

Autonomous Maintenance and Health Monitoring of Rechargeable Batteries

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Abstract

A major issue facing the military in the utilization of a lithium ion battery renewable energy source is to develop solutions for the logistical problems associated with self discharge of rechargeable batteries while in storage aboard amphibious vehicles, Maritime Prepositioning Force (MPF) ships, and at ground-based storage facilities. A second issue is having a methodology for rapidly and cost effectively determining the state of health (SOH) of a large number of batteries during storage.

Due to the high volume of batteries used by the Department of Defense (DoD), it becomes impractical from a time, safety, and cost prospective for DoD personnel to perform maintenance recharges on all stored batteries every 3 to 6 months. In addition, several locations, such as ship platforms, currently prohibit charging of lithium batteries due to safety concerns, adding to the logistical problems.

What the DoD requires is an autonomous battery maintenance technology that will help to maintain batteries in a safe and controlled manner while undergoing long term storage aboard ship or in a warehouse environment. This technology should be able to remove any safety impacts to the storage facility if a battery were to enter a thermal runaway event. The technology should also:

- *Compensate for self discharge rates within the battery*
- *Require no significant manpower to operate or maintain the batteries*
- *Autonomously recognize and maintain a wide variety of lithium batteries*
- *Have a minimal overall impact to cost*
- *Not alter the battery or influence performance when being used during deployment*
- *Enable the system to be easily monitored by the depot workers to help rapidly determine the health of a large quantity of batteries (query mode)*
- *Proactively alert depot workers when either a battery is not performing/charging/maintaining charge within the desired performance parameters or the autonomous battery maintenance system has detected a system issue using its built in test [BIT] (alert mode)*

This paper offers a viable approach for accomplishing these actions.

Introduction

Lithium-ion batteries are attractive for military applications because they have a number of important advantages over competing technologies: They are generally much lighter than other types of rechargeable batteries of the same size, have higher capacities, good rate capabilities, lower self discharge rates, and better storage characteristics. For example, a typical lithium-ion battery can store 150 watt-hours of electricity in 1 kilogram of battery, while a NiMH (nickel-metal hydride) battery pack can store perhaps 100 watt-hours per kilogram, although 60 to 70 watt-hours might be more typical. A lead-acid battery can

store only 25 watt-hours per kilogram. Using lead-acid technology, it takes 6 kilograms to store the same amount of energy that a 1 kilogram lithium-ion battery can handle.

Furthermore, movement of batteries to and from the battlefield and remote locations has large negative logistics implications in terms of both increased threat to resupply lines and cost. Lithium-ion batteries, due to their technical advantages noted above, are one of the only rechargeable chemistries capable of adequate replacing a large number of primary batteries in the combat environment.

Cell Configurations

A Li-ion battery consists of an anode, a cathode, a separator, and a non-aqueous electrolyte. Lithium ions move from the anode to the cathode during discharging and are deposited within (intercalated into) the cathode. The ions reverse direction during charging. In a cell, alternating layers of anode and cathode are separated by a porous film (separator). An inorganic electrolyte provides the media for lithium ion transport. A cell can be constructed by stacking alternating layers of electrodes (typical for high rate capability prismatic cells), or by winding long strips of electrodes into a “jelly roll” configuration typical for cylindrical cells (an example is shown in Figure 1). Electrode stacks or rolls can be inserted into hard cases that are sealed with gaskets (most commercial cylindrical cells), hard cases that are laser welded, or enclosed in foil pouches with heat sealed seams (commonly referred to as lithium-ion polymer cells). A variety of safety mechanisms might also be included in a cell mechanical design. The Li-ion battery pack is made from multiple individual cells that are packaged together.

Some common cathode materials include LiCoO_2 , LiMn_2O_4 , LiNiO_2 , LiFePO_4 , $\text{Li}_2\text{FePO}_4\text{F}$, and various nickel, manganese, and cobalt oxide mixtures ($\text{Li}(\text{Ni}_x\text{Mn}_y\text{Co}_z)\text{O}_2$). The most common anode material is some form of carbon, usually a graphite. Carbon particle morphology and crystallinity can vary widely. Application of $\text{Li}_{22}\text{Si}_5$, $\text{Li}_{22}\text{Ge}_5$, and Titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$) anodes is also being attempted. Cathode and anode material and morphology research is ongoing and quickly evolving, with surprisingly short latencies in bringing new technologies to market. Current research centered on nanostructure anodes and cathodes constructed of various materials, nominally promises vast gains in both energy density and durability.

