Sion Power Lithium Metal Battery Technology Assessment Report

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"Sion Power could be an important driver in helping to accelerate U.S. domestic production of lithium metal batteries."

About the Author

Y. Shirley Meng is a professor of molecular engineering at the Pritzker School of Molecular Engineering. She also serves as the chief scientist of the Argonne Collaborative Center for Energy Storage Science (ACCESS) Argonne National Laboratory. Her work pioneers in discovering and designing better materials for energy storage by a unique combination of first-principles computation guided materials discovery and design, and advanced characterization with electron/neutron/photon sources. Dr. Meng is the principal investigator of the research group — Laboratory for Energy Storage and Conversion (LESC).

Executive Summary

Sion Power has developed a novel approach to manufacturing high quality thin lithium metal anodes—this is unique among all the lithium metal battery companies (including QuantumScape, Cuberg, Factorial, and SES).

- The first company to patent a pressure control strategy to eliminate formation of lithium dendrites, a requirement for safety and cycle life. After confirming the importance of compression in experiments in our research group, it is likely that any Li metal system will require similar compression ranges to achieve acceptable commercial performance.
- Third-party verified performance of large format cells was impressive, as good or better than competitors in this space.
- Independent safety testing of large format cells at Energy Assurance was excellent, though the same successful safety tests demonstrated on fresh cells must be verified on aged cells and cells at the end of life.
- 100% based in the United States, with a strong patent portfolio and unique VDLi lithium metal anode production, surface protection and pressure control. Sion Power could be an important driver in helping to accelerate U.S. domestic production of lithium metal batteries.

Background

In 1976, the first publication on using a lithium metal anode for rechargeable batteries was published in the journal of Science by Nobel Prize Winner Stanley Whittingham. However, the journey to commercialize rechargeable lithium metal batteries has suffered many setbacks due to unpredictable cell failures. At the same time, graphite was identified as the promising intercalation type anode. Paired with discovering a new electrolyte, lithium-ion batteries (LIBs) have dominated the portable devices and consumer electronics market for the past three decades. Today, LIBs are gradually penetrating emerging technologies such as electric vehicles (EVs) and grid storage. However, the justification for LIB's widespread adoption entails overcoming fundamental barriers, including high cost due to supply chain shortage and manufacturing methods, safety hazards from battery fires and explosions, demands for higher energy density, and broader operating temperature ranges for applications in various climates (hot and cold regions).

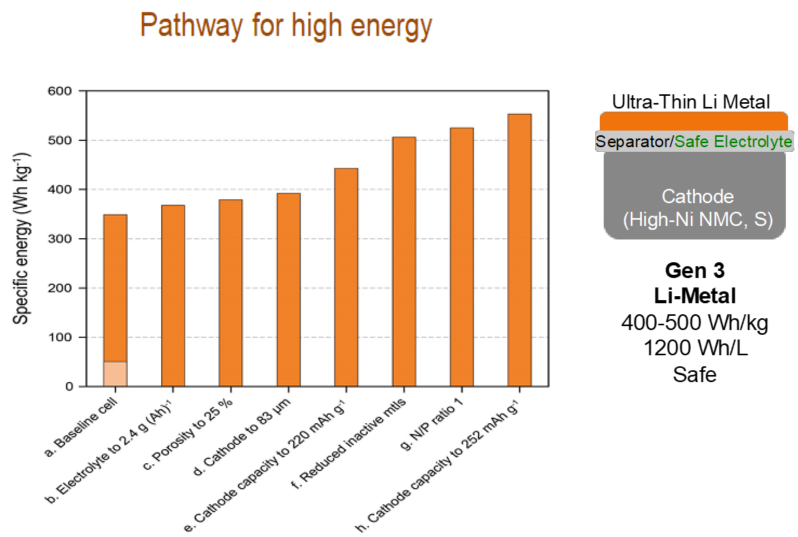

Figure 1. Battery500 Consortium's strategy is to reach 500 Wh/kg for lithium metal battery technology.

