COMMERCIAL LITHIUM ION RESERVE POWER SYSTEMS

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ABSTRACT

Commercial applications for Lithium Ion Reserve Power Systems are emerging for niche applications that have traditionally utilized lead acid or nickel based systems. Lithium-ion systems are higher in energy density than traditional systems, but are hybrid in nature since they include both lithium ion cells and electronic controls. The hybrid nature of the systems, require unique design, development, and testing considerations for system developers. They also present new variables that the end user must consider when evaluating and purchasing these new technology products.

HISTORY OF LITHIUM BATTERY DEVELOPMENT

In relation to lead and nickel based battery technologies, lithium cells are in their infancy, with most developments occurring in the last 30 years. Lithium cell chemistries were first developed by M.S. Whittingham in the 1970s using titanium sulfide as the cathode and lithium metal as the anode. In 1980, Rachid Yazami discovered the reversible intercalation of lithium into graphite and in 1981 Bell Labs developed a workable graphite anode which was very critical since it allowed the highly reactive (and therefore unsafe) lithium metal anode to be replaced. In the 1980s, scientists developed new cathode chemistries and by 1991 Sony first released a commercial lithium-ion rechargeable battery in their consumer electronics products. Later in the 1990s, scientists lead by Dr. Goodenough of the University of Texas identified lithium iron phosphate and other phosphor-olivines as cathode materials for lithium-ion batteries. These materials were selected due to their lower cost, stability, safety and performance characteristics. Lithium Ion cells continue to emerge with varying cathode and anode materials which dictate the cell operating voltage, operating characteristics and applications. Various anode and cathodes can be combined to form unique cell types. Chemistries such as cobalt oxide, manganese oxide (spinel), iron phosphate and titanate are readily available in the marketplace, with many new chemistry variations expected in the years ahead. Continued work using new materials and nano-based versions of existing materials will move lithium-ion chemistries forward in both energy density and safety.

CELL FORM FACTORS AND QUANTITIES

Historically, lithium-ion cells have been produced in the 18650 size cylindrical format (18650 equates to 18 mm in diameter by 65 mm in length). This form factor could be mass produced and was developed to power consumer electronic devices such as laptop computers. The goal was to improve the performance of the typical nickel cadmium cells which exhibited capacity loss due to memory effect, limited cycle life and high self discharge rates. As larger, more power hungry applications have emerged, new form factors such as larger cylindrical formats, foil pouch flat cells and prismatic cells have been developed which increase the options for system capacities, configurations and physical size. System design applications can package these new form factors to vary cell quantities and enhance system packaging and performance. These newer cell form factors allow system designers to reduce cell counts and therefore reduce the number of internal connections and associated failure modes. They also allow system designers to enhance thermal management.

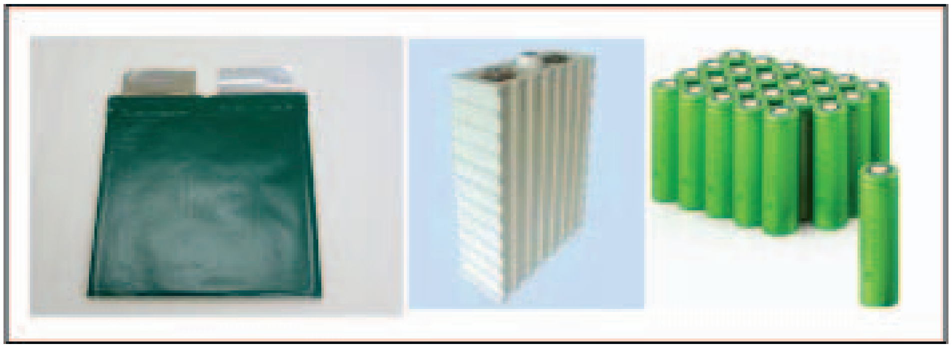

Figure 1. Various Lithium-Ion Cell Form Factors

Table 1. Examples of Electrode Materials

Anode Materials	**Average Voltage vs. Li/Li$^+$**	**Gravimetric Capacity**
Graphite	0.1-0.2 V	372 mAH/g
Titanate	1-2 V	160 mAH/g