To increase the storage capacity of the battery it is desirable for the anode and cathode materials to be porous with large surface area to enable more sites for intercalation of lithium ions. Thus electrodes are constructed of pastes composed of fine particles coated on thin current collectors (usually thin copper or aluminum foils). Although smaller particle sizes and higher porosities will generally lead to higher capacities and rate capabilities, other cell properties such as cycle life, self discharge rate, and thermal stability can be negatively affected by increased surface area (nanostructures promise to limit these drawbacks, explaining their popularity in research).

Lithium-ion cell separators are most commonly porous polyethylene or polyethylene / polypropylene films that will melt and close pores at elevated temperatures: these are referred to as “shut down” separators and serve to help stop a reaction that could lead to a thermal runaway failure. Separator thickness, porosity, and permeability can vary considerably, depending on desired cell properties. For example, one way to increase the capacity and rate capability of a cell design, is to select a thinner separator, and thus include more electrode material in a given, fixed, cell case. However, it is generally known that this strategy has led to cell failures in the past as some suppliers found that metal fragments that were too small to short a cell with a thicker separator started to cause failures when the separator was made thinner. New shutdown separators continue to be developed and applied to commercial cells. In addition, a number of separator manufacturers are currently experimenting with separators of different designs, for example separators that incorporate ceramic coatings or separators made of thermally stable non-woven fabrics.

Lithium-ion cell electrolytes are most commonly composed of LiPF_6 , LiBF_4 , or LiClF_4 salts dissolved in a mixture of ethylene carbonate, dimethyl carbonate, and/or diethylene carbonate. The mixture ratios will vary depending upon desired cell properties; for example, a cell designed for low temperature applications will likely contain a lower viscosity electrolyte than one optimized for room temperature applications. Cell manufactures also typically include low concentrations of a variety of additives to improve performance characteristics such as overcharge resistance, cycle life, calendar life, and cell stability.

Cell components, chemistry, electrode materials, particle sizes, particle size distributions, coatings on individual particles, binder materials, cell construction styles, etc., will generally be selected by a cell designer to optimize a family of cell properties and performance criteria. As a result, no “standard” lithium-ion cell exists, and even cells that nominally appear to be the same (e.g. cobalt oxide / graphite electrodes) can exhibit significantly different performance, cycle life, and ageing characteristics. In addition, since lithium ion cell chemistry is an area of active research, one can expect that cell manufacturers will continue to change cell designs for the foreseeable future.

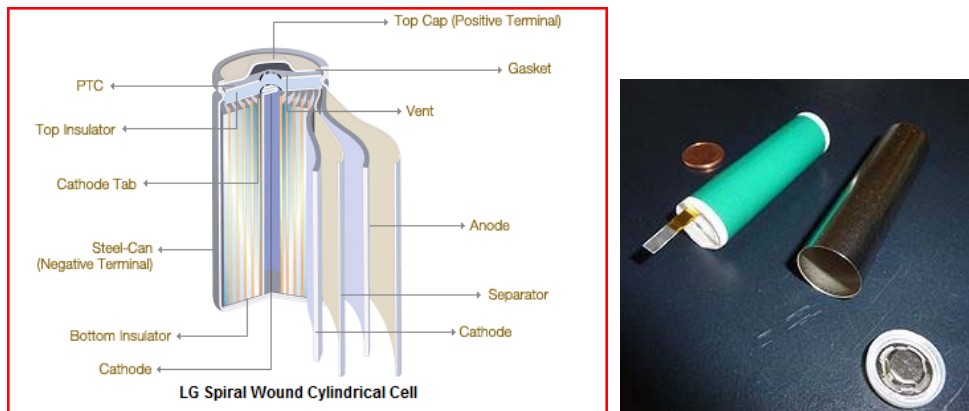


Figure 1. Example of a Li-ion battery cell.

