24th ANNUAL MDEC CONFERENCE
Toronto Airport Hilton Hotel, Canada
October 2 – 4, 2018

MDEC DIESEL WORKSHOP
Diesel Workshop - Battery Technology – Lithium Ion Cells and Diesel Engine Technology & DPF Strategies & Guidelines

PRESENTED BY:

Bapi Surampudi (SwRI)
Evelynn Stirling (Cummins)
Sean McGinn (MKNIZD Factors)
Jan Czerwinski (AFHB)

COORDINATED BY
David Young (Natural Resources Canada)

OCTOBER 4, 2018

MDEC Diesel Workshop

Hilton Toronto Airport Hilton
Ontario, Canada

Thursday, October 4, 2018

BATTERY TECHNOLOGY – LITHIUM ION CELLS

08:15 – 8:45	Overview of Automotive xEV markets and vehicle electrification	(**Pg 1-32**)
08:45 – 9:45	Overview of fundamentals and state of the art Lithium Ion Cells	**(Pg 33-81)**
09:45 – 10:15	Benchmarking of Lithium Ion Cells	**(Pg 82-104)**
10:15 – 10:30	**Break Time**	
10:30 – 10:45	Benchmarking of Lithium Ion Cells (continued)	**(Pg 82-104)**
10:45 – 11:30	Case Study: Diesel Engine Accessory Electrification on a Class 8 Truck	**(Pg 105-116)**
11:30 – 12:15	Testing of Electrified Powertrains at Southwest Research Institute	**(Pg 117-129)**
12:15 – 12:45	**LUNCH**	
12:45 – 13:15	Q&A	

DIESEL ENGINE TECHNOLOGY & DPF STRATEGIES & GUIDELINES

13:15 – 14:30	Enabling Technologies - Diesel through hybrid, Evelynn Stirling (Cummins)	**(Pg 130-139)**
14:30 – 14:45	**Break Time**	
14:45 – 15:30	Retrofit of DPF Technology to Mining Engines – Technical Aspects, Sean McGinn (MKNIZD Factors Inc.)	**(Pg 140-149)**
15:30 – 16:15	Experiences of VERT in DPF- retrofitting and I&M, Professor Jan Czerwinski (AFHB)	**(Pg 150-162)**
16:15 – 16:30	Q&A, Adjournment	

MDEC – 2018
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Overview Of Automotive xEV Markets and Vehicle Electrification

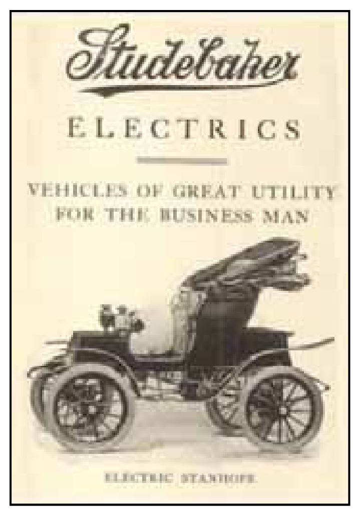
Bapi Surampudi, Ph.D.

Brief History of Vehicle Electrification

Electric Vehicle Technology Cycles

Inventor: Robert Anderson
From Scotland
1832

Baker Electric Runabout
1909



Peak Electric Vehicle Sales
37% EV
40% Steam
22% ICE

Electric Vehicle Technology Cycles

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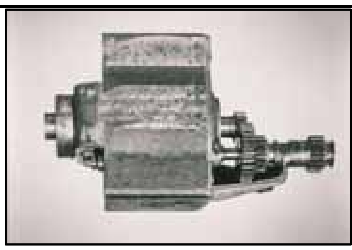

Invention of Electric Starter
1912

Oil Tycoons/Cheap Oil
1920 - 1930

Extinction of Electric Vehicle
1935

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Electric Vehicle Technology Cycles

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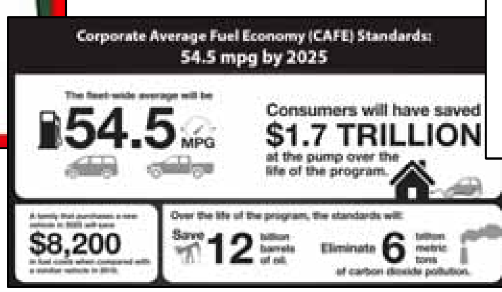
OPEC Embargo
1973

GM EVI &
Prius Hybrid
1996-97



CAFE Standards – 1973

CARB ZEV Regulation
1990

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Electric Vehicle Technology Cycles

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Cheap Oil – 1997-2007

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Electric Vehicle Technology Cycles

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$145/Barrel
2008

Nissan Leaf
2011

Tesla Model S
2013

Chevy Bolt
2016

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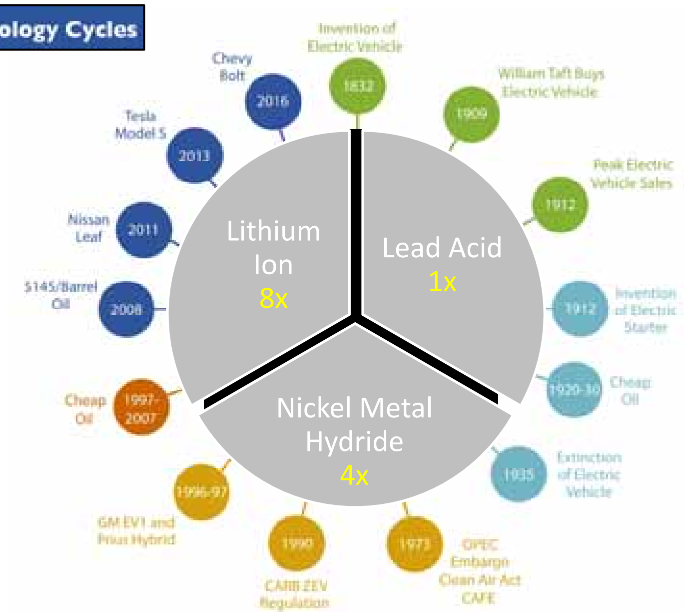
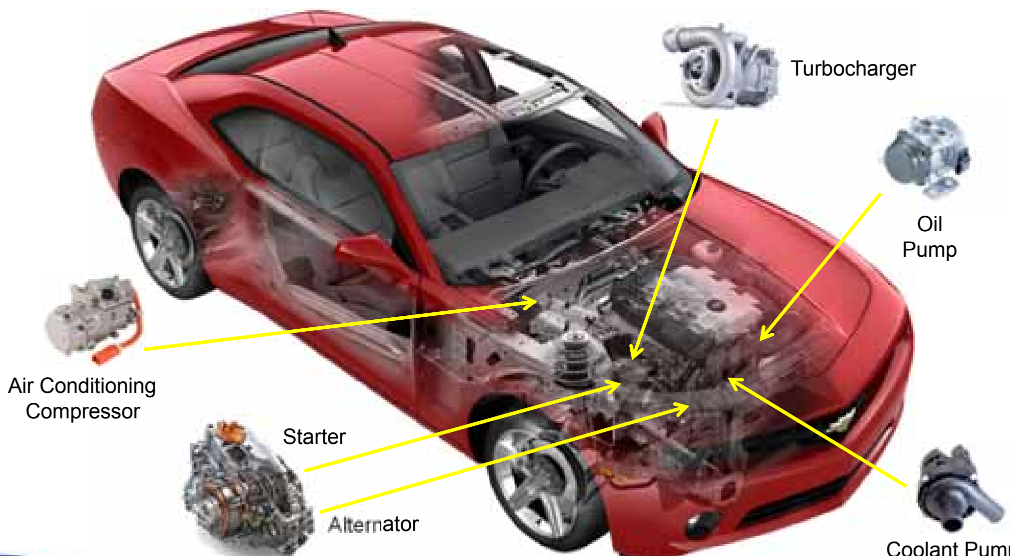
Electric Vehicle Technology Cycles



Electrification Opportunities



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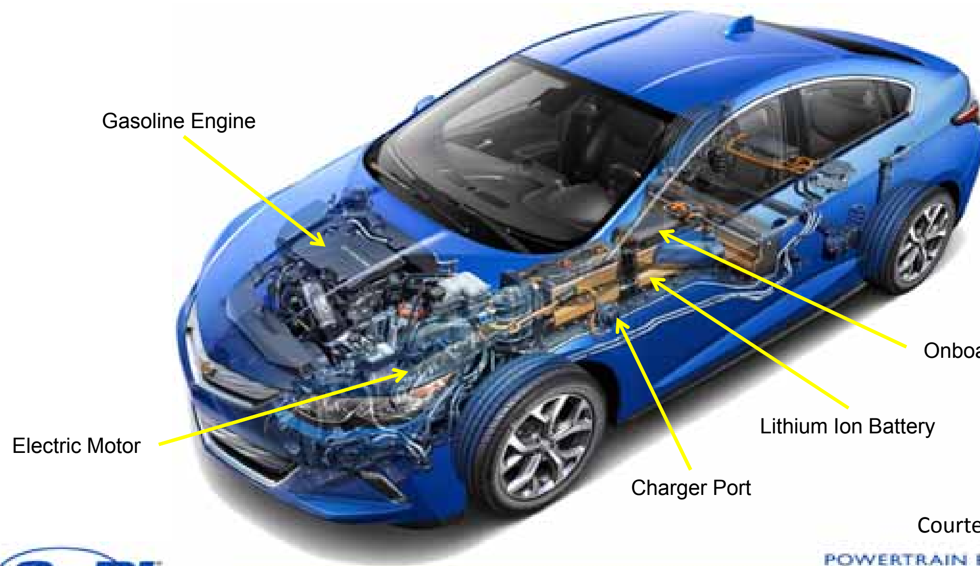
Plug-In Hybrid EV or Range-Extended EV



Courtesy: General Motors

Forecasts in Electrification

OEM Electric Car Announcements

- **BMW** – have 15-25% of BMW group's sales be all electric and 25 electrified vehicles by 2025
- **Daimler** – 0.1 million annual electric car sales by 2020
- **VW** – 2-3 million annual electric car sales by 2025
- **Ford** – 13 new EV models by 2020
- **Honda** – 2/3 of 2030 sales be HEVs, PHEVs, BEVs and FCEVs
- **Renault-Nissan** – 1.5 million cumulative annual electric car sales by 2020
- **Volvo** – 1 million cumulative electric car sales by 2025
- **Tesla** – 1 million annual electric car sales by 2020

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xEV Growth

China overtook the United States in electric vehicle stock

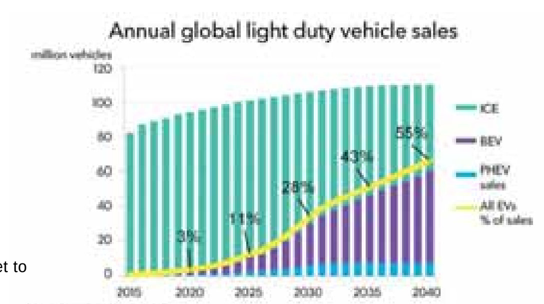
- 200,000 electric two-wheelers & 300,000 buses

Courtesy of the International Energy Agency
Global EV Outlook 2017

EV Sales Projections

- 2017 1.1 million
- 2025 11 million (50% China)
- 2030 30 million (39% China)
- 2040 60 million
  - 80% of global municipal bus fleet to be electric

Courtesy of the Bloomberg
Electric Vehicle Outlook 2018



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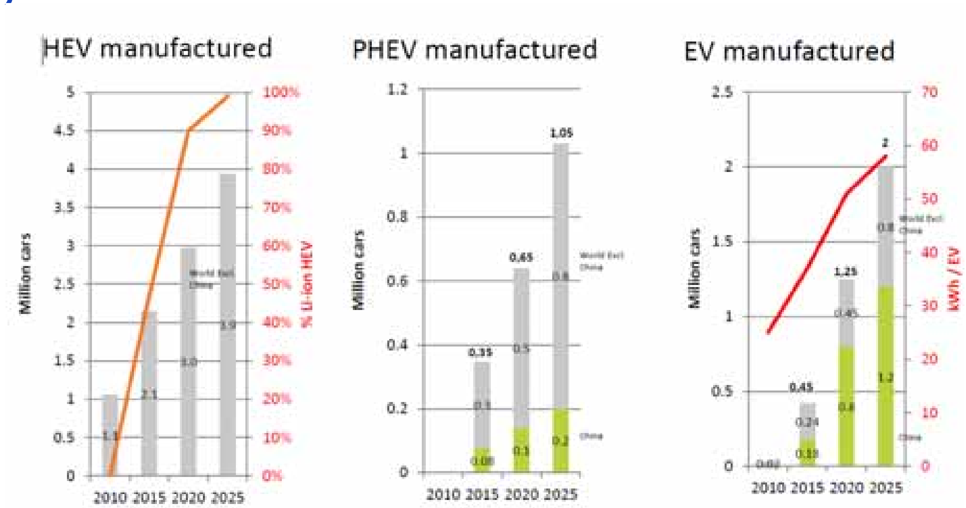
HEV, PHEV and EV Forecasts



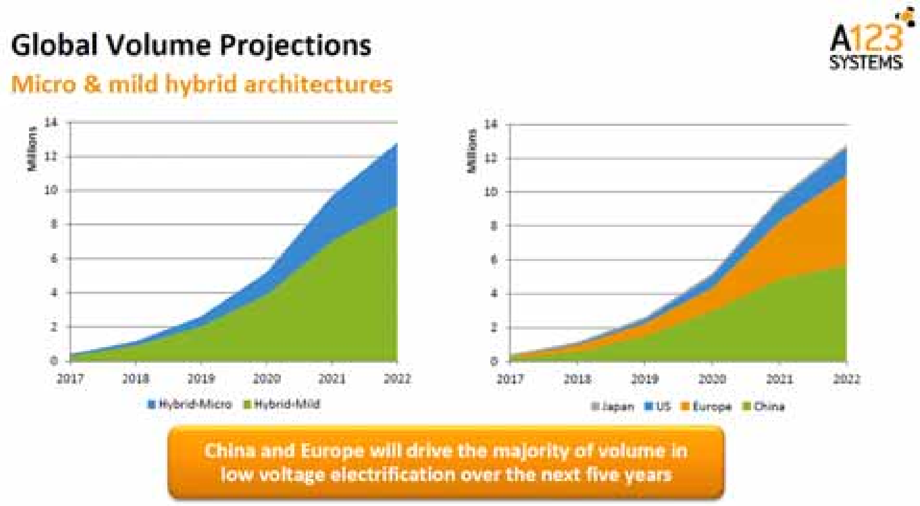
Courtesy: Avicenne Energy, 2017

Rise of the 48V Mild Hybrid

- **FCA eTorque System**
  - Jeep Wrangler & Dodge Ram
  - 48V BiSG (up to 90 Nm of torque)
  - 0.3 kWh lithium-ion battery pack

- **Mercedes M256 Engine**
  - Mercedes' first 48V system
  - 5 kW electric compressor (off to full boost in 0.3 seconds)
  - Integrated starter generator (between engine & transmission)
  - 48V 1 kWh lithium-ion battery pack
  - 48V electrified AC compressor & water pump

Low Voltage Hybrid Market Projections



Courtesy: A123 Systems

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Trends in Energy Storage

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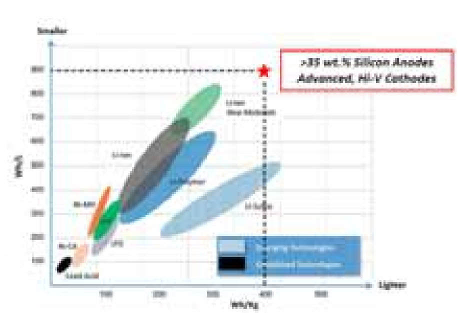
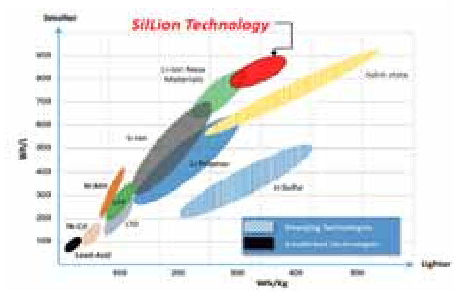
Trends in Energy and Volume Density

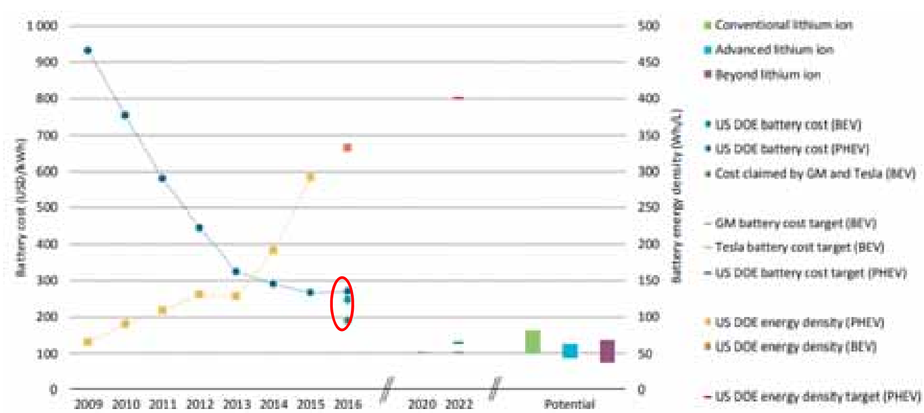
- Silicon in Anode and Nickel in Cathode will increase to deliver higher energy densities
- High energy (350 Wh/kg, 800 Wh/L designs currently proven)
- Non-flammable electrolyte + high temperature operation
- Low cost (30% lower $/kWh, cell level)



Courtesy: SilLion Inc



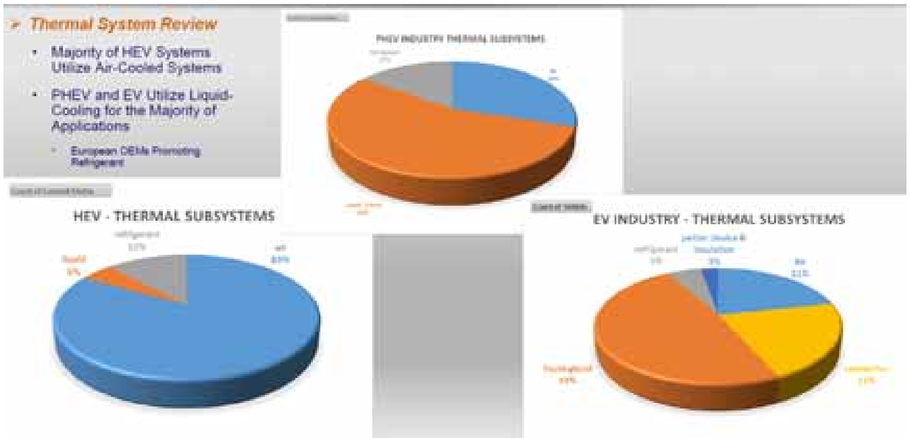
Battery Cost & Energy Density



Assumes battery pack capable of delivering 320 km of range (~100 kW)

Courtesy of the International Energy Agency Global EV Outlook 2017

Thermal Systems Review



Courtesy: kevin Konecky - Total Battery Consulting and AABC 2017 SFO

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State of the Art Vehicles and View of OEMs

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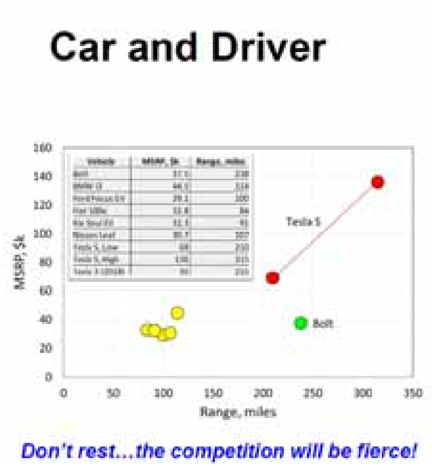
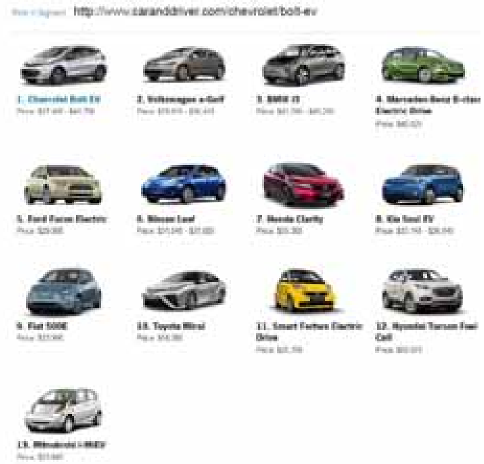
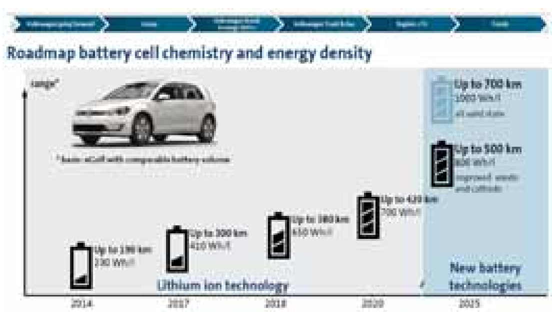
EV Price vs Range





Volkswagen Roadmap



- Shift focus from diesel towards electrification & EV
- Four new light-duty vehicles
  - 250+ mile range expected for all
- Pull of electrification making its way into motorsports
  - VW I.D. R breaks Pikes Peak World Record

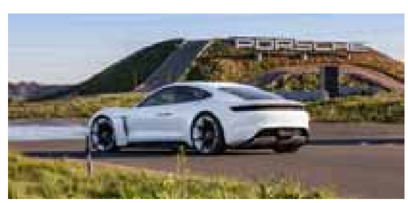
Courtesy: Volkswagen and Dr. Adermann at AABC 2017

BMW

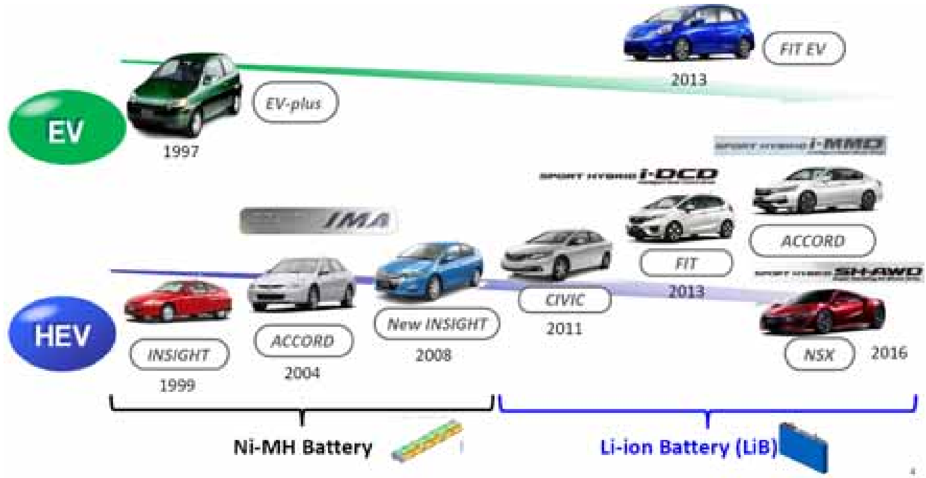
- By 2025 BMW will have 25 electrified vehicles including 12 fully electric models
  - All-electric Mini in 2019
  - All-electric iX3 in 2020
  - iNext & i4 expected to hit production 2021
    - 340 to 435 mile range (over WLTP)

Porsche

- **Panamera E-Hybrid**
  - Plug-in hybrid capable of 30 miles all-electric range
  - 14.1 kWh battery pack (104 liquid-cooled Li-Ion cells)
  - 101 kW electric motor
- **Taycan (prev. Mission E)**
  - Target release moved forward to 2019
  - Two electric motors for 440 kW
  - 800 VDC
    - Inductive charging
  - 250 mile range with 200 miles in just 15 minutes (@ 350 kW charging)



Honda Roadmap - Vehicles



Courtesy: Honda and AABC SFO 2017

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Hyundai Ioniq Project

Courtesy: HYUNDAI

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Kia-Niro HEV & EV

16 electrified vehicles by 2025

Niro EV

- 64 kWh lithium-polymer battery
- 150 kW electric motor
- 238 mi range
- Autonomous driving features

Courtesy: HYUNDAI

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Tesla

- **Roadster** announced November 2017
  - 200 kWh pack
  - 620 mile range
  - Estimated production of 2020

- **Semi** announced November 2017
  - Class 8 truck
  - 36 metric ton towing capacity
  - Recovers 98% of braking energy
  - Megachargers – 400 mile range in 30 minutes
  - 500 mile range with < 2kW/mi

Courtesy: Tesla

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Shenzhen Bus Fleet Converted to Full Electric

- China chose Shenzhen to be a pilot city for electric transportation in 2009
- 16,359 all-electric buses
  - BYD providing 80%
  - Over10,000 more buses than all of NYC's buses
  - 510 charging stations and 8,000 poles installed
- The city's 17,000+ taxis are next on the radar
  - 63% are already electric

Heavy-Duty Electrification

- This trend of electrification and a push towards xEV has not been limited to just the light-duty sector
  - **Cummins, Daimler, Volvo** and more have announced concepts & plans for electric versions of their products

eCanter Truck

- Claimed range is 62 miles on an 83 kWh battery pack
- Cargo capacity is 3 – 4.5 tons

Urban Hauler EV

- 8,164 kg curb weight
- 100 mile range on 140 kWh battery
- 1-hour charge time
- Can tow a 20 metric ton trailer

All Electric Class 8 Tractor from TransPower

- http://www.truckinginfo.com/channel/fuel-smarts/article/story/2015/10/transpower-s-totally-electric-class-8-tractor-video.aspx
- TransPower USA is located in Long Beach, California, engineered the electric powertrain
- Chassis and Cab are from International
- Two 200 hp electric mtoors
- Range 80 miles when pulling 80,000 lbs at 65 mph
- Next gen technology range 120 miles

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Off Highway Applications

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Grouping of Electrical Technology
HITACHI
Grouping based on power supply
by Hybrid
(Diesel and Electric source)
ZH210LC-5, 21 t, 122 kW
L130, 13 m³, 105 t, 735 kW
by Battery
2 way supply
by Electrically
EX5500E-6, 2 x 860 kW
EH4500, 280 t
by Electrically
by Diesel
Electrically
EH3500, 190 t payload
Courtesy: Hitachi
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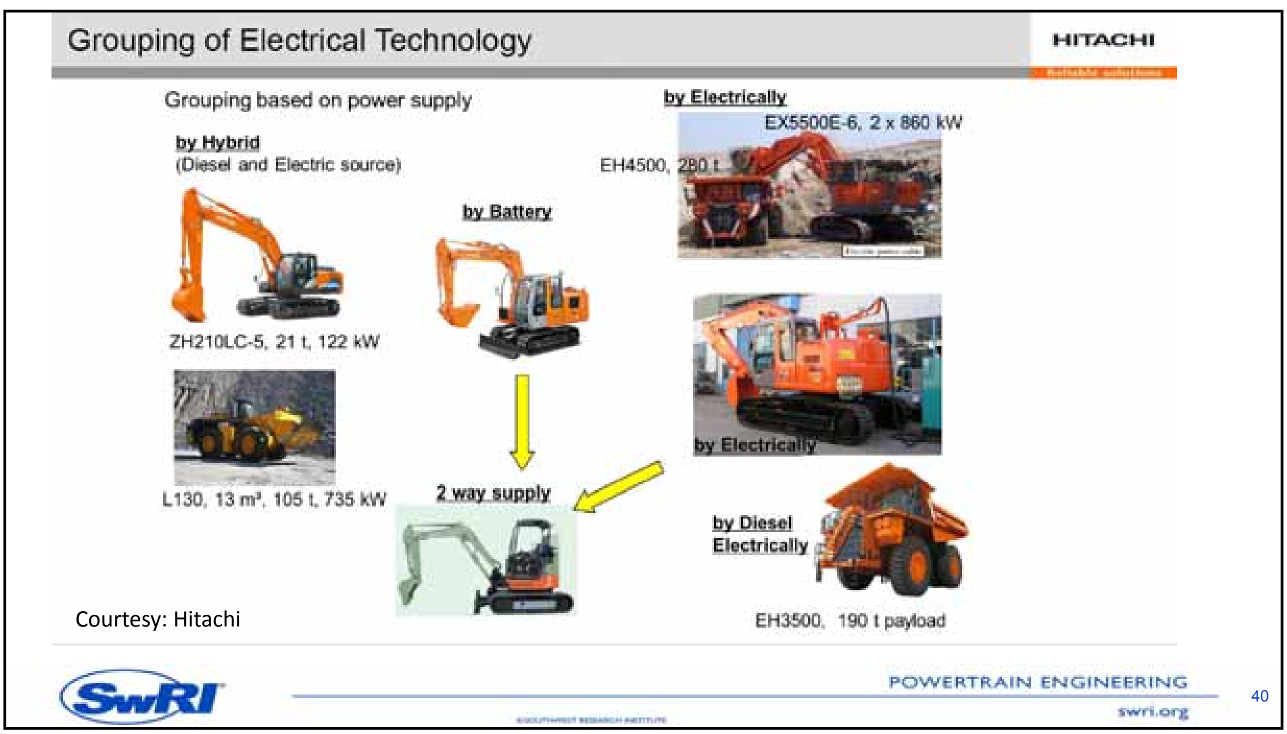
Grouping of Electrical Technology
HITACHI
Grouping based on power supply
by Hybrid
(Diesel and Electric source)
ZH210LC-5, 21 t, 122 kW
L130, 13 m³, 105 t, 735 kW
by Battery
2 way supply
by Electrically
EX5500E-6, 2 x 860 kW
EH4500, 280 t
by Electrically
by Diesel
Electrically
EH3500, 190 t payload
Courtesy: Hitachi
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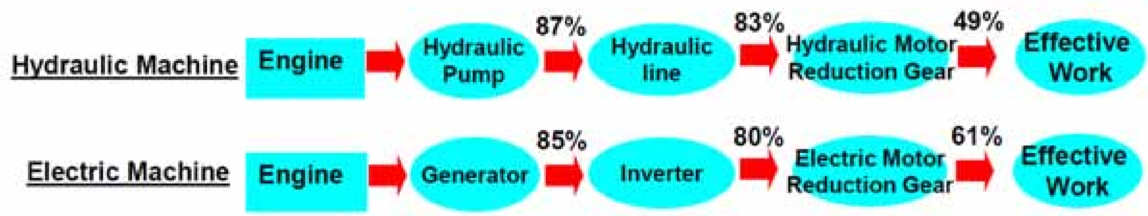
Energy loss at hydraulic and electric power systems

HITACHI



Fuel consumption of different hybrid systems

System	Fuel Consumption Ratio
2-pump System (Conventional System)	1
Serial Hybrid 2-pump System	1.10
Parallel Hybrid 2-pump System	0.86
Serial Hybrid 4-pump System	0.46
Parallel Hybrid 4-pump System	0.40
Double-pump Regeneration System	0.43
4-pump Hydraulic System	0.41

Source: Ochiai, M. Hybrid in Construction Machinery. Hitachi, Japan, 2008

Courtesy: Hitachi

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New Hybrid Excavator ZH210LC-5B

HITACHI

Courtesy: Hitachi

Empower your Vision.

