Automotive Lithium-Ion Batteries: Dangers and Safety Measures

Eugene Lee
University of Illinois at Chicago, Chicago, IL 60607

Due to various economic, environmental, and political pressures, the automotive industry is beginning to put greater research efforts towards developing alternative energy storage technologies for vehicles, with a particular focus on lithium-ion batteries. This new technology poses new dangers which requires new technology to mitigate these dangers. Current and immediately next-generation safety concerns and technologies are reviewed.

Introduction

Much of what determines whether a particular energy storage technology will gain traction in the automobile industry is its technical capabilities - specifically density, capacity, and charge rate. However, a technologys safety is another major and equally pertinent concern, particularly in the realm of vehicles. There have already been a number of highly publicized occurrences of energy storage-related automotive failures, and each incident has been the cause of concern for the companies, largely due to the possible financial ramifications. Although no information was found of cases resulting in injury, the mere potential has the capability of impacting a companys financial workings. This paper will describe the basic workings of a common lithium ion battery system so as to understand the dangers inherent in the most frequently seen alternative energy storage system to gasoline, and will review currently implemented safety measures to counteract these dangers.

Overview

In larger formats such as those for vehicles, lithium ion batteries are constructed from groups of electrochemical cells, usually separated into groups that are wired in parallel (to increase capacity, since current draw per cell is decreased), which are themselves wired in series (to increase voltage). The operation of a basic electrochemical cell will be described so that the operation and risks of a battery can be understood.

An electrochemical cell operates by taking advantage of the free energy difference between two electrodes of different materials, such that when under no polarization, one electrode acts as an electron donor (oxidizes) and the other electrode acts as an electron acceptor (reduces). Both electrodes are in contact with an electrolyte that allows ions to pass between them while preventing electron flow. If the cell is constructed such that there is a possibility of the electrodes coming in physical contact with one another, a separator is added to the cell. The electrodes are then joined to an external circuit with a load, and since there is an overall transfer of electrons, current is generated. In a common modern lithium ion cell, the positive electrode is composed of lithium cobalt oxide (LCO, LiCoO$_2$), the negative electrode is composed of graphite, the liquid electrolyte is a combination of organic solvents and lithium salts such as LiPF$_6$, and the separator is made of a polymer plastic like polyethylene or polypropylene.

A quick clarification on nomenclature: the negative electrode and the positive electrode are often referred to as the anode and the cathode respectively. This is not strictly correct since lithium ion cells are rechargeable, which means that the role of the anode (electron donor) and cathode (electron acceptor) can be reversed depending on whether one is charging or discharging the cell. However, this document will follow convention for the purposes of simplicity, the result being that for this example, the graphite will be labeled the anode and the oxide will be labeled the cathode.

It should be noted that there are a variety of different materials that can be used for the electrodes (in particular the cathode), each with its own advantages and disadvantages related to energy capacity, charge/discharge rate, and other characteristics. This paper will use the LCO chemistry here as an example because it is one of the most extensively used - and therefore well studied - materials. Furthermore, even though the lithium cobalt oxide chemistry is primarily used in smaller-form battery packs such as those used in mobile electronics, the fundamental mechanisms remain similar for many different
lithium compounds used in vehicles. The half-cell and full reactions during discharge are as follows:\(^6\)

**Cathode:**

\[
Li_{1-x}CoO_2 + xLi^+ + xe^- \rightarrow LiCoO_2 \quad (1)
\]

**Anode:**

\[
Li_xC_6 \rightarrow xLi^+ + xe^- + C_6 \quad (2)
\]

**Full Cell:**

\[
CoO_2 + LiC_6 \rightarrow LiCoO_2 + C_6 \quad (3)
\]

In this reaction, lithium that was inserted between graphite layers (a state called intercalation) detaches from the carbons and oxidizes into lithium ions. The electrolyte and separator act as a semi-permeable membrane, permitting the disassociated lithium ions to pass through it and reassociate with CoO\(_2\). Additionally, during the first charging process, the compounds that form the makeup of the electrolyte decompose onto the anodes surface, resulting in a layer called the solid electrolyte interphase (SEI).\(^7\) This layer of electrolyte material is quite stable and crucial to the cells operation, since it prevents more electrolyte from reducing onto the surface of the anode while continuing to act as an ion-conducting path between the graphite and electrolyte.\(^8\) The effect of the SEI on cell safety will be further discussed in the Current Safety Measures section.

