

SOLID-STATE BATTERY LANDSCAPE

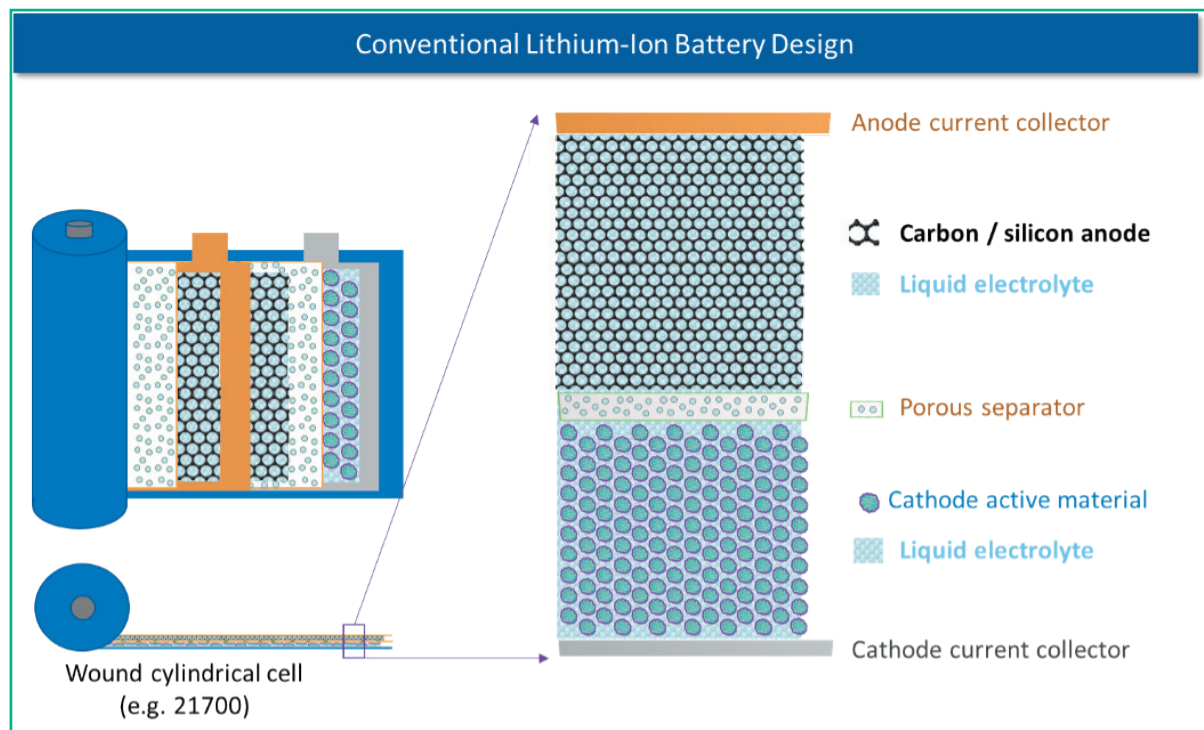
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Following the announcement of QuantumScape’s solid-state lithium-metal battery technology results in December 2020, there has been a lot of excitement in the industry related to the potential of this new technology and the impact it could have on the automotive EV powertrain.

As with any technology, when there is a lot of excitement, there can also be a lot of misconceptions. The purpose of this paper is to help investors, customers, and others interested in this technology to understand the broader technology landscape of solid-state battery technology.

