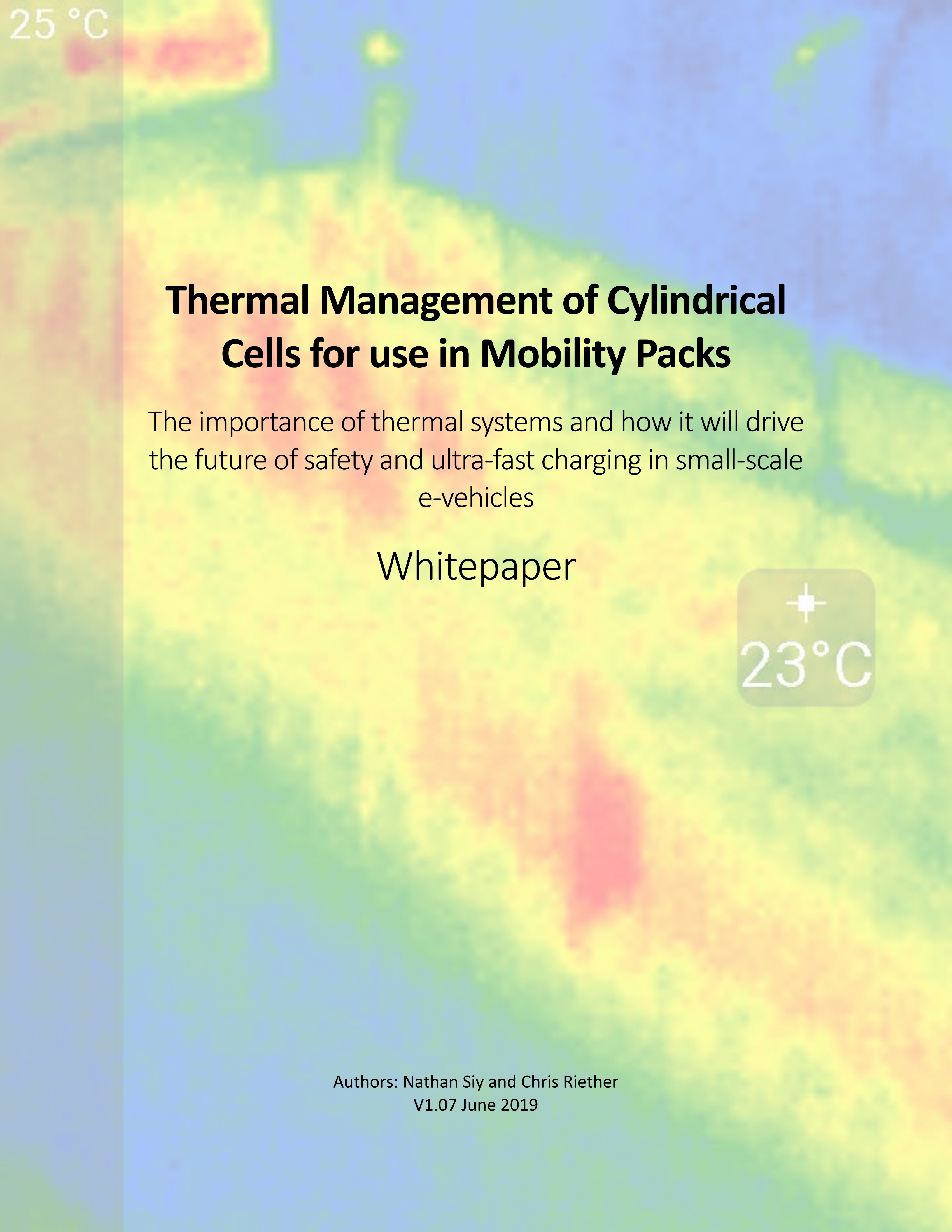

Thermal Management of Cylindrical Cells for use in Mobility Packs

The importance of thermal systems and how it will drive the future of safety and ultra-fast charging in small-scale e-vehicles

Whitepaper

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Abstract

As electric vehicles become more prevalent in society, electric vehicle battery performance and life cycle demands are higher than ever. As such, battery pack designers need to consider thermal management systems for ensuring their batteries provide the best life and performance possible within their design and cost restraints. In this whitepaper we will discuss the benefits, drawbacks and challenges of designing a thermal management system and give battery system designers and electric system designers the background to understand the overall benefits of an active thermal management system for mobility applications.

Introduction

Why do we need thermal management in small scale (light) mobility battery packs? The benefits of thermal management include longer lifecycles in the battery pack, the ability to fast charge, super charge or ultra-fast charge, stable operation in a wider temperature range and is overall safer to operate with additional levels of security in the battery pack itself. Battery designers, EV businesses and OEMs will need to analyze their use case to determine whether the benefits outweigh the additional cost and manufacturing complexity.

The mass proliferation of electric vehicles will occur when a product comes to market that is an improvement over the current product available without having to compromise on more than a few elements. Tesla has been able to disrupt the market with their products being quicker, with similar range, similar in power and features than their gas / ICE counterparts, while the compromises being marginally slower fill up times and price. When we look at the small-scale electric vehicle industry, a shift to thermally managed battery packs will allow future small-scale electric vehicles to improve on what is currently available with faster charge times, higher power output and battery packs that outlast the vehicle itself.

The demand for thermally managed battery packs in small-scale applications is also becoming more apparent through new use cases, such as dockless electric scooter sharing, food delivery and fleet use, as most of these use cases rely on a long period of time to amortize their battery assets. Unmanaged battery packs have a standard life cycle count of 500 – 1000 cycles for readily available lithium based cells, where a 50% - 300% increase on lifespan can be had with the use of thermal management. This allows a higher level of stability, which translates into a longer use of the asset on the road, a longer minimum use of the asset spanning 5 – 10 years vs 1 – 2 years in heavy use applications, and allows for use in a wider span of climates.

This whitepaper will take readers through the intricacies of managing heat creation through the design process and then through an active system thereby offering information to evaluate if an active thermally managed battery pack is right for the application.

Background

Why doesn't anyone use thermal management in small-scale mobility packs now? Currently, the scope of small-scale electric vehicles typically encompasses 2, 3 or 4 wheeled vehicles with battery capacities of 1.0kWh – 20.0kWh. For the pretense of this whitepaper, discussions will revolve mainly around this form factor of vehicle, and not set to include micro electric vehicles (constituting electric vehicles with less than 1.0kWh battery capacities, such as Segways, electric balance boards, electric unicycles, etc.) or automotive electric vehicles, constituting EVs with a capacity greater than 20kWh.

As of 2019 in China, most small-scale electric vehicles are still using lead acid batteries for systems within the 48v and 60v systems using 12.0 or 20.0 Ah cells. A slow shift to lithium ion battery packs are happening within major cities as pricing for lithium battery pricing continues to decline year over year and consumers are becoming more aware of the general benefits. Companies such as Aima, Xiao Niu, and Sunra are selling a small percentage of their electric scooters with prepackaged lithium ion batteries, continuing to help educate the market from a bottom-up marketing approach. Currently, lithium ion based packs used in these types of vehicles are non-thermally managed battery packs.

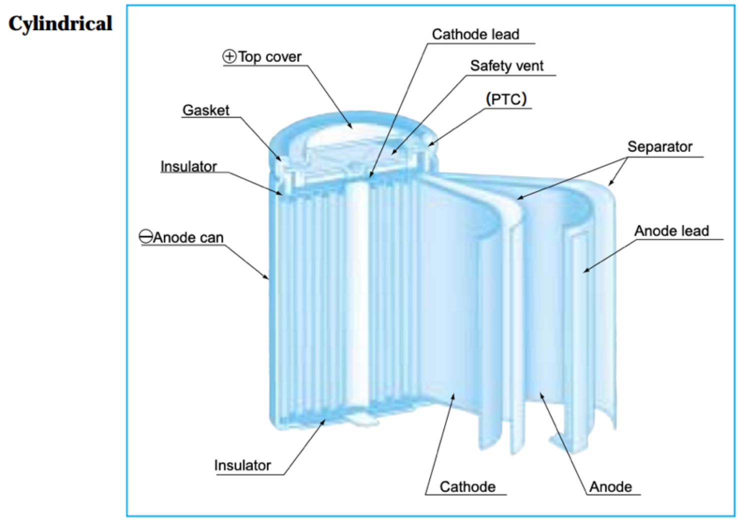
Depending on road conditions, legalities and safety standards, most of the manufacturers listed above produce electric scooters or electric vehicles that are not road legal. Because they are not road legal for public streets, the expectations of them to operate and run like a road-worthy vehicles are forfeited. That lack of road-worthiness impacts the amount of R&D that goes into a vehicle, the life expectancy of the vehicle and severely restricts the performance capabilities. Most of the China made electric scooters are utilized as neighborhood last-mile vehicles and has very little R&D put into it, a short 1 – 3 year life expectancy for all the components including the battery and are limited in performance to less than 45km/h in speed.

