



Safeguarding
lithium-ion battery
cell separators



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Executive Summary



Technical advances in the design and construction of lithium-ion battery cells have played an essential role in the widespread deployment of mobile technologies. They have made possible important innovations in all types of energy-using devices, while also successfully expanding the scope of battery-powered applications to include automobiles and other forms of vehicular transportation, as well as industrial, commercial and residential power systems.

At the same time, some battery cell design and construction changes that contribute to increased energy density and cycle life may also increase possible safety risks, specifically, issues related to the selection, design or manufacture of separator materials used in lithium-ion batteries when used within cells that have flammable electrolyte. These issues can contribute to problems that compromise battery integrity and increase the potential for internal short circuits that can lead to thermal runaway, fire and even explosions.

This UL white paper discusses the importance of the separator material in lithium-ion battery cells, and the role that a separator material certification can play in reducing battery cell-related safety risks. The paper discusses general concerns regarding battery safety and specific safety concerns related to battery separator materials. The white paper then describes separator component testing under UL 2591, “Outline of Investigation for Battery Separators,” and describes the potential benefits of component certification.

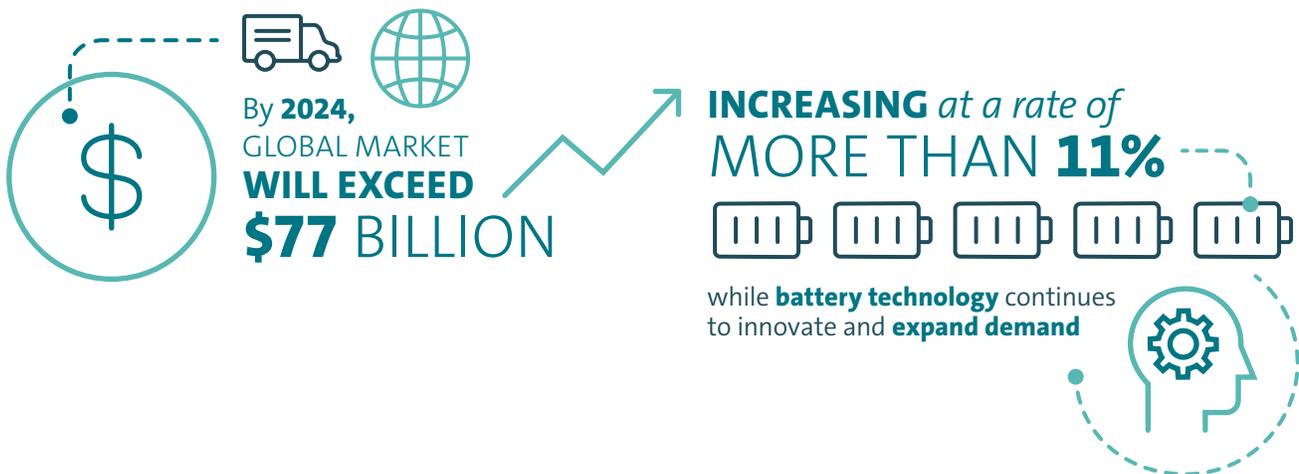
Lithium-ion battery cell use in the 21st century

In just a few decades, rechargeable (also known as secondary) lithium-ion battery cell technologies have transformed the global landscape. From humble beginnings in the early 1980s, the current generation of lithium-ion battery cells offers users significantly greater energy density, longer cycle life and improved reliability, even when compared with state-of-the-art batteries from just five years ago. These advances have made possible dramatic improvements in the portability of advanced electronic technologies, spearheading the rise of the phenomenon known as the internet of things (IoT), and supporting worldwide efforts to improve energy efficiencies and reduce the planet's dependence on fossil fuels.

Today, commercial lithium-ion battery cells, modules and packs power a wide range of electrical and electronic technologies, including systems and devices in the following categories:

- **Consumer electrical and electronic devices** – Smartphones, laptop and tablet computers to health and wellness trackers. Typically a portable application.
- **Medical devices** – Medical diagnostic equipment, including patient monitors, handheld surgical tools and portable diagnostic equipment.
- **Industrial equipment** – Cordless tools, telecommunications systems, wireless security systems, and stationary, motive or portable electronic equipment.
- **Automotive applications** – Battery-electric vehicles, hybrid-electric vehicles, plug-in hybrid-electric vehicles and light-electric vehicles.
- **Utility and energy infrastructure** – Used in combination with utility, commercial and residential solar and other alternative power systems to store generated energy for later use.