Cathode Materials	**Average Voltage vs. Li/Li$^+$**	**Gravimetric Capacity**
Cobalt Oxide ($LiCoO_2$)	3.7 V	140 mAH/g
Manganese Oxide ($LiMn_2O_4$)	4.0 V	100 mAH/g
Tri-metal Oxide ($LiCo_{⅓}Ni_{⅓}Mn_{⅓}O_2$)	3.6 V	160 mAH/g
Iron Phosphate ($LiFePO_4$)	3.3 V	150 mAH/g

CELL TESTING: VOLTAGE EFFECTS

Lithium-ion cells have historically been designed for consumer electronics' cycling applications, and therefore the cells operate very well in this duty cycle. In these applications, the end user operates a device until the 'low battery' light illuminates; the battery fuel gage indicates only minutes of use remain or the device ceases to function (low voltage cut off shuts off the device automatically). Since many laptop users prefer continuous operation of their devices (while working on their desks), they continue to use AC power to operate the computer and also continuously charge the battery pack. Since most lithium-ion cell designs prefer to cycle versus being maintained at a constant fully charged state, battery life is reduced due to this type of float service usage.

Many commercial applications also do not operate in a cycling mode, but operate in a standby or float mode which attempts to maintain the battery system in a highly available state. Since lithium cell chemistries were not historically developed for this type of application; commercial applications require a significant amount of cell testing and data collection to understand the parameters to optimize cell performance and longevity in these applications. A very effective solution to offset the effects of a continual high voltage float charge is to operate the system at a partial state of charge (PSOC). Typical testing for these applications should include: 1) long duration cell testing at various float voltages to determine available capacity, 2) cell testing at varying voltages to assess cell life, and 3) cell testing at various voltages and varying temperatures to assess the temperature effect on these selected voltages. These tests have shown that a mere 0.1V overcharge can reduce a cells life by 50%. Add in an elevated temperature and cell life can be reduced by as much as 90%.

