Things Flight Testers Should Know About Batteries for Electric Propulsion

Alberto Favier, Pipistrel Vertical Solutions d.o.o.; Stephan Roberts, AeroTEC Inc.;
Josh Esfeld, Individual Contributor; Jennifer Uchida, AeroTEC Inc.

Abstract

The implementation of flight test techniques for electrically powered aircraft is still very unknown to the average flight tester. This paper is for the flight testers that are starting to evaluate battery powered propulsion technologies in new or current aircraft. This guide is scalable to program scope: from small UAV's to large aircraft. This paper's Safety and Risk Analysis will be taking time proven approaches and implementing them to this new technology. Since electric propulsion technology is handled differently than conventional propulsion systems, we have developed a set of performance metrics suitable for these new electric-powered propulsion systems. How these new systems integrate into the aircraft will also be considered as different battery/power plant combinations can impact flight test approaches.

Introduction

There are many types of batteries that can be used for electric aircraft propulsion, the right one is obviously based on the mission and requirements of the aircraft. Typically, Lithium-Ion (Li-ion) batteries are used but even among Li-ion there are several types that can bring various advantages and disadvantages to an aircraft propulsion system. Assuming the battery chemistry requirements have been fulfilled in the design phase, this paper will focus on integration into the aircraft systems, battery performance and flight test operational limits and safety.

Systems Integration

Although a flight test engineer is not responsible to integrate the battery system into an electric aircraft, certain aspects of the integration such as installation, instrumentation, and interfaces with other systems must be understood, scrutinized, and verified against requirements prior to testing the full system. FTEs and test pilots are the ones putting their lives on the line by operating vehicles powered by such cutting edge and unproven technology, so it is imperative that any operator has a high degree of confidence in the system's ability to perform safely. Some of these considerations would be applicable to any aircraft such as the installation meeting industry structural crashworthiness standards, and high voltage equipment bonding and grounding requirements, so for the purposes of this paper only topics relevant to batteries and electric aircraft will be covered.

While each individual airframe and battery pack combination will be uniquely designed and integrated, there are several requirements relating to integration that are based on first principles for every flight test that should be verified and validated prior to flight. The physical location of the battery pack - whether it is installed in its own compartment, incorporated into the airframe, or occupying the wing ullage in place of fuel - must adhere to the aircraft's CG range, must never exceed zonal loading limits, and must be adequately isolated from potential hazards and personnel. The battery pack must also be accessible such that the system can be properly inspected and maintained. EMI, HIRF and Environmental Conditions are other critical elements of system integration and should be thoroughly investigated, tested, and verified to not affect the battery or any other system's ability to perform.

Regardless of whether the battery pack and Battery Management System (BMS) were supplied in-house or by an external company, there needs to be a high level of confidence that the system was qualified to the standards outlined in Environmental Standards in RTCA DO-160 and in the current battery testing standards found in RTCA DO-311. Since many battery manufacturers have yet to be fully involved in the aerospace or flight test world, the FTE is entitled to scrutinize the supplier and the responsible engineer to ensure adequate levels of safety and reliability - most important of which is proof that thermal runaway propagation has been addressed and will not occur under the intended operating conditions expected in the flight test.

Typically, some form of battery specification sheet, user guide and certificates of complying with applicable industry standards are delivered with the pack. This is important, as these items offer grounds in which to verify and validate several important system and subsystem level requirements via the bench testing performed by the battery pack manufacturer before aircraft installation. Testing on a subsystem level must be conducted to validate functionality and several of the aforementioned considerations before testing the entire integrated aircraft. Test requirements should be derived from the battery specification sheet and any associated documents. At a minimum, this testing should cover the following:

1) Normal system power-up and power-down procedures, as well as non-normal/emergency power-down procedures
2) BMS calibration testing to ensure the BMS properly interfaces with Electric Propulsion Unit (EPU), powertrain control software, and aircraft controls
3) CAS message testing to confirm the system displays the appropriate advisory, caution, or warning messages to the test operator depending on the specific fault / failure scenario
    a. This testing could be done by the supplier and provided to the FTE
4) Normal charging procedure to verify the battery system can be safely and reliably charged 1) (i.e. the first time charging the battery pack should be treated as a test)

Another important consideration is the battery systems' internal instrumentation and means of indicating this information. It should be established during the design process, or at least at the battery specification level if the battery is delivered from a supplier. The FTE should become familiar with the internal instrumentation parameters deemed critical to the safety and performance of the battery pack, as well as how this information will be related to the test operator. The minimum instrumentation should reflect the critical parameters listed in the Safety of Flight Test Operations section to provide adequate visibility into the internals of the battery pack and BMS for any critical parameter exceedances. Furthermore, it is just as imperative to understanding the location within these components and the fidelity of sensor data within the pack (e.g. 1 temperature sensor per 10 cells paints a much clearer picture versus 1 sensor per 50 cells), and how this info is displayed (e.g. an internal 'heat map' of temperature data within the pack for monitoring during test versus limited visibility during test and being able to check more in-depth afterward).

The detailed battery system user guide is another essential consideration in understanding how the system is configured and intended to operate safely. At a minimum, there are several crucial pieces of information the user guide should include: an overview of the system architecture (e.g. how many BMS's and strings of batteries exist for redundancy), safety features (e.g. kill switches, fire detection, etc), system controls, and all human machine interface (HMI) related indications. Within the HMI display section of the user guide, a flight tester should be able to extract information such as how control inputs, battery performance, critical parameters and their limits are displayed, as well as all CAS messages, what causes them, and how to react in non-normal situations. An example of an electric aircraft HMI display with CAS messages is shown in Figure 1 with the following indications:

1) Engine RPM
2) Menu selection
3) Power Output
4) SOC for each module
5) DTE (Distance till empty) indication
6) Battery Voltages
7) Aux Battery Voltage
8,9,10) Motor and Battery Temperature

FLIGHT SYSTEM

BATTERY

Position:	front	rear
Status:	Active	Active
SOH:	99	100
Temp:	41℃	41℃
MIN volt:	4.090V	4.100V
MAX volt:	4.100V	4.123V
Voltage:	379V	379V
Current:	89.0A	75.0A
Balancing:	off	off
Coolant:	20℃	

ENGINE

Status: active
Temp M: 65℃
Temp I: 51℃
Coolant: 46℃ IN
Coolant: 63℃ OUT
Hobbs: 8h 20min

POWER LEVER

Status: active
Seen zero: yes

DC/DC

Status: active
Out volt: 0.5V
Out curr: 1.0A
In volt: 369.0V
In curr: 0.3A

Figure 1 The Pipistrel VELIS Electro powertrain interface contains critical battery parameters laid out in an interpretable fashion using existing industry display guidelines. The Flight page is displayed on the left, and the System page is displayed on the right.

