Lithium-Ion Battery Design for Safety

Summary

Lithium-ion cells, modules, and battery packs have been in use for over 20 years. Their small size and weight, and high energy density have made them common in many rechargeable consumer electronic devices, and more recently in industrial, automotive, and military applications. The benefits of lithium-ion over other battery chemistries are being realized in a number of new and emerging applications and use cases. The utility and benefit of lithium-ion is well known, but so are the unique challenges associated with this chemistry.

Challenge

The deployment of lithium-ion batteries has been very successful. Their overall failure rate is very low when compared to the total number of batteries in use worldwide. However, in recent years there have been high-profile examples of lithium-ion battery failures, which have resulted in fires.

Are lithium-ion batteries safe? Lithium-ion, while offering high energy density, is also a reactive element, leading to the possibility of 'thermal runaway' if abused.

Some of the abuses that can cause failures are:

- Over-charging – may cause the positive electrode to react with the electrolyte, resulting in heat and pressure, and possible fire.
- Over-discharging – may cause damage to the cell cathode, and possible internal short circuit and lithium plating.
- Over-heating – may cause the negative electrode to react with the electrolyte.
- Short circuit (on terminals) – may cause battery over-heating and over-pressure.
- Mechanical stress – may cause damage to the lithium-ion cells or battery packs, which could lead to possible internal short circuits and other failures.

Discussion

Lithium-ion cell reliability and safety starts with the use of high quality electrode, electrolyte, and separator materials. The cell manufacturing process is critical to insure the quality and consistency of the end product. Today, there are a number of high volume manufacturers of lithium-ion cells that provide quality products with high reliability. These cells are manufactured into three popular package styles: cylindrical, prismatic, or polymer.

Most applications for lithium-ion cells are for modules or batteries that are complete assemblies of multiple cells arranged in series and/or parallel configurations. The number of cells and their configuration determines the nominal voltage and capacity of the module or battery. Batteries come in a wide variety of custom and standard packages depending on the end application, requirements, and cost.

A battery can experience abuse from an incorrect connection across its terminals such as a short circuit. Other types of abuse can occur from extremes in temperature, charge, discharge, mechanical stress and load imbalance.

At a system level where two or more batteries are connected together, abuse can occur from incorrect connection between the batteries, mismatched load or charger circuits to the batteries, or from the same extremes that can affect an individual battery.

To mitigate the effects of abuse and misuse, emphasis must be placed in the selection of the battery technology, configuration, and specifications that fully address system needs and safety.

Solution

The key points to a safe and robust design are to identify the characteristics and requirements of energy storage needs for a particular application. Optimum performance and safety of lithium-ion cells and batteries are achieved when close attention is paid to the specifications, electrical and mechanical design, and regulatory standards.

Regulatory Standards for Cells and Battery Modules

Most countries follow safety standards and regulations that require products to be evaluated against a set of established criteria demonstrating product safety for their intended use.

The most common and widely accepted standards are based on International Electrotechnical Commission (**IEC**), Underwriters Laboratories (**UL**), and United Nations (**UN**) publications. The list below describes some of the key standards for lithium-ion cells, battery packs and modules as they apply to portable, Light Electric Rail (**LER**) and *stationary* applications.
Note: Regulatory standards for *nonstationary* applications, although an important part of the design and product safety for the *nonstationary* applications, are not discussed in this paper.

- **UL 1642** Lithium batteries – this is a safety standard with requirements intended to reduce the risk of fire or explosion when lithium batteries (cells) are used in a product.
- **IEC 62133** Secondary cells and batteries containing alkaline or other nonacid electrolytes – Safety requirements for portable sealed secondary cells and for batteries made from them, for use in portable applications.
- **UL 1973** Batteries for Use in Light Electric Rail (**LER**) Applications and Stationary Applications – The standard evaluates the electric energy storage system's ability to safely withstand simulated abuse conditions.