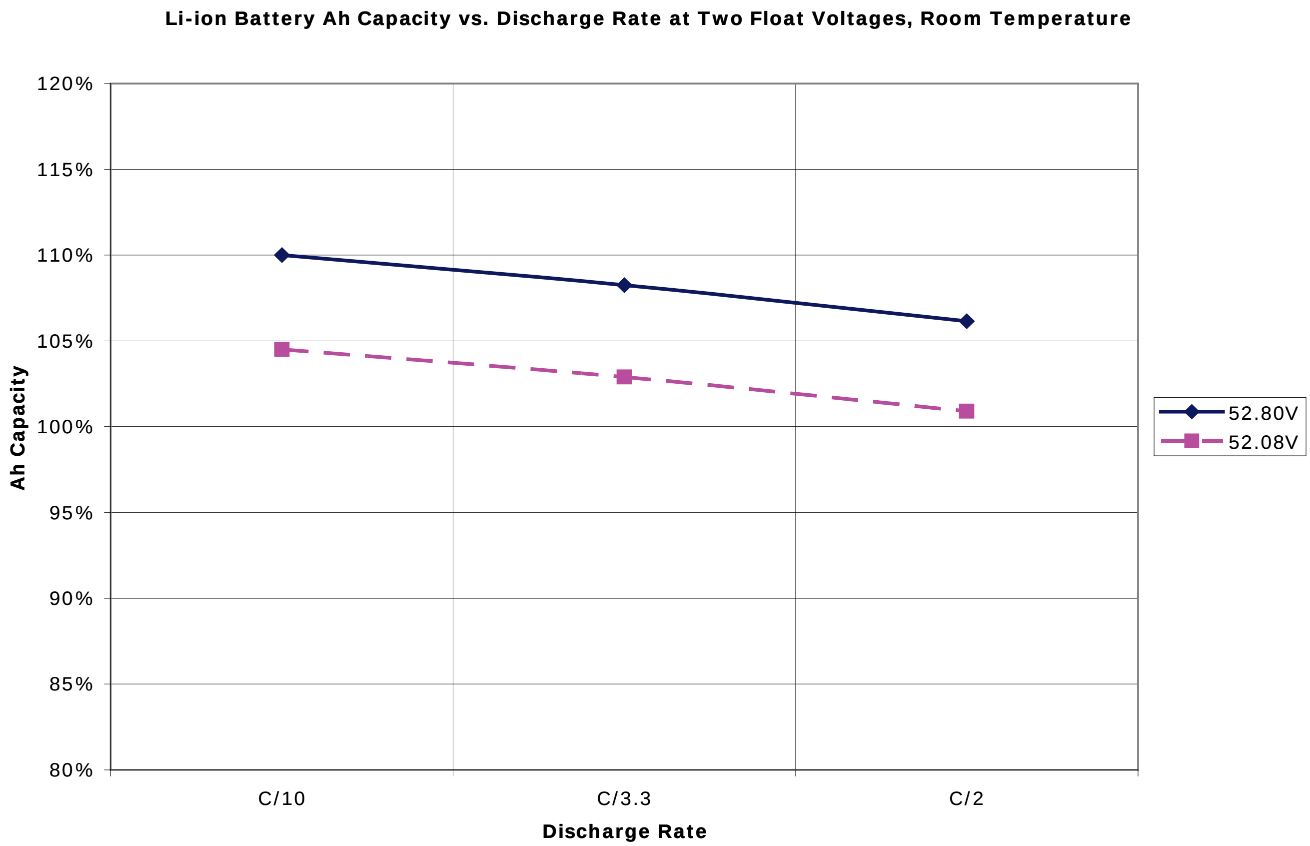

Figure 2. PSOC Discharge Performance

Figure 2 shown above demonstrates that when operating cells at two different PSOC levels, the cell outputs remain consistent to one another as the rate varies (lines remain parallel as the rate varies).

Figure 3. Laboratory Testing Equipment

TEMPERATURE EFFECTS

Cell testing at various temperatures including the effects at various states of charge (and associated float voltage levels) is necessary to develop an Arrhenius plot for each cell chemistry and form factor. This testing has typically not been done by the cell manufacturers since it requires a significant amount of time and resources and also since most cell applications tend to be cyclic in nature. Since many early lithium metal designs performed well at high temperatures, it has been assumed by most end users that lithium-ion cells are equally well suited for high temperature operation. As you can see in the Figure below, data from testing of multiple chemistries at various temperatures has shown that lithium-ion chemistries in general have a greatly reduced life expectancy as ambient temperatures rise. Operation of most lithium-ion chemistries should be maintained in the 0°C to 50°C range to prevent unsafe conditions from occurring.

