



**SuperLIB – DELIVERABLE**

**Cell Specification with Cell Data**

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## DOCUMENT HISTORY

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0.2	12.3.2012	EB, suggested corrections
0.3	2.4.2012	EB, added chapters
0.4	9.4.2012	EB, final small editions

## TABLE OF CONTENT



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<b>1</b>	<b>Introduction</b>	<b>4</b>
1.1	Purpose and Scope of the Deliverable .....	5
<b>2</b>	<b>Comparison of different battery chemistries</b>	<b>6</b>
2.1	Why LFP? .....	9
2.2	Choice of cell materials and interaction with separator/electrolyte system .....	12
<b>3</b>	<b>Basic characterization of the EB HE cell</b>	<b>17</b>
3.1	Basic cycling data .....	17
3.2	Notes on charging at cold temperatures.....	20
3.3	C-rate performance.....	20
3.4	Calendar life of an EB 45 Ah HE cell .....	23
3.5	Cell resistivity .....	25
<b>Annex A</b>	<b>EB energy cell specifications</b>	<b>26</b>
<b>Annex B</b>	<b>Specifications for HE cells (fall 2011).</b>	<b>27</b>
<b>Annex C</b>	<b>Specifications for HE cells.</b>	<b>28</b>
<b>Annex D</b>	<b>Specifications for HP cells.</b>	<b>29</b>
<b>Annex E</b>	<b>Datasheet of EIG 14 Ah HP cell</b>	<b>30</b>
<b>Annex F</b>	<b>Datasheet of EIG 7 Ah HP cell</b>	<b>31</b>

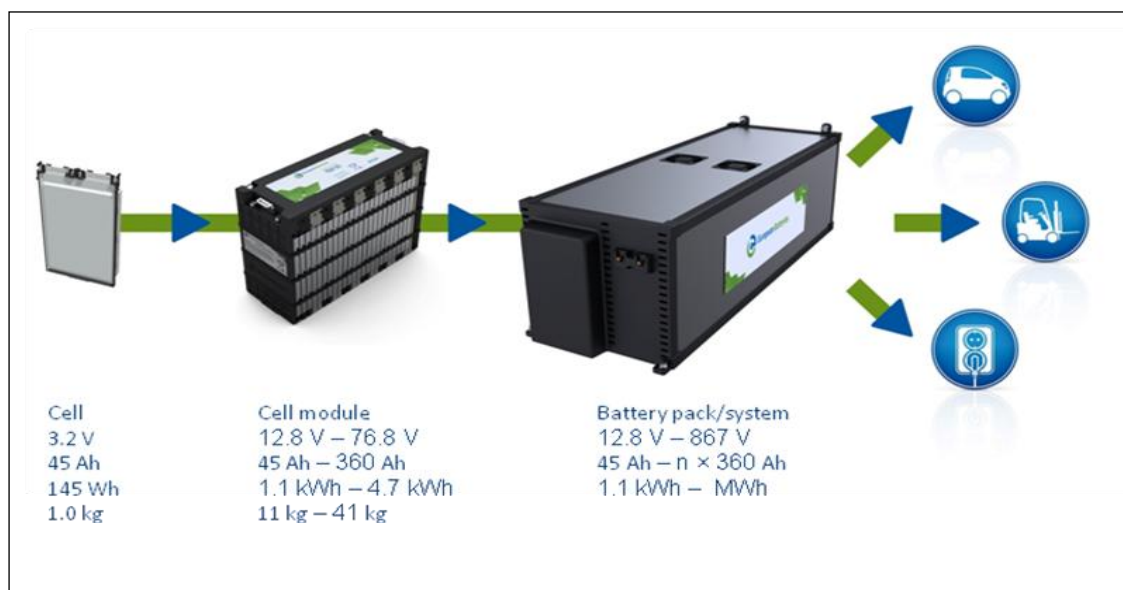
## Executive Summary

This deliverable D4.1 provides aid for system development by providing individual cell specifications and available cell data. Through the knowledge of the performance and operational conditions one can make intelligent estimates of the performance or the actual system. New data is continuously been produced and will be provided for the project.

Present day lithium ion batteries have limitations, but significant improvements have recently been achieved. The main challenges of lithium ion batteries are related to material deterioration, operating temperatures, energy and power output, and lifetime.

Increased lifetime combined with a higher recycling rate of battery materials is essential for the sustainable energy conversion industry. There are a number of options involving different chemical processes and battery types.

The chemistry used in this project is lithium iron phosphate, which has shown good thermal, cycle and storage life performances.



**Fig. 1** From individual cell into real applications. From left: rechargeable lithium-ion battery cell with a frame, a cell module, and battery pack/system. The module and system include a BMS and temperature control. The system also includes a liquid cooling/heating unit.

# 1 Introduction

The number of battery powered and fuel cell applications is expected to increase rapidly in next few years. Rechargeable batteries are extensively studied for their use as stationary power sources, in electric vehicles (EVs), hybrid electric vehicles (HEVs), marine applications, and in industrial vehicles. The energy capacity required for global electrification of vehicles is large and one has to be reminded that in terms of car production, the energy required to make batteries for 3000 electric cars is about 100 MWh. Consequently, for an annual production of a million cars requires 100 lithium ion battery factories each with a capacity of 300 MWh.

Battery applications include mature technology related to nickel-metal hydride batteries (NiMH) and lead acid batteries as well as the new lithium ion batteries. The manufacturing capacity of the latter is expanding to meet the increasing demand. Many plants are already in place for mass production of several lithium ion technologies. Production of lithium iron phosphate (LFP) is rapidly growing and this type of battery will be a strong contender when it comes to choosing a large battery meeting increased safety requirements. In early growth stage is also lithium titanate (LTO) that is used as anode material. In mass production stage are lithium cobalt oxide (LCO), lithium nickel cobalt manganese oxide (NCM), and lithium nickel manganese aluminum oxide (NCA).

## Advantages of lithium iron phosphate cells (LFP)

- Safety
  - No free oxygen in the cells, no thermal runaway
  - Increased safety offers cost advantages from perspective of vehicle's total cost
- High energy density
  - More energy in same volume and weight
  - Lighter and smaller systems
- Cost efficient active materials
  - Cost competitive compared to other Li-ion chemistries
- Long life
  - Cycle life estimated at approx. 3,000 cycles
  - 5-10 times more than lead-acid and NiMH
  - Longer than other Li-ion chemistries
- Environmental safety
  - Environmental impact minimized
  - Recyclable

*"LFP is the most promising chemistry due to advantages in cost, safety and cycle life."*



Source: Rocky Mountain Institute analysis, K2, Merrill Lynch analysis, Company

Fig. 2 Some advantages of lithium iron phosphate

### 1.1 Purpose and Scope of the Deliverable

The documents show the usable operational range of the European Batteries (EB) High Energy (HE) cells. The high energy cells have been in production at EB since 2010. All cell performance data shown in this document have been measured at EB Varkaus factory or at Aalto University (i.e. former Helsinki University of Technology).

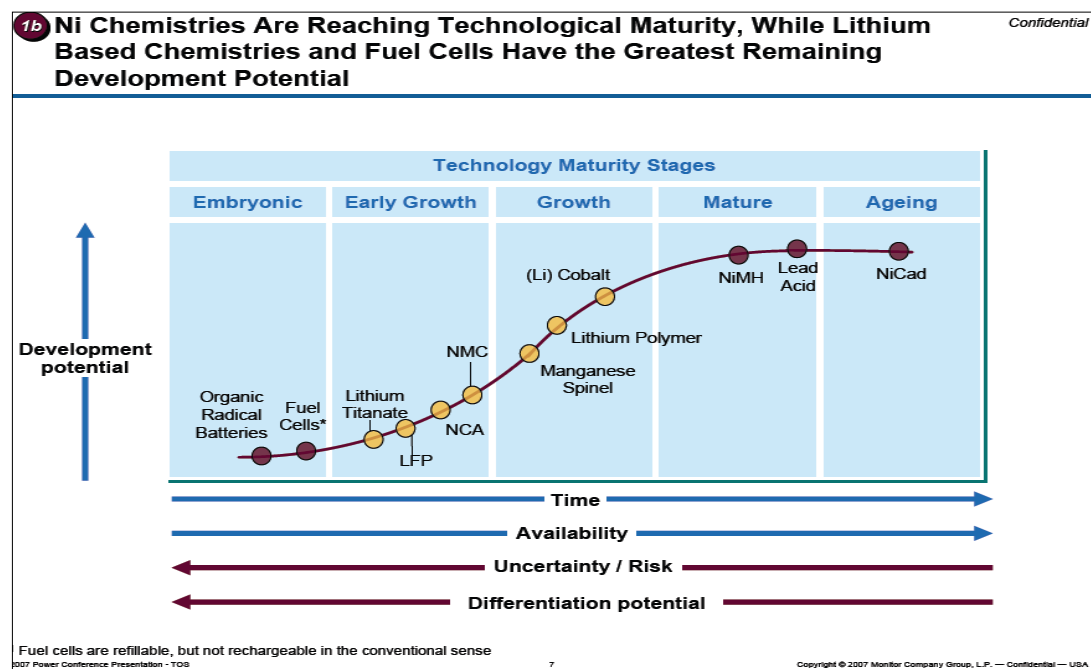
For high power (HP) cells only the specification is available at the moment. Cell specifications are prepared in co-operation with WP1 in deliverable 1.2.

Due to the delay in HP cell development and tight schedule in other WPs the project has decided to investigate EIG HP cells (14 Ah or 7 Ah) for their use in calibration experiments for WP5, see annex E. EB will provide HP cells based on the specifications shown in this document with cell data.

## 2 Comparison of different battery chemistries

Batteries are devices that convert stored chemical energy into electricity within a closed system. Electrochemical conversion occurs at two electrodes, cathode (positive electrode) and anode (negative electrode). The nature of the reaction is dependent on the chemistry of the electrodes. Positive electrode is usually lithium metal oxide or metal phosphate and anode is usually carbon based or rarely lithium titanate. The power of the battery is more determined directly by the surface area of the electrodes in contact with the electrolyte while the energy content depends more on mass and volume of the active material. In a rechargeable battery (secondary battery), if the external load is replaced with power supply the direction of electrons (and lithium ions) are reversed, and the battery is charged. Lithium ions ( $\text{Li}^+$ ) move from anode to cathode (in discharging) and in reverse direction in charging. Electrons move in the external circuit into the same direction as  $\text{Li}^+$ -ions. Anode (negative electrode) is usually graphite or rarely lithium titanate. Cathode (positive electrode) is typically lithium metal oxide or metal phosphate.