We are beginning to see a shift in consumer expectations in China for electric scooters and electric motorcycles, where the demand in increasing for higher quality e-vehicles that are closer to, or meet automotive grade standards; this entails e-scooters or e-motorcycles that meet a 5 to 7 year minimum lifecycle inclusive of the battery, with higher operating requirements more similar to the ICE / gas counterparts, such as 70+km/h minimum top speeds. The China consumer is also looking to more intuitive dashboard layouts with more accurate SOC calculations, where in the past, a simple voltmeter would do to estimate remaining range of the battery. The shift for better quality e-vehicles is government led, with a recent restructuring of the legal framework in China. 2 wheeled EVs with a top speed of 25km/h or greater are classified in a new scope as "Motorized Electric Motorcycles" with requirements for license plates and drivers' licenses moving beyond May 2019. With the onset of this new classification, electric riders shopping for the 25+km/h product category will have a much wider selection. With the new product category being so wide, we'll see the bottom of the category facing the biggest challenges in the market, where the shift from competing on price will move to competing on performance. With better performance e-vehicles on the horizon, we will see a benefit from moving to a thermally managed pack in the short and long term in the 2 wheeled electric vehicle industry.

Cylindrical Cell Heat Buildup

Cylindrical Cell construction

To understand the thermal properties, one must first understand the underlying construction of a typical 18650 lithium ion cell.



Blow apart of a cylindrical li-ion cell

"As for cylindrical and prismatic batteries, sheet like cathodes and anodes are wound together in a spiral shape. Between the cathodes and anodes is wound a polymer separator film which acts to obstruct micropores and interrupts the reaction should the cell temperature rise excessively for some reason. In order to ensure cell safety, for example, the cylindrical battery incorporates a safety mechanism consisting of a circuit breaker, rupture disk, and PTC (positive temperature coefficient) device. The electrolyte is an organic solvent which is stable up to high voltage, in which a lithium salt is dissolved." [(1)]

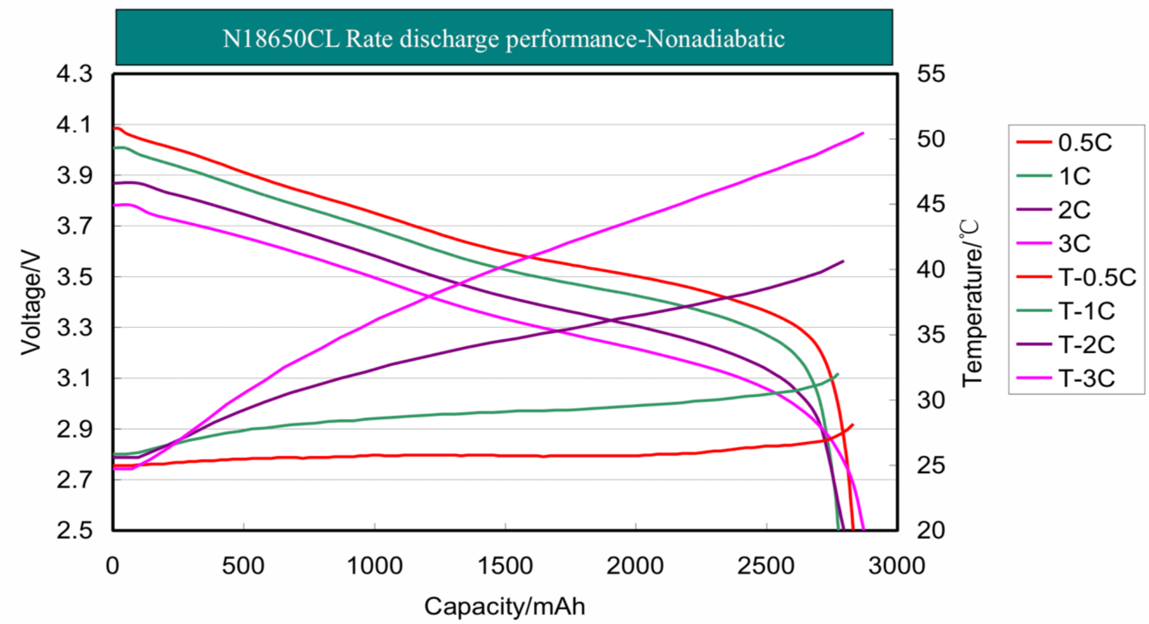
Since the inherent construction of a cylindrical li-ion battery is a wound configuration, and chemical reaction between the cathode and anode occur equally across the whole sheet and separator combination, there is an build-up of heat that becomes trapped within the inner layers of the cylindrical cell, while layers closer to the Anode can allow heat to transition into the ambient air surrounding the cylindrical cell itself.

Therefore, the need arises in how to effectively cool the entire anode/cathode/separator sheet combination equally. The high demands of mobility applications then lead to new high efficiency cooling and heating methods.

Cell Properties

Any time a charge or discharge occurs within a li-ion battery, a chemical reaction is taking place, moving the lithium ions to and from the cathode. This chemical reaction creates heat within the cell itself. In this charge, you can see how the rate of charge and discharge impacts the amount of heat created, dependant on how quickly migration of the lithium ions occur. On a typical 18650, manufactured by BAK, at an ambient 25°C temperature, discharging the 18650 li-ion cell at a rate of 0.5C over the complete cycle of the cell induces a final temperature of about 28°C, a temperature delta of 3°C. Utilizing the same li-ion cell at a discharge rate of 3.0C over the complete cycle of the cell induces a final temperature of about 51°C, getting close to the thermal threshold of the cell limits.

In mobility applications, dynamic ranges of up to 3 – 4C for periods of time is very common, therefore cells designed for this application must have lower internal resistances that result in lower temperatures when pushed to these limits.



Applications of Power Source

To better understand the application condition of a battery pack, one must first understand terminology and what makes a battery cell and battery pack suitable for a particular application. Major terminology that will be utilized when discussing cells, packs and viability in an application are going to be:

- Voltage: Voltage in an electrical circuit is measure in Volts (V), and is the electrical "pressure" within a circuit. On the cell level, individual battery cells will contain a voltage of 2.0v to 4.35v depending on chemistry, manufacturer, form factor, etc. For the purpose of this whitepaper, the most common types of li-ion cells are going to be Lithium Iron Phosphate (LiFePo4), Lithium Cobalt Oxide (LCO) or Lithium Nickel Manganese Cobalt Oxide (NMC).
  - LiFePo4 will typically have a 2.0v – 3.65v voltage range
  - LCO & NMC will typically have a 3.0v – 4.20v voltage range
- Current: Current in an electric circuit is measured Amps (A), and is typically the "amount of energy" within a circuit. This is not to be confused with Capacity below, as their means of measurement is quite similar.
- Capacity: Capacity in a battery configuration is measured in Amp-hours (Ah) and is the measurement of how much energy a medium can store. The measurement

rating is a direct correlation with the storage capacity, meaning that a 1Ah battery can discharge 1A for 1 hour.

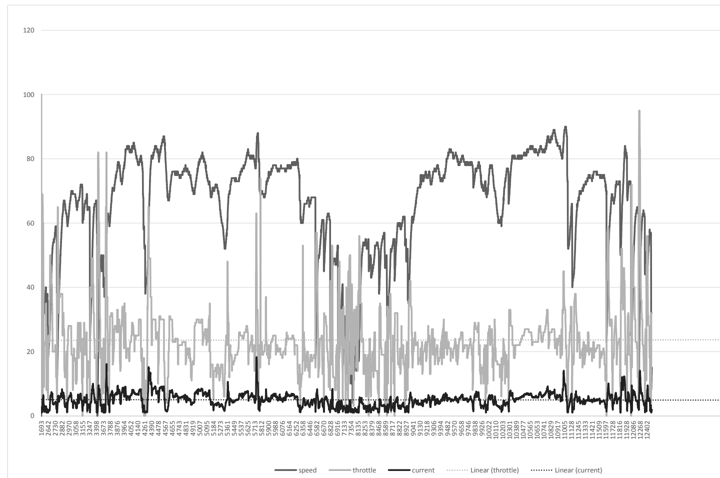
- String: In a lithium ion battery pack, total battery voltage is achieved by electrically connecting battery cells together in a series or parallel configuration to result in a particular voltage level and capacity level suitable for the application. A paralleled bank of cells together makes up a string, in which strings are electrically connected together to form a series connection and ultimately the proper voltage for the pack.
- C rating: An arbitrary measurement of a charge or discharge level of a battery pack in relation to the total capacity of the pack itself. The C rating of a charge or discharge action is the instantaneous charge or discharge current divided by the total pack capacity.
  C rating = Current (A) / Pack Capacity (Ah)

Charge / Discharge rates based on SOC & C ratings

Mobility Application

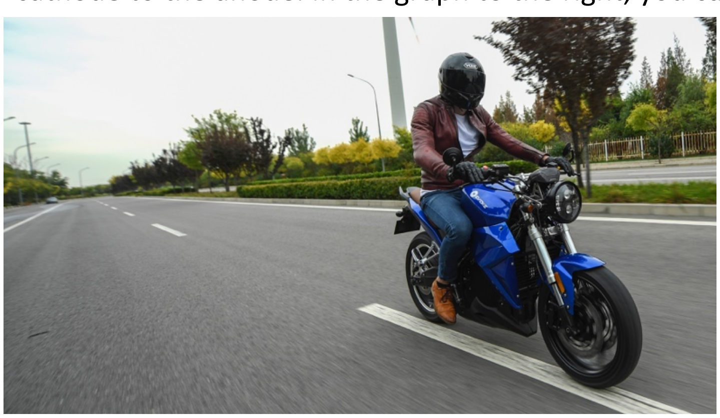
For the main sections of this whitepaper, we will be focusing on small-scale vehicle application, including Evoke's product line of ultra-fast charging electric motorcycles. In addition, this class of vehicles may also include:
E-scooters, electric kick scooters, other e-motorcycles, electric trikes, electric 4 wheelers (under 20kWh of capacity), electric boats, electric gliders, etc.