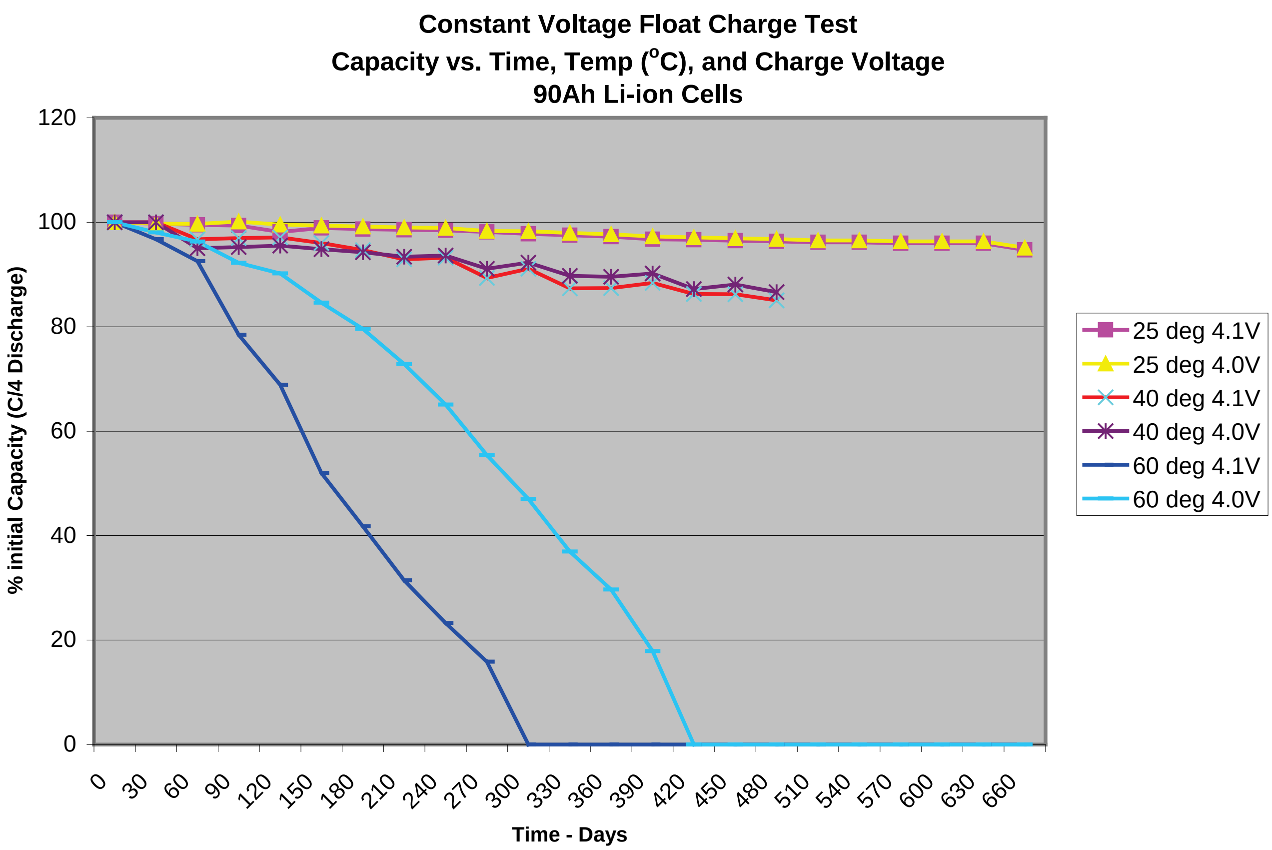

Figure 4. Lithium-Ion Cell Temperature and Voltage Effects

When lithium-ion cells are utilized in a cold environment, their energy output is not diminished at the same rate as lead acid batteries (see Table 2). One challenge for system designers is that it is not recommended by cell manufacturers to recharge these cells when temperatures are 0°C and below. For installations in these environments, an internal heating device or external heating mat must be used to safely operate the lithium-ion cells.

Table 2. Temperature Effect versus Performance for Lead Acid and Lithium-Ion

Ambient Temperature	Lead Acid Capacity	Lithium-Ion Capacity
40 °C	112 %	107 %
25 °C	100 %	100 %
0 °C	70 %	96 %
-30 °C	48 %	67 %

SYSTEM DESIGN CONSIDERATIONS

Lithium-ion systems are much different than traditional energy storage systems since they must incorporate electronic controls, also referred to as a Battery Management System (BMS), to manage the cells' performance and also insure safe operation. The BMS can effectively protect the system from unacceptable user events, but may not be able to eliminate all unsafe conditions such as an internal cell short or other internal cell phenomenon. Lead acid and nickel based systems typically only require a charger set at the proper voltage to operate and then provide the needed reserve energy when called upon. These chemistries do not need electronic management controls or a low voltage cut-off mechanism to operate safely. The following sections will discuss key design elements and testing of these elements for lithium-ion systems.

SYSTEM RATINGS AND FACTORS OF INFLUENCE

Similar to Nickel and Lead based systems, lithium-ion cells are customized to perform specific duty cycles. Lithium-ion cells are typically categorized as either power or energy cells. Internal cell designs vary by anode and cathode materials, electrolytes and even mechanical connections. These designs dictate the maximum cell output and recharge rate. In general, energy cells can operate up to their 'C' rate and power cells can operate to a '4C' or '8C' level for short periods of time.

SYSTEM CURRENT CONSIDERATIONS

Cell designs, chemistries, form factors and electronic interconnections dictate the maximum charge and discharge currents that a system can provide or accept. For small format (18650 type) cells, the limit is typically no more than 40 amps. For larger format cells, current levels equal to the 'C' rate are acceptable and do not damage or weaken the cell. Maximum charge and discharge currents for these cells can reach 100 or more amperes. In addition, many cells have a continuous current rating and also an intermittent rating which is typically most applicable to HEV and PHEV applications with regenerative braking. The continuous current rating is typically much lower than the intermittent rating due to the stresses that a continuous rate of current can inflict on the cell. Since managing maximum cell currents while charging or discharging are also critical for system designers due to the safety aspects of a lithium-ion system, both software and electronic components (fusing or breakers) are used redundantly to provide for safe operation. Unlike lead acid and nickel based systems, high rates of charge or discharge can cause a lithium-ion cell to fail and even create a fire or explosive event. Managing the charge and discharge current is therefore, a critical safety consideration for system designers.

