EBOOK

LONG-TERM PRODUCT SUCCESS BEGINS WITH UNDERSTANDING THE DATA BEHIND YOUR BATTERIES

VOLTAIQ

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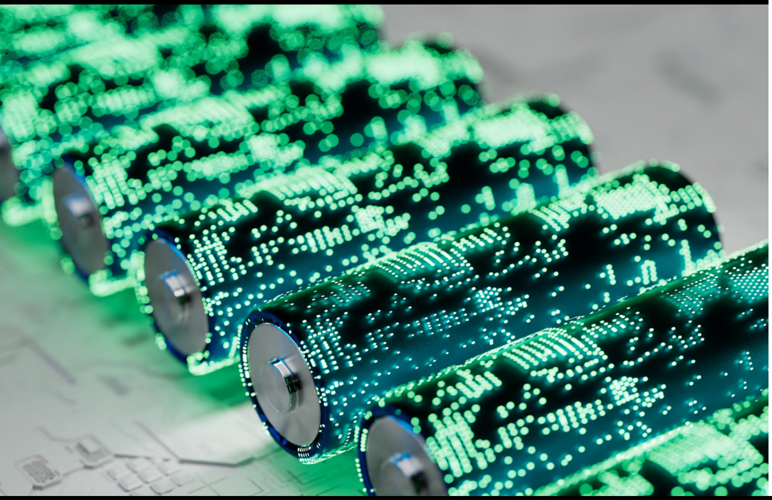
Executive Summary:

Batteries are powerful. But they are also dangerous. Mishandled batteries can lead to catastrophic safety incidents, damaging brand image, and customer trust, while unpredictable battery performance can jeopardize customer experience and business success. However, decoding batteries through data can pave the way for unique opportunities for a competitive edge and superior product creation.

In this eBook, we explore seven potent but lesser-known techniques to extract valuable insights from battery data, all accelerated by Enterprise Battery Intelligence (EBI). These strategies save time, ramp up productivity, and cut down risk by facilitating a deeper dive into the battery's world — from setting performance baselines, and identifying unique battery 'fingerprints', to predicting end-of-life with machine learning and understanding battery aging.

The importance of a robust traceability system is also emphasized, along with the game-changing role of automation in simplifying record-keeping and data analysis. Amid evolving supply chains, keeping a comprehensive benchmark of tested cells is key, offering swift qualification and development.



Why it's important to understand your batteries — consequences & competitive advantages

Batteries are spectacular. For centuries, and with increasing pace, they have transformed human life — how we communicate, how we travel, and how we live. The next few years and decades are set to bring forth battery innovations that will make life even more dynamic, comfortable, and productive.

However, like most powerful technologies, batteries can also be dangerous.

> **Batteries store energy that can be released very quickly, which is a recipe for disaster if not handled properly.**

This is why they deserve special consideration. They're not like any other part of your bill of materials; screws, gaskets, or microchips. Batteries store energy that can be released very quickly, which is a recipe for disaster if not handled properly.

As we have learned from the infamous case of the Samsung Galaxy Note 7 — where Samsung shipped phones with batteries that weren't fully understood and weren't fully characterized — these devices started exploding after getting into the hands of 2 million consumers. Even today, several years later, the brand is still associated with battery problems. If you Google Samsung Galaxy Note, auto-complete still suggests failure and battery concerns.

> **If there is a problem with your product's battery, the customer calls you and not your battery vendor, and it is your brand that is tarnished.**

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Samsung had to conduct a product recall, and aside from the cost of replacing or refunding 2 million phones, this disaster damaged their reputation, their future prospects, and the entire industry as a whole. What's interesting from this case study is that Samsung's investigation found that the blame lay with their battery vendor's manufacturing process — but despite this, the recall is still remembered as the exploding Samsung Galaxy Note 7, not the exploding batteries from their supplier ATL. The key takeaway is that if there is a problem with your product's battery, the customer calls you and not your battery vendor, and it is your brand that is tarnished. It's very important to fully understand and characterize the battery that goes into your application.

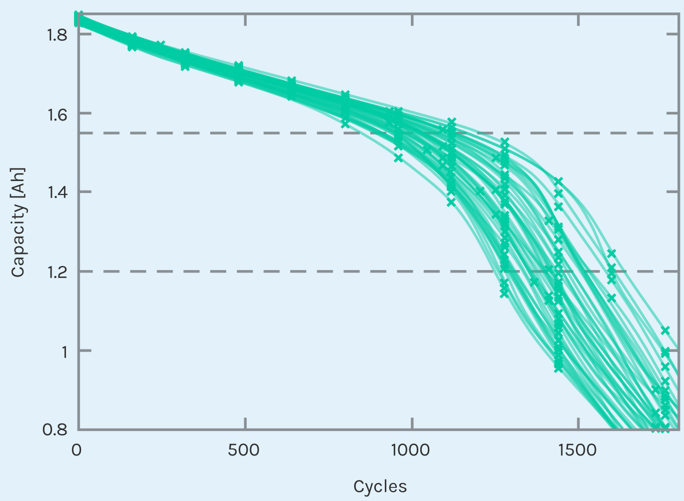
Even if batteries don't catch on fire and explode, there are still many reasons to care about your battery. Figure 1 shows that out of 48 nominally identical Panasonic battery cells, all operated identically, there is still tremendous variation as to how many cycles an individual cell will last. The worst cells reach end-of-life after 750 cycles while the best ones last up to 1300 cycles. These large variations in battery performance directly impact how much capital you have tied up in warranty reserves. There are other costs associated with this variability as well. You have to engineer your application to accommodate the worst-performing cell, which leads to overbuilding & increased cost. Operators and technicians have to spend time troubleshooting and dealing with these defects lowering your overall productivity and throughput, and customers have to deal with products that have an inconsistent lifetime.

> **Even if a battery doesn't explode, additional battery issues still affect customer experience, and ultimately the bottom line.**

Another example of battery behavior that can significantly impact your end product is battery swelling. A battery starts swelling because of a gas buildup inside the battery. It doesn't catch on fire, but the risk is always there in the back of your mind that this probably isn't right, and it's probably not the way the product was designed. Your phone's case starts to bulge a bit, or maybe your laptop's mousepad won't click the same way it did when it was new. The key message is that even if a battery doesn't explode, additional battery issues still affect customer experience, and ultimately the bottom line.

Figure 1. Different aging trends from 48 equal cells under same aging conditions profiles.

Source: T. Baumhöfer et al., Journal of Power Sources 247 (2014) 332-338



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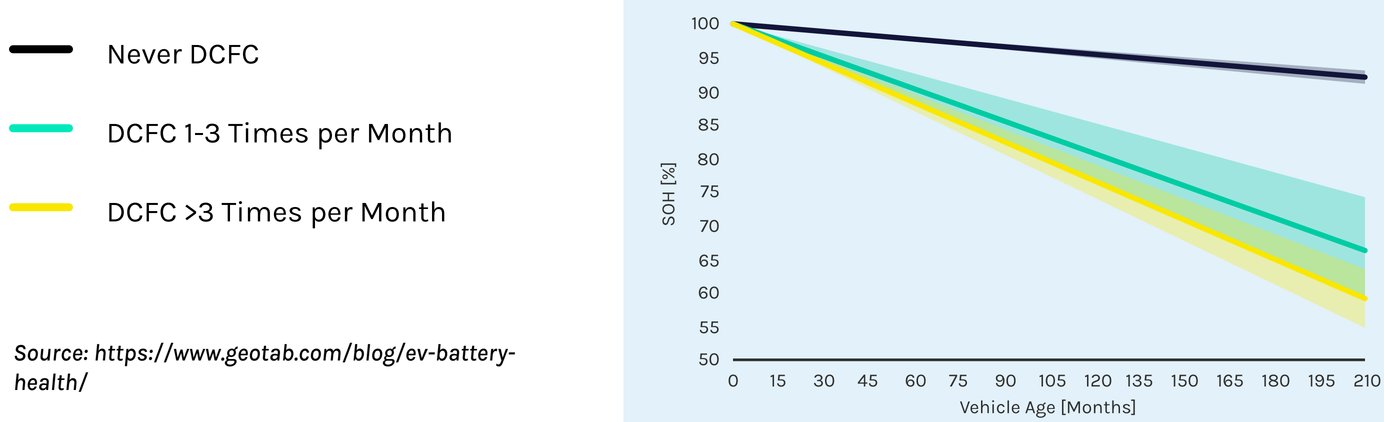
Now that we've touched on how batteries can go wrong, let's discuss some of the potential benefits. Because of the complexity of batteries, there is also an opportunity for your organization to develop a competitive advantage. The most obvious example is battery lifetime. Figure 2 shows a typical EV battery lifetime. The black line shows that the battery behaves with a good lifetime under normal conditions, but the green line shows that if you fast charge this EV battery, it significantly degrades the battery's lifetime. Battery vendors, of course, will give you only the data about the black line and it's up to you to find out about the green line.