Battery Performance

To understand how a battery operates in different conditions, it is important to know how the cell characteristics depend on the battery status. This section focuses on the most relevant dependencies of the two main battery specifications: the battery capacity and the battery internal resistance.

Battery Capacity

The battery capacity depends mainly on the battery temperature, battery age, and the current setting. Several studies, listed in the References, analyzed the effects of battery temperature over battery capacity, considering different battery chemistries. The general trend is similar for all battery chemistries and features a capacity increase with an increasing battery temperature. As a reference, the voltage evolution and the capacity measured by Reference 2 for Li-ion cell batteries are shown in Figure 2.

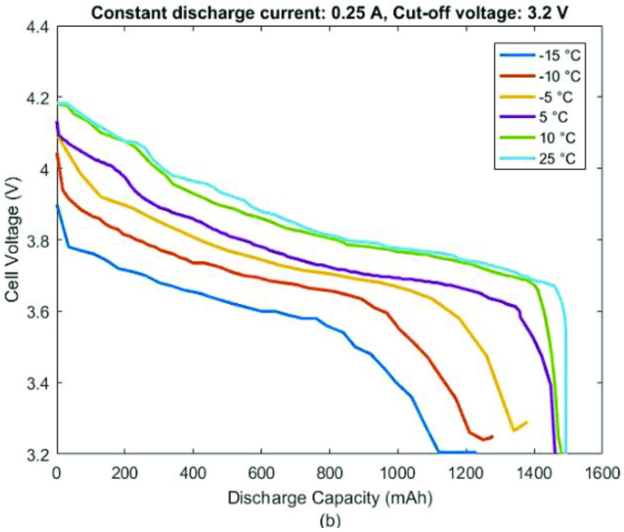

Figure 2 Cell Voltage vs Discharge Capacity at Various Temperatures

As the battery ages, the capacity decreases. Several studies investigated the capacity degradation due to the aging effect (References 4, 5 and 6). Figure 3 shows measurements of battery capacity drop with the battery cycles at different discharging currents (Reference 7).

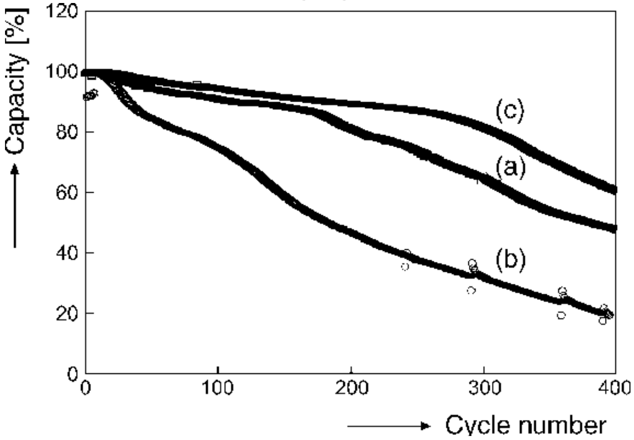

Figure 3 Cycle life of cylindrical Li-ion batteries under high charging load conditions at I max = 4.5 C, V max = 4.2 V (a) and I max = 4.5 C, V max = 4.3 V (b). Cycle life upon standard CCCV-charging (I max = 1 C, V max = 4.2 V) is indicated in curve (c)

For more detailed reading you can find the following information in the following references:

- Reference 1 focuses on lithium iron phosphate battery
- Reference 2 experimentally investigates the behavior of a Li-ion cell operating at low temperatures
- Reference 3 provides the temperature effects on Li-ion batteries

Battery Internal Resistance

Battery internal resistance depends on the battery age, the battery temperature, and the battery SOC. The References provide several studies about such dependencies. For instance, Figure 4 from Reference 8 shows aged Li-ion 18650 SAMSUNG ICR18650 cells to failure, recording important aging parameters such as capacity and internal resistance.

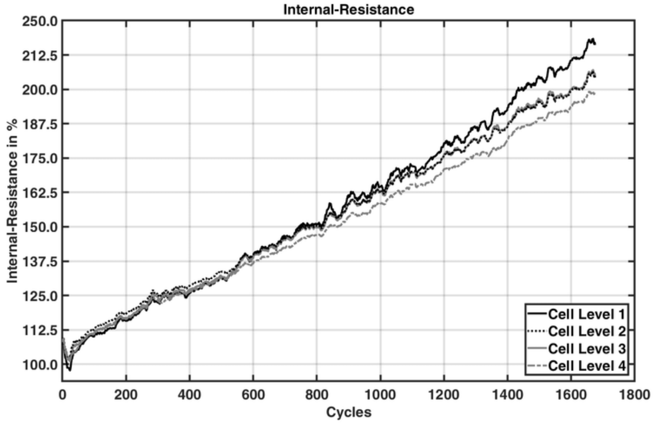

Figure 4 Aged Li-ion Cells Taken to Failure

Reference 9 recorded internal resistance for different battery temperatures and ages as part of its temperature and short-circuit research (Figure 5). It is worth noting that most battery cells feature a sharp internal increase at low temperatures. Other cells may also feature internal resistance increase at high temperatures.

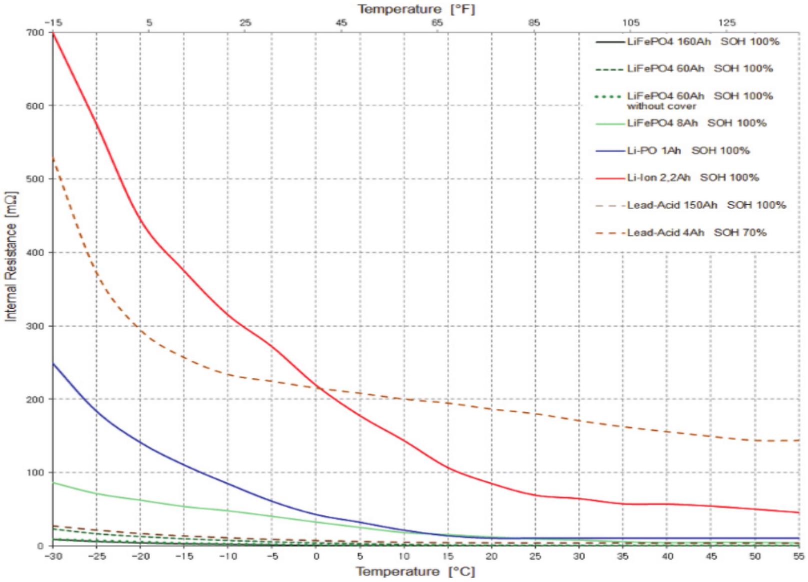

Figure 5 Different Batteries Temperatures and Ages in Short Circuit Research

Reference 10 developed a Kalman filter for Li-ion battery SOC and run measurements of internal resistance dependency on the SOC (Figure 6).