Figure 3 shows the development potential of different batteries at 2008. At early growth stage still include lithium titanate (LTO). Lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), lithium nickel manganese aluminum oxide (NCA) are in rapid growth stage at the moment.



**Fig. 3 Development potential of different batteries.** In early growth stage are interesting lithium materials like lithium titanate (LTO), lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), lithium nickel manganese aluminum oxide (NCA). Source Monitor Consulting, 2008.

## COMPARISON OF DIFFERENT BATTERY CHEMISTRIES

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Lead acid, nickel-metal hydride and lithium ion batteries are the most common rechargeable batteries. Lead acid battery technology is well proven and is more than a century old. However lead acid battery shows low gravimetric and volumetric energy density.

Nickel-metal hydride batteries (NiMH) provide reliable cyclability and are commonly used in hybrid vehicles. Their downside is relatively low energy density and low cycle life and relatively high self discharge rate up to 10% / month. They also consume rare earth metals which production may become a limiting factor in the future. That makes lithium ion systems an attractive alternative. Figure 2 shows crudely volumetric and gravimetric energy densities of some common batteries.

Lithium ion cells provide a cell configuration that operates at over twice the potential of lead acid or NiMH cells. The reactivity of lithium has been problematic and the low cycle life has been a problem especially under high current densities. However, modern lithium based electrodes provide much better power density and cycle life, and chemical stability and as a result lithium ion cells are being considered for use in larger applications like vehicles.

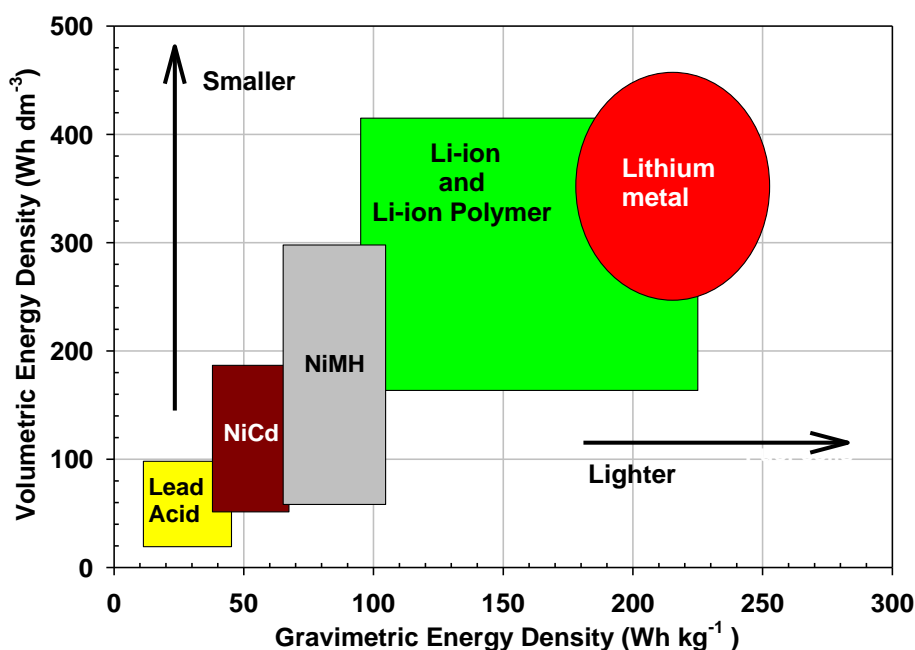


Fig. 4 Volumetric and gravimetric energy densities of common batteries.

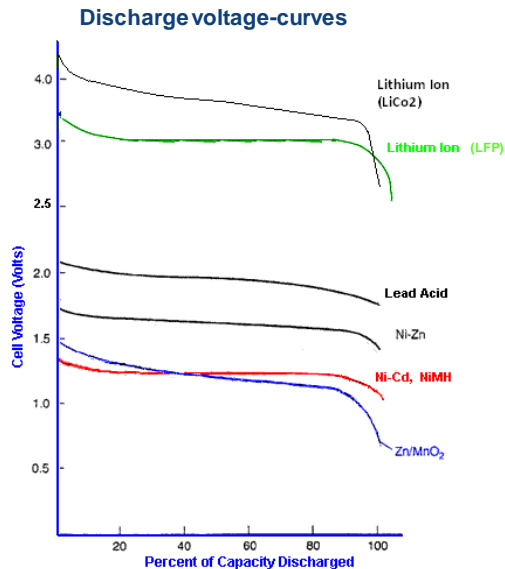


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### Discharge curve shapes of different battery chemistries



Higher cell-voltage in lithium-ion increases the energy density.

Low cell voltage in (1.2V) in NiMH requires many cells to build up a high-voltage system,

In lead-acid, the voltage drops linearly, when the cell is discharged. To keep the average power constant, the current must be increased.

NiMH and lithium-ion (LFP) have nearly constant voltage, which does not depend on state of charge.

Fig. 5 Discharge curves for some common battery types.

Battery electrodes provide electron conductivity outside, they store chemical energy, and generate electrical energy by releasing of stored energy.

All these functions should be completed isothermally, and with as little mechanical or chemical strain as possible. New novel lithium cathode materials are continuously developed in universities and company research laboratories to improve battery performance, lifetime, thermal tolerance, power performance, energy density and charge rate, as well as to obtain desired size, thickness, and flexibility.

Lithium cobalt oxide, LiCoO<sub>2</sub> is the oldest type of lithium-ion batteries. It has been produced since 1991 (Sony). Many other structures developed since which include LiCo<sub>1/3</sub>Ni<sub>1/3</sub>Mn<sub>1/3</sub>O<sub>2</sub> (NCM), LiMn<sub>2</sub>O<sub>4</sub> (LMO), LiNi<sub>0.8</sub>Co<sub>0.15</sub>Al<sub>0.05</sub>O<sub>2</sub> (NCA), and LiFePO<sub>4</sub> (LFP). Lithium cobalt oxide cells benefit from well established powder and cell production processes. 100's of millions cells are produced annually. Cobalt based cathodes are easier to produce than LFP-based cells. Currently there exist tens of manufacturers for different battery applications, variations, sizes and shapes. The move from small cell sizes to large-format cells has caused new issues to cell manufacturers. Novel materials like LFP have been introduced to increase the safety in large-format cells.

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Table 1. Properties of different lithium ion cathode materials.

Cathode	Formula	Type	Energy density Wh/kg	Energy density Wh/l	Relative cycle life	V
LCO	$\text{LiCoO}_2$	Energy/Power	170-185	450-500	1	3,65
NCM	$\text{LiCo}_{1/3}\text{Ni}_{1/3}\text{Mn}_{1/3}\text{O}_2$	Energy	155-185	330-365	3	3,7
NCA	$\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$	Energy/Power	145-165	270-350	3	3,65
LFP	$\text{LiFePO}_4$	Energy	100-140	200-330	>4	3,2
LMO	$\text{LiMn}_2\text{O}_4$	Energy/Power	90-120	260-300	1	3,8

The temperature range of operation for special purpose batteries or vehicle applications is from  $-40^\circ\text{C}$  to above hundred degrees. In practice current lithium-ion batteries operate within  $-20^\circ\text{C}$  to  $60^\circ\text{C}$ . Development is going on in order to improve the low temperature and high temperature performance, and lifetime at higher temperatures.

Low temperature performance is limited by temperature dependencies of electrochemical reactions, transport properties and phase changes of the electrolyte. Good ionic transport properties correspond to high conductivity, low viscosity, and sufficiently high diffusion coefficient of  $\text{Li}^+$  while charging and discharging the battery.

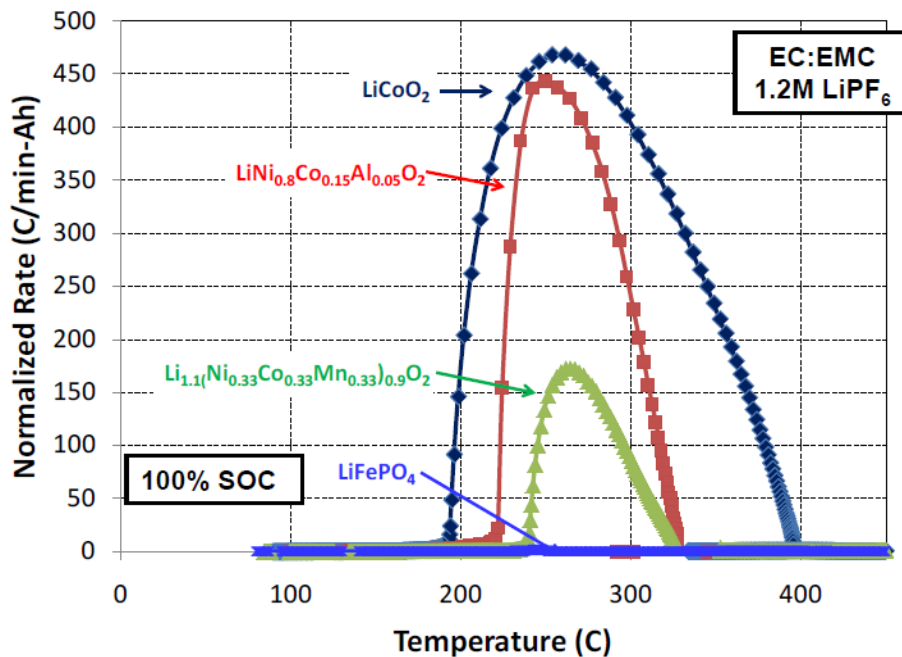
### 2.1 Why LFP?

The most recent lithium-ion cathode material: discovered 1995 and development to commercial products started in 1997.  $\text{LiFePO}_4$  (LFP) is considered the most promising lithium-ion technology for large-format batteries due its long cycle life and safety. The LFP material has passed the pilot phase and powder production is ramping into mass production. During 2011 new LFP production licences were distributed around the world making it easier for the manufacturer in the long run. Safe materials supply is a key element in manufacturing business. The production of high quality LFP-powder is difficult. The advantages of  $\text{LiFePO}_4$  (LFP) are summarized shortly. LFP shows reasonable good cell voltage 3.2 V depending on the active materials. LFP also shows extremely good safety features.