Typically, this class of vehicle outputs 500W – 50kW of motive power with weight classifications of less than 1T, while most of the vehicle's in the classification will average a few hundred pounds at most. They feature highly irregular power output patterns, which indicates proper patterns with on road use. This varies as the environment includes stop lights, inclines, meshing with traffic, speeding up for on ramps and sometimes coasting. What this equates to from a power usage point of view is extremely dynamic and high discharges with environmental factors ranging from -20°C to over 50°C in high heat areas. All of this equals high C discharge scenarios on a daily use case.

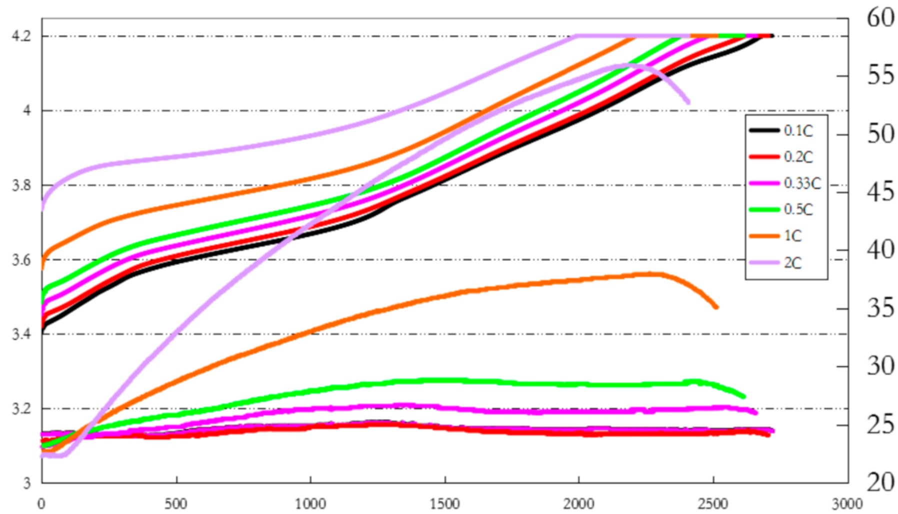


Riding data from an Evoke Urban Classic; speed, throttle response and DC current

With consumers further demanding fast charging, super charging and ultra-fast charging, this continues to add to the stress of the battery pack itself, as high C charges put the most strain on the chemical reaction itself, moving lithium ions away from the cathode to the anode. In the graph to the right, you can see putting a 0.1C charge onto a typical BAK 18650 yields an almost nondescript temperature rise, while a 2.0C charge ramps the cells temperature up to 56°C within a single charge cycle. Repeated actions at this temperature level will cause accelerated degradation in the full capacity of the cell, thereby shortening its usable lifecycle and increasing the risk of combustion.



2019 Evoke Urban Classic electric motorcycle; 200 km of range, 60 min super charge to full



Single 18650 cell charging cycle at various charging rates

In the datasheets provided within this whitepaper, the cells are charged at the appropriate rate with only convection cooling and done within a safe testing environment. Charging at these speeds without a proper monitoring, safety and thermal management system is highly unsafe.

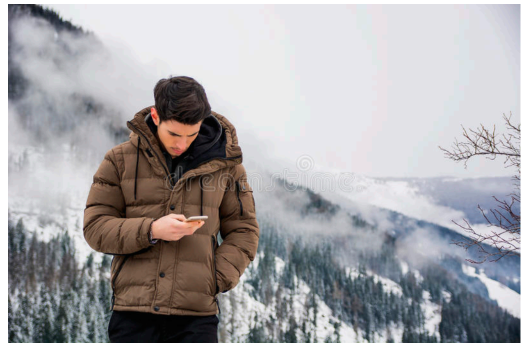
Consumer Electronic Application

Alternatively, 18650 and 21700 cylindrical cells have achieved their manufacturing scale primarily through their use in consumer electronic applications. The rise in popularity of lithium batteries in the 90s and 2000s was due to its affordability and large application range, from laptops to cordless power tools to power banks.

Consumer electronic applications for cylindrical cells have a much more mundane charge and discharge cycle along with a much simpler solution of managing extreme temperatures. When we look at the typical current draw of consumer electronics, many of them have intricate chip level power management algorithms built in, throttling or overclocking calculations when need by and conserving power when unneeded. From the battery end of things, what this means is a very light discharge cycle majority of the time with short bursts of heavy CPU workload a minority of the time. This is a polar opposite to mobility applications where most vehicles need to accelerate from stop light to stop light, while coasting for shorter periods of time.

On the simplistic solution of managing extreme temperatures, most consumer electronics are used indoors, where temperatures range from 23 – 28 degrees. More extreme cases would be using your mobile phone outdoors in the sunlight or in sub-zero environments, but this is usually short periods of time, where if battery issues begin to occur, they can be easily rectified by placing the mobile device back in a warm environment, such as on person, in a pocket or bring it back indoors. Mobility applications require the vehicle to be situated outdoors most of the time, and may be parked infrequently in a parking garage which may be a few degrees warmer than fully outdoors.

With the additional stress of mobility applications, a more stringent thermal management design must be put in place to account for the wide range of conditions.



Personal electronics' battery temperature ranges are significantly smaller than mobility

Total System Inefficiencies that Create Heat

Background

Total system inefficiencies when it comes to battery pack development can have a significant impact on the thermal scenario if not factored in correctly. When looking at the total system design, 2 factors needs to be considered:

1. Electrical efficiencies
2. Thermal inefficiencies

Within this whitepaper, the 2 factors tie together as inverse proportions; the higher the electrical efficiency, the lower the thermal impact on the system will be. From this perspective, we'll address the 2 factors from the thermal point of view, albeit improvements on the thermal end will help on the electrical end.

Total system inefficiencies can be attributed primarily to internal resistance of the cells and electrical resistance of various connectors throughout the pack. As we covered in the background, cylindrical lithium ion battery packs are made up of series and parallel connections to obtain the proper voltage and capacity. Typical e-scooter packs can contain 200+ cylindrical cells while a high- power e-motorcycle, such as an Evoke 6061 can contain up 1300+ cells, each one of these cells has an electrical connection and therefore a potential point of thermal inefficiency. For manufacturing purposes, most cells are grouped into modules and module to module interconnects are usually another type of interconnect system and another potential thermal inefficiently point.

Evoke 6061; 400km of range, 15kWh pack, 15 min charging to 80% using a 50kW DC fast charge station

As per good battery design, a selection of the right cells will balance cost and internal resistance (IR). A lower internal resistance of the cell will help to offer higher energy cells, allowing high C bursts of discharge. Manufacturing lower IR cells increases overall production costs but allows for higher discharges without the build up of heat.

For the following section, we will focus mainly on electrical efficiencies and methods on reducing thermal inefficiencies from the electrical interconnect standpoint. Reducing these will be a step forward in reducing total system heat and producing a more efficient battery pack.

Peripheral Heat Sources

For the following section, we will break out peripheral heat sources into 2 major segmentations, internal and external. Internal encompassing heat sources and inefficiencies commonly found inside the battery pack itself, and external which will cover inefficiencies found outside the battery pack and affecting the total system more so.

Internal Peripheral Heat Sources

Connection to cell

In today's battery pack construction industry, there are 4 major types of electro-mechanical connections to the individual cylindrical cells:

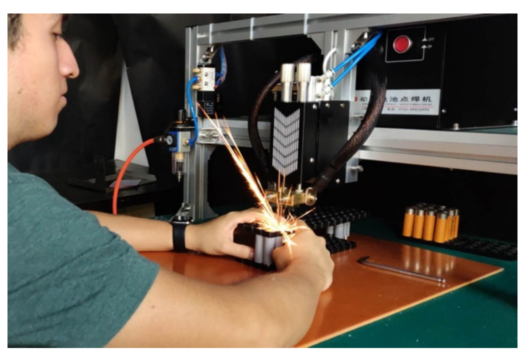
1. Soldering
2. Spot Welding
3. Ultrasonic Welding
4. Laser Welding

From a lower production standpoint, soldering and spot welding offer solid and hearty connection with lower cost production assets, while ultrasonic and laser welding offer strong connections for higher value assets.

