Recent Li-Ion Battery Development for LEV Applications

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August, 2014

Contents

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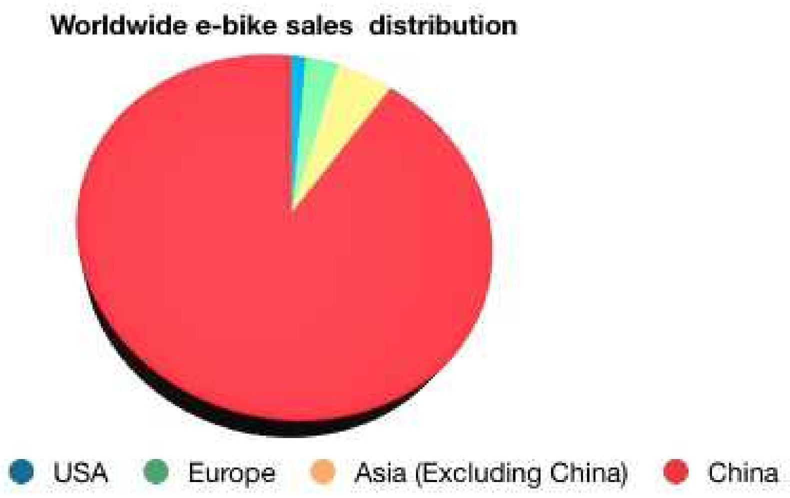
LEV Developments

- **Market**
- **Design**
- **Technology**

Worldwide e-bike sales in 2013 estimated to be more than 35 million.

- 0.3 million USA,
- 1.5 million in Europe,
- 1.5 million in India, Japan and Taiwan,
- 32 million in China



LEV-Design

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LEV-Technology

Motor Propulsion System

Energy Storage System

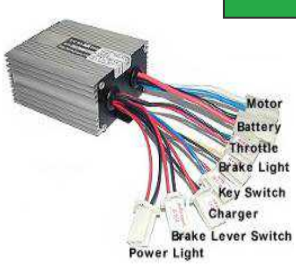
Electric motor &

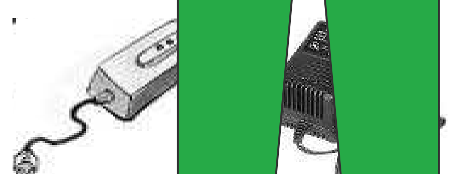
& Battery system

Communication

Power

Communication





Charger

System Integration

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Energy Management System

Supply side

Demand side

Energy Storage System

Power distribution

EnergyBus

Motor Propulsion System

EnergyBus

Battery System

Motor System

Efficiency in transport operations **is as important as battery and motor choice**

- More energy consumption cost your money
- High efficiency system is route to profit

Questions of a System Designer

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Design Consideration for Battery System

Discharge Ability

- How much energy is available in the storage ?
- With what power can LEV draw this energy from the storage ?
- May LEV still perform a certain (critical) function relying on the storage ?
- How long can LEV still continue drawing a certain power ?

Recharge Ability

- How much energy can I still store into the storage ?
- How fast (with what power or current) can I store energy into the storage ?
- What will be my energy losses under different charging conditions ?

operation conditions influent to battery performance

Safety & Cycle life

Battery Requirements from LEV






Voltage:
24V
36V
48V

LEV:
E-Bike
E-Scooter
Motor:
250W-2kW

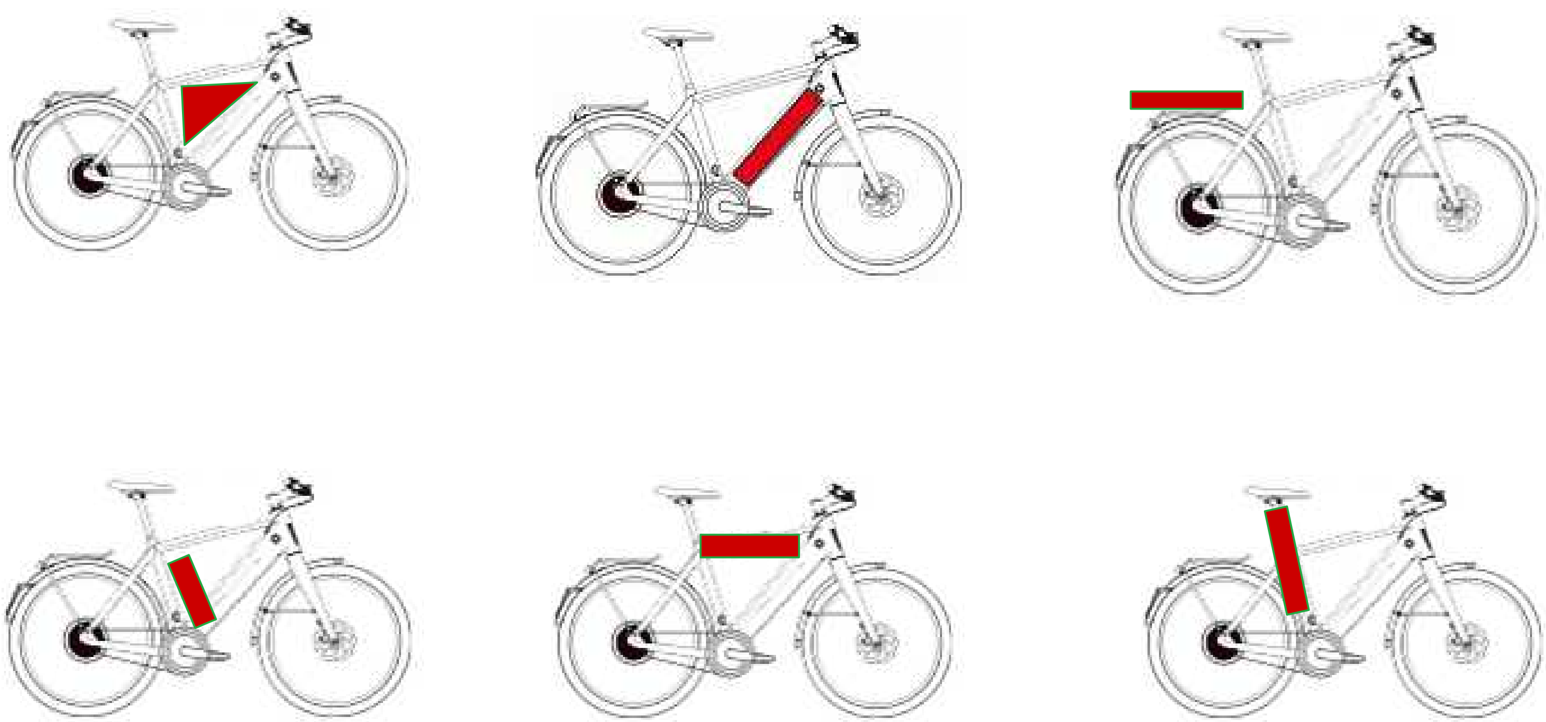
Capacity:
10Ah-30Ah

>50Km Range

Discharge rate capability:
2C-5C

starting, acceleration, climbing


Battery Location



From Material to LEV

Battery Te

El ic Tech.

Syste control Tech.

LEV

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Cell

Materials

Cathode Material

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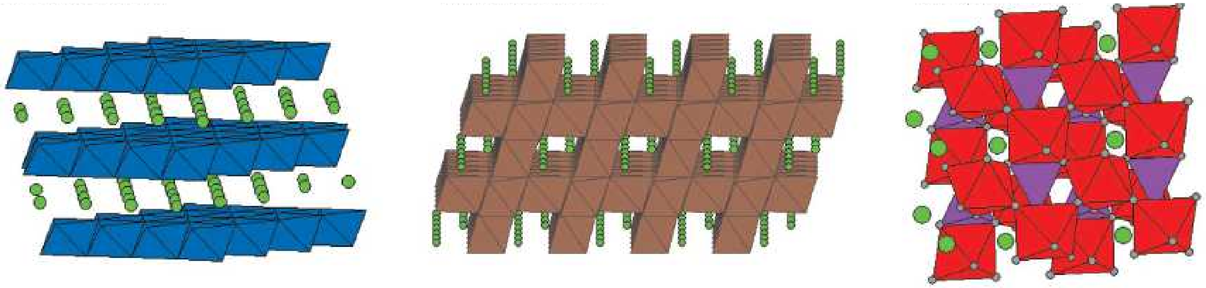


layered structure　　spinel structure　　olivine structure

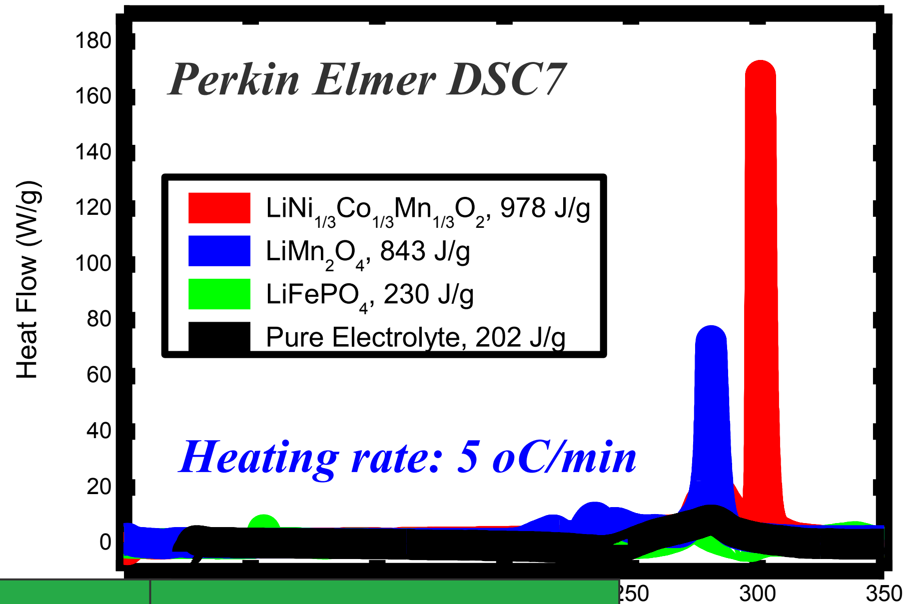
	Li diffusion	Material system	Capacity (mAh/g)	Nominal V. (V)	Safety	Cost
Olivine structure	**1D**	**LiFePO4**	**160**	**3.4**	**excellent**	**low**
Layered structure	**2D**	**LiCoO2** **Li(Co-Ni)O2** **Li(Ni-Mn)O2** **LiCo1/3Ni1/3Mn1/3O2**	**160** **180** **160** **190**	**3.6~3.7**	**accept**	**high**
Spinel structure	**3D**	**LiMn2O4**	**110**	**3.7**	**good**	**low**

Characteristics of Different Cathode Materials

	LiCoO2	Li(NiCoMn)O2	LiMn2O4	LiFePO4
Nominal voltage	3.6V	3.7V	3.8V	3.2V
Specific energy (material) mAh/g	145 (4.2V)	165 (4.2V)	110 (4.2V)	150 (3.6V)
Specific energy (cell) Wh/kg	120-150 (4.2V)	130-160 (4.2V)	90-110 (4.2V)	90-120 (3.6V)
Material decomposition (in presence of electrolyte)	>1000J/g at 220℃	>1000J/g at 300℃	>800J/g at 280℃	N.A
Over charging voltage	<5.5 V	<5.5 V	<12V	>18V
Cycle life (>80%)	>500 at rt >500 at ht	>500 at rt >500 at ht	>500 at rt <300 at ht	>1000 at rt >1000 at ht

LiFePO4	LiFePO4←→Li + + e - + FePO4
LiCoO2	LiCoO2←→0.5Li + + 0.5e - + Li0.5CoO2
LiMn2O4	LiMn2O4←→x Li + + x e - + Li1-xMn2O4
LiCo1/3Ni1/3Mn1/3O2	LiNi1/3Co1/3Mn1/3O2←→x Li + + x e - + Li1-x Ni1/3Co1/3Mn1/3O2

Heat Generation of Different Cathode Materials



LiCoO2 + Co

Thermal Runaway

LiMn2O4 Mn2O3+ O2

Thermal Runaway

LiFePO4 Charge FePO4

A stable chemical agent can easily buy from store

Very strong chemical bond P-O (Bond length of P-O/ Co-O: 0.153nm/ 0.191nm)is in FePO4, and no active O2 release even at high temperature than 500ºC.

Li-ion Cell Design

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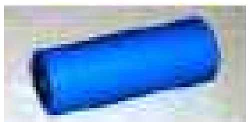
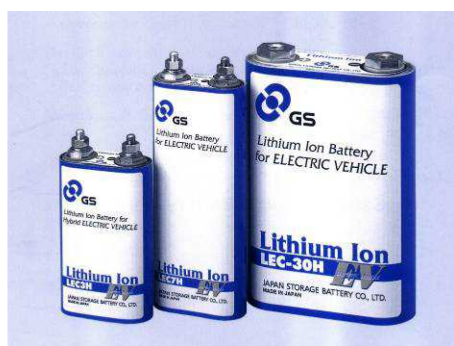
Cylindrical type



Prismatic type



Laminated type

Small Cell vs. Large Cell

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Large Format cell

Development considering HEV / PEV use

- High pack reliability
- Low cell quality (poor uniformity)
- High cell price (>800USD/kWh)

18650 type cell

Application of current technology

- High cell reliability
- Low cell price (<400USD/kWh)

For a 36V/10Ah battery pack

10S1P (10 cells)

10Ah cell

10S2P (20 cells)

5Ah cell

10S 4P/5P (40/50 cells)

2.2-2.9 Ah cell

Small Format vs. Large Format Cell

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Cell

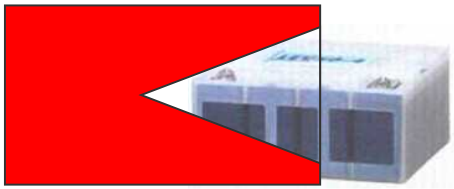
Module

Pack 360V, 16kWh

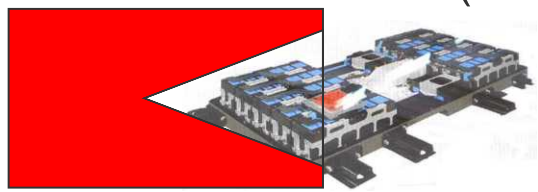
MITSUBISHI MOTORS

50 Ah

4 Cells



22 Modules (88 cells)

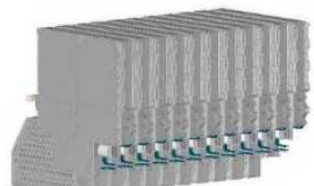


Speed: 80 mph (130 km/h)
Range: 100 mi (160 km)

2 Ah

621 Cells

11 Modules (6831 cells)



TESLA MOTORS

CELLS

- Lithium ion cells
- Built IP around 18650 form factor
- Evaluate, not manufacture cells
- Leverage industry battery chemistry investments

SHEET

- Sheet: 621 Cells
- Modular, scalable design
- IP in charge balancing and cooling
- Battery longevity (cycle & calendar life)

BATTERY

- Battery Pack: 6,831 cells
- 53 kWh
- Battery system safety
- Battery system durability
- Up to 150,000 mile life
- Scalable, automated assembly
- Worldwide approval for transport and use

Speed: 125 mph (200 km/h)
Range: 236 mi (378 km)

What We Learn from Small Li-ion Battery?