EB chose LFP chemistry due to safety reasons. The graphite anode was chosen because it is proven material, has high energy capacity, and is a mass product.

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**Fig. 6 Thermal stabilities of different lithium cathode materials. Lithium iron phosphate shows the best thermal stability.** Source: G. Nagasubramanian, C. Orendorff and D. Ingersoll, SANDIA National Laboratories, Safety Related Material Issues for Batteries, New Industrial Chemistry and Engineering Workshop on Materials For Large-Scale Energy Storage, September 16-17, 2010, Gaithersburg, MD.

LiFePO<sub>4</sub> powder is non toxic, shows no thermal runaway, and is chemically stable. It shows long cycle (>3000 cycles) and long calendar life (+5 years), and reasonably large energy density, 110-150 Wh/kg, 1/4 weight and 1/3 size of lead acid batteries. The self-discharge rate of LFP battery is extremely small and it can be stored fully charged or partially charged, unlike a lead acid battery. Figure 4 shows the typical flat discharge curve for LiFePO<sub>4</sub> chemistry. From the figure one can see that the voltage remains almost stable and independent of discharge over wide capacity % (SOC) range. Overcharging of the cell does not cause major problems below 4.5 V.

Figure 7 shows discharge curves of 42 Ah capacity battery (source EB) based on LFP chemistry. Lithium iron-phosphate (LFP) cell has a very stable discharge voltage. The only drawback of a stable voltage behavior, like in figure 7, is estimation of state of charge, SOC. Due to a nearly constant voltage from 5% to 90% state of charge, estimation of SOC is usually based on coulomb counting (integration of current).

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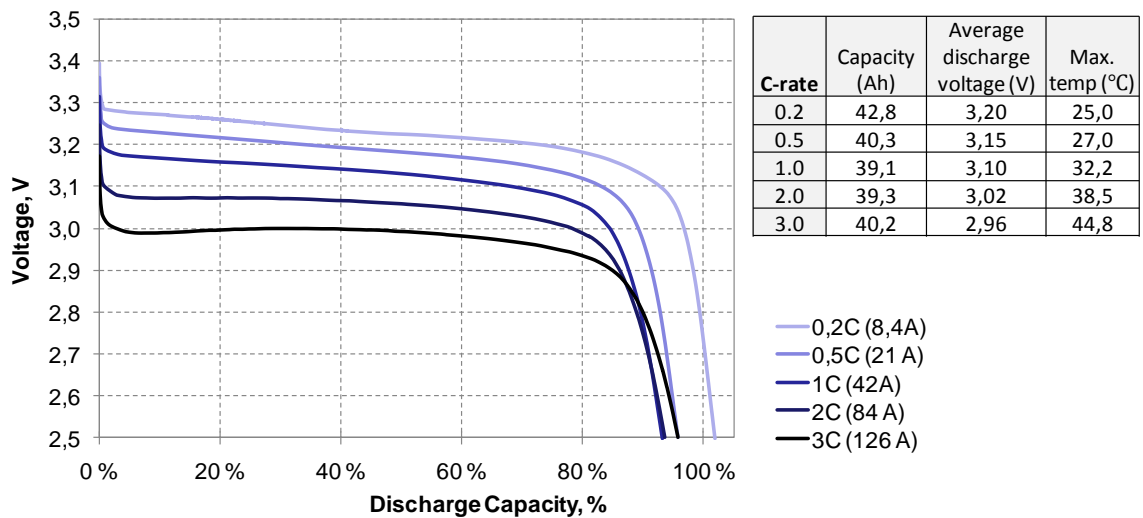


Fig 7. Voltage curves at different discharge rates for 42 Ah capacity LFP battery cell. Measurements were carried out at room temperature. Source: EB.

The safety of the LFP chemistry and EB45Ah cell is highlighted as follows. The figures show the effect of 9.1 kg load drop. Also hard short – nail penetration is shown. It may cause minor smoking but no propagation. In the case of overheating LFP does not react prior pressure/electrolyte release in a pouch cell which minimizes the thermal runaway that is more likely with energetic cobalt based oxide materials. In the nail test 6 zinc plated iron nails were hit through the cell. The cell remained stable overnight and no smoke was detected. Small temperature increase was noticed but dissipated quickly after each nail.

### Cell Abuse Tests

#### Abuse tests (UN approval)

##### European Batteries cell after 9,1 kg load drop onto the cell.

- NO thermal runaway
- NO short circuit
- NO leaks of electrolyte
- Normal cell voltage after the test



##### Some other passed tests:

- Thermal test (from -40 °C to 75 °C)
- Altitude simulation
- External short
- Overcharge
- Forced discharge



Fig 8. Safety points of the LFP chemistry and EB45Ah cell.

In another example of a misused cell is shown in figure 9. The cover bag was shredded badly exposing the cell into open air and moisture. The chemical reactions at the surface dissipated quickly. The cell remained stable under air for few days until it was studied and disposed.



Fig 9. Badly mistreated cell was stable under air.

## 2.2 Choice of cell materials and interaction with separator/electrolyte system

The choice of the cell materials and structure is looked at in this chapter. Specific electrode, coating, or separator thicknesses and recipes of the EB45Ah production cell or prototype cell cannot be disclosed.

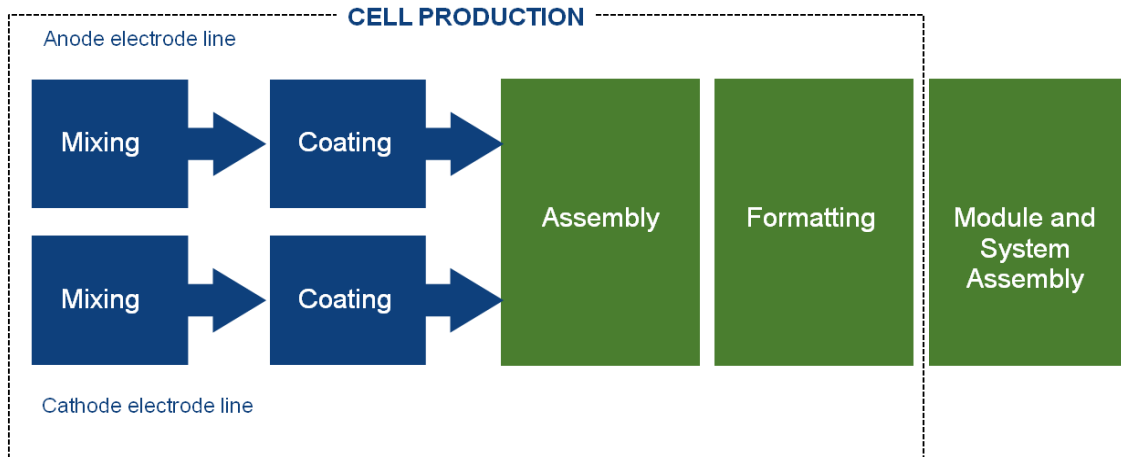
The battery consists of cathode, separator, anode, electrolyte, and surrounding and insulating pouch. The whole system must tolerate chemically, electrochemically and mechanically the specified uses. These include different voltages, charging - discharging, temperatures, vibrations, altitudes, mechanical strain, corrosion etc.

Also all parts of the cell must be able to be produced or assembled industrially. Mechanical properties of the copper foil and aluminium foil are crucial in coating, calendaring, slitting, shaping, drying, as well as in cell assembly. Same applies for the separator in the cell assembly; it must work without tearing, wrinkling, or shrinking during automated process. All components and chemicals must be available in large quantities. All materials that are in laboratory or pilot stage production cannot be an option for a battery manufacturer.

After the cell are assembled and the electrolyte is in both chemical and electrochemical reactions start to play role. The both electrodes must be stable with the electrolyte solution during storage at constant voltage and when current is passed. If the cell voltage increases too high the organic components oxidizes forming gaseous products destroying the vacuum of the cell. Generally below 4.5 V is safe limit for typical solvents like for organic carbonates.

Figure 10 shows roughly the manufacturing steps and figure 11 one of the coating lines.

## Production Process – Cell Production



**Fig 10. Manufacturing steps of LFP cells.**



**Fig 11. Overview of one of the electrode coating lines in European Batteries plant at Varkaus, Finland. The annual capacity of the plant is 100 MWh.**

The components of the cell and their role in the system are discussed briefly as follows. Accurate production electrode dimensions or recipes are not disclosed but the direction of the change in each component from high energy cell to high power cell is explained. Figures 13a-b shows typical materials used in a lithium ion battery. The main components of battery are:

Negative electrode (anode): graphite,  $\text{LiC}_6$ .

Positive electrode (cathode): lithium iron phosphate,  $\text{LiFePO}_4$ .

Electrolyte (liquid): organic carbonates mixed with lithium salt.



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Fig. 12 Prismatic cell.

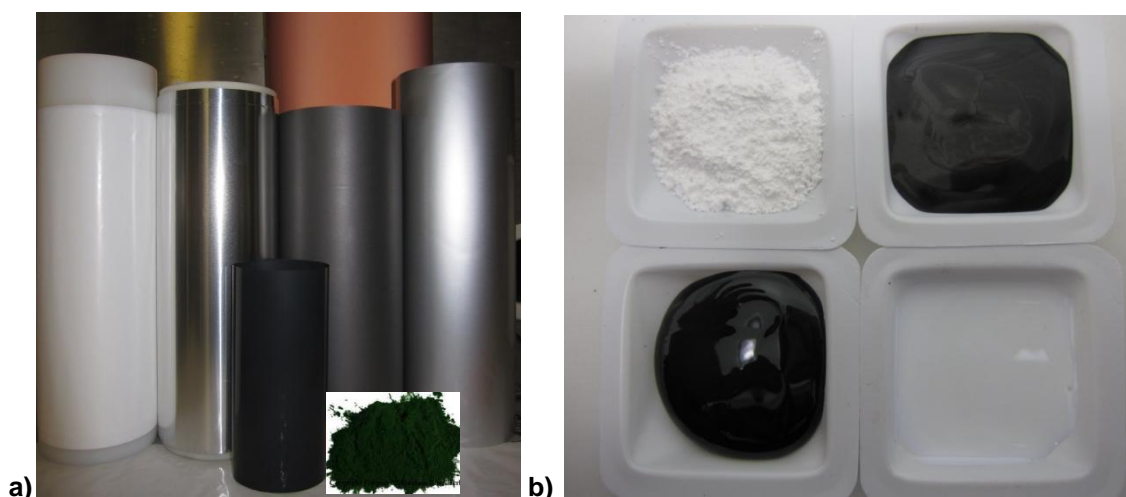


Fig. 13a Typical materials used in a lithium ion battery (prismatic cell, i.e. pouch type cell). From left: separator polymer film, aluminium foil, lithium cathode paste coated on aluminium foil, graphite paste coated on copper foil, cover bag material. At the front, LFP powder, at the back roll of copper foil.

