Enhancing the Reliability & Safety of Lithium Ion Batteries

Over the past 20 years, significant advances have been made in rechargeable lithium-ion (Li-Ion) battery technologies. Li-Ion batteries now offer greater energy density and lower self-discharge rates compared with nickelbased (NiCd/NiMH) chemistries. Another major advantage of Li-Ion is the variety of packaging options available. Li-Ion batteries can be used in a wide range of portable consumer electronic devices, medical devices, industrial equipment, and electric vehicles.

However, these advantages come at a price. Li-Ion is the only mainstream battery chemistry that uses a flammable substance as an electrolyte SO while it's much more efficient in terms of energy density compared with water-based electrolytes, it's also potentially more susceptible to explosion and fire risk. Although the failure rate associated with Li-Ion batteries is very low, there have been several recent well-publicized incidents related to multi-cell Li-Ion battery fires, which raised concerns about the overall safety of consumer products containing Li-Ion batteries. To address these safety risks, design standards and testing protocols have been developed to provide battery pack manufacturers and device integration manufacturers with guidance on how to safely construct and use Li-Ion batteries.

This paper seeks to answer the question: *If the basic science and construction of the Li-Ion cell is well understood from the past two decades of research and development and if new battery designs are subjected to rigorous testing protocols, why then are there still incidents where batteries fail?*

Li-Ion Battery Technology

A lithium-ion battery is an energy storage device in which lithium ions move through an electrolyte from the negative electrode (the "anode") to the positive electrode (the "cathode") during battery discharge, and from the positive electrode to the negative electrode when the battery is in the charge state. Many types of anode/cathode materials and electrolyte chemistries can be used depending on end-application requirements such as storage capacity, long cycle life, and high discharge current -for example, up to 40A peak discharge current for motors. The electrochemically active materials in LiIon batteries are typically a lithium metal oxide (LiCoO,, LiFePO LiMn,0,) for the cathode, and a graphite composite for the anode. Electrolytes usually take the form of a solution or gel composed of lithium salts and organic solvents. A thin micro-porous film separator provides electrical isolation between the cathode and anode, while also allowing for ionic conductivity.
Li-Ion cells are available in three basic form factors: cylindrical, prismatic (rectangular shape)

and lithium polymer (pouch) cells. As shown in Figure 1 below, each Li-Ion package technology has tradeoffs related to specific attributes such as cost per watt-hour, energy density, weight, volumetric packing efficiency, standard versus custom package sizes, and potential for swelling under adverse conditions.

