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An Experimental Investigation of Capacity Performance Evaluation in New and Second Life Lithium-Ion Batteries

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Abstract: There is a significant demand for cylindrical cells, particularly those with the 18650 sizes, in the field of power electronics and electric vehicles application. Charge/discharge rates and battery temperature significantly affect cell performance. The effectiveness of different approaches for evaluating the temperature effect is assessed across diverse charge/discharge rate. This study explores the experimental cycle test of lithium-ion cells from a handheld vacuum cleaner utilizing accelerated tests to evaluate their second life. A pair of new lithium-ion batteries (LIBs) and a pair of second life batteries produced by Murata model US186505D were subjected to tests to verify the state of charge. The findings indicated a decline in performance relative to the manufacturer's specified nominal capacity. The state of health (SOH) for new batteries varied from 93.66% to 83.59% of their initial capacity. Second-life batteries maintained a SOH between 66.22% and 75.40% of their original capacity. The relatively elevated values render second-life batteries appropriate for less rigorous applications. An evaluation is undertaken on how well the battery performs under varied C-rate currents and 25°C ambient temperatures. The paper focuses on analysing battery cell performance and identifying as well as validating the variation in battery capacity over battery cycle. All tests were conducted using a battery tester software, BK Precision. These results will greatly aid in estimating second life batteries (SLBs) effectively.

Keywords: Lithium-ion Battery, New Cells, Second Life Cells, Battery Testing, Capacity Fade, Temperature, State of Health (SOH)

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1. INTRODUCTION

Rechargeable lithium-ion batteries play a crucial role as energy storage solutions across a wide range of usage including portable electronics, electric vehicles and micro-grids. This is attributed to their outstanding characteristics such as high energy and power density along with a low rate of self-discharge [1][2]. Battery state of health (SOH) decreases over time as a result of permanent chemical and physical deterioration [3]. Over the last two decades lithium-ion batteries have increasingly served as the primary power source for portable electronic devices such as power tools laptops and mobile phones. Simultaneously, the next generation of lithium-ion batteries is expanding into larger applications like electric vehicles, power grids and energy storage. Temperature control is critical in lithium-ion batteries applications and understanding heat production and temperature distribution within batteries and packs is essential for developing effective thermal management solutions. Panchal have proposed a solution to tackle this challenge [4][5]. The thermal behaviour of the battery has been the subject of both computational and experimental study [6].

The time or number of cycles required for a battery's capacity to reach a specific threshold such as 80% or 70% is often used to evaluate its lifespan. Consequently, the usable capacity commonly expressed as state of health (SOH) is the most frequently analyzed parameter in ageing studies and is typically used as the primary objective in lifespan prediction models. Additionally, the increase in resistance over a battery's lifetime is examined in numerous ageing studies and is often incorporated into cells designed to study ageing behavior [7].

However, The retired battery can find a new purpose in applications with lower power demands such as battery energy storage systems for renewable energy storage (RES) [8]. Second-life battery (SLB) demonstrations are currently available in a relatively small quantity thus no particularly significant amount of effort is being exerted on the industrial sector to address the use of these batteries [9]. Batteries repurposed for a second life have been thoroughly examined from technological, environmental, and financial perspectives. It has been established that reusing lithium-ion batteries for a second life is feasible offering a way to extend their lifespan for various applications [10][11]. Retired batteries often experience a decline in performance due to increased internal resistance and reduced energy capacity. However, technical analysis alone cannot ensure the safe operation of a second-life battery (SLB) because significant changes occur in cell characteristics as they age. The energy and power capacities of a cell diminish over time due to internal degradation mechanisms, as reflected in capacity loss and increased internal resistance. These rates remain relatively stable for most of a lithium-ion battery's lifespan as the primary degradation processes continue. However, additional aging mechanisms such as lithium plating become more prominent at a later stage in the battery's life [12][13].

This study investigates the relationship between identified degradation mechanisms and the second-use lifespan through a comprehensive experimental framework. Commercial lithium-ion 18650 batteries were cycled at a 1C rate under two specific ambient temperatures 0°C to induce lithium plating and +25°C to promote lithium-ion migration. While electric vehicles typically operate at lower C-rates and temperatures above 0°C these two degradation mechanisms are recognized as relevant to the performance of lithium-ion batteries in electric vehicles [14]. Two second-life scenarios were evaluated using 15 NMC/graphite 20Ah lithium-ion batteries subjected to various cycling and calendar conditions during their first life. The study highlighted that lithium-ion heterogeneities caused by initial aging conditions result in significantly different second lifespans. Cells with a state of health (SOH) below 80% at the end of their first life exhibit particularly short second lifespans. Only cells repurposed after an initial degradation phase demonstrate a relatively extended second lifespan. Building on this, our research aims to assess how first-life aging factors influence the second lifetime. To achieve this, we focus on diagnosing degradation processes at the end of the first life cycle using ante- and post-mortem characterization methods [15].

