

INVESTIGATION OF C-RATE AND POST-DISCHARGE REST EFFECTS ON VOLTAGE RECOVERY AND CAPACITY IN LI-ION BATTERY PACK FOR LEO SATELLITE APPLICATIONS

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Abstract. Lithium-ion batteries are extensively employed in LEO satellites because of their high energy density, lightweight design, and superior cycle efficiency; however, their on-orbit performance is strongly influenced by discharge rate and post-discharge voltage relaxation during repetitive eclipse-sunlight cycling. In this study, an experimental investigation was conducted on an 8s6p Li-ion battery pack with a nominal capacity of 19.2 Ah and nominal voltage of 28.8 V. The battery was tested under three different discharge rates – C/20, C/10, and C/5 – followed by rest periods of 30 minutes, 1 hour, and 2 hours. The results indicate that increasing the C-rate significantly enhances the voltage recovery amplitude, whereas extending the rest duration provides only marginal improvement in effective capacity. The voltage relaxation behaviors is well described by a double-exponential model. The proposed model ($R^2 > 0.99$, RMSE < 0.03) confirms the coexistence of fast and slow relaxation processes driven by Li-ion redistribution and electrode structure relaxation. These findings demonstrate that orbit-aware management of discharge rates and rest phase can improve voltage stability and effective energy utilization without increasing system mass or volume, offering practical guidance for battery management strategies in power-constrained LEO missions, including CubeSats and nanosatellites.

Keywords: Li-ion batteries, C-rate, voltage recovery, effective capacity, rest duration, LEO satellites, energy management.

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1. Introduction

Lithium-ion (Li-ion) batteries are widely adopted as the primary energy storage system in LEO satellites owing to their high energy density, superior cycle efficiency, and capability to deliver power under varying operational demands (Bandhauer et al., 2011; Goodenough & Park, 2013; Pathak et al., 2023). LEO satellites perform a broad range of functions, including communication, remote sensing, and GPS (Global Positioning System)-based navigation, all of which rely heavily on reliable onboard power availability. As illustrated in Figure 1, a LEO satellite typically follows a near-circular orbit with a period of approximately 90 minutes, comprising a sunlight phase of about 60 minutes and an eclipse phase lasting 30 minutes (Halpert et al., 1999). During the sunlight phase, solar arrays recharge the battery, while during eclipse, the stored energy is discharged to maintain system operation. Over one year, this cycling results in approximately 5,000 charge-discharge cycles, and for a 4–5 year mission lifetime, the number of operational cycles may exceed 25,000. Such repetitive cycling,

coupled with alternating sunlight-eclipse transition and dynamic loads, subjects the battery to diverse C-rate profiles and variable rest periods. These operational stressors influence the battery's long-term performance, State of Health (SOH), and Remaining Useful Life (RUL).

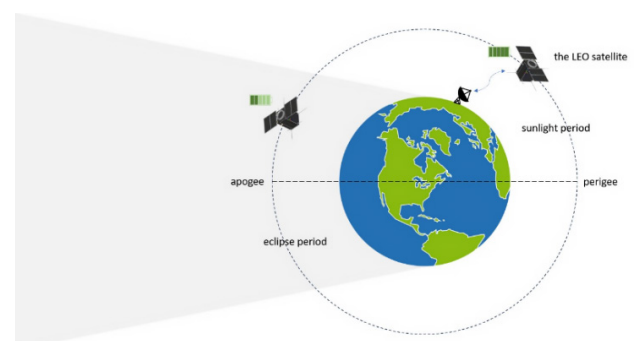


Figure 1. Sunlight–eclipse periods of a Low Earth Orbit (LEO) satellite and the concept of energy storage in a Li-ion battery

Recent investigations have demonstrated that both discharge rate and temperature play crucial roles in shaping voltage recovery and relaxation behavior. High C-rate discharge tends to create steep Li-ion concentration gradients, delaying electrochemical equilibrium and extending relaxation time constant (Chen et al., 2025; Gonzalez Malabet et al., 2024). Moreover, temperature fluctuations in LEO orbits accelerate kinetic heterogeneity and alter the Open-Circuit-Voltage (OCV) recovery characteristic (X. Li et al., 2025; Madani et al., 2025). Reduced-order electrochemical models have been developed to predict voltage relaxation dynamics under high C-rates with improved computational efficiency (Gao & Lu, 2024). These studies emphasize that rest duration, C-rates, and temperature collectively determine the apparent reversible capacity and voltage recovery magnitude.

Within the context of space power system, Reid et al. (2007) reported that higher C-rates yielded greater apparent capacity, primarily due to post-discharge voltage recovery effects. Cook et al. (2021) further showed that under low-temperature conditions, LiNiCoAlO₂ (NCA) cells exhibited faster voltage relaxation following high discharge current. In a broader perspective, Pathak et al. (2023) emphasized that NCA chemistry offers superior cycle stability and energy density, making it a promising candidate for energy storage systems in LEO satellites that experience fluctuating power demands and recurrent eclipse periods.

