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EFFECT OF LOAD AND OPERATIONAL TIME ON THE PERFORMANCE OF LITHIUM-ION BATTERIES

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Abstract

Lithium-ion (Li-ion) batteries have attracted significant global attention due to their widespread applications in portable electronic devices, electric vehicles, and renewable energy storage systems, largely because of their high energy density and long cycle life. Despite these advantages, their performance and longevity are highly influenced by operational stresses such as load intensity and duration of use. This study investigated the effects of load and operating time on the performance of Li-ion batteries using three load conditions: 100 W (light load with a target discharge duration of 15–30 minutes), 200 W (moderate load with a discharge duration of 30–45 minutes), and 300 W (heavy load designed to achieve approximately 1 Ah ±10% consumption), while monitoring performance over operating times ranging from 0 to 60 minutes. The results showed that under light load conditions, the batteries maintained a relatively stable output voltage of approximately 12 V with minimal variation, indicating stable electrochemical behaviour and low internal stress. However, under moderate load conditions, polarization and internal impedance increased gradually with time, leading to a progressive voltage decline to about 8–7 V and a noticeable reduction in efficiency. When subjected to heavy load, the batteries experienced rapid voltage drop to approximately 7 V, accompanied by increased electrochemical and thermal stress that accelerated performance degradation. The findings also revealed a nonlinear interaction between load intensity and operating duration, meaning that prolonged operation at moderate loads could produce degradation effects similar to those caused by short periods of heavy loading. The dominant degradation mechanisms identified included solid electrolyte interphase (SEI) thickening, electrolyte decomposition, particle cracking within electrodes, and lithium plating. Overall, the study highlights that repeated moderate-to-high load cycling significantly shortens battery cycle life and emphasizes the importance of implementing advanced battery management systems incorporating current regulation, optimized depth-of-discharge control, and effective thermal management strategies.

Keywords
lithium-ion batteries, operational time, performance degradation, thermal management, battery management system

1. INTRODUCTION

The storage of energy has attracted greater importance in the 21st century due to current global migration towards renewable energy, electromobility and rapid development of portable electronic devices [1]. Lithium-ion (Li-ion) batteries among the rechargeable battery chemistries are becoming one of the most popular choices due to their high energy density, non-aqueous nature, light weight construction materials, long life span and low self-discharge [2]. Since their first commercialisation in 1990s, the application spectrum of Li-ion batteries has become increasingly demanding from consumer electronics and Electric Vehicles (EV) to aerospace and grid storage systems [3].

Li-ion battery is based on reversible electrochemical reactions, in which the lithium ions can move to and from anode and cathode through electrolyte during charge (discharge) process. During discharge, the lithium ions move from the anode to the cathode and are encapsulated in cathodic material. During discharge, the reverse process occurs and ions move from anode to cathode; electrical energy is discharged. Structurally, a normal lithium-ion cell consists of four basic elements as shown in Fig 1.

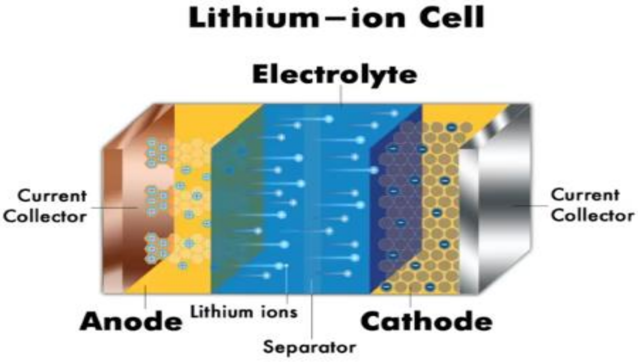

Fig. 1: Structure of a typical lithium-ion battery [4]

Significant advances in Li-ion battery technology have come as a result of the spectacular rise of electric mobility. Both governments and the automobile manufacturers are making significant investment in battery research as well as EV infrastructure to reduce CO_2 emissions, and also reduce dependence on fossil fuel [3]. Leading car manufacturers, including Tesla, BYD, Volkswagen, General Motors and Toyota, are using Li-ion batteries (LBs) to power electric fleets with the aim of enhancing their energy density, safety features, charging rate and thermal management [5]. In the renewable energy field, Li-ion batteries are also considered to address intermittency issues of solar and wind power generation for a stable energy supply and grid support [2].