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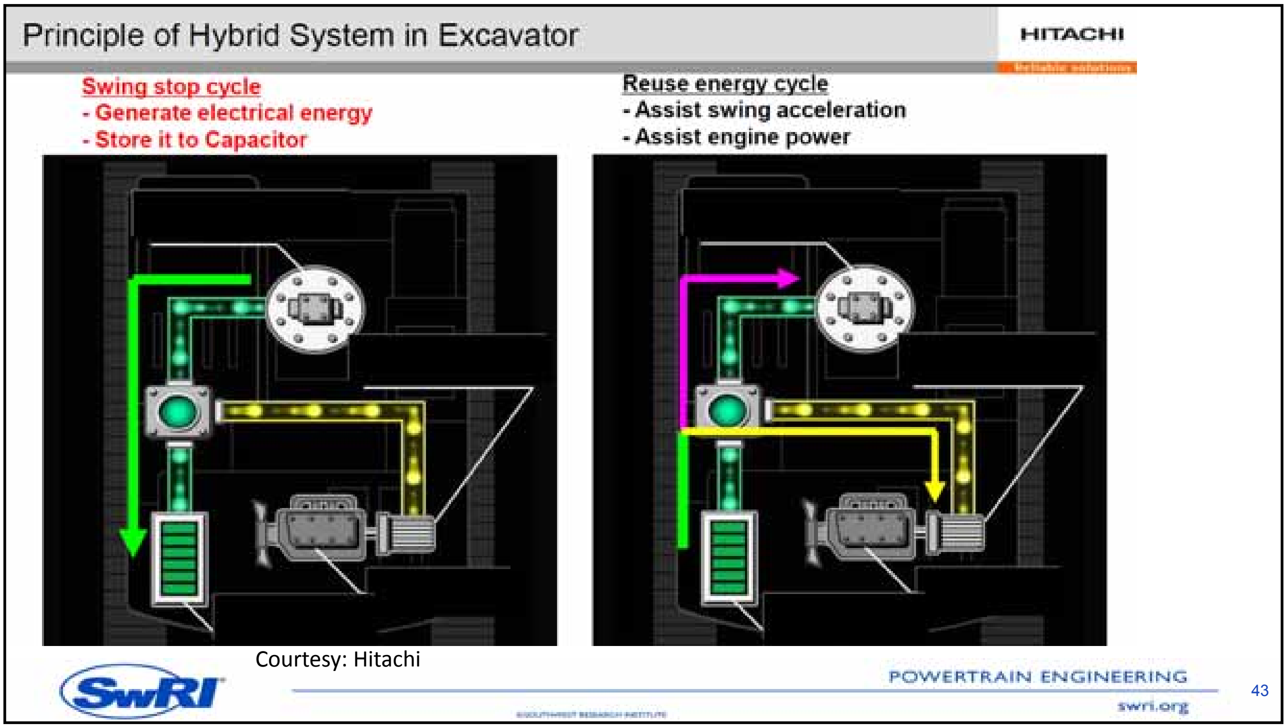
Principle of Hybrid System in Excavator
HITACHI
Swing stop cycle
- Generate electrical energy
- Store it to Capacitor
Reuse energy cycle
- Assist swing acceleration
- Assist engine power
Courtesy: Hitachi
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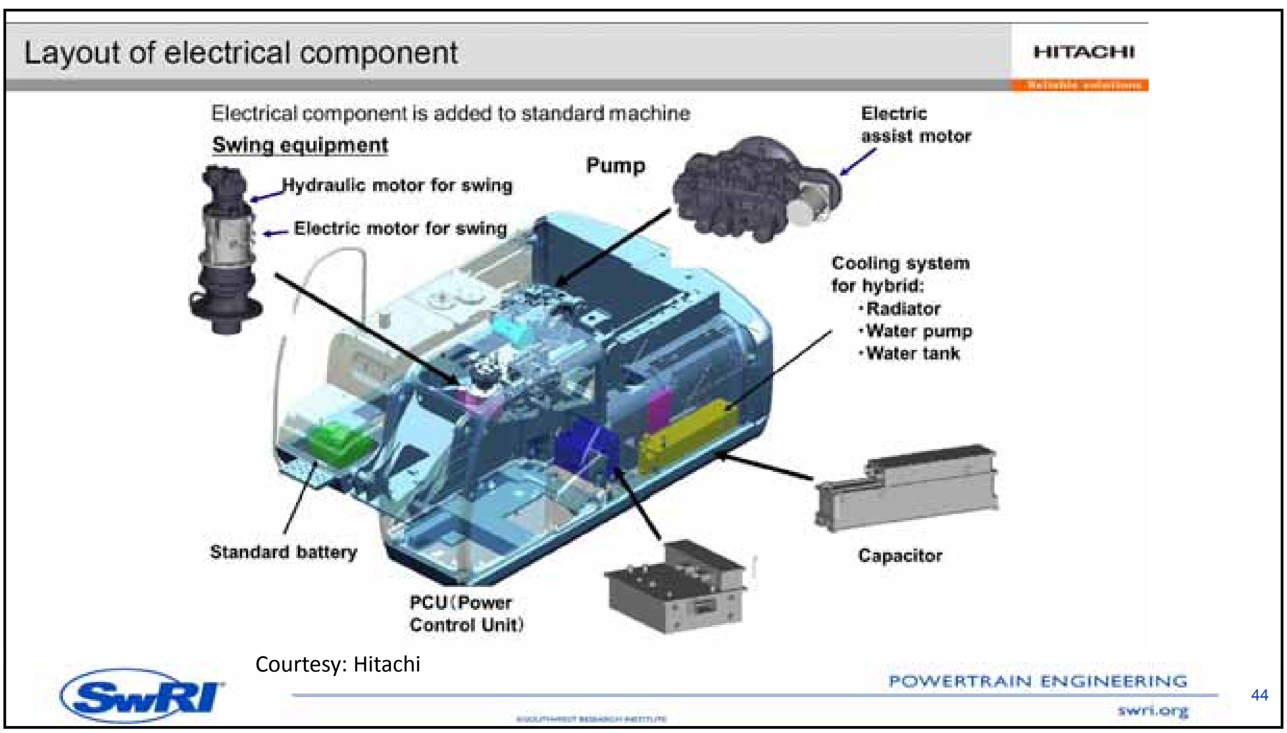
Layout of electrical component
HITACHI
Electrical component is added to standard machine
Swing equipment
Hydraulic motor for swing
Electric motor for swing
Pump
Electric assist motor
Cooling system for hybrid:
・Radiator
・Water pump
・Water tank
Standard battery
PCU (Power Control Unit)
Capacitor
Courtesy: Hitachi
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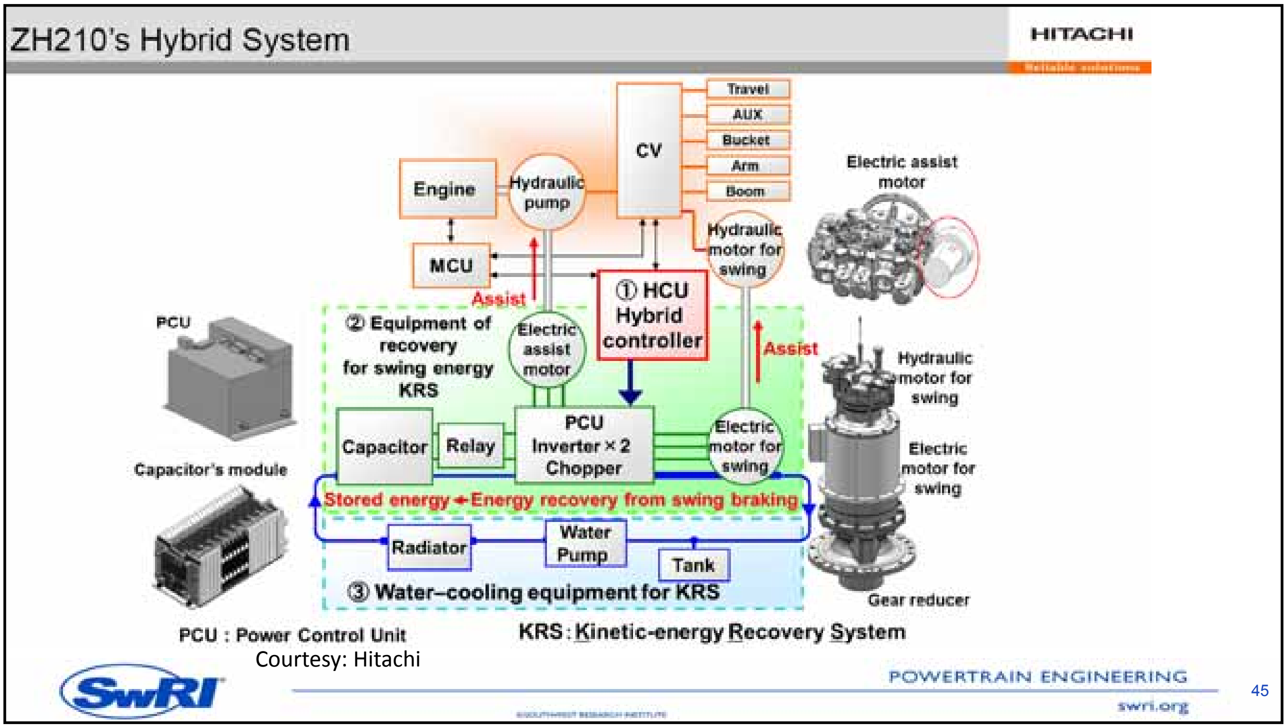
ZH210's Hybrid System
HITACHI
Travel
AUX
Bucket
Arm
Boom
CV
Engine
Hydraulic pump
MCU
Assist
Hydraulic motor for swing
Electric assist motor
① HCU Hybrid controller
② Equipment of recovery for swing energy KRS
Electric assist motor
Assist
PCU
Capacitor
Relay
PCU Inverter × 2 Chopper
Electric motor for swing
Hydraulic motor for swing
Electric motor for swing
Capacitor's module
Stored energy ← Energy recovery from swing braking
Radiator
Water Pump
Tank
③ Water–cooling equipment for KRS
Gear reducer
PCU : Power Control Unit
KRS : Kinetic-energy Recovery System
Courtesy: Hitachi
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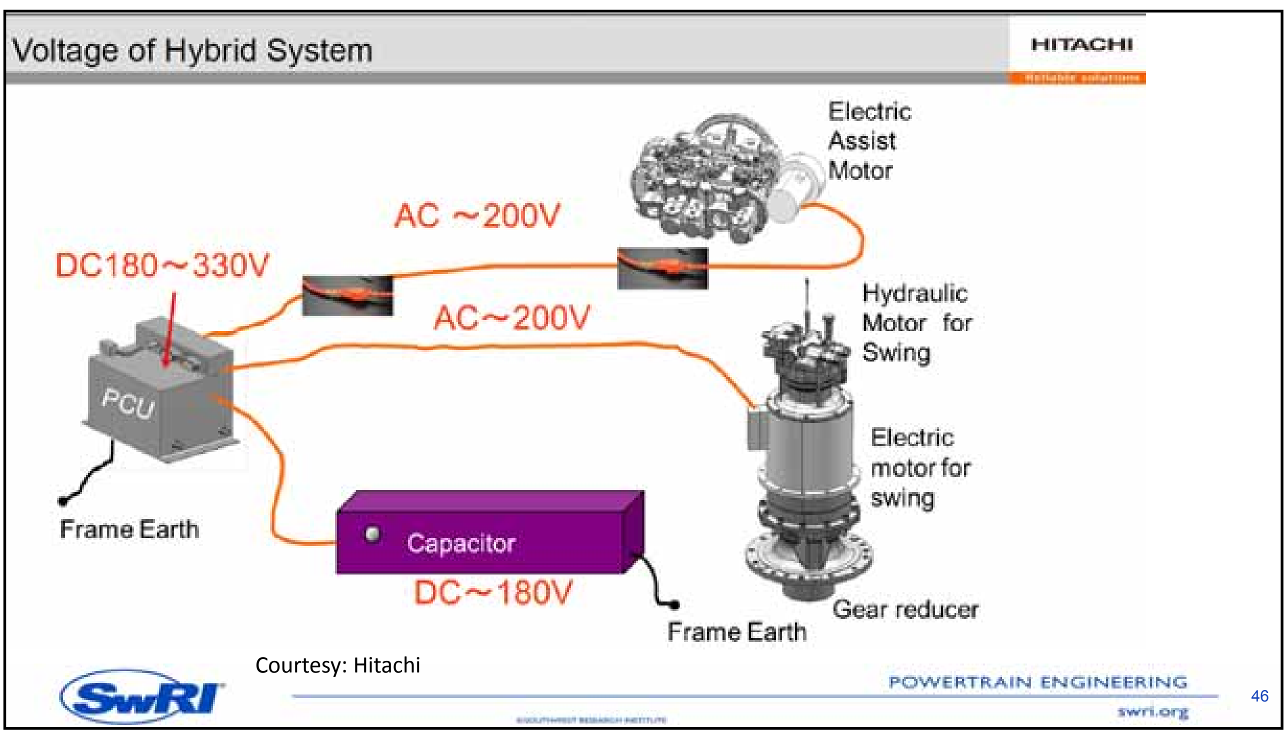
Voltage of Hybrid System
HITACHI
Electric Assist Motor
AC ~200V
DC180~330V
AC~200V
Hydraulic Motor for Swing
PCU
Electric motor for swing
Frame Earth
Capacitor
DC~180V
Frame Earth
Gear reducer
Courtesy: Hitachi
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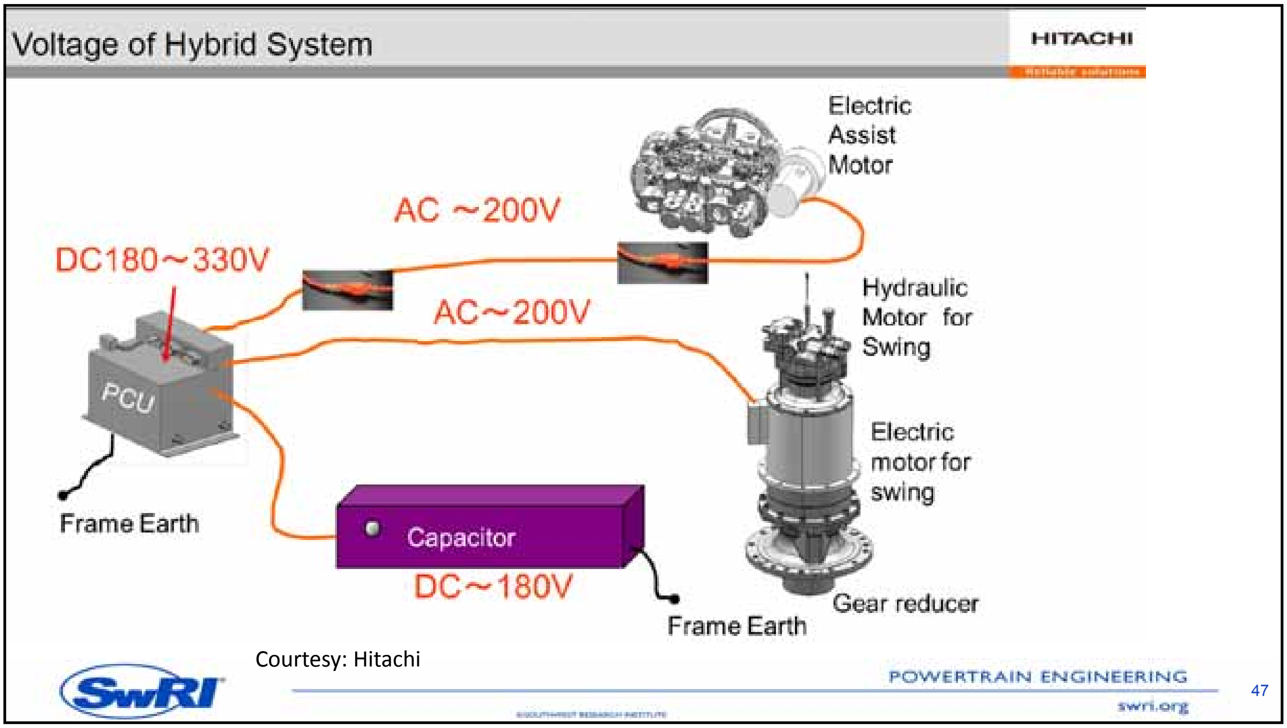
Voltage of Hybrid System
HITACHI
Electric Assist Motor
AC ～200V
DC180～330V
AC～200V
Hydraulic Motor for Swing
PCU
Electric motor for swing
Frame Earth
Capacitor
DC～180V
Gear reducer
Frame Earth
Courtesy: Hitachi
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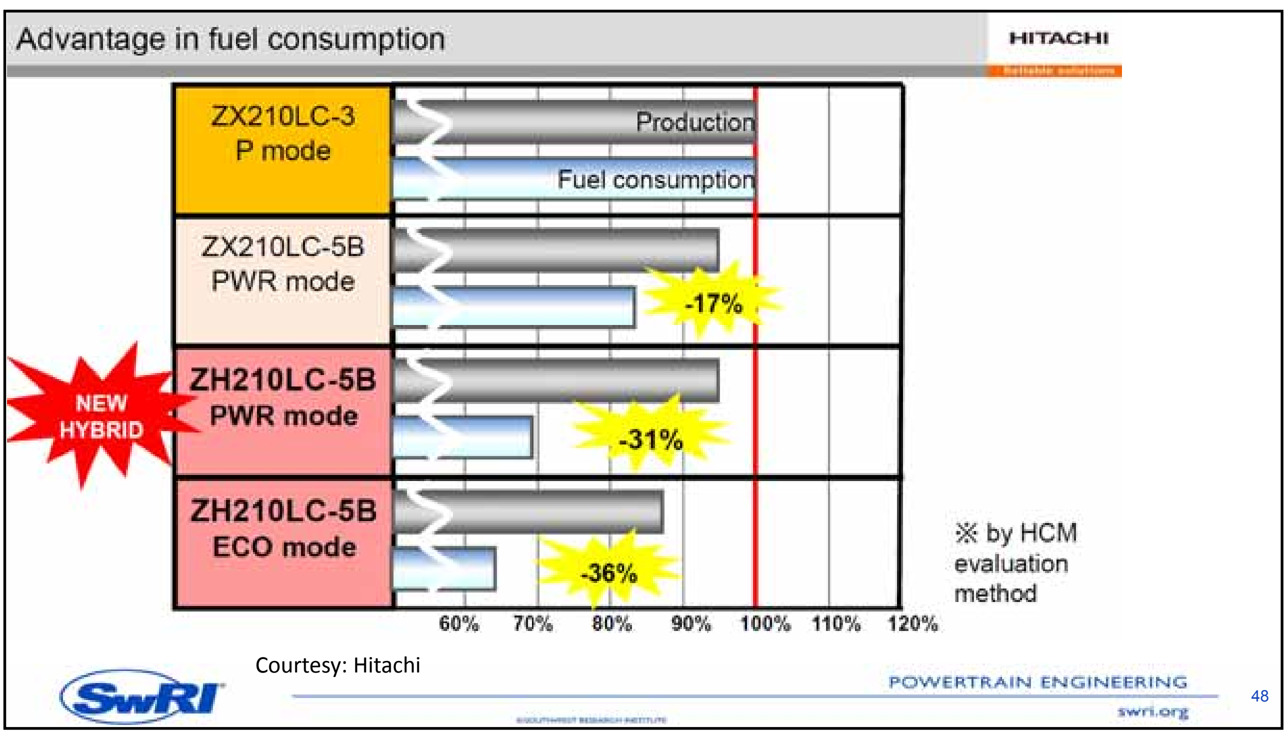
Advantage in fuel consumption
HITACHI
ZX210LC-3
P mode
Production
Fuel consumption
ZX210LC-5B
PWR mode
-17%
NEW HYBRID
ZH210LC-5B
PWR mode
-31%
ZH210LC-5B
ECO mode
-36%
※ by HCM evaluation method
60%
70%
80%
90%
100%
110%
120%
Courtesy: Hitachi
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Development Concept Wheel Loader

HITACHI

1. Provide the first commercial Hybrid wheel loader with state of the art technology in the world.
2. Introduce Hitachi advanced technology with over 30% reduction of fuel consumption.
3. Communicate the strong brand image of Hitachi Wheel Loader.

Courtesy: Hitachi

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Solar Electric Speed Boat – NAVAL DC

- 10 m cfrp Solar Electric Speed Boat
  - Low resistance electric hull design
  - Embedded solar cells (Si & GaAs)
  - 30 knots maximum speed
  - Autonomy from fossil fuels at 7 knots average speed on sunny days
  - 80 kW AC motor
  - 36 kWh Lithium Polymer Battery at 400V
- Voyaging Catamarans
  - Embedded solar cells (Si & GaAs)
  - 7 knots maximum speed
  - Autonomy from fossil fuels at 4 knots average speed on sunny days
  - 2 – 10 kW AC motors
  - 30-60 kWh Lithium Polymer Battery at 48 V
  - Proven for 280 nautical miles

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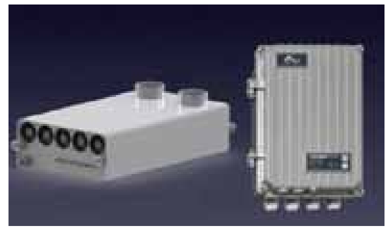
NAVAL DC Lithium Polymer Battery Packs

- 48 V 15.5 kWh to 800 V 2MWh

- Integrated On Board Chargers



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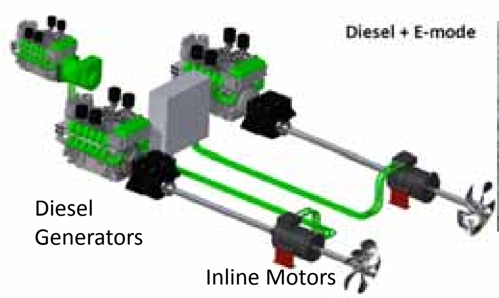
Hybrid System to Meet EU Stage V Regulations

MITSUBISHI MARINE ENGINE | BAUMULLER | IndusTrans S.A.

- EU Stage V rules for SOx, NOx & CO for new ships and reduction of CO_2 footprint
- Comfort – Lower noise and vibration
- Faster maneuvering to save time
- 60 % Electric (2x285 kW Motors)
- 40 % Diesel (2x635 kW Engines)
- Boost Mode (Electric+ Diesel)



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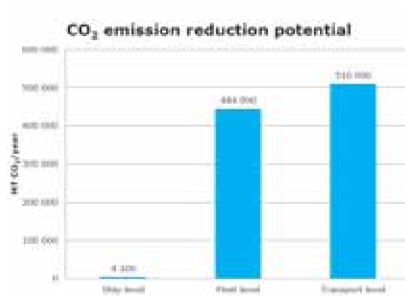
DNV GL – Autonomous Pure Electric Cargo

- Range: 100 Nautical Miles
- Capacity: 100 TEU (Twenty-Foot Equivalent Unit)
- Speed: 6 Knots
- Battery capacity: 5.5 MWh

Courtesy: http://www.dnvgl.com/

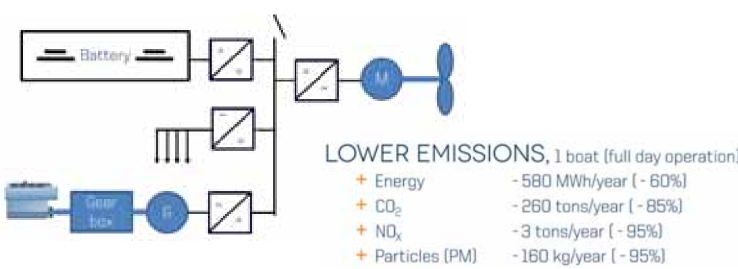


Emission reduction potential with autonomous and pure EV technology: Courtesy: DNV GL

Echandia Marine Hybrid System

ECHANDIA MARINE

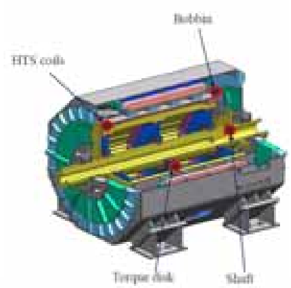
- Supercharged Electric Ferry in Sweden
- 180 kWh NiMH battery pack
- 2x125 kW Electric Motors
- 2x90 kW Gensets
- Investment and Operating costs same as conventional

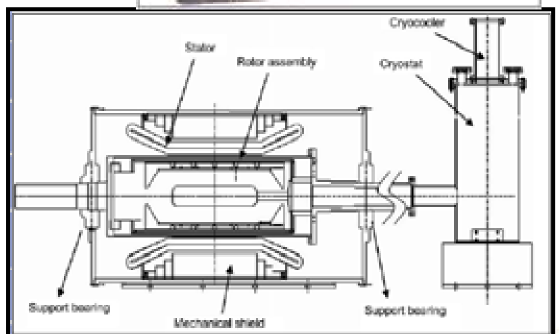


High Temperature Superc… (HTS)

Doosan Heavy Industries & Construction

- Rated Power: 1 MW (Also has 5 MW type)
- Rated Speed: 3600 RPM
- Number of Poles: 2
- Frequency: 60 Hz
- Synchronous Reactance: 0.13 p.u
- Armature Terminal Voltage: 3300 V
- Field Coil Current: 150 A
- Armature Current: 180 A
- Machine Efficiency: 97.77%



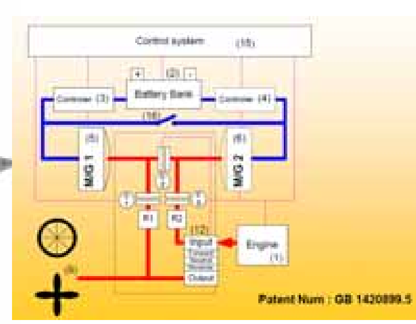


Yanmar 70 with Twin Motors -

HybridMarine

- Patent Number: GB 2417378
- Multi-mode hybrid system – 30 modes
- Pulse charging of battery bank
- Controller tracking high efficiency contour on engine map

Example Systems



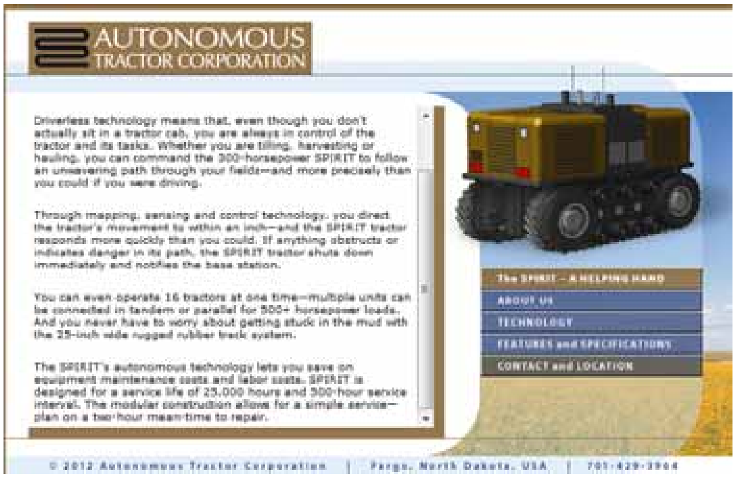
John Deere

- http://www.deere.com/wps/dcom/en_INT/products/equipment/autonomous_mower/tango_e5/tango_e5.page

Lawnbotts

- http://www.lawnbotts.com/

Spirit



- http://www.autonomoustractor.com/features1.html
- http://farmindustrynews.com/tractors/spirit-autonomous-tractor-eliminates-need-driver

CASE

Case IH utilize "follow me" technology and vehicle-to-vehicle communication with a driverless tractor that follows one operated by a person.

Just read a press release saying that Case IH won a gold medal for the SIMA Innovation Prize (the SIMA is the world's second largest farm show in the world after Agritechnica and is based in Paris). Press release was in French only, so there's no point posting it here.

The medal was awarded for Case IH's new V2V communication system, which allows an operator to control a second machine in the field (master-slave concept). For example, the combine driver could also steer and adjust the speed of the grain cart tractor in the field. Or one operator could take care of two tractors doing tillage in a field. It is not mentionned whether or not an operator must be present in the cab of the second vehicle, and what is the distance range over which V2V is effective. However it is definitely a step towards master-slave and autonomous tractors. Deere is testing a similar system, but Case IH got ahead!

In other news, Case IH also won a silver medal for a CVT PTO transmission, that allows to adjust PTO speed independently of engine speed to adapt to varying field conditions, and providing nice fuel savings. One other thing Deere is working on, but got behind others.

- http://www.farm-equipment.com/pages/Ahead-of-the-Curve-Autonomous-Tractors-are-on-the-Horizon.php

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Fendt Electric Tractors

- http://www.fendt.com/us/2466.asp

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Kinze's Electric Tractor

- http://www.kinze.com

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Summary

- Global sales of xEVs continue to increase
  - China leading the way in BEV (buses and small vehicles)
- HEVs & EVs forecast to be commonplace among OEM offerings come 2025
  - Tesla aim for 1 million cumulative EV sales by 2020
  - VW aim for 2-3 million annual EV sales by 2025
- HEV and EV not limited to light-duty
  - Tesla & Cummins announce EV semi
- Battery voltage increasing
  - Porsche Mission E will use 800V battery system

Summary ...

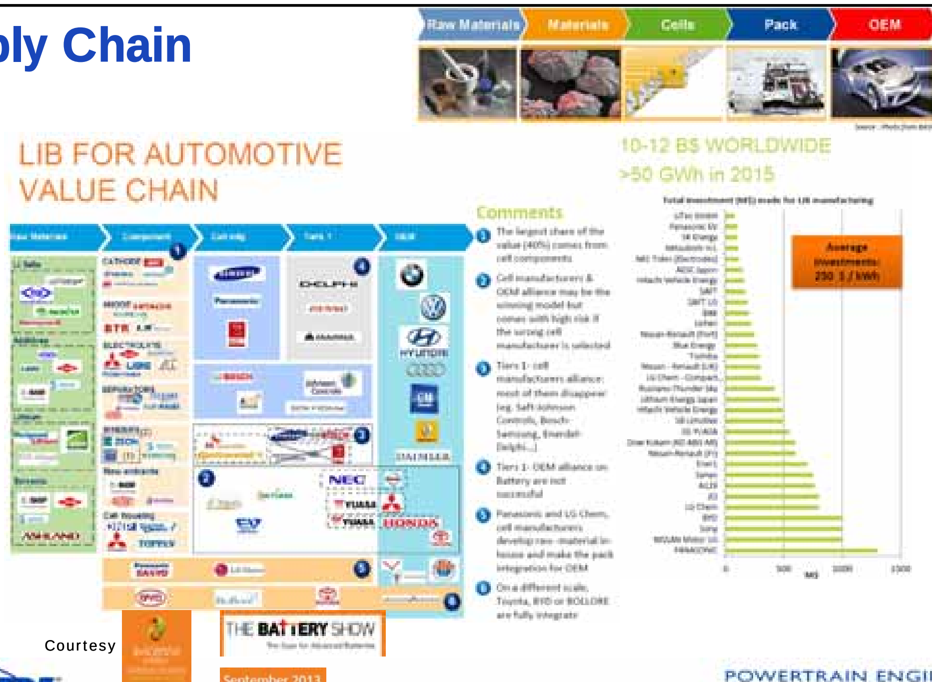
- Electrification of off highway and marine machinery is primary driven by emission regulation, comfort and efficiency considerations
- All off highway OEMs are in the process of developing new electric versions of their products
- Standards and regulations in the electric and battery system area are in early stages of development with several working committees
- As battery prices decreases manufacturers are preparing to meet impending volume production opportunities

Overview of fundamentals and state of the art Lithium Ion Cells

Bapi Surampudi, Ph.D.

Overview

Supply Chain



Courtesy

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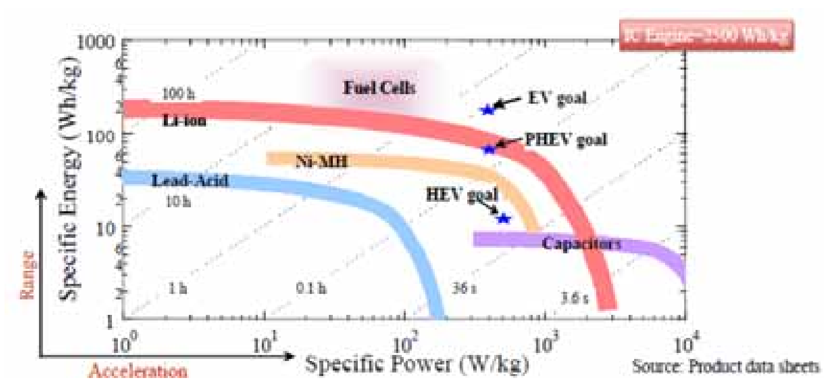
Electric Vehicle Targets



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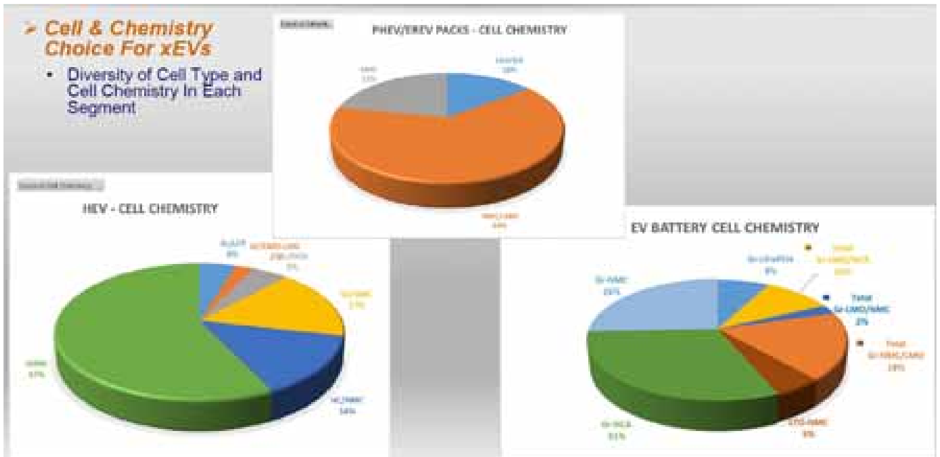
Cell Chemistry Review



Courtesy: kevin Konecky - Total Battery Consulting and AABC 2017 SFO

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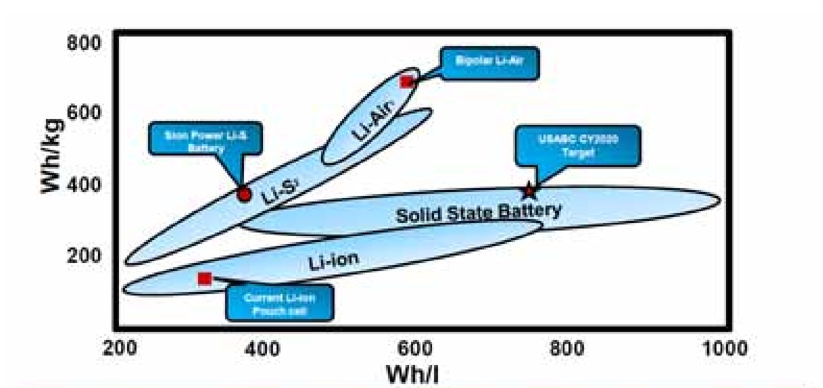
Beyond Conventional Lithium-ion



solid state batteries could deliver high volumetric energy density than other technologies

Courtesy:

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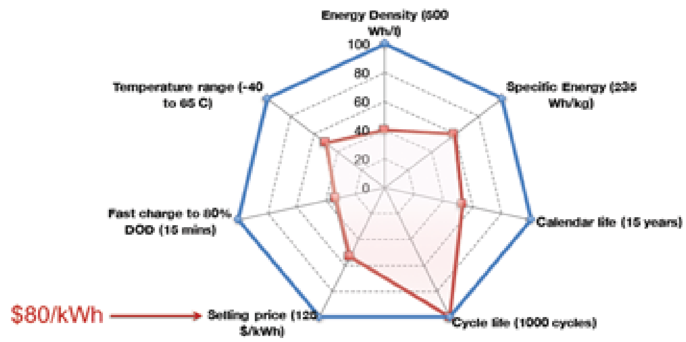
Metrics for Batteries

Comparison of today's batteries with USABC 200 mile battery electric vehicle goals. All numbers are at the pack level



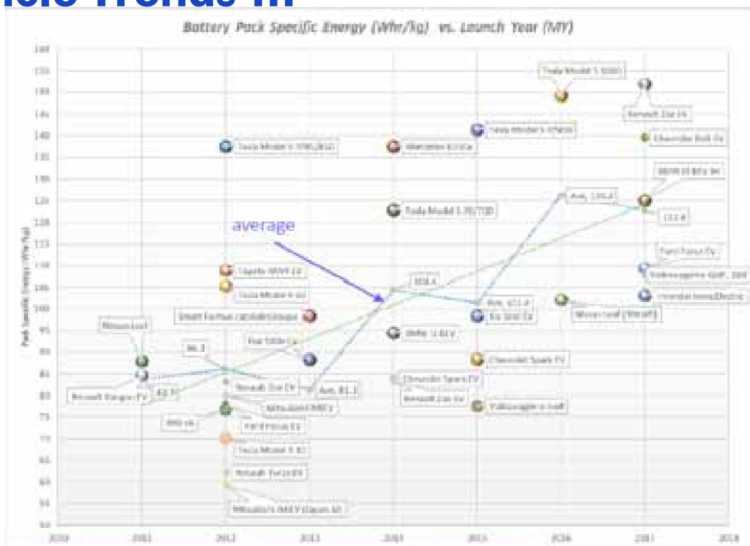
Cost remains a big challenge
Fast charge becoming the next big focus area

EV Cell Trends

LiIon Chemistry	Specific Energy Cell-level (Whr/kg)	Specific Energy Pack-level (Whr/kg)	Cell Type	Application Example
LTO-NMC	89	57.5	Metal Can Prismatic	Toshiba – Honda Fit
LiFePO4	131	83.9	Prismatic Pouch	A123 – Chevy Spark
LiNMC/LMO	129	88.2	Metal Can Prismatic	Samsung – Fiat 500e
LiNCA	272	149.3	Cylindrical 18650	Panasonic – Tesla Model S/X 100D
LiNMC (Ni-rich)	244	151.9	Prismatic Pouch	LG Chem. – Renault Zoe

Courtesy: kevin Konecky - Total Battery Consulting and AABC 2017 SFO

EV Vehicle Trends …



Courtesy: kevin Konecky - Total Battery Consulting and AABC 2017 SFO

50% Increase In Pack-Level Specific Energy in 5 yrs!

