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A Review of Internal Resistance and Temperature Relationship, State of Health and Thermal Runaway for Lithium-Ion Battery Beyond Normal Operating Condition

Muhammad Fikri Irsyad Mat Razi[1], Zul Hilmi Che Daud[2,*], Zainab Asus[2], Izhari Izmi Mazali[1], Mohd Ibtisyam Ardani[1], Mohd Kameil Abdul Hamid[1]

[1] School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, Johor Bahru, Johor, Malaysia
[2] Automotive Development Centre, School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, Johor Bahru Johor, Malaysia

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ABSTRACT

One of the most popular energy sources in electrical circuitry is the lithium-ion battery (LIB) and it can be found in a variety of products from the smallest unit such as Airpod, smartwatch, smartphone to as big as farming drones, industrial robots, and electric vehicles. But the usage of lithium-ion batteries is limited to a range of temperatures. The normal operating temperature range for LIB is 40°C~65°C. Despite this, there are still cases where operating LIB at high temperature is unavoidable for example deep earth pipeline inspection in the oil & gas industry, sterilization of medical tools in the medical industry, harsh condition robots and drones in the industrial sector, and high ambient power storage for photovoltaic system. Operating LIB beyond normal conditions will affect the battery in several ways. In this paper, the effect of temperature on internal resistance is demonstrated by several studies, the results show LIB internal resistance decrease as temperature increase. Operating LIB beyond normal operating conditions can also lead to faster battery degradation. Battery state of health (SOH) is used to indicate battery degradation level. A battery with a low SOH performs poorly in terms of power delivery compared to a high SOH battery. In addition, operating LIB beyond normal operating conditions, stresses such as thermal stress can damage the battery and instigate thermal runaway causing violent combustion and explosion.

1. Introduction

As global warming has become a concern, various parties are now trying measures that can reduce the effects of global warming. Amongst the popular measures is to replace non-renewable energy with renewable energy. On the other hand, energy consumption also raises the issue of energy security. The European Union has already begun to put concern in the particular matter [1]. In Malaysia, a sustainable energy plan was also planned [2]. In Indonesia, there is ongoing research

* *Corresponding author.*
E-mail address: hilmi@mail.fkm.utm.my

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in using biowaste such as burning rice husk was as a renewable energy source [3]. The latest research is using a microbial fuel cell to generate electricity [4]. There is also research in small-scale electricity generation where the impact of rainwater is converted to electricity using piezoelectric cells [5]. In addition, electric and hybrid vehicle technology has also expanded to the plantation sector where tractors adopting electrical power [6]. This brings advantages because the use of energy in a hybrid can save the cost of fuel consumption [7]. In parallel with electric and hybrid vehicles, these vehicles use batteries as energy storage. There are a variety of batteries available nowadays including non-rechargeable such as zinc-carbon batteries, alkaline batteries and rechargeable batteries including lead-acid batteries, nickel-metal hydride batteries (NiMH), nickel-cadmium batteries (NiCd) and lithium-ion batteries (LIB). Amongst rechargeable batteries, LIB is widely used in electric vehicles, smartphones, and laptops because LIB is stable with high power density and low self-discharge [8-10]. Hence, it became the most popular power source in electrical circuits [11].

LIBs are normally operated at a temperature range of 40°C ~ 65°C as recommended by battery manufacturers for safe operating temperature [12-14]. This is called a normal operating temperature. A warning for the user not to use batteries that exceed the temperature sets by the manufacturer was also stated on the batteries description. The operating temperature for LIB is significantly important because temperature affects the performance and health of the battery [15].

When operating beyond normal conditions, especially at the upper bound of the temperature limit, the probability for a LIB to undergo thermal runaway is high [16-18]. This means that a slight mistake in handling will trigger the thermal runaway of LIB. The hazard of battery thermal runaway is a serious issue because it could cause burn injuries to consumers [19]. The main things that need to be taken extra precautions are internal short-circuiting, external overheating, overcharged voltage and charging after over-discharge [20-22].

Charging and discharging a LIB cause the battery to generate heat because of the chemical reaction between the electrode and the electrolyte that have a highly exothermic reaction nature [23]. When the exothermic reaction inside the cell reached extreme temperature, thermal runaway occurs, and the LIB started to explode [24]. In essence, thermal runaway is a process where energy is released at higher rates which causes rapid temperature rise. More on thermal runaway will be discussed in Section 5.