An excellent case study of this behavior comes from Nissan and Tesla in the mid-2010s. Tesla developed a significant competitive advantage by becoming essentially the first EV with a reliable and cost-effective battery, which they leveraged to capture significant market share. During this time period, one of their primary competitors was the Nissan Leaf, which unfortunately suffered from really poor press as a result of its battery issues. The Nissan Leaf sold well in the southwest United States, however in that climate where summer temperatures can exceed 120 degrees Fahrenheit (50 degrees Celsius), the Leaf frequently exhibited tremendous battery degradation in the first few years due to insufficient cooling systems. (The Nissan Leaf battery was air-cooled, while Tesla and most other contemporary EVs use active liquid cooling systems.) The Leaf has an advertised range of 84 miles, but Leafs were showing up in CarMax lots with ranges of only 10 miles. Why did this happen to Nissan but not Tesla? The answer is that there was a lack of test data about the effect of temperature on the battery's lifetime. This is an example that knowing more about your battery translates into significant advantages in the marketplace.

You wouldn't rent an apartment based solely on how many bedrooms it has. Likewise with a battery, a single plot of capacity versus number of cycles is insufficient to determine if a battery is right for your application.

Figure 2. Impact of DC fast-charging (DCFC) use on battery state of health (SOH)



Source: https://www.geotab.com/blog/ev-battery-health/

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Hopefully, at this point, you fully understand why it's important to understand your battery. But what information do you actually need? The majority of battery vendors will send you a battery lifetime plot and some basic specs. You should ask whether that's all you really need in order to make an intelligent decision. You wouldn't rent an apartment based solely on how many bedrooms it has. You obviously need more information such as where the apartment is located, what amenities it has, and if it's a good fit for your life. Likewise, with a battery, a single plot of capacity versus a number of cycles is insufficient to determine if a battery is right for your application. If your application uses a lot of power, you need to know how this plot changes with increasing power demand. If your application requires a long shelf storage time before use, you need to know how this plot changes if the battery is not operated for long periods.

> **Batteries are like organisms in that no two batteries are exactly the same. This is very problematic for mass production because it's very hard to tell when those small variations will suddenly matter a lot.**

Essentially, you need additional information to make an informed decision. But where do you start? Batteries are extremely complex electrochemical devices that have many underlying reactions evolving constantly. It's hard to know what data to collect, how to interpret this data, and to know what to look for. The question always comes down to, "How do you tell if a battery is good or not?" Unfortunately, there really is no simple equation. Batteries are like organisms in that no two batteries are exactly the same. This is very problematic for mass production because it's very hard to tell when those small variations will suddenly matter a lot.

Going back to the Samsung Galaxy Note 7 case study, the battery fires were caused by a corner of the pouch enclosure being pinched, which caused the internal separator to not insulate correctly. The question then becomes, how can we tell which batteries have pinched corners and which don't? Especially if we're unable to look inside the battery. What we need to do is to capture the signature of what a battery with pinched corners looks like. Luckily, these physical issues like pinched corners have an impact on battery metrics such as capacity, resistance, and cycle life. This simplifies things so that it's not necessary for most people to deeply understand the underlying electrochemistry. The solution is to use data to catch these problems.

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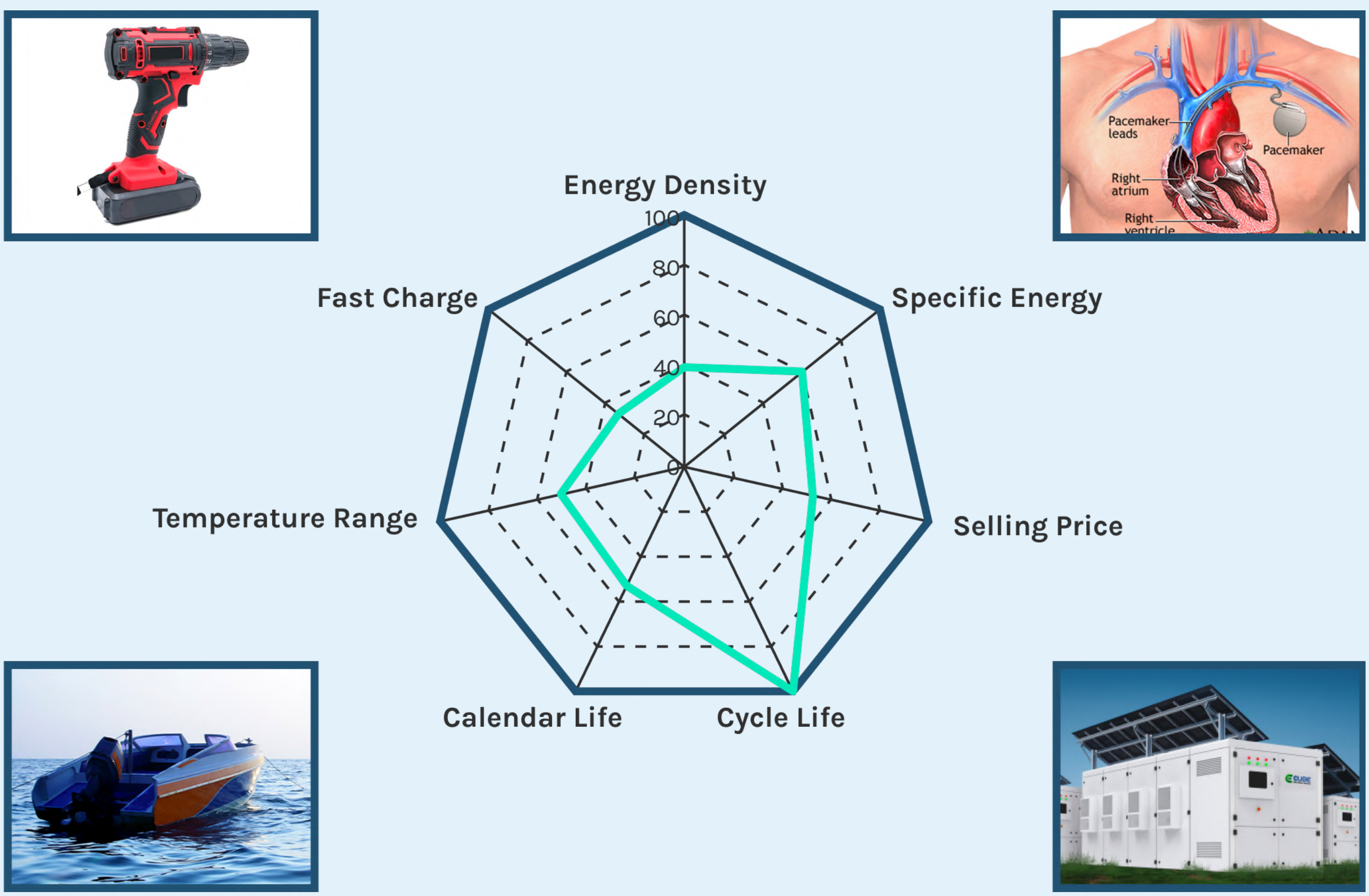
We've established why it's important to understand batteries, and how metrics are the key to developing that understanding. The most common battery metrics are displayed on the spider chart below. You have attributes such as energy density, specific energy, cycle life temperature, etc. The next challenge is that different applications care about different battery metrics. A battery that's optimized to be great for one application would be terrible for another. For example, power tools prioritize a battery's ability to charge and discharge quickly, and the battery must be lightweight.

This is the exact opposite of the requirements for a battery paired with a solar photovoltaic system, to enable continuous power when the sun isn't shining.

This application needs a battery that has a long cycle life and is inexpensive. The battery's weight doesn't matter in this case.

Similarly, what you want in a pacemaker is the exact opposite of what you'd want in a speedboat. You need to identify which key metrics are relevant to your application so you can determine what target you're aiming for. The next step is to analyze the data and generate insight into how to turn this knowledge into a competitive advantage.

Figure 3. Spider chart comparing battery attributes for different applications



Non-obvious techniques for extracting useful information from your battery data

Note: This section assumes your organization has access to battery data for product development, either generated internally or through a third-party test lab or benchmarking database such as The Battery Index.

We're going to review seven non-obvious techniques for extracting useful information from your battery data. These techniques are supported by a new software sector known as Enterprise Battery Intelligence (EBI). EBI is useful for simplifying your workflows by automating tedious analysis to provide the insight to answer tough battery questions, saving your organization time and money by reducing defects and allowing you to get products to market faster. Most organizations store their battery data in multiple locations, transferring data via a USB drive, and conducting slow analysis that's both cumbersome and manual with all plotting taking place in spreadsheet software.

This legacy approach to analyzing batteries is reactive and stage gated — not ideal.

