rightleftharpoons Cu$	0.52
$I_2 + 2e \rightleftharpoons 2I^-$	0.54
$2AgO + H_2O + 2e \rightleftharpoons Ag_2O + 2OH^-$	0.57
$Hg^{2+} + 2e \rightleftharpoons 2Hg$	0.80
$Ag^+ + e \rightleftharpoons Ag$	0.80
$Pd^{2+} + 2e \rightleftharpoons Pd$	0.83
$Ir^{3+} + 3e \rightleftharpoons Ir$	1.00
$Br_2 + 2e \rightleftharpoons 2Br^-$	1.07
$O_2 + 4H^+ + 4e \rightleftharpoons 2H_2O$	1.23
$MnO_2 + 4H^+ + 2e \rightleftharpoons Mn^{2+} + 2H_2O$	1.23
$Cl_2 + 2e \rightleftharpoons 2Cl^-$	1.36
$PbO_2 + 4H^+ + 2e \rightleftharpoons Pb^{2+} + 2H_2O$	1.46
$PbO_2 + SO_4^{2-} + 4H^+ + 2e \rightleftharpoons PbSO_4 + 2H_2O$	1.69
$F_2 + 2e \rightleftharpoons 2F^-$	2.87

H_2O stability window in acid

IV. Battery Pack Design



The battery pack's power and energy specifications are dictated by the vehicle's acceleration and range requirements

- **Battery Pack System: Cell, Module, Pack.**

70

- **Capacity and Voltage**
- **Pack Design Options: Cell Configuration – Module**
- **Cell Manufacturing**
  - **Cell Construction**
  - **Electrode Coating**
  - **Cell Assembly Process**
- **Battery Pack Design Considerations**

Electro-Chemical Battery

Definition: An energy storage device consisting of one or more electrochemical cells connected in series to convert chemical energy into electricity generating:

Power = Voltage x Current **Energy** = Power x time

Primary Battery: not rechargeable (eg. dry cell)

Secondary Battery: rechargeable (eg. NiCd battery)

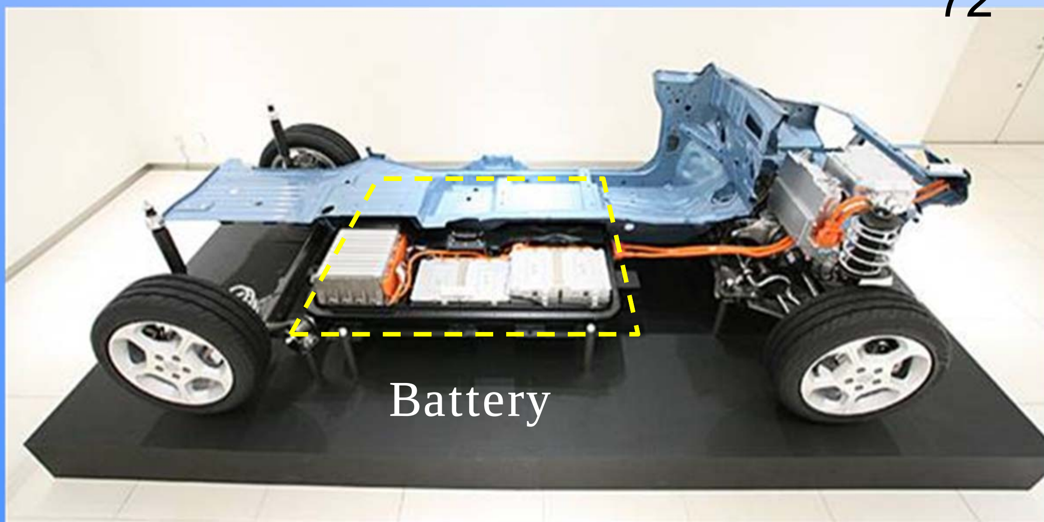
Battery Cell: one electrochemical cell (1 ~ 4 V)

Battery Module: several series connected cells (5 ~ 24 V)

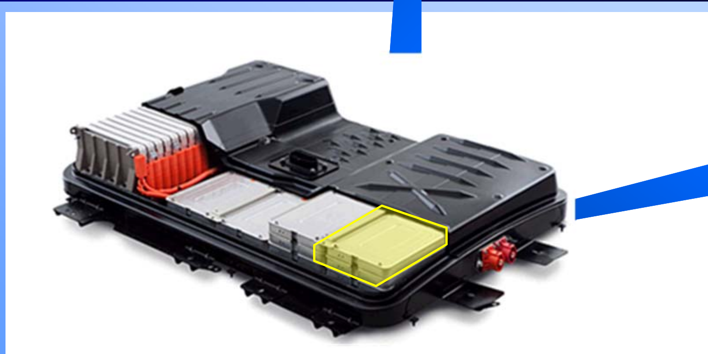
Battery Pack: several series connected modules (36~600 V)

Nissan LEAF Battery Pack

Chassis



Battery pack

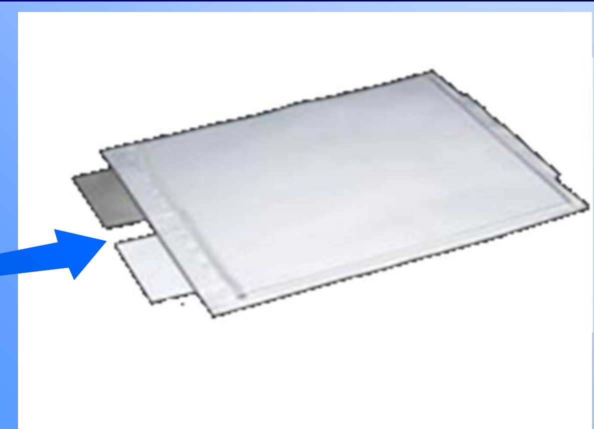


Battery Management System
Junction Box
Service Disconnect Switch, etc

Module

48 modules / vehicle

Cell



192 cells / vehicle
4 cells / module

Nissan LEAF Battery Specifications

Cell

Module

Pack

Cell	Structure	Laminated type
	Capacity	33Ah
	Cathode	Original blended (LMO based)
	Anode	Graphite
Module	Consist of Cell numbers	4 cells
	Cell connection	2 parallel-2series
Pack	Consist of Module numbers	48 Modules (in series)
	Total Energy	24 kWh
	Max. Power	>90kW
	Power/Energy ratio	4

IV. Battery Pack Design Basics

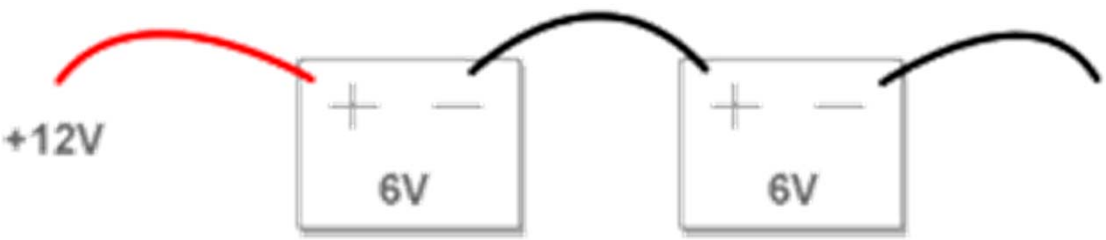
Goal: Convenient integrated power source, black box design.

- Enable higher voltage or high capacity systems to be built up from low voltage, low capacity cells.
- House bank of cells together with associated interconnections.
- Accommodates any necessary monitoring and electronic protection devices or circuits.
- Accommodate additional circuitry, such as indicator lights, heaters, cooling ducts, etc.
- Integration into cavity of product which the battery is intended, providing both electrical and mechanical interfaces.
- Provide unique electrical and mechanical interfaces to ensure compatibility, both of the battery and the charging device.

Capacity and Voltage

Connecting in Series

- Doubles the voltage
- Maintains the same capacity rating (amp hours)
- Typical in construction of modules



Connecting in Parallel

- Doubles the capacity (amp hours)
- Maintains the voltage
- Typical in stringing together modules for pack construction

Power = voltage x current
(P = V x I)

Energy = power x time
(E = P x t)

Charge = current x time
(Q = I x t)

Energy = voltage x charge
(E = V x Q)

Capacity and Voltage

Increasing Battery **Voltage**

- Achieved by adding more cells in a series chain
- Voltage = (Voltage of single cell) x (# of cells in the chain)
- Does not increase amp hour capacity
- Increases total stored energy (Watt-hour capacity)

Increasing Battery **Capacity**

- Achieved by adding more parallel cells
- Capacity = (Capacity of individual chain) x (# of parallel chains)
- Does not increase voltage
- Increases total stored energy (Watt-hour capacity)

Pack Design Options

Cell Configuration

- Shape and design governed by cavity in which pack will be installed
- Packaging space dictates possible cell sizes and layouts
  - Best space utilization ➡ prismatic cells
  - Simplified cooling system ➡ cylindrical cells
  - Compact, design freedom ➡ pouch cells
- Cell orientation designed to minimize interconnections between cells

Pack Design Options

There are infinite variety of battery pack design combinations
Popular configurations using cylindrical cells:

Ladder

B Format

Cells are placed end to end welded in line to maintain a good connection

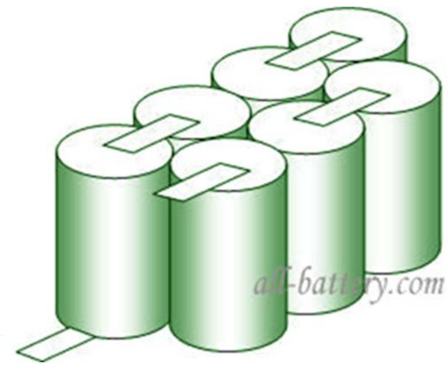
C Format

Cells are secured side by side and then welded together to build up the battery

Cluster

Cells are secured into a cluster formation and interlinked with solder tags to form the battery

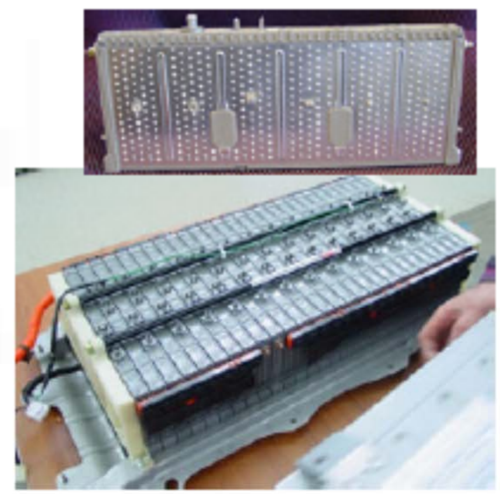
Nested



Cells are secured into an in-line nested formation and interlinked, with solder tags to form the battery

Battery Pack Packaging

- Many small cells
  - — Low cell cost (commodity market)
  - — Improved safety (faster heat rejection)
  - — Many interconnects
  - — Low weight and volume efficiency
  - — Reliability (many components, but some redundancy)
  - — Higher assembly cost
  - — Electrical management (costly)
  - — Life?



- Fewer large cells
  - — Higher cost
  - — Increased reliability
  - — Lower assembly cost
  - — Higher weight and volume efficiency
  - — Thermal management (tougher)
  - — Safety ??
  - — Better Reliability (lower number of components)
  - — Life?

V. Battery Management System (BMS)

A BMS is an embedded system (purpose-built electronics plus processing)

- Protects the safety of vehicle operator and passengers - detects unsafe operating conditions and responds
- Protects the cells of the battery from damage (abuse/ failure cases), and prolongs the life of the battery (normal operating cases)
- Maintains the battery in a state in which it can fulfill its functional design requirements
- Informs the vehicle controller how to make the best use of the battery pack (maximum power limits), control the charger, and so forth

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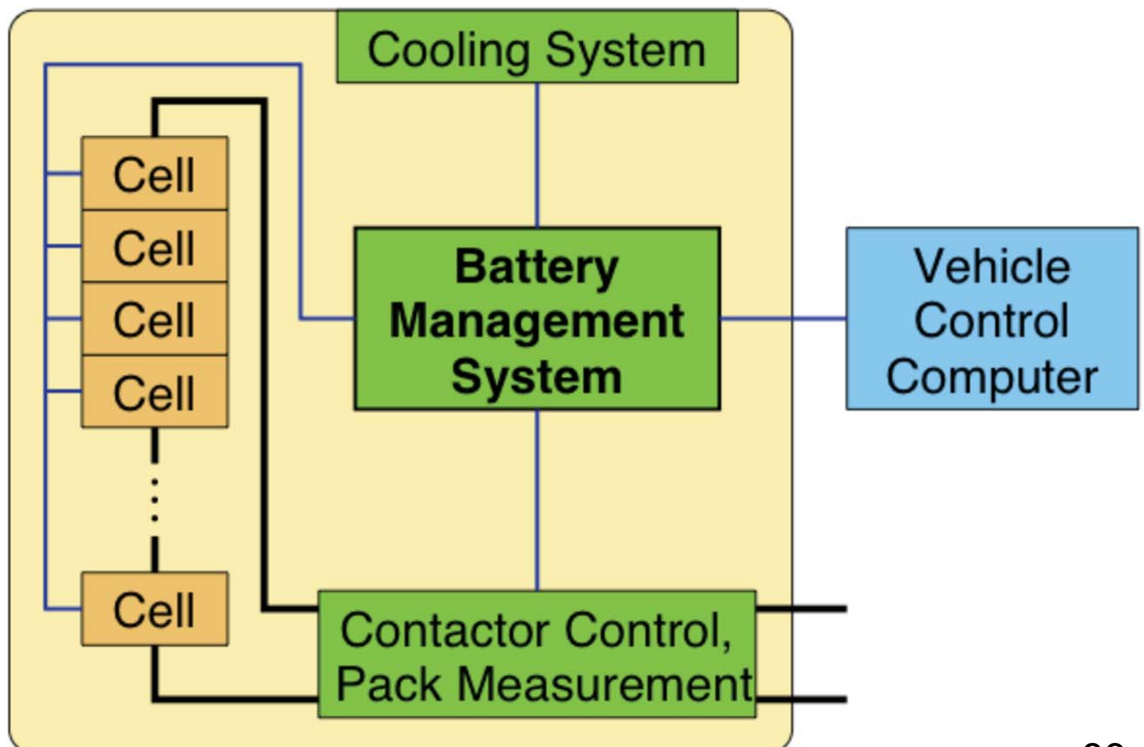
Acronyms we will use

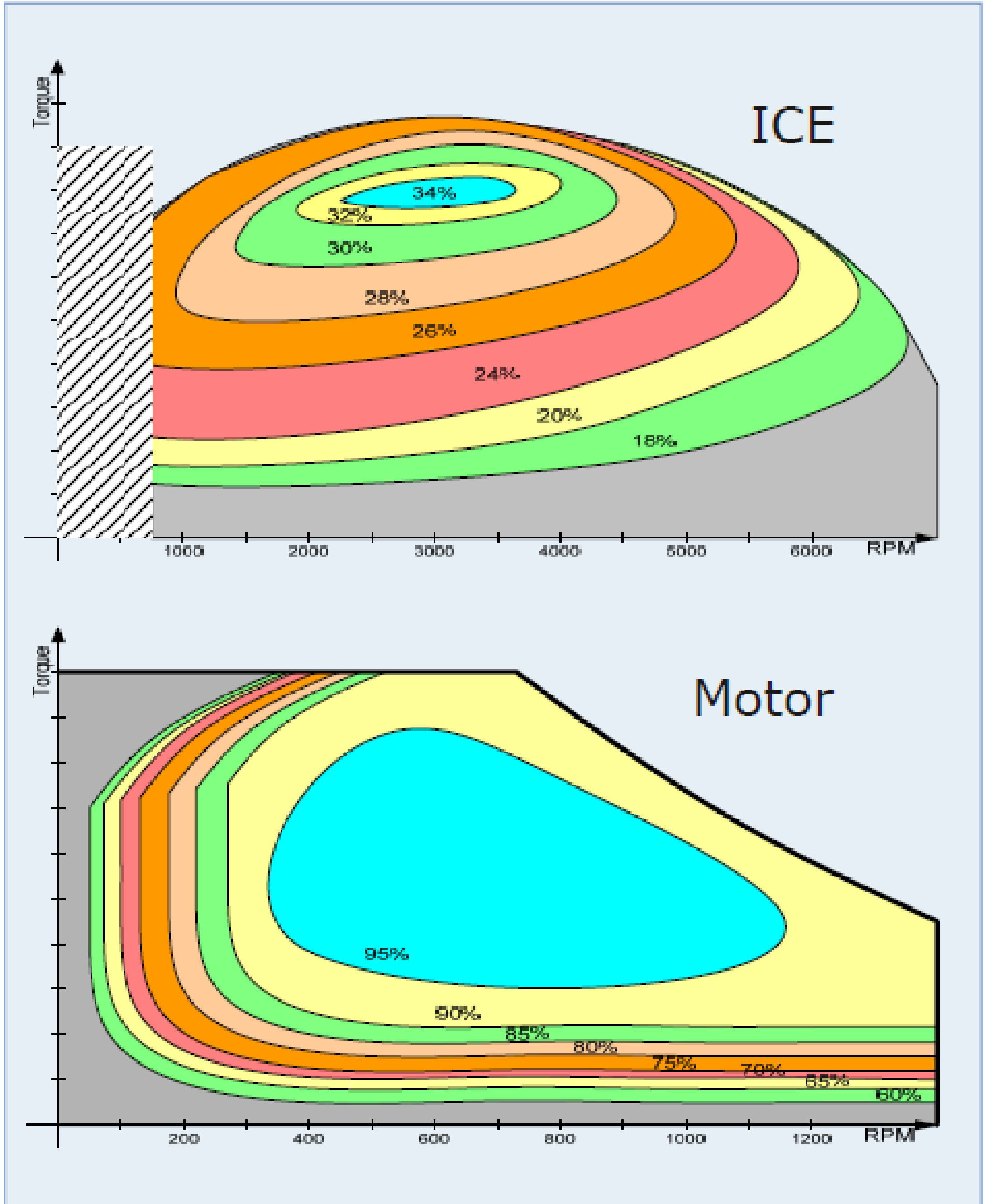
- BMS: Battery Management System
- SOC: State of Charge
- SOH: State of Health
- SOL: State of Life
- EV: Electric Vehicle (i.e., Battery Electric Vehicle)
- HEV: Hybrid Electric Vehicle
- PHEV: Plug-in Hybrid Electric Vehicle
- E-REV: Extended Range Electric Vehicle
- xEV: Any of EV/HEV/PHEV/E-REV

BMS for Electric-drive Vehicles

- Vehicle energy management functions
- Battery management system building blocks
- Cell protection
- Battery stack voltage measurement
- Current sensing
- Main contactor controls
- Temperature sensing
- Isolation leak detection
- Battery power management
- Vehicle network
- BMS topology

BMS Design Challenge: Bringing Down the Cost of Safety!!!



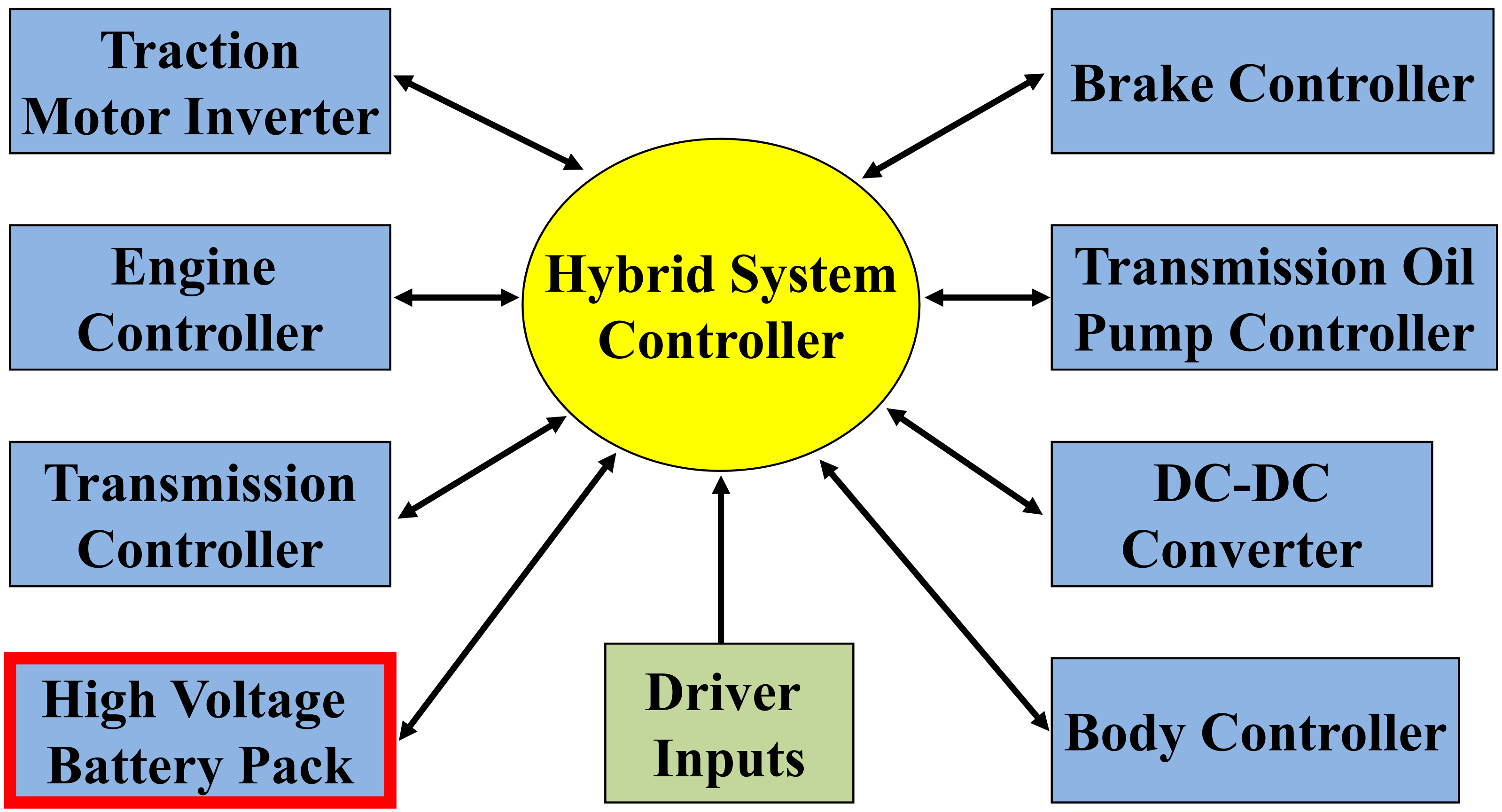


Efficiency ICE vs Motor

- ICE Internal Combustion Engine
  - The sweet point is very small
  - 34% for Gasoline
  - 40% for Diesel
  - Requires complex transmission
- Motor
  - High efficiency wide area 95%
  - Torque at low speed
  - The Inverter efficiency must be included
  - Requires simple transmission
    - e.g. Low speed, high speed
  - The vehicle dynamic is very different
  - With Permanent Magnet the efficiency will change over lifetime
- Battery
  - The battery efficiency will change over lifetime
  - The battery capacity will change over lifetime

Review: Functions of Hybrid System Controller

Hybrid system control algorithm will determine **the best combination of energy sources** based on **driver request torque**, **available power**, **achieved power,** and **sub-system efficiency.**



Summary of NiMH vs. Li-ion Battery

- Battery (cell) technology is critical for EV, HEV and PHEV.
- Battery pack is the assembly of large amount of battery cells plus controlling, monitoring and maintenance functions.
- High voltage battery pack is design for the vehicle power demands: start/stop functionality, power assist during acceleration and recovery of regenerative braking energy.
- The typical battery in a production hybrid vehicle today is nickel metal hydride (NiMH).
- Li-ion batteries are considered the front-runner for Plug-in Hybrids and EVs because of the higher specific energy and power compare to NiMH.
- **The control strategy in the hybrids ensures that the battery is not deep-discharged.**
- Today's hybrids typically maintain the state-of-charge approximately 60% SOC.

Source: US Department of Energy Publication:phev_rd_plan_02-28-07.pdf

Lithium BMS Challenges

1. Must not Over-charge an individual cell
2. Must not Over-discharge an individual cell
3. Must not let cells get too hot during charge or discharge

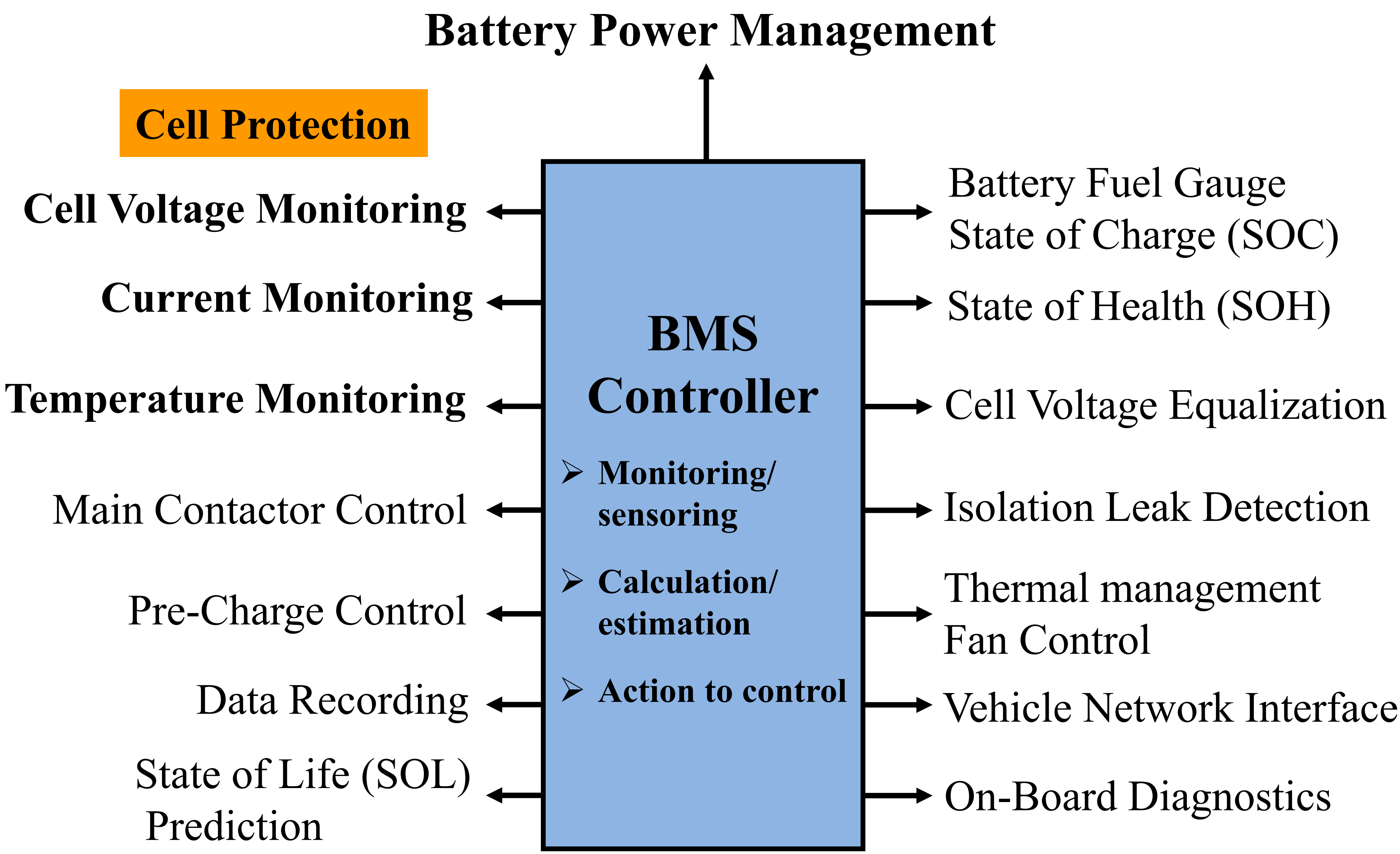
Safety with Higher Energy Li-Ion Batteries

- More energy in same weight and volume
  - Higher energy density
- Lower heat capacity
  - Lower heat capacity electrolyte (flammable)
- Thin separators
- Intolerance to overcharge

Battery Power Management

- BMS function: Estimating charging and discharging power capability of high voltage battery packs.
- Vehicle system controller requires continuous up-to-date information from BMS regarding the power that may be supplied to the electric motor from the battery pack and the power may supply to the battery pack via regenerative braking or by active recharging via the generator.
- Calculating maximum charging and discharging power by calculating the maximum charging and discharging current using any combination of the four primary limits:
  - State of Charge (SOC) limits
  - Voltage limits
  - Current limits
  - Power limits

Battery Management System (BMS) Functions



BMS must produce two critical estimates

- xEVs need to know two battery quantities:
  - How much **energy** is available in the battery pack
  - How much **power** is available in the immediate future
- An estimate of energy is most important for **EV**
- An estimate of power is most important for **HEV**
- Both are important for **E-REV/PHEV**

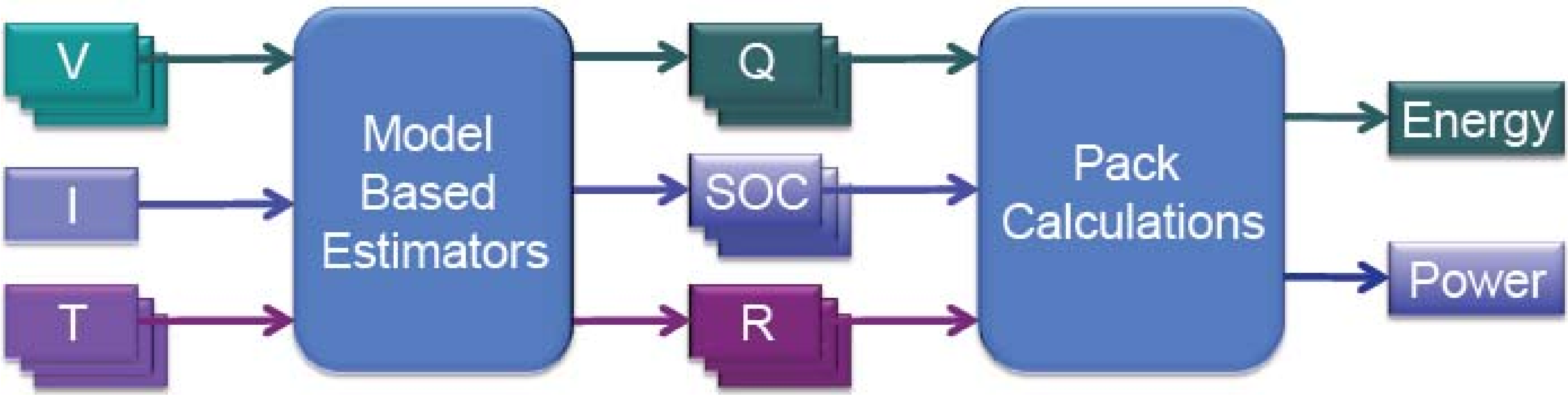
Inputs and Outputs of BMS

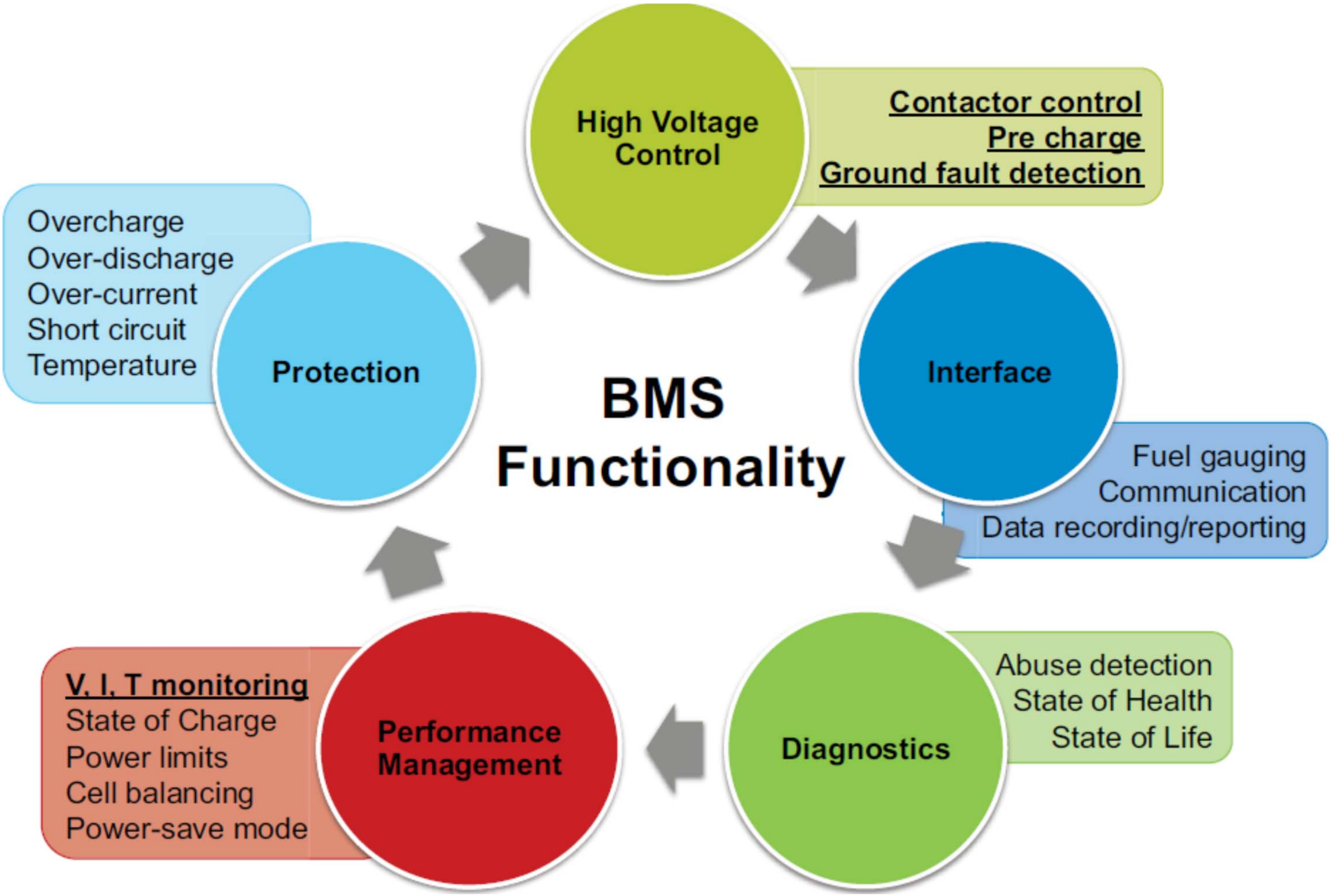
Energy: must know all cell SOCs, capacities Q

Power: must know all cell SOCs, resistances

✓ But, cannot directly measure these parameters – must estimate these quantities as well.

✓ Available inputs include all cell voltages, pack current, and temperatures of cells or modules.