	PROS	CONS	MATERIALS
SOLDERING	• Inexpensive asset • Simple to learn • Large electrical surface area for connection	• Injects heat into the cell while soldering • Extremely slow	Nickel, copper strips 0.1 – 0.4mm Wire 8 awg – 24 awg
SPOT WELDING	• Semi-expensive asset • Very fast	• Electrical surface area small for connection • Limited material thickness	Nickel, copper strips 0.1 – 0.4mm
ULTRASONIC WELDING	• Fast • Very large electrical surface area for connection	• Expensive asset • Very new process, many cell manufacturers do not support ultrasonic yet	Nickel, copper strips Nickel, copper bus bars 0.1 – 10+mm
LASER WELDING	• Fast • Small to large electrical surface area for connection	• Expensive asset • High learning curve	Nickel, copper strips 0.1 – 1.0mm

Cell connections

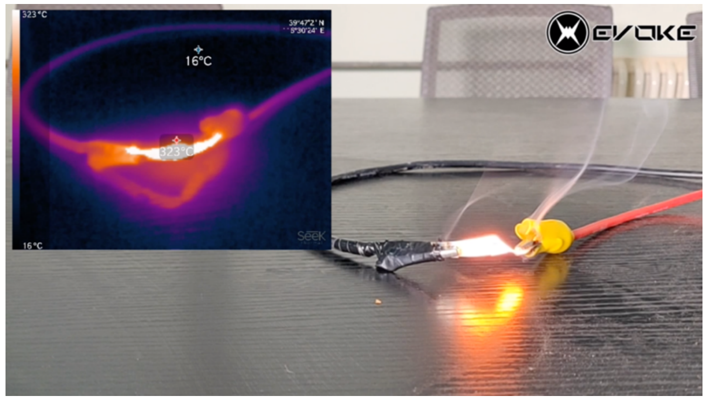
Exploring the thermal efficiencies of parallel and series connections between the individual cells is an interesting one. As we look at the thermal image, we see most of the heat being generated at the series connection while the parallel connections between the cells stay relatively cool. This is a property of the electrical connection in which cell is parallel share the distributed current, where each cell would see 1/x of the



Spot welding cell nodes together

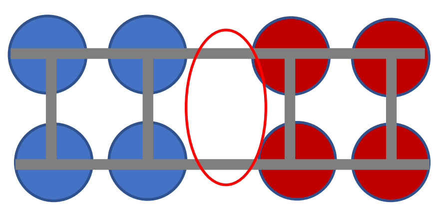
total power being delivered to the load. The series connection leaves a single path for all electrons to flow through, therefore you'll notice the entire current load flowing through the series connection strips.

When designing a pack, careful consideration must be addressed on the total amperage of the system, in peak and RMS (continuous) measurements. While a certain connector may take a peak current burst without damage, current over time causes connectors and terminals to increase in heat and sometime glow due to the current passing through it. Running a constant current (CC) test on a single 8.0mm x 0.1mm thick nickel strip at 40A, we can see that the strip exhibits a 46°C to 323°C increase in a matter of 5 seconds. In mobility usage cases, accelerating at wide open throttle (WOT) can draw in excess of a few hundred amps on a full speed electric motorcycle and can cause serious heat issues if not properly designed.



Current transfer test, 0.15mm nickel sheet, 40A RMS

Analyzing the distribution of current flow in your battery pack design, careful attention needs to paid to the series connections from bank to bank of the pack. Since within each bank, current is distributed between each connection, the series connections handle the total flow of current.   With the setup of a 2s4p 18650 pack, positive and negative terminals will need to be taken from the ends of the structure at the furthest most points, electrically. Therefore, looking from the bottom of the pack, the series connection happens at the red highlighted area, and all current flows through these nickel sheets. If the total draw of the system is projected at 40A peak discharge at a nominal voltage, then each nickel strip will need to support 20A on a peak, which will also depend on what the pack designers' idea of "support" means. At 20A, the thickest usable nickel strip that is spot weldable is 0.4mm and it will definitely experience heat rise, and the idea is what is tolerable from a designer perspective, user perspective and a safety perspective. With standard nickel strips range from 0.1mm to 0.4mm, and typical spot welders also being able to support these thicknesses, sometimes double or triple stacking nickels strips is necessary to increase the current carrying capacity of the node.



Typical string to string series interconnect

Module Interconnect Methods

For ease of mass production, building out modules, which are a grouping of cell strings electrically and mechanically connected together, allow for scalability and saves on production time and increases points to test for quality control. A module may consist of 3 – 9 strings, connected together, depending on pack design and installation method.
A few key reasons for developing a module production method:

1. Scalability, ease of manufacturing allows to produce more battery packs consistently and without problems by addressing quality control at several points of the build, instead of testing at final assembly
2. Safety, allowing a lower voltage to be produced before joining the modules together to the final voltage
3. Reparability, allowing sections of the pack to be replaced in the case of a bad string

The most common module to module interconnect methods are:

- Nickel strip connection
- Copper strip connection
- PCB connection
- Wire connection
- Bus bar connection

Choosing the interconnect method that works best for you from a heat perspective needs to take 2 factors into account:

1. The distance of travel
2. The cross-sectional area of the connection medium

Nickel and copper strips have been covered in the above section, referred to the "Connection to Cell" section. The same rules apply, checking the total cross-sectional area that current passes through into account and setting temperature rise allowances for the application. But moving from module to module now requires length to be taken into the equation. Each medium such as nickel, copper, aluminum all have conductivity properties, measure in Ohms per 1000m or milliOhms per meter. Understanding the resistance over a distance will be proportional to the temperature rise of the medium over the allotted distance.

	Diameter		Cross-Sectional Area		Resistance	
AWG	(inches)	(mm)	(kcmil)	(mm^2)	Ohms per 1000ft	Ohms per 1000m
0000 (4/0)	0.46	11.684	211.6	107.22	0.049	0.1608
000 (3/0)	0.4096	10.405	167.81	85.029	0.0618	0.2028
00 (2/0)	0.3648	9.266	133.08	67.431	0.0779	0.2557
0 (1/0)	0.3249	8.251	105.53	53.475	0.0983	0.3224
1	0.2893	7.348	83.693	42.408	0.1239	0.4066
2	0.2576	6.544	66.371	33.631	0.1563	0.5127
3	0.2294	5.827	52.635	26.67	0.197	0.6464
4	0.2043	5.189	41.741	21.151	0.2485	0.8152
5	0.1819	4.621	33.102	16.773	0.3133	1.028
6	0.162	4.115	26.251	13.302	0.3951	1.296
7	0.1443	3.665	20.818	10.549	0.4982	1.634
8	0.1285	3.264	16.51	8.366	0.6282	2.061
9	0.1144	2.906	13.093	6.634	0.7921	2.599
10	0.1019	2.588	10.383	5.261	0.9988	3.277
11	0.0907	2.305	8.234	4.172	1.26	4.132
12	0.0808	2.053	6.53	3.309	1.588	5.211
13	0.072	1.828	5.178	2.624	2.003	6.571
14	0.0641	1.628	4.107	2.081	2.525	8.285
15	0.0571	1.45	3.257	1.65	3.184	10.448
16	0.0508	1.291	2.583	1.309	4.015	13.174

Typically, using a 10 – 15°C rise in medium over the allotted distance is an acceptable value, presuming that the wire or nickel routing does not impact any temperature sensitive components. In common applications, drawing 2.0 – 3.0C from the batteries on short bursts will increase the cylindrical cells temperatures up to 50°C degrees. Balancing interconnect costs, thickness and routing with a suitable wire size or cross sectional area, we are able to properly estimate the interconnect wire gauge.

As a quick example, if there is a usage case of 100A peak draw from a theoretical battery pack, 3 modules connected together in series. An AWG8 wire has a cross sectional area of 8.366 mm^2 (additionally, care must be made as to if your supplier adheres to the American Wire Gauge standards (AWG) and to insure that the wire interconnect has at least the cross sectional area of the comparable AWG standard), which has a total resistance of 2.061 Ω per 1000m or 0.002061 Ω per m. The module to module interconnect wire is 0.1m long, delivering 0.0002061 ohms per section.

2.061Ω / 1000m = 0.002061/m

Using Ohms Law to determine power ($p = I^2 \times r$), at theoretical peak current draw of 100A and a resistance of 0.0002061Ω per section, the AWG8 wire interconnect section will experience $100^2 \times 0.0002061\Omega$ = 2.61w of heating power; depending on the designer this may or may not be an acceptable level of heat generated for the small duration of the time that the e-vehicle will be at WOT.

$100A^2 \times 0.0002061\Omega = 2.61w$

Equating the heating power of 2.61w to a quantifiable temperature rise over an estimated acceleration of 30 seconds at WOT (wide open throttle), we need to take in the following equations:
1 watt = 1 joule/ sec
2.61 joules / sec
30 seconds of acceleration at WOT
2.61*30 = 78.3 joules

The 10cm long AWG8 wire weighs approx:
46.98 lbs / 1000ft = 21.31kg / 304.8m = 0.0699kg / m
10cm then = 6.9g
78.3 joules of energy / 6.9g mass = 11.35 joules / gram

Specific Heat of Copper = 0.572 J/(g. K)
11.35 / 0.572 = 19.84°K increase or a 19.84°C increase
If base ambient temperature of the 10cm interconnect wire is 28°C = 301.1°K
then
301.1°K + 19.84°K = 320.94°K = 47.79°C

Increasing wire thickness to AWG6 would decrease the resistance per foot, along with increasing the total mass of the interconnect wire, thereby decreasing the temperature rise from 2 different factors. Therefore, a nominal increase in wire or interconnect conductivity usually has a dramatic effect on decreasing the total temperature rise.