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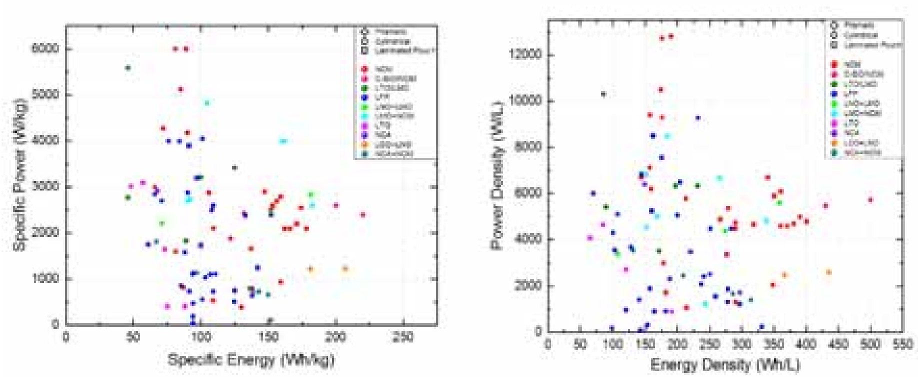
Automotive Cell Landscape



Courtesy: JM and AABC SFO 2017

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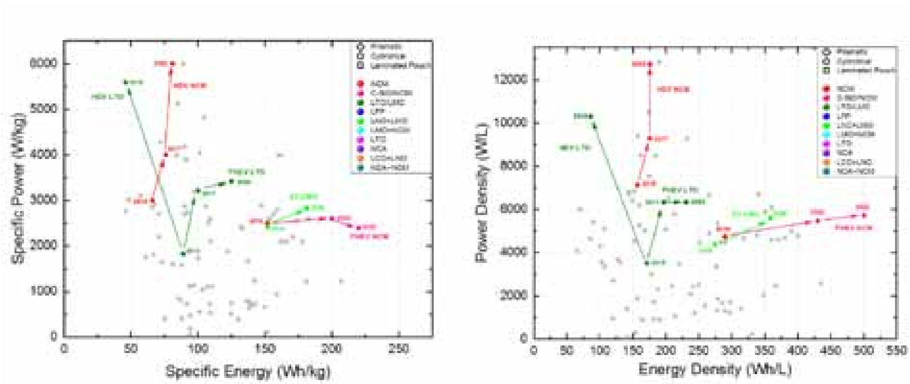
Automotive Cell Landscape Predictions



Courtesy: JM and AABC SFO 2017

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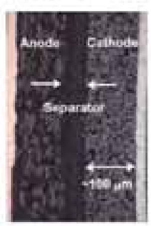
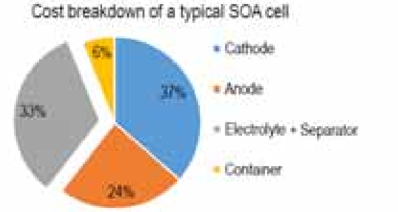
State of Art Lithium Ion Price Breakdown





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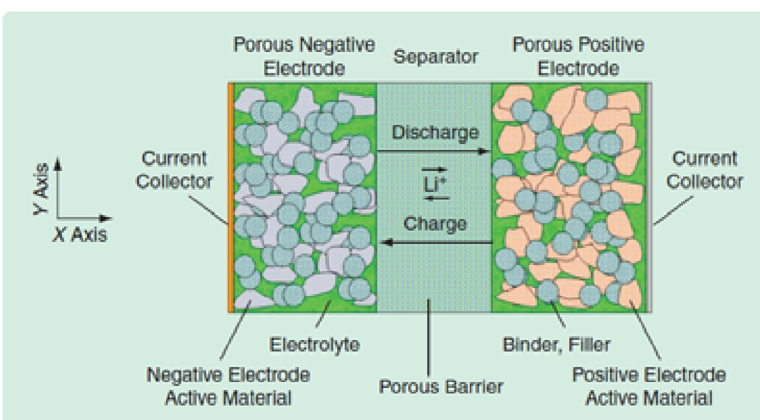
Working Principles of a Lithium Ion Cell

Lithium Ion Cell Components



Courtesy IEEE Control Systems Magazine, June2010

Lithium Ion Cell Components ...

- A porous negative electrode of a Li-ion cell is connected to the negative terminal of the cell. This electrode usually contains graphite, which is an intercalation material
- A porous positive electrode is connected to the positive terminal of the cell. The positive electrode can be comprised of various chemistries, but it is usually a metal oxide or a blend of multiple metal oxides, such as $LixMn_2O_4$ and $LixCoO_2$
- A separator is a thin porous medium that separates the negative from the positive electrode. The separator is an electrical insulator that does not allow electrons to flow between the positive and negative electrodes. However, being porous, the separator allows ions to pass through it by means of the electrolyte
- The electrolyte is a concentrated solution that contains charged species. These charged species can move in response to an electrochemical potential gradient. Note that some Li-ion batteries have a solid electrolyte, which serves both as an ionic conducting medium and an electronically insulating separator

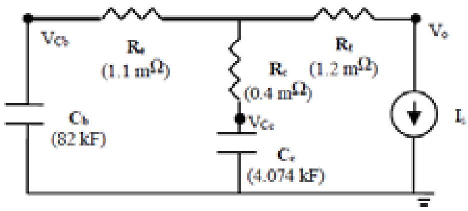
Working Principle of a Lithium Ion Battery

- The process of moving ions in and out of an interstitial site in a lattice is called intercalation
- Both electrodes have lattice sites that can store lithium
- Charging (discharging) causes the Li ions to leave the lattice sites in the positive (negative) electrode and enter the lattice sites of the negative (positive) electrode
- The difference in energy states of the intercalated lithium in the positive and negative electrodes governs the energy stored in the Li-ion cell
- Each Lithium-Ion cell has a typical operating voltage that is subset or in between 2.0 V and 4.2 V
- The actual cell voltage depends on State of Charge (SOC)
- Temperatures variations and change in rate of charging compared to recommended rate will deteriorate the cells

Equivalent Circuit Model of a Lithium Ion Cell

$$\begin{bmatrix}\dot{V}_{Cb}\\ \dot{V}_{Cc}\end{bmatrix}=\begin{bmatrix}-\frac{1}{C_b(R_e+R_c)} & \frac{1}{C_b(R_e+R_c)}\\ \frac{1}{C_c(R_e+R_c)} & \frac{-1}{C_c(R_e+R_c)}\end{bmatrix}\begin{bmatrix}V_{Cb}\\ V_{Cc}\end{bmatrix}+\begin{bmatrix}\frac{-R_c}{C_b(R_e+R_c)}\\ -\frac{1}{C_c}+\frac{R_c}{C_c(R_e+R_c)}\end{bmatrix}[I_s]$$

$$[V_o]=\begin{bmatrix}\frac{R_c}{(R_e+R_c)} & \frac{R_e}{(R_e+R_c)}\end{bmatrix}\begin{bmatrix}V_{Cb}\\ V_{Cc}\end{bmatrix}+\begin{bmatrix}R_t-\frac{R_cR_e}{(R_e+R_c)}\end{bmatrix}[I_s]$$



Courtesy NREL http://www.nrel.gov/vehiclesandfuels/energystorage/pdfs/evs17paper2.pdf

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What is a Battery Management System (BMS)?

- A BMS is composed of hardware and software that control the charging and discharging of the battery while guaranteeing reliable and safe operation
- BMS also does cell balancing and thermal management of the pack
- BMS requires a battery model that describes the internal states and dynamics as pack ages
- BMS limits available discharge power and the charging power under cold temperatures to protect the life span of the battery pack
- BMS communicates and coordinates with vehicle supervisory controller and electric motor controller to deliver best performance in a safe and graceful manner

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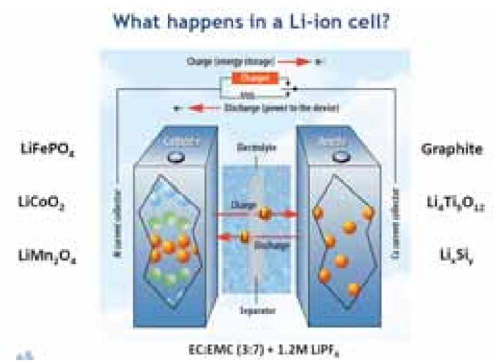
A View of Aging

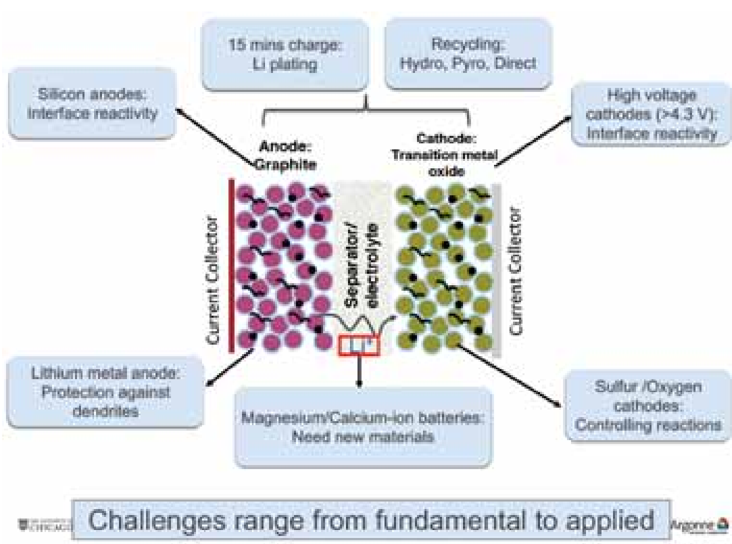


Source:

Lithium-Ion Batteries: *Materials and Chemistries*
Daniel Abraham
Argonne National Laboratory
Battery Show Conference – 2013
September 17-19, 2013
Novi, Michigan

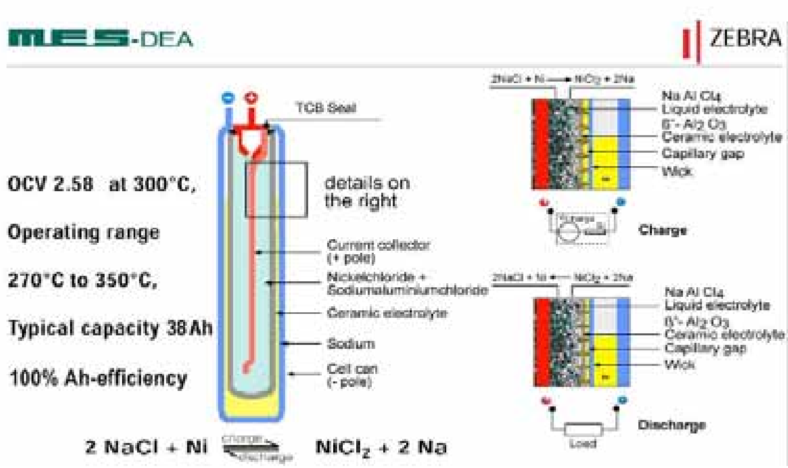
- Impedance rise
  - Arises mainly from the positive electrode
- Capacity fade
  - Originates at the positive electrode
  - Manifests itself at the negative electrode as a thick SEI
- Voltage fade
  - Arises from crystal structure changes

Cell R&D Areas



Advanced Lead Acid Batteries

ZEBRA Batteries (NaNiCl)



The ZEBRA cell has a central positive electrode mainly consisting of Nickel and sodium chloride plus some additives and a liquid electrolyte tetrachloroaluminate contained within a beta alumina tube electrolyte.The cell works in a range of temperature between 270°C-350°C and during charge sodium ions formed in the central positive electrode moves through the wall of the beta alumina tube to form the liquid sodium negative electrode which is contained by a square section mild steel case

Source: Developments and Improvements in Zebra Nickel Sodium Chloride Batteries Dr. A. Turconi, - MES-DEA Sa, Via Laveggio 15, 6855 Stabio Switzerland

ZEBRA Cell Characteristics

Cell Characteristics	ML3C	ML3P	ML3X
Capacity	32Ah	38Ah	38Ah
OCV	2.58V	2.58V	2.58V
Deep Disc. Cy. Stability	Very Good	Good	Very Good
Normal Charge	10A: 2,67V/cell	6A: 2,67V/cell	10A: 2,67V/cell
Fast charge	30A: 2,85V/cell	NO	NO (To be defined)
Regen. breaking	3,1V/cell, 60A, 4%SOC	3,1V/cell, 60A, 4%SOC	3,1V/cell, 60A, 4%SOC
Voltage Max generator	2,85V/cell up to 70%SOC, then 2,58V/cell from 80% to 100%SOC	2,67V/cell up to 70%SOC, then 2,58V/cell from 80% to 100%SOC	2,67V/cell up to 70%SOC, then 2,58V/cell from 80% to 100%SOC

Source: Developments and Improvements in Zebra Nickel Sodium Chloride Batteries Dr.A.Turconi, - MES-DEA Sa,Via Laveggio 15, 6855 Stabio Switzerland

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Ultra Battery

EASTPENN ecoult

Energy Storage Excellence

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Ultra battery Principle

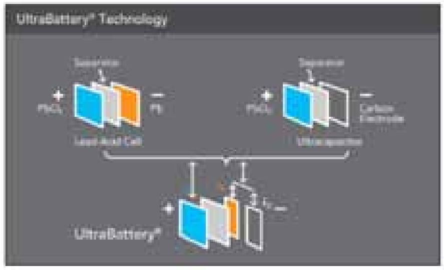

Figure 1: Schematics of standard lead-acid cell (top left), ultracapacitor (top right) and their combination in the UltraBattery® cell (bottom)

Breakthrough: Reduced Sulfation Leads to Wider Applicability and Longer Life

The reduction of the rate of negative plate sulfation, which is the dominant cause of aging of valve regulated lead-acid (VRLA) batteries when used in high-rate partial State of Charge (pSoC), is achieved in UltraBattery® cells as an outcome of the carbon-based supercapacitor both being in parallel and sharing a common electrolyte with the negative electrode of the lead-acid cell.

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Ultra Battery …

Why UltraBattery®?

Total lifetime energy throughput capacity, when used in pSoC applications, is far beyond previous lead-acid technology

- leads to lower lifetime cost per kWh

Ability to operate continuously in a pSoC regime (i.e. operating in a band of charge that is neither totally full nor totally empty)

- leads to viability of use models where energy is charged and discharged at significantly higher efficiency

Enhanced charge acceptance (charge and discharge occur at similar or equal rates, whereas traditional lead-acid cells can discharge quickly but charge more slowly)

- leads to quicker recharge, increased uptime, and wider applicability

Consistency of behavior of individual cells in long strings

- leads to lower maintenance

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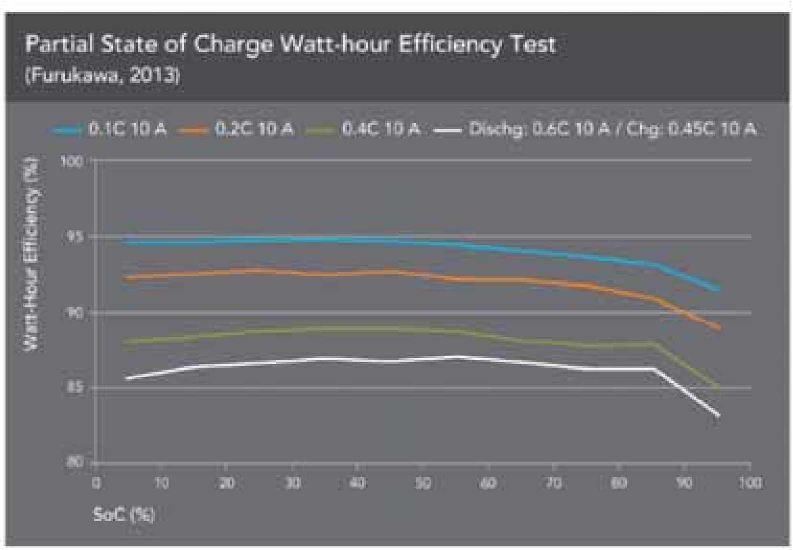
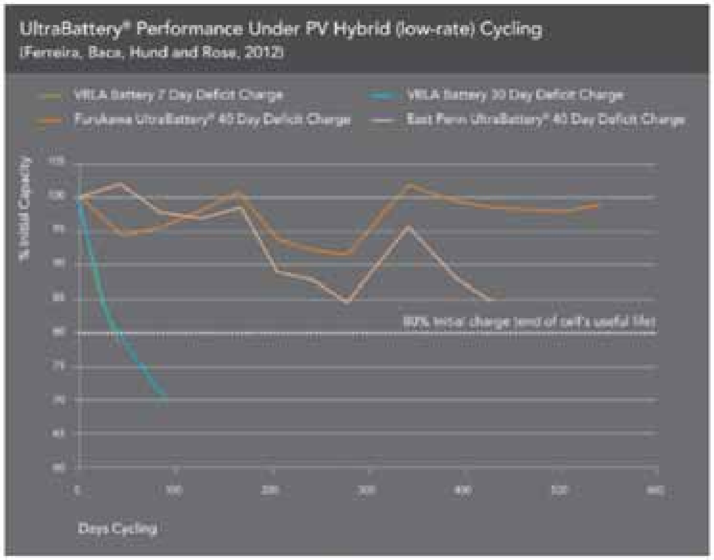
Ultra Battery Cycle Life…

Ultra Battery Efficiency…



Ultra Battery PV Hybrid Cycling



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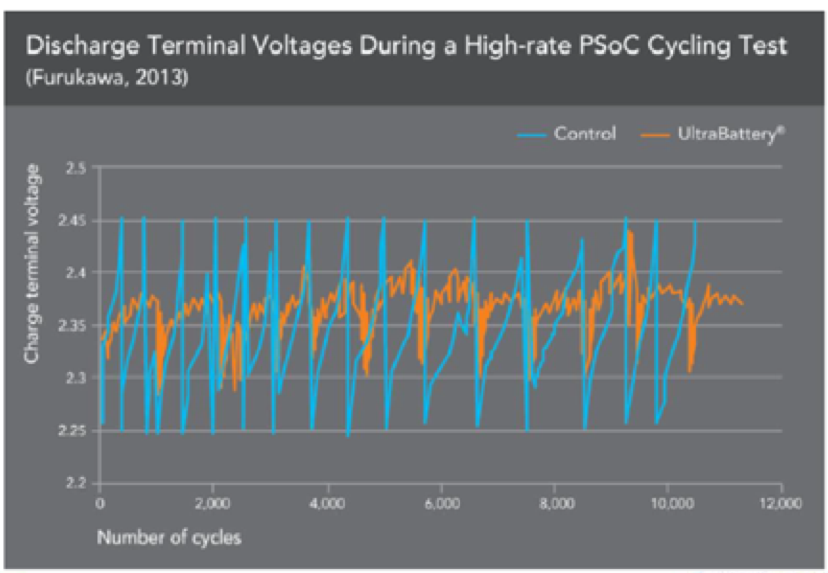
Ultra Battery Charge Acceptance



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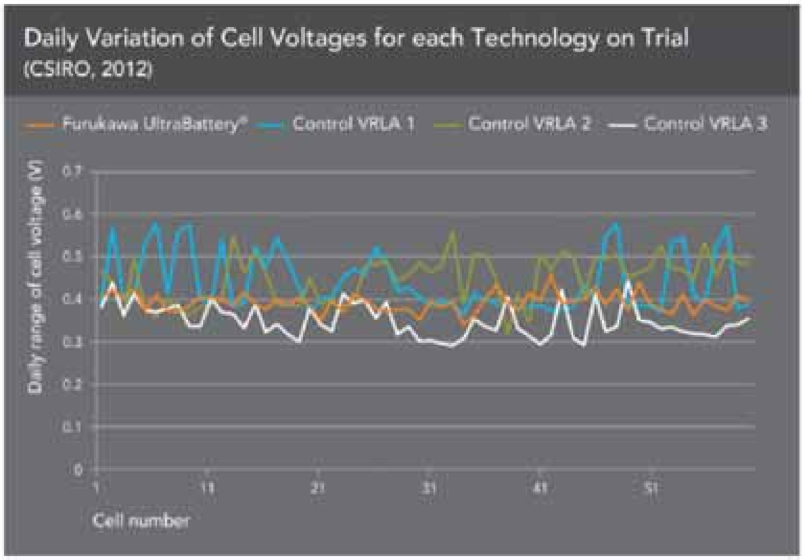
Ultra Battery Has Low Cell to Cell Variability

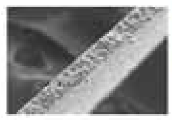


Lithium Ion Cell Makers

ENEVATE
Innovating Energy Storage

Pure-Silicon Lithium-Ion Battery System for Reducing Barriers to EV Adoption

Dr. Benjamin Park, Founder & CTO
4 June 2018



1 4 June 2018 AABC 2018 - San Diego

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Enevate's- Silicon Dominant Anode

- Breakthrough Li-ion battery technology: Novel silicon-dominant composite anode approach
- Nanoscale SiC layer increases performance while being cost-effective and manufacturing-friendly
- Fab-light manufacturing strategy is capital efficient while enabling fast and efficient low-cost manufacturing
  - Anode production line 1 operational today
  - Safety certs completed for first product
- Capable of accepting charge at ultra-high rates

Courtesy: Enevate

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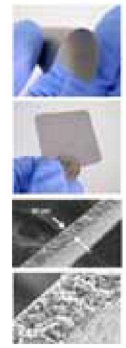
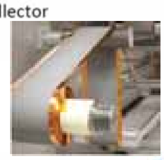
Enevate's- Silicon Dominant Anode

- **HD-Energy® Anode: Silicon-Dominant Composite Micro-Matrix**
  - Enevate manufactures active material film from raw materials
  - Silicon source is inexpensive
  - Self-standing, monolithic, single-particle
- **Properties**
  - Silicon-dominant: >70% silicon
  - Gravimetric energy density: ~2800 mAh/g
    - 1500 mAh/g utilized in cell designs, volumetric and energy densities of ~750 Wh/L, ~300 Wh/kg
  - High initial Coulombic efficiency: 93% for anode, ~90% for full cells
  - High density of anode: 1-1.5 g/cc
  - Silicon surface area: <10 m^2/g
  - Compatible with existing high volume manufacturing processes
    - Unlike nanowire or silicon wafer approaches



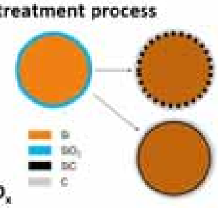
- Composite comprised of carbon as conductive matrix, silicon as main active material, silicon-carbide as silicon-surface protecting nanometer-scale layer
- Anodes are bonded with proprietary process to the current collector
- Anodes are then sent to Enevate's cell assembly partners

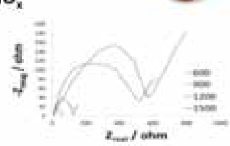


Courtesy: Enevate

Enevate's- Silicon Dominant Anode

- **"Free" process – coating is created as part of normal heat-treatment process**
- **Self-limiting process**
  - Native oxide layer thickness is converted
  - Nanoscale thickness
  - Conformal layer
- **Prevents side-reactions with lithium consumption from SiO_x**
- **Improves coulombic efficiency**
- **Reduces Impedance**



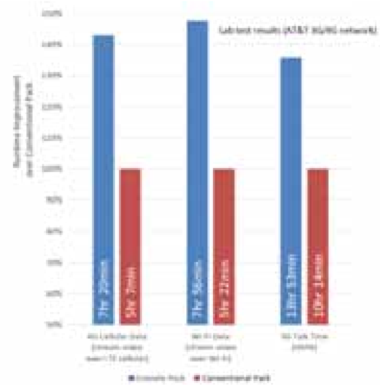


- **Both Ultrafast Charging + High Energy Density Cells:**
  15 minutes full charge with uncompromised cycle life and energy density
  - Deliver up to 3X runtime (i.e. talk time) with 15 minutes charging
  - 750Wh/L energy density now, roadmap to 1000Wh/L
- **Longer Runtime**
- **Excellent low temperature performance, tested to -20degC**

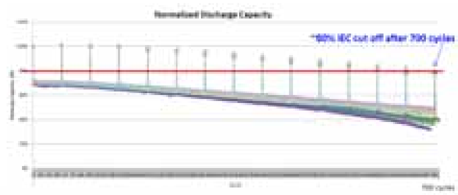
Courtesy: Enevate

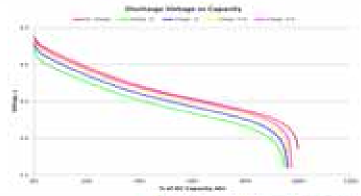
Enevate's- Benchmark Results

Courtesy



Tests done on Android Smartphone
~35-50% longer smartphone runtime





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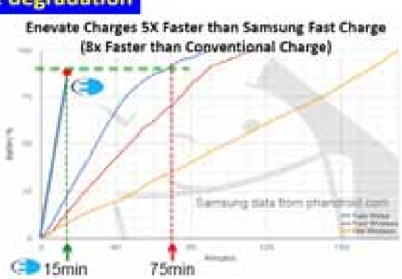
Enevate's- Fast Charging

- **Conventional graphite cells fade quickly if charged at high rates**
  - Root cause: lithium plating
- **Enevate's cells can support higher rates of charge because:**
  - Cell design has excess capacity on the anode
  - Enevate's anode voltage is higher when the cell is fully-charged – more margin to 0V vs Li/Li+
- **Cycling done with CC/CV charge regimes using 4C currents without any noticeable degradation**
  - Max rate of charge above 4C is unknown

4C charge currents without noticeable degradation



Courtesy: Enevate

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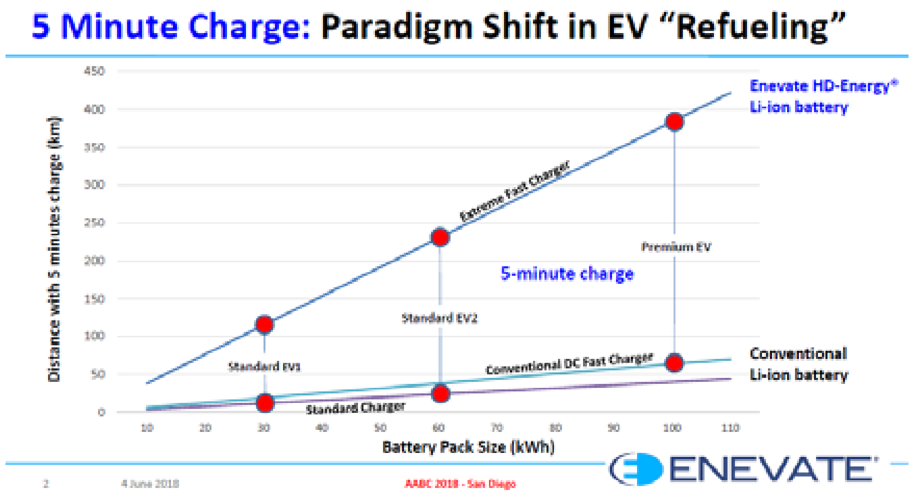
Fast Charging



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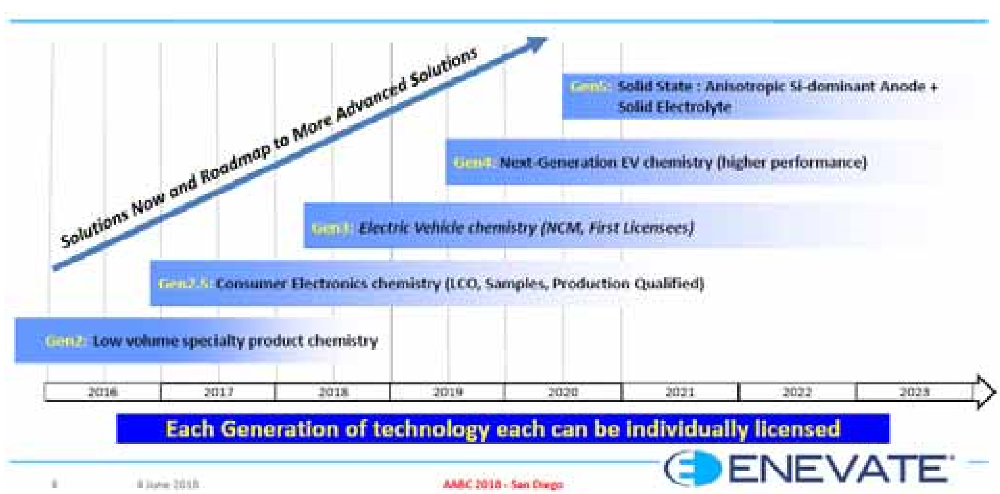
Enevate Technology Roadmap



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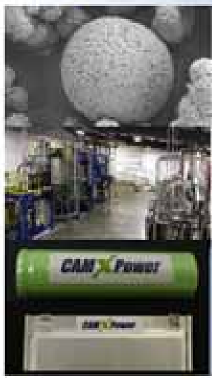
CAMX Power



Challenges and Opportunities for Implementing High-Nickel Cathode Materials in High-Performance Li-ion Cells

D. Kaplan, A. Pullen, J. Rempel, D. Ofer, S. Dalton-Castor, B. Barnett, Suresh Sriramulu

San Diego, USA
June 4th, 2018

CAMX Power
35 Hartwell Avenue
Lexington, MA
02421-3102

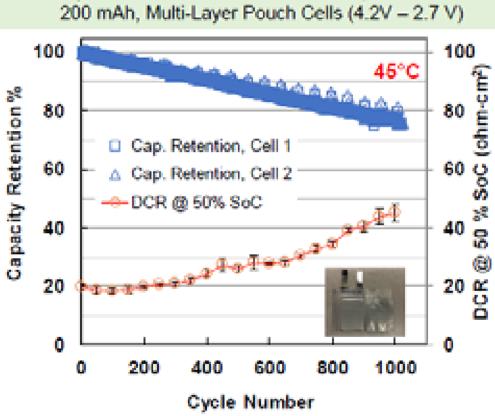
www.CAMXPOWER.com

suresh@camxpower.com

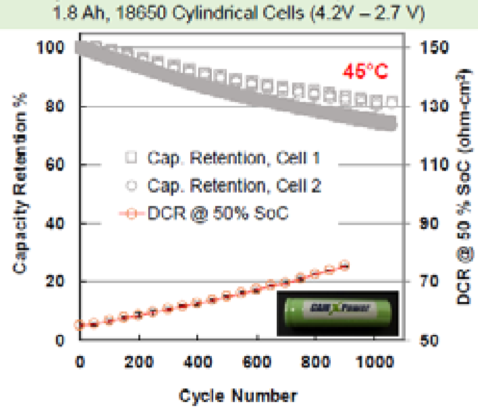
Ni Rich Cathodes

With the selection of suitable cell components, high-Ni cathode materials can be implemented in Li-ion pouch cells or cylindrical cells with long cycle life even at elevated temperatures.

Cycle Life of CAM-7.3 Cathode /Graphite Anode
200 mAh, Multi-Layer Pouch Cells (4.2V – 2.7 V)



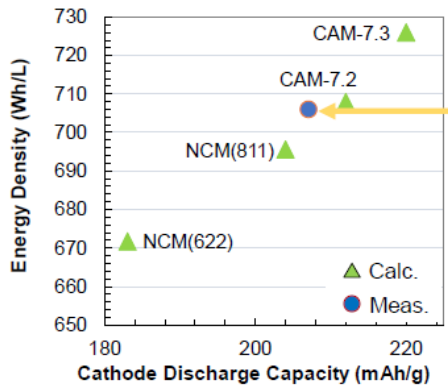
Cycle Life of CAM-7.3 cathode /Graphite Anode
1.8 Ah, 18650 Cylindrical Cells (4.2V – 2.7 V)



High Ni Cathodes …

With the high discharge capacity of such cathode materials, energy > 700 Wh/L can be achieved with graphite anode.

Cell-Level Energy Density with Graphite Anode (4.2V -2.7V)*



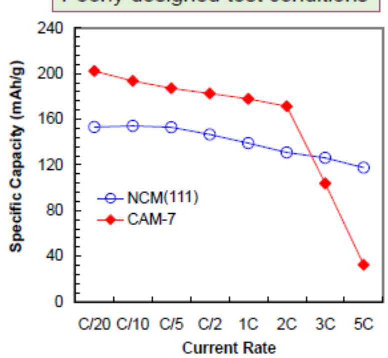
Photograph of 5.3Ah CAM-7/Graphite Cell#

*5mAh/cm² electrode loading, ~20% porosity

Impact of Separator on Capacity at High C Rates

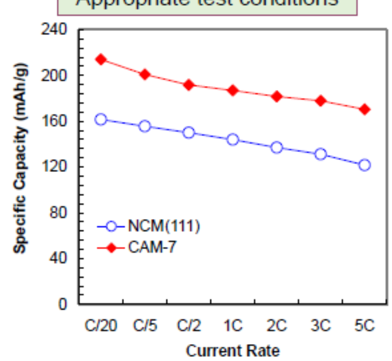
One implication of our findings is that improper selection of test conditions can result in erroneous characterization of active material performance.

Poorly designed test conditions



NCM loading: ~ 10 mg/cm², ~ 2 mAh/cm²
CAM-7 loading: ~ 15 mg/cm², ~ 3 mAh/cm²
Separator: glass
Anode: Li metal, 4.3 V – 3.0 V

Appropriate test conditions

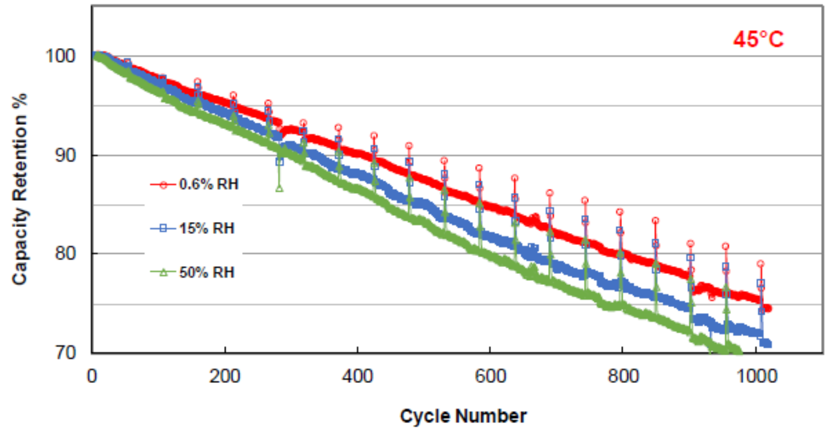


NCM electrode: ~ 17 mg/cm², , ~ 3.4 mAh/cm²
CAM-7 electrode: ~ 17 mg/cm², ~ 3.4 mAh/cm²
Separator: high power separator
Anode: Li metal, 4.3 V – 3.0 V

Impact of Relative Humidity on Life

Exposure of calendared electrodes to high RH (for 24 h) adversely affects the 45°C cycle life.

Capacity Retention during 45°C Cycling of CAM-7/Graphite
200 mAh Pouch Cells (4.2V – 2.7V)*

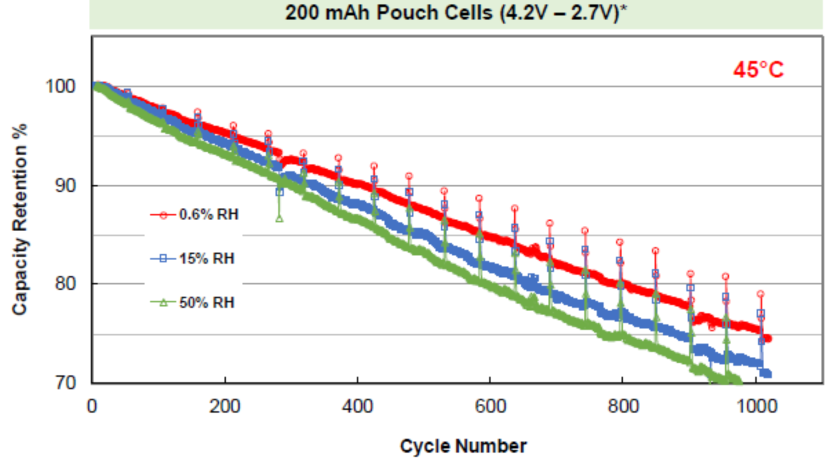


* Data shown are the average of three cells. 4.2 V – 2.7 V, 1C CCCV charge – 1C discharge, DCR measurement at 45C every 50 cycles;

Impact of Relative Humidity on Life

Exposure of calendared electrodes to high RH (for 24 h) adversely affects the 45°C cycle life.

