BATTERY SAFETY:
A SYSTEMATIC STUDY OF BATTERY PERFORMANCE UNDER EXTREME CONDITIONS

A Thesis in
Mechanical Engineering

by
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Safety has become a critical issue for Li-ion batteries, which are becoming more frequently used in new generation vehicles. In this study, commercial coin cells (2032, with capacity 40 mAh) and cylindrical cells (18650, with capacity of 2250 mAh) are studied systematically under extreme conditions to investigate the safety issue of Li-ion batteries. The cells were subjected to standard short circuit (constant resistance) tests and a novel constant voltage test. The constant voltage discharge test was used to determine how batteries perform under low voltages to calculate the limiting current. The cells were tested at their nominal voltage, 3.6 V, as well as 3 V, and 2 V. The coin cell was also tested at 1 V and 0.5 V. Upon the start of each discharge the cell current shows a sharp peak and then gradually decreases. This test was repeated at one higher and three lower ambient temperatures for coin cells with similar current and temperature trends observed for each test. Linear trends were observed for the coin cell with respect to inrush current and maximum temperature rise vs. discharge voltage. The 18650 cell test was performed at room temperature and also exhibited linear trends for inrush current and maximum temperature rise vs. discharge voltage. The results of the constant voltage tests are used to determine the limiting current of the cells using a linear regression of the data to extrapolate to 0V. The limiting current was 2.23 A (equivalent to 56 C) for the coin cell and 88.1 A (equivalent to 39 C) for the 18650 cell. The constant resistance tests were performed on the cell to determine how it behaves under short circuit conditions as well as to obtain limiting current data for comparison with the calculations from constant voltage tests. Both cell types showed very high inrush current at the start of discharge but rapidly decreased to lower values and then gradually decreased. The inrush currents increased with decreasing resistance for both cell types, however the 18650 cell experienced higher currents overall. The maximum temperature rise for the coin cell tests did not vary much with the external resistance, while that for the 18650 cell increased with decreasing
external resistance. The inrush current during short circuit test was 2.51 A for the coin cell (with constant resistance of 0.026 Ω) and 85 A for 18650 cell (with constant resistance of 0.050 Ω). These inrush current values are very close to the limiting currents obtained from the constant voltage tests. The coin cells survived all the extreme condition tests with maximum temperature lower than 50 °C, but 18650 cells failed during 2 V constant voltage test and 0.050 Ω short circuit test with surface temperature up to 122 °C. The results clearly demonstrate that safety issue is much more serious for larger format Li-ion batteries and more efforts are warranted.
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Chapter 1

Introduction

Battery safety has become an important issue in recent years as the United States moves towards reducing its dependence on foreign oil. Key to this endeavor is increasing fuel economy of consumer vehicles. The transportation sector accounts for 27.8% of energy used in the United States and 97% of this energy comes from petroleum products.²

According to 2006 data from the United States Department of Transportation, passenger cars account for 43% of the total energy used for transportation in the U.S. (among passenger cars, busses, and trucks).¹ Electric and hybrid vehicles provide an elegant solution to increasing fuel economy in American passenger cars.

A hybrid vehicle combines the use of fuel and an electric motor powered by a battery pack to increase the fuel economy of the car. Plug in hybrids and fully electric vehicles are now starting to come onto the market. These vehicles include larger battery packs and thus carry more potential for disaster onboard.

Along with the increasing presence of hybrid and electric vehicles in the market comes a new set of challenges. Safety of the battery packs used in hybrid and electric vehicles is especially crucial to the long term success of electric transportation. Vehicles must withstand a wide range of conditions from high speed highway travel to congested city roads, from freezing Alaskan winters
to boiling Arizona summers. Through all of these conditions, above all else, these vehicles must remain safe.

1.1 Battery Safety in Recent News

Several well-known hybrid vehicles have had headlining failures of their battery packs which resulted in fires and ultimately destruction of the battery packs and in some cases the vehicles themselves. The damage caused by these incidents not only results in loss of the battery pack, but in loss of money by all parties involved – including the manufacturer of the battery. If the nation plans to continue to utilize battery technologies many advances in safety need to be made.

In January 2013, Boeing made headlines when two of its state of the art 787 Dreamliners experienced failure of their lithium ion battery packs. On January 7th, 2013 the battery of a Dreamliner owned by Japan Airlines caught fire in Boston. The 32V, 8 cell lithium ion battery experienced a short circuit in cell 6. The short escalated into thermal runaway, causing the fire and ultimately destruction of the battery pack.

On January 16th, 2013, just over a week after the first incident, a Dreamliner owned by All Nippon Airways experienced overheating of its batteries which resulted in an emergency landing. Analysis of the battery show charring across 6 of the 8 cells and evidence of a short circuit was again present (See Figure 1-1). It is yet unclear what has caused the shorts within these cells, however, the most likely causes are manufacturing defects, design flaws, or problems during charging.
After the January 16th fires, the entire fleet of Dreamliners was grounded until the cause of the short circuit incidents could be determined. Boeing has suffered significant losses due to the grounding of the planes, having to pay airlines millions in compensation for every month of down time as well as losses from new planes they cannot ship to buyers. The company who manufactured the batteries, GS Yuasa, has also suffered significant losses in profit during the aftermath of these incidents.

Figure 1-1: The damaged lithium ion battery (left) from the All Nippon Airways Dreamliner that had an emergency landing on Jan 16th. A new battery is shown on the right.

In June of 2011, a Chevy Volt caught fire at a GM test facility after its battery sustained damage during a crash test. The vehicle was used in a side impact crash test on May 12th, 2011. After the crash the car was rotated 360°. During the crash test a part of the driver’s seat broke and punctured the battery housing causing the electrolyte within some of the cells to leak out as well as damaging the battery’s cooling system. In the course of the roll test, the electrolyte and coolant leaked throughout the battery casing. The car caught on fire several weeks later during the weekend preceding June 6th, 2011. The fire originated from the Volt’s battery and, in addition
to destroying the Volt, also destroyed four other vehicles parked in the vicinity (See Figure 1-2 and Figure 1-3).

The exact cause of the fire is not known, however, a short circuit caused by either the puncture of the cell housing or the leakage of cell electrolyte into the pack electronics is the most likely cause. Prior to catching on fire, the Volt’s battery experienced a pressure event, most likely caused by cell venting due to a thermal response. The latency of the fire was difficult to explain, however, tests were conducted on three new batteries in an effort to reproduce the effects. Two of the three batteries tested caught fire within a week of a side impact roll crash test, however all batteries tested showed some reaction to the crash. The exact result of the May 12th crash test was not able to be reproduced. Fortunately, no fires have occurred in consumer vehicles even after a crash.

Figure 1-2: The Chevy Volt (circled) caught on fire destroying 3 other vehicles parked nearby.
The Fisker Karma, a plug in electric vehicle with a price tag of over $100,000, has been plagued with battery related recalls since its release in October, 2011. In December of 2011, 239 Karmas were recalled by Fisker due to the risk of a coolant leak that could start a fire in the battery. There was a second recall in March of 2012 when the batteries of 600 Karmas were recalled due to manufacturing defects by A123. This recall cost A123 $55 million and played a key role in the company’s financial problems. In August of 2012 Fisker recalled 2,400 Karmas after one of the cars caught fire while parked at a Woodside, CA grocery store. The fire was caused by an issue with a cooling fan due to an internal fault that eventually caused it to start a slow burning fire. While unrelated to the battery itself, the fire could have easily caused a thermal event with in the car’s lithium ion battery.

In October of 2012, sixteen Karmas were burned to the ground when Hurricane Sandy hit New Jersey (See Figure 1-4). The flood waters caused a short circuit within one vehicle’s control unit, which caught fire once the waters receded. The fire that started in that vehicle consumed the others sitting nearby. In addition to these widely publicized incidents, several other
fires involving the Karma have occurred, including a fire from unknown causes in a Sugar Land, TX garage. ¹¹,¹²

Figure 1-4: Sixteen Fisker Karmas were damaged after flooding caused a short circuit in the vehicle control unit of one vehicle. ⁶

These above examples illustrate why battery safety is of utmost importance not just in the battery pack itself, but also in those systems associated with it. Further understanding of the short circuit event and other low voltage/high current situations will allow manufacturers to make better decisions about battery pack design. Additionally, even if the battery itself is not at fault it can contribute to the magnitude of the damage if involved in a fire.

1.2 Background and Theory

The work presented in the rest of this paper relies heavily on Ohm’s Law (Equation 1). During short circuit conditions the cell current travels along an unintended, low resistance path. As the external (circuit) resistance decreases the current increases. The internal resistance is a property of the cell and cannot be changed experimentally. The internal resistance, however, may
change as the internal environment of the cell changes due to cell ageing, or even cycling at high/low ambient temperatures.\textsuperscript{33} The external resistance can be changed and used to cause a short circuit if it is a low enough value. Typically the external resistance is in the form of a high resistance load.

\[ I = \frac{V}{(R_{\text{internal}} + R_{\text{external}})} \]

Equation 1: Ohm's Law

A short circuit is an event that can occur within any electronic system. Short circuits develop when current surpasses the load and flows along an unintended path with lower resistance. The low resistance allows the current to reach a very high value. Two types of short circuits occur in batteries: external and internal. An external short circuit arises when the negative and positive terminals of the battery are directly connected by a conductive material outside of the circuit containing the load.\textsuperscript{26} These types of shorts are very easy to cause accidentally and intentionally. An internal short circuit may stem from various causes including dendrite formation on the anode, impurities in the electrode, or manufacturing flaws in any of the internal components of the cell.\textsuperscript{26} An internal short circuit typically results in damage to the separator which allows the cell contents to mix freely.