Interconnect Medium	Pros	Cons
Nickel strips	• Inexpensive & commonly available	• Lowest conductivity of the list
Copper strips	• High conductivity, commonly available	• More expensive than nickel • Potential to rust with humidity
PCB	• High conductivity depending on board thickness • High precision	• Custom made • Most expensive module / cell interconnect method
Wire	• Inexpensive & very commonly available • Available in wide variety of thickness	• Soldering heavy gauge injects a lot of heat into the cell when manufacturing
Buss bar	• High conductivity • May provide structural assistance to the pack	• Custom stamped or custom cut

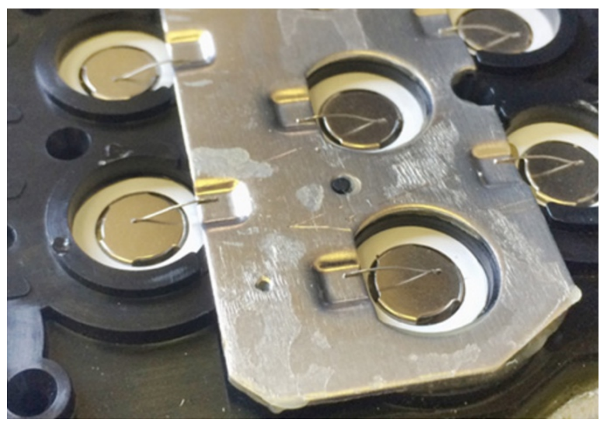
Developing a solid module to module interconnect method that works for your production capabilities, facilities and assets are important to controlling costs and becoming a scalable production facility, but on the design end, cross sectional area of the interconnector, installation method and routing are careful factors to consider pre-production.

Cell level Fusing

Fusing at any level has a very interesting task; the official definition of an electrical based fuse is:

NOUN
a safety device consisting of a strip of wire that melts and breaks an electric circuit if the current exceeds a safe level.

From a safety design standpoint, adding fuses at various connection points in the circuit provides a higher level of safety. On the electrical efficiency standpoint, meticulous selection of the fuses will have grave effects on the total pack design. As we take a look at the definition it's "a strip of wire that melts and breaks"; in order to melt or break, a resistance must be introduced into the strip of wire thereby creating heat at a certain current level sufficient enough to break the electrical connection.

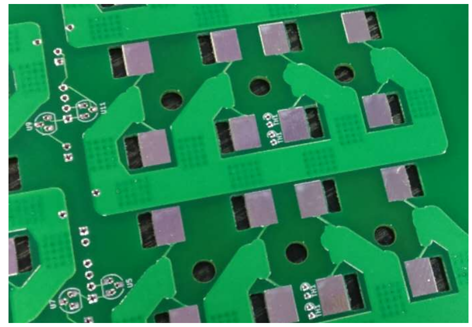


Tesla's Model S / X wirebonding fuse system

When dealing with cell level fusing, the individual current cell nodes can experience are small relative to the whole pack. Being able to balance a non-restrictive electrical pathway and the ability to melt a strip of wire to a point of disconnecting the circuit are counterintuitive to each other. Typically, cell level fusing has the job of removing an individual cell from a parallel bank in case of cell issues, which will allow continued use of the entire pack minus the singe cell with issues. When designing a battery system, individual cell failures are infrequent depending on the cell manufacturer and quality control process, but if they occur, removing them from the bank early allows the remaining parallel cells to continue functioning without issue.

Tesla made it more prominent in their Model S packs utilizing a wire bond method. The cell level fusing offers a straightforward approach, but requires expensive machinery on initial investment to securely place and ultrasonic weld the 2 ends of the wire to the cell terminal and distribution block.

Another method, which has gained popularity recently is the PCB trace method, which Evoke is currently using. With careful calculation on what you want your current limit to be, traces on a PCB can be laid out similar to a standard fuse, offering a calculated amount of resistance to then melt the trace and break the electrical connection, thereby removing the weak cell out of the parallel bank.



Evoke's PCB fusing system

Battery management system & other active components

In most small to mid-size battery packs, active electronics are usually going to be packaged together with the individual cells to save on space, molding costs and reduce the number of interconnects between active electronics and other various components. When considering this integration method, there needs to be a fine balance between integrating and separating when it comes to heat generating components.

Onboard any control circuitry you will find resistors, balancing FETs, voltage conversion, power FETS, contactors or relays, all which produce heat while active. On Evoke's integrated BMS, active components may reach up to 50 to 60°C, which is within the components working properties (while balancing, charging on controlling thermal management) but the temperature rise of the BMS propagates to nearby cells. Careful attention must be paid to then insulate the BMS from the individual cells without hindering the installation method, interconnections and overall placement.

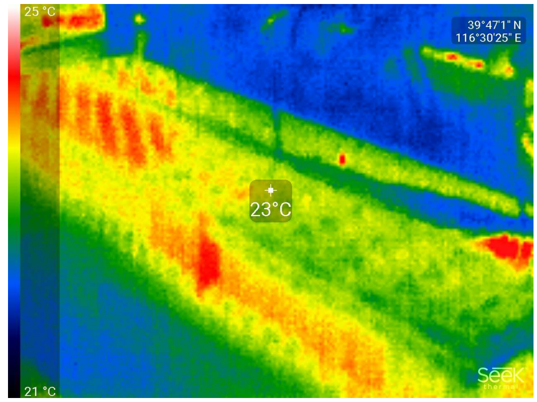
External Peripheral Heat Sources

Propagation

Finally, the last element to discuss in this white paper on peripheral heat sources within a battery pack, external to internal propagation and cell to cell propagation.

With battery packs weighing in at a few KG to a few hundred KG, there is a wide range of thermal mass when it comes to discussing external to internal propagation. When dealing with a hot external temperature with a medium external temperature scenario, or vice versa, beyond adding an active thermal management system like the systems offered by Evoke's battery packs, there is little that can be done to control the internal temperatures to better balance them. Additional challenges present themselves when dealing with mid-size battery packs with multilayers, as layers and cells closer to the enclosure walls begin to shift in temperatures before those closer to the center.

Within an active thermally management battery pack, you can see the uniformity of the cell temperatures within the pack itself. A uniform temperature over the pack helps to extend cell and pack life by maintaining a uniform capacity level of each cell, thereby offering a more balanced string levels during operation and longer use per charge.



Thermal image of Evoke's battery pack; internally balanced temperatures due to thermal management

Active thermal management

Comparison to passively cooled systems

The main difference of active thermal management is the it offers the opportunity of heating or cooling the pack beyond the temperature of the ambient air. This is critical when operating in extreme hot or cold environments. Passive thermal management systems suffer when the ambient air either exceed the maximum thermal limits or goes below the minimum thermal requirements for charging or discharging. When encountering situations such as this, passive systems are only able to shut down charging and discharging to prevent the battery pack system from being damaged, leaving the pack unusable during the duration.

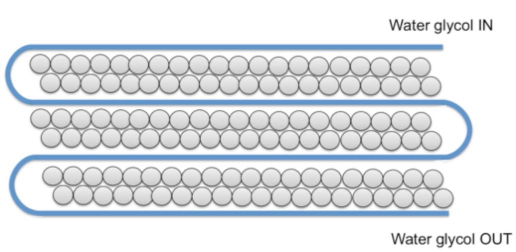
This is often not acceptable in mobility or automotive applications where the vehicle must continue operating within large temperature ranges and be required to function consistently within those temperature deltas. Furthermore, passive thermal management systems often suffer from extreme limiting of power in situations that the ambient temperature is close to, but has not reached the battery pack's peak operating temperature. If there isn't an active thermal management system to regulate the temperature to a desired level, performance and power output of the pack may have to be reduced to prevent the pack internal temperatures from being pushed beyond their rated thermal limits. This reduces the effective performance of the pack by not allowing it to output the rated levels the cells are capable of.

Active thermal management uses one or multiple cooling solutions to lower pack temperature to either beyond or below ambient temperatures. This allows the pack to operate in a wider temperature range as well as have increased performance in that temperature range as the pack has an increased thermal buffer from which to operate.

General introduction of various types of cooling

Cooling the side of an 18650 via air or liquid has, up to this date, been the staple of thermal management methods. The most basic of thermal management is radiating the heat of the cell into the surrounding air. Cell spacing and, conversely, pack density suffers from having allowance gaps between each cell to reduce the amount of cell to cell propagation when dissipating cell heat.

