BATTERY
WHITE PAPER

The Safety Aspects of the BYD Iron-Phosphate Battery
(“LiFePO4”, “LFP”, or “Fe” Battery)

TABLE OF CONTENTS

BACKGROUND AND VISION

BYD's overarching corporate goal is to spur the mass-market adoption of green technologies and drive dramatic global economic and environmental recovery. BYD believes that we are in a unique position to do this as we have developed the industries only environmentally friendly battery chemistry: BYD "Iron-Phosphate" Battery (hereafter, Fe Battery). This battery technology has been facilitator for two major technological breakthroughs within the global push to eliminate the dependence on heavy pollution emitting fossil fuels. (1) It enables renewable power generation to be relevant for grid operations with firm "dispatch able" capacity. (2) It enables the introduction of long-range, long-service life, and fast charging capable electric vehicles. Utilizing BYD's Fe Battery chemistry, we are capable of linking affordable solar/renewable energy power made relevant with environmentally friendly battery storage that is delivered responsibly to transportation—this in essence has completed the true ZERO Emissions Ecosystem. Being able to deliver a true zero-emissions solution that is mass-market scalable is the cornerstone of BYD's "Three Green Dreams" strategy and BYD's "Green City Solutions" (GCS) initiatives.

Figure 1: Green City Solution

The first step of BYD's GCS is providing an efficient and effective 100% battery electric transportation solution, which when integrated offers immediate environmental benefits. BYD's battery electric trucks utilizes the same environmentally friendly Fe Battery that is supplied within our large scale fixed Energy Storage Stations (ESS). BYD develped its Fe Battery Chemistry to not contain any heavy metals or toxic electrolytes as well as have the least amount of enviornmental impact of any electric vehicle battery system in the market today. In comparison to traditional diesel engine or CNG powered transit buses, BYD's all electric buses provide both qualitative and quantitative benefits that will have short- and long-term impacts on both a micro-level fleet operation and the marco-level enviornmental impacts.

On the micro-level, BYD’s Battery Elecric trucks will cut operating cost by over 30% in comparison to utilizing an equivalent diesel or CNG vehicle. This added influx of overhead capital to a transit agency will produce an immediate impact on the community in terms of job growth, which will in turn lead to a downstream economic growth in the same community. Futhermore, utilizing BYD’s Battery Electric buses, which per Altoona Test results are on average 5% quieter than other electric bus manufactures, extremely reduces the overall noise pollution generated by not only diesel and CNG buses but with other electric bus manufactures. On the marco-level, replacing the existing diesel and/or CNG buses with BYD battery electric buses will lead to over 80% reduction in CO2 emissions per day. The CO2 emissions from one diesel and/or CNG bus per day is equilvent to the lose of over 400 acres, however, replacing those existing engine times with BYD Battery Electric Buses will lead to an over 75% reduction in the amount of forest lost per year from one vehicle.

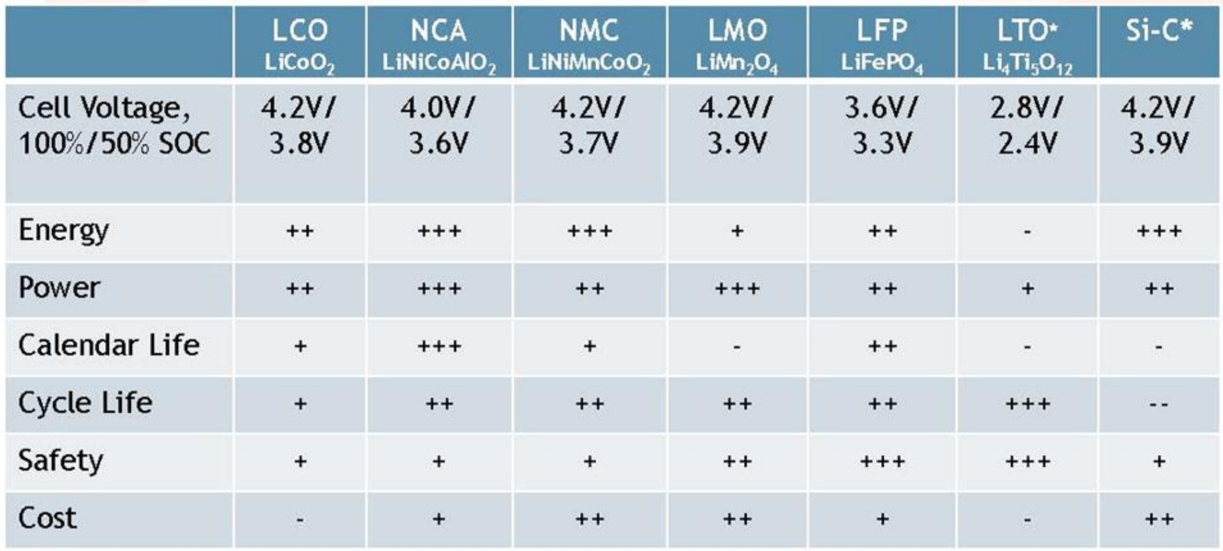
BYD will transform the world’s public transportation through use of our environmentally friendly long-range zero emissions battery electric transit bus through reduction of the overall carbon footprint by providing a solution to eliminating the overarching dependance on oil. BYD’s believes that our electric bus will ultimately increase ridership while reducing the total life-cost by more than half a million dollars per bus through the 12-year normal transit operating life cycle. BYD’s battery technology allows the bus to travel up to an unprecedented 250+ miles on a single overnight charge. Through our continued standardization of our electric buses, it has lead to large-scale manufacturing in the US and significant component cost reductions that translate into growth the US Jobs market for Green Technology. Today, there are not any large-scale US battery manufactures of safe, stable, and environmentally friendly rechargeable batteries, nor are there any long-range all-electric US Bus Manufactures that are capable of meeting the demands of a zero-emissions battery electric transit bus without a signficant premium capital cost to a transit agency. BYD’s battery technology has been proven both in the US as well as worldwide. As of 2017, we have over 800 million battery electric transit bus fleet miles that have provide daily revenue service.

Furthermore, when BYD produces our Fe Battery, we consider the Total Life Cycle of each cell. Unlike other electric bus manufactures that provide a single use of their batteries, BYD is in a unique position, because of our vertical integration, to repurpose batteries from our transit buses (once they reach their useful life cycle) into our own Energy Storage Systems. We are our own customer for repurposing as well as recertifying packs and modules.

CHAPTER 1: BATTERY DESIGN

Figure 2: Total Life Cycle of Cell

BYD internally developed the Fe Battery chemistry to ensure the stability and safety of each of our electric vehicles. BYD calls our batteries "Iron-Phosphate" versus "Lithium-Iron-Phosphate" because the dominate materials within the chemistry are Iron and Phosphate with only trace amounts of lithium doped on the cathode/anode and in the salts of electrolyte. For the purpose of this paper, battery "safety" will be categorized into Cell, Module, and Pack "electricity safety" and "thermal stability". To begin, we have provided a general comparison of the most prevalent EV battery chemistries (including the BYD Fe Battery which is listed as "LiFePO4").



	LCO $LiCoO_2$	NCA $LiNiCoAlO_2$	NMC $LiNiMnCoO_2$	LMO $LiMn_2O_4$	LFP $LiFePO_4$	LTO* $Li_4Ti_5O_{12}$	Si-C*
Cell Voltage, 100%/50% SOC	4.2V/ 3.8V	4.0V/ 3.6V	4.2V/ 3.7V	4.2V/ 3.9V	3.6V/ 3.3V	2.8V/ 2.4V	4.2V/ 3.9V
Energy	++	+++	+++	+	++	-	+++
Power	++	+++	++	+++	++	+	++
Calendar Life	+	+++	+	-	++	-	-
Cycle Life	+	++	++	++	++	+++	--
Safety	+	+	+	++	+++	+++	+
Cost	-	+	++	++	+	-	++

Figure 3: Overview of Available Battery Chemistries[1]

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[1] Choices in Lithium Ion Battery Chemistries (Wiaux and Chanson 2013)

BYD Chemical Make-Up Discussion

The make-up of all commercially available lithium ion batteries consists of an inorganic lithium-intercalating compound as a positive electrode, a lithium-intercalating carbon negative electrode, and a lithium salt in an organic liquid, known as the electrolyte. Both electrodes must be separated by an insulator like a thermoplastic polymer. Most manufacturers use a polypropylene. Polypropylene has a melting point of 160°C (320°F) and is very resistant to most chemical solvents, bases, and acids. When a cell charges and discharges, lithium ions shuttle between the cathode (positive electrode) and anode (negative electrode). Upon discharge, the anode undergoes oxidation, or loss of electrons, and the cathode sees a reduction, or a gain of electrons. Charging reverses this sequence a depiction is provided in the figure below.

