DESIGNING LITHIUM-METAL-POLYMER BATTERIES FOR SAFETY

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INTRODUCTION

This paper will describe the tools and considerations in designing a Lithium-Metal-Polymer (LMP) battery for safety. Safety is the most important design goal. With technology seeming to change at nearly the speed of light squared, anytime you have mass, particularly in a small space, as Einstein demonstrated 100 years ago, you have a lot of energy. This paper will focus on the key challenges in making this lithium-based energy storage system safe and the design methodology employed.

DESIGN FOR SAFETY

In designing a safe battery, it is of paramount importance to first determine the safe operational limits of the technology, taking into account such factors as maximum operating and storage temperatures, maximum discharge and charge currents and minimum and maximum voltages. Furthermore, a detailed knowledge of the failure modes of the technology is required. By combining this information with the environmental requirements imposed by the applications, a map can be constructed of the operational constraints of the product.

Once the preliminary design of the battery has been developed, more detailed studies using design tools such as failure modes and effects analysis (FMEA) and fault tree analysis can be performed. The FMEA is used to verify the safety of various design features while the fault tree analysis is used to select the appropriate choice from various technical options. A good example of when the Design FMEA (DFMEA) was used was in response to an incident with a prototype battery in a laboratory. The tool was used to revisit the safety design requirements of the battery considering new data on the operational environment. Some changes were made in the final battery design based on this analysis.

Technology

The basic electrochemistry of an LMP battery consists of a metallic lithium anode, a vanadium oxide cathode and a solid, dry polymer electrolyte. Lithium melts at 180°C (350°F). Below this temperature, no exothermic reaction occurs between the different materials and, because the battery is solid, no liquid can vaporize. If the lithium melts and becomes in contact with the cathode, the reaction will generate heat and energy, resulting in a fire. Under 180°C this can't happen and there is no concern of melting and flaring. If the battery had a liquid or gel electrolyte, the temperature at which a self-sustaining exothermic reaction would start could be as low as 120°C. So the selection of a solid, dry polymer electrolyte that will not react with the lithium helps insure a safer battery.

Process of manufacturing a thin film LMP battery

Manufacturing batteries from thin film electrodes at the micron level requires a very precise process to insure a safe product. Filtration of the solid polymer electrolyte at the micron level removes impurities or metallic particles, which could cause soft short-circuits that would generate leakage currents across the electrodes and would affect the life expectancy of the battery.

Use of on-line laser measurement systems prevents the mismatch of the electrolyte and electrode layers, preventing the occurrence of both soft and hard short-circuits. This system also has the ability to detect and reject films that have microscopic holes and could create soft or hard short-circuits.

In the unlikely event that the on-line measurement and detection system has not rejected a defective cell, voltage drop measurements are used at assembly stations of the line, including during a cell pre-discharge test performed under pressure, where any remaining defective cells will be detected.

The final quality-control step consists of a discharge and recharge test during which each individual cell voltage and balancing current is monitored to detect any abnormality.

Product Integration

The cell integration requires attention to preserve the safety integrity of the battery. An LMP battery uses a pressure system that is used to provide uniform contacts between the films and assure good cycling performance and life of the battery. An uneven pressure on the films could result in decreased life of the battery, but more importantly, in some extreme conditions, it could result in displacement and shorting of the individual cells, leading to battery flaring. To prevent such incidents, evenness and flatness of the films are controlled by the on-line measurement systems, a distributed spring system is used to insure uniform pressure and verification of alignment before and after installation of the pressure system is performed. Finally wrapping of cells with a film of proper adhesive properties maintains the alignment of the cells.

Additional to preserving safety integrity of the battery, product integration is aimed at assuring optimum life and performance of the battery. For example, the electrochemistry of the LMP battery is enclosed in a sealed aluminum case. This prevents contamination and reaction of the chemistry with oxygen and moisture. The casing has a burst disc, which would allow the escape of gases generated by the combustion of the lithium and cathode material reaction under melting condition of the lithium at 350°F or above, should the battery be heated to this extreme temperature.

Battery System

The primary design requirement of the supporting battery control systems is safety. Both external environment and internal battery operating requirements are considered. Telcordia, IEEE and other standards organizations have outlined basic operating environmental requirements for industrial, utility, and telecommunications central office, premises and outside plant applications. Generally batteries must be able to operate in uncontrolled environments in temperatures from –40°C to + 65°C (149°F), although our customers have indicated that temperatures in excess of 150°F could occur. The electrolyte selected for LMP batteries operates most efficiently from 42°C to 60°C. To accomplish this, 4 thin heat pads are placed between cells inside the battery to operate the battery at these temperatures, even with cold ambient temperatures. These heat pads must be safely controlled to make sure the melting point of lithium is not exceeded. Extreme voltages or high current discharges or recharges could cause localized heating, and must also be controlled.