Fig. 13b Slurries and binders. Upper right, carbon slurry and lower left, lithium iron phosphate slurry. Up left, shows typical binders PvDF powder and downright the styrene butadiene rubber solution (SBR).

### Cathode

Cathode is LFP coated aluminium. Aluminium foil has typical thicknesses of 15-30  $\mu\text{m}$ . It is important that it is mechanically durable throughout the production. The thicknesses of the cathode electrode typically vary within 100-200  $\mu\text{m}$ .

Relative change from HE cells: Aluminum foil thickness has minor importance in cell resistivity. More important is to have the foil thickness that is mechanically strong enough for processing mentioned above. No change necessary.

## COMPARISON OF DIFFERENT BATTERY CHEMISTRIES



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By reducing the thickness and the coat weight of the LFP one consequently reduces the electrode resistivity. Compared to HE cells the electrode thickness of a HP cell is over 30-40 % less. The particle size and shape vary from energy type cell to power type. Coating thickness/electrode will be thinner for HP cells.

### Anode

Anode is carbon coated copper foil. Typical copper foil thicknesses used are 6-20  $\mu\text{m}$ . Carbon can be in different forms and shapes including, graphite, natural carbon or artificial carbon. It is also important that the anode is mechanically durable throughout the production and its use. The thicknesses of the anode electrode typically vary within 100-200  $\mu\text{m}$ .

Relative change from HE cells: Copper foil thickness has minor importance in cell resistivity. More important is to have copper foil thickness that is mechanically strong enough for processing mentioned above. No change necessary.

Coating thickness has effect on the power performance of the cell. In high energy cell the coating weight and thickness is high. The cell can be charged with low or moderate rates. For example EB45Ah cells the recommended charging/discharge rate is max 3 C or 135 A. This can also be done only occasionally not continuously. Thick electrodes are meant for longer use with smaller current densities.

By reducing the thickness and the coating weight of the carbon one consequently reduce the electrode resistivity thus allowing higher rates both in charging and discharging. The particle size and shape vary from energy type cell to power type. Compared to HE cells the electrode thickness of a HP cell is over 30-40 % less.

### Separator

Typical separator materials are poly ethylene (PE), poly ethylene oxide (PEO), polypropylene (PP) or multilayer combinations of these. Also different kinds of ceramic separators or polymer separators coated with ceramic layers are studied intensively. Typical thickness varies within 15-25  $\mu\text{m}$ . Important parameters to look at are porosity, tensile strength, and shrinkage % at elevated temperatures. Also it is crucial that the separator is chemically stable and maintains the pore size and insulation during battery use. The separator is highly important for the safe operation of the battery. The pores of polymer separators will shrink or close in case of sudden temperature increase thus protecting the electrodes just a little bit longer. The separator will prevent shortage due to dendrites that forms during battery operation thus it must have no pin-holes.

Relative change from HE cells: Separator contributes on the bulk resistivity and going into thinner separator reduces the cell resistivity. That is a compromise between price, performance, mechanical and chemical durability.

### Cover bag

The covering bag pouch consists of different polymer layers. Its purpose is to be the mechanical, chemical, and electrical protection of the cell. The pouch consists of layers of nylon, aluminum foil, polymer films, and adhesives.



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Relative change from HE cells: The cell dimensions change and that has influence on the pouch dimensions mostly on the deepness of the forming parameters. The cold forming parameters can be adjusted to produce thinner cells suitable for HP application.

### Electrolyte

Electrolyte provides the media for the movement of lithium ions between the electrodes. The choice of the electrolyte is important and difficult because it has to be chemically and electrochemically stable with both cathode and anode.

The electrolyte has to be chemically inert within the reduction and oxidation potentials the cell is during charging and discharging. Within the usable range (2.0 - 3.65V) of LFP battery the electrolyte is stable. When going above 4.5 V the oxidation reactions of the electrolyte occurs. At the lower range (<1.5 V) electrolyte reduction reaction may occur and copper starts dissolving.

In commercial industrial application typically 2-5 organic solvents are mixed with lithium salt. Lithium salt composition is usually 0.5-2 mol/kg of solvent. Most common lithium salts include lithium hexafluorophosphate, lithium tetrafluoroborate, and lithium bistrifluoromethylsulfonimide. Organic solvents are usually different mixtures carbonates like ethylene carbonate (EC,  $C_3H_4O_3$ ), ethylmethyl carbonate (EMC,  $C_4H_8O_3$ ), diethyl carbonate (DEC,  $C_5H_{10}O_3$ ), and dimethyl carbonate (DMC,  $C_3H_6O_3$ ). In addition small quantities of additives are used for specific function like increased thermal tolerance, cold temperature durability, moisture capture, and protective layer creation.

Relative change from HE cells: The composition of the electrolyte can be different between HE and HP cells. The choice of an electrolyte depends hugely on the usage and on the chemistry of the cell.

### 3 Basic characterization of the EB HE cell

The data sheet of EB HE cell is shown in Annex A. It is also known as production 1.3 cell. The cell specification used in WP1 is in most parts based on that. The specification sheet, also used in WP1 is shown in Annex B.

#### 3.1 Basic cycling data

EB energy cells have characteristic activation, which means that the capacity of the cell increases in the first 50-200 cycles up to 45 Ah capacity at 25°C (0.2C rate is used). The activation effect is not shown in most lithium iron phosphate based lithium ion cells.

The initial cycle can easily yield a 37 Ah discharge capacity using 1C/1C charging. But the capacity will increase for the first 50-200 repeated cycles and then begin to decrease almost linearly (see figures 14 and 15).

EB typically uses smaller rates for determining the capacity (0.2C). The activation effect of EB's LFP cell can be seen below in figures 14 and 15. This activation effect is typical for the LFP type used at EB.

Figure 14 shows cycling of a cell that is charged and discharged using 0,5C current rate around +24°C. Every 30<sup>th</sup> discharge is done at 0,2C shown as peaks in the graph. 0.2C is used as a reference measurement for cell capacity. The rest time after charging is 15 minutes and after discharging is 5 minutes.

Constant Current Charge 0,5C

- cut off voltage 3,65 V

Constant Voltage Charge 3,65 V

- cut off current 0.03C

Rest 15 min

Constant Current Discharge 0,5C

- cut off voltage 2,5 V

Rest 5 min

Every 30<sup>th</sup> discharge:

Constant Current Discharge 0,2C (the capacity measurement)

- cut off voltage 2,5 V

Rest 5 min

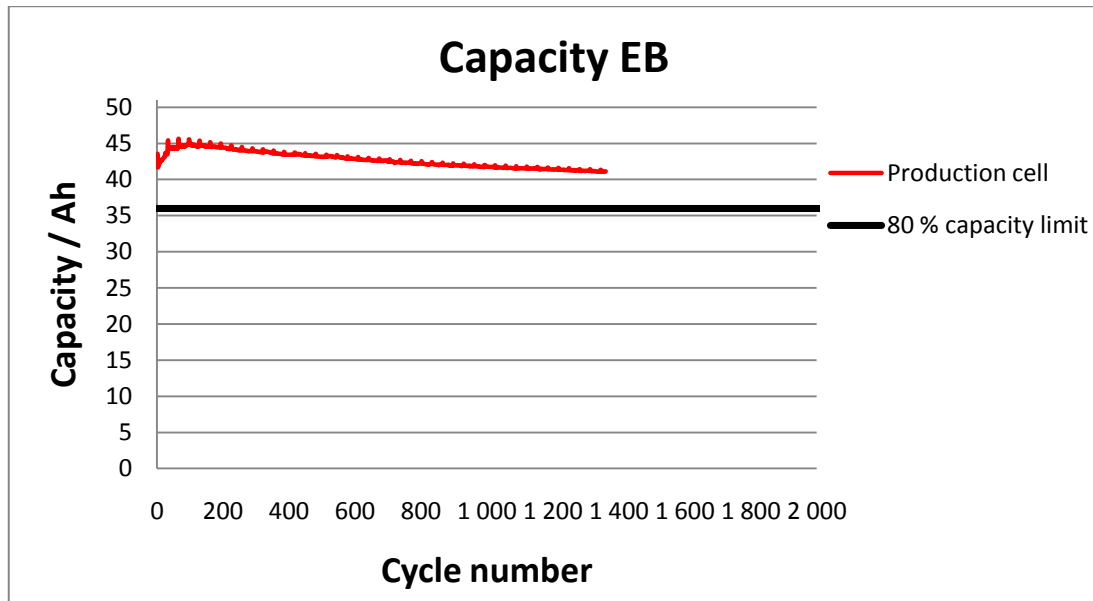


Fig. 14 Charging and discharging of an EB cell using 0,5C current rate around +24 Celsius. Every 30<sup>th</sup> discharge is done using 0,2C. These are shown as peaks in the graph. 0,2C is used as a reference measurement for cell capacity. The activation of the cell is seen clearly at the beginning. After activation the capacity decreases almost linearly.

Figure 15 shows cycling of a cell that is charged at 0.5C and discharged using 1C current rate at +22°C. Every 50<sup>th</sup> discharge is done at 0,2C shown as peaks in the graph. 0,2C is used as a reference measurement for cell capacity. The rest time after charging is 15 minutes and after discharging is 5 minutes.