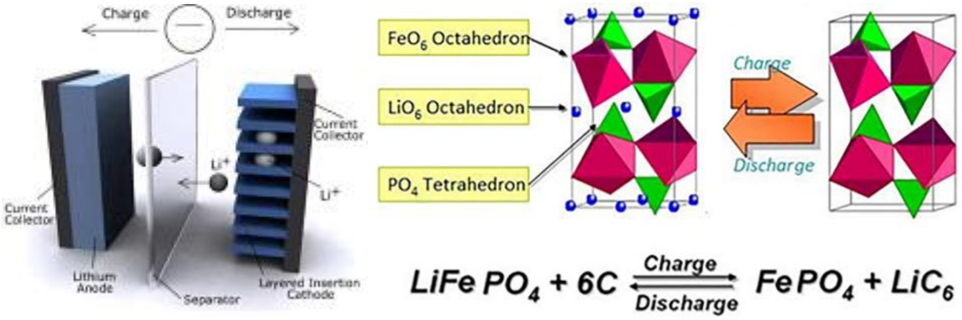


Figure 4: BYD Fe Battery Chemistry Make-Up

Lithium-ion cells have historically used lithium-metal-oxides as cathode materials due to their high capacity for lithium intercalation, and have suitable chemical and physical properties required for Lithium-ion electrodes. Layered materials, such as LiCoO2 and LiNiO2, or a combination of these metals, have been the most extensively used and investigated cathodes (most consumer electronic single-cell applications use these because of their very high energy density). These type of cathodes show instability (LiCoO2, LiNiO2).

When BYD refers to “thermal instability”, we mean that these battery chemistries (LiCoO2, LiNiO2) can at times have an internal thermal event that can escalate quickly causing rapid-disassembly and explosion producing dangerous shrapnel as well as projecting those flames. This is at times understated by the industry as “venting”. In order to avoid thermal instability, other lithium-metal oxide materials with a “spinel” structure (e.g. LiMn2O4) have been manufactured to substitute the layered materials. This oxide is inexpensive and environmentally friendly, but has significant disadvantages related to capacity depreciation, especially at high temperatures (these chemistries are not suitable for long-cycle requirements in vehicle applications especially if rapid-charging is required. Many EV manufactures will not honor batteries warranties if the vehicle is utilizing daily rapid charging). BYD has developed olivine structures materials (e.g. LiFePO4) and these have emerged as a reasonable cathode replacement for the safety levels required in vehicle application. Iron-Phosphate has the following properties which set it apart:

- Relatively inexpensive material cost
- High average cycling voltage due to flat potential of 3.4 V vs Li/Li+
- Reasonably high theoretical capacity
- Designed less “toxic” compared with other Li-Ion, LiCoO2 systems
- Suppressed thermal runaway

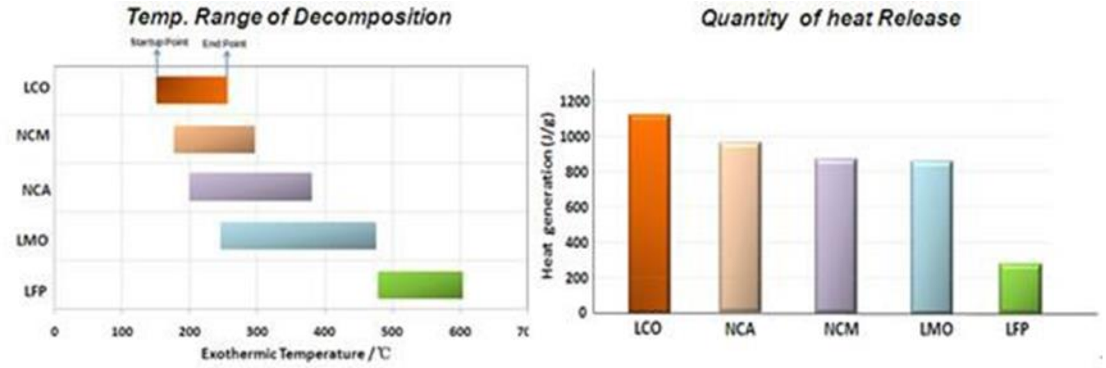


Figure 5: Battery Thermal Properties

The figures above show Iron-Phosphate (called LFP) has the highest required decomposition temperatures and the lowest thermal release. LFP has the best safety performance in comparison to various kinds of lithium technologies. This property is attributed to the high covalent feature of the P-O bonds in the tetrahedral (PO4) units (shown below), which stabilizes the olivine structure between charging and discharging and completely prevents oxygen release from the charged olivine materials up to 600C.

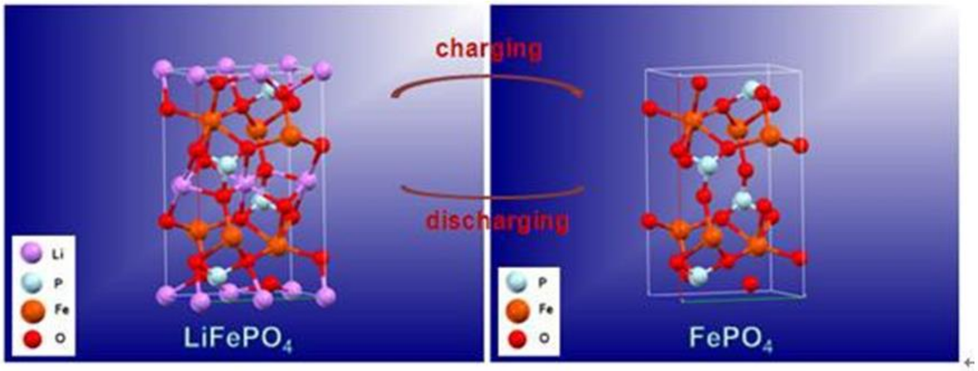


Figure 6: Fe Battery Chemistry Decomposition

LiFePO4 and FePO4 have excellent thermal stability. FePO4 releases in temps around 410C and at a rate of 210J/g. In contrast, LiCoO2 begins to decompose oxygen at only 240C and at a rate of over 1000J/g. This drastic release of O2 is the main reason why lithium batteries explode (“vent”) during thermal events. There is an overall industry agreement on the remarkable thermal stability of the LiFePO4 and its delithiated counterpart, and the recognition that LiFePO4 is a safer cathode material than the commonly used lithium metal oxide cathodes.

BYD Cell Design

Proper design of the cell, battery and the battery compartment is important to assure optimum, reliable, and safe operation. Many problems that are normally attributed to the battery could be prevented with proper precautions taken with both during the design of the cell and battery-pack themselves.   Here are the areas that need to be reviewed:

- **Cell chemistry** - The quest for long-powered run-times results in higher energy and power densities, so even more reactive chemical mixes have been utilized. But these highly reactive properties which are needed to provide the higher energy densities are likely to increase the risk of danger in case of cell failures.   For safety reasons, BYD balances maximum power and safety by optimizing the component proportion (active materials, binder, conductive, etc.)
- **Electrode design –** BYD confirms the electrode structures according to many experiential models, such as current distribution models, thermal models, electrochemical models, and mechanics models, to reduce the resistance, optimize the current distribution and thermal distribution in the cell. Good current and thermal distribution can ensure the long-term stability and safety of the cell.
- **Pack Capacity design –** Generally, for a cell, the higher capacity, the lower the safety. However, BYD optimizes the balancing point of the cell capacity and the safety according to internal math models and safety testing. Using a higher capacity cell design, the total number of cells in a pack can decrease, and thus reliability of the battery system can increase (eg. Instead of using 8134 individual cells as in the Tesla Roadster, BYD is able to achieve the same capacity and range with about 100 larger-format cells with fewer connection points and potential points of failure).
- **Mechanics design –** BYD cell adopts high strength aluminum cases, and EPI, CHS patented seal- technology, which increases the seal integrity and anti-eroding levels, and also satisfies a more-than-15 years seal and life requirement.
- **Cell construction** - For higher power cells, the thermal design can be a source of weakness. Getting the excess heat out of the cells can be a problem and poor designs can result in localized hotspots within the cell which may cause cell failure. Good thermal performance for high power cells requires substantial thermal conduction paths. BYD uses thermal imaging to confirm our best-in-class thermal balancing inside a cell:

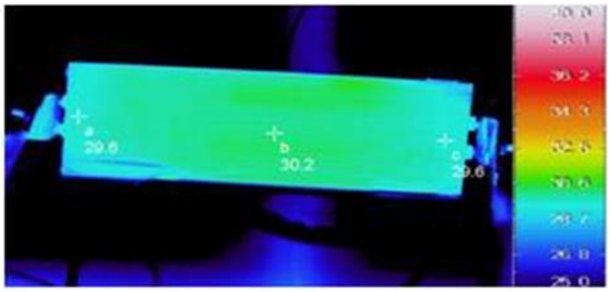


Figure 7:Fe Battery Thermal Distribution

- **Vent** - If other safety devices fail and a cell is exposed to high heat, chemical reactions can result in out-gassing and the active materials will expand due to the increasing temperatures. This can cause a build-up of pressures inside the sealed cell which could result in rupture of the case that would possibly make a disconcerting pop or loud bang. Safety vents are needed as a final safety precaution to release this potential pressure before it reaches a rupture level. Automatic release guard vents prevent the absorption of external air into the cell, but allow controlled release of excess internal pressure to avoid leakage and prevent uncontrolled rupture of the cell case.

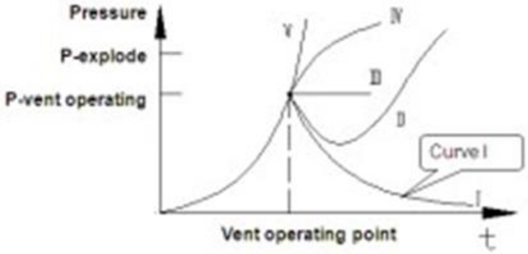


Figure 8: Vent Design Curve

BYD Cell Manufacturing

BYD's manufacturing for the battery cells is percision controlled process that magnifies the already steller design and safety feeatures of the Fe Battery. To ensure proper manufactring of the individual cells, BYD procedural proecess incompasses the following:

- Burrs on the electrodes;
- misaligned or out of tolerance components;
- contaminated electrode coatings or electrolytes can all cause short circuits or penetration of the separator.

BYD produces each of its batteriers in a fully automatic assembly line that provides strict environment controls and high precision accuracy. Shown in the figures below is BYD's full automatic lines.

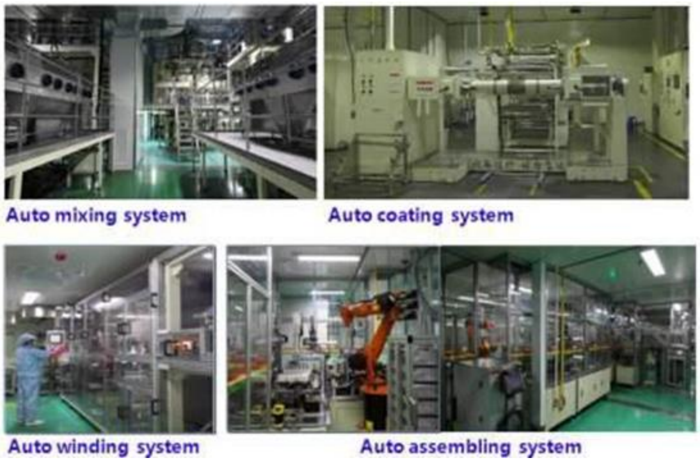


Figure 9: Cell Manufacturing

BYD Pack Connection Design

BYD’s battery packs when constructed use the most reliable welding methods available for assembling battery cells within a module. BYD uses both laser and ultrasonic welding to ensure that each battery assemble is not only reliable but provide the most efficient thermal distribution.

Figure 10: Laser Welding Between Batteries and Ultrasonic welding in the cell

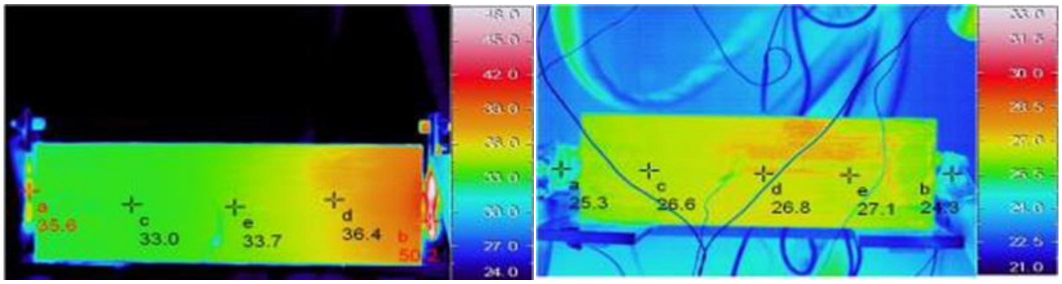


Figure 11: Thermal Distribution

BYD High Voltage Battery Layout Design

BYD has designed the layout of the High Voltage Batteries (HVB) to minimize the risk for both bus riders and maintenance personnel in a manner that specifically segments the high voltage and low voltage battery so that there are not any dangerous areas within easily accessible areas. As shown in figure, the HVB is segmented into several parts. There are breaker units that separate each battery, these breaker points segment it into smaller parts with lower voltages (48V, 60V or 100V), which are then safer to touch. This will further allow for a safe shut down of BYD's electric bus.

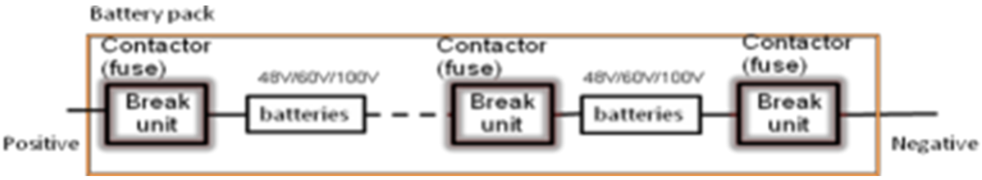


Figure 12: Battery Segmentation

From a safety and protection standpoint each of the containers that form the components within the battery packs have a safety system designed within. The example provided below is for our 40-Foot Battery Electric Bus (K9M). For PACK 1, there is one voltage divider/contactor in each one of the two rear overhang battery packs, and one in the left front wheel area (figure 13). For PACK 2, there are two voltage divider contactors in the rooftop pack, and one in the right front wheel area (figure 13). The voltage divider contactors are located inside of the battery compartment so that it can open and close the high voltage circuit, and also can keep any live parts inside of the battery compartment when shutting down the electricity. Since the positive electrode and the negative electrode of every single battery pack are disconnected when the contactor is open, putting the contactors between each of the physical locations that comprise the two packs achieves the same safety outcome as putting the contactor between the positive and negative node of the battery, which is to isolate the positive and negative harness. The failure probability of a Voltage Divider Contactor is one in one Hundred thousand (1/100,000).

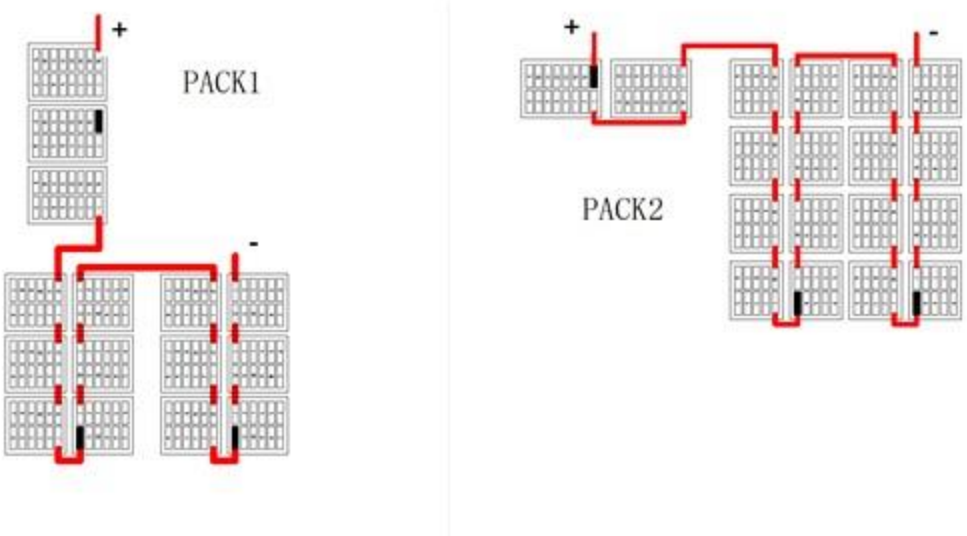


Figure 13: Pack Dividers

BYD Battery Management System

BYD’s battery management system is an imbedded diagnostic and managing unit to high voltage batteries. The system utilizes controllers and data collectors. Each bus is fitted with one primary controller and one auxiliary controller for each battery pack and the appropriate number of data collectors.