Moving up to the next stage of thermal management is liquid surface cooling of the cells. Companies like Tesla have chosen this route for their cooling method. They run a hollow metal ribbon between the cells where they pump water-glycol mix through bringing the adjacent cell temperatures down to a more manageable level. Cell spacing can be reduced and thus increasing pack density by moving each cell closer together and closing



Tesla's water cooling system

the gap between them. The water-glycol mix cools the metal ribbon, which thus cools the side of the cells.

The major downside of surface cooling on 18650s is the inclusion of a heat shrink layer around the cell itself. This prevents the cell from making electrical connections to metal objects touching the casing, and also mitigates self-shorting from the + terminal to the -. This heat shrink wrap itself is made of a thermoplastic and is therefore an electrical and heat insulator. By doing any sort heat transfer through the thermoplastic is a massive reduction in thermal efficiency. Tesla & Evoke goes one step further to mitigate this by removing a section of, or the entire heat shrink layer from the 18650 cells. Careful attention needs to be paid that if the shrink wrap is removed, there is a high chance of self-shorting without a very stable manufacturing process and solid battery designs.

18650 heat shrink wrappers

Finally, the highest stage of thermal management of 18650 cells are the most thermally efficient way to transfer heat out, but also the most difficult to design around due to the electrical conductivity of the thermal management method, which is tab cooling.

"*Tab cooling is difficult due to the need to electrically isolate the cooling system to prevent a short circuit of the pack and also to ensure that no failure of the cooling system at a joint, results in the release of coolant into the battery pack itself."*

--- Ryan Maughan, MD of AVID Technology Group Ltd.

Tab cooling is, by far, the most efficient, but most challenge method of moving out heat from the cell. With Evoke's thermal management system, to diminish the issue of release of coolant into the pack itself, we design the entire system using solid state cooling plates with no liquids or coolants. This offers the best of both worlds, getting direct cooling from the negative terminal itself with no liquids to pump through the system. Evoke has also devised a method to electrically isolate the system while allowing a high rate of thermal transfer.

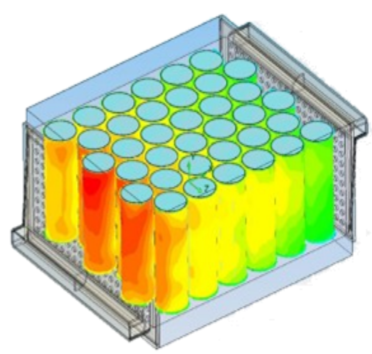
Pros and Cons of Active and Passive Thermal Management

Active management comes with many benefits and several drawbacks that must be considered when deciding to go with an active thermal management solution. The chart below shows the characteristics of both active and passive management systems. In the section below we will go into more detail on the different characteristics and points that pack designers will need to consider when choosing either an active or passively managed thermal system.

	ACTIVE MANAGEMENT	PASSIVE MANAGEMENT
COSTS	Medium to high	Low
PACK LIFETIME	Increased lifetime and cycles of packs, especially in extreme temperatures	Inferior lifetime and cycles of packs. This becomes more apparent in extreme temperature applications
PACK DENSITY	Lower density due to active thermal management systems requiring space in the battery pack.	High density due to the lack of active thermal management systems to take up space in the pack.
PACK PERFORMANCE	High pack performance is due to the pack not needing to limit power output when the pack is close to peak temperatures	Must reduce pack performance drastically when approaching thermal limits.
POWER CONSUMPTION	Minimal to large depending on the pack size and application	No power consumption spent on thermal management
CHARGING TEMPERATURE RANGE	Wide temperature ranges	Narrow temperature ranges due need to minimize battery degradation at temperature extremes

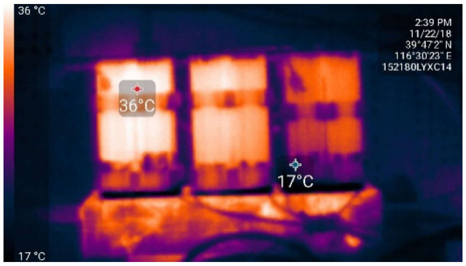
Pack Lifetime

Life of the battery pack is an important consideration in many battery systems, as a longer lasting pack will decrease the cost of use of the asset over its lifetime. This is especially prevalent in industrial or commercial applications where cost vs lifetime of the asset is crucial for effective cost control.



Cylindrical cell pack imbalances

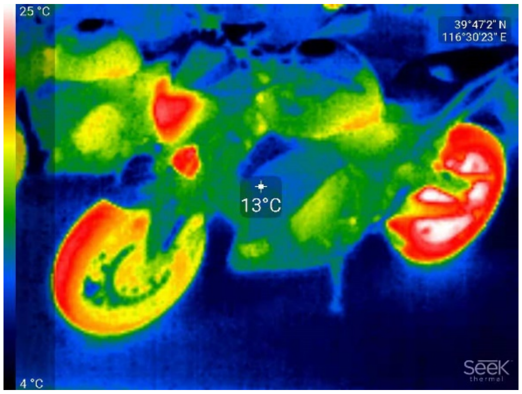
Temperature deltas within a battery pack are crucial in maintaining longer lifetimes of battery packs. Localized hot or cold spots can cause increased internal resistance deltas within the pack that may over time imbalance the battery packs strings. These imbalanced strings will slowly degrade their capacity relative to the rest of the pack. Due to battery packs capacity being based off their weakest string, one highly unbalanced string can greatly reduce the usable capacity of the battery pack.



Thermal image of hot / cold spots

This can happen by the battery pack cells themselves heating the pack or by internal connections within the battery pack creating a temperature imbalance. Another source of temperature imbalance is due to localized heat sources outside of the battery pack. Direct sunlight, radiators, motors, inverters and battery chargers can all provide significant amounts of heat generated and depending on the location and placement of components. In the diagram below you can see a thermal image of Evoke's Urban S after hard riding. You can see the thermal differences of the different components on the vehicle. Depending on the design and placement of components, these high heat sources can create localized hotspots on the battery and over time create temperature imbalances.

Hotspots will cause the strings of the pack to become more and more imbalanced overtime, resulting in decreasing performance and capacity drops in the battery pack. This can become a continuous cycle of degradation and imbalance as the cells' internal temperature difference from the rest of the pack will cause the cell impedance to increase even more. This will further strain the cells that are experiencing the temperature imbalance.



Component level hot spots; thermal image of an Evoke Urban S

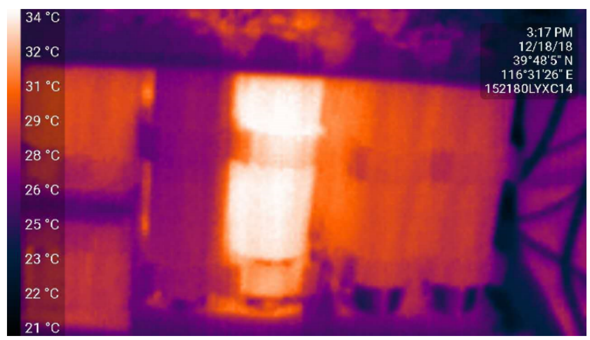
As well as minimizing temperature deltas from different cells within the pack, consideration must be taken to minimize temperature deltas within the battery cell itself. While many battery temperature simulation models view the battery cells as one continuous system, the different layers of the cell can experience significant temperature deltas within the cell. It is this area in particular that lack of proper active thermal management can create undetectable stress in the battery pack due to temperature deltas within the cell.

As discussed earlier, heat buildup occurs in the cell during its charging and discharging cycle. Due to the makeup of lithium cells being multiple layers stacked tightly together in a metallic case, the layers on the edge of the cell will cool significantly faster than at layers in the middle of the cell, this can cause the cell internally to heat up and have a much higher temperature than layers at the edge of the cell. Increased heat buildup may cause the internal layers of the battery cell to be well beyond its ideal temperature range.

This can cause capacity degradation and cycle reduction within the cell as different sections of the cell experience different levels of degradation. This will further decrease the lifetime and capacity of the cell as different sections of the cell will output higher current amount to compensate for the lower current output of the other sections of the cell.

Uniform IR within the cell

Another benefit of active temperature management is that the internal resistance (IR) of the pack will be lower during the operation of charging and discharging of the packs as the cells will be kept closer to the ideal temperature range. Low IR will further increase the capacity of the cell per cycle as well as decrease the self-heating of the cell during charging and discharging.