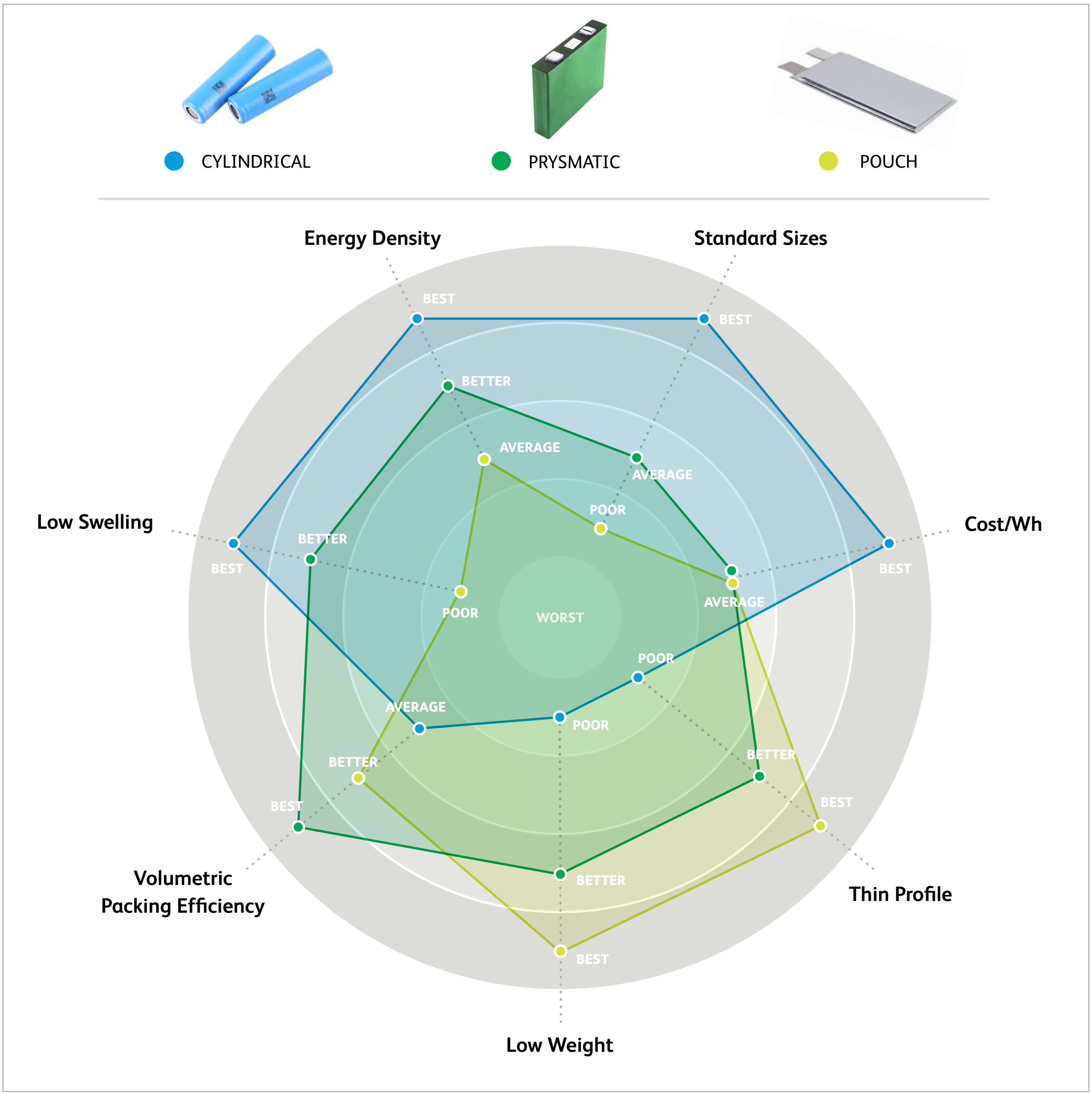

Figure 1: Li-Ion Cell Package Options and Attributes[1]

The most commonly used Li-Ion cell is the cylindrical 18650 cell which has the highest energy density and offers the lowest cost per watt hour. Prismatic cells are customized to meet specific industrial and military applications. Polymer (pouch) cells can be designed to have a low-profile customized shape (including irregular, curved, and/ or flexible shapes) and are used mainly in consumer electronics products like smartphones and laptop computers.

Each type of Li-Ion package and associated chemistry has unique characteristics that affect how it performs in a particular portable device. To meet battery reliability and safety requirements, there are specific characteristics with respect to cycle life, load current, energy density, charge time, maximum discharge rate, and package swelling which must be understood to specify an appropriate cell for an application. However, regardless of the type of anode/cathode/electrolyte chemistry or the internal construction, all Li-Ion battery packs have electrical, mechanical, and environmental hazards associated with them. If a battery pack IS not designed, manufactured or used properly, it's possible for one or more internal battery cells to rupture, explode and/or catch fire -especially when overcharged or overheated. Therefore, it is imperative that safety features be incorporated to protect the integrity of the battery pack from over-voltage, over-current, and overtemperature conditions.

Battery Management System

The primary method of protecting a multi-cell battery pack from potential damage caused by manufacturing defects is to incorporate electronic circuitry that monitors the state of the battery (temperature and charge/discharge current) and disables the battery's output if it detects a fault condition.