Other studies have also highlighted the correlation between discharge rate and voltage recovery mechanisms within the context of LEO satellite operations. Ramakrishnan et al. (2010) investigated the behavior of End of Discharge Voltage (EODV) and retained capacity throughout daily orbital cycles, while *Design and Management of Satellite Power Systems* (Lee et al., 2013) discussed the recovery efficiency that occurs during transitions from load to rest conditions. These findings were further supported by Park and Yun (2025), who developed a data-driven degradation estimation method to monitor on-orbit voltage variations during the relaxation phase. Overall, an increase in C-rate has been shown to enhance the contribution of voltage relaxation, which indirectly improves the effective capacity and extends the functional performance of Li-ion batteries in LEO satellite operations.

In addition to the influence of C-rate, several studies have demonstrated that the voltage recovery phenomenon is strongly affected by the rest period following a discharge cycle. A. Li et al. (2016) reported that when a Li-ion cell is allowed to rest for several hours after discharge, its voltage can increase by more than 1 V compared to the voltage measured immediately after load removal. This phenomenon is associated with the relaxation of Li-ion concentration within the active particles and the release of internal voltage gradients formed during current flow. A more recent study by Qian et al. (2022) reinforced these findings, showing that at low State of Charge (SOC) and room temperature, longer rest periods (≥ 3 h) produce

greater voltage recovery compared to shorter rest durations (<30 min). The dominant mechanisms were identified as the slow diffusion of lithium into graphite particles and the relaxation of potential caused by charge accumulation within the electrical double layer.

Epding et al. (2019) further noted that this phenomenon is associated with the so-called apparent reversible capacity, which arises from the difference between the instantaneous voltage and the equilibrium voltage after relaxation. Theuerkauf and Swan (2022) also emphasized that the voltage relaxation process can extend over several hours, depending on the Depth of Discharge (DOD) and operating temperature. These findings highlight that the rest period is a critical parameter that should not be overlooked in battery capacity evaluation, as the voltage measured after prolonged relaxation may exceed the nominal voltage, leading to a biased interpretation of the effective capacity.

The voltage relaxation phenomenon also holds significant relevance for battery diagnostics and modeling. Bharathraj et al. (2023) employed voltage relaxation response analysis for early short-circuit prognosis; C. Li et al. (2022) developed an Equivalent Circuit Model (ECM) incorporating nonlinear solid-phase diffusion effects to describe the voltage relaxation behavior of high-energy cells, while Skurtveit et al. (2025) demonstrated a gradual structural relaxation in electrode materials contributing to the observed relaxation profiles.

Although numerous studies have independently explored the effects of C-rate and voltage relaxation, investigations that interrelate these two phenomena in the context of Li-ion battery packs for space applications remain limited. Most prior studies on Li-ion battery voltage recovery have focused on single-cell configurations, tightly controlled temperature conditions, or terrestrial load scenarios that do not adequately represent the operational characteristics of LEO satellites. Furthermore, discussions of voltage recovery are often decoupled from its implications for effective capacity and voltage cut-off logic within satellite power management systems. The novelty of this study lies in a systematic evaluation of the effects of C-rate and post-discharge rest duration on voltage recovery and effective capacity at the battery pack level, under ambient temperature conditions representative of the early-stage testing of satellite power systems. This approach is further complemented by voltage relaxation modeling using a double-exponential formulation, enabling the association of fast and slow recovery time constants with polarization and ion diffusion mechanisms. Consequently, this study provides a methodologically relevant contribution to the preliminary design and evaluation of battery management strategies for LEO satellites, particularly with respect to voltage margin definition and cut-off decision-making in accordance with the European Cooperation for Space Standardization (ECSS) standards and the National Aeronautics and Space Administration (NASA) technical guideline.

2. Methodology

This study was designed to analyze the influence of discharge rate (C-rate) and post-discharge rest duration on the voltage recovery characteristics, effective capacity, and health indicators of a commercial Li-ion battery. The primary focus is directed toward the initial phase of cycling, which is relevant to the daily cyclic operating profile of LEO satellites. The methodological framework consists of four main stages: sample and instrumentation, experimental procedures, data analysis, and results and discussion based on experimental observations.

2.1. Sample and instrumentation

The main specifications of the battery pack used in this study are summarized in Table 1. The pack consists of cylindrical Panasonic NCR18650B cells configured in an 8s6p arrangement. The LiNiCoAlO₂ (NCA) chemistry was selected due to its excellent cycle stability and high energy density, making it well-suited for space applications, particularly for LEO satellites.

The experimental setup employed a programmable DC power supply for charging and a programmable electronic load for discharging, both controlled via a computer interface to ensure precise current and voltage regulation. Data acquisition was performed using a high-resolution multichannel data logger capable of recording voltage, current, and temperature at a one-second interval. The current measurement accuracy was $\pm 0.1\%$ F.S., while voltage accuracy reached ± 1 mV, enabling the detection of small variations associated with the voltage recovery phenomenon. The use of a high-resolution data logger was essential, as voltage relaxation typically occurs at the millivolt scale, requiring high precision to avoid analytical bias (Theuerkauf & Swan, 2022).