Exploring the experimental cycle testing of lithium-ion modules provides valuable insights into battery performance lifespan and degradation patterns. It helps evaluate capacity retention, internal resistance, and energy efficiency over time allowing for the identification of factors that affect longevity. This testing is particularly useful for assessing the suitability of repurposed batteries for second-life applications, ensuring their safety and efficiency. Additionally, the data obtained can inform improved battery designs, enhance safety and optimize maintenance contributing to cost-effectiveness. Overall, cycle testing supports sustainability by promoting battery reuse and extending their lifespan, thus reducing waste and supporting a circular economy.

In light of the growing demand for cylindrical cells particularly 18650 formats in power electronics and electric vehicles understanding the factors that influence their performance is crucial. Charge-discharge rates are relatively easy to assess due to their stability over time, but cell temperature presents a more complex challenge due to its temporal and spatial fluctuations. Evaluating the impact of temperature on cell performance under varying conditions is essential to ensure reliability. This study focuses on characterizing the performance of lithium-ion battery modules through experimental cycle testing especially in second-life applications. By investigating the behaviour of Murata US18650SD cells under different C-rate currents and controlled ambient temperatures. The novelty offers valuable insights into optimizing second-life battery usage contributing to sustainable energy solutions. These results are expected to support changeability analysis for SLB applications.

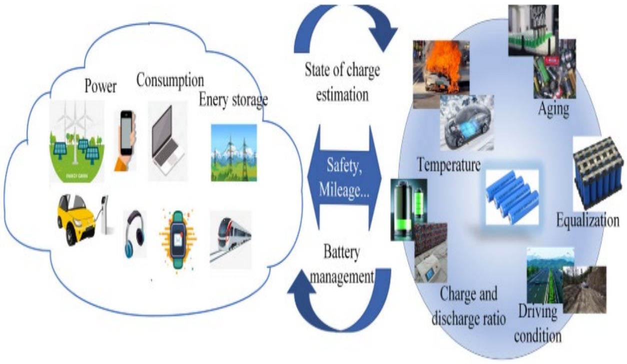
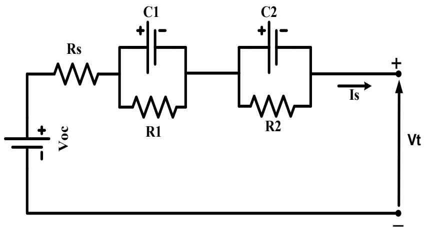


Figure 1. Factors influencing the performance and lifespan of lithium-ion batteries in complex operating conditions [16].

Table 1. Cell Specification of Lithium Ion Battery

Battery Type	Lithium-Ion Murata
Model	US18650VTC5D
Nominal Capacity	2.8 Ah
Nominal Voltage	3.6V
Charging Voltage	4.2V
Minimum Operating Voltage	2.5V
Charging Method	Constant Current (CC)
	Constant Voltage (CV)
Weight	46.7 g
Dimensions	Diameter - 18.5mm
	Height - 65.25mm

(a)



(b)

Figure 2. (a) The physical appearance of lithium-ion battery (b) Thevenin equivalent circuit of lithium-ion battery [17].

2. EXPERIMENTAL SETUP

The test uses a brand new and second life Murata model US186505D battery with a nominal capacity of 2.8Ah. Two electrical devices, an electronic load and a power supply were used to perform the electrical test of the cell as shown in Figure 3. The electronic load provides a steady electrical load that empties the cell at a particular current requirement while the power supply provides a charging current to guarantee the cell is at 100% state of health before discharging tests. BK precision electrical equipment and customized software to switch between charge and discharge were also part of the test configuration. The system is unidirectional, with current flowing from either the electronic load or the power source in one direction depending on the established programmer at a time.