**Thermal Runaway**

Since the reactions in a lithium ion cell are inherently exothermic, the greatest source of concern comes from the possibility of thermal runaway, which is a situation in which increasing temperatures cause a greater increase of temperatures in other words, a thermal feedback loop. Such a process can eventually result in catastrophic failure, usually in the form of structural damage, flames, or in extreme cases, an explosion. This system can be seen as nearly adiabatic because of the enclosed nature of the environment, and can only happen when the internal temperature of the cell reaches a chemistry-dependent temperature threshold at which a series of exothermic reactions begin to take place in a cascading fashion. This is not to say that these reactions happen in an orderly, consecutive manner, but there are different temperature thresholds that must be reached for each process to take place, with each threshold varying with the materials involved. Once individual temperatures are reached, the processes will contribute and receive energy from other systems in an interconnected manner.\(^9\) These reactions are detailed below.

The first component of the cell that breaks down is the SEI. This can begin to happen at temperatures as low as 69 °C if LiPF\(_6\) is present in the electrolyte.\(^10\) Once the SEI layer begins to disappear, the electrolyte can continue to exothermically react with the anode surface. This also exposes the intercalated lithium to the electrolyte at elevated temperatures. At lower temperatures, lithium does not tend to react with the organic solvents in the electrolyte, but as the internal temperature rises, a hydrocarbon-generating reaction can proceed.\(^8\) For example, in the case of ethylene carbonate,

\[
2Li + C_3H_4O_3 \rightarrow Li_2CO_3 + C_2H_4 \quad (4)
\]

The result is the presence of flammable gases such as ethylene.

At higher temperatures, the cathode itself begins to break down to produce oxygen. This is the point at which the cell truly becomes its own heat source, and is referred to as the onset temperature. In the case of LiCoO\(_2\), the reactions occur at \(\approx 130^\circ\)C and are as follows:\(^9\)

\[
Li_xCoO_2 \rightarrow xLiCoO_2 + 1/3(1 - x)Co_3O_4 + 1/3(1 - x)O_2 \quad (5)
\]

\[
Co_3O_4 \rightarrow 3CoO + 1/2O_2 \quad (6)
\]

\[
CoO \rightarrow Co + 1/2O_2 \quad (7)
\]

As the temperature climbs even higher, the separator begins to melt, causing short circuits to form. The reaction rates and pressure continue to increase, eventually resulting in a ruined cell, and possibly - depending on a variety of factors, including initial charge state and cell chemistry - explosion and fire.

**Causes of Thermal Runaway**

The major potential thermal runaway initiators are overcharge, external heat, mechanical damage, external shorts, and internal shorts. For the purposes of this paper, only overcharge, external shorts, and induced internal shorts will be considered, since external heat is fairly self-explanatory, and the mechanisms behind mechanical damage and external shorts are similar to those involved in external object-caused internal shorts.

The concept of overcharge is much like it sounds: the act of charging a battery past the recommended voltage. In the extreme case, the result is the complete removal of all the lithium from the cathode. The result is that any current passing through the electrochemical cell generates heat through joule heating (also known as Joules First Law, \(Q \propto I^2\)). Eventually, the rising temperature results in thermal runaway.\(^11\)

A standard testing practice for simulating internal shorts is to slowly drive a nail through the cell.\(^12\) For the automotive industry, this would be analogous to hitting metal debris on the road, which then punches through the battery pack. As the nail passes through the cell, it eventually contacts both the cathode and anode after puncturing the separator, causing an immediate short circuit.
and a sudden release of heat due to joule heating. Much like the case of overcharging, this causes thermal runaway by rapidly rising internal temperatures. Here it should be noted that pressure buildup resulting in explosion is mitigated by the breaching nature of the process, since the opening created by the puncture relieves pressure. Mechanical stress cases (i.e. torsion, impact, crushing) are quite similar in their mechanics, since the eventual result is the tearing of the separation layer, resulting in a short circuit followed by thermal runaway. Additionally, there is often tearing of the cell casing, which relieves the pent up pressure inside the case and prevents an explosion.