  From **UL 1973** a key part of the requirement states:

  5.7.3 Electronic circuits and software controls relied upon, as the primary safety protection, shall be evaluated to the Standard for ***Tests for Safety-Related Controls Employing Solid-State Devices, UL 991,*** *and the Standard for Software in Programmable Components, UL 1998, or the Standard for Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems, IEC 61508 series as applicable based upon the design and complexity of the controls.*

- **UL 991** – the section covering solid state devices states:

  6.4 A failure-mode and effect analysis (FMEA) in accordance with Failure-Mode and Effect Analysis (FMEA), Section 7 is required to identify critical components.
  6.5 The failure of a solid-state device or an electronic component (such as due to an open or short circuit within a component) during operation of a control shall result in one or more of the following conditions:
    a) No loss of declared protective function as a result of control shutdown or on the intended operation.
    b) For attended products, activation of a trouble indication considered as acceptable in the end product standard.
    c) Shutdown in a manner that complies with the end-product application if the protective function has been negated.

- **UN 38.3** "Recommendations on the Transportation of Dangerous Goods Manual of Tests and Criteria", **Section 38.3** requirements are used to ensure the safety of lithium batteries during transport.

Cell: UL 1642, IEC 62133, UN 38.3, IEC 62619 (draft)

Module: UL 1973, IEC 62619 (draft) IEC 62485-1 (draft), UN 38.3

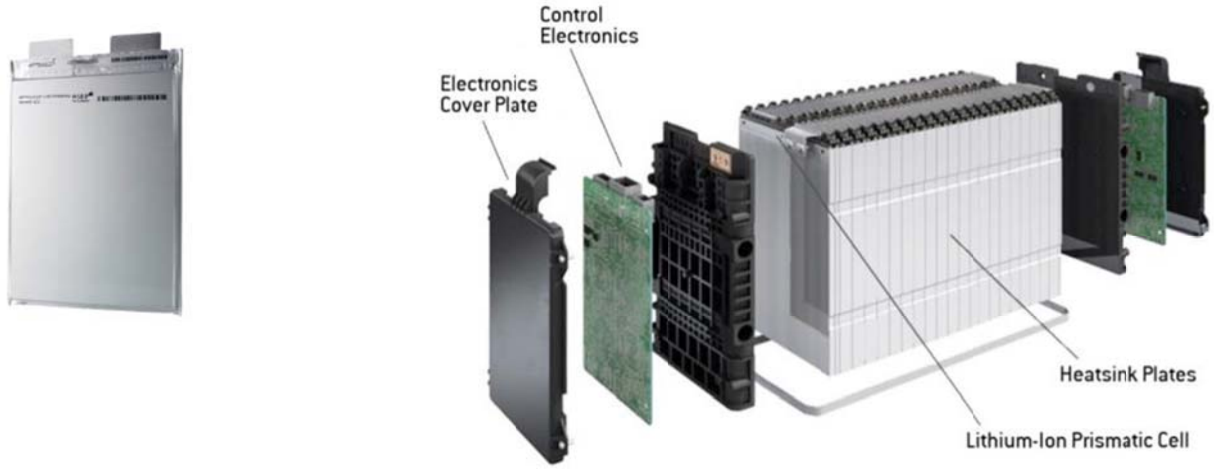


Figure 1 Regulatory Standards for Cells and Modules

Key Requirements for Battery Pack Design

For a battery pack or energy storage system design, the end application and requirements drive the design and selection of cells, components, and modules. Some of the key requirements are voltage, energy, capacity, temperature, humidity, cycling characteristics, and service life. Service life is derived from the combined effects of float/calendar life and cycle life. Cycling effects, particularly those that are periodic and frequent can impact battery life and safety. The selection of a lithium-ion cell or module is based on these key requirements, as well as, cost and size. Typically, they are engineered for either energy or power applications. Finally, the requirements for the mechanical integrity of cells, components, and wiring are an important part of battery pack performance and safety.

Smart Battery Design for Safety

Regardless of the cell chemistry used, most energy storage and battery pack designs use a Battery Management System (**BMS**), which is composed of electrical circuits to manage cell, load sharing, and other operational functions. The most common industry name for batteries with an integrated BMS is “Smart Battery”. However, not all BMS or Smart Batteries are designed with adequate safety and protection measures to address cell, battery, or system level abuses. Knowing how variable battery cell failure modes can be when damaged, standards such as UL 1973 require tests for safety. For example, tests for overcharge, short circuit, forced discharge, and over temperature at the product level [1]. Since BMS designs use solid state devices to implement safety critical functions, they should be designed using UL 1973, and the applicable UL 991 standards and tests, to validate safe operation after a single fault is applied anywhere in the system. A robust BMS design should include fail safe redundant circuits as further protection against abuse. In some designs redundant protection circuits maybe required to pass UL 1973 tests.