Due to the arrangement of the experimental setup the power supply and electronic load are connected in parallel. The cell's positive and negative tabs are attached to the electronic load and power supply as shown in Figure 3. This ultimately creates a parallel string that connects both systems. To guarantee that the cell is always at 100% (SOH) before the discharge test. The constant charging (CC) current is set at various C rate. The current is delivered until the cell voltage reaches 4.2 volts after which the charging mode changes to constant voltage (CV) until the current reach 0.1C (0.27A). This maintains the voltage at 4.2V while allowing the cell operation at minimum voltage 2.5 V. A completely discharged cell is defined as one in which the voltage decreases to 2.5 V and thermal equilibrium is attained with respect to the thermal chamber temperature.

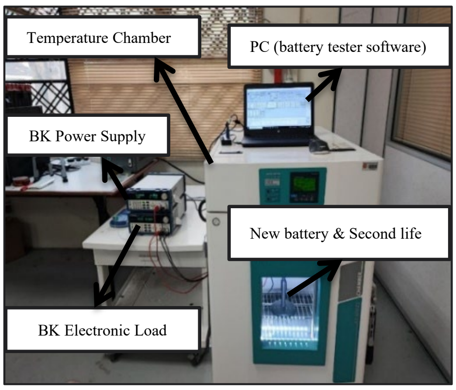


Figure 3. Experimental setup for new cells and SLB test

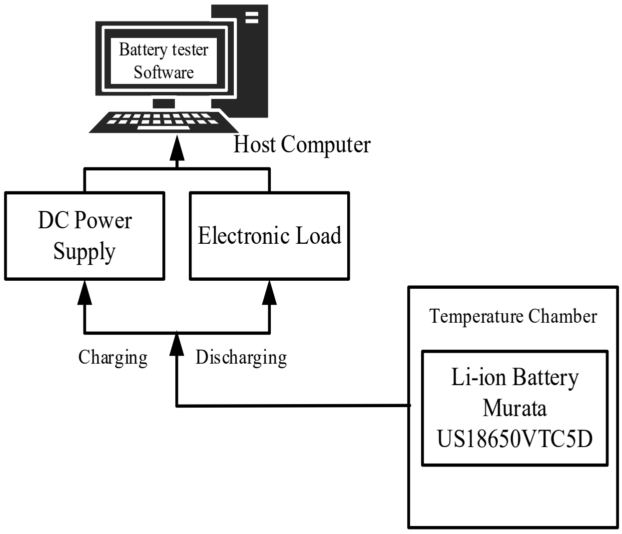


Figure 4. Block diagram of the battery cells test setup

2.1 Experimental Procedure Description

This study explores the impact of deterioration on the functioning of lithium-ion batteries in new and second life handheld vacuum cleaners manufactured by Murata. To achieve these three key experimental procedures are conducted: characterization tests, power measurements and capacity measurements.

The influence of the charge current rate and temperature on the electrical performance of both a new cell and a SLB cells were investigated. The research involves comprehensive analyses to investigate their behaviours under diverse circumstances. The battery modules were tested focusing on understanding how C-rate and temperature affect their performance. The batteries are assessed at 25°C temperature and different charge C-rate for second-life battery applications while preventing additional aging effects such as lithium plating at lower temperatures [18].

2.1.1 Temperature Measurement

An analysis of the fluctuations in temperature's impacts on cylindrical lithium-ion cells is essential to ascertain the degree to which thermal behaviours influences their capacity, power, and lifespan. A thermocouple measures temporal temperature variations hence, thermal mapping of the cell's surface may be achieved by positioning many thermocouples at different points throughout the cell surface. This is extremely important since the cell is going through an electrochemical process which causes it to produce heat and eventually causes it to change its performance owing to differences in temperature. By using high and varied discharge current rates which are an effective way that will enhance heat generation it is possible to monitor large temperature rises. This is done in order to investigate the temperature fluctuations that occur along the surface of the cell. The temperature measurement is conducted by securing thermocouples on the cell's surface using a Kapton tape.

Figure 5, shows the placement of one thermocouple at a specific point on the cell surfaces. The position is adjacent to the cell centre tab. The position was selected primarily because of the significant variations in thermal resistance of the cylindrical cell. Nevertheless, positioning the thermocouple directly at the tab is intrinsically difficult owing to spatial limitations. Electrical connections at both tabs are necessary completely encircling the tab hence the thermocouples are positioned somewhat offset from the tab as seen in figure 5. These locations could represent the average temperature between both tabs. Subsequently, the cell is positioned in an environment where the temperature condition on its surface is controlled and maintained at 25°C.