Given these challenges, lithium metal batteries (LMBs) are widely considered one of the most promising next-generation battery technologies. According to the projection of the Battery500 consortium, a Department of Energy-funded consortium that is focusing on LMB research and development, LMBs will reach an energy density of 500 Wh/kg (see Figure 1) with the appropriate cell designs. LMBs use lithium metal as the anode rather than graphite used in traditional LIBs, thus potentially significantly improving volumetric and gravimetric energy densities. With lithium metal as the anode, solid-state electrolytes (SSEs) are often considered to be the ultimate solution for the safe, high-energy battery; however current solid-state battery (SSB) technology carry a significant drawback in more complex (thus costly) manufacturing processes. In addition, SSBs also introduce new difficulties, such as the considerable stack pressure required to ensure solid-solid interfacial contacts, which can significantly hamper energy density and, so far, have not proven real-world performance by third-party testing houses. In short, SSBs require more years to mature.

In April 2021, I did a due diligence assessment report for SES (Solid Energy Systems), a company with a lithium metal battery technology platform (battery + software) that became a publicly listed company in February 2022 (NYSE, #SES). The following assessment report uses information from Sion Power provided to me. I have used publicly available information from the SES website for comparison purposes. Using the combined company data from Sion Power and SES, I have applied over two decades of experience working in the areas of lithium metal anode, electrolyte development, and electro-chemistry of batteries.

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Comments on Sion Power's Anode Strategy

Sion Power has had a long history in the battery field with a strong and positive reputation in lithium-sulfur batteries. In the file named Anode Summary 20220409.pdf provided by Sion Power, I learned the dual approach strategy where on one side, Sion Power uses 30-50 um thick lithium foil from vendors, while on the other side, Sion Power develops a propriety vacuum deposition technique for producing thinner lithium film (double side possible). There is no current collector in the anode other than bulk lithium in the lithium foil approach, which is very cost-effective. I have received those anode foils in my group and verified that the thickness is around 30+um with an excellent surface protection layer (see Figure 2). Such a current collector-free approach reduces the use of expensive Cu and allows for maintaining a high lithium inventory overbalance.

In my assessment, Sion Power has a unique competitive edge, as most lithium metal anode manufacturers are making lithium anodes using lamination and extrusion processes (where Cu current collector must be used). Lamination and extrusion are always considered the most proven process; however, the exact cost competitiveness remains unknown. It is reassuring that Sion Power has its proprietary Vapor Deposited Lithium Film (VDLi) technology. This technology is important because Li metal foil is very expensive and not widely available. Also, Li foil cannot be made thin enough to allow the attainment of energy and cost targets. The extrusion process produces a metal sheet with grains preferred oriented, while the evaporation process produces more randomly oriented grains. Its effects on lithium stripping and re-deposition are still unclear today.

Controlling lithium deposition morphology is critical, as we have pointed out in our early publications (Nature 2019). As the work funded by the Battery500 consortium has revealed, the conventional SEM cannot reveal lithium metal's actual morphology (grain size, orientation, and crystallinity), resulting in a critical understanding of lithium metal in the field. My group has developed cryogenic imaging methods and titration gas-chromatography (TGC) method to quantify the 3D morphology of lithium metal. Using our TGC method, we were able to assess Sion Power's lithium metal anode with confidence.

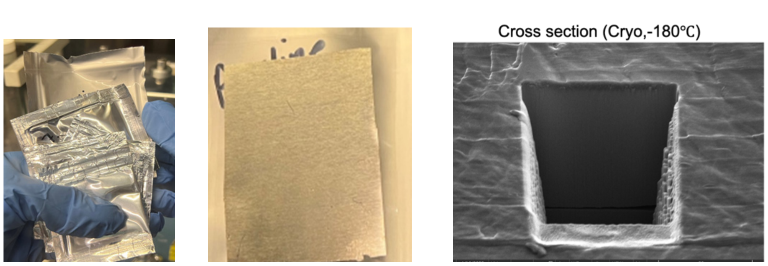

Figure 2. As received lithium foil from Sion Power, imaged by Cryo focused ion beam (FIB), scanning electron microscopy (SEM) to reveal the thickness of 34um.