Despite various advantages, LBs have encountered performance deterioration over long-term use. Multiple charge–discharge cycles induce electrochemical and mechanical reactions that deteriorate the battery capacity and efficiency [6] . Significant deterioration is attributed to Solid Electrolyte Interphase (SEI) layer growth, electrochemical decomposition of the charging/discharging electrolyte, cracking of the electrode particles and lithium plating on the anode surface [7]. Load intensity (current) and time of operation (use duration and cycling frequency) are two most significant factors which prompt these mechanisms. Temperature and internal resistance increases even further and degradation accelerates when the system is in high load conditions (for example, vehicle acceleration or heavy electronic use) [8]. Also, extended exposure leads to a continuous structural and chemical damage; this reduces cycle life of TS batteries [9].

The relationship between load and discharge time is also of great significance on the reliabilities and lifetime of Li-ion batteries. Batteries are rarely subjected to only one stress. For instance, in the acceleration conditions of electric vehicle (EV), the discharge current is high during driving along with a longer driving period on long distance trip, which has multiple degradation effects [10]. In renewable energy storage, the efficiency can be reduced and ageing accelerated by cycling continuously at different loads [11]. While the independent effects of either load or operational time on battery aging have been studied by many researchers, little is known about how they jointly impair the battery degradation for realistic scenarios [12], [13].

In this study, a systematic investigation on the combined effects of both load and operation time over the performance of Li-ion battery was performed with the specific aim of assesing battery capacity and efficiency dependence as affected by load conditions, investigating the battery degradation dependence on cycling time at different loads, and establishing how these two variables play off in affecting battery lifecycle.

2. MATERIALS AND METHOD

2.1. Methodology

This work was an experimental investigation to determine the effect of load and duration of operation on the performance of lithium-ion batteries. The study adopted laboratory experiments to determine battery performance under varying load current and cycling hours, while observing performance metrics such as rate of heat generation over long-term time.

2.2. Materials and Equipment

The following materials and apparatus were used in the study:

i. **Lithium-ion cells:** Commercial cylindrical lithium-ion cells (18650 format, NMC chemistry, with a rated capacity of 2600 mAh) were used for the study.

ii. **Battery testing system:** The experiment was conducted using a programmable Arbin battery cycler, which enabled precise charge–discharge control, load variation, and real-time data logging.
iii. **Power Supply and Electronic Load:** A programmable DC power supply and electronic load capable of simulating both constant and dynamic discharge conditions was used. The system had an output voltage range of 0–30 V, current range of 0–20 A, and power rating of up to 300 W. It featured constant current (CC), constant voltage (CV), and constant resistance (CR) modes, with a measurement accuracy of ±0.5% and real-time data logging capability for voltage, current, and power.
iv. **Battery Management System (BMS) Module:** The BMS module was used to monitor battery safety parameters and detect heat generation during operation. It operated within a voltage range of 3.0–4.2 V per cell, with current monitoring up to 20 A. The system included temperature sensing through integrated NTC thermistors, overcharge protection at approximately 4.25 V, over-discharge protection at about 2.5 V, and thermal protection within a temperature range of 0–60 °C.
v. **Thermal Monitoring Devices:** Infrared thermocouples and temperature sensors were used to measure battery surface and internal temperature variations during testing. The devices had a measurement range of −50 °C to 300 °C, accuracy of ±0.5–1 °C, temperature resolution of 0.1 °C, and a response time of less than 1 second, allowing continuous monitoring of thermal behaviour during battery discharge experiments.

2.3. Experimental procedure

2.3.1. Battery preparation

A total of fifteen (15) lithium-ion battery cells were selected and assembled into a battery module for the experimental investigation. The cells used in this study were commercial cylindrical lithium-ion cells (18650 format) with Nickel–Manganese–Cobalt (NMC) chemistry, each having a nominal voltage of 3.7 V, rated capacity of 2600 mAh, maximum charge voltage of 4.2 V, and cut-off discharge voltage of 2.5 V. The cells also possessed an internal resistance of approximately 20–40 mΩ and a maximum continuous discharge current of about 10 A. The batteries were connected in a series–parallel configuration, where series connection refers to linking cells end-to-end to increase the overall voltage, while parallel connection involves connecting cells side-by-side to increase the overall capacity and current capability of the battery module.