The battery module data collector detects the voltage and temperature of each cell in each module. It sends the data to the auxiliary controller. The auxiliary controller sends the battery pack data to the primary controller. The primary controller controls the power battery charge/discharge, battery balancing and communicates with other modules installed on the bus. The two types of controllers are physically the same with the exception of their programming. The primary controller is programed to communicate with the CAN (control area network).

The High Voltage Battery Management System manages the charging and discharging of the HV battery, power limit, current detection, battery temperature, voltage sampling etc.... It protects the HV batteries by controlling battery contactors if electrical leakage occurs, in the event of a collision, voltage is too high or too low, or when the temperature is outside operating parameters.

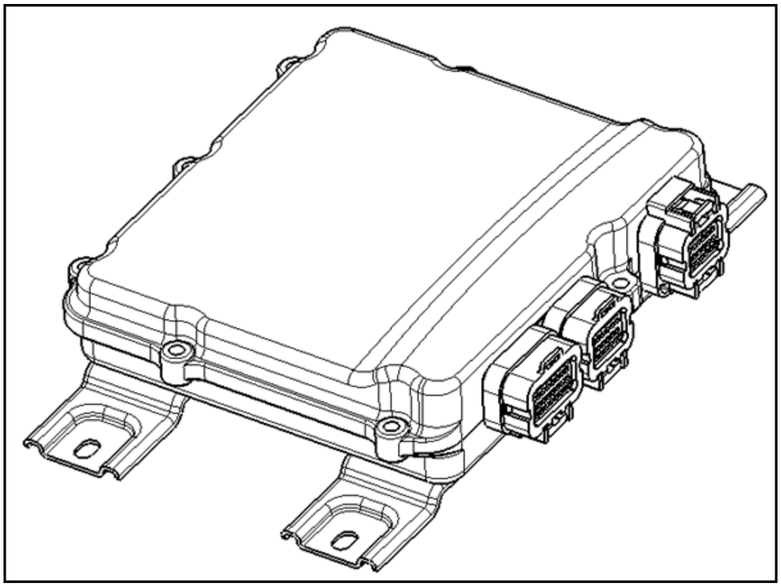


Figure 14: Primary BMS Controller

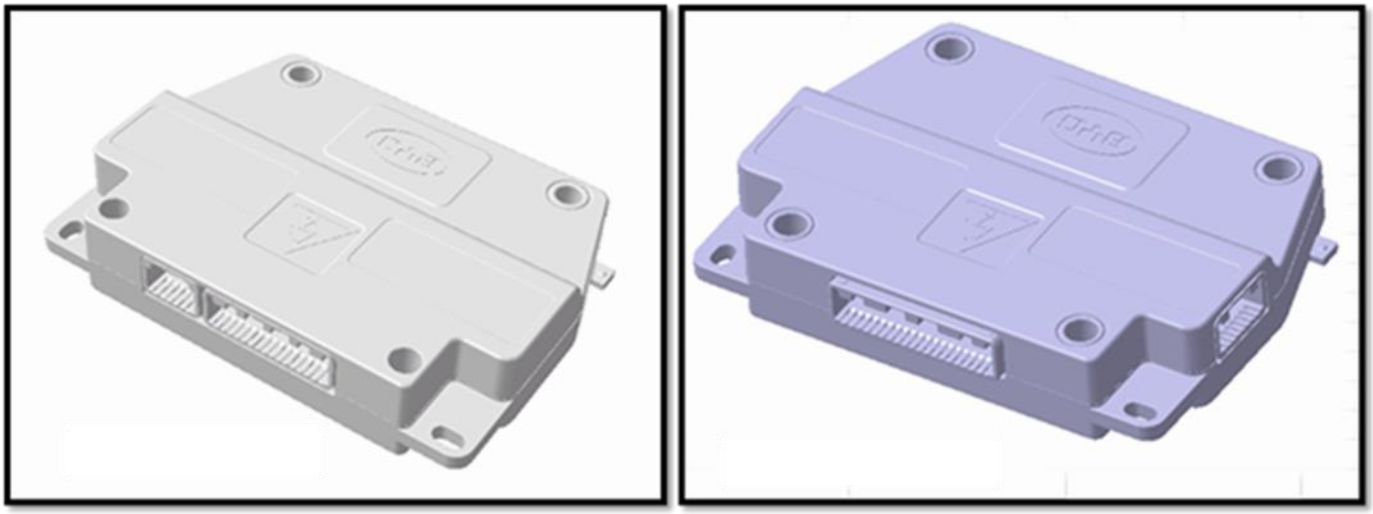


Figure 15: Auxiliary BMS Controller(s)

In the figure below provides a layout of our K9M bus BMS:

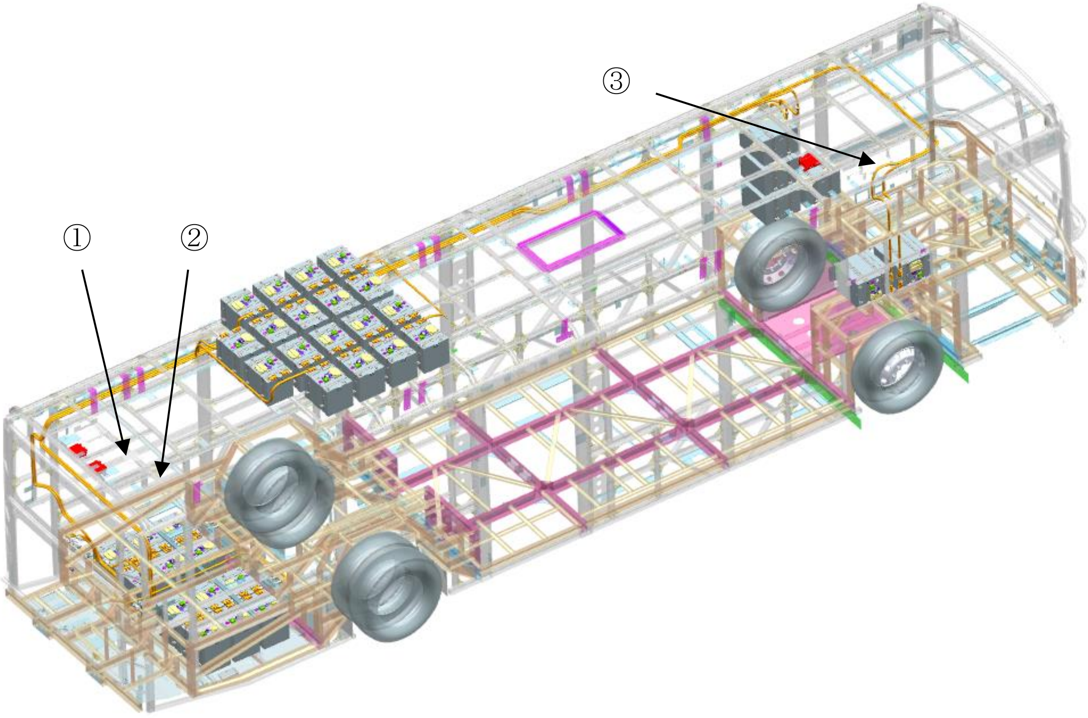


Figure 16: K9M BMS Layout

1. Primary Controller	2. Auxiliary Controller #1	3. Auxiliary Controller #2

Distributed Management Information Collectors Layout.