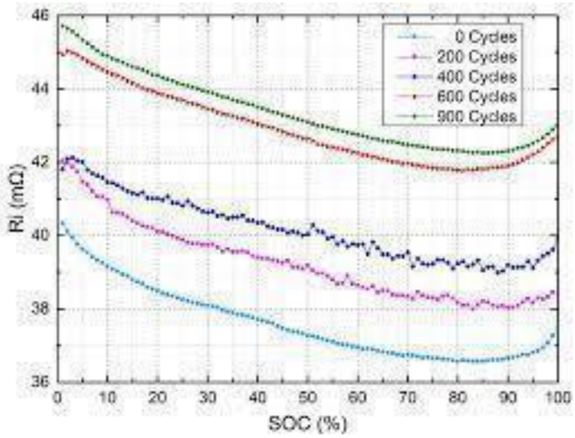

Figure 6 Kalman Filter for Li-ion Battery SOC

Battery Discharge Performance

Battery discharge performance refers to the battery’s ability to supply power and energy. Battery performance stems from the battery pack capacity and internal resistance, which primarily depend on the cell characteristics and the battery pack configuration, namely the number of cells and their disposition/assembly within a battery pack. Besides those features established during the design process, the battery performance is significantly affected by the battery’s current status. The main parameters playing a role in this regard are the battery voltage, the battery temperature, and the battery age or State of Health (SOH). Despite battery power and battery energy being strictly correlated, it is helpful to treat battery discharge performance under two separate headings: the battery maximum discharge power and the battery available energy. In the following subparagraphs, the battery SOH is assumed to be constant and the temperature effect is ignored. Further paragraphs will investigate the specific effect of each item. In addition, the following paragraphs consider the performance of a battery pack. Within the battery pack, all cell modules are assumed identical and equally balanced.

The Battery Maximum Discharge Power

The battery discharge power is defined as the instantaneous power that the battery pack can supply to an external load. The battery discharge power is computed as the product of battery current and battery voltage.

$$P_{pack} = I_{pack} * V_{pack}$$

Equation 1

Given this definition, it is possible to deduce that the maximum discharge power is obtained when the battery is at maximum current and maximum voltage. The battery maximum discharge current is set by the cell characteristics and the battery configuration. Cell manufacturers specify the cell maximum discharge current as part of the standard cell datasheet. From the cell maximum discharge current, the battery pack maximum discharge current depends on the number of cells installed in parallel within the battery pack.

$$I_{max} = I_{max}\,(cell) * N_{cell\ Parallel}$$

Equation 2

Whenever a battery supplies current, the battery voltage suffers from a voltage drop because of the internal resistance. The voltage drop depends on the internal resistance and current. In a preliminary and simplified approach, this dependency can be expressed with a linear relationship as described in Equation 3.

$$\Delta V_{pack} = I_{pack} * R_{pack}$$

Equation 3

Considering Equation 3, the definition of battery power in Equation 1 and Open Circuit Voltage (OCV), it is possible to develop the expression of the available discharging power as

$$P = I * V = I * (OCV - \Delta V)$$

Equation 4

Accounting for the voltage drop expressed in Equation 3 and considering the internal resistance dependencies, it is possible to retrieve that the maximum battery voltage is reached only in a specific battery condition; at its full charge point. In all other conditions, the battery maximum discharge power is a function of the battery SOC. The available power is at its highest in the SOC top range and regularly decreases for lower SOC, down to 0kW for an empty battery. A graphical representation of the maximum discharge power as a function of the SOC is available in Figure 7. Note that depending on the battery specs, the available power may feature a top value between 80%-90% SOC and slightly decrease for SOC 100%. In general, all batteries show power degradation for low SOC ranges.

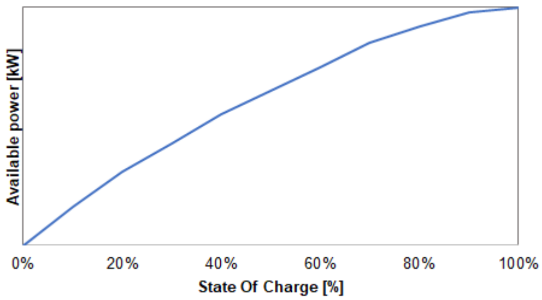

Figure 7 Relative Available Power vs SOC (generic y-axis scale shown for general application)

Depending on the battery type and configuration, the natural power degradation may vary significantly and be more or less severe. The key aspect to understand is that power degradation has a significant effect in both operational and test environments since operating the battery at low SOC may compromise the aircraft performance, for instance, preventing the aircraft from performing a go-around to a safe landing. Mapping the battery performance accurately in the entire SOC range is not only required to characterize the aircraft performance but is also a safety measure. The definition of SOC thresholds is a good practice. If SOC calculations are not accurate, additional risk can be introduced. A reasonable mitigation strategy would be operating the battery within a conservative envelope or having the SOC accuracy thoroughly verified before the flight campaign. A possible interpretation of Figure 7 and recommended definition of SOC thresholds are presented in Figure 8. Knowing the desired performance of the aircraft and the related necessary power, it is possible to determine the minimum SOC at which such performances are met. A further recommendation is also to avoid using power settings higher than necessary as they will imply faster discharge and more heat generation. The same approach used for the desired performance is followed to define the minimum SOC at which the aircraft features minimum acceptable performance. For a conventional aircraft, this may represent the power to perform a go-around. The test plan should describe that the flight test will operate within the normal SOC range and that the FTE should monitor that it is within normal range.