Conventional Lithium-Ion Batteries

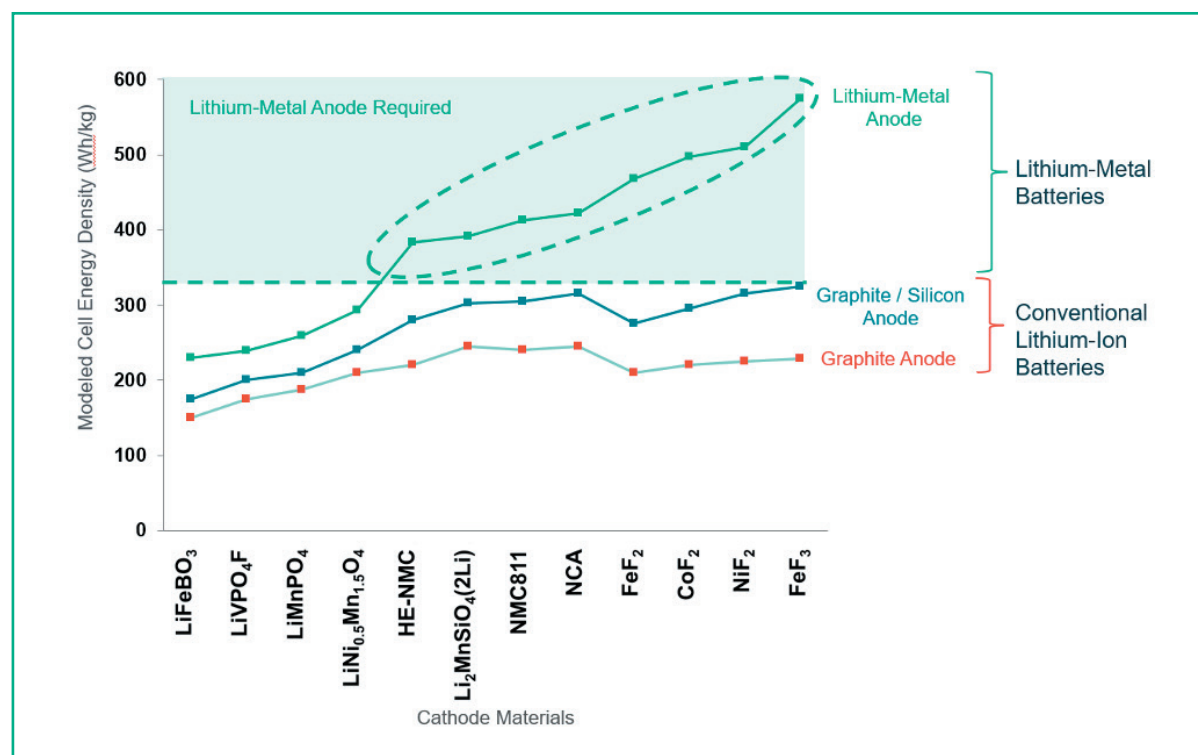
We start with a quick review of how conventional lithium-ion batteries work. As shown in the figure below, a lithium-ion battery consists of three main layers: A cathode, or positive electrode, consisting of a lithium containing mixed-metal oxide material; an anode, or negative electrode, consisting of carbon or a mix of carbon and silicon; a separator, an electrical insulator made of a porous polymer material; and an electrolyte, the medium through which lithium ions move through the battery, typically consisting of a hydrocarbon solvent and dissolved lithium salt. (In this document, we will use “carbon anode” to mean either a pure carbon anode or a hybrid carbon-silicon anode.)



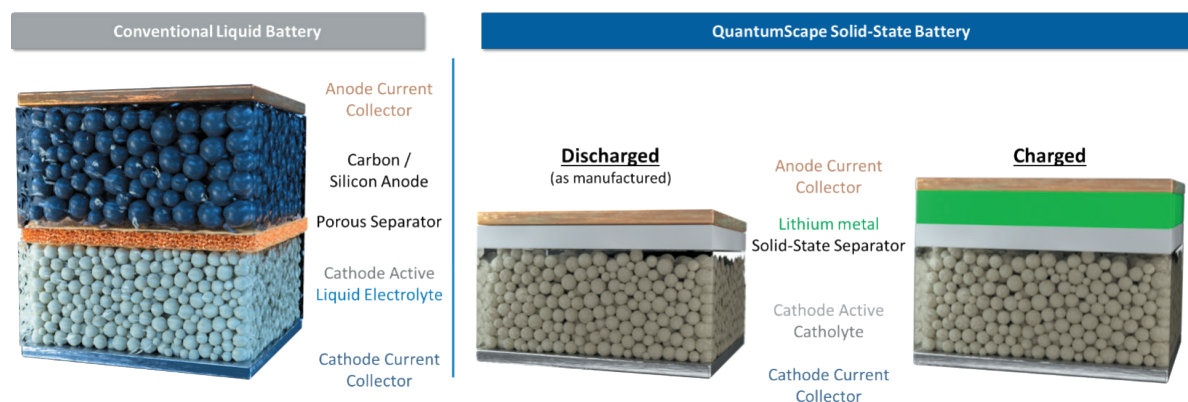
A battery may be envisioned as the electrochemical equivalent of rolling a ball uphill, which requires work to be put into the system, increasing potential energy in the system during the process, and letting it roll back downhill on its own, to release stored energy and do useful work. In a fully-discharged cell, the lithium in the cell resides in the cathode, the “downhill” state. When the cell is charged, work is put into the system to drive lithium ions from the cathode to the anode, where they diffuse into the carbon particles that make up the anode. In the fully charged state the lithium ions sit in the anode, like balls that have been rolled uphill, waiting until they can be freed to roll back downhill again. When the battery is discharged, these lithium ions are allowed to move back from the anode to the cathode, and in the process, energy can be extracted from the system, just like the ball rolling downhill can release its stored energy in the form of useful work.