You want a solution that aggregates your battery data sources, manufacturing line, test labs, and in-field data sources to enable you to get your data faster, understand it sooner, and make intelligent decisions to get your products to market quicker.

We're going to begin reviewing seven categories of techniques, each corresponding to a different business challenge. We're going to review techniques that increase your productivity, mitigate risk, and save you time.

This legacy approach to analyzing batteries is reactive and stage gated — not ideal. You want a solution that aggregates your battery data sources, manufacturing line, test labs, and in-field data sources to enable you to get your data faster, understand it sooner, and make intelligent decisions to get your products to market quicker.

Introduction to Enterprise Battery Intelligence

As electrification gains momentum globally, companies across sectors are finding that their business depends in some critical way on batteries. In this highly competitive and rapidly evolving market, Enterprise Battery Intelligence (EBI) is a key enabler to product and commercial success. EBI empowers an organization to marshal data from throughout your organization and across the product lifecycle to optimize the impact of batteries on every part of your business, including:

- **Bring products to market faster**
- **Ensure high-quality battery supply**
- **Accelerate manufacturing ramp-up**
- **Minimize battery product risk**
- **Optimize systems in the field**
- **Maximize financial performance**

An EBI solution works by automatically collecting battery data (materials, manufacturing, performance), from across the test lab, manufacturing line, and systems in the field into a single, unified system, surfacing correlations and insights that drive key business outcomes. As a centralized, single source of truth and insight for batteries, EBI streamlines collaboration across remote teams and external partners, helping to accelerate toward success for every battery-powered business.

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1. Plot your statistics to establish a baseline

The first technique is to plot your statistics. This gives you an immediate and objective baseline of your current status. Figure 4 shows a sample of 20 cells, displaying each cell's discharge capacity as the cell is cycled several hundred times. This type of plot is a standard way of evaluating a battery's "cycle life", or how long it will last when charged and discharged repeatedly.

The actual data traces on this plot show the mean performance and two standard deviations for this population of cells. If your application has upper and lower spec limits, you can also add these and compute a statistical process control chart commonly known as an SPC chart. You can also calculate a CPK known as a process capability. Once you have a statistical baseline, you can use it as a reference for comparison.

For example, you can compare cell-to-cell performance to quantify how much variation you can or should expect, and thus compute incoming quality control parameters such as rejection rates.

You can also compute batch-to-batch variation by comparing samples of cells that determine if a new batch that's coming in is still meeting the specs you originally qualified. Batch-to-batch comparison can also indicate when a supplier has made some sort of change to their cell recipe or manufacturing process, hoping you wouldn't notice — a practice that is, unfortunately, more common than you might think.

> **This statistical view enables you to proactively detect and respond to trends, instead of suddenly getting an unexpected red flag and having to respond to it.**

Figure 4. Cycle life of 20 identical battery cells

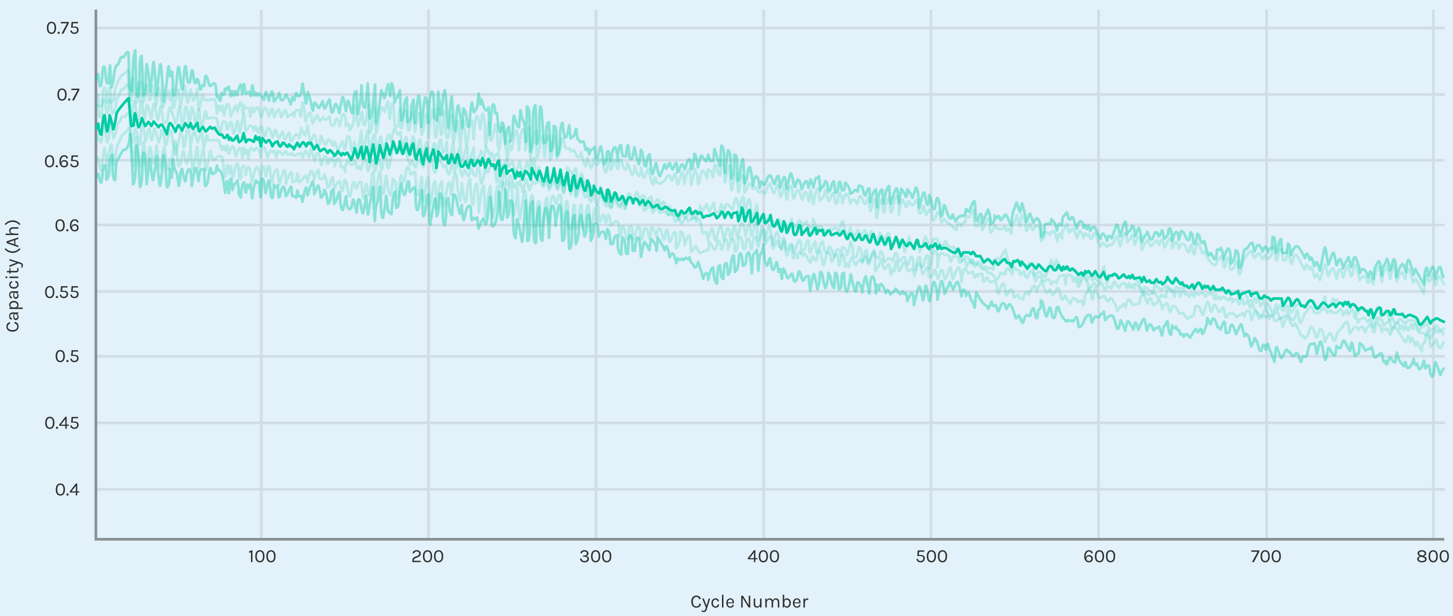
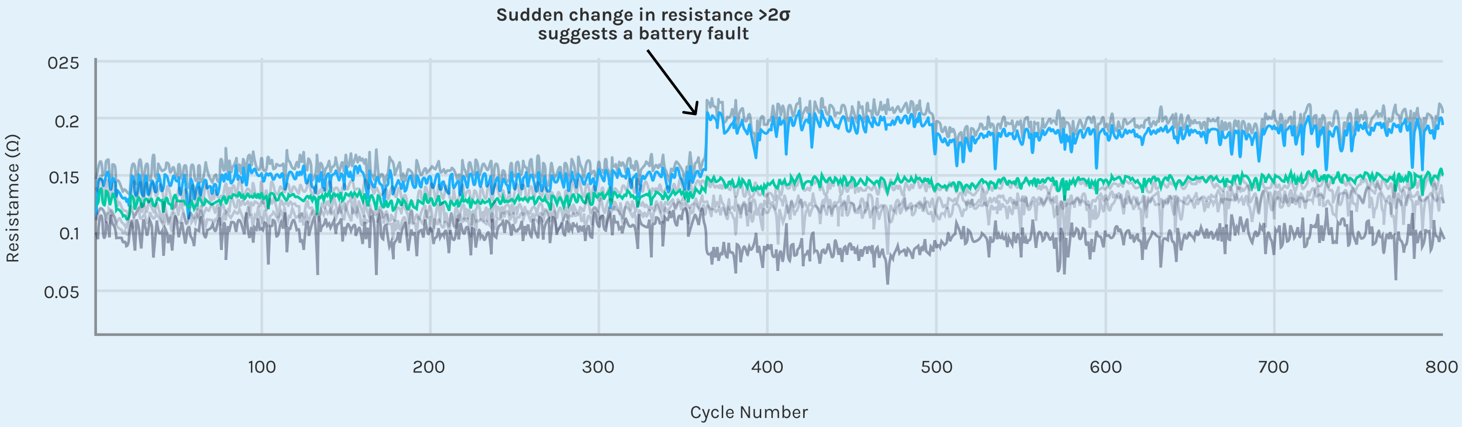


Figure 5. DC resistance of 20 identical cells under long-term cycling



Finally, you can compare system-to-system performance to understand what types of issues and lifetimes your end users will experience. Why is it important to do the cell-to-cell, batch-to-batch comparisons? It lets your manufacturing be more proactive instead of reactive. Just because something is currently within spec limits doesn't mean it's not increasing or decreasing and about to be out of control shortly. This statistical view enables you to proactively detect and respond to trends, instead of suddenly getting an unexpected red flag and having to respond to it.

Here's a non-trivial example. We took another set of 20 cells and plotted their internal resistance, the mean, and two standard deviations. You'll notice in the middle, about 350 cycles in, you can see that there is a large step increase in internal resistance in one of the cells highlighted in blue.

You can see that this change in internal resistance is much higher than two standard deviations of the rest of the sample. This gives you a compelling reason to investigate this cell without plotting the statistics. There is no objective way to determine if this cell is good or bad, and you're basically at the mercy of your test technician who has to squint at the graph and say, "Eh, does this feel right? Does it feel wrong?" The key point of this technique is to develop a baseline for objective comparison.

