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Mitigating Battery Swell in Device Labs

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ABSTRACT Large fleets of lithium polymer (LiPo) battery-powered devices are deployed in device labs for software testing. These dense arrays of devices are typically powered over USB and connected continuously for long periods of time, often years. Maintaining batteries at a fully charged state can result in swelling battery packs, device failure, and even cause fires. This paper describes the specific causes of device battery swelling and failure, and how to mitigate using Acroname programmable USB hubs.

I. THE PROBLEM

Users want their mobile devices to work as long as possible between charges, so these devices are designed to charge fully to maximize run time. This is great for the user, but in a device test lab environment this approach is problematic. Device test labs deploy dense arrays of often thousands of mobile devices, typically tethered by USB for charging and data connection. Continuous battery charging, high processor usage, and high temperatures in test lab racks create unique challenges to device longevity because these devices were not designed for these applications. The most prominent failure mechanism under these conditions is battery swelling. If left unchecked, these devices may undergo RUD: rapid unplanned disassembly. Such an event can be catastrophically expensive and even dangerous.

To mitigate battery-swell in device labs, it is useful to understand the underlying causes of the issue. It is obvious that battery-swelling is caused by generation of gas within the cell. Forced overcharging can cause gas generation [3], but almost all modern devices have protection systems to prevent overcharging. A deeper understanding of the root causes of this gas generation enables engineers to design and implement systems that reduce battery-swell frequency in device-lab environments.

II. LITHIUM BATTERY CHEMISTRY

Electrochemical batteries are constructed of two electrodes, a cathode and an anode, separated by an electrolyte. Normally the electrodes are named cathode or anode based on what type of reaction happens at each site. With lithium-based cells, both electrodes act as an anode or cathode if the cell is charging or discharging. As such, it is more accurate to define the electrodes by their relative potentials: positive-electrode and negative-electrode [1].

Almost all modern mobile devices use "lithium-ion" (Li+) or "lithium polymer" (LiPO) electrochemical batteries, and there are a variety of chemistries used to make these cells. The specific chemistries used in the battery cell determine the cell's power density, energy density, and, most notably for this investigation, failure mechanisms.

FIGURE 1. iPhone 5c damaged by swollen battery.

The negative-electrode in lithium-based cells is some form of lithiated carbon such as graphite or another form of carbon lattice, such as silicon-carbon. The positive-electrode is a metal oxide. Between the electrodes is an electrolyte comprising a lithium salt in an organic solvent or polymer.

In addition to the electrodes and electrolyte, these batteries comprise various separators, current collectors and housing materials. Some of these additional components play a role in preventing failures but can also contribute negatively to the damage after a failure occurs.

The positive-electrode in lithium-base cells is usually lithium cobalt oxide ($LiCoO_2$) or lithium manganese oxide ($LiMn_2O_4$ or Li_2MnO_3). Variations that include nickel ($LiNiMnCoO_2$ or NMC) and other metals are starting to be used as these structures may reduce capacity degradation over charge cycles. Iron-containing positive-electrodes ($LiFePO_4$) are also common for improved temperature stability, cycle-life, and power density. For simplicity, the different transition metal oxides are generalized herein as M in chemical equations. These positive-electrode materials all form lattices or matrices that allow lithium ions to migrate in and out of the structure during charging and discharging. The lithium ions then migrate through the electrolyte into the negative-electrode structure.
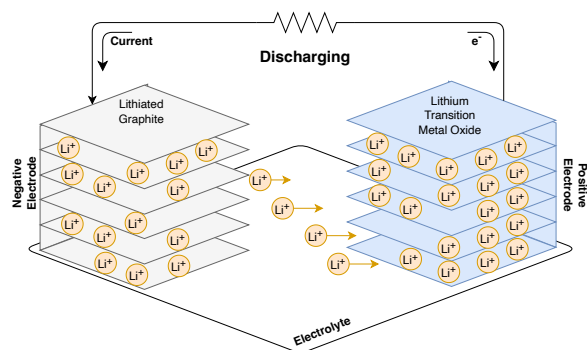
Figure 2. Pictorial representation of lithium battery operation. Discharging moves lithium ions from the lithiated carbon negative-electrode through the electrolyte and into the lithium metal-oxide positive-electrode. Charging reverses the ion flow.

Lithium-Ion Batteries

The Li+ battery's electrolyte distinguishes it from LiPo cells. A Li+ cell's electrolytes are generally a lithium salt such as $LiPF_6$ or $LiClO_4$ in an organic solvent. This solvent must be non-aqueous because lithium reacts violently when exposed to water; this fact will be important later. Typically, these solvents are organic carbonates such as ethylene carbonate (EC), dimethyl carbonate (DMC), diethyl carbonate (DEC), propylene carbonate (PC), or a combination of these. These organic solvent mixtures are almost all highly flammable [4]; e.g.: DMC has a flash point around 17˚C. In part due to the liquid electrolyte form, Li+ batteries are commonly found in rigid cylindrical metal housings.

