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EXPERIMENTAL INVESTIGATION ON LITHIUM-ION BATTERY AGING UNDER UZBEKISTAN'S CLIMATE

Almataev Tojiboy Orzikulovich
Professor of Automotive Engineering and Transport Department,
Andijan State Technical Institute.
E-mail: tojiboy@astiedu.uz

Zokirjonov Azizbek Zokirjon ugli
Ph.D. Student of Automotive Engineering and Transport Department,
Andijan State Technical Institute.
E-mail: azokirjonov@astiedu.uz

Annotation. Lithium-ion batteries constitute the primary energy source in modern electric vehicles however their long-term degradation represents a fundamental challenge in electrochemical energy-storage research. Temperature extremes such as intense summer heat or severe winter cold can intensify electrochemical degradation, hasten performance decline, and shorten battery life. Recognizing that Uzbekistan exhibits a wide temperature range throughout the year, this study concentrates on the specific impacts of the country's climatic conditions on battery aging, vehicle reliability, and long-term operational costs. First, the internal aging mechanisms of lithium-ion batteries are reviewed with respect to various anode and cathode chemistries to provide a clearer understanding of capacity fade and performance deterioration. Subsequently, key influencing factors particularly temperature-driven effects on battery life are examined in detail to identify pathways for improving long-term performance. Finally, acknowledging the distinctions between cell-level and system-level behavior, the degradation mechanisms of complete battery systems are analyzed.

Key words: Electric vehicles, lithium-ion battery, aging mechanism, degradation, performance loss.

O'ZBEKISTON IQLIM SHAROITIDA LITIY-ION AKKUMULYATORLARINING ESKIRISH JARAYONINI EKSPERIMENTAL TADQIQ QILISH

Almatayev Tojiboy Orziqulovich
"Andijon davlat texnika instituti"ning "Avtomobilsozlik va transport" kafedrasi professori.

Zokirjonov Azizbek Zokirjon o'g'li
"Andijon davlat texnika instituti"ning "Avtomobilsozlik va transport" kafedrasi PhD doktoranti.

Annotatsiya. Litiy-ion akkumulyatorlari zamonaviy elektr transport vositalarining asosiy energiya manbai hisoblanadi, biroq ularning uzoq muddatli degradatsiyasi elektroximiyaviy energiya saqlash tizimlari sohasidagi muhim ilmiy muammolardan biri bo'lib qolmoqda. Yoz faslidagi yuqori issiqlik yoki qish faslidagi keskin sovuq kabi ekstremal harorat sharoitlari elektroximiyaviy degradatsiya jarayonlarini kuchaytirishi, ishlash samaradorligining pasayishini tezlashtirishi hamda akkumulyatorlarning xizmat muddatini qisqartirishi mumkin. O'zbekiston iqlimi yil davomida sezilarli harorat o'zgarishlari bilan tavsiflanishini inobatga olgan holda, mazkur tadqiqot mamlakat iqlim sharoitlarining akkumulyatorlarning eskirish jarayoniga, transport vositalarining ishonchliligiga va uzoq muddatli ekspluatatsiya xarajatlariga ta'sirini o'rganishga qaratilgan. Dastlab, sig'imning kamayishi va ishlash ko'rsatkichlarining yomonlashuvini chuqurroq tushunish maqsadida turli xil anod va katod materiallari asosidagi litiy-ion akkumulyatorlarining ichki eskirish mexanizmlari ko'rib chiqiladi. Keyinchalik, akkumulyatorlarning xizmat muddatiga ta'sir etuvchi asosiy omillar, ayniqsa harorat ta'siri batafsil tahlil qilinadi hamda uzoq muddatli samaradorlikni oshirish yo'llari aniqlanadi. Yakunda esa alohida element darajasi va tizim

darajasidagi xatti-harakatlar oʻrtasidagi farqlarni hisobga olgan holda, toʻliq akkumulyator tizimlarining degradatsiya mexanizmlari tahlil qilinadi.

Kalit soʻzlar: elektr transport vositalari, litiy-ion akkumulyatori, eskirish mexanizmi, degradatsiya, ishlash samaradorligining pasayishi.

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1. Introduction.

Driven by the global energy crisis and the adverse environmental impacts associated with petroleum-based transportation, electric vehicles have undergone rapid development over the past decades. This progress is especially evident in the rise of fully electric vehicles, where the battery constitutes one of the most critical components. Among existing energy-storage technologies, lithium-ion batteries have emerged as the leading choice for automotive applications due to their high energy and power densities, long cycle life, and absence of memory effects. Recently, enhancing the performance of electric vehicles has increasingly depended on advancements in battery systems, including the production of higher-performance cells and the development of more sophisticated battery management systems. Among the battery management system functions, state estimation primarily encompassing the state of charge, state of health, state of function, and state of safety are particularly critical. In this context, state of health is one of the most important indicators, as it enables the battery management system to accurately assess battery performance and allows the vehicle control unit to utilize the battery more effectively. However, current state of health estimation methods is typically limited to evaluating a few individual parameters, such as capacity fade or internal resistance growth, and comparing these values with those of a new battery. Such simplified approaches fail to capture the complex internal conditions of the battery and are insufficient for advanced battery management system requirements. Therefore, a deeper understanding and identification of the underlying battery aging mechanisms are essential for improving state of health estimation accuracy. The aging mechanisms and cycle life of lithium-ion batteries vary significantly depending on the types of cathode and anode materials used. Currently, commercial cathode materials include $LiFePO_4$ (LFP), $LiMn_2O_4$ (LMO), and $LiNi_xCo_yMn_{1-x-y}O_2$ (NCM), while commonly used anode materials include $Li_4Ti_5O_{12}$ (LTO) and graphite (C). Batteries with different electrode chemistries exhibit distinct performance characteristics, particularly in terms of cycle life and degradation behavior. It should be noted that this paper does not aim to provide a comprehensive study of battery aging mechanisms. Battery degradation is influenced by numerous factors and complex processes; however, the focus of this study is specifically on the effects of weather conditions and temperature-driven degradation. The research evaluates the performance of several lithium-ion batteries suitable for electric vehicles before and after cycling under these environmental conditions. In particular, several types of electric vehicles operating in Uzbekistan were tested, and their performance was assessed with respect to battery chemistry and local driving conditions. From a battery design perspective, it is essential to investigate aging mechanisms and degradation models at the cell level, particularly the effects of key structural and material parameters on battery lifetime and performance indicators such as energy density and power density. These critical parameters include the thickness of anode and cathode active materials, electrode porosity, particle size, cell dimensions, and cell geometry. By applying multi-objective

optimization algorithms, these parameters can be systematically optimized to develop battery cells with enhanced durability and improved operational performance.

At the battery system level, understanding aging mechanisms and degradation behavior remains equally important. The impacts of electrical, mechanical, and thermal factors on battery lifespan should be carefully analyzed using appropriate degradation models. Based on this analysis, system-level design improvements such as optimizing cell preload conditions and enhancing the battery thermal management system (TMS) can significantly contribute to extending overall battery system lifetime. From the perspective of battery management, accurate aging mechanism analysis and