In conclusion, LIB usage capability is limited by a narrow temperature range. Using LIB at extremely hot temperature and it will destruct the battery due to ageing and thermal runaway. On the other hand, using LIB at a low temperature (below zero Celsius) will cause LIB to lose the ability to deliver power and cannot be charged. Most of the time designs that use LIB as a power source will try to avoid and prevent the battery from operating at high temperature. But some unavoidable cases require the LIB to be used at high temperature. The upcoming section in this paper will discuss high temperature LIB applications, internal resistance and temperature relationship, internal resistance and battery state of health and finally, thermal runaway.

2. High Temperature LIB Applications

In 2019, CUSTOMCELLS® developed and released its new battery brand which is HT-Li-ion specifically for high temperature utilization as shown in Figure 1 [25]. According to CUSTOMCELLS®, few examples where LIB are used in high temperature conditions are including the medical field where wireless devices that use a battery as a power source need to be sterilized above 120°C, in the oil and gas sector where logging equipment is used far below the earth surface where tremendous pressure and temperature condition exist, and as well as the military used for surveillance and monitoring where devices that are sent out will be operated at high ambient temperature. In Figure

2, the difference between CUSTOMCELLS® HT-Li-ion battery and standard LIB in terms of capacity percentage at temperature 75°C is very significant where CUSTOMCELLS® HT-Li-ion battery can maintain more than 80% capacity for 500 cycles compare to standard LIB.

Fig. 1. CUSTOMCELLS® HT-Li-ion battery [25]

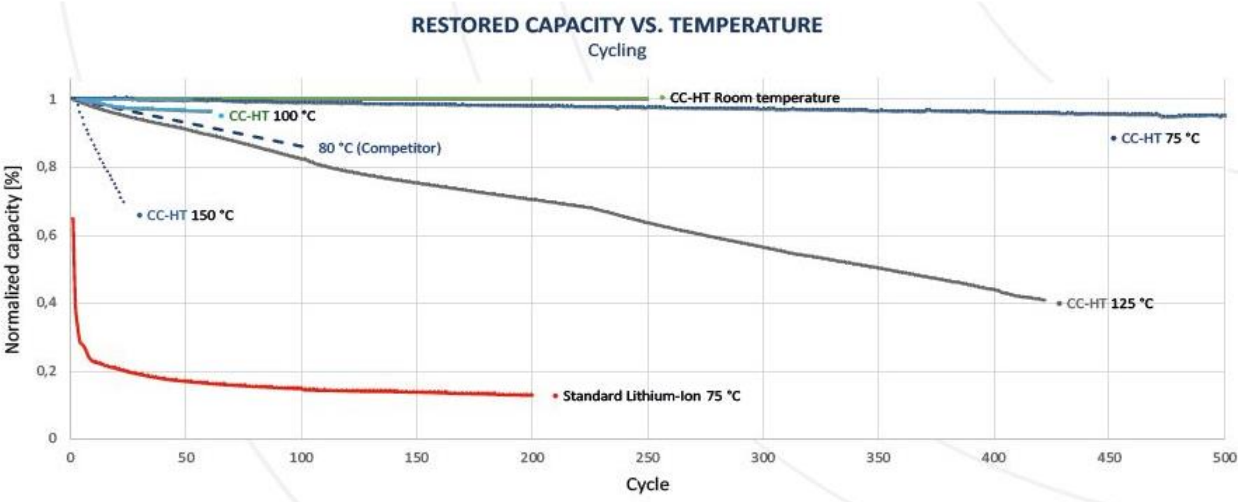

Fig. 2. Comparison for capacity against temperature for CUSTOMCELLS® HT-Li-ion battery and standard LIB [25]

Another example of research for high temperature LIB application is extreme fast charging. Yang *et al.,* [26] proposed a novel method of extreme fast charging by elevating the battery temperature to 60°C periodically. They were able to retain 91.7% battery capacity for 2500 cycles of 10 minutes of extreme fast charging.

In electric motorsport, Formula E uses a high discharging rate to get a lot of power to supply to the motors. This will cause a significant increase in LIB temperature. This can also bring advantages as high temperature battery will cause the internal resistance to drop resulting in better power delivery. As been said by Douglas Campling, chief engineer at Williams Motorsport, “Formula 1 racing uses their batteries way above the recommended spec sheet in terms of temperature to get a lot more performance out of the batteries” in his interview with Racecar Engineering magazine [27]. High charging/discharging rates are also applied in hybrid and electric cars when climbing a steep hill, electric motor requires high amperage to move the vehicle [28].