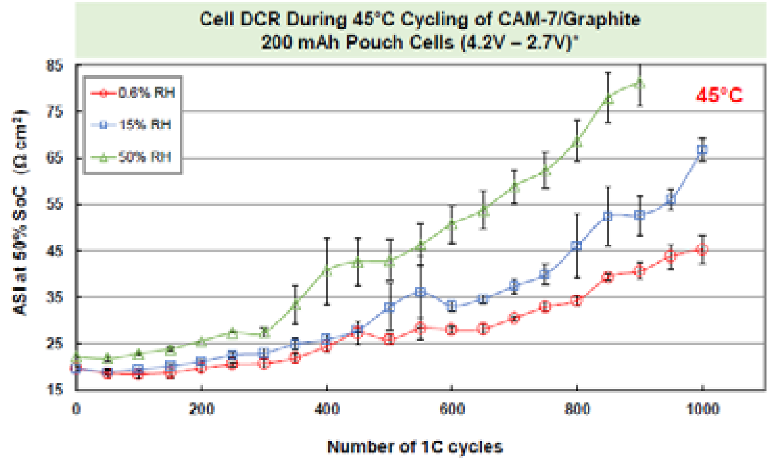
Capacity Retention during 45°C Cycling of CAM-7/Graphite
200 mAh Pouch Cells (4.2V – 2.7V)*



* Data shown are the average of three cells. 4.2 V – 2.7 V, 1C CCCV charge – 1C discharge, DCR measurement at 45C every 50 cycles;

Impact of Relative Humidity on DCR

RH exposure adversely affects the initial DCR, as well as the rate of DCR increase at 50% SoC .



* Data shown are the average of three cells, except for the 50% RH condition – average of 2 cells

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solid energy

Batteries with Wings

How Electric Cars Impacted Electric Airplanes in Driving High Energy Density Batteries

Qichao Hu, Founder & CEO, SolidEnergy Systems Corp.

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History and Timeline

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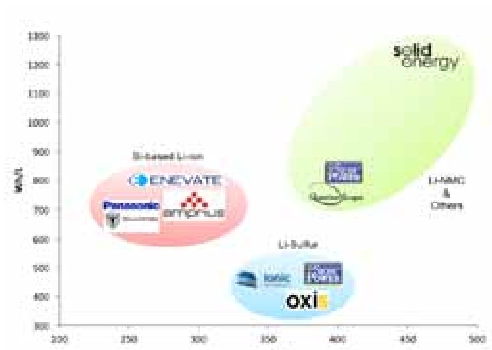
Solid Energy on Ragonne Chart



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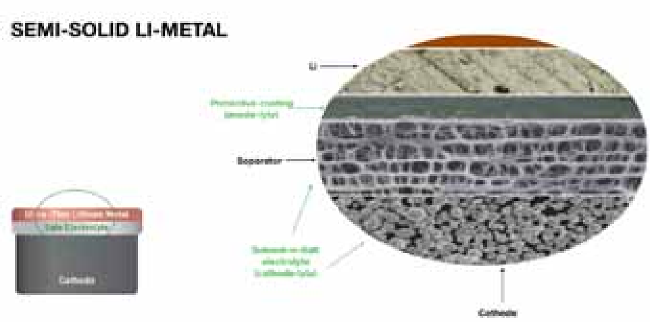
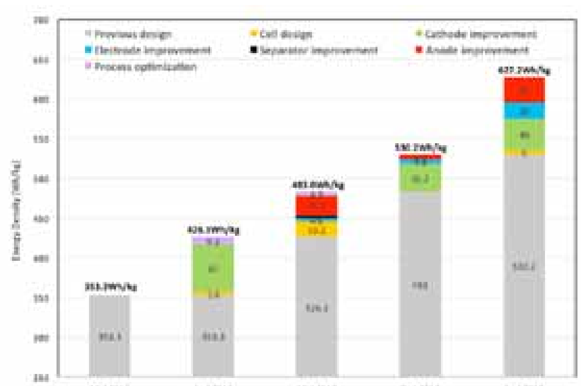
Solid Energy Lithium Metal Anode



Energy Density

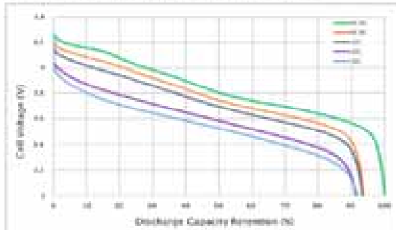


Characteristics

Discharge Rate Characteristics

Charge: CC-CV 0.1C(std.) 4.3V, C/20A cut-off at 25°C

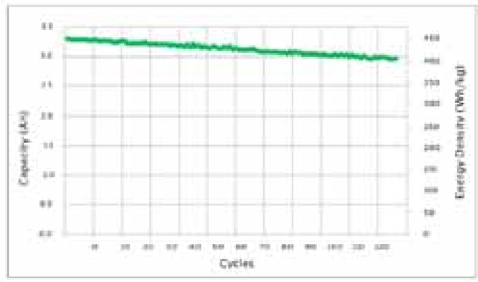
Discharge: CC 0.1C/ 0.5C / 1C/ 2C/ 3C, 3V cut-off at 25°C



Discharge Characteristics at 25°C	0.1 C	0.5 C	1.0 C	2.0 C
Capacity, Ah	3.4	3.2	3.2	3.1
Capacity Retention, %	100	93	93	91
Energy, Wh	13.0	12.0	11.8	11.2
Gravimetric Energy Density, Wh/kg	450	411	400	386
Volumetric Energy Density, Wh/L	1157	1068	1050	996

Cycle Life Characteristics

Charge: CC-CV 0.1C (std.) 4.3V, C/20A cut-off at 25°C Discharge: CC 0.5C, 3V cut-off at 25°C



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Lithium Sulfur Cells

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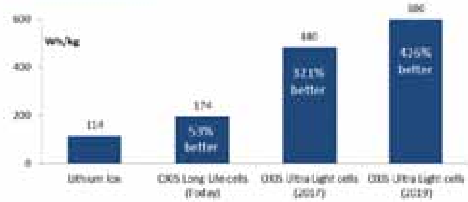
Lithium Sulfur Overview

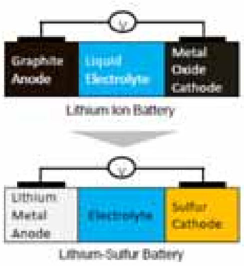
- High theoretical capacity, energy and power density – Expected for practical 300 to 600 Wh/kg
- Sulfur cost is cheap and environmentally safe
- Li-S can provide the break through we are waiting for – but farther development needed
- Developers: Sion power (U.S.A.), Eagle-Picher (USA), PulyPlus (U.S.A.), Oxis Energy (U.K.) - Oxis is leading with a 310 Wh/kg pre-production

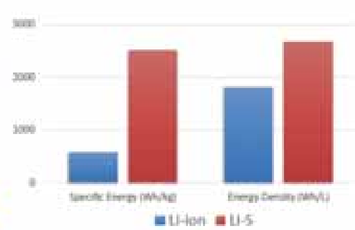


	Li-S	Li-Ion
Wh/Kg	2500	580
Wh/L	2660	1810

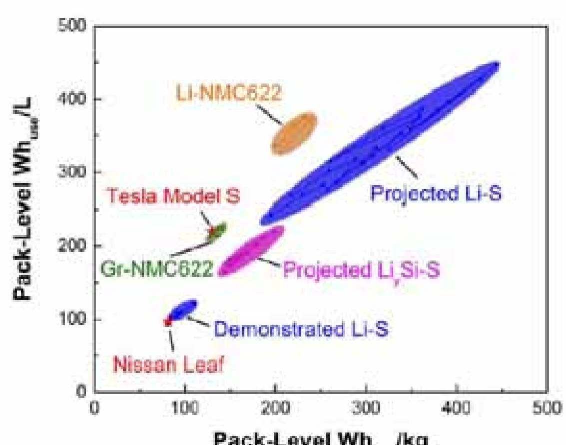
Courtesy: Shmuel De-Leon

Preview, Merits





$$S + 2Li^+ + 2e^- \leftrightarrow Li_2S$$

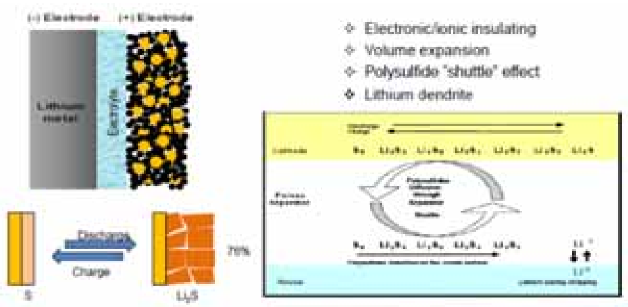


Eroglu, D., et al. (2015). "Critical Link between Materials Chemistry and Cell-Level Design for High Energy Density and Low Cost Lithium-Sulfur Transportation Battery." Journal of The Electrochemical Society **162(6): A982-A990.**

Courtesy:

material	Li [at%]	Ni [at%]	Mn [at%]	Co [at%]
811	0.94	0.79	0.11	0.10
71515	0.95	0.69	0.16	0.15
622	1.04	0.6	0.21	0.23
532	1.02	0.5	0.29	0.2
552	1.04	0.43	0.42	0.17
442	1.06	0.4	0.39	0.2
333	1.07	0.33	0.35	0.32

Preview, Challenges



	Challenges
Anode	Volume change, reactivity with electrolyte and polysulfides
Cathode	Mechanical stress, conductivity, kinetics of reaction, polysulfide confinement, balance loading
Binder	Mechanical and chemical requirements are difficult to achieve
Electrolyte	Minimizing amount, stable against anode, conductivity (depends on viscosity, ion coordination and other factors)
Packaging	Minimize while ensuring thermal management and safety

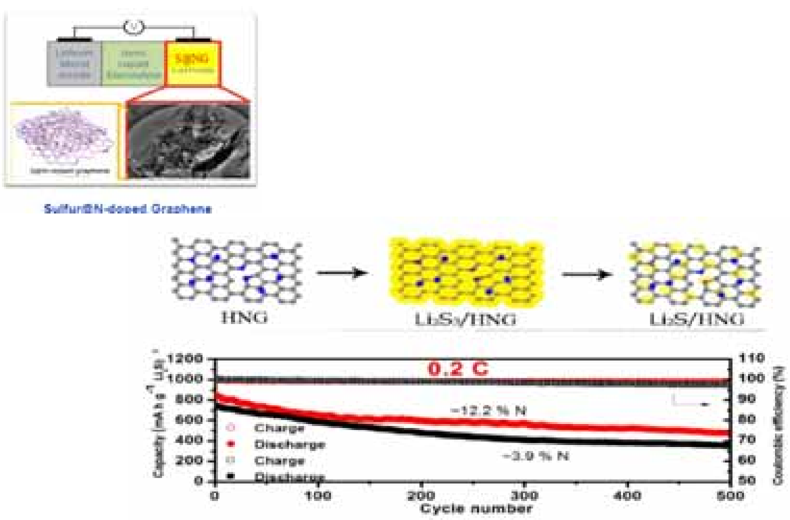
Courtesy:

Li S Developments from China

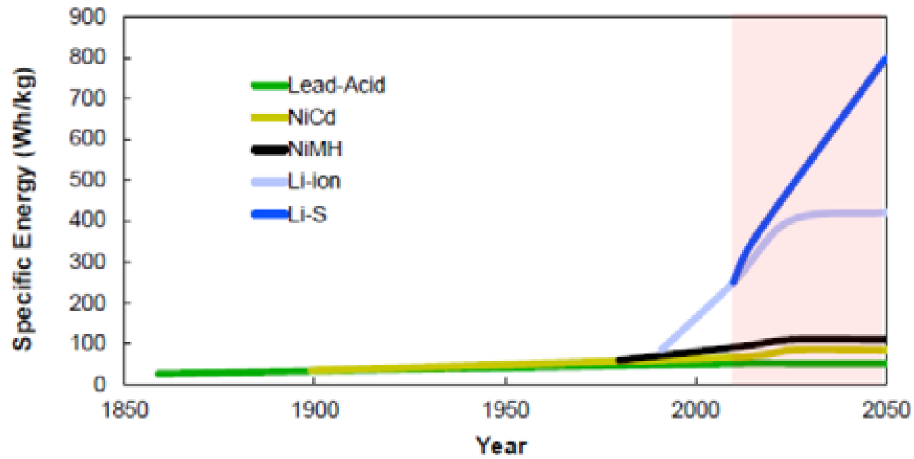
Stability via Encapsulation of S

- Need an open carbon structure to increase the sulfur content in composite cathodes
- Need chemically functionalized carbon to effectively anchor sulfur or polysulfides
- Need more conductive, robust 3D porous carbon scaffolds to reach a commercial-level areal mass loading for practical sulfur cathodes

Highly Nitrated Graphene Cathode



Predicted Roadmap from China



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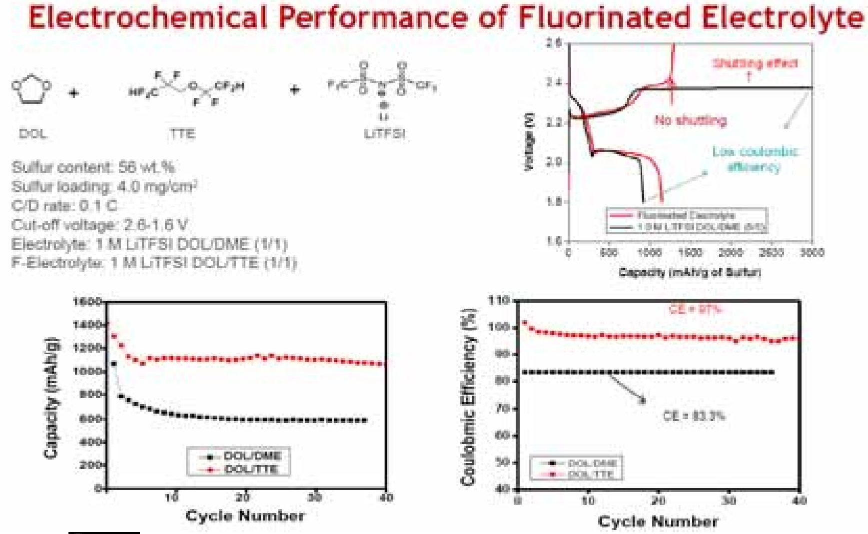
Li-S Battery with Fluorinated Electrolyte

Electrochemical Performance of Fluorinated Electrolyte



Courtesy:

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Li-S Battery with Fluorinated Electrolyte - Conclusions

- ✓ A new electrolyte based on an organo-fluorine ether solvent was developed. The new fluorinated electrolyte prevents the redox shuttling effect and significantly improves the performance of the Li-S battery.
- ✓ Self-discharge of Li-S battery with fluorinated electrolyte was significantly mitigated.
- ✓ A deep understanding of the enabling mechanism of Li-S battery with DOL/TTE fluorinated electrolyte was gained by analytical techniques of HPLC, XPS, SEM/EDX, and operando UV-Vis:
- ✓ Low solubility of high-order polysulfides in the fluorinated electrolyte mitigates the shuttle effect and enhances the capacity retention of Li-S cell.
- ✓ SEI formation on the sulfur particles by reductive decomposition of fluoroether further prevents the dissolution of the polysulfide and improves the sulfur utilization.
- ✓ Chemical reaction of fluoroether with lithium anode forms a protective layer acting as a physical barrier eliminating the parasitic reactions of dissolved polysulfides with lithium.

Courtesy:

Toyota Prius Prime NCM Cells

Prius Prime – Cell Specification

PHV cell specs.	Prius plug-in	Prius Prime
Voltage (V)	3.7	3.7
Capacity (Ah)	**21.5** (17% UP →)	**25**
Weight (g)	726	720
Dimensions (mm)	148 (W) 26.5 (T) 105 (h)	148 (W) 26.5 (T) 105 (h)

TOYOTA

Courtesy: Toyota and AABC SFO 2017

Prius Prime – Cell Specification …

Output power at low temperatures and SOCs improved to expand EV mode range

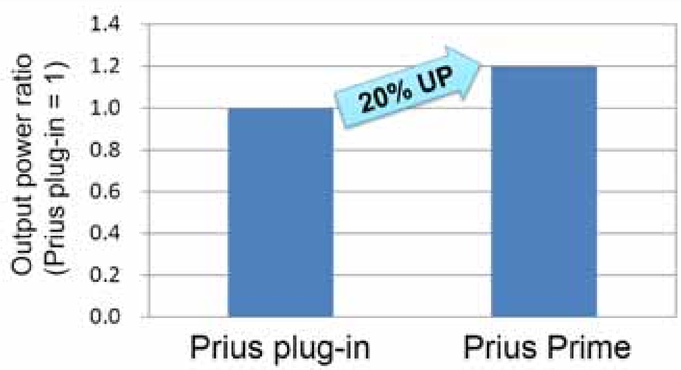


Fig. Output power performance of the cell at 0°C, SOC 10%

Courtesy: Toyota and AABC SFO 2017

Prius Prime – Safety Test List

Category	Test items	Regulations and standards	Result
Mechanical	Vibration	• UN38.3 • GB/T31485 • IEC62660	Good
	Mechanical shock		Good
	Impact/crush		Good
	Drop		Good
	Nail penetration		Good
	Altitude simulation		Good
Thermal	High temperature endurance		Good
	Temperature cycling		Good
Electrical	External short circuit		Good
	Overcharge		Good
	Forced discharge		Good
	Forced internal short circuit		Good
	Seawater immersion		Good

Courtesy: Toyota and AABC SFO 2017

Envia Cells

Envia High Energy Pouch Cells

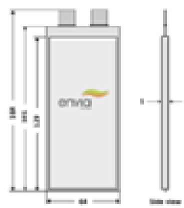
High Energy Drone Pouch Cells
(ENV35011-CRC)

Key Features & Benefits:
- ✓ 350Wh/Kg usable specific energy at C/10 rate
- ✓ 840Wh/L usable energy density (without terrace) at C/10 rate
- ✓ Excellent high voltage (4.47V) stability
- ✓ Proprietary Si-based anode and Cobalt-rich composite (CRC) cathode
- ✓ Low cost

Applications:
- ✓ Unmanned aerial vehicles (UAVs)
- ✓ Flying automobiles
- ✓ Military applications
- ✓ Grid applications

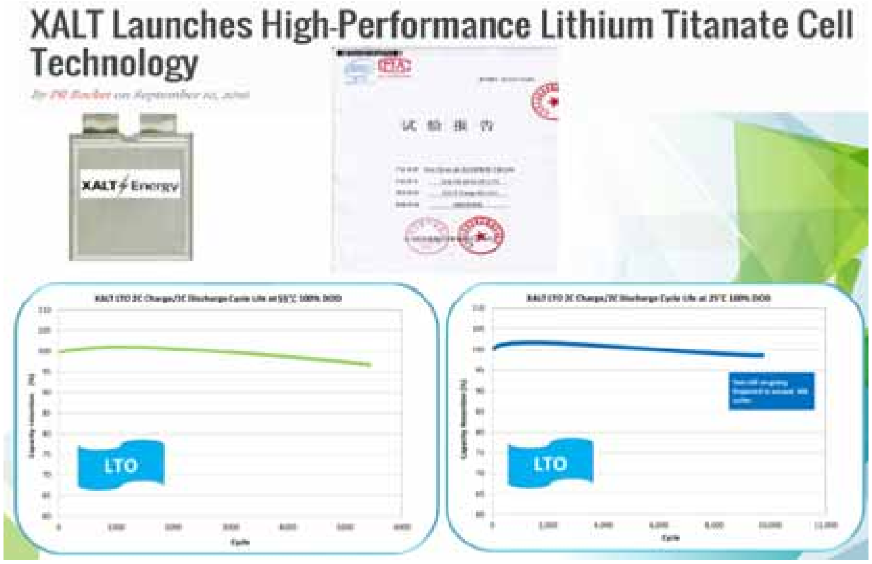
Cell characteristics	Units	Value
Cell capacity at C/10 rate	Ah	10.6
Specific energy at C/10 rate	Wh/Kg	350
Energy density at C/10 rate	Wh/L	840
Cell weight (g)	g	111
Cell dimensions	mm	145 x 64 x 5
Nominal voltage (V)	V	3.65
Operating temperature (°C)	degrees °C	-10 to 55
Voltage range	V	2.5 to 4.47

Courtesy: Shmuel De-Leon



XALT Cells

Lithium Titanate



Courtesy: XALT

XALT – LIB Portfolio

- Currently using Two Chemistries *(more possible)*:
  - NMC/Graphite & NMC/LTO
- Three electrode designs HP, HE, UHP
- Two standard formats
  - *255mmX255mm*
  - *216mmX216mm*

	Current Products (Ah)	Energy Density Wh/kg	Max Charge (C Rate)	Max Discharge (C Rate)	Peak Power <10 sec (C Rate)	Power to Energy Ratio
High Energy NMC	25 - 75	178	2	3 – 5	5 – 8	2:1 to 3:1
High Power NMC	31 - 75	156	3	6 – 8	10 – 12	3:1 to 6:1
Ultra High Power NMC	31	110	3	15	25	6:1 to 11:1
High Power LTO	60	80	6	6	10	5:1 to 8:1

Courtesy: XALT

XALT Cells in Marine Service

- **Hybrid Electric Ferry**
  - Prinsesse Benedikte
  - 2.7 MWh (NMC)

Newly Awarded 8.4 MWh for Two Ferries: 4.2 MWh each

Capacity: 1,250 Passengers, 240 cars, 539 trucks; transporting up to 50,000 passengers and 9,000 cars daily

- **Full Electric Ferry**
  - Ampere (Zero Cat)
  - 1.4 MWh (NMC)

New 532 kWh OSV application

- **OSV Applications**
  - 300 kWh (NMC)

Courtesy: XALT

Alveo Energy

Alveo Energy

- Spin out from Stanford in 2012.
- Raised series A and ARPA-E award in 2013.
- Raised series B in 2016.
- Novel sodium-ion cell chemistry based on Prussian blue (PB) electrodes and an aqueous-organic cosolvent electrolyte.
- Technology benefits: lower capex, longer life, and higher power than lead acid in the same footprint, with no lead or acid.
- Present status: initial manufacturing scale up and product engineering.
- Next major milestone: first packs to customer demo testing in <2 years.

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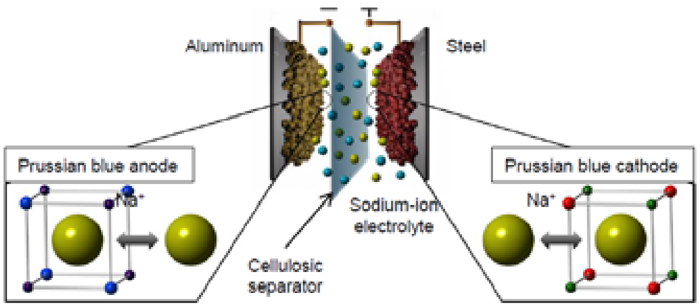
Alveo Cell Technology

- Prussian blue (PB) anode and cathode:
  - Zero-strain Na^+ intercalation in both electrodes. Neither limits cell cycle life.
  - Open framework PB structure cycles Na^+ at very high C-rates.
  - Modest specific capacity (70 mAh/g) but at a very low price ($2/kg).
- Aqueous-organic cosolvent electrolyte.
  - High Na^+ conductivity enables high power.
  - Good safety: nonflammable, pH-neutral.
- Cell architecture requires no new manufacturing methods.

Schematic of Alveo Cell



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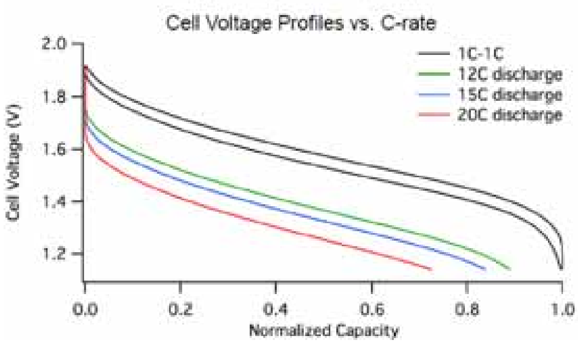
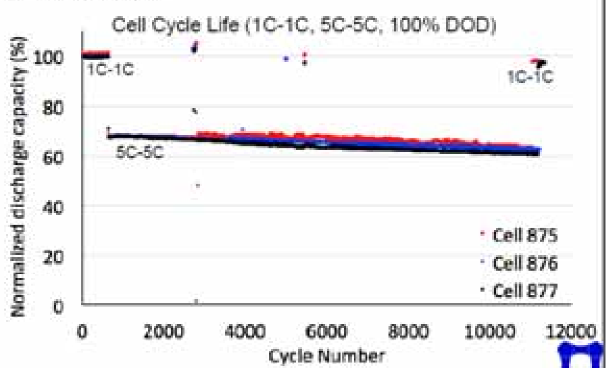
Alveo Cell Performance

- Nominal 1.6 V cell with energy density up to ~55 Wh/L.
- High power:
  - Up to 80% energy extraction during 12C discharge.
  - Lead acid: 25-30%.
- Long cycle life:
  - ~3% capacity loss after 12,000 deep discharge cycles/6 months of testing.
  - Projected cycle life >30,000 cycles.





Solid Electrolytes

Solid State Battery Companies

Courtesy: Solid Power

Solid State Battery Advantages

Solid-state allows for the parallel pursuit of high energy density and safety

- Non-flammable, high temperature stability
- Benign failure under abuse conditions (e.g., puncture, overcharge, etc.)
- 5V+ stable voltage window (sometimes)
- Long calendar life
- Enables entirely new classes of electrode materials
- Allows for more packaging options (bipolar designs, unpackaged cells, etc.)

Courtesy: Solid Power

Solid State Battery Challenges

- Rate capability limitations
  - Conductivity drops with temperature
  - No liquid to conform to interparticle and interlayer interfaces
  - High C-rates require higher current densities than for thin films
- Cycling with Li metal anode
  - Separator and/or any protection layers must be dense, stiff, Li^+-conductive, and chemically compatible
  - Lithium can propagate across open pores or grain boundaries
  - May require conservative charge rates and temperatures
- Other miscellaneous
  - Needs to approach cost parity with Li-ion
  - Higher stack pressure may be needed than for Li-ion
  - Layer thicknesses and material loadings must be appropriate for high energy density

Courtesy: SolidPower

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Bollore Solid State Battery

Bolloré

LMP Battery Characteristics	
Battery	
Volume (L)	300
Weight (kg)	300
Electrical Specifications	
Energy	30KWh
Peak Power	45kW (30s)
Nominal Voltage	410V
Thermal Characteristics	
Internal Temperature	60°C - 80°C
Ambient Temperature	-20°C - +160°C

- Based on Poly(ethylene oxide) (PEO)
- Low conductivity requires high cell temperature
- Can safely use Li metal if charge and discharge conditions tightly controlled

→ Modest 100 Wh/kg and 100 Wh/L

→ Scalable

→ Modest 150 W/L peak power

→ Narrow temperature window

http://www.bluecar.fr/les-batteries-lmp-lithium-metal-polymere

Courtesy: SolidPower

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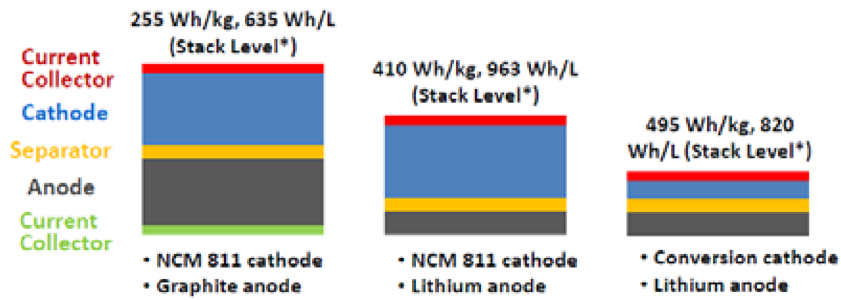
Solid State Battery – Energy Density Improvement

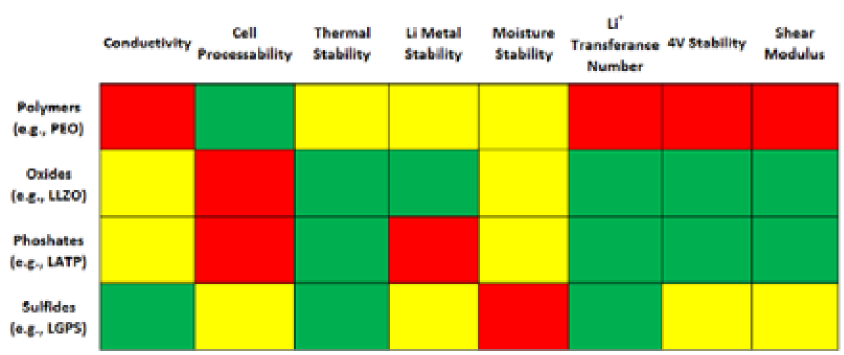
Li metal anode is key to solid-state cells matching and surpassing Li-ion cell-level energy density



*Includes cathode, anode, separator, and current collectors. Assumes 20 micron separator and 4.0 mAh/cm² capacity loading

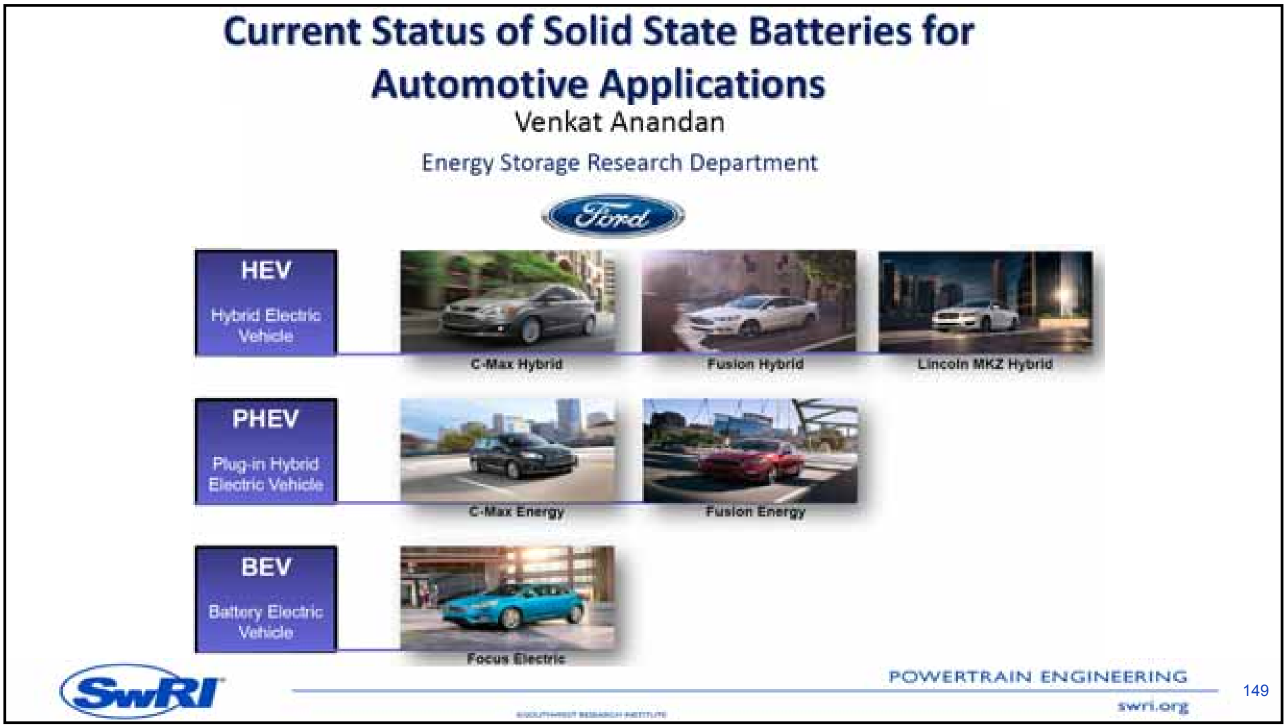
Courtesy: Solid Power

Solid State Battery – Electrolytes



- Ion transport number, also called the transference number, is the fraction of the total current carried in an electrolyte by a given ionic species
- Shear modulus impacts the tendency for dendrites to form on the anode surface during cycling and should be at least twice that of Li metal in order to prevent dendrite nucleation

Courtesy: Solid Power


Current Status of Solid State Batteries for Automotive Applications
Venkat Anandan
Energy Storage Research Department
Ford
HEV
Hybrid Electric Vehicle
C-Max Hybrid
Fusion Hybrid
Lincoln MKZ Hybrid
PHEV
Plug-in Hybrid Electric Vehicle
C-Max Energy
Fusion Energy
BEV
Battery Electric Vehicle
Focus Electric
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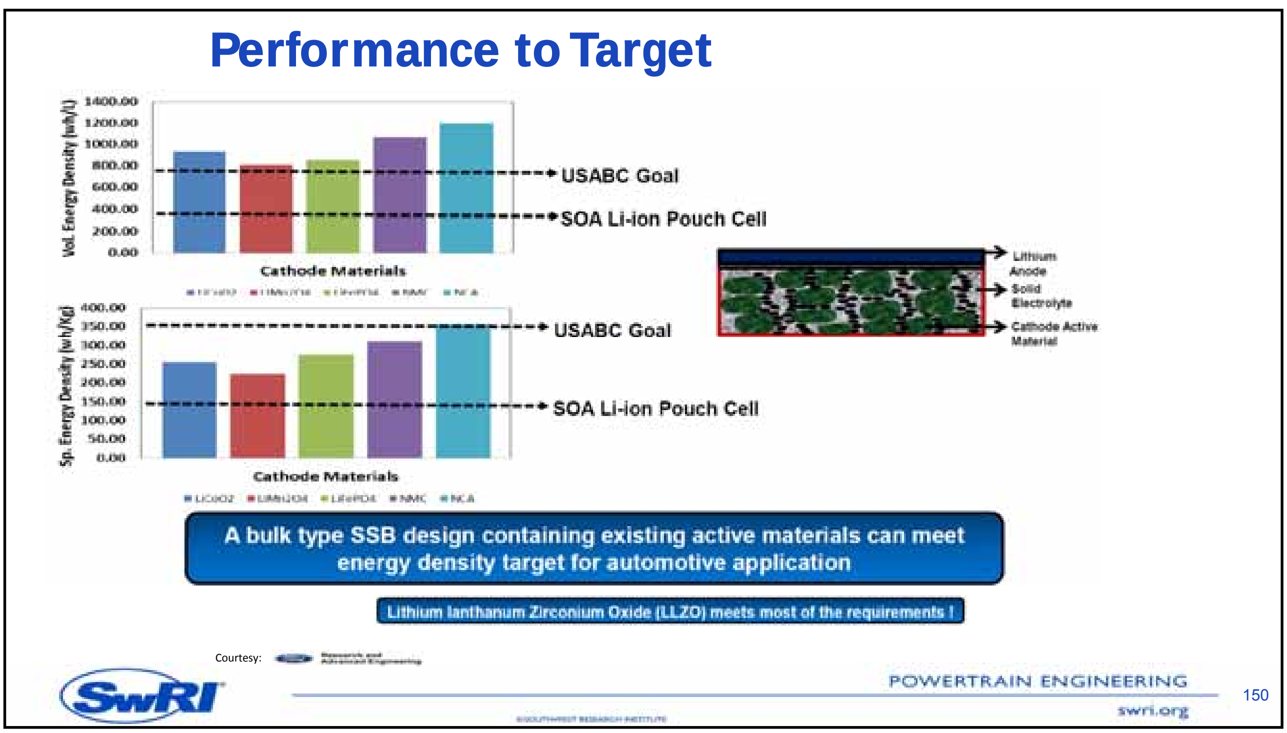
Performance to Target
Vol. Energy Density (wh/L)
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
USABC Goal
SOA Li-ion Pouch Cell
Cathode Materials
Sp. Energy Density (wh/Kg)
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
USABC Goal
SOA Li-ion Pouch Cell
Cathode Materials
LiCoO2
LiMn2O4
LiFePO4
NMC
NCA
Lithium Anode
Solid Electrolyte
Cathode Active Material
A bulk type SSB design containing existing active materials can meet energy density target for automotive application
Lithium lanthanum Zirconium Oxide (LLZO) meets most of the requirements !
Courtesy:
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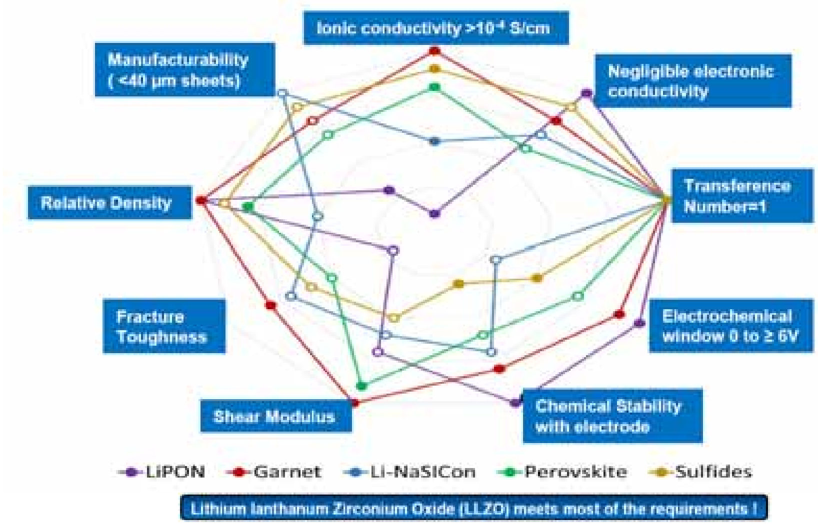
Current Solid Electrolytes



Courtesy:

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Packs

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Prius Prime – Pack Specification

Energy doubled and energy density improved

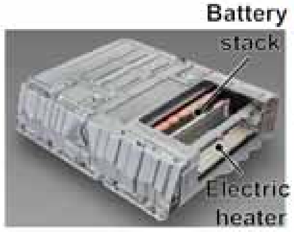


Fig. Internal structure of battery pack

Table. Battery specs

Battery specs.	Prius plug-in	Prius Prime
Cells	56 cells (16 cells × 4 stacks)	95 cells (19 cells × 5 stacks)
Voltage	207.2 V	351.5 V
Energy	4.4 kWh	Doubled 8.8 kWh
Weight (Specific energy)	80 kg (55 Wh/kg)	120 kg (73 Wh/kg)
Volume (Energy density)	87 L (50 Wh/L)	145 L (60 Wh/L)

TOYOTA

Courtesy: Toyota and AABC SFO 2017

Prius Prime – Thermal Management

Battery warming system expands EV mode at low temperatures

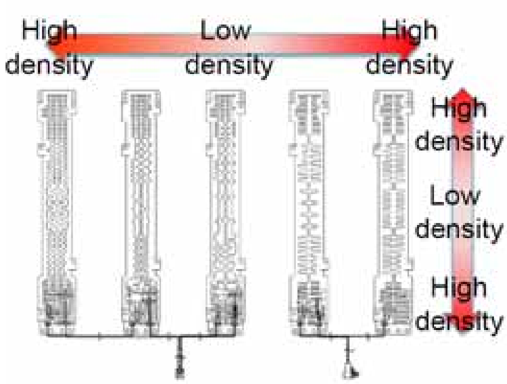


Fig.1. Electric heater pattern

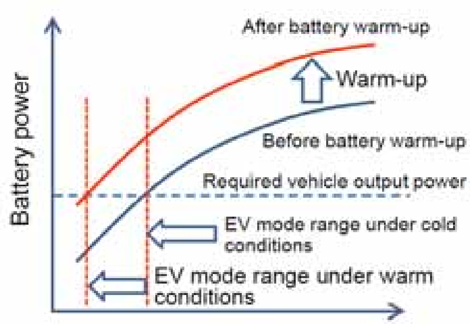


Fig.2. Illustration of output increase with battery warm-up system.