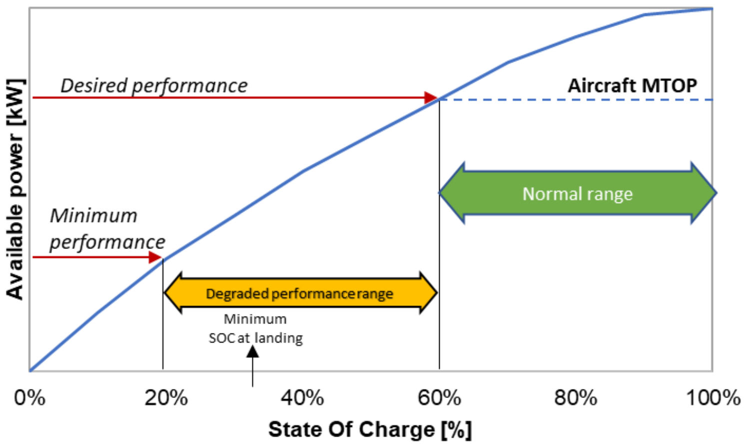

Figure 8 Available Power at SOC% (generic y-axis scale shown for general application)

Temperature and SOH Effects

The battery internal resistance plays a fundamental role in the definition of the maximum discharge power because it generates voltage drops (power losses) whenever power is supplied. As the battery ages, its internal resistance increases, which yields to continuous degradation of the maximum power that batteries can generate. A comparison between the available power at different levels of battery SOH is presented in Figure 9.

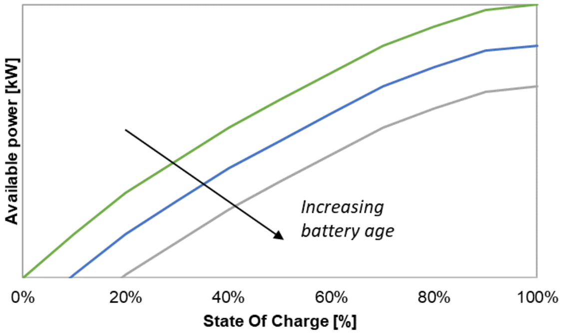

Figure 9 Relative Available Power at Various SOC% (generic y-axis scale shown for general application)

The natural degradation of power performance may vary significantly especially if the battery is designed to have a long lifetime. Such degradation requires proper testing to track the degradation of the aircraft's performance in its lifetime. For instance, performance measurements should be repeated with periodic frequency until battery SOH reaches 0%. A reasonable alternative would be to own a battery numerical model that predicts the battery power degradation accurately. The model could be used to select relevant levels of battery power and perform the tests simulating battery degraded conditions. When testing a low SOH battery, specific attention should be paid when exploring the low SOC range. Indeed, the aircraft may feature a significantly different performance and behaviors from the observations gathered when batteries were brand new. SOC thresholds and ranges presented in Figure 8 should be updated accordingly.

Internal resistance decreases when battery temperature increases. A lower internal resistance generates a lower voltage drop which, considering equation 4, ensures higher values of battery discharge power. The effects of the battery temperature over the available discharging power are graphically represented in Figure 10. Most batteries have an optimal temperature in which they have the best power output. Such temperature depends on the evolution of the internal resistance with the battery temperature (see Figure 5) which stems from the cell chemistry and battery characteristics. Given this dependency, it is important to record battery temperature whenever the aircraft performance is measured. Different tests for different battery temperatures may be performed, as an alternative, performance may be measured in the most conservative conditions, i.e. for the lowest battery temperature approved by the cell manufacturer.

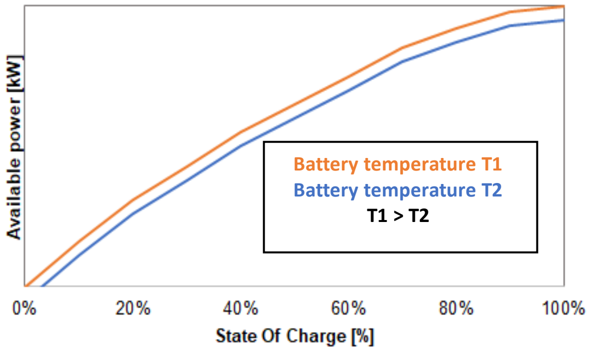

Figure 10 Available Power vs SOC (battery temperature effect) (generic y-axis scale shown for general application)

Available Energy

Battery manufacturers measure and specify battery performance using constant current discharge profiles. Such profiles are useful to characterize the battery cells, but they are not representative of operations in the aerospace industry. Aircraft can achieve level flight provided the engines/motors can provide the required power. Since the battery voltage is not constant throughout a battery discharge, batteries must supply an increasing current to maintain steady power. Such behavior prevents the FTEs from using the battery capacity as a reference from the aircraft performance. Battery capacity also is typically specified for low current levels that are not in line with the battery pack operations once installed in a propulsive system. A more useful parameter is the so-called “Available energy”. The available energy is the amount of kWh that the battery can supply to an external load at a certain commanded battery power setting. The available energy differs from the stored energy because it accounts for energy losses due to thermal effects. The available energy approach reflects how the battery performs in reality and allows for highlighting the dependencies of the battery performance. This is opposed to the performance stated by the cell manufacturers that are hardly backed by real operations empirical data. The available energy depends on the cell characteristics and the battery configuration, and also on the battery status. In order of magnitude, the battery parameters affecting the available energy are battery voltage (SOC), battery SOH, the specific power setting, and battery temperature. Logically, the amount of available energy depends on the initial value of SOC. However, including such a simplification may complicate the understanding of the cross-effects of all other factors. To simplify the discussion, the available energy will be considered accounting for a full discharge cycle, hence considering the energy available between SOC 100% and SOC 0%. The available energy can be measured by integrating the value of battery power with time. Repeating the measurements for different power settings, it is possible to obtain the results graphically presented in Figure 11. As for the available power, the available energy is initially presented, neglecting the SOH and battery temperature effects.

