Robust testing requirements for Li-ion battery performance analysis

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Abstract. Lithium-ion batteries are considered reliable option for Electric vehicle propulsion and portable applications. Various battery chemistries are being developed to enhance safety and performance of batteries to improve lifespan and reliability. Battery use case scenario often dictate requirements of different li-ion battery types. When target applications are fulfilled, other key considerations are implemented which include testing and characterisation to understand useful performance indicators from chosen battery type. This paper investigates current testing and characterisation needs to understand capacity fade and battery degradation with respect to temperature variations. Cycling tests followed by reference performance tests are used to analyse capacity fade. Due to limitation for the paper size only capacity fade analysis along with immersed test setup are focused to understand battery degradation with respect to various C-rates. Key findings are discussed, and comparative analysis is provided with future recommendations.

Introduction

Lithium-Ion batteries (LIBs) have attracted more attention due to their great energy storage capacity, high current density, extended lifespan, low self-discharge, lack of memory effects, and minimal environmental impact [1]. LIBs are mostly used in portable electronics, energy storage systems, and electric vehicles (EVs) throughout a variety of industries, including transportation and aerospace [2][3], such as Tesla (Model 'S' and Roadster) and Nissan (Leaf) are among the main automotive manufacturers using LIBs for their fleets [4]. LIBs are the widely used technology for energy storage applications, despite the existence of alternative technologies [5]. This is due to their ability to fast-charging capacity with higher cycle life and energy density when compared to established technologies that are available commercially [6]–[8].

Battery Safety

LIBs are an effective energy source for present electric vehicles (EVs), their safety must be taken into consideration before these batteries are large-scale deployment. One of the issues is short circuits in batteries, which can propagate fast within battery packs or modules if they are not managed at the cell level [9]. Battery failures are evident once they are exposed to abusive conditions, however, when using test and validation techniques to determine battery potential, predicting these failures before the time is extremely essential [10]. Various LIBs have been recalled in recent years as a result of explosion and fire incidents [12–15], significantly damaging LIBs reputation and causing serious economic problems for associated market sectors [11].

Although LIBs provide many advantages, it is important to carefully assess their durability and safety [12]. When a battery's capacity approaches 80% of its initial value, battery is at the end of its life. Excessive use of a battery beyond its end-of-life (EOL) specifications can result in bad system performance and occasionally catastrophic events [13][14]. Remaining usable life (RUL) prediction is therefore required to ensure battery safety and reliable operation. Battery's operation can be managed via a battery management system (BMS), based on the RUL prediction results. Accurately estimating the state of health (SOH) of lithium batteries has become difficult, because of the uncertainty and diversity of their internal side reactions and external working conditions [15].

The chemistry of the battery [16][17], its working environment, and its abuse tolerance [18] all have a significant impact on battery safety. Electrochemical system instability is the root cause of a LIBs internal failure [19]. Optimising battery design and making thoughtful selections regarding electrode materials, separators, and electrolytes can greatly increase LIB safety and performance stability. In typical circumstances, external techniques such as cell balancing and cooling can also significantly improve LIBs safety performance [11]. Therefore, it is essential to include appropriate safety precautions in the design, manufacture, and second life of LIBs, such as through the appropriate design of short circuit protection or temperature management systems [20].

Capacity degradation

The actual capacity degrades as the battery cycles, It affects the vehicle's driving range and increases "range anxiety"[21]. Repeated cycles of charging and discharging can cause LIBs to degrade over time in terms of their durability. This might affect their charge retention capacity and their lifespan. Cycle-life performance of LIBs is intrinsically correlated to the fundamental understanding of ageing mechanisms [22]. Therefore, continuous research is carried out to advancements in materials, battery management systems and electrode designs. The goal of LIB development is to increase their efficiency by using eco-friendly components [23]. Batteries can fail at any point in their life cycle for several reasons, including degradation, abuse conditions, and manufacturing errors. Battery abuse loads, both mechanical and thermal, have been simulated through the development of tests [24]. In the EV industry, new techniques that enable continuous battery condition monitoring are currently being used [12].