Constant Current Charge 0,5C

- cut off voltage 3,65 V

Constant Voltage Charge 3,65 V

- cut off current 0.03C

Rest 15 min

Constant Current Discharge 1C

- cut off voltage 2,5 V

Rest 5 min

Every 50<sup>th</sup> discharge:

Constant Current Discharge 0,2C (the capacity measurement)

- cut off voltage 2,5 V

Rest 5 min

## BASIC CHARACTERIZATION OF THE EB HE CELL



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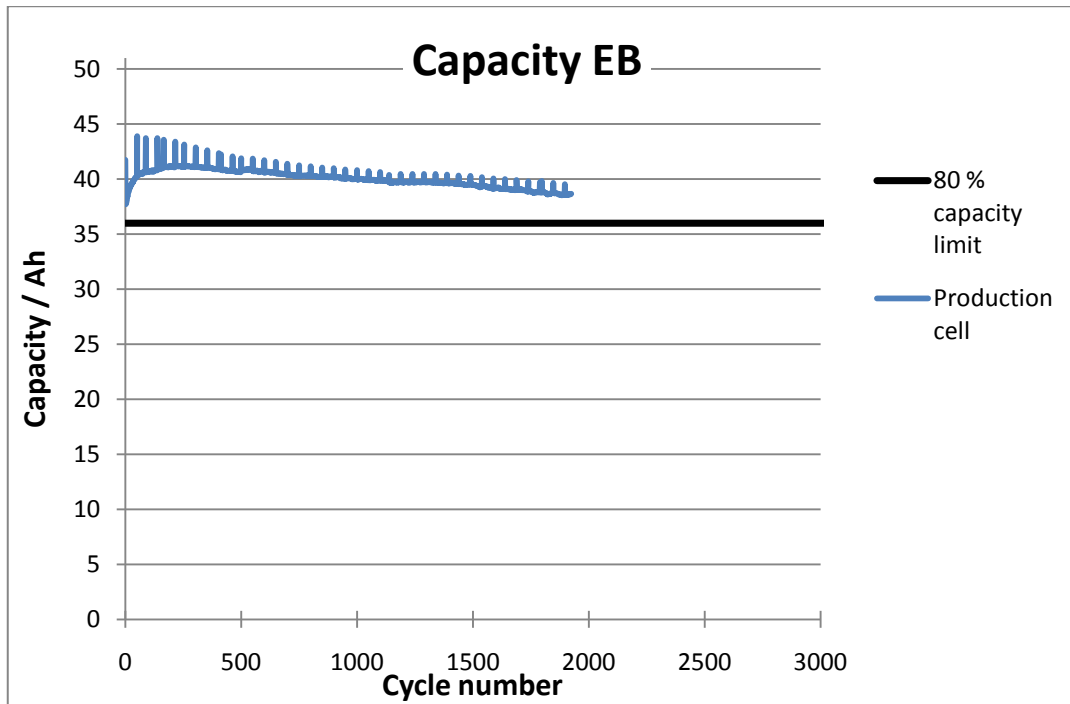


Fig. 15 Charging 0.5C and discharging using 1C of an EB cell around +22°C. Every 50<sup>th</sup> discharge is done using 0.2C. These are shown as peaks in the graph. 0.2C is used as a reference measurement for cell capacity. The activation of the cell is seen clearly at the beginning. After activation the capacity decreases almost linearly. First 1C discharge yielded 38 Ah.

Figure 16 shows the difference between the first discharge when using 0.2C and when using 1C at 22°C. In both cases the charging rate was the same.

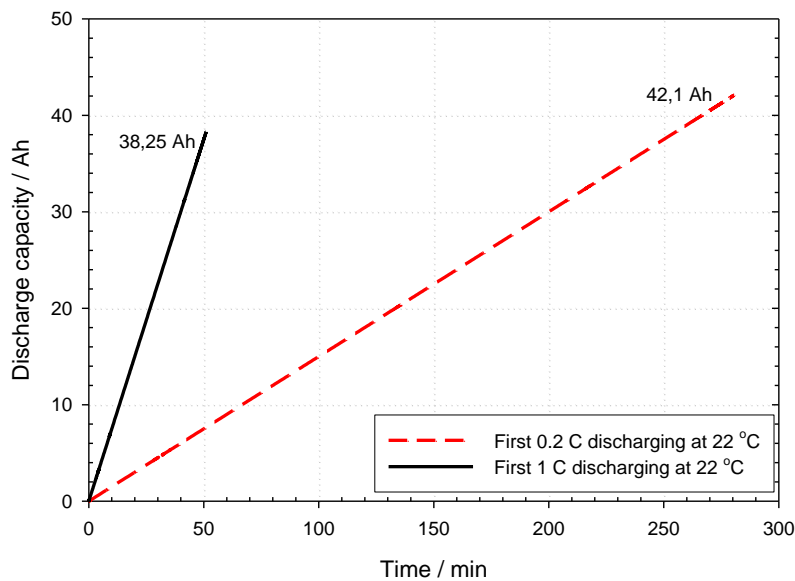


Fig. 16 Difference between first discharging using 0.2C or 1C at 22°C. In both cases the charging rate was the same. In repeated charging the cell capacity increases according to figures 3 and 4.

### 3.2 Notes on charging at cold temperatures

Charging at cold temperatures should be avoided due to the fact that the lithium diffusion and intercalation in carbon anode are limited. It is not recommended the charging of the battery when below 0°C. Only very small currents can be used without detrimental effects for the battery.

At -10°C the cell can be charged using 0.2C without significant capacity loss. In a module the cells are stacked together and during charging heat is transferred between cells aiding the temperature rise and transport of lithium ions.

So, it is recommended that the system is heated at least above 0°C prior to charging and use smaller rates at lower temperatures. For example 1C charging is recommended above room temperature in order to meet the lifetime expectations.

### 3.3 C-rate performance

Tables 2 and 3 show respectively the C-rate performance of an EB HE cell after discharging and charging. The cells were charged at 0.5C at room temperature (+23°C) before every discharge test, and discharged at 0.5C at room temperature (+23°C) before every charge test. The voltage limits were 2.50 V (discharge cut off) and 3.65 V (charge, cut-off at 0.03C). The voltage shown in the tables are average discharge voltages.

**Table 2. C-rate performance of an EB HE cell in discharge**

**T1.3 Discharge**

Temperature	0,2C			0,5C			1C			2C		
	Ah	Wh	V	Ah	Wh	V	Ah	Wh	V	Ah	Wh	V
-30 °C	19,92	54,0	2,714	18,16	47,7	2,627						
-20 °C	24,85	72,1	2,903	22,69	63,4	2,796	22,61	61,4	2,717			
-10 °C	30,31	92,0	3,036	27,52	80,8	2,936	26,99	77,0	2,854	28,87	79,3	2,748
0 °C	36,50	113,6	3,112	32,88	99,6	3,030	31,74	93,8	2,956	33,12	94,7	2,860
10 °C	41,48	131,3	3,165	38,32	118,9	3,102	36,65	111,2	3,032	36,89	108,4	2,938
20 °C	43,81	140,4	3,204	42,09	132,6	3,151	40,69	125,8	3,091	40,31	121,0	3,002
25 °C	44,39	142,8	3,217	43,27	137,2	3,172	42,21	131,5	3,115	41,63	126,1	3,029
30 °C	44,63	143,9	3,224	44,13	140,6	3,186	43,38	135,9	3,133	42,84	130,7	3,050
40 °C	44,97	145,5	3,235	45,01	144,2	3,205	44,74	141,4	3,160	44,33	136,7	3,083
50 °C	45,68	148,1	3,241	45,58	146,6	3,216	45,48	144,4	3,176	45,21	140,3	3,103
60 °C	46,05	149,4	3,245	45,95	148,0	3,220	45,88	146,0	3,182	45,64	141,8	3,108

## BASIC CHARACTERIZATION OF THE EB HE CELL



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Table 3. C-rate performance of an EB HE cell in charging

### T1.3 Charge

Temperature	0,2C			0,5C			1C		
	Ah	Wh	V	Ah	Wh	V	Ah	Wh	V
-10 °C	41,54	147,4	3,548						
0 °C	42,45	146,8	3,457						
10 °C	42,68	144,8	3,392	43,96	151,9	3,456			
20 °C	43,10	145,0	3,363	43,06	146,9	3,411			
25 °C	43,24	144,9	3,351	43,18	146,5	3,391	44,6	154,1	3,453
30 °C	44,16	147,5	3,340	44,11	149,0	3,377	44,1	151,1	3,424
40 °C	45,18	150,3	3,326	45,15	151,6	3,357	45,2	153,6	3,399
50 °C	45,75	151,9	3,320	45,72	153,1	3,348	45,7	155,0	3,388
60 °C	46,03	152,7	3,318	45,97	153,8	3,345	46,0	155,7	3,387

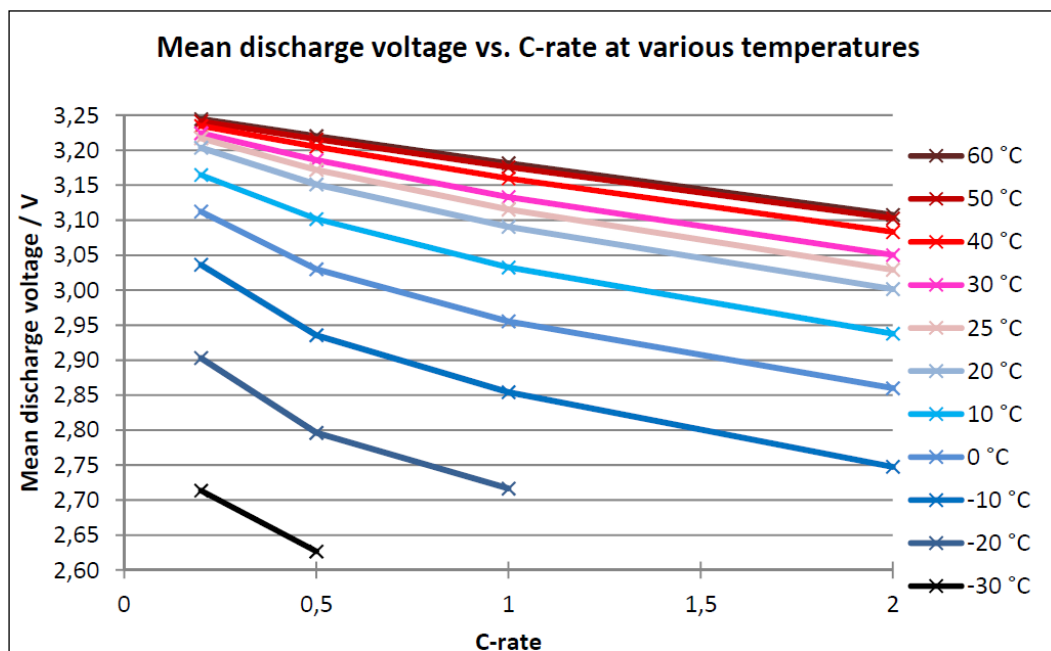


Fig. 17 Mean discharge voltage as a function of C-rate at different temperatures for an EB HE cell.