Lithium ion batteries are based on complex intercalation and deintercalation reactions which occur at the cell electrodes. An electrode in a lithium ion battery is made up of mostly active material – the stuff the reacts. The electronic conductivity of most lithium ion active materials is relatively low so a carbon based conductive material is usually added to the electrode, along with binders which stick it all to the current collector.\textsuperscript{14} The porous electrode is soaked
with electrolyte that includes a lithium salt (usually LiPF$_6$). If the porosity of the electrode is not sufficient there will not be adequate contact between the electrolyte and the active material. The electrolyte conducts lithium ions and is the medium through which the ions move from one electrode to the other.

During charge the reactive lithium ions are liberated from the cathode active material via the electrode reaction, transported through the electrolyte, and are intercalated into the anode active material via that electrode’s reaction. The reverse happens on discharge. The electrons produced during the electrode reaction are transported to the current collector by the carbon based conductive material. Good mixing is essential for efficient electron transport. If there is not good connection between the particles of the carbon material the pathway for electron transport will be longer. Once the electrons reach the current collector they pass through the circuit, creating “current”, and then participate in the electrode reaction of the opposite electrode.

The limiting current of the cell is the highest current that can be obtained from the cell and occurs when the electrolyte concentration at the surface of one of the electrodes reaches zero. This occurs when the cell is nearing the point of full discharge (0V). At this point the negative electrode will be nearly depleted of lithium ions and diffusion of said ions to the surface of the active material particles will be slow. The ions must diffuse to the surface of the electrode material to participate in the electrochemical reactions that produce electrons. Diffusion through the active material and reaction of the lithium ions with (rate of electron production) depend on many factors including state of charge, active material particle size, electrolyte conductivity (ions travel between electrodes via the electrolyte), and the ability of the electrons to travel efficiently through the conductive electrode materials to the current collector. Many aspects can affect the cell’s performance including active material particle size, electrolyte salt concentration,
adequacy of electrode slurry mixing, electrode porosity, electrode thickness, and ambient temperature.\textsuperscript{15, 16, 17, 18}

Safety incidents have two primary causes: abuse or spontaneous internal failure.\textsuperscript{38} Abuse failures are caused by use of the battery outside of its design parameters and include overcharging, over-discharging, or even using the battery past its designated lifetime (typically caused by the user of the battery).\textsuperscript{38} Spontaneous internal failures are caused by manufacturing defects in the cell.\textsuperscript{38} Abuse failures are by far the most common type of failure. The most serious consequences of battery failure occur when the energy stored in the battery is released all at once in an unintended manner, creating large amounts of heat and gas.\textsuperscript{38} Lithium ion batteries contain 1/3 to ½ the amount of energy of TNT, or 1282 Wh/kg.\textsuperscript{39} If electrolyte combustion is included, the value is even higher than that of TNT.\textsuperscript{39} The consequences of a lithium ion battery failure can be severe and may result in loss of equipment or life. Recall that the battery incident in the Chevy Volt caused a fire that burned three other cars. Lithium ion batteries present an excellent solution for lightweight energy storage, however due to their very high energy content they can cause a greater deal of damage than other popular batteries if not used properly.

The overarching goal of battery safety studies is to prevent batteries from failing violently. In other words, batteries need to fail gracefully and in a benign manner.\textsuperscript{38} Furthermore, it is important that should a cell with in a large battery pack fail, that the failure does not spread throughout the pack, but remains isolated to that cell.\textsuperscript{38} One battery failing alone will not cause nearly as much damage as an entire battery pack failing. Heat generation within a batter increases exponentially with temperature.\textsuperscript{38} One cell creating heat during a failure will raise the temperature of adjacent cells and could cause a chain reaction of failure events in the entire pack if not mitigated.
When studying battery safety, it is important to understand the methods by which a battery may fail and cause a safety concern. Battery failures fall into one of two categories: Non-energetic failures and energetic failures. Non-energetic failures include capacity loss, increase in internal impedance, activation of disabling safety mechanisms, electrolyte leakage, and cell swelling. These failures are, for the most part, harmless to the cell’s surroundings. Non-energetic failures are typically related to cell ageing. Energetic cell failures typically result from an increase in the internal cell temperature and include thermal runaway, venting (and ignition of associated gasses), decomposition of cell components, and ejection of cell contents. These failures can affect the cell’s surroundings and may result in explosion, fire, property damage, or personal injury. Table 1-1, below, shows a list of ways to classify battery failures. It will be employed in the discussion of the results in Chapter 4.

Table 1-1: Battery failure classification criteria established by Sandia National Labs.
Most commercial cells have safety devices that will increase the chances of a cell failing in a non-energetic manner. When these devices fail or are subjected to conditions outside of their specified range of safety an energetic failure may occur. It is for this reason that batteries and their associated systems should always be well maintained and monitored.

1.3 Government and Research Contributions

Battery abuse testing is key to the prevention of energetic failures, like the ones involving the Boeing 787, Chevy Volt, and Fisker Karma. The government and other private agencies have developed criteria for such tests. Sandia National Lab has recommended a set of abuse tests which are designed to help manufacturers of electric and hybrid electric vehicles overcome some of the safety concerns impeding widespread commercialization of these vehicles. Some examples of abuse tests include short circuit, overcharge, over-discharge, crush, impact, free fall, and temperature cycling. Batteries that cannot withstand the specified conditions of a given test should not be utilized in battery packs for consumer vehicles.

Table 1-2 and Table 1-3, taken from SAE J2464 “EV & HEV Rechargeable Energy Storage System (RESS) Safety and Abuse Testing Procedure” by Daniel H. Doughty (Sandia National Labs), shows an outline of some safety tests as specified by several organizations. It is important to note that all tests with the potential for a large current response are performed only at room temperature and at higher ambient temperatures, neglecting the lower temperature range.
<table>
<thead>
<tr>
<th>Test Title</th>
<th>Cell Testing</th>
<th>Portable Electronics</th>
<th>Cell &amp; Pack Testing</th>
<th>Automotive Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shipping</td>
<td>Portable Electronics</td>
<td>Automotive Applications</td>
<td></td>
</tr>
<tr>
<td>Altitude</td>
<td>6hr @ 0.11 atm</td>
<td>6hr @ 0.11 atm</td>
<td>6hr @ 0.11 atm</td>
<td>Analysis of electrolyte vapors and airborne volatile and particulates released during abuse tests</td>
</tr>
<tr>
<td>Hazardous Substance Monitoring</td>
<td>10 cycles of 6hr @ 75°C &amp; -40°C</td>
<td>10 cycles of 6hr @ 70°C &amp; -40°C</td>
<td>5 cycles of 4hr @ 75°C &amp; -20°C</td>
<td>5 cycles between +70°C &amp; -40°C – hold cells for 1 hour hold modules and packs for 6 hours.</td>
</tr>
<tr>
<td>Temperature Cycling</td>
<td>130°C for 10 min</td>
<td>130°C for 10 min</td>
<td>130°C for 60 min</td>
<td>Determine maximum temperature at which cell is table indefinitely</td>
</tr>
<tr>
<td>High Temperature</td>
<td>12 reps up to 8 g peak</td>
<td>10 to 55 Hz at 1 Hz/min</td>
<td>10 to 55 Hz at 1 Hz/min</td>
<td>18 ea. 15 msec 25g shocks = XYZ negative &amp; positive directions x 3 times.</td>
</tr>
<tr>
<td>Vibration</td>
<td>3 ea. 150g shocks for cells, 50g shocks for modules and packs</td>
<td>3 ea. 125-175g shocks</td>
<td>3 ea. 125 – 175g shocks</td>
<td></td>
</tr>
<tr>
<td>Mechanical Shock</td>
<td>Less than 100mΩ at 55°C</td>
<td>Less than 100mΩ at 20°C &amp; 55°C</td>
<td>Less than 100mΩ at 20°C &amp; 55°C</td>
<td>Perform 2 short circuit tests: a hard short (≤ 5mΩ) and moderate short at resistance comparable to the test article resistance at 25°C ± 5°C</td>
</tr>
<tr>
<td>External Short Circuit</td>
<td>Less than 100mΩ at 55°C</td>
<td>Less than 100mΩ at 55°C</td>
<td>Less than 50 mΩ at 55°C</td>
<td></td>
</tr>
<tr>
<td>External Short Circuit on Cycled Cells</td>
<td>Less than 100mΩ at 55°C</td>
<td>Less than 50mΩ at 55°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact</td>
<td>9.1kg from 61cm</td>
<td>9.1kg from 61cm</td>
<td>Cell should be charged at two rates: a) 1C-Rate constant current and b) at the maximum use current to 200% SOC</td>
<td></td>
</tr>
<tr>
<td>Overcharge</td>
<td>To 200% SOC</td>
<td>To 250% SOC</td>
<td>To 250% SOC</td>
<td>Cell test to -100% SOC and additional module test</td>
</tr>
<tr>
<td>Forced Discharge (Overdischarge)</td>
<td>To -100% SOC</td>
<td>To -100% SOC</td>
<td>To -150% SOC</td>
<td></td>
</tr>
<tr>
<td>Crush</td>
<td>3000lbs force</td>
<td>13kN force</td>
<td>To 85% of the initial dimension; hold for 5 min. &amp; continue to crust to 50%.</td>
<td></td>
</tr>
<tr>
<td>Open Flame Test (Fuel Fire)</td>
<td>A cell contained in a wire cage is heated from below by a burner flame – No projectiles</td>
<td>A cell contained in a wire cage is heated from below by a burner flame – No projectiles</td>
<td>10 min at 890°C – simulated fuel fire</td>
<td></td>
</tr>
</tbody>
</table>
Table 1-3: Comparison of test conditions found in SAE J2464 to UN, UL, IEEE Safety and Abuse Testing Standards (Part 2).

