Commercial and Consumer Battery Fire Trends-Learning from Mistakes of Others

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Abstract

Batteries are everywhere in our daily lives. Most battery-powered devices aid to make our daily lives more convenient. However, there are daily occurrences of batteries causing damage to structures and bodily harm to users. End users demand more and more portable power, and the battery industry has responded. Unfortunately, at the same time, the overall quality of the industry as a whole has significantly decreased. The result is that failures are more catastrophic, with higher loss of property and life. The push to go more electric and be off grid has created unanticipated failures that require investigation. This paper will discuss the most common failure modes we have been identifying in the consumer space and how the occurrence could have been mitigated.

Introduction

In the past 25 years lithium-ion battery technology has grown in market share, energy and power density. This has provided end users with capabilities that would have been considered impossible just 20 years ago in power tools, cell phones and vehicles. The battery powered devices have become ubiquitous in modern society. Unfortunately, these high energy and power devices can also cause substantial damage including fire and explosion resulting in large financial losses and bodily harm.

Many of these instances of failure undergo analysis to determine probable cause of failure. These analyses can take place years after the incident has occurred and with little known history of use prior to the occurrence.

When the origin of the incident can be identified a study of the remains of the artifact is undertaken. In the case of battery cells, a CT scan is typically included along with physical examination and at times destructive analysis of the artifact. Electrical testing of an exemplar is performed in an effort to eliminate the possible reasons for failure. It has been our experience that the majority of the failures that are occurring are not related to poor original cell manufacturing but poor battery pack and cell management.

Low Voltage Operation of Lithium Ion

Thermal runaway in lithium-ion (Li-ion) cells can be induced by several factors, including manufacturing defects, exposure to very high external temperatures, or mechanical abuse or damage. The safety of (Li-ion) cells also depends in part on the way they are used. This is particularly true if cells are operated outside of the safe potential range. Overcharge (charging a cell at excessively high potential or significantly beyond the rated cell capacity; mAhr) is known to damage cells and/or create safety hazards. Over discharge (discharge of a cell below the minimum safe value or beyond the rated cell capacity) can also degrade Li-ion cells and cause unsafe conditions.

Over discharge of cells can be prevented using proper control circuits on individual cells, that stop discharge when the cell potential reaches the minimum (cutoff) potential. If multiple cells are connected in series without monitoring and control of individual cells, there is a risk of overdischarging weaker cells. In addition, operating cells at very high rates during either charge or discharge, such as during high current pulses, can temporarily cause the local potentials values adjacent to the electrode surfaces, to be either too high or too low. This is especially true for cells or batteries that are operated at very low temperatures. Over discharge can also take place after the discharge is shut off by the control circuit (for having reached the minimum cutoff potential), if a trickle discharge current is used to operate the Battery Management control circuit. Internal self-discharge of discharged cells allowed to sit at open circuit for extended time can also be over discharged.

Li-ion cells rarely fail directly due to over discharge; rather they fail in subsequent charging. There are physical and chemical changes to the cell, particularly the negative electrode, that make normal healthy recharging of the cell difficult or impossible. This report contains a survey of reported studies of the effects of over discharge on Li-ion cells, particularly with respect to safety. Before that some evidence of gas evolution in the cells from the over discharged cells from fires will be briefly presented.

Long term storage of over discharge cells will usually show bulging at the bottom of their containers upon recharging. This type of swelling is caused by the significant rise of internal cell pressure due to gas evolution, rather than damage from a fire external to the cells. As will be shown in this report, over discharge of a Li-ion cell leads to gas evolution. (This is in contrast to healthy cells undergoing fire attack which will cause bulging of the negative end from thermal decomposition of electrolyte and separator). In a pouch cell this is mainly manifest in increased cell thickness (due to the buildup of additional gaseous species). In a more constrained cell configuration, such as a spirally-wound 18650 cell (housed in a sealed steel can), the presence of evolved gases is manifest in an increase in internal pressure, and possibly in bulging of the cell can.