All experiments were conducted under controlled ambient temperature conditions of 25 °C. This temperature range aligns with laboratory testing conventions and with ECSS (2019), NASA (2010) technical guidelines, which recommend ambient conditions (≈ 20 – 25 °C) for verification of Li-ion battery performance and life-cycle testing

in space applications. Such consistency ensures reliable comparison across experiments and minimizes the influence of thermal variability on voltage and capacity measurements. Consequently, the experimental setup not only satisfies standard laboratory requirements but also ensures the interpretability of results within the context of LEO satellite power management.

2.2. Experimental procedure

During the charging stage, the Li-ion battery pack was fully charged using the constant current–constant voltage (CC–CV) method under three different C-rates: C/20 (1 A), C/10 (2 A), and C/5 (3.8 A). The selection of discharge rates of C/20, C/10, and C/5 in this study was motivated by the need to represent a realistic range of load profiles encountered during LEO satellite operations. Specifically, the C/20 rate represents low-load (housekeeping) conditions commonly observed during sunlight phase or safe mode operations, where power consumption is dominated by essential subsystems. The C/10 rate was chosen to reflect nominal load conditions during the eclipse phase, when the power system supports standard platform and payload operations. In contrast, the C/5 rate was employed to simulate moderate to relatively high load conditions that may occur during intensive payload activities, communication maneuvers, or specific operational transitions.

The rest time of 30 minutes, 1 hour, and 2 hours were selected to represent realistic operational scenarios within LEO satellites' power systems, particularly during eclipse-to-sunlight transitions, low-load phases, and safe mode operations. This range is consistent with space power system testing guidelines outlined in ECSS standards and the NASA technical guideline, which recommend rest periods on the order of tens of minutes to several hours to evaluate voltage relaxation dynamics without disrupting orbital cycle continuity.

The charging process continued until the terminal voltage of the pack reached the upper limit of 33.6 V (equivalent to 4.2 V per cell). Subsequently, the voltage was held constant at 33.6 V until the charging current decreased to 600 mA, marking the end of the charging phase.

Table 1. Specifications of the Li-ion battery pack (8s6p configuration)

Parameter	Specification	Description
Battery type	Lithium-ion (Li-ion)	–
Pack configuration	8s6p	8 cells in series X 6 cells in parallel
Total number of cells	48 sel	8 X 6 = 48
Cell type	Panasonic NCR18650B	Cylinder 18650 cell
Nominal cell capacity, Ah	3.2	–
Nominal pack capacity, Ah	19.2	3.2 Ah X 6 parallel
Nominal pack voltage, V	28.8	3.6 V X 8 series
Maximum pack voltage, V	33.6	4.2 V X 8 series
Minimum pack voltage, V	20.0	2.5 V X 8 series
Operating voltage (per cell), V	2.5–4.2	–

Immediately after charging, the pack was left in an open-circuit condition with three different rest durations – 30 minutes, 1 hour, and 2 hours – to observe the voltage recovery dynamics. The terminal voltage was continuously monitored at a sampling interval of 6 seconds to capture the transient relaxation behavior throughout the rest period.

The discharging process was then carried out at the same three C-rates (C/20, C/10, and C/5) until the terminal voltage reached the lower limit of 20.0 V (2.5 V per cell). Following each discharge, the pack was again left under open-circuit conditions for the same set of rest durations (30 minutes, 1 hour, and 2 hours).

In total, nine charge–discharge cycles were performed, covering all combinations of C-rate and rest duration. The recorded voltage recovery data were analyzed using a double-exponential fitting approach to extract the fast (τ_1) and slow (τ_2) relaxation time constants, following the methodology established in previous studies (Fernando et al., 2024; Skurtveit et al., 2025; Theuerkauf & Swan, 2022).

This procedure enables a quantitative assessment of the relationship between C-rate, rest duration, and the voltage recovery phenomenon, thereby facilitating evaluation of the effective capacity and relaxation behavior of Li-ion battery packs within the operational context of LEO satellite applications.

2.3. Data analysis

The experimental data acquired include terminal voltage, current, and time throughout each charge–discharge cycle. The effective discharge capacity for each cycle was calculated by integrating the discharge current over time according to the fundamental relationship:

$$Q = \int_{t_0}^{t_f} I(t) dt, \quad (1)$$

where Q denotes the discharge capacity (Ah), $I(t)$ is the instantaneous discharge current (A), and t_0 and t_f represent the initial and final times of the discharge process, respectively. The numerical integration was performed using discrete current and time data acquired from the high-resolution data acquisition system to ensure accurate estimation of the delivered capacity under each test condition.

The obtained capacity values were then normalized to the nominal battery pack capacity (19.2 Ah) to facilitate comparison across different test cycles (Zhang et al., 2025; Zhu et al., 2022). The voltage recovery phenomenon was subsequently analyzed by defining the recovery amplitude as:

$$\Delta V = V_\infty - V_0, \quad (2)$$

where V_0 is the terminal voltage immediately after the discharge process, and V_∞ represents the steady-state voltage after the relaxation period (Fernando et al., 2024; Theuerkauf & Swan, 2022). This parameter quantifies the total magnitude of voltage recovery and serves as an indicator of the electrochemical relaxation occurring within the cell.