Literature shows that the causes of capacity fade can be classified into two groups namely calendar ageing and cycling ageing. Whereas cycling ageing is usually influenced by ambient temperature, the number of charge cycles or charge throughput, C-rate, and DoD, calendar ageing is generally primarily affected by the storing temperature, SoC, and time, which represents how long the battery placed in the storage or in resting state [25].

Battery Capacity Fading

Battery capacity fading can be divided into three stages; constant capacity fading, rapid capacity fading, and repetition between capacity increase and decrease [26]. According to Jialong et al, they used incremental capacity analysis and electrochemical impedance spectroscopy to investigate relevant aging mechanisms in their experiment work [27]. They found; The formation of solid electrolyte interface (SEI) films causes a rapid decrease in capacity during the first stage. The capacity decreases slowly due to the stable state of the lithium-ion battery in the second stage. In the third stage, the capacity decreases rapidly again due to the decrease in charge acceptance capability and damage to active materials.

To optimise battery design, management, and operation, precise measurement and prediction of LIBs performance and degradation are essential. As a result, a lot of study has been done to look at the models and testing procedures used to determine the lifetime and capacity fading of LIBs. Several tests to identify capacity fading have been suggested in the literature such as tests based on electrochemical models [28],equivalent circuit models [29], an analytical model with empirical data fitting [30], and performance-based models have been proposed. Safari et al created an electrochemical model to investigate how ageing affects impedance rise and capacity fading [31]. Wang t al proposed advanced data-driven methods for predicting the remaining useful life (RUL) and whole life cycle state of charge (SOC) of lithium-ion batteries [32]. Selcuk et al; presented a novel ageing mechanism, this mechanism improves upon the standard approach of transport limited models that incorporates (i) multi-layered SEI, (ii) lithium-plating, and (iii) reduction of anode porosity. This method attempted to represent more realistic ageing kinetics in order to obtain an understanding of linear and nonlinear capacity fading [22]. Muhammad et al developed dataset for rapid state of health estimation of lithium batteries using EIS and machine learning, this dataset encompasses all ageing statistics for commercially accessible and commonly used lithium-ion batteries. It also evaluates how increased charge throughput (ageing) affects the cell's retained energy capacity and impedance. The dataset quantities the inter-dependency between LIB impedance's temperature and SOC at various ageing states between 100% and 80% SOH [33]. A variety of scientists and engineers working on battery-related projects can use the datasets. Truong et al. report a thorough investigation on decreased lithium-ion battery degradation, through state-of-charge pre-conditioning techniques that enable an electric car to engage in vehicle-to-grid activities when the vehicle is parked [34].

Test procedure and experimental results

This section provides details of the test procedures used on the cells under examination for ageing analysis. These include cycle ageing at various charge/discharge rates and temperatures. Preconditioning and characterisation of cells are done prior to cell testing. The experiment conditions were selected from an originally more comprehensive test matrix.

When conducting long term ageing tests, equipment selection is crucial as it has direct impact on cell performance estimation. To overcome the high-temperature issue and ensure the safety of cells, schematic of a fully immersed setup is shown in figure 1(a), where dielectric oil (Kryo-51) is used and cell fixtures are shown in figure 1(b). The initial characterisation tests proved this method of thermal management more effective, enabling improved temperature control throughout the test.