Another important control parameter needed for a functional rechargeable lithium metal battery is the applied stack pressure (Nature Energy 2021) for a single layer small pouch cell of 226 Newton per square inch (or 54 Newton per square cm).

Sion Power has developed a novel approach to manufacturing high-quality thin lithium metal anodes (10um single side and double side possible) — this is unique among all the lithium metal battery companies (including QuantumScape, Cuberg, Factorial, and SES). Sion Power is also the first company that patented its pressure control strategy. Sion Power has a rich history of working on Li-sulfur batteries and has filed a series of patents where they were clearly stated that pressure would be required in metallic lithium batteries and the pressure ranges such as minimum value and pressure as a percentage of the yield stress of lithium are stated in the patents. In reviewing Sion Power's domestic and international patents, one of the most impressive ones is EP11164912.5 which clearly stated *"the cell is constructed and arranged to apply, during at least one period of time during the charge and/or discharge of the cell, an anisotropic force with a component normal to the active surface of the anode defining a pressure between about 68.6 Newtons per square cm and about 147 Newtons per square cm (50 psi to 145 psi)."* A similar range is found in my own research group's research for single-layer cells (50 psi) to 12-layer cells (145 psi) — the robustness of the pressure range claim is confirmed.

Comments on Electrolyte Strategy

The key enabling factor for lithium metal batteries is the electrolytes, liquid, solid, or a combination of both. Sion Power has about 68 patents and patent applications that focus on optimized electrolyte solvents and additives to protect the electrodes for extended cycle life.

There are several key criteria met in electrolyte development, including

1. Dense Li deposition ▸ Low self-discharge and shelf life
2. High Li metal cycling coulombic efficiency ▸ High energy and long cycle

Figure 3. Lithium metal foil was provided by Sion Power before and after one-week immersion in LHCE electrolytes.

3. High conductivity for high power ▸ Fast charging
4. Low flammability ▸ Safety
5. Chemical stability and thermal stability ▸ Low self-discharge and safety
6. Efficient manufacturing process ▸ Low cost
7. Passivating anode (SEI) and cathode (CEI) ▸ Cycle life
8. Wider electrochemical window ▸ High voltage operation

Electrolyte is one of the most critical differentiators in the life and safety of lithium metal batteries. We can see how Sion Power's lithium metal anode stays stable in the new generation of localized high-concentration electrolytes (LHCE) based on LiTFSI/LiFSI salts before and after immersion in the electrolytes (Figure 3). It is recommended that Sion Power should study the coulombic efficiency (CE) of its cells using these advanced electrolytes, though the observed cycle life demonstrated so far is impressive.

Comments on Cathode Strategy

Sion Power uses NMC811 cathode material with a loading of 1.8 mAh/cm^2. (Note that the Battery500 consortium requires cathode loading to reach 4 mAh/cm^2 to reach claimed energy density of 350 Wh/kg in 2 Ah cells). The company will need to carefully design its cathode loading and electrolyte amount to meet its energy and cycle life targets simultaneously.

I was very impressed that the Sion Power large-format 6 Ah cells evaluated by Energy Assurance (EA-4203 file) achieved over 360 Wh/kg, demonstrating that cathode loading

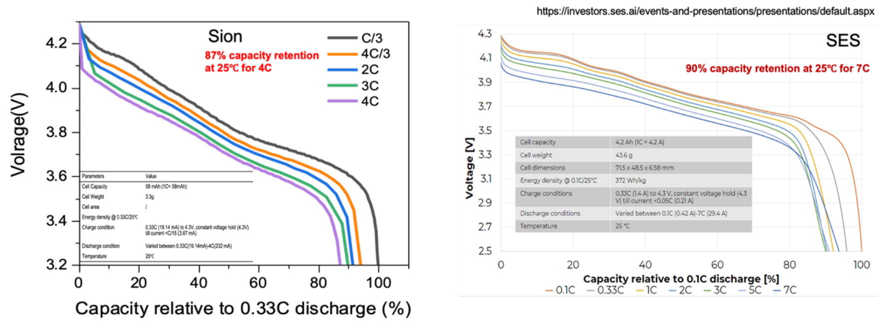

Figure 4. Sion Power data is obtained in a small format cell by my research groupthrough contracted work.