High Voltage Control
Contactor control
Pre charge
Ground fault detection
Overcharge
Over-discharge
Over-current
Short circuit
Temperature
Protection
BMS Functionality
Interface
Fuel gauging
Communication
Data recording/reporting
V, I, T monitoring
State of Charge
Power limits
Cell balancing
Power-save mode
Performance Management
Diagnostics
Abuse detection
State of Health
State of Life

Why/how to measure ALL cell voltages?

Cell voltage (under load) is a critical indicator of

– Relative balance of cells

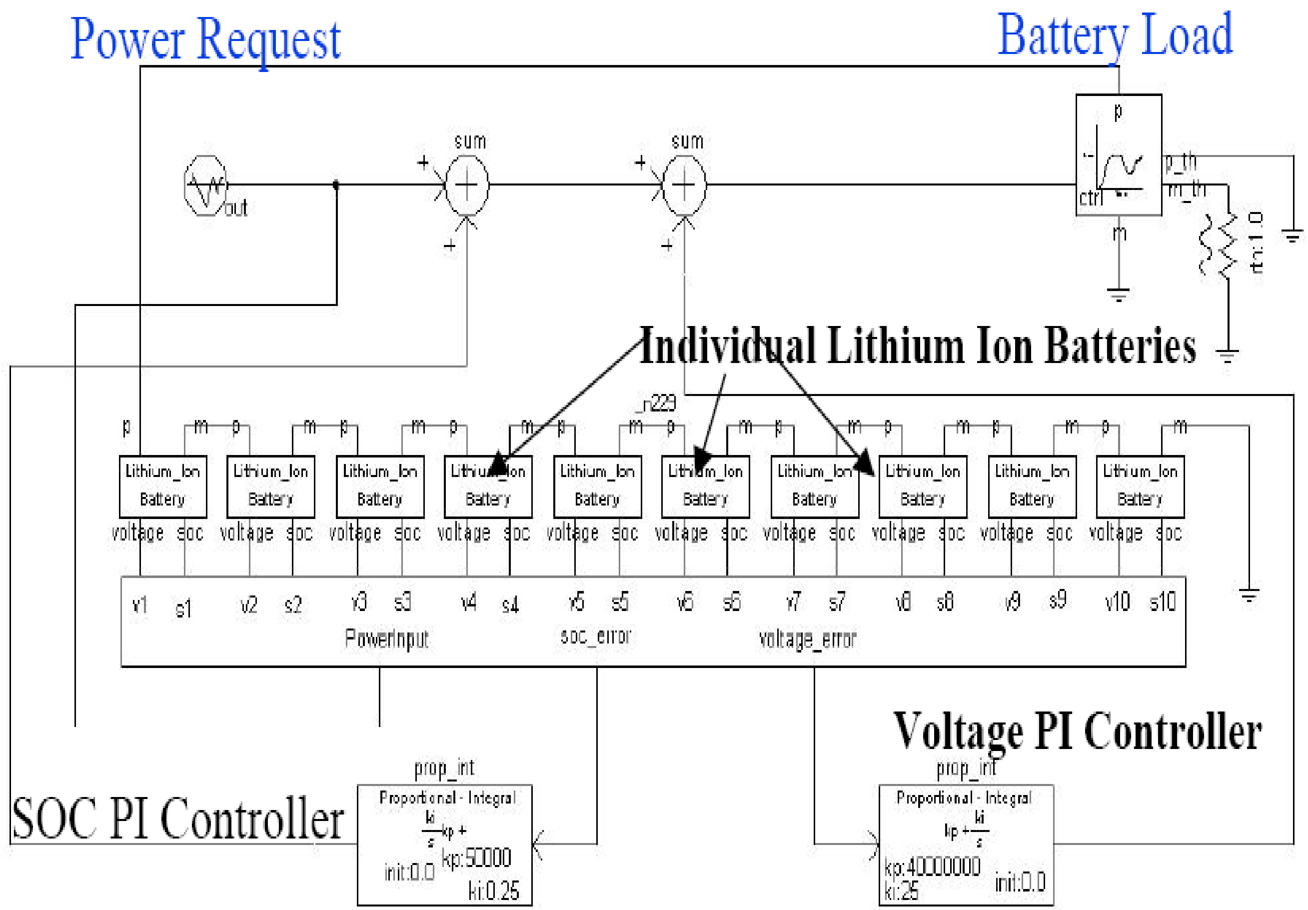
– Pack safety and health (if within limits)

- Lithium ion cells are very sensitive to overcharge

Voltage is a critical input to most state-of-health and state-of-charge algorithms

Voltage sensed with standard A2D parts: special chips designed to measure voltages of series string cells

Reliable predictions of state-of-charge (SOC), state-of-health (SOH) and state-of-life (SOL) are one of the main functions for the battery pack controller



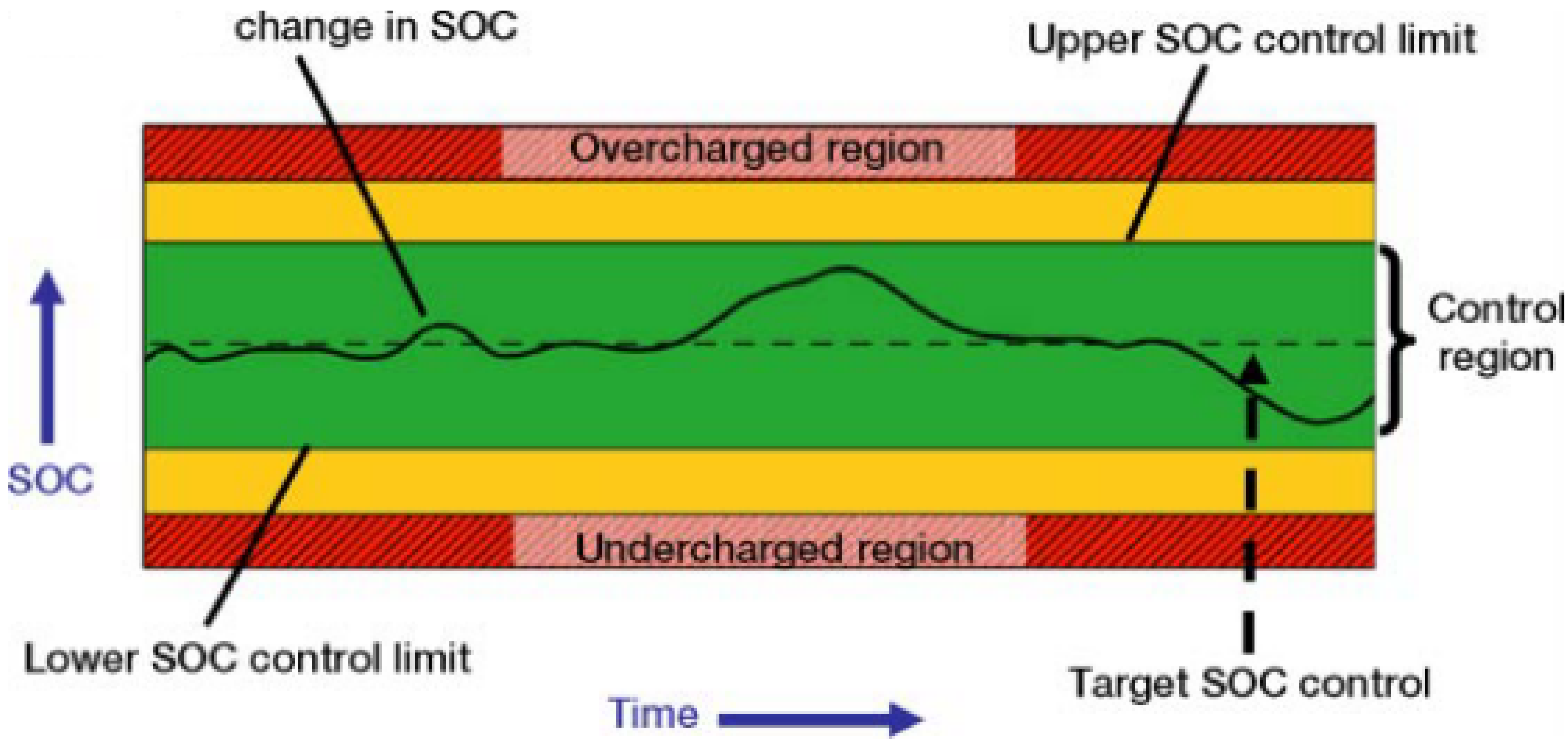
Source: National Renewable Energy Laboratory

Battery Cell Management

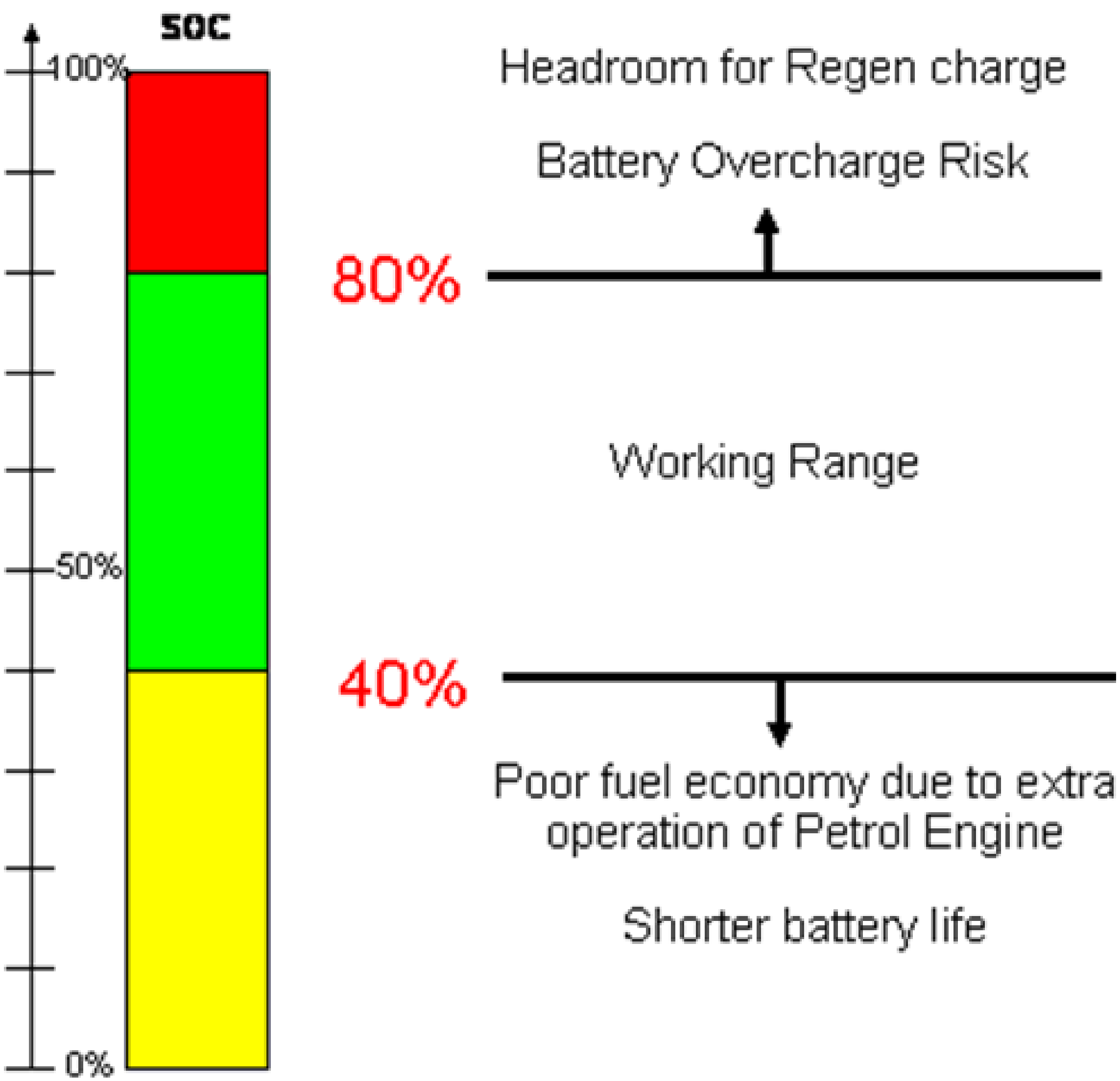
- **State of Charge (SOC)** is the **instantaneous capacity** of the battery. It does not give a good indication of the future life of the battery, or how many times it can be recharged before it will fail.
- **State of Health (SOH)** is the **physical condition** of a battery. SOH is used to estimate losses in rated capacity, as well as predicting impending failures such as shorts or severe corrosion. Impedance measurement is a good choice for checking SOH.
- **State of Life (SOL)** is the **remaining life** of the battery. SOL is used to estimate the number of remaining charge/discharge cycles for a battery.

State of Charge (SOC)

- **The state of charge (SOC)** of a battery is a measure of the instantaneous energy level of the battery and is expressed as a percentage from 0%, when the battery is flat, to 100% for a fully charged battery, which has not yet been used.



Example: HEV Battery Operating Range



- Knowing SOC is particularly important for large Lithium batteries. Lithium is the most chemically reactive and it needs battery management systems (BMS) to keep the battery within **a safe operating window** and to ensure a long cycle life.
- Control of the SOC is a major function of the BMS.

Battery Electrical Power and Energy

Power = voltage x current (P = V x I)
Energy = power x time (E = P x t)
Charge = current x time (q = I x t)
Energy = voltage x charge (E = V x q)

Units:
Power: watts (W) or kilowatts (kW)
Energy: watt-hours (Wh) or joules (1 Wh = 3600 J)
Voltage: volts (V)
Charge: ampere-hours (Ah) or coulombs (1 Ah = 3600 C)*

* Charge stored in battery also called Electrochemical Capacity

Examples:

AA primary alkaline cell	1.5V x 3 Ah = 4 Wh
Li Ion Laptop Battery	10 V x 5 Ah = 50 Wh
Lead Acid SLI Battery	12 V x 50 Ah = 600 Wh
Prius NiMH Battery	288V x 6 Ah = 1.7 kWh
EV1 NiMH Battery Pack	350V x 90 Ah = 32 kWh
Tank of Gasoline	600 kWh

Basic Battery Terminology

Capacity, Power and Energy

- Capacity(Charge) = Current * Time
  - 1 Ah = 1 A x 1 h
  - 1 kAh = 1000 Ah
    - 1 Ah = 3600 C (coulombs)

- Power = Voltage x Current
  - 1 W (watt) = 1 V (volt) x 1 A (ampere)
  - 1 kW = 1000 W

- Energy = Power x Time
  - 1 Wh (watt-hour) = 1 W x 1 h (hour)
  - 1 kWh = 1000 Wh
  - 1 Wh = 3600 J (joules)

What is C-rate?

- The charge and discharge current of a battery is measured in C-rate. Most portable batteries are rated at 1C.
- 1C is often referred to as the current a battery can fully discharge in one hour. Thus a 1000mAh battery would provide 1000mA for one hour if discharged at 1C rate.
- Ideally, for the same battery:

  0.5C = 500mA (for two hours)

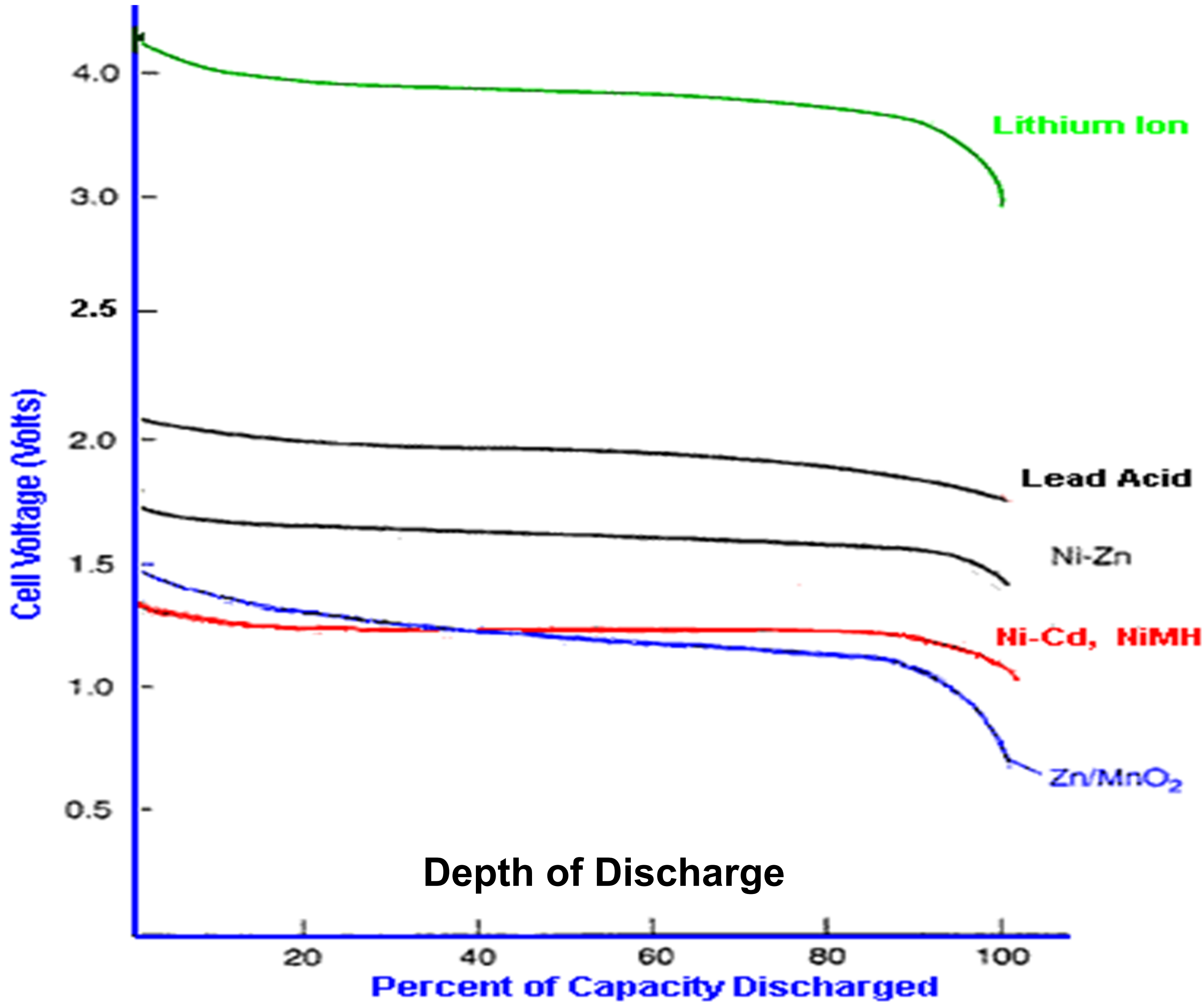
  2C = 2000mA (for 30 minutes)

Example: 5 x D-size, alkaline batteries each has 1.5V, 6 Ah capacity, connecting in series: Voltage = 5 x 1.5V = 7.5V

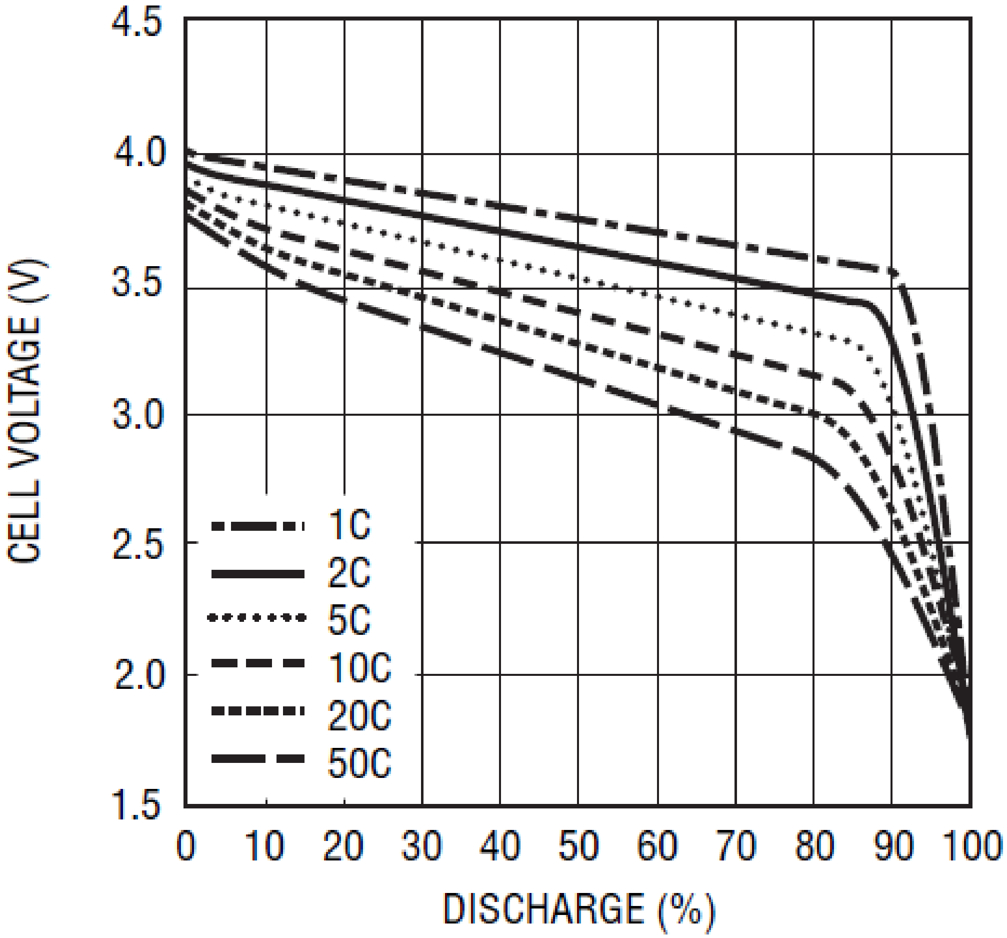
Capacity = 6 Ah

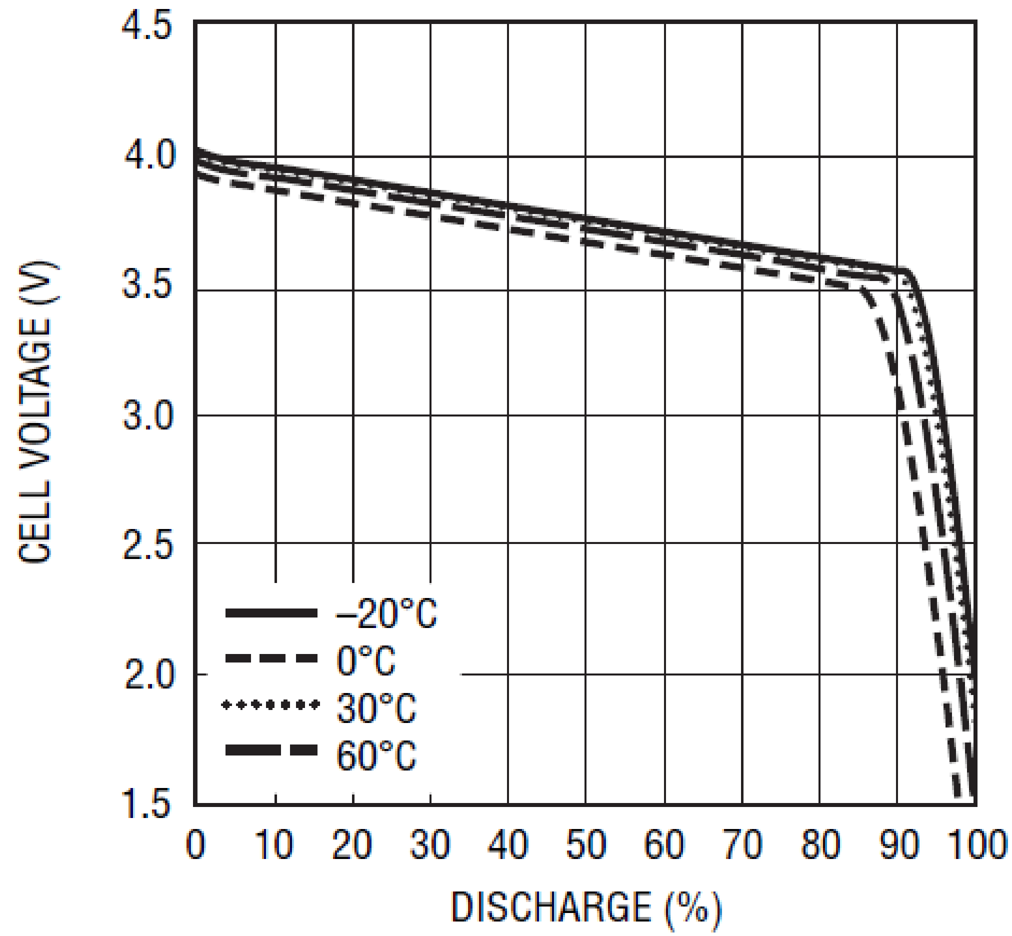
Energy = 7.5V x 6 Ah = 45Wh

Cell Chemistry, Cell Voltage and State of Charge



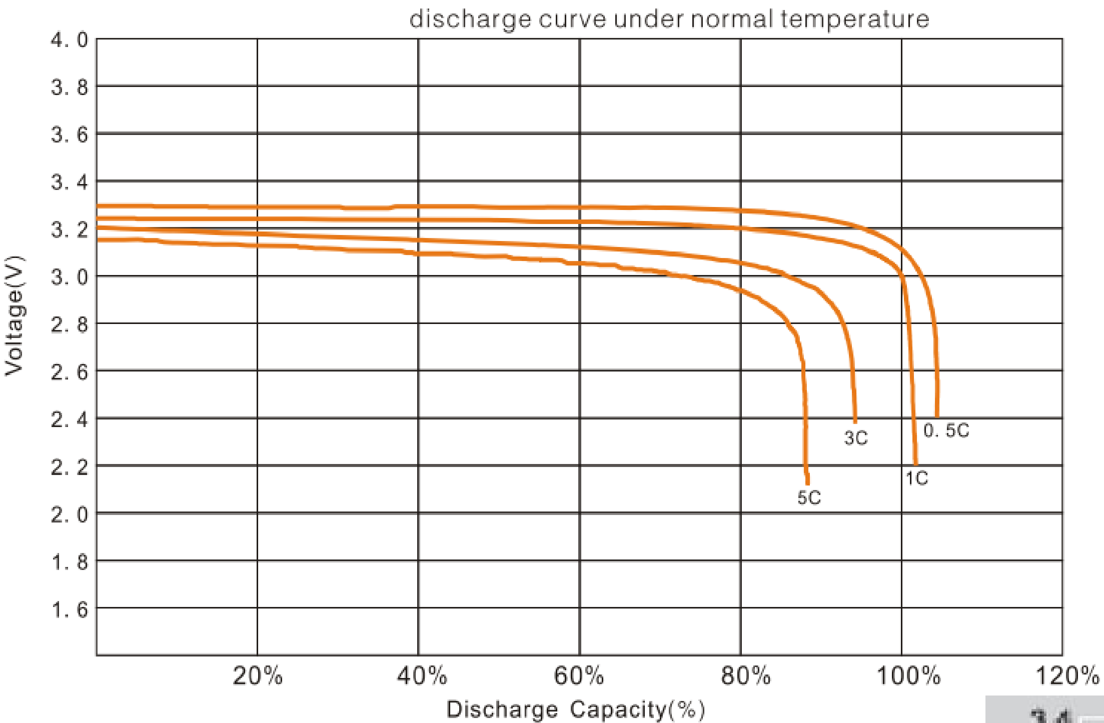
State of Charge (SOC) vs Current and Temperature for a Typical Li-ion Cell





Source: Linear Technology

Challenges: The discharging curves for most lithium batteries are almost flat at 40%-30% SOC



Specifications Model:SE100AHA

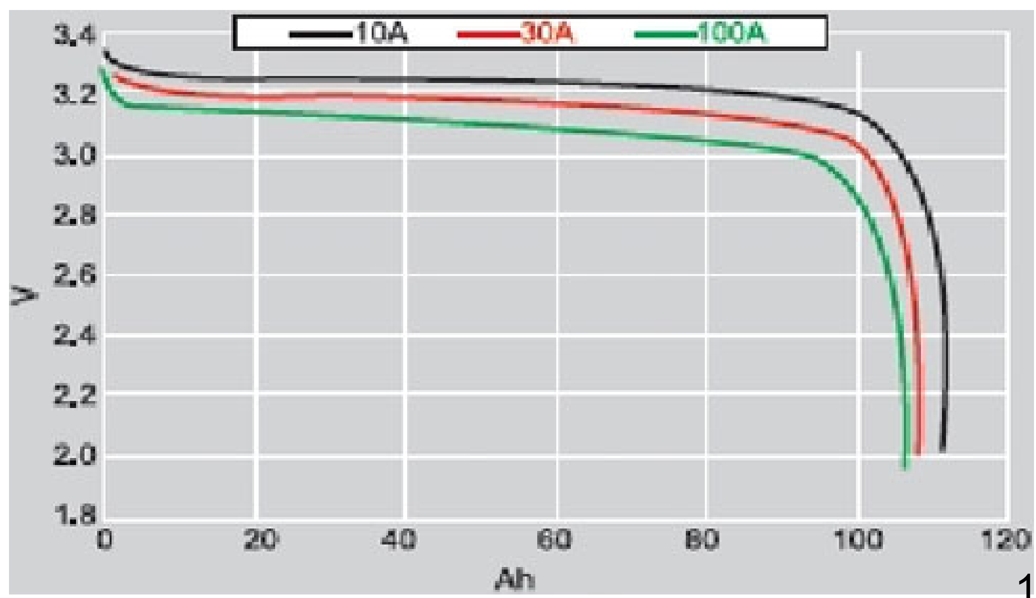
Size:142mm*67mm*218mm

Weight:3.2kg

Source: www.calibpower.com

Nominal capacity	90AH	Operation Voltage	Charge:	4.25V
			Discharge:	2.5V
Max Charge Current	≤3CA	Max Discharge Current	Constant Current	≤3CA
			Impulse Current	≤10CA
Standard Charge/ Discharge Current	0.3CA	Cycle Life	(80DOD%)	≥2000Times
			(70DOD%)	≥3000Times
Temperature Durability Of Case	≤250℃	Operating Temperature	Charge:	-25℃~75℃
			Discharge:	-25℃~75℃
Self-discharge Rate	≤3%	Weight	3kg±100g	

Source: www.thunder-sky.com



SOC Accuracy Requirements

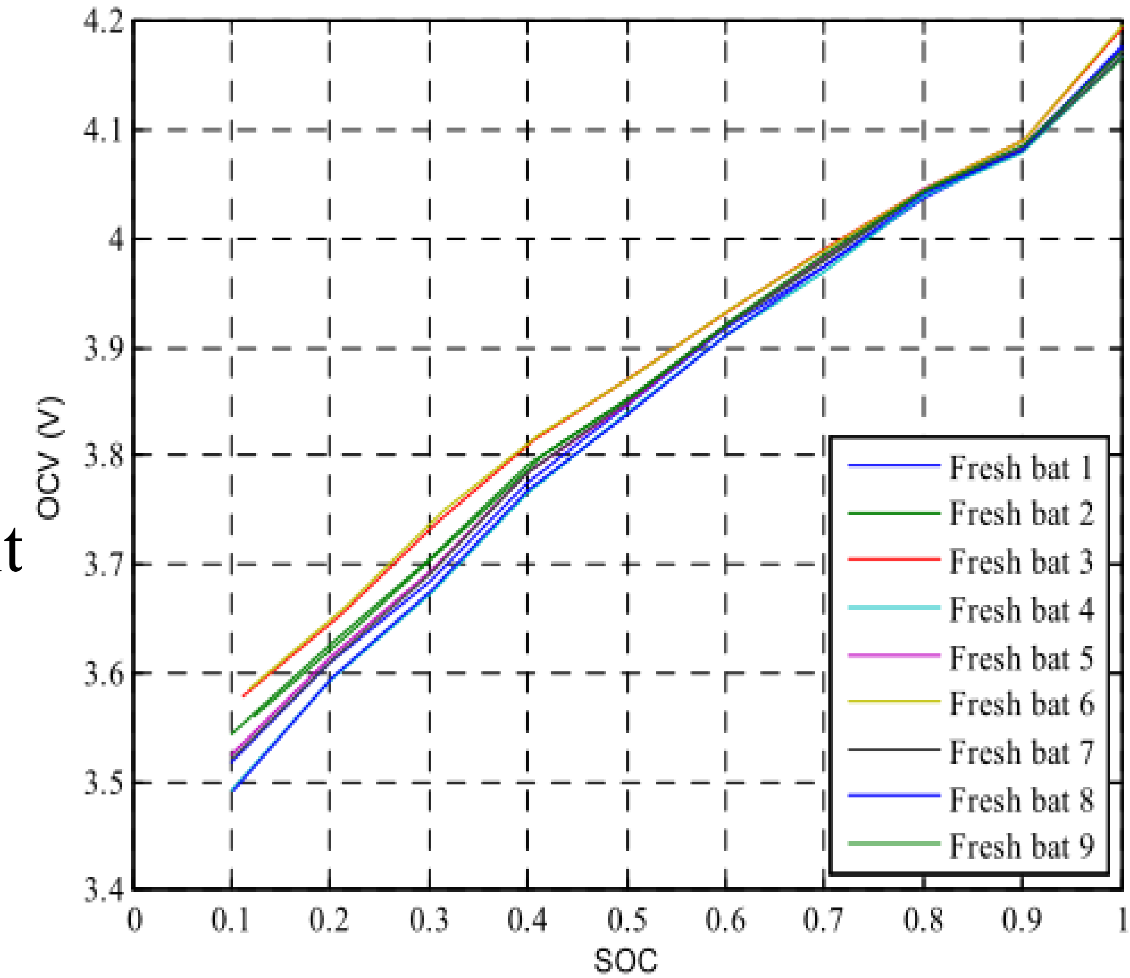
- In **EV applications** the SOC is used to **determine range**. It should be an absolute value based on capacity of the battery when new, not a percentage of current capacity which could result in an error of 20% or more due to battery ageing. Automotive fuel gauges are notoriously imprecise so an SOC accuracy of 5%, if it could be achieved, would probably be satisfactory for such applications.
- In **HEV applications** the SOC determines when the engine is switched on and off. SOC errors over 5% could seriously affect the system fuel efficiency. An accuracy significantly better than 5% is therefore desirable.

The Estimation of the SOC

- The open circuit voltage (OCV) is widely used to estimate the SOC.

- The conventional relationship of the OCV-SOC is obtained by measuring the open circuit voltage at each battery.

- The relationship between the OCV and SOC **can not be exactly same for all batteries**.