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18650 Cell

in 1991, 0.7Ah

in 1995, 1.3Ah/8USD

Safety, cost

Energy

in 2006, 2.6Ah

Energy

in 2005, 2.6Ah/3USD

Safety, Cost

Safety

Cycle life

Cost

Energy

Power

18650 Cell Developments

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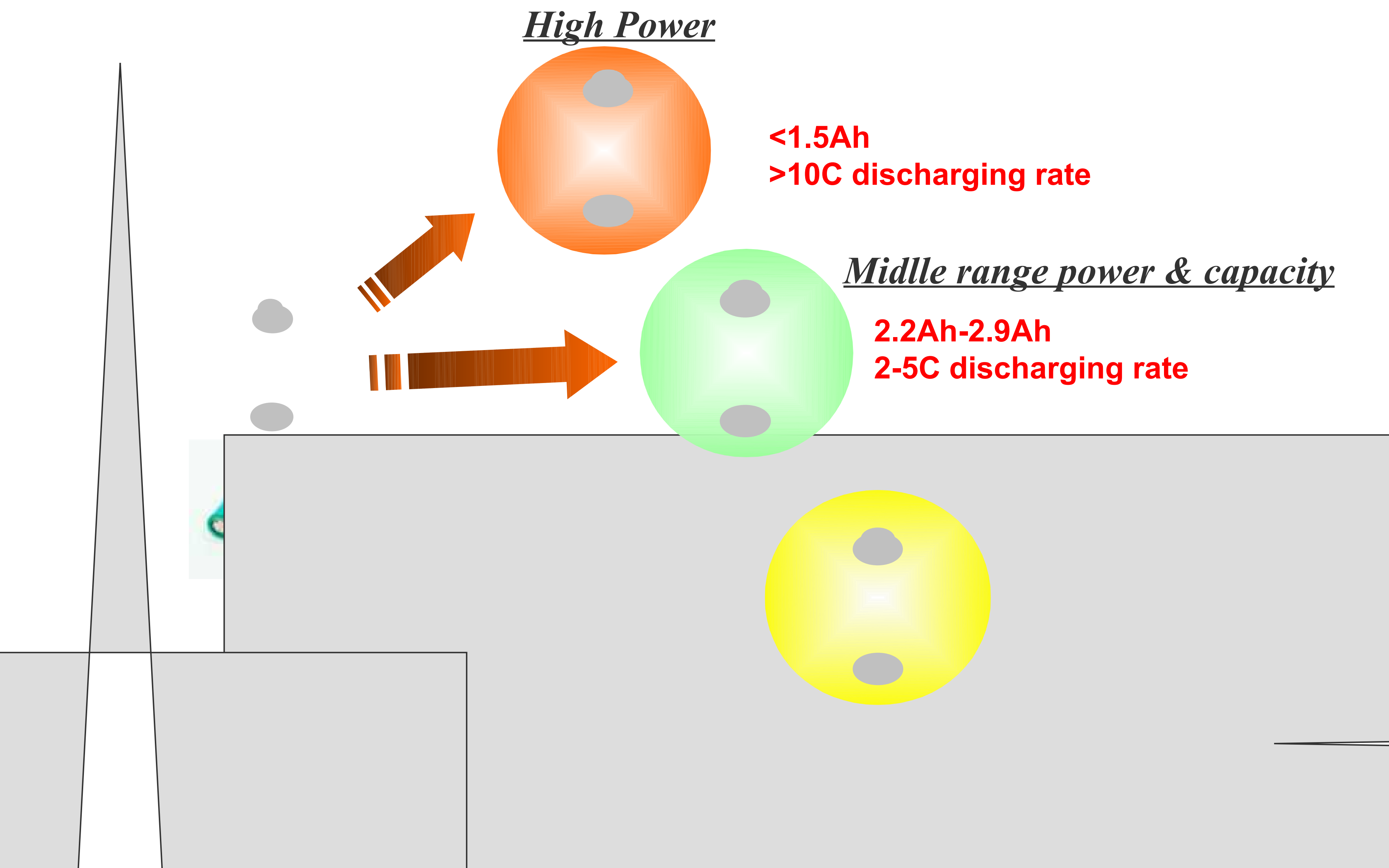

LIB Material Developments

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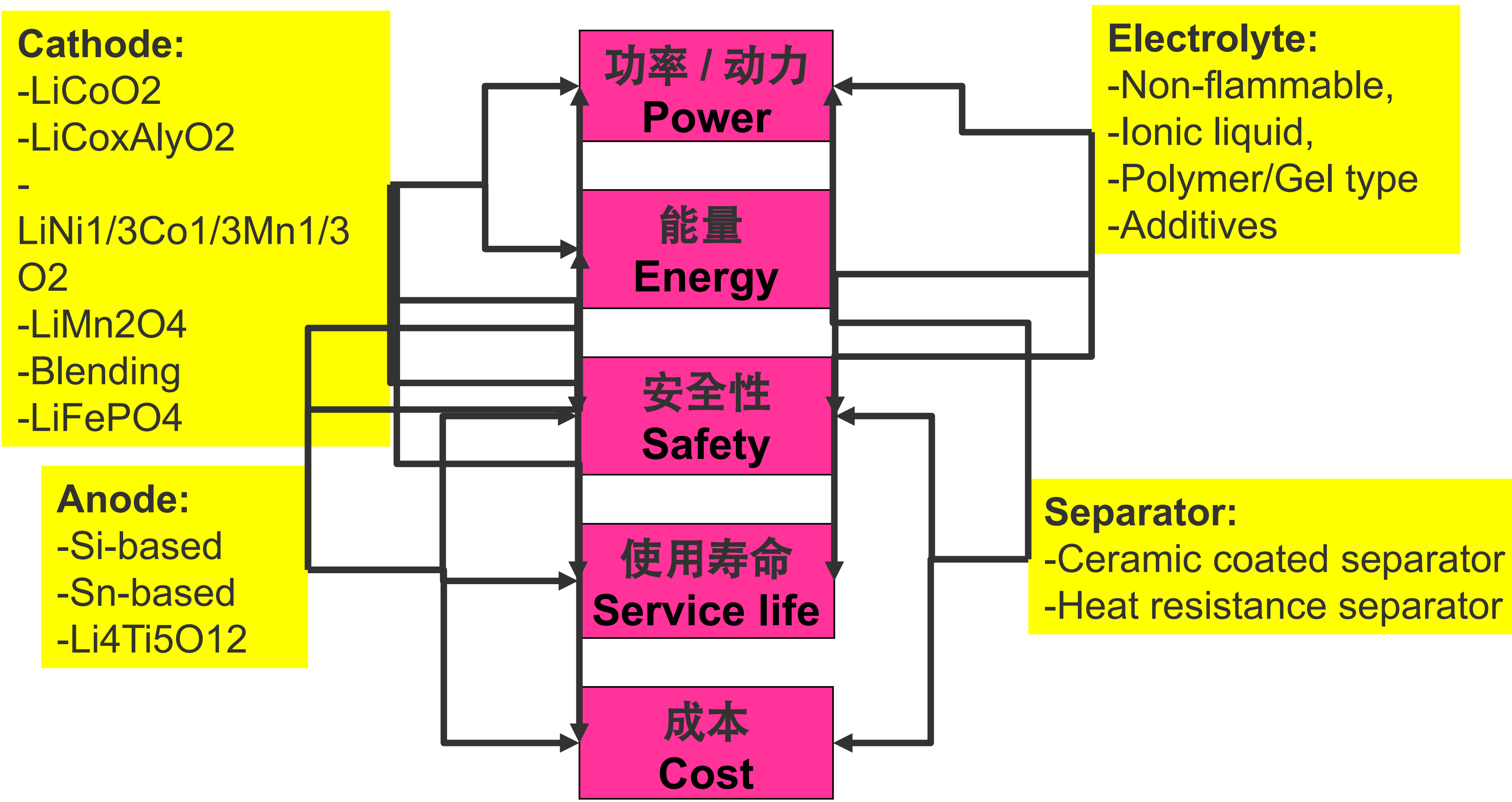

18650 Cell Design

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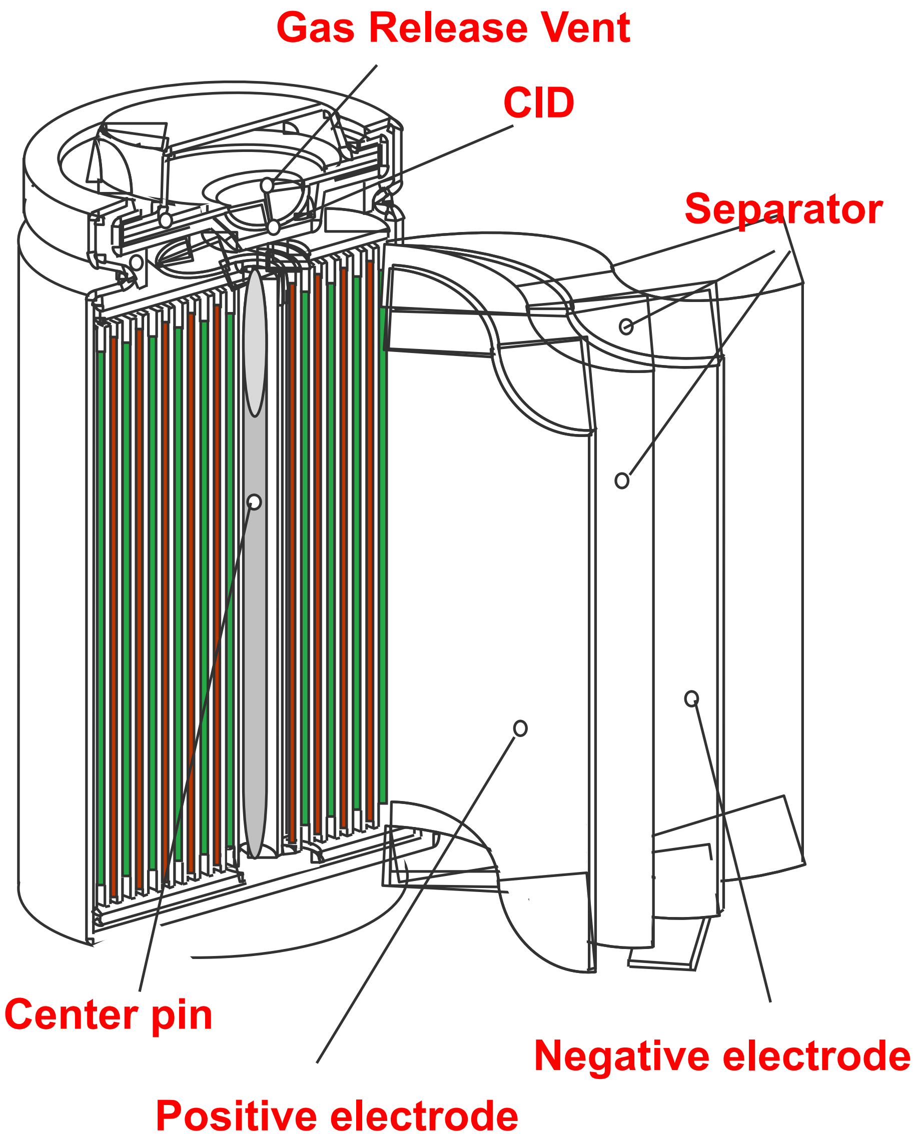
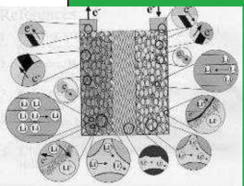


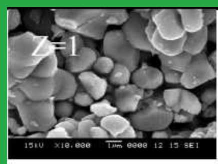
Design for safety

- CID (Current interrupt device)
- gas release vent
- shutdown separator
- separator coating
- center pin
- thermal stable active material
- stable electrolyte
- protection tape on weak point (Al and Ni tab)

Design for power performance

- NMC, NCA cathode material introduce
- PTC remove
- increase electrode tab number
- lower internal resistance (<30mΩ)





Cell

Module/Pack

Electronics

Battery management system :

Cell monitoring (T, V, A)

Module/pack protection

Ca
Li
Bl
Ar
Si
N
N
P
S
C
A
Re

Battery Management System

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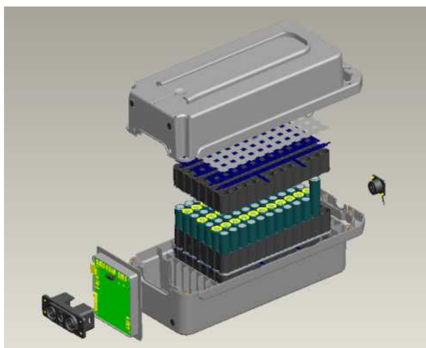
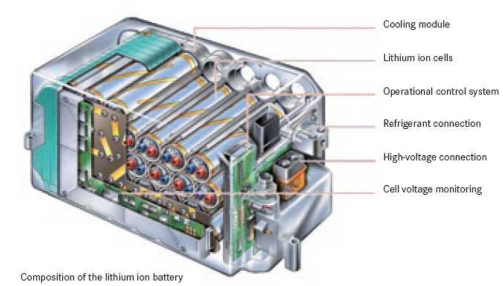
Cell & cell assembly (電芯及電芯組裝)
- cell selection and grouping (電芯選用及群組)
- cell array & cell holder des… 電芯串並聯排列)
- cell connection & weldin… 連接)

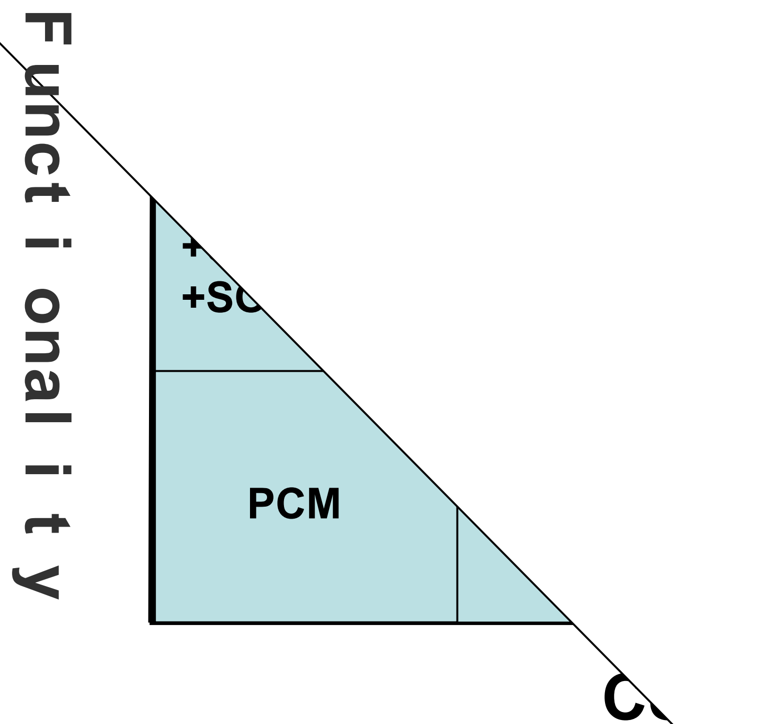
Thermal management (散熱管理)
- air … cooling （氣體或液體冷卻)
- … ation material design (散熱材料設計)





System electronics (電氣…
- battery management sy… 電池管理系統)
- software & firmware control (軟體及韌體監控)
- electrical circuit (電子線路)

Mech… ectronic Integration(機電整合)
- co… cation interface (溝通介面)
- power interface (電氣介面)
- high voltage Connectors (高電壓接頭)