To further characterize the voltage relaxation behavior, the temporal evolution of the Open-Circuit Voltage (OCV) during the rest period was modeled using a double-exponential fitting function expressed as:

$$V(t) = V_\infty + A_1 e^{-\frac{t}{\tau_1}} + A_2 e^{-\frac{t}{\tau_2}}, \quad (3)$$

where $V(t)$ denotes the terminal voltage at time t , V_∞ is the steady-state voltage after a sufficiently long rest period, A_1 and A_2 are amplitude coefficients corresponding to the fast and slow relaxation components, respectively, and τ_1 and τ_2 represent their associated time constants. The fast relaxation constant (τ_1) is generally associated with charge redistribution and double-layer relaxation, whereas the slow relaxation constant (τ_2) reflects solid-state lithium diffusion and structural relaxation processes within the electrode materials (Theuerkauf & Swan, 2022; Skurtveit et al., 2025).

The voltage relaxation modeling was carried out using a double-exponential function or an equivalent circuit representation fitted to the experimental OCV relaxation data. In several studies, the mean values and standard deviations obtained from repeated measurements were reported to represent inter-cell variability, while statistical indicators such as the coefficient of determination (R^2) and the Root Mean Square Error (RMSE) were used to evaluate how well the model captured the actual relaxation behavior (Fernando et al., 2024; Theuerkauf & Swan, 2022; Zhu et al., 2022).

3. Result and discussion

3.1. Electrochemical mechanism and interpretation

Figure 2 shows that increasing the C-rate leads to a progressively larger voltage recovery amplitude (ΔV) following the rest period. The annotations of V_0 and V_∞ at each C-rate, clarify that the observed voltage recovery is primarily driven by the magnitude of polarization and Li-ion concentration gradients developed during higher-rate discharge. This behavior is further examined through the double-exponential modeling presented in Figure 3, which identifies two dominant relaxation mechanisms: a fast recovery component (τ_1) and a slow recovery component (τ_2). At higher C-rate, the slow component becomes increasingly dominant, reflecting diffusion limitations of Li-ions within the electrode structure. Quantitatively, this relationship is summarized in Table 2, which indicates that increasing the C-rate from C/20 to C/5 results in a substantial increase in ΔV , while the corresponding gain in effective capacity does not scale proportionally, even when longer rest durations are applied. This finding confirms that the observed voltage recovery primarily reflects electrochemical relaxation processes rather than true capacity recovery. Considering that typical LEO missions experience approximately 14 orbital cycles per day, these results are operationally relevant, as they demonstrate that managing the C-rate profile has a more pronounced impact on bus voltage stability than extending rest duration alone.

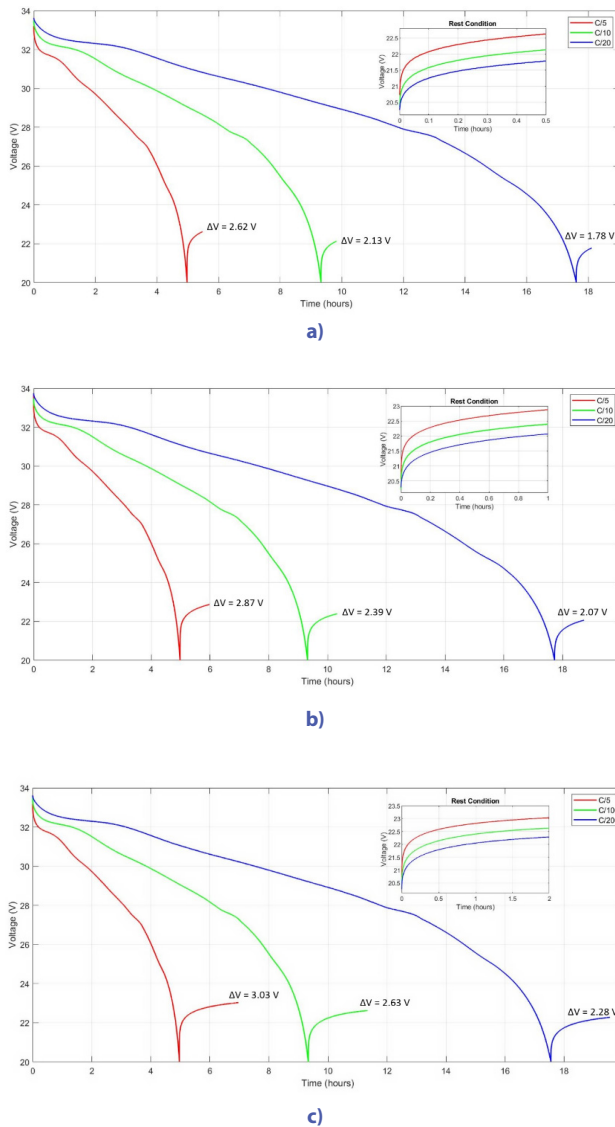


Figure 2. Comparison of discharge curves at various C-rates (C/20, C/10, and C/5) and corresponding voltage recovery profiles during the rest periods of 30 minutes – (a), 1 hour – (b), and 2 hours – (c)

The voltage recovery or voltage relaxation phenomenon is illustrated in Figure 2, where the terminal voltage increases once the discharge current is interrupted. This behavior indicates the redistribution of electrochemical potential within the cell following the removal of the load. Table 2 summarizes the measured effective capacities and the voltage differences observed after the relaxation period, highlighting the influence of both C-rate and rest duration on the recovery magnitude.