The conventional relationship of the OCV-SOC

Source: Seong-jun Lee, Jong-hoon Kim

OCV vs. SOC vs. Capacity

- In most cases, SOC may NOT be a good indication for the capacity. For example, when a battery degraded, Open Circuit Voltage (OCV) may looks fine, so as SOC, but capacity may already drops 10%.
- For example, when a 50% SOC is calculated from the OCV, it means that there are 50 Ah capacity remaining for a brand new 100 Ah battery.
- However, toward the end of its life time, a 50% SOC means there are only 40 Ah capacity remaining (assuming the battery already lose 20% of its capacity).
- When an EV is running, we need to use the measured voltage, current, and impedance to calculate the capacity, and then estimate the SOC from a calculated capacity.

Ways to Estimate the SOC of a Battery

- The ampere-hour counting method
  - simple and easy to utilize, but has problems such as an initial value error and accumulated errors
- The open circuit voltage (OCV) method
  - it needs a rest time to estimate the SOC
- The extended Kalman filter (EKF) method
  - known to be the optimal adaptive algorithm based on recursive estimation the resistance, capacity and OCV-SOC.
- Impedance measurement
  - good accuracy but difficult to implement in the vehicle application
- Self-learning model (Neural Networks/Fuzzy Logic)
- Look Up Tables

SOC = f(T, OCV, Ohmic R, Charge Rate, Dis-Charge Rate, Cycle)

State of Health (SOH)

- The State of Health (SOH) indicting the degree of aging of a battery. It is also an important factor that determines the accuracy of estimate Sate of Charge (SOC).

- The SOH is an indictor of how much battery capacity can be released at the reference discharge rate after usage, **with respect to the initial available capacity when the battery is brand new.**

$$SOH = \frac{C_{I_{ref}}}{C_0}$$

How is the SOH Determined?

- Because the SOH indication is relative to the condition of a new battery, the measurement system must hold a record of the initial conditions or at least a set of standard conditions.
- **Any parameter which changes significantly with age**, such as cell impedance or conductance, can be used as a basis for providing an indication of the SOH of the cell.

Data Recording – Log Book Function for SOH

- One alternative method of specifying the SOH is to base the estimation on the usage history (the number of charge - discharge cycles) of the battery.
- It is possible to record the duration of any periods during which the battery has been subject to abuse from out of tolerance voltages, currents or temperatures as well as the magnitude of the deviations.
- It does not take into account any extreme operating conditions experienced by the battery.
- Battery usage (or abusage) data can be stored in the BMS
- The log book function could add complexity and cost to the battery pack.

State of Life (SOL) Prediction

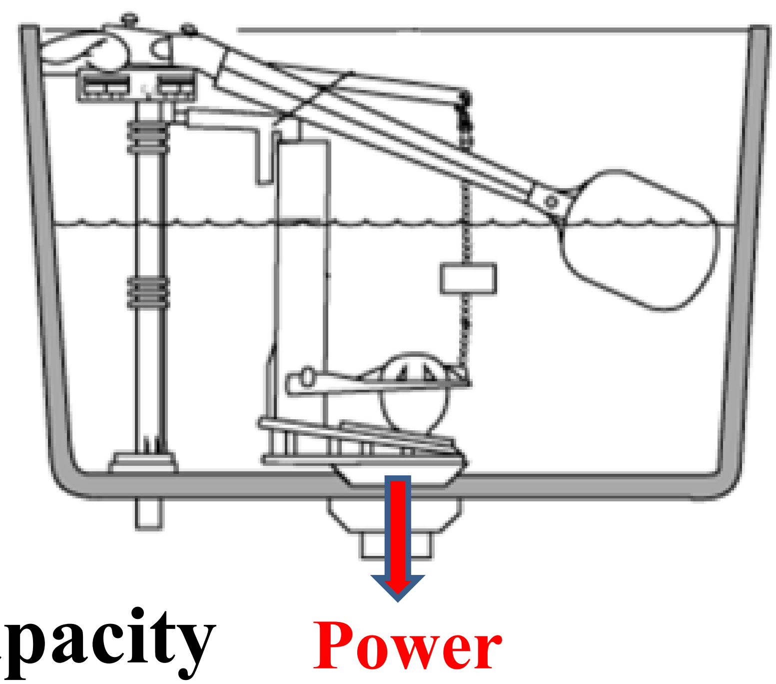
- State of Life (SOL) is the remaining life of the battery. SOL is used to estimate the number of remaining charge/discharge cycles for a battery.
- End of service life of a battery pack may be indicated by **ohmic resistance** of the battery pack.
- The ohmic resistance of the battery pack is typically flat during much of the service life of the vehicle and battery pack however, thus preventing a reliable estimate of real-time state-of-life (SOL) of the battery pack throughout most of the service life. Ohmic resistance is most useful to indicate "an initial" end of service life of the battery pack.

What Consider a Degraded or Dead Battery?

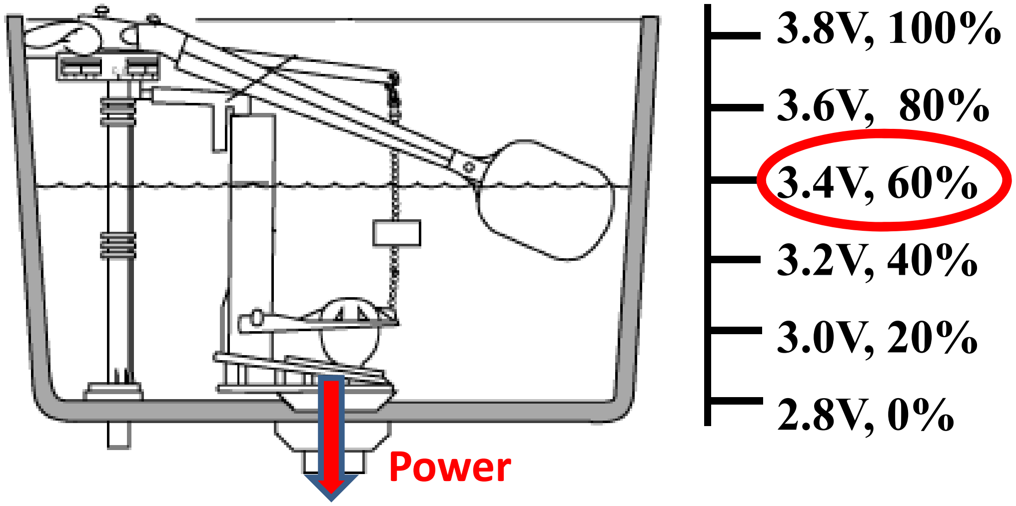
- When we talk about "degraded" or "dead" batteries, it's important to understand two performance metrics: energy and power
- The rate that can get energy out of the battery is very important.
- A lithium-ion battery will have approximately 80% of its capacity remaining at the end of its useful life in a vehicle
- In electric vehicles, high power enables rapid acceleration and also regenerative braking, in which the battery needs to discharge or accept a charge within a couple of seconds.
- In cell phones, on the other hand, high power is less important than capacity, or how much energy the battery can hold. Higher-capacity batteries last longer on a single charge
- Over time the battery degrades in a number of ways that can affect both power and capacity until eventually it simply can't perform its basic functions.

The Toilet Tank Analogy

- Charging a battery is like filling a toilet tank with water from a tap.
- The volume of the tank represents the battery's energy, or capacity.
- The rate at which we flush it on full blast or just a trickle is the power.
- However time, high temperatures, extensive cycling and other factors end up creating a stone in the tank.



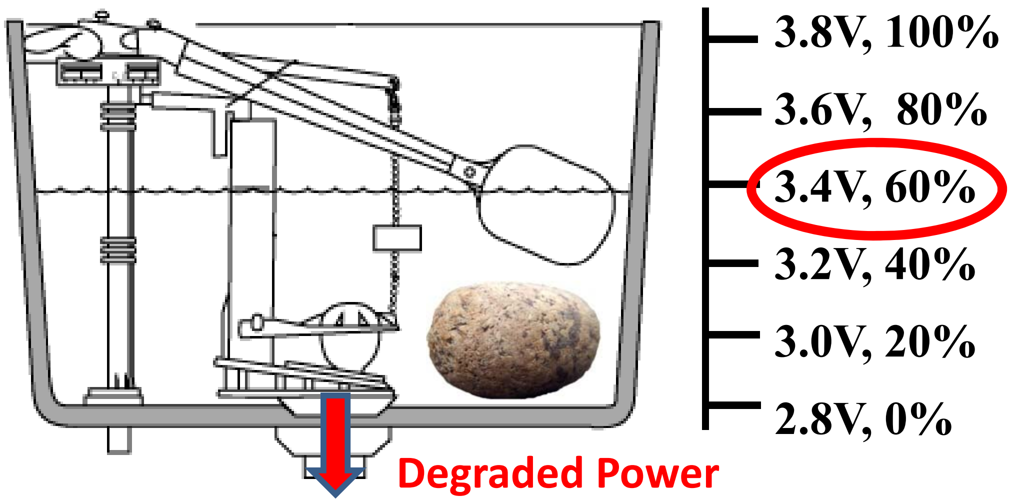
Tank volume ~ Energy ~ Capacity



Good Battery

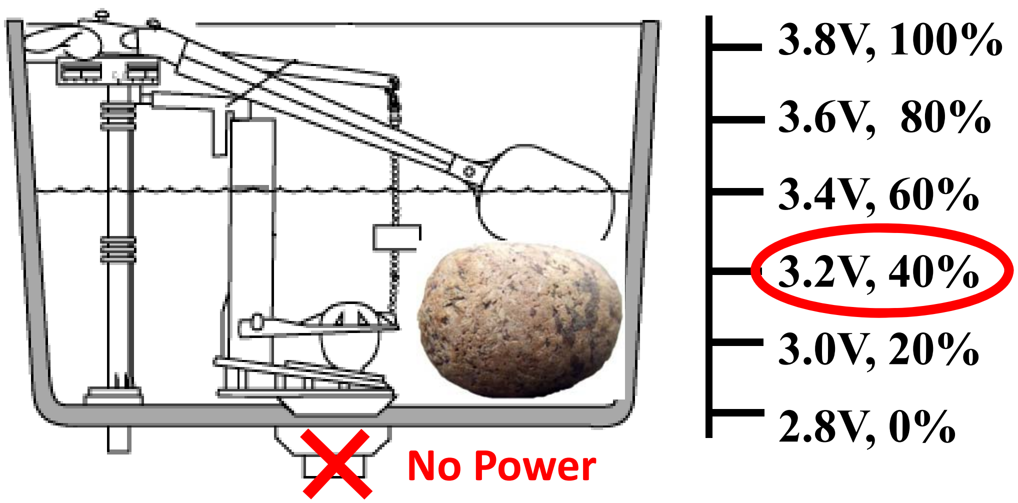
Battery terminal voltage = 3.4V, SOC=60%
Capacity(Ah)=100Ah, SOH=100%

Tank volume ~ Energy ~ Capacity



Degraded Battery

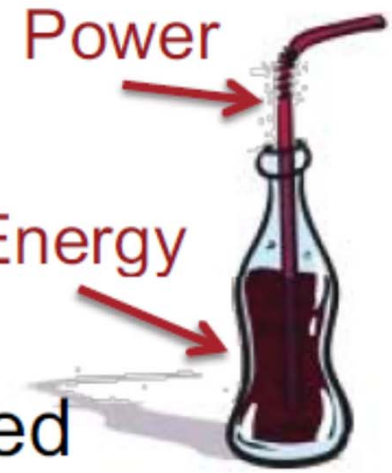
Battery terminal voltage = 3.4V, SOC=60%
Capacity(Ah)=80Ah, SOH=80%



Dead Battery

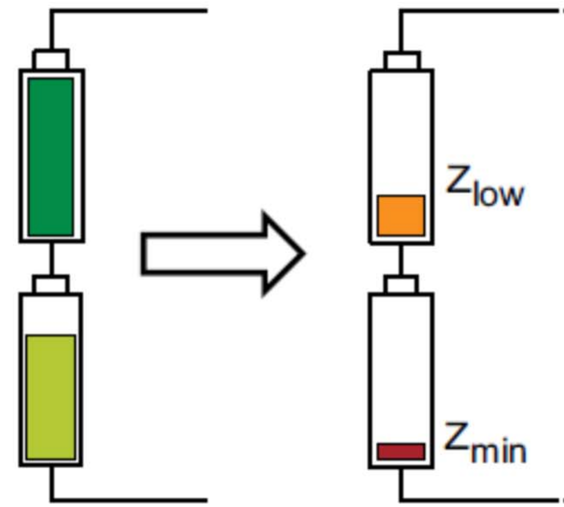
Battery terminal voltage = 3.2V, SOC=40%
Capacity(Ah)=60Ah, SOH=60%

Cell total energy versus cell power



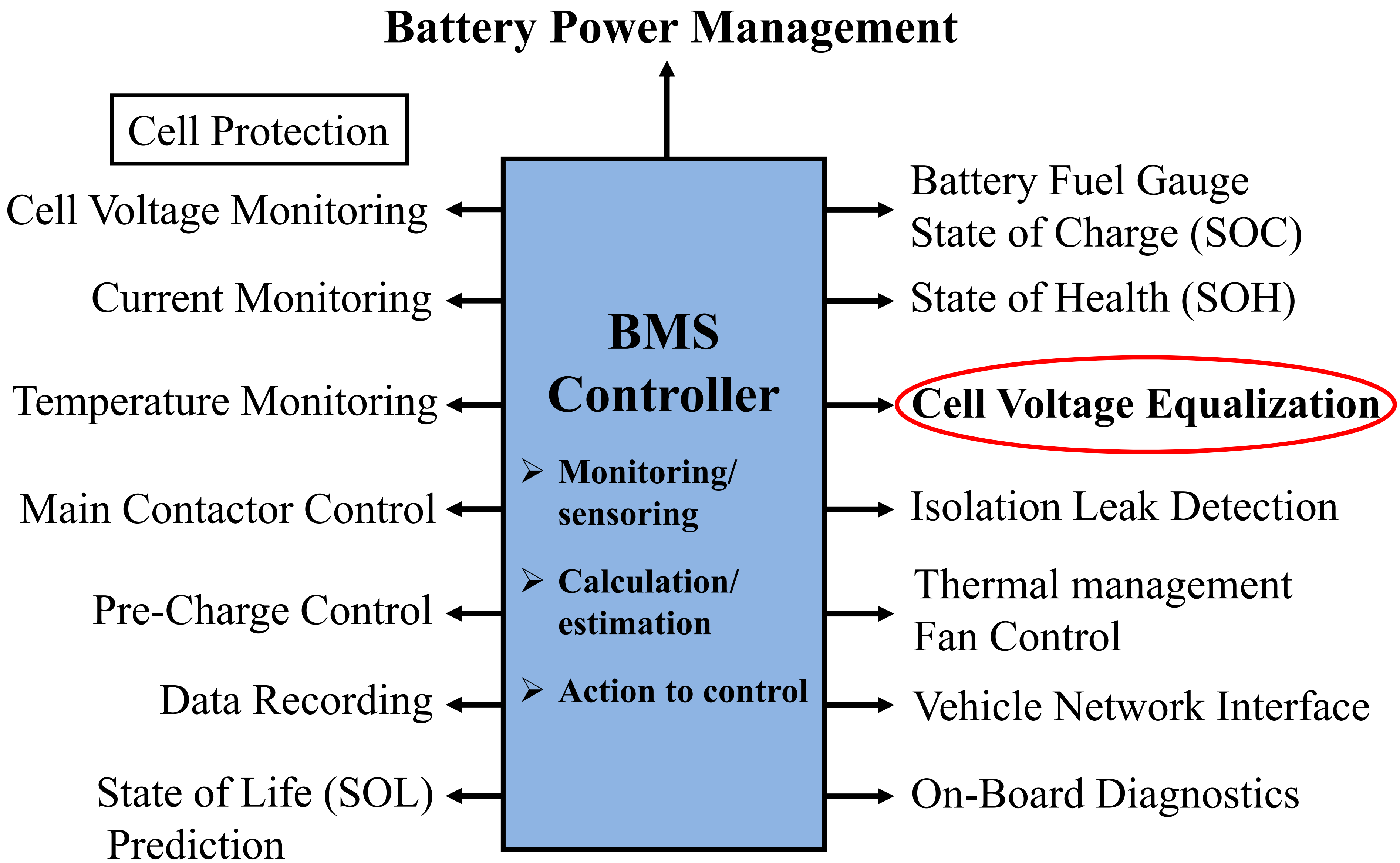
- Energy is an ability to do work
- Energy is a total quantity in Wh or kWh
- Power is rate at which energy can be moved without exceeding cell or electronics design limits
- Power is an instantaneous quantity $P = I \times V$, in W or kW
- Dis/charging at too high a power level will accelerate cell degradation ➠ premature battery pack failure
- Calculate cell power to enforce limits on cell voltage and current, predictive over the next ΔT seconds; update at faster rate than once every ΔT seconds

Computing pack total energy

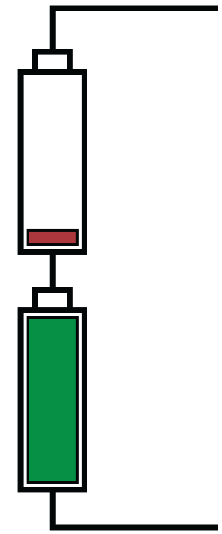


- To compute pack energy, determine $\min(Q_j(z_j - z_{\min}))$: how many Ah to discharge lowest cell to z_{min}
- For this many Ah discharged, find low SOC for all cells, $z_{\text{low},j}$
- Compute: $E_{\text{pack}}(t) = \sum_j Q_j \int_{z_{\text{low},j}}^{z(t)} \text{OCV}(\xi)\, d\xi$
- Note: Integrated OCV function is stored in a table for instant computation via table lookup

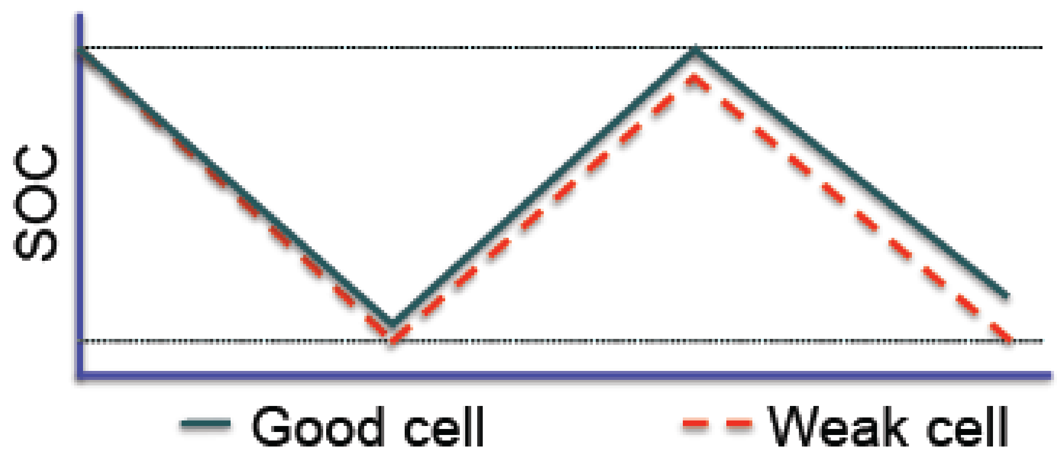
Battery Management System (BMS) Functions

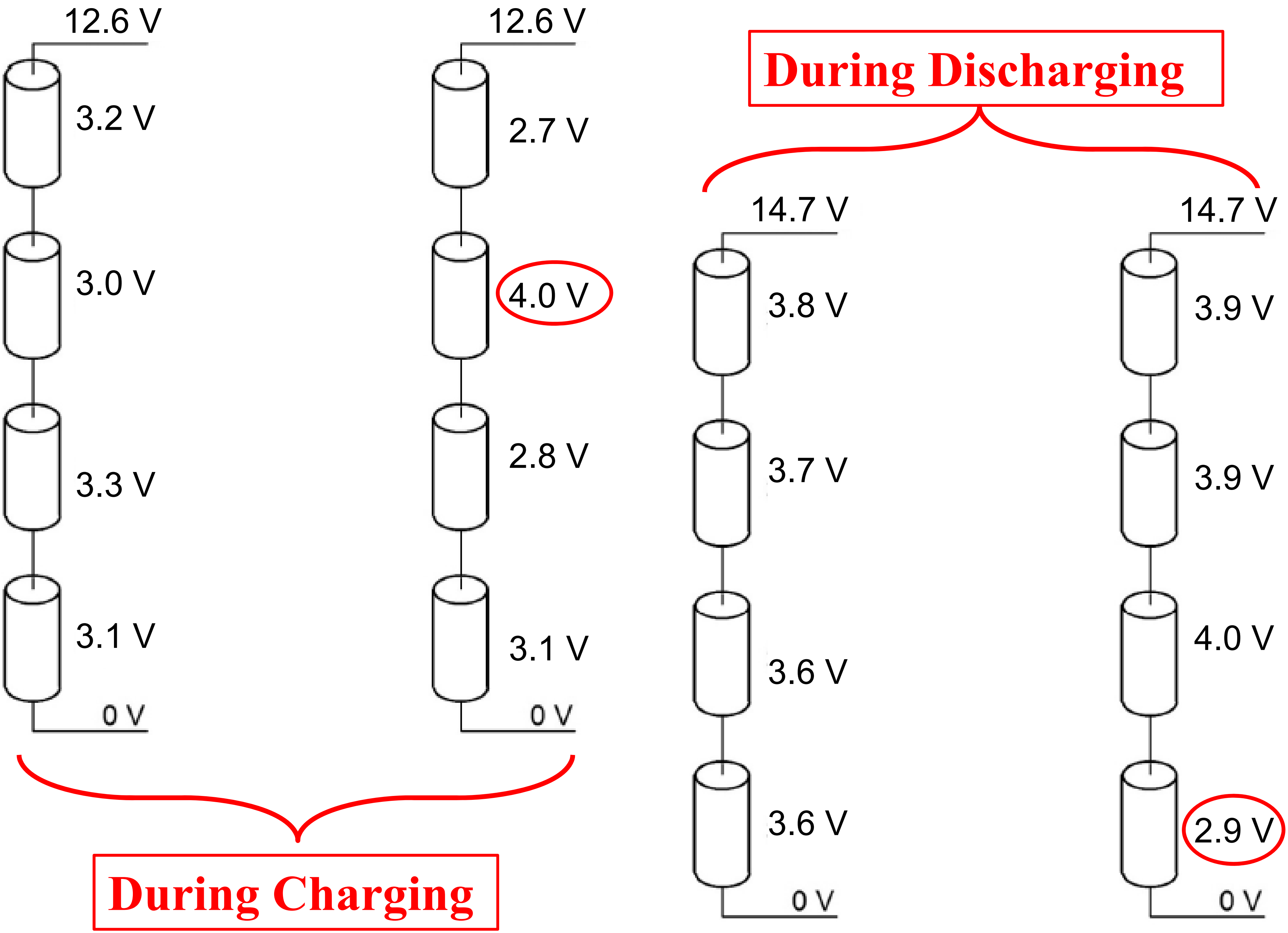


Motivation to Balance Cells



- If cells become out of balance (different SOCs) pack energy/power is limited
- Battery "pack" on right can neither deliver power nor receive power
- Generally, a "weak" cell will limit pack's performance, and will ultimately render the pack useless unless cells are "balanced"



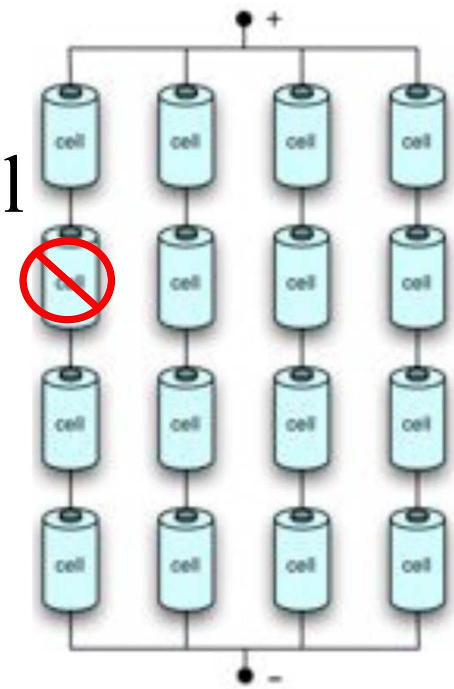

During Charging
12.6 V
3.2 V
3.0 V
3.3 V
3.1 V
0 V
12.6 V
2.7 V
4.0 V
2.8 V
3.1 V
0 V
During Discharging
14.7 V
3.8 V
3.7 V
3.6 V
3.6 V
0 V
14.7 V
3.9 V
3.9 V
4.0 V
2.9 V
0 V

All Cells Are Not Created Equal!!
Cell Balancing

- Because of **production tolerances, uneven temperature distribution** and differences in the **ageing characteristics** of particular cells it is possible that individual cells in a series chain could become overstressed leading to premature failure of the cell.
- Batteries such as those used for EV and HEV applications are made up from **long strings of cells in series** in order to achieve higher operating voltages.
- The problems can be compounded **if parallel packs of cells are required** to achieve the desired capacity or power levels.

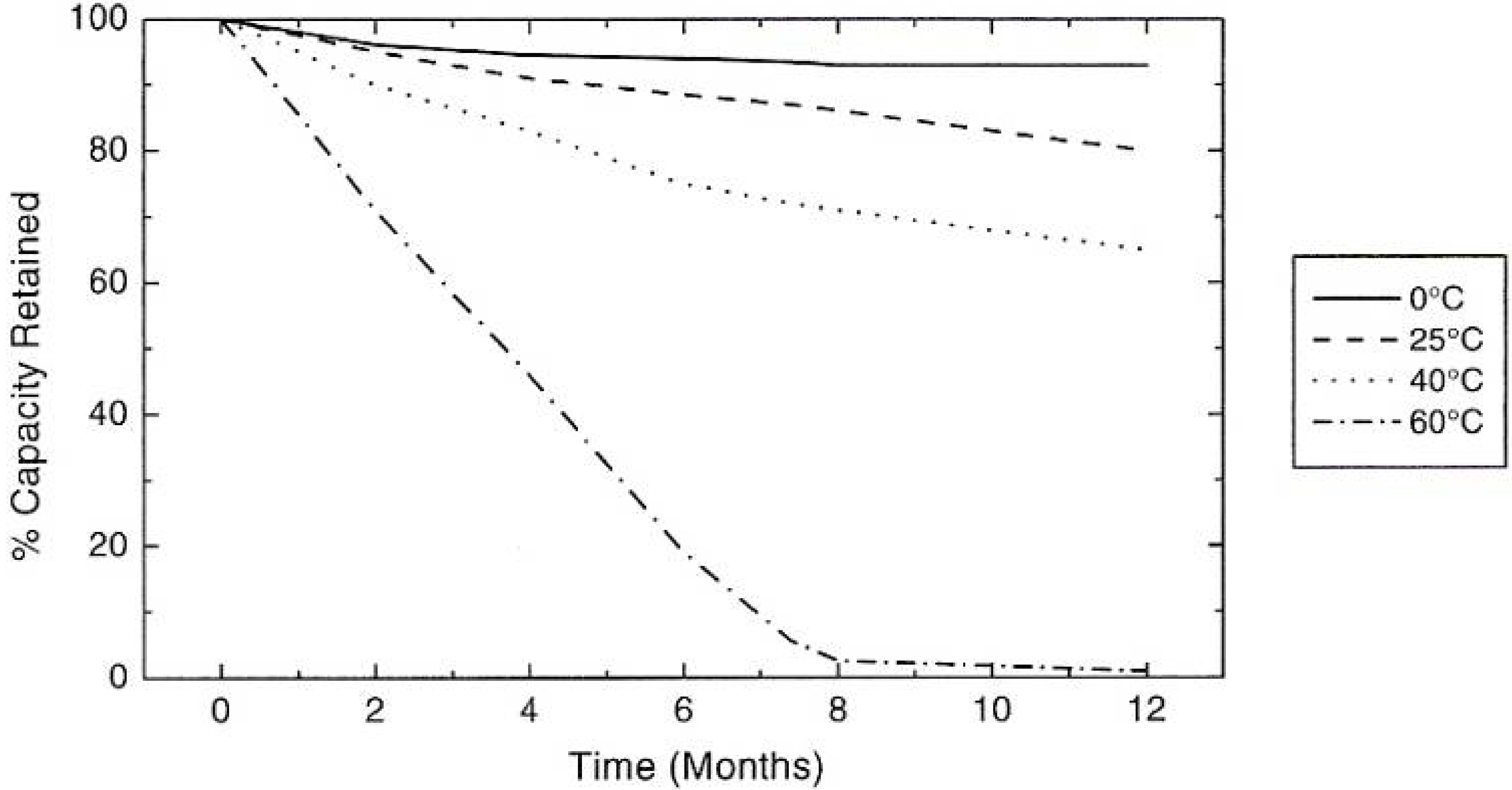
If there is a degraded cell in the stack…

- **During the charging cycle**, the degraded cell in the chain with a diminished capacity, there is a danger that once it has reached its full charge it will be subject to overcharging until the rest of the cells in the chain reach their full charge.
- **During discharging cycle**, the weakest cell will have the greatest depth of discharge and will tend to fail before the others. It is even possible for the voltage on the weaker cells to be reversed as they become fully discharged before the rest of the cells resulting in early failure of the cell.



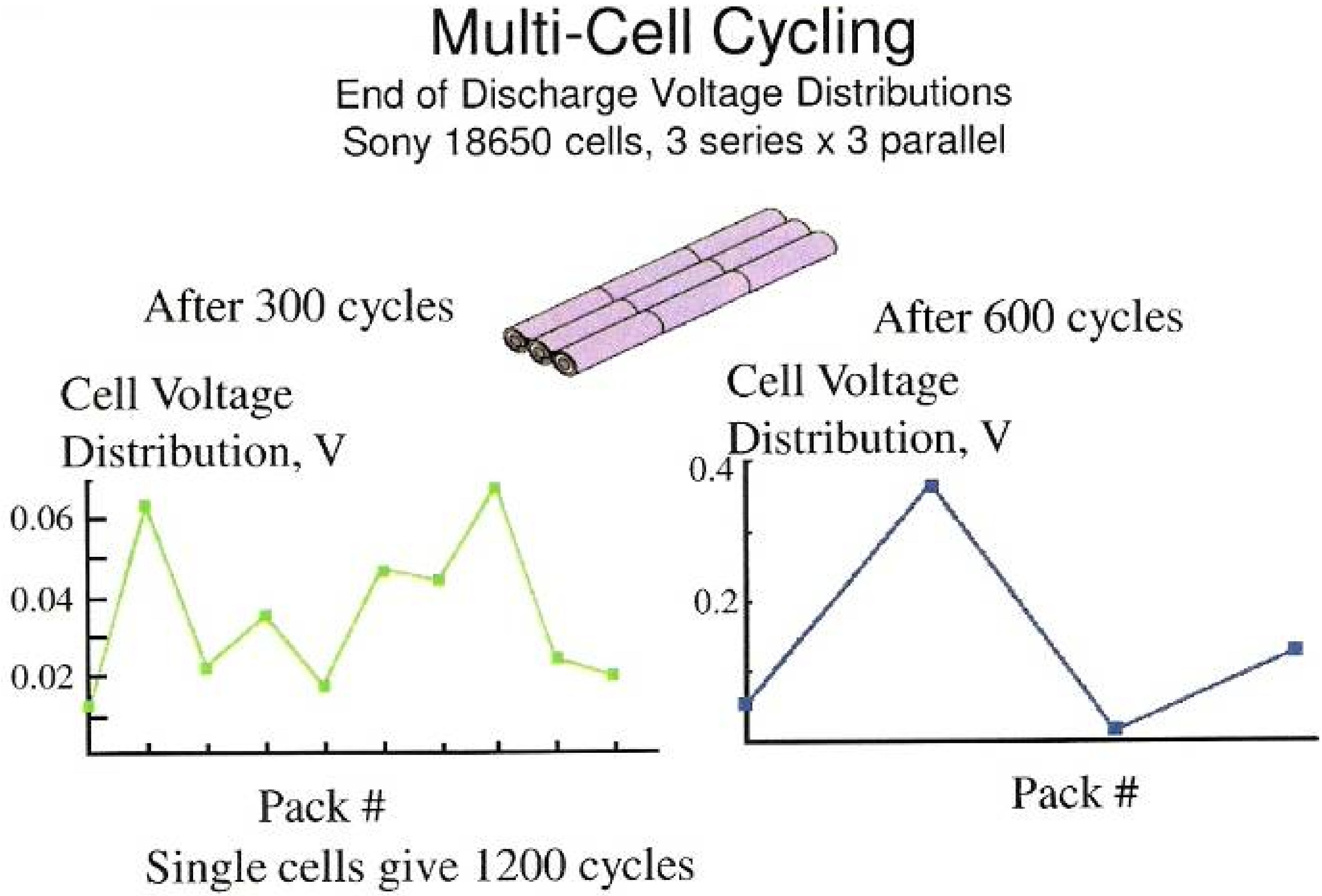
Root Cause of Imbalance: Self Discharge

Excellent charge retention is a strong attribute for Li-Ion. However, **small temperature dependent self-discharge leads to cell imbalances**.



Self-discharge performance of fully charged 18650 $C/LiCoO_2$ Li-ion batteries over a range of temperatures (Courtesy of Sanyo)

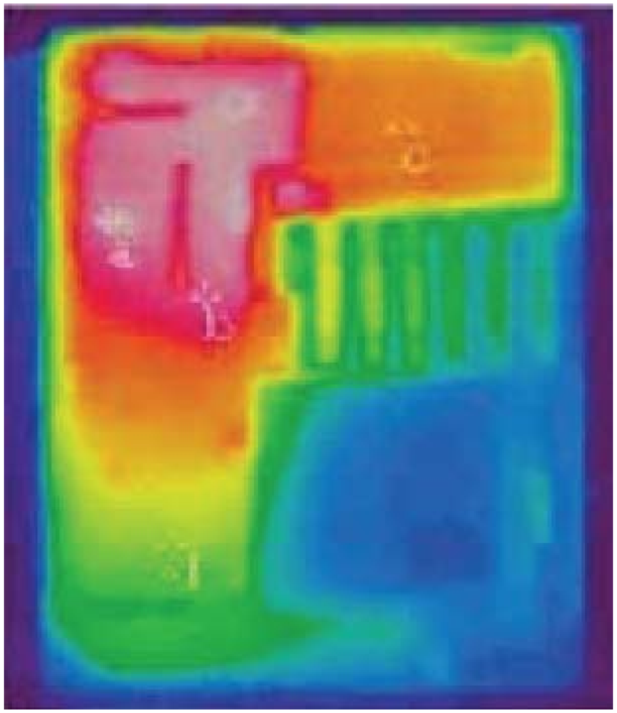
Li-Ion Cell-to-Cell Voltage Imbalance



K. Ozawa, T. Aita, 11th Intl. Seminar on Primary & Secondary Battery Technology & Application, 1994.

The Challenge of Cell Balance

- Poor cell capacity matching can cripple a battery pack right off the manufacturing floor
- Cells must be matched so that the pack does not start out of balance
- A quality battery pack manufacturer will test all incoming lots and should reject lots of cells with high variance
- Impedance and chemical efficiency variations in the cells can have a similar effect to poor capacity matching
- Battery packs should never be assembled using more than one manufacturer or even more than one lot
- Non-uniform thermal stress is a common problem and **self discharge doubles for each 10º C rise in temperature**
- The solution is to employ cell balancing



Cell Balancing (Equalization)

- The high voltage battery pack usually comprises a large number of cells because of the quantity of energy to be stored.
- Cell balancing is intended to **prevent large long term unbalance** rather than small short term deviations.
- Balanced cell can deliver as much energy during discharge as possible and extend the cycle life of the battery pack by minimizing the difference in energy stored in each cell.
- The charging/discharging of series-connected cells must stop when any cell reaches its maximum or minimum allowable state of charge.