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2. Take a battery's fingerprint with differential capacity analysis

The second technique to increase your productivity is something called differential capacity analysis, a battery fingerprinting technique. Since you likely have significantly more battery data than you can realistically analyze, this method will condense all of that battery data into a format that is easy to visualize and digest. Once you identify the fingerprint or signature of what a bad battery looks like, you can look at a differential capacity plot & determine if any given battery matches your profile of a bad battery. Think of it as being able to pick out a troublemaker from a police lineup, and it's not just limited to bad or defective cells.

You can also understand if a vendor changes material or if they're suddenly sending you something different, or they're using a different ingredient or less of it, or if they do something else that changes how the battery performs. Differential capacity analysis gives you proof, and you have the before and after. Any production change will be visible using this technique.

Another major advantage to battery fingerprinting is that it can be done with a single charge-discharge cycle instead of having to test 500 or 1,000 cycles, which is standard. Even better, battery vendors often conduct a single charge & discharge cycle on cells as part of their manufacturing process on cells before they ship them to you, so this analysis can be conducted on that single cycle sent to you by your battery supplier, eliminating the need to do testing on your end.

Once you identify the fingerprint or signature of what a bad battery looks like, you can look at a differential capacity plot and determine if any given battery matches your profile of a bad battery. Think of it as being able to pick out a troublemaker from a police lineup, and it's not just limited to bad or defective cells.

Figure 6 shows the differential capacity "battery fingerprints" for a set of nominally identical cells. Each loop shows a full charge-discharge cycle for an individual cell, with the top half of the loop showing charge, and the bottom half showing discharge. The loops run counter-clockwise. In this plot, you'll notice that the blue curve looks very different from the rest of them.

This anomaly clearly warrants some level of investigation. In Figure 7 (next page), the internal resistance for each cell over several hundred cycles is plotted in gray, and our anomalous cell is now highlighted in green. This is a low-resistance cell that could be problematic if used in an application.

Figure 6. First-cycle differential capacity plots of several identical lithium-ion cells

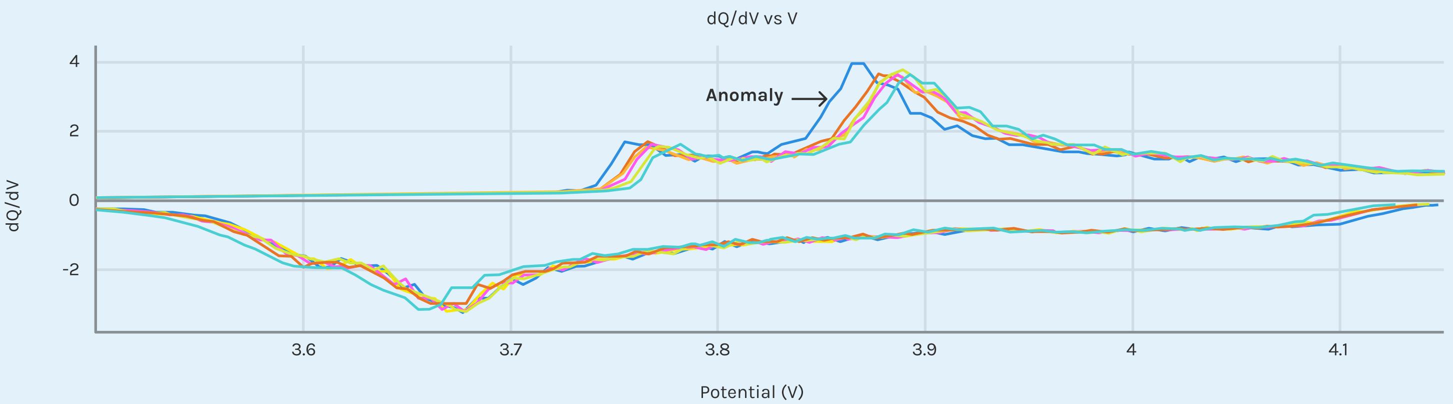

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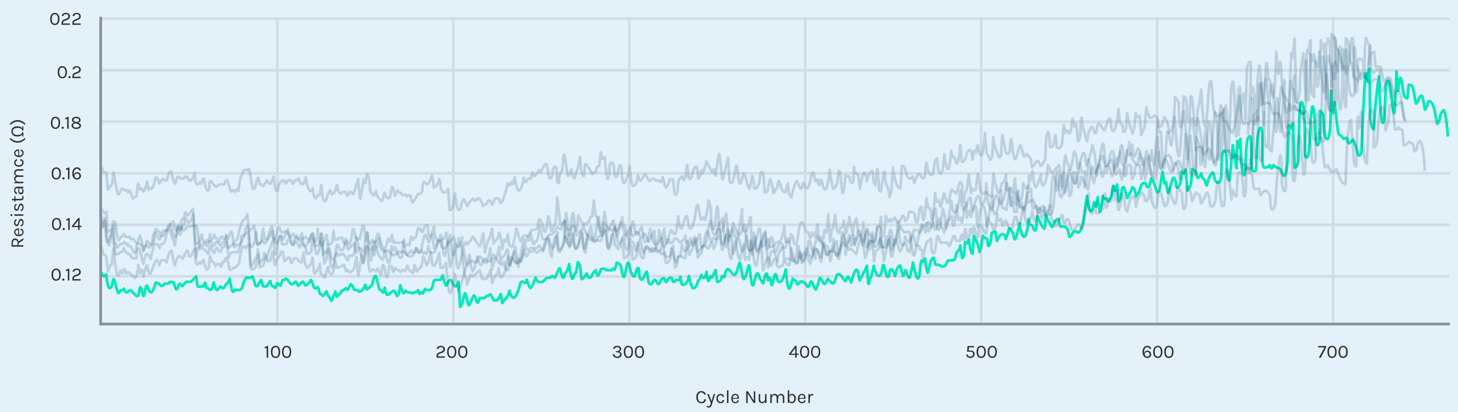
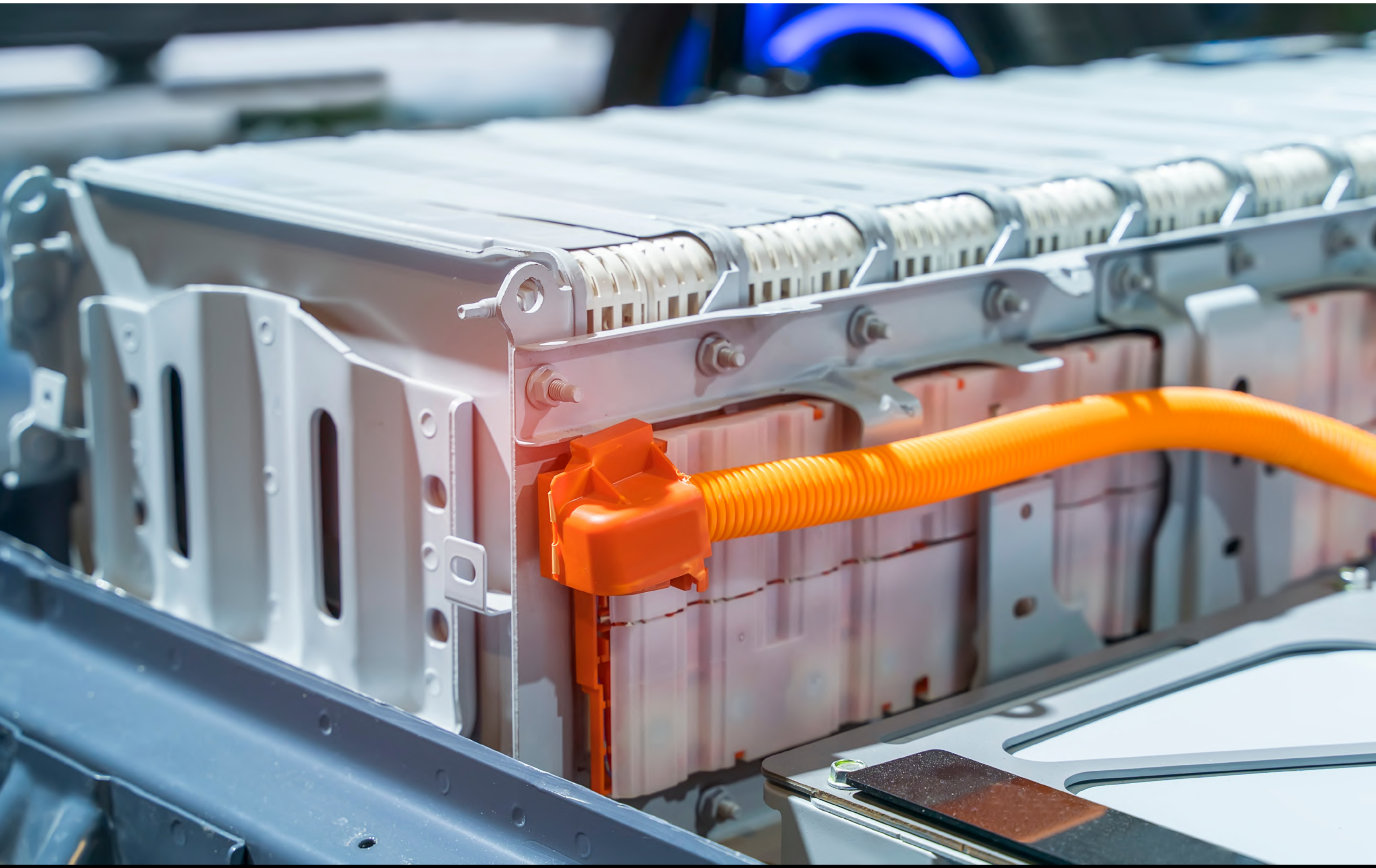
Figure 7. DC resistance of identical lithium-ion cells under long-term cycling



This technique has now shown us the fingerprint of what a low-resistance cell looks like for future analysis. The differential capacity analysis used one cycle of data, and the data analysis takes about one minute using an EBI platform. On the other hand, the green line above took 700 cycles to reveal a trend, requiring several months of testing.