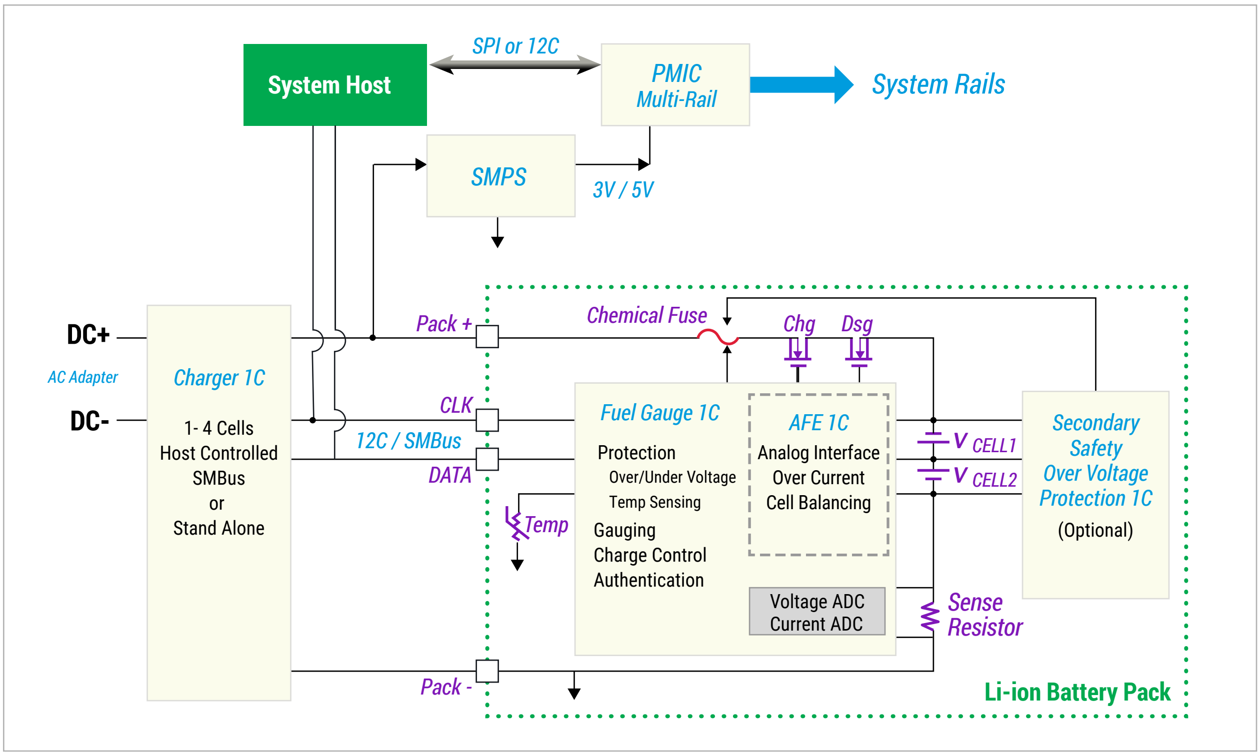

Figure 2: Multi-Cell Battery Management System[2]

An internal battery management system (BMS) is an electronic module (Figure 2) which is contained inside the battery pack and provides the following safety features:

- Over-charge protection to cut-off the charge path if battery voltage exceeds a pre-set voltage.

- Over-discharge protection to cut-off the discharge path if the battery voltage drops too low.
- Over-current protection to cut-off the current discharge path if the current exceeds a pre-set value.
- Temperature sensing to cut-off the current path if cell temperature exceeds a specified value.
- Thermal resettable fuse which provides second level protection to prevent excessive current draw.
- Communication with host controller over SMBus/12C to monitor battery status.

A battery management system (shown within dotted box of Figure 1) typically consists of several functional blocks, including cutoff field effect transistors (FETs), fuel-gauge monitor, cell-voltage monitor/ balance circuit, temperature monitor, and a state machine and/or microcontroller (MCU). The MCU is used to communicate with the cell balancing and fuel gauge circuitry and also to control the load FETs. The FET-driver functional block is designed to provide bi-directional isolation between the load and charging device. The cell voltage monitor/balancer circuitry tracks the voltage of each series/parallel cell to balance weaker and stronger cells and to prevent over-charging or over-discharging. The temperature monitor circuit uses one or more thermistors to monitor the internal battery pack temperature. A secondary protection circuit is often used in case the primary safety circuit fails.

Regulatory Agency Safety Testing Standards

Battery pack suppliers and manufacturers of battery-powered products must meet specific safety performance specifications prior to offering their products for sale. To ensure these safety conditions are met, there are several global independent agencies that have developed standards for electrical design certification and safety testing intended to address potential failure modes and end-customer abuses of Li-Ion batteries.
These regulatory agencies include the Institute of Electrical and Electronics Engineers (IEEE), Underwriters Laboratories (UL), International Electrotechnical Commission (IEC), and the Japanese Standards Association (JIS).

Institute of Electrical and Electronics Engineers (IEEE)

- **IEEE 1625:** Rechargeable batteries for multi-cell mobile computing devices

Underwriters Laboratories (UL)

- **UL 1642:** Lithium battery cells
- **UL 2054:** Household and commercial batteries
- **UL 2575:** Lithium-Ion battery systems for use in electric power tool and motor operated, heating and lighting appliances

International Electrotechnical Commission (IEC)

- **IEC 62133:** Secondary cells and batteries containing alkaline or other non-acid electrolytes safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications
- **IEC 62281:** Safety of primary and secondary lithium cells and batteries during transportation

Japanese Standards Association (JIS)

- **JIS C8714:** Safety tests for portable LithiumIon secondary cells and batteries for use in portable electronic applications

In the United States, the most recognized safety agency is Underwriters Laboratories (UL). Table 1 below, provides details of the UL 2054 requirements which specify electrical, mechanical, and environmental safety tests related to temperature, venting, leakage, explosion, and fire.