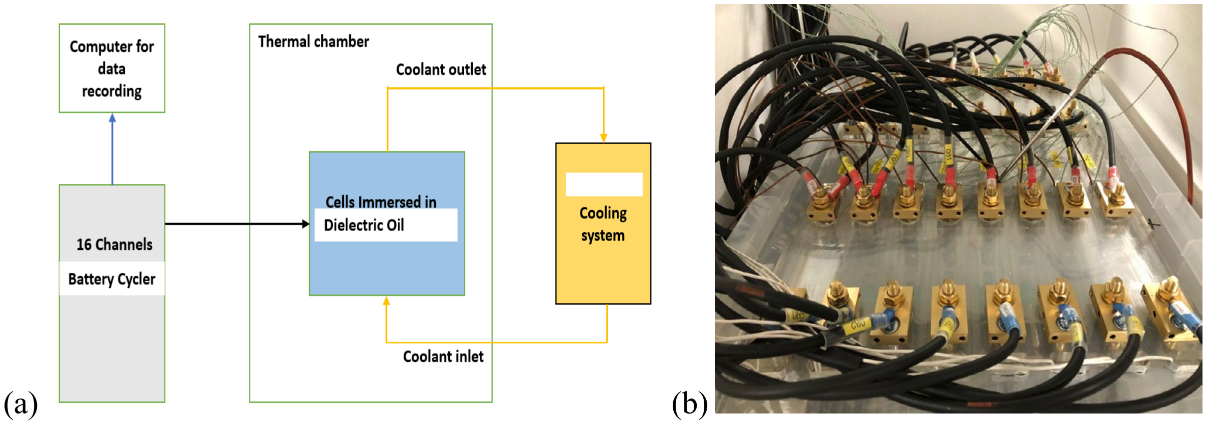


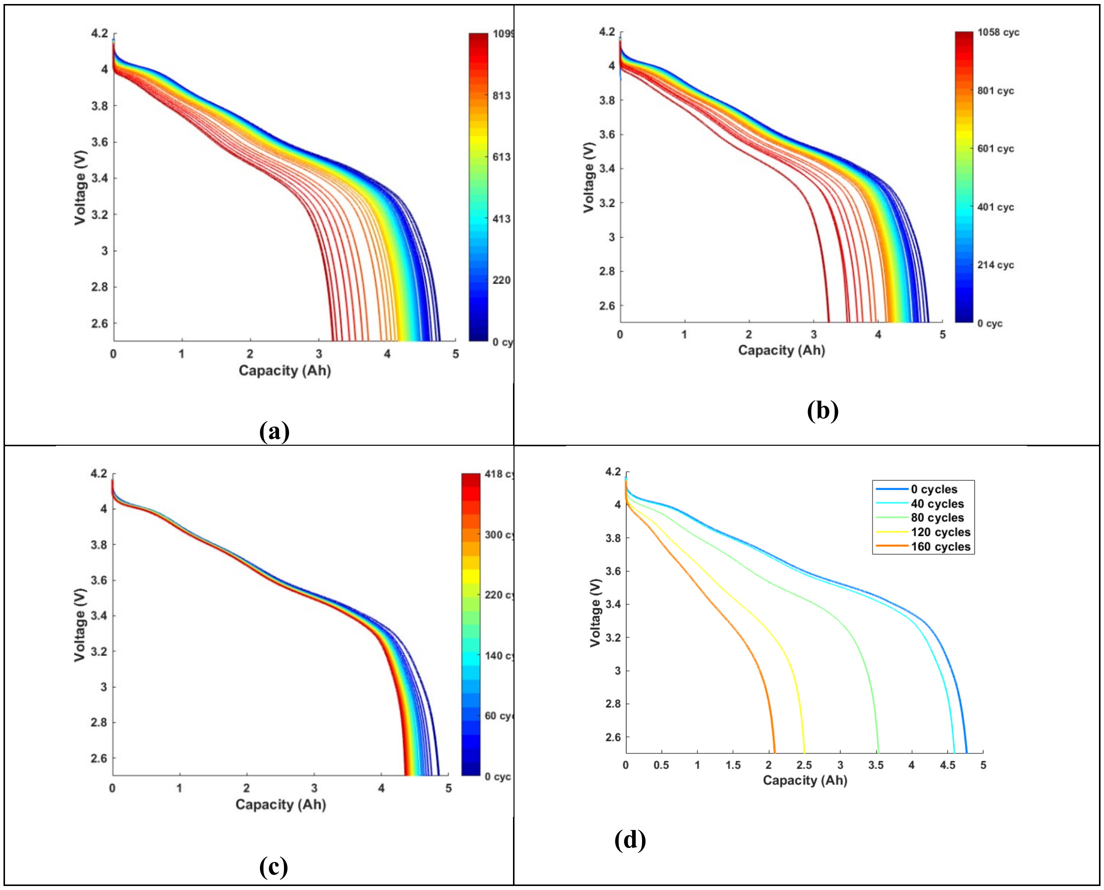
Figure 1: (a) Schematic of ully immersed test setup, (b) Cell fixtures for immersed setup

To record caapcity variations, reference performance tests (RPT) are recorded periodically, and the data is analysed according to the ageing test conditions. The results are discussed in detail in the following sections. The cell capacity is tracked periodically to analyse capacity fade to a given usage profile, with uncertainty intervals based on the four cells used per experiment. To ensure the safe running of the tests, routine monitoring of the oil-rig test setup, running programs and the live readings of the cycler data are performed.