The experimental results demonstrate that the discharge rate (C-rate) is the primary factor influencing the occurrence of the voltage recovery phenomenon, whereas variation in post-discharge rest duration (30 min, 1 h, and 2 h) mainly affects the time required to reach the steady-state voltage condition of the Li-ion battery pack. Increasing the C-rate from C/20 to C/5 significantly enhanced the amplitude of voltage recovery – from approximately 2.27 V at C/20 to 2.38 V at C/10, and up to 3.41 V at C/5 (see Table 2). In contrast, extending the rest duration at each C-rate produced no substantial improvement in the effective capacity.

These findings suggest that voltage recovery is predominantly governed by Li-ion concentration gradients that develop under high discharge rates, while short relaxation periods are insufficient to yield capacity recovery. In the context of LEO satellite operations, this implies that appropriate load management and rest scheduling during the eclipse-sunlight transitions can be exploited to optimize voltage recovery, ensuring energy availability and extending the operational lifetime of the power subsystem.

The experimental voltage recovery data were further analyzed using the double-exponential model (Eq. (3)). Table 3 summarizes the parameters obtained from double-exponential fitting of the Li-ion battery voltage relaxation data under different discharge rates (C/20, C/10, and C/5) and rest durations (30 minutes, 1 hour, and 2 hours). The reported parameters include the steady-state voltage (V_{∞}), the amplitudes of the fast and slow exponential components (A_1 and A_2), the relaxation time constants (τ_1) and (τ_2), as well as statistical

Table 2. Measured capacity and voltage recovery characteristics under different C-rates and rest durations

Cycle	Discharge Load	Rest Time (hour)	End of Discharge Voltage (V_0)	End of Rest Voltage (V_{∞})	Δ Voltage Recovery (ΔV)	Effective Capacity (Ah)
1	C/20	0.5	20	21.78	1.78	17.607
2	C/20	1	20	22.07	2.07	17.727
3	C/20	2	20	22.28	2.28	17.553
1	C/10	0.5	20	22.13	2.13	18.636
2	C/10	1	20	22.39	2.39	18.632
3	C/10	2	20	22.63	2.63	18.644
1	C/5	0.5	20	22.62	2.62	18.903
2	C/5	1	20	22.87	2.87	18.927
3	C/5	2	20	23.03	3.03	18.878

Notes: Δ Voltage recovery is defined as the difference between the average terminal voltage measured after the rest period and the voltage immediately after discharge termination; the battery capacity (Ah) was calculated by integrating the discharge current over time.

goodness-of-fit indicators (R^2 and RMSE). Collectively, these parameters are used to assess the accuracy and consistency of the model in capturing the voltage recovery dynamics across the tested operating conditions.

To facilitate a clearer interpretation of the discharge-rate effect while minimizing the influence of rest-time variability, Table 4 presents a reduced set of fitted parameters corresponding to a fixed rest time of 2 hours for each C-rate. The fitted curves, show in Figure 3, reveal two dominant relaxation mechanisms: a fast relaxation component (τ_1) associated with interfacial charge redistribution, and slow relaxation component (τ_2) corresponding to Li-ion diffusion within the electrode bulk (Bharathraj et al., 2023).

Consistent with the fitted parameters summarized in Table 4, the reliability of the voltage recovery analysis was

evaluated using statistical indicators commonly applied in space power system verification. The high coefficients of determination ($R^2 > 0.99$) combined with low Root Mean Squared Error values (RMSE < 0.03 V) indicate that the double-exponential model consistently captures the voltage relaxation dynamics across all tested C-rate conditions. The negative amplitudes A_1 and A_2 indicate that both exponential components contribute to the voltage rise toward the steady-state voltage (V_∞) during the relaxation period.

Furthermore, the fast (τ_1) and slow (τ_2) time constants represent two distinct electrochemical relaxation mechanisms. The fast time constant (τ_1) is associated with rapid recovery processes related to ohmic polarization relaxation and charge-transfer phenomena at the electrode-electrolyte interface, occurring on the order of minutes.