## BASIC CHARACTERIZATION OF THE EB HE CELL



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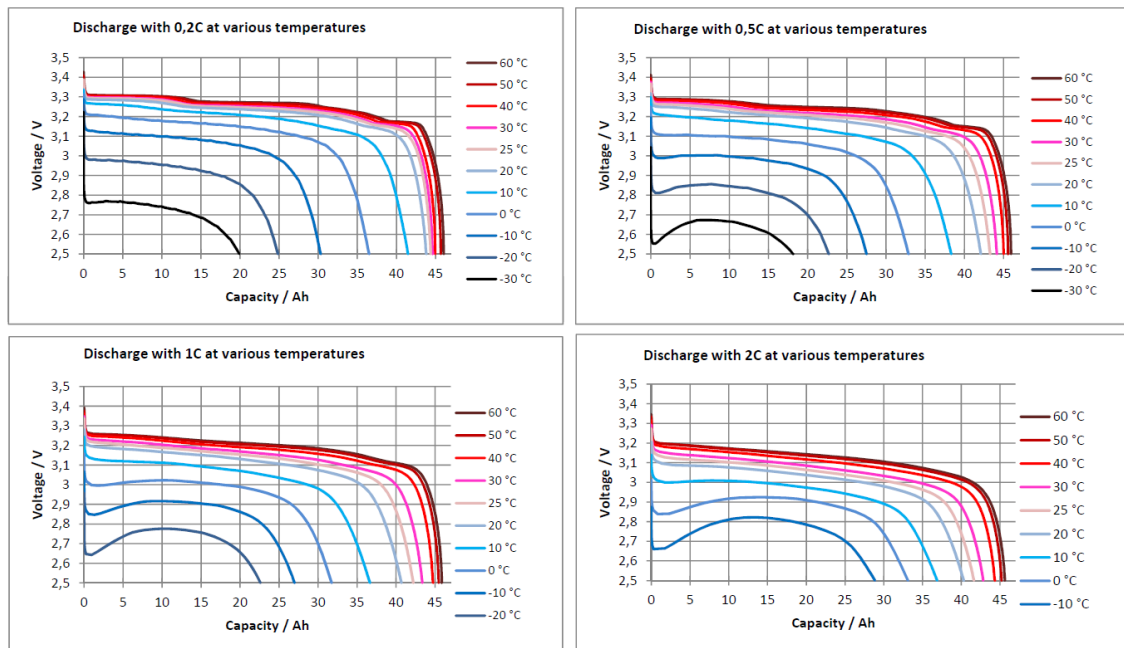


Fig. 18 Voltage capacity curves during discharging at different temperatures

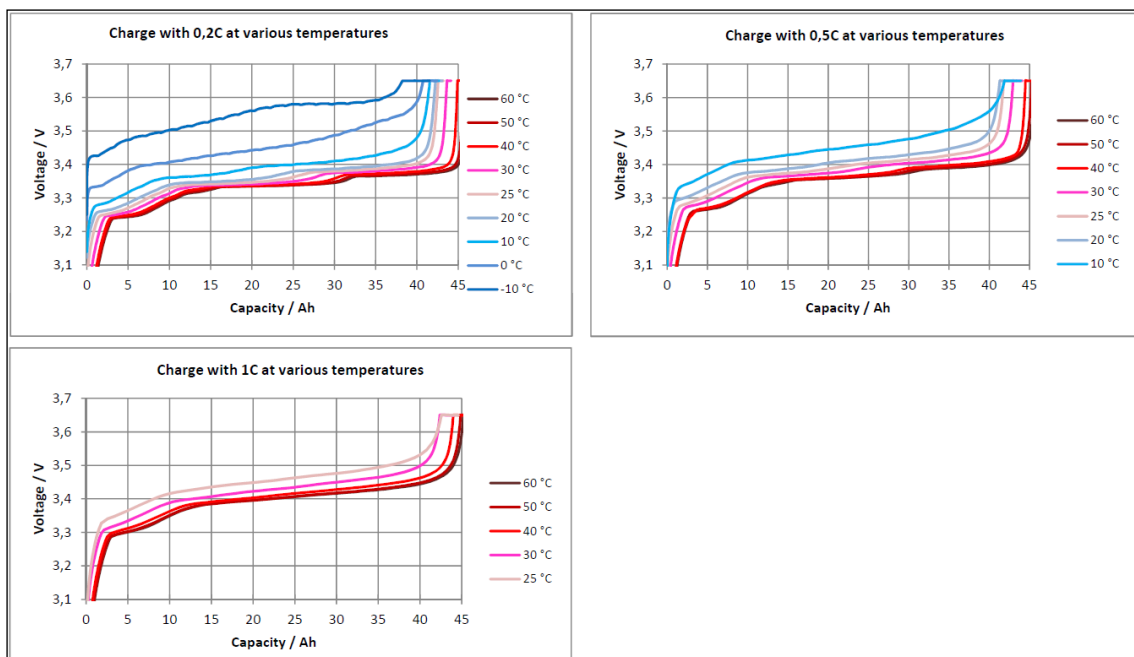
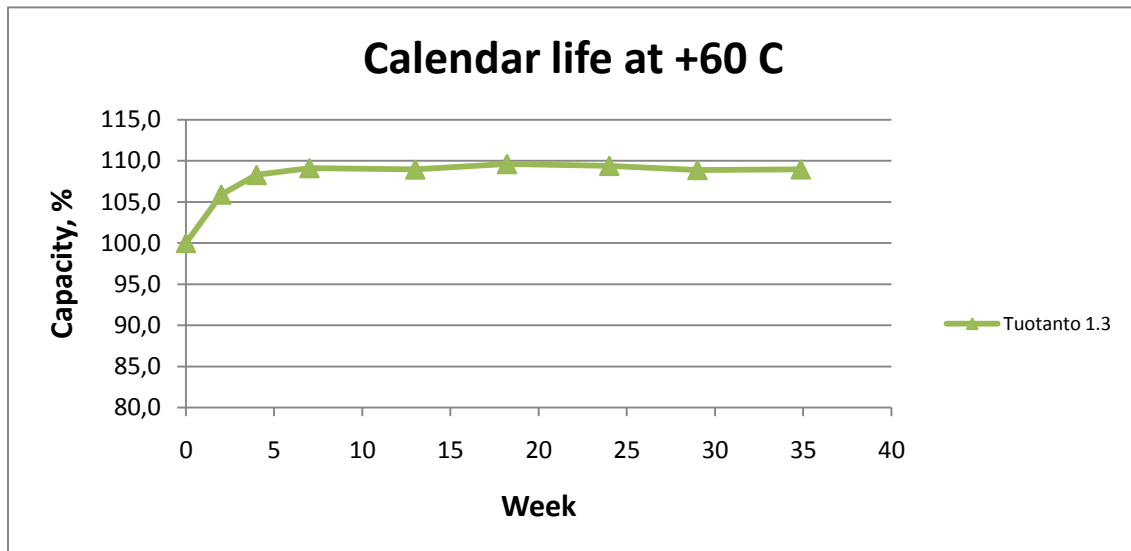


Fig. 19 Voltage capacity curves during charging at different temperatures

### 3.4 Calendar life of an EB 45 Ah HE cell

The calendar life of a lithium ion battery is dependent on the temperature. An EB HE cell has an upper temperature limit of 60°C for occasional use. Figures 20 and 21 show calendar life measurements for an EB 45 Ah 1.3 production cell kept at 60°C for 35 weeks. This measurement is ongoing. The cell was at 30 % SOC level in the heat chamber. Measured capacity % changes and voltages are shown as a function of time. The capacity checks were carried out at room temperature. In each capacity check measurement the cell was taken out from the oven and was allowed to cool down to room temperature, circa 22°C. The cell capacity was defined at 22°C using the following sequence:

- Constant Current Charge 0,5C
  - cut off voltage 3,65 V
- Constant Voltage Charge 3,65 V
  - cut off current 0.03C
- Rest 15 min
- Constant Current Discharge 0,2C (the capacity measurement)
  - cut off voltage 2,5 V
- Rest 5 min
- Constant Current Charge 0,5C
  - cut off voltage 3,65 V
- Constant Voltage Charge 3,65 V
  - cut off current 0.03C
- Rest 15 min
- Constant Current Discharge 0,5C
  - 84 min (70% discharge)



**Fig. 20 Calendar life measurement for the EB 45 Ah 1.3 production cell at 60°C. Measured capacity % changes as a function of time. The cell was kept at 30% SOC level in the oven.**