and electrolyte amount was well controlled. The tests were completed in January 2021. On page six of EA-4203, all three cells show excellent cycling performance with more than 86% capacity retention up to 600 cycles. Energy density under various rates seems reasonable – it is understandable that the lithium metal battery (LMB) needs "slow charging" (C/3) and can sustain high power discharge (4C/3), and the cell can sustain very high-power discharge up to 7000 W/kg at 50% state-of-charge (SOC). The 55 °C storage test data were presented by the same report on page 13 of EA4203. The stability of the cell at 80% SOC was impressive, even though those data were obtained from the fresh (new) cells. Considering Energy Assurance, a third-party independent validation, the results are indeed quite excellent. I want to caution the readers of the report that a similar set of data must be done with aged or cycled cells to complete the evaluation of the stability of Sion Power's technology.

So far, we did not verify the company's power performance beyond 4C capability using the small format cell. Sion Power's large-format 6 Ah cell power capability is comparable to SES's publicly available data. In the future, we will also test the 6 Ah cells to verify this observation.

Comments on Separator and Other Inactive Components

The separator is of critical importance for cell performance and safety. This ultra-thin and porous layer is moistened with a liquid electrolyte to allow optimum ionic conductivity while preventing electronic short circuits. Separator coating with ceramics, such as Al2O3, was invented and patented by Celgard, which improved the safety of lithium-ion batteries in the past decades. According to Sion Power's patent portfolio, 27 patents and patent applications were obtained (Note: I did not analyze the portfolio). The important players in the field of separators include QuantumScape (QS) and PolyPlus. QS is utilizing Lithium Lanthanum Zirconia Oxide (LLZO) based ceramics where the cost of the LLZO remains a major issue. PolyPlus is developing lithium metal anodes bonded to an ultra-thin continuous glass sheet. PolyPlus claims the unique glass separator is inherently scalable as it is glassy, and it contains no heavy elements like lanthanum (La) and zirconium (Zr). Another approach being explored is a type of polymer-based coating on lithium metal anode (a company called Bolloré), though the room temperature performance of the polymer films has not been satisfactory up to today. At elevated temperatures, Li metal anodes with polymer membrane have shown some success with Bolloré Bluecar (operating at 70 °C). Over the next phase of the research and development (R & D), more quantitative assessment is needed to understand the effects of these layers and, more importantly, down-select the chemistries and methods for the final manufacturing plan. The cost of these layers is as important as the