Table 3. The parameters obtained from double-exponential fitting of the voltage relaxation data under discharge rate (C/20, C/10, and C/5) and rest condition variants (a, b, and c)

Load	V_∞	A_1	A_2	τ_1	τ_2	R^2	RMSE
C/20a	21.89	-0.5384	-0.9743	63.0119	859.1065	0.9984	0.01165
C/20b	22.19	-0.6174	-1.133	123.8390	1725.6255	0.9987	0.01163
C/20c	22.35	-0.7162	-1.105	206.1856	2730.003	0.9982	0.01393
C/10a	22.21	-0.6975	-1.042	38.2848	758.7253	0.9967	0.01848
C/10b	22.44	-0.8620	-1.144	58.7889	1343.9053	0.9952	0.02346
C/10c	22.67	-0.8335	-1.154	152.4855	2416.043	0.9968	0.01989
C/5a	22.7	-0.7853	-1.031	38.2555	776.397	0.9968	0.01772
C/5b	22.93	-0.9348	-1.127	56.2746	1391.7884	0.9945	0.025
C/5c	23.06	-0.8982	-1.057	134.9892	2420.136	0.9955	0.02177

Note: a = 30 minutes rest time, b = 1 hour rest time, c = 2 hours rest time.

Table 4. The parameters obtained from double-exponential fitting of the voltage relaxation data under discharge rate (C/20, C/10, and C/5) and rest condition of 2 hours

Load	V_∞	A_1	A_2	τ_1	τ_2	R^2	RMSE
C/20c	22.35	-0.7162	-1.105	206.1856	2730.003	0.9982	0.01393
C/10c	22.67	-0.8335	-1.154	152.4855	2416.043	0.9968	0.01989
C/5c	23.06	-0.8982	-1.057	134.9892	2420.136	0.9955	0.02177

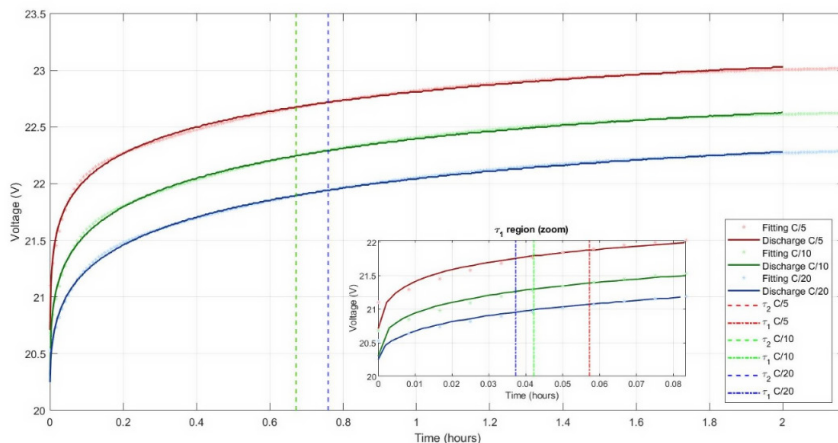


Figure 3. Double-exponential fitting of the voltage recovery behavior of the Li-ion battery pack under various C-rates and rest durations

In contrast, the slow time constant (τ_2) represents recovery mechanisms dominated by Li-ion diffusion and the redistribution of concentration gradients within the bulk electrode, evolving over time scales of tens of minutes up to approximately one hour. Accordingly, a rest duration of 2 hours encompasses the majority of the relevant electrochemical relaxation processes. The increase in the fast (τ_1) and, in particular, the slow (τ_2) time constants at higher C-rates indicate that the relaxation processes become progressively slower as the discharge current increases. This behavior arises from the larger Li-ion concentration gradients established during high-rate discharge, which require longer times to reach potential equilibrium and a homogeneous concentration distribution. Meanwhile, variation in rest duration primarily affects the extent to which the slow relaxation process (τ_2) can evolve toward a steady-state condition, but do not significantly alter the amplitude of voltage recovery. These findings indicate that the voltage recovery phenomena are governed more strongly by the degree of electrochemical disequilibrium

induced by the preceding discharge rate than by the absolute duration of the rest period itself. Accordingly, the time constants τ_1 and τ_2 should not be regarded merely as mathematical curve-fitting parameters, but rather as physically meaningful descriptors that directly link the effects of C-rate and rest duration to the underlying voltage recovery mechanisms in Li-ion batteries.

To further evaluate the robustness of the selected double-exponential model, Table 5 reports the statistical error indicators, namely R^2 and RMSE, for all tested discharge rates and experimental conditions. These metrics are used to quantify the goodness of fit and the reliability of the model in capturing the voltage relaxation dynamics following discharge. The consistently high R^2 values (> 0.97) and low RMSE across all test conditions confirm that the model reliably captures the dominant voltage recovery dynamics, with only minor deviations observed at higher C-rates due to increased nonlinear diffusion effects.

In the context of Battery Management System (BMS) for LEO satellites, the results of this study suggest that extending rest durations is effective only to a certain limit. Once the fast relaxation mechanisms have largely completed, additional recovery governed by slow diffusion processes does not necessarily translate into a significant gain in effective capacity. Therefore, energy management strategies must account for internal diffusion limitations and voltage cut-off logic rather than relying solely on prolonged rest periods.

Based on these considerations, longer rest periods were not explored further, as they are considered less representative of the time-constrained and cyclic nature of LEO operations (approximately 14 orbital cycles per day). Nevertheless, extended relaxation durations may remain relevant for specific or off-nominal operational scenarios.

To further strengthen the validity of the modeling results, a comparison was conducted with voltage relaxation prediction and analysis approaches reported in the recent literature, as discussed in Table 6.