Functionality
+
+SC
PCM
C

Product Development in next 1-3 Years

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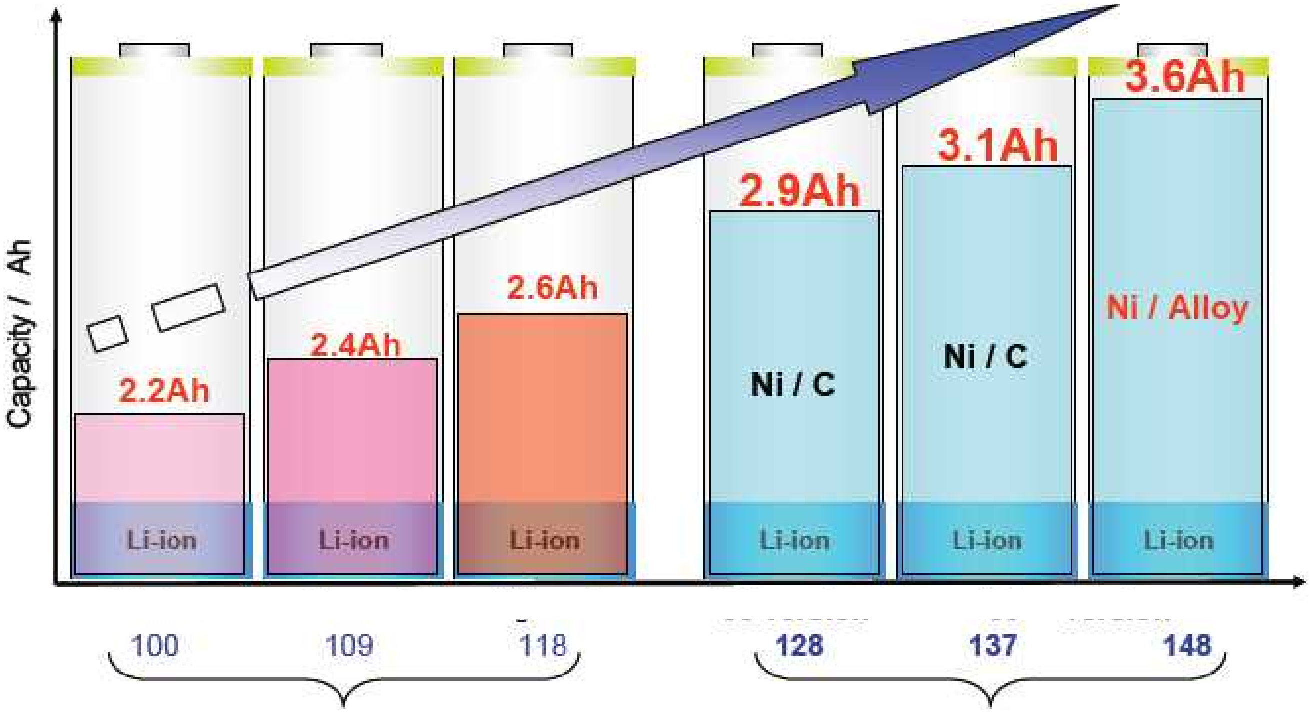
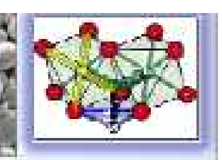
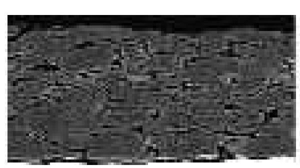
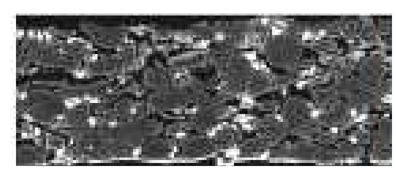


Cathode NMC  Ni-based (NCA)  

Anode Graphite  Graphite+Si 

18650 Cell for LEV Applications

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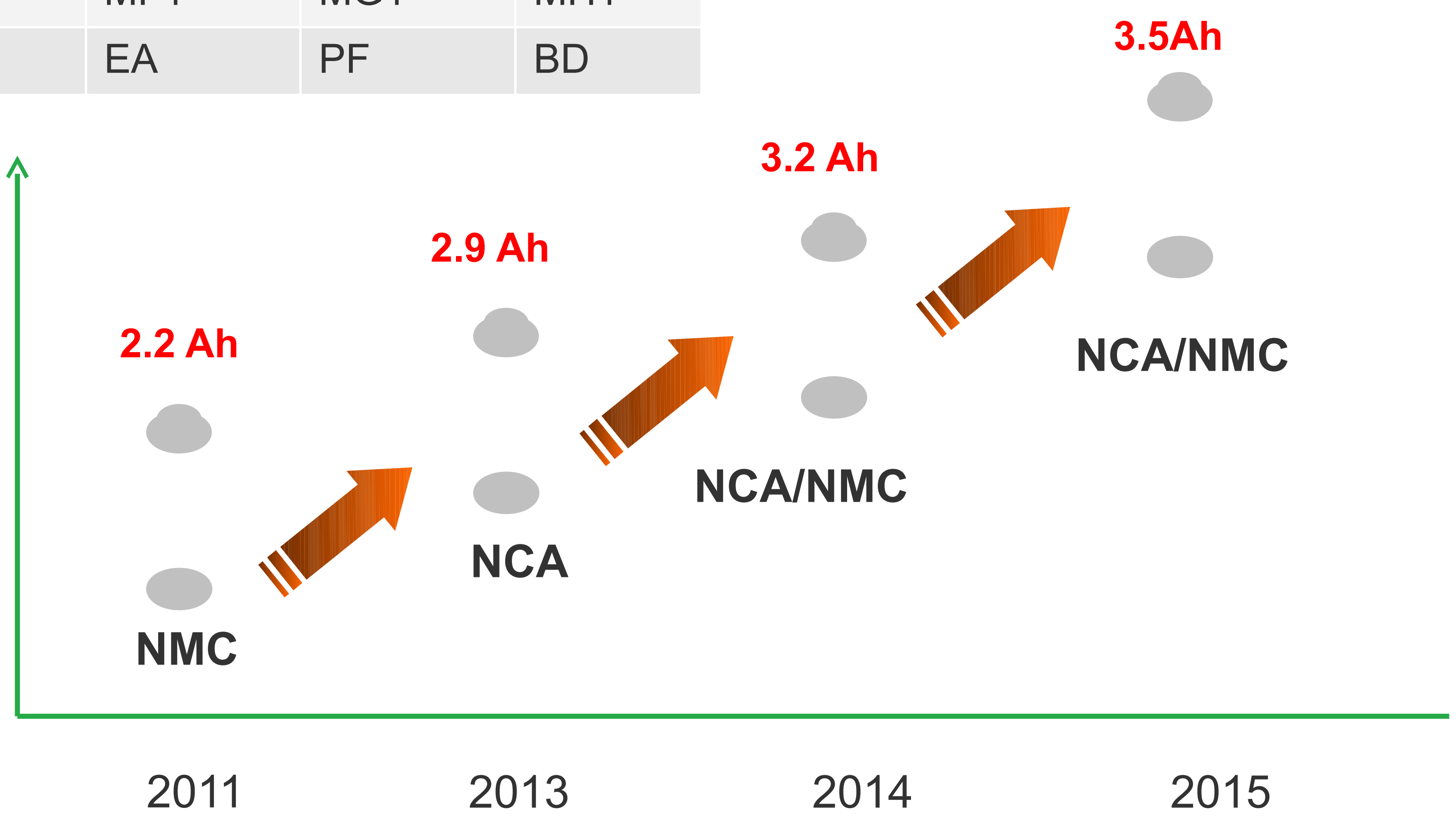
	2.2Ah	2.9Ah	3.2Ah
Samsung SDI	22P	29E	32E
LG Chem	MF1	MG1	MH1
Panasonic	EA	PF	BD



Application for Li-ion Batteries

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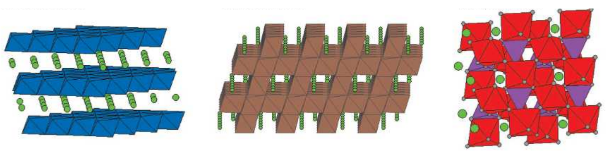
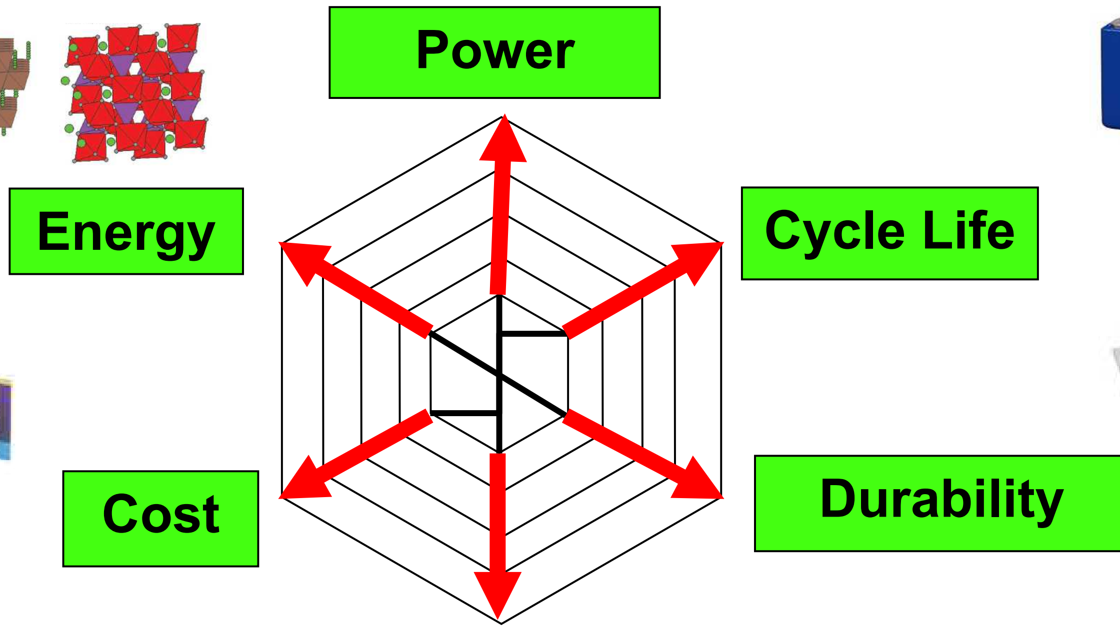
Opening New Markets

Trade-off relationship in various battery performances





Right material

Right cell design

Right application

Key Successes Factors For LEV Market

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- **Interface standardization: Energy Bus**

  www.energybus.org

  Universal charging interface
  IEC/ISO/TC69/JPT61851-3

  EnergyBus

- **Safety Standardization: BATSO**

  www.batso.org

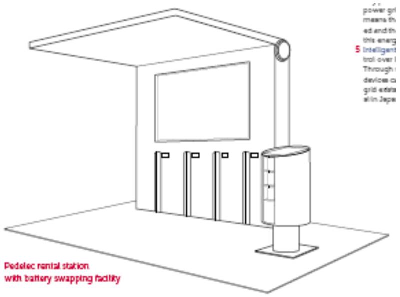
ISO 18243 & CLC/TC21X

BATSO

- **Energy supply service system**

  -Battery exchange system (SWAP)
  -Charging Station

Public LEV Infrastructure Initiative:
IEA HEV IA Task 23



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謝謝 Thank you

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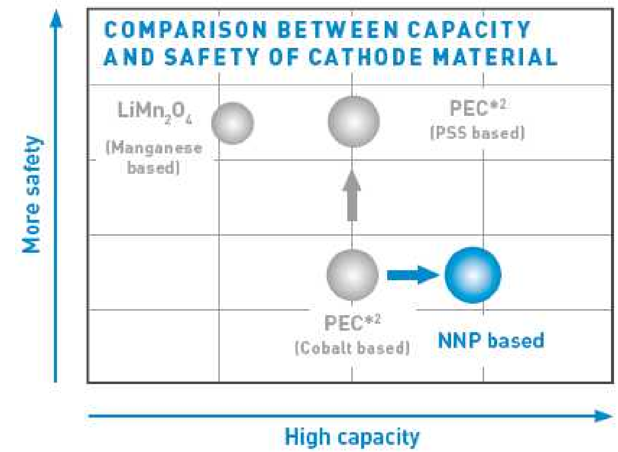
- _Tel +886-2-796-5990_
- _Fax +886-2-2796-5970_

High Capacity Cell Development

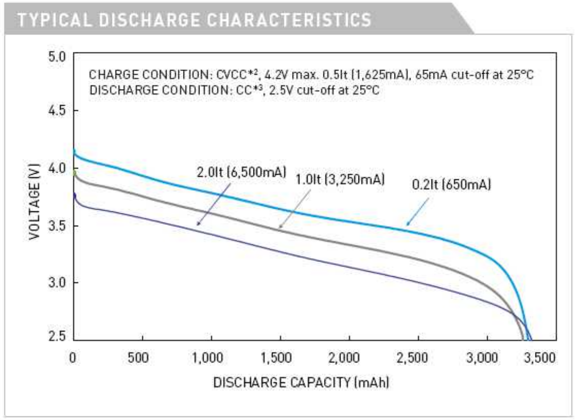
Characteristics of the Panasonic NNP technology:
- Good cycle life performance
- High energy density
- The new Nickel positive electrode excels in durability in actual use and charge retention
- Low self-discharge
- Long storage reliability through reduced metal elution



NNP: Nickel Oxide Based New Platform

SPECIFICATIONS

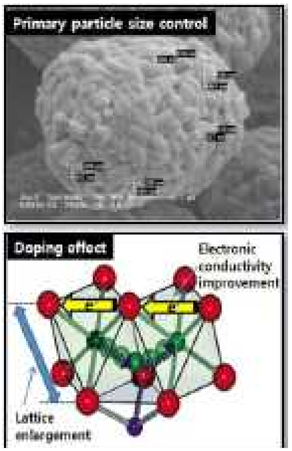
Model number	NCR-18650B
Nominal voltage (V)	3.6
Nominal capacity*1 - Minimum (mAh)	3,250
Nominal capacity*1 - Typical (mAh)	3,350
Dimensions - Diameter (mm)	18.5
Dimensions - Height (mm)	65.3
Approx. w^eight (g)	47.5



sources: Panasonic

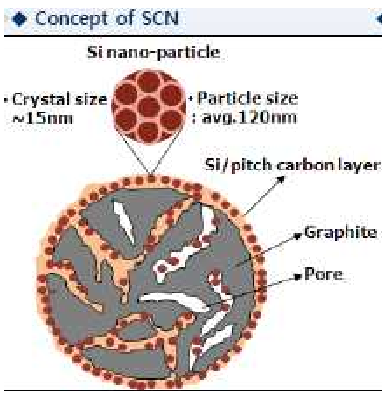
High Capacity Cell Development

Cathode Material Design:
high-Ni NCA

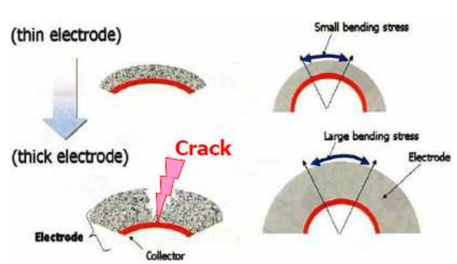


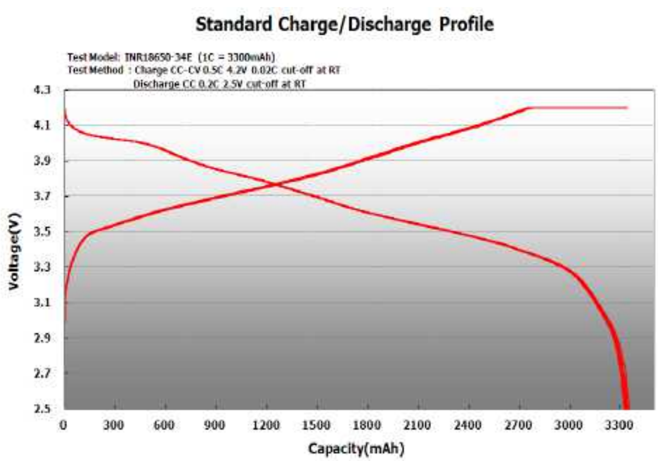
Item		Target INR18650-34E
Capacity (Typical, 0.2C discharge)		3350mAh
Capacity (Min, 0.2C discharge)		3250mAh
AC IR (1KHz)		< 35mΩ
Nominal voltage (0.2C discharge)		3.60V
Charging voltage		4.2V
Discharging end voltage		2.5V
Charging current	Standard	1650mA/ 0.5C
Max. discharge current		10050mA/3C
Cycle Life (0.5C ch./1C disch.)		80%@500cy
Cycle Life (3C discharge)		N/A
Weight (g)		TBD

Anode Material Design:
high energy density

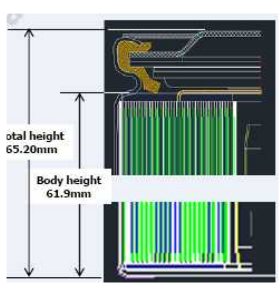


Thick electrode technology





Can-height up:
Capacity-up design



sources: Samsung SDI

Battery Safety !!!