Storage Issues

Properly designed and manufactured lithium-ion cells have very low self-discharge rates – commonly quoted in the range of 1-5% per month. When stored at 25 C or below, and initially at approximately 50% SOC, a high quality lithium-ion cell can be expected to experience minimal internal impedance growth, and remain within an acceptable voltage range for many years. Storage (calendar life aging) at elevated temperatures and high voltages (e.g. at full charge) results in enhanced degradation of cell components resulting in increased internal impedance. Storage at low voltages (and low temperatures) reduces the magnitude of the calendar life aging effect, and would thus seem to indicate that storage at low voltages is preferable for maximizing cell life. However, most lithium-ion cell designs suffer from degradation if allowed to remain in a severely over-discharged state (cell voltage ~ 1 V): corrosion of copper current collectors can occur that will lead to rapid impedance growth, and can even result in cell thermal runaway upon cell recharging. Thus putting a discharged cell (at ~ 3 V) into storage is generally discouraged as extended storage periods can result in cell over-discharge. Based on these factors, lithium-ion cell manufacturers have determined that placing cells into storage at $\sim 50\%$ full state of charge (50% SOC) is optimal: the reduced cell voltage reduces the effects of calendar aging, while the remaining capacity in the cell will prevent cell over-discharge for significant periods.

There are a limited number of conditions that will cause a high quality cell initially stored at 50% SOC to discharge relatively rapidly:

1. The cell may be contained in a poorly designed battery pack with a high power drain rate that does not incorporate an appropriately designed sleep mode for long term storage.
2. The cell may be contained in a poorly assembled battery pack that has a high power drain rate due to an unintended leakage current (e.g. poor soldering results in a small short circuit).
3. The cell is drained by an internal short caused by a manufacturing defect such as a metallic contaminant or subsequent cell damage (weak cell).

4. The cell is connected in parallel with a weak cell and drained by the internal short within the weak cell.
5. The cell has become degraded (for example by long term exposure to high temperatures) and has lost significant capacity.

All of these cases indicate a problematic cell or device or poor control of the storage conditions. In fact, long term storage provides an opportunity to identify and dispose of cells with high self discharge rates that could perform poorly in the field or result in a thermal runaway failure on recharge.

Thermal Runaway

Thermal runaway refers to rapid self heating of a cell. It can occur due to a variety of causes, for example: internal or external shorting of a cell, external heating of a cell, or overcharge of a cell. Due to the high energy densities of modern lithium-ion cells (electrical energy) and the presence of a flammable electrolyte (chemical energy), a lithium-ion cell thermal runaway event can be very energetic. Thermal runaway in a single cell can easily provide the necessary heat to neighboring cells to begin internal exothermic decomposition reactions, causing propagation of thermal runaway events to neighboring cells. Thermal runaway can result in destruction of the battery, fire, and damage to nearby equipment or personnel.

It has been observed that the vast majority of thermal runaway reactions that occur in the field occur during or shortly after cell charging. Purely from an energy perspective, cell thermal runaway is unlikely to occur in a cell at a low state of charge. Exponent's own testing has shown that for many lithium ion cells, even severe crushing of cells that are below ~50% SOC will not lead to a severe reaction (only relatively mild cell heating). In addition, research suggests that cell charging can precipitate thermal runaway through a lithium plating / dendritic growth / microshorting mechanism that can occur at the point of a cell defect.

Based on this knowledge, we believe that charging cells or battery packs that are in storage should be avoided if at all possible, as a single cell in thermal runaway can ignite surrounding combustible materials and propagate the reaction to surrounding cells or battery packs. If unavoidable, cells or battery packs that are in storage should not be charged above 50% SOC. We propose to develop a system that will provide a decision matrix to determine whether limited recharging should be attempted, or whether battery packs containing these cells should be disposed of. This system necessarily includes a method to identify cells or packs that exhibit high self discharge rates over extended storage periods. These cells or packs would be marked for disposal to reduce the risk of cell thermal runaway reactions. The system must also assess poor cell performance and provide feedback on that status to those responsible for maintaining the cells.