A Battery Management System (BMS) was integrated into the battery pack to ensure safe operation and effective monitoring of the cells. A BMS is an electronic control unit designed to supervise battery performance and protect the cells from unsafe operating conditions. In this study, the BMS provided functions such as overcharge protection (preventing the voltage from exceeding 4.2 V per cell), over-discharge protection (preventing voltage from dropping below 2.5 V), over-current protection, short-circuit protection, and temperature monitoring. It also enabled cell balancing, which is the process of equalizing the state of charge (SOC) among cells to ensure uniform energy distribution and prevent uneven degradation. State of charge refers to the percentage of the battery's available capacity relative to its fully charged state.

Before assembling the battery module, each cell was individually inspected to verify its integrity and conformity with the manufacturer's specifications, including nominal voltage, rated capacity, internal resistance, and open-circuit voltage (OCV). Open-circuit voltage is the voltage measured across the battery terminals when no load is connected.

Prior to the experimental tests, all cells were fully charged to their nominal capacity according to the manufacturer's recommended charging protocol. This step ensured that all batteries began the experiment under identical initial conditions, thereby eliminating bias in the experimental results. After charging, the BMS performed cell balancing to equalize the SOC across all cells and minimize cell-to-cell variations that could lead to uneven stress distribution during discharge cycles [14], [15].

To reduce environmental influence on battery performance, the experiment was conducted under controlled laboratory conditions. The ambient temperature was maintained at 25 ± 2 °C using a temperature-controlled laboratory environment. Maintaining a stable temperature is important because lithium-ion battery performance is strongly affected by thermal conditions; fluctuations in temperature can accelerate electrolyte decomposition and alter electrode reaction kinetics. Maintaining a near-room temperature environment therefore helps ensure that any observed performance variations are primarily due to load intensity and operational time, rather than environmental factors [16].

Following the initial charging and balancing process, the batteries were allowed to stabilize for a short resting period to achieve electrochemical equilibrium, which refers to a stable internal state where ion distribution and electrode potentials are balanced. This stabilization step helps reduce transient effects at the start of testing. All preparation procedures were carefully documented, and the initial engineering parameters of each cell such as capacity, internal resistance, and open-circuit voltage were recorded as baseline reference values for subsequent performance evaluation.

2.3.2. Load variation testing

To assess the impact of load situation on Li-ion battery performance the specially made battery module was analysed at three different load conditions i.e., Low, medium and high load operations. The selected load levels were intended to represent typical applications, ranging from household power demand to higher energy utilisation. The low-load condition was set at 100 W to simulate low-energy applications such as home electronics and portable devices. The medium load was set at 200 W to represent the demand of moderate household or small commercial appliances, such as compact water pumps, desktop systems, and small refrigeration devices. Finally, the high-load case was simulated at 300 W to represent relatively high energy utilisation typical of medium-power battery applications, such as small DC pumps, portable cooling units, and auxiliary power systems. The batteries were steadily discharged under the applied load conditions, and heat generation was continuously monitored across all load levels using paired temperature sensors installed at opposite sections of the Battery Management System (BMS) chamber, together with sensors placed in the surrounding ambient environment.

This dual-sensing approach provided a means of ascertaining the internal thermal response of the battery system under load, as well as the influence of ambient temperature variations on performance and thermal stability. The recordings of the temperature changes were acquired using a data logging device with 5-minute interval to obtain precision and reduce experimental error.

The tests were continued until the 12 V battery reached the manufacturer-recommended cut-off voltage of approximately 9.0 V (≈3.0 V per cell) to prevent over-discharge and potential damage to the lithium-ion cells. This process was repeated for several load cases to ensure the trends were consistent.