Lithium-Polymer Batteries

LiPo batteries use the same $LiPF_6$ as the active electrolytic salt, but instead of being dissolved in a liquid organic solvent, they use a solid polymer electrolyte such as poly(ethylene oxide), poly(acrylonitrile), poly(methyl methacrylate) or poly(vinylidene fluoride). While the polymer electrolyte of LiPo batteries is commonly thought of as a solid, it sometimes takes a gel-like form; i.e. it is more correctly not a liquid like the electrolyte in Li+ cells. The gel-like form of the electrolyte used in LiPo batteries allows them to be packaged in flexible, foil-backed polymer laminate casing.

III. LITHIUM BATTERY ELECTROCHEMISTRY

There are many complicated details to electrochemistry of these batteries; this is literally the topic of thousands of doctoral dissertations. For purposes of understanding battery swelling, the electrochemistry can be vastly simplified. Regardless of the electrolyte (Li+ or LiPo) or specific electrode materials, lithium batteries generally work with a similar electrochemistry based on oxidation at the negative electrode which produces lithium ions and electrons. The lithium ions migrate through the electrolyte to the positive-electrode where they recombine through a reduction reaction with the electrons which were conducted through an external electrical circuit. The simplified and generalized

electrochemical reaction is shown below and diagrammed in Figure 2. The specific negative-electrode and positive-electrode materials can be substituted without loss impacting further discussions.

$$LiC_6 + MO_2 \leftrightarrows C_6 + LiMO_2$$
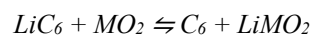
where left to right is discharging and right to left is charging. This reaction is split between the negative electrode and positive-electrode in the cell. At the positive-electrode:

$$MO_2 + Li^+ + e^- \leftrightarrows LiMO_2$$
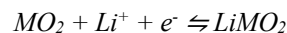
and at the negative-electrode:

$$LiC_6 \leftrightarrows C_6 + Li^+ + e^-$$
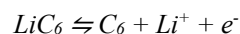
None of these reagents are gaseous. That is, nothing in the normal operation appears to be able to cause battery swelling. There are small volumetric changes during charge or discharge cycles [2], but these changes do not result in catastrophic failures.

Several side reactions can occur during overcharging:

$$LiMO_2 \Rightarrow Li^+ + MO_2 + e^-$$
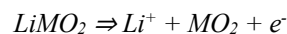
or over-discharging

$$Li^+ + e^- + LiMO_2 \Rightarrow Li_2O + MO$$

These side-reactions can lead to permanent degradation of the electrode materials and reduce the capacity or energy of the cell. However, the reactions generally do not result in gas formation or battery swelling.

IV. BOUNDARY ISSUES AT THE ELECTRODES

Negative-Electrode

The first-order approximation of the lithium battery electrochemistry did not yield a gas generator. As such, the cause of battery swelling must be in a more subtle aspect of the reactions. The interfaces between the electrodes and electrolyte hold many complex interactions. Commonly referred to as the solid electrolyte interface (SEI), this boundary is where lithium ions transition between the electrodes and electrolyte. A passivation layer forms at the negative-electrode SEI when the liquid electrolyte contacts the conductive surface of the negative-electrode. This layer expands on the first cycle of the cell [1]. The passivation layer acts like a corrosion that forms a protective film around the electrode, but still allows Li^+ migration between the electrode and electrolyte. The passivation layer continues to grow throughout the cell's age, and several compounds are formed in conjunction with the SEI at the negative-electrode such as LiF, Li_2CO_3, $LiOCO_2CH_3$, $LiOCO_2CH_2$, and Li_2O [5]; again, none of these are in a gas phase.

Positive-Electrode

The positive-electrode's SEI chemistry is more complicated than the negative-electrode's, and the wide variety of positive-electrode materials and material-ratios complicates the

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analysis. As they are delithiated through charge cycles, the transition-metal oxides of the positive-electrode decompose into a hard, glassy, disordered mineral called spinel, and eventual into the rock-salt phases. This decomposition forms a passivation layer at the SEI and releases oxygen through the reaction:

$$Li_xMO_2 \Rightarrow Li_xM_3O_4 \Rightarrow Li_xMO + [O];$$

$$[O] + [O] \Rightarrow O_2\ (g)$$
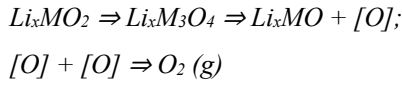
The formation of spinel and rock-salt metal-oxides is more prevalent as the negative-electrode becomes more delithiated.