There is another pathway to forming an internal short that is unique to lithium-ion cells, and that is the formation of what are called lithium dendrites. Under certain conditions (usually involving high charge rates), the lithium being transported within the cell can deposit onto the graphite anode, eventually creating thin, branching threads of lithium. Though the exact mechanisms that drive the formation of the dendrites is not yet clear, the main cause is due to the low relative voltage differential compared to Li/Li+. In conjunction with high charging currents, the lithium will electroplate onto the graphite anode, growing larger and larger with each deposition. Much like the nail test, a dendrite that grows long enough to contact the cathode creates a path with minimal resistivity, and thus can cause a short circuit and rapid release of stored energy. In the case of an external short, the anode and cathode become connected through a material of low resistance, resulting in a continuous, high discharge rate. Unlike the cases of overcharge and internal shorts, the internal heat generated from an external short stems largely from the high rate of chemical reactions, since any current-generated heat would be radiating from the conductor outside of the cell.

It must be reiterated that larger battery packs are composed of hundreds or even thousands of electrochemical cells to form one large power source. This means that if a damaged cell begins thermal runaway, the entire pack is likely to do so as well, since they are all in close spatial proximity to each other. The first cell would begin heating up and become a heat source, causing a domino effect. The released energy would then be correspondingly multiplied by the number of cells.

**Current Safety Measures**

Safety measures can be categorized into three broad categories: education, prevention, and correction. The latter two are presently the categories of interest, since they can be directly controlled on the manufacturing level and are relatively separate from the possibility of human error. This paper will further divide safety measures into two categories for the sake of organization: internal and external, or inside-of-cell and outside-of-cell.

**External Measures**

External safety measures are more macroscopic in nature than their internal counterparts, consisting of additional components attached to the cell, pack, or even the vehicle itself.

The remedy for overcharging is to use protection circuits, which are common and installed in most rechargeable battery technology, regardless of chemistry. Fundamentally, the circuits operate by rerouting current past the cell if the cell is detected as being fully charged.

Fixes for external shorts are far more varied, and are often employed in conjunction with one another to provide a more complete solution. The simplest of these is the thermal fuse, which starts off as a conductor but abruptly changes to an insulator at a temperature threshold, cutting off current flowing to the cell. This process is irreversible, much like a blown fuse in a power box, so it is not a preferred failure method since the fuse must be manually replaced for the system to continue operation.

The natural extension to the concept of the thermal fuse would be to have a reversible version, such that after the temperature restabilizes, the system could resume normal operation. Such devices exist in the forms of bimetallic switches and positive temperature coefficient (PTC) devices.

Bimetallic switches work by taking advantage of the differing thermal expansion rates of two attached pieces of metal. Upon heating, the overall geometry will warp, with the metals curling in a direction perpendicular to the bonded surface. This change in shape can be used as a switch, and will disconnect itself when too much current is running through the system. These switches can come in a variety of forms, such as a cantilever like Figure 22 or a disc, but the basic concept of movement due to thermal expansion is the same.

The preferred solution for modern lithium ion battery packs is the positive temperature coefficient (PTC) device. A material with a positive temperature coefficient...
will increase its resistance with increasing temperature. In polymeric PTCs (PPTCs), this is done by using a material made of a combination of conductive particles and a polymer that transitions between a crystalline state and an amorphous state at a temperature threshold. Under normal operating temperatures, the conductive particles are held closely enough in the polymer crystal to conduct current, but when heated, the polymer expands and increases the interparticle distances, which increases the resistance. This will eventually result in a much decreased flow of current, and will return to its initial state once the temperature drops, ensuring that the cell does not resume operation until the environment is stable. This device effectively acts like a reversible thermal fuse. PPTCs hold a number of advantages over bimetallic switches, including lack of mechanical wear, decreased size, and lower operating resistances.

On a larger scale, the solution for preventing foreign objects from intruding into the cells is fairly straightforward, since the battery simply needs to be physically protected. Tesla Motors, Inc. makes for an excellent case study for this, having suffered from two such incidents in 2013, despite being equipped with a quarter inch of ballistic grade aluminum plate armor on their Model S. The eventual adjustment was to add three more protective components to allow the vehicle to deflect, crush, or roll over unexpected objects in the road: a rounded aluminum bar, a titanium plate, and a slightly angled aluminum extrusion. The efficacy of these measures is unknown due to lack of data, though the video evidence of simulated situations under controlled settings provided by Tesla Motors, Inc. is reassuring.

The most direct and brute-force way to prevent thermal runaway is to use an active cooling method. In the case of the Chevrolet Volt, this is addressed by using a cooling system that consists of aluminum cooling plates and a coolant composed of a solution of ethylene glycol and water. Each individual cell is always in contact with a fin which has coolant running through it, while they are individually monitored using temperature probes.