The use of lighting bulbs as the test load was intentional because they provide stable, predictable, and purely resistive loads, which help ensure consistent power consumption during the experiment. This approach minimizes external variations in energy demand and allows for more reliable evaluation of battery performance under controlled conditions. The results obtained from these step-load tests were subsequently used to investigate how cyclic operation influences heat generation, accelerated ageing, and efficiency degradation in lithium-ion batteries. By applying these controlled load conditions, the study aimed to simulate realistic operational scenarios and provide practical insights into how repeated load cycles affect both the short-term and long-term performance of lithium-ion batteries, particularly in relation to thermal behaviour and energy efficiency.

2.3.3. Operational time testing

In addition to load decay, pristine and functionalized battery cells were also tested at constant discharge for different amounts of time to determine the influence of run-time. Operation time here referred to the number of consecutive discharge and charge cycles that the Li-ion batteries were subjected too, to imitate real-world use where devices or systems maybe in operation for hours at a time. A digital stopwatch was used to take readings to the nearest second of cycling times, and thus discharge times across several tests could be carefully monitored for accurate comparison.

The batteries were discharged to the manufacturer recommended cut-off volts under constant loading for this experiment. The length of each discharge cycle was measured and the cells recharged at a controlled laboratory rate to service their rated capacity. In such kind of repetitive cycles (discharge–recharge), investigation of the influence of duration/operating time on characteristics like capacity retention, efficiency and voltage stability becomes imperative. In doing so, the experiment yielded new information on the rate of degradation of cells as a function of long-term usage.

The thermal information was recorded while the operational time was being tested. The thermal behaviour of the system was recorded using sandwich-type thermocouples embedded within the BMS chamber, alongside ambient temperature measurements, to monitor any potential overheating associated with prolonged operation. This enabled the comparison of short vs. long duration cycle within a given cell footprint on stability, capacity fade and safety.

To eliminate any possible experimental errors and maintain reproducibility, all the experiments were performed in a controlled laboratory environment, at an ambient temperature of 25 ± 2 °C, and the data obtained were analysed towards relationships among operational time, performance loss and overall cycle life. This methodology enabled the study to account for compounded time-dependent stress factors, such as heat buildup and electrochemical wear, that often accelerate battery aging during long-term operation.

2.4. Combined Effect Testing

To evaluate **interaction effects**, selected cells were subjected simultaneously to high load and long operational time. Comparison was made with cells under controlled conditions (moderate load, short-term operation). The rate of thermal instability was used to quantify combined degradation effects.

2.5. Thermal Management Strategy

Battery Thermal Management System (BTMS) based on temperature measurement and load variation, utilising forced air cooling and heat sink was applied. Control and BTMS-treated test groups were contrasted to evaluate the ability of BTMS in reducing thermal stress and extending longevity. The resultant BTMS is shown in Fig 2. The data was automatically recorded by the battery test system and dispatching a Data Acquisition System (DAQ) at every test steps. A DAQ is an electronic system used to collect, measure, and record physical data from sensors and instruments during an experiment. In battery testing, a DAQ system gathers signals from sensors (such as temperature sensors, voltage probes, and current sensors), converts these signals into digital data, and stores them on a computer for monitoring and analysis. The dimensions include the surface and battery internal temperature (°C).

2.6. Data Analysis

The data were analysed using quantitative and comparative approaches. Graphical analysis was conducted to assess temperature variation trends, whereas Analysis of Variance (ANOVA) was applied to determine the effects of load and operating time on battery performance. Regression analysis and trend research were employed to build temperature variation models above the thermal insulation under different loads and duration of time. Findings were extrapolated for low, medium, and high loads and short, medium, and long operation periods. Load and run time were tested for interaction through a Two-factor ANOVA to assess if they impact, he rates at which temperature fluctuates.