Table 5. Statistical error indicator (RMSE and R^2) evaluating the accuracy of the selected double-exponential model in representing voltage relaxation dynamics under different discharge rates and test conditions

Load	R^2	RMSE
C/20a	0.993	0.02404
C/20b	0.9961	0.02052
C/20c	0.9982	0.01393
C/10a	0.9866	0.03688
C/10b	0.9909	0.03206
C/10c	0.9968	0.01989
C/5a	0.9678	0.05573
C/5b	0.9752	0.05289
C/5c	0.9955	0.02177

Table 6. Comparison of modeling approaches and main findings with related literature

Study	Methodology	Key Parameters	Application Context	Relevance to This Study
Nair et al. (2024)	Data-driven digital twin combining electrochemical features and AI regression	Voltage, current, temperature, extracted latent electrochemical features	General-purpose LIB systems (EVs, grid storage, generic energy systems)	Demonstrates AI-based capacity prediction but does not address voltage recovery or space constraints
Nair et al. (2023)	Explainable Deep Factorization Machine (XDFM) integrated with ML models to estimate RUL from cycling data	Voltage, capacity fade trends, cycle number, and statistical health indicators	Generic Li-ion battery prognostics under laboratory cycling	Provides explainable RUL estimation but lacks orbital operational coupling
Vakharia et al. (2023)	Stacked LSTM neural network with optimized feature selection and explainable-AI post-analysis	Voltage, current, cycle history, and engineered temporal features	Terrestrial battery management systems and predictive maintenance	Advances ML-based capacity estimation without addressing rest-time physics
This study	Physical-based experimental methodology focusing on controlled discharge-rest protocols and double-exponential voltage recovery modeling	C-rate (C/20 – C/5), rest duration (30 min – 2 h), voltage recovery amplitude, relaxation time constants (τ_1, τ_2)	LEO satellite power system (orbit-aware)	Directly addresses the operational gap between laboratory testing and real LEO satellite power system behavior

3.2. Operational implications for LEO satellites

The findings of this study have significant implications for energy management strategies in LEO satellites, as illustrated in Figure 4.

The experimental results clearly demonstrate that the discharge rate (C-rate) is the dominant factor governing the magnitude of the voltage recovery phenomenon in Li-ion battery packs, whereas variation in post-discharge rest duration primarily influences the time required to reach a steady-state voltage. Within the operational context of LEO satellites, this finding highlights that active management of load profiles during eclipse phases and eclipse-to-sunlight transitions is more critical for maintaining bus voltage stability than passively extending battery rest periods. Given the strict mass and volume constraints of most LEO missions, operational optimization through load control represents a more economical and practical strategy than increasing battery capacity or the number of battery modules (Gitzendanner et al., 2019; Reid et al., 2007). From a spacecraft power system perspective, these results can be directly mapped onto established power and energy management frameworks defined in ECSS standards and NASA guidelines. Specifically, controlling peak discharge C-rate during eclipse periods emerges as a key lever for preserving voltage margin and ensuring energy availability throughout the orbit. This insight is particularly relevant for power-limited platforms such as CubeSats and nanosatellites, where aggressive payload operation during eclipse can rapidly erode voltage margins and compromise mission reliability.

At the electrochemical level, higher C-rates induce steeper Li-ion concentration gradients within the electrodes, which can increase polarization and transient voltage losses. However, these effects can be mitigated through mode-based load scheduling strategies that align power demand with the satellite's operational priorities. For instance, reducing non-essential payload activities, deferring high-power data transmission, or applying current-limiting measures during eclipse phases can help maintain electrochemical balance and minimize reversible capacity loss. Such strategies are consistent with established spacecraft power system design practices aimed at preserving bus voltage stability under high-rate discharge conditions.

Beyond immediate operational control, the observed voltage recovery behavior also presents an opportunity

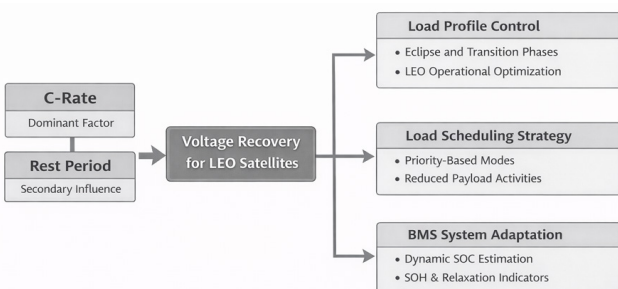


Figure 4. Conceptual scheme of the energy management strategy for a LEO satellite

for enhanced BMS functionality. The relaxation dynamics are characterized by the dual-exponential time constant (τ_1 and τ_2) can serve as informative indicators of the battery's internal state and, potentially, its SOH. By integrating these relaxation parameters into SOC and energy estimation algorithms, an adaptive BMS could dynamically correct SOC estimates during naturally occurring rest periods, improving power prediction accuracy and supporting more robust EODV logic. This approach enables more effective utilization of the available battery capacity without imposing additional hardware penalties.