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BATSO

Safety issue can cause the damage or slow down new application market

Safety Issue

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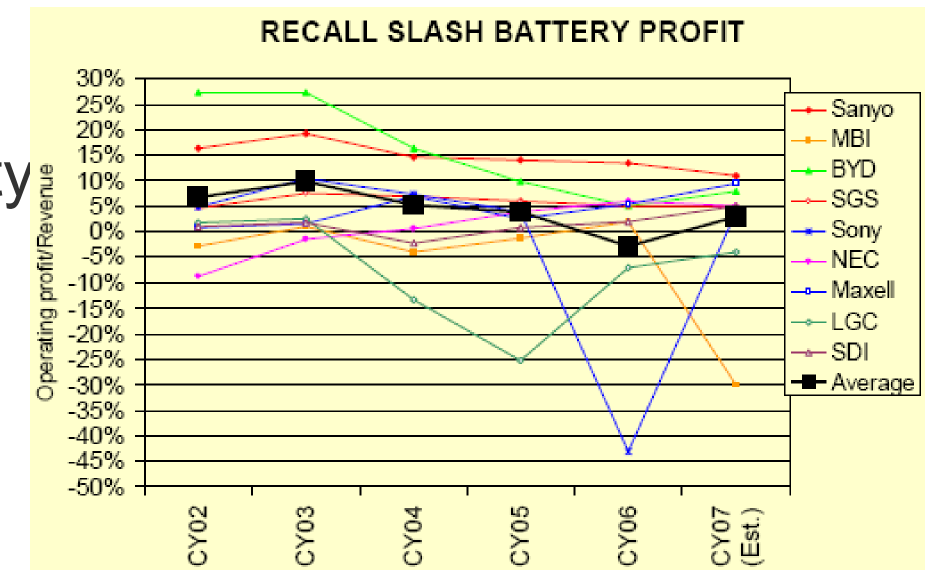
- More & more incidents & accidents
- All the battery makers and the OEM are concerned
- Recall cost impact drastically the battery business and the profitability

Battery Makers	OEM	Battery recall	Date	Cost
Matsushita	Nokia	46 M cells	08/07	100-200 M$
Sanyo	Mitsubishi	1.3 M cells	12/06	35 M $
Sony	Dell, Apple, Toshiba, Lenovo,...	10 M Packs 65 M cells	2006	430 M$
...				



What Safety Issue Come From?

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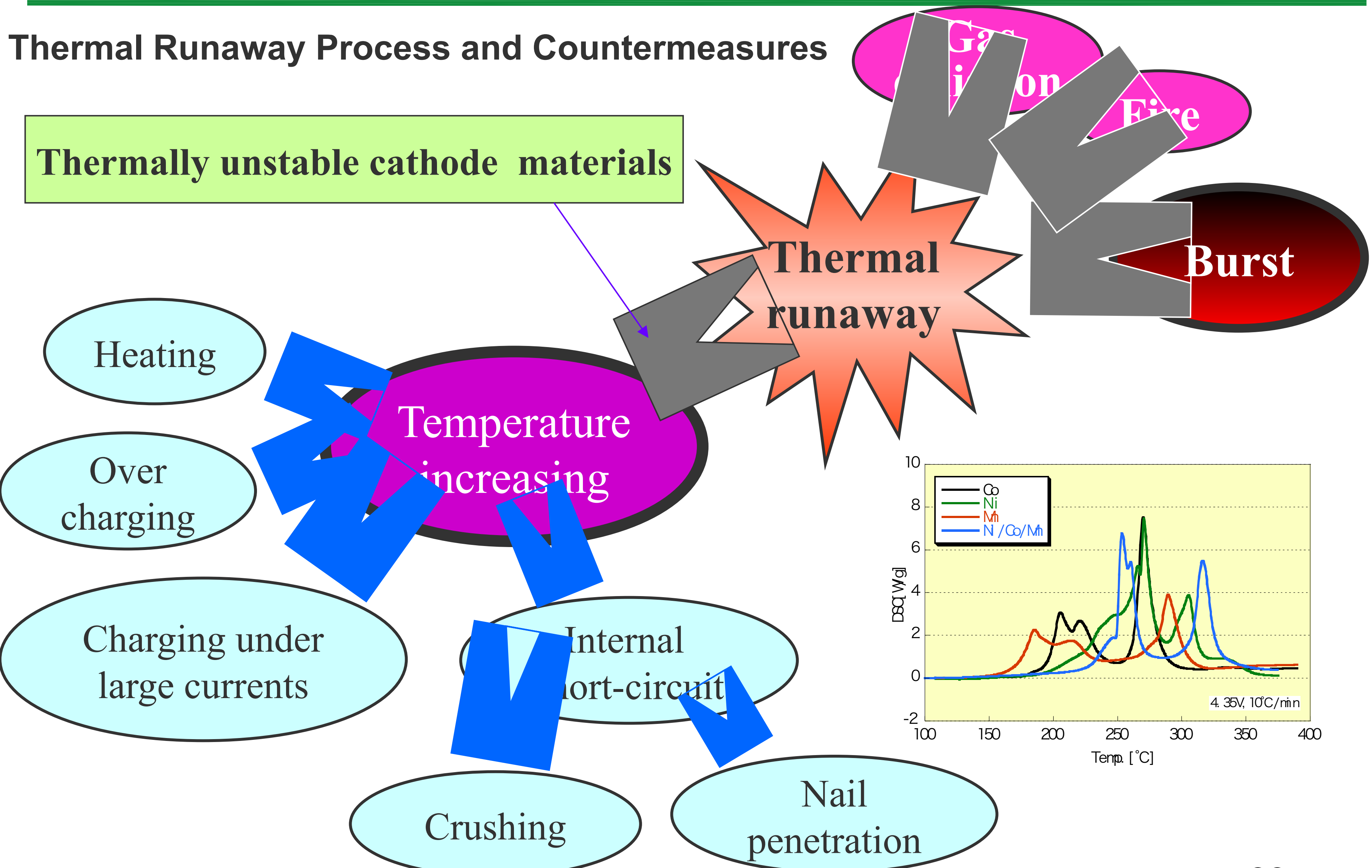
Thermal Runaway Process and Countermeasures



Conclusions

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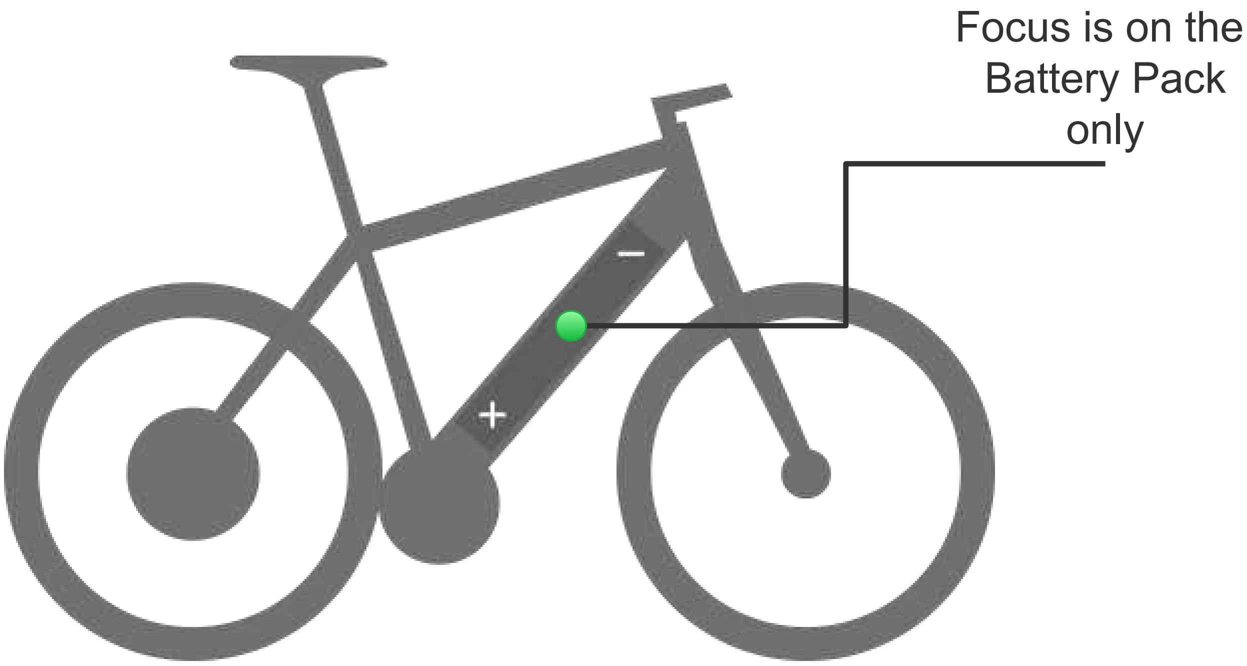
- A 1865 cell design with 2.9Ah capacity is appropriate for LEV/EV application by the following design characteristics:
  - cathode material- based on NCA to increase the capacity and discharge rate capability
  - thickness of separator- about 10~20μm
  - electrode design: long and thin electrode, nickel tape is located in the middle of cathode electrode to lower cell IR
  - cell design: no PTC but CID and center pin are remain for safety
- Low internal resistance of cell and safety improvement are the key design factors for the LIB in EV application
- Cell capacity could be increase to 3.2-3.6Ah by safety improvement in 2-3 years

LEV: Capabilities & Services

If you develop with an average Battery Pack Assembly Company…



Capability & Services

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Development with HT Energy: turnkey Solutions

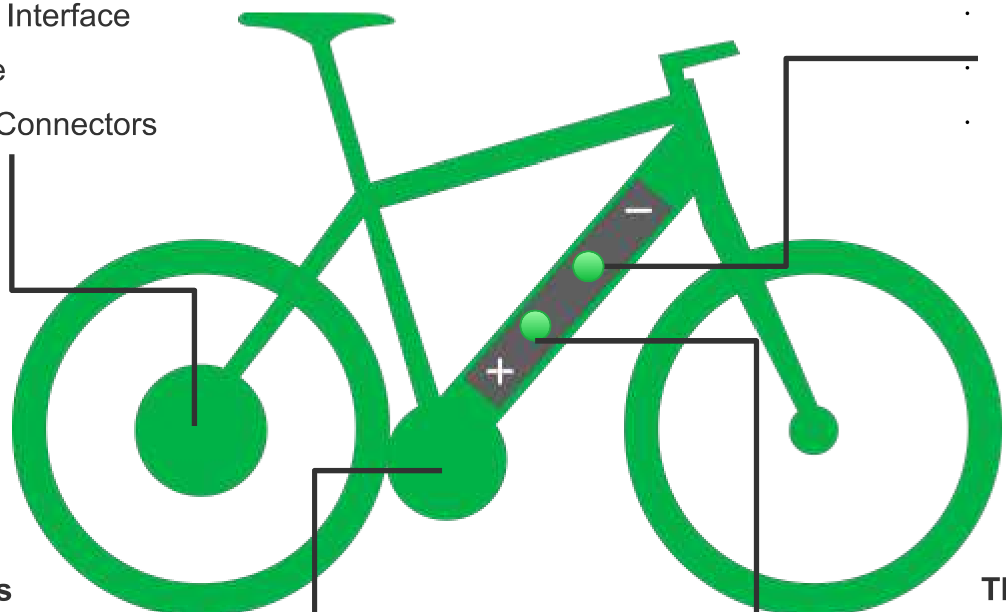
Mechanical & Electronic Integration

- communication Interface
- Power Interface
- safe & reliable Connectors

Cell & Cell Assembly

- Cell Selection and Grouping
- Cell Array & Cell Holder Design
- Cell Connection & Welding

System Integration



Battery Architecture

System Electronics

- Battery Management System
- Software & Firmware Control
- Electrical Circuit

Thermal management

- Air or Liquid Cooling
- Heat conduction and dissipation
- equipped with heat-absorbing Material

Products – costumized solution

Eflow Nitro 2014 - 36V

CURRIE TECHNOLOGIES
Hybrid Electric Bicycles & Scooters

Products – costumized solution

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Chainless, foldable bike - 36V

mandofootloose

Products – customized solution

HITECH ENERGY

Customized Solution – 44V

KLEVER

Products – customised solution

HITECH ENERGY

Customized Solution - 36V

EMOCIONES DE COMPETICION






Products – customised solution

HITECH ENERGY

Customized Solution - 48V

TERRA MOTORS

A4000I

Products – customized solution

HITECH ENERGY

Stromer-ST2

Products – customized solution

HITECH ENERGY

Stromer-ST2

More Design

More Power

More Range

More Connectivity

Products – customized solution

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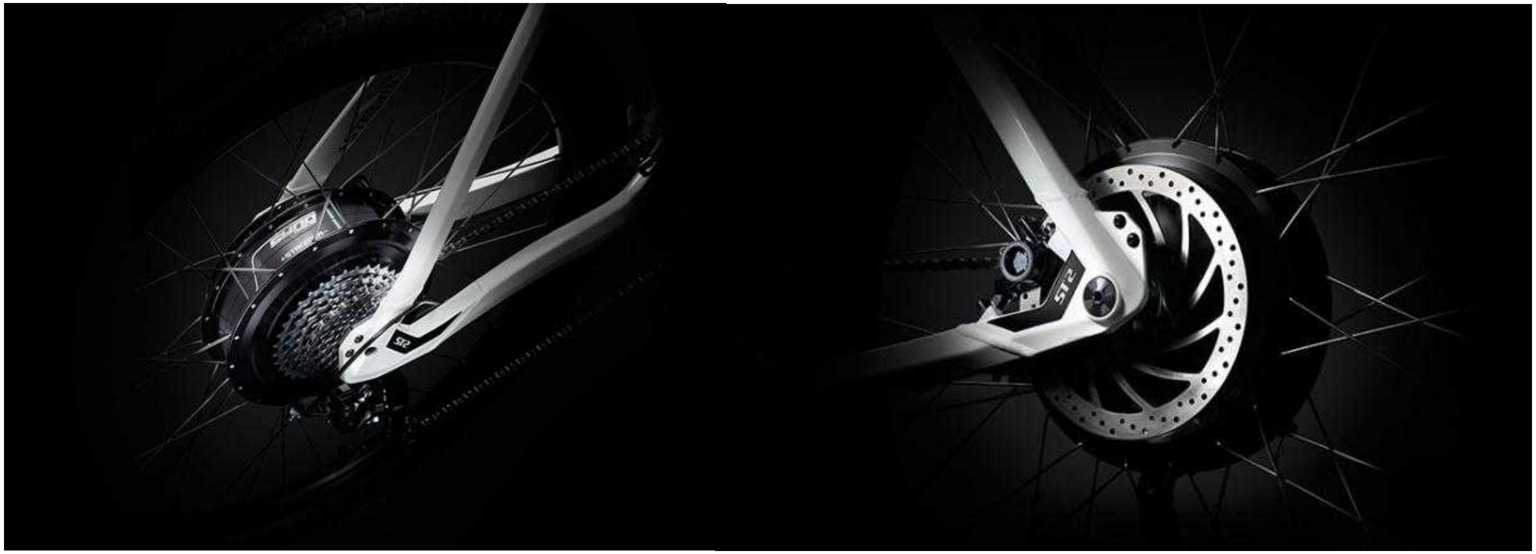
Stromer-ST2

Motor:

-brushless, direct-current motor
-located in the bike’s rear hub
-500W, 35Nm of torque