<table>
<thead>
<tr>
<th>Test Title</th>
<th>Cell Testing</th>
<th>Cell &amp; Pack Testing</th>
<th>Automotive Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Shipping</strong></td>
<td><strong>Portable Electronics</strong></td>
<td><strong>SAE J2464 HEV and EV Rechargeable Energy Storage System (RESS) Safety and Abuse Testing</strong></td>
</tr>
<tr>
<td>Float Charge</td>
<td>28 days at 20°C and 100% SOC (float charge)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Rate Discharge</td>
<td></td>
<td>With active thermal controls disabled, 20 full charge/discharge cycles at maximum expected rate with no rest period</td>
<td></td>
</tr>
<tr>
<td>Drop Test</td>
<td>From 1 m</td>
<td>From 2m</td>
<td></td>
</tr>
<tr>
<td>Separator High Temperature Stability</td>
<td>150°C for 10 min</td>
<td>Apply 20+ volts at 5°C above the measured shutdown temperature</td>
<td></td>
</tr>
<tr>
<td>Nail Penetration</td>
<td>8 cm/s or greater and rode diameter shall be 3 mm rod (for cells) and 20 mm rod (for modules and packs).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roll-Over</td>
<td>Complete revolution in 1 minute. Then rotate the RESS in 90 degree increments for one full revolution.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immersion</td>
<td>In salt water for a minimum of 2 hr.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passive Propagation Resistance</td>
<td>Does cell failure propagate in battery pack?</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
For more detailed information on the safety tests presented in the tables above see the reports prepared by NFPA and Sandia National Labs.\textsuperscript{19,27}

Abuse test standards, as listed in Table 1-2 require that a battery withstand an external short circuit of 0.1\,Ω or lower at both 20 \,°C and 55 \,°C.\textsuperscript{19,20} A battery pack must be able to withstand two short circuit tests - 5m\,Ω or less and a resistance that is comparable to the internal resistance of the pack being tested – at 20 ± 5 \,°C.\textsuperscript{20} These types of external short circuit tests have been performed on cylindrical, prismatic, 18650, and other larger sized batteries of various chemistries, with temperature, voltage, and current being monitored.\textsuperscript{22,24,25} Notably, the work by Conte, et al shows that the peak current response to a short circuit increases nearly linearly with increasing cell capacity.\textsuperscript{24} The results obtained by Conte, et al, Kallfa, et al, and Kitoh et al all showed similar trends in current, voltage, and temperature during the short circuit despite the difference in type of cell used. Several research groups have also prepared models to study a cell’s response to both internal and external short circuit events by varying cell SOC, type of short, and area of the short.\textsuperscript{23,26} The results obtained in these aforementioned models show similar trends to those found by the experimental works.

The results presented in all cited works observe the cell under short circuit conditions for only as long as 30 minutes and all used higher capacity cells such as 18650, 22650, and larger. The work presented in this paper will observe the cell under short circuit conditions for up to one hour and will look at a smaller capacity coin cell as well as an 18650 cell. The one hour test time will allow additional insight about the temperature profile of the cell (notably the coin cell) during the short circuit that has not been observed in previous experimental or modeling work.
The larger capacity 18650 cell was also observed for an extended time, but did not show similar trends to the coin cell.

Low temperature performance of batteries has been a popular topic recently due to the desire to use batteries for space applications as well as to ensure that hybrid and electric vehicles will continue to operate properly during the winter in the coldest climates. At low ambient temperatures, battery performance decreases significantly. A crippling decrease in electrolyte conductivity at low temperatures has been identified as one reason for decreased performance. A second widely researched reason for decreased battery performance at low temperatures is an increase in the charge transfer resistance.

M.C. Smart et al. look specifically at lithium ion batteries for operation on the surface of Mars. MCMB-NCO cells are charged and discharged between -40°C and 23°C and the effects of different electrolytes are observed. Tikhonov, et al. also examine the effects of electrolyte on battery performance, however the studied temperature range is -40 to 80 °C. Simple discharge tests were performed with some specially formulated electrolytes.

Li et al. observes a notable decrease in cell discharge capacity, attributed to the charge transfer resistance and low ionic conductivity of the electrolyte, as the ambient temperature is decreased from room temperature to -40°C. Two lithium ion salts are compared to determine how they affect the performance of LFP/Li and graphite/Li half cells.

The work by Fan examines the discharge capacities of LCO 18650 cells at room temperature as well as -20, -30 and -40°C. The batteries show a significant decrease in
performance below -20°C, even at low C rates (0.2C), and also the cell internal resistance is shown to increase with decreasing temperature.\textsuperscript{33}

Cho, et al. also found that an increase in the interfacial charge transfer resistance (via EIS) on the cathode and anode of an LCO/graphite cell caused lower performance during pulse discharge tests\textsuperscript{31}. Liao et al. examined both charge and discharge at low temperatures, concluding that both charge and discharge capacity decrease with decreasing temperature. The temperature range studied was from 20 to -20°C and the charge transfer resistance was shown by EIS to be the most significantly increased with decreasing temperatures among the three resistances studied (bulk resistance, SEI layer resistance, and charge transfer resistance).\textsuperscript{32} The bulk and SEI layer resistances changed very little with decreasing temperature compared to the charge transfer resistance.\textsuperscript{32}

While the short circuit test has been well defined by both government protocol and experimental research, the constant voltage discharge test detailed in this work is novel. The purpose of this test is to observe the cell’s reaction to low voltage (and therefore high current) circumstances and to determine the limiting current of the cell by extrapolation. As the voltage approaches zero the current response will approach the cell’s limiting current. It is also the goal of this work to observe the effects of temperature, namely low ambient temperatures, on the cell’s reaction during the constant voltage tests. Since low performance was observed in all experimental works, it is expected that the batteries will produce a much lower current during the low temperature tests.
1.4 In This Work

As mentioned above, extensive work with short circuit testing has been performed. Additionally, much work has been done to analyze battery performance at low temperatures. In the work detailed in the remaining chapters four experiments will be discussed. Two commercial lithium ion cells were used for these experiments: A 40mAh LCO coin cell manufactured by AA Portable Power Corp. and purchased from Dantona Inc. and a 2250mAh Panasonic LCO 18650 cell.

Equation 2: LCO electrode reactions during discharge.

Cathode Reaction: \( \text{Li}^+ + \text{Li}_{1-x}\text{CoO}_2 + x\ e^- \rightarrow \text{LiCoO}_2 \)

Anode Reaction: \( \text{Li}_x\text{C}_6 \rightarrow x\ \text{Li}^+ + x\ e^- + \text{C}_6 \)

Each type of cell is subjected to short circuit testing with varying external resistances where current and cell surface temperature are monitored. Additionally, each cell is tested over a constant voltage discharge where the discharge voltage ranges from nominal voltage (3.6V) down to 0.5V for the coin cell and 2V for the 18650 cell. This test will examine conditions approaching short circuit as the voltage is changed from its nominal value to a value close to zero. The constant voltage discharge test for the coin cell is performed at room temperature, several low ambient temperatures, and at one high temperature in order to examine the effects of the discharge over the entire operating range for a vehicle. The 18650 cell is only tested at room temperature. The results from the well studied short circuit test will be compared with those from the novel constant voltage discharge tests.
Chapter 2

Experimental

Five sets of tests were performed: (1) Constant voltage tests on recycled coin cells (preliminary cell tests), (2) constant voltage tests on commercial 40mAh LCO coin cells, (3) constant resistance tests (short circuit) on commercial 40mAh LCO coin cells, (4) constant voltage tests on 2250 mAh LCO Panasonic 18650 cells, and (5) constant resistance tests on 2250 mAh LCO Panasonic 18650 cells.

Arbin battery testers, -100mA to 100mA for preliminary testing and -20A to 20A for commercial cell testing, were used for all testing to measure voltage, current, and capacity. An Agilent data acquisition was used to measure temperature, voltage, and current (via a shunt resistor in constant resistance tests). Various safety devices were also employed and are described further below.

2.1 Half Cell Preliminary Tests

Since the constant voltage test has not been previously studied, a preliminary round of testing was performed on low capacity half cells. Five previously cycled half cells were obtained for preliminary testing. The cathode was LFP on 15um aluminum foil and the anode was Li foil. The electrolyte was Novolyte 1.2M LiPF₆ and separator was Celgard with 20 µm thickness. The cells were prepared following a similar method as described by Marks, et al. The cathode was 83% LFP. The cells had a cathode coating of 7 to 9 um and discharge capacities between 1.2 and 1.4mAh. The viability of the cells was determined by charging and discharging
the cells at 0.1C and 0.5C (C Rate test). A commercial plastic coin cell holder was used for preliminary testing. The cell and holder were placed in a custom-made safety box, shown in Figure 2-1.

![Safety box](image)

Figure 2-1: Safety box used in all testing.