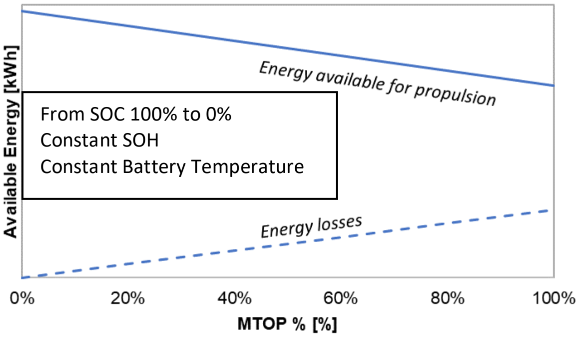

Figure 11 Available Energy vs Power Setting (generic y-axis scale shown for general application)

The primary outcome of Figure 11 is that as more power is used during the discharge cycle, not only do batteries discharge faster, but also less energy is made available for the propulsive system. Therefore, for optimal use, batteries should operate at the lowest possible power setting and the application of high power should be avoided as much as possible. In this sense, power management is possibly the biggest challenge electric aircraft are facing in the current times, especially if we consider that any electric aircraft has about 5 -10% of the available energy of a comparable piston-powered aircraft. In a test environment, this translates to the need to optimally plan the mission and carefully define the flight profile. Particular attention should be given to the safety of flight parameters such as altitude since electric aircraft cannot reach the same test altitudes as conventional aircraft. The flight crew may be forced to make significant compromises on the minimum test altitude or, as an alternative, find a clever way to bring the aircraft at altitude before starting the batteries. As an example, Pipistrel used a conventional aircraft to tow electric aircraft in the air before measuring glide performance. The evolution of battery aging over battery capacity and internal resistance shows their most prominent effect when considering the available energy. Figure 12 shows the qualitative relations between the available energy at different battery SOH.

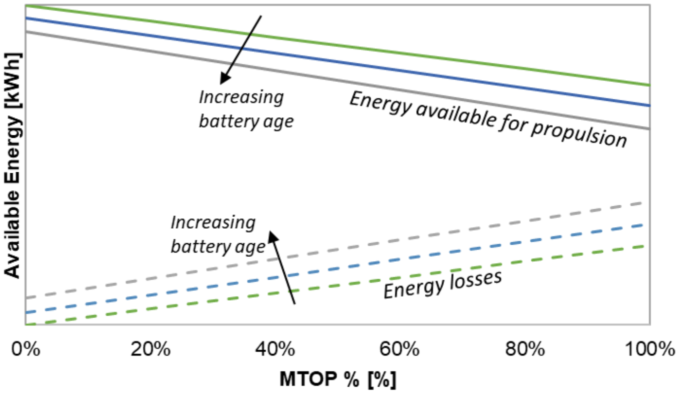

Figure 12 Available Energy, SOH Effect (generic y-axis scale shown for general application)

Figure 12 intentionally does not provide any quantitative reference because the relationship between the different performances is strictly related to the battery design. A battery with a limited lifetime may show more homogeneous performance. On the other hand, batteries with long life may feature available energy degradation of up to 50%. In a test environment, this translates into the need for repeating performance measurements for all relevant SOH conditions. As presented earlier, internal resistance decreases when battery temperature increases. Lower internal resistance reduces the power loss, increasing the available energy. The effect of battery temperature over available energy is presented graphically in Figure 4. When the battery supplies low power settings, battery temperature does not affect the available energy significantly. The energy available is significantly lower when middle to high power (current) is applied.

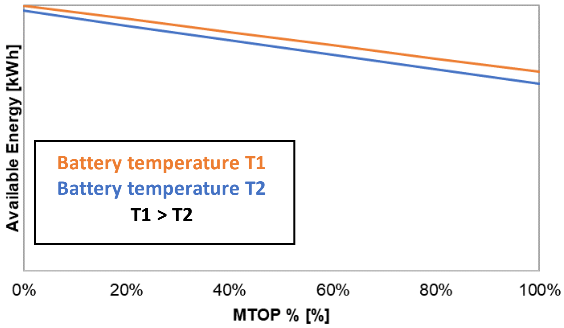

Figure 13 Available Energy, Battery Temperature Effect (generic y-axis scale shown for general application)

In a test environment, battery temperature plays a fundamental role in the definition of battery performance. Battery temperature should be recorded precisely at the beginning and at the end of each test point.

Battery Temperature Management

Phenomena related to battery temperature are complex and need a multidisciplinary approach. The battery temperature has three main consequences over the battery characteristics:

1) From a safety point of view, an excessively high battery temperature is one condition that favors the genesis of a battery fire.
2) From a performance point of view, the lowest range of battery temperature is to be avoided to preserve the battery performance
3) From a lifetime management perspective, too low and too high battery temperatures will speed up the natural battery performance degradation, reducing the lifetime of the battery system and its performance in the long term.

Some battery manufacturers already provide a recommended battery temperature range. If not available, specific measures should be performed to map the cell characteristics as well as how these characteristics change at different battery temperatures.
Once the desired temperature range is identified, specific evaluations of the battery cooling system are needed in the entire operational OAT range. On top of that, cooling system evaluations are to be repeated with a periodic frequency because battery cells change their thermal behavior as they age. Indeed, the increased thermal resistance implies an increased heat generation which is hardly quantifiable when the battery is brand new.

Battery charging performance refers to the battery capacity to be recharged. Despite the fact that the market attention on battery recharging is fully focused on the recharge time, the recharge duration is only one aspect of the recharge process. The battery recharge is complex and covers diverse phenomena of battery physics depending on battery chemistry. As a result, the charging performance is always a compromise of the following points:

1) Recharge cell limitations
2) Ground infrastructure
3) Recharge duration
4) Battery temperature management
5) Battery lifetime management

Each battery has a different configuration, therefore different limits and different performance. This section will focus on general behaviors and phenomena that apply to a standard Li-ion design. As for the discharging power, the charging power can be expressed as the multiplication of the battery voltage and the battery current. The charging current, usually recorded with a negative sign, will induce a voltage loss in the battery resistance that will reduce the power available for charging. In a simplified scenario, the voltage drop can be expressed as a linear function of internal resistance and current.

$$P_{charge} = I_{charge} * V = I_{charge} * (OCV - \Delta V)$$

Equation 4

The evolution of the battery parameters during the recharge depends on the battery design, but also on the way the ground infrastructure recharges the battery. The charging protocol consists of the current and voltage evolutions set-up during the recharging process. The most widely used charging protocol is the so-called “constant current constant voltage” (CCCV). The charge starts with a constant current value and continues until the voltage reaches the target set-up value. Then, the charging current is regularly reduced to maintain the voltage level constant. The charged ends when the current reaches 0A and the battery voltage is equal to the OCV for SOC 100%. Cell manufacturers specify the maximum charging current and the maximum voltage in the standard cell datasheet. It is worth mentioning that charging limitations are usually more strict than the discharging limitations. This suggests that the charging process is a more delicate procedure and should always be performed within the manufacturer’s limitations. This is because, in the long term, charging the battery is the procedure that deteriorates the battery the most.