Cell Management Approach

One methodology for managing a large number of lithium ion batteries is through the use of a tag and sensor system that can be integrated onto a disposable cap placed on individual battery packs. This system collects data on battery voltage and temperature, and has the capability to provide this data to a monitor. Each tag will contain specific codes identifying the cell specific chemistry and battery type. The monitor system will contain a library of data that will allow evaluation of appropriate voltages, temperature histories, and recharging instructions for each battery type.

All tags will contain a non-rechargeable primary cell to provide power. The tag will also be able to draw power from the battery to which it is attached. The tag will be designed to draw from the battery pack to be monitored if that pack is at a voltage higher than ~ 50% SOC, but to draw power from the on-board primary cell if the monitored battery pack voltage drops below some nominal voltage. Should the primary battery become exhausted the tag will again be able to use the subject battery power, but will set a warning flag indicating that this has occurred and that the subject battery pack may have been drained.

The focus of this effort is to create a sensor approach that would exploit early failure symptoms and effectively identify battery packs that are likely to suffer thermal runaway failures if left unmitigated. That is an excessive block (cell) voltage drop during extended rest periods, indicating high self-discharge rates

consistent with micro-shorting. Testing has shown that this symptom is a good indicator of a problematic cell¹.

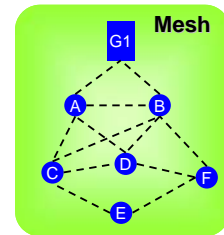
Monitoring and tracking battery health and status through the installed tags would require an expenditure of effort dependent on the approach used for communication between the tag and the monitor.

Communication Approaches

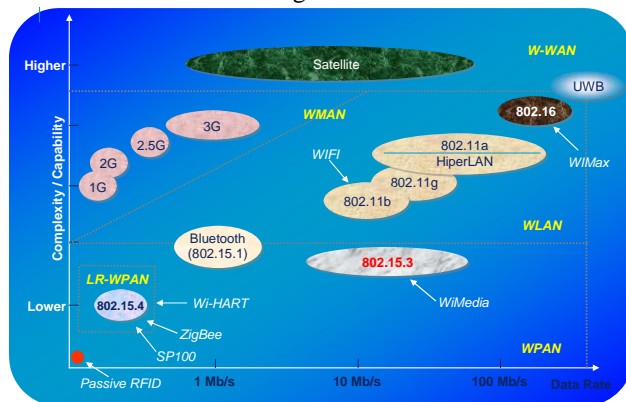
Two possible communication technologies for communicating battery status to warehouse personnel via a monitor system are Radio Frequency Identification (RFID) and Wireless Mesh Networking. Selection between these two approaches and others would be driven by installation requirements, such as cost, size, weight, range, and the need to either ‘pull’ or ‘push’ information to warehouse personnel.

Wireless MESH Network

A Wireless Mesh Network is a series of sensors that use their ability to both wirelessly transmit and receive data (as well as frequency hopping and time synchronization) to create a self-organizing network that is self-healing, highly adaptive, and highly reliable in communicating data to the end user.



There are several advantages of the Wireless Mesh Network over RFID. Wireless



Mesh Networks are able to gather and send more complex information to the user through higher data rates, are able to send information over greater distances due to higher power and the ability of each sensor to transmit and receive data, and can maintain very high data reliability in complex and noisy environments through multiple path redundancy. However, the primary advantage is its ability to push information to warehouse personnel through a network manager device, eliminating the need for walk-arounds and ensuring that all lithium-ion batteries are being continuously monitored

for degradation. Data could be sent over a fairly long distance with relatively small power consumption by using each tag node as a repeater to pass information along to the network manager.

The Wireless Mesh Network is based on the Dust Networks’ SmartMesh IA-510 WirelessHART (IEEE 802.15.4). The advantage of this arrangement is its recognition as the standard in the process control industry (where low cost and high reliability are a priority), prior confirmation of 10 year lifetime based on standard battery technology and the easy availability of Research Development Kits.

