Implementation and development of standards for lithium-ion energy storage technologies within the South African context.

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Batteries with enhanced characteristics to power portable devices has become crucial in modern society, which has led to the development of a range of batteries, typically in the lithium-ion sphere, to not only power the device, but also to provide a battery that is long lasting, reliable and light weight. The hazardous nature of lithium-ion technology have resulted in many safety incidents in recent years that has highlighted the importance of testing energy storage devices for use in consumer electronics. This has prompted rigorous development and well established standards to allow for guaranteed performance and safety regarding portable devices such as cell phones, tablets and notebooks to name but a few.

The development of better performing lithium-ion batteries has led to an increased uptake of the technology into a range of applications such as portable power tools, electric vehicles and stationary storage power supplies. This has been amplified further by the global drive for environmental friendly technologies that requires the replacement of many types of portable batteries that contain harmful chemicals to be replaced with more environmental friendly alternatives such as lithium-ion batteries. A typical example being the replacement of the vehicle starter lead-acid battery with an equivalent lithium-ion battery that can provide extended life-cycle, higher energy densities and contain relatively benign chemicals.

The use of lithium-ion batteries in larger applications such as full electric vehicles and energy storage for stationary applications has come with new challenges, where the increase in battery size results in an increase in the safety risks associated with it. The quick uptake of this technology has resulted in a delay in response to the development of national standards and implementation thereof in order to assure the performance and safety of systems that now resides in the consumer's homes.

This article will look at importance and benefits of testing according to standardised methods and discuss the complexities surrounding lithium-ion battery testing as well as the interpretation of the results. The article will also review the standards available for locally manufactured lithium-ion battery packs which are typically used for stationary storage or e-mobility type applications and the negative effects of not having standards to guide emerging technologies.

Batteries with enhanced characteristics to power portable devices has become crucial in modern society, which has led to the development of a range of rechargeable batteries. Lithium has a low atomic number and a high electrode potential that results in significantly high energy density when compared to that of traditional rechargeable batteries that contains lead or cadmium. The development of lithium-ion batteries has not been an easy task and breakthrough technologies over the past three decades based on new anodes, cathodes and non-aqueous electrolytes continues the improvement of lithium batteries. The first lithium batteries, were primary batteries, which utilised lithium-metal as the anode and propylene carbonate-lithium perchlorate as the electrolyte in the 1970s, which was follow by lithium-manganese oxide primary cells with li-carbon mono-fluoride as electrolyte in 1975. These cells were mainly used for LED fishing floats, camera and memory back up devices to name but a few. However, the need for rechargeable lithium-ion batteries with high energy density was growing fast and various efforts were made in the 1980s, which concentrated on the development of inorganic cathode compounds, conducting polymer materials for use as possible negative and positive electrode materials but offered no competitive advantage when scaled up [1].

Early rechargeable lithium-ion batteries were plagued with safety problems. The lithium anodes and high performance perchlorate electrolytes had a tendency to form dendrites and very reactive fine powder deposits during recharging which led to thermal events. Attempts were made to use li-al alloy anodes for AA size cells to allow for better safety, however the metallurgy of this alloy proved to be incompatible for the winding process implemented during the manufacturing process. To improve the safety of lithium metal cells with a dioxolane-based electrolyte was developed that spontaneously polymerised at temperatures higher than 110°C. The polymer electrolyte provided a safety mechanism which shut down the cell's chemistry and reduced the possibility of any possible fire hazard [1].

Lithium-ion cells/batteries

With the lithium metal batteries facing various safety problems, new technology was developed and the metal anode was replaced with an intercalation material whereby lithium-ions could be inserted during operation. The first intercalation material was patented in 1981, a year before the patent for the $LiCoO_2$ patent for an intercalation material, where after a new cell design using an intercalation carbon anode and a $LiCoO_2$ cathode was developed. Sony Energytec was the first company to produce commercial cells called lithium-ion cells in 1991. They also introduced electronic circuitry to control the charge and discharge operations, a short circuit device to interrupt current flow on buildup of excess internal cell pressure and the use of a shutdown polymer to further increase the safety of these types of cells [1].

The movement of lithium ions in between the anode and cathode lead to these types of cells being dubbed and accepted by the battery community as "lithium-ion" batteries as there was no lithium metal in the battery. Contrary to the significant improvement in safety due to implementation of intercalation chemistry the deposition of lithium-metal on the graphite anode still occurs and caused some safety concerns. "Safety" of the technology has generally become the watchword for lithium-ion batteries as they have the ability to undergo thermal runaway relatively easily if abused or excessively damaged. Manufacturers have to ensure that the cells are safe under normal operating conditions. In addition to this, some cells have features that shut off the current flow when an abuse situation arises [1].

