Improving lithium battery safety

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New experiments characterize battery thermodynamics and highlight ubiquitous design problems that increase the risk of failure.

Lithium-ion (Li-ion) batteries have the highest energy density of all existing battery technologies. However, widespread reports of lithium battery fires aboard Boeing’s Dreamliner airplanes and in other consumer-facing applications have raised questions concerning their use. The recent Li-ion problems are due to a fundamental misunderstanding among the engineering community of the governing principles of battery thermodynamics. Existing solutions for battery safety focus on mitigating symptoms rather than treating the root cause.

The sensational nature of battery fires means that the public’s perceived risk of failure outpaces actual failure rates. As such, brand identities are directly threatened, and companies are being forced to choose less efficient energy storage solutions. For example, a 2008 incident with the US Navy’s Advanced Seal Delivery System attributed to Li-ion failure prompted the Navy to revert to older, less dense battery technologies like zinc-silver and nickel-cadmium (NiCd) for many of their field operations. More recently, Airbus dropped Li-ion technologies in favor of less energy dense NiCd batteries. We have focused on characterizing the thermodynamic basis of heat generation in lithium batteries in an effort to strengthen the foundational knowledge needed to make the operation of Li-ion technologies safe and reliable.

Lithium batteries heat up during charging and discharging. Although, the precise sources of the heat generation are not understood, it is known that they are dependent on factors that include the ambient temperature and the state of charge. The standard explanation for battery heating focuses on internal resistance, \( R_i \), which includes electrolyte resistance, \( R_s \), anode resistance, \( R_a \), and cathode resistance, \( R_c \) (and where \( R_i \) is often equated with \( R_s \)). In actuality, there are at least five different internal components in lithium batteries that generate heat. These include \( R_s \), \( R_a \), \( R_c \), entropy change at the anode, \( \Delta S_a \), and entropy change at the cathode, \( \Delta S_c \). Our work shows that internal components other than \( R_s \) depend strongly on temperature (see Figure 1).

Component to heating were measured in a 4.4Ah Li-ion cell with a 1C discharge rate at different environment temperatures, \( T_{\text{env}} \). \( R \) is the ampere-hour (Ah) capacity of the cell. Thus, a 4.4Ah cell discharging at 4.4A rate is said to discharge at 1C rate. Our results confirm that \( R_s \) is not the dominant source of heating at any temperature.

We also examined the relation between heat dissipated by the battery, \( Q \), and \( T_{\text{env}} \) (see Figure 2). In our experiments, the total dissipated heat, \( Q_{\text{sum}} \), included contributions during charging, \( Q_{\text{charge}} \), and during one hour of discharging at a 1C rate, \( Q_{\text{discharge}} \). Although \( Q_{\text{sum}} \) can be measured using a calorimeter, our work demonstrates a new way to make real-time \( Q \) measurements with a real-world form factor, i.e., Li-ion cells used in everyday devices.

There is mounting evidence that suggests failure during charging primarily involves \( R_a \) and \( \Delta S_a \), rather than \( R_s \), \( R_c \), or \( \Delta S_c \). Both \( R_a \) and \( \Delta S_a \) can change rapidly as they approach catastrophic values. We made use of our ability to make online anode temperature, \( T_{\text{anode}} \), measurements to examine this parameter during the charging process as a proxy for \( R_a \) and \( \Delta S_a \). In these experiments, \( T_{\text{anode}} \) increased gradually during normal

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Figure 2. Heat generated during one charge-discharge cycle and one complete discharge (at 1C rate) of a 4.4Ah Li-ion cell.

Figure 3. Anode temperature ($T_{\text{anode}}$) of a 2.6Ah Li-ion cell, under constant-current charging at C/2 rate is shown in red. There is a sudden increase in $T_{\text{anode}}$ when the cell becomes overcharged. The surface and environment temperatures ($T_{\text{surface}}$ and $T_{\text{env}}$, respectively), cell current, and cell voltage are all shown.

charging, but the rate of increase jumped sharply milliseconds after the cell moved into the overcharged state (see Figure 3).

Although our results highlight the importance of monitoring $T_{\text{anode}}$, existing battery safety is based on surface-mounted sensors that measure the temperature at the battery surface, $T_{\text{surface}}$. The thermal inertia of the cell can cause $T_{\text{surface}}$ to deviate significantly from $T_{\text{anode}}$, especially under rapid shifts in $T_{\text{env}}$. In these circumstances, the ubiquitous design choice that results in the measurement of $T_{\text{surface}}$ instead of $T_{\text{anode}}$ poses a risk to safe operations of Li-ion technologies.

We are currently pursuing a state-of-the-art battery management system that includes a sensor suite, controls algorithm, and an intelligent power routing device. Our work, which is concurrent with that of others, is only beginning to elucidate the first principles necessary for robust advances in Li-ion safety. Sustained investment and research commitment is needed to address this issue properly.

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Rengaswamy (Srini) Srinivasan is a recognized leader in lithium battery science and technology, and is an innovator with a wide range of experience in science and engineering. He is an electrochemist by training, and is known for his work on electrochemical power sources, power-energy-thermal management, corrosion, and microelectrochemical sensors. He is currently the co-chair of the American Institute of Aeronautics and Astronautics’ Space System Battery Committee on safety.

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