SYSTEM VOLTAGE CONSIDERATIONS

Since most commercial systems utilize lead acid or nickel based solutions, lithium-ion systems must be tailored to operate in the proper voltage range to allow the lithium-ion system to obtain a reasonable life expectancy and operate at an acceptable state of charge. Design and operation of these systems is critical since every 0.1 volt in excess charge voltage can reduce the lithium-ion system's life by 50%. Since each lithium-ion cell chemistry has a unique and optimal voltage for efficiently charging, as system designs are compared, identify that part of a system review to include documentation of the cell chemistry utilized and the related data showing that the planned float voltage range will provide optimal life and adequate energy reserve (Table 3).

Table 3. Cobalt Chemistry Based System Example

Cell Float Voltage	13 Cell Battery Voltage	14 Cell Battery Voltage	Available Capacity	Life Effect
4.2 VPC	54.6 V	58.8 V	100 %	50 % Loss
4.0 VPC	52.0 V	56.0 V	75 %	No Loss

SYSTEM CELL BALANCING

Since lithium-ion cells tend to behave independently when operated in a multi-cell system, each cell must be monitored and managed during float, recharge and discharge to improve system performance and cell life. System hardware and software must continuously monitor cell parameters and apply shunting or other means to keep all cells in the system within a tight voltage window. It has been proven via testing, that maintaining all system cells in a preferred voltage and temperature range will provide the best life expectancy and overall system performance[1].

SYSTEM AND CELL DISCHARGE CURVES

Lithium-ion systems typically have a relatively flat discharge curve when compared with lead acid or nickel based chemistries (see Figure 5 below). In many cases, the discharge curve is so flat that the system designer must develop a method to determine the level of discharge obtained and the remaining available system capacity. Three methods can be utilized to make this determination: 1) coulomb counting (works best for cycling), 2) assessing historic voltage versus state of charge data, and 3) measuring impedance. Once a typical lithium-ion system (or an individual cell) reaches 3 volts, the system software typically disconnects the battery from the load to protect the cells from over-discharging. Since lithium-ion cells can become unstable and therefore dangerous if over-discharged and then recharged, this is a key safety element necessary in all system designs. System software and hardware should provide a shut down and hard lock out if this type of event ever occurs.