The rapidly-expanding range of battery uses and applications will spur significant increase in worldwide demand for lithium-ion batteries in coming years. According to one estimate, the global market for lithium-ion battery cells, modules and packs will exceed more than \$77 billion (USD) in annual sales by the year 2024, increasing at a compound annual growth rate (CAGR) of more than 11 percent.¹ At the same time, ongoing innovations in battery technologies can be expected to further broaden applications for lithium-ion batteries and contribute to increased demand well into the future.





Safety issues related to lithium-ion battery cells

A lithium-ion battery cell is an energy storage device in which lithium ions move through an electrolyte from the negative electrode (the “anode”) to the positive electrode (the “cathode”) during battery discharge, and from the positive electrode to the negative electrode during charging. The electrochemically active materials in lithium-ion battery cells are typically a lithium metal oxide for the cathode, and a lithiated carbon for the anode. The electrolytes can be liquid, gel, polymer or ceramic. For liquid electrolytes, a thin (on the order of microns) micro-porous film (the battery separator) provides electrical isolation between the cathode and anode, while still allowing for ionic conductivity. Variations on the basic lithium chemistry also exist to address various performance and safety issues.

Reputable manufacturers of lithium-ion battery cells design their products to deliver specified performance in a safe manner under the full range of anticipated use conditions. Further, passive and active safeguards are typically integrated into battery cell designs to prevent or mitigate the risk of

many types of failures, such as those related to thermal stability and internal short circuits. As such, performance or safety failures are generally caused by some combination of poor quality battery design, materials or construction, or through misuse or abuse by users.

Internal short circuits in lithium-ion battery cells represents an area of particular concern to battery cell manufacturers, since even well-designed cells with integrated safety features are susceptible. Most often, internal short circuits are caused when a breach in the battery separator creates an unintended pathway between the cathode and the anode of the battery. This pathway can result in the heating of the battery’s active materials, which in turn starts a self-sustaining exothermic reaction that can lead to thermal runaway and fire or explosion.



Typically, breaches in lithium-ion battery separators have been linked to the application of some severe external force that deforms the battery's inner layers sufficiently to compromise the separator structure. As a result, most regulations applicable to the safety and performance of lithium-ion battery cells mandate a number of mechanical tests intended to assess the strength and resilience of the battery to crushing and other direct impacts, as well as shock and vibration. UL has pioneered safety testing at the battery module and pack levels, and has also been instrumental in the development of advanced test methods to assess the mechanical strength of lithium-ion battery cells, including a test that measures ability of a lithium-ion battery to sustain pressure from a localized indentation in the battery surface.

At the same time, efforts to develop lithium-ion battery cells that offer improved performance characteristics and that are smaller and lighter in weight have also resulted in major modifications in battery separators and other essential battery materials. For example, the use of a thinner separator material can allow for more active materials to be used in the same size cell, potentially contributing to a significant increase in energy density. These findings have led many lithium-ion battery cell manufacturers to reduce the thickness of the separator material they use, or to make other modifications to separator materials to enhance performance.

However, these changes have also potentially compromised the capability of some battery separators to perform essential safety functions. The overall reduction in separator thickness means that separator material may be more susceptible to defects that can occur during the material manufacturing or battery cell assembly process that adversely affect the strength, stability or permeability of the material. And thinner separator material also makes the battery potentially more vulnerable to external damage, thereby increasing the risk of overheating and thermal runaway.

UL's research on lithium-ion battery separator material

To assess the extent of how different separator materials impact safety of lithium-ion batteries, UL has recently conducted a comprehensive assessment of lithium cobalt oxide (LiCoO₂) graphic pouch cells incorporating several different types and thicknesses of commercial battery separators. Completed in early 2018, the assessment tested sample cells incorporating five different separator materials, including polypropylene, polyethylene and ceramic coated polyethylene. In addition, cells tested included integrated separator materials ranging in thickness from 16 micrometers (µm) to just 7µm.