The C Rate testing protocol for the preliminary cell tests is described below:

1. CC Charge to 4.3V at C/10 followed by CV charge until C/100 at 4.3V
2. 10 minute rest
3. Discharge cell to 2.5V at C/10. Voltage range 2.5 to 4.5V
4. 10 minute rest
5. CC Charge to 4.3V and C/5 followed by CV charge until C/100 at 4.3V
6. 10 minute rest
7. Discharge cell to 2.5V at C/2
8. Discharge cell to 2.5V at C/5 to ensure cell is completely discharged

The cells were considered viable if the discharge capacity was greater than 1mAh at 0.5C. Data points were measured at 1 second intervals using the -100 to 100 mA Arbin battery tester and the voltage range was 2.5 to 4.5V.
Three of the five recycled cells were viable after the C Rate test. The cells were named as follows: 11292, 10171, and 10173. Cell 11292 had a cathode thickness of 9um, while cells 10171 and 10173 had a cathode thickness of 7um. The three viable cells were tested using the constant voltage discharge test outlined below:

1. C/5 CC charge to 4.3V and 4.3V CV charge to C/50
2. 1 hour rest
3. Discharge cell at constant voltage (3.2, 3, 2.5, 2, 1, 0.5) to C/50
4. 1 hour rest

The -100 to 100 mA Arbin battery tester was used to measure current and voltage. Data points were taken every one second. Temperature was not measured during preliminary cell testing. The voltage range was 4.5 to 2.5V. A schematic of the experimental set up for the preliminary tests is shown in Figure 2-2.

![Figure 2-2. Experimental schematic for preliminary cell tests.](image)
2.2 Commercial 40mAh LCO Coin Cell Constant Voltage Test

A Dantona 40mAh LCO coin cell (LIR2032), was used for the constant voltage discharge tests. The cells had an LCO cathode, a graphite anode, and a PP/PC separator. The nominal voltage for this cell was 3.6V. The cell had a maximum pulse discharge current of 75mA and a maximum discharge current of 12mA. A C Rate test was performed on the 40mAh cells, as specified by the data sheet, in order to determine the nominal cell capacity. The minimum voltage for these cells was 3V and the maximum voltage was 4.2V. The charging voltage was 4.2V. The C Rate test is outlined below:

1. C/2 CC charge to 4.2 V followed by 4.2V CV charge to C/50
2. 1 hour rest
3. Discharge (0.2C, 0.5C, 1C, 2C) to 3V
4. Discharge at 0.2C to 3V (this step only used for C Rates above 0.2C) to ensure the cell is discharged the same extent for each C rate.
5. 1 hour rest

The constant voltage tests were performed at room temperature as well as 0, -10, -20, and 45°C (in that order). The cell, called Cell 9, was used for all CV discharge tests to ensure repeatability. The ambient temperature was maintained using a Tenney environmental chamber. The -20A to 20A Arbin battery tester was used to measure current and voltage. Data points were measured every one minute except during discharge when the interval was one second. Temperature and voltage data were collected at one second intervals for the entire test using the Agilent data acquisition. Two thermocouples were attached to the cell – one on each side- in order to obtain the most accurate temperature reading. The cell was placed in a special cell holder (discussed later in this section). A third thermocouple was attached to the cell holder in
order to most accurately measure the ambient temperature the cell experienced. The experimental set up is illustrated in Figure 2-4.

Anticipated higher temperatures during these tests required the development of a special coin cell holder. This holder was designed such that it would not become damaged by higher temperatures and would not inhibit heat transfer between the cell and ambient environment. The cell holder is shown below in Figure 2-3.

![Coin cell holder](image)

Figure 2-3: Coin cell holder used in constant voltage and constant resistance tests

The protocol for the constant voltage test is outlined below.

- 1C CC charge to 4.2V followed by 4.2V CV charge to C/20 at room temperature
- 1 hour rest (cell cooling if applicable)
- CV discharge for 30 minutes (3.6, 3, 2, 1, 0.5V)
- 2 hour rest (cell warming if applicable)
- Repeat

The room temperature constant voltage test on Cell 9 included a 1 hour discharge, rather than 30 minutes and 4 hour rest after discharge, rather than 2 hours. Additionally, the cell was charged at 0.5C and the CV charge went until C/50. The test procedure was altered after the room temperature test to meet time constraints.
Two additional tests were required after the 45°C results from Cell 9 did not match expectations. Cell 9 was tested a second time at room temperature to determine if a decrease in cell performance had occurred during the test. When cell 9 showed a notable decrease in performance during the second room temperature test, a fresh cell, Cell 10, was used to repeat the 45°C test to determine if the initially observed results were valid. The second room temperature test and the tests on Cell 10 followed the standard protocol, above.

![Experimental schematic for coin cell constant voltage test.](image)

**2.3 Commercial 40mAh LCO Coin Cell Constant Resistance Test**

The coin cell constant resistance test was performed on three different Dantona 40mAh LCO coin cells and follows a similar method as that used by Conte, et al.\textsuperscript{24} The ohmic resistance of a fresh Dantona cell was \( \sim 0.7\Omega \). Constant resistance tests were performed for two low (0.026 and 0.055 \( \Omega \)) and one high external resistance (1.03\( \Omega \)) at room temperature. The first set of tests included the 1.03 \( \Omega \) and 0.026 \( \Omega \) tests. These tests were performed on the cells called Cell 3 and Cell 4. A second low resistance test (0.055 \( \Omega \)) was performed as part of a class project which studied the constant resistance test over a wide temperature range. The 0.055\( \Omega \) test was
performed on the cell called Cell 8. Only the room temperature data point from Cell 8’s test is included in this analysis.

The 1.03Ω resistance was achieved by including a 1 ± 0.001 Ω resistor in the circuit. The 0.026 Ω resistance was simply the resistance of the circuit with no resistor added. The temperature tests performed on Cell 8 required longer wires to reach into the environmental chamber – the resistance of this circuit was 0.055Ω.

An experimental circuit was designed for the constant resistance tests (see Figure 2-5 and Figure 2-6). A 2mΩ shunt resistor was used to measure current. The same cell holder used for the constant voltage tests was also employed here. The tests were carried out in the safety box. Two insulated thermocouples were attached to the cell (one on each side) in order to obtain the most accurate temperature measurement. A third thermocouple was inserted into the safety box to measure the ambient temperature. The Agilent data acquisition was used to measure temperature, voltage, and current via the shunt resistor. Data points were taken at one second intervals. The -20 to 20 A Arbin battery tester was used to charge the cell.

The experimental procedure is outlined below:

1. Start data acquisition
2. After 10 minutes close switch (cell temperature will increase)
3. Once cell temperature returns to room temperature open switch
4. Rest for 4 hours
5. C/2 CC charge to 4.2V followed by 4.2V CV charge to C/50
Figure 2-5: Schematic for constant resistance coin cell experiment. The load resistor is not included in the 0.026 and 0.050 Ω tests.

Figure 2-6: The circuit board for the coin cell constant resistance test as used for the 0.050 and 0.026 Ohm tests.
2.4 Commercial 2250mAh LCO 18650 Cell Constant Voltage Test

One 2250mAh LCO Panasonic 18650 cell was used for the constant voltage test. The cell had an LiCoO$_2$ cathode and a proprietary carbon anode. The separator and electrolyte contained in the cell were not specified by the cell manufacturer. The nominal cell voltage was 3.6V. A C rate test was performed on this cell in order to determine the nominal discharge capacity. The minimum voltage for these cells was 3V and the maximum voltage was 4.2V. The charging voltage was 4.2V. The C Rate test is outlined below:

1. C/2 CC charge to 4.2 V followed by 4.2V CV charge to C/50
2. 1 hour rest
3. Discharge (0.2C, 0.5C, 1C, 2C, 5C) to 3V
4. Discharge at 0.2C to 3V (this step only used for C Rates above 0.2C) to ensure the cell is discharged the same extent for each C rate.
5. 1 hour rest

The constant voltage tests were performed at room temperature. A single cell, called cell J3, was used for all constant voltage tests to ensure repeatability. The -20A to 20A Arbin battery tester was used to measure current and voltage. The current for the 18650 cell is expected to exceed 20A, especially at low voltages, so five Arbin channels were required to obtain the -100A to 100A current limit needed. Data points were measured every one second. Temperature and voltage data were collected at one second intervals using the Agilent data acquisition. Three thermocouples were attached to the cell – one near the positive end, one in the middle, and one near the negative end - in order to obtain the most accurate temperature reading. The cell was placed in the 18650 cell holder and then into the safety box. The experimental set up is illustrated in Figure 2-7. Additional photos of the experimental set up are shown in Figure 2-8 and Figure 2-9.
The protocol for the constant voltage test is outlined below:

- 1C CC charge to 4.2V followed by 4.2V CV charge to C/20 at room temperature
- 1 hour rest
- CV discharge for 30 minutes (3.6V) or up to 10 minutes*** (3, 2V)
- 2 hour rest
- Repeat

***The discharge time was set for 10 minutes for both the 3V and 2V tests, however, due to the high temperatures achieved during the 3V test the 2V discharge was altered. During the 2V test the discharge time was shortened in an effort to prevent permanent damage to the cell. The discharge was performed up until 1 minute after the maximum temperature was reached. After this point, the rest step was initiated. Despite these efforts the cell was still irreparably damaged during the 2V test.

Figure 2-7: Schematic for 18650 cell constant voltage discharge test.
Figure 2-8: Five channels of the Arbin battery tester were combined to make the current range - 100A to 100 A.

Figure 2-9: Close up of the “hubs” connecting the 5 Arbin channels to the battery terminals.
2.5 Commercial 2250mAh LCO 18650 Cell Constant Resistance Test

One 2250mAh LCO Panasonic 18650 (CGR18650CH) cell, called cell J2, was used for this constant resistance test. The internal resistance of the cell was 0.030Ω. The test was first performed on a previously cycled 18650 cell of the same type, in order to test the strength of the safety box and to determine what sort of reaction to expect. The recycled cell underwent venting during the test and experienced a temperature rise of 80°C.