UL 2054 Tests and Requirements for Battery Packs	
Electrical Tests	**Requirements**
Short Circuit Test	No explosion, no fire, temperature < 150°C
Abnormal charging test	No explosion, no fire
Abusive overcharge test	No explosion, no fire
Forced discharge test	No explosion, no fire
Limited power source test	No explosion, no fire
Battery pack component temperature test	Temperature within specification
Battery pack surface temperature test	Temperature within specification
Environmental Tests	**Requirements**
Heating test	No explosion, no fire
Temperature cycling test	No explosion, no fire, no venting, no leaking
Mechanical Tests	**Requirements**
Crush	No explosion, no ignite
Impact	No explosion, no ignite
Shock	No explosion, no fire, no venting, no leaking
Vibration	No explosion, no fire, no venting, no leaking
Battery Enclosure Tests	**Requirements**
250lb. crush	No explosion, no fire
Mold stress relief	No explosion, no fire
Drop impact	No explosion, no fire
Fire Exposure Tests	**Requirements**
Projectile	No explosion, no ignite

Table 1: Tests and Requirements for Battery Packs[3]

To maintain brand image and to mitigate potential liability, consumer electronics device manufacturers focus primarily on obtaining the following two Li-Ion battery safety certifications which have achieved global recognition: UN/DOT 38.3 (required for transporting batteries, especially on aircrafts) and UL 2054. Normally, the cell manufacturer is responsible for UL 1642 certification and the application device manufacturer is responsible for obtaining the UL 2054 listing for custom battery pack designs.

Li-Ion Battery Failure

The majority of Li-Ion battery manufacturing defects are the result of poor quality control processes which allow damage or contamination to occur to the extremely thin micro-porous film separator that provides electrical isolation between the cathode and anode. This can lead to an internal short circuit and a subsequent buildup of heat (especially during a high charge state) which can then trigger a thermal runaway condition in which a battery cell overheats potentially causing adjacent cells to also overheat. This buildup of heat exerts pressure inside the battery which can then lead to an explosion and/or fire. Since the construction of lithium polymer (Li-Po) cells typically include a relatively fragile external casing (pouch), a fire hazard can also be caused by a high force puncture that creates a spark and ignites the reactive lithium.

Therefore, rigorous manufacturing quality control and testing for Li-Ion batteries in general, and more specifically for low profile lithium polymer batteries, is required.

End-User Precautions

The risk of an explosion or fire can be greatly reduced by following some simple guidelines for handling Li-Ion batteries. Most importantly, the electronic device which contains the Li-Ion battery should be kept away from high temperature environments, especially if connected to a charger. This includes not leaving electronic devices in a hot vehicle for prolonged periods or using a smartphone, laptop, etc., in a nonventilated environment. For example, using a smart-phone in a non-open-air environment (e.g. jean pocket) or using a laptop on a bedspread (which blocks the laptop's airflow vents) is not advisable. Under these types of conditions, an electronic device can quickly generate a significant buildup of internal heat that can cause the battery pack to overheat.

Protecting a smartphone from excessive mechanical stress or shock is very important to ensure

Two scenarios that could lead to the batteries of electronic devices overheating

the battery assembly does not incur internal damage which could lead to a shortcircuit. Another important user precaution is to make sure the correct battery charger is used for charging the battery pack. Using the device manufacturer's recommended charger will prevent the possibility of an incompatible charging algorithm damaging the battery pack.

Conclusion

The vast majority of reliability and safety concerns over the past ten years have been targeted at Lithium Polymer (Li-Po) cells rather than cylindrical or prismatic cells. The reason for this can probably best be understood as a byproduct of the significant competition between several of the major consumer electronics manufacturers. For example, a focus on thinner and lighter devices, as well as higher capacity batteries with faster charge cycles, has been pushing Li-Po battery technology beyond the quality control limits of even the most modern high-volume production environments in Korea and China.

The goal of any battery manufacturer should be to ship batteries that can safely fail (vent or puff up rather than explode), even under a combination of internal battery damage, external package stresses, and/or electronic battery management failures. Detecting a potential short circuit resulting from internal battery damage is very difficult, even with 100 % machine vision sampling at the final X-ray inspection station. The best way to prevent future large-scale battery failure incidents is to reassess battery design/packaging tradeoffs to allow for more robust electrode/separator materials and less aggressive dimensional construction parameters. Also, improving the battery's exterior package protection inside a smartphone will go a long way towards preventing isolated device failures due to mechanical stress.

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Jon has a thorough understanding of the product development process and specializes in hardware design, system integration and high-volume consumer electronics manufacturing.
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