Redundancy in the battery design is essential to insure safe and reliable operation under normal and abusive conditions. Despite having a robust design, the reality of manufactured products is that some level of component failure is possible. Even if the expected failure rate is low, at .05% for example, shipping 10k pieces means that 5 pieces are going to fail, and when they do, it should not be catastrophic. Standards bodies have recognized the need for lithium-ion products to be “fail safe” in the presence of component faults and known failure conditions. To validate the design methods used for product safety, single fault test conditions are applied to individual components and/or components within identified safety circuits to insure the design effectiveness. These critical safety functions and components are identified using a Failure Modes and Effects Analysis (**FMEA**) process. Components which are typically faulted include the main protection switches in a design, as well as, the drive circuits which control them. After the fault has been applied, over charge, over current and over temperature tests are performed. This means that a product which bears the UL 1973 mark will be designed and tested to tolerate a single fault event anywhere in the system and maintains a “fail safe” response.[3]

Transport of Dangerous Goods: Lithium-ion Cells and Battery Packs

Lithium-ion cells, battery packs, and systems are considered Dangerous Goods (Hazardous Material) and must abide by national and international requirements which are based on the UN Recommendations on the Transport of Dangerous Goods, Model Regulations. The model regulations are further refined for air and sea transport by two specialized UN agencies, International Civil Aviation Organization (ICAO) and International Maritime Organization (IMO). ICAO works with Member States and global aviation organizations to develop international Standards and Recommended Practices (SARP). ICAO works closely with the International Air Transport Association (IATA) to achieve this result. For transport by sea the IMO (International Maritime Organization) is the United Nations agency that has the responsibility for the safety and security of shipping and the prevention of marine pollution. Its regulatory publication is the International Maritime Dangerous Goods (IMDG) Code. The regulations that are published, UN Recommendations on the Transport of Dangerous Goods, Model Regulations, ICAO, IATA, and IMDG are referenced by "States" or sovereign countries when developing their legally-enforceable national sea, air and land dangerous goods regulations.

In the United States, transportation of hazardous material is regulated by Title (part) 49 of the Code of Federal Regulations (**CFR**s). Title 49 CFR Sections 100-185 of the U.S. Hazardous Materials Regulations (**HMR**) contains the requirements for transporting cells and batteries. Before transportation can take place the battery cell, battery, and battery assemblies must meet the criteria contained in the UN Recommendations on the Transport of Dangerous Goods – Manual of Tests and Criteria, Part III, Section 38.3. The cell or battery pack manufacturer needs to realize lithium-ion products are dangerous goods (hazardous materials). They must ensure their products meets the criteria of UN 38.3 to legally ship product between facilities or return product under a Return Material Authorization (**RMA**).[3]

UN 38.3 also requires short circuit and overcharge testing after the product has gone through altitude, thermal, vibration, and shock testing[2]. It is important to note the significance of the order of the testing. Battery packs that have insufficient mechanical support will start to mechanically fail during vibration and shock testing. When the test sequence gets to the electrical section containing the BMS functions it will likely fail if the mechanical part of the design is inadequate. For example, designs with sizeable electrical components on a printed circuit board (**PCB**) with no mechanical support, or poorly designed cell interconnections, will not pass UN 38.3 tests.

The energy storage industry has to be diligent to obtain from lithium-ion battery vendors documentation showing conformance to UN 38.3 regulations prior to purchase or use of their products. For examples of currently available commercial battery packs that show questionable design and manufacturing practice, refer to Figure 6 through Figure 9.

NEC Energy Solutions – ALM Family Electrical & Mechanical Design

NEC Energy Solutions ALM family of batteries includes EverSafe™ battery protection technology as a Battery Management System (BMS) that provides fully redundant protection from internal failures or external abuse. It provides system-level protections for battery strings and power system operation, with automatic adjustments and recovery from system level faults or abusive applications.