TOYOTA

Courtesy: Toyota and AABC SFO 2017

Prius Prime – Charge Scheduling

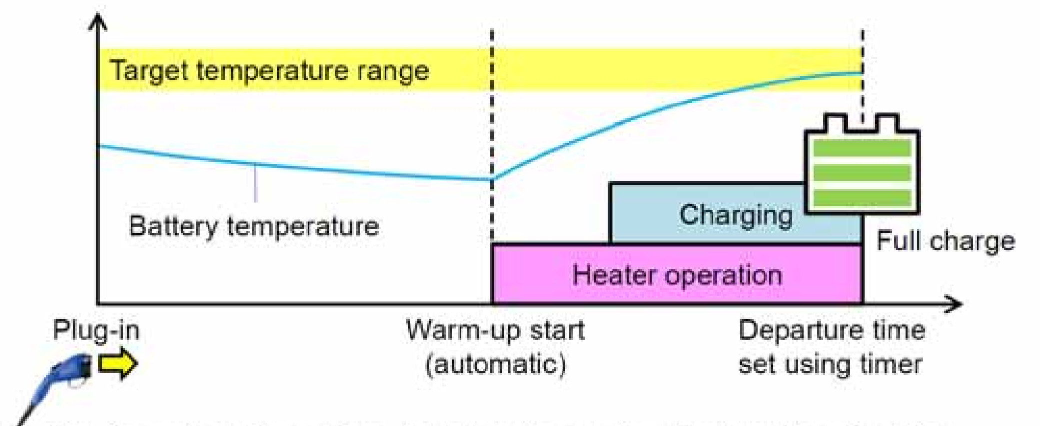


Fig. Operation after setting departure time using charging timer function

TOYOTA

Courtesy: Toyota and AABC SFO 2017

Prius Prime – Pack Safety Tests

Table 1. Vehicle tests

Test item	Result
Frontal impact	Good
Rear impact	Good
Side impact	Good
Water spray	Good
Load resistance	Good
High-voltage safety	Good
Immersed road	Good

Table 2. Battery pack tests

Category	Test item	Result
Mechanical	Vibration	Good
	High-altitude simulation	Good
	Impact/crush	Good
	Mechanical shock	Good
	Drop	Good
Thermal	Thermal propagation	Good
	Thermal shock and cycling	Good
	Fire resistance	Good
	Over temperature protection	Good
Electrical	External short circuit	Good
	Over charge protection	Good
	Over discharge protection	Good
	Salt water immersion	Good
Others	Humidity/moisture exposure	Good
	Smoke exhaust performance	Good

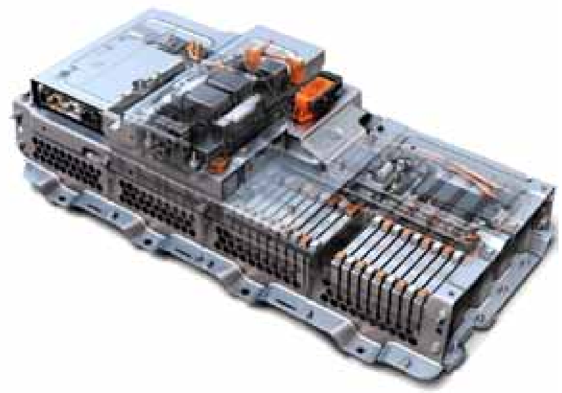
TOYOTA

Courtesy: Toyota and AABC SFO 2017

Malibu Hybrid Pack

Battery

- *1.5 kWh lithium-ion battery*
- *80 Prismatic can cells from Hitachi*
- *300V*
- *Air Cooled*
- *Accessory loads efficiently supplied by battery pack and DC-DC converter*
- *Built in Brownstown, Michigan*



Courtesy: GM and AABC SFO 2017

Volt 2 PHEV Pack

Battery

- *18.4 kWh lithium-ion battery*
- *96s2p Pouch cells from LG*
- *360V*
- *Liquid Cooled*
- *Common Cell, Module, Electronics with Gen2 Volt*
- *Built in Brownstown, Michigan*

Courtesy: GM and AABC SFO 2017

Bolt EV Pack

CHEVROLET BOLT EV BATTERY PACK DETAILS	
Cell Chemistry	Ni-Rich NMC
Cell Configuration	96S 3P (288cells)
Energy	60 kWh
Power	160 kW
Nominal Voltage	350 V
Mass	436 kg
Cooling System	Liquid Cooled
# of Sections	5

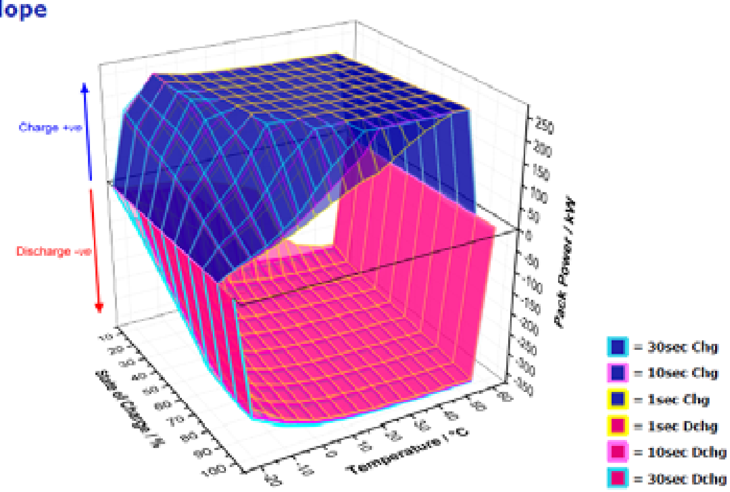
Courtesy: GM and AABC SFO 2017

Pack Operating Envelope

Applications Analysis

Battery Pack Operating Envelope

- Cell/Module Current Limited operating envelope, power capability as a function of :
  - Temperature
  - State of Charge
  - Pulse duration
- Derived from HPPC cell data



Courtesy: JM and AABC SFO 2017

Summary

- In this presentation we reviewed:
  - Cell supplier and chemistry landscapes along with performance metrics and future directions
  - Fundamental operation of a lithium ion cell
  - Two types of advanced lead acid batteries
  - Several samples of production lithium ion cells
  - Upcoming chemistries such as Lithium Sulfur and safer solid state technology
  - Samples of several battery pack constructions

Energy Storage System Evaluation and Safety Consortium

EssEs.SwRI.org

Benchmarking of Lithium Ion Cells

SOUTHWEST RESEARCH INSTITUTE®

Bapi Surampudi, Ph.D.

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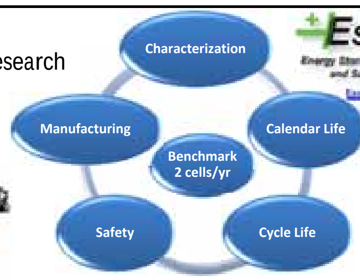
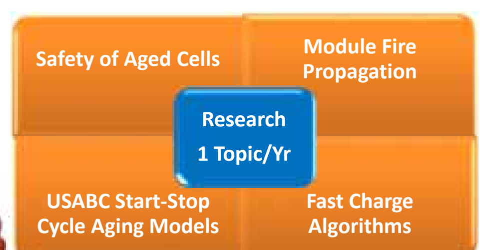
- Period: Nov 30 2015 - Nov 30, 2019
- 70% Cell/Vehicle benchmarking and 30% research
- Basic benchmark of one xEV per year



Members



Basic Vehicle Benchmark

VW e-Golf

Chevy Bolt

KIA Soul EV

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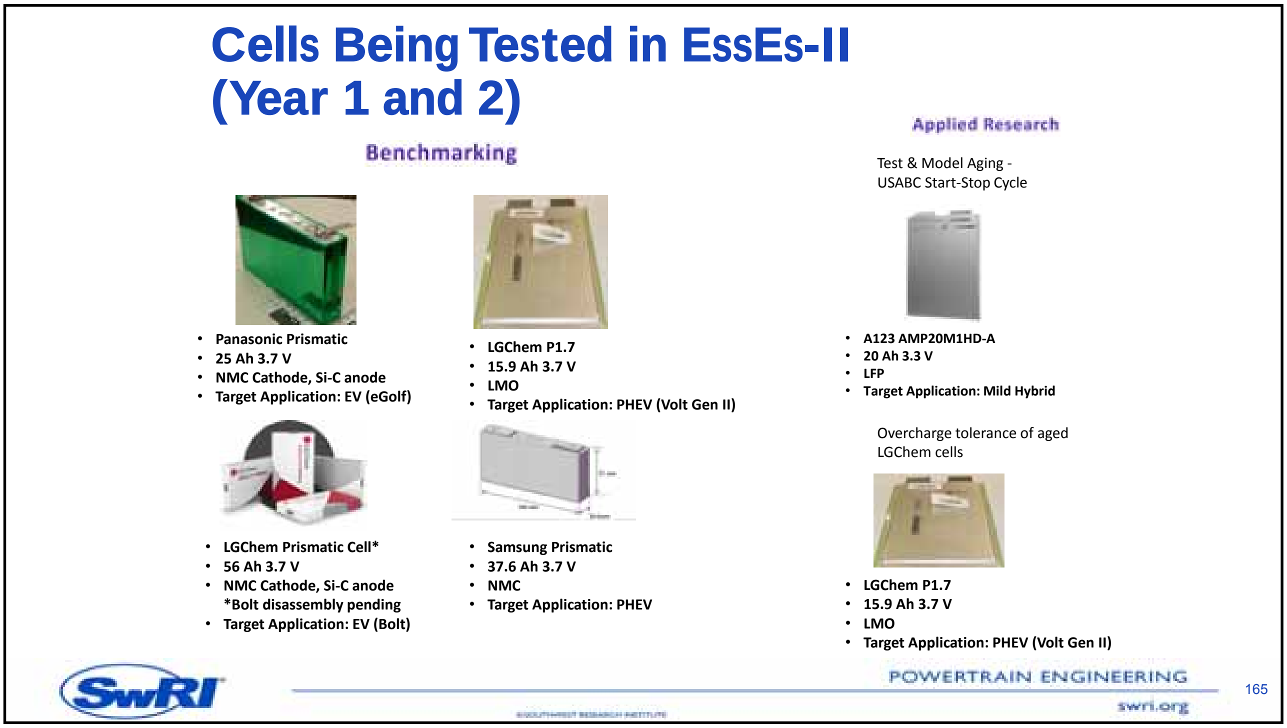
Cells Being Tested in EssEs-II
(Year 1 and 2)
Benchmarking
Panasonic Prismatic
25 Ah 3.7 V
NMC Cathode, Si-C anode
Target Application: EV (eGolf)
LGChem P1.7
15.9 Ah 3.7 V
LMO
Target Application: PHEV (Volt Gen II)
LGChem Prismatic Cell*
56 Ah 3.7 V
NMC Cathode, Si-C anode
*Bolt disassembly pending
Target Application: EV (Bolt)
Samsung Prismatic
37.6 Ah 3.7 V
NMC
Target Application: PHEV
Applied Research
Test & Model Aging -
USABC Start-Stop Cycle
A123 AMP20M1HD-A
20 Ah 3.3 V
LFP
Target Application: Mild Hybrid
Overcharge tolerance of aged
LGChem cells
LGChem P1.7
15.9 Ah 3.7 V
LMO
Target Application: PHEV (Volt Gen II)
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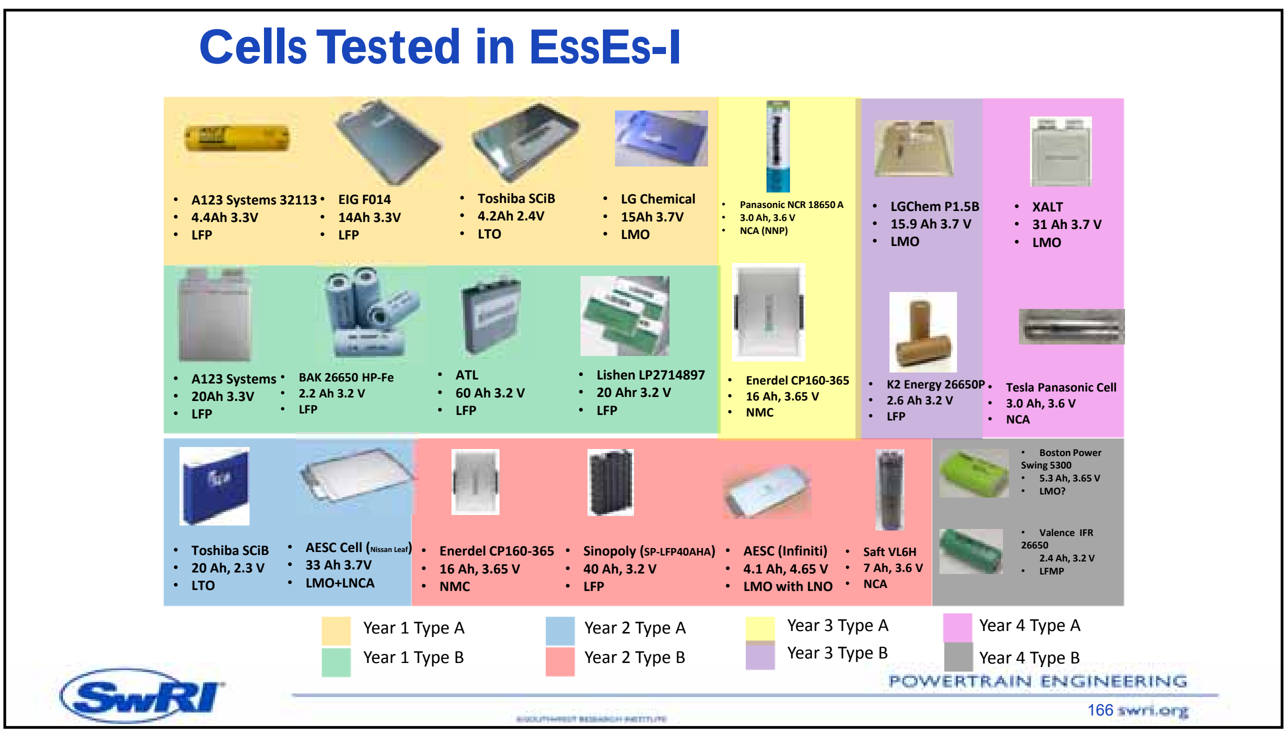
Cells Tested in EssEs-I
A123 Systems 32113
4.4Ah 3.3V
LFP
EIG F014
14Ah 3.3V
LFP
Toshiba SCiB
4.2Ah 2.4V
LTO
LG Chemical
15Ah 3.7V
LMO
Panasonic NCR 18650 A
3.0 Ah, 3.6 V
NCA (NNP)
LGChem P1.5B
15.9 Ah 3.7 V
LMO
XALT
31 Ah 3.7 V
LMO
A123 Systems
20Ah 3.3V
LFP
BAK 26650 HP-Fe
2.2 Ah 3.2 V
LFP
ATL
60 Ah 3.2 V
LFP
Lishen LP2714897
20 Ahr 3.2 V
LFP
Enerdel CP160-365
16 Ah, 3.65 V
NMC
K2 Energy 26650P
2.6 Ah 3.2 V
LFP
Tesla Panasonic Cell
3.0 Ah, 3.6 V
NCA
Toshiba SCiB
20 Ah, 2.3 V
LTO
AESC Cell (Nissan Leaf)
33 Ah 3.7V
LMO+LNCA
Enerdel CP160-365
16 Ah, 3.65 V
NMC
Sinopoly (SP-LFP40AHA)
40 Ah, 3.2 V
LFP
AESC (Infiniti)
4.1 Ah, 4.65 V
LMO with LNO
Saft VL6H
7 Ah, 3.6 V
NCA
Boston Power Swing 5300
5.3 Ah, 3.65 V
LMO?
Valence IFR 26650
2.4 Ah, 3.2 V
LFMP
Year 1 Type A
Year 1 Type B
Year 2 Type A
Year 2 Type B
Year 3 Type A
Year 3 Type B
Year 4 Type A
Year 4 Type B
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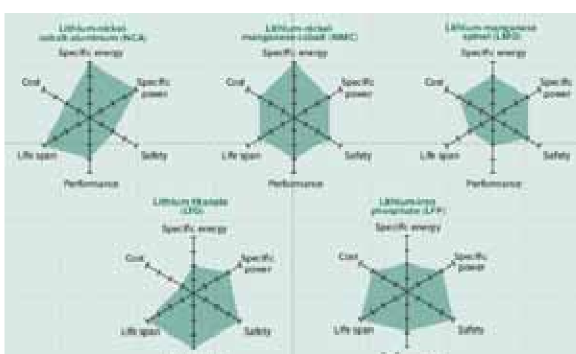
Benefits of Sharing Test Data Across Industries

- Batteries are used in many industries and each application needs test data to design, diagnose and control for safe and long performance
- EssEs creates unique test procedures that are battery size factor agnostic and applicable across all industries
- Bringing together testing needs from all industries to produce a generic data base that can be applied across multiple applications is very cost effective for all participants

Intent of Testing

- There are many chemistry, size and format, price and safety differences
- There will be no clear 'winner' but rather a best match for a particular application



Source : AABC 2010, Pasadena, California and Boston Consulting Group

EssEs Consortium Model

- SwRI Cooperative Research Program to serve market need to test commercial energy storage components and do precompetitive research
- Consortium is a group of companies that form an organization for a finite duration to meet a common goal
- Each phase is for a duration of 4 years and EssEs phase 2 is in Year 1 now
- Example testing hours for EssEs-I Year 1
  - Cycle Life and Characterization – 160,000
  - Safety/Abuse - 300
  - Calendar Life – 170,000
- Each member pays an annual membership fee
- Designated representatives from each member company will form a group called 'Program Advisory Committee' or PAC

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EssEs Operations

- Two PAC meetings per year
  - PAC meetings have an informal atmosphere and high levels of interaction
  - Members are encouraged to interject with questions and comments at any time
- PAC members vote how to direct the consortium work
  - SwRI proposes test procedures, list of cells and a few topical research projects to PAC
  - SwRI will poll PAC for majority opinion after SwRI and PAC discuss plans and agree on approved course of action during PAC meetings
- Relationships between members and their suppliers are confidential
- Material analysis will be done as part of topical research
- Specific member feedback is kept confidential
- Data and reports are uploaded to Vault on a monthly basis

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How to Join EssEs-II ?

- SwRI will provide the standard consortium contract to you for approvals
- Membership cost for EssEs II is
  - $65,000 a year for EssEs-I members
  - $75,000 a year for new members
  - $32,000 a year for small companies with restricted data access and voting rights
- SwRI will invoice every year in March

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List of Deliverables

- Complete data set in binary (mat) and ascii (text) format
  - SwRI executes PAC plan and presents test data at PAC meetings
  - Test Procedures and Raw data are posted on EssEs Web Site for secure member access (https://vault.swri.org/esses)
- Basic and comparative data analysis
- Monthly progress reports
- Two PAC meetings every year
- Status on SwRI internal research during PAC meetings
- Results of one topical research per year
- Industry update from conferences
- Guest presentations

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EssEs Work Scope

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Scope of Work



xEV Benchmarking
Procurement and Inspection
CAN bus decrypt for
battery operation signals
Performance testing on road
Charge testing
Vehicle and pack disassembly
Part inspection at EssEs meetings

Cell Benchmarking for BMS development
Procurement of cells
Performance testing
Quality testing
Life testing modeling
Safety testing

Topical Research
Member picked topics
Charge algorithms
Diagnostic algorithms
Safety of aged cells
Life duty cycles
Fire propagation

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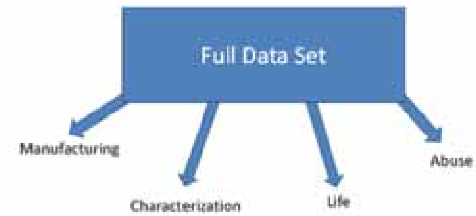
Type of Tests

- Perform testing regime on three battery cell types per year:
  - Manufacturing
  - Characterization
  - Life
  - Safety/Abuse

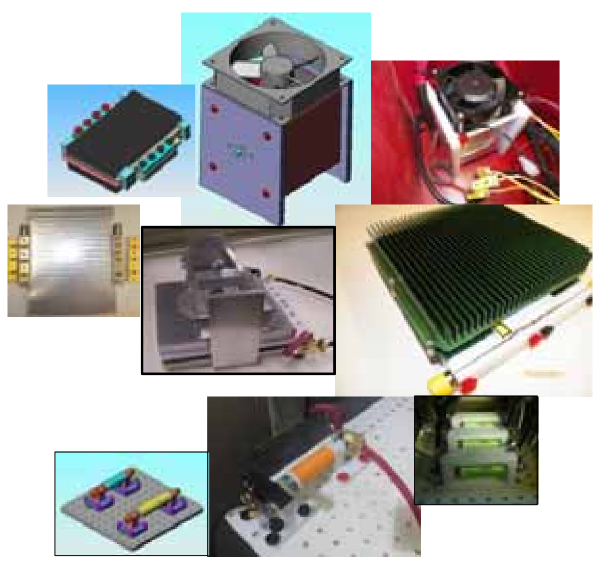


Total tests per cell type

Test Type	# of Test types	# of Samples per test	Total tests
Manufacturing	3	60	180
Characterization	22	4	88
Cycle Life	9	2	18
Calendar Life	9	2	18
Abuse	3	2	6

EssEs Builds Custom Cell Fixtures

- SwRI designed and fabricated fixtures for cell testing
- More accurate and consistent results
- Fixtures for different geometries e.g.
  - Cylindrical
  - Pouch
- Ability to calibrate normal pressure on flat cells
- Active or passive cooling as needed
- Good electrical contact



EssEs Builds upon Available Standards

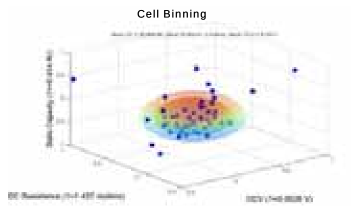
- SwRI cell testing procedures have been sourced from
  - SAE J2464
  - UN 38.3
  - USABC
  - US DOE Battery Test Manual for PHEV
  - IEEE
  - UL
- Test procedures have been modified as needed based on member feedback and SwRI experience
- SwRI is certified to ISO 9001:2008 and ISO 14001:2004 and accredited to ISO/IEC 17025:2005

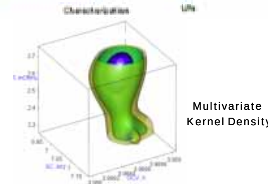
List of Tests Conducted in EssEs

- Manufacturing
  - Physical and Electrochemical
- Characterization
  - Static Capacity, Cold Cranking and HPPC
- Cycle Life
  - Taguchi L9
- Calendar Life
  - Taguchi L9
- Safety
  - Overcharge, Penetration, Thermal Stability
- Topical Research
  - Member selected (e.g. Material analysis, Module tests, Cost share in a US Government solicitation)

Manufacturing Testing

- Average sample size is 60
- Provide statistical information on variation due to manufacturing process
- Measured Beginning of Life (BOL) parameters:
  - Manufactured Weight
  - Open Circuit Voltage
  - Internal impedance
  - Capacity
- Nyquist analysis
- Cells are binned or down-selected based on measured parameters



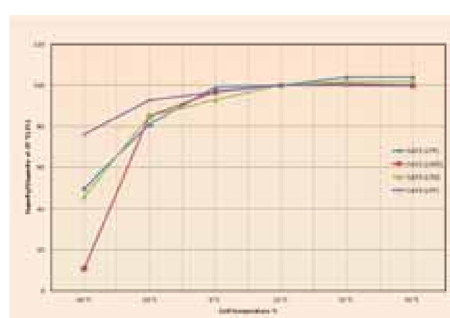


	Cell 1	Cell 2
Weight		
BOL conditioning		
EIS		

Characterization Testing

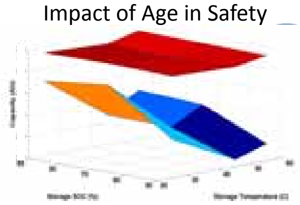
	Cell 1	Cell 2
HPPC		
Static Capacity		
Cold Cranking		

- Hybrid pulse power characterization (HPPC) test is done at 0, 25 and 45 deg C and allows for
  - Design of life test matrix
  - Sizing battery pack for an application
- Static capacity test is done at 4 C-Rates and 4 temperatures for each cell type
  - It includes charge capacity tests that allows for calculating charge and discharge efficiency map for the battery
- Cold cranking follows VDA standard and is BSF (Battery Size Factor) agnostic



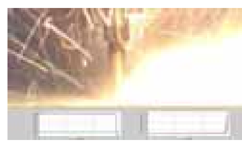
Safety Testing

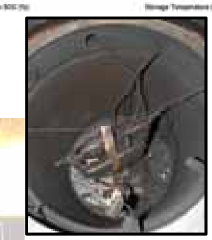
Impact of Age in Safety



Ambient Temperature: 50 deg C

		Cell 1	Cell 2	Cell 3
Penetration				
Over charge	3C			
Thermal Stability	100% SOC			





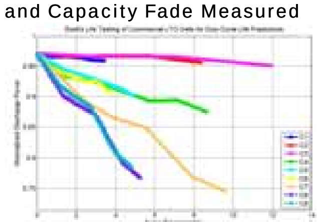
Cycle Life Testing: EssEs Approach

- Map-based instead of target based
- Generate statistical model
- Use model to predict life for applications in multiple domains (Transportation, Stationary, Off-highway and Consumer electronics)

Taguchi L9

Test	T (°C)	Nom SOC	ΔSOC	Pd	Pc
1	25	50	80	10	10
2	25	50	90	25	25
3	25	50	100	40	40
4	45	50	80	25	40
5	45	50	90	40	10
6	45	50	100	10	10
7	55	50	80	40	25
8	55	50	90	10	40
9	55	50	100	25	10

Power and Capacity Fade Measured

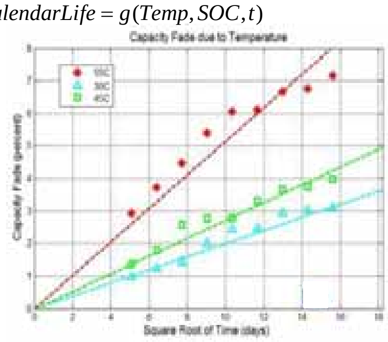


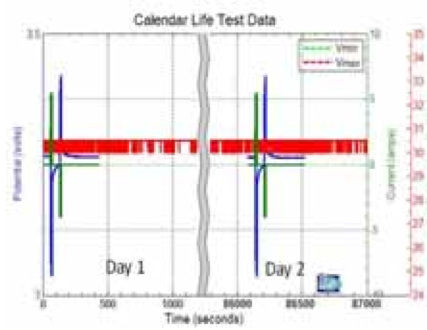
$$CycleLife = f(Temp, DOD, ChargePow, DischPow, Ah\_hrThru)$$

Calendar Life

- Taguchi L9 Design used with
  - Temperatures 25, 45 and 55 ˚C
  - SOC 50, 70 and 90%
- Reference Point Test (RPT) data taken once every 28 days
- Battery is disconnected from all equipment during rest period
- Thermocouple continues to monitor temperature

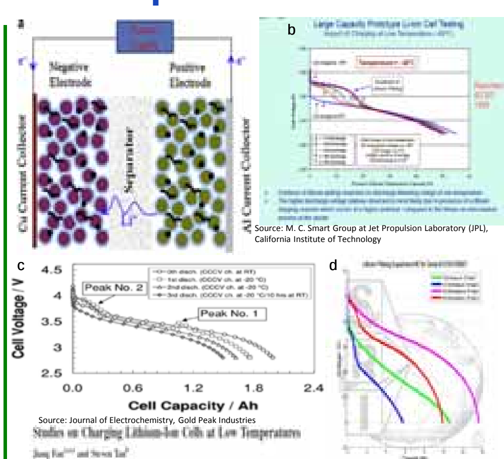
$$CalendarLife = g(Temp, SOC, t)$$





Sample Topical Area of Research:
Lithium Plating Effect at Low Temperatures

- Lithium plating mainly occurs at anode side due to intercalation kinetics at cold temperature during charging process
- Comprehensive literature review done
- BMS calibration data for inception of Lithium plating was identified so it can be avoided in operation
- A real time diagnostic feature was identified for identifying as it occurs

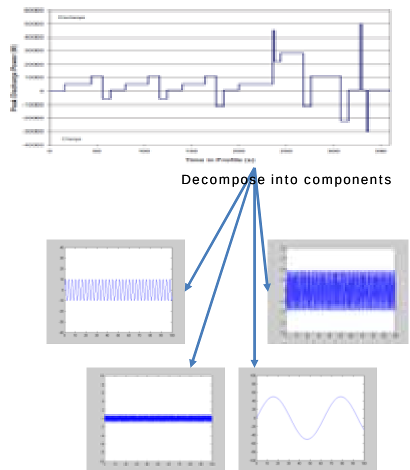


Sample Topical Area of Research:

Frequency Regulation Decomposition for Cycle Life Prediction

- Each battery application has several load duty cycles
  - Hybrid Vehicles (Micro, Mild and Full)
  - Plug in Hybrid Vehicles (PHEVs)
  - Electric Vehicles (EVs)
  - Grid Storage Frequency Regulation
  - Grid Storage Renewables (Wind, Solar)
  - Niche Applications (Space, Under Water, Aerospace, Medical)
  - Stationary Applications (UPS, Telecom towers)
- To test batteries for any application life, several duty cycles have to be run for many years
- Any duty cycle can be broken down into several basic components
- By testing for life of battery at each of these components and the full duty cycles a relationship can be established to construct life estimates from components to any duty cycle
- SwRI has a patent awarded – Royalty free usage for EssEs members

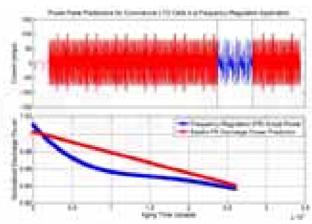
Life testing of actual duty cycle



Decompose into components

Do Life testing at each component

Then, relate component life to duty cycle life



Cell Acquisition

Chevy Volt Pack Evaluation …

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Chevy Volt Pack Evaluation…

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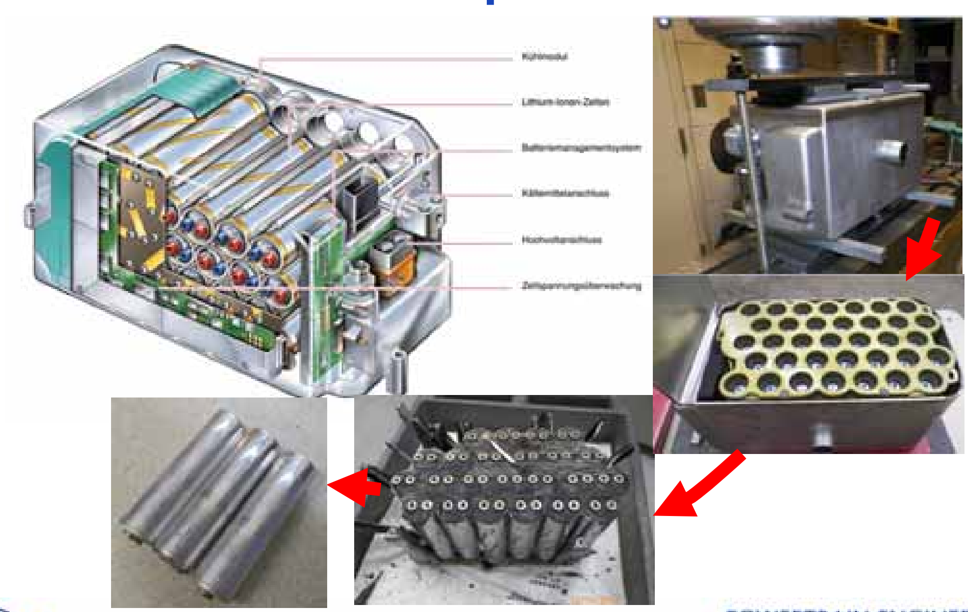
Chevy Volt Pack Evaluation …

Mercedes Start-Stop Saft Pack

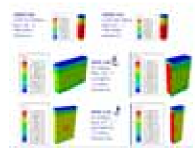


Nissan Leaf AESC Battery Pack

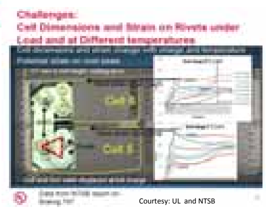
VW e-Golf Battery Pack

Sample Guest & Internal Presentations

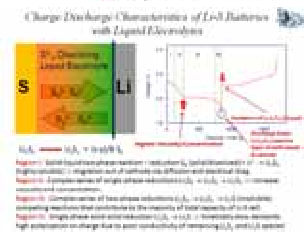
- Guest
  - Toshiba
  - ATL
  - CATARC
  - Li-S chemistry commentary by SwRI
  - Silicon Clathrate anodes by SwRI
  - UL
- Internal Research
  - Format and Thermal Analysis of Lithium Ion Cells
  - Emissions from LiB abuse
  - Fatigue component of cycle life
  - High fidelity heuristic calendar and cycle life model development
  - Modeling and Customization of hybrid pulse power testing



Courtesy: ATL



Courtesy: UL and NTSB



Courtesy: SwRI and Dr. Miller

How are Members using EssEs Data?