How to Improve Cell Balancing

- **Cell Selection**

  Batteries should be constructed from matched cells, preferably from the same manufacturing batch. Testing can be employed to classify and select cells into groups with tighter tolerance spreads to minimize variability within groups.

- **Battery Pack Construction**

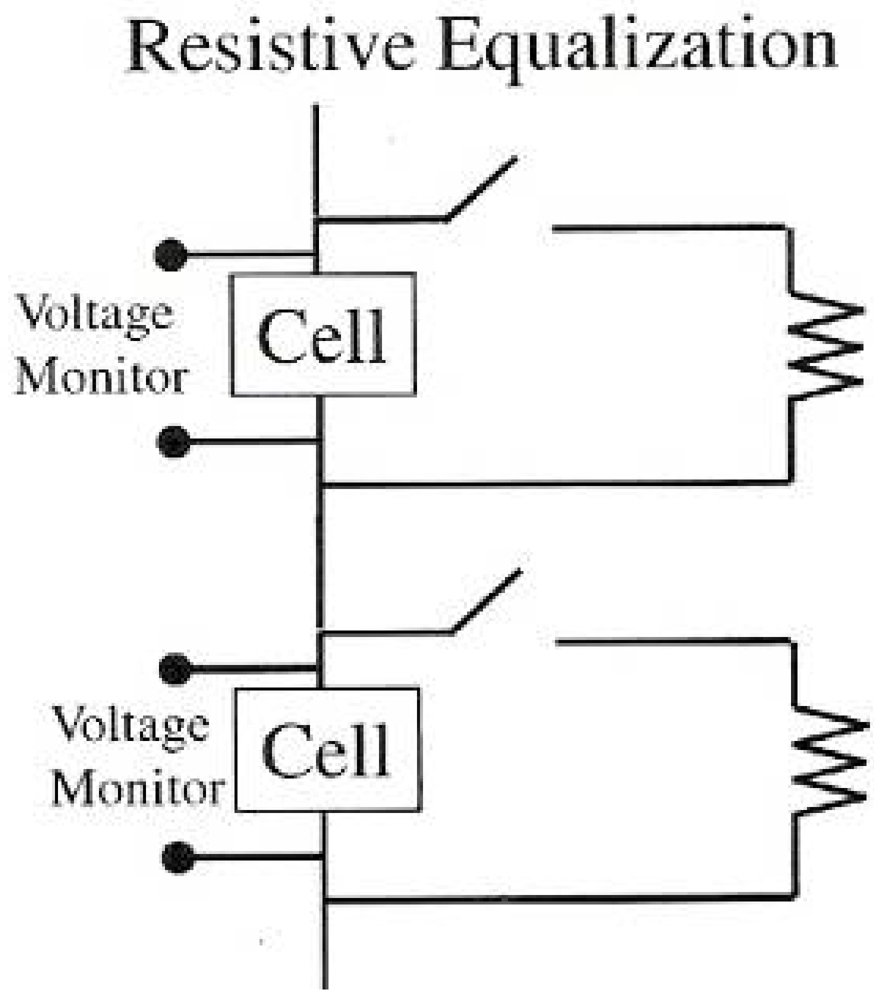
  To ensure at all times an even temperature distribution across all cells in the battery pack. In EV or HEV application, the ambient temperature in the engine compartment, the passenger compartment and the floor can be significantly different. It can give rise to unbalanced thermal operating conditions.

Strategies to Implement Cell Balancing

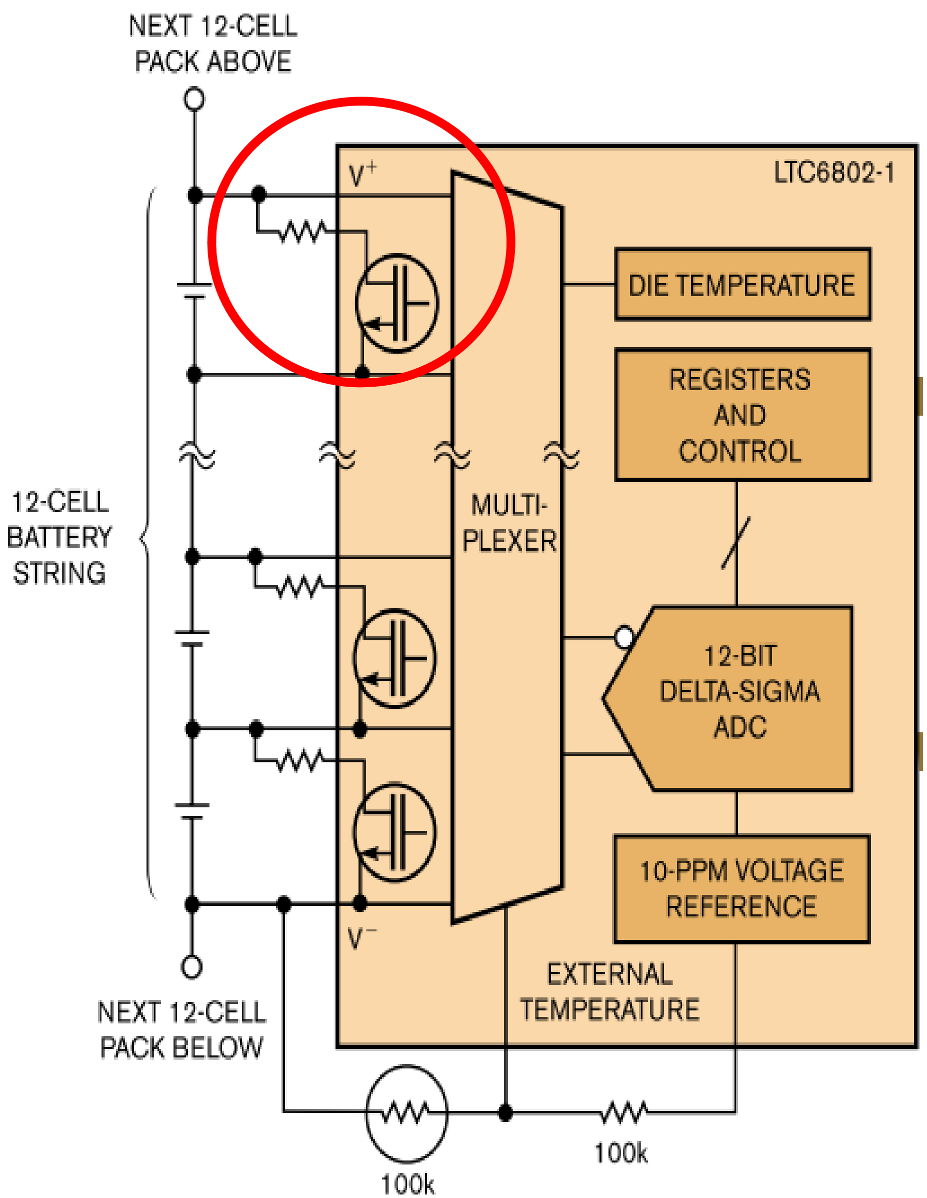
- To provide a dynamic solution to this problem which takes into account the ageing and operating conditions of the cells, the BMS may incorporate a Cell Balancing scheme to prevent individual cells from becoming overstressed.
- Balancing a battery requires different currents to flow through its various cells.
- Balancing techniques
  - Active balancing
  - Passive balancing
- Balancing techniques depend on being able to determine the SOC of the individual cells in the chain.

Electrical Cell Balancing

- Dissipative
  - Resistive equalization
  - Analog shunt equalization
- Non-dissipative
  - Switched capacitor equalization
  - Resonant equalization

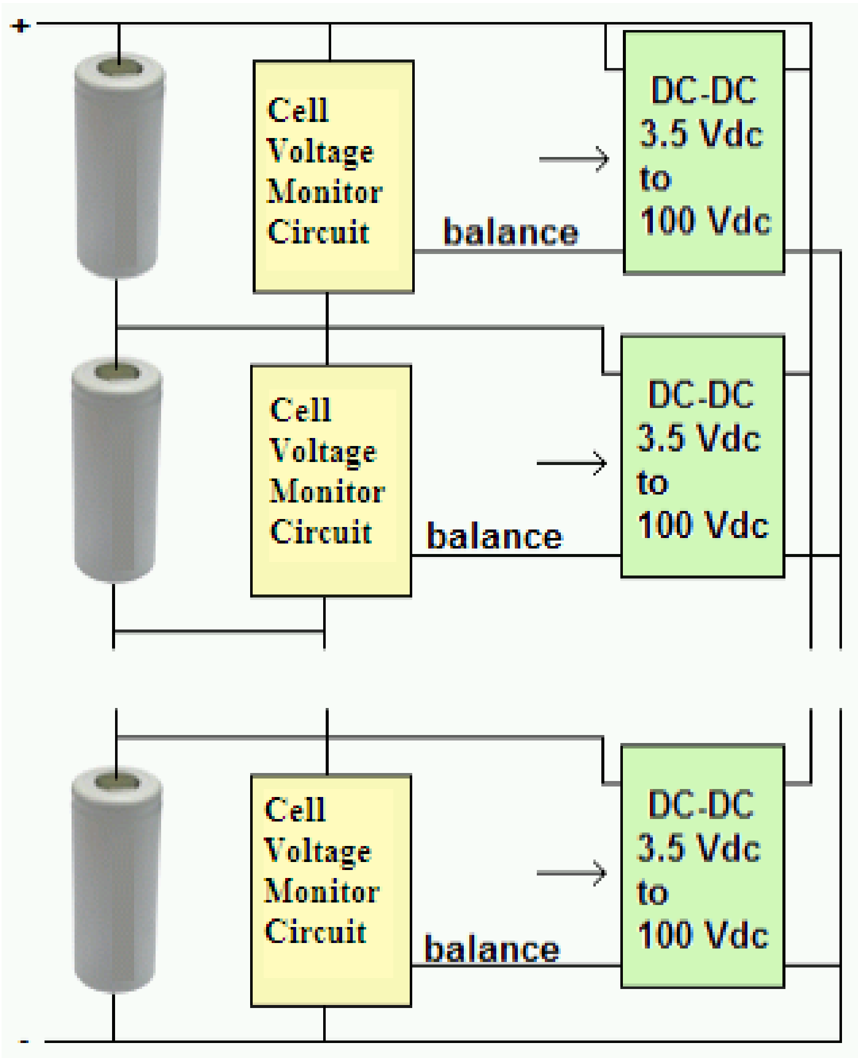


Passive Balancing



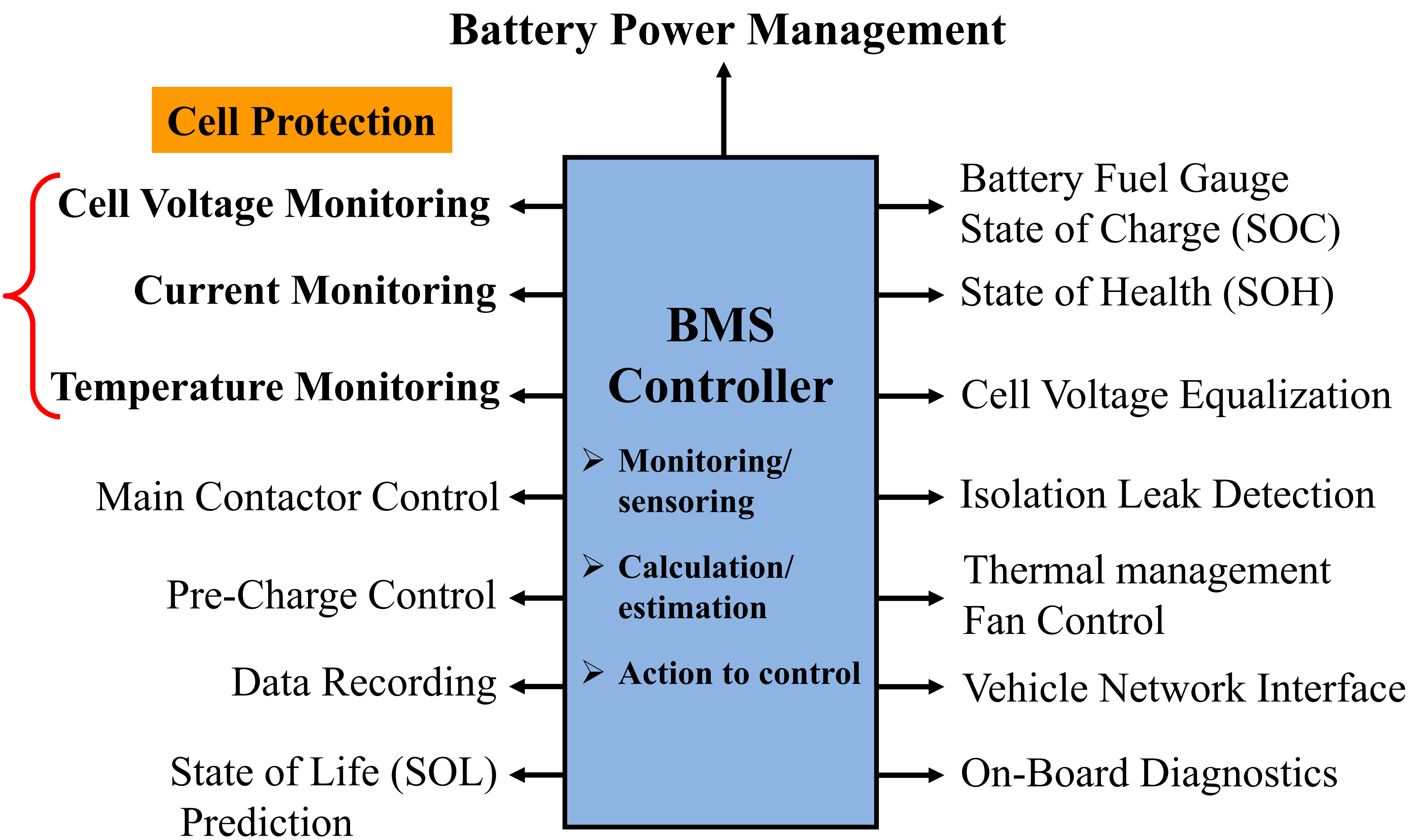
- The same charging or discharging current generally flows through the series-connected cells of battery.
- Balancing a battery requires different currents to flow through its various cells.
- Balancing a battery by discharging one cell by means of an individual shunt connected in parallel with the cell.
- The shunt includes a resistor for dissipating energy and a switch to turn shunt on/off.
- The bypass current then flows through the shunt and reduces the current flowing through the cell.

Active Balancing



- To implement active balancing, the balance resistor is replaced with a DC-DC converter, whose output is connected to the entire pack.
- When the BMS turns on balancing for a particular cell, the DC-DC input converter is powered, and the cell's excess charge is transferred to the entire pack.
- The cost, complexity and space requirement of an active balance circuit can hardly be justified in Li-Ion batteries.

Battery Management System (BMS) Functions



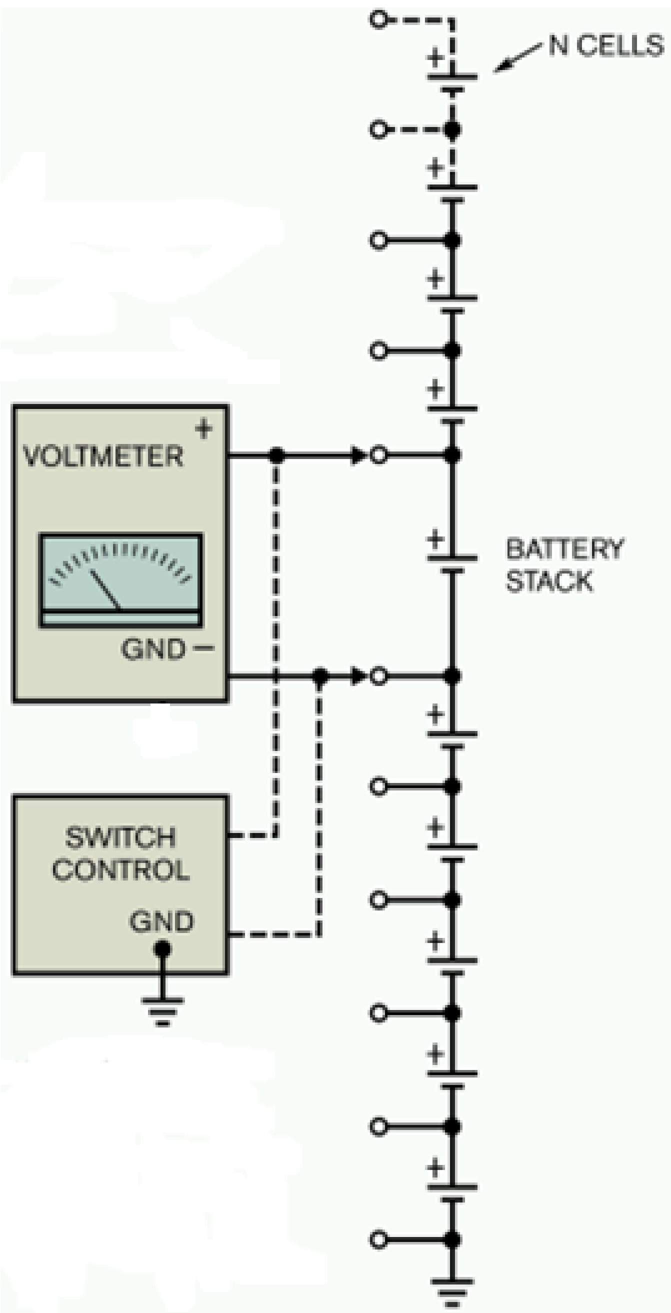
Cell Protection

- The purpose of cell protection is to provide the necessary monitoring and control to protect the cells from out of tolerance ambient or operating conditions and to protect the user from the consequences of battery failures
- Cell protection can be external to the battery and this is one of the of the prime functions of the Battery Management System (BMS)
- Cell protection includes: Cell voltage, current and temperature monitoring

Battery Cell Protection Should Address the Following Undesirable Events or Conditions

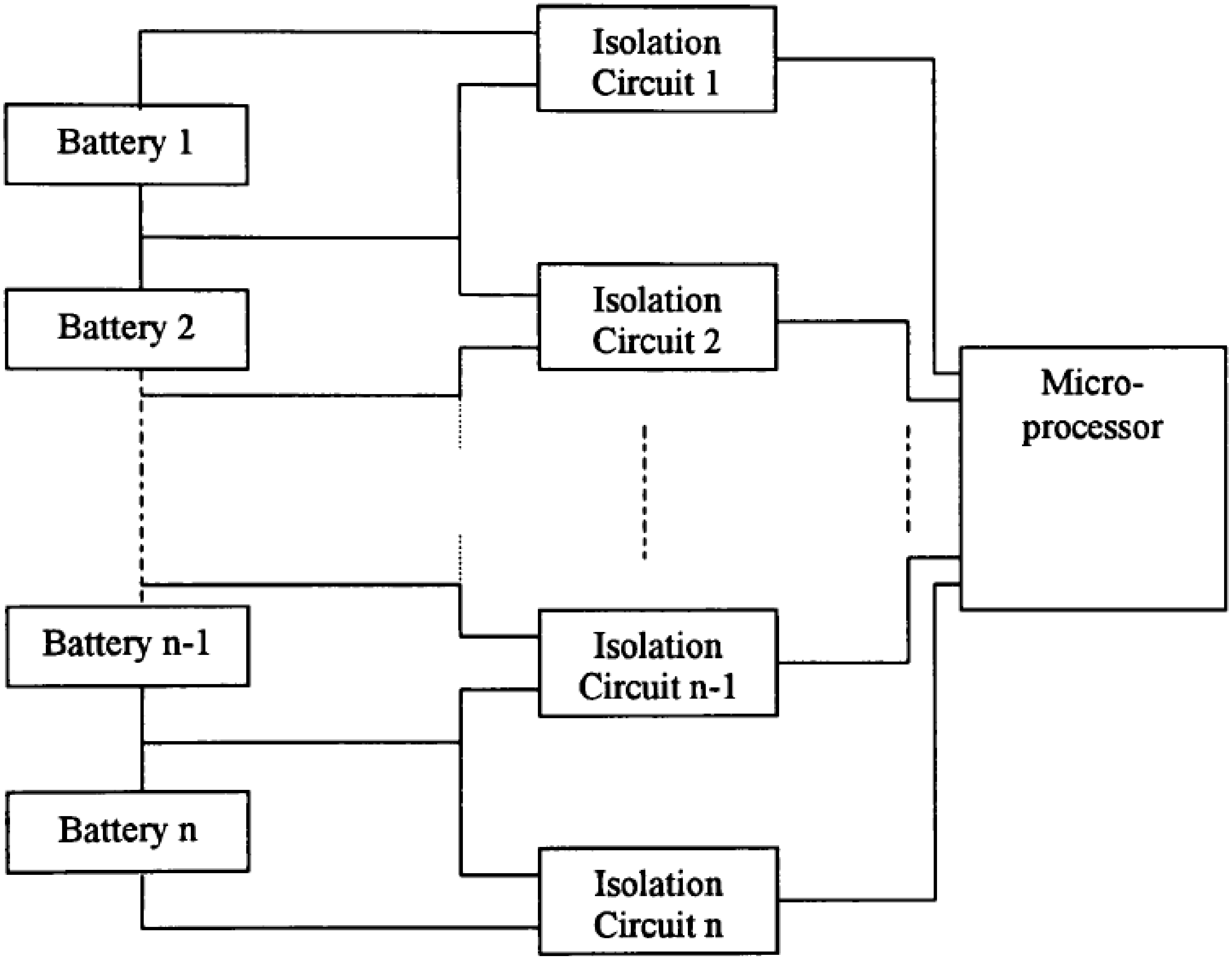
- Excessive current during charging or discharging.
- Short circuit
- Over voltage - Overcharging
- Under voltage - Exceeding preset Depth of Discharge (DOD) limits
- High ambient temperature
- Overheating - Exceeding the cell temperature limit
- Pressure build up inside the cell
- System isolation in case of an accident
- Abuse

Battery Stack Voltage Measurement

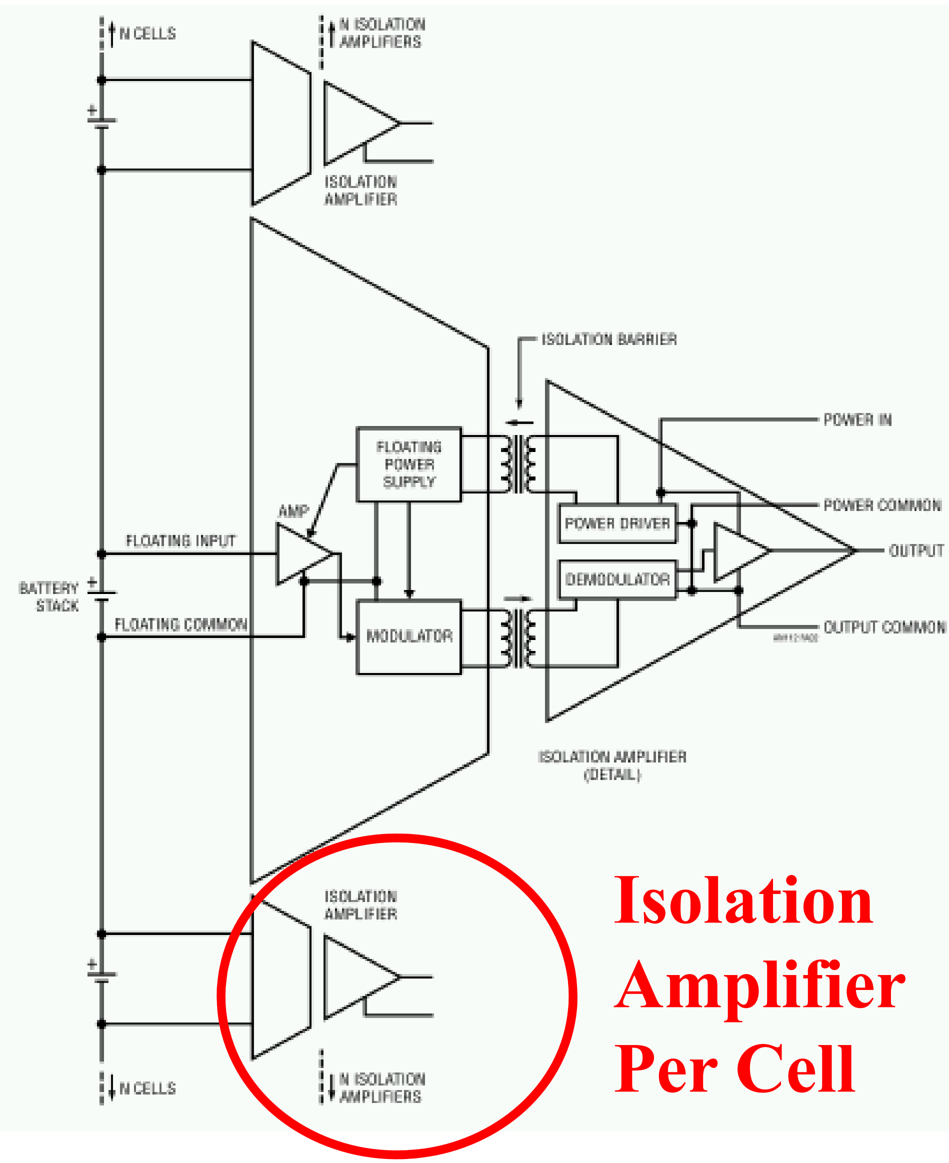


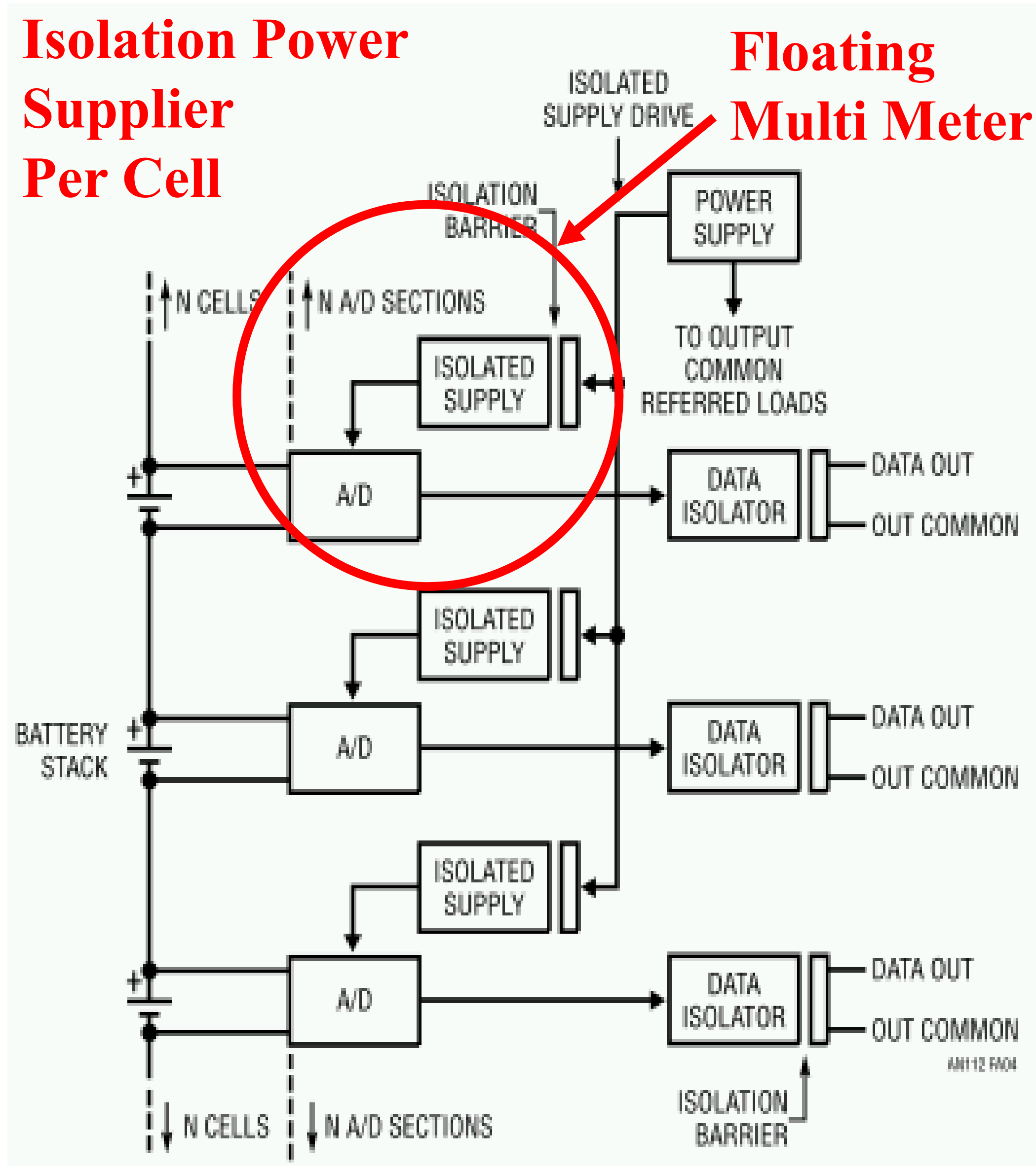
- **Cell voltage is an important parameter to estimate SOC**
- How to measure individual cell voltage in a series-connected battery stack is a challenge
- The voltmeter must be switched between the cells to determine each individual cell's voltage
- The voltmeter, normally composed of relatively low voltage breakdown components, must withstand input voltage relative to its ground terminal.
- This "common mode" voltage may reach hundreds of volts in a large series connected battery stack such as is used in an automobile.