The Lithium-Metal Battery

A next generation battery may include next generation cathode material or next generation anode material (or both). The chart below, based on a paper published by a group from BMW, shows a dozen different next generation cathode materials and three different anode materials. What this chart makes clear is that the energy density gains from using next-generation cathode materials are limited, unless lithium metal is used as the anode. The principal reason for this limitation is that higher capacity cathodes need correspondingly thicker anodes to hold the increased amount of lithium, drowning out some of the benefits of the cathode improvement.



Traditional lithium-ion cells use a hosted anode in which the host material, such as carbon or silicon, provides a structure to hold the lithium. For example, in the case of carbon, it takes six carbon atoms to hold one lithium atom. **If, however, an anode of pure metallic lithium were to be used, as shown in the schematic below, all the carbon in the anode could be eliminated and the energy could be stored in a much smaller volume, thereby dramatically increasing the energy density of the cell.**



The potential increase in energy density for a lithium-metal anode battery has been known since the mid-1970s. However, it has also been known that lithium-metal anodes do not work with conventional liquid electrolytes due to the twin issues of dendrite formation when a battery is being charged and rapid impedance growth from a chemical side-reaction between the liquid electrolyte and the lithium metal. Dendrites are needle-like formations of lithium metal which can grow across the separator and short-circuit the cell. Impedance refers to the internal resistance of the cell; growth in this resistance reduces the energy capacity of the cell as well as its ability to work at high rates of power.

Thus, it is widely believed that to make a lithium-metal anode battery, one needs a solid-state separator which is roughly as conductive as a liquid but resists dendrite formation and does not react with metallic lithium. For 40+ years, the industry has been searching for such a material.

The Promise of the Solid-State Lithium-Metal Battery

It turns out that **the lithium-metal anode enabled by such a solid-state separator could address not only the energy density problem, but also a number of the other limitations of conventional lithium-ion batteries, since many of these stem from the carbon anode as well**, including:

- 1. Energy density:** Since the carbon that makes up the anode takes up space and has mass, eliminating it increases the energy density of the cell.
- 2. Power density/fast charge:** The lithium that cycles through the cell into the anode has to diffuse into the carbon at a rate that is governed by fundamental material properties of graphite. Any attempts to drive the lithium ions into the carbon anode particles faster than this natural rate of diffusion can result in the lithium “plating” on the surface of the particle instead of diffusing into it causing capacity loss and failures. Eliminating the carbon removes this limitation, allowing for fast charge without any adverse impacts.
- 3. Cycle life:** The cycle life of the cell is partly limited by an irreversible chemical side reaction (i.e., an unwanted reaction) at the interface of the carbon particle and the liquid electrolyte, which consumes a little bit of lithium on every charge-discharge cycle, resulting in a cumulative loss of capacity (and therefore energy) over the life of the cell. With no carbon in the anode this side

reaction should be eliminated, resulting in improved cycle life for the cell.

- 4. Safety:** The polymer separator and the liquid electrolyte used in lithium-ion batteries are both hydrocarbons and are combustible. Starting a fire requires three elements: A fuel, an oxygen source, and a heat source. Because the electrolyte -- a fuel -- is in direct contact with the cathode, which is an oxide, the only other element needed to cause a fire is a heat source. Many abuse conditions, from internal short-circuits to accidents, can provide that heat source. Replacing the polymer separator with a solid-state ceramic separator that is thermally stable to very high temperatures and does not burn (since it is already oxidized) both reduces the fuel content of the cell and provides a thermally stable barrier between the anode and cathode.
- 5. Cost:** The costs of the materials associated with the carbon anode and the anode electrode manufacturing process can be eliminated by replacing the carbon anode with a lithium-metal anode. In addition, the conventional formation process, one of the most expensive parts of the battery manufacturing process in which the assembled cells must sit in storage for a period of weeks to form the proper interfaces on the electrode particles and allow for the identification of manufacturing defects, can be dramatically simplified.

The Challenge

This is the promise of solid-state lithium-metal batteries and is why the industry is so excited about the possibilities. However, making the solid-state ceramic separator required to deliver on this promise has turned out to be a very difficult challenge. More specifically, such a separator needs to:

- have **lithium-ion conductivity** similar to or better than today's liquid electrolytes;
- be **chemically and electrochemically stable to lithium metal**; and
- resist the formation of** lithium-metal **dendrites**.