Safety Assessment

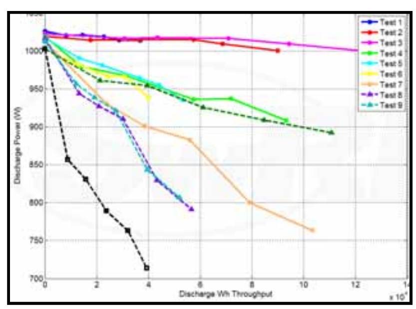
- **Objective**
  - Evaluate SAE or EUCAR rating for cells and fire propagation propensity in modules
- **Approach**
  - EssEs consortium addresses most common field safety incidents by focusing on data for penetration, overcharge and thermal stability
  - One production per year will be subjected to penetration and fire progradation will be studied
- **End-Goal**
  - Select the safest cell for member product build and learn from benchmarking packaging from other OEMs

Safety Assessment of Fresh and Aged Cells

Life Predictions

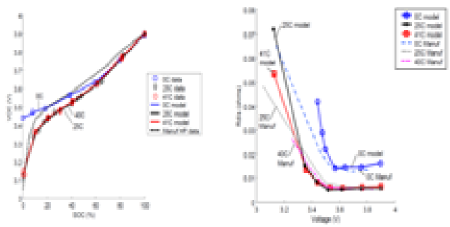
- **Objective**
  - Generate data driven life models
- **Approach**
  - EssEs consortium generates life data on duty cycle components
  - Life model was created from these components
  - Life prediction from model and an actual frequency regulations test were compared
- **End-Goal**
  - Validated life model for grid storage applications

Prediction of Life of Battery
Under Frequency Regulation Cycle

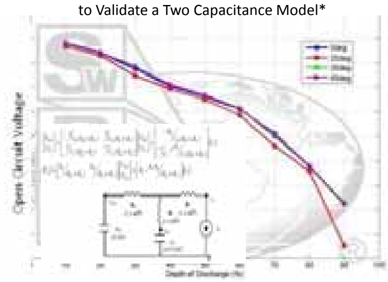


Calibrate Equivalent Circuit Models

- **Objective**
  - Generate equivalent circuit models for cell for use in BMS
- **Approach**
  - EssEs consortium generates data that can be used to calibrate equivalent circuits
  - Circuit component values can be calibrated to be valid across cell performance variations with temperature and age
- **End-Goal**
  - Validated Equivalent Circuit models are used to actively control battery packs and maintain state of health



Data of OCV vs SOC for Saft 6 Ah Cell at Various Temperatures used to Validate a Two Capacitance Model*



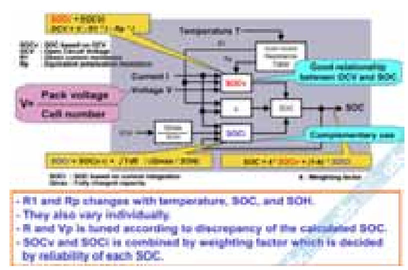
EssEs data was used To calibrate models

*Source:

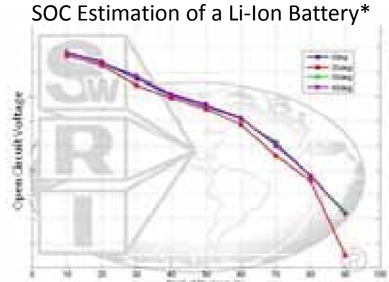
SOC Estimation for BMS

- Objective
  - Generate calibration data needed for SOC estimation in BMS
- Approach
  - EssEs data has information regarding following relationships
    - OCV estimation from HPPC data
    - OCV vs SOC
  - Look up SOC based on OCV from EssEs data
  - Coulomb counting or integration of current can also be used to estimate SOC
  - A Weighted sum of both methods may be used as shown in Hitachi's illustration
- End-Goal
  - Improve fidelity of SOC estimation for BMS control

*Source: Kei Sakabe et.al, Hitachi, Presentation at AABC Europe 2012



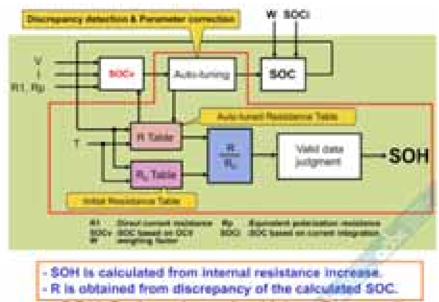
SOC Estimation of a Li-Ion Battery*



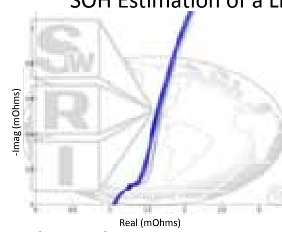
OCV Data from EssEs

SOH Estimation for BMS

- Objective
  - Generate calibration data needed for SOH estimation in BMS
- Approach
  - EssEs data has information regarding following relationships
    - Temperature based resistance from HPPC tests
    - Initial DC resistance is acquired from (Electrochemical Impedance Spectroscopy) EIS tests
  - Estimated resistance is auto tuned by BMS controller based on error on estimated SOC
- End-Goal
  - Internal resistance based adaptive SOH estimation



SOH Estimation of a Li-Ion Battery*

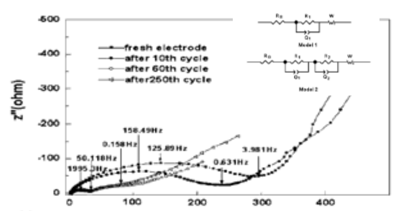


Initial DC Resistance from EssEs EIS Data

*Source: Kei Sakabe et.al, Hitachi, Presentation at AABC Europe 2012

Lumped Parameter View of Ageing

- Objective
  - Identify dominant age related parameters in an equivalent circuit model
- Approach
  - EssEs data
    - BOL EIS
    - Cycle Life RPT (HPPC and Static Capacity)
  - Calibrate equivalent circuit model in illustration to EssEs data
  - Generate Nyquist diagrams from model at different ages
  - Observe change in ohmic resistance, and Warburg diffusion resistance
- End-Goal
  - The equivalent circuit shown could be used in an diagnostic algorithm of BMS



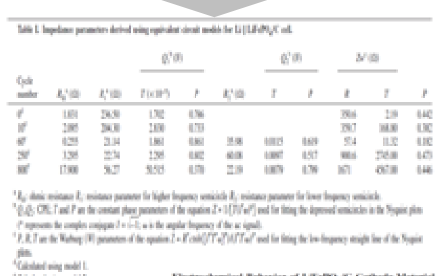
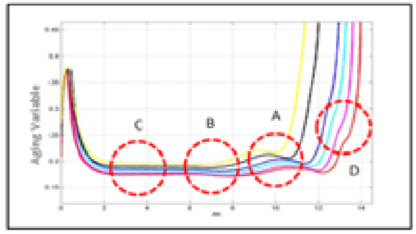


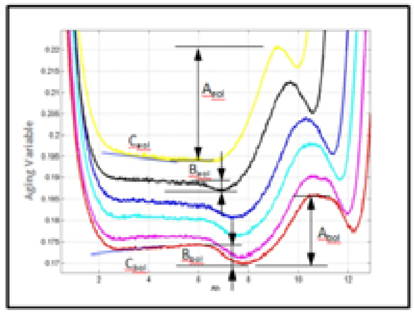
Table I. Impedance parameters derived using equivalent circuit models for Li | LiFePO4/C cell.

Source: Electrochemical Behavior of LiFePO4/C Cathode Material for Rechargeable Lithium Batteries

Aging Metrics Identification and Quantification through Heuristic Patterns

- Problem
  - Significant amount of cell-aging data needs to be deciphered
- Approach
  - Post-process EssEs cycle life data
  - Examine specific cycling parameters such as hysteresis
  - Identify key features of the behavior that correlates to cycling
- End-Goal
  - Find a feature or combination of features that correlates to cycle life degradation

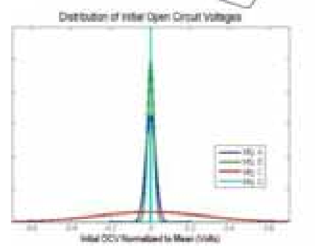




Facilities Dedicated to EssEs

Gamry EIS Equipment

- 8 Channels
- 20V compliance
- 300mA current source
- Useful to measure
  - Internal Impedance
  - Open Circuit Voltage
  - Equivalent circuit fit

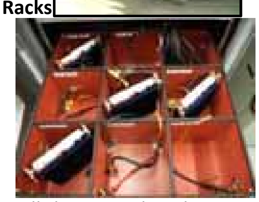


Thermal Chambers

- **Cincinnati Sub-Zero (CSZ) make**
- **Six chambers**
  - 32 Cu ft
  - -34 to 190 deg C
  - 10% to 98% RH
- **One chamber**
  - 16 Cu ft
  - 34 to 190 deg C
  - 10% to 98% RH
- **One chamber**
  - 16 Cu ft
  - -45 to 190 deg C
  - 10% to 98% RH
- **ESPEC chamber**
  - 1.5 Cu-ft
  - -70 to 180 deg C

Cincinnati Sub Zero Thermal Chambers Customized with Racks

ESPEC Thermal Shock Chamber



Cell slots in each rack

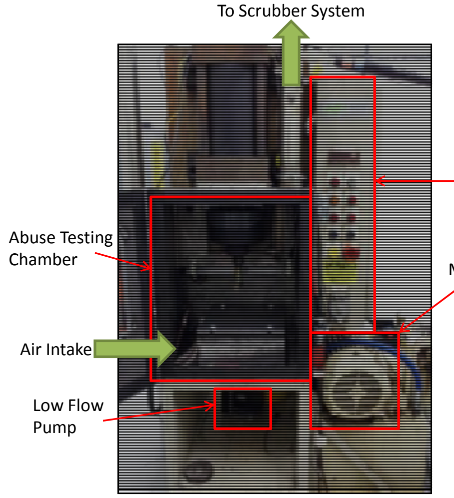
Power Cyclers

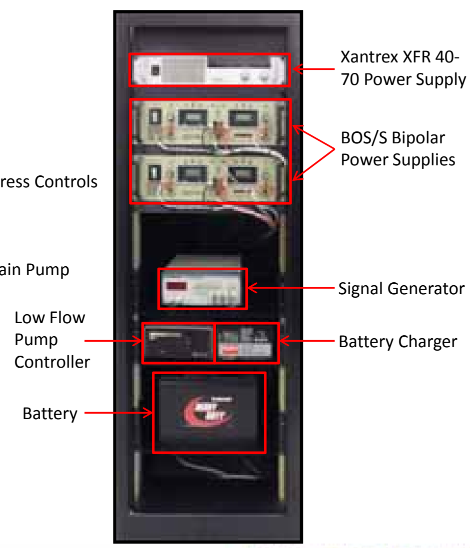
- Bitrode MCV-18-100
  - 8 channels
  - 0 to 18 Volts DC
  - 100 A
  - Resolution: 0.01 sec, 0.001 V, 0.01 A, 0.1 W, 0.01 Ah, 0.01 Whr, 0.5 C
- PEC Corp SBT 05250
  - 68 channels
  - 0 to 6 Volts DC, 250 Amps
  - 2 automatic load ranges
  - 25A, 250A
  - Accuracy: current 0.03%FS, voltage 0.03%FS, resistance 0.05%FS, power 0.05%FS

Bitrode Cycler

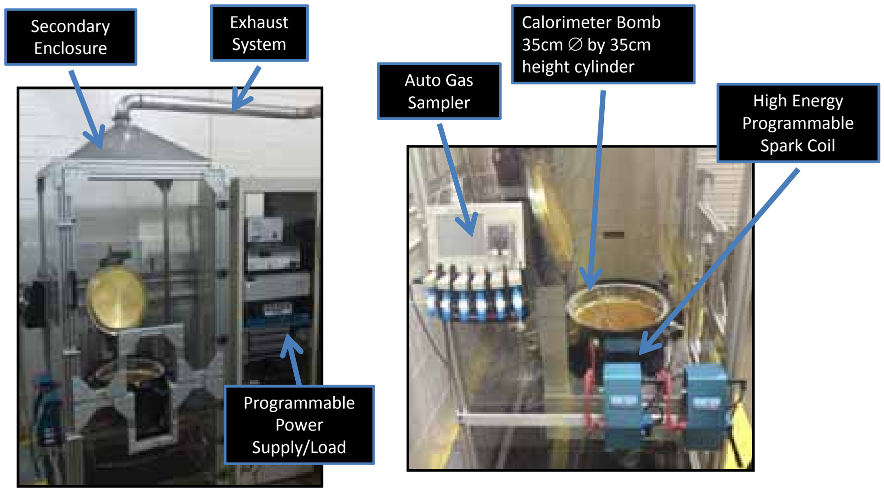
PEC Cyclers

Abuse Chambers





Adiabatic Calorimeter



Specification: Exothermic sensitivity of up to 0.2 C/min, tracking rate of up to 20 C/min, integrated charger 60V/50A, discharge 60A

Diesel Engine Accessory Electrification of a Class 8 Truck

Bapi Surampudi, Ph.D.

Presentation Overview

- Program Objective
- Electrification Overview/Components
- Vehicle Integration
- Testing And Analysis
- Conclusions

SunLine Truck Platform for Accessory Electrification

Program Objective

- Design, Construct and Demonstrate a Diesel Reformer/Fuel Cell Hybrid Electric Class 8 Tractor
- Evaluate New Technologies
- Electrification of Engine Driven Systems
- Verify System Performance by Demonstrating the Vehicle in Commercial Service
- Demonstrate Spinoff/Dual-Use Technologies Useable in Other Military and Commercial Applications
- Disseminate Information Valuable to Trucking/Transit Industry

System Electrification

- Cooling System
  - Water pump
  - Thermostat
  - OEM radiator and cooling fan remain
- A/C System
  - Compressor
  - Expansion valve
  - OEM Condenser and evaporator remain
- 14/42VDC alternator installed (as fuel cell backup)

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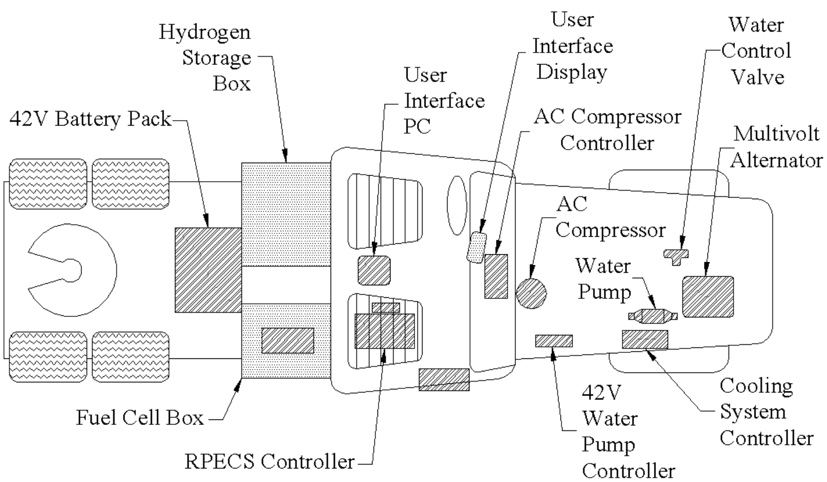
Electrified Component Layout



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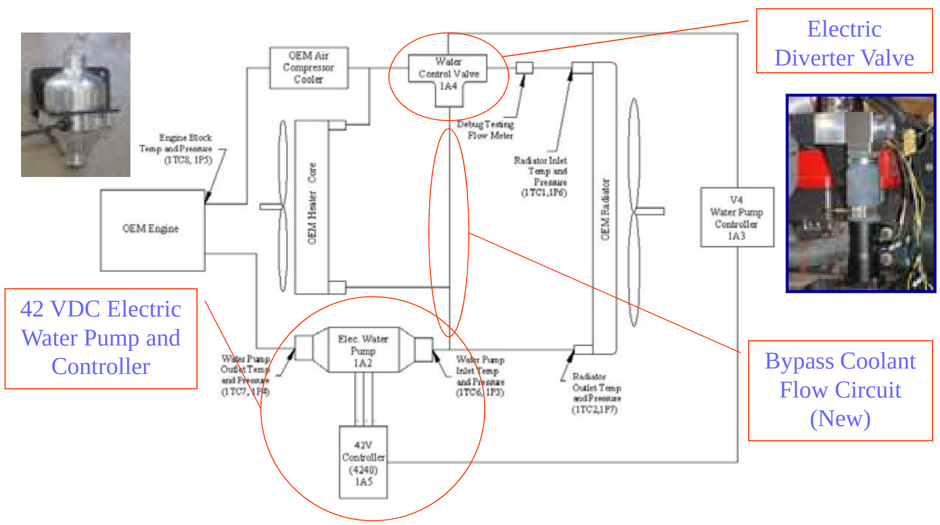
Cooling System Block Diagram



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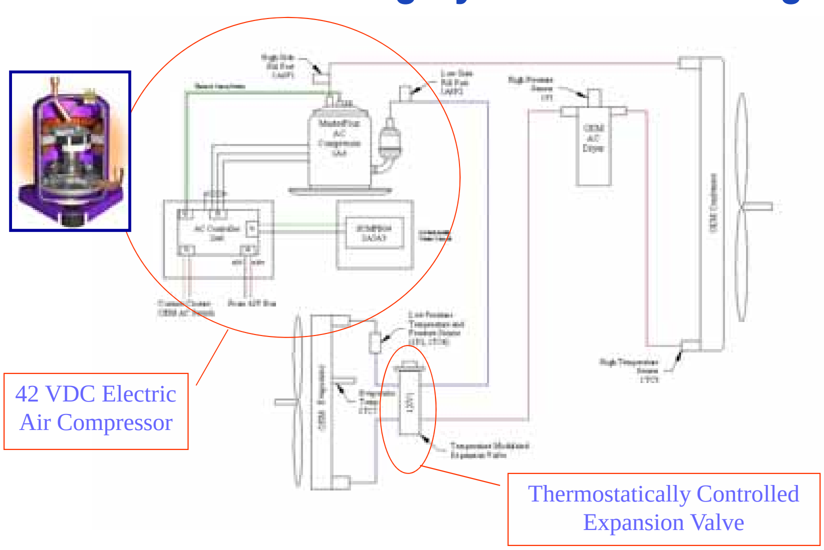
Air Conditioning System Block Diagram



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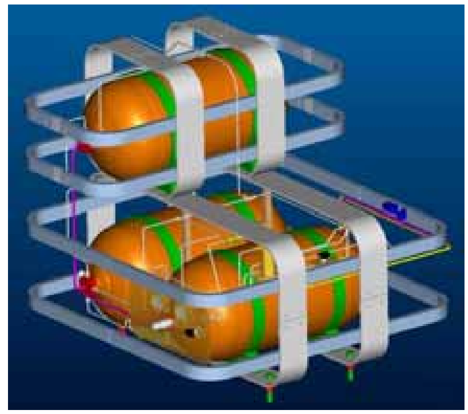
Fuel Cell and Hydrogen Supply

- 2 – Ballard Nexa™ 1.2 kW Fuel Cells



- 5 kg of 5,000 psi Hydrogen Gas Storage

User Interface

- Dash Mounted
- Touch Screen Display
- GUI Computer
  - Xenarc PC
  - Win 2000
  - LabView™
  - Located in Center Console

Rapid Prototype Electronic Control System (RPECS)

- PC 104 Form Factor
- QNX Real-time Operating System

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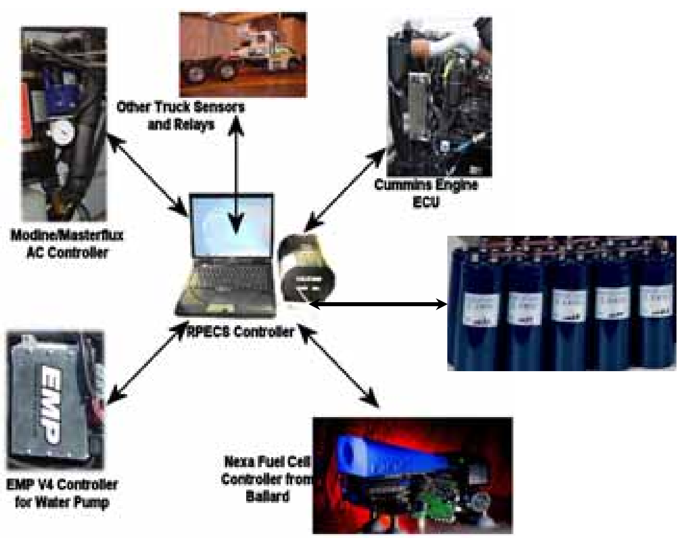
Supervisory Control



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Communications

- ECU
  - J1939 communications between RPECS and ECU (real-time)
- Fuel Cells
  - RS232 serial link between each of the two fuel cells (250 ms)
- User GUI
  - TCP/IP communications between RPECS and GUI (250 ms)
- SwRI FTP site
  - FTP protocol between RPECS and SwRI site for data upload (on demand)

On-Road Testing and Analysis

- Data Storage
  - Stored 193 elements at 5 second interval
  - Vehicle data from CAN
  - RPECS parameters
  - Fuel cell parameters
  - Uploaded from truck on a operator driven basis (Daily)
- Data Reduction
  - Daily data reduction based on energy consumption

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Energy Analysis Assumptions

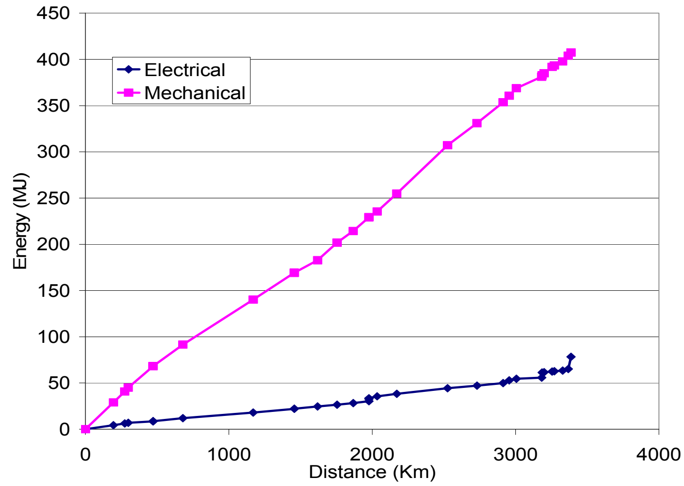
- Cooling System
  - Mechanical water pump calculations
  - No consideration for thermostat
- AC System
  - Mechanical compressor energy NOT considered
  - AC energy savings based on engine fan On/Off

On-Road Testing

Total Distance (km) [miles]	3,387 [2,105]	Engine Run Time (hours)	82
Total Fuel Cell Energy Output (MJ)	193	Fuel Cell Run Time (hours)	75
Total Engine Output Energy (MJ)	12,807	AC Run-time (hours)	46
Total AC Fan Consumption (MJ)	1,850	Diesel Fuel Consumed (l) [gallons US]	4,266 [1,127]
Total Water Pump Consumption (MJ)	78	Hydrogen Consumed (kg)	3
14 V Alternator Energy (MJ)	140	Average Engine Efficiency	29%
42 V Alternator Energy (MJ)	51	Average Fuel Cell Efficiency	51%
Max Ambient Temp (C) [F]	54 [130]	Average Fuel Economy (l/100km) [mpg]	30.5 [7.7]

Water Pump System

- Cumulative pumping energy comparing estimated mechanical pump and electric pump



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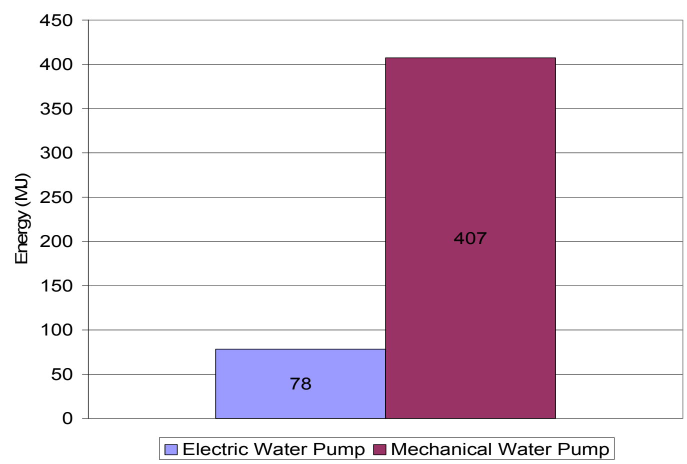
Cooling System Energy Savings

- Electric water pump achieved 81% energy savings over mechanical water pump



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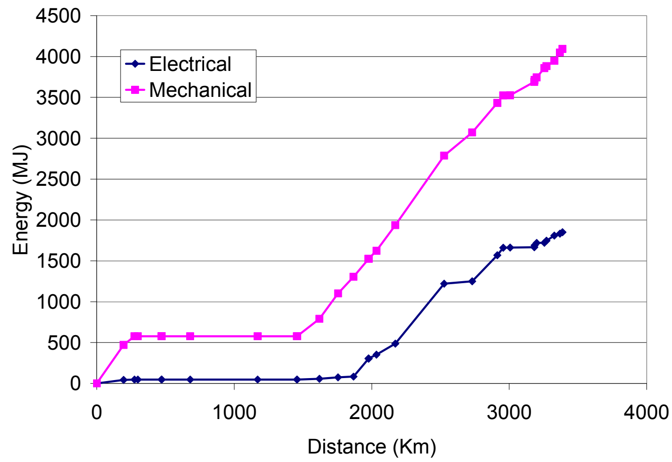
A/C System Energy Analysis

- Cumulative fan energy comparing OEM control algorithm to electric compressor control algorithm



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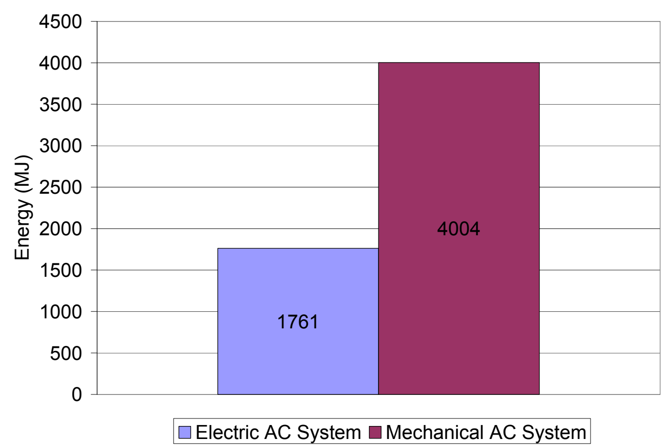
AC Cumulative Energy Consumption

- Electric A/C compressor achieved 56% energy savings over OEM system based on fan control



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Conclusions

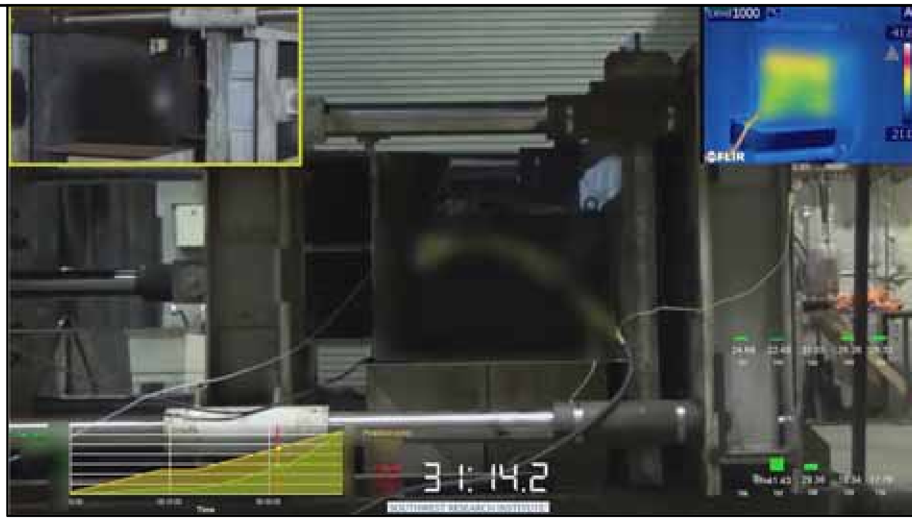
- System Operation
  - Operational strategies have a dominant effect on net energy savings
  - Net energy savings could be realized with the supply of electric energy from efficient alternator
- Cooling System
  - Cumulative savings from electrified water pump can be substantial
  - For maximum energy savings engine fan operation needs to be integrated into cooling system control strategy
- A/C Compressor Electrification
  - A/C system savings dominated by Engine Fan On/Off strategy
  - Location of electric compressor in engine compartment results in reduced performance
  - Relocation of condenser will decouple cooling system and A/C system control strategies

SunLine Program Activities Summary

- Upgraded to 20 kW fuel cell
- Replaced engine driven fan with electric fans
- Replaced and relocated OEM A/C condenser and added electric cooling fan
- Electrified truck air compressor (scroll type, oil-less)
- Measured 13% fuel economy savings over baseline vehicle in dyno testing
- Currently in service at SunLine Transit

Acknowledgements

- US Army TARDEC NAC
- SunLine Transit Agency
- Engineered Machine Products
- Modine
- Masterflux
- Peterbilt
- Cummins
- CE Niehoff & Co

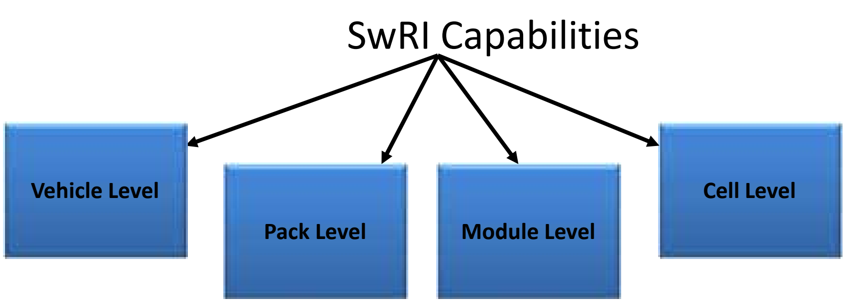


Testing of Electrified Powertrains at Southwest Research Institute

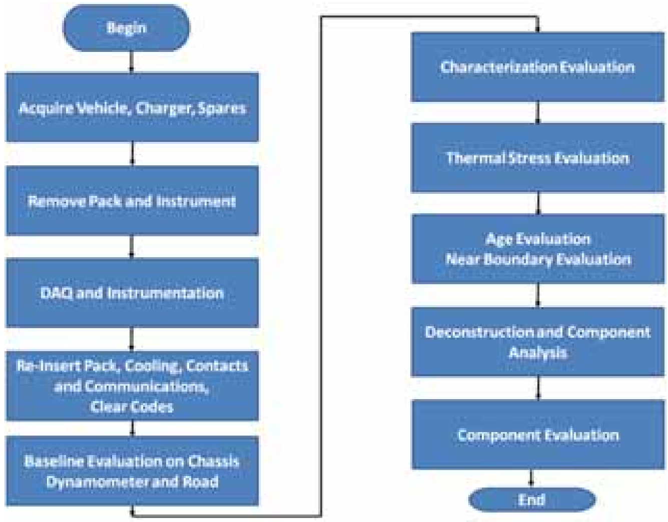
Bapi Surampudi, Ph.D.