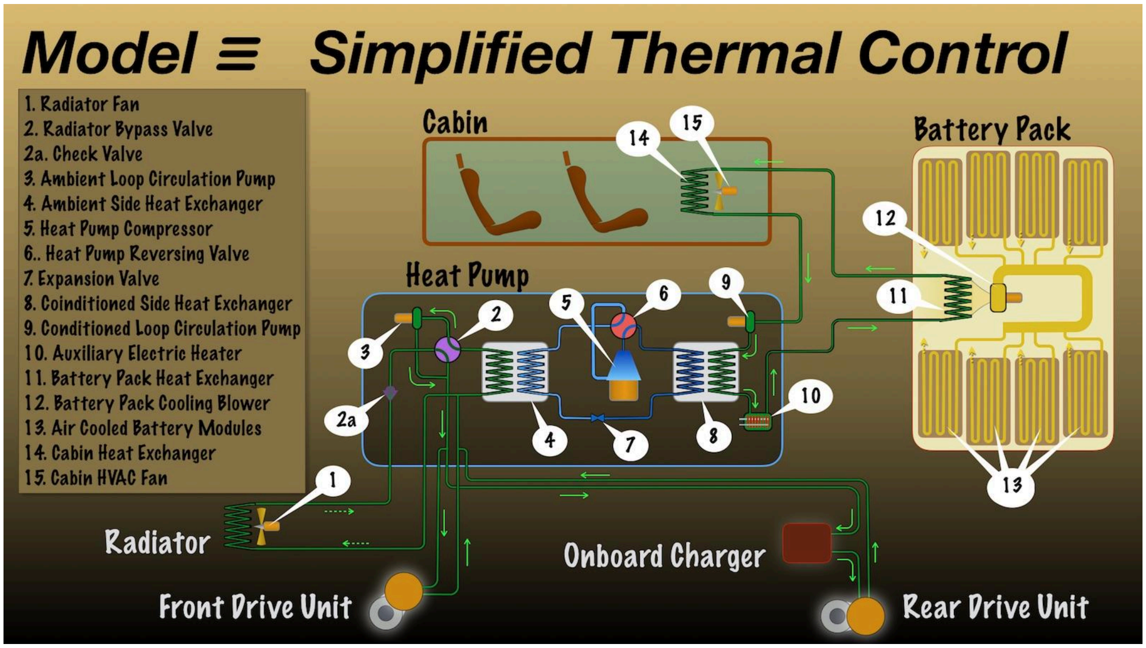


String level imbalances; IR build up

Imbalanced IR within the cell further adds to the IR imbalance, thereby creating a downwards spiral towards the death of the individual cell. By stabilizing the internal resistance of the cell will then ensure that the internal resistance of the pack is much more even compared to a passive thermal management system. This will prevent additional heating of the stress cells due to increased IR in the cells and electrical connections of the cell, further improving degradation due to heat buildup in the battery pack.

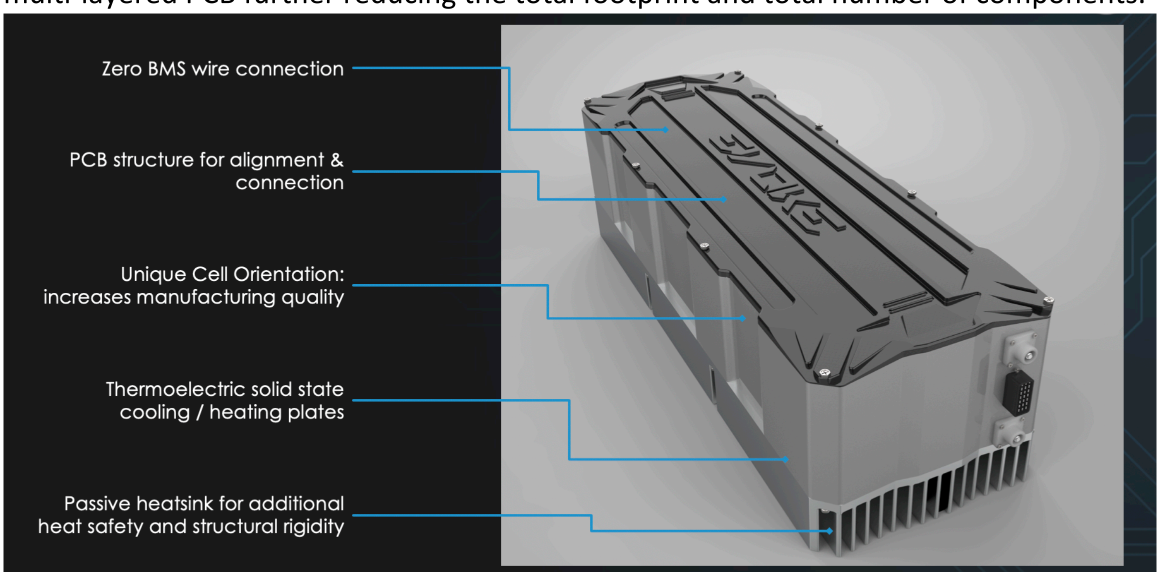
Pack density

When designing a battery with higher safety standards and adding in additional electromechanical components to allow faster charging safer and longer life, there must always be a balance. With the additional electromechanical components such as condensers, cooling ribbons, Evoke's solid state cooling plates or other additional control electronics, size is going to be a consideration. Depending on the complexity and ancillary components available for use with the thermal management system, automotive style thermal systems will share functionality of the AC compressor, freon piping, heat exchanger, heat exchanger fans, blowers and control systems.



When you compare to the battery pack density of an Evoke Gen 2 battery pack, the thermal management uses no liquids or compressors. With its solid-state thermoelectric cooling and heating plates exchanging hot and cold from the cells to the lower heatsink which then passively or actively radiates the heat out, this provides one of the highest pack densities for a thermally managed pack.

Additionally, the multi-layered printed circuit board (PCB) in Evoke's Gen 2 battery packs offers structural and electrical connection while passing all cell level information to the BMS without any traditional wires. Finally, all electronics are then embedded onto the multi-layered PCB further reducing the total footprint and total number of components.



Compared to non-thermally managed battery packs, automotive style can see a 10% to 20% increase in total footprint, taking into account all the ancillary components required for their system. Evoke’s Gen 2 battery packs will see minimal increase of sizing and weight compared to off-the-shelf lithium ion batteries. Finally, with the added benefit of Evoke’s battery packs features a liquid-less cooling system, this alleviates vehicle OEMs from having to incorporate liquid reservoirs into their design and end user consumers aren’t required to flush coolant or add antifreeze to the battery coolant system in the future.

	Evoke Gen 2	Lead Acid	Lithium Ion
Volumetric Energy Density (wH/L) Gravimetric Energy Density (wH/kg)	185.2 wH/L 152.4 wH/kg	60 wH/L 30 wH/kg	148.1 wH/L 148.1 wH/kg
Capacity	1.37kWh	1.2kWh	1.2kWh
Charging Speed	15 min – 2.5 hours	8 – 10 hours	3 – 8 hours
Lifecycles	1000 – 4000 cycles	200 - 400 cycles	500 – 800 cycles
Smart Monitoring system	Yes	No	No
Heating	Yes	No	No
Cooling	Yes	No	No
Cell fusing	Yes	No	Usually no

Pack Performance During Charging

A well designed active thermal management system will enable the pack to have higher peak power levels and longer constant power levels than would be possible within a passive thermally managed system. Battery pack designers now face the task of having higher peak power usage as well as higher RMS charge and discharge current levels than ever. As battery packs are required to be have both physically higher capacity as well and be able to both provide and receive significantly larger amounts of power for longer periods of time, the battery packs thermal management system has become a critical component to keep up with increasingly more difficult requirements and expectations.

A major source of heat generation of a battery pack is during charging. Heat is generated by both the internal resistance of the cell during charging as well as heat buildup from the chemical reactions occurring in the cell during the charging process. Heat generated during the charging process can be especially high compared to discharging as the cell has to undergo a much more strenuous chemical change to store lithium ions than when discharging. This change in cell temperature can degrade battery life and if it rises too far can cause the cells to experience thermal runaway or even cause the battery pack to catch on fire. At best it will raise the cells beyond recommended limits, thus decreasing performance and life of the battery pack.

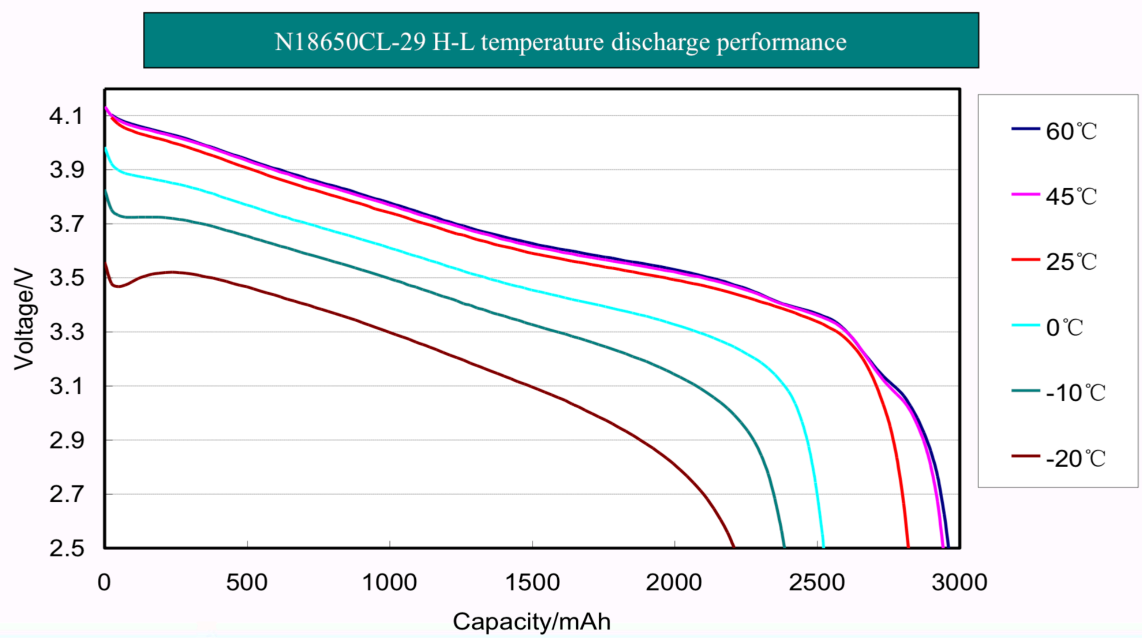
Using an active thermal management system can greatly reduce the impact of the heat buildup as the heat is transferred away from the cells during the charging process. This allows the cells to stay cooler for longer periods of time and prevents the IR raise that occurs because of the temperature increase in the cell and pack materials.