Cell J2 was tested at 3 high (1, 2, 5 Ω) and one low resistance (0.050 Ω). The -20 to 20 A Arbin battery tester was used to maintain the constant resistances during the high resistance tests. The Arbin was also used to collect voltage and current data as well as to charge the cell. The Agilent data acquisition was used to measure temperature, voltage, and current via the 2mΩ shunt resistor. Data points were taken every one second for temperature measurements and during constant resistance discharge (every one minute otherwise). The experimental set up is illustrated below in Figure 2-10.

Figure 2-10: Experimental set up for 5, 2, and 1 Ohm constant resistance tests.
The wrapping was removed from the cell and three thermocouples – anode, cathode, and middle – were attached to the cell using aluminum tape (see Figure 2-12). The cell was placed in a custom made cell holder (pictured in Figure 2-11) and then inside the safety box. A fourth thermocouple was placed in the safety box to measure ambient temperature. The safety box was contained inside of a Thermal Hazard Technology Calroimetry box (pictured in Figure 2-13).

The three highest resistance tests were performed with the Arbin battery tester using the following protocol:

1. 3 hour 0.5C CC charge to 4.2V
2. 2 hour 4.2V CV charge to C/50
3. 1 hour rest
4. 10 minute constant resistance discharge (5, 2, 1 Ω)
5. 2 hour rest

Figure 2-11: Cell holder used for 18650 cell tests.
Figure 2-12: Three thermocouples were attached to the 18650 cell

One low resistance test was performed on the 18650 cell. An experimental circuit was designed to test the cell at 50mΩ. The Arbin battery tester is unable to control the voltage at this low resistance, so it could not be used. The same circuit used in the constant resistance coin cell testing was used for the 18650 cell tests (see Figure 2-5). The same thermocouple configuration as the high resistance tests was used to monitor cell and ambient temperature. Figure 2-14 shows the switch used for this test.

Figure 2-13: Thermal Hazard Technology Calorimetry safety box
Figure 2-14: A switch that could handle a higher current was needed for this experiment. This figure shows the switch in its closed position.

The test protocol for the 0.050Ω test is outlined below:

1. Start data acquisition.
2. After 10 minutes close switch (cell temperature will increase)
3. Turn off data acquisition once cell temperature returns to room temperature.

Temperature, current (via the 2mΩ shunt resistor), and voltage were measured using the Agilent data acquisition. Data points were taken every one second.
Chapter 3

Results

3.1 Preliminary Cell Tests

The constant voltage discharge curves for cell 11292 are shown below (results for the 10171 and 10173 can be found in Appendix A) in Figure 3-1.

![Constant Voltage Discharge Curves for 11292](image)

Figure 3-1. Constant voltage discharge curves for preliminary test cell 11292

The 3V and 3.2V curves did not differ greatly, so the 3.2V test was eliminated in further preliminary cell testing. The cells all scored a 0 on the battery failure classification criteria.
3.2 Commercial 40mAh LCO Coin Cell Constant Voltage Test

The first test performed on the 40mAh coin cells was a C Rate test to determine the nominal capacity of the cells. The results of this test are shown in Figure 3-2.

![Discharge Curves for 40mAh Cell](image)

Figure 3-2: C Rate test results for 40mAh LCO commercial coin cells

The current and temperature profiles for the constant voltage test for the first room temperature run are shown below in Figure 3-3 and Figure 3-4. The results for the 0, -10, -20, and 45 °C tests are included in Appendix A (including repeated tests).
The result of the initial constant voltage discharge test for Cell 9 is shown in Figure 3-5. It was expected that the 45°C test would yield currents higher than those observed during the room temperature test. Cell 9 was tested again at room temperature to determine if the
cell performance had decreased during testing, causing the lower than expected inrush current values during the 45°C test.

The temperature results for the initial tests on Cell 9 are shown below in Figure 3-6. As for the current results shown above, the 45°C result was lower than expected. The ΔT was calculated using the following formula:

\[ ΔT = T_{avg} - \text{Average}(T_{ambient}) \]

Equation 3

\( T_{avg} \) is the average temperature measured by the two thermocouples at a given point in time. The average of the ambient temperature was calculated over the entire discharge for a given voltage.
The results for the repeated room temperature test on Cell 9 are compared with the results from the initial room temperature test on cell 9 in Figure 3-7 and Figure 3-8. The repeated room temperature test on Cell 9 shows a marked decrease in cell performance indicating that during the testing the cell became damaged, so a new cell, cell 10, is used to repeat the 45°C test. The results for the 45°C test on Cell 10 are compared with the 45°C test on cell 9 in Figure 3-9 and Figure 3-10. An increase in the inrush current was observed during the repeated test at all voltages, indicating that the initial 45°C test was affected by the decrease in performance observed in cell 9. Therefore, the Cell 10 45°C results are used in all further analysis and the final results for the constant voltage discharge tests can be found in Figure 4-1 and Figure 4-5.
Figure 3-7: Constant voltage discharge results comparing original and repeated room temperature results.

Figure 3-8: Constant voltage temperature results comparing original and repeated room temperature tests.
Figure 3-9: Constant voltage inrush current results comparing original and repeated 45°C tests.

Figure 3-10: Constant voltage temperature results comparing original and repeated 45°C tests.

The rate of temperature rise was calculated for each voltage using Equation 4 below:
As shown below, in Figure 3-11 the rate of the temperature rise increases with increasing ambient temperature and decreasing voltage.

\[
\text{Rate of Temperature Rise} = \frac{\text{maximum } \Delta T}{\text{time to max. } \Delta T}
\]

Equation 4

**Figure 3-11: Rate of temperature rise during constant voltage tests.**

### 3.3 Commercial 40mAh LCO Coin Cell Constant Resistance Test

The last test performed on the commercial coin cells was the constant resistance or short circuit test. The cells were tested at three resistances: 0.026, 0.055, and 1 Ω. The ambient temperature was room temperature for all tests. Current and temperature profiles are shown for the 0.026Ω test in Figure 3-12 and Figure 3-13. It can be seen that a very high inrush current, up to 2.51 A (equivalent to 63 C) occurs at the start of discharge but rapidly drops to a lower value.
The current then gradually decreases. The temperature also increased correspondingly, but the temperature peak is not as sharp as the current peak and the temperature response is slower than that of the current.

Figure 3-12: 0.026 Ω short circuit current profile.

Figure 3-13: 0.026 Ω short circuit temperature profile.
The voltage profile for the 0.026Ω test is shown in Figure 3-14. It is interesting to compare this to the voltage profile for the 1Ω test in Figure 3-15. There is an obvious difference in the shape of the voltage curve between these two tests.

Figure 3-14: Voltage profile for 0.026Ω short circuit test.

Figure 3-15: Voltage profile for 1Ω short circuit.
Current and temperature profiles for the 1 and 0.055Ω tests can be found in Appendix A. The voltage profile for the 0.055Ω test can also be found in Appendix A.

### 3.4 Commercial 2250 mAh 18650 Cell Constant Voltage Test

The first test performed on the 18650 battery was a C Rate test to determine the nominal capacity of the cell. The results of this test are shown in Figure 3-16. It can be seen that the discharge capacity agrees well with the nominal capacity from manufacturer.

![C Rate Test for Panasonic 18650 Cell](image)

**Figure 3-16:** C Rate test results for 2250mAh 18650 cell.

The current and temperature profiles for the 18650 cell constant voltage test are shown in Figure 3-17 and Figure 3-18, below. The change in temperature, ΔT was calculated using Equation 3. The inrush current and maximum ΔT are plotted against the discharge voltage in Figure 3-19 and Figure 3-20.
Figure 3-17: Current profiles for the 18650 cell constant voltage discharge tests.

Figure 3-18: Temperature profiles for the 18650 cell constant voltage discharge tests.
The rate of temperature rise for the 18650 cell is shown in Figure 3-21. The rate was calculated using Equation 4.
Figure 3-21: The rate of temperature rise experienced by the 18650 cell vs. the discharge voltage.

3.5 Commercial 2250 mAh 18650 Cell Constant Resistance Test

The current and temperature profiles for the high resistance short circuit tests are shown in Figure 3-22 and Figure 3-23. The shape of the current profiles for the high resistance 18650 cell tests varies greatly from the shape of the current profiles measured for the coin cells. Comparing the 1 Ω case, especially, the 18650 cell undergoes a much more gradual change in current than the coin cell at the same resistance. The 18650 cell temperature profiles also differ greatly in shape from those observed for the coin cells.
Figure 3-22: High resistance short circuit current profiles for 18650 cell.

Figure 3-23: High resistance short circuit temperature profiles for 18650 cell.
The current and temperature profiles for the low resistance (0.05 \( \Omega \)) short circuit test are shown in Figure 3-24 and Figure 3-25. The shape of the current and temperature profiles for this low resistance test differ greatly from those of the high resistance tests. It is also interesting to compare the shape of the 18650 cell current profile to the shape of the current profile measured for the coin cell. The current for the coin cell shows only one peak when the switch is closed and then gradually decreases, while the 18650 cell’s current peaks twice and decreases to 0 immediately after the second peak. The voltage profile for the 0.050\( \Omega \) short is shown in Figure 3-26. The voltage drops upon the start of the short circuit test, but becomes unstable shortly thereafter.

Figure 3-24: 18650 cell 0.050 \( \Omega \) short circuit current profile.
Figure 3-25: 18650 cell 0.050 Ω short circuit temperature profile.

Figure 3-26: Voltage profile for 0.050Ω short circuit test for the 18650 cell.
Chapter 4
Discussion

4.1 Commercial 40mAh LCO Coin Cell Constant Voltage Test

The final results of the constant voltage discharge are shown in Figure 4-1 and Figure 4-5. As mentioned in the experimental section, cell 9 had been damaged during testing based on the marked decrease in performance at room temperature (see Figure 3-7 and Figure 3-8). The 45°C test on cell 10 is included as the final result in lieu of that same test on cell 9.