Even with such preventative measures in place, system failures are inevitable so corrective measures are required as well. In the case of absolute failure and rapidly rising internal temperatures, the last resort is to purposefully open a safety vent so as to prevent pressure buildup. This is irreversible since it physically breaches the cell, but is necessary to decrease the chance of explosive rupture.

The automotive manufacturer can also design against worst case scenarios, constructing battery pack fire walls to trap flames in preferred areas.

### Internal Measures

Internal safety measures are dominated by novel material chemistries, designed with properties such that the cells components themselves (i.e. cathode, anode, etc.) do not fail in the aforementioned modes.

### Cathode

Though widely used for mobile devices, the LiCoO₂ chemistry that was used as an example at the beginning of this article is unsuitable for vehicular applications due to its low thermal stability. Its tendency to decompose at relatively low temperatures to produce oxygen which goes on to react with the electrolyte and generate more heat - is not acceptable, especially for a situation that requires greater dependability as in a motor vehicle. Alternative chemistries that have been proposed to solve this issue generally fall under three structural types (see Table I: layered, such as lithium nickel manganese cobalt oxide (NMC, LiNiₓMn₁₋ₓCo₁₋₂ₓO₂); spinel, such as lithium manganese oxide (LMO, LiMn₂O₄); and olivine, such as lithium iron phosphate (LFP, LiFePO₄). These molecular structures determine how the lithium is stored in the cathode, as well as how the cathode materials interact with their environment. Though this paper will not cover the specifics of the either the structures or their effects, such knowledge is key to understanding the reasons for the following results.

<table>
<thead>
<tr>
<th>Structure Type</th>
<th>Material</th>
<th>Chemical Formula</th>
<th>Abbrev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layered</td>
<td>Lithium Nickel Manganese Cobalt Oxide</td>
<td>LiNiₓMn₁₋ₓCo₁₋₂ₓO₂, LiNi(₁₋₂ₓ₋₉)MnₓCo₂O₄</td>
<td>NMC</td>
</tr>
<tr>
<td>Spinel</td>
<td>Lithium Manganese Oxide</td>
<td>LiMn₂O₄</td>
<td>LMO</td>
</tr>
<tr>
<td>Olivine</td>
<td>Lithium Iron Phosphate</td>
<td>LiFePO₄</td>
<td>LFP</td>
</tr>
</tbody>
</table>

The NMC chemistry is most simply viewed as a highly modified version of the LCO chemistry, which also falls under the umbrella of layered structures. If all of the cobalt is replaced with nickel, there is a significant increase of theoretical capacity, but the problems of decomposition at moderate temperatures are not solved. This can be remedied by adding Mn and Co as stabilizing structural elements. It is apparent from the vagueness of the stated chemical formulae in Table I that Mn and Co quantities can vary greatly, but for the purposes of safety, it was seen that the greatest thermal stability was achieved when Mn and Co were added in ratios greater than 1 to 8 versus Ni (i.e. LiNi₁₋ₓ₋₉MnₓCo₂O₂, both x and y > 0.1). As an example, fully charged LCO-based and NMC-based cells have been directly compared through the same induced runaway process. The NMC composition was LiNi₁/₃Mn₁/₃Co₁/₃O₂. The onset temperature in the LCO cell was seen to be 131.5 °C versus the NMC cells notably higher 175.4 °C. NMC is thus seen

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as a promising next-generation material, but these stability improvements still have much room for improvement, especially in light of the following two materials.

The LMO cathode type has a spinel structure that allows for the lithium ions to flow easily through the lattice, resulting in high charging and discharging rates. More pertinently, the material begins to decompose at much higher temperatures than the layered materials due to structural stability regardless of charge state. The result is an impressive onset temperature of roughly 260°C. In addition, the total amount of released energy is less than half of that of the tested layered cathode. The main drawbacks of LMO as a cathode material stem from issues with cycleability (i.e. short overall lifetime), and less theoretical capacity than the layered cathode chemistries.

The LFP cathode type also boasts excellent safety characteristics. Not only is the onset temperature comparable to the LMO spinel at around 240 °C, the released energy is also only slightly more than half of that of the LMO material. This is attributed to the construction of the olivine structure, which does not allow reactions that release oxygen to proceed until temperatures as high as 600 °C. However much like the LMO cathode, the most significant difficulty that the LFP chemistry faces is a much decreased capacity compared to either the LCO or NMC chemistry, showing a theoretical capacity only two-thirds that of LCO.