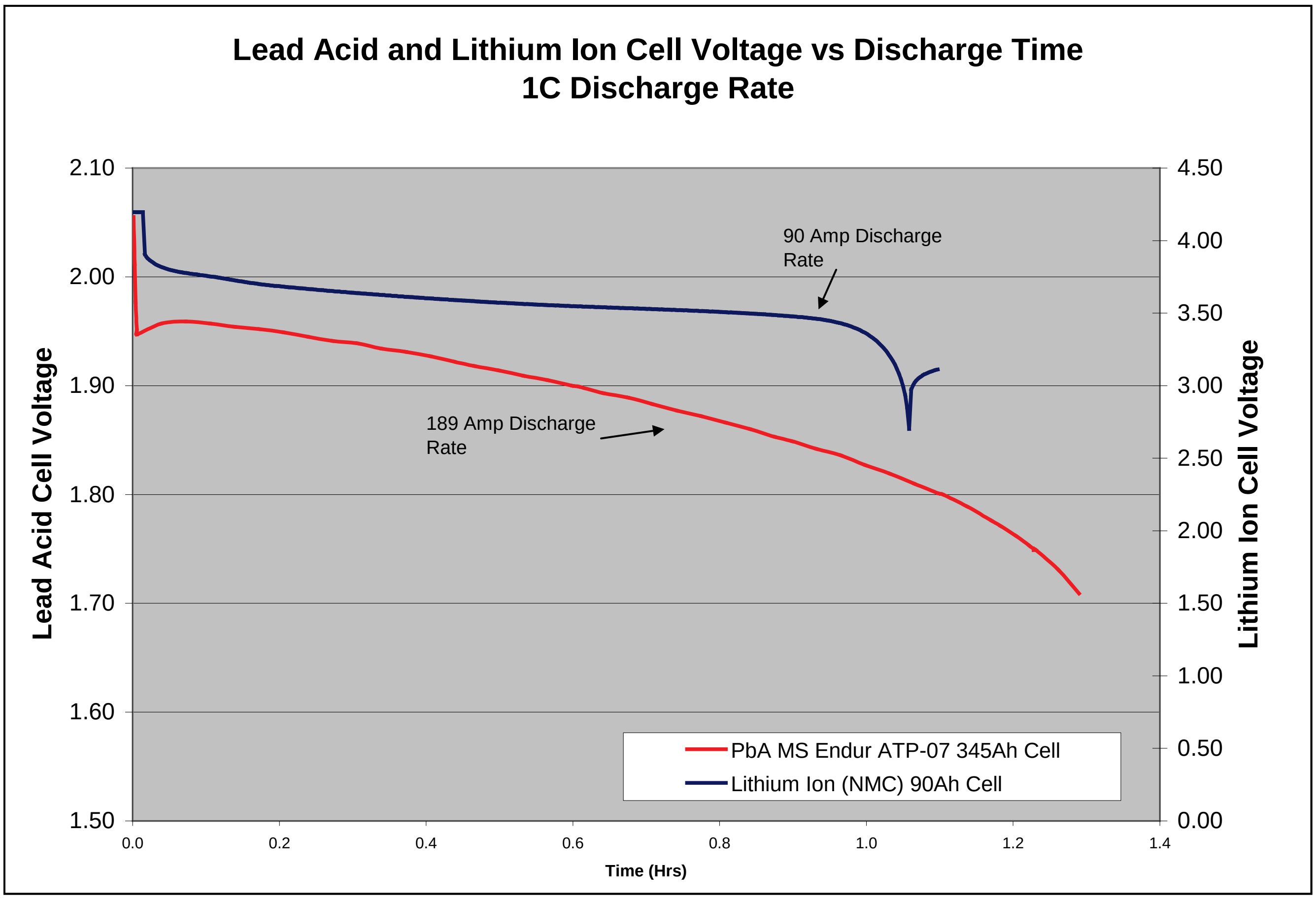

Figure 5. Discharge Curve Comparison: Lead Acid versus Lithium Ion

SYSTEM COMPONENTS
MECHANICAL CONSIDERATIONS

The system mechanical design must include assessing both the cells and other components necessary to provide a safe and fully functional package. Since lithium-ion cells are currently in various form factors, and vary in cell count (to best accommodate the system operating voltage) mechanical systems must be developed by the system integrator to uniquely package the appropriate number of cells, space and restrain them as necessary, and provide robust connections for both energy output, cell management, and data collection. For larger cells, copper bus bars or large cables are used to carry the output and charging currents. For smaller 18650 cylindrical cells, many small welds and wires are utilized to perform this function (Figure 6 below).

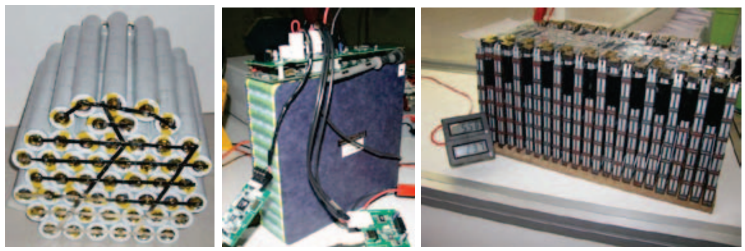

Figure 6. Large Cell Count Battery Packs With Numerous Connections

Additional mechanical features that must be addressed include thermal management (ventilation and airflow), isolation of electronic circuitry, and providing connections to an external load and power source. A thermal management system must be designed to limit the cell temperature gradient while charging, discharging and balancing to maximize cell life and to maintain a safe environment. Failure to effectively manage cell temperatures will lead to increased cell impedance and decreased life due to electrolyte decomposition and related degradation of the active materials in the cells[1]. System ventilation can be provided by using natural convection, or by means of forced air fans deployed in a similar fashion to modular DC rectifier fans.

EXTERNAL SYSTEM CONNECTIONS

Connections to the load and power source typically consist of an area for landing a two (2) hole compression style lug with an insulator providing separation of the polarities. The two (2) hole connection is preferred to prevent the connection from rotating (such as a single hole lug could do) and therefore maintains a solid, reliable connection. The grounding connection is also typically a two (2) hole crimp style lug to allow for a solid connection to the chassis.

Connections for communications, alarms, or diagnosis can be done via a terminal block, USB port and/or a computer network connector (Figure 7 below). Since these connections use industry standard connectors, they provide a straight forward means of connection for a wide range of users.

Figure 7. Example of External Communication Connections

SYSTEM SOFTWARE

Since commercial lithium-ion systems include various components to provide cell and system data on a continuous basis, software is a key element of these systems. The software must manage all the collected data, make decisions based on this data, control devices based on this data and also output key elements of the data for a user friendly GUI for the end user. Output to the end user can be via Ethernet, USB or even wireless means.