## BASIC CHARACTERIZATION OF THE EB HE CELL



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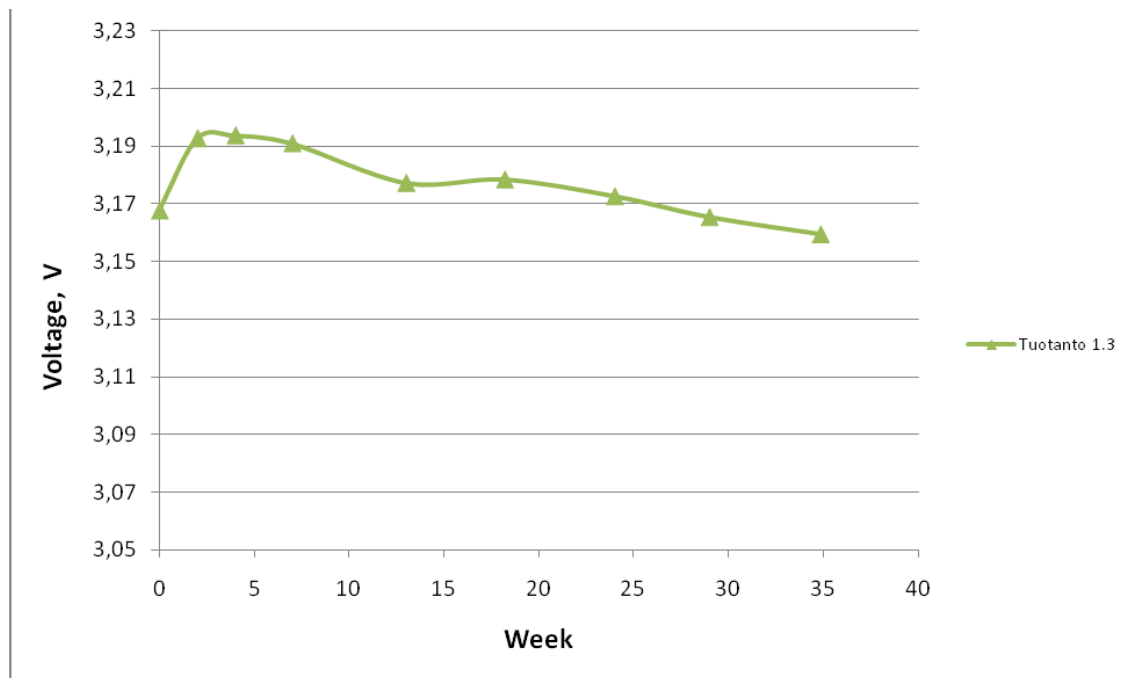


Fig. 21 Calendar life measurement for the EB 45 Ah 1.3 production cell at 60°C. Measured voltages as a function of time. The voltage is the discharging mean voltage.

### 3.5 Cell resistivity

Figure 22 shows typical impedance data as a function of temperature for EB45Ah cell. The plot shows the definitions of  $R(\text{Ohmic})$  and  $R(\text{Electrode})$ . At low temperature the resistance of the solid electrodes increases hugely. This fact is realised especially in cold temperature charging.

#### $R(\text{Ohmic})$ :

$\text{Re}(Z)$  mOhm:

-20 °C: 1,30 mOhm

0 °C: 1,06 mOhm

+20 °C: 0,93 mOhm

+40 °C: 0,85 mOhm

+60 °C: 0,76 mOhm

#### $R(\text{Electrode})$ :

$\text{Re}(Z)$  / mOhm:

-20 °C: 147 mOhm

0 °C: 15,9 mOhm

+20 °C: 2,3 mOhm

+40 °C: 0,35 mOhm

+60 °C: 0,05 mOhm

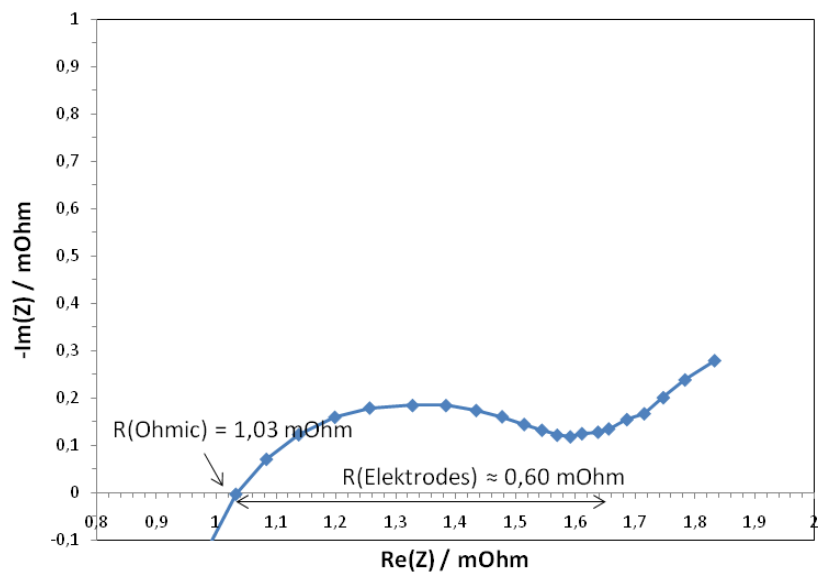


Fig. 22 Cell resistivity as a function of temperature at 30 % SOC level for EB45 Ah cell.

## BASIC CHARACTERIZATION OF THE EB HE CELL

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## Annex A EB energy cell specifications



EV 45 AH

European Batteries EV 45 Ah  
Type: High Energy Cell

Model: 001 Version: 1.3

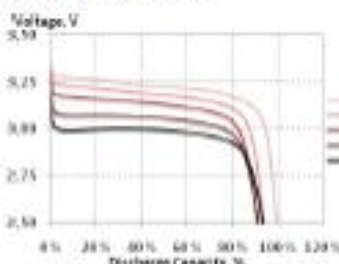
Electrical characteristics at 25 °C	
Nominal Capacity @ C/5 (Ah)	45
Average Operating Voltage @ C/5 (V)	3.2
Internal Impedance AC 1000 Hz (mΩ)	<2.0
Energy Density (Wh/kg)	146
System Lithium-Iron-Phosphate LiFePO <sub>4</sub> cathode Graphite anode	
Recommended Operating Conditions	
Continuous Discharge (A)	45 (144 W)
Pulse Discharge (A), 30 s, Voltage>2.5 V	135 (410 W)
Pulse Discharge (A), 10 s, Voltage>2.5 V	160 (520 W)
Charge Current (A)	22,5
Maximum Charge Voltage (V)	3.65
Discharge Voltage Cutoff (V)	2.5
	Min Max
Storage Temperature (°C)	-30 45
Charge Temperature (°C)	0 40
Discharge Temperature (°C)	-20 45
Maximum Operating Conditions	
Continuous Discharge (A)	135 (410 W)
Pulse Discharge (A), 30 s, Voltage>2.5 V	160 (520 W)
Pulse Discharge (A), 10 s, Voltage>2.5 V	210 (600 W)
Charge Current (A)	45
Pulse Charge (below 80% SOC, A)	135
Maximum Charge Voltage (V)	3.65
Discharge Voltage Cutoff (V)	2.5
	Min Max
Storage Temperature (°C)	-40 60
Charge Temperature (°C)	-10 45
Discharge Temperature (°C)	-25 60

Mechanical characteristics	
Width (mm)	165 ± 1
Height (without terminal, mm)	275 ± 1
Thickness (mm)	13 ± 0.5
Weight (g)	990 ± 10

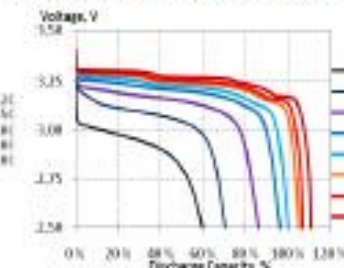


Cell Performance

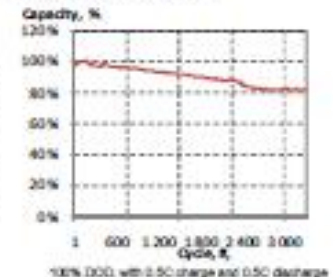
Voltage Curves at 25 °C



Temperature characteristics with 0.5 discharge



Life cycle performance



The information contained in this datasheet is average at the time of publication. This information cannot be guarantee or warranty claims and can be derived on the product properties of cells. The actual characteristics and the lifetime of the cells are mainly influenced by the temperature, storage conditions, unloading and loading conditions of the application. It is the responsibility of the user that the application complies with all relevant operating and safety instructions to the cells in accordance with existing standards and regulations. Specifications are subject to change without notice.

FOR THE LONG RUN

European Batteries Oy | Kauppiatie 11 | FI-02610 ESPOO, Finland | info@europeanbatteries.com | www.europeanbatteries.com

## BASIC CHARACTERIZATION OF THE EB HE CELL

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### Annex B Specifications for HE cells (fall 2011).

	EB Energy cell (current product)	Power cell (Koe 11.05.12)	
Cell type (product code, cell chemistry)	EB45E LFP	EB40P LFP	
Nominal discharge voltage (V) at C/5	3.2V	3.2V	
Nominal capacity (Ah) at C/5	45 Ah	40 Ah	
Energy density (Wh/kg)	145 Wh/kg	130 Wh/kg	
Internal impedance (DCIR)	< 2 mOhm	< 1 mOhm	
Max allowed cell temperature during cycling	60°C (recommended below 45 °C)	60°C (recommended below 45 °C)	
Min allowed cell temperature during cycling*	-20°C (recommended above 0 °C)	-25°C (recommended above 0 °C)	
Cycle life**	> 3000 cycles	> 3000 cycles	
Storage life**	5 years	5 years	
Width	165 mm	165 mm	
Height	275 mm	275 mm	
Thickness	13 mm	13 mm	
Weight	990 g	940-980 g	
Recommended discharge C-rate/current (A)	Max. 1C / 42 A	Max. 3C / 120A	
Discharge cut-off voltage (V)	2.5 V	2.0V	
Recommended charge C-rate/current (A)	Max. 0.5C / 21 A	Max. 1C / 40 A	
Charge cut-off voltage (V)	3.65 V	3.65 V	
Depth of discharge/charge	100 %	100 %	
Max. continuous discharge C-rate/current (A)	3C / 146 A	6C / 240A	
Discharge cut-off voltage	2.5 V	2.0V	
Max. continuous charge C-rate/current (A)	1C / 42 A	2C / 80 A	
Charge cut-off voltage	3.65 V	3.65 V	
Depth of discharge/charge	90 %	90 %	
Max discharge peak pulse C-rate/current (A) at 10 s	4C / 168 A	15C / 600 A	
Max discharge peak pulse C-rate/current (A) at 30 s	4C / 168 A	10C / 400A	
Max charge peak pulse C-rate/current (A) at 10 s	2C / 84 A	3C / 120 A	
Max charge peak pulse C-rate/current (A) at 30 s	2C / 84 A	3C / 120 A	
Discharge cut-off voltage (V)	2.5 V	2.0 V	
*On request low temperature performance can be improved, this will however have effect on high temperature performance			
** Storing and using cells in elevated temperatures will have negative effect on the life time			

The prototype cell, Koe 11.05.12 was made in the EB Varkaus factory to be tested in the project. It shows more power capabilities but still is a HE type cell. The active surface was increased with over 10% compared production 1.3 cell. 100 1.3 Production cells and 90 prototype cells were delivered for testing at VUB.