Redundant temperature sensors and voltage measurements are part of the design used to monitor the cells. Voltage, current, and temperature sensor monitors are employed at the battery level for an additional layer of safety. When a fault condition is detected, power electronics (FETs as eFuse) disconnect charging or discharging of the battery for further protection. As an extra protection layer, redundant FETs are used in the charging path. No processor or software is used in the cell management or protection circuits. See Figure 2, on page 6.

ALM Family: Specific Layers of Protection

- Fast response to direct short-circuits (e-fuse).
- Automatic balancing of batteries at different State of Charge (SOC**)** in series and parallel strings.
- Easy recovery from fault conditions.
- Over temperature protection
- Fast retry and reconnect from short circuits and other protection conditions.
- Voltage present on terminals for diagnostic purposes even when in voltage protection modes
- Pre-charger circuit allows charging and recovery from under-voltage protection event, including smart chargers.

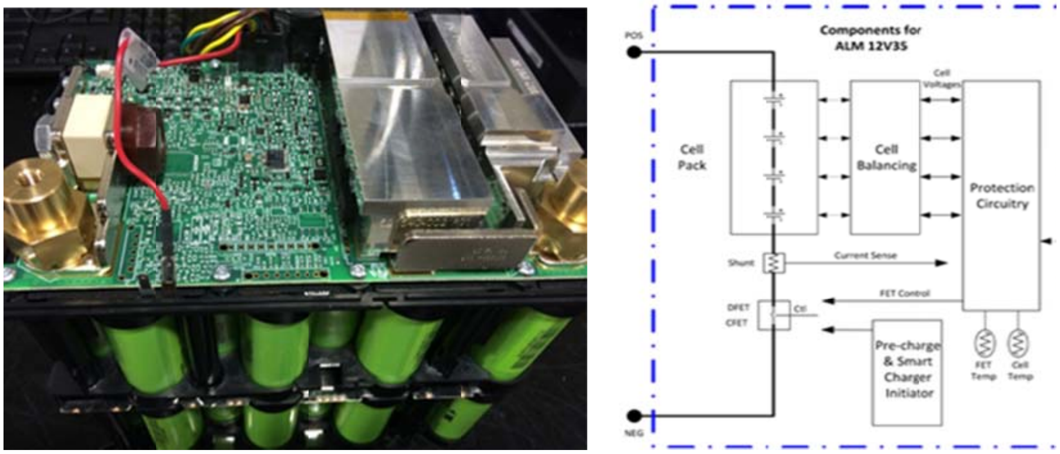


Figure 2 ALM 12V35 Cell Management Protection Circuitry

NEC Energy Solutions ALM products are designed, tested, and certified to IEC 62133 and UL 1973. They are also designed and tested to meet applicable EMC emission/immunity regulations. The ALM products are compliant with UN 38.3.

The ALM 12V35 i-Series model provides monitoring, logging, alarms, and reporting of fault events. This series provides remote monitoring and control using SMBus or CAN Bus communications protocols. The ALM 12V35 monitoring may be enabled even if the battery is disabled due to protection events. This feature can be critical during system trouble shooting.

Mechanical Design

Equally important as the electrical design are the mechanical interconnections of battery pack assemblies. Passing drop and vibration testing per the relevant safety and compliance standards, such as UN 38.3, is required to sell lithium-ion energy storage products and also provides for a mechanically robust design. The mechanical design includes proper wire routing, cell interconnections, mechanical supports, and chassis features.

Module Design

Key features found in a quality module design should provide for balanced current flow between cell configurations to prevent local heating and insure robust mechanical attachment of the cells. This is achieved from a weld strap design that facilitates reliable and consistent weld points to each cell, and provides mechanical and thermal integrity. Reverse current protection of cells connected in parallel is another critical safety factor. This protection can be achieved by providing fusing into the cell interconnection design. Figure 3 shows the weld strap used in the NEC Energy Solutions ALM 12V35 battery. It shows the weld tab, fusing, and basic structure of the interconnection design. Its design insures a balanced current flow between cells to prevent local heating. Additionally, cell fusing is built into the tab to provide a failsafe against short circuit, reverse current, and other severe abuse conditions.