Extra cooling power can be provided during charging due to the availability of the charging power source as power to cool the cells. As long as the charging circuitry and power supply can handle the increase of current, the benefit is then being able to provide increased cooling power to the pack while it is charging while not consuming precious capacity of the battery. As such, many cooling systems will provide extra power during the charging cycle if it is needed to maintain the appropriate temperature range required during charging. Once the battery pack is finished charging and if the vehicle is still connected to the charger, the cooling system may continue to stay on to bring the battery pack to an ideal temperature range for battery life and to provide optimal performance when the vehicle is used.

During discharge the thermal management system may also be engaged to allow the battery pack to provide better performance of the battery pack. However, care must be taken to how much power is provided to the cooling system vs the loss of range the battery system will experience due to the battery capacity being used for cooling instead of providing motive power for the vehicle. As such, unless the battery pack is approaching its thermal discharge limits, usually light to moderate cooling is deployed as a comprise of keeping the battery pack closer to its ideal temperature range while also allowing the majority of power to be used for motive purposes.

Active thermal management can be especially useful in sub-zero or close to zero environments to increase both performance, and capacity of the battery pack. As mentioned previously, when the battery cells approach O°C, the electrolytes can freeze and cause the cells internal resistance to increase significantly. This can decrease the discharge power that the battery pack is able to provide while also decreasing the capacity of the battery pack. Power decreases in cold temperatures can be especially prevalent when the pack SOC is low, as such battery packs with passive thermal management systems can experience significant limitations on power output temperatures are subzero.

2.3 High-Low Temperature Discharge



Looking at the above discharge graph of a BAK N18650CL-29 cell, a full cycle from 4.20v to 2.50v discharge at 1C at 25°C and -20°C yields a 2,860mAh to 2298mAh capacity respectively, with a typical 20% capacity drop per cell.

With an Evoke Gen 2 battery pack, with a nominal capacity of 2.24kWh at a string charge of 4.15v per string, without the thermal management system / battery heating system engaged, at -20°C users would experience a 20% capacity reduction of usable capacity; this equates to 0.448kWh of capacity.

Power Consumption

Any active cooling system will consume some power in regulating the temperature of the battery pack. A good pack designer will balance the cooling power needed to maintain the temperature to an ideal level while also considering the power required to cool the battery pack. As such, a smart designer will regulate the cooling system to situations that will maximize cell and battery performance.

With Evoke's thermal management system / battery heating system engaged, typical power draw used to heat the batteries to +5°C from -20°C is about 400w of heat or about 0.4kW; engaging for over an hour would utilize about 0.4kWh of battery capacity. The thermal management system cycles the heating / cooling plates to maximize range of the vehicle and pre-heats the batteries before charging to a safe charging temperature to ensure maximum life and ultimate convenience.

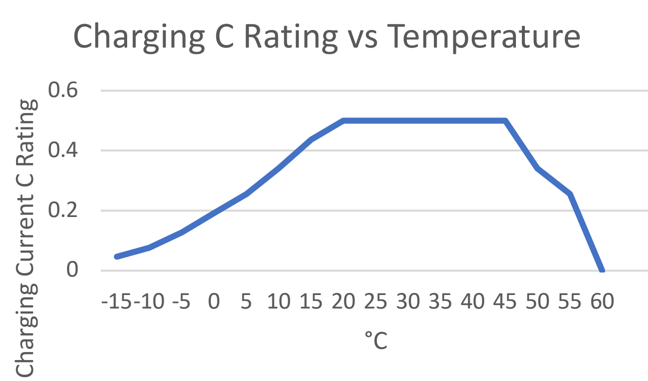
Moreover, Evoke's Gen 2 battery packs and thermal management system can be run in low power mode, passively radiating heat from negative cell terminal to heat sink. A light duty battery can also be manufactured for customer requirements that do not require extreme charging and discharging cycles and simply want a safer, more stable, and longer life battery pack. This light duty battery pack uses a combination of passively radiating heat from the heatsink and combines it with forced air.

Charging temperature range

Charging in subzero temperatures

Another area of concern is that pack designers must pay attention to is charging at subzero temperatures. As we explained previously, charging at temperatures below zero can cause extensive damage and shorten the life of the battery pack greatly. While increased internal resistance of the cells due to the cold temperatures will heat the battery pack cells a little during charging, very often it is not enough to heat the battery pack to an acceptable temperature. As such, heating the battery pack can increase the life of the cell significantly while also allowing the battery the battery pack to be charged and used in environments where passive thermal management battery packs would not be able to be operated in.

Most cells require charging power reductions starting at temperatures below ten degrees Celsius. This can be problematic for battery packs that require battery designs to be charged at higher consistent speed. As such being able to heat the battery pack can allow for higher charging speeds while preventing the battery pack cells from being damaged.



This is less of an issue in home or handheld electronics applications, where the assumption is that the device will be operated in a well-regulated environment where the human operator will use the device. However, this becomes increasing problematic in mobility applications where the vehicle is charged outdoors for safety and practical reasons.

The user experience is also often affected by the fact that the battery maybe left charging for long periods of time when the user is not with the vehicle. This extended time can allow for the ambient temperature to change quite drastically, causing the battery to stop charging and the user returning to a vehicle that is not fully charged. Since users do not understand the intricacies of battery systems and chargers, they often blame the device manufacture for making a system that does not change in the environment they are using it in.

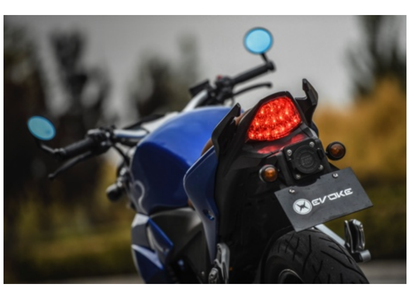
Active thermal management systems are especially important for battery systems that work in industrial or commercial applications. Because the potential loss of revenue due to devices not being operate the equipment using the battery systems. Batteries for these solutions require high reliability guarantees that the device will continue to operate in a wide temperature range. In applications such as this, active thermal management systems are critical to ensuring that the machinery can fulfill its uptime requirements. The reliability and increased temperature range the batteries are able to operate in greatly outweigh the slight cost increases for active thermal management systems.

A case study in the financial impacts of a using passive thermal management systems was a battery system designed for a large delivery vehicle fleet operator in China. The vehicles were used in a temperate environment and the fleet operator did not feel that the vehicle systems would require an active thermal management system. After analyzing the usage case and the temperature range that the batteries would be operated in the fleet decided to go with cheaper passive thermal management systems instead.

However, several months into operation of the vehicles, a sudden and unexpected cold spell caused the temperature to drop below zero for several days. This caused the battery BMS systems to disable charging for the battery, causing the fleets vehicle to not be used for several days. This caused their whole delivery fleet to not be usable, which incurred a significant cost to their customers who used their fleet for their own delivery services. The loss of business, coupled with the financial penalties incurred for the extended down time incurred significant financial costs for the company. In situations like this an active thermal management would elevate the situation and prevent the situation from happening and allow the fleet to operate in spite of these issues.

Evoke's ultra-fast charging Gen 2 battery packs in a swap station; offering heating in cold climates

Conclusion



Active thermal management in small-scale and large-scale battery packs are important to guarantee a certain level of pack life, allow proper operation in a wide temperature range, increased overall performance that begins to match or exceed gas vehicles and an overall level of stability over the duration of pack use.

Challenges in thermally managing small or light application battery packs remain to be the balance of power consumption and the heating and cooling algorithms to maximize pack capacity vs heat and cooling of the cell, an overall lack of R&D put into battery design that encompass active thermal management, maintaining usable pack density and the development of the control systems on the battery and thermal control side. Key development on small-scale EV thermal management battery packs are constantly being led at Evoke due to the expertise and experience from Evoke's EV development division. Core use case scenarios set forth by creating high-power electric motorcycles are translated over to battery and thermal management development as we continue to **push the boundaries of ultra-fast charging down to minutes** while maintaining the **stringent safety requirements** and stability of new energy batteries.

We invite you to learn more about how a thermally managed battery pack can help **increase your e-vehicle's performance while extended the life of your battery pack** for years to come. Please contact us at contact@evokeev.com for more information.

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