Logically, charging the battery with the highest possible current ensures the minimum recharging time, but it does not come without drawbacks. It is this condition that accelerates battery aging the most. On the other hand, charging with the minimum possible current setting ensures a longer lifetime, but it may imply unacceptable charging durations. One additional parameter that plays a role in the charge duration vs life-optimization scenario is the battery temperature. During the recharge, a part of the charging power is lost due to the voltage drop in the battery internal resistance; such losses can be reduced if the battery temperature is maintained within certain limits. In addition, charging the batteries in the middle-temperature range prevents fast aging phenomena.

Battery temperature management during recharge is one of the biggest challenges for an electric aircraft. Batteries heat up during the recharge and temperature may rise excessively if proper cooling provisions are not in place. Compensating the heat generated during recharge must be performed while the aircraft stands still with no natural cooling effects. On the other side, during the cold season, battery temperature should be monitored to avoid excessive cooling which may compromise the battery lifetime. In conclusion, the only way to charge the battery while preserving its lifetime is to charge at low power. If the recharging time is not acceptable, the current may be increased up to the limitations specified by the cell manufacturer while avoiding recharge at too low and too high battery temperature, as depicted in Figure 14. The FTE should monitor these conditions and note it prior to the flight test.

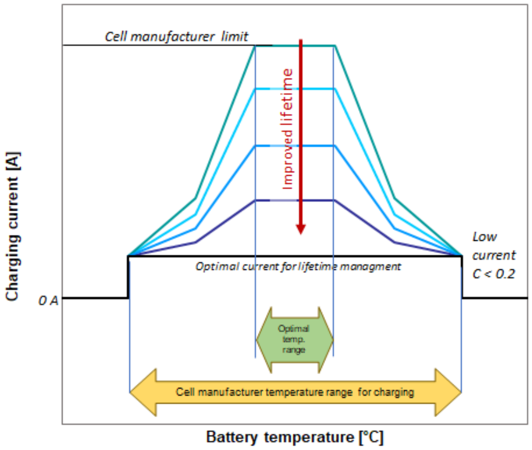

Figure 14 Charging Current vs Battery Temperature

Safety of Flight Operations

When operating a battery system for electric propulsion, safety of flight considerations must be properly characterized and examined carefully. These considerations include understanding limitations and hazards associated with battery operation, knowing the aspects that impact the day-to-day operations of battery powered flight test, and understanding the battery system on the appropriate level to safely operate, troubleshoot, and navigate squawks. The current climate of the electric aircraft industry has no accepted standard nor guidance to refer to such practices, however, the time-tested approaches serve as a foundation to build on for the future of battery powered flight.

Limitations & Hazards

Across all power plants, exceeding critical parameter limitations can have dire consequences. Over-torquing a turbine or exceeding the ITT limit of a turbofan can have an immediate operational consequence. However, the immediate mitigation is typically the same, i.e. a reduction in EPR, N1, ITT, etc., with worst case putting the engine back to idle. This is generally speaking, of course. Because batteries are the main energy source, much like the fuel system in a traditional configuration, the same approach is carried, as batteries are designed to work in an envelope specified by the manufacturer. These envelopes are usually defined from the following critical parameters:

1) Temperature range
2) Pack Voltage Range
3) Pack Current Range
4) Pack Power output
5) Cell Temperature range
6) Cell Voltage Range
7) Cell Current Range
8) State of Charge

Operation of batteries in these envelopes are often straightforward, however, there is very little room for exceedances. Surpassing limits may not immediately endanger the crew, but you may easily damage or deteriorate the battery system. Battery packs are comprised of large numbers of individual cells. All it takes is a single cell, out of thousands, to operate outside of its limits for slightly too long to cause a thermal runaway event which could propagate to other cells and result in a battery fire. A thermal runaway is an extremely fast event with little direct indication that it has occurred. It is possible for this sort of event to occur after it is too late. A proactive approach must be taken. As a flight tester, hazard analysis is the bread and butter of safe operating practices. Being on the forefront of battery propulsion, there are many unknowns that need to be navigated. A flight tester's responsibility to this task is to step into the unknown in incremental steps with the appropriate build up. High voltage battery packs can introduce the following hazards during test activities:

1) Battery Fire
2) Electrocution
3) Explosion or pressure burst
4) Pack Failure (total or partial loss of power)

The hazards listed above, with the exception of pack failure, can be categorized as catastrophic if they were to occur during operation, and each hazard can have a multitude of root causes. Historically, the biggest hazard associated with battery technology is battery fires, as seen on a number of electric aircraft. This hazard is catastrophic and once started, is virtually unstoppable. Battery fires can happen due to exceeding limitations such as maximum temperatures and more indirectly, pack or cell level voltage imbalances. As a flight tester, how can we use our tools to execute this type of flight test with an acceptable amount of risk? The risk matrix below is one that many flight testers use, as stated in FAA order 4040.26B (Figure 15). Flight testers initially identify the associated hazards, the probability and severity, then start drafting mitigations. Flight test hazards regarding batteries will yield a challenge in controlling and minimizing severity. In the event of a battery fire, the consequences are severe, with very few mitigations to reduce it. Thus, vigilance by the FTE of potential conditions that might cause a cell runaway is imperative. In terms of the probability, the risk of a battery fire can be reduced if robust mitigations and procedures are in place. Examples being operating in the conservative envelope or having a robustly designed BMS or a fault detection system. Having early Knock-It-Off (KIOs) criteria can keep the flight tester from taking inadvertent "bites" into the edge of the envelope and keep themselves under the umbrella of safety they provide themselves. In all, one of the most important mitigations that will lower the probability is having cycles and times on the battery. This can be safely done through ground testing to the maximum extent possible, so the confidence of durability and reliability is there during build up to a proper flight test phase. Finally, if there are emergency systems, such as battery pack venting, ensure that they are operational and practice procedures with the crew.