Cathodes which use integrate positive temperature coefficient of additives have also been suggested. As PTC devices are normally located outside of the cell, they do not prevent internal shorts. This solution would prevent the internal heat of the cell from ever surpassing a certain temperature limit as set by the PTC elements, even in the advent of a cell puncture or dendrite contact. Naturally, the largest hurdle for this material is that substituting some of the active material with PTC compounds results in a lower capacity.

### Anode

Due to its low price, respectable capacity, and good thermal stability, graphite is the de facto standard anode material for lithium ion cells regardless of application. There is great variation within graphite products, with differences in structure, morphology, and particle size, but the material itself remains unchanged. This creates a large differential in amount of research being done on the negative electrode versus the positive electrode since battery performance, capacity, and safety is not bottlenecked by the anode. However, major concerns still exist: as newer cathode materials with higher decomposition temperatures are introduced into the cell, the SEIs role in thermal runaway becomes a more notable issue. Additionally, since dendrite formation begins on the graphitic electrode, that safety concern must be addressed as well.

The material with the greatest promise to solve both problems is lithium titanate (LTO, LiTi$_2$O$_{12}$). Until recently, it was believed that LTO did not form an SEI at all, which would remove concerns of SEI decomposition forming flammable gases. Indeed, experiments were run on a cell with an LMO cathode and LTO anode where the cell was discharged and heated to 100°C for 12 hours, and no trace of any flammable hydrocarbons were detected. This has since been shown to be untrue; a stable SEI film develops on LTO anodes during normal cycling processes. From a practical standpoint, this finding has no impact on LTOs efficacy in terms of safety. It does not void previous results, so the conclusion remains much the same as before, since experimental results continue to show excellent thermal stability.

LTO also provides an effective solution to the problem of dendrite formation. Since lithium plating (and therefore dendrite formation) is dependent on the close relative voltage of lithium intercalation in graphite, the simple solution is to have the lithium interjection process happen at a higher voltage separation. In the case of LTO, this happens at around 1.55 V versus Li/Li$^+$. Effectively negating the possibility of dendrite formation.

There are two large downsides of LTO: first, in its basic, unaltered form, it has a low conductivity, which means that it has poor power characteristics. Equally importantly, the cell has a smaller operating voltage, also reducing the capacity. Research is currently being done on either modifying the structure (by doping) or the surface (by using additives such as carbon nanotubes) to increase conductivity, while the possibility of coating graphite with a layer of LTO to combine the best features of both materials remains.

### Separator

Though the separators role in the lithium ion cell is straightforward, it must contend with a stringent list of requirements. It is crucial that it maintains structural integrity throughout the cells operation. If there was either mechanical or thermal breakdown, the electrodes would come into direct contact with each other and start thermal runaway. The separator can also be designed such that if a runaway event begins, it can react at a temperature threshold and prevent any further chemical reactions from taking place - a process referred to as shutdown. Assuming reasonable ion conductivity, this means that an ideal separator material must rate highly in both puncture strength (for prevention of short circuits during manufacturing) and chemical stability, all while having an acceptable shutdown temperature (above optimal operating temperature and near the temperature where thermal runaway begins), low thermal shrinkage, and a high breakdown point. Though any and all of the above can be improved, current separators have acceptable puncture strength and chemical stability, so most research is being dedicated towards improving the latter three properties.
Most modern separators are made of polyethylene (PE), polypropylene (PP), or a combination of the two.\textsuperscript{39} PE has a lower melting point (135°C) than PP (165°C) while PP has better mechanical properties, so combining the two allows for a shutdown response at the lower temperature while still maintaining physical separation.\textsuperscript{39} This fairly small temperature buffer of 30°C and a large amount of material shrinkage\textsuperscript{39} are what are trying to be improved.

One possible method is to coat the polymer. It was found that coating a PE separator with a thin film of SiO\textsubscript{2} caused the PE to have hardly any shrinkage at all, even when held for 20 minutes above PEs melting point.\textsuperscript{40} However, because the stability of the separator stemmed directly from the SiO\textsubscript{2} layer, it was also theorized that shutdown would not occur at the normal PE melting temperature either. That is, since the SiO\textsubscript{2} was reinforcing the separator, the separator would not be able to melt until SiO\textsubscript{2} melted, which would be at a much, much higher temperature.