This analysis is powerful because instead of reacting to a factory problem six months from now, you know today that there is an issue and you can do something about it. You can use this technique to build a library of what defects look like, and it can help you identify them while using minimal resources.



3. Metadata-to-Performance — the “Magic 8 Ball” that tells you how this affects that

The third and last technique for improving your productivity is incredibly powerful for answering tough questions. It’s called Metadata-to-Performance and it’s an analysis that can determine the effect of changing any sort of recipe, process, or operational variable. In really simple terms, it answers the question of how changing this affects that. The strength of this technique is its versatility. Some important questions you can answer include:

- How does temperature affect rate capability?
- How do cells that have been sitting around for a year affect the system’s lifetime?
- How does the vibration of my factory affect the integrity of the cell?
- What happens if we sprinkle a few low-capacity cells in each pack?
- How does changing to a new vendor affect the cycle life promises that we made for our end product?

When you take a step back and consider how many times you ask your battery engineers and technicians these kinds of how does this affect that questions, you begin to realize how powerful this technique is.

When you take a step back and consider how many times you ask your battery engineers and technicians these kinds of “how does this affect that” questions, you begin to realize how powerful this technique is. This happens all the time in the industry because there are always subtle changes taking place, from materials to suppliers to the current state of the supply chain. Everyone knows there is a lithium shortage, and it’s only getting worse. Lithium mines are not coming online as fast as they need to in order to meet market demand. Thus substitutions and manufacturing changes are going to be a rule and not an exception in the future.

Figure 8. Metadata-to-Performance example showing the capacity distribution of different cathode compositions

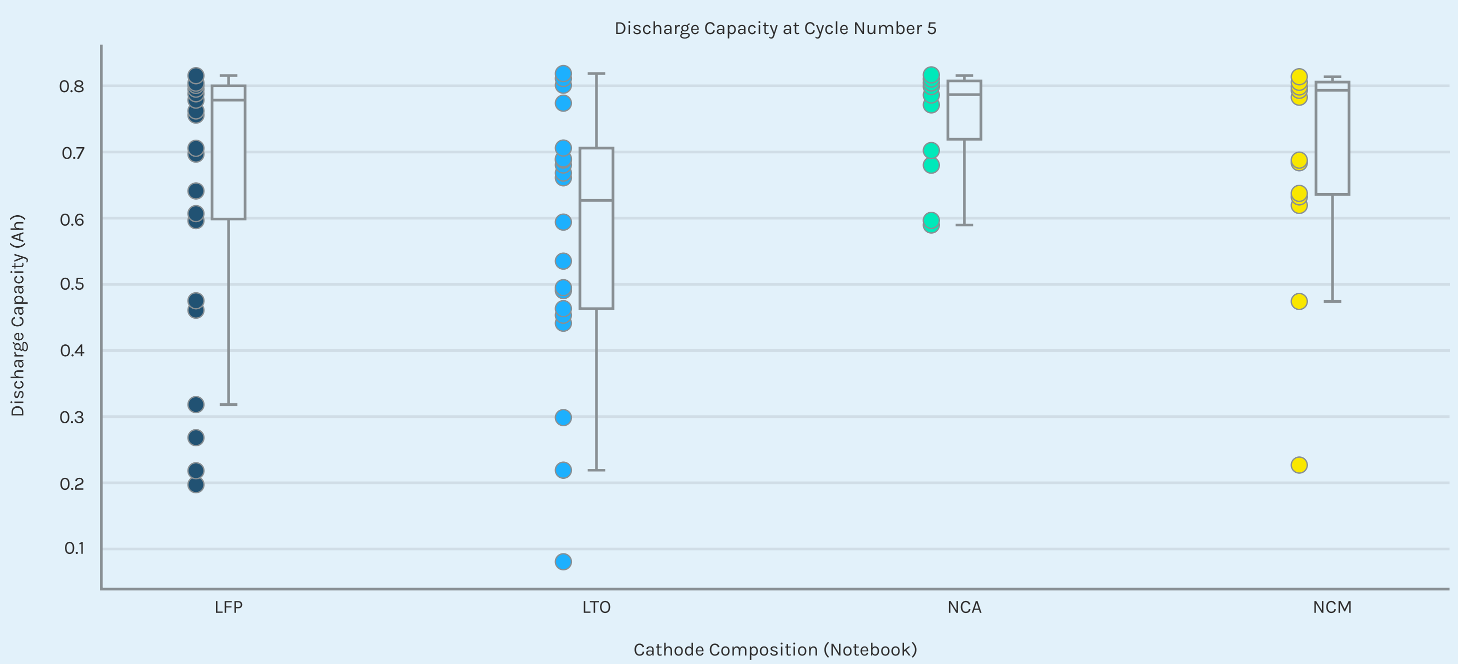


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Figure 8 displays performance for a few different aftermarket iPhone batteries, showing the discharge capacity (i.e. product runtime) early in the battery's life. You can see four different chemistry types that we'll compare, LFP, LTO, NCA, and NCM. From this box plot, you can see that some chemistries are more consistent or they have longer runtimes than others. If we had to make a decision on which one we wanted to go with, this kind of analysis makes it really straightforward. The only prerequisite with this type of analysis is it requires well-labeled and well-organized data. Obviously, it's not possible for us to do this analysis if we don't know which data belongs to which chemistry. That's why it's crucially important to enable this type of powerful analysis by supporting it with well-cleaned and well-organized data.

At the start of this chapter, we provided a bunch of examples of how organizations use this type of analysis to answer tough battery questions. We encourage you to think about what kind of design and manufacturing problems are specific to your company that could be answered with this type of analysis. You'll be surprised by where the data will take you. You can try any combination of factors to see what the result is. The alternative is to send your engineers on a wild goose chase, searching for linkages between seemingly unrelated variables and how they affect battery performance.

The next set of techniques allows you to mitigate risk and minimize the chances of a recall or similar safety event. Returning again to the Samsung Galaxy Note 7 case study, let's look at how Samsung describes its approach to evaluating battery safety.

Samsung's 8-Point Battery Safety Check Test

Durability Test
It starts with enhanced battery testing, including overcharging tests, nail puncture tests and extreme temperature stress tests.

Visual Inspection
We visually inspect each battery under the guidelines of standardized and objective criteria.

X-Ray
We use X-ray to see the inside of the battery for any abnormalities.

Charge and Discharge Test
The batteries undergo a large-scale charging and discharging test.

TVOC Test
(Total Volatile Organic Compound) We test to make sure there isn't the slightest possibility of leakage of the volatile organic compound.

Disassembling Test
We disassemble the battery to assess its quality, including the battery tab welding and insulation tape conditions.

Accelerated Usage Test
We do an intensive test simulating accelerated consumer usage scenarios.

OCV Test
(Delta Open Circuit Voltage) We check for any change in voltage throughout the manufacturing process from component level to assembled device.

Figure 9. This battery safety protocol appears in Samsung's official materials. Their response to the Galaxy Note 7 incident was to publish this eight-point plan for how they're going to improve and prevent a catastrophe of this magnitude moving forward.

Source: https://www.samsung.com/us/explore/committed-to-quality/

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These standard protocols have been adopted as industry-accepted best practices. Of these protocols, the Charge-Discharge Test, Accelerated Usage Test, and Delta Open Circuit Voltage Test are the most critical, as they will catch the majority of defects that would otherwise reach your end user. These three end-of-line tests will all provide very useful information that can be used to populate control charts and critical-to-quality reports like those shown in Figure 10 below.