The demands for high temperature LIB exist. Indirectly, this opens more research opportunities for LIB application at high temperature as well. Take the F1 racing for example, operating LIB at high temperature can push more performance out of the battery. This is because the internal resistance that blocking the power delivery by the LIB is minimal when the temperature is high. Hence, this sparked a discussion topic for internal resistance and temperature relationship.

3. Internal Resistance and Temperature

Internal resistance is a concept where a flow of current is opposed within the battery [29]. This will cause a phenomenon where a measured voltage output with load is lower than during no-load voltage when a power source delivers current. For electrical current to flow across an electrical circuit, the movement of electrons are a must. When the movement of electrons is obstructed along the circuit path, it is subjected to a certain amount of resistance. Internal resistance occurs inside the power source and connecting wire itself without external load present and hence the name internal resistance. The resistance in a battery is term as battery internal resistance. In LIB, the internal resistance occurs due to the resistivity of the component materials and an ionic component due to electrochemical factors such as electrolyte conductivity, ion mobility and electrode surface area [30].

There are several methods in identifying internal resistance. Among the methods includes VDA current step method, ISO current step method, current-off method, switching current method, AC internal resistance, impedance spectroscopy, energy loss method and Quasi-adiabatic calorimeter [31]. The official battery test method available is Hybrid Pulse Power Characterization (HPPC), proposed by PNGV [32]. HPPC method calculates discharge and charging resistance by using discharge and charge pulse current. The period of discharge pulse current provided by PNGV is 18 seconds while 2 seconds for charge pulse current. In 2008, this method was adopted and improvised and became Battery Test Manual for Power Assist Hybrid Electric Vehicles where the period of discharge and charge was unified to be 10 seconds as seen in Figure 3. pulse power characterization profile below [33].

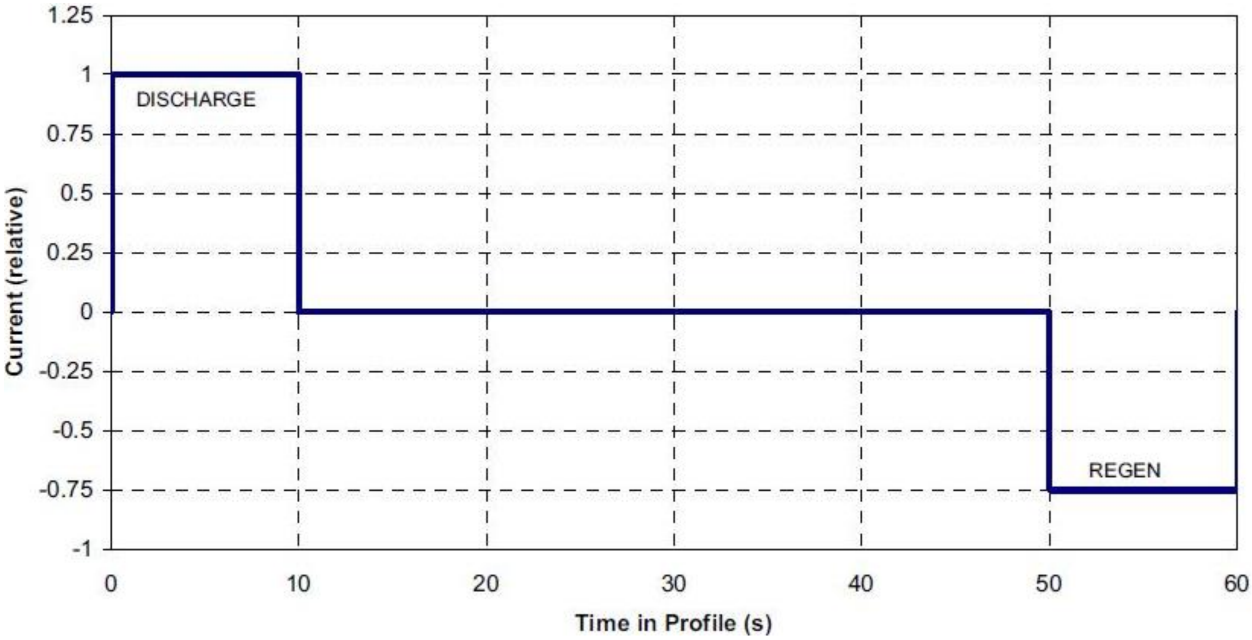

Fig. 3. Pulse Power Characterization Profile [33]

One of the external factors that affecting battery internal resistance is temperature. Zhang *et al.,* [34] show the relationship between internal resistance and temperature in their study. Figure 4 shows the graph of internal resistance and temperature. Battery with different values of SOC was tested and the result shows that internal resistance decrease as temperature increase. The same trendline was also achieved by Łebkowski's [35] and Lou's *et al.,* [36] as in Figure 4 and Figure 5 respectively.

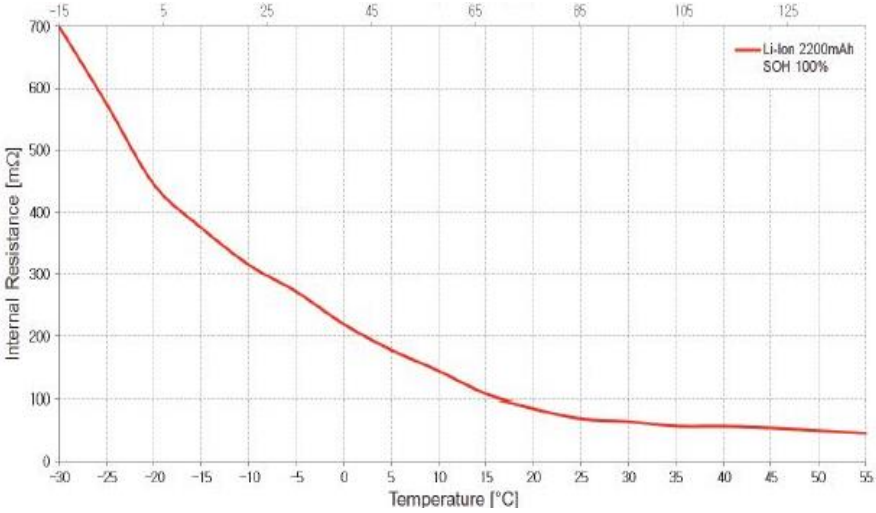

Fig. 4. Łebkowski's [35] Internal Resistance profile

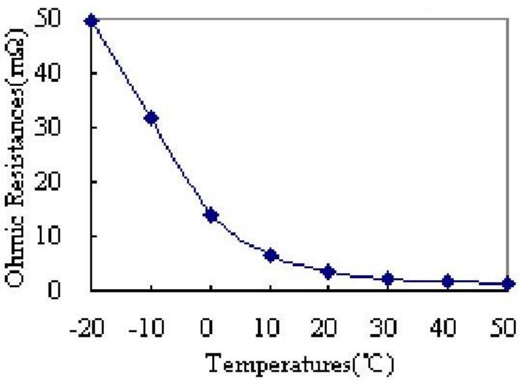

Fig. 5. Lou's *et al.,* [36] internal resistance against temperature profile

The interesting particular about internal resistance relationship with temperature is that it can be used to predict or model the thermal behaviour of LIB. Yoo and Kim [37] in their work use equivalent resistance to run a thermal analysis model for a Li-Ion battery based on the Joule-heating mechanism. The equivalent resistance was obtained from the EIS test which was then validated via both theoretical analysis and thermal analysis. The thermal analysis successfully predicted the temperature of the battery via simulation and agreed well with experimental results [37]. Another study was carried out by Noelle *et al.,* [38] about investigating the internal resistance and polarization dynamics to examine the joule heating regime of LIB. Their analysis includes how increasing ohmic or polarization resistance would affect the heating rate as well as their relevance to a different timescale. They claimed that the results from their work could help bridge the gap in thermal runaway mitigation technological development between primary structures and thermally activated failsafe features [38].

LIB internal resistance trendline decrease almost exponentially as the battery temperature increases. That is true for LIB normal operating temperature range. But most studies stop below or at ideal LIB operating temperature. This creates a knowledge gap about internal resistance beyond normal operating temperature that needs to be filled in. If the trendline continues to decline even in high temperature region, thus logically it is more beneficial to use LIB at high temperature because of low internal resistance properties. But there will be another problem for long term usage as LIBs degrade faster at high temperature. Battery degradation is related to battery state of health (SOH) and it is also one of the popular topics other than internal resistance.

4. Internal Resistance and State of Health (SOH)

Battery state of health is used to indicate how much a battery has degraded. A degraded battery can be distinguished into a decrease in battery capacity and an increase in internal resistance. There are 3 causes for battery degradation mechanism which are chemical, mechanical, thermal and all of them depend strongly on the electrode's composition. Furthermore, a battery can be considered to have reached its end of life (EOL) when its capacity has dropped to 80% from its original state [39].

Remmlinger *et al.,* [40] has done a study in comparing a degraded battery where the state of health of the battery has been compromised with a fresh new battery with a good state of health in terms of its internal resistance. Figure 6 shows the result of new cell and degraded cell internal resistance at a temperature ranging from -20°C to 60°C.

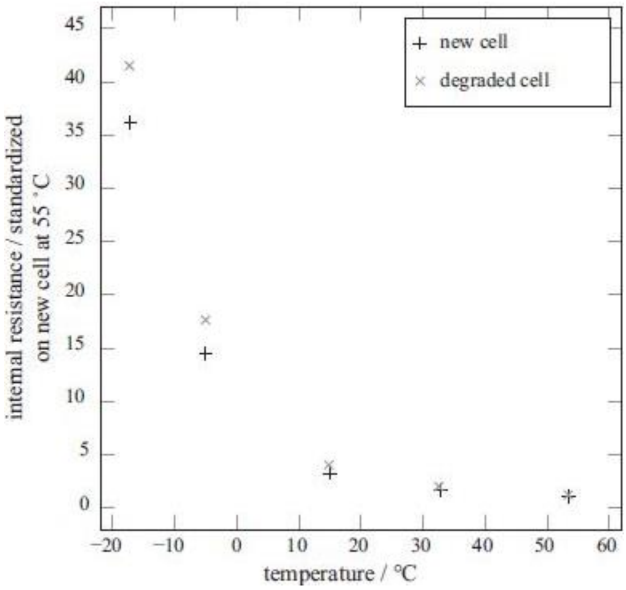

Fig. 6. Comparison for internal resistance of degraded cell and new cell [40]

5. Thermal Runaway

In a recent study carried by Wang *et al.,* [16] thermal runaway behaviour has three distinguishable stages. The first stage is where the battery is swollen because gas and heat accumulate in the battery without any presence of flame. The second stage is when the manifestation of bright flame, material jetting and gas venting occurs. The battery temperature may reach hundreds of degrees Celsius at this stage. The gas venting from the battery consists of hydrocarbons, CO_2, CO and H_2 [16]. The third stage is when the flame around the battery is gradually reduced and extinguished. Although the thermal runaway ends, the temperature of the battery still might remain high for some period. Figure 7 shows the picture of several thermal runaway behaviours for LIB under different heating methods, the top row with a cylindrical heater and the bottom row with an electrical furnace.

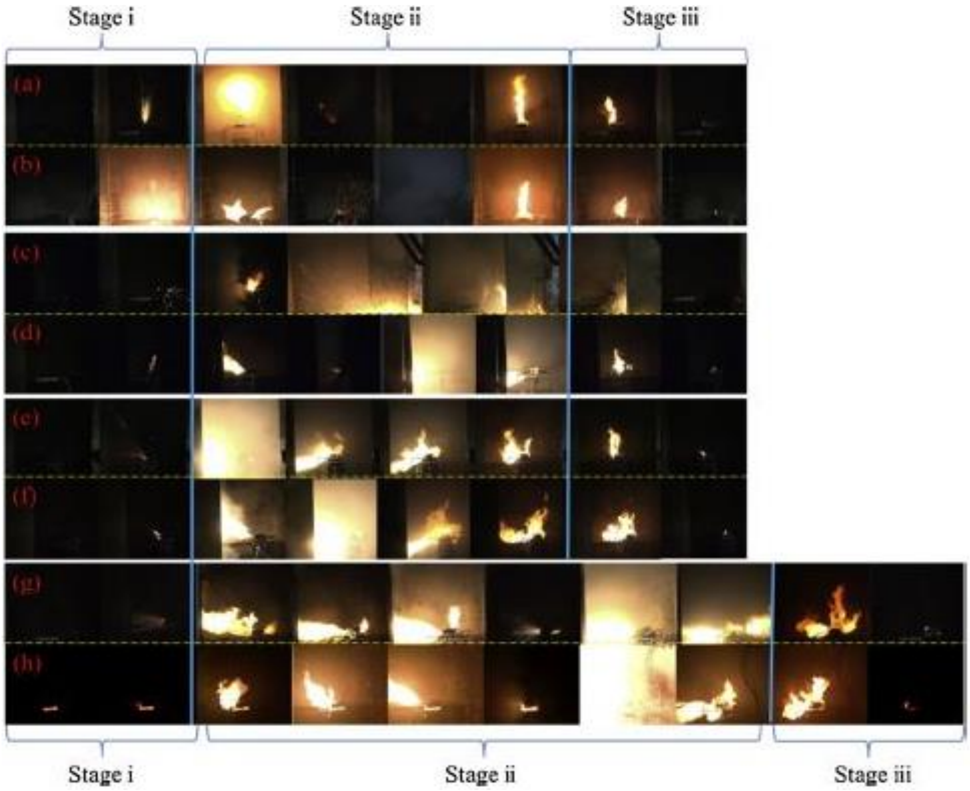

Fig. 7. Thermal runaway behaviour for LIB under different heating methods [16]

Other literature categorized thermal runaway behaviour in a more specific stage such as Li *et al.,* [41] where thermal runaway was categorized in four stages which is rising of temperature, Solid electrolyte interface (SEI) film decomposition and gas accumulation, melting of the separator and finally gas venting. While Huang *et al.,* [42] put thermal runaway behaviour in five stages which the first stage starts with rising of temperature, beginning of expansion in the second stage, noticeable expansion in the third stage, severe swelling and gas ejection in the fourth stage and the last stage is where fire manifestation and battery rupture occurs. In contrast, these three literatures, Wang *et al.,* [16], Li *et al.,* [41], and Huang *et al.,* [42] show that the LIB starts to burst into flame vigorously and getting destroyed only when the temperature exceeds 100°C.

Si *et al.,* [43] plotted the combustion temperature curve of LIB as shown in Figure 8. At the initial stage, the heat started to build up in the battery and causing the temperature to rise slowly. This stage continues from 0s until smoke began to present and the battery casing was damaged at the 2500s. The next stage was when rapid temperature rising occurred at the time after 2500s and peak temperature reaching up to 700°C. At this stage, a vigorous flame began to present followed by loud sound which according to the author, flame reached as far as 4m. Lastly, the decay stage took place with temperature decrease and flame begin to distinguish until combustion stopped. The whole combustion process took about 4000s from start to end [43].

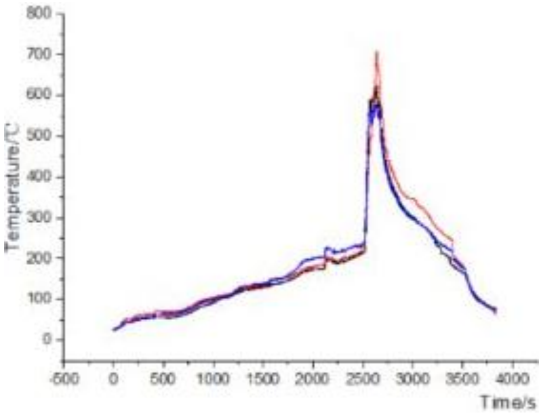

Fig. 8. Temperature curve of LIB combustion [43]

In conclusion, thermal runaway is best to be described as a spontaneous reaction of battery cell self-destruct. One thing to be highlight is that the reaction occurs in split second, although the time taken for the battery temperature to reach the point where thermal runaway is induced is a relatively time taken process.

6. Conclusion

Lithium-ion battery is generally used as an energy source in temperature ranges between 40°C~65°C for ideal usage. But there are also unavoidable situations where LIB needs to be used beyond the ideal normal temperature. Because of that, battery manufacturer has conducted research and development to produce high temperature LIB to fill in the demands. In addition, using LIB at high temperature also brings advantages. This is due to a decrease of internal resistance when the battery temperature is high, allowing more performance to be extracted from the battery. But the downside of using LIB at high temperature is that it will degrade faster and cannot be used for long-lasting. While degraded battery with state of health (SOH) 80% are already considered to meet its end of life (EOL) compare to a fresh new battery with 100% SOH. On the other hand, using LIB at extreme temperature (>100°C) can induce thermal runaway which is the situation n where the battery destroys itself.

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