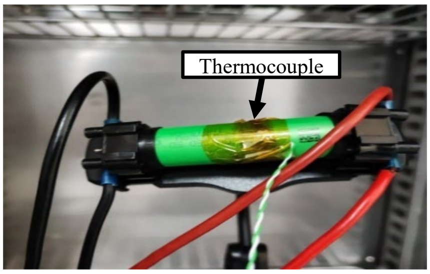


Figure 5. Thermocouple location along the cylindrical to the cell canter tab

Figure 6. Top view of cylindrical cell inside thermal chamber

Figure 6, illustrates the implementation of a test location designed to evaluate the potential for thermal fluctuations based on the cell's position during testing. The cell is positioned horizontally relative to the placement of the thermal chamber fan. This arrangement ensures that the test results are unaffected by the cell's orientation. This initial comparison is crucial because heat transfer is inherently directional making it essential to minimize the influence of external heat transfer variations to obtain reliable results.

A thermal chamber is employed to provide a varying temperature which artificially creates different external conditions for the cell under investigation. A fan is utilized inside the chamber to establish a forced convection condition on the cell surface thereby controlling the thermal environment within the chamber. Prior to conducting the discharge test the cell is kept in the thermal chamber for at least 1 hour. This duration allows the cell to reach thermal equilibrium at the desired test temperature before the discharging test is initiated. Once the test is completed, the chamber's temperature is switched to another test temperature. Subsequently, the cell is allowed to rest in order to reach thermal equilibrium at the new test temperature.

3. RESULTS AND DISCUSSION

Testing lithium-ion batteries for both new and second-life applications is crucial to evaluate their performance, safety, and durability. New batteries are tested to assess capacity, energy efficiency and charge-discharge behaviour under various conditions helping to establish key parameters such as energy density and cycle life. Electrical and thermal models are validated by comparing experimental data with theoretical predictions, ensuring accurate performance forecasting.

For second-life batteries, the focus shifts to evaluating the remaining capacity and performance after their initial use, often in electric vehicles. These tests determine whether the batteries can be repurposed for applications like stationary energy storage. Degradation trends are analysed and further cycling tests are performed to estimate the remaining lifespan. Since aging can affect thermal properties, thermal analysis is essential, along with safety tests to identify risks such as internal shorts or thermal runaway. Together, these assessments ensure that lithium-ion batteries can be safely and effectively reused in second-life applications or recycled if they are no longer viable.

Figure 7 compares the performance of a new battery and a second-life battery at various C-rates. The new battery shows smooth curves and consistently better performance across all C-rates with each C-rate represented by a different colour. In contrast, the second-life battery shown with dashed lines exhibits a decline in performance at all C-rates with lower curves indicating weaker performance compared to the new battery. The figure clearly demonstrates that the new battery consistently outperforms the second-life battery with the performance gap increasing as the C-rate rises. The lower curves of the second-life battery reflect its reduced performance.

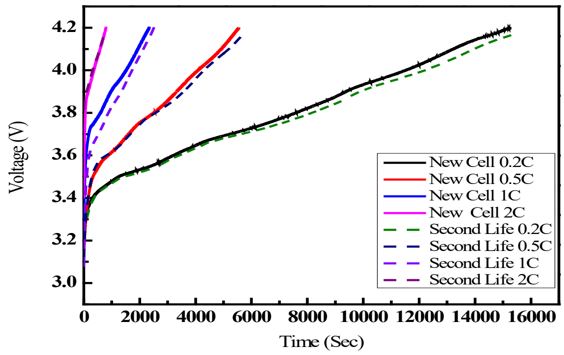


Figure 7. The voltage signal and time at four charge currents for new and second life cells at 25°C

Figure 8 presents the performance characteristics of a new battery and a second-life battery under different discharge rates, highlighting voltage variations. Different colours and line styles are used to represent specific discharge rates. The new battery series is depicted with solid lines: black for 0.2C, red for 0.5C, blue for 1C, and purple for 2C. The second-life battery series is shown with dashed lines: green for 0.2C, light blue for 0.5C, orange for 1C, and purple for 2C.

The curves demonstrate how voltage changes at various charge and discharge rates with the new battery consistently maintaining a higher voltage compared to the second-life battery especially at higher discharge rates. This indicates that the new battery performs better particularly under more demanding conditions. The graph provides useful insights into battery efficiency and longevity across different operating conditions.