Charge-discharge tests are great because they provide several key metrics such as capacity and rate performance. Accelerated use tests provide cycle life and temperature performance. Delta OCV tests tell you about storage shelf life and self-discharge. Having these metrics for each system allows you to get a historical trend that you can analyze, which is important for any continuous improvement program.

Otherwise, how would you know if something is getting better or getting worse? You need that end-of-line data. Every organization should definitely implement these end-of-line tests to catch most defects before they get to their customers.

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Figure 10. A sample battery quality report

15	Sealing	Pull strength tester	Top sealing pull strength (N)	20		53.419	5.35	2.082	Pass
15	Sealing	Micrometer	Top sealing thickness (mm)	.15	0.2	0.18	0.002	3.478	Pass
15	Sealing	Pull strength tester	Side sealing pull strength (N)	15		52.823	2.766	4.559	Pass
15	Sealing	Micrometer	Side sealing thickness (mm)	0.1	0.2	0.18	0.001	7.966	Pass
15	Sealing	Micrometer	Ni tab are sealing thickness (mm)	0.4	0.5	0.407	0.002	1.398	Pass
15	Sealing	Pull strength tester	Ni sealant vs packing foil sealing strength (N)	3.3		14.035	2.405	1.488	Pass
15	Sealing	Micrometer	Al tab area sealing thickness (mm)	0.1	0.5	0.409	0.001	24.503	Pass
15	Sealing	Pull strength tester	Al sealant vs packing foil Sealing strength (N)	3.5		12.701	2.312	1.327	Fail
16	Vacuum baking	Karl-Fischer analyser	Water content		200	85.46	11.227	3.401	Pass
17	Electrolyte injection	Electronic balance	Injection weight (g)	1	1.2	1.125	0.007	3.536	Pass
18	Capacity	Capacity Tester	Capacity (mAh)	1000		999.73	8.084	-0.011	Fail
19	Degassing	Balance	Electrolyte removal by degassing (g)		0.4	0.282	0.019	2.075	Pass

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4. Automate defect detection — avoid the risks of manual QA/QC

The next technique is to mitigate risk by automating your defect detection. Human QA/QC is a very manual process that is highly prone to errors. Artificial intelligence and machine learning can identify defects and defect patterns automatically, which is really important when you consider the danger of batteries. If your human quality employee is really good, she or he might catch 99% of all defects, which would be great in any other industry.

But, with batteries, that 1% can mess up your entire production. As a thought experiment, consider an electric vehicle battery pack comprised of hundreds or thousands of cells. A 1% defect rate would mean that several bad cells are likely to make it into every pack. Some of these bad cells have the potential to explode at some point in the vehicle's service life, with the further possibility of igniting adjacent cells and leading to a "thermal runaway propagation event" (in other words, a very large fire). Clearly, you should not rely on human inspection alone for ensuring cell quality.

Figure 11 shows a very simple example of machine learning based on outlier detection for battery performance over several hundred cycles. The black line represents battery performance data points determined by the algorithm to be "normal", while the green data points have been identified as anomalous or defective. What we're doing is comparing neighboring data points and calculating if they're outliers or not.

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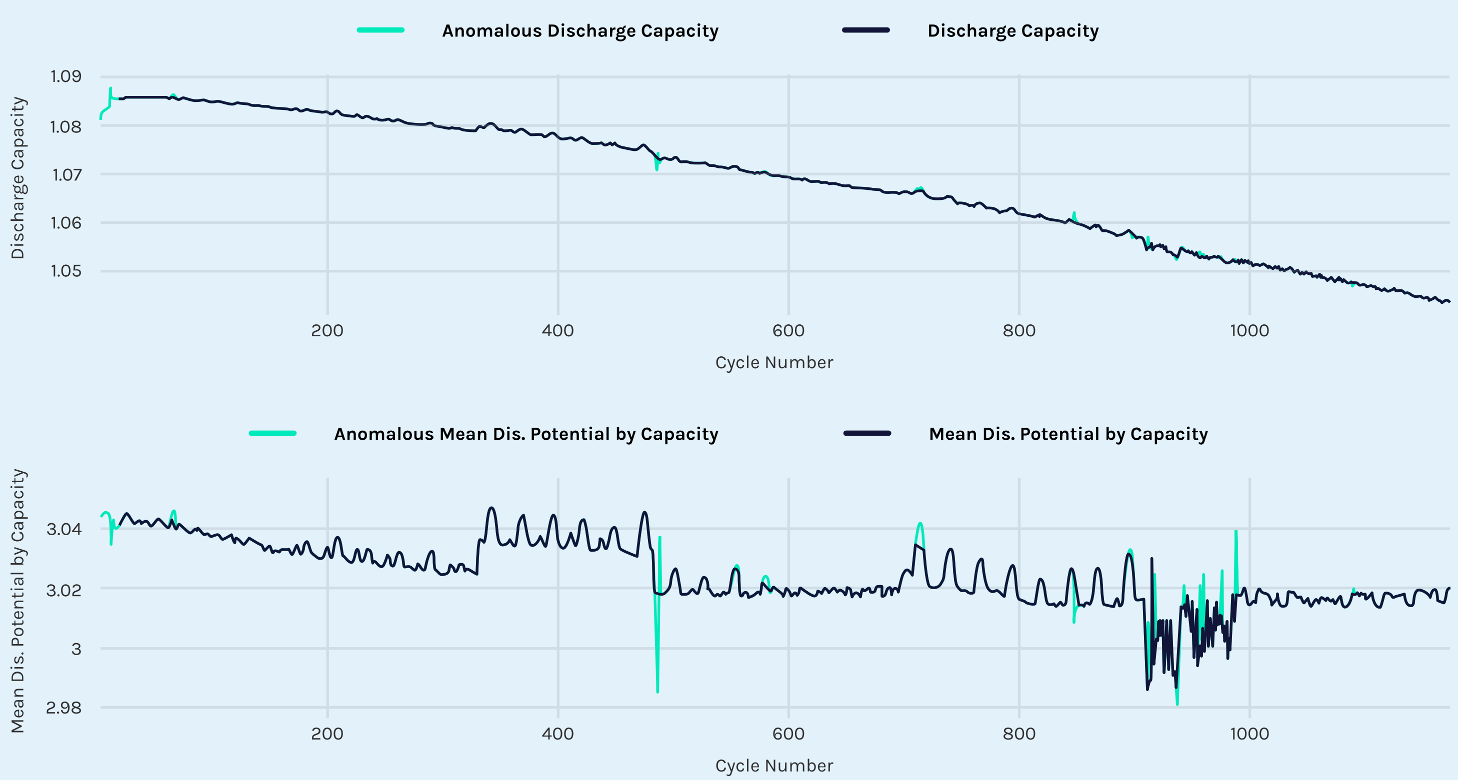
Figure 11. Automating quality control through machine learning anomaly detection



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The power of this technique is that you can generate and compare enormous amounts of data, far more than most engineering teams are capable of combing through. Machine learning can conduct the analysis for you, pouring over hundreds of different conditions and statistics. If a human looks at the top graph of discharge capacity, they wouldn't think anything is out of the ordinary because you can see that little blue blip at about 500 cycles, and it appears to be well within the natural variation of the data. But, when you compare it to another statistic, the bottom graph of average voltage shows that it's an anomaly. The average voltage of the cell went way down.

> **A practical real-world application of machine learning is predicting battery hazards and fires before they happen. By reading electrochemical data, things like voltage and current, and then computing a handful of different parameters, we can determine what the level of risk is.**

A practical real-world application of machine learning is predicting battery hazards and fires before they happen. By reading electrochemical data, things like voltage and current, and then computing a handful of different parameters, we can determine what the level of risk is. The benefit of an application like this is to alert an end user to an imminent fire, hours or even days before it happens. This is something you would definitely want to know before climbing into your EV or putting your power tools in the garage for the night.

5. Set up a battery-specific traceability system

The next technique is to set up a battery-specific traceability system. Traceability systems are required to intelligently handle product recalls, warranty claims, and audits. Moreover, forthcoming regulations in Europe and North America will legally require traceability for every battery sold (also known as a "Battery Passport").

> **One thing to consider — is your process enough to stand up to scrutiny in court five or six years from now when you have a potential product recall?**

Everyone knows that battery problems are inevitable. A good traceability system inspires confidence in customers when they have a problem. Traceability systems are typically confined to spreadsheets. One thing to consider — is your process enough to stand up to scrutiny in court five or six years from now when you have a potential product recall? Regardless, spreadsheet-based systems will definitely not pass muster with regard to the legal requirements of a Battery Passport.

When a battery issue arises, an audit team is sent to your manufacturing plant, and you hand the auditors all the records. You want to identify all the root causes, what equipment was affected, and what products were affected. If possible, you want to clearly identify that it was a specific lot and one batch has the problem so that the size and impact of the recall are limited.