Despite decades of work, the industry has not found any separator materials capable of meeting these requirements.

Comparing Separator Materials

Many classes of separator materials have been tried, none of which have been shown to simultaneously meet the key requirements. These include:

- Polymers:** Lithium-conducting polymers, such as polyethylene oxide, were initially thought to be a candidate for a solid-state separator. Unfortunately, they are generally deficient on all three of the requirements outlined above. First, their conductivity is too low, requiring elevated temperatures to operate. Second, the poor stability of polymers in contact with lithium metal results in impedance growth over life and requires the anode to use a lithium foil to supply excess lithium to the cell, reducing energy density and increasing cost. Third, they are too soft to prevent penetration of lithium-metal dendrites through them. In addition, they are not stable above 3.8 volts, further compromising energy density by requiring a low energy cathode material.
- Sulfides:** The discovery of lithium-conducting sulfides, such as LGPS by Professor Ryoji Kanno in Japan in 2011, generated excitement because they are highly conductive of lithium ions, addressing requirement (a) above. However, they are among the most thermodynamically unstable of the widely investigated solid-state electrolytes – reacting on both the high voltage cathode side and the low voltage lithium side. To offset this reactivity, the cathode materials are

typically coated. Unfortunately, these coatings often raise the internal resistance of the cell and make the cell unable to perform at high rates of power or low temperatures. But most fatally, it turns out that despite years of work, sulfides have not been shown to prevent dendrites at low temperature and high charge rates, making them simply unusable in commercial battery systems for EVs.

- **Oxides:** Lithium conducting oxide separators were discovered over the past few decades, but while some oxides have sufficient conductivity and stability towards lithium metal, conventional oxides, too, have been unsuccessful at suppressing dendrite formation at automotive charge rate requirements.
- **Composites:** Some groups have worked on composites consisting of polymers and ceramics, in hopes that they could capture the “best of both worlds” – the ease of working with polymers with the hardness of ceramics. Unfortunately, such approaches end up instead with the “worst of both worlds”, resulting in an unstable material that fails to prevent dendrites, as dendrites appear to grow through the interface between the two materials.
- **Liquids:** Some groups continued to work on conventional liquid electrolytes, but these efforts are still challenged by the twin problems of dendrite formation and impedance growth from the chemical side-reaction between the liquid and the lithium metal. One famous such effort was the Canadian company, Moli Energy, led by Jeff Dahn, now at Dalhousie University in Halifax, Canada, and one of the premier battery researchers in the world. Moli shipped lithium-metal batteries with liquid electrolytes thinking dendrites were not an issue, only to find mobile phones with their batteries were catching fire, resulting in the demise of the company. Dahn has since become a leading researcher in conventional liquid electrolyte-based lithium-ion batteries.

It is important to note that if one has a system using any of the foregoing separator materials, it is still possible to make cells and report cycling results, but this cycling has to be done under compromised test conditions. In particular, the following are some of the most used compromises:

1. **A carbon or carbon-silicon anode instead of lithium metal:** Reverting to a hosted anode sacrifices the benefits of lithium-metal anodes, such as energy density, fast charge, cycle life, safety, and lower cost. Thus, these approaches are not the step-change in performance required for mass market EVs.
2. **Low current density:** At low current density, such as 1-2 mA/cm², even liquid can be made to cycle with lithium metal. However, such low current densities are not useful for automotive applications.
3. **Elevated temperatures or pressures:** At elevated temperatures, lithium metal is softer and less likely to form dendrites. In addition, high temperatures increase the conductivity of materials like polymers and sulfides and reduce the resistivity of cathode coatings. However, requiring elevated temperature makes the cell impractical and too expensive for most commercial applications. Elevated pressures similarly provide a way to “squeeze” lithium into smoother structure, but overly high pressures such as those above 10 atmospheres are simply impractical even in automotive applications.
4. **Low cycle life:** Because of the stochastic nature of dendrites and the progressive nature of impedance growth, many cells made with materials that do not meet the above requirements can deliver some cycles, but not enough to be commercially viable, and the cells are not reliable

enough to be usable in real applications.

- 5. Excess lithium on the anode:** Some efforts start with an excess layer of lithium on the anode, which makes the process of plating lithium easier, but at the expense of energy density and cost, rendering these approaches impractical for automotive applications as well.