To accomplish this, the final commercial battery has numerous, redundant or backed-up electronics systems to control critical battery operation. For instance, the electronics controls the operation and temperature level of the heat pads. If heat pads get stuck on or a temperature sensor fails to operate, there is a passive electronic thermal cut-off and a software protection that will automatically disconnect the heat pads from the activation source. So there are essentially 2 independent levels of protection to make sure the heat pads don't overheat the lithium inside the battery. A current limiter is built into the battery to limit the current to recharge the electrochemistry. If this malfunctions, the electronics will automatically shut the battery down on a high recharge current. Excess current discharge is protected by an automatic, self-resetting software disconnect, followed by a hardware disconnect, backed-up by a permanent (until it's physically replaced) fuse. Thus, any system or possible external cause of a safety event has been protected by multiple, redundant systems to disconnect or shut down the battery well before the safety limits are approached.

Safety features were integrated in the battery design as the result of a well-defined design process that uses specific tools such as the FMEAs and Fault Tree Analysis. An example of a partial fault tree analysis can be found in Figure 1, where the potential causes of a problem, such as the battery LVD malfunctioning and staying closed at all times, were entered in the tree. The probability of each condition in the tree was scored to identify the weak branches to focus the design effort on decreasing these probabilities.

Figure 1. Fault Tree Analysis Example		
LVD Switch always ON	Power Transistor signal malfunction & stays ON	Software corruption
		Bad battery voltage reading
		AND
		Bad reading of cell voltage sum
		Transistor gate floating
		Bad transistor gate signal

Validation

To make sure the LMP battery would be safe when used for various applications, an accurate understanding of the operating environment batteries are subjected to had to be developed. Telcordia, IEEE, UL and other standards bodies have requirements for different battery technologies, and these were consulted. Early on we conducted extensive customer surveys, field trials, and lab trials and further customer input helped us understand the truly demanding nature of the applications, and the legacy systems backed up by and controlling batteries. Telcordia tested the final commercial battery to applicable NEBS standards. UL determined the requirements to test the battery that is now a UL Recognized component. Where our customers outlined a requirement or application that we felt wasn't covered by one of the standards, we designed our own test. For instance, to insure safety in case a battery was accidentally dropped down a CEV, we dropped charged batteries from 20 feet at various angles to make sure the battery would remain safe. Even when the electronics were significantly damaged, the batteries were safe.

As part of our work with standards bodies, we also worked with several experts on the uniform and international fire and building codes. The LMP battery isn't specifically covered by these codes, but to answer customer questions on how our battery is treated by the various codes, we requested their input. Generally the experts indicated that some local Authorities Having Jurisdiction would classify the battery like a VRLA battery (because of lack of existing LMP battery standards) and/or by the amount of lithium in the battery, which is approximately 2 pounds by weight. Based on this, there are specific quantities allowed for storing and using the batteries inside a building, which double if a water sprinkler system is used or if a ventilation system is available. The interpretation doesn't make sense in certain cases, as the battery doesn't vent or gas like VRLAs, making ventilation irrelevant. Until the code writers can specifically cover this new technology, some local authorities may hold customers to this interpretation of the standards.

Further to this work, we engaged a laboratory specializing in thermal analysis, to test the water reactivity of our battery following the NFPA 704 procedure. Lithium metal is highly reactive with water, but since the LMP battery design has the lithium encapsulated between layers of a solid, dry polymer and vanadium oxide, the objective of the test was to determine the reaction and temperature increase of the electrochemical cells when subjected to water.

The NFPA standard gives rating criteria for water reactivity hazards. The test concluded "a degree of hazard rating of'0' best describes the result of the experiments conducted during this study." A hazard of "0" corresponds to an exotherm of less than 30 cal/g. The maximum exotherm recorded during the three sets of experiments was 5.4 cal/g, well within the range of 0 to 30 cal/g given in the "0" rating criteria. Based on these results, the AVESTOR LMP batteries should not be considered as pure lithium. This is now reflected in the MSDS, which recommends that copious amounts of water be used in case of a battery fire.

CONCLUSION

Using well-known design safety and quality tools such as DFMEA and Fault Tree Analysis, safety was made an intrinsic part of the LMP battery. Realizing the inherent limitations of metallic lithium, it's important to make sure that all aspects of the battery including the process, technology, product integration, battery systems and testing were all carefully designed to provide a safe battery.