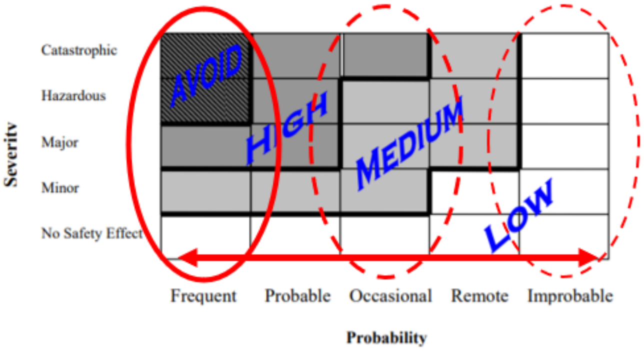

Figure 15 FAA Order 4040.26B Risk Matrix

High Voltage and Charging

Another key hazard associated with battery propulsion is high voltage handling and safety. Many battery systems can produce on the order of 1000 volts in an electric aircraft with the potential for creating a massive hazard. Many designs or provisions can be in place to mitigate this hazard such as arc flash protection/training, fault systems that are put into place, etc. However, it is important to identify that this risk often reveals itself during ground handling and charging of the battery. Until charging electric aircraft becomes purely a maintenance activity, much like how refueling is now, the risks must be managed and be treated like a test itself. High voltage is a hazard for several reasons, but one being the lack of indication before incidents. Fires, for example, can often be smelled or seen by the presence of smoke or fire. Loss of power incidents are self-evident to the flight crew. High voltage alone has no indicators outside of undesirable outcomes. When dealing with high voltage it is important to not only follow OSHA guidelines, which are mostly facilities based, but also have appropriate placards for crew, or coloring voltage critical items if able. Monitoring safety critical items via instrumentation systems is also a good approach. If something potentially has high voltage, it needs to be apparent to the ground and flight crew. If there are emergency disconnect procedures, practice them frequently with the crew.

Aircraft Rescue & Fire Fighting (ARFF)

For flight testers who are unfamiliar, Airport Rescue and Fire Fighting (ARFF) are the emergency responders in many flight test incidents. ARFF is made up of professional firefighters and first responders and is highly recommended to have on the field of any flight test organization. In the event that something unexpected happens with your electric vehicle, these will be the personnel first on the scene that pull crew from the aircraft/vicinity. The most critical part of ARFF being ready to first respond for flight tests is being familiar with your battery system in particular. It should be standard practice to hold an ARFF familiarization meeting as you are building up to the flight test phase of your battery system. This meeting should consist of the following:

1) Type of battery chemistry so the appropriate retardant is on hand
2) Overview of high voltage systems. Location of batteries and associated cables
3) Flight crew stations and egress path. Mark out “Do not cut” sections on the aircraft so first response doesn’t cut through a high voltage system to rescue flight crew
4) Discuss risks of battery case pressurization and venting provisions to mitigate such things, if installed
5) Discuss hazardous gases and gear needed to initiate rescue in that environment
6) Provide aircraft diagrams, battery information, and flight crew emergency procedures to ARFF so the correct information is on hand
7) Develop and practice emergency procedure with your flight test team and ARFF

ARFF is an important component of battery flight test and this conversation should be transparent regardless of programmatic and commercial components. Effective communication with ARFF will produce an effective and well informed first responder when an unwanted event happens with your electric propelled aircraft.

Operational Considerations

Batteries, much like fuel systems for traditional engines, can often have a “personality” of their own on both a pack and cell level. Meaning that in a system that has many intricate components, both electrically and chemically, it is common to have a cell that reaches a temperature limit faster than others. Or a cell that charges more quickly at slightly different temperatures than the neighboring cells. This can be due to how a cell or pack was manufactured and if no safety threat is present, can be acceptable. A flight tester can easily observe this on the data system during charge/discharge, and trends should be observed from test to test.

Another interesting characteristic of batteries compared to traditional aircraft power sources is the fact that batteries maintain the same weight throughout operation. When planning for a flight and loading the aircraft, the weight and CG envelope will simply have a ‘dot’, as opposed to a traditional fuel burn curve.

Battery Balancing Impacts

Flight testers have an obligation to conduct test properly, however, they also have a basic responsibility to complete flight test tasks as quickly as they can in order to meet schedule. Through the myriad of activities, and the development of a soon to be product, it is usually the flight tester on the “pointy end of the spear”. This is important to the flight test department, as batteries require a given amount of time to charge to a desired capacity. As the battery approaches this capacity, temperature and/or voltage variability can be a major factor in the charging process. Most battery packs have a certain tolerance to different cell voltages within packs or BMUs. Depending how the balancing system is designed, this can directly equate to extended charging times. If “corners are cut” on battery balancing, the lowest voltage cell might reach the minimum voltage when the others are healthy. If flight were to happen with an unacceptable amount of balancing, lowest voltage cell will limit the discharging of all other cells, impacting flight time.

As stated previously, there are two types of balancing systems that can handle cell imbalances; active and passive balancing systems. Active balancing systems are more complex, commonly having a designated system that keeps each cell within tolerance, reducing the total charging time. Passive balancing is the more simplistic approach from an engineering perspective, however, can allow cells to leave the allowed voltage differences between cells, causing either prolonged or paused charging. If the flight tester was to proceed with imbalanced battery cells, you may be operating near the edge of the battery envelope at best (see Figure 16).

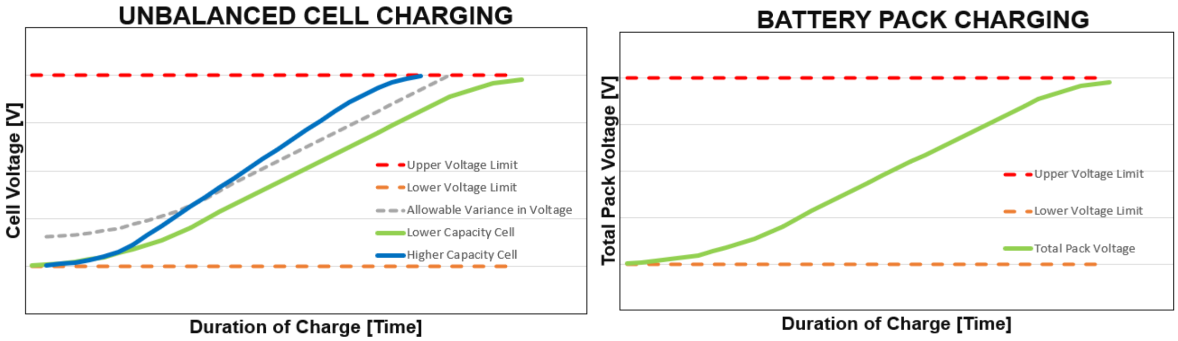

Figure 16 Cell Voltage Charging Over Time of a Cell vs Pack

Swappable Vs Plug-In Charging

The most traditional configuration of electric aircraft is more such a plug-in style charging system, where the battery systems remain in the aircraft and the charging is plugged into the aircraft itself, much like electric automobile. This approach is much simpler from an engineering perspective, as nothing has to be removed from the aircraft, nor are there any complex systems to accommodate.