Isolation Between Battery Cells and BMS Processor



Battery Stack Voltage Measurement





Source: Linear Technology

Battery Stack Voltage Measurement Flying Capacitor Method

Battery Cells

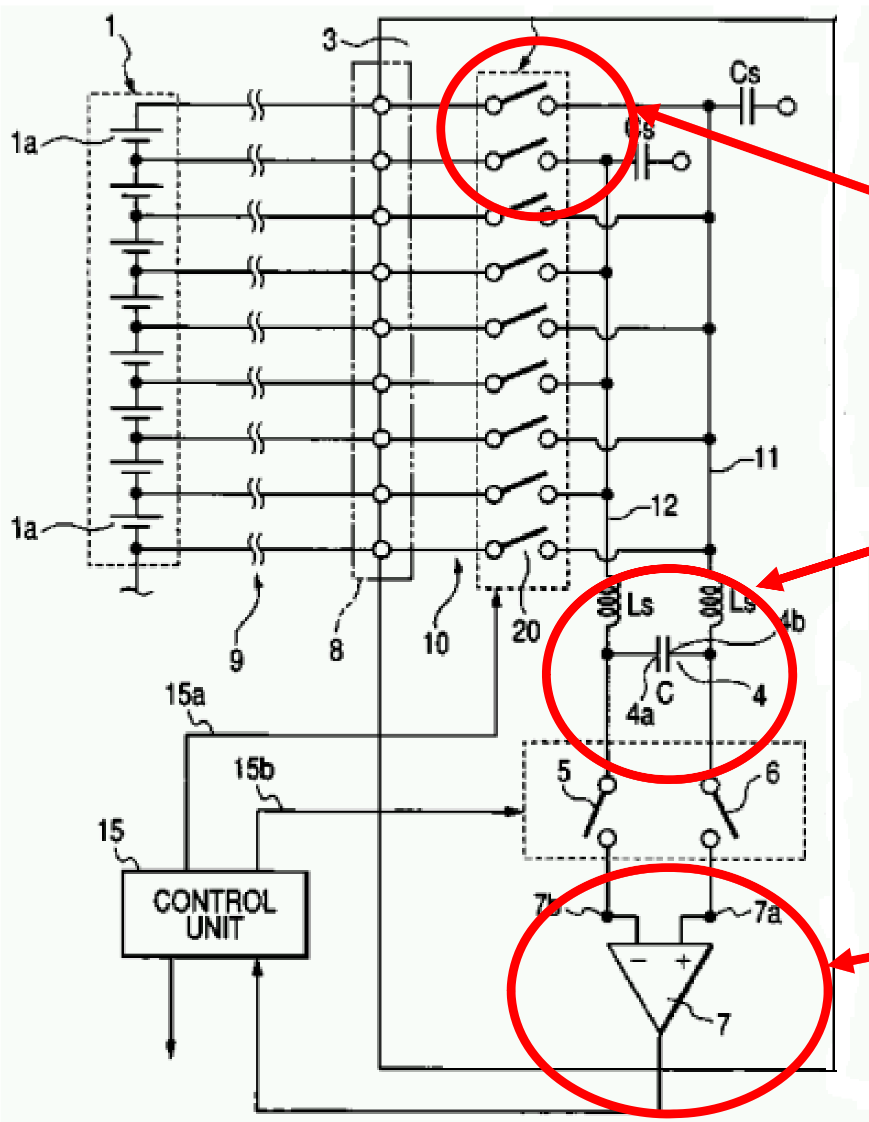


Photo MOS Relay or Analog Switches

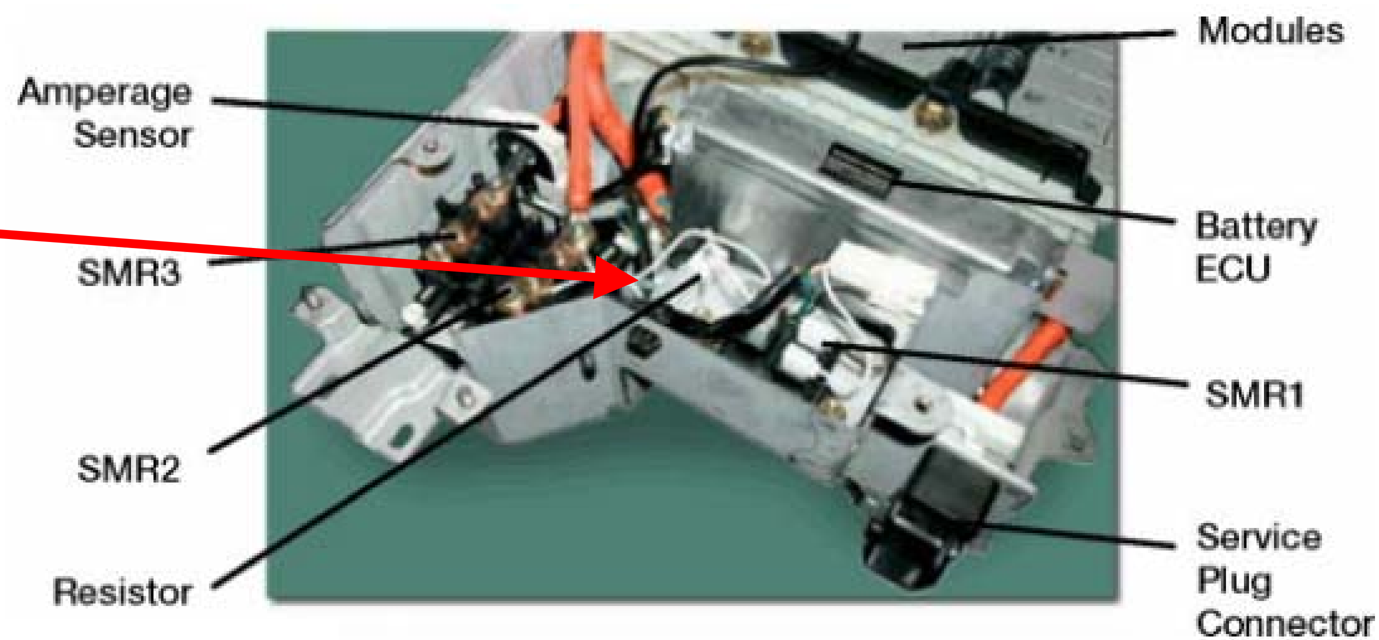
Flying capacitor to store cell voltage

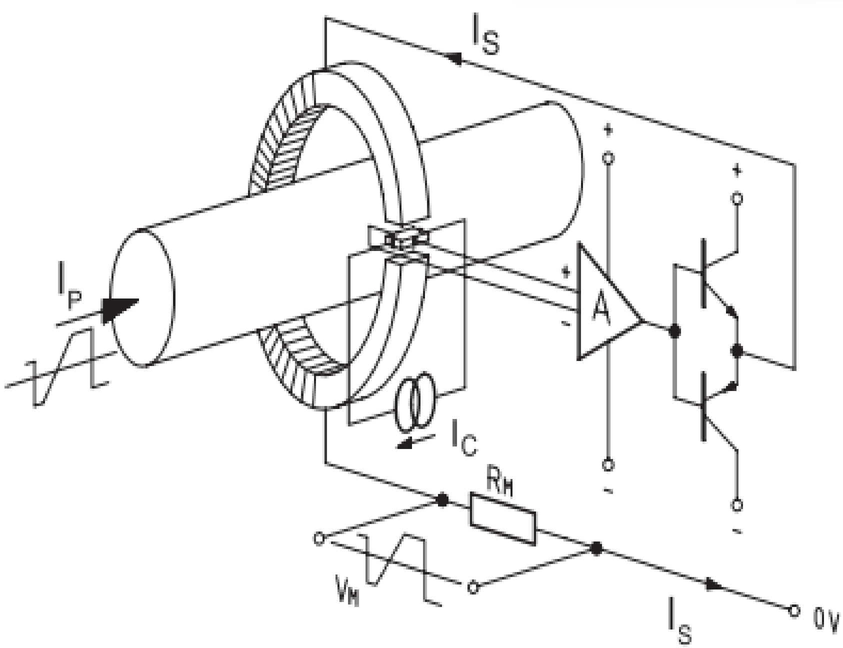
Differential Amplifier

Source: US Patent 7362588

Battery Pack Current Monitoring

Non-Contact, Hall effect current sensor

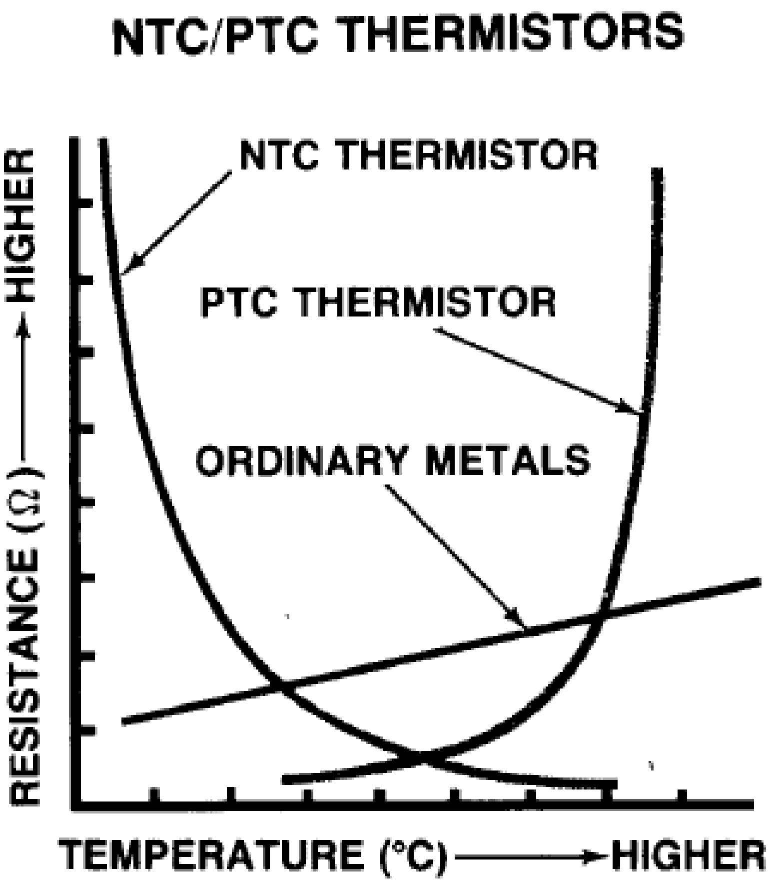




Temperature Sensing

- Accurate battery temperature measurement is very important during battery charge.
- Temperature of a traction battery can be measured using a NTC thermister or other temperature sensing device that is attached to the surface of the cell.
- For Li-ion batteries, the charge is only allowed when the temperature falls within the predefined range.
- For Ni-Cd and Ni-MH batteries, the battery temperature is used to switch between rapid (large charge current) and trickle (small charge current) charges.

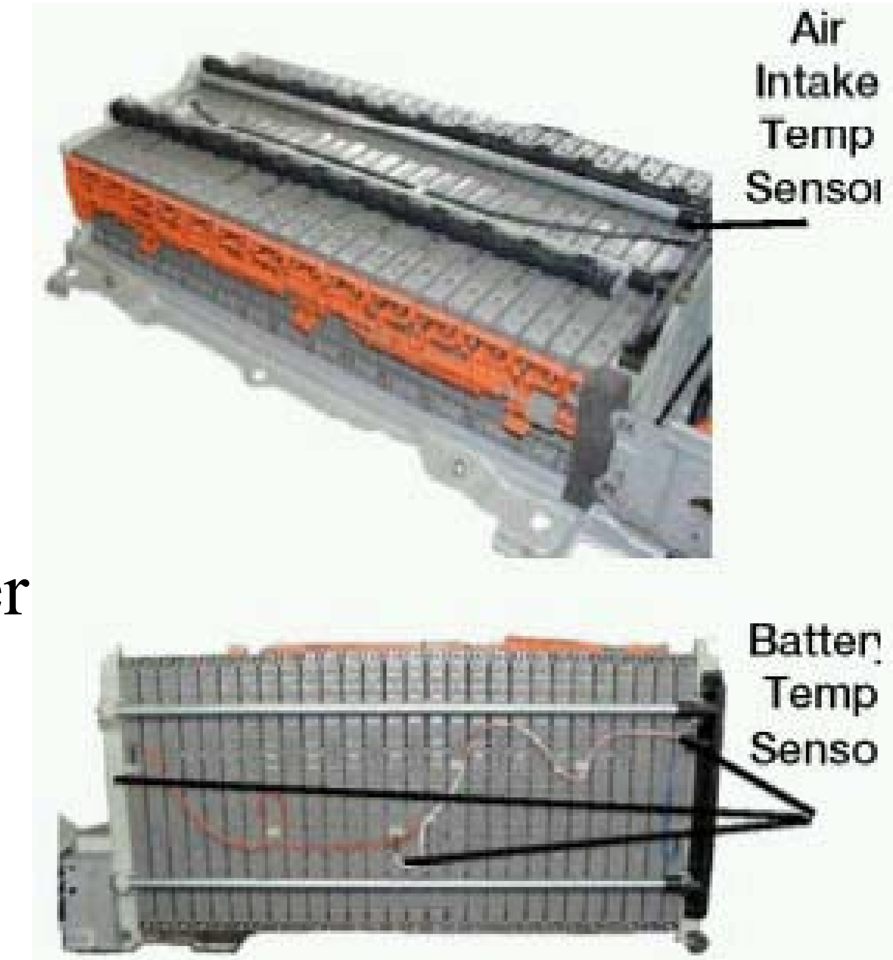
NTC/PTC Thermistor



- A thermistor is a type of resistor used to measure temperature changes.
- Both types of thermistors changes resistance with increasing temperature.
- NTC - Negative Temperature Coefficient, resistance goes down as temperature goes up.
- PTC – Positive Temperature Coefficient, resistance goes up as temperature goes up.

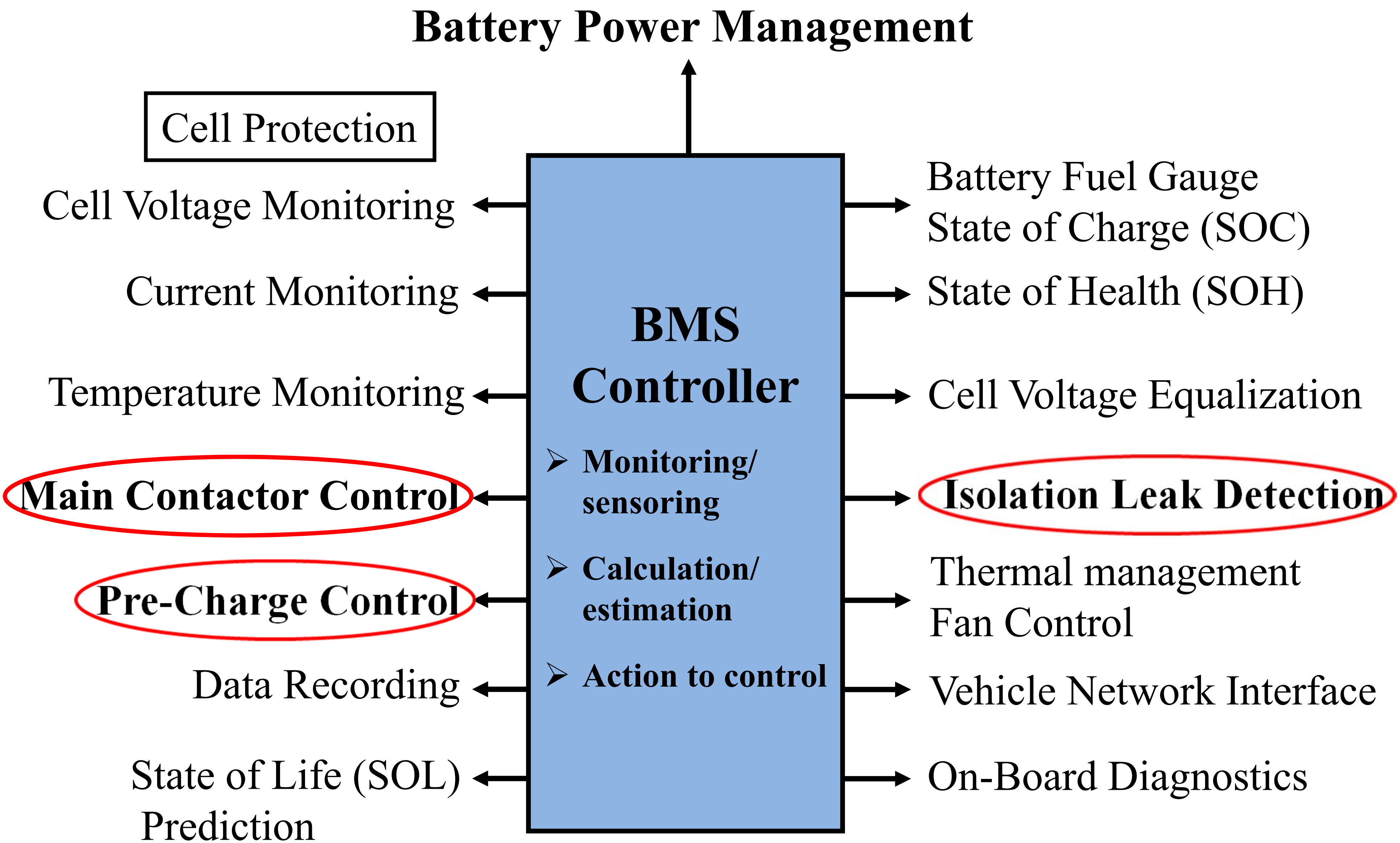
Temperature Sensing

- Temperature sensing with thermister relies on the transfer of heat due to conduction.
- This measurement is often skewed by loss of heat from the cell surface due to convection and radiation, and depends upon the ability of the battery to transfer heat generated at the core of the cell to the surface.
- This factor is also known as thermal impedance of the battery varies with construction and cell size.

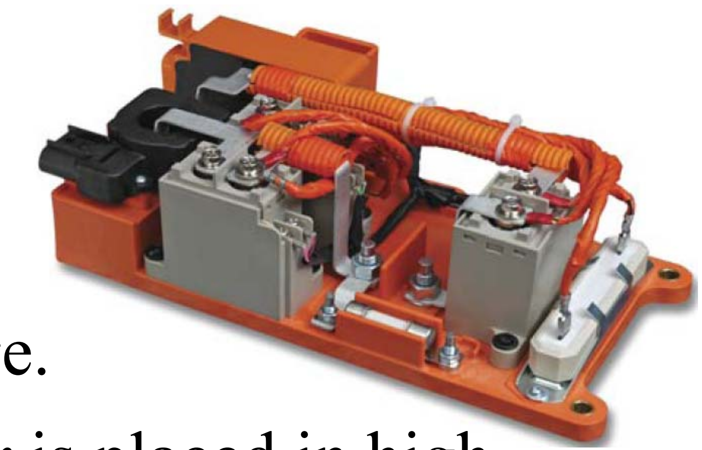


Source: Autoshop101

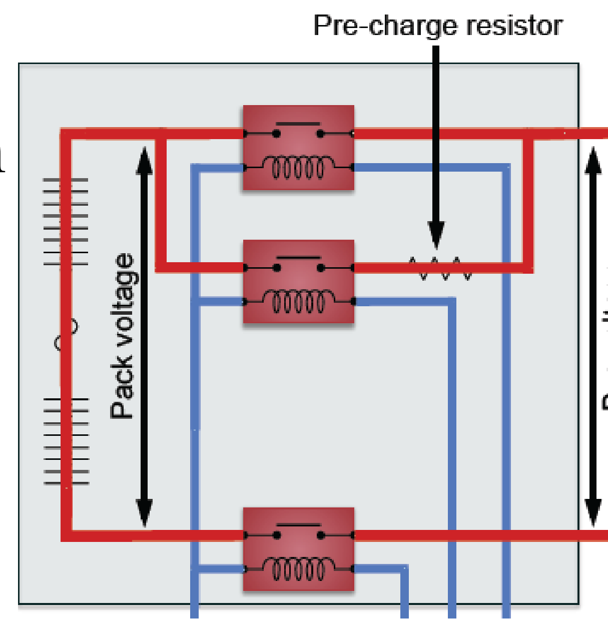
Battery Management System (BMS) Functions



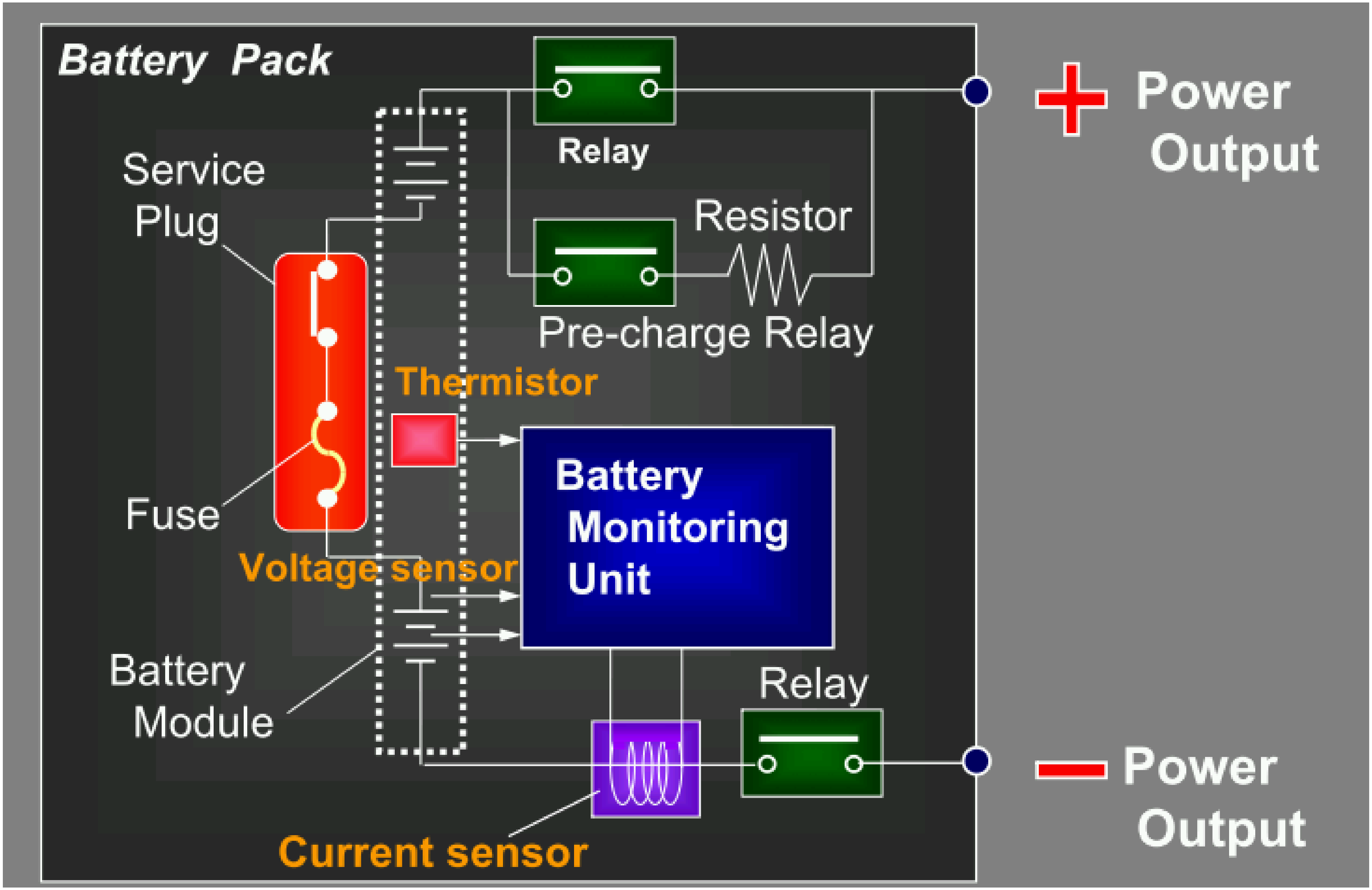
Main Contactors



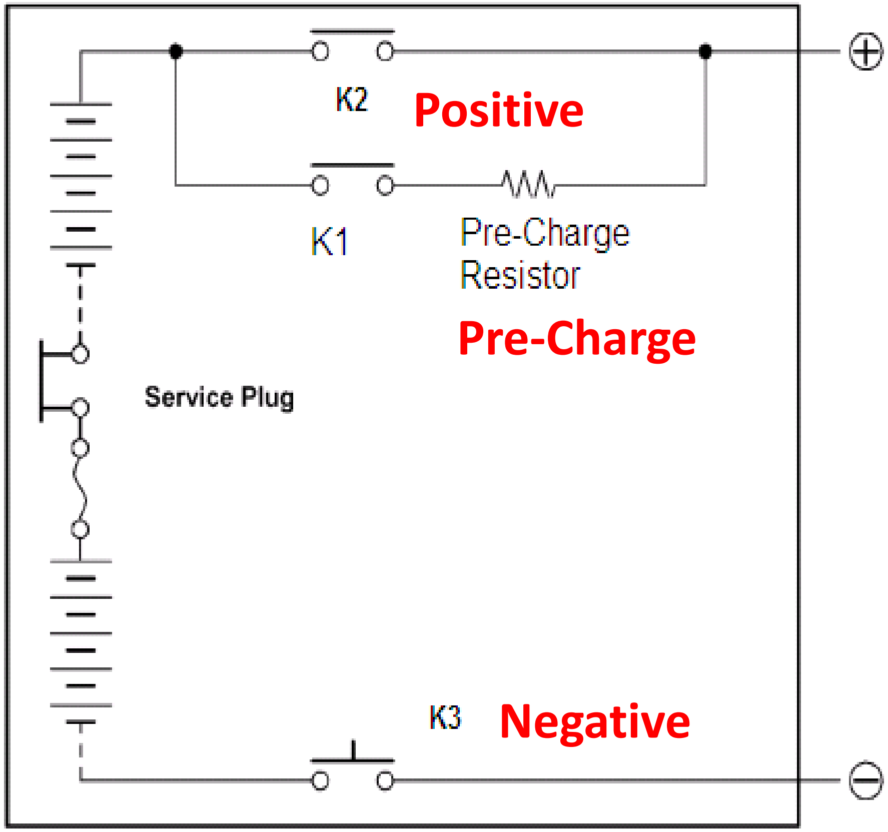
- A contactor works just like a relay.
  Its heavy-duty contacts (typically rated at 150 to 250 amp continuous) allow BMS to control high currents with a low level voltage.
- A single-pole, normally open main contactor is placed in high current circuit between the battery, the inverter and the motor.
- When energize it, typically by turning the ignition key-on, high current power is made available to the inverter and motor.
- To conserve energy, the coil of the main contactor could be controlled by Pulse-Width Modulation (PWM) signal (Economizer).
- The contactor will be closed ONLY when there are no OBD fault conditions detected from other controllers on the vehicle network.

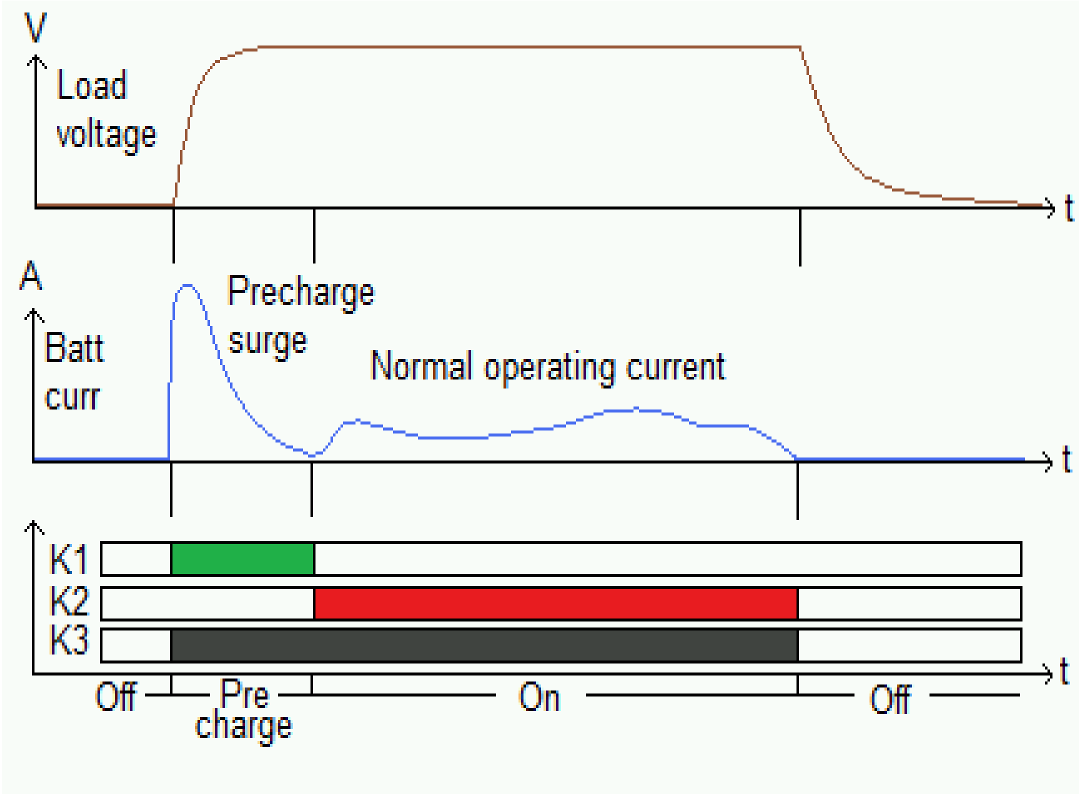


Battery Monitoring and Controlling System



Pre-Charge/Main Contactor Operations





Typical precharge waveforms.

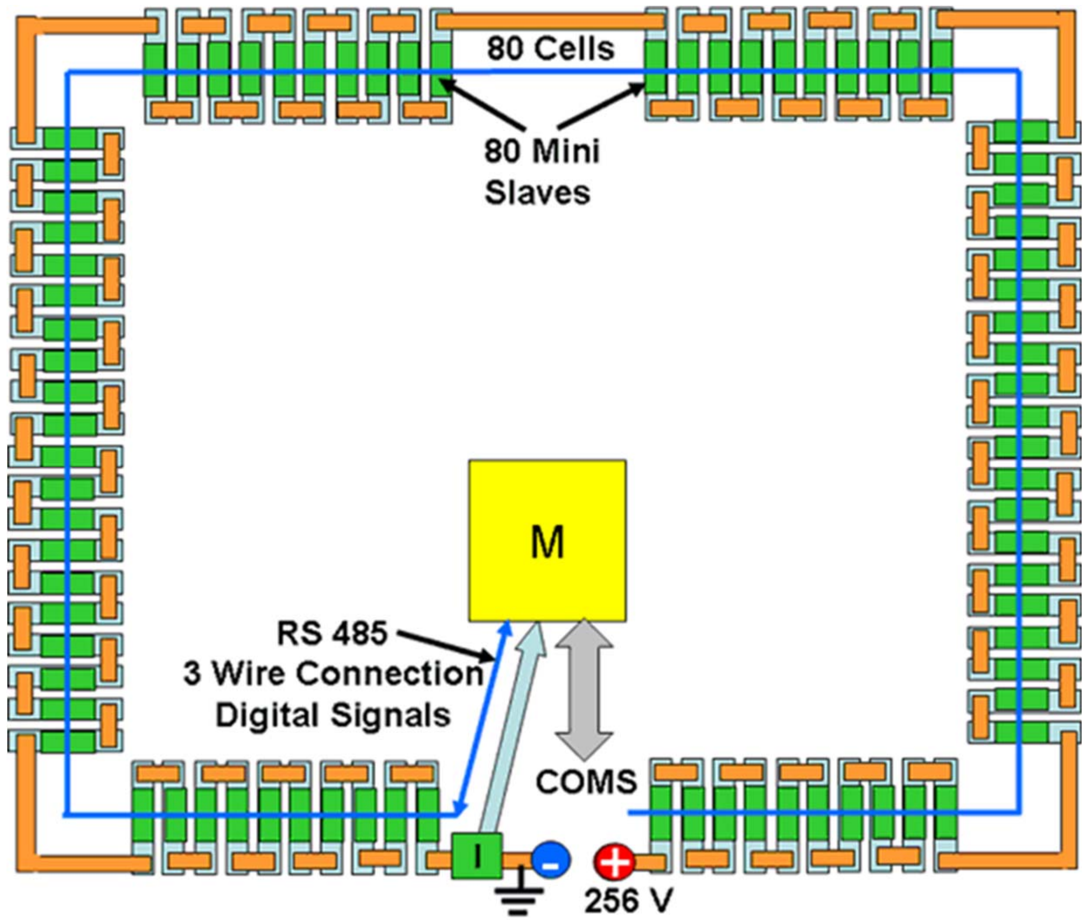
(1) Off: When the system is off, all relays / contactors are off (open).

(2) Precharge: When the system is first turned on, K1 and K3 are turned on (closed), to precharge the load, until the inrush current has subsided.

(3) After precharge, contactor K2 is turned on (relay K1 may be turned off to save coil power).

BMS Topology: Distributed

Mini-slaves: One per cell
- Voltage, temperature sense
- Switch for cell bucking
- Isolated transceiver for communicating with master
- Powered by its own cell
- A single serial data bus connects all the slaves to the master, which polls each node in turn and requests an update of its cell conditions



Master: Performs all signal processing, monitoring, protection and communications functions

Advantages/Disadvantages of Distributed BMS

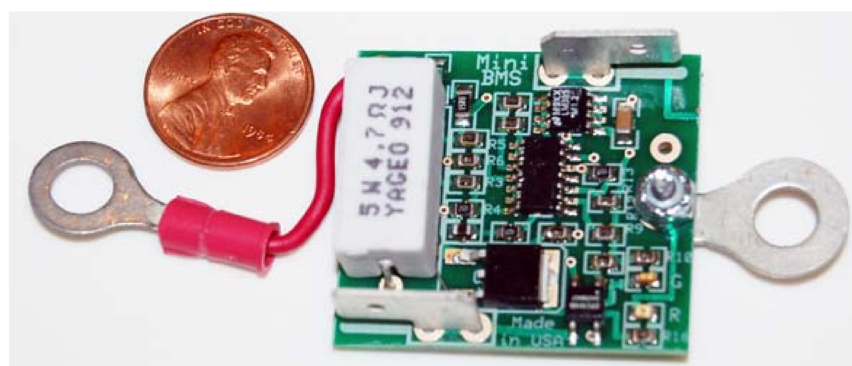
Advantage

Simplicity of design

Disadvantage

- Large number of mini-slaves are needed, high individual cost (≈$15/cell), and difficulty of mounting on some cell types
- In addition the master has a higher processing load.
- Presently used mostly by hobbyists who need turnkey solution to build EV conversions

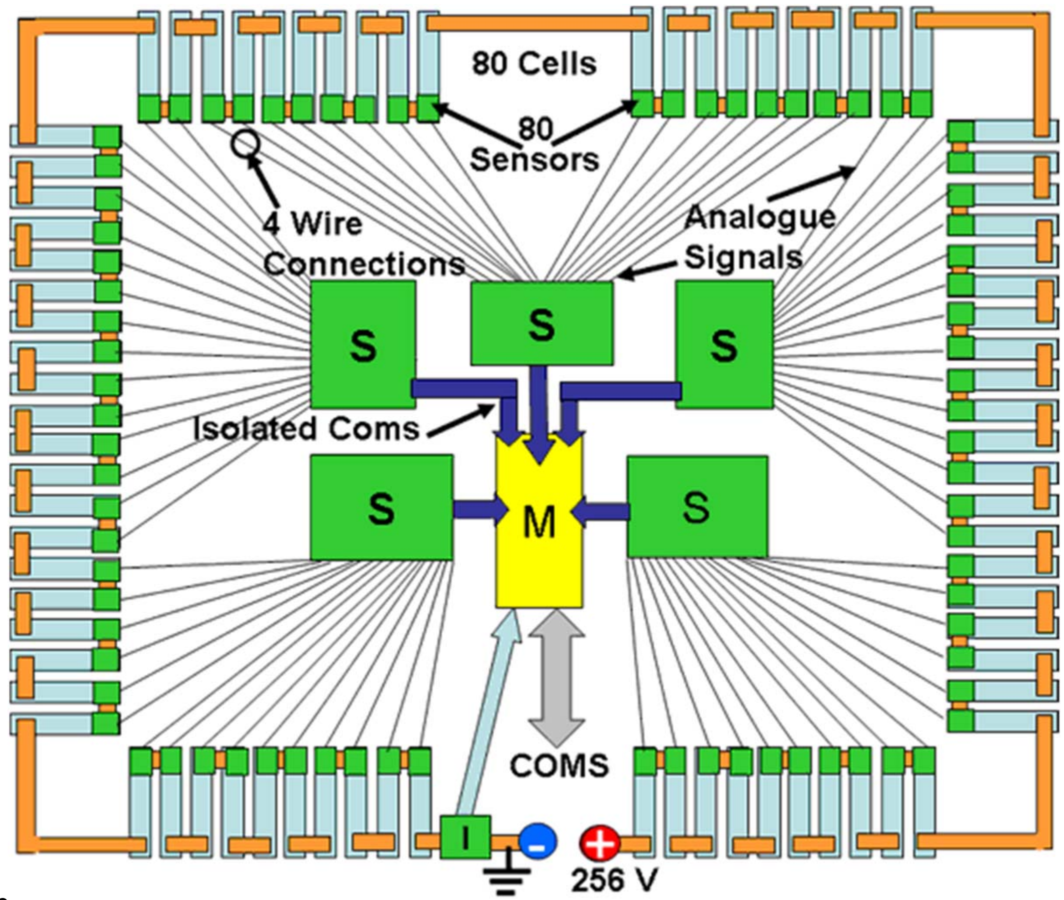
Single cell mini-slave by CleanPowerAuto LLC



BMS Topology: Modular

Slaves: Individual voltage sense, temperature sensor(s), cell balancing
➠ *handles multiple cells*

Master: Communicates with slaves; monitors battery pack current and voltage; executes algorithms; controls contactor, maintains battery pack safety, communicates with vehicle, etc.



Advantages/Disadvantages of Modular BMS

Advantages

– Doesn’t need circuit boards connected to individual cells

– High-voltage batteries requires only adding modules

– As the main battery current doesn’t pass through slaves, can also be used for high current batteries.

– Signal processing shared between master and slaves, simplifies management of information processing load.