When multiple units comprise the system, it is advantageous for the system software to denote a unit identifier for each unit and to allow an end user to connect to one unit via a direct USB or other connection and then view data from all system units. This allows for a more comprehensive system perspective and simplifies the end user's task. Multiple levels of password protection prevent unauthorized system intrusion.

SYSTEM NETWORK

The lithium-ion system network is critical since data must constantly be assessed and decisions made in a timely, effective manner. Controller Area Network (CAN) is the best choice to perform these functions. CAN is a high integrity serial data communications bus. Many automotive systems and commercial systems have adopted CAN data bus due to its robust functionality, excellent error detection and confinement capabilities. Since CAN effectively executes messages based on a priority level basis, system safety is effectively managed. CAN has proven to be very reliable for key automotive systems such as motor controllers, anti-lock brakes and environmental control functions. CAN is an international standard: ISO 11898.

SYSTEM TESTING

Since lithium-ion based systems are a combination of battery cells, electronics and software, traditional testing methods must incorporate analysis and testing for many critical areas. These tests require unique design considerations that are not required for other traditional battery technologies. A good starting point is to perform a system review of Failure Modes and Effects Analysis (FMEA). This FMEA approach analyzes the potential failure modes within a system for classification by severity or determination of effect of failures on the system. The failure modes that have the highest Risk Priority Number (RPN) should be given the highest priority for further review and subsequent corrective action.

AGENCY TESTING

Various agencies have been developing specifications for testing both cells and systems. Cell testing protocols have been evolving at agencies such as UL and UN mostly to accommodate consumer electronics cells. The goal of most of these tests has been to assess cell safety when abused, handled or packaged. Since these agencies have been modifying many of their tests or requirements rather frequently, it has been challenging for many manufacturers to be cognizant and compliant with the very latest standards.

System test requirements have been a work in progress as well with agencies such as UL, UN, Telcordia and SAE developing testing protocols and methods. Traditional testing to Telcordia NEBS tests, for example, is being conducted by various laboratories, but since many of these tests were developed for either batteries or electronics, the lithium-ion system (as a combination of both elements) must be tested to a variety of individual and combined tests.

Table 4. Agency Testing Examples

Agency	Test Type	Test Function
UN	Mechanical and Electrical	Shipping and Handling
UL	Abuse	Safety
Telcordia GR-63-CORE	Mechanical	Seismic, Vibration, Packaging
Telcordia GR-1089-CORE	Electrical	Bonding and Grounding
Telcordia GR-3150-CORE	Electrical and Mechanical	Safety and Operation

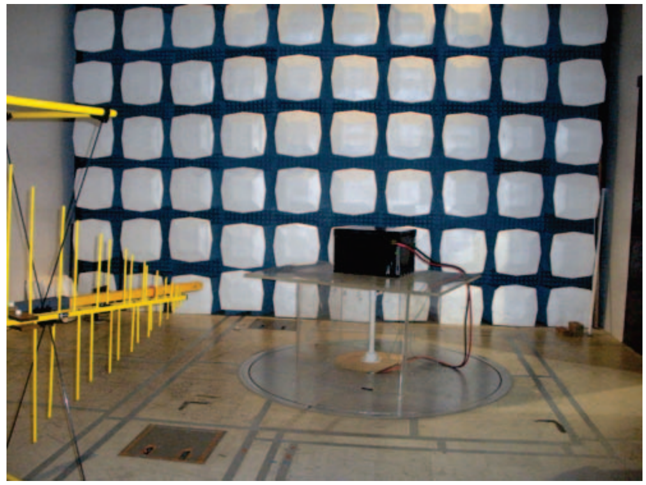

Figure 8. NEBS Fire Resistance Test **Figure 9. NEBS EMI Emissions Testing**

SYSTEM STORAGE

Since commercial energy storage is typically just a component of a larger commercial project, many energy storage projects do not reach completion when planned. As this occurs, battery systems can remain in a warehouse or other storage location for a significant period of time. For lithium-ion systems this situation can be even more challenging since lithium-ion packs are only allowed by law to ship at a partial state of charge (typically 50% or less due to UN and DOT regulations). Lithium-ion packs also have onboard electronics that drain battery power when active to continually assess system parameters and monitor for unsafe conditions. Because of these factors, special provisions should be made to reduce the self discharge rate of the system by minimizing the electronics' parasitic load effect on the battery pack. One means of doing this is to provide a reduced energy consumption state or 'sleep state' for the battery pack. This provision will allow the pack to periodically 'wake up', assess the state of health, determine if any unsafe conditions exist and report this information to a system visual indicator. After doing an internal assessment and reporting as needed, the unit can then return itself to the 'sleep state' once more to prolong the allowable storage time.