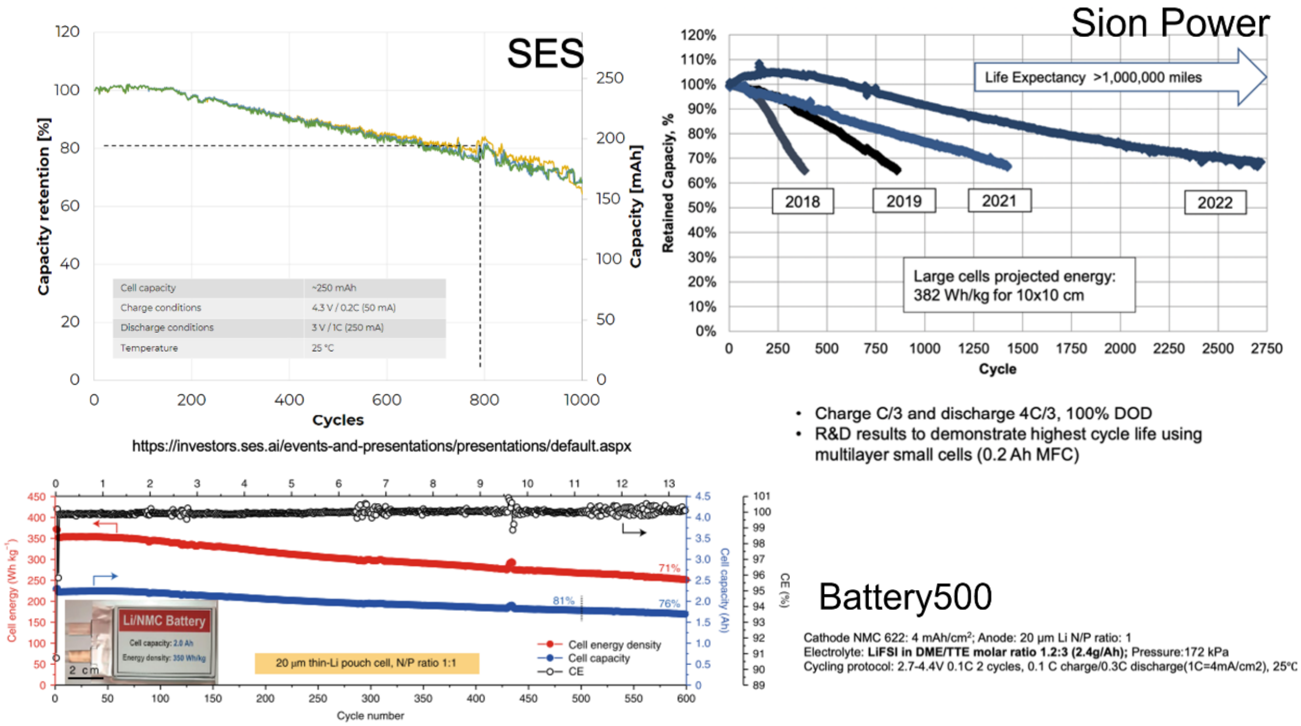

Figure 5. Comparison of the multi-layer pouch cells among SES, Sion Power, and Battery500. SES has the most aggress (fast) charging/discharge rate.

performance improvement — as the industry knows, only if the marginal cost is less than the marginal benefit can one then lower the $/kWh for LMB.

Comments on Multi-layer Pouch Cell

Compared to the data released by Battery500 in 2021 and SES's public data (see Figure 5), Sion Power is in a very good position. It is very encouraging to see such consistent data from both companies. It means the industry is converging on a set of optimized parameters for LMB technology. There are some important distinctions between these data — Battery500 consortium is a publicly funded consortium, and we are not for commercial purposes; therefore, the data reporting is completely transparent and standard.

Figure 6 shows the power rate capability between Sion Power and SES — SES excelled in terms of aggressive rate tests, though I predict that Sion Power will do well in a similar manner. Cathode chemistry does play an important role in the power capability of pouch cells since Sion Power and SES use different cathodes. The low-temperature performance of Sion Power does need improvement based on the current data set.

Comments on Safety

Sion Power's initial safety testing on 6 Ah large format cells is good on the fresh and lightly cycled cells evaluated by the third-party laboratory. Sion Power's safety at this level is impressive compared to competitors in that safety has been demonstrated on large format cells.

The data shown in the Energy Assurance report (EA4203 file) is good but not sufficient in that safety should also be verified on degraded cells. All the safety data so far are obtained from fresh or lightly cycled cells. One of the most important testing criteria for safety is that the history of the cell operation must be fully transparent. It is logical that fresh cells, even at a very high state of charge,