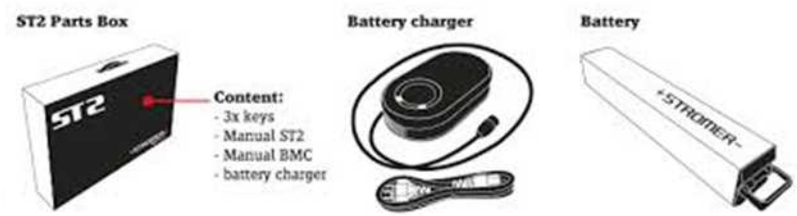


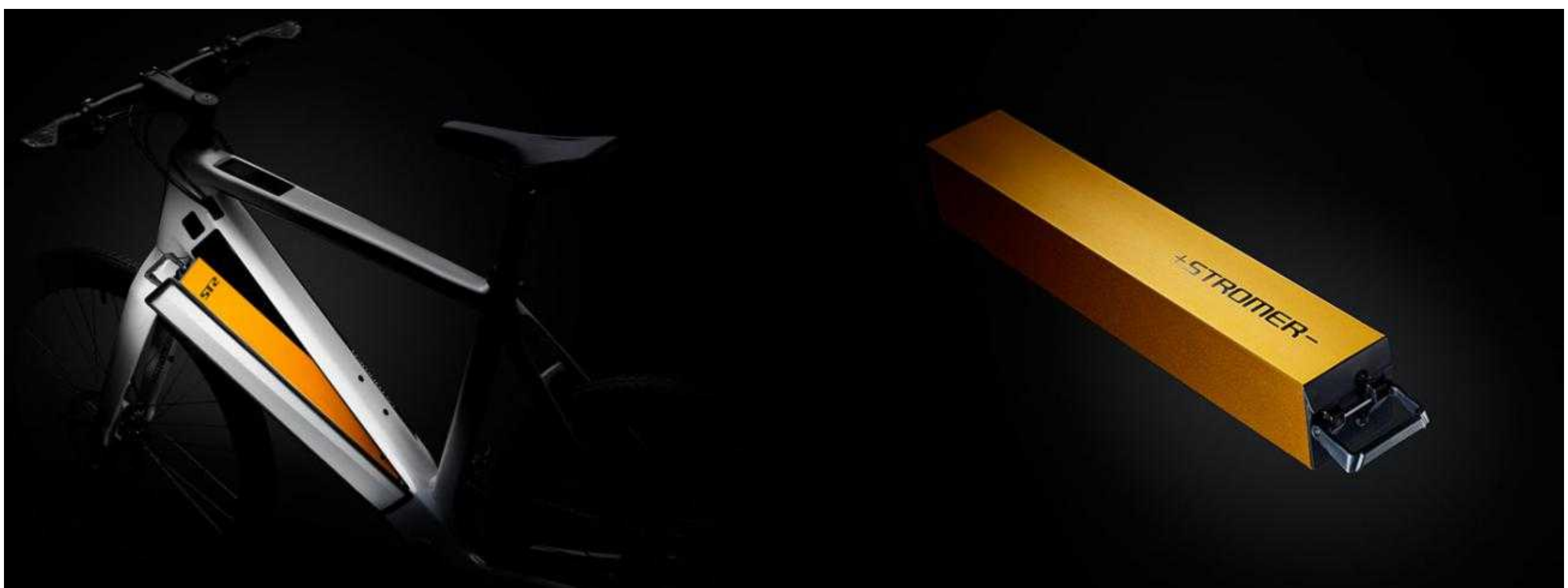
Products – customized solution

Stromer-ST2

Battery:

-Energy: 814Wh (150km)
-Voltage: 48V
-Weight: 5kg
-EnergyBus connector





Products – customized solution

HITECH ENERGY

Stromer-ST2

Products – customized solution

HITECH ENERGY

ST2 Models

Sport

Sport model is available in a 20” and 17” frame

Comfort

Comfort model is available in a 17” frame

Shimano 20-speed drivetrain

Products – customized solution

Stromer-ST2

E-Bike- Revolution Products

HITECH ENERGY

Stromer-ST2

Battery:

-Energy: 814Wh (150km)
-Voltage: 48V
-Weight: 5kg
-EnergyBus connector

http://www.stromerbike.com/en/int

Design-related Definitions-1

HITECH ENERGY

- **Anode (陽極):**

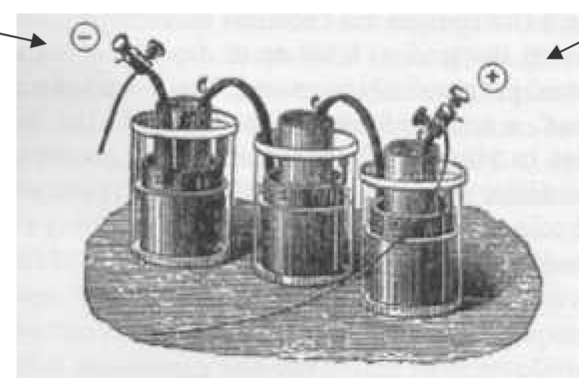
  The electrode at which an oxidation reaction occurs. Usually, a cell’s anode is specified during discharging and hence the name anode is commonly used for the negative electrode.

- **Cathode (陰極):**

  The electrode at which a reduction reaction occurs. Usually, a cell’s cathode is specified during discharging and hence the name anode is commonly used for the positive electrode.

John Frederic Daniell
(1790-1845)

photo credit: Bioanalytical Systems, Inc.



Design-related Definitions-2

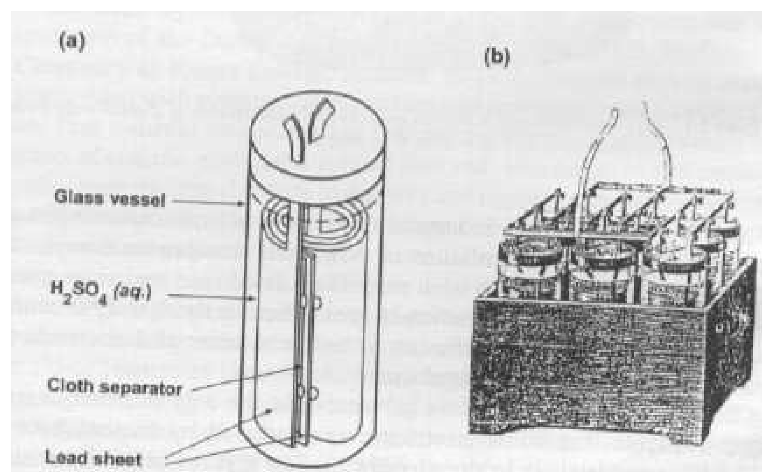
- **Electrolyte:**

  The medium that provides the essential ionic conductivity between the positive and negative electrode of a cell.

- **Separator:**

  An ion-permeable, electronically non-conductive material or spacer that prevents short-circuiting of the positive and negative electrodes of a cell.

Gaston Plante
(1834-1889)



Application-related Definitions-1

- **C-rate :**

  A charge or discharge current equal in Amperes to the rated capacity in Ah. Multiples large or smaller than the C-rate are used to express large or small currents.

- **Cycle Life:**

  The number of cycles that a cell or battery can be charged and discharged under specific conditions, before the available capacity in (Ah) fails to meet specific performance criteria. This will usually be 80% of the rated capacity.

Application-related Definitions-2

- **Cut-off voltage:**

  The cell or battery voltage at which the discharge is terminated. Also often referred to as End-of-Discharge voltage.

- **Self-Discharge:**

  Recoverable loss of capacity of a cell or battery. This is usually expressed in a percentage of the rated capacity lost per month at a certain temperature, because self-discharge rates of batteries are strongly temperature-dependent.

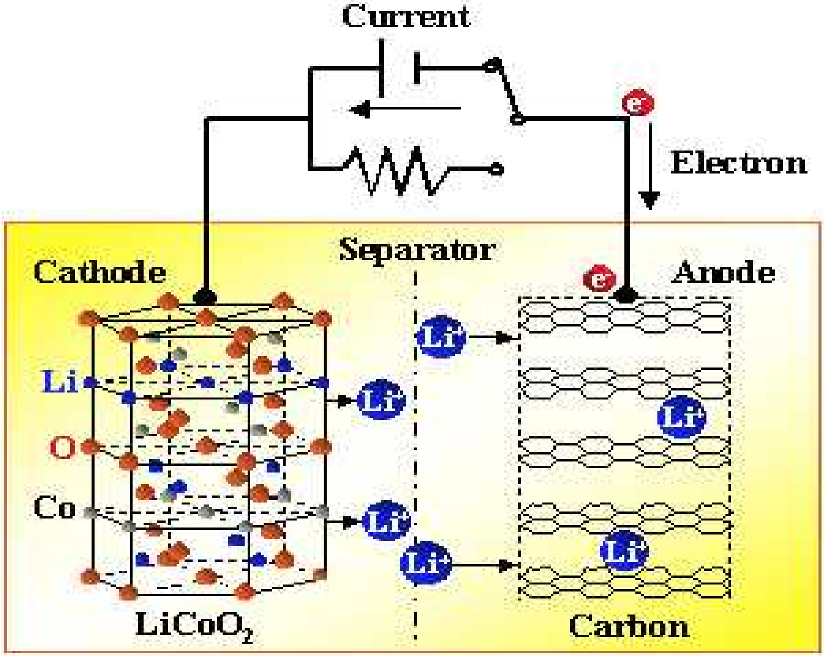
Principal of Li-ion Battery

HITECH ENERGY

Anode: graphite (C)

Cathode: lithium cobalt ($LiCoO2$)

Electrolyte: non-aqueous organic solvent



Cathode: LiCoO2 ⟶ Li(1-x) CoO2+xLi+ +xe-

Anode: C6 +xLi ++xe- ⟶ Lix C6

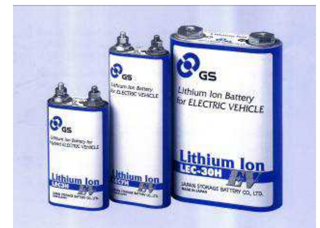
TotalRxn.: LiCoO2+C6 $\underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftharpoons}}$ **Li(1-x) CoO2+LixC6**