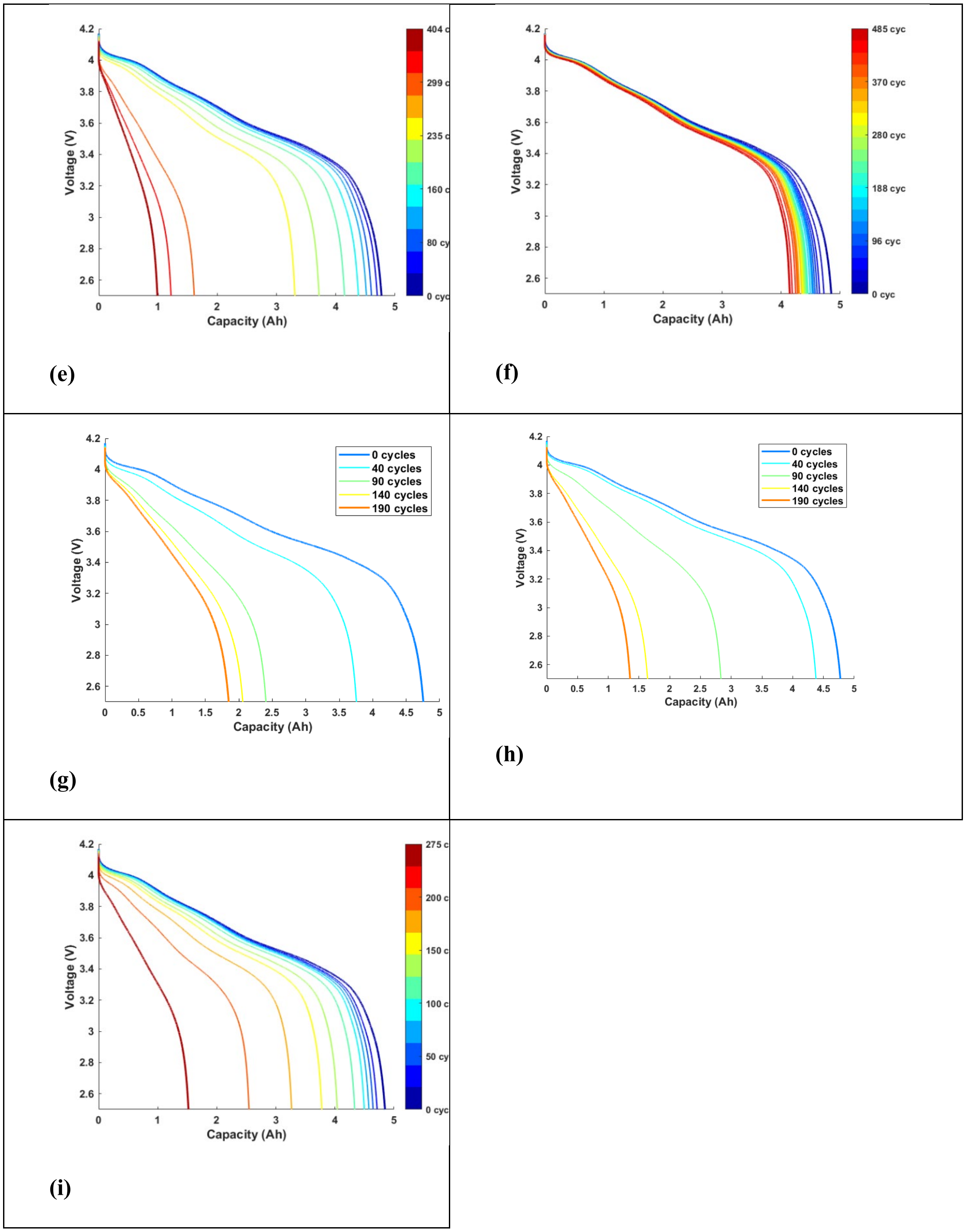
Table 1: Summary of the cycle ageing tests performed