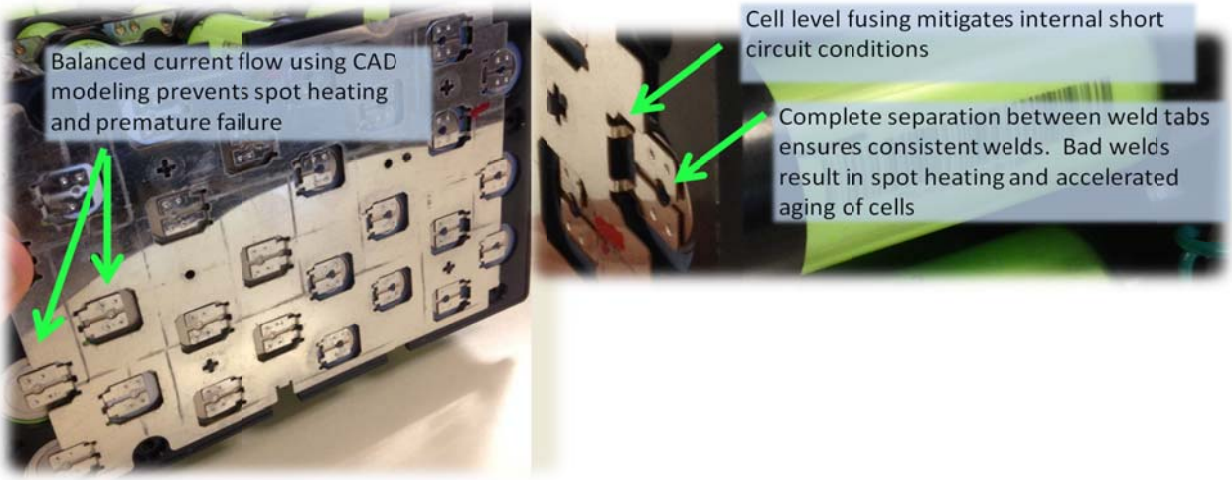


Figure 3 ALM 12V35 Weld Strapping Features

Mechanical Integrity

The battery module design should protect the mechanical integrity of the cells, wiring, and other sub-assemblies within the battery pack. Figure 4 shows molded assemblies (black) used in the ALM 12V35 that hold the cells in place and eliminates mechanical force on the cells and weld strap. Further steps in the design included the use of tooled parts to secure the cell pack to other assemblies within the battery chassis. These assemblies are designed to limit mechanical stress and prevent breakage or failures during their manufacture and use. This robust design enabled the ALM 12V35 to pass challenging mechanical and vibration tests required by UN 38.3.