The tag would be configured to accept and record voltage and temperature measurements gathered from an integrated sensor. Measurement data would be periodically transmitted to a network manager device, with the duty cycle driven by the operational profile of the end user, amount of data being transmitted, network configuration, and the need to minimize battery usage. In any usage situation, battery drain would be higher than for RFID technology due to the need for an active transmit/receive function.

RFID Concept

Another approach involves a design concept for utilizing a programmable RFID tag methodology incorporating the battery sensor for inclusion as a disposable cap placed on individual battery packs. This

¹ Celina Mikolajczak, John Harmon, et al. Detecting Lithium-Ion Cell Internal Fault Development in Real Time. Power Electronics Technology; March 2010.

tag would communicate with a portable reader that provides feedback on the status of the proximate batteries to the user. Figure 2 illustrates the elements of the proposed approach.

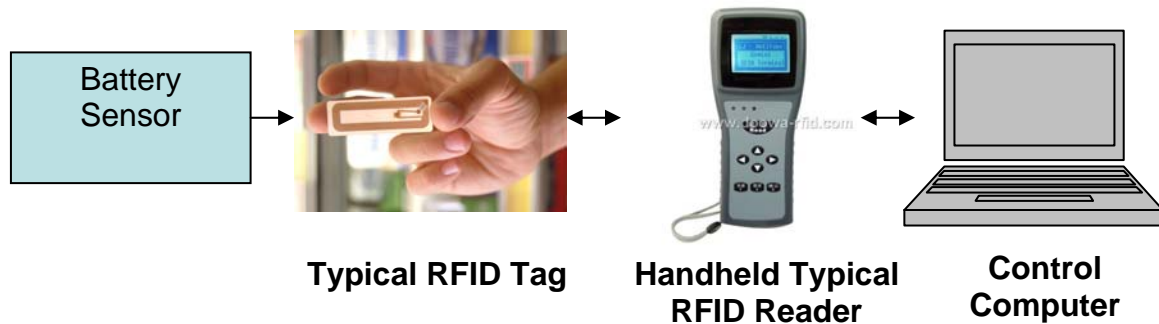


Figure 2 – Proposed concept for Battery Sensor/RFID Measurement Approach

Wireless Interface to RFID tag

Existing portable RFID readers could be utilized for performing the measurements of the lithium-ion batteries in-situ of their storage locations.

A simple reader, combined with a single antenna, provides a cost effective solution when 1) there is already a local controller, 2) tags are consistently oriented the same way and always located in the same place, and 3) only a few tags travel through the RF field at a time, relatively slowly. Simple readers with multiple antennas can potentially alleviate issues with tag orientation, quantity and speed by increasing the “read field”. Additionally, simple scanners offer a more economical option for measurements in controlled configurations

When the application requires real-time decision making based on the data collected from the tag, smart readers provide the best technical approach in RFID technology. Local intelligence within the smart reader allows it to not only evaluate the data on the tag, but also respond to it, such as triggering a red signal light to indicate that manual intervention is required. Because decisions are made by the reader, they occur without communications or server-induced delay. Smart readers combined with multiple antennas are better equipped to cope with unpredictable tag placement, tag volume, and speed, while also providing local filtering. Smart readers with a single antenna are often mobile and therefore offer best solution for exception reading and subsequent tag re-writing because local decision making can be taken directly to the item to be read.

There is also a third option, which is a hybrid of the two. Batteries have RFID tags, but boxes of batteries have a reader and mesh network node to push the battery box data around to a main system control.

Conclusions

A methodology for monitoring and evaluating lithium batteries implemented in military installations, but having commercial application as well has been presented. This approach utilizes materials, packaging, communication, and system level concepts to structure a viable approach and thus touches on all areas of IMAPS expertise. Application of this methodology will be dependent of the specific needs of a battery storage facility, including cost, personnel involvement, and safety. In the future, such a system might even be integrated into a more permanent network, involving (wired) power sources for sensors and the ability to provide maintenance charges where necessary without personnel intervention. More research is required to examine new concepts in lithium ion battery technology as these renewable energy sources evolve and begin replacing other battery technologies and opening new applications for battery technology.