Full Charge-Discharge cycling			
Temperature/Rate	0.3C Charge-0.3C Discharg	0.5C Charge-0.3C Discharge	0.7C Charge- 0.3C Discharge
0°C	4 cells	4 cells	4 cells
10°C	4 cells	4 cells	4 cells
25°C	4 cells	4 cells	4 cells

Table 1 provide details of ageing test conditions used where three temperature conditions are monitored with differect charge and discharge currents applied. The battery investigated was a 5Ah, 21700 cylindrical cell manufactured by LG Chem. This cell utilises nickel-rich NMC811 and SiOy-graphite active materials. For cycle ageing testing we have considered three test conditions which are 0.3C charge-0.3C discharge, 0.5C charge-0.3C discharge, 0.7C charge-0.3C discharge, and three temperature conditions at 0°C, 10°C, and 25°C. Four cells are used for each cycling ageing test condition and the same cell numbers are used throughout this work. Capacity checks are done after one week of cycling for all temperatures. The End-of-Life (EoL) for these cells are defined as 80% capacity compared to the initial capacity (5Ah). Figure 2 shows voltage vs capacity changes with respect to total number of cycles for each cycling condition underwent before reaching EoL.



(a) (b) (c) (d)



(e)

(f)

(g)

(h)

(i)

Figure 2: Capacity Test Voltage Curves (a) 0.3C/0.3C–0°C (b) 0.3C/0.3C–10°C (c) 0.3C/0.3C–25°C (d) 0.5C/0.3C–0°C (e) 0.5C/0.3C–10°C (f) 0.5C/0.3C–25°C (g) 0.7C/0.3C–0°C (h) 0.7C/0.3C–10°C (i) 0.7C/0.3C–25°C

Figures 2(a-c), show there is less affect of immersed temperature with low charge-discharge currents (1.67A). Analysis is further broaden to compare number of cycles and at the same number of cycles (418 cycles) we have same capacity fade. When charge current is increased and testing is done at 0.5C (2.5A) charge and 0.3C (1.67A) discharge as shown in figures 2(d-f), we can see less number of cycles are completed at 0°C and 10°C and capacity fade is rapid which, but at 25°C high number of cycles are achieved and capacity fade is lower which is only 20% after 485 cycles.

Figures 2(g-i) show that fewer cycles are achieved with the 0.7C charge (3.5A) and 0.3C discharge (1.67A) for all temperature cases.

Overall, it can be observed that with the low charge current (0.3C) condition, degradation has occurred more slowly compared with high charge currents (0.5C and 0.7C) for all temperature conditions except 25°C, whereby the performance becomes more comparable. However, ordinarily at lower temperatures, the diffusion kinetics for Li are slower and there is an inevitable trade-off in some performance level. Thus, higher cycling currents would not be sustainable to achieve a long lifespan.

Summary

This paper investigated current testing and characterisation needs to understand capacity fade, battery degradation and temperature dependance. Capacity fade analysis along with immersed test setup is provided to understand battery degradation with respect to various C-rates. Low temperatures in general, can induce deterioration in battery performance for a whole host of reasons; ultimately reducing the discharge voltage and accelerating capacity decay. The most severe capacity fading process has been reported to relate to effects from Li-plating on the anodes. This will result in lowered lithium inventory and reductions in accessible active material – capacity decay will thus continue. This at first may appear counterintuitive; however, this indicates that while cycling within the maximum and minimum voltage limits, the lower discharge current causes lower voltage losses in the battery and allows a higher utilisation of the electrodes. As a result, the charge throughput increases and the cells are worked harder while operating with the constant discharge, resulting in fewer cycles to reach EoL.

Author Contributions

Methodology, M.S.; formal analysis, M.S. and S.R.; investigation M.S. and M.R.; writing—original draft, M.S., M.R. and S.R., writing—review and editing, M.S. All authors have read and agreed to the published version of the manuscript.

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