Disadvantages

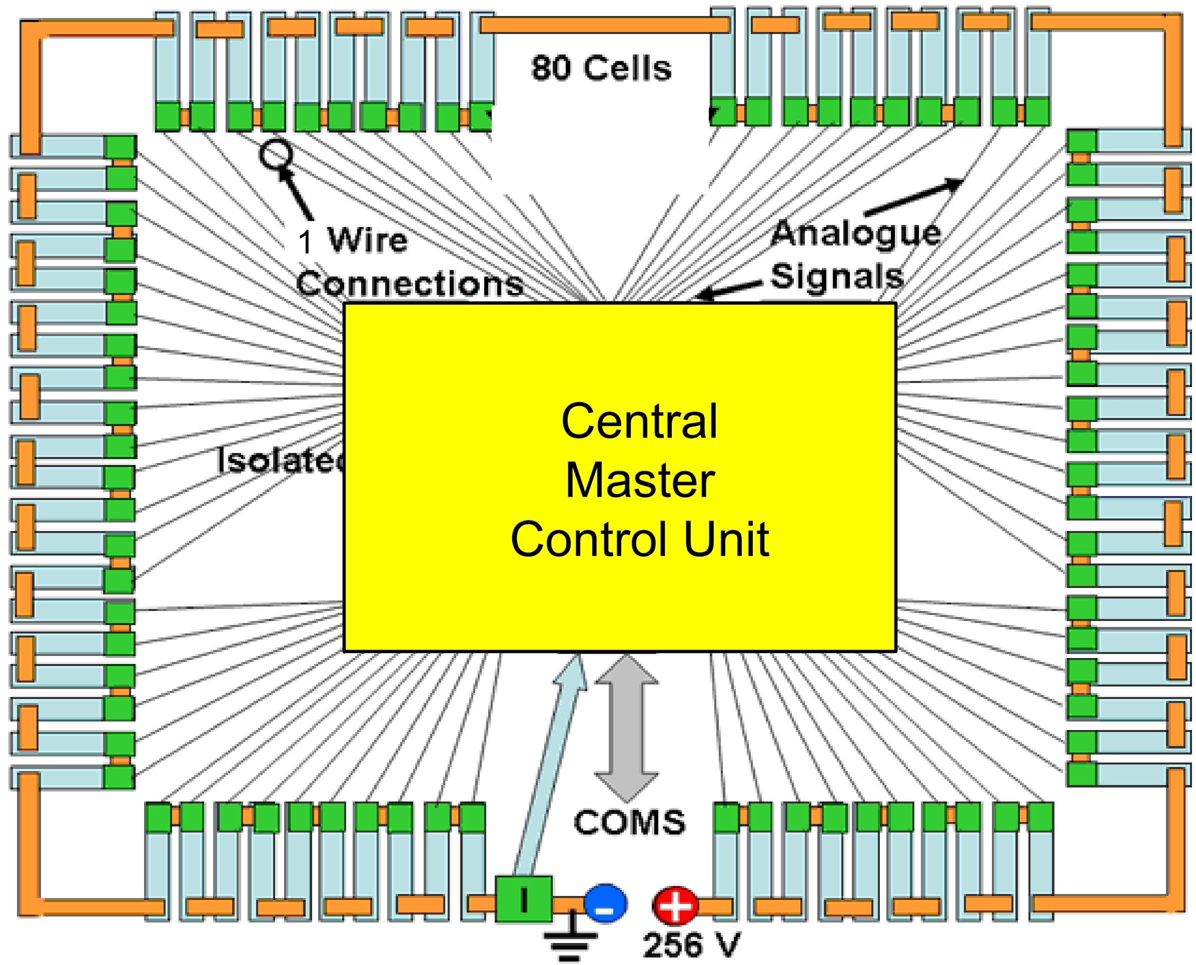
– Analog communication between sensors and slaves, susceptible to noise (so, must mount slaves proximate to cells)

– Large number of sensor wires, two to four per cell

– Isolated connections between slaves and master required as voltages on slaves approach full battery voltage

BMS Topology: Centralized

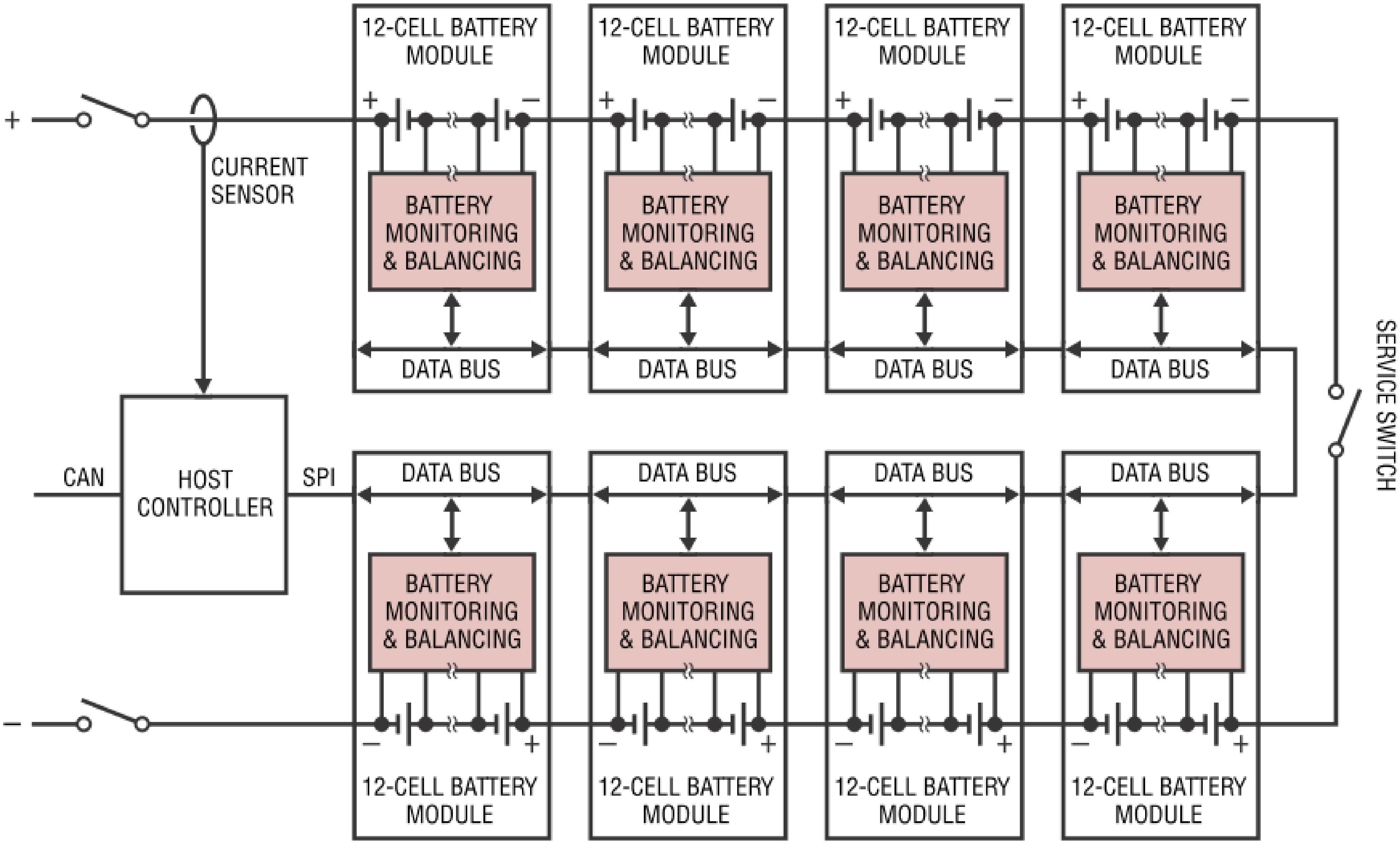
- Centralized Master Control Unit



Advantages: Single installation point. No complex inter-battery communications

Disadvantages: Typical EV batteries are distributed in the vehicle, requiring wiring to a central location.

Example: 96-Cell (355V) Battery Pack



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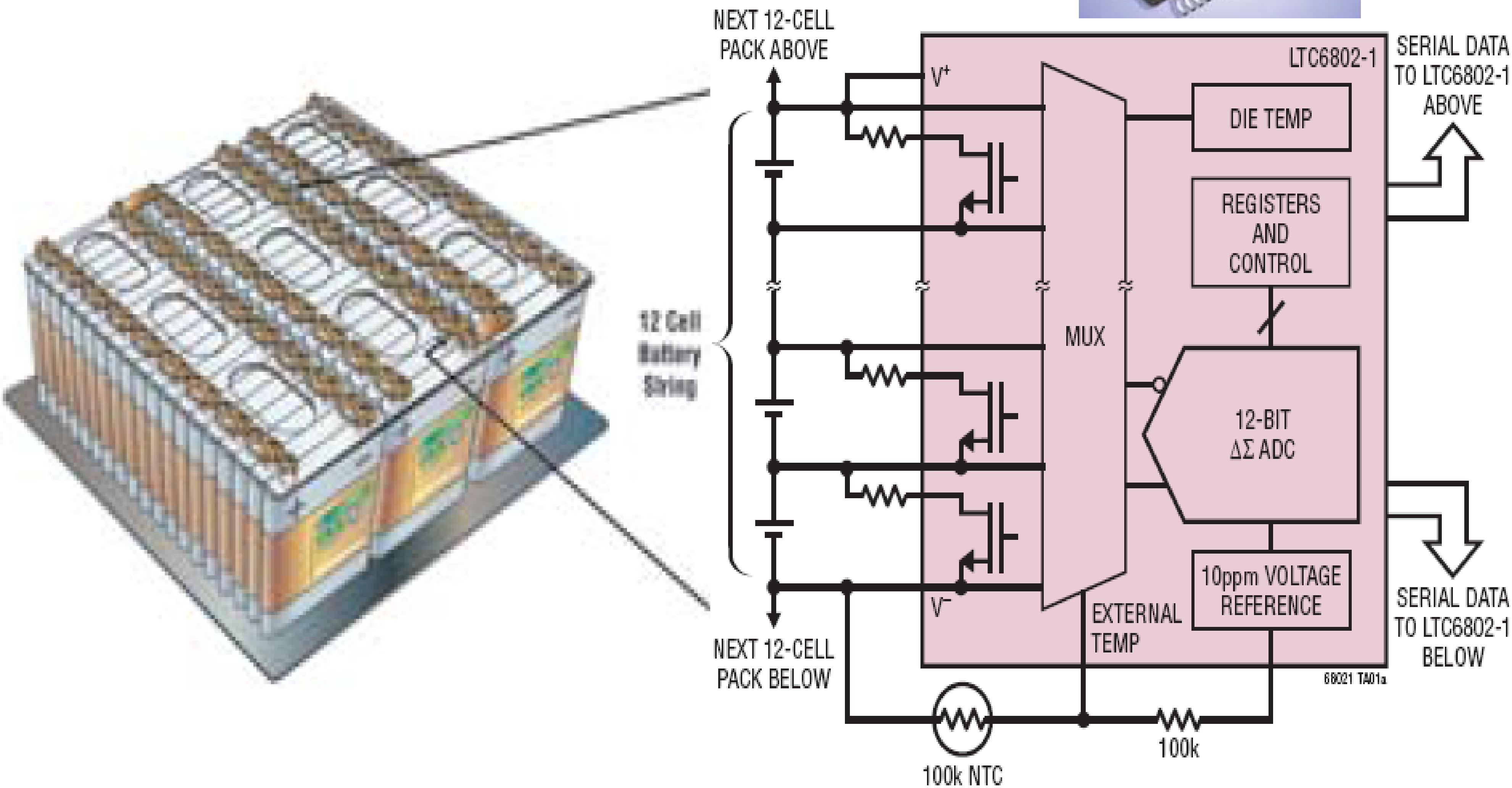
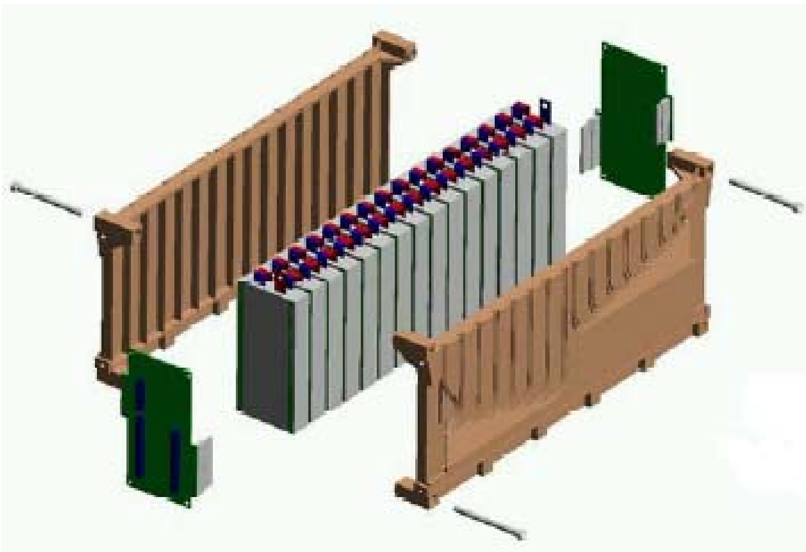
Battery Stack Voltage Monitor IC



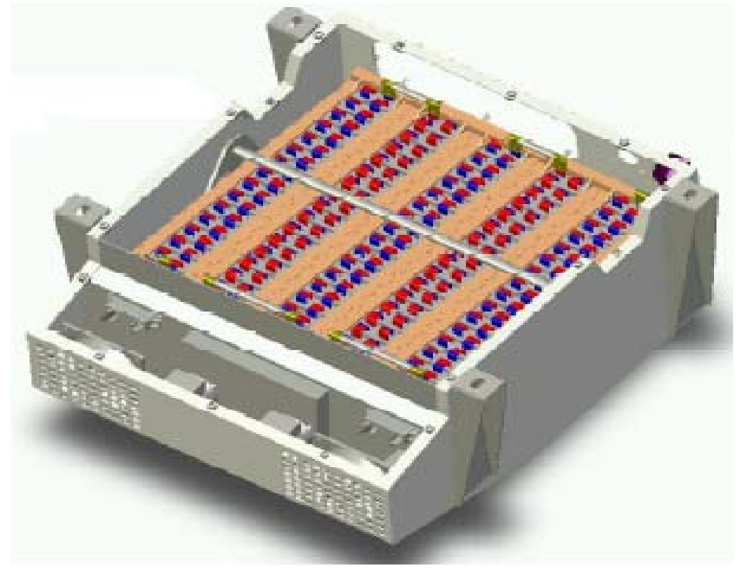
Monitor cell voltage and perform cell balancing

Source: Linear Technology

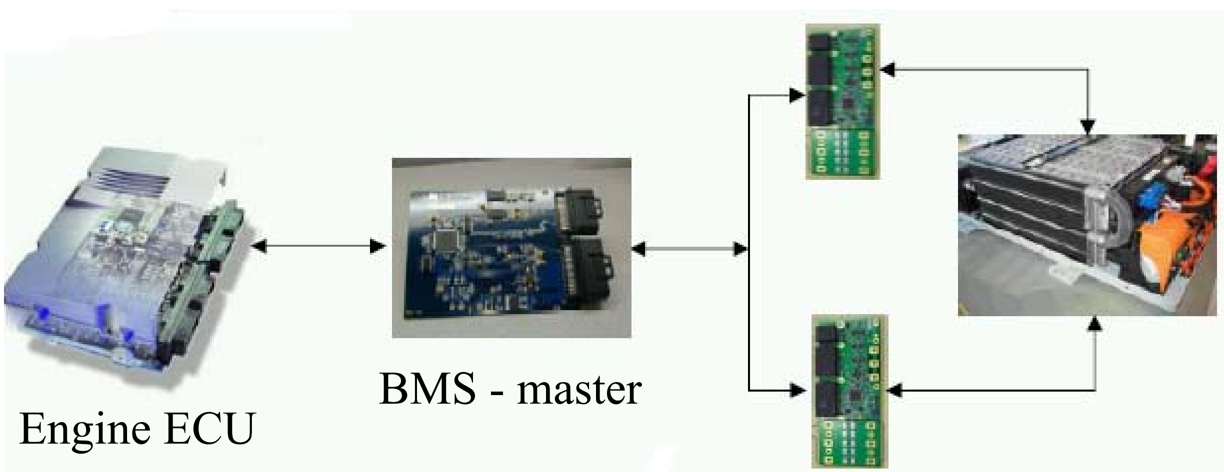
A Battery Pack is Composed of Modules, with each Module Being Monitored and Controlled



Battery Module



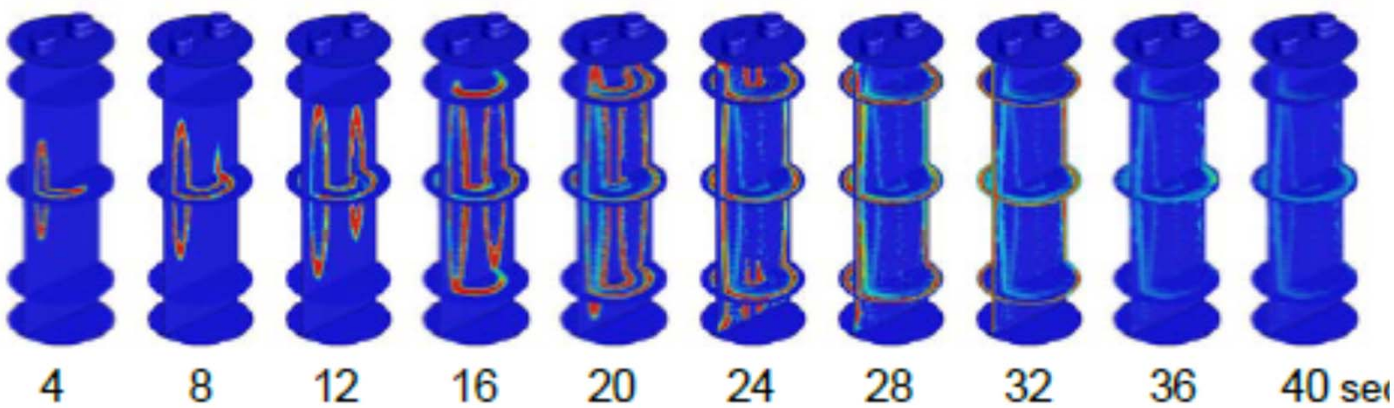
Battery Pack

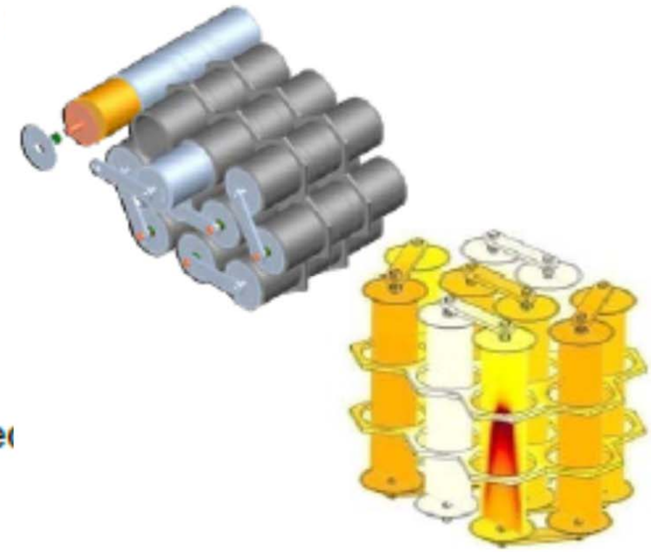


Modular Type Battery Management System (BMS)

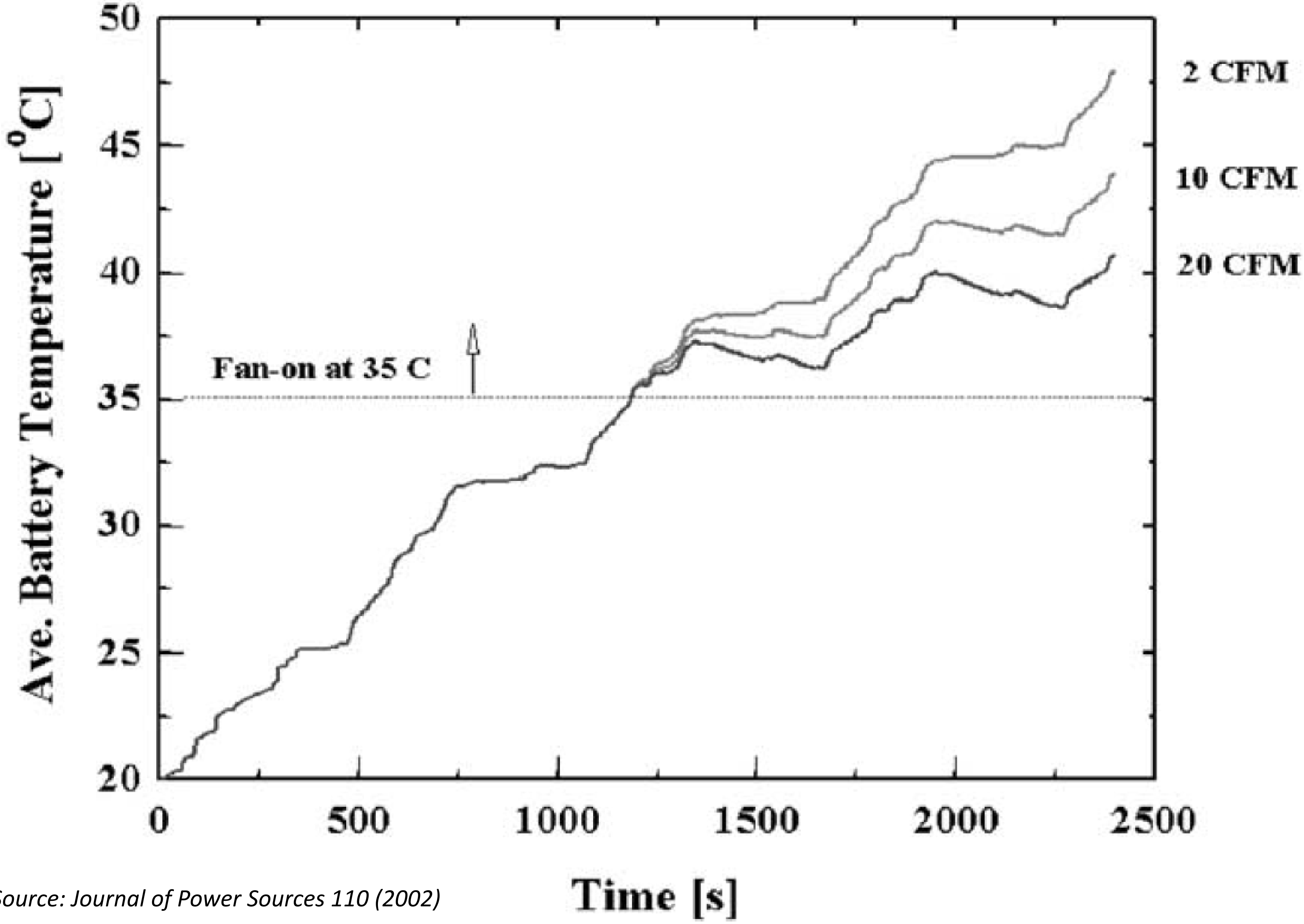
Source: www.Ricardo.com

VI. Battery Systems Thermal Management



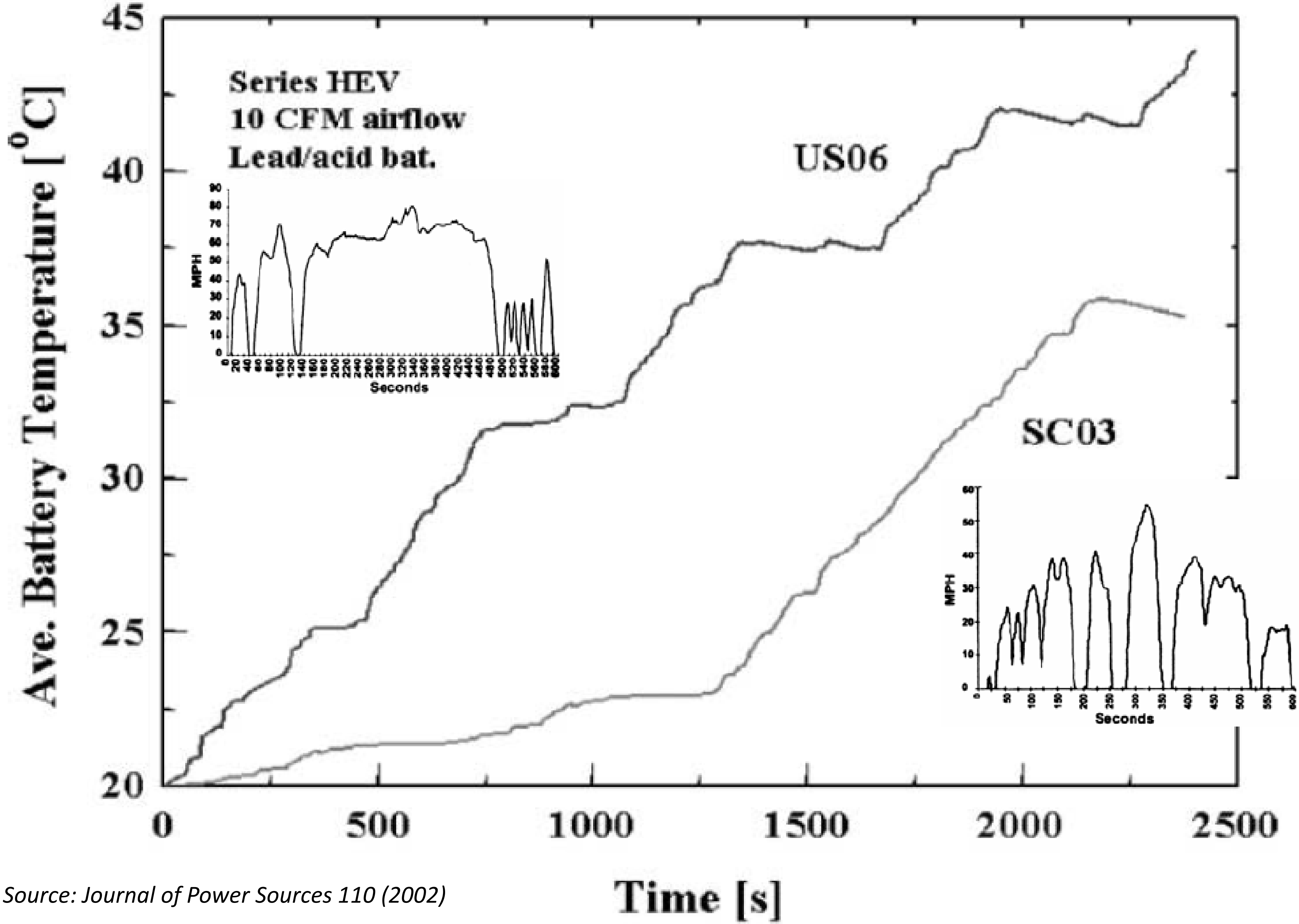


Effect of Cooling Airflow on Battery Temperature



Source: Journal of Power Sources 110 (2002)

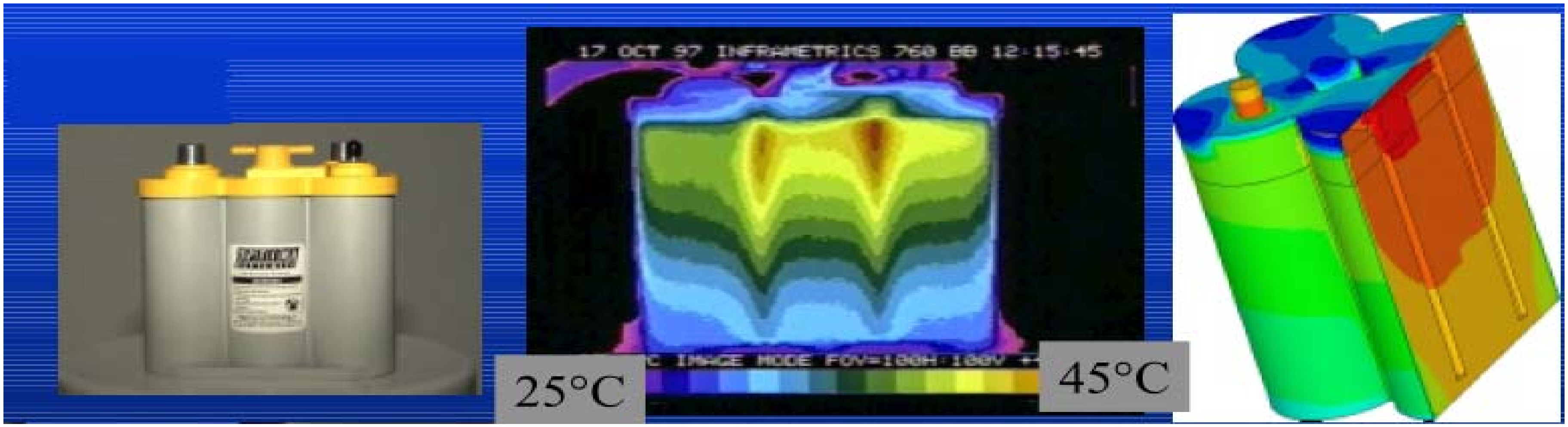
Effect of Drive Cycle on Battery Temperature



Source: Journal of Power Sources 110 (2002)

Temperature Distribution is Dictated by Module/Cell Design

Control Factors: Aspect Ratio, Number of Cells, Geometry, Thermal conductivity, Location of terminals, Current density.



20°C Difference

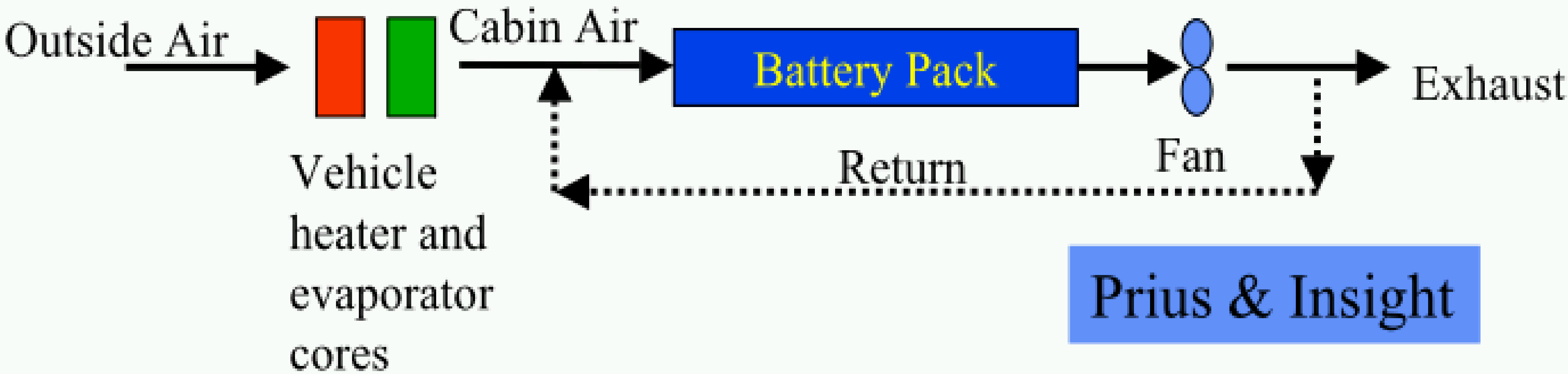
Only 2°C Difference

Air Cooling vs. Liquid Cooling

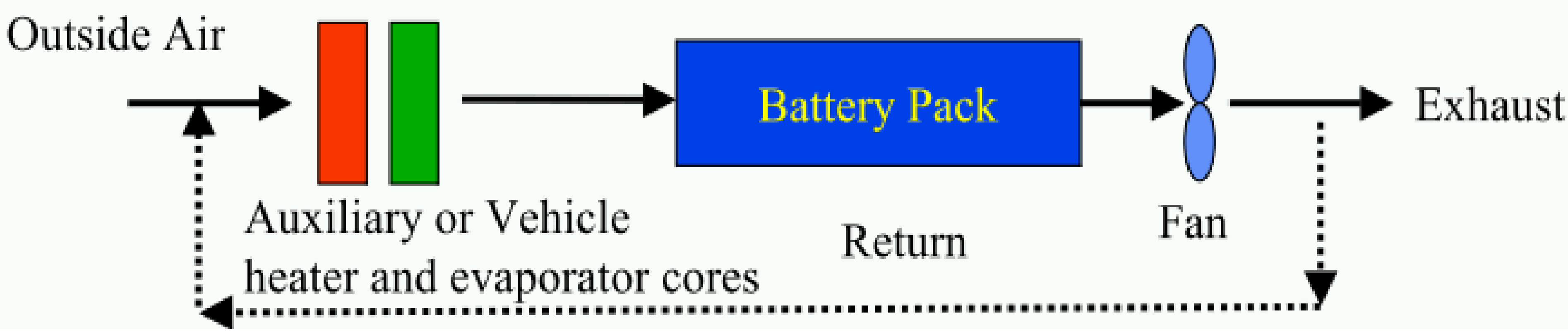
- Using the air as the heat transfer medium may be the simplest approach, but it may not be as effective as heat transfer by liquid.
- The rate of heat transfer between the walls of the module and the heat transfer fluid depends on the thermal conductivity, viscosity, density, and velocity of the fluid.
- For the same flow rate, the heat-transfer rate for most practical **direct-contact liquids such as oil** is much higher than with air because of the thinner boundary layer and higher fluid thermal conductivity.
- Because of oil's higher viscosity and associated higher pumping power, a lower flow rate is usually used, making the oil heat transfer coefficient only 1.5 to 3 times higher than with air.
- **Indirect-contact heat transfer liquids such as water or water/glycol solutions** generally have lower viscosity and higher thermal conductivity than most oils, resulting in higher heat transfer coefficients.