In a nightmare scenario, they send in auditors, they show up to your plant, and they begin asking all these probing questions, to which of course you reply "I don't know" because you don't have the proper data. You hand over reams of spreadsheet data, and it's impossible to trace anything. You don't know what products were made on what machines, or which input materials came from which suppliers. At this point, the ethical thing to do is to recall everything that could possibly be affected. The financial impact of recalling everything is enormous.

So, what is a bare minimum traceability system? Generally speaking, it's going to consist of serial numbers, dates, and critical information. Let's say we have a battery pack, which consists of many cells, each cell made up of a cathode, anode, and separator. If there is a problem at the separator supplier and you receive a notice that everything produced between a certain date range is unsafe to use, the traceability system needs to be robust enough that it's possible to identify which cells use this separator and which battery packs those cells went into so hazardous packs are identified and the scope of the recall is minimized.

> **Your traceability system needs to be flexible enough so that you can trace both forwards and backwards. You should be able to select a battery pack at random and see what cells went into it and what the batch IDs of the cathode material were. This type of traceability is extremely important.**

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Your traceability system needs to be flexible enough so that you can trace both forwards and backwards. You should be able to select a battery pack at random and see what cells went into it and what the batch IDs of the cathode material were. This type of traceability is extremely important. Doubly so as industry pressures tend to (unfortunately) prioritize getting products to market quickly over product quality and safety.

In our Metadata-to-Performance analysis, we compare how different chemistries affect a system's lifetime. Suppose, however, that at the start of your product development program, you were already locked into a specific chemistry type and you didn't consider different chemistries. That means that the battery data that you have wouldn't have any information about what type of chemistry it is. Someone on your team would have to conduct what is the equivalent of retail inventory, where you go in with a price gun and relabel thousands of files.

The solution is to automate this record-keeping process. Automation allows you to track and store large volumes of this type of "metadata" that may not be immediately useful today but can sometimes turn out to be extremely valuable down the road. For example, tracking the cell manufacturer may not be important today, but it might be in a decade if/when there is some sort of warranty issue.

The trick is to anticipate what kind of information might be useful in the future. There is manufacturing information, so things like batch numbers, serials, data manufacturer, and traceability information. What went where, what vendor, and the material types? Then, there is also process information. For example, the equipment used, the weld energy used to weld it, and the operator that handled the operation. It's important to invest in record-keeping now to prevent having to pay that debt with interest down the road. One benefit that often isn't mentioned with record-keeping is that it's a prerequisite for enabling other powerful analyses such as Metadata-to-Performance or "how this affects that" analysis.

6. Automate frequently used analyses

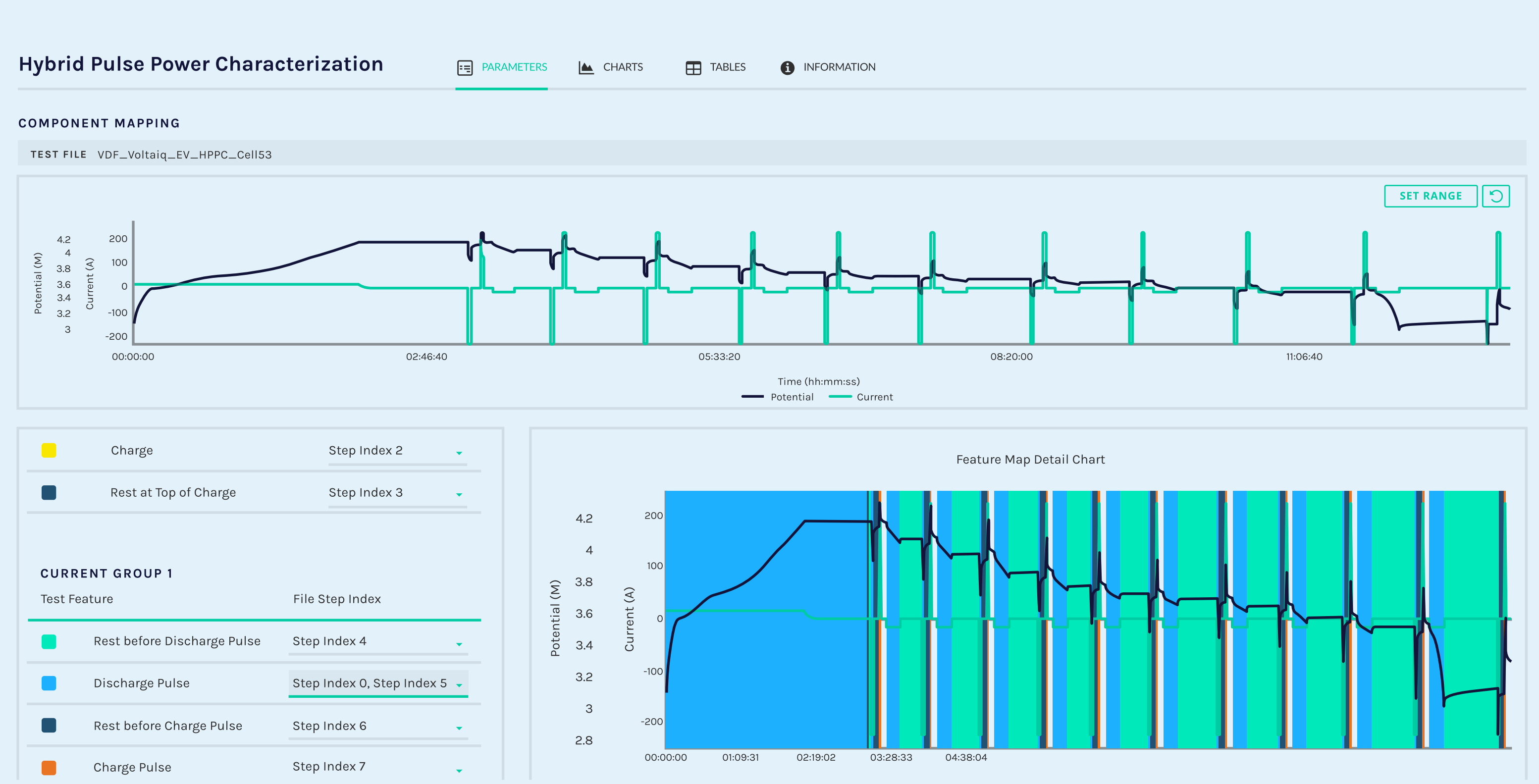
The next technique for saving time is to automate your most frequently used analyses. It's really important to understand that the core competency of most engineering teams is usually not battery-specific. It will take them much longer to do a battery-related task than it would take a battery expert. This is why automation is so powerful. By solidifying the know-how of a battery expert into a single button click, you can capture the expertise and use it, and reuse it. It's kept at your organization forever, and there is no risk of losing that expertise.

Keep in mind that the most frequently used analyses of course depend on your specific industry. Let's take the automotive industry for example. Figure 12 shows an HPPC protocol, which stands for Hybrid Pulse Power Characterization, which simulates the demand that a hybrid vehicle places on its "traction battery" (the one that helps drive the wheels).

This is a very common industry-standard test to determine how much power a battery can deliver at various stages of charge, as well as interesting things such as internal resistance. This is an incredibly powerful but tedious analysis that engineers at automotive manufacturers routinely take two and a half hours to manually analyze per test.

> **It's really important to understand that the core competency of most engineering teams is usually not battery-specific. It will take them much longer to do a battery-related task than it would take a battery expert. This is exactly why automation is so powerful.**

Figure 12. Automated analysis of the Hybrid Pulse Power Characterization (HPPC) test protocol.



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You can see the problem here — if they need to analyze 50 cells a week as well as qualify new vendors and keep tabs on old ones, this can take their engineering department an entire week to do what can be basically done in one minute through automation.

The key to automating these types of analyses is component mapping. The HPPC protocol is a series of charge and discharge pulses that a specialized EBI analysis package can map automatically, finding where each charge or discharge pulse occurs. The program can then detect the rest of the hundreds of pulses and apply the map to it. Automating these analyses doesn't just help you do it faster, but it also retains the expertise in your organization.

7. And finally, benchmark yourself

The last technique for saving time is benchmarking yourselves. Any part of a development program is going to be looking at many vendors, many different chemistry types, and many different samples. Rather than just leaving it as a checkbox in a Gantt chart, you're going to accrue tremendous value by keeping a data library of all the cells you qualify.

The key benefit is being able to select the best cells for your application as well as the second and third choices. Having that data on hand already allows you supply chain agility because instead of having to wait to requalify and retest cells, you have all of the information readily available. As we've seen over the past two years, supply chain uncertainty can cause lead times to go from four weeks to 50 weeks, and it has been a crazy ride. Keeping a benchmark of all the cells that you tested keeps options open, and it accelerates qualification and development.