Lithium-ion batteries and safety

The hazardous nature of lithium-ion technology have resulted in many safety incidents in recent years that has highlighted the importance of thorough testing of energy storage devices for use in consumer electronics be it cellphones, laptops, airplanes or electric vehicles. Some of the more recent incidences that made the media were the battery fires of the Samsung Galaxy Note 7 and the battery pack fire on a Boeing 787 Dreamliner (Figs. 1, 2). The failure of the Samsung battery was well described by M Gikas & J Beilinson in their Consumer Report [2] and were due to a manufacturing problems that occurred. The sheer volume and speed at which these manufacturing process operates can easily lead to an increase in errors, as slight imperfections in cell electrode alignment and inconsistent welds can contribute to short circuits that lead to failures with disastrous consequences. What is interesting and noteworthy of mentioning is that the each manufacturing problem resulted from two different suppliers, this further highlights a very important aspect of the manufacturing of such high volume batteries where only very small tolerances are allowed [2].

Fig. 1: Galaxy Note 7 battery problems [2].

Fig. 2: Boeing 787 Dreamliner battery failure [3].

The other incident was the fire that was caused by lithium-ion batteries on a Boeing 787 Dreamliner (Fig. 2) which was due to an internal short circuit within a cell of the auxiliary power unit lithium-ion battery which led to a thermal runaway that propagated into adjacent cells, resulting in the release of smoke and fire [3]. These are but only two examples that were highlighted in recent media where the need for thorough validation and safety testing of lithium-ion batteries for commercial use is important. The fires caused by lithium-ion batteries are generally very difficult to extinguish and should be avoided. In addition, the batteries also contain metal oxide intercalation materials and organic electrolytes, which when burning can release gases that are carcinogenic in nature and can have further consequences to human health. Other well know incident reported in the media was the full EV Tesla model S that caught fire after hitting metal debris that was lying on the freeway. Even though these were external incidences to the vehicle and battery system, it does however highlight that when large battery packs are damaged significantly fierce fires can occur [4]. With the increase in the use of full and hybrid EV on the roads, the frequency of accidents will increase where the users and rescue services need to be made aware of the correct emergency procedure that should be followed when dealing with high voltage and the flammability of lithium ion batteries.

Lithium-ion technology developments

Besides numerous hazards that is associated with the use of lithium-ion batteries, their uptake as a suitable power source has increased drastically over the last couple of decades. This ranges from the increased use of e-bikes, drones, power tools and portable computers, to name but a few. This increase has partly been due to improvements in the materials performance, improvement in manufacturing processes, a reduction in costs and the use of restrictive materials. Recent EU legislations prohibits the use of portable (<1 kg) batteries that contains restrictive materials such as mercury, cadmium and more relevant, lead, that is not allowed to be more that 0,004% by weight (or 40 ppm) [5]. The environmental policy covers the use of portable batteries but it is anticipated that it will also be implemented in applications such as the SLI lead-acid batteries used for starting of the internal combustion engine in vehicles. The SLI battery is heavier than 1 kg but generally still considered portable [5]. According to a review of battery technologies for automotive applications that was compiled by a number of battery consortiums regarding the future of automotive lead-acid battery the battery will still be around for a number of years whereby it will be used in micro-hybrid applications and as auxiliary batteries for lithium-ion based HEV or BEV's [6]. Micro-hybrid applications such as start-stop technology requires batteries to operate in a partial state of charge and be cranked multiple times during a drive cycle, which puts additional stress on the battery [6].

Start-stop batteries have already been developed for such purposes whereby carbon additives are added to the negative electrode to reduce the rate of sulphation of the negative plate as well as the development of a hybrid type lead-acid battery, known as the Ultra-battery incorporates super-capacitor technology within the functionality of the lead-acid battery chemistry [7, 8]. These technologies have shown that the charge acceptance and cranking ability of lead-acid batteries can be significantly improved. The challenge regarding the latter is that the production and raw materials for such hybrid technologies become very complicated and expensive. OEMs are also requiring that batteries should typically last or be guaranteed for roughly six years, which becomes intrinsically difficult for the battery supplier when trying to keep the cost of the battery as low as possible. The replacement of the lead-acid battery with lithium-ion batteries have already started with OEM's such as Porsche, BMW and Mercedes utilising these batteries in their internal combustion engine (ICE) vehicles. Considering the increasing demand for lithium-ion batteries, it is only a matter of time when the price of lithium-ion batteries will start to drop and the technology be implemented in conventional (ICE) automotive vehicles.