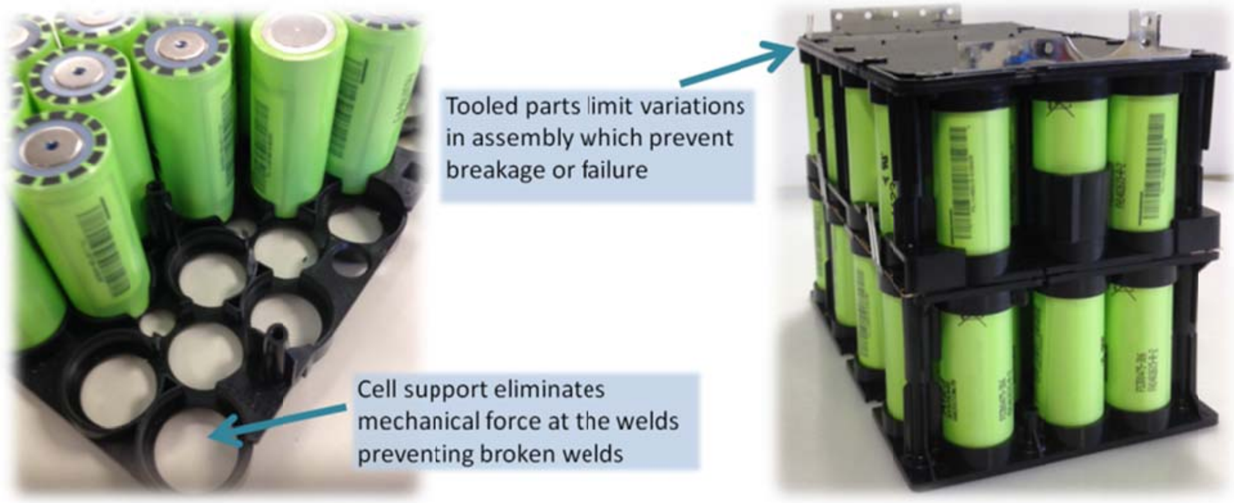


Figure 4 ALM 12V35 Mechanical Design Integrity

Cell packs within a battery may have internal wiring to connect cells or sensors. For NEC Energy Solutions ALM 12V35 battery, the mechanical design incorporates wire retention gaps (Figure 5) into the molded assembly to route wires within the pack preventing them from being pinched or chaffed.

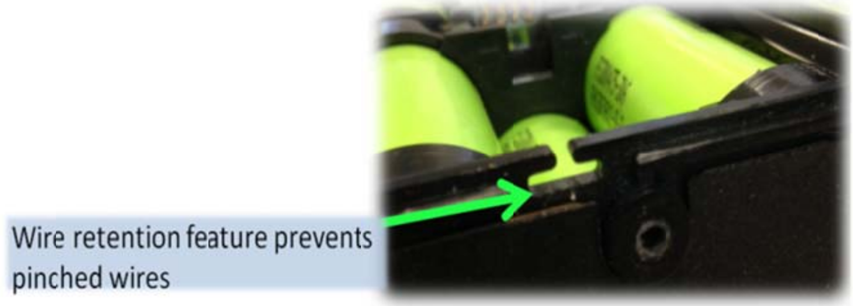


Figure 5 ALM 12V35 Mechanical Design, Wire Retention

Examples - Poor Mechanical & Electrical Design

Examples of Poor Electrical Design

There are commercial lithium-ion batteries on the market that are not certified to UL 1973, IEC 62133, or UN 38.3. Figure 4 is an example of a commercial lithium-ion battery with a BMS for cell balancing, but without overvoltage protection. It would not pass UL certification. This is a risky proposition for the end user. Vendors who do not certify their products to UL 1973 call into question the safety of their products. Energy storage designers and manufactures should not place a risk on safety by using uncertified lithium-ion products.


This Lithium Iron Phosphate battery has NO OVERVOLTAGE PROTECTION! This is an accident waiting to happen! (board shown is “balancing” only)

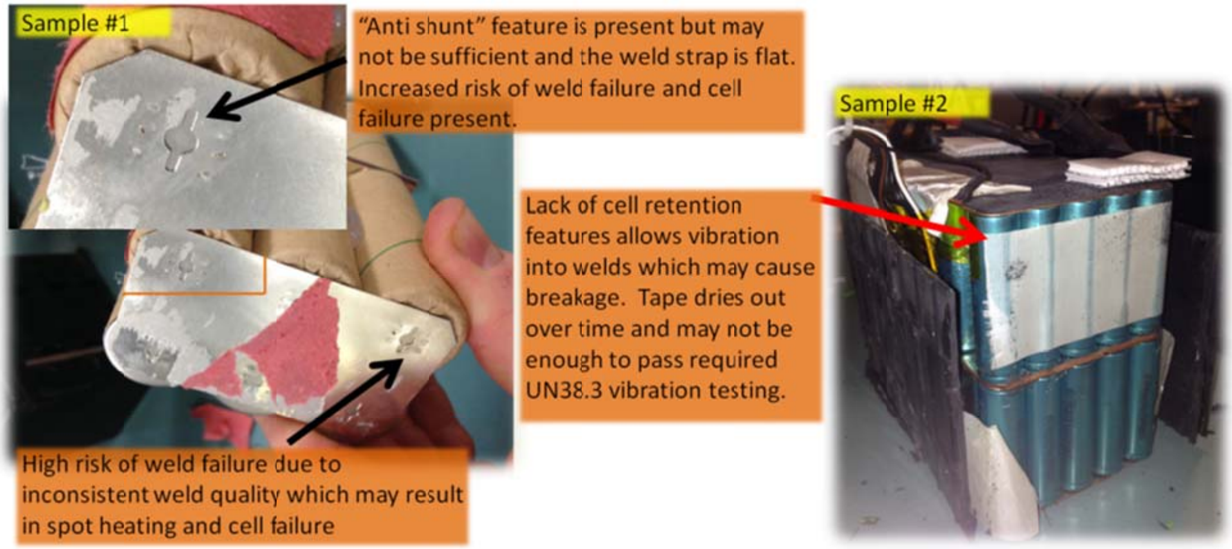
Figure 6 Example of Lithium-ion Battery with a BMS for Cell Balancing, but without Over Voltage Protection