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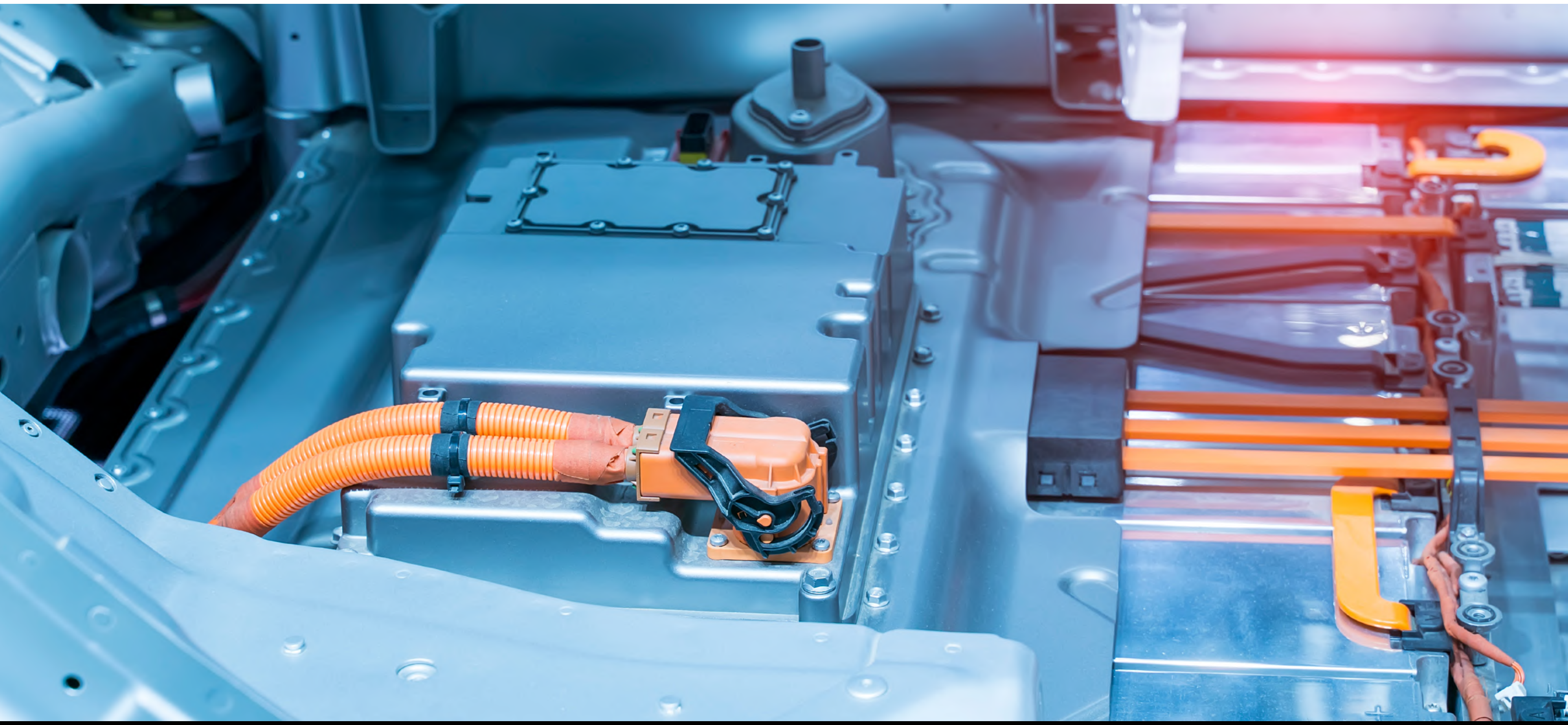

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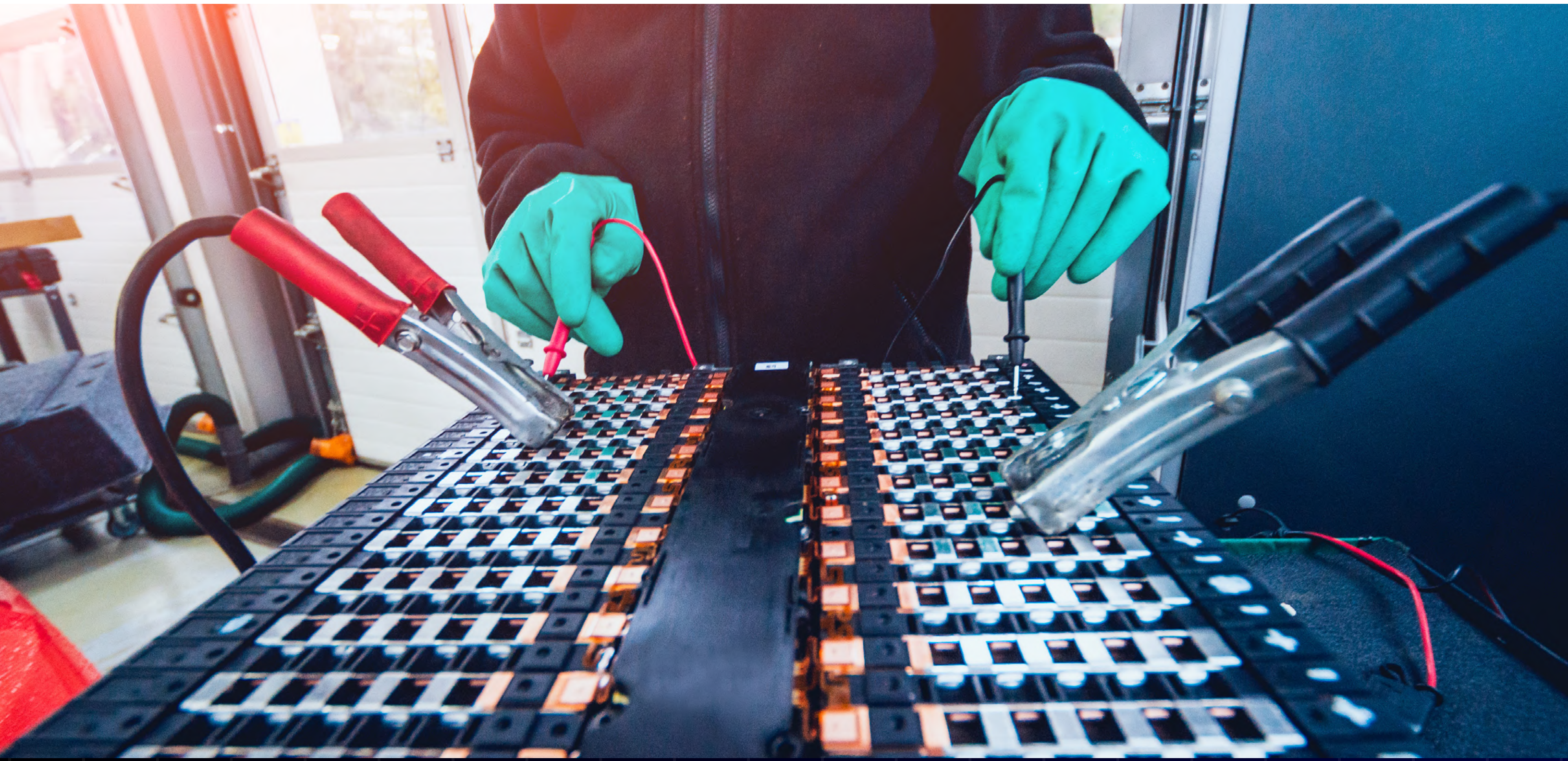
Batteries: Mission-critical and highly complex

In this eBook, we have discussed why batteries matter, and their importance because they are often mission and business-critical for any electrified product. Because of how complex batteries are, it's also an opportunity to develop a competitive advantage in the marketplace. These advantages are increased productivity, risk mitigation, and saving time. Under increasing productivity, you have to plot your statistics so you know where your baseline is, battery fingerprinting with differential capacity analysis, and you can see how changing this affects that with metadata as a performance metric.

Under mitigating risk, you capture data from industry standard end-of-line tests and automate defect detection with machine learning so you're not reliant on human QA. You also want to develop a battery-specific traceability program. To save time, you want to automate your record keeping and data labeling, automate your most frequently used analyses, and of course, benchmark your data so you don't have to conduct the same tests on the same vendor over and over.



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About Voltaiq

Voltaiq has built the industry's first Enterprise Battery Intelligence (EBI) software platform, helping its customers optimize battery performance, reliability and financing, while avoiding costly recalls and catastrophic battery fires. Voltaiq's EBI platform is the only purpose-built, fully automated software solution that marshals vast quantities of battery data from across the full product lifecycle, providing a window into real-time battery function and a detailed view into future performance and behavior. Founded in 2012 by veteran battery and software entrepreneurs, Voltaiq's global customer base includes industry leaders in transportation, consumer electronics, energy storage, and the full battery supply chain. For more information, please visit www.voltaiq.com