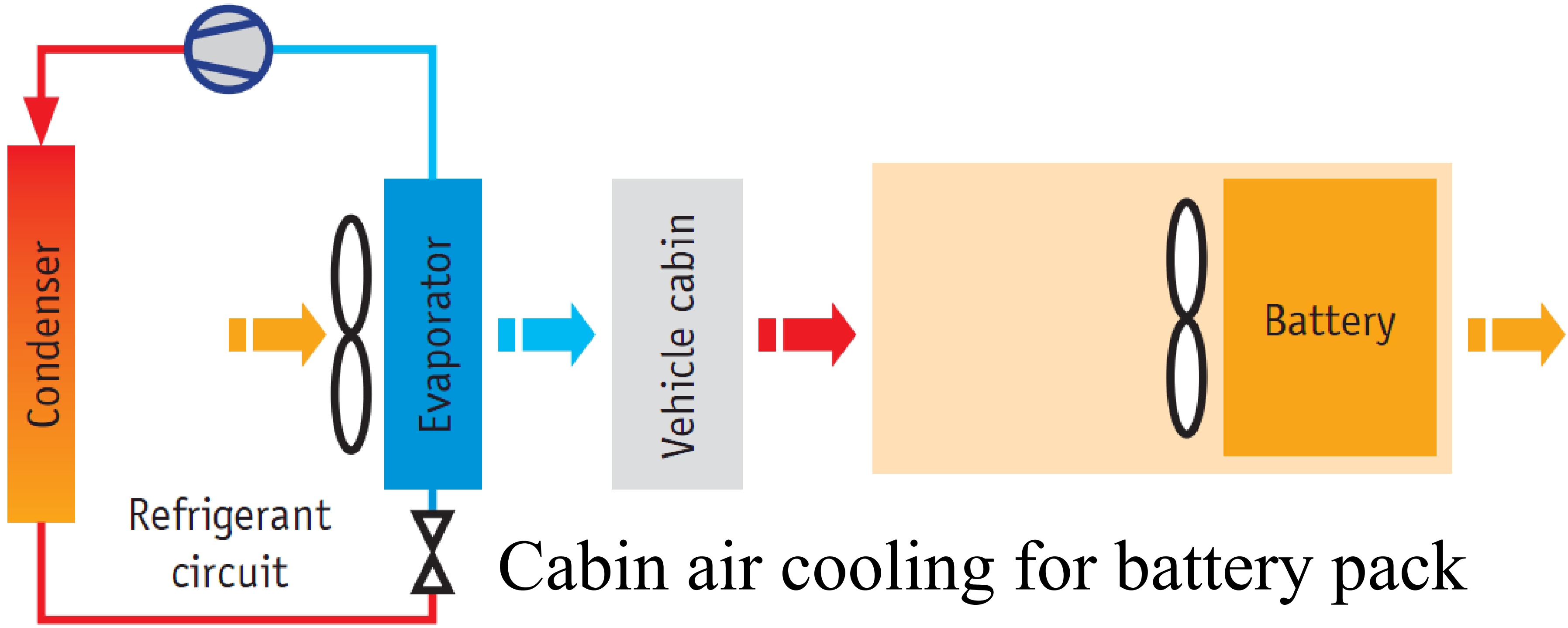
Passive cooling- Outside Air Ventilation

Passive heating/cooling- Cabin Air Ventilation

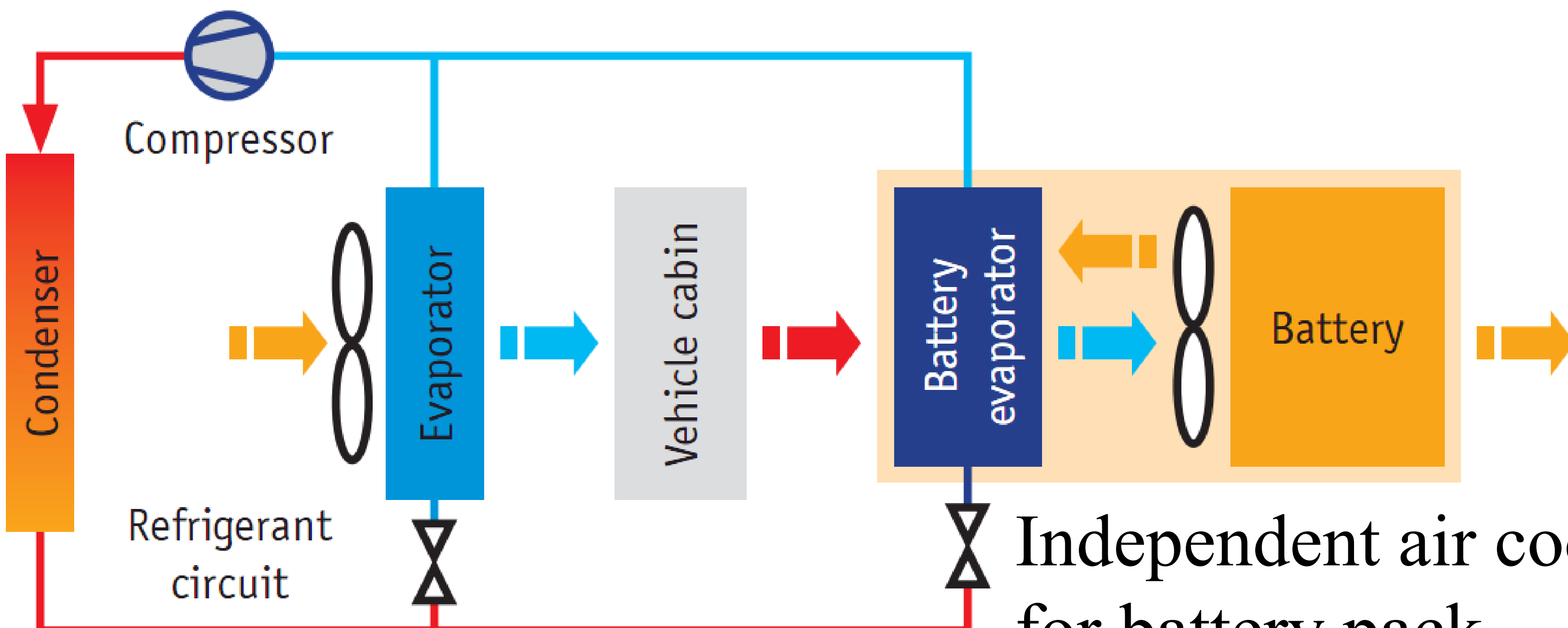


Active heating/cooling- Outside or Cabin Air



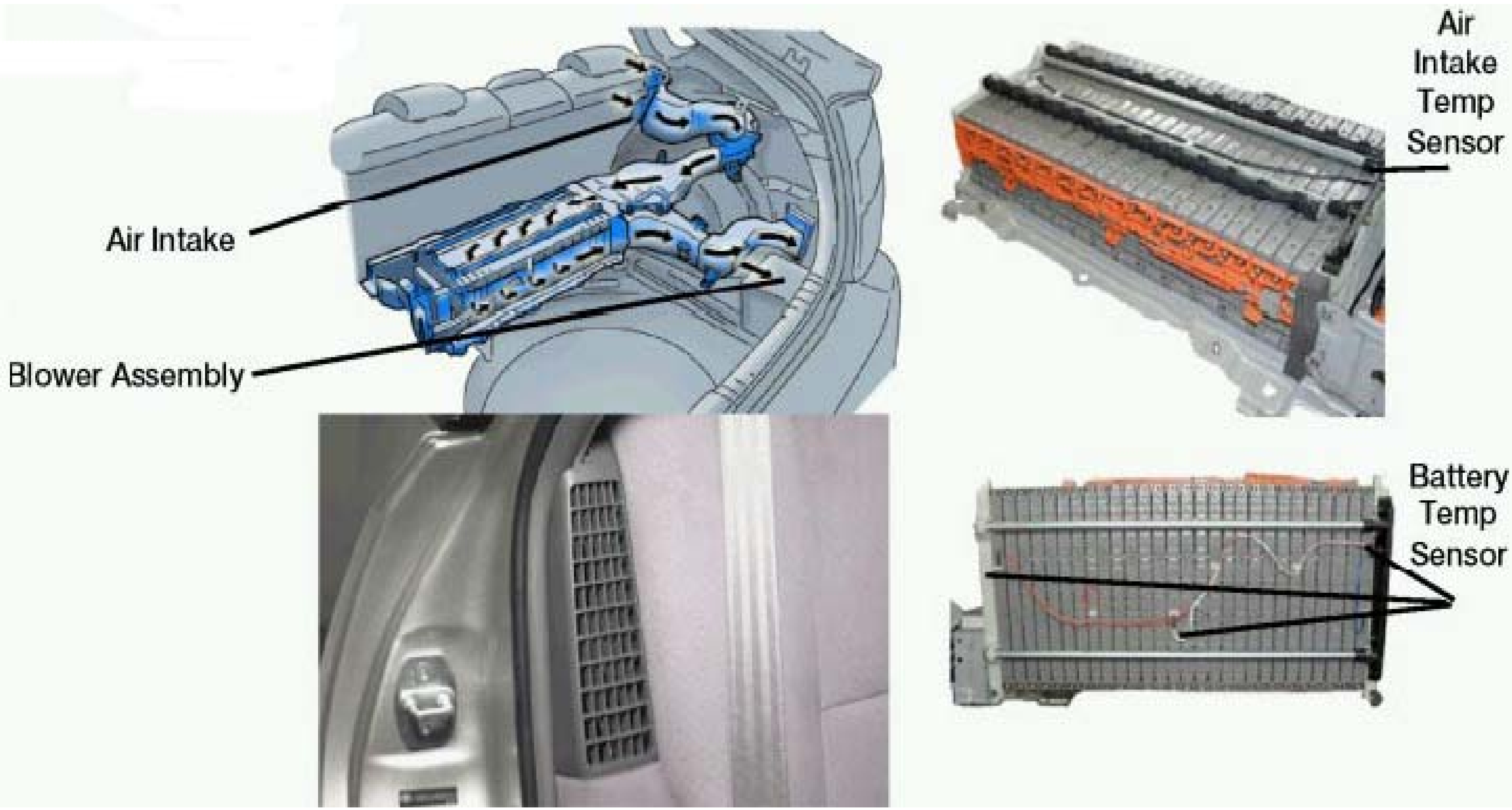


Cabin air cooling for battery pack

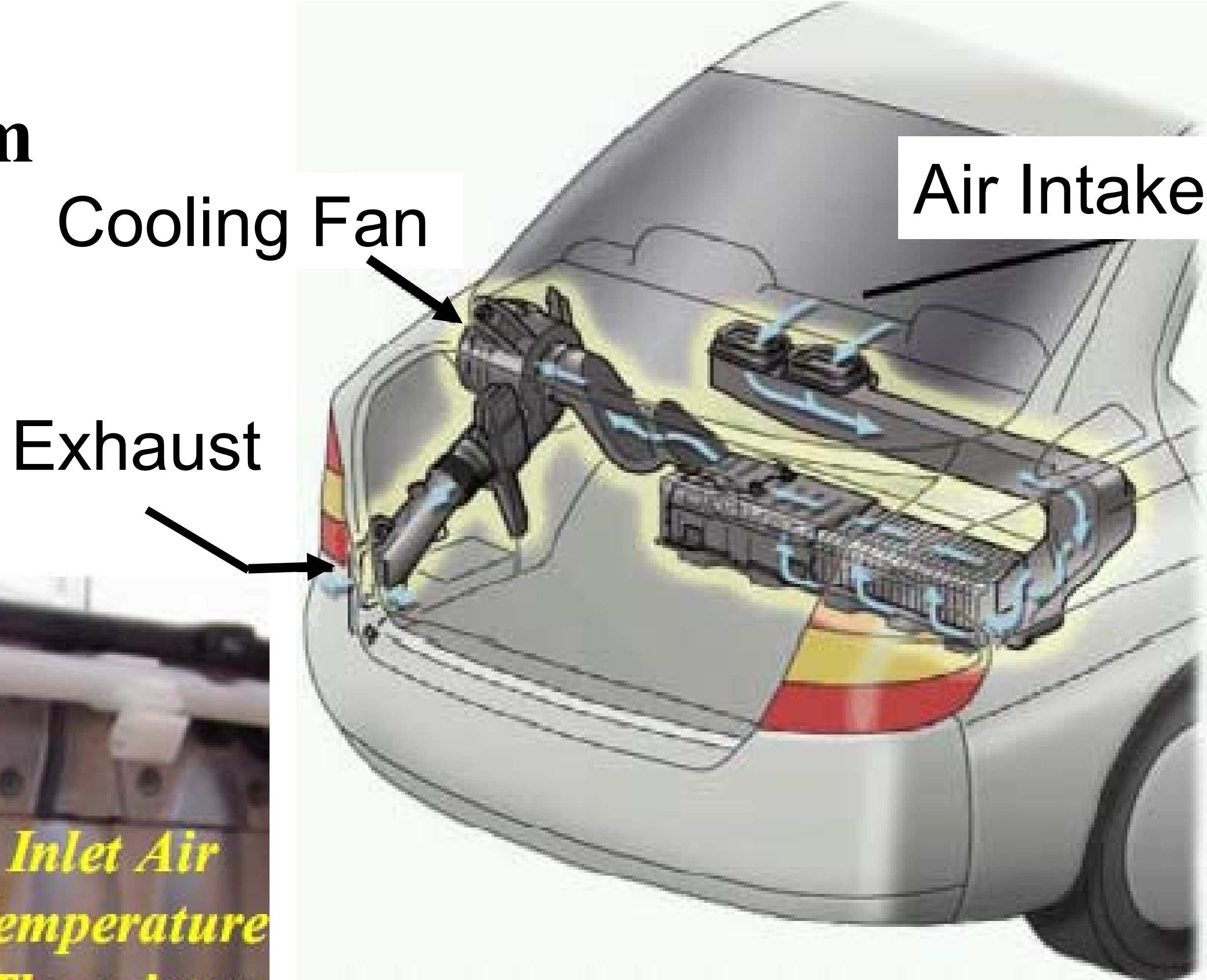


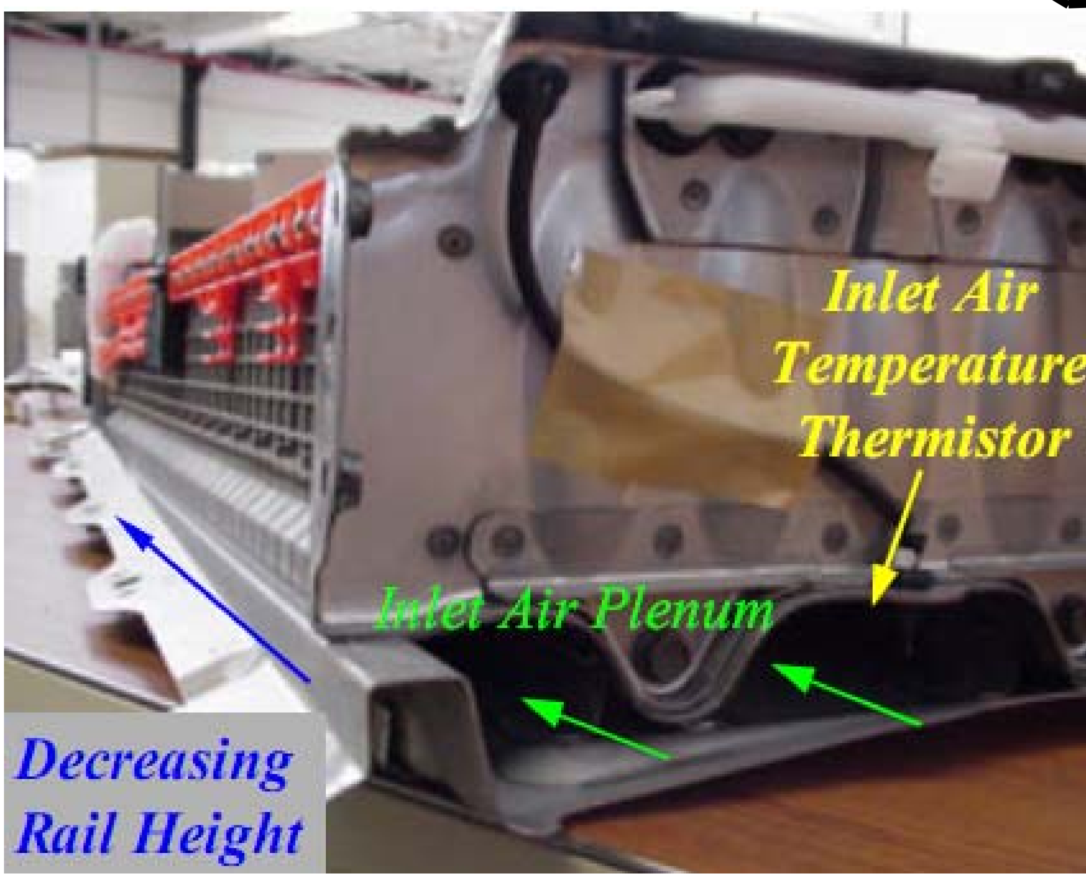
Independent air cooling
for battery pack

’04 Toyota Prius
Cooling System for Battery Pack



’01 ~ ’03 Toyota Prius Battery Cooling System



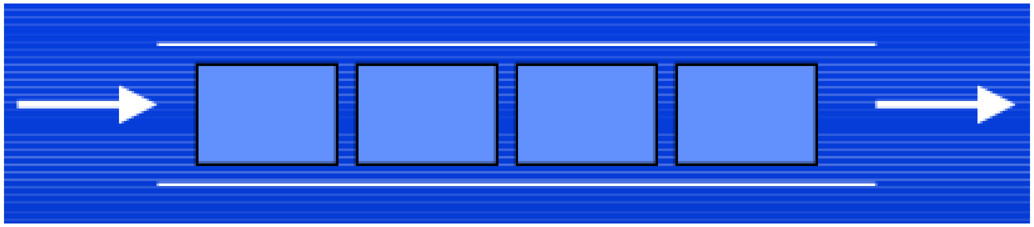


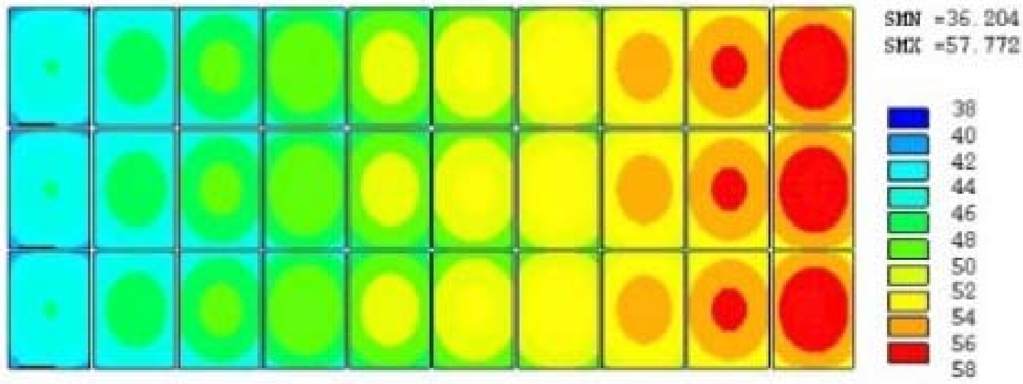
Toyota Prius HEV: Passive air cooling

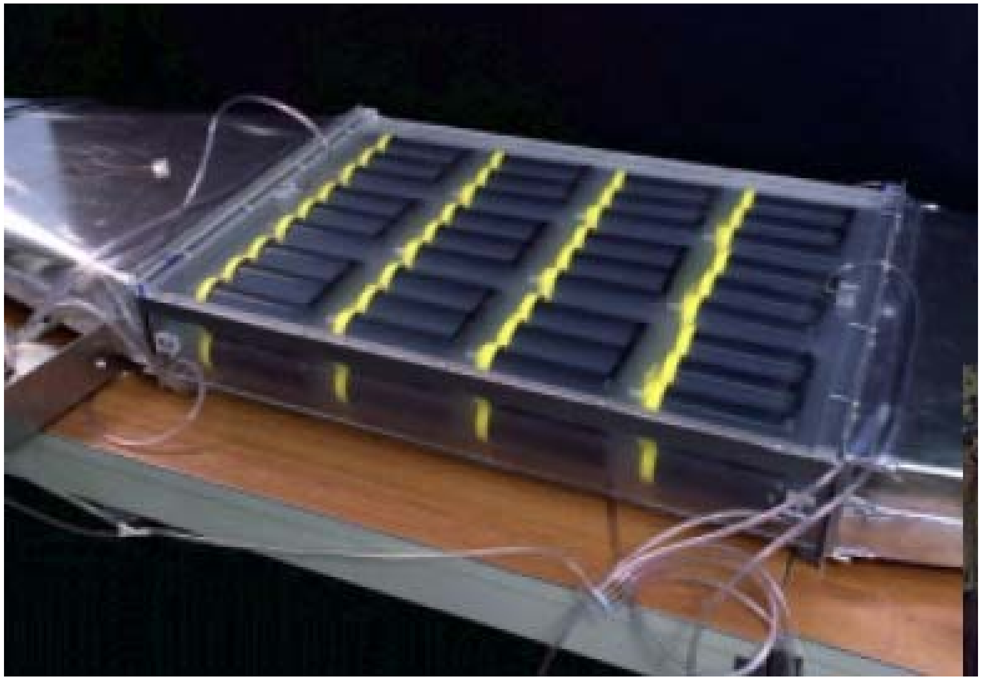
Panasonic prismatic NiMH module

Series Air Distribution

- Series cooling, where air enters from one end of the battery pack and leaves from the other



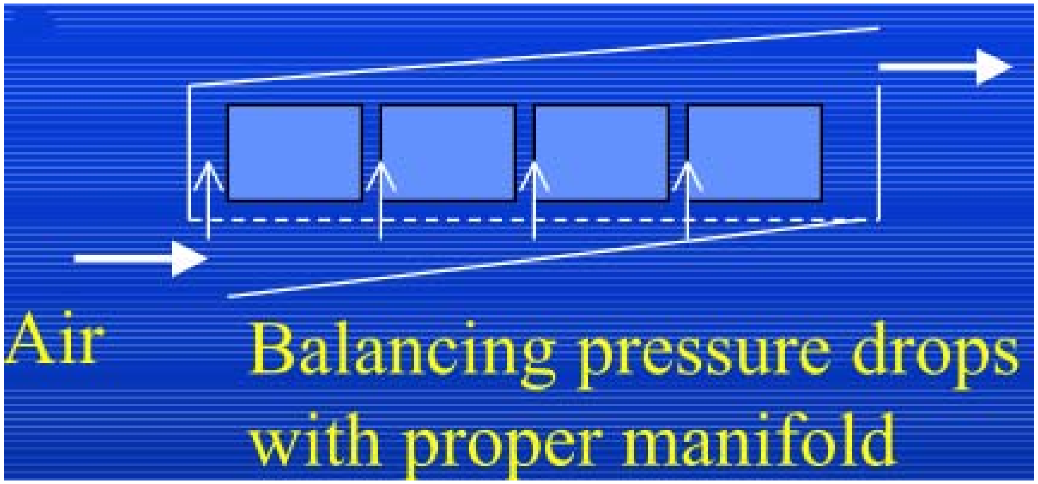




Source: NREL

Parallel Air Distribution

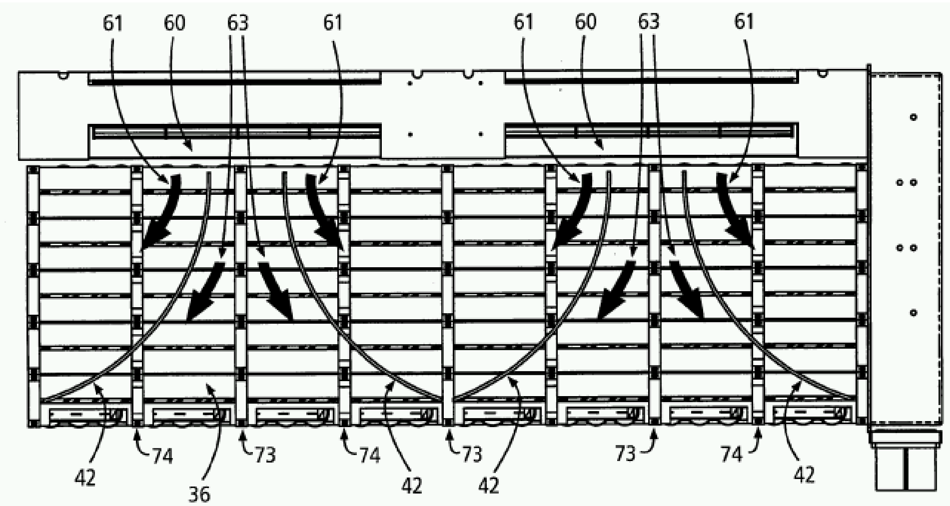
- Parallel cooling, where the same total airflow rate is split into equal portions, and each portion flows over a single module
- EV packs in GM EV1, Toyota RAV4-EV, Honda Insight HEV, and Prius all have either series or series-parallel air distribution.
- In parallel flow design, distributing airflow uniformly to a large battery pack will require a careful design of the air manifold.



Parallel flow Modules upright airflow up

Source: NREL

Parallel Air Distribution



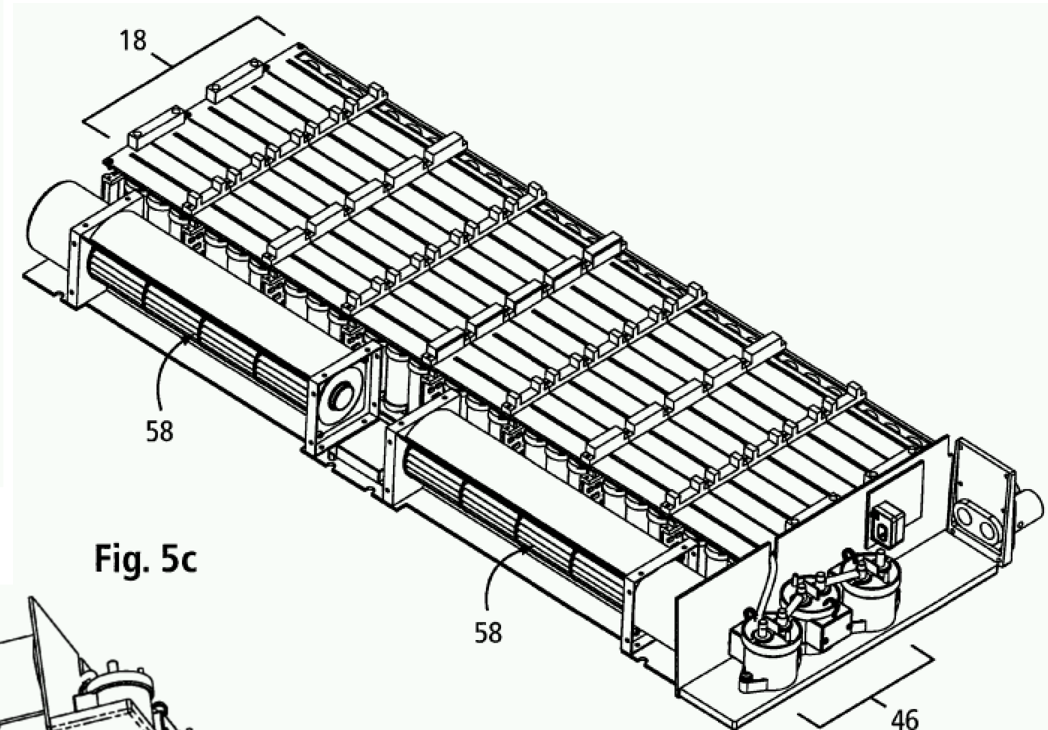
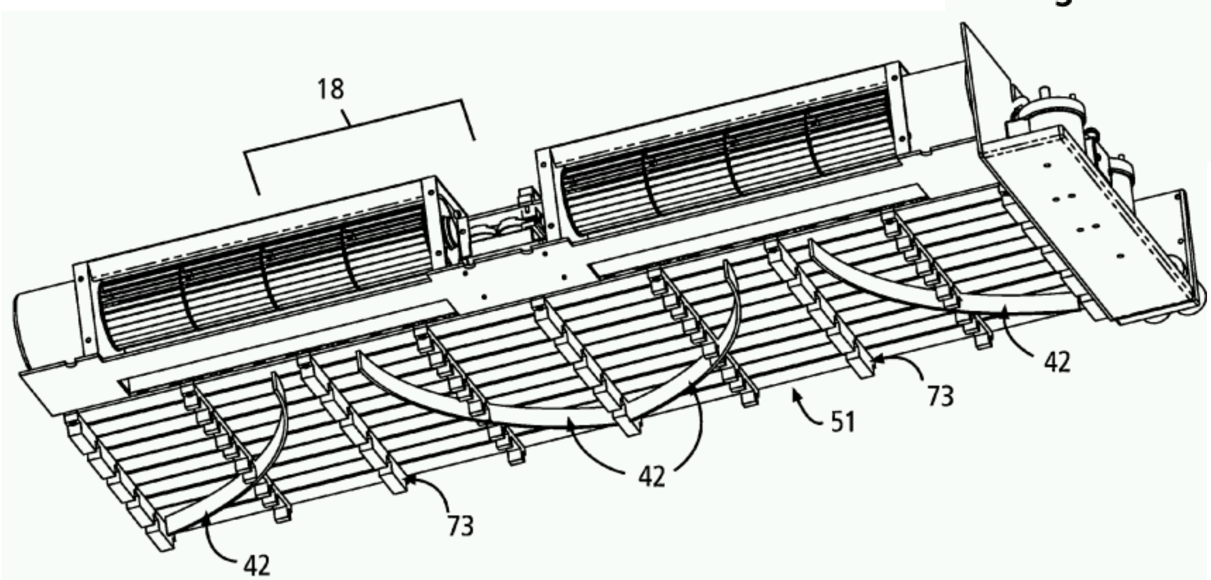
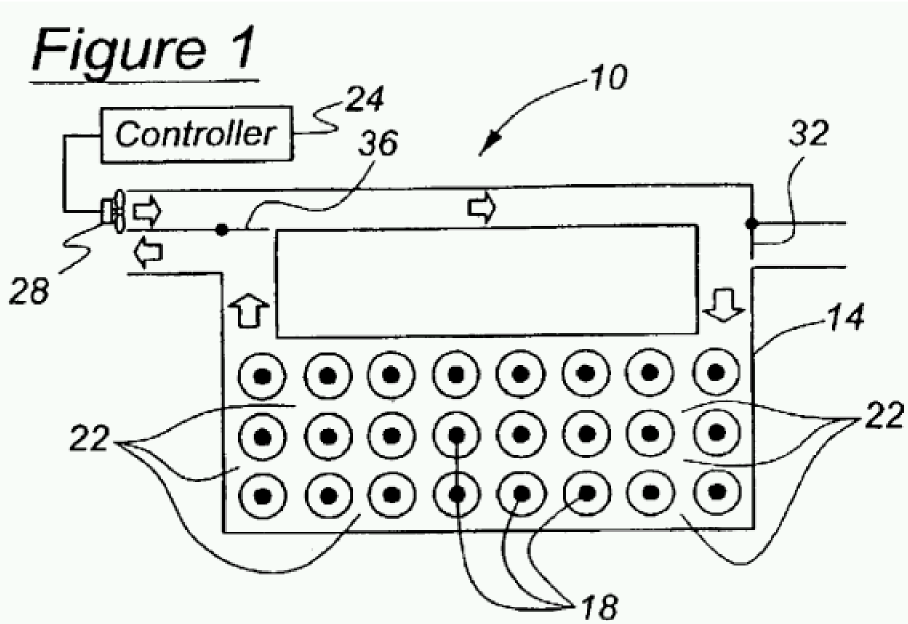