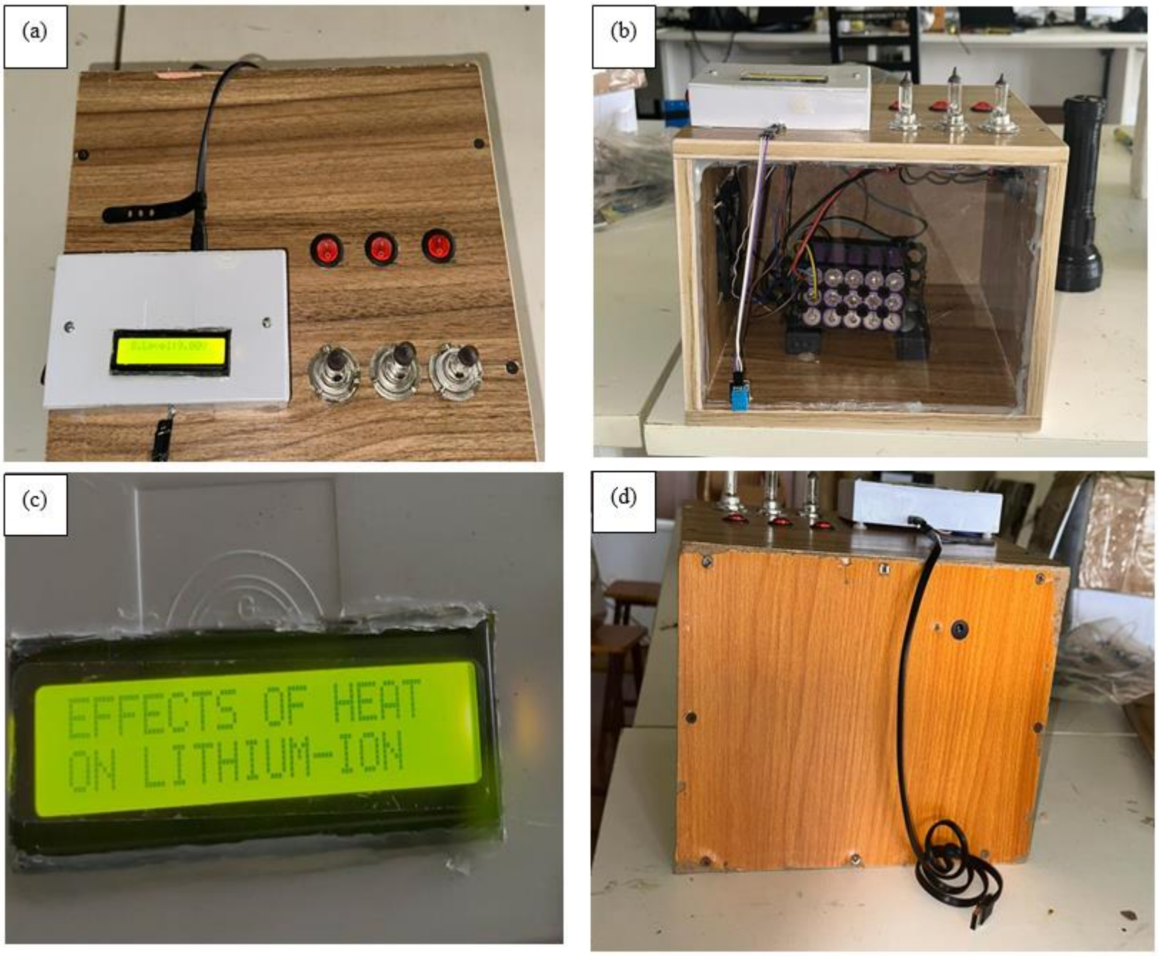

Figure 2a, b, c, d: BTMS Top View, BTMS Internal View, The LCD screen of the BTMS, Back View of the BTMS

3. RESULTS AND DISCUSSION

The experimental results of the effects of load (100, 200 and 300 W) and operational time ($0 < t < 60$ minutes) on lithium-ion battery performance in terms of voltage, battery temperature, and ambient temperature are discussed in this section. These results are discussed in the light of recent literature on degradation mechanisms, especially concerning charge/discharge rate effects, thermal stress and combined cycle and aging as defined within the scope of the present study. Table 1 shows that ANOVA reveals that load, and operational time as well as their interaction are significant ($p < 0.05$) for the battery temperature, ambient temperature and battery voltage. The adjusted R^2 value for the ANOVA were 0.990, 0.928 and 0.982, root mean square error was 0.126, 0.234 and 0.142 for the battery temperature, ambient temperature and battery voltage respectively.