There have also been proposals in which the electrodes themselves are coated with a separator material, forming a single electrode-separator unit. In one example, a graphite anode was coated with a poly(p-phenylene oxide) and SiO\textsubscript{2} layer.\textsuperscript{40} The resultant unit (referred to as the Separator/Electrode Assembly or SEA) showed negligible shrinking and no noticeable change in operation at 170°C. Though the SEA is unable to provide shutdown functionality, the authors suggest that since it provides such high thermal stability, such functionality is unnecessary.

Another proposed alternative is to fabricate a ceramic separator, which is made of tiny inorganic particles all together (called, unsurprisingly, the binder). In one study, Al\textsubscript{2}O\textsubscript{3} was crushed into powder using a ball mill and distributed into a poly(vinylidene-fluoride) (PVDF) binder.\textsuperscript{41} This material was then heated to 150°C and held there for 30 minutes. The Al\textsubscript{2}O\textsubscript{3}-PVDF separator exhibited very little shrinkage despite the high temperature. Though mechanical results were not listed for this study, a common problem with many inorganic separators is a lack of mechanical strength, making them incapable of being tightly wound, which is a necessity for most cell constructions.\textsuperscript{42}

Electrolyte

Most commercial cells use lithium hexafluorophosphate (LiPF\textsubscript{6}) salts dissolved in organic solvents such as ethylene carbonate (EC), propylene carbonate (PC), dimethyl carbonate (DMC), and ethyl methyl carbonate (EMC), among others.\textsuperscript{43} The salts can transport lithium between the electrodes by splitting into a cation and an anion:

\[ \text{LiPF}_6 \rightarrow \text{Li}^+ + \text{PF}_6^- \]  \hspace{1cm} (9)

However, this salt can also decompose into slightly different pair:

\[ \text{LiPF}_6 \rightarrow \text{LiF} + \text{PF}_5 \]  \hspace{1cm} (10)

PF\textsubscript{5} is known to be a powerful Lewis acid, which can result in both damage to the SEI\textsuperscript{10} and the direct decomposition of solvents like EC,\textsuperscript{44} resulting in flammable gases. Since the primary concerns are the breakdown of the SEI and the release of flammable gases, many proposed solutions revolve around adding compounds to stabilize the salt, as well as developing new solvent mixtures to prevent the generation of flammable hydrocarbons. Additionally, compounds can also be added to counteract overcharge.

The simplest method to decrease the production of PF\textsubscript{5} is to increase the amount of present LiF, since that would imbalance the equilibrium towards LiPF\textsubscript{6}.\textsuperscript{43} However, there will always be some amount of PF\textsubscript{5} present in the cell, so in order to decrease the amount of PF\textsubscript{5} that will react with the SEI or the solvents, a small amount of a weak Lewis base can also be added.\textsuperscript{45} Examples of such a compound include tris(2,2,2-trifluoroethyl) phosphite (TTFP) and 1-methyl-2-pyrrolidinone (NMP).\textsuperscript{45}

A promising group of solvent materials are liquid salts, also referred to as ionic liquids (ILs). ILs are non-flammable, non-volatile, and highly stable, but have lower conductivities than LiPF\textsubscript{6} and form unstable SEI layers with graphite.\textsuperscript{46} However, it was found that when various ILs were mixed with traditional solvents (and vinylen carbonate for assisting in SEI stability) at a percentage of around 40% IL by volume, it was possible to achieve good conductivity while preventing combustion, even under direct flame. Less than 3% weight loss was observed even with the mixture held at 350°C, demonstrating very good thermal stability.\textsuperscript{46}

There are a wide variety of electrolyte compounds that can also confer overcharge protection either by using the extra electric current to progress a redox reaction, or by increasing the resistance by insulating the cathode.\textsuperscript{43} In the case of the latter situation, a compound can go through polymerization (in which individual molecules can link together to form long chains) at the cathode, forming a physical layer which increases the resistance of the system.\textsuperscript{43}

Conclusion

The current state of automotive energy storage safety seems fairly well-considered, though advancements in technology for capacity or energy transfer will require parallel developments in safety technology. As society demands batteries with greater capacities and power, engineers and scientists will have to contend with the increase in stored energy. Yet even with all the theoretical and laboratory work, the true safety challenges in the space of automotive lithium-ion batteries will only come to light...
after extensive use in real-world scenarios. Until electric vehicles achieve greater market penetration, thereby increasing the sample size of failures, developments will have to continue to depend on scientific investigation and human intuition.

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