Proper standards needs to be developed in conjunction with experts and the manufacturer within the relevant legislative framework, to ensure the conformance of the product. Sighting the move towards the development of the 12 V SLI lithium-ion battery, the challenge would be the implementation of a new set of standards and validation testing of a 12 V lithium-ion automotive battery that is similar to the current automotive lead-acid batteries requirements (SANS2:2013 or IEC60095-1). The redrafting of the specifications will have to take the different chemistries of the two battery types into consideration. For example, testing for water loss and internal grid corrosion analysis that is done on lead acid batteries according to sections 9.7 and 9.6.1 in IEC60095-1 would not be possible for the same 12 V SLI battery that is a lithium-ion type. Instead, additional testing requirements might be required that rather considers the thermal management of the battery and short circuit tests.

Importance of lithium-ion cell testing

Large scale lithium-ion batteries have already been developed for a range of stationary applications such as telecom, uninterruptible power supplies (UPS), electrical storage systems, utility switching, emergency power and various mobility applications. These can include forklifts, golf carts, autonomously guided vehicles, railways as well as marine applications. Yet the international standard (IEC62620 – Secondary lithium cells and battery for use in industrial applications) for these types of applications have only recently (2017) been adopted by the South African Bureau of Standards.

The timeously implementation of standard testing practices by manufacturers are very important as the results provide a basis for the introduction of new technologies and innovations, and ensures that products, components and services supplied by a different companies will be mutually compatible which results in better trade and manufacturing practices. Cell assemblers in the local marked generally rely on the relevant product specification sheets for the manufacturing of lithium-ion product that has defined ratings. Upon experience with the testing of lithium-ion cells the capacity values experimentally determined through testing and the value stated on the specification sheet can differ by as much as 20%.

Due to lack of testing, most battery assemblers are not aware of these variables, which could lead to unnecessary performance issues and claims. When assembling a lithium-ion pack with various serial and parallel configurations, the effective capacity and cycle life would be influenced by an underperforming cell. This is particularly true when the battery has a protection circuit board, which is more cost effective, instead of a sophisticated balancing system which elevates the cost of the battery.

Complexity of lithium-ion battery testing: Example

The testing of lithium-ion batteries comes with its own challenges. The complexity and technical problems which have been experienced during the implementation of IEC62620:2014 are used as an example and discussed below:

Test environment

Traditional testing of lead acid batteries at ambient or elevated temperature conditions was done by simply immersing them in a temperature controlled water bath. Lithium-ion cells, due to their safety concerns, or batteries have to be tested in specialised explosion proof chambers that are controlled to simulate various temperature conditions. These chambers tend to be pricey which adds to the testing cost of cells or batteries and are not always accessible to the battery manufacturer. For the testing of larger lithium-ion assemblies such as modules of up to 60 V packs of up to 600 V, the complexity and safety requirements becomes significantly larger and in general, these tests are often done in isolated containers that are located away from sensitive infrastructure such as building and public spaces.

Fig. 3: Explosion proof temperature chamber for the testing of lithium-ion cells and air-conditioned container system for larger battery packs.

Operating voltages

Traditional secondary storage battery such as lead-acid batteries have the same voltage range over a range models due to the chemistry of the batteries being the same. With lithium-ion batteries, voltage ranges differ with regards to the chemistry contained within the cell and their operating voltages must be taken into account when testing them. These characteristics are not always forthcoming unless the product is supplied with a product specification sheet. This plays an important role when, in particular, cells are tested that do not have any protection circuitry connected to them. Charging a lithium iron phosphate cell at the voltage of a lithium-ion nickle-manganese-cobalt-oxide charging voltage will lead to the plating of lithium-ion onto the graphite anode and cause dendrite formation which could easily allow for a short circuit which will lead to a thermal event.

Calculation of discharge currents

It should be noted that the standard lithium-ion test methods do not specify set charging regimes, but refers laboratory analyst to the charging recommendations as specified by the cell manufacturer, which is in contrast to lead-acid battery testing standards where (IEC60095-1) these parameters are set. This knowledge is important for the safe operation of the cells during testing and also to prevent damage to customer's cells. Interpretation of lithium-ion standard test methods are not always forthcoming as various terminologies are used which are different from those specified for well-known rechargeable batteries such as the automotive lead acid battery where the capacity is generally stated as a function of its ability to be discharged at a specific rate for 20 hours called the 20 hour capacity rate or short C_{20}. The nominal capacity for lithium-ion batteries depend on whether the cells or batteries are considered of H, E, M or S type cells, which reflect the discharge rate (High, Medium or Slow discharge) for which the cells are intended. Typically the nominal capacities are stated as C_n where "n" is generally ≤ 5 for "H" type cells and 5 for "E" and "M" type cells and can range up to 240 for "S" type cells.
The discharge currents are generally calculated using the following equation which illustrates why the time base "n" for a specified capacity is required to determine the relevant discharge currents.