Now we have gaseous oxygen in the battery cell. The oxygen in the SEI lattice is highly reactive, as is the gaseous oxygen. Both can react with the organic electrolyte to form other reactive peroxides and other gases. For example, an EC electrolyte will react with oxygen to form CO and CO_2 by:

$$(CH_2O)_2CO + [O] \Rightarrow 2CO_2\ (g) + CO\ (g) + 2H_2O$$

V.   SMOKE ON THE WATER

An astute observer will notice the formation of water by the oxidation of the electrolyte. This water rapidly reacts with the lithiated electrolyte to produce H_2 gas and reactive OH^- which further hydrolyzes the electrolyte. The water also reacts with the lithiated electrolyte directly to form fluorinated lithium phosphates ($Li_xPO_yF_z$).

These gas generating reactions continue throughout each charge cycle of the battery. Figure 4 shows these reactions are exacerbated by the increasing cell voltage as the cell cross about 85% of its specific capacity. These reactions are also accelerated by higher temperatures [1]. By keeping charge well below 85% and minimizing temperatures, gas generating reactions and the resulting battery swelling can be minimized. Even if the maximum state of charge is kept low, cell
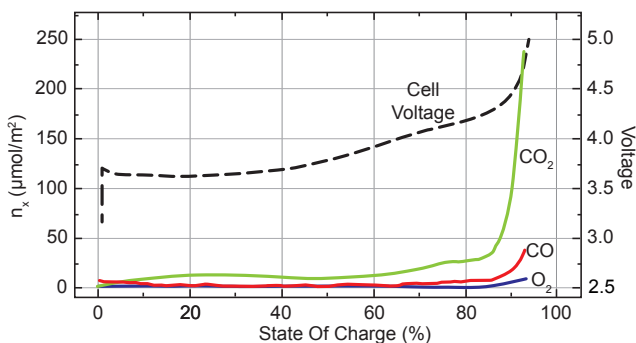
Figure 4. Gas generation during charging from a Li+ NMC (LiNi$_{0.8}$Mn$_{0.1}$Co$_{0.1}$O$_2$) cell. [3]

temperature can still have a dramatic effect [6]. In fact, the benefits of lower temperatures are more significant at lower maximum charge state. Figure 3 shows the number of weeks until a cell exhibits swelling of more than 5% by volume for three temperature ranges when the battery charge is cycled in various charge level zones. In this experiment, if the battery was kept below 70% charge and 30C, it took almost three years to reach 5% swelling (Table 1).
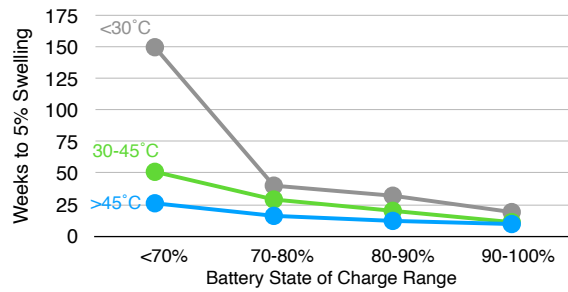
Figure 3. Lower temperatures significantly decrease battery swelling when charging is kept below 70% [6].

Charge Range	Battery Temperature	Time to 5% Swelling
<70%	>45˚C	26 weeks
	30-45˚C	51 weeks
	<30˚C	150 weeks
80-90%	>45˚C	12 weeks
	30-45˚C	20 weeks
	<30˚C	32 weeks

Table 1. Effect of temperature and maximum charge on battery swelling rate [6].

VI.   SWELLING MITIGATION IN THE DEVICE LAB

While battery developers are working on electrode and electrolyte chemistries to improve lifetimes and mitigate swelling in the batteries of tomorrow, device labs must deal with the batteries of today and yesterday. For these devices, the simplest mitigations are to:

1. Avoid high cell voltages by monitoring charge state and vary charge current to allow charge-discharge cycles in the "comfort zone" (Figure 5) of the battery. Since the devices don't need to operate untethered, charge state can remain near the middle of the charge range.
2. Provide the minimum charging voltage that keeps up with the device workload to minimize device heating.
3. Provide active cooling and ventilation to the devices.