Key Questions

Recently, there have been a number of announcements and claims relating to solid-state batteries. The first question to ask when evaluating solid-state cell claims, is whether the cells use a lithium-metal anode or a conventional hosted (carbon or carbon-silicon) anode. If they do use a hosted anode, the key performance metrics for these batteries will be similar to conventional lithium-ion batteries and not realize the benefits of the solid-state lithium-metal approach (significantly higher energy density, fast charge, life, and cost). A number of recent claims fall into this category.

If the solid-state cell in question does use a lithium-metal anode, the next question to ask is whether it can perform under uncompromised test conditions, including near and below room temperature and high current density (i.e., high rates of power such as 1-hour charge or 15-minute charge). Specifically, what cycle life does the cell deliver at near-room temperature ($\sim 30^{\circ}\text{C}$) with automotive rates of power ($>3\text{ mA/cm}^2$, required for one hour charge)? If the cells cannot perform under these conditions, we believe they are not commercially viable. Many of the other solid-state lithium-metal announcements fall into this category.

QuantumScape's Approach

Many solid-state announcements either do not show any data at all, or leave out some of the above parameters when they report data, leaving an incomplete picture at best. At QuantumScape, we have developed a solid-state ceramic separator capable of meeting these requirements without requiring the compromised test conditions described above. We have [presented data](#) showing single-layer versions of our solid-state lithium-metal cells can cycle more than 1000 cycles and retain over 90% of their initial energy when cycling at aggressive 1C rates of power, near room temperature, and with modest pressure. More recently, we have presented data showing multilayer cells cycling to close to 800 cycles with similar capacity retention.

We hope that this paper helps our stakeholders understand the broader technology landscape of solid-state battery technology and QuantumScape's distinctive approach.

Forward-Looking Statements

This current report contains forward-looking statements within the meaning of the federal securities laws and information based on management's current expectations as of the date of this current report. All statements other than statements of historical fact contained in this current report, including statements regarding the future development of the Company's battery technology, the anticipated benefits of the Company's technologies and the performance of its batteries, plans and objectives for future operations, forecasted cash usage, including spending and investment, are forward-looking statements. When used in this current report, the words "may," "will," "estimate," "pro forma," "expect," "plan," "believe," "potential," "predict," "target," "should," "would," "could," "continue," "believe," "project," "intend," "anticipates" the negative of such terms and other similar expressions are intended to identify forward-looking statements, although not all forward-looking statements contain such identifying words. These forward-looking statements are based on management's current expectations, assumptions, hopes, beliefs, intentions, and strategies regarding future events and are based on currently available information as to the outcome and timing of future events.

These forward-looking statements involve significant risks and uncertainties that could cause the actual results to differ materially from the expected results. Many of these factors are outside the Company's control and are difficult to predict. Factors that may cause such differences include, but are not limited to ones listed here. The Company faces significant barriers in its attempts to produce a solid-state battery cell and may not be able to successfully develop its solid-state battery cell. Building high volumes of multi-layer cells in the commercial form factor and with higher layer count requires substantial development effort. The Company could encounter significant delays and/or technical challenges in replicating the performance seen in its single-layer cells and early tests of the smaller form factor four-layer cells and in achieving the high yield, reliability, uniformity and performance targets required for commercial production and sale. The Company may encounter delays and other obstacles in acquiring, installing and operating new manufacturing equipment for automated and/or continuous-flow processes, including vendor delays (which we have already experienced) and challenges optimizing complex manufacturing processes. The Company may encounter delays in hiring the engineers it needs to expand its development and production efforts, delays in acquiring the facility for QS-0, and delays caused by the COVID-19 pandemic. Delays in increasing production of engineering samples would slow the Company's development efforts. The Company may be unable to adequately control the costs associated with its operations and the components necessary to build its solid-state battery cells at competitive prices. The Company's spending may be higher than currently anticipated. The final closing under the Company's financing agreement with VW may not occur if the Company does not achieve certain interim technical targets by the end of the quarter. The Company may not be successful in competing in the battery market industry or establishing and maintaining confidence in its long-term business prospectus among current and future partners and customers and the duration and impact of the COVID-19 pandemic on the Company's business. The Company cautions that the foregoing list of factors is not exclusive. The Company cautions readers not to place undue reliance upon any forward-looking statements, which speak only as of the date made.

Except as otherwise required by applicable law, the Company disclaims any duty to update any forward-looking statements. Should underlying assumptions prove incorrect, actual results and projections could differ materially from those expressed in any forward-looking statements. Additional information concerning these and other factors that could materially affect the Company's actual results can be found in the Company's periodic filings with the SEC. The Company's SEC filings are available publicly on the SEC's website at www.sec.gov.