It should be noted that all experiments were conducted at an ambient temperature of 25 °C, which lies within the upper bound of the standby temperature range recommended for satellite batteries (−10 °C to +25 °C) (Maral et al., 2020). In operational LEO power systems, Li-ion batteries are typically housed within thermally controlled compartments to maintain a relatively narrow temperature window, commonly around 0 °C to +10 °C (Maral et al., 2020), due to the strong temperature dependence of electrochemical kinetics. Accordingly, the present results are positioned as a conservative baseline characterization of voltage recovery and relaxation time constant (τ_1 and τ_2) are expected to shift under colder orbital temperatures, the underlying fast (interfacial charge redistribution) and slow (solid-state Li-ion diffusion) relaxation mechanisms identified in this study remain directly relevant at the system level.

In interpreting these findings, it is also important to consider the operational context of LEO satellites, which typically experience approximately 14 orbital cycles per day, corresponding to more than 5,000 charge-discharge events per year as the spacecraft alternates between sunlight and eclipse discharge. Under such highly enhanced effective cycling, even modest relaxation-driven voltage recovery can cumulatively enhance effective energy availability and contribute using a single type of Li-ion battery pack in its early life stage, and did not explicitly account for long-term aging effects or variations across different battery chemistries. Degradation mechanisms such as internal impedance growth, loss of active lithium, and structural change in electrode materials may alter relaxation dynamics as the cycle count increases. Nevertheless, this study employed a single type of commercial Li-ion battery pack in its early life stage and did not explicitly account for long-term aging effects or variations across different battery chemistries. Degradation mechanisms such as internal impedance growth, loss of active lithium, and structural change in electrode materials may alter relaxation dynamics as cycle count increases. In addition, the experiments were conducted under laboratory ambient conditions and did not incorporate space environmental factors such as vacuum, radiation exposure, or thermal cycling. These factors may further influence diffusion kinetics, impedance evolution, and overall relaxation behavior. Therefore, while the present findings provide clear evidence of C-rate and rest-time effects on voltage recovery, their direct translation to orbital environments should be interpreted in conjunction with these additional environmental considerations.

4. Future work

This work highlights several opportunities for future research aimed at bringing the experimental findings closer to actual LEO satellite operating conditions. The LEO environment is inherently complex, characterized by large temperature swings, continuous radiation exposure, and highly dynamic load profiles driven by repeated sunlight-eclipse cycles. As a result, more representative testing frameworks are needed to fully assess voltage recovery behavior and its impact on battery performance and energy management in orbit.

Future studies are therefore expected to reproduce LEO operational conditions more realistically by incorporating thermal-vacuum cycling, radiation exposure, and orbit-representative load profiles with approximately 14 charge-discharge cycles per day. Such testing will enable validation of voltage recovery phenomena under realistic temperature gradients and radiation fluxes, thereby improving confidence in in-orbit battery performance predictions.

In parallel, the integration of orbit-aware BMS functions will be explored, leveraging natural rest phase as real-time indicators of electrochemical equilibration to enhance energy utilization during satellite operations. Experimental validation using CubeSat-scale battery packs and realistic sunlight-eclipse-based energy management strategies under practical mission constraints.

5. Conclusions

This study evaluates the effects of discharge rate (C-rate) and post-discharge rest duration on voltage recovery and effective capacity in NCA-based Li-ion battery packs for LEO satellite power system applications. The results demonstrate that C-rate is the primary parameter governing the magnitude of voltage recovery, while rest duration mainly affects the time required to reach a steady-state voltage. From an operational standpoint, this indicates that active control of load profiles during eclipse phases and eclipse-to-sunlight transitions is more effective for maintaining voltage stability than extending rest periods.

Double-exponential modeling identifies two principal relaxation mechanisms (τ_1 and τ_2) associated with polarization and Li-ion diffusion, with increased time constants observed at higher C-rates due to larger concentration gradients. From a satellite power system perspective, voltage recovery contributes to increased voltage margin relative to the EODV, in accordance with ECSS standards and the NASA technical guideline, without a corresponding increase in usable capacity.

The experiments were conducted without active temperature control; therefore, the generalization of the results to on-orbit environments remains limited and requires further validation through temperature-controlled and thermal-vacuum cycling tests.

Overall, this study provides an initial contribution towards the development of orbit-aware energy manage-

ment strategies for LEO satellites, demonstrating that the utilization of rest periods and voltage recovery can serve as an efficient approach to maintaining performance, SOH/RUL estimation accuracy, and extending Li-ion battery lifetime under low Earth orbit conditions.

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Author contributions

Desti Ika Suryanti contributed to the conceptualization, methodology, investigation, and initial manuscript drafting. Tri Eko Putra Manvi was responsible for data curation, formal analysis, visualization, and manuscript writing. Prawito Prajitno participated in methodology development, validation, and writing – review & editing. Mukhamad Fajar contributed to the investigation, instrumentation, and data acquisition. Mohamad Mukhayadi provided input on literature review, data interpretation, and writing – review & editing. Budhy Kurniawan served as the principal supervisor, focusing on supervision and writing – final editing.

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