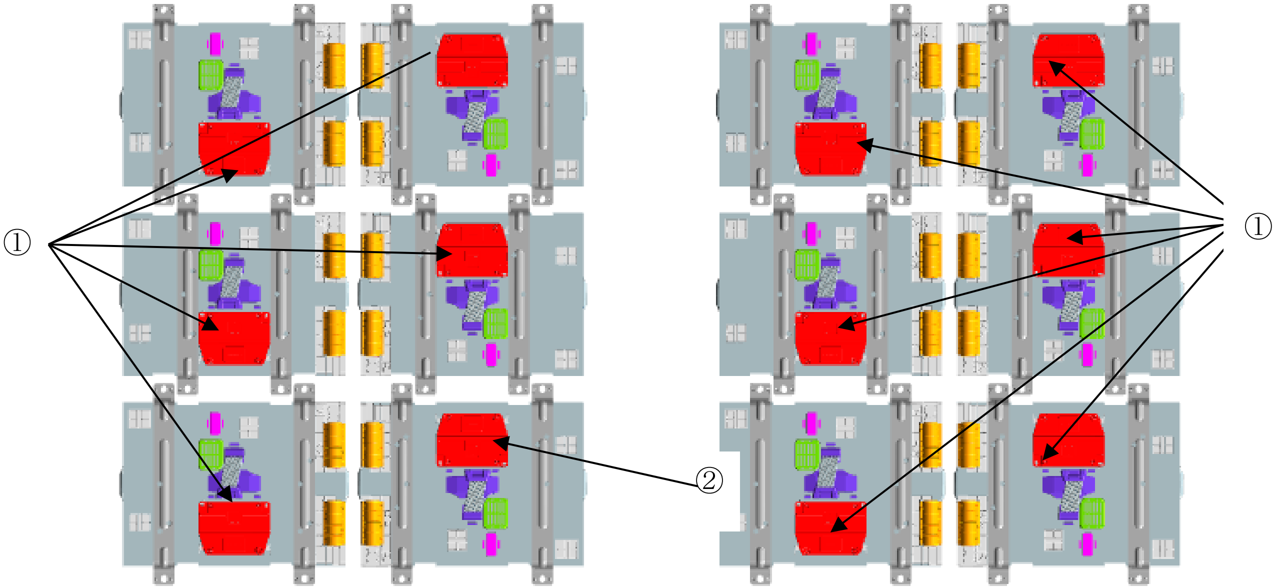


Figure 17: BMS Collector Layout (Underfloor Battery Pack)

1：12 Cell Information Collector
2：12 Cell Information Collector with Terminating Resistor

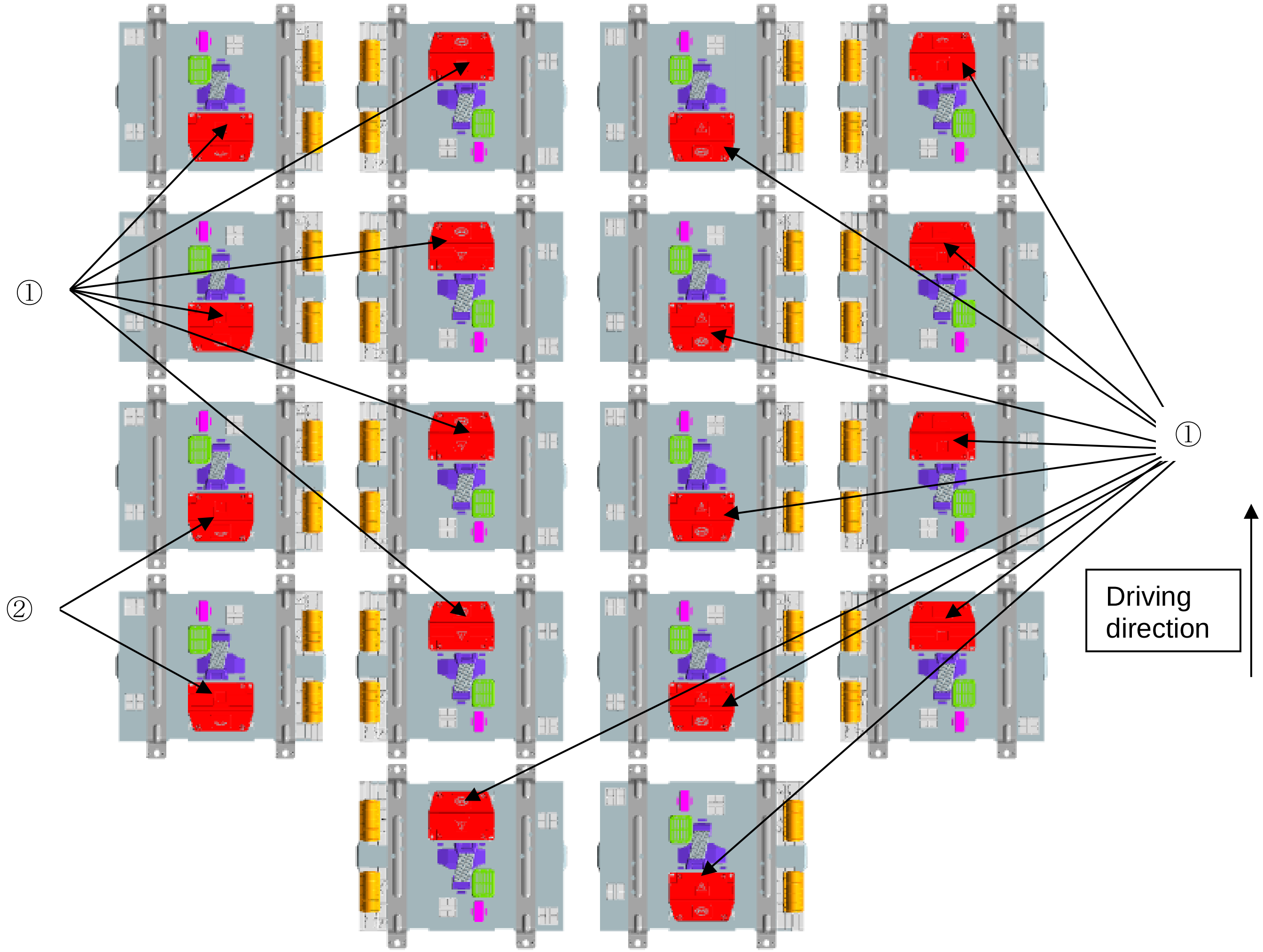


Figure 18: BMS Collector Layout (Roof Top Battery Pack)

1：10 Cell Information Collector

2：10 Cell Information Collector with Terminating Resistor

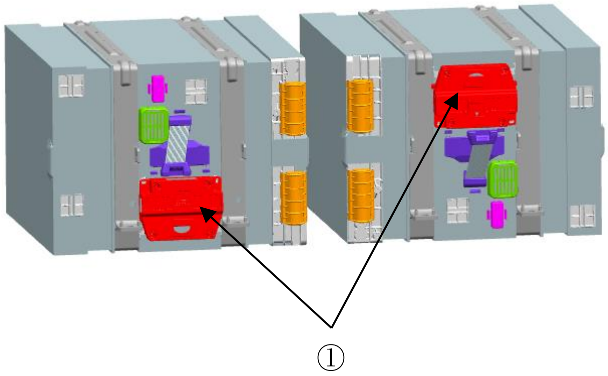


Figure 19: BMS Collector Layout (Right Side Interior Pack)

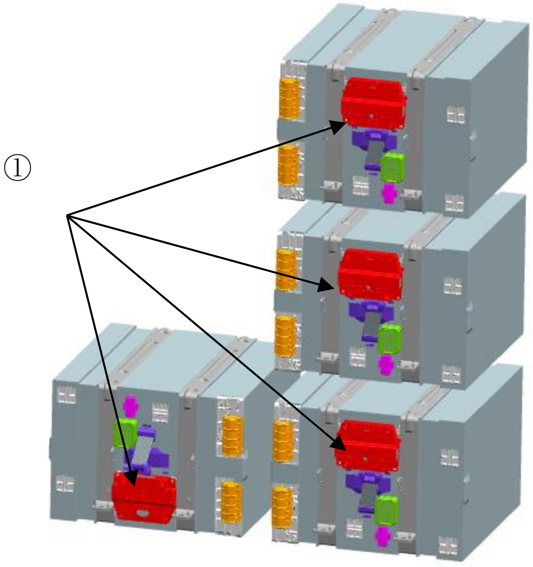


Figure 20:BMS Collector Layout (Left Side Interior Pack)

1. 14 Cell Information Collector

In the series-connected multi-cell battery, the cell with the lowest capacity will determine the duration of the discharge, while the one with the highest capacity will control the capacity returned during the charge. For safety, special controls are used for management of charge and discharge. Typically, the control circuit will address the following items that affect battery life and safety:

- Temperature monitor and control
- Voltage monitor and control
- Current monitor and control
- SOC
- Short circuit protection

The BMS has corresponding actions to take if there are any parameters exceeding the critical set points, to make sure the safety of the battery.