Mitigations 1 and 2 can be implemented using device management software (MDM) to monitor state of charge, and a software-controlled power control such as Acroname's programmable USB hubs to monitor and control charge current and voltage.
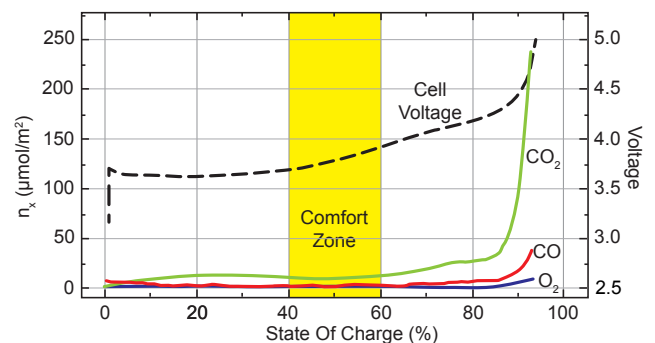
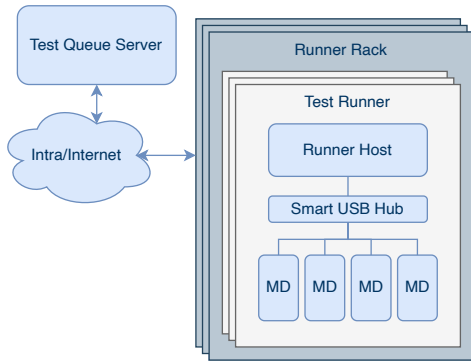**Figure 5. Lithium battery "comfort zone" [6].**

Figure 6. Example high-level device test lab architecture.

Typical Architecture

Figure 6 shows an example of a simplified device test lab architecture. A test queue server communicates with test runner hosts dedicated to groups of mobile devices (MD) under test. The MDs are connected to the test runner hosts via a programmable USB hub. The USB hub provides data connection and charging to the MDs and can have each of these connections controlled by software. The test runner host uses device management software read the state of charge of each MD, and then sends commands to the USB hub to change the MD's charge rate in order to keep the MD state of charge within the desired range. This setup also allows the lab to test the device software and hardware against various charging and discharging scenarios. With careful design, the system can maximize MD lifespan while maintaining reasonable MD availability to test operations.

Example 1: Charge control for legacy devices

Legacy devices which do not implement the USB Power Delivery (PD) specification instead rely on the USB Battery Charge specification (BC-v1.2). Such devices are limited to a few discrete charging modes. The Acroname USBHub3+ and USBHub2x4 programmable hubs can switch between slow charge (≤0.5A) and fast charge (up to 2.4A) with both modes maintaining a data connection. The hubs can also fully disable charging; however, many devices cannot maintain a data connection without the presence of power.

An example process to maintain a MD state of charge between 40% and 60% is shown in Figure 8. When the MD
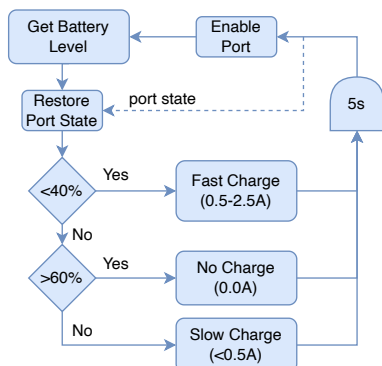

Figure 8. Example charging flowchart for legacy devices.

charge is below 40%, the hub switches to fast charge mode and the device can draw up to 2.5A. When the charge is above 40%, the hub switches to slow charge mode and provides a maximum of 500mA. Above 60%, charging turns off to allow the device to discharge, though this temporarily disconnects the legacy device. MD availability is >90% in typical use with BC-v1.2 compliant devices. Modern USB-C devices which support PD can have 100% availability.

Example 2: Charge control for USB-C and PD devices

The Acroname USBHub3c programmable USB hub can directly control and monitor charge current at each port. By communicating via PD, the USBHub3c and MD can adjust charge current all the way to 0A while maintaining their USB data connection. In the device lab application, the lowest sufficient charge current can be selected manually or automatically to keep the device within the desired range of charge. Figure 7 shows an updated charging flowchart without disconnections using three current levels.
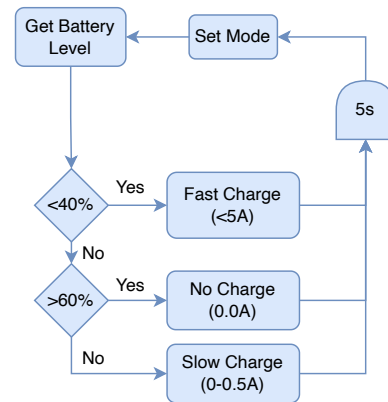

Figure 7. Example charging flowchart for USB-C devices.

VI. CONCLUSION

Mitigating battery swell in device labs is important to ensure the longevity and safety of lithium battery-powered devices used for software testing. The dense arrays of devices in these labs are typically connected continuously for long periods of time, which can lead to battery swelling, device failure, and even fires. Understanding the underlying causes of battery swelling is important for designing and implementing systems that extend device service life. Battery swelling is inevitable, but the rate is dependent on temperature and battery state of charge. Acroname's programable USB hubs can measure and control battery charging currents to keep battery state of charge in specific battery "comfort zones". In conjunction with sufficient cooling and ventilation, proper control of charge levels can significantly increase device lifespans. Device lab managers implementing these solutions can ensure the safe and efficient operation of their fleets of devices.

VII. REFERENCES

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