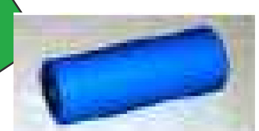
HITECH ENERGY

Power Type Li-ion Battery Development

Performance Improvement

- Power
- Energy
- Safety
- Cycle Life
- Cost

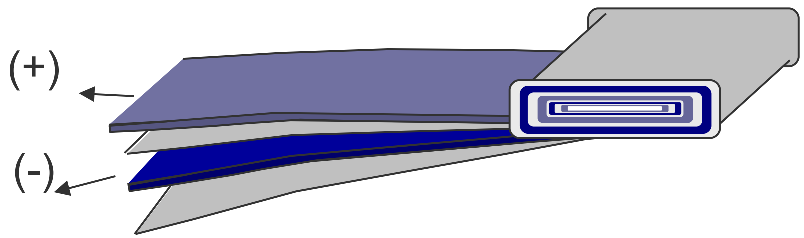


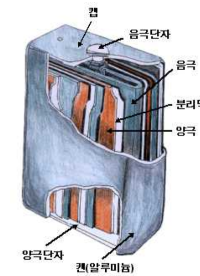


Electrode Assembly

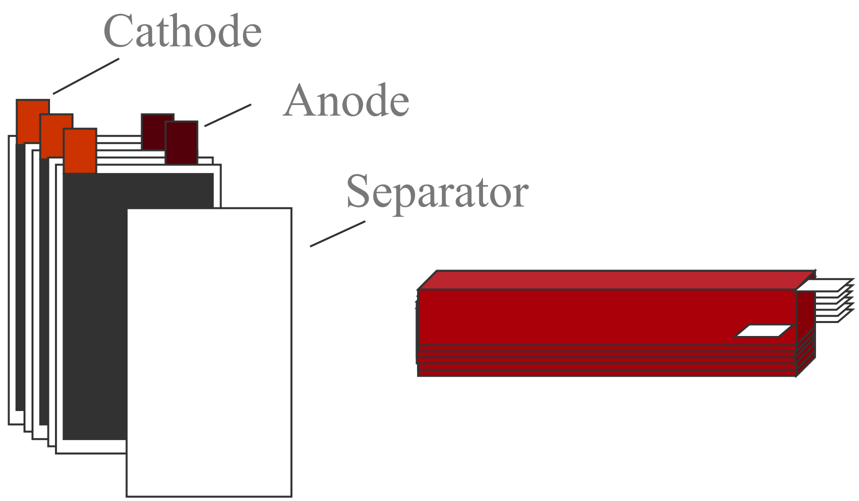
HITECH ENERGY

Winding

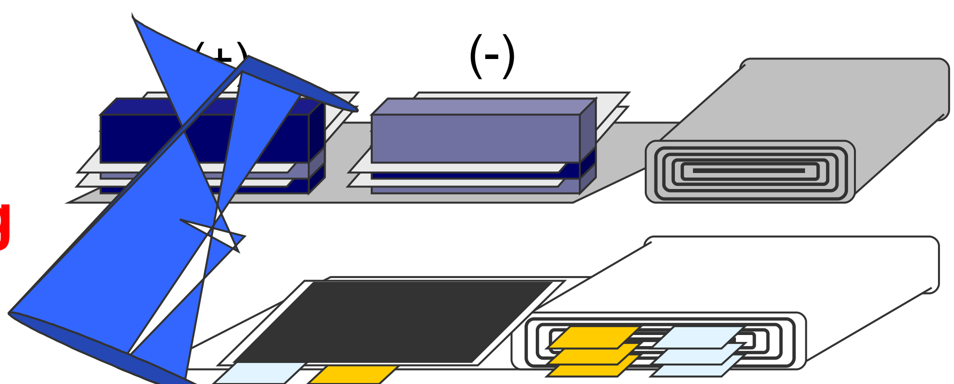




Stacking

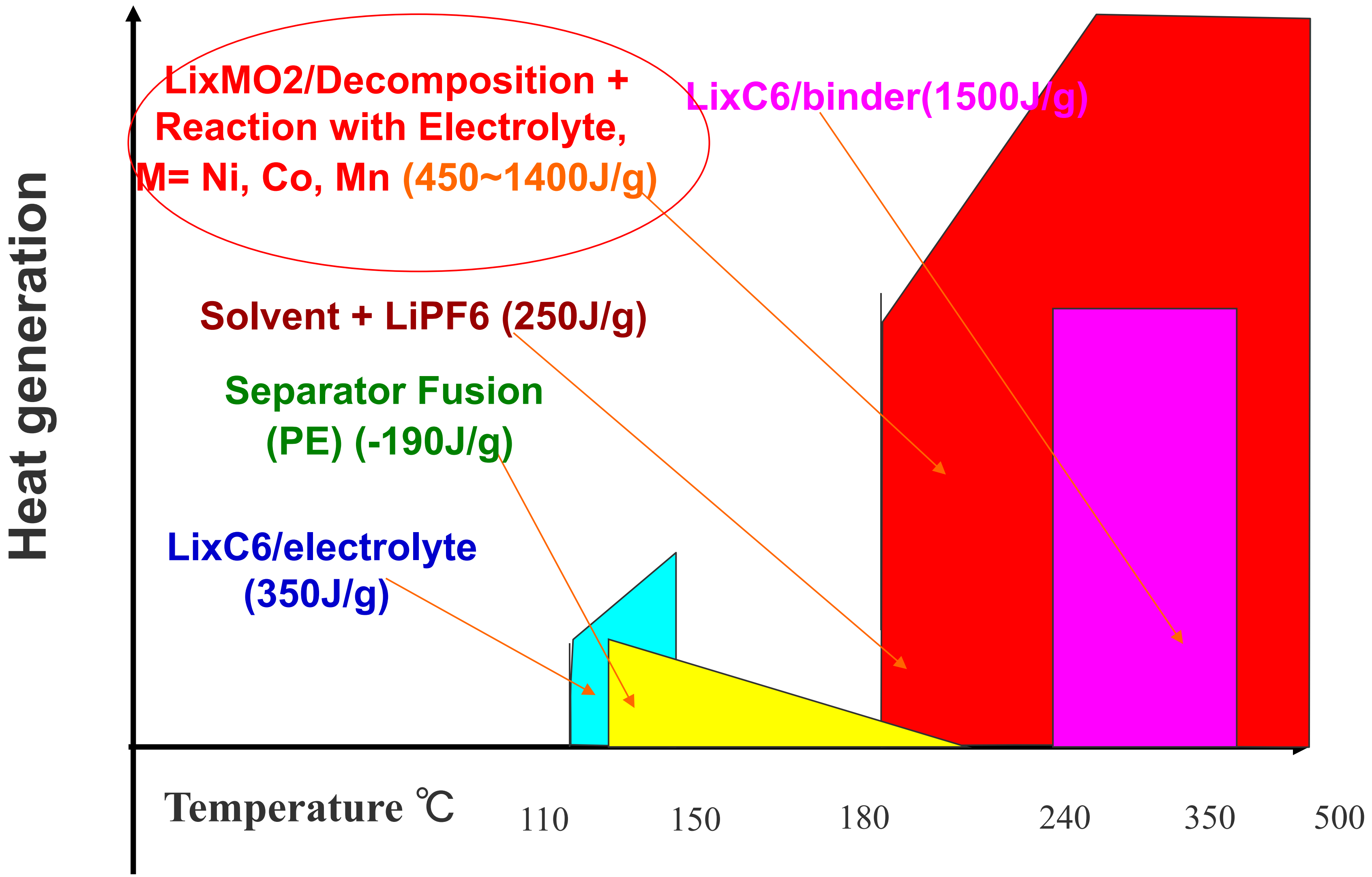


Stacking +Winding

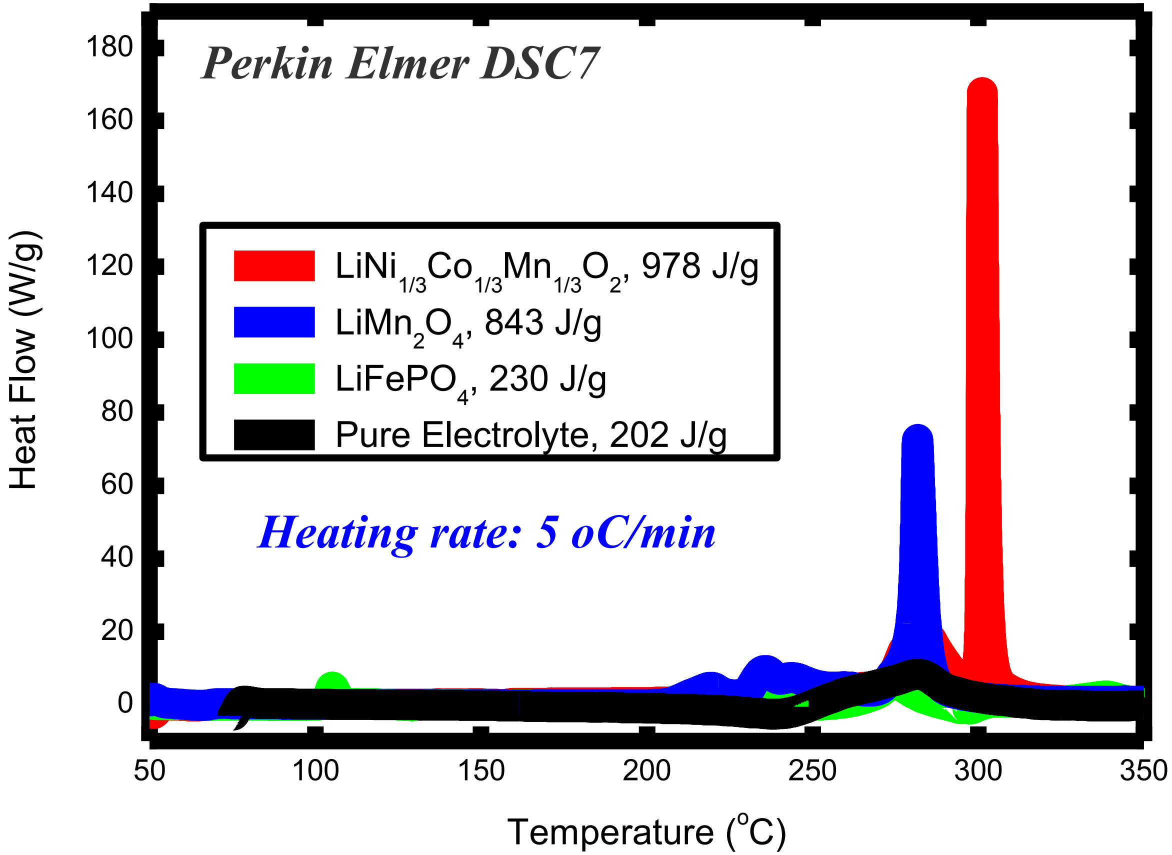


Heat Generation of Materials in LIB

HITECH ENERGY



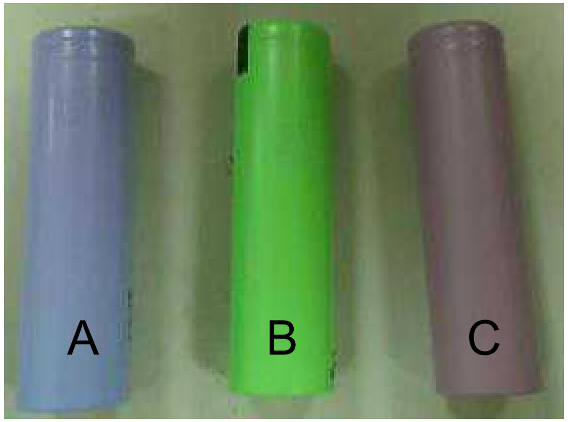
Heat Generation of Different Cathode Materials



- Thermal heat: LiNiCoMnO2 > LiMn2O4>> LiFePO4
- The thermal heat of charged LiFePO4 electrode was mainly contribute from the pure electrolyte

Commercial 18650 cell for Evaluation

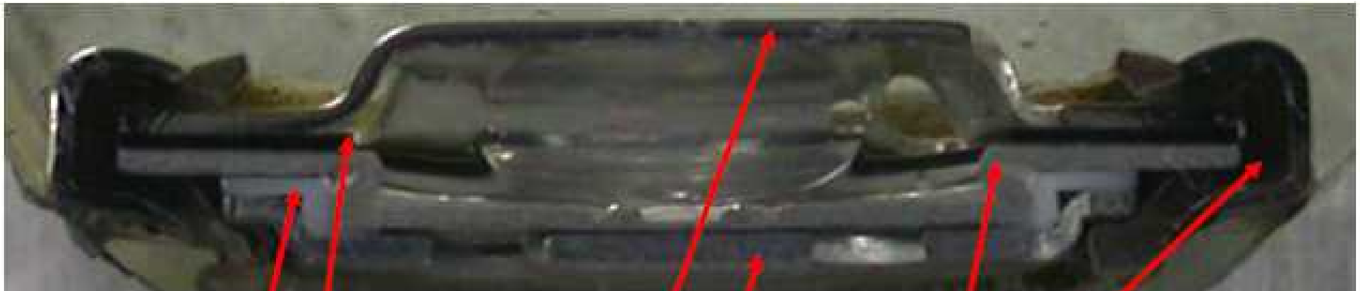
Company	Capacity
A	2.9Ah
B	2.9Ah
C	2.9Ah

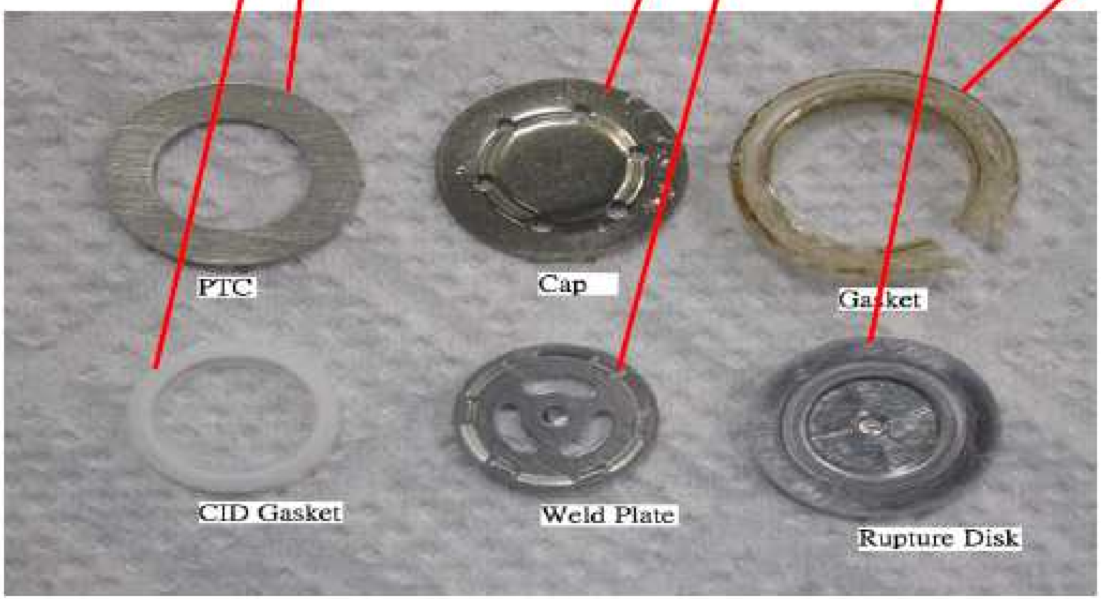


1 cell models received from Japan
2 cell models received from Korea

Structure of Top Cover (Caps)

HITECH ENERGY





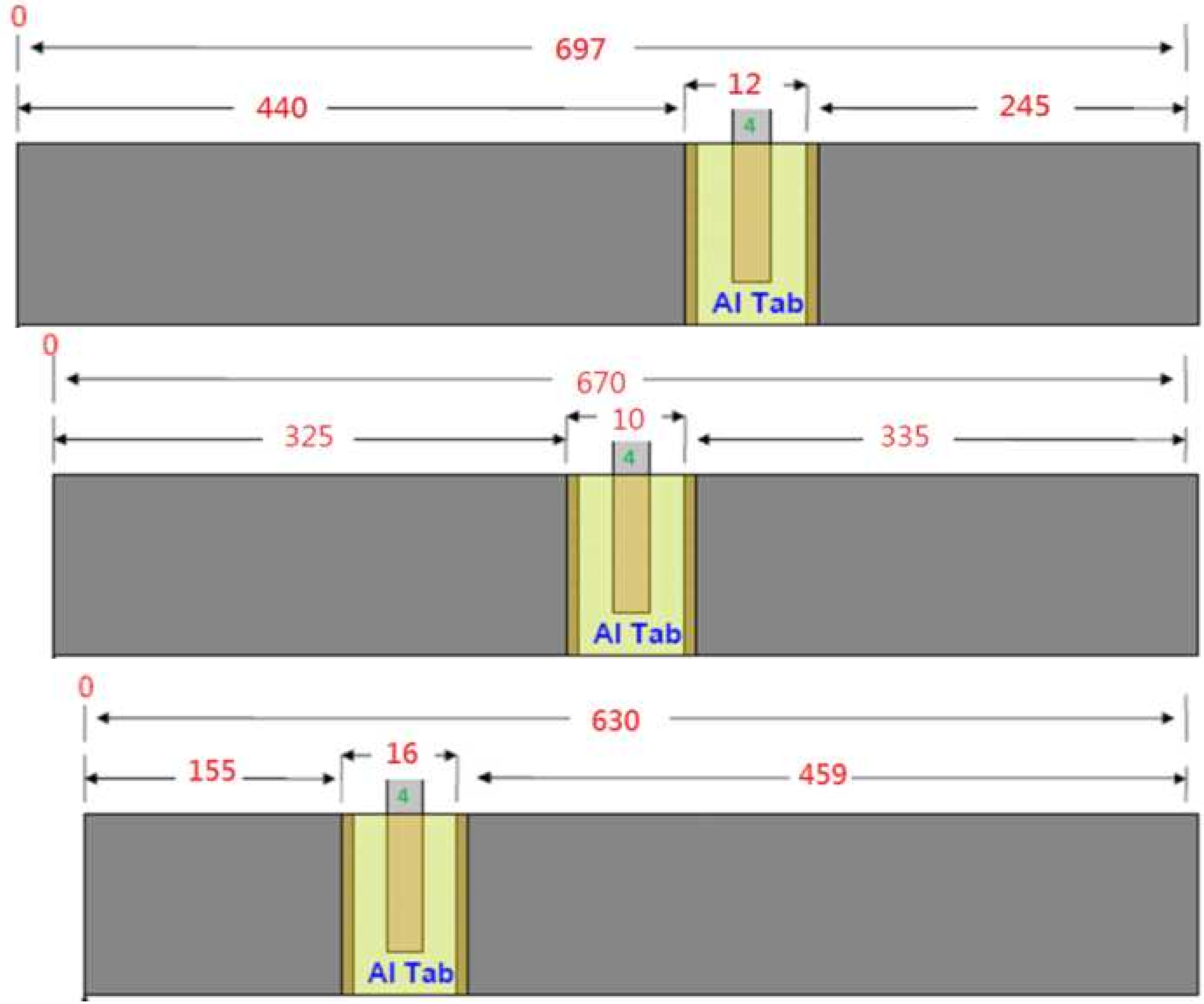
Electrode Structure - Cathode

HITECH ENERGY

A Company

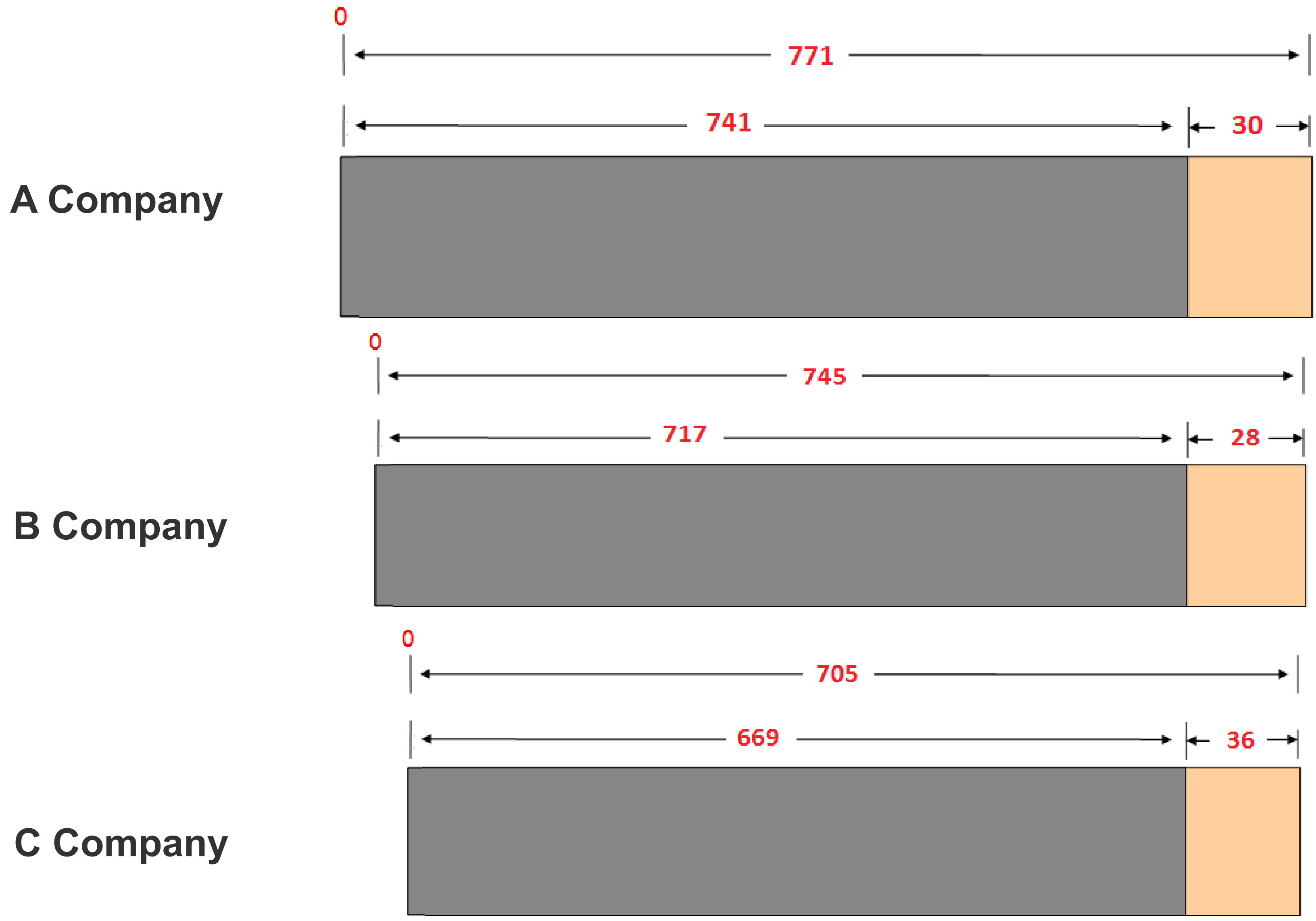
B Company

C Company



Electrode Structure of Anode-A Company

HITECH ENERGY



Cathode Material Analysis

HITECH ENERGY

A Company

Element	Line Type	Wt%	Wt% Sigma	Atomic %
O	K series	35.70	0.49	66.45
Al	K series	1.03	0.12	1.13
P	K series	0.76	0.12	0.73
Co	K series	9.94	0.43	5.02
Ni	K series	52.58	0.58	26.67
Total:		100.00		100.00