SYSTEM PACKAGING, LABELING, AND SHIPPING

Since lithium-ion systems contain a significant amount of stored energy, various agencies such as UN and DOT have been engaged in establishing guidelines and requirements. At this time, lithium-ion cells and systems fall under Class 9 of the UN3480 shipping guidelines. Most Class 9 shipments require special packaging and labeling and have air transport restrictions. These guidelines are continually changing due to the rapid cell and system development, so it is best to keep apprised of the latest requirements. In 2008, for instance, the US DOT issued a new rule regarding air transport of lithium based batteries and actually further enhanced their product definitions by adding separate categories for lithium metal cells and lithium-ion cells. It also defined the 'Equivalent Lithium Content' (ELC) levels to determine how many cells or batteries could be transported at one time. Since this ELC calculation was difficult for many to interpret, the DOT again modified their requirement and now use battery or cell listed 'watt-hours' as the basis for the maximum quantity of lithium allowed for a shipment or commercial flight.

Table 5. UN Shipping Classifications[2]

Lithium-Ion Cells and Batteries	UN3480
Lithium-Ion Cells and Batteries packed with or contained in Equipment	UN3481

RECYCLING OF SPENT CELLS

Since lithium cells are a relatively modern development, with many offshore manufacturers producing the cells and also many consumer electronics companies integrating cells into their devices, there initially was not an entity or trade group that implemented or developed a cell collection and recycling channel. Some early commercial system manufacturers boasted to their customer audience the fact that their units could be 'thrown in the normal trash' and therefore were less of a nuisance than other battery chemistries that over time developed a nationwide collection and recycling system. As more and more cells have been deployed, the power tool industry has begun to collect lithium-ion cell packs in locations such as Lowe's and Home Depot, but little collection or recycling has been done by consumer electronics companies in the US. Global pressures for a greener earth and the development of larger format batteries for automobiles have driven agencies such as the Department of Energy to provide incentives for companies to become lithium cell collectors and recyclers. These companies must develop financially viable methods for collecting and disassembling cells, and then extracting enough materials such as copper, aluminum, cobalt, nickel, etc to offset and exceed the cost of collection and disassembly. Stay tuned for further advancements and news in this area, but it is expected that lithium-ion cells will be recycled effectively in the future.

SYSTEM SUMMARY AND CHECKLIST

Lithium-ion energy storage systems are sophisticated systems comprised of an integrated package of lithium-ion cells, mechanical structure, battery management electronics and software. Each element is critical when evaluating a system design for deployment and variations of these elements may be desired for a specific application. Although life and cost are important considerations for most commercial customers, design elements and safety considerations need to be evaluated thoroughly since the amount of stored energy in these systems can easily produce an explosion, fire, or even cause loss of life if a system is misapplied, installed improperly, or not maintained. Specifications for the system must include a safety lock out mechanism that will not allow the system to operate if key parameters such as temperature, voltage, or current have been exceeded. Software and hardware component diagnostics should also be present to shut the system down if polling and reporting is not consistent. Table 6 below is a Key Design Element Checklist to provide a simple guide for end users to evaluate systems for basic, but critical system design elements.

Table 6. Key Design Element Checklist

System Design Element	Functional Requirement
Mechanical Enclosure	Seismic, Thermal Management, Modular
Provisions for Power Connections	Two (2) hole lug connection with insulated polarities
Provisions for Chassis Grounding	Two (2) hole lug connection
Monitor/Limit Charge and Discharge Current	Software, Contactor, Fuse and/or Breaker to prevent unsafe condition
Visual Alarm and Fault outputs	LEDs or Visual indicator lights
Software Lockout for unsafe conditions	Render unusable without supplier support
Software surveillance of electronic control functions	Robust software (CAN bus) with redundant electronic components
Storage of System Data History	Memory to capture data for operating parameters, safety and functionality review
Sleep or Storage Mode	Reduce energy consumption, extend storage time and monitor safety
USB or Computer Network Connection	Means to Monitor System Information and Events

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