Figure 4-1: Final inrush current results from coin cell constant voltage testing over a wide temperature range.

The inrush current varies nearly linearly with voltage as shown in Figure 4-1. Increasingly lower currents are observed, overall, as the ambient temperature decreases (see
Figure 4-2). This trend indicates a lesser risk for an energetic failure at low ambient temperatures, as evidenced by the decreased response for the given stimulus. Reasons for this decreased response include increased charge transfer resistance and decreased electrolyte ionic conductivity at lower temperatures.32,36,37 These effects can cause irreparable damage to the cell, resulting in ageing of the cell components and decreased performance and possibly cycle life. These problems can be mitigated by changing different aspects of cell design including electrolyte composition, active material particle size, electrode thickness, and electrolyte additives designed to increase low temperature performance.

Figure 4-2: The current response to changing ambient temperature without the 45°C data.
The current response of the cell at the high temperature, 45°C, is lower than expected. Based on the linear trend of the current with respect to ambient temperature (see Figure 4-2), it was assumed that the cell would exhibit a larger current response at 45°C for each voltage, following the linear trend established during the earlier tests. Based on the marked decrease in the $R^2$ values observed in Figure 4-3, it is clear that the cell performance at 45°C did not follow the same trend as earlier tests. Since the charge transfer resistance does not change much at higher temperatures this result is not entirely unforeseen.\(^{32}\)

A possibility also exists that the Arbin battery tester may not have been able to measure the first data point of the discharge accurately enough. Since the 45°C current response was expected to be close to, albeit higher than, the room temperature current response, missing the very beginning of the discharge by even a small amount of time could miss the actual highest current. The fastest (accurate) sample time for this machine is 1 second. The current response lasts for a short amount of time and measuring the current even one second after the peak would
record a very different value. Figure 4-4 is a zoomed in version of Figure 3-3, showing that the majority of the current response to the change in voltage, especially at low voltages, occurs in a 3 second time period. A more sensitive instrument would likely be able to more accurately measure the current response during these tests.

![Constant Voltage Discharge - RT](chart.png)

Figure 4-4: Zoomed in version of Figure 3-3 to show the length of time for the current response.

Similarly to the inrush current, the maximum change in temperature achieved during each constant voltage discharge varies nearly linearly with discharge voltage. The maximum ΔT for each set of tests decreases with decreasing ambient temperature but increases with decreasing voltage (see Figure 4-5). The rate at which the maximum temperature is reached varies inversely with discharge voltage (see Figure 3-11). These observed results correlate with the higher current responses observed at the lowest voltages for all ambient temperatures. It is clear that a higher current response will elicit a higher and faster temperature response. The rate at which the electrode reactions increases during high current situations. This leads to an increase in heat production which manifests as the increase in surface temperature that was measured in this experiment.
Figure 4-5: Final $\Delta T$ results for coin cell constant voltage testing over a wide temperature range.

Figure 4-6: Maximum $\Delta T$ results for each voltage as they change with varying ambient temperature.
Figure 4-6 shows the maximum $\Delta T$ for the constant voltage discharge as it varies with the ambient temperature for each constant voltage discharge. The 45°C temperature result does not follow the same trend established during the lower temperature tests. A higher temperature response from the cell was anticipated at all voltages for this test based on the linear trends established in earlier testing (see Figure 4-7). The conditions within the environmental chamber are the likely cause. The ambient temperature during the room temperature tests was not maintained at a constant value and varied with the ambient temperature in the lab. During the other tests the environmental chamber was used to maintain the ambient temperature. The climate inside the environmental chamber has a stronger cooling effect than that of the room at which the room temperature tests were conducted. This cooling effect contributed to the lower than expected temperatures that were recorded during the 45°C test.

![Constant Voltage Discharge Max $\Delta T$ vs. Amb. Temp](image)

**Figure 4-7:** A linear trend was established in the tests leading up to the 45°C test.
The temperature profiles observed at room temperature and below for the constant voltage tests exhibit two distinct rates of temperature change at the higher voltages, most notably 3.6V. Reviewing Figure 3-4 as well as Figure A-4, Figure A-6, and Figure A-8 will show that, while less pronounced at lower temperatures, all cells seemed to experience a rapid decrease from the maximum temperature followed by a more gradual return to room temperature. Similar results were observed in all short circuit tests for the coin cells. Trends such as these were not observed in any other works, but are likely due to a lag in the temperature response to the rapid current increase and subsequent decrease during discharge.

The coin cell sustained some damage during the first set of tests on cell 9, however it never failed. It was able to be recharged to the appropriate voltage and did not exhibit any outward signs of failure. Both cell 9 and cell 10 scored a 0 based on the battery failure classification criteria shown in Table 1-1 in all testing.

4.2 Commercial 40mAh LCO Coin Cell Constant Resistance Test

The overall goal of the constant resistance test was to determine how the inrush current and maximum change in temperature vary with external resistance. These results are summarized below in Figure 4-8. It can be clearly seen that current increases with decreasing resistance. The maximum temperature, however, does not seem to change with external resistance. Based on the constant voltage results, shown in Figure 4-5, it was anticipated that at lower resistances the rise in temperature would increase in a nearly linear fashion. However, the linear regression of these temperature points in Figure 4-8 shows little correlation between temperature and external resistance.
Figure 4-8: Current increases with decreasing resistance. Temperature does not seem to change regardless of resistance.

While current seems to vary somewhat linearly with resistance, further work is needed to determine the actual trend in the maximum current. The three data points obtained give a general trend, however additional data will give a more detailed shape of the curve. The constant resistance tests for the 18650 cells, discussed below, indicate that the current response to decreasing resistance is not linear. Despite the uncertainty of the actual trend with which the current varies, it is irrefutable that it increases with decreasing resistance. Further work will allow for additional information pertaining to the current trend and may also clarify the lack of correlation between maximum temperature and external resistance.

As mentioned in the previous section, the temperature profiles during short circuit tests exhibited similar behaviors as that observed in the low voltage constant voltage tests. The cells experienced very low voltage during the short circuit test, down to 0.059 V, when the short circuit resistance is 0.026 Ω (see Table 4-1).
The voltage profiles for the constant resistance tests possess significantly different shapes. During the high resistance tests the voltage goes through a gradual voltage drop to nearly 0V while the low resistance test shows a very sharp drop in voltage. Due to this difference the voltage observed at the peak current is much different. The results are summarized in Table 4-1. The data from cell 4 was used exclusively in all data analysis since higher inrush currents were recorded during that test.

Table 4-1: Summary of constant resistance voltages during inrush current.

<table>
<thead>
<tr>
<th>Resistance (Ω)</th>
<th>Inrush Current (A)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.42</td>
<td>1.50</td>
</tr>
<tr>
<td>0.055</td>
<td>2.37</td>
<td>0.133</td>
</tr>
<tr>
<td>0.026</td>
<td>2.51</td>
<td>0.059</td>
</tr>
</tbody>
</table>

Remarkably the coin cells used for these short circuit tests did not fail and were, in fact, able to recover from the short circuit tests, be recharged, and tested again. Cell 3 and 4 were both tested once each at 1Ω and 0.026mΩ and the results agreed very closely indicating excellent repeatability for this test. Table 4-2 summarizes the inrush currents measured during the tests on cells 3 and 4. The cells again scored a 0 on the battery failure classification criteria.

Table 4-2: Summary of current results for cell 3 and 4.

<table>
<thead>
<tr>
<th>Cell #</th>
<th>Resistance (Ω)</th>
<th>Inrush Current (A)</th>
<th>Percentage of Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1</td>
<td>1.39</td>
<td>2.11%</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1.42</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.026</td>
<td>2.50</td>
<td>0.04%</td>
</tr>
<tr>
<td>4</td>
<td>0.026</td>
<td>2.51</td>
<td></td>
</tr>
</tbody>
</table>
4.3 Comparison of Coin Cell Constant Voltage and Constant Resistance Tests

Figure 4-9, below, shows the inrush currents for both the room temperature constant voltage test and the three constant resistance tests. The linear trend observed in both tests separately is observed between them collectively as well. There is a notable change in slope of the data after the 1V constant voltage data point.

![Constant Voltage and Resistance Inrush Current - RT](image)

Figure 4-9: Constant voltage and constant resistance inrush current results compared.

It is possible to calculate the limiting current using the results from the constant voltage discharge test. The limiting current occurs when the cell voltage reaches 0V, so finding the y-intercept of a best fit line is a good approximation for this value. The raw data is shown by the markers in Figure 4-10. The data is fairly linear, so a linear regression can be used to extrapolate to 0V and determine the limiting current. Assuming that the cell inrush current continues to increase linearly for all voltages up to 0V, the y-intercept (V=0) of the trendline equation is equal to the value of the limiting current based on the constant voltage discharge data points. Using this
method the limiting current is 2.23 A (around 56°C). This value is very close to the inrush current, 2.51 A, during 0.026 Ω short circuit test, suggesting reliability of the results.

![Coin Cell Limiting Current at Room Temperature](image)

Figure 4-10: The limiting current was calculated graphically.