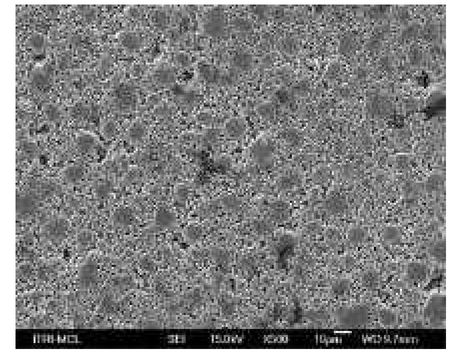
B Company

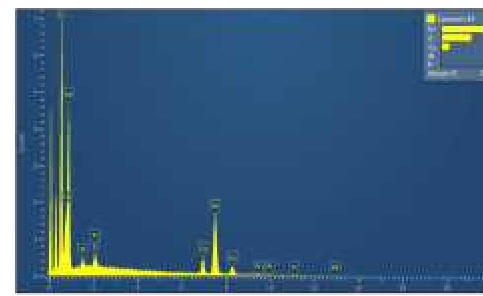
Element	Line Type	Wt%	Wt% Sigma	Atomic %
O	K series	23.87	0.47	39.98
F	K series	25.17	0.63	35.50
Al	K series	1.28	0.14	1.27
P	K series	1.42	0.15	1.23
Co	K series	7.87	0.46	3.58
Ni	K series	40.40	0.71	18.44
Total:		100.00		100.00

C Company

Element	Line Type	Wt%	Wt% Sigma	Atomic %
O	K series	23.87	0.47	39.98
F	K series	25.17	0.63	35.50
Al	K series	1.28	0.14	1.27
P	K series	1.42	0.15	1.23
Co	K series	7.87	0.46	3.58
Ni	K series	40.40	0.71	18.44
Total:		100.00		100.00

SEM and EDS Analysis





Anode Material Analysis

HITECH ENERGY

A Company

Element	Line Type	Wt%	Wt% Sigma	Atomic %
C	K series	83.61	0.41	87.76
O	K series	13.56	0.38	10.69
F	K series	1.99	0.17	1.32
P	K series	0.33	0.04	0.14
Cu	L series	0.50	0.12	0.10
Total:		100.00		100.00

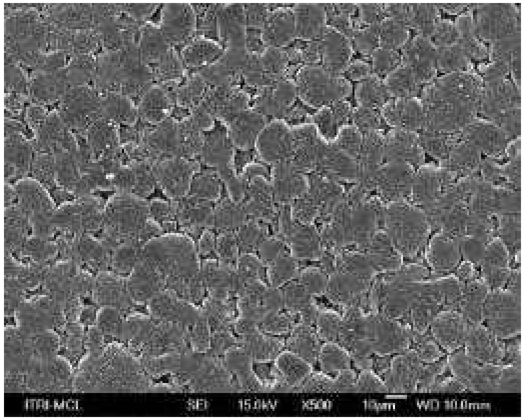
B Company

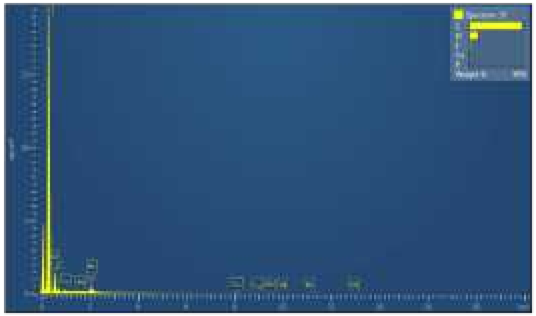
Element	Line Type	Wt%	Wt% Sigma	Atomic %
C	K series	86.26	0.39	90.00
O	K series	9.98	0.35	7.82
F	K series	2.90	0.18	1.91
P	K series	0.46	0.04	0.19
Cu	L series	0.40	0.12	0.08
Total:		100.00		100.00

C Company

Element	Line Type	Wt%	Wt% Sigma	Atomic %
C	K series	81.04	0.39	85.80
O	K series	14.93	0.37	11.87
F	K series	2.42	0.17	1.62
Si	K series	1.28	0.05	0.58
P	K series	0.33	0.04	0.13
Cu	L series	0.00	0.00	0.00
Total:		100.00		100.00

SEM and EDS Analysis





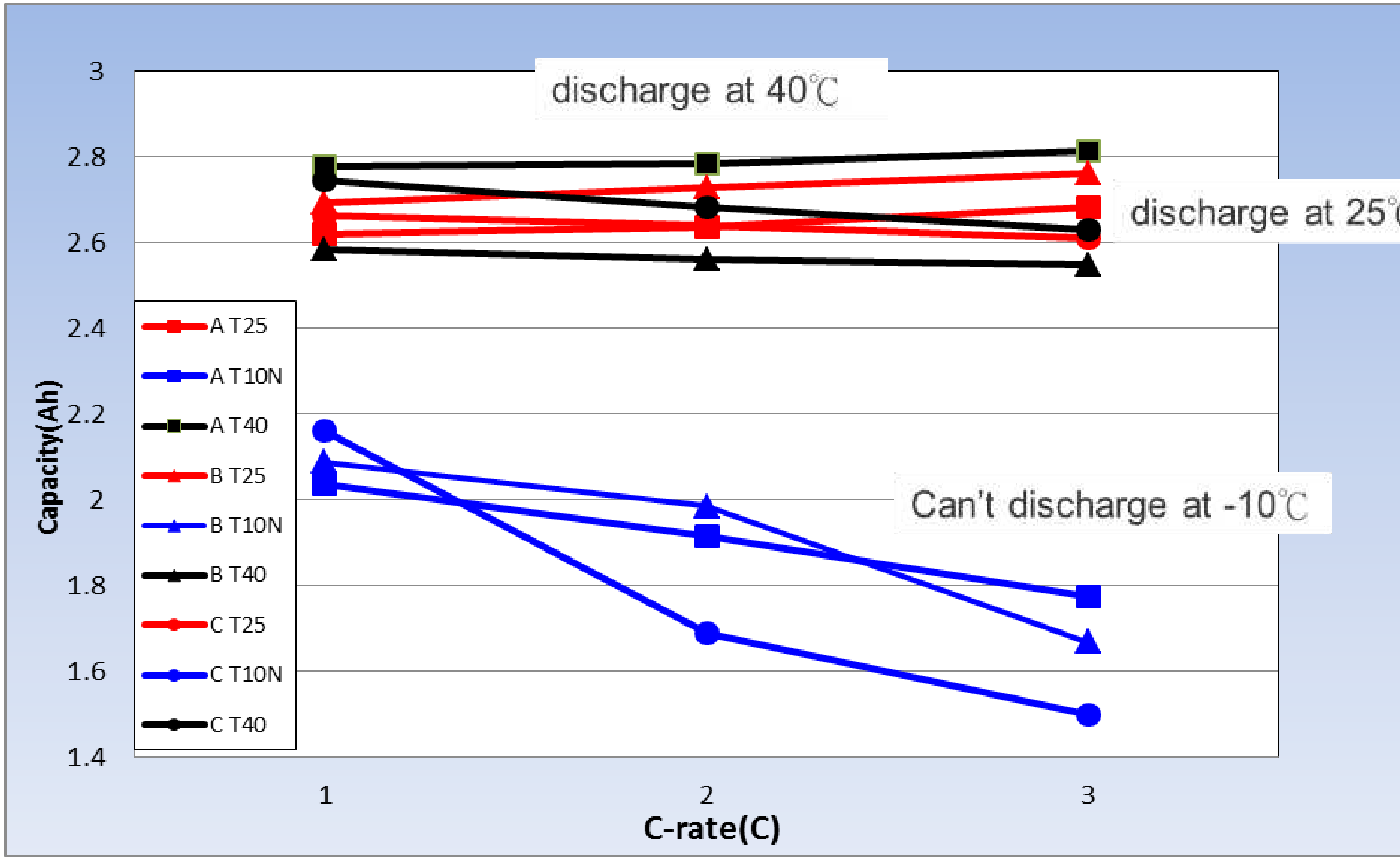
Structure and Material Analysis

HITECH ENERGY

Symbol	Capacity (mAh)	Tab location Cathode/Anode	ACIR (mΩ)	Cathode materials	CID	PTC
A	2900	~2/3from the left/Edge	23	NCA	Y	N
B	2900	Center/Edge	22	NCA	Y	N
C	2900	~¼ from the left/Edge	23	NCA	Y	N

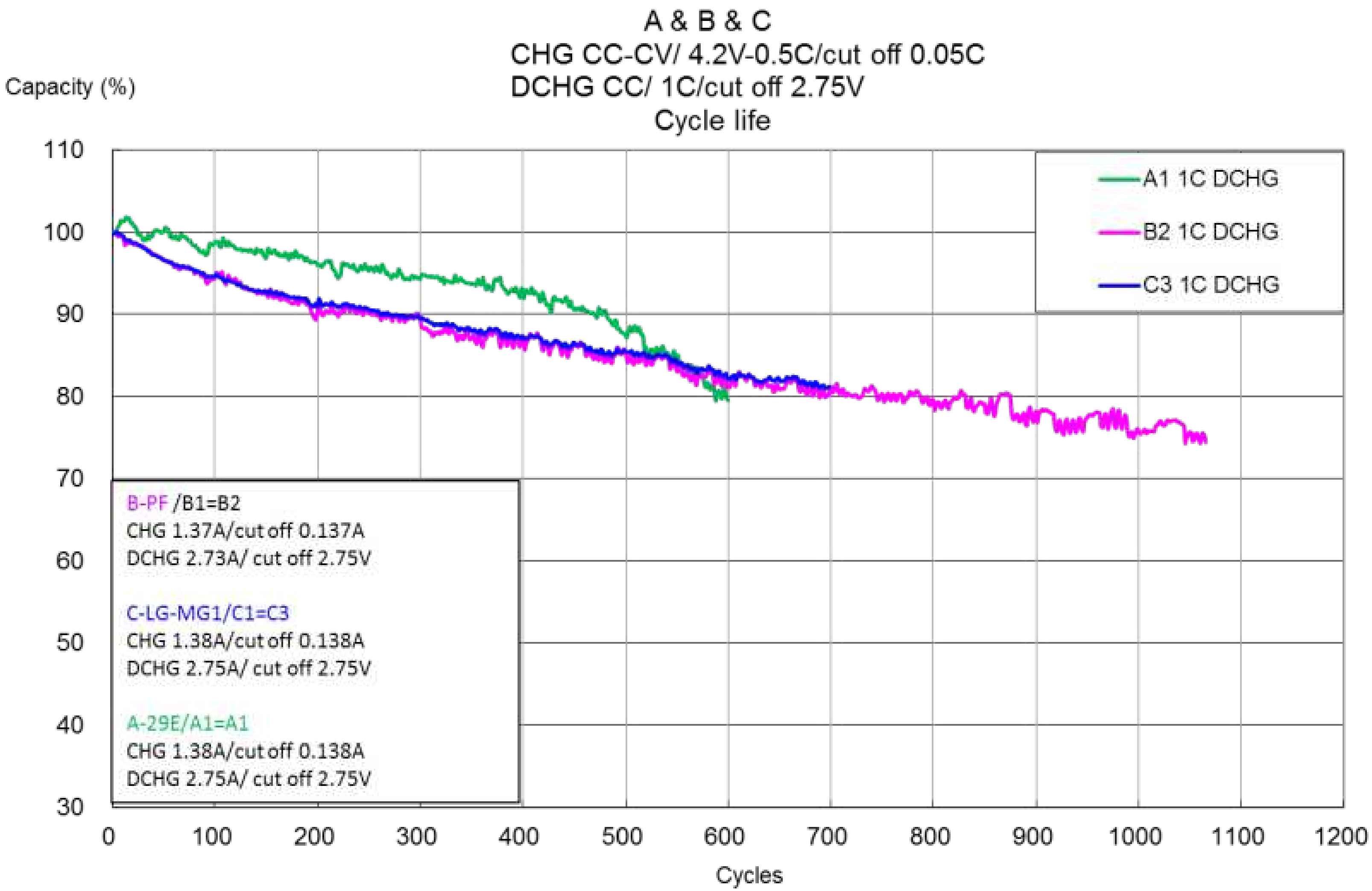
Symbol	PTC/Ni Ring	Length of Electrode	Thickness of Electrode	Thickness of substrate	Sep.
		Cathode/Anode	Cathode/Anode	Cathode/Anode	
		mm	µm	µm	µm
A	Ni Tab	697/771	130/150	15/10	20
B	Ni Tab	670/745	130/150	15/10	10
C	Ni Tab	630/705	160/160	15/10	20

C-rate Test for the Cells



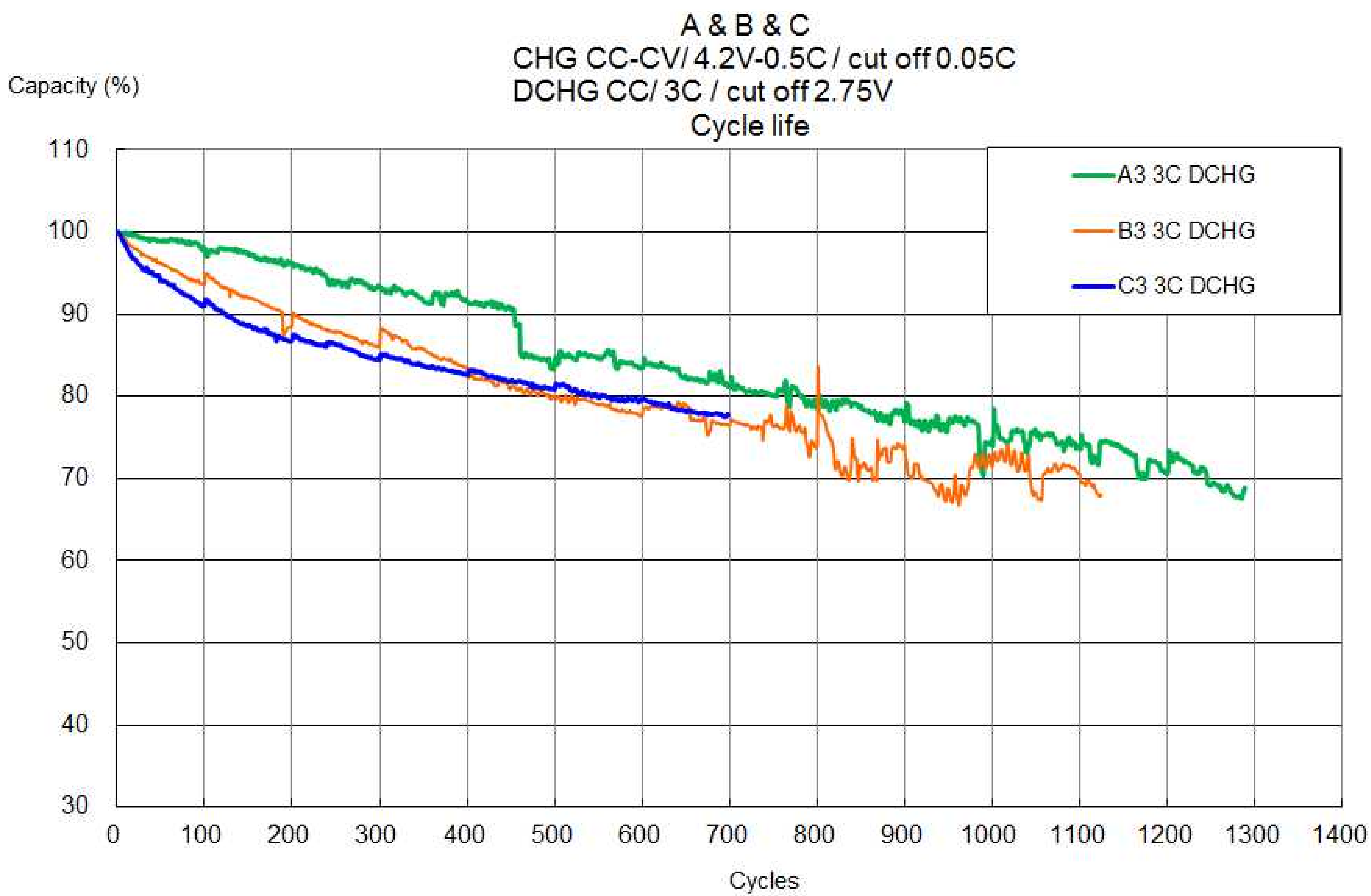
CHG :0.5C to 4.2V,cut-off 0.05C
DCHG:1C/2C/3C cut-off 2.75V