During UL's assessment, each sample cell was subject to four separate testing evaluations that simulate common battery cell abuse conditions. These included:

- thermal ramp test;
- overcharge test;
- internal short circuit test; and
- external short circuit test.

At the same time, separator materials used in the cell samples were characterized for their specific physical properties, including:

- melt temperature;
- melt rupture temperature;
- puncture resistance;
- dimensional stability;
- shutdown function; and
- thickness.

This enabled UL researchers to evaluate possible correlations between cell failure conditions and the properties of their respective separator materials.

In general, UL's analysis of test data generated during this assessment concluded that extremely thin separator material alone is not necessarily the main cause of battery cell failures. Rather, UL's testing clearly demonstrated that it is the physical characteristics of separator materials, such as puncture strength, melting point, melt integrity and dimensional stability, that play an equal if not greater critical role in battery performance and safety. While subject to further study, these results clearly point to the importance of having a thorough understanding of the physical characteristics of separator material during the battery cell specification process, and how those characteristics may affect battery cell safety and performance.

UL is continuing its research into battery separator materials. Building on its recently completed assessment, UL will conduct a second study in 2018 that is expected to include an expanded variety of separator materials, including materials composed of non-woven fibers. UL is also conducting benchmark testing on more than 40 different types of separator materials currently on the market in order to evaluate their physical properties. The results of that benchmark testing will be recorded in a comprehensive database that will detail the quality and performance of battery separator materials, and help facilitate the selection of materials for further testing and evaluation.



Finally, UL is evaluating the degradation of battery separator materials under long-term charge and discharge cycles, from 150 cycles to over 1,200. This evaluation is expected to provide insight into how separator properties change over time, and may help guide the appropriate selection of separator materials based on their intended use and their expected life.

UL 2591 and battery cell separator safety

UL 2591, Outline of Investigation for Battery Cell Separators, is the primary Standard for assessing the safety of separator materials used in lithium-ion battery cells. The Standard covers test procedures for battery separator materials intended to provide electrical insulation between the cathode and the anode. As such, it serves as a useful tool to assist lithium-ion battery manufacturers in the evaluation and selection of appropriate separator materials.

When first published in 2009, UL 2591 was part of an industry-wide effort to address numerous instances of battery cell failures, and specifically failures attributable to poorly manufactured battery separator material. In recent years, further experience and research by UL and others has contributed to an increased understanding of specific factors that may contribute to battery separator failure. As a result, UL 2591 is currently undergoing a further revision, with a third edition of the Standard expected to be published sometime during the second half of 2018.

The 3rd Edition of UL 2591 updates test procedures for battery cell separator materials in the areas of thickness, dimensional stability, shutdown and melting temperatures, air permeability, tensile strength and puncture strength. In addition, the revision adds new criteria for battery separator materials to address material porosity, pore size and distribution, wettability and heat of combustion. In brief, the 3rd Edition of UL 2591 will now subject separator material samples to each of the following tests:

Physical characteristics

- **Air permeability** – Air permeability testing is intended to assess a separator material's resistance to the passage of air under a specified pressure. Testing follows the test method detailed in ASTM D726;
- **Thickness** – Thickness testing uses a specialized instrument to determine the degree of thickness uniformity in the separator sample material, and is intended to assess product consistency;
- **Porosity** – Porosity measures the absorption capacity of separator material by soaking the material sufficiently to wet the substrate, and weighing the materials both before and after the soaking;
- **Pore size and distribution** – This test determines the size and distribution of pores in the separator material by measuring the pressure and flow rate at which gas flows through the material. The specific test methods used are described in SAE J2983;



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- **Wettability** – Wettability testing measures the time required for separator material to become completely wetted when it comes in contact with electrolyte; testing and measurements specific are described in NASA/TM 2010-216099.

Mechanical characteristics

- **Tensile strength** – Tensile strength testing assesses a separator material's resistance to elongation when subject to tension. Tensile strength testing follows the test method described in ASTM D882;
- **Puncture strength** – Puncture strength testing is intended to assess a material's resistance to penetration from both a sharp object or through blunt force. Testing follows the test method described in ASTM D3763.