Outline

- Vehicle Bench Marking
- Pack and Module Evaluation
- Cell Evaluation

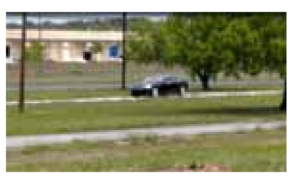


Vehicle Benchmarking Overview

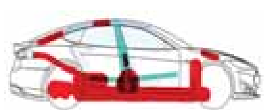


Vehicle Acquisition and Pack Removal

Acquire xEV



Break In & Baseline Check



Disable HV Interlcoks

Remove Pack

Instrumentation, Control and Data Acquisition

Thermocouples & Voltage Sensors on Modules

Splicing BMS Wiring for Signals

NI Compact RIO

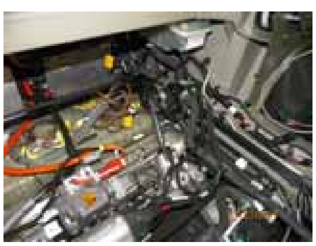
Voltage and Current Sensors on Junction Boxes and Contactors

Camera on Driver Interface

Thermocouples on Coolant Lines

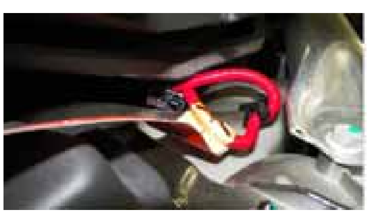
Robot Driver on Dyno

Pack Re-Assembly

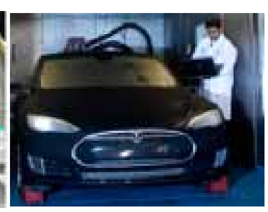


Attach Cooling Lines

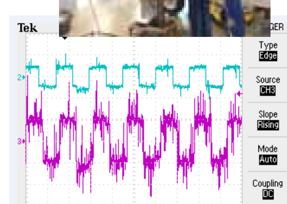
Attach Pack and Communication Wiring



Re-Enable Interlocks



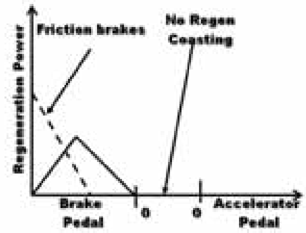
Clear Codes



Install Circuits to Enable Regeneration On 2 Wheel Chassis Dyno

Characterization Testing

- Range
- Performance
- Charging



Regeneration Modes, Blend with Friction Brakes

110 V and 240 V Charging

DC Fast Charging

On Road Metrics

Thermal Stress Evaluation

Hot Temperature Testing (45 °C)

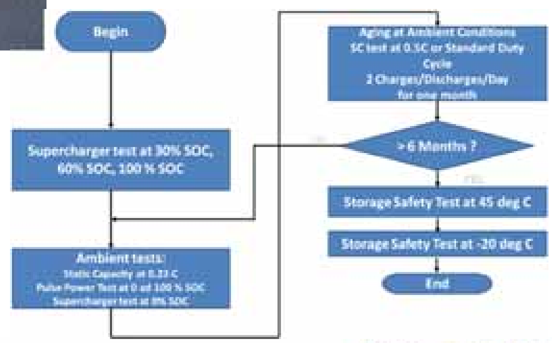
Cold Temperature Testing (-20 °C)

Effect on

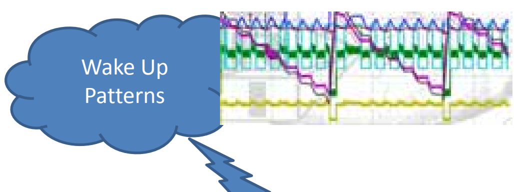
- Range
- In-Situ Pack Performance
- 10 Sec Pulse Power
- Charge strategy

Impact of Aging

- Every 10, 000 miles Study effect on
  - Range
  - In-Situ Pack Performance
  - 10 Sec Pulse Power
  - Charge strategy
- 100,000 mile test



Operation Near Boundaries



Long Storage at ambient,
Hot and cold

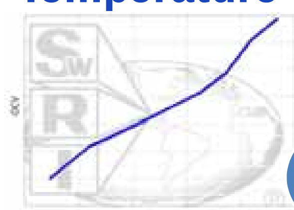
Deep Discharge

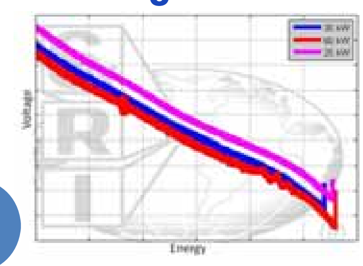
With and Without Charger Plugged In

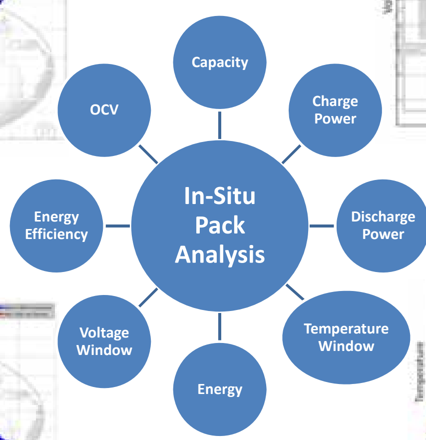
Limp Mode?
Trade off with Life …

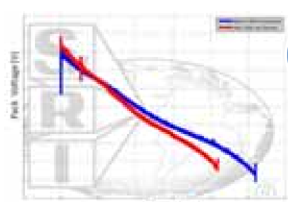
Vehicle Disassembly and Inspection

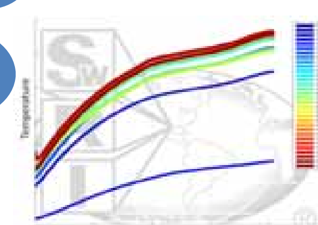
Metrics Extracted as a Function of Age and Temperature





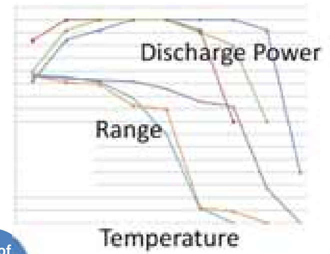


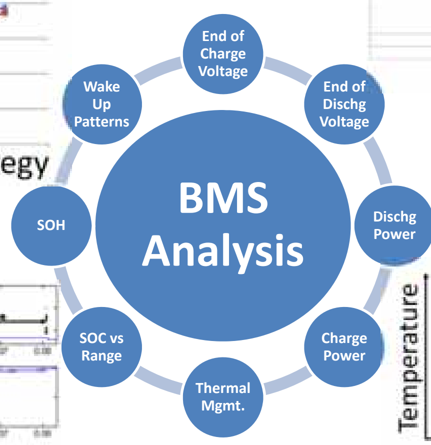


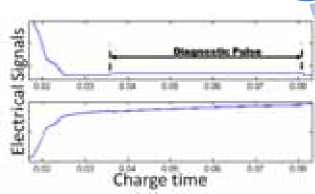


In-Situ BMS Analysis

- Management algorithms are extracted as a function of age and temperature







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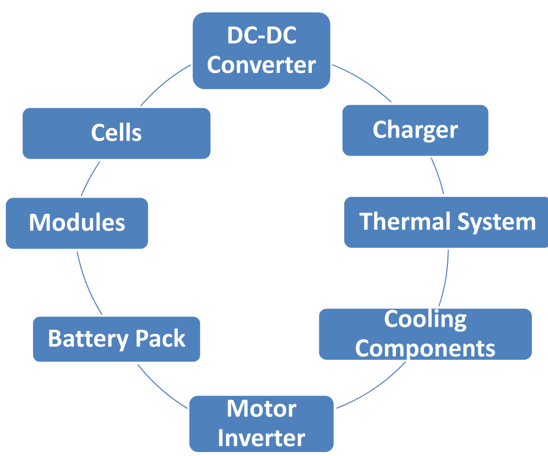
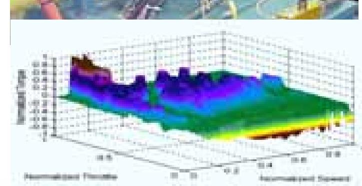
Component Evaluations





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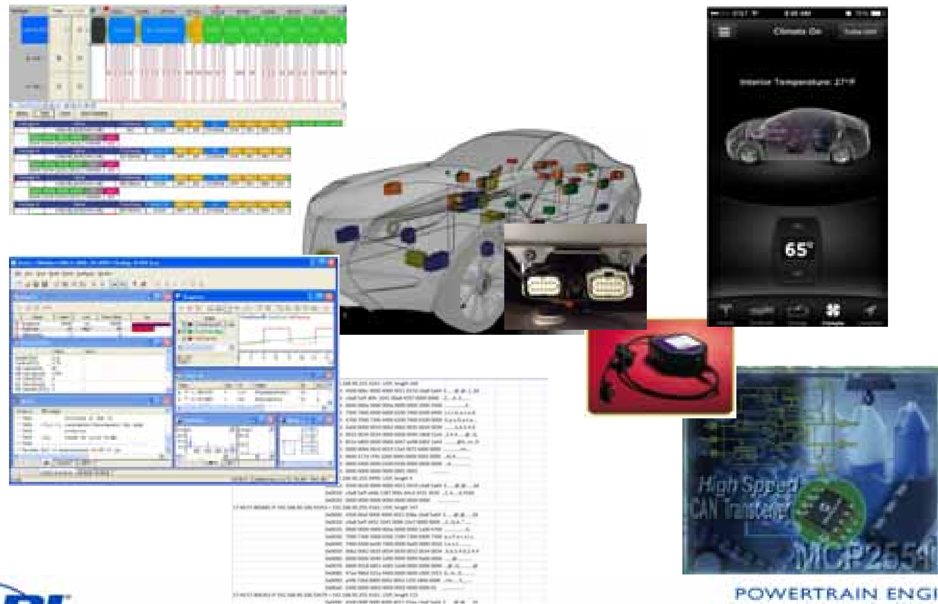
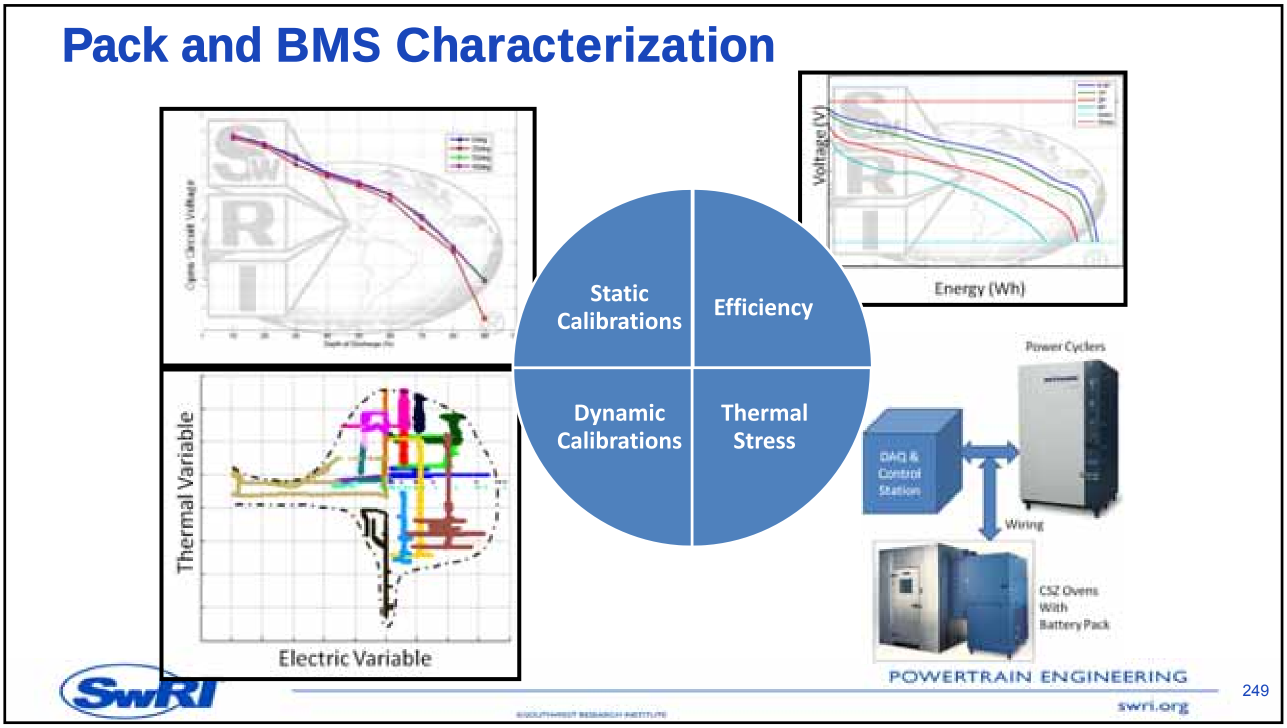
Communication Evaluation



Pack Evaluation Overview

- Characterization
- Cycle Life
- Safety
- Calendar Life
- Custom


Pack and BMS Characterization
Thermal Variable
Electric Variable
Voltage (V)
Energy (Wh)
Static Calibrations
Efficiency
Dynamic Calibrations
Thermal Stress
Power Cyclers
DAQ & Control Station
Wiring
CSZ Ovens With Battery Pack
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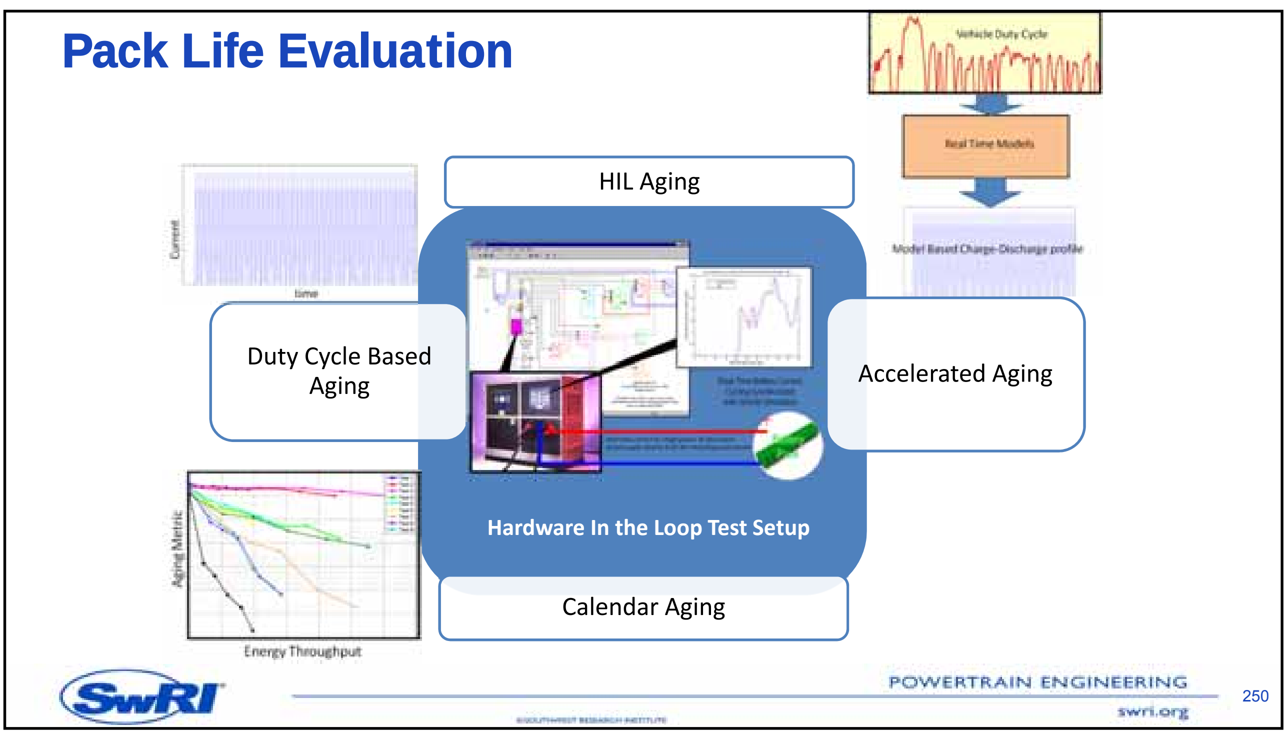
Pack Life Evaluation
Vehicle Duty Cycle
Real Time Models
Model Based Charge-Discharge profile
Current
time
HIL Aging
Duty Cycle Based Aging
Accelerated Aging
Hardware In the Loop Test Setup
Calendar Aging
Aging Metric
Energy Throughput
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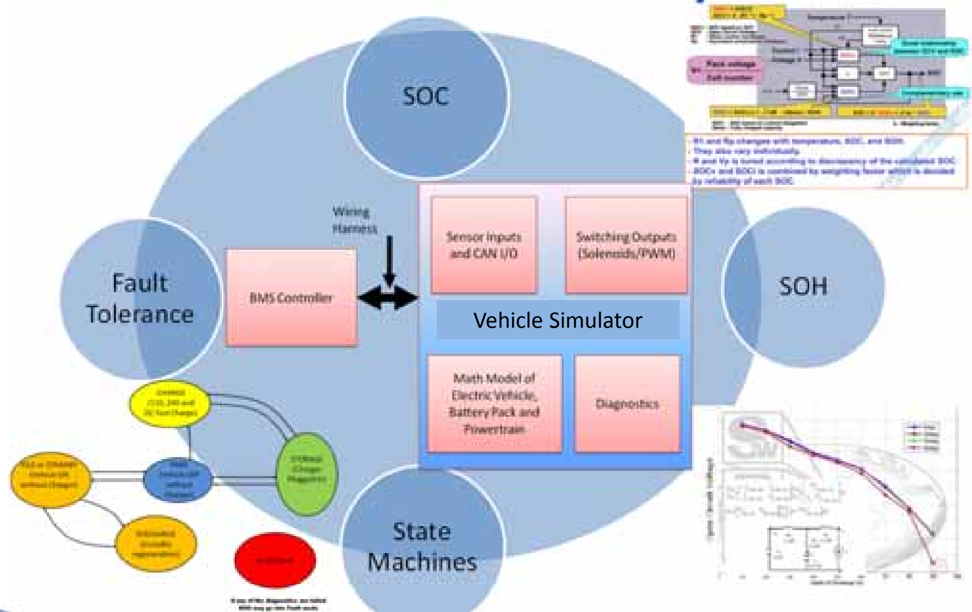
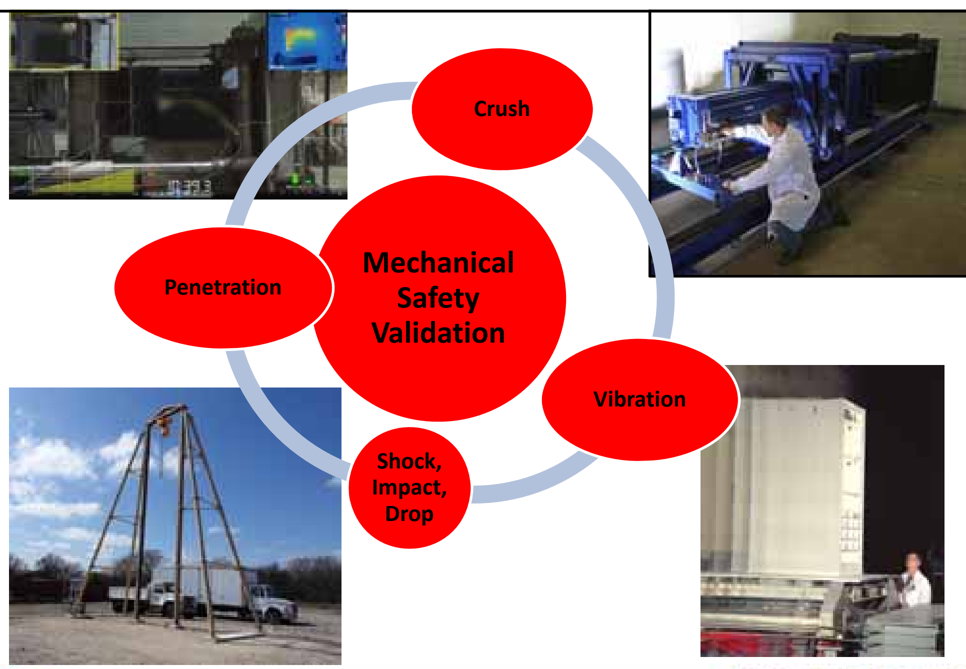
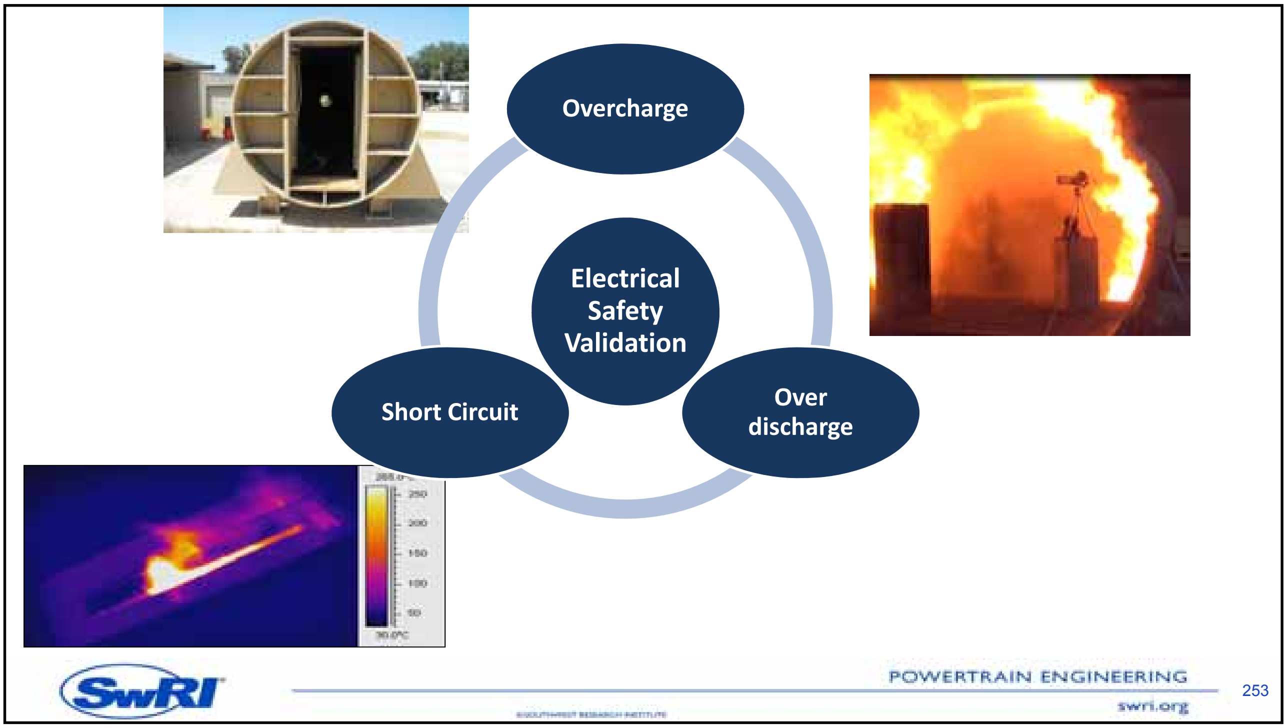
BMS SIL Evaluation or Development






Overcharge
Electrical Safety Validation
Short Circuit
Over discharge
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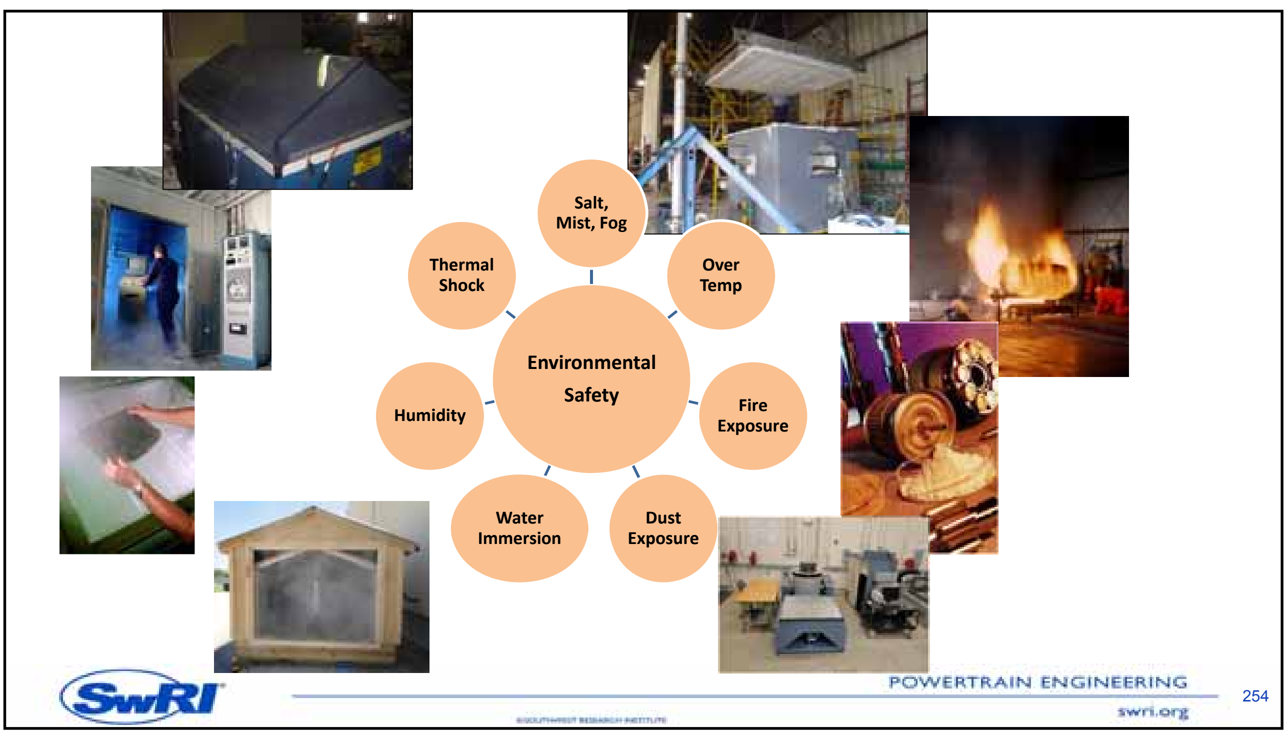
Salt, Mist, Fog
Thermal Shock
Over Temp
Environmental Safety
Humidity
Fire Exposure
Water Immersion
Dust Exposure
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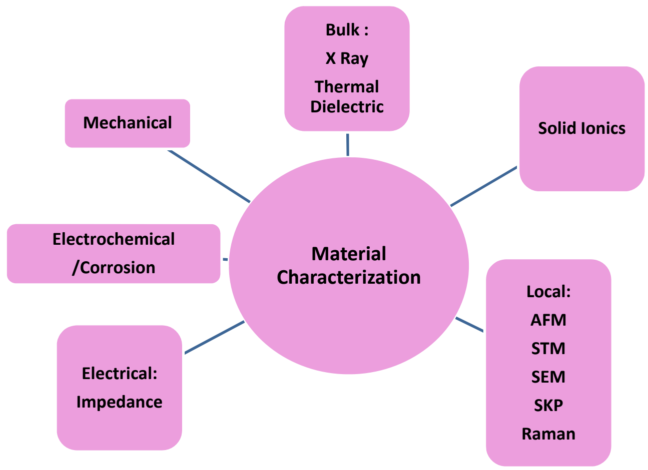
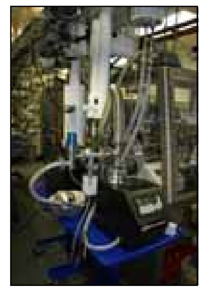
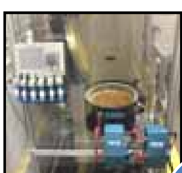
Post Test and Material Analysis

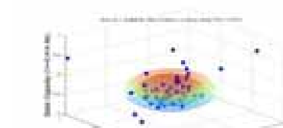


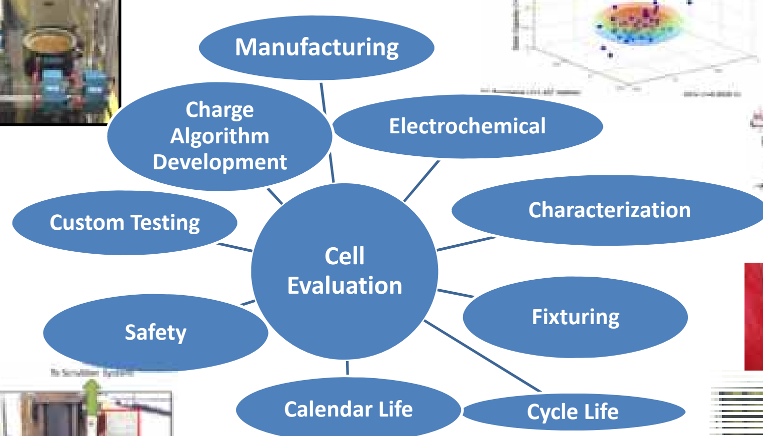
North Star CT Scanning System

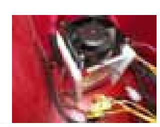


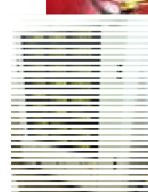
Argon Glove Box











Summary

- SwRI can support customer with cell, module and pack development and evaluation
- SwRI can assist in BMS development or evaluation
- SwRI can perform xEV benchmarking for aiding and accelerating product development
- SwRI can build complete vehicle prototypes of light duty, heavy duty and commercial off high way vehicles

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Contact Information

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  - Desk: (001)-210-522-3278
  - Cell: (001)-210-249-6265
  - bsurampudi@swri.org

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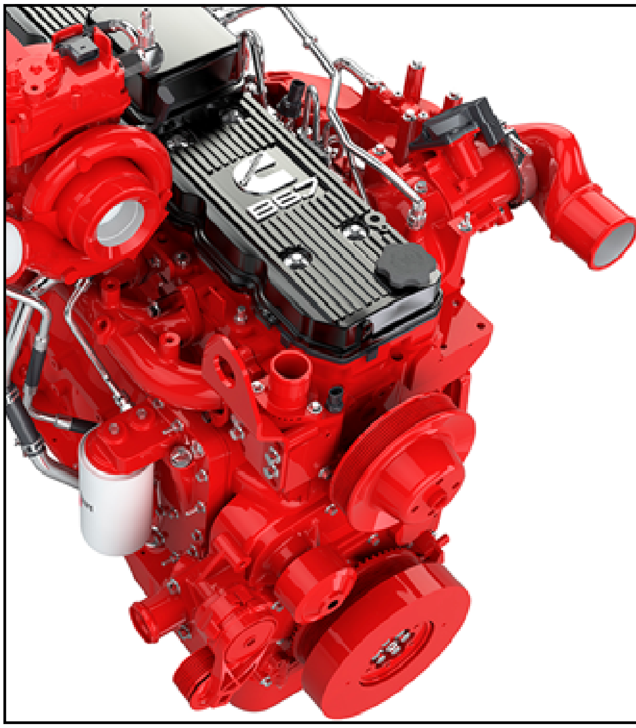

Enabling Technologies - Diesel through hybrid

Evelynn Stirling

October 2018

Acknowledgements

Thank you to the following individuals for their contributions to this presentation:-

Joan Wills	Technical Executive Director, Cummins Inc.
Chris Brown	Off-Highway Aftermarket Director, Cummins Inc.
Jeremy Harsin	Industrial Global Product Manager, Cummins Inc.

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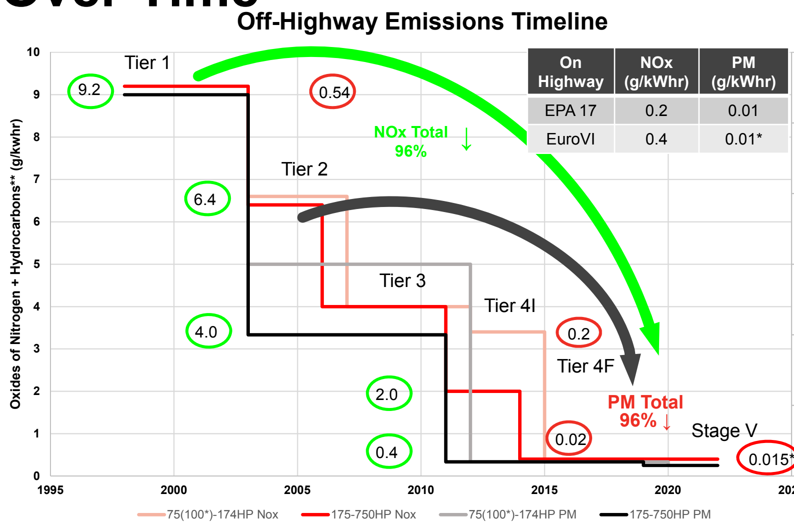
Enabling technology

Definition

An **enabling technology** is an invention or innovation, that can be applied to drive radical change in the capabilities of a user or culture. Enabling technologies are characterized by rapid development of subsequent derivative technologies, often in diverse fields. Equipment and/or methodology that, alone or in combination with associated technologies, provides the means to increase performance and capabilities of the user, product or process.

https://educalingo.com/en/dic-en/enabling-technology

Significant Reduction in Emissions Over Time



On Highway	NOx (g/kWhr)	PM (g/kWhr)
EPA 17	0.2	0.01
EuroVI	0.4	0.01*

Technology Levers Available
-Exhaust Gas Recirculation (EGR)
-Selective Catalytic Reduction (SCR)
-Diesel Oxidation Catalyst (DOC)

Technology Levers Available.
-Diesel Particulate Filter (DPF)
-Fuel Injection Pressure

* Includes Particle Count of 10^12 and 6^11 for off vs on highway ETC respectively

Why we act.

BY 2030…

55% MORE MATERIAL EXTRACTION

30% MORE ENERGY

40% MORE FRESH WATER

45% OF CUMMINS OPERATIONS ARE IN WATER STRESSED AREAS

UNEVEN REGULATORY ENFORCEMENT

REAL BUSINESS EFFECTS
Inability to sell products • supply chain disruption • material price volatility • competition for metals and minerals • community distress

Technology Introduction - Recent Tiers

Connected Diagnostics

Start/Stop Technology

HYBRID

Tier 4i (Stage 3B) Emissions

Stage V Emissions (2019/20 CMI Products)

2006 — 2011 — 2014 — 2019 — 2022+

TPEM Effect

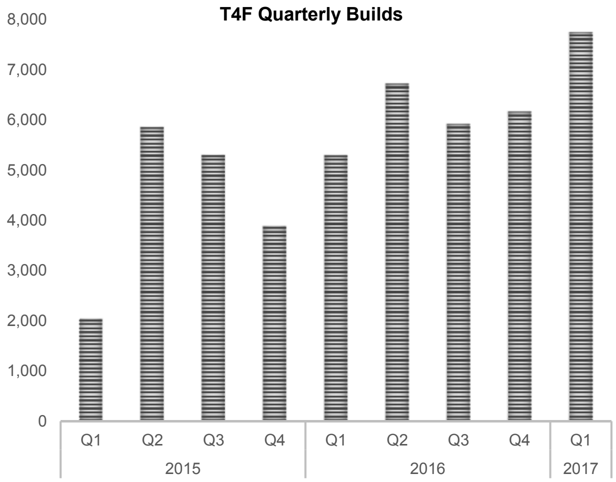
Tier 3 (Stage 3A) Emissions

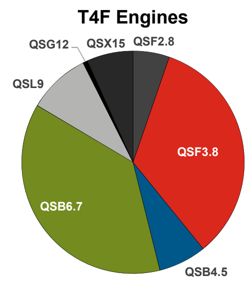
Tier 4F (Stage IV) Emissions

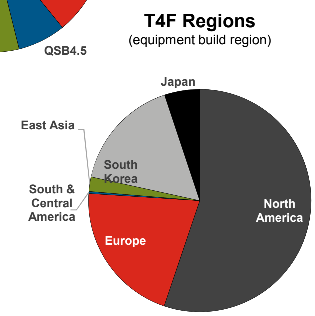
TBD Emissions Standards
-NA Tier5 potential remains gray.
-Likely to see an increase in the availability of new technologies such as hybrid, start/stop, electrification, etc.

Public

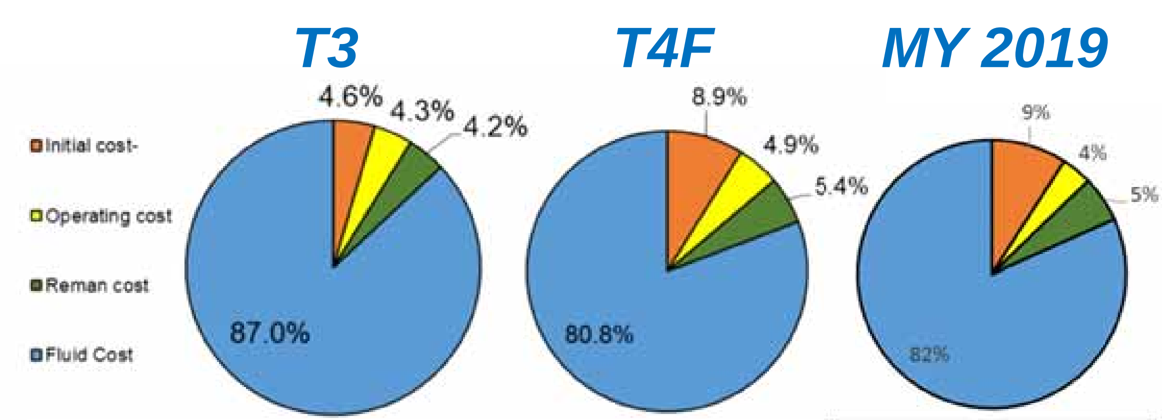
Over 50k Tier 4 Final engines produced







Operating TCO Comparison: 6.7L



Total Cost	1	0.93	0.91
Maint Cost	1	1.08	.78

**TCO savings realized with newer products is highly duty cycle dependent.*
**Regional diesel & DEF pricing have direct affects on the above.*

Stage V & DPF Regeneration Capability

Historical Experience

- In production with DPF equipped engines since 2007.
- Automotive learnings continuously leveraged in off-highway.
- Off-Highway DPF experience since 2011.
- Millions of validation hours/miles with aftertreatment systems.