Cycle Life for the cells-1C

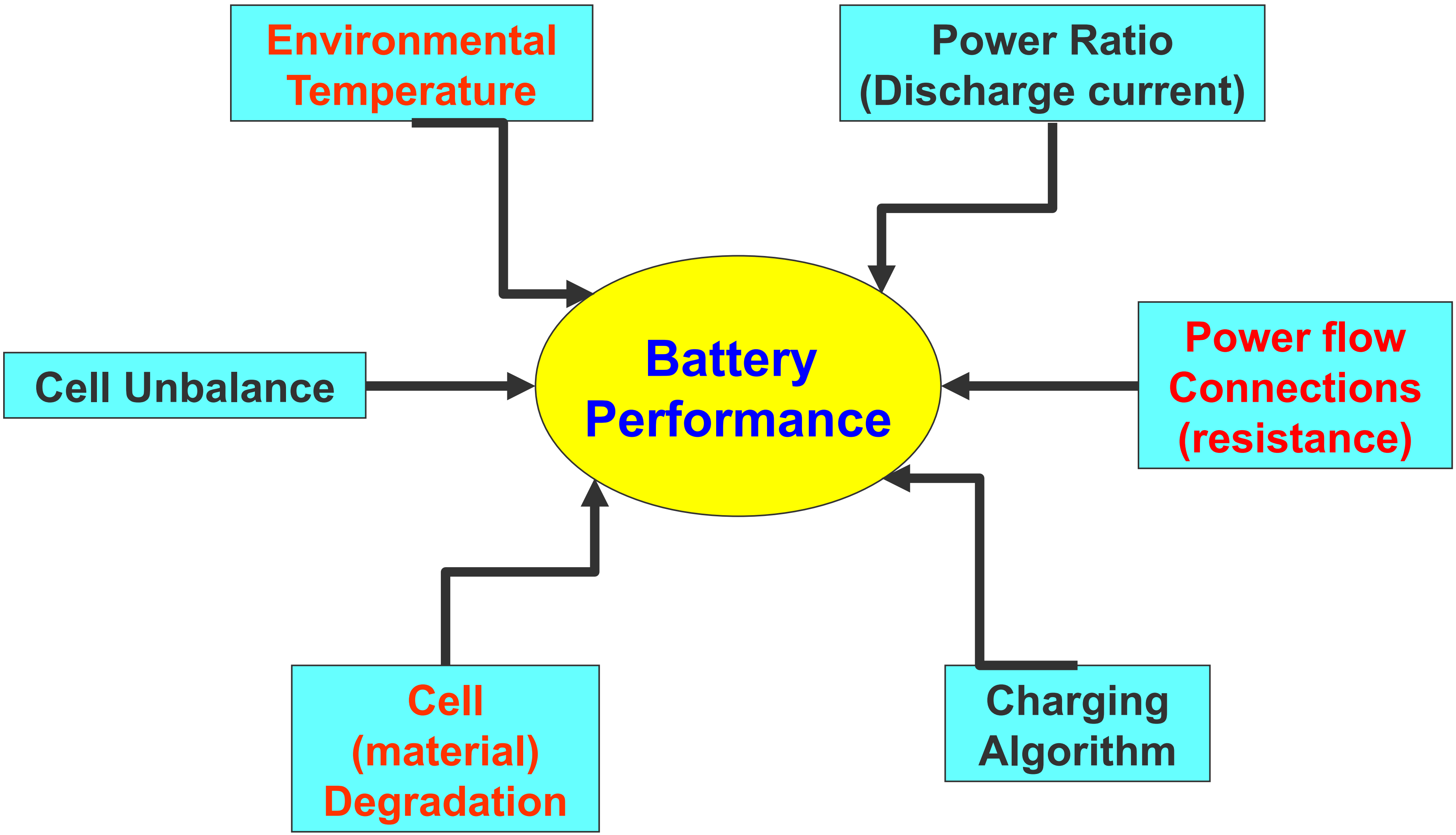


Cycle Life for the cells-3C

HITECH ENERGY



Factors Influent to Battery Performance



Battery Module Technologies

HITECH ENERGY

Cell selection
- cell chemistry
- cell design
- cell characterization
- cell sorting & grouping

Cell balance

Protection
- cell condition monitoring (T,V,C)
- cell control of operation conditions
- circuit design
- mechanical design (vibration, impact…)

安全 Safety
可靠 Reliability
效率 Efficiency
智能 Intelligent

Diagnosis
- monitoring & alarm
- recording

Thermal management
- cell layout (mechanical design)
- cooling design

Status Indication
- SOC & SCH
  …imations

Charger
- precise current and voltage control
- multi-mode charging control

Communication protocol
- Data and energy control interface

Products – costumized solution

HITECH ENERGY

Grace One - 44V

MIFA DAS FAHRRAD GRACE

8.398,00 €

Key Successes Factors For LEV Market

- 技術 Technology
- 設計 Design
- 市場 Marketing
- 合作 Collaboratio














HITECH ENERGY

How to Accelerate LEV Market

Development

Verification & Validation

Cell

Module/Pack

EnergyBus

BATSO

LEV Manufacture

EnergyBus

BATSO

LEV Market

The Challenge of Li-ion Battery in LEV

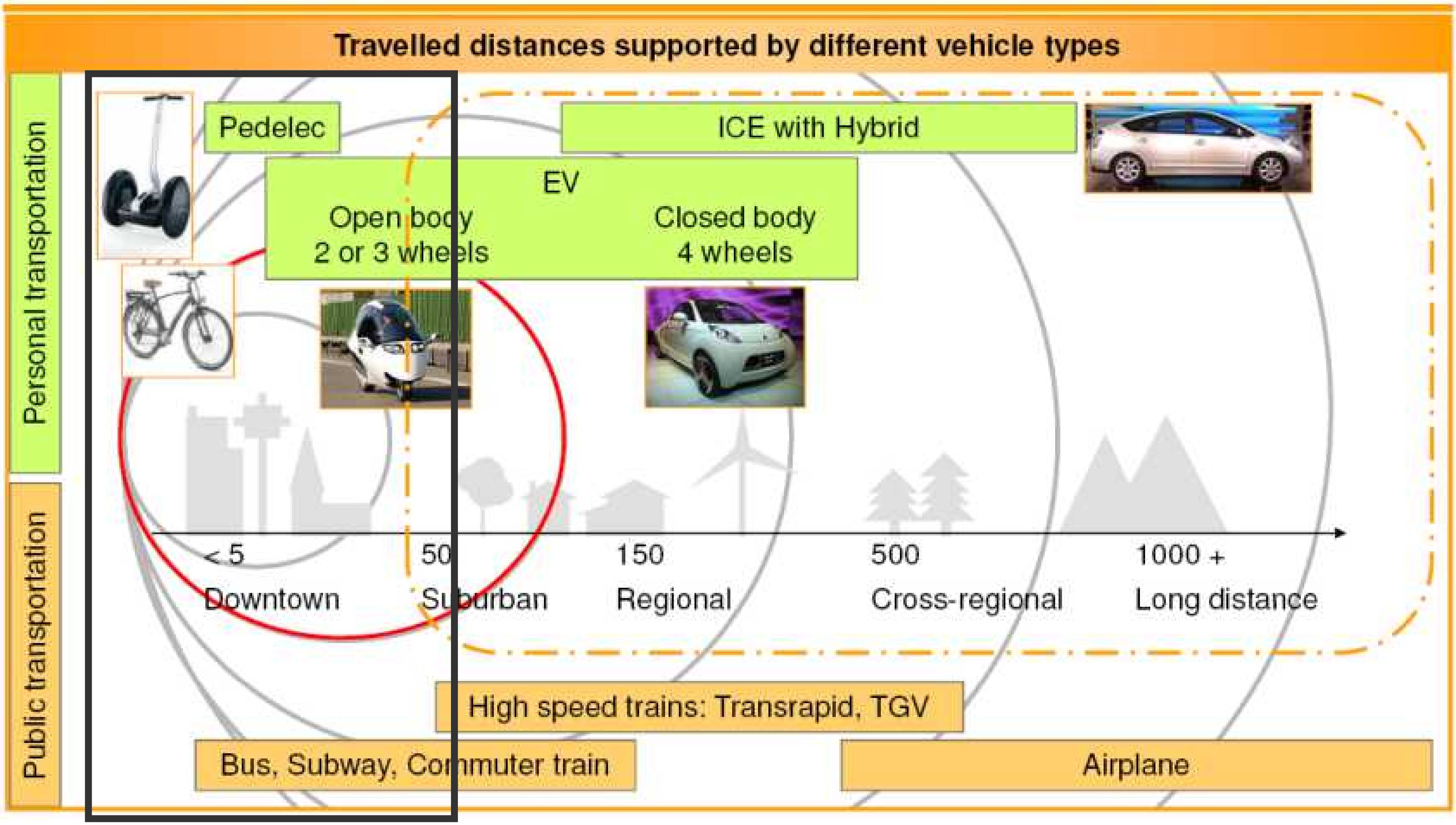
Technology Revolution

VS.

Verification & Validation Time

Why LEV

Driving Range & Convenience



Continental, 2010

Urban Mobility

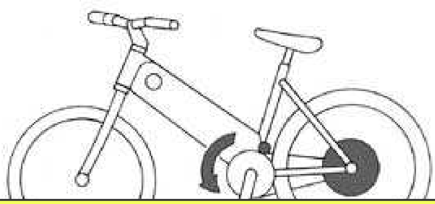
Personal Motilities

LEV Categories

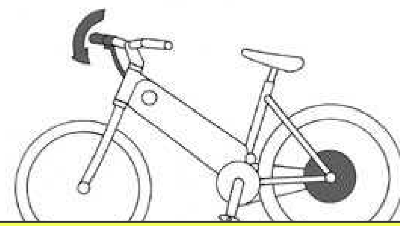
HITECH ENERGY

Personal mobility

Pedelec



E-Bike



E-Scooter

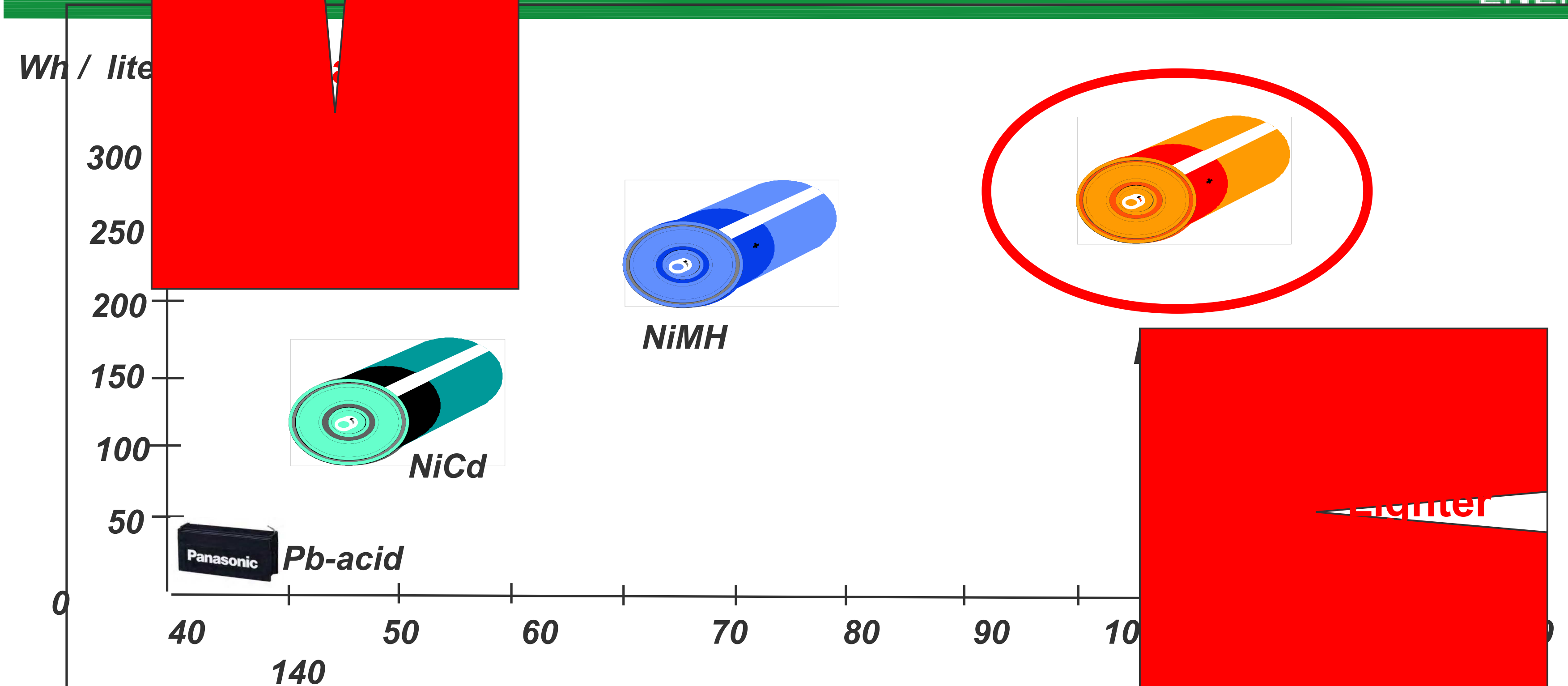
Power on demand

Rechargeable Battery

HITECH ENERGY

	Pb-acid	Ni-Cd	Ni-MH	Li-ion
Commercialization	1890	1956	1990	1991
Working voltage	2.0V	1.2V	1.2V	3.6V
Energy density	100 Wh/l 30Wh/kg	150 Wh/l 50Wh/kg	250 Wh/l 80Wh/kg	350-400 Wh/l 150Wh/kg
Cycle life	300	1000	500	500
Self-discharge	20%/month	20%/month	20%/month	5%/month
Memory effect	no	yes	partially	no
Price	<0.2 $/Wh	0.5 $/Wh	0.5-1 $/Wh	0.5-1 $/Wh
Green product	no	no	yes	yes

Ba y ergy Density

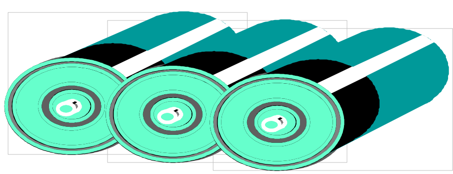


To get 3.6 v, we need , in one pack :

- 2 Pb-acid cell

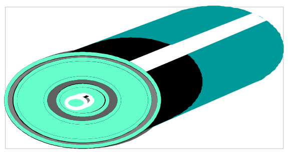
Pb-acid
4.0 volts

- 3 NiCd cells or
- 3 NiMH cells



NiCd or NiMH 3.6 volts

- 1 Li-ion cell



Li-ion 3.6 volts