However, with plug in charging, you are committed to only using one battery pack compared to replacing a low charged or dysfunctional set with either a new or fully charged battery.

As electric aviation evolves, the excitement of a removable pack configuration can be more attractive to implement in an electric aircraft. This configuration contains its own ecosystem of challenges and problems; however, it is a possible alternative to efforts that reduce battery charge time and increase life cycle.

SOC/SOH Based Test Cadence

There is a level of confidence that the future holds a massive potential for flight duration using batteries as a power source. However, today's demonstrators hold about a little more than an hour duration for time aloft, excluding 30-minute VFR reserves. In today's current flight test climate of ETOP capable jets and FADEC turbines, battery propulsion sorties are going to be a sliver of time compared to current OEM flight operations. A commercial jet derivative would often take off, join with the chase aircraft (if required) in a warning area after a 30-minute transit, execute the test, and be back before crew duty times expire. A battery powered aircraft may hold 45 minutes total in the glide cone of the home airport, before landing on minimum SOC. Traditionally powered aircraft are also not as limited to fuel on board or range, but rather other variables depending on tests, such as CG, W/Delta, Weight, etc. A battery powered flight test will be dependent on SOC and the SOH of the battery system. Each aircraft will have their limitations; however, any limitation will still have to live in the envelope of the SOC. This can shrink the operational envelope substantially from a flight test of a traditional aircraft, and therefore makes monitoring critical parameters with state of charge more critical.

With the above stated, expect short flight durations driving the cadence and scope of each flight. Every phase of flight will have to be utilized to collect critical data with minimal loitering or transit in the flights. Don't waste a taxi or takeoff, as all data is acceptable. An ideal sequenced electric flight test would have conditions stacked very close to one another, with quick go-no go decisions to continue or abort. When conducting flight tests with battery propulsion, it is recommended to have as much recorded on a data system as possible, as manually inputting data might not yield the appropriate utilization of time. Take advantage of practicing your flight card on the ground to get your timing down pat.

Conclusion

The current industry landscape contains a variety of platforms that can utilize battery technology in a drastically different way with little to no standardization. With such new and novel technology, it is surprisingly easy to operate the battery system such that it behaves than what was intended. This puts an onus on the flight tester to have an intimate understanding of the aircraft, battery system, and powertrain architecture on a fundamental engineering level. An effective flight tester has hands-on-experience with the aircraft and battery systems to really understand what is happening on a system and component level. The aerospace community has spent the last 50 years iterating and refining known technology, such that we are now inherently familiar with many models of gas-powered engines; Once the fundamentals are understood, safe operation of a new gas-powered system is in turn a derivative of those that came before it. Batteries and their management systems do not, yet, have such a foundation. Reaching that level of familiarity will warrant close collaboration with engineers and SMEs in order to know how a battery system works on the component level. Your insights as a FTE will form the basis for standard practices that will generate new industry standards being developed for batteries.

The implementation of flight test techniques for electric aircraft is still very unknown to flight testers that are starting to evaluate battery powered propulsion technologies in new or converted aircraft. Transitioning manufacturing specifications into test requirements and limitations are key to system and subsystem level validation and verification. Verifying any instrumentation that is pre-integrated in the battery should be treated as a minimum requirement and not accept anything less. Since electric propulsion technology is handled differently than current propulsion systems, different performance metrics need to be considered such as SOH, SOC, and voltage/temperature effects. Safety and Risk Analysis also typically takes a time proven approach to implement for this new technology, since there are still many lesser-understood things to consider. Understanding the common hazards when flight testing batteries, the impacts battery balancing can have on flight operations, and SOC/SOH based test cadences are all foundational pieces of knowledge for FTEs when executing flight tests. Lastly, the importance of engineering and SME involvement when conducting flight tests, as a technical voice in the test crew makes for an effective flight test of this new electric propulsion technology that will be conducted safely.

References

1) Marongiu, Andrea & Damiano, Alfonso & Heuer, M.. (2010). Experimental analysis of lithium iron phosphate battery performances. IEEE International Symposium on Industrial Electronics. 3420 - 3424. 10.1109/ISIE.2010.5637749.
2) Mohamad Aris, Asma & Shabani, Bahman. (2017). An Experimental Study of a Lithium Ion Cell Operation at Low Temperature Conditions. Energy Procedia. 110. 128-135. 10.1016/j.egypro.2017.03.117.
3) Li-Tec, "HEA 40 High Energy Zelle ICMNP 110190240," 2008.
4) Capron, Odile & Gopalakrishnan, Rahul & Jaguemont, Joris & Van den Bossche, Peter & Omar, Noshin & Van Mierlo, Joeri. (2018). On the Ageing of High Energy Lithium-Ion Batteries—Comprehensive Electrochemical Diffusivity Studies of Harvested Nickel Manganese Cobalt Electrodes. Materials. 11. 10.3390/ma11020176.
5) Anthony Barré, Frédéric Suard, Mathias Gérard, Maxime Montaru, Delphine Riu. Statistical analysis for understanding and predicting battery degradations in real-life electric vehicle use. Journal of Power Sources, Elsevier, 2014, 245, pp.846-856. ff10.1016/j.jpowsour.2013.07.052ff. ffhal-01071585
6) Waldmann, Thomas (September 2014). "Temperature dependent ageing mechanisms in Lithium-ion batteries – A Post-Mortem study". *Journal of Power Sources*. **262**: 129–135. Bibcode:2014JPS...262..129W. doi:10.1016/j.jpowsour.2014.03.112
7) Notten, Peter & Veld, Bert & Beek, J.R.G.. (2005). Boostcharging Li-ion batteries: A challenging new charging concept. Journal of Power Sources. 145. 89-94. 10.1016/j.jpowsour.2004.12.038.
8) Ziegler, Andreas & Oeser, David & Hein, Thiemo & Montesinos-Miracle, Daniel & Ackva, Ansgar. (2020). Run to Failure: Aging of Commercial Battery Cells beyond Their End of Life. Energies. 13. 1858. 10.3390/en13081858.
9) Łebkowski, Andrzej. (2017). Temperature, Overcharge and Short-Circuit Studies of Batteries used in Electric Vehicles. Przeglad Elektrotechniczny. 1. 10.15199/48.2017.05.13.
10) Dian Wang, Yun Bao * and Jianjun Shi. (2017) Online Lithium-Ion Battery Internal Resistance Measurement Application in State-of-Charge Estimation Using the Extended Kalman Filter. Energies 2017, 10, 1284; doi:10.3390/en10091284