3.1. Effect of Varying Load Conditions on Li-ion Battery Performance

The results represent high differences in voltage response for different loading conditions. The battery also maintained the nominal voltage of 12 V during the entire light-load discharge (60 min) even at a higher power of 100 W, demonstrating good cycling performance in low discharging current conditions. However, at 200 W we experienced a slow decrease in the voltage (down from 12 V to 8 V after 30 min of charging), and therefore we suspect only half charge was cycled. The voltage instantaneously stepped down to 7 V under the maximum load of 300 W and maintained the level over one operation cycle. This sharp drop-off indicates the battery has difficulty delivering heavy loads and its run time capacity is decreased. These findings are consistent with [17], who reported that excessive active loads promote internal polarization and increase ohmic resistance, thereby leading to premature voltage drop. Similarly, [18] also confirmed that Li-ion cells demonstrate non-linear discharge behaviour under high loads due to less lithium ions being engaged in intercalation–deintercalation processes for the voltage stability. This study revealing that overloading greatly reduces voltage retention and utility of batteries.

The finding also implies that the discharge efficiency is closely related to the load intensity. The battery worked with only marginal wastage (100 W) near its rated output, which demonstrated very efficient use of motes-energy. However, efficiency decreased at 200 W because of the decrease in run time and the increased depletion of stored energy. Efficiency plummeted below 300 W load (with battery doing nowhere near max capacity prior to loss of voltage). It thus follows from these findings that these higher loading rates do not just reduce effective capacity, but also the overall efficiency. These observations are also in agreement with [19] showed higher current draws result in reduced coulombic efficiency and fast cathode charge depleting, thus reducing run time. Moreover, [20] pointed out that lithium plating, as well as solid electrolyte interphase (SEI) instability can cause capacity loss of the battery when operated under heavy load condition, and these two pathways reduce the number of active ions for charge transfer. These results therefore provide, that the loss of efficiency under heavy load conditions is more electrochemical than thermal.

Battery temperature differences were minimal under all load conditions, varying from 24.4 to 28.3°C. In particular, at 100 W the temperature ranged from 24 to 27°C, while slightly higher temperatures of up to about 28°C were observed at higher output powers of 200 W and 300 W. At higher loading rates, there was no significant temperature rise (T.R.) and no corresponding increase in ampere-hour output, indicating that temperature rise was not the primary factor responsible for capacity loss under these conditions. This finding is in accordance with the study by [2] who proposed that for short-term high loads temperature may not increase significantly for Li-ion batteries, even though higher levels of destruction will take place inside of the device due to electrochemical degradation leading to efficiency losses. Likewise, [21] stated that although thermal effects are widely recognized as major drivers of battery degradation over its lifetime or under harsh operating conditions, short-cycle performance is predominantly governed by internal resistance and electrochemical kinetics. Thus, the results presented in this work are focused on highlighting that mileage fading at high loading rates is due more to electrochemical breakdown than thermal.

3.2. Influence of Operational Time on Battery Degradation and Performance

The results indicated that operating time significantly affected battery performance across all load conditions. During the initial 0–10 min, the battery voltage was relatively stable at 12 V under low-load operation; however, at higher loads (200 and 300 W), early voltage decay was observed, with the voltage decreasing to 8 V and 7 V, respectively. Beyond 15 min of operation, batteries discharging under higher loads more quickly started to degrade and voltage dropped consistently below 8 V. At 30 min, the discharge at 100 W was still close to full nominal while it had already come down to around 8 V for the condition at 200 W, and stayed steady around some where close to or at only about 7 V throughout for that at 300 W. This is an indication that operational duration enhances the negative effects of load, faster depleting remaining capacity at high discharge rates. Similarly, [22] reported that prolonged operating time leads to rapid polarization of electrodes, thereby significantly reducing voltage stability at high current demand. Likewise, [23] continuous discharge cycling of Li-ion batteries accelerates the consumption of active lithium, which results in a decline in capacity at 30–40 min of operation. Therefore, the current findings confirm that operational time is an important factor influencing effective runtime and this is compounded when combined with high load stress.