BYD HVB Flame Retardant Design

BYD’s HVBs use polymer materials that are flame retardant at the lowest levels (a class UL94 V1). This means that short durations of direct flames will not damage this package (as required by UL).

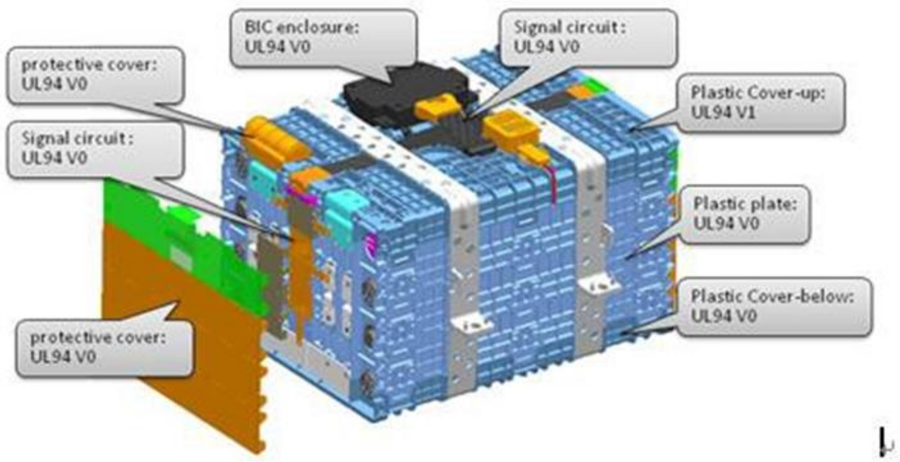


Figure 21: BYD HVB Flame Retardant Design

BYD Signal Circuits

High safety and reliability for the signal circuits can insure that the status of every cell can be monitored real-time. According to the voltage and temperature signals, Battery Management System (BMS) protects the battery very well with control strategy.

- FPC signal line to avoid line intersected, to avoid short circuit of voltage monitoring line inside
- At least one fuse in every voltage monitoring line to protect HVB when short circuit in signal circuit out of HVB
- easy to automate production

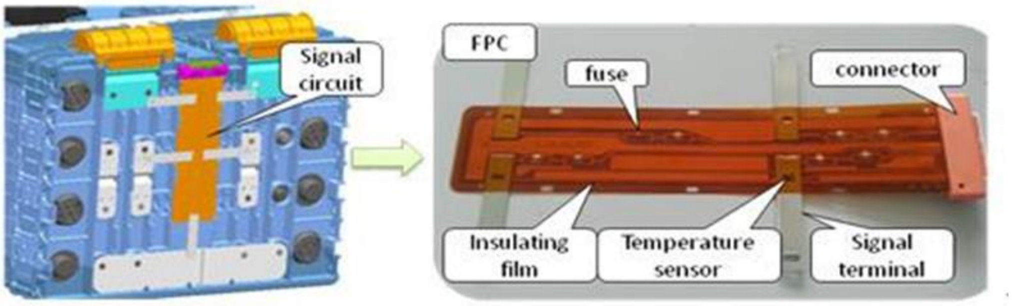
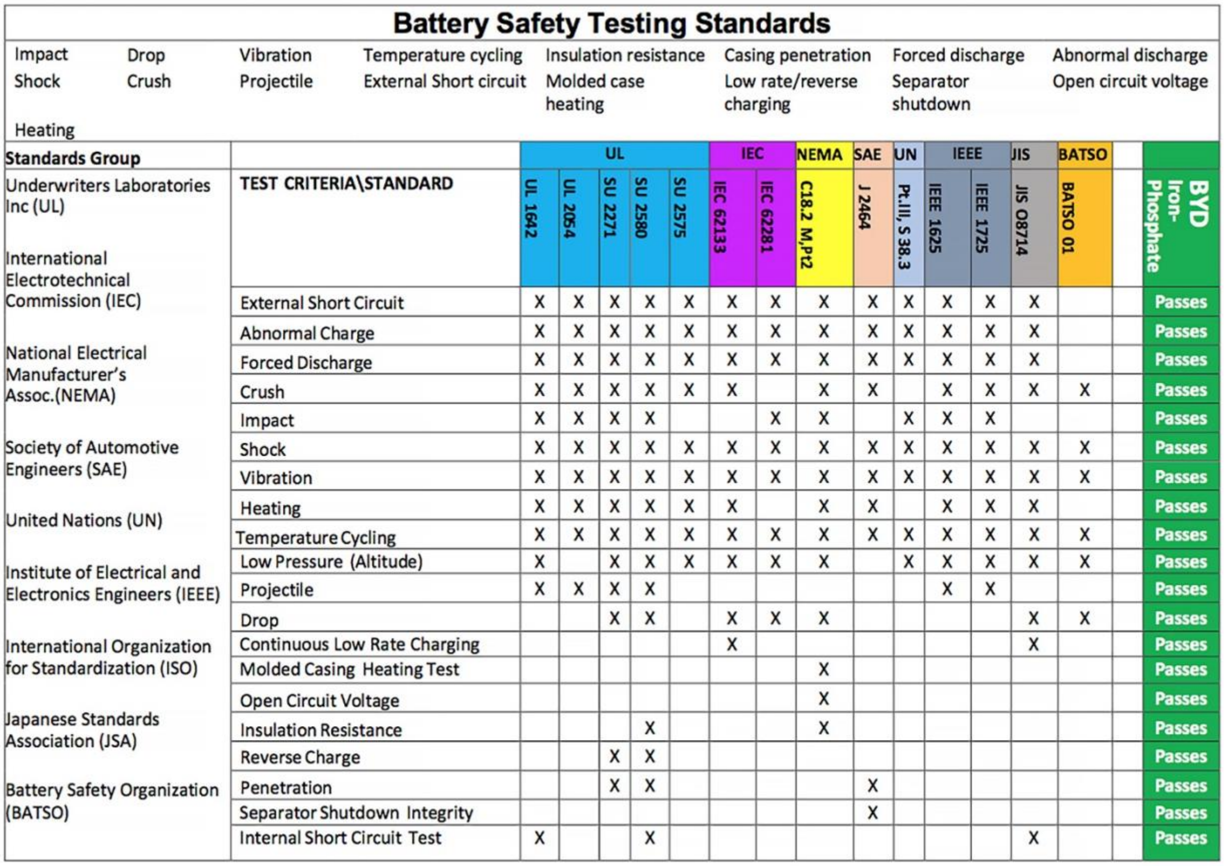


Figure 22: Circuit Layout

BYD Cell Design Conclusion

BYD's Fe Battery cathode is not only the safest cathode material because there is no thermal run-away mechanism nor Oxygen generated when decomposing, it also is the most robust when cycled because there is no net-net volume gain causing premature cell swelling or impedance growth. The Fe Battery is also more tolerant than competitor's batteries for rapid charging with supreme cycle life and C-Rate capabilities. The Fe Battery packs not only meet all of the US regulations, but they also surpass the stringent US DOT and FMVSS vehicle standards. Tests in the following chapters were preformed not only at the vehicle level, but also at the pack and module levels where abuses could more easily be directed, focused and controlled for the worst case evaluations (well beyond the specification requirements). In fact, BYD performs testing beyond required as seen below:



Battery Safety Testing Standards

Impact
Shock
Heating
Drop
Crush
Vibration
Projectile
Temperature cycling
External Short circuit
Insulation resistance
Molded case heating
Casing penetration
Low rate/reverse charging
Forced discharge
Separator shutdown
Abnormal discharge
Open circuit voltage