Thermal characteristics

- **Dimensional stability** – Dimensional stability testing assesses a material's ability to resist shrinkage or distortion when subject to the elevated internal temperatures experienced inside a lithium-ion battery;
- **Shutdown temperature** – Shutdown temperature testing is designed to evaluate changes in material impedance over a range of temperatures;
- **Melting temperature** – Melting temperature testing assesses the temperature level at which a separator material disintegrates due to heat exposure. Testing follows the test method described in UL 746A (ASTM D3418).

Combustion characteristics

- **Heat of combustion** – This test evaluates the energy released as a result of the combustion of a separator material, and utilizes the test method described in ASTM D5865.

Material characterization

- **Material identification/characterization** – Material identification and characterization tests establish the characteristics of a given separator material, including material composition, construction and coatings.

The revised version of UL 2591 is also expected to differentiate key performance criteria values in order to assist lithium-ion battery manufacturers in the selection of separator materials that are most appropriate for their specific application.



The importance of UL's battery cell separator component certification

Expressly developed for manufacturers of both lithium-ion battery cells and battery separator materials, UL's Battery Cell Separator Recognition Program is designed to support industry efforts to ensure the quality of separator materials used in today's advanced lithium-ion battery cells. The Recognition Program utilizes the material parameters and testing protocols detailed in UL 2591 to assess separator material quality factors that are critical for both battery safety and performance.



It is important to note that battery separator material can vary greatly depending on a battery's intended use, as well as the anticipated abuse conditions. For example, a battery cell may require separator material that has a high-melt temperature for one type of application, but high-puncture resistance or good dimensional stability for another. Ultimately, these factors must be also considered in determining the optimal product specifications of the battery separator material selected.

Therefore, UL's Recognition Program is intended to identify and characterize the properties of separator materials, and does not impose pass/fail criteria in connection with the results of any individual test. This approach enables separator material manufacturers to accurately represent critical safety qualities and limitations of their products. It also facilitates the selection of separator materials by lithium-ion battery cell manufacturers that most closely meets the requirements of their given battery application.

UL's follow-up services (FUS) inspections are an essential component of the Battery Separator Recognition Program.

Periodic testing of production samples of separator materials under FUS enables manufacturers to verify the consistency of material parameters, and to identify possible deviations from established material specifications that could adversely impact battery safety and performance. This increases supply chain integrity for cell manufacturers, and helps to ensure that the quality of the battery separator material continues to meet UL's requirements.

Finally, separator materials evaluated under UL's Battery Separator Recognition Program are published in UL's publicly-available UL Product iQ, along with detailed information about the performance parameters of each recognized separator material. This enables manufacturers of lithium-ion battery cells to search for separator materials that most closely match the design requirements of their intended application. It also reduces the time and effort required for cell manufacturers to achieve certification, as additional testing and surveillance may not be required for separator materials that have already been certified by UL.

Summary + Conclusion



As the use of lithium-ion battery cells continues to expand and evolve, cell developers will continue to evaluate design changes and the use of different battery materials to increase battery life and to improve energy efficiency. The success of these efforts will depend in part on a more detailed understanding of the specific characteristics of separator materials, so that design and material selection decisions are consistent with the requirements of the battery's intended use. As such, separator material manufacturers should test and qualify their materials to help ensure proper material selection and suitable levels of battery safety.

UL 2591 and UL's Battery Cell Separator Recognition Program can play an essential role in these efforts by providing independent, third-party characterization testing of battery separator materials, and through follow-up post-production product inspections and testing that help to ensure that separator materials continue to meet established specifications.

For more information on UL's testing of lithium-ion battery cell separators, as well as UL's other battery testing programs, contact UL at PMSales@ul.com.

End Notes

1. “Lithium-ion Battery Market by Power Capacity Analysis, by Application Analysis, and by Regional Analysis—Global Forecast by 2016-2024,” a report produced by Market Research Engine, April 2017. Web. 20 May 2018. <https://www.marketresearchengine.com/lithium-ion-battery-market>.