With respect to the temperature fluctuation, the battery temperatures are changes in a limited (24.4°C–28. 3°C) over the 60-min testing interval, closely following ambient conditions. This implies that temperature effects were not primarily responsible for battery aging within short-term operation. Rather, the degradation in performance at longer discharge is effectively due to electrochemical limitations such as lithium plating, SEI instability and an increase in internal resistance (these unfold more rapidly with continued discharge time). This is in agreement with the work of [24], who concluded that long duration operation of Liion degrades mainly because of the accumulated electrochemical strain rather than thermal runaway under moderate cycling. In general, the findings emphasize that runtime does affect battery voltage stability and useful life. Temperature did not exceed safe operating conditions, but extended discharging led to performance decay because of electrochemical stress. These results suggest that the operation time needs to be actively controlled in comparison with a load demand for preventing battery degradation and ensuring efficient use of batteries.

Table 1: ANOVA of battery temperature, ambient temperature and battery Volt

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Time	Battery Temperature	365.045	12	30.420	190.128	<.001
	Ambient Temperature	29.491	12	2.458	15.360	<.001
	Battey Volt	65.077	12	5.423	33.894	<.001
Load	Battery Temperature	51.787	2	25.893	161.834	<.001
	Ambient Temperature	119.937	2	59.968	374.803	<.001
	Battey Volt	487.846	2	243.923	1524.519	<.001
Time * Load	Battery Temperature	803.958	24	33.498	209.364	<.001
	Ambient Temperature	11.923	24	0.497	3.105	<.001
	Battey Volt	130.154	24	5.423	33.894	<.001

a. R Squared = .990 (Adjusted R Squared = .985)
b. R Squared = .928 (Adjusted R Squared = .893)
c. R Squared = .982 (Adjusted R Squared = .973)

Table 2: Mean effect of battery temperature, ambient temperature and battery volt

		Battery Temperature	**Ambient Temperature**	**Battery Volt**
Time	0	26.80^{b}	24.83^{c}	10.33^{a}
	5	26.90^{b}	25.47^{b}	10.33^{a}
	10	27.73^{a}	24.97^{c}	10.33^{a}
	15	28.17^{a}	25.40^{b}	10.33^{a}
	20	28.10^{a}	25.63^{bc}	10.33^{a}
	25	28.03^{a}	25.93^{bc}	10.33^{a}
	30	28.17^{a}	25.93^{ab}	9.00^{b}
	35	28.00^{a}	26.07^{ab}	9.00^{b}
	40	28.10^{a}	26.17^{ab}	9.00^{b}
	45	21.43^{c}	26.27^{ab}	9.00^{b}
	50	28.10^{a}	26.33^{ab}	8.67^{b}
	55	28.03^{a}	26.33^{ab}	8.67^{b}
	60	28.10^{a}	26.43^{a}	8.67^{b}
Load	100	27.43^{b}	26.51^{c}	28.13^{a}
	200	24.72^{c}	25.58^{b}	27.16^{a}
	300	12.00^{a}	9.62^{b}	7.00^{c}

3.3. Combined Effect of Load and Operational Time on Cycle Life

The experimental results and the discussion above indicate that load intensity and operational time collaborate to promote the degradation of lithium-ion batteries so as to reduce the cycle life. This overall effect is nonlinear and strongly depending on the operations. As one can see in the data, there are three regimes. At light-duty (≈100 W), the terminal voltage of battery was steady at 12 V and only a slight temperature increase occurred during discharging for 60 min. This suggests low short-term stress and cumulative decay would thus be small under such conditions. At intermediate loads (≈200 W), battery performance started out acceptable but progressively decreased, with the voltage dropping to ≈8–7 V after 30–60 min. This trend reflects the cumulative progression of polarization, resistance increase and capacity loss associated with recurring cycles. At high current (≈300 W) the voltage almost suddenly fell to ≈7 V and stayed at this level, indicating that already from the start kinetic and transport limits were dominating and overly large overpotentials, which will shortly destroy such a system if it is continuously running. This finding is consistent with the recent report by [25], who found that Li-ion cells under high rates of discharge exhibited a sudden drop in voltage and enhanced degradation, as well as moderate continuous loads over an extended period causing substantial cycle life harm.