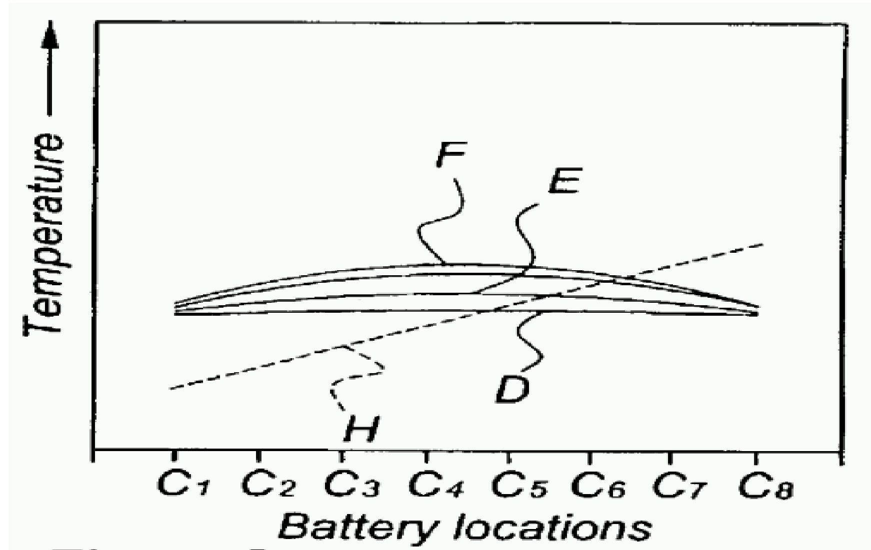
Fig. 5c

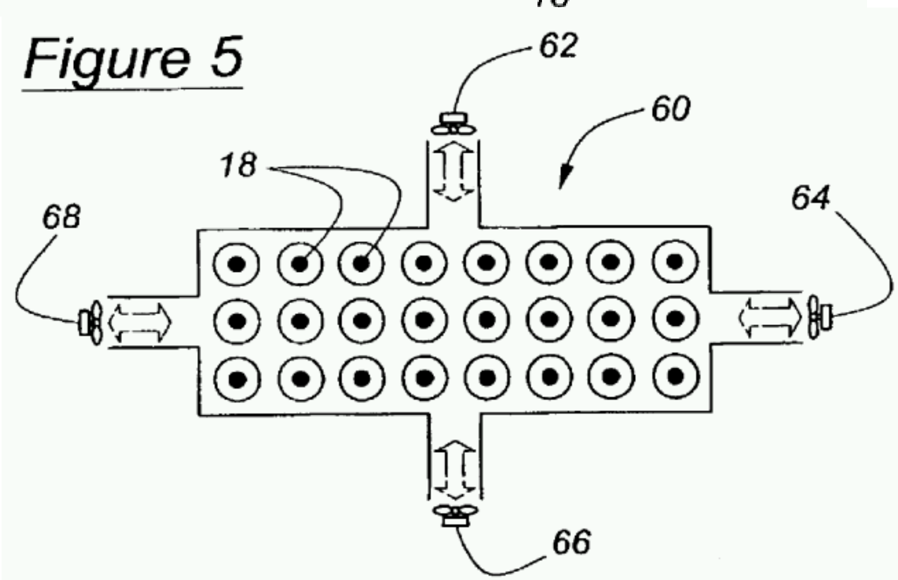


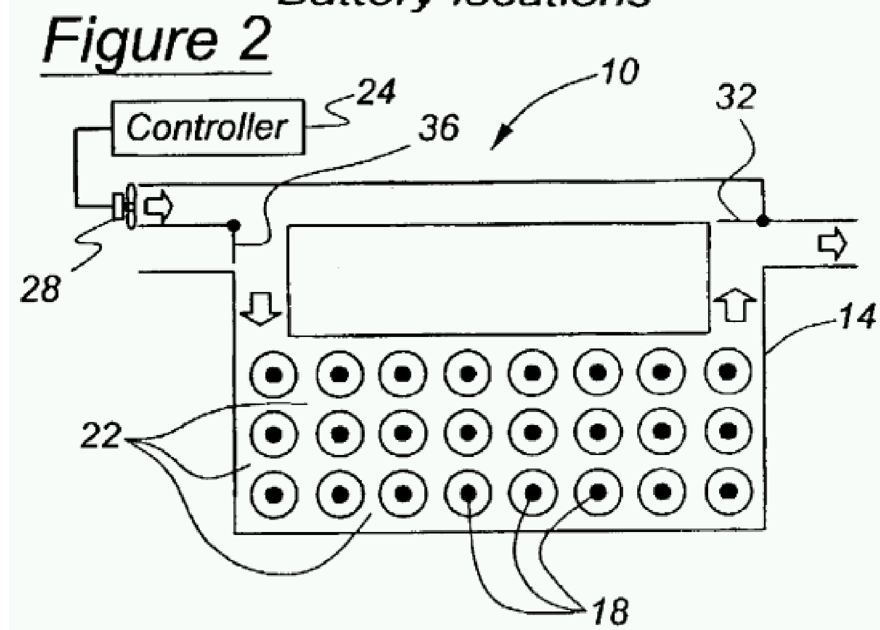
Source: US Patent 2008028019

Reciprocating/Bi-Directional Heat Transfer for Battery Heating or Cooling



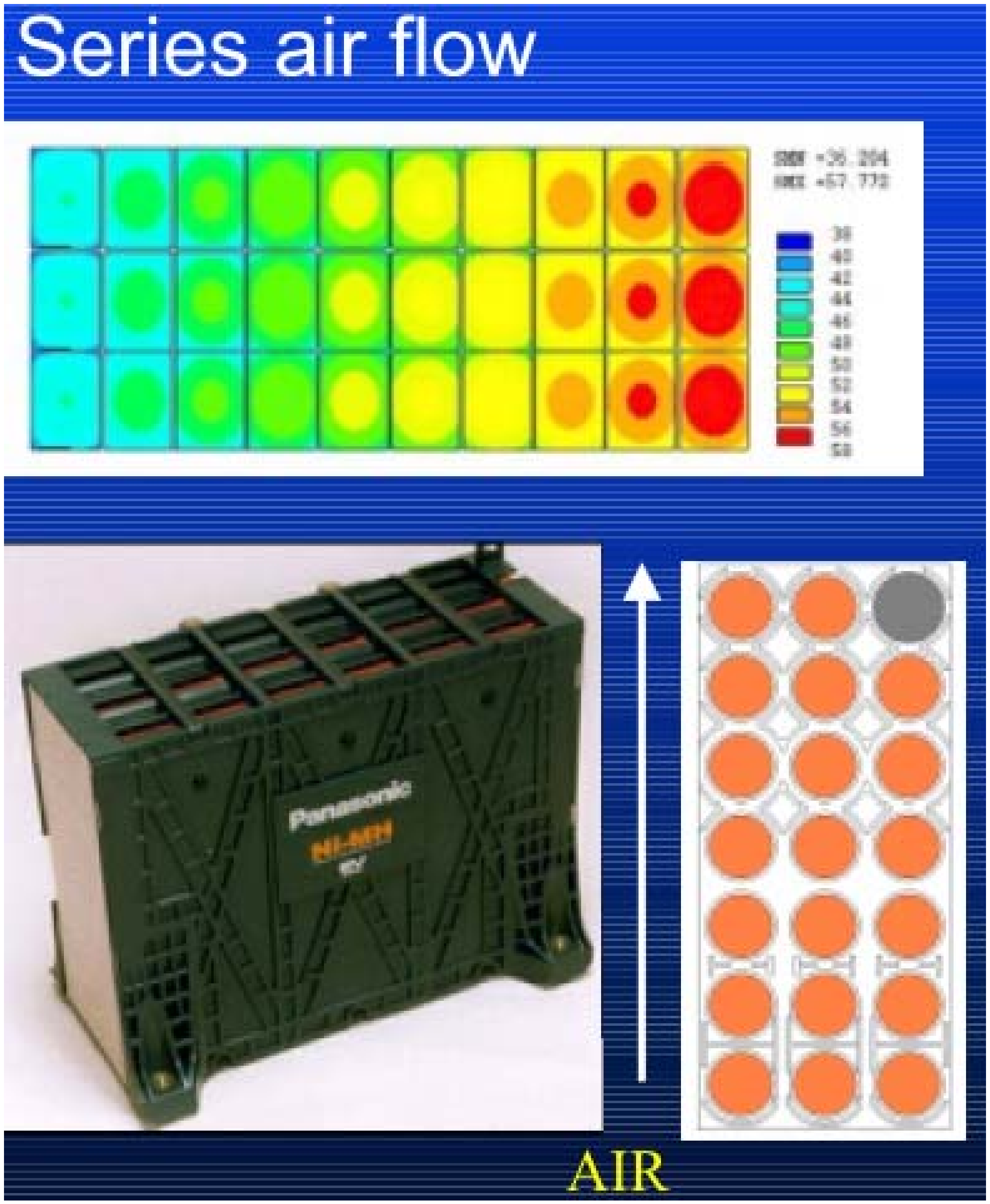


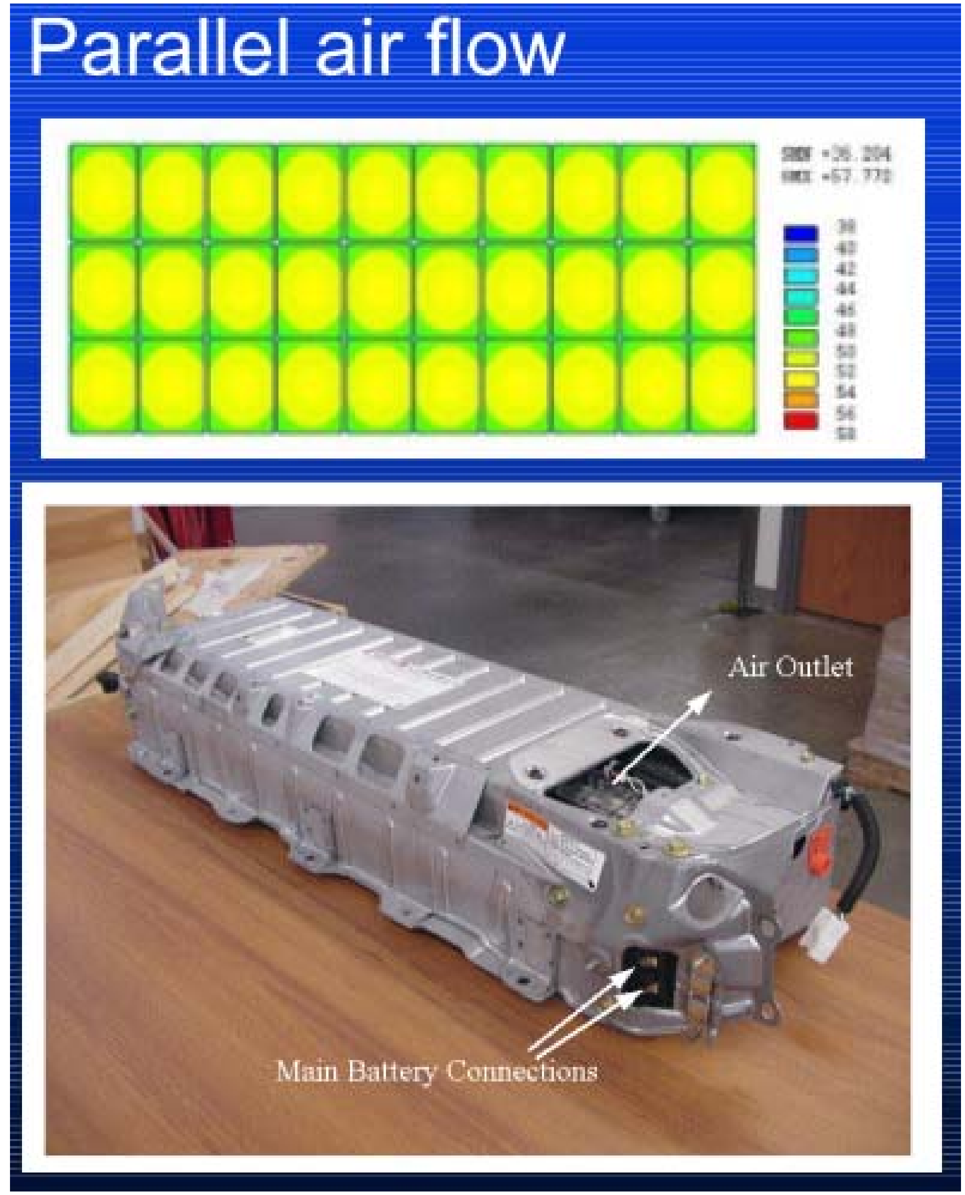




Source: US Patent 7172831

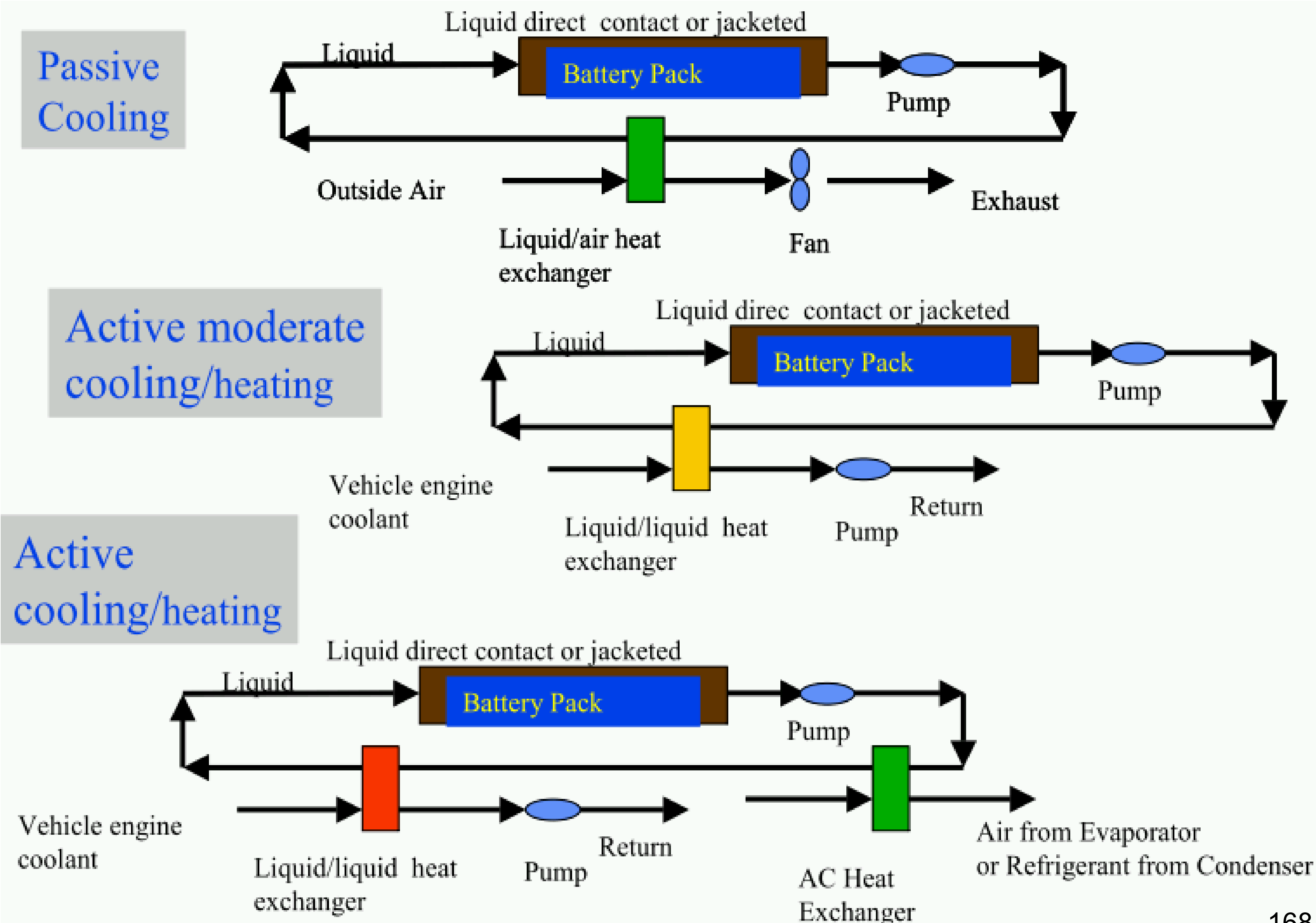
Parallel air flows provides a better temperature distribution





Source: NREL

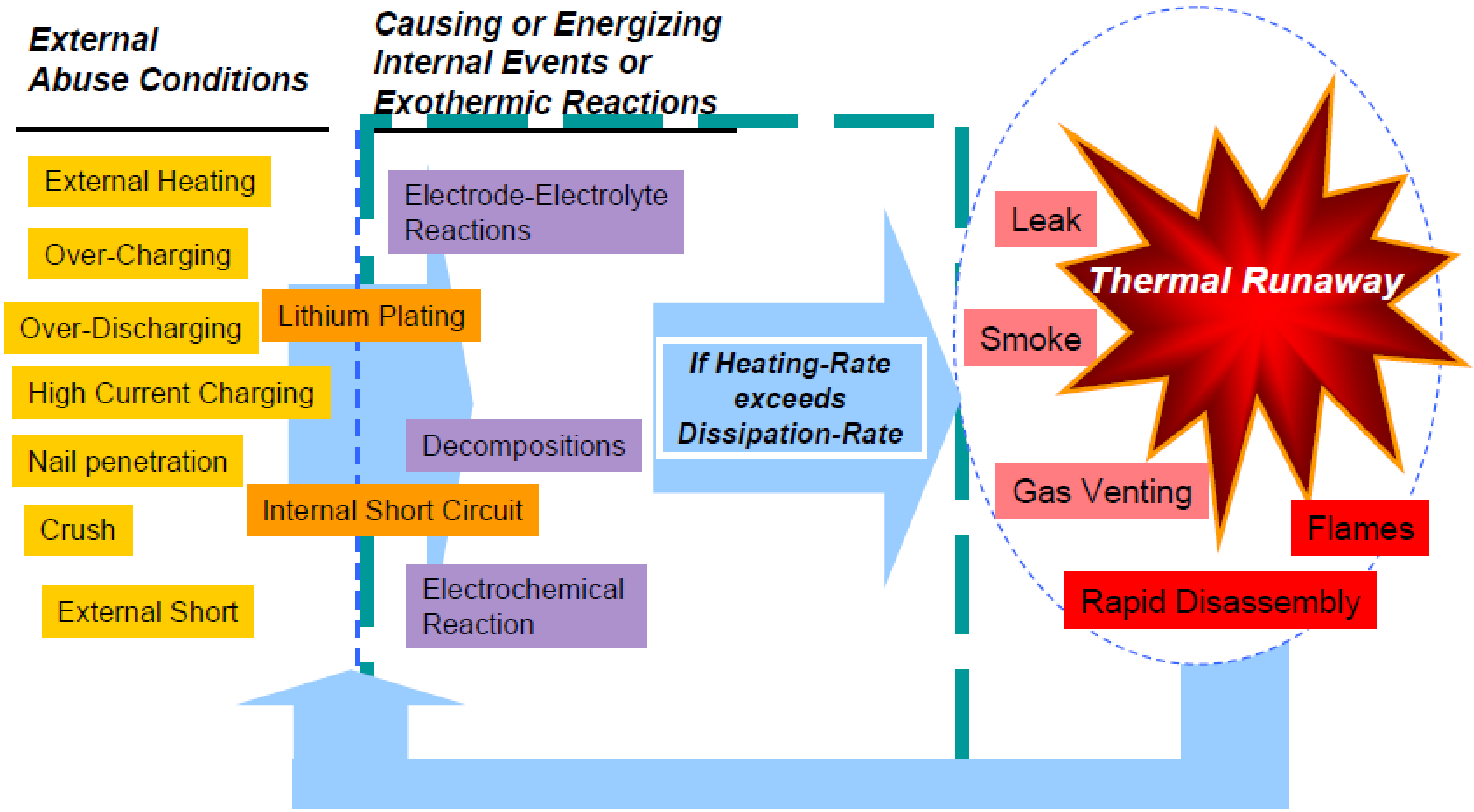
Liquid Cooling



Lithium Battery Thermal Issues

- Li-ion battery are thermally sensitive. Excessive temperature rise could cause the battery to degrade or shorten life cycles.
- Li-ion batteries operating temperature are best to be maintained within -10^{o} to 50^{o}C.
- Cooling of the battery pack is usually a challenge due to strict and limited packaging space.
- Uneven cooling could cause different modules to perform differently.

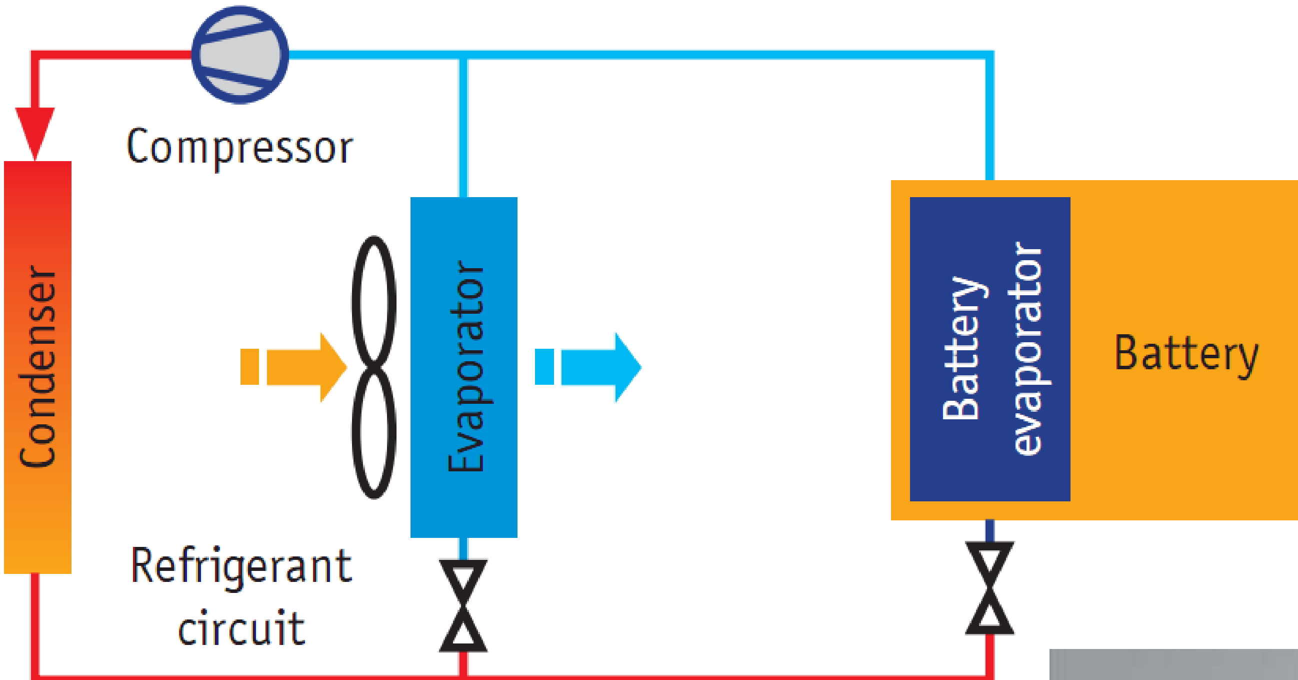
Li-Ion Batteries have highest energy but are the most volatile thermally



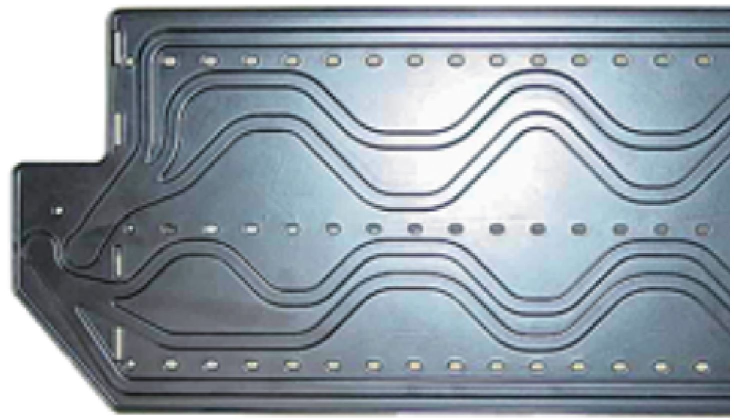
Li-Ion Battery Thermal Management

- Lithium battery packs in hybrid and electric vehicles undergo charging and discharging and active battery cooling is necessary to maintain the cell temperatures within allowable temperature limits ($25^oC \sim 40^oC$).
- Temperature is one of the most significant factors impacting both the performance and life of lithium batteries.
- In order to improve the durability of lithium batteries, it is desirable that the cell temperature remains uniform across the entire pack ($<1^oC$).

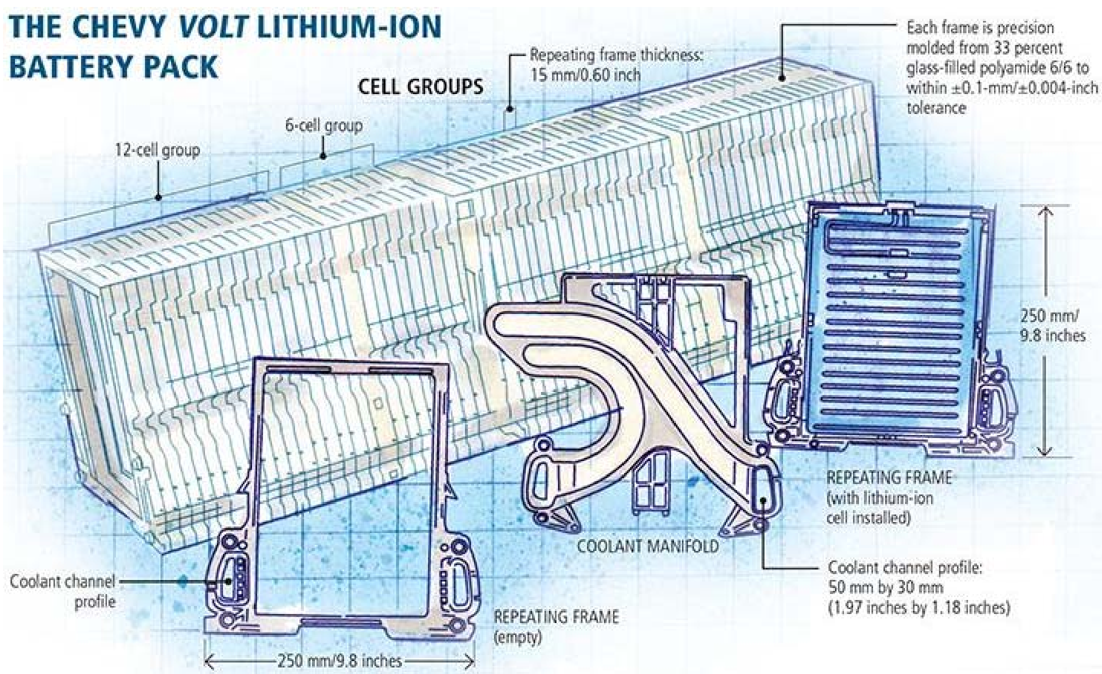
Direct Refrigerant-based Cooling System for Battery Pack

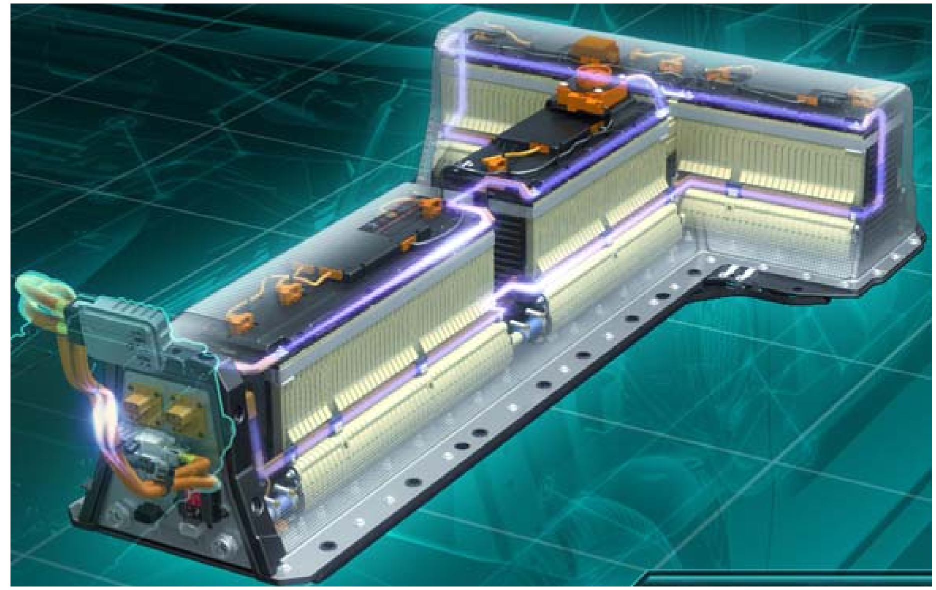


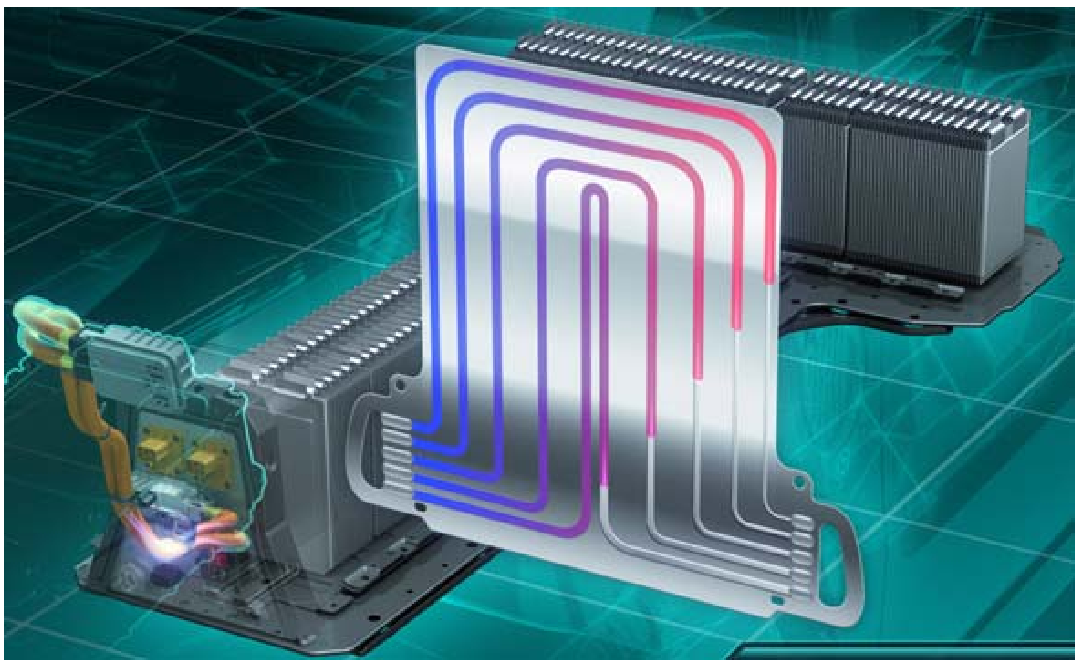
Evaporator plate

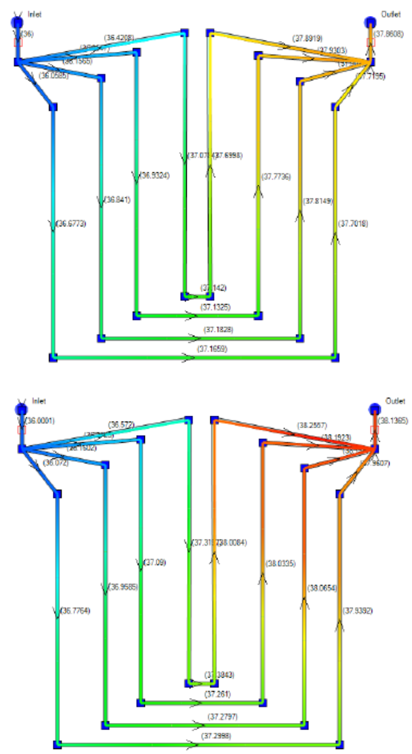


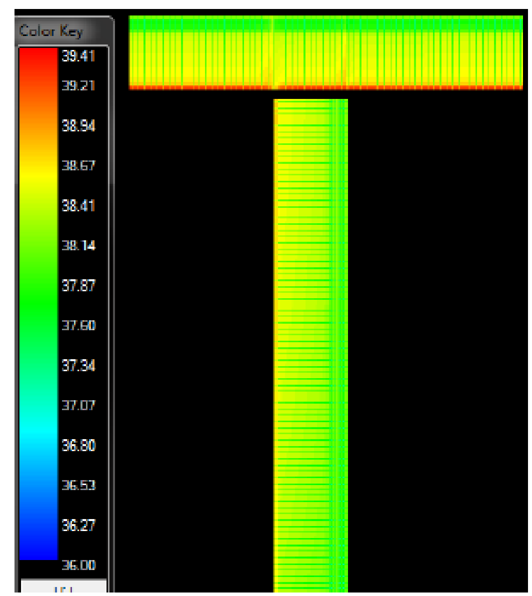
GM Volt PHEV40
Liquid cooled


THE CHEVY VOLT LITHIUM-ION BATTERY PACK
CELL GROUPS
Repeating frame thickness: 15 mm/0.60 inch
Each frame is precision molded from 33 percent glass-filled polyamide 6/6 to within ±0.1-mm/±0.004-inch tolerance
6-cell group
12-cell group
250 mm/ 9.8 inches
REPEATING FRAME (with lithium-ion cell installed)
COOLANT MANIFOLD
Coolant channel profile: 50 mm by 30 mm (1.97 inches by 1.18 inches)
Coolant channel profile
REPEATING FRAME (empty)
250 mm/9.8 inches





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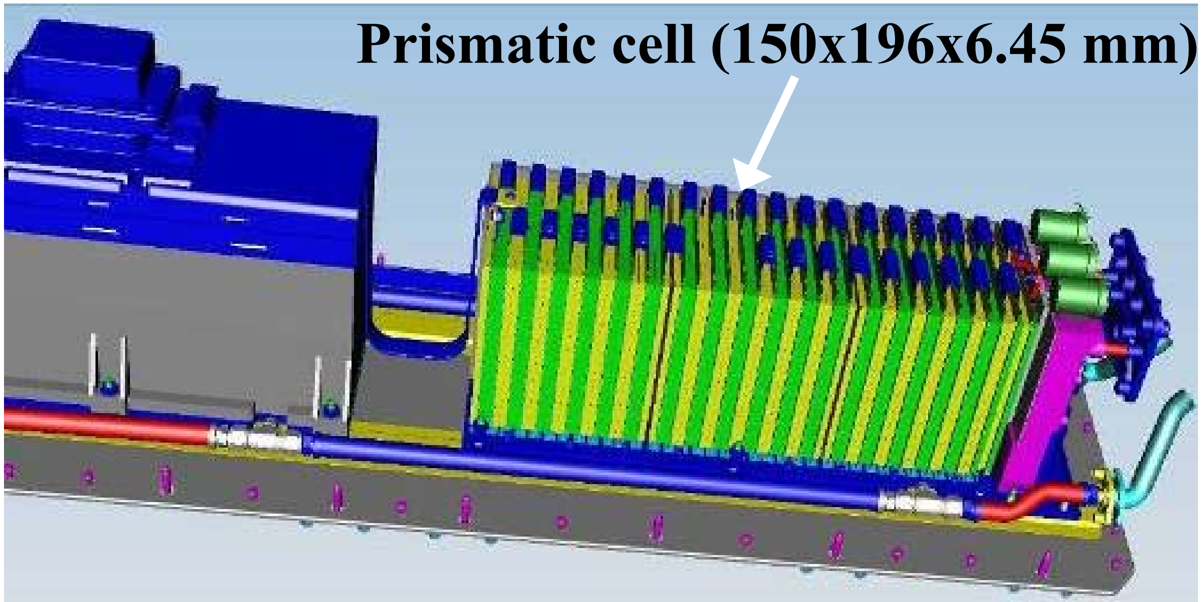
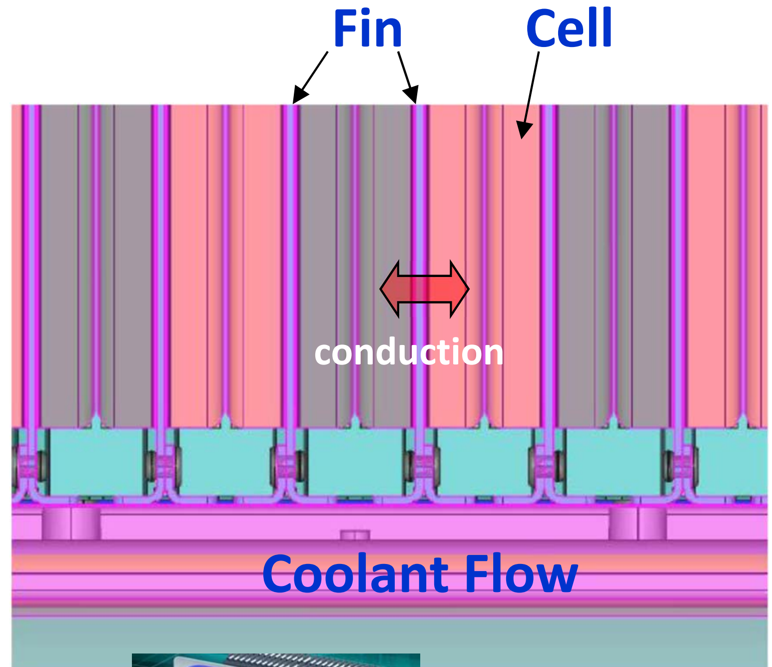
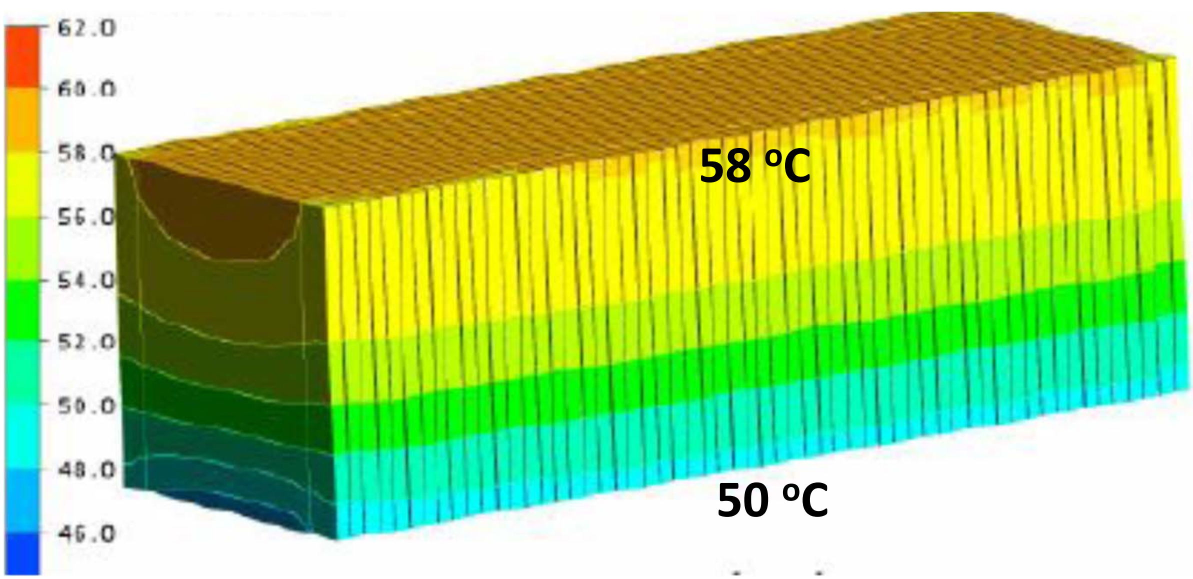
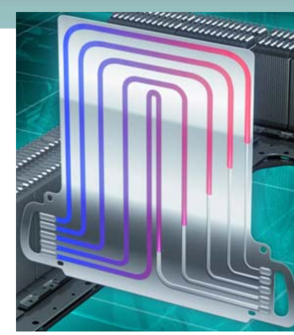
36.00

Liquid Cooled Battery Pack









Fin

Potential Issues

- Fluid pressure drop
- Heat transfer
- Cell temperature uniformity