**4.4 Commercial 2250mAh 18650 Cell Constant Resistance Test**

The final results from the 18650 cell testing are shown below in Figure 4-11. The insert in Figure 4-11 illustrates the simple circuit used for the low resistance test, including the direction of current flow. The inrush current increases slowly with decreasing resistance for the high resistance tests, while the inrush current for the low resistance (0.05 Ω) test is much higher, ~20 times higher than that of the 1Ω test. Interestingly, the maximum ΔT follows a very similar trend as the inrush current, indicating more heat generation during lower resistance short circuit test.
The cell was able to be recharged following each high resistance test, but became irreversibly damaged during the low resistance test. During the low resistance test it underwent venting with electrolyte ejection (Figure 4-12 and Figure 4-13). It is likely that the separator melted since the surface temperature of cell reached above 120 °C and the current decreased abruptly to 0 after that. Further testing at low resistances (below 1Ω) could be useful in determining the point at which the inrush current increase moves from being benign to the cell’s functionality to being destructive. Finding the value of the external resistance where the cell response becomes more violent could be crucial to understanding the point at which a short circuit may cause an energetic failure.

The current and temperature profiles obtained for the low resistance tests agree closely with the results shown in the work with 18650 cells by Kallfa et al. This work included results from two cells – a transition metal oxide 18650 cell and a LFP 18650 cell. The external
resistance for the work by Kallfa et al. was \( \leq 0.03 \, \Omega \). During this testing, the LFP cell failed similarly to the 18650 cell tested in this work, and the current profile exhibited a similar shape as the 18650 cell in this work, showing two peaks.\(^2\) Kallfa et al.’s inrush current is 108 A, which is higher than the value in this study (85.0A).\(^2\) The lower value in this study is likely due to the higher short circuit resistance (0.05 \( \Omega \) vs 0.03 \( \Omega \)) as well as the difference in cell chemistry. The temperature profile obtained in this study also agreed closely with that obtained by Kallfa et al. The maximum temperature achieved is also very close: 370K for their LFP cell vs 371 K for the cell in this study.\(^2\)

The high resistance tests exhibited unusual current profiles. These profiles are significantly different than those obtained for the coin cell tests at the same resistance (compare Figure 3-22 and Figure A-15). The coin cell exhibited a sharp peak during its 1\( \Omega \) short circuit test. The 18650 cell exhibits the same sharp increase in current at the onset of the short, however after the peak, the current seems to plateau and only decreases very slightly. At the end of the 10 minute test the current is still quite high. This can be attributed to the much higher capacity of the18650 cells. The inrush current increased with decreasing resistance, similar to the behavior of coin cell. The temperature profiles exhibit a similar shape to those found in literature. The maximum change in temperature increases with decreasing resistance as expected.

Unlike the coin cell, the 18650 cell was not able to recover after the 0.050\( \Omega \) test. The cell was irreversibly damaged when its internal safety devices were activated causing cell venting and expulsion of electrolyte into the safety box. The cell’s reaction to the short circuit test scored between a 3 and a 4 on the battery failure classification criteria. Venting occurred, but less than 50% of the cell electrolyte was lost. After this event the cell voltage hovered around 0V and the damage was visible, see Figure 4-12 and Figure 4-13. Some damage that is not visible may also
have occurred. At high temperatures, the separator in the 18650 cell is designed to melt, thus quenching the cell reactions before they can proceed to the point of thermal runaway.

Figure 4-12: The failed 18650 cell with safety mechanism activated.

Figure 4-13: The expelled electrolyte splashed onto the cell.
4.5 Comparison of Coin Cell and 18650 Cell Constant Resistance Test

Both the coin cell and 18650 cell were tested at 1Ω and around 0.050Ω external resistance. Table 4-3 summarizes these results. It is interesting to note that the current and temperature profiles for these two cells are significantly different. The current profiles for the coin cell show a fast peak followed by a gradual decrease back to 0A (see Figure A-15 and Figure A-17). During the low resistance test the 18650 cell also shows a fast initial peak, but this is followed by a decrease and then a second peak (see Figure 3-24). Rather than gradually decreasing back to zero, the current returns to 0 immediately after the second peak. This trend is likely due to the activation of the cell safety mechanisms during the short. The high resistance current profiles for the 18650 tests are radically different than those for the coin cells (see Figure 3-22). While the coin cell current profile for 1Ω still exhibits sharp peak in current, the 18650 cell reaches its maximum current value and then very gradually begins to decrease. The plateau shape exhibited in Figure 3-22 is due to the test ending after 10 minutes (600s).

The temperature profiles for these two cells also exhibit very different shapes (see Figure 3-23: High resistance short circuit temperature profiles for 18650 cell. Figure 3-25, Figure A-16, and Figure A-18). The 18650 cell does not exhibit the second temperature increase seen in the coin cell constant resistance testing. This is likely due to the fact that the temperature rise seen by the 18650 cell caused a rapid failure, while the shorted coin cells did not fail. The increase in temperature for the 18650 cell becomes faster as the external resistance is decreased. This is contrary to the coin cell testing where, not only are the temperature profiles all the same shape, but the maximum temperature achieved does not change.
Table 4-3: Comparison of constant resistance results for the coin and 18650 cells at 1 and 0.050Ω.

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>External Resistance (Ω)</th>
<th>Current (A)</th>
<th>C Rate</th>
<th>Max. ΔT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18650</td>
<td>1</td>
<td>4.01</td>
<td>1.85</td>
<td>9.33</td>
</tr>
<tr>
<td>Coin</td>
<td>1</td>
<td>1.42</td>
<td>35.5</td>
<td>26.2</td>
</tr>
<tr>
<td>18650</td>
<td>0.050</td>
<td>85.0</td>
<td>39.2</td>
<td>97.7</td>
</tr>
<tr>
<td>Coin</td>
<td>0.055</td>
<td>2.37</td>
<td>59.3</td>
<td>26.2</td>
</tr>
</tbody>
</table>

The results in Table 4-3 illustrate the differences between the results for the constant resistance tests on the two cells. Most surprisingly is the large difference between the C Rate experienced by the coin cell during the 1Ω test as compared to that experienced by the 18650 cell. The C rate of the coin cell current response is nearly 30 times higher than that of the 18650 cell. This large variation is due to the difference between the internal resistances of the two cell types. The coin cell internal resistance is much higher than that of the 18650 cell – 0.70Ω vs. 0.03Ω.

The 0.050Ω tests exhibited much more similar results. The coin cell C rate is only 1.5 times higher than that of the 18650 cell. This result is reasonable as the coin cell does not possess any safety mechanisms by which it can be disabled at high C rates. The 18650 cell does include these mechanisms and they were activated during this test. If the current was not stopped by the cell safety devices the current may have gone much higher and an energetic failure may have occurred. The surface temperature of the 18650 cell rose 97.7°C – nearly four times higher than the coin cell. Conversely, the surface temperature of the 18650 cell during the 1Ω test only increased by around 9°C while the coin cell surface temperature increased by 26°C (nearly 3 times higher). It is interesting to note that the coin cell temperature rise was exactly the same regardless of the external resistance value. Meanwhile, the 18650 cell saw a 10 fold increase in temperature rise between the two resistances. Based on these observations about the temperature
profiles for the coin cell and 18650 cell constant resistance test, it is clear that as cell capacity increases so does the cell’s thermal reaction to a stimulus.

This increase in the temperature response for the 18650 cell versus the coin cell is due to the higher energy to surface area ratio of the 18650 cell. The cell’s ability to dissipate heat depends heavily on its surface area. The 18650 cell’s surface area is not large enough (high energy to surface area ratio) to dissipate the energy produced during the short circuit test. The coin cell on the other hand, has a low energy to surface area ratio and is adequately able to dissipate the amount of heat generated. This problem is seen to a greater extent as the size of the battery increases. The amount of energy output the cell increases with size, but the surface area may not increase enough to compensate for this. The energy to surface area ratio is the primary reason why energetic failures are seen more commonly in large capacity cells.

Figure 4-14 compares the inrush current and maximum ΔT results of the coin cell and 18650 cell graphically. While the 18650 cell experienced higher current at all resistances, the coin cell experienced the higher C rates. The maximum ΔT for the 18650 cell varies with external resistance similarly to the C Rate for that cell, however the maximum ΔT for the coin cell appears not to depend on the resistance at all.
4.6 Commercial 2250mAh 18650 Cell Constant Voltage Test

The 18650 cell exhibited similar trends as the coin cell in inrush current and temperature rise during room temperature testing. Due to this the constant voltage discharge test was performed on an 18650 cell at only room temperature. The cell’s performance at low temperatures can be inferred from the trends observed during the coin cell tests.

The inrush current for the 18650 cell varied linearly with discharge voltage (see Figure 4-15). Similarly to the inrush current for the coin cell constant voltage tests, as discharge voltage is decreased, the inrush current for the 18650 cell increases. Initially four voltage tests were planned for this cell: 3.6V, 3V, 2V, and 1V. However, during the 2V test the cell reached a temperature of 122°C (measured on the middle thermocouple) and did not recover to a normal
voltage after the discharge step, suggesting failure of cell. Charging was attempted, but the cell would no longer accept charge.

Figure 4-15: Inrush current for 18650 cell constant voltage discharge test.

The maximum $\Delta T$ for the cell increases with decreasing voltage (see Figure 3-20). This result agrees closely with that observed during the coin cell constant voltage tests. The trend for the maximum $\Delta T$ seems to increase linearly based on the data collected, however it will be observed later that the cell, in fact, reaches a temperature limit upon which irreversible cell failure, most likely related to melting of the separator, occurs.
The rate of temperature rise for the 18650 cell increased quickly with decreasing voltage (see Figure 3-21). The values from Figure 3-21 are summarized below in Table 4-4. The rate changes by a factor of 6 to 8 with each 1V decrease in voltage. This trend indicates a more volatile response to decreasing voltage and therefore a higher risk for an energetic failure at low voltages.