To further illustrate the buildup of pressure, we use the well-known ideal gas law,

$$P = \frac{nRT}{V}$$

Where P is the pressure, n is the number of moles of the gas, R is the Universal Gas Constant, T is the temperature, and V is the volume of the gas (which is essentially constant inside of the cell). Pressure increases with temperature, and it increases with the number of moles of gas. The cell when first fabricated contains a small amount of gas. As gas is evolved, the number of moles of gas goes up quickly[1]. The number of moles can go from an equivalent of 1 to 18 during over discharge. It does not take a great deal of gas evolution to increase the pressure to several times its initial value; pressures of several tens of psi are easily achieved. As the cell is recharged it is not uncommon for T to go from 20 to 60. Most 18650 Li-ion cells have a built-in pressure relief valve, to vent gas when the pressure reaches a threshold value (such as 140 psi). Still, poorly constructed cells can have a non-functioning relief valve, or a container that can bulge before the pressure reaches the threshold for venting gas. The net effect is that P can increase substantially and would cause distortion of the flat bottom of the 18650 prior to venting of the cells that have been over discharged and subsequently recharged without an immediate thermal event. The probability of a delayed shorting event after charging is increased.

As pointed out in many studies, high levels of over discharge can result in Cu dissolution and then re-deposition in either on the negative electrode, positive electrode or in the separator. This can cause the formation of internal shorts, via Cu dendritic growths. The growth of Cu dendrites is possible after a single over discharge, especially if subsequently charged aggressively.

Changes in the SEI layer invariably took place due to over discharging. In some cases, the SEI layer can disintegrate, raising the increased possibility of catastrophic cell failure during subsequent charging. In other situations, it is made more resistive, due to incorporation of either copper of other species such as hydrogen or growth. Thicker SEI layers of course causes higher internal cell resistance. Cu deposition is the most important result of over discharge, that affects the health or composition of the SEI layer on the negative electrode surface.

All over discharged cells showed evidence of gas buildup in cells. The composition of the gases varied from study to study, but the fact that gas evolution took place is established.

These two factors (Cu dissolution/precipitation and alteration of the SEI layer) are the principal safety concerns for over discharged Li-ion cells. Care should therefore be taken to prevent over discharge for maximum battery safety.

Battery Pack Battery Management System

Lithium-ion chemistry requires the addition of a Battery Management System (BMS). These systems would benefit all battery chemistries if they were implemented. ETP has found that the majority of the BMS prevent overcharge of lithium-ion battery cells. ETP has also found that many of the BMS are not programmed properly to detect failing cells on discharge, to prevent over discharge, to prevent zero or low cells to be recharged; creating instability and possible thermal runaway.

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[1] It does not matter what type of gas molecules are involved; one mole of hydrogen gas, the lightest gas known, leads to the same pressure as much heavier gases, such as oxygen, nitrogen or water vapor (at the same temperature, and in the same volume).

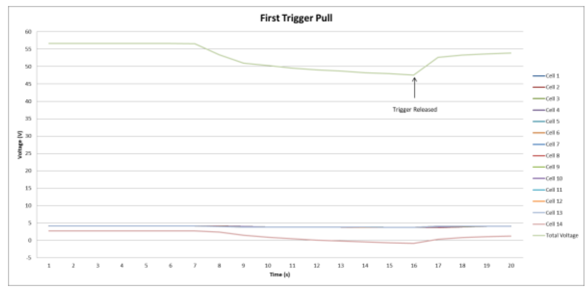
The typical low end BMS will have 30+ registers that can help protect a battery pack. Higher end BMS may have more than 60 registers. The typical battery packs that are sold to the consumer, such as laptops, power tools etc, have 5 of those registers activated. These registers are typically called GG files or gas gauge files. As the name implies, the first 5 registers provide information to the computer so that the user knows how much run time they have remaining while on battery power. The computer also uses a 2 wire communication system called SMBus. This system allows the computer to communicate with its components, including the battery. It could prevent poor quality batteries from being operated in the computer, or could be used communicate with the battery to assist in detecting a failing cell. Sadly, in many computers the SMBus is not activated as it relates to the battery. Instead, the computer will charge anything connected in the battery bay whether it is a healthy battery or a battery that has been sitting discharged for several years.

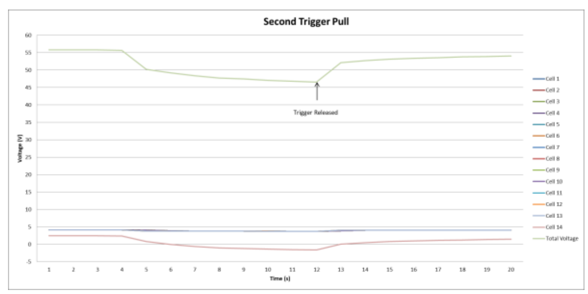
Testing of Exemplars to Determine BMS Settings