Stage V
The Right Architecture

- Non-EGR engines run naturally higher exhaust temps that assist with keeping the aftertreatment passively clean.
- Combination of VGT+IntakeThrottle enhances thermal management capability.
- Single canister aftertreatment mitigates temperature losses thereby keeping more heat in the system.

Extensive Validation

- Over 60k Stage V specific field test hours achieved to date.
- Team of engineers have consistently monitoring field test data to make calibration and tuning optimization to support regen capability.

Result: Confidence & Optional Regen Interface

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Power Advancements Support Downsizing

Proven downsizing success stories from the T3 to T4 transition.

http://www.hyster.com/north-america/en-us/announcements/press-releases/manufacturer-evaluation-proves-long-term-performance-and-durabilty-of-hyster-tier-4-engines/

Manufacturer Evaluation Proves Long-Term Performance and Durability of Hyster® Tier 4 Engines

-Tier 3 11L replaced with Tier 4 9L.

-Engine torn down at 10K hours revealing minimal wear to critical engine components!

"This test proves to the entire industry what Hyster, Cummins and our customers using Tier 4 engines have known all along: Tier 4 engines combine all of the performance, durability and toughness traditionally associated with Hyster® lift trucks, with significantly enhanced fuel economy and sustainability benefits to achieve compliance and help increase profitability," said Brett Schemerhorn, President of Big Trucks for Hyster.

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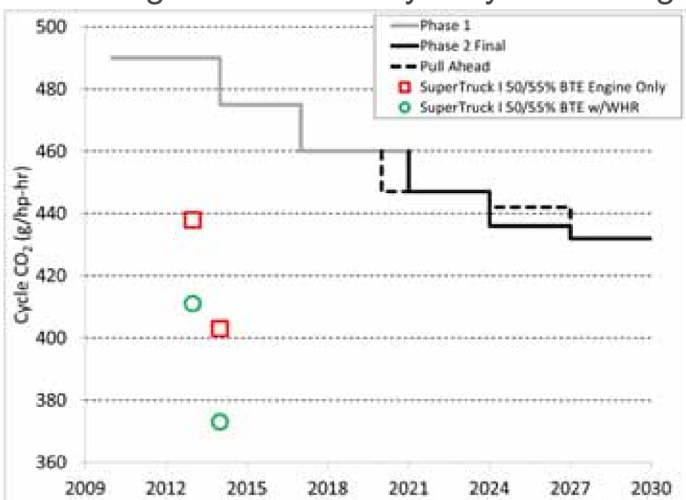
Coming in **2022**

the next generation heavy-duty diesel engine



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CONNECTED CUSTOMER CARE

We are going digital.

CONNECTED PRODUCTS

CONNECTED SOFTWARE

CONNECTED ENTERPRISE

CONNECTED ADVISOR

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Guidanz Overview

- A suite of genuine service products, features and capabilities.
- Maximizes efficiency by streamlining processes associated with a service event.
    - Eliminates non value-added steps
- Products include Guidanz Web, mobile app, and, INLINE™ 7 and INLINE™ Mini vehicle datalink adapters.
- Single sign-on interface to access common Cummins service systems.

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Value Proposition

Customers

- Ability to read J1939 public and engine related faults to share with service provider
- Increased uptime
- More efficient service experience
- Reduced downtime

Fleets

- Reduced travel when technician is equipped with the right parts
- Access to a certified service provider and 1-800-CUMMINS™

Service Providers

- Streamlined service flow
- Single sign-on guided workflow.
- Expedited warranty claims processing.
- Immediate Assessment

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Service Journey – Benefits of Guidanz

Read fault code information
Identify nearest service location

Share location and fault code information with the service location

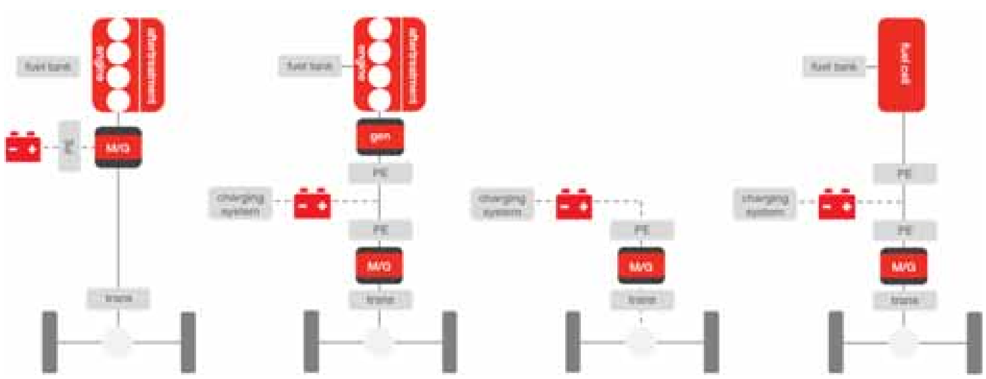
Prepare Technicians with right parts and tools needed to perform the repair

GPS location helps technicians to identify and reach customer location per scheduled time

Perform diagnosis and complete repair with reduced number of site visits

Reduced equipment downtime
Improved service experience

POWERTRAIN OF CHOICE



IC Engine

Hybrid
(Range Extended)
2020

Battery
Electric
2019

Fuel Cell
Electric

Wide Range of Development in Progress

Purolator BEV Program	Quebec PHEV Program	DOE PHEV Program	CERC Program	SuperTruck 2 Program	
North America & Europe				North America	Region
Class 4 P&D	Class 7 & 8 Bus	Class 6 P&D	Class 5 P&D	Class 8 LH	Market
xEV (BEV)	xEV (REEV)			Mild Hybrid	Architecture
SAE J1772	SAE J3105 (WIP)	SAE J1772	SAE J2954 (WIP)	SAE J1772	Charging
No Engine	ISB 4.5L Diesel		ISF 2.8L SI	-	Gen Set
50 - 111 kWHr NMC & LTO Chemistries				5 kWHr (48V)	ESS Energy
2017	2018		2020	2021	Demos
2 years	3 years		5 years		Program
TM4 / Purolator	STL / TM4 / IVI	PACCAR / OSU / ANL / NREL	FCCC / ANL / OSU / Purdue / ORNL	Peterbuilt / Eaton / ORNL / NREL	Partners

Cummins

- Cummins is committed to being a diverse powertrain supplier across our regions and markets.
- We are in a period of transformative change within the industry. With change comes opportunity.

The future includes:

- Internal combustion powertrain fueled by conventional and non-conventional fuels.

Electric powertrain as pure EV, range extended EV and hybrid.

Connected solutions to drive the demands of digital business.

energy diversity **is KEY**

Q+A

Retrofit of DPF Technology to Mining Engines – Technical Aspects

Sean McGinn

MKNIZD | Factors

mdec

October 4th, 2018

Overview

- Maintenance
- Duty Cycle Profiling
- Management – By - Numbers
- Passive DPFs
- Fully Integrated Tier 4

Maintenance

Emissions Testing

- Monthly CO tests ?
- O_2, CO, NO, NO_2, NOx, CO_2, Exhaust Temp … DPM

Which is better for underground mining?

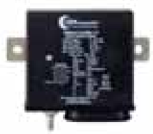
Option 1	Option 2
NO = 400 ppm	NO = 150 ppm
NO_2 = 50 ppm	NO_2 = 150 ppm
NOx = 450 ppm	NOx = 300 ppm

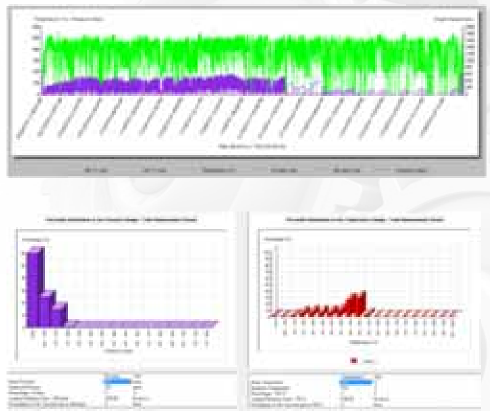
Maintenance

- **Quantified vs Qualified**
- **Pressures**
  - **Boost, Fuel, Oil , Intake Restriction , Backpressure**
- **Temperatures**
  - **Cooling delta T, charge air, fuel**
- **ECM data and verification testing**
- **Your current 250 hr PM inspection list (engine) ?**
- **AD30 retrofit DPF example**

Duty Cycle Profiles

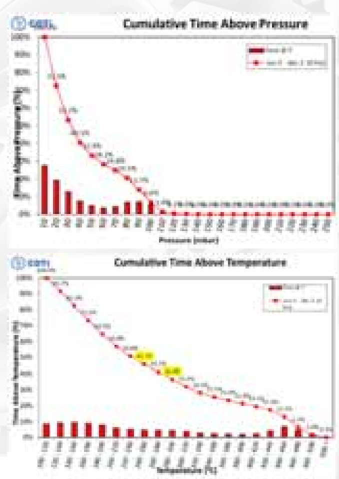
Logger / Monitors – CPK Dyntest





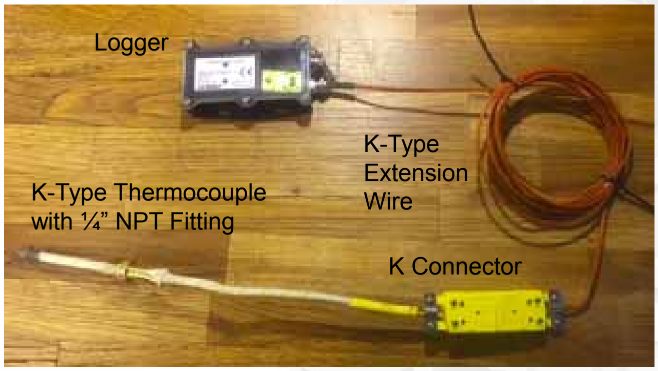
Duty Cycle Profiles

Logger / Monitors – ECS / CDTi



Duty Cycle Profiles

Logger – Omega (temperature only)

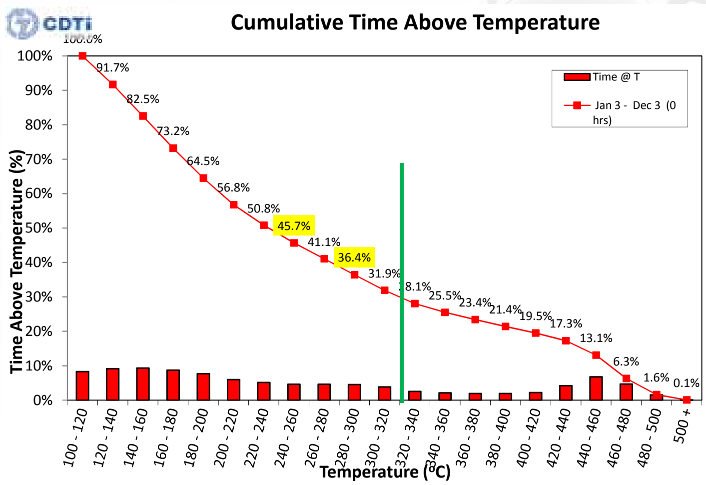


Duty Cycle Profiles

Magnehelic – backpressure – 0-100 iwg

Management By Numbers

AD30 Exhaust Temperature

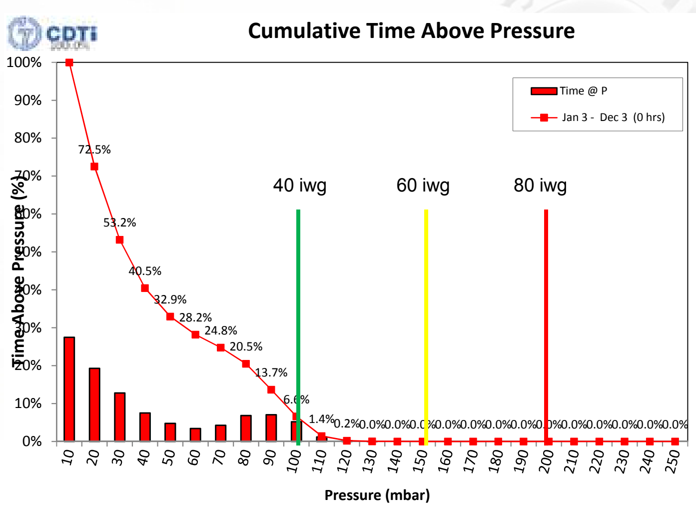


30% Cutoff

Note: 340 to 590 hrs on DPF

Management By Numbers

AD30 Exhaust Backpressure

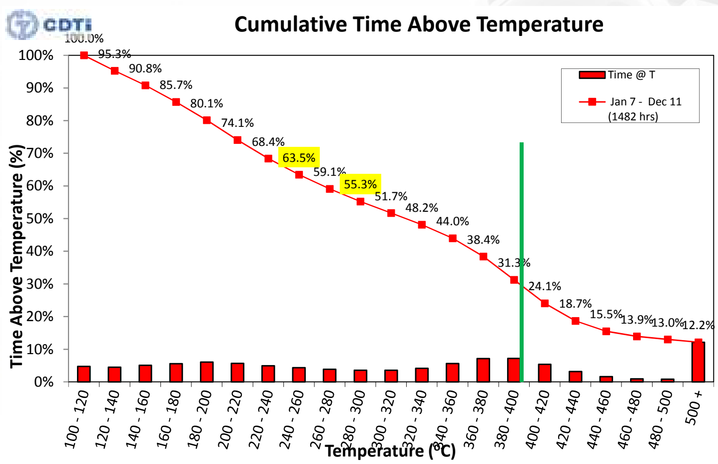


40 / 60 / 80 Rule

Note: 340 to 590 hrs on DPF

Management By Numbers

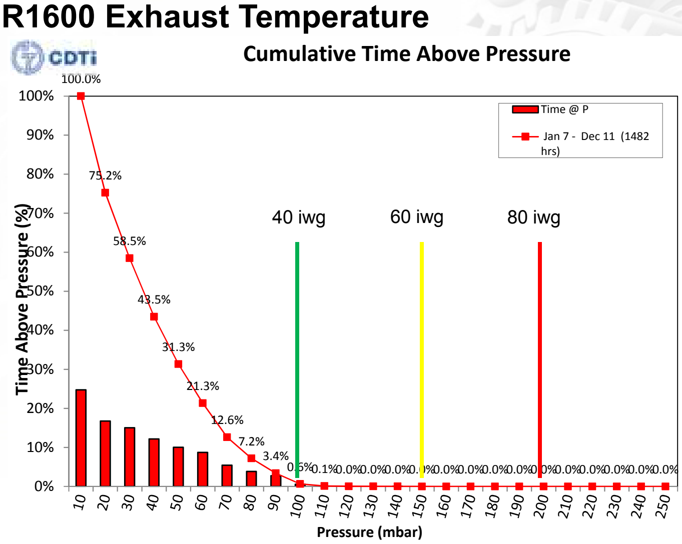
R1600 Exhaust Temperature



30% Cutoff

Management By Numbers

R1600 Exhaust Temperature



40 / 60 / 80 Rule

Management By Numbers

AD30 Clariant Emissions Results

Catalyst 1 – Higher NO_2

ENGINESPEED	TESTLOCATION	AVG	MIN	MAX	PARAM	ENGINE_TYPE	MODEL	EMISSIONS_CONTROL
1950	Inlet DPF	9	0	0	SMOKE	C15 408 HP	AD30	DPF
1950	Inlet DPF	10.5	10.5	10.7	O2	C15 408 HP	AD30	DPF
1950	Inlet DPF	220	210	228	CO	C15 408 HP	AD30	DPF
1950	Inlet DPF	405.4	395	415	NO	C15 408 HP	AD30	DPF
1950	Inlet DPF	35.8	34	37	NO2	C15 408 HP	AD30	DPF
1950	Inlet DPF	7.7	7.6	7.7	CO2	C15 408 HP	AD30	DPF
1950	Inlet DPF	747	721	767.9	T.GAS	C15 408 HP	AD30	DPF
1950	Inlet DPF	37	36.5	37.4	MEQI	C15 408 HP	AD30	DPF
1950	Inlet DPF	441.1	432	450	NOx	C15 408 HP	AD30	DPF
1950	Outlet DPF	1	0	0	SMOKE	C15 408 HP	AD30	DPF
1950	Outlet DPF	10.2	10.1	10.4	O2	C15 408 HP	AD30	DPF
1950	Outlet DPF	0	0	0	CO	C15 408 HP	AD30	DPF
1950	Outlet DPF	323.9	317	336	NO	C15 408 HP	AD30	DPF
1950	Outlet DPF	96.8	93	98	NO2	C15 408 HP	AD30	DPF
1950	Outlet DPF	7.9	7.8	8	CO2	C15 408 HP	AD30	DPF
1950	Outlet DPF	723.1	672.3	767.2	T.GAS	C15 408 HP	AD30	DPF
1950	Outlet DPF	45.2	43.8	46	MEQI	C15 408 HP	AD30	DPF
1950	Outlet DPF	420.7	412	433	NOx	C15 408 HP	AD30	DPF

Management By Numbers

AD30 Clariant Emissions Results

Catalyst 2 – Lower NO_2

ENGINESPEED	TESTLOCATION	AVG	MIN	MAX	PARAM	ENGINE_TYPE	MODEL	EMISSIONS_CONTROL
1950	Inlet DPF	9	0	0	SMOKE	C15 408 HP	AD30	DPF
1950	Inlet DPF	10.6	10.6	10.8	O2	C15 408 HP	AD30	DPF
1950	Inlet DPF	201.9	194	217	CO	C15 408 HP	AD30	DPF
1950	Inlet DPF	440.9	438	442	NO	C15 408 HP	AD30	DPF
1950	Inlet DPF	43.9	43	46	NO2	C15 408 HP	AD30	DPF
1950	Inlet DPF	7.6	7.5	7.6	CO2	C15 408 HP	AD30	DPF
1950	Inlet DPF	603.6	561.7	643.8	T.GAS	C15 408 HP	AD30	DPF
1950	Inlet DPF	40.4	39.7	41.7	MEQI	C15 408 HP	AD30	DPF
1950	Inlet DPF	484.9	481	487	NOx	C15 408 HP	AD30	DPF
1950	Outlet DPF	1	0	0	SMOKE	C15 408 HP	AD30	DPF
1950	Outlet DPF	10.6	10.5	10.7	O2	C15 408 HP	AD30	DPF
1950	Outlet DPF	0	0	0	CO	C15 408 HP	AD30	DPF
1950	Outlet DPF	403.3	395	412	NO	C15 408 HP	AD30	DPF
1950	Outlet DPF	78.7	68	89	NO2	C15 408 HP	AD30	DPF
1950	Outlet DPF	7.6	7.6	7.7	CO2	C15 408 HP	AD30	DPF
1950	Outlet DPF	695.6	634.2	751	T.GAS	C15 408 HP	AD30	DPF
1950	Outlet DPF	42.2	39.1	45.5	MEQI	C15 408 HP	AD30	DPF
1950	Outlet DPF	481.8	480	484	NOx	C15 408 HP	AD30	DPF

Management By Numbers

R1600 Clariant Emissions Results

ENGINESPEED	TESTLOCATION	AVG	MIN	MAX	PARAM	ENGINE_TYPE	MODEL	EMISSIONS_CONTROL
1950	Inlet DPF	9	0	0	SMOKE	3176C 270 HP	R1600	DPF
1950	Inlet DPF	10.4	10.4	10.4	O2	3176C 270 HP	R1600	DPF
1950	Inlet DPF	220.3	214	230	CO	3176C 270 HP	R1600	DPF
1950	Inlet DPF	406.8	395	420	NO	3176C 270 HP	R1600	DPF
1950	Inlet DPF	15.8	14	18	NO2	3176C 270 HP	R1600	DPF
1950	Inlet DPF	7.8	7.8	7.8	CO2	3176C 270 HP	R1600	DPF
1950	Inlet DPF	810.5	794.4	824.3	T.GAS	3176C 270 HP	R1600	DPF
1950	Inlet DPF	30.3	29.7	31.1	MEQI	3176C 270 HP	R1600	DPF
1950	Inlet DPF	422.5	412	434	NOx	3176C 270 HP	R1600	DPF
1950	Outlet DPF	3	0	0	SMOKE	3176C 270 HP	R1600	DPF
1950	Outlet DPF	10.2	10.2	10.2	O2	3176C 270 HP	R1600	DPF
1950	Outlet DPF	0	0	0	CO	3176C 270 HP	R1600	DPF
1950	Outlet DPF	395.7	394	396	NO	3176C 270 HP	R1600	DPF
1950	Outlet DPF	47.6	40	52	NO2	3176C 270 HP	R1600	DPF
1950	Outlet DPF	7.9	7.9	7.9	CO2	3176C 270 HP	R1600	DPF
1950	Outlet DPF	607.5	548.8	653.2	T.GAS	3176C 270 HP	R1600	DPF
1950	Outlet DPF	31.7	28.8	33.2	MEQI	3176C 270 HP	R1600	DPF
1950	Outlet DPF	443.2	433	448	NOx	3176C 270 HP	R1600	DPF

Management By Numbers

DPF Life Cycle Management

GOLDCORP PORCUPINE GOLD MINES

DPF COMPONENT TRACKING

DPF ID	DPF MODEL	MACHINE	MODEL	INSTALL WO#	DATE ON	METER ON	METER CURRENT	DATE OFF	REMOVE WO#	METER OFF	LTD HRS	AUDIT DATE	BACKPRESSURE IWG	DETAILS
8001	20985	SC2904	R2900		03-03-2013	2445	4581	01-10-2014		4581	2136	02-08-2014	25	Off for cleaning
8004	20985	SC1602	R1600		05-05-2013	1452	5115				3663	23-09-2014	10	
8135	20990	SC2901	R2900		04-01-2012	1866	4108	05-03-2014		4108	2242		0	
8006	20990	SC1601	R1600		01-02-2014	3377	4848				1471	04-09-2014	50	
8009		SC2905	R2900		14-10-2013	2889	4399	01-10-2014		4399	1510	04-09-2014	25	
8011		SC1604	R1600		01-08-2013	3188	6127	30-08-2014		6127	2939		0	
8003		SC1603	R1600		23-05-2014	4122	4888				766	04-09-2014	100	
8016		SC2901	R2900		05-03-2014	4108	4886				778	04-09-2014	100	
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Passive DPF Technology

- Catalyzed wallflow monolith filters – ceramic or silicon carbide
- Variables – materials, assembly, catalyst

Fully Integrated Tier 4

- **Engine + Emission Control all-in-one single manufacturer**
- **Reliability by engineering and design**
- **Catalyzed DPF based systems (no SCR)**
- **SCR based systems (no DPF)**
- **DPF + SCR based systems**
- **Emissions performance – never assume!**
- **NO_2**

Summary

- Retrofit DPFs can be a very successful solution
  - DPM
  - Gases
- Basic rules to being successful – follow them
- Maintenance impact – protecting investments
- Tier 4 engines – design for reliability
  - Real-world performance may vary and be ready to measure
  - Knowing is always better than hoping

Experiences of VERT in DPF-retrofitting and I&M

MEDC Diesel Workshop, Toronto – October 4th, 2018

J. Czerwinski, A. Mayer, V. Hensel, Th. Lutz, VERT Association

Content

- History
- VERT
- Best Practice Guide
- Manipulation and Tempering
- Summary

VERT

History

VERT

Energy, Mines and Resources Canada | Energie, Mines et Ressources Canada

CANMET
Canada Centre for Mineral and Energy Technology | Centre canadien de la technologie des minéraux et de l'énergie

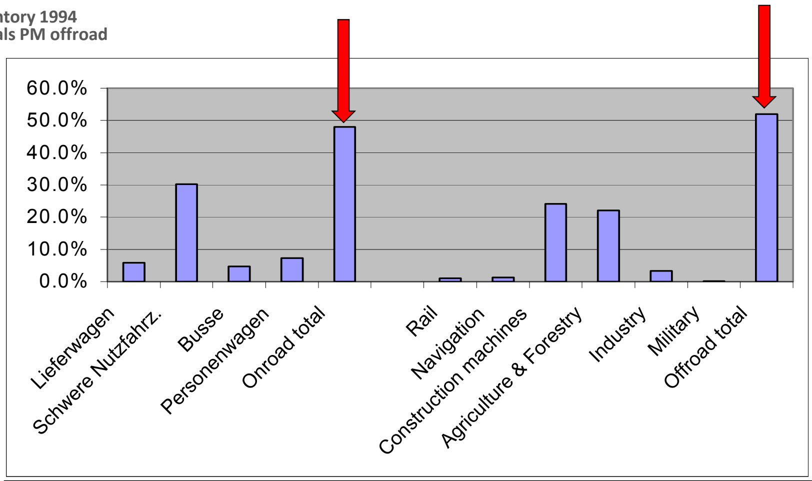
A SUMMARY OF UNDERGROUND MINE INVESTIGATIONS OF CERAMIC DIESEL PARTICULATE FILTERS AND CATALYTIC PURIFIERS

E.D. Dainty, M.K. Gangal, D.H. Carlson, H.C. Vergeer and E.W. Mitchell

1986

February 1986

Emission – Inventory 1994
PM onroad equals PM offroad



Onroad: Switzerland must follow EU-regulations
Offroad: Switzerland was free to accellerate Emission Reduction

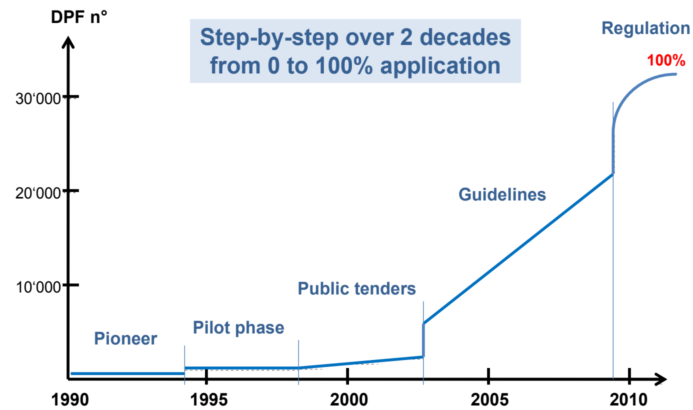
Learning Curve in Switzerland
Success need a Vision and Persistance

Inspiration & Transpiration

Year	Fuel Sulfur ppm	Retrofits total	Retro-fitters	Failures % p.a.	VERT DPF
1988	2000	100	2	> 10	-
1992	2000	350	2	> 10	-
1995	500	500	3	> 10	5
1998	500	900	8	10	16
2000	350	2'500	12	8	23
2002	50	4'900	7	3	8
2003	50	6'500	11	2	22
2005	50	11'500	21	<2	30
2007	50	17'500	26	<2	50
2010	10	25'000	30	< 2	71
2012	*10*	*35'000*	*30*	*< 1*	*80*

The Swiss Learning Curve

DPF Retrofit of Construction Machines Switzerland



Introduction | What does VERT® stand for?

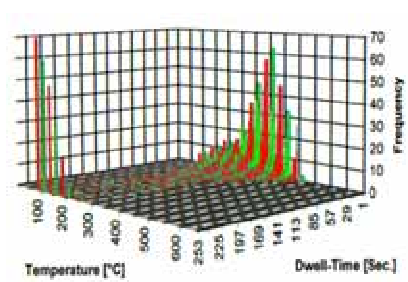
- Non-profit organization to eliminate particles and harmful substances from internal combustion engines - **concentrating on PN-Elimination since 1994**
- Certification of diesel particle filters with Best Available Technology (VERT® filter list) - for PN, NO_2, CO, HC, PH and secondary emissions
- International membership out of manufacturers of DPF / SCR systems and testing devices as well as substrate producers, chassis builders, engine manufacturers, and others
- VERT-network with ETH, EMPA, Berne, Fribourg, Biel (Enginering, Science, Biology, Medicine) → **ETH-Nanoparticle conference since 1997**
- Acting as partner of megacities to support and execute **pollution reduction programs** from road traffic and non-road vehicles

  Projects in: Switzerland, Berlin, California, China, Iran, Bogotá, Chile, Mexico, Tel Aviv, …

Best Practice

Best Practice | Vehicle Matching and Filter Selection

- Filter selection **in special cases requires analysis** of the duty profile
- Instrumented **data logger** to determine typical operating conditions during 2-3 weeks



- The results indicate whether the filter can **be passively regenerated or whether active regeneration** is necessary
- Both methods are **available and proven** in many product families

VERT

Electronical Controlling of the Filter Systems

DPF Inlet Module with sensor connections

309

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Best Practice | Vehicle Matching and Filter Selection

- **No Diesel engine without filter** is the imperative for ambient air quality
  Every vehicle can be retrofitted
- **No age limits** for retrofitting but benefits do diminish **with residual deployment expectancy**
- **High raw emissions are a challenge** - has to be controlled via **maintenance** of the vehicle

Best Practice | Fitting Procedure

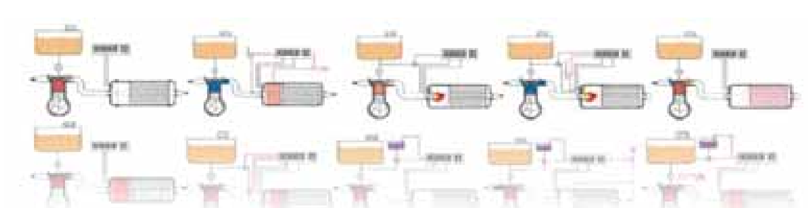
- The engine of the vehicle has to be brought in **good technical conditions**

Lubricant consumption	< 0.5% of fuel consumption
Change to low ash Oil (so-called Low-SAPS oils)	increase of DPF service interval
Exhaust opacity	k < 1,5 m−1

- The Engine has to be in a **good maintenance condition**. Diesel Particle Filters can not repair problems of the engine.

Best Practice | Vehicle Matching and Filter Selection

- **Selection of the right filter systems is necessary**
- **Experience is key**
- VERT filter manufacturers **select the correct filter** from their portfolio
- About **8,000 retrofits are documented and accessible** in the VERT database: www.vert-certification.eu



Best Practice | Filter Certification

- **VERT certification requires:**
  - **Filtration > 98%** for particles 10nm-500 nm
  - No toxic **secondary emissions**
  - **Back pressure** when new is < 50 mbar
  - **Maximum back pressure** < 200 mbar
  - **Endurance test** 2000 h without deterioration
  - Electronic onboard diagnosis **OBD integrated**
  - **Design** verified
  - See **VERT Filter List** www.vert-certification.eu

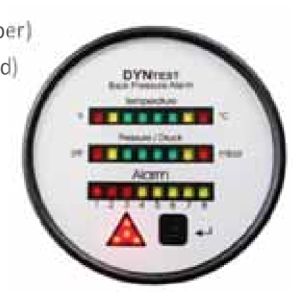
- VERT filter manufacturers are **audited** and give **warranty** for minimum 2 years.

Best Practice | Function, Test and Approval

- Test functioning filter, electronics and display
- Verify exhaust gas values with a particle counter
- The filter manufacturer and vehicle/engine owner sign the approval report
  - Addresses of operator and filter manufacturer
  - Vehicle, engine and filter data
  - Back pressure at maximum RPM
  - Opacity before and after filter retrofit
  - Optional: noise level before and after filter retrofit
  - Optional: function check OBD and alarm display
  - Signature of filter retrofitter and operator
- **This test /approval has a contractual character between buyer and seller and for the authorities**

Best Practice | Control and Diagnosis | Alarms

- **Alarms annunciated acoustic and optic** to driver or wirelessly transmitted to central supervisor
- Alarms are **stored tamper proof**
- **Enables determining cause of failure** in damage claims
  - Pre alarm if backpressure exceeds 150 mbar (amber)
  - Main alarm if backpressure exceeds 200 mbar (red)
  - Filter damage if backpressure decreases rapidly
  - Cleaning when backpressure exceeds 200 mbar
- **Countermeasures to reduce engine power** are permissible - Operator must approve

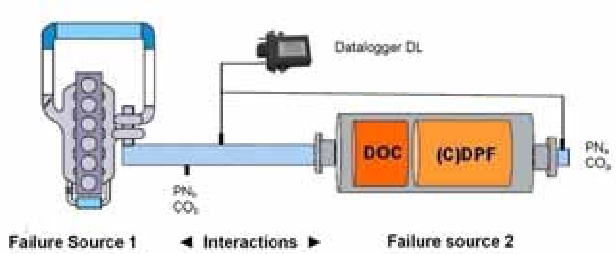


Best Practice | Faults & Remedies | Filter Cleaning

- Due to high **ash burden in the filter** the exhaust backpressure can gradually exceed 200 mbar
- Consequently **the filter must be cleaned**
- The usual **interval is about 1,000 operating hours**
- **Ceramic filters shall not be cleaned with hot water**, steam or compressed air
- A **special filter cleaning machine** must be used
- Filter cleaning must be **done in a hermetically closed machine**
- **Metal filters can be manually cleaned** with a high pressure water cleaner

Best Practice | Diagnosis tools and instruments:

- Filter monitoring system (datalogger analysis, DLA)
- PN counter
- Opacimeter
- Gaseous emission measuring device (CO, HC, NOx, O2)



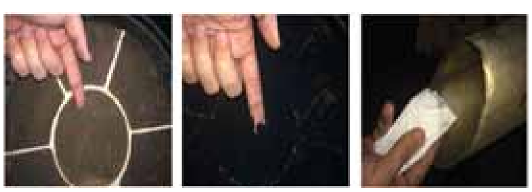
Manipulation & Tempering

Manipulation and Tempering

- Software manipulation alone **cannot** increase emission of a DPF
- It can reset failure or simulate dismounted systems
- Manipulation of DPF has to be done physically!
- Drilling holes in ceramic, dismounting filters ….

Manipulation and Tempering

Particle filters (DPF) eliminate soot

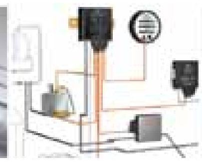
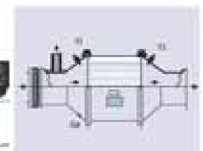


- Filters attains **filtration rate exceeding 98%** for particles in the toxic size range of 10nm - 500 nm
- It the filter is missing or manipulated it **can be seen easily** by visual inspection

Manipulation and Tempering

- During maintenance, the particle emission must be measured at low idling using a certified PN (Particle Number counting) instrument
- If the specified tail pipe PN limit is exceeded, then a second PN measurement must be done upstream of the filter to determine the filtration efficiency
- The cause of low efficiency might be filter damage
- It can be repaired if less than 10% of the filter surface is damaged
- PN count is excessive ahead of the filter, the problem is in the engine



Summary

- Retrofit of Diesel Particle Filter is an efficient method to reduce cancirogenic Ultra Fine Particles below ambient level
- Certificated systems are available
  -> depending on the vehicle, temperature profile and application
- Inspection and Maintenance of the engine is key
- Regular field inspections in the field with particle number counters secure the effectiveness of the investment
- Particle number counters easily detect tempering and failures in the field
- Make use of Best Practice experience from > 100.000 retrofitted vehicles and machines around the world

VERT

Steps to be considered for DPF-retrofitting

- Matching of DPF-System to the vehicle and to the operating profile – suitable regeneration process
- Preparations before fitting, quality & safety of DPF
- Fitting procedure
- Operation & maintenance (inspection)
- Faults reasons actions
- Control instruments & diagnostics
- Organization, motivation, training and behavior

VERT

Thank your for your attention

For more information: Best Practice, Technical Inspection and Information about projects visit

www.vert-dpf.eu