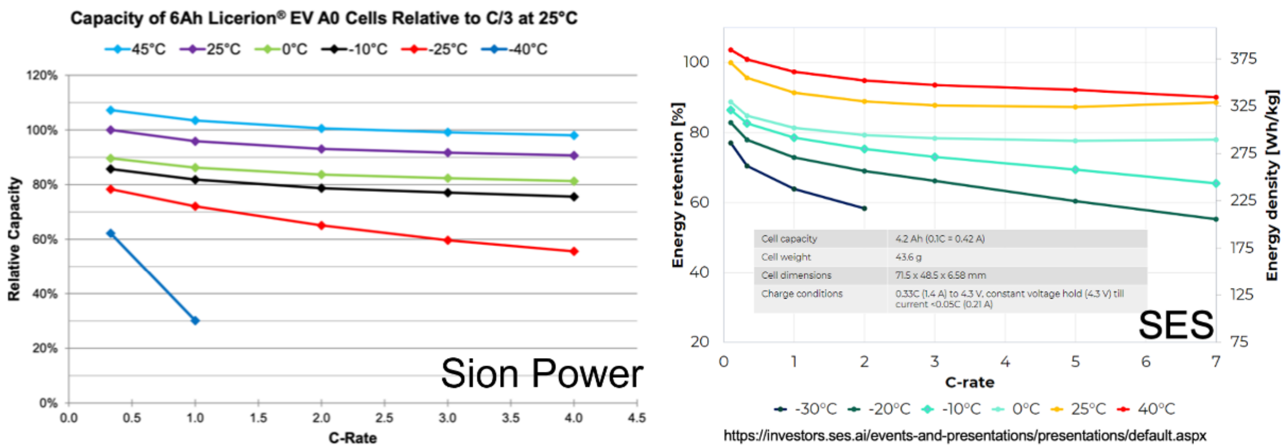

Figure 6. Comparison of pouch cell rate performance in Sion Power and SES pouch cells. (Note: both data sets were obtained by Y. S. Meng.)

can still pass all the safety tests, including overcharge, nail penetration, thermal, and mechanical abuse tests. However, aged and long-cycled LMB must also pass these same abuse tests. The cycled lithium metal anode often has more porosity and is not as dense as the fresh anode; they are extremely sensitive to thermal and mechanical abuse. I understand that Sion Power is conducting these same safety tests on highly cycled cells internally and plans to submit these same batteries for third-party verification.

Safety protocol for LMB was recommended by Battery 500 consortium in 2019. Investment in hardware should be made to manage the safe dissembling of LMB after long-term cycling. My experience with Sion Power is that they are very responsible with the cell disassembly protocol, even for our 60 mAh small cells. As a result, we sent the cells back to Sion Power for dissembling. In a publication by Pacific Northwestern National Lab, the lead institute for Battery500 shown in Figure 7, there are many factors that need to be considered when evaluating the safety of LMB at the end of service life.