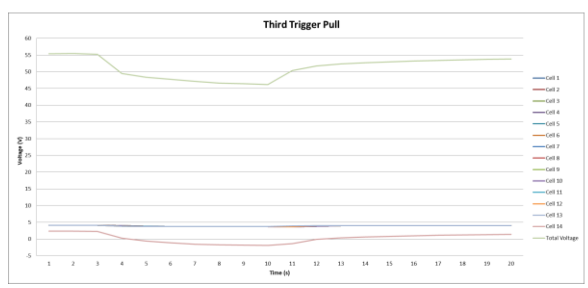
Unfortunately, OEM's do not want to provide their GG file settings to those investigating a fire involving their products. To obtain the data required a few simple electrical tests are performed. The battery pack is wired to record pack and individual cell voltage. If possible, connections will be made to determine if any communication is occurring between the battery and device. The unit is charged and discharged with the voltages and currents recorded. This provides the baseline. Many times this test will show that the exemplar is defective out of the box. Next a cell or cell pair is connected to a 10 to 20 ohm resistor. The cycle test is repeated. The resistor will make the cell behave like it has an internal short and each cycle the cell will run down further and not be fully recharged. The good BMS that is set up properly will detect the failing cell. The cell is allowed to stand after device shut down for increasing duration to determine if the battery will be recharged by the charging station as the voltage is stepped down from 1.0, 0.5, 0.0, -0.5 volts. It is not unusual that the product may reverse a cell in this test. The BMS should be set up to detect the failure.

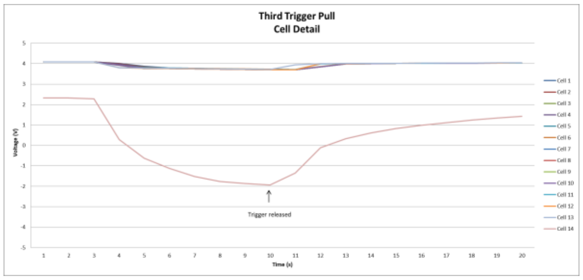
Some power tools will stop operating as the battery hits the lower cut off. If the trigger is pulled again a lower cut off voltage occurs. Holding the tool trigger down allows the battery pack to further discharge resulting in reversal of one or more cells in the battery pack.

The plots below are of a 40-volt battery pack on a name brand tool from 2018. The sequence of the plots after run down and three trigger pulls. What can be seen is that there was already some weakness in the battery pack with mismatched cells. No resistor needed to be added for this test because the exemplar battery pack already showed a major defect. Each time the trigger was pulled the weakest battery cell was driven lower until it reversed. At this point SEI and copper dissolution and plating has occurred and the cell is severely damaged.









Sadly after this abuse the battery pack was placed on the charger and the charger recharged the battery.

Zero volt recharge capability is in many products both brand name and knock offs. The manufactures believe that with the requirement to ship at low state of charge the capability needs to be enabled so that the customers do not get a dead on delivery product. Unfortunately, it can make a soft shorted or otherwise poor quality cell into a dangerous bomb. ETP has experienced many first charge product fires from a cross section of industry. More importantly, zero volt recharge is seen late in life to play a significant role in catastrophic failures. Whether it is an old MP3 player that is sitting in desk drawer or old toy such as a hoverboard in a closet, or old laptop computer slid under a desk for a year or two, someday someone will decide to plug it in and see if the missing file or maybe to play with it. It might not work immediately or ever, but they leave it on charge in hopes of getting one last shot at it. Unfortunately, the lithium-ion battery chemistry has some very nasty low voltage characteristics occurring. The Solid Electrolyte Interface (SEI) degrades, copper from the anode goes into solution, decrepitation of the anode active material and the cathode can occur. Then when placed on charge even worse reactions occur. The damaged SEI layer attaches to some healthy electrode surface while the are where it fell from the graphitic anode attempts to grow a new SEI with gas generation as a by-product. The copper may have plated on the cathode is not being driven back through the separator and is plated on the graphite potentially growing a dendrite back through the separator and shorting. This does not always result in a fire that burns the house or factory down but it might.

Summary

Lithium-ion batteries are not the most powerful batteries manufactured but they are powerful enough and are widely used enough that they need to be handled properly and respected for the damage they can do. The authors have seen single lithium ion battery cells severe legs, hands and cause substantial bodily injury. They have seen them level 14 acre buildings and farms. The larger systems have generated enough gas to throw fire fighters over 75 feet, and they have caused enough damage that government officials suspected a mortar attack.

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