## Annex C Specifications for HE cells.

HE Cell physical characteristics	unit		Comment
Width	mm	165	
Height	mm	275	
Thickness	mm	13	
Weight	g	990	
Internal impedance (DCIR)	mΩ	<2	
Operating temperatures			
min	°C	-20	at charging: 0°C
max	°C	45	60°C in peak
HE Cell performance	unit		Comment
Specific Energy	Wh/kg	145*	within V limits
Rate Capacity	Ah	45*	at 0.2C @ 25°C
Rate Capability	Ah	45*	at C/10, C/5, C @ 25°C
Specific discharge power	W/kg	140*	at 1C, 50% SOC and 25°C
Specific charge power	W/kg	150*	at 1C, 50% SOC and 25°C
Max discharge power (peak power)	W	576	
max peak duration	s	10	
Max charge power (regen power)	W	288	
max peak duration	s	10	
<b>Self discharge</b>			
in % SOC / 3 months	%	<1*	Measured during 12 month period
Calendar non-reversible capacity loss (/ month)	%	0,2	
<b>Lifetime</b>			
cycle life	cycles	>3000	
storage life	y	5	
<b>Voltage</b>			
Voltage Levels			
nominal disch voltage	V	3.2	at C/5
max voltage	V	3.65	
min voltage	V	2.5	
<b>Current</b>			
continuous			
Imax , discharge	A	135	
Imax, charge	A	45	
peak			
Imax, 10s, discharge	A (rate)	180 (4C)	
Imax, 30s, discharge	A (rate)	180 (4C)	
Imax, 10s, charge	A (rate)	90 (2C)	
Imax, 30s, charge	A (rate)	90 (2C)	
* measured			

This datasheet was prepared in co-operation with WP1 earlier.

One change: charging recommendation changed from -10°C into 0°C.

The cell can tolerate only up to 0.2C charging at -10°C without losing capacity.

## BASIC CHARACTERIZATION OF THE EB HE CELL



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## Annex D Specifications for HP cells.

HP Cell physical characteristics	unit		Comment
Width	mm	165	
Height	mm	275	
Thickness	mm	7.5 **	
Weight	g	500 **	
Internal impedance (DCIR)	mΩ	<1.5	
Operating temperatures			
min	°C	-20	at charging: 0°C
max	°C	45	60°C in peak

HP Cell performance	unit		Comment
Specific Energy	Wh/kg	130**	within V limits
Rate Capacity	Ah	20**	at 1C @ 25°C
Rate Capability	Ah	20**	at C/10, C/5, C @ 25°C
Specific discharge power	W/kg	160**	at 1C, 50% SOC and 25°C
Specific charge power	W/kg	150**	at 1C, 50% SOC and 25°C
Max discharge power (peak power)	W	2160**	
max peak duration	s	10	
Max charge power (regen power)	W	432**	
max peak duration	s	10	
<b>Self discharge</b>			
in % SOC / 3 months	%	< 3	
Calendar non-reversible capacity loss (/ month)	%	0,2	
<b>Lifetime</b>			
cycle life	cycles	>3000	
storage life	y	5	
<b>Voltage</b>			
Voltage Levels			
nominal disch voltage	V	3.2	at C/5
max voltage	V	3.65	
min voltage	V	2.0	
<b>Current</b>			
continuous			
Imax , discharge	A	270**	
Imax, charge	A	90	
peak			
Imax, 10s, discharge	A (rate)	675 (15C)**	
Imax, 30s, discharge	A (rate)	450 (10C)**	
Imax, 10s, charge	A (rate)	135 (3C)**	
Imax, 30s, charge	A (rate)	135 (3C)**	

\*\* estimated performance or value

This datasheet was prepared in co-operation with WP1 earlier.

One change: charging recommendation changed from -10°C into 0°C.

The cell can tolerate only up to 0.2C charging at -10°C without losing capacity.

## Annex E Datasheet of EIG 14 Ah HP cell

Due to the delay of HP cell development at EB and tight schedule the project has decided to consider EIG high power cells (14 Ah or 7 Ah) for their use in calibration experiments for WP5. EB will provide HP cells based on the specifications shown in this document with cell data. These are based on LFP chemistry.

Creative Power For Future Energy

### ePLB F High Power Product



#### Technology

Lithium Ion Polymer Battery  
LiFePO<sub>4</sub>-based Cathode  
Carbon-based Anode  
High Power Density  
Optimized for PHEV, EV

#### Product General Specification

##### Mechanical Characteristics

Model	F014
Length	221 ± 1 mm (excluding terminal)
Width	130 ± 1 mm
Thickness	7.1 ± 0.2 mm
Weight	approx. 380 g

##### Electrical Characteristics

Nominal Voltage	3.2 V
Nominal Capacity	14 Ah
AC Impedance [ 1 KHz ]	< 5 mΩ
Specific Energy	120 Wh/Kg
Energy Density	230 Wh/L
Specific Power(DOD50%, 10sec)	2500 W/Kg
Power Density(DOD50%, 10sec)	4500 W/L

##### Operating Conditions

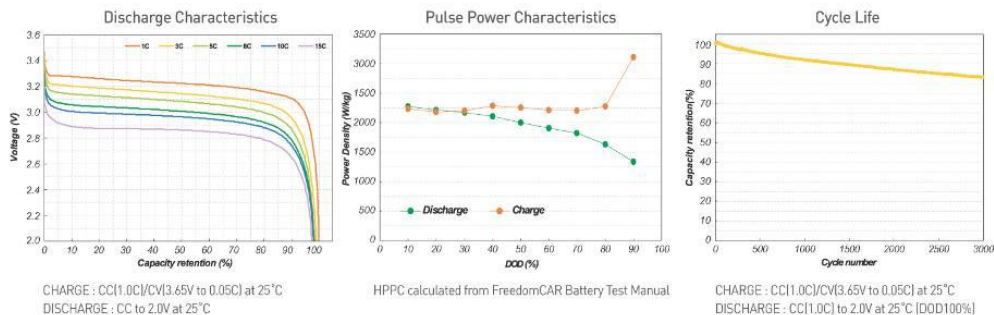
Charge Conditions :	
Recommended Charge Method	CC/CV
Maximum Charge Voltage	3.65 V
Recommended Charge Current	0.5 C Current

Discharge Conditions :	
Lower Voltage Limit for Discharge	2.0 V
Maximum Discharge Current (Continuous)	10 C Current
Maximum Discharge Current (Peak < 10 sec)	20 C Current

Operating Temperature :	-30°C / + 50°C
Recommended Charge Temperature	0°C / + 40°C
Storage Temperature	-30°C / + 50°C

Cycle Life at 25°C : [ 1 C Charge / 1 C Discharge, DOD100%]  
3000 Cycles to 80% Nominal Capacity

#### ePLB F014 Performance



**EIG** Energy Innovation Group

All specifications are subject to change without notice. For your system requirements, please contact [info@eigbattery.com](mailto:info@eigbattery.com)





Lithium Ion Polymer Battery  
LiFePO<sub>4</sub>-based Cathode  
Carbon-based Anode  
High Power Density  
Optimized for HEV

Model	FGC7
Length	221 ± 1 mm (excluding terminal)
Width	130 ± 1 mm
Thickness	4.5 ± 0.2 mm
Weight	approx. 237 g

Charge Conditions :	
Recommended Charge Method	CC/CV
Maximum Charge Voltage	3.65 V
Recommended Charge Current	0.5 C Current

Lower Voltage Limit for Discharge	2.0V
Maximum Discharge Current (Continuous)	30C Current
Maximum Discharge Current (Peak < 10 sec)	30C Current

Nominal Voltage	3.2V
Nominal Capacity	7 Ah
AC Impedance (1 KHz)	< 3 mΩ
Specific Energy	95 Wh/kg
Energy Density	180 Wh/L
Specific Power (DD50%, 10sec)	3200 W/kg
Power Density (DD60%, 10sec)	4700 W/L

Operating Temperature	-30°C / +50°C
Recommended Change Temperature	0°C / +40°C
Storage Temperature	-30°C / +50°C

## 3000 Cycles to 80% Nominal Capacity

CHARGE: 0.01000000 W to 0.00000000 at 25°C  
DISCHARGE: CC is 7.00% at 25°C

Year	<i>D. dentata</i> (Relative Density)	<i>C. dentata</i> (Relative Density)
1973	2800	2800
1974	2800	2800
1975	2800	2800
1976	2800	2800
1977	2800	2800
1978	2800	2800
1979	2800	2800
1980	2800	2800
1981	2800	2800
1982	2800	2800
1983	2800	2800
1984	2800	2800
1985	2800	2800
1986	2800	2800
1987	2800	2800
1988	2800	2800
1989	2800	2800
1990	2800	2800
1991	2800	2800
1992	2800	2800
1993	2800	2800
1994	2800	2800

4494722 provided via Email and CD-ROM Gateway to all interested

Cycle number	Polymer weight (%)
0	100
100	98
200	97
300	96
400	95
500	94
600	93
700	92
800	91
900	90
1000	92

(3-HL)GTF = CO<sub>2</sub>H (3-HL)GTF in 0.05 M NaOH  
(3-HL)GTF = CO<sub>2</sub>H (3-HL)GTF in 0.05 M NaOH



All specifications are subject to change without notice. For your system requirements, please contact: [info@leighattery.com](mailto:info@leighattery.com)



## BASIC CHARACTERIZATION OF THE EB HE CELL



**C O N F I D E N T I A L** until public release by the SuperLIB project consortium

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### <sup>1</sup> Nature

R = Report, P = Prototype, D = Demonstrator, O = Other

### Dissemination level

- PU = Public
- PP = Restricted to other programme participants (including the Commission Services)
- RE = Restricted to a group specified by the consortium (including the Commission Services)
- CO = Confidential, only for members of the consortium (including the Commission Services)
- Restreint UE = Classified with the classification level "Restreint UE" according to Commission Decision 2001/844 and amendments
- Confidentiel UE = Classified with the mention of the classification level "Confidentiel UE" according to Commission Decision 2001/844 and amendments
- Secret UE = Classified with the mention of the classification level "Secret UE" according to Commission Decision 2001/844 and amendments