Standards Group		UL					IEC		NEMA	SAE	UN	IEEE		JIS	BATSO		
Underwriters Laboratories Inc (UL)	**TEST CRITERIA\STANDARD**	UL 1642	UL 2054	SU 2271	SU 2580	SU 2575	IEC 62133	IEC 62281	C18.2 M,Pt2	J 2464	Pt.III, S 38.3	IEEE 1625	IEEE 1725	JIS O8714	BATSO 01		**BYD Iron-Phosphate**
International Electrotechnical Commission (IEC)	External Short Circuit	X	X	X	X	X	X	X	X	X	X	X	X	X			Passes
	Abnormal Charge	X	X	X	X	X	X	X	X	X	X	X	X	X			Passes
National Electrical Manufacturer's Assoc.(NEMA)	Forced Discharge	X	X	X	X	X	X	X	X	X	X	X	X	X			Passes
	Crush	X	X	X	X	X	X		X	X		X	X	X	X		Passes
	Impact	X	X	X	X			X	X		X	X	X				Passes
Society of Automotive Engineers (SAE)	Shock	X	X	X	X	X	X	X	X	X	X	X	X	X	X		Passes
	Vibration	X	X	X	X	X	X	X	X	X	X	X	X	X	X		Passes
United Nations (UN)	Heating	X	X	X	X	X	X		X	X		X	X	X			Passes
	Temperature Cycling	X	X	X	X	X	X	X	X	X	X	X	X	X	X		Passes
Institute of Electrical and Electronics Engineers (IEEE)	Low Pressure (Altitude)	X		X	X	X	X	X	X		X	X	X	X	X		Passes
	Projectile	X	X	X	X							X	X				Passes
	Drop			X	X		X	X	X					X	X		Passes
International Organization for Standardization (ISO)	Continuous Low Rate Charging						X							X			Passes
	Molded Casing Heating Test								X								Passes
	Open Circuit Voltage								X								Passes
Japanese Standards Association (JSA)	Insulation Resistance				X				X								Passes
	Reverse Charge			X	X												Passes
Battery Safety Organization (BATSO)	Penetration			X	X					X							Passes
	Separator Shutdown Integrity									X							Passes
	Internal Short Circuit Test	X			X									X			Passes

Figure 23: BYD Battery Safety Testing Standards

CHAPTER 2: BATTERY SAFETY

Within this chapter, we will present the full results from the specific testing that electric bus battery modules and packs are subjected to and passed.

Vibration/Shaker-Table Testing

BYD simulated roadway vibrations with a vigorous vibration spectrum. The test conditions included; Battery at 100% SOC, frequency range: 10 - 2000HZ. BYD performed the testing with reference to the IEC 60068-2-64 random vibration. BYD used a test duration of over 8 hours for each plane of the test packs. As shown in Figure: Pack after vibration, the module wasn't damaged during and after the vibration test.

Figure 24: Vibration Testing

Thermal Shock Test

BYD tested the reliability of the battery when the vehicle would be operated at extreme temperature ranges. The battery module was charged to 100% SOC, temperature range is 85 ±2°C to -40 ±2°C. Temperatures were cycled with durations of 15 minutes to reach each temperature extreme, then remain soaked for 6 hours or reach uniform temperature. Five (5) cycles were completed, and then the sample was returned to ambient and charged and discharged 2 cycles. The battery module did not catch fire or explode no rupture of enclosure or leakage of electrolyte outside of enclosure – Pack was is still operational (Figure: Thermal Chamber).

Figure 25: Thermal Shock Testing

Salt Spray Test

BYD tested the reliability of the battery when exposed to a high-salt environment, such as somewhere near the ocean or road-way salts. The battery module was charged to 100% SOC. The test conditions included: a constant salt mist: 5% NaCl, PH: 6.5 -7.2, eight (8) test cycles, 7 days for 1 cycle = 56 days of testing. The battery module didn't catch fire or explode, there was no rupture of enclosure or leakage of electrolyte outside of enclosure, and it was still operational as shown in the figure.

Figure 26: Salt Spray Testing

Crush Testing

BYD tested the safety of the battery when the vehicle would be crushed, and the battery is impacted directly. The battery module is charged to 100%SOC and crushed until the module experienced over 100 kN of force. The module didn't catch fire or explode, but was rendered non-functional.

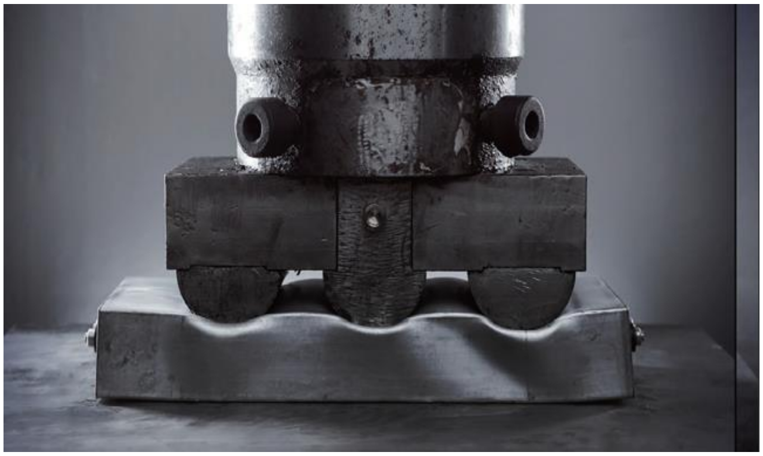


Figure 27: Crush Testing

Short-Circuit Testing

BYD tested the safety of the battery when all the PCBA protection circuit devices failed to work, and the battery was “hard” short current. The battery module was charged to 100%SOC and a short across the battery with a total resistance of less than ≤ 5 mΩ. The module didn’t catch fire or explode, but was rendered non-functional.

Figure 28: Short Circuit Testing

Pack Level Tests

Collision Test

BYD tested the safety of the entire battery packs simulating when a vehicle collided with objects at different speeds. In this test, the collision could be inflicted directly on the pack without protection from aluminum cages or bus body materials. The test conditions and the results are shown in Figure. The pack did not catch fire or explode, but was rendered non-functional.

	SOC : 100% Inbreak Angle : rear-end collision Speed : 20Kmph	SOC : 100% Inbreak Angle : rear-end collision Speed : 64 Kmph
Photo		
Result	Lightly destroyed No fire, No exploding	Smoking No fire, No exploding

Figure 29: Collision Testing

Short Current Test

BYD tested the safety of the entire battery pack when all the in-line protection devices failed to work, and the battery was placed into a “hard” short circuit condition. The battery pack was charged to 100% SOC, short circuited with the battery total resistance less than ≤ 5 mΩ. The pack did not catch fire or explode, but was rendered non-functional.

Figure 30: Short Circuit Testing

One Hour Fire Simulation Test

No other manufacturer conducts an abuse test like what will describe now, or if they do, they do not report the results, because they all know that of any the chemistries already compared above – Only the BYD chemistry will not explode. The Fire simulation test will estimate the safety of the battery in the most extreme condition that the vehicle has caught fire from some external combustion source. The battery pack was charged to 100%SOC, and then burned for a period of 1 hour. The BYD pack did not catch fire or explode with the test conducted for just one hour, but is normally rendered non-functional.

Gas Flaming Test—Total Consumption of Pack (Unlimited Time)

The BYD Iron-Phosphate battery is explosion proof even when placed in direct flames. BYD have tested these cells, modules and entire battery packs in harsher conditions than any competitor. The individual cells, modules and pack-casings may be consumed, the separators melt, the plastic components of the battery and organics will be consumed in the flames, but there is no risk of flying debris or shrapnel as is common in other EV batteries due to cascading failures of thermal events. Again, no other manufacturer will conduct an abuse test like the following. The Gas Flaming Test, a total consumption test, tests the ultimate safety and stability of the battery and chemistry in the most extreme condition that the vehicle is continually bombarded with flame from an external source. The battery pack was charged to 100% SOC, and burnt until the entire pack is consumed in the flame and any flames from the ashes have died out. The BYD pack will clearly catch fire and ash (as wanted); however, in no case will the pack explode.

Figure 31: Flame Testing

Official Certifications

The battery used in the BYD electric buses and the e6 has achieved certifications by UL and CQC.