In terms of mechanism the combined action of load and time-in-operation accelerates the degradation mechanisms taking place. Elevated discharge currents increase local current density, causing overpotentials to rise and internal heating to occur. Long-term exposure to these states promotes the decomposition of electrolyte and the Solid Electrolyte Interphase (SEI)layer thickening, to cause an increase in impedance [27]. In addition, prolonged cycling at high stress may lead to electrode particle fracture and loss of electrical contact, which would exacerbate irreversible capacity decay [28]. With high-rate charging, lithium plating and irreversible loss of cyclable lithium are more possible, so the cycle life is further decreased [29]. These processes act on one another; they are not discrete or independent of each other. For example, moderate heating induced by high current accelerating the growth of SEI comes as thickened SEI raising yet more resistance, bringing in another amount of drop at voltage and also heating under the same load. These combined degradation mechanisms could be a reason behind why even a moderate increase in loading or operation time may cause an unevenly relatively large decrease in cycle life, a tendency also observed in [30], who showed that non-linear aging effects were caused by already small-time extensions (in discharge time) at low loading-rates.

The practical cycle life implications of these results are significant. Battery use with cyclic loading, such as sustained midrange (≈ 200 W / 10 min) and frequent discharge to relatively high power (≈300 W) operating conditions, will cause the battery to degrade rapidly and reduces its useful cycle life dramatically. While the current dataset only reports short-term operational performance, the voltage collapse at heavy loads and gradual decrease as a function of power at moderate load imply that cycle life in real applications of these duty cycles is expected to be much shorter compared to predominant operations under light-duty. This is further motivated by recent modelling and empirical observations showing that even modest increases in discharge rate or duty duration to the cells lead to nonlinear decrease in cycle life on account of multiplicative effects of heat generation, impedance rise and electrode degradation [30], [31].

Practical approaches are needed to counter this double-barrelled impact. Such effective actions include constraining the duration and frequency of high-current discharges (with rules in the battery management system BMS), implementing active thermal management to mitigate cell hotspots, restricting depth of discharge to discourage deep cycles under heavy loads, as well as incorporating predictive scheduling strategies that maximize performance for long-term health [32]. Future work must investigate capacity-retention curves using fast charge-and-discharge cycling protocols at different loading rates and controlled duty time, along with impedance spectroscopy and post-mortem analyses to identify the dominant failure modes. This work would thus establish a reliable lifetime model to predict Li-ion battery durability under combined load–time stresses.

4. CONCLUSION

This study examined how load intensity and operational time influence the performance and degradation behaviour of lithium-ion (Li-ion) batteries. The findings show that both factors play a critical and interconnected role in determining battery efficiency, voltage stability, and long-term capacity retention. At low load conditions (approximately 100 W), the batteries maintained relatively stable voltage profiles around 12 V with minimal temperature rise, indicating efficient electrochemical operation and limited internal stress. However, when the load increased to moderate levels (around 200 W), battery performance gradually deteriorated over time. A noticeable voltage sag of about 8–7 V was observed after 30–60 minutes of operation, suggesting growing internal resistance, polarization effects, and accelerated capacity loss. Under very high load conditions (around 300 W), the batteries experienced a rapid voltage drop to about 7 V within seconds, indicating severe electrochemical stress and the onset of irreversible degradation mechanisms.

The study further revealed that the negative impact of load becomes more pronounced with prolonged operational time. While short-term exposure to high loads may sometimes be partially reversible, sustained operation even at moderate loads can trigger cumulative degradation processes such as solid electrolyte interphase (SEI) growth, electrolyte decomposition, lithium plating, and increased internal resistance. These mechanisms collectively reduce the cycle life and overall reliability of Li-ion batteries. The results therefore confirm that battery degradation under load–time interaction is nonlinear, meaning that moderate stress over long durations can be as damaging as short-term high-intensity operation.

Based on these findings, effective battery management and operational strategies are essential to enhance battery lifespan and safety. Advanced battery management systems should regulate discharge rates, incorporate adaptive current limits, and schedule rest periods to reduce cumulative stress. Thermal management systems that maintain operating temperatures between 20 °C and 35 °C are also necessary to prevent overheating and accelerated degradation. In addition, manufacturers should define safe load profiles and discharge limits, while researchers should continue developing predictive lifetime models through accelerated testing and electrochemical diagnostics. Implementing these measures will improve the reliability, safety, and longevity of Li-ion batteries used in electric vehicles, renewable energy storage systems, and consumer electronics.

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