Table 4-4: Summary of Rate of Temperature Rise data from the 18650 Cell Constant Voltage Test

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Rate of Temperature Rise (°C/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>1.67</td>
</tr>
<tr>
<td>3</td>
<td>6.07</td>
</tr>
<tr>
<td>2</td>
<td>49.03</td>
</tr>
</tbody>
</table>

This cell scored a 2 on the battery failure classification criteria for its failure during the 2V discharge. This score corresponds to an irreversible failure causing activation of safety
mechanism but showing no outward signs of failure such as thermal runaway, explosion, or electrolyte leakage. The failure during the 2V test was most likely due to melting of the separator within the cell due to the high surface temperature.

Combining the values for the maximum $\Delta T$ for the three constant voltage discharge tests and the 0.050$\Omega$ constant resistance test, a limit to the maximum achievable $\Delta T$ becomes clear (see Figure 4-17). The maximum $\Delta T$ is nearly the same between the 2V and 0.050$\Omega$ tests, despite the fact that the inrush current differed by a factor of two. Cell failure occurred during both of these tests, indicating that a temperature dependent failure mechanism, most likely separator melting, was activated during each test. An additional failure mechanism was activated during the constant resistance test which caused venting, however this was likely related to either the low voltage or very high current. Lower voltage or resistance tests would likely yield a similar maximum temperature as these tests.

![18650 Cell Maximum Temperature vs. Voltage](image_url)

Figure 4-17: The maximum temperature reaches a limit.
4.7 Comparison of Coin Cell and 18650 Cell Constant Voltage Test

The 18650 cell and the coin cell exhibit similar trends in both inrush current and maximum ΔT during the room temperature test, because of this the low ambient temperature tests were not performed on the 18650 cell. This decision was made due to the more reactive nature of the 18650 cell, which puts it at a higher risk for experiencing an energetic safety event. Since the results between the two cells do follow a similar trend, the reaction of the 18650 cell at low temperatures can be inferred from that of the coin cell.

Both the 18650 cell and the coin cell experience similar C Rates during their respective constant voltage tests (see Figure 4-18). The two cells, however, experience a great difference in their maximum ΔT values (see Figure 4-19). While the ΔT values for the two cells follow a similar trend, the 18650 cell experiences much higher temperatures overall. The larger energy to surface area ratio of the 18650 cell is the primary reason for this difference.

![Constant Voltage Inrush Current Results](image)

Figure 4-18: Comparison of coin cell and 18650 cell constant voltage inrush currents.
4.8 Comparison of 18650 Tests and Coin Cell Tests

The inrush current results for the constant voltage and constant resistance discharge tests on the 18650 cell are shown in Figure 4-20. Notice that the voltages experienced for the 18650 cell during the high resistance tests are much higher than those experienced by the coin cells during their high resistance test. See Figure 4-21 for a comparison between the two cells. Despite the differences in voltage, the coin cell and 18650 cell inrush currents both increase with decreasing discharge voltage/short circuit resistance.

The results for the maximum $\Delta T$ for both the constant voltage and constant resistance coin cell and 18650 cell tests are shown in Figure 4-22. The 18650 cell reaches higher temperatures overall and seems to reach a limit around $\Delta T = 100^\circ C$ (or a surface temperature of...
120°C), but is fairly linear up until this point (see Figure 4-16). The data for the coin cell is fairly linear and does not increase as quickly as the 18650 cell values.

Figure 4-20: Summary of 18650 cell constant resistance and constant voltage results.

Figure 4-21: Summary of coin cell and 18650 cell inrush current results.
The limiting current for the 18650 cell is calculated using the constant voltage data. The data is well fit by a linear regression (see Figure 4-23). The limiting current occurs when the cell voltage reaches 0V, so the y-intercept of the best fit equation is an excellent approximation of the cell limiting current. This calculation assumes that the cell inrush current continues to increase in the same manner for all voltages up to 0V. The limiting current based on the best fit line found in Figure 4-23 is 88.1 A. This is equal to a C Rate of 41C. The calculated limiting current is very close to the inrush current, 85A, observed during the constant resistance test at the lowest resistance, 0.050 Ω, suggesting good reliability of the results.

Figure 4-22: Summary of maximum ΔT results for the coin cell and 18650 cell.
Figure 4-23: The 18650 data is well fit by a polynomial of order two. Extrapolation to 0 will give the limiting current.

\[ y = -21.975x + 88.119 \]

\[ R^2 = 0.9953 \]
Chapter 5

Conclusion

In conclusion, abuse testing of batteries can help to understand the causes of various battery failures during both operation and accidents. It is crucial to consider the methods of battery failure when designing individual cells, battery packs, and their supporting systems. With a better understanding of battery safety, events such as those with the Boeing Dreamliner, Chevy Volt, and Fisker Karma can be avoided. In this study, commercial coin cells (2032, with capacity 40 mAh) and cylindrical cells (18650, with capacity of 2250 mAh) are studied systematically under extreme conditions to investigate the safety issue of Li-ion batteries. The cells were subjected to standard short circuit (constant resistance) tests and a novel constant voltage test.

The constant voltage discharge test was used to determine how batteries perform under low voltages to calculate the limiting current. The cells were tested at their nominal voltage, 3.6V, as well as 3, and 2V. The coin cell was also tested at 1V and 0.5V. Upon the start of each discharge, a peak in the cell current was observed. An increase in the cell surface temperature was also seen. This test was repeated on the coin cells at 0, -10, -20, and 45°C. Similar current and temperature profiles were obtained for each test. Linear trends were observed for the coin cell with respect to inrush current vs. discharge voltage, maximum $\Delta T$ vs. discharge voltage, rate of temperature rise vs. discharge voltage, and inrush current vs. ambient temperature.
The 18650 cell constant voltage test was performed at room temperature only and exhibited linear trends for inrush current and maximum ΔT vs. discharge voltage. The rate of temperature rise for the 18650 cell increased by a factor of 6 to 8 with each 1V decrease in voltage. Since the 18650 cell showed similar trends to the coin cell in current and temperature, the performance of the 18650 cell at low temperatures can be inferred from the data collected on the coin cells.

The results of the constant voltage tests are used to determine the limiting current of the cells using a linear regression of the data to extrapolate to 0V. The limiting current was determined to be 2.23 A (equivalent to 56 C) for the coin cell and 88.1 A (equivalent to 39 C) for the 18650 cell. The results are very close to the inrush current during short circuit test was 2.51 A for the coin cell (with constant resistance of 0.026 Ω) and 85 A for 18650 cell (with constant resistance of 0.050 Ω), confirming the reliability of the results.

The constant resistance tests were performed on the cells to determine how the two different cell sizes would behave under short circuit conditions as well as to collect current data for comparison with the limiting current calculations. The constant resistance inrush currents increased with decreasing resistance for both cell types, however the 18650 cell experienced higher currents overall. The maximum ΔT for the coin cell tests did not vary with the external resistance. In comparison, the 18650 cell experienced an increase in the maximum ΔT with decreasing external resistance.

The coin cells survived all the extreme condition tests with maximum temperature lower than 50 ºC, but 18650 cells failed during 2 V constant voltage test and 0.050 Ω short circuit test with
surface temperature up to 122 °C. The results clearly demonstrate that safety issue is more serious for larger format Li-ion batteries and more efforts are warranted.
Chapter 6

References


Appendix A – Additional Data

Preliminary Cell 10171

![Constant Voltage Discharge Curves for Cell 10171](image)

Figure A-1: Constant voltage discharge results for 10171
Preliminary Cell 10173

Figure A-2: Constant voltage discharge results for cell 10173
Coin Cell - 0°C Constant Voltage Current and Temp. Profiles

**Figure A-3**: 0°C constant voltage current profiles.

**Figure A-4**: 0°C constant voltage temperature profiles.
Coin Cell – -10°C Constant Voltage Current and Temp. Profiles

Figure A-5: -10°C constant voltage current profiles.

Figure A-6: -10°C constant voltage temperature profiles.
Coin Cell - -20°C Constant Voltage Current and Temp. Profiles

![Graph showing constant voltage discharge at -20°C.](image)

Figure A-7: -20°C constant voltage current profiles.

Note the very short discharge time for 3V and 3.6V tests. This may be due to inadequate self-heating within the cell to sustain the reactions at such a low temperature. Note that the temperature increase for the lower voltages is much greater than for the 3V and 3.6V tests.
Figure A-8: -20°C constant voltage temperature profiles.

Coin Cell - 45°C Constant Voltage Test Current and Temp. Profiles – Cell 9 Test

Figure A-9: 45°C constant voltage current profiles for initial cell 9 test.
Figure A-10: 45°C constant voltage temperature profiles.

Coin Cell - 20°C Constant Voltage Current and Temp. Profiles – Repeated

Figure A-11: 20°C constant voltage current profiles for repeated test on cell 9.
Figure A-12: 20°C constant voltage temperature profiles for repeated test on cell 9.

Coin Cell - 45°C Constant Voltage Current and Temp. Profiles – Cell 10

Figure A-13: 45°C constant voltage current profiles for the cell 10 test.
Figure A-14: 45°C constant voltage temperature profiles for the test on cell 10.

Coin Cell - 1Ω Constant Resistance Current and Temp. Profiles

Figure A-15: Current profile for 1Ω short circuit
Figure A-16: Temperature profile for 1Ω short circuit.

Coin Cell – 0.055Ω Constant Resistance Current, Temp., and Voltage Profiles

Figure A-17: Current profile for 0.055Ω short circuit.
Figure A-18: Temperature profile for 0.055Ω short circuit.

Figure A-19: Voltage profile for 0.055Ω short circuit.