CERTIFICATE OF COMPLIANCE

PRODUCT CERTIFICATE

President:

CHINA QUALITY CERTIFICATION CENTRE

CHAPTER 3-BATTERY CYCLE LIFE

Cycle Life Testing

The BYD Iron-Phosphate has achieved an industry benchmark in cycle life because it has overcome some of the most common failure-modes. In many Li-Ion batteries, when the cell charges and discharges anode undergoing oxidation and the cathode experiencing reduction there is a net-net volume gain causing increased pressures to build up in the cell layers as the cell is cycled. Eventually the layers “swell” so much that the pressure at the separator is so extreme that the electrolyte is pushed out of the gaps and electrolyte starvation occurs. This phenomenon immediately reduces the recoverable capacity of the cell and it dies very quickly. Because BYD’s Iron-Phosphate has the same crystal lattice between $LiFe_{1-x}Co_xPO_4$ and $Fe_{1-x}Co_xPO_4$, there is only a minute volume change (from m0.2914 nm^3→0.2724 nm^3). In fact, the oxidation capability of $Fe_{1-x}Co_xPO_4$ is low that it results in no net-net volume gain during cycling. Therefore, the degradation curves shown in a normal cycle life format are very straight and predictable. There is no other chemistry that does this. All others show a rapid drop-off or “knee” on the curve when nearing the end-of-life at about 80% of the original capacity.

BYD has continuously been cycling our very large individual modules (multiple cells in each) for many years. As shown in Figure: Multi-Cell Module Cycling Results, after 9,500 cycles, the battery capacity still remains at over 70.7% and the degradation curve is much more stable than any competitor’s modules.   This data was collected on a series of many modules all performing similarly – 6 cycles of charging and discharging were completed daily and this 9,500-cycle test has currently taken 5 years to get the data shown below.

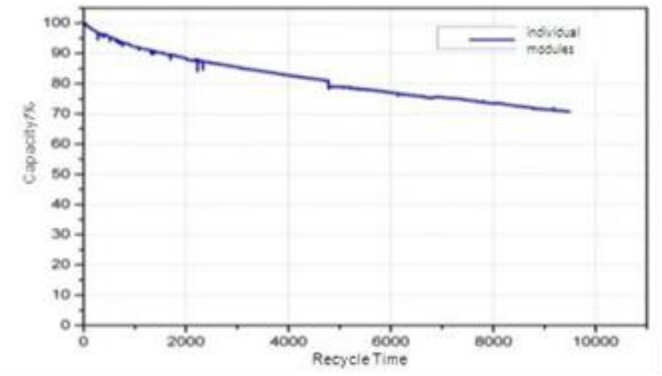


Figure 32: Multi-Cell Module Cycling

Whole vehicle packs (with multiple modules) have been tested under continuous load, raising the surface temperature of the modules to about 40C. However, even under these harsh conditions, the capacity has remained at over 85% after 2,000 cycles, and over 75% after 4,000 cycles.

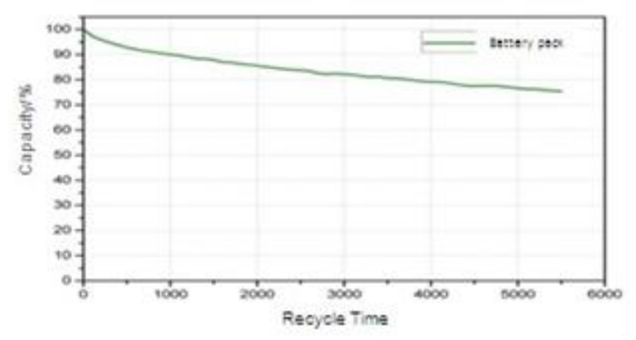


Figure 33: Pack Cycling Results

The best case laboratory cycling tests are shown with Single cells. BYD have shown that these achieve well over 10,000 cycles, and the cell capacities can still reach 70% of the initial capacity. 10,000 single cell cycle testing includes six cycles each day. Five years of this testing has resulted as follows:

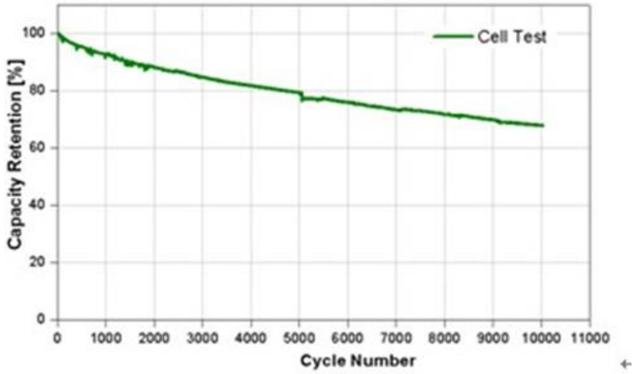
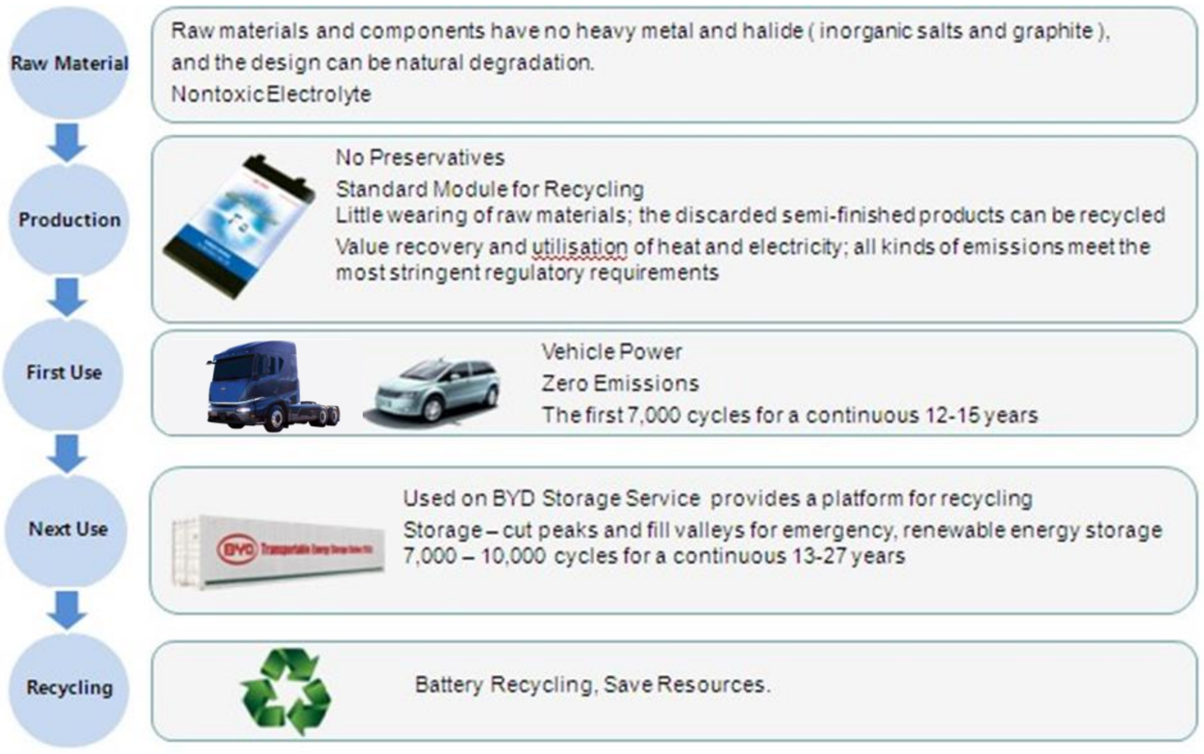


Figure 34: Single Cell Cycling

CHAPTER 4-BYD FE BATTERY ENVIRONMENTALLY FRIENDLY FEATURES

BYD's Iron-Phosphate batteries contain no toxic electrolytes, no heavy metals in either the cathode or the anode and are not manufactured with any caustic or harmful materials. This is the world's first environmentally-friendly, high energy density, and rechargeable chemistry! The BYD electric bus is also outfitted with LED lighting, the highest efficiency lighting available.



Raw Material

Raw materials and components have no heavy metal and halide (inorganic salts and graphite), and the design can be natural degradation.
Nontoxic Electrolyte

Production

No Preservatives
Standard Module for Recycling
Little wearing of raw materials; the discarded semi-finished products can be recycled
Value recovery and utilisation of heat and electricity; all kinds of emissions meet the most stringent regulatory requirements

First Use

Vehicle Power
Zero Emissions
The first 7,000 cycles for a continuous 12-15 years

Next Use

Used on BYD Storage Service provides a platform for recycling
Storage – cut peaks and fill valleys for emergency, renewable energy storage
7,000 – 10,000 cycles for a continuous 13-27 years

Recycling

Battery Recycling, Save Resources.

Figure 35: BYD Environmentally Friendly Features