Examples of Poor Mechanical Design

There are a number of lithium-ion battery suppliers who provide battery packs that use questionable design practices to address mechanical stress and integrity, shown in Figure 7, Figure 8, and Figure 9. These show module designs of commercially available lithium-ion batteries with a number of issues where safety could be compromised.

Sample #1, Figure 7 shows an anti-shunt feature that may not be sufficient, with a weld strap that is flat and prone to mechanical failure under stress. Furthermore, the weld quality across the cell pack is inconsistent which could lead to local heating and eventual cell failure.

Sample #2, Figure 7 shows a cell pack design that does not provide any cell retention elements or assemblies to mitigate vibration and other mechanical stress. The assembly in the picture uses tape to provide a level of retention, which is not reliable or effective as the tape will eventual dry out and lose its adherence qualities to hold cells in place. This design practice exposes the weld straps to vibration and possible breakage. It is not clear how the battery pack shown could pass the rigors of UN 38.3 vibration testing required of all lithium-ion batteries.



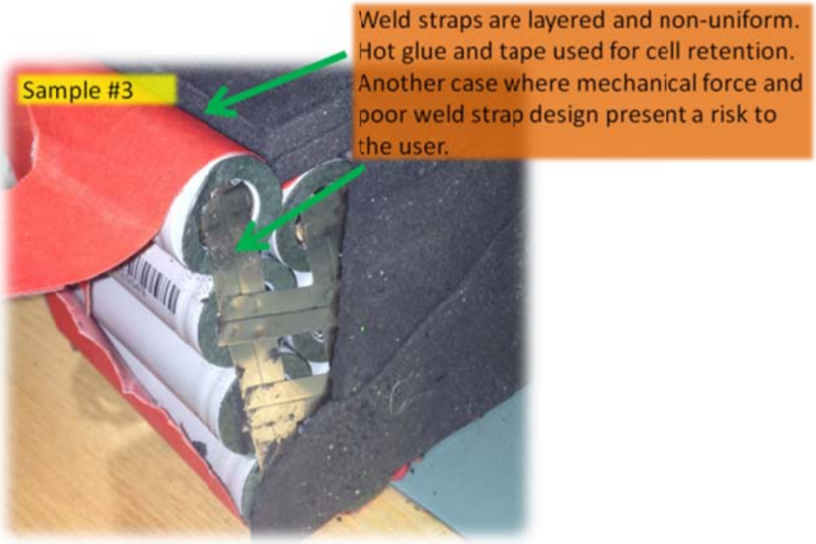
“Anti shunt” feature is present but may not be sufficient and the weld strap is flat. Increased risk of weld failure and cell failure present.

Lack of cell retention features allows vibration into welds which may cause breakage. Tape dries out over time and may not be enough to pass required UN38.3 vibration testing.

High risk of weld failure due to inconsistent weld quality which may result in spot heating and cell failure

Figure 7 Sample #1 and Sample #2 Poor Mechanical Design

Sample #3, Figure 8, on page 10 shows weld strap design with straps that are layered and non-uniform. This design provides poor weld strap integrity and is prone to easy breakage from mechanical stress and force. This presents another safety issue for the battery user. The cell retention design is tape and hot glue with surrounding foam. This is questionable in providing good support of the cells and weld strap against vibration, adding further risk to breakage.