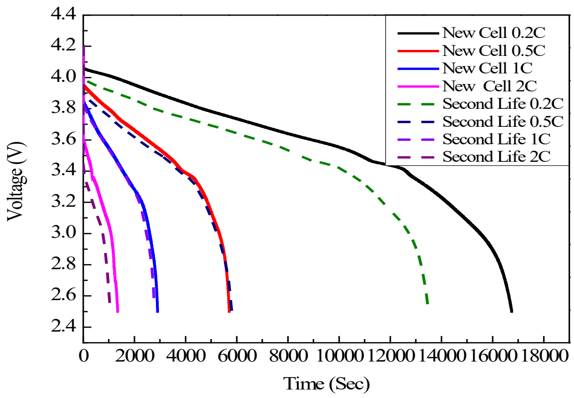


Figure 8. The voltage signal and time at four discharges currents for new and second life cells at 25°C

3.1 Batteries Capacity

The state of health (SOH) is defined as the ratio of the actual capacity of a cell to its nominal capacity as expressed in Eq (1). for the cell relative with a nominal capacity Q_n as shown in Eq. (2). Means a SOH of 80% would have an actual capacity Q_a

$$Q = I \times t \tag{1}$$

Q is capacity
I is the current
t is the time

$$\mathrm{SoH}[\%] = \frac{Q_a}{Q_n} \cdot 100 \tag{2}$$

The measured capacity of the evaluated battery exhibits a linear trend over time due to the constant discharge current with the final values presented in Table 2. This table compares the performance of new and second-life batteries at various C-rates with all measurements taken at a constant temperature of 25°C. The capacity and SOH of the new battery vary depending on the C-rate. At 0.2C, it achieves a capacity of 2.529 Ah and an SOH of 93.66%. At 0.5C, the capacity decreases slightly to 2.503 Ah with an SOH of 92.70%. At 1C, the capacity reduces to 2.373 Ah, with an SOH of 87.88%, and at 2C, the capacity is 2.257 Ah with 83.59% SOH. In contrast, the second-life battery reflecting performance after reuse shows a decline in both capacity and SOH at every C-rate. At 0.2C, the capacity is 2.036 Ah with 75.40% SOH at 0.5C, it drops to 2.096 Ah with 74.62% SOH at 1C, the capacity is 2.007 Ah with 70.33% SOH and at 2C, it falls to 1.788 Ah with 66.22% SOH. This comparison highlights the significant reduction in both capacity and SOH in the second-life battery especially at higher C-rates. In both cell groups, the SOH percentage decreases significantly when charged or discharged at a high C-rate. These findings align well with theoretical predictions [19].

Table 2. Average capacity in new pair of cells and a pair of second life cells

Temperature 25°C		
New Cell		
C-rate	Actual Capacity (Ah)	SOH (%)
0.2C	2.529	93.66
0.5C	2.503	92.70
1C	2.373	87 .88
2C	2.257	83.59
Second Life		
C-rate	Actual Capacity (Ah)	SOH (%)
0.2C	2.036	75.40
0.5C	2.096	74.62
1C	2.007	70.33
2C	1.788	66.22

Table 3. Summary of related works

Ref	C-rate	SOH [%]	Temperature (°C)	Finding
[20]	varied	91.6	25	The findings of this research confirm the battery pack's performance predictions
[21]	0.2	80	35	Further research is needed on lithium inventory and electrode health. Heterogeneous electrode degradation
[15]	C/2	88	25	A sharp drop in starting temperature to 60–70 °C is a critical issue

3. CONCLUSION

The study conducted an experimental investigation on the capacity of new and second-life batteries tested at ambient temperature under varying C-rates. The results showed a reduction in performance compared to the manufacturer's stated nominal capacity. For new batteries, the state of health (SOH) ranged from 93.66% to 83.59% of their original capacity. Second-life batteries retained an SOH ranging from 66.22% to 75.40% of their initial capacity. These moderately high values make second-life batteries suitable for less demanding applications such as renewable energy storage, backup power systems and certain electrical appliances like vacuum cleaners or blenders [22]. While their cycle life is reduced many second-life batteries can still endure several additional charge-discharge cycles. The performance variability among second-life batteries highlights the need for thorough testing and classification prior to reuse. It is established that repurposing second-life batteries provides substantial economic and environmental benefits, such as lowering energy storage costs and reducing electronic waste.

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