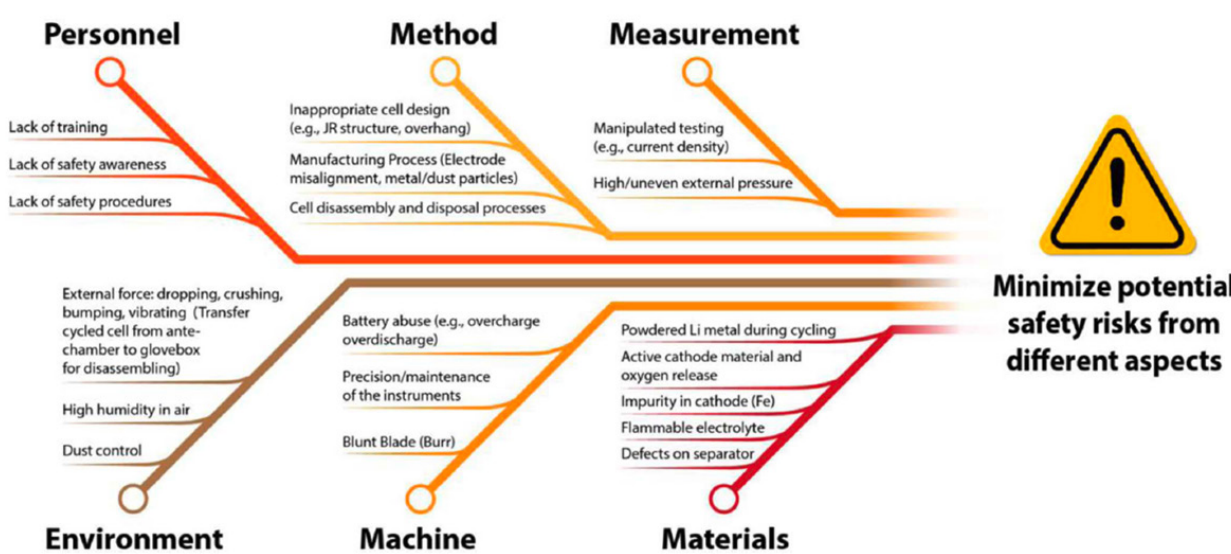

Figure 7. The fishbone diagram shows the leading causes of all six aspects of root cause analysis of the safety threats of Li metal pouch cells in the laboratory.

Other Interesting Observations

Sion Power is 100% based in the United States. It has 30 years of work in Li metal batteries, with an early focus on sulfur cathodes. In 2016 the company pivoted its focus to nickel-based NMC cathodes. Sion Power has a strong portfolio of patents on the topic of lithium metal anode production (by vacuum deposition), surface protection, and pressure control. From this aspect, Sion Power could be an important driver in helping accelerate the U.S. domestic manufacturing of lithium metal batteries. Suggestion to tighten up the patent portfolio — for example, the pressure control claim is very broad with a wide range of numbers throughout the years. This might be a potential issue for the enforcement of patent claims.

Conclusions

The LMB community has successfully enabled rechargeability imparted by novel electrolytes for Li metal anodes. While we enabled successful chemistries to use historical precedents in electrolyte design, we are still struggling to control the Li irreversible capacity in each cycle if a thin solid electrolyte interphase (SEI) is re-formed at every cycle, even on a completely dense lithium morphology. Hence, engineering approaches such as stack pressure may be necessary to reduce electrode porosity, limiting chemical exposure of Li to the electrolyte. Such compression jigs might negatively impact LMB commercialization. This is a common issue faced by the entire LMB field, and we need to work together to overcome these barriers.

In conclusion, Sion Power has demonstrated excellent progress in enabling lithium metal batteries. In my assessment, the ability to make high-quality lithium metal with dry room processibility is a major differentiator. Close attention should be given to optimizing pressure control methods and engineering strategy. Sion Power should also consider engaging in R&D efforts to study and control the safety of LMB after aging and long cycles.

I confirm that in this document I have sent, except for Sion Power related confidential information, the contents here (1) do not contain any non-public information (2) do not infringe any ownership or intellectual property rights of any third party and (3) comply fully with my obligations under the Terms of Engagement.

Author Biography

Y. Shirley Meng is a professor of molecular engineering at the Pritzker School of Molecular Engineering. She also serves as the chief scientist of the Argonne Collaborative Center for Energy Storage Science (ACCESS) Argonne National Laboratory.

Her work pioneers in discovering and designing better materials for energy storage by a unique combination of first-principles computation guided materials discovery and design, and advanced characterization with electron/neutron/photon sources. Meng is the principal investigator of the research group - Laboratory for Energy Storage and Conversion (LESC). She has received several prestigious awards, including the Faraday Medal of Royal Chemistry Society (2020), International Battery Association Battery IBA Research Award (2019), Blavatnik Awards for Young Scientists Finalist (2018), C.W. Tobias Young Investigator Award of the Electrochemical Society (2016), Science Award Electrochemistry by BASF and Volkswagen (2014) and NSF CAREER Award (2011). Meng is the elected fellow of Electrochemical Society (FECS) and elected fellow of Materials Research Society (FMRS). She serves as the editor-in-chief for

Materials Research Society MRS Energy & Sustainability Journal.

Meng received her PhD in Advanced Materials for Micro & Nano Systems from the Singapore-MIT Alliance in 2005, and her bachelor's degree with first-class honor from Nanyang Technological University, Singapore in 2000. She worked as a postdoctoral research fellow and became a research scientist at MIT from 2005-2007. Meng was the Zable Endowed Chair Professor in Energy Technologies at the University of California-San Diego (UCSD) before joining PME at the University of Chicago.

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