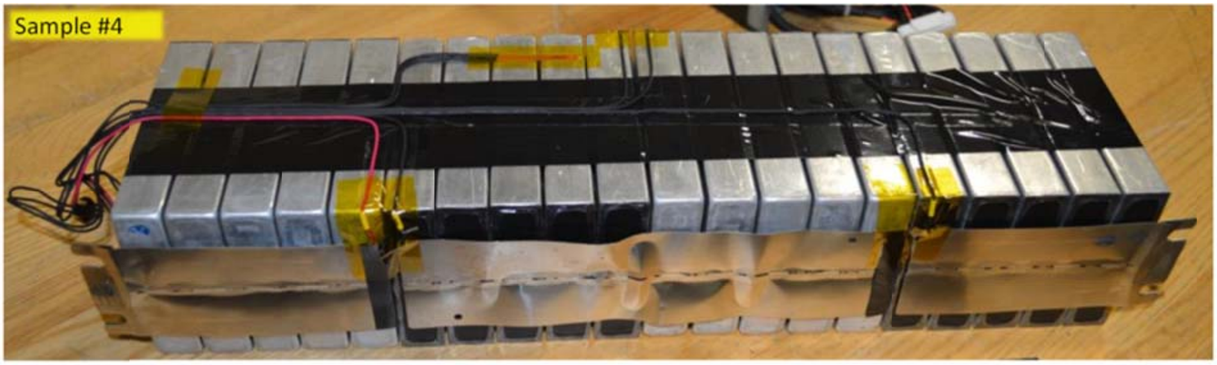


Weld straps are layered and non-uniform. Hot glue and tape used for cell retention. Another case where mechanical force and poor weld strap design present a risk to the user.

Figure 8 Sample #3 Non-uniform Weld Strap Design Present Risk to the User

Example of Poor Electrical & Mechanical Design

Sample #4 shows a pack of prismatic cells. This assembly (Figure 9) has a number of electrical and mechanical issues. The first is no cell fusing. This presents the real risk of the failure propagating from the shorted cell, via thermal run away, into other cells. The weld strap is minimal in its design where the weld integrity may not withstand mechanical stress and vibration. This is especially problematic as the cell pack's only mechanical retention is black tape. It is unlikely this unit will survive UN 38.3 testing. The combination of poor weld strap design and no retention could create unintended shorting of the cells. This would present a real safety issue.



- No cell level fusing → Risk of failure propagation
- Lack of weld strap design → Weld failure may result in cell failure by over stressing individual cells
- Held together with tape → Module may fail in shipping or not pass UN38.3. Unintended shorting possible

Figure 9 Sample #4 Prismatic Cells with Multiple Electrical and Mechanical Issues

The products shown in Figure 6, through Figure 9 are only a few examples of questionable lithium-ion batteries commercially available today. It is imperative when procuring battery packs and other lithium-ion energy storage products to obtain proof of UN 38.3 certification. This should be done not only for the hazardous material requirements, but to insure the safety of the product. Additionally, it is essential to procure products certified to standards such as IEC 62133, UL 1973, and other safety regulations and standards required for the end application. For products that have a UL mark, the end user should ask if there are any Conditions of Acceptability **(CofA).** Sometimes the CofA lists exceptions reached in product design or testing. Verify if these conditions have an impact on the target system requirements or application.

NEC Energy Solutions, Further Information

NEC Energy Solutions ALM family of lithium-ion batteries are designed, manufactured, and tested to ensure international product safety conformity, as well as, application specific certifications.

NEC Energy Solutions ALM products are designed and tested to IEC 62133, UN 38.3, and UL 1973 results in robust products that meet transportation and safety requirements. Proof of certification is available upon request.

Visit www.neces.com for the latest information and data sheets.

References

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2. UN Recommendations on the Transport of Dangerous Goods – Manuel of Test and Criteria 5th revised edition, Amendment 2 Section 38.3 - Lithium metal and lithium Ion batteries
3. Safety First: Required Industry Practices to Enable the Widespread Adoption of Energy Storage, G. Tremelling. Conference Proceedings, Battcon 2015, Vol. 1,2015