$$\mathrm{I}t\mathrm{A} = \frac{\mathrm{C}n\mathrm{Ah}}{1\mathrm{h}} \quad (1)$$

Where:

I*t*	is the reference current in Amperes
C*n*	is the rated capacity declared by the manufacturer in Ampere-hours
n	is the time base (hours) for which the capacity is declared

Manufacturer specifications are not always clear regarding the time base at which a given capacity was determined, which results in the testing laboratory having to make a decisions based on experience to determine the parameters with which to test and can have an influence on the test results.

Connection of cells to the cell tester

A particular problem encountered when testing of lithium-ion cells is not only the safety concerns, but in reality how to connect them to the testing equipment that executes the required discharge and charging currents which are set in the respective test programme. Cell testers generally have thick cables to accommodate the large currents that can typically be drawn from or accepted by lithium-ion cells. These are in some instances very difficult to connect to the tester cables especially considering the vast amount cell geometries which are available on the market today. Below illustrates some of the types of cells and how they are dealt with during testing.

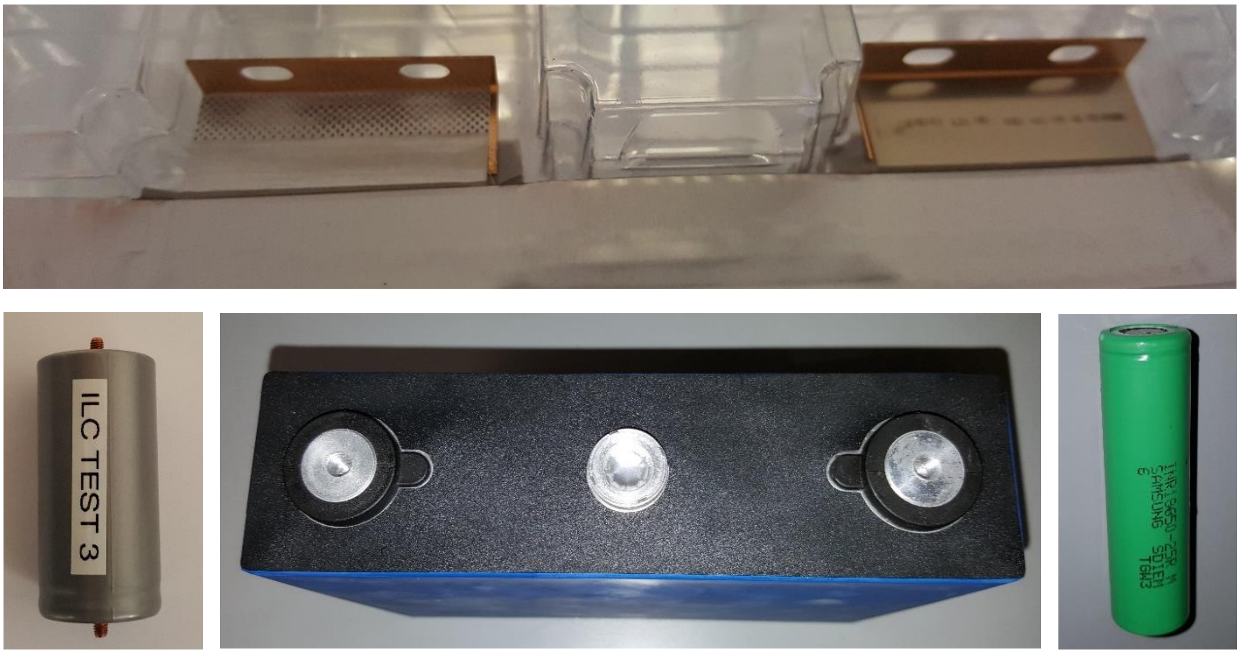

Fig. 4: Various types of lithium-ion cells showing different connection requirements.

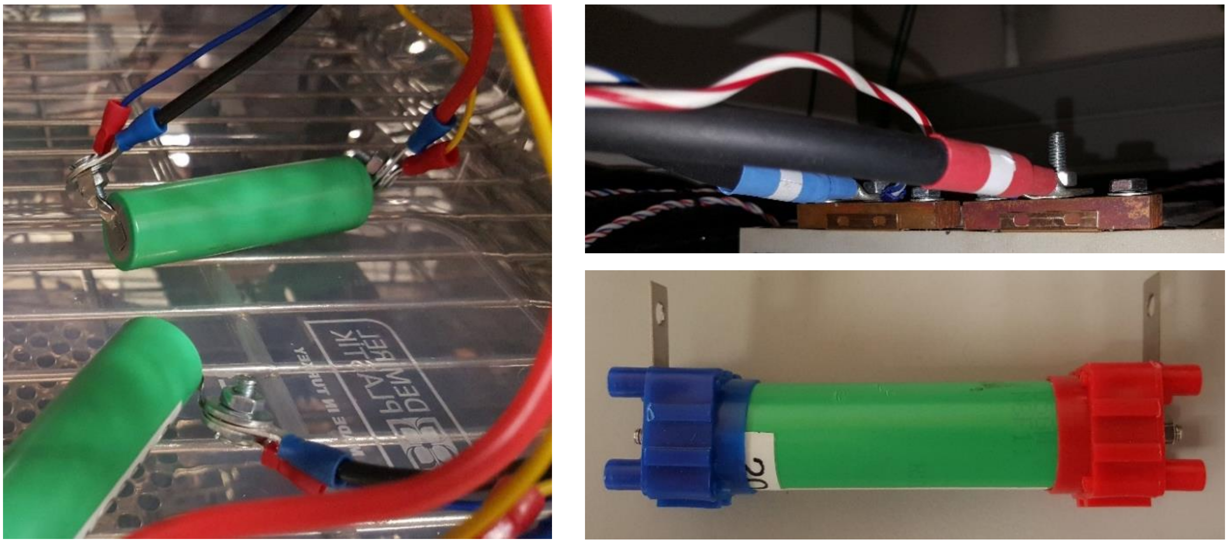

Fig. 5: Connectors used to allow for cells to connect to the battery testing equipment.

Impedance testing

Impedance analysis has emerged as a feasible technique that can give insight into the cell or battery's functionality in application. As a battery ages, its impedance generally increases which would result in the battery heating up during charging or voltage drops under load. Impedance of a cell according to IEC62620 are measured by either Alternating Current (AC) or Direct Current (DC) measurements. The former employs an AC current and measures the phase shift and angle whereby the impedance is determined, where the latter applies high and low discharge currents whereby the resulting voltage drops for each current is used to determine the DC impedance. According to the standard these measurements should be conducted a 50% state of charge (SOC). What is noteworthy is that many manufacturers state the impedance of their cells, but do not specify at which SOC the value was obtained. By performing AC and DC impedance studies on various cells the two impedance values differ significantly as can be seen in the table below.

Table 1: Impedance differences obtained during AC and DC measurements (18650 –LMNC cells).

Cell	AC impedance (mΩ)	DC impedance (mΩ)
1	14	570
2	14	665
3	13	715
4	14	645
5	14	760*

*DC impedance measured for cell 5 when using spot-welded tabs was 340 mΩ

The measurements are also sensitive to the type of holders used where it is difficult to connect the cell to the testing equipment and should be taken into account. The values with and without cell holders and how they were performed are demonstrated below.

Table 2: Impedance differences obtained during AC measurements with and without cell holders (18650 – LMNC cells).

Cell	AC impedance (mΩ) – With cell holder	AC impedance (mΩ) – Without cell holder
1	63	38
2	65	39
3	65	40
4	72	40
5	81	40

Conclusion

More focus should be given to the regulation of these lithium-ion secondary storage devices to provide a safe alternative for the end user due to the high risks associated with these types of batteries. Currently, there also exists a situation in South Africa where insurance companies are new to the concept of storage systems being implemented in residential properties for use as back up or off grid energy storage solutions. Hence, this could amount to the insurer not being willing to approve the claim, should a house burn down due to a fire caused by a lithium-ion storage device that was due to a manufacturing problem or the assembly of cells with varying performance and would refer the client back to the manufacturer to account for the damage that has occurred. In this case the battery manufacturer should make sure that he has covered all the relevant basis regarding the validation testing of his product to the relevant standards available [9] to avoid legal prosecution. The use of accredited battery testing facilities in this instance would be recommended as these facilities have demonstrated to a third party accreditation body that they are technically proficient regarding relevant testing activities, in this case battery testing, which gives credibility to their test results. Besides the aforementioned need for validation and performance testing, there are a range of abuse and safety tests that lithium-ion cells and batteries have to comply to. These include short-circuit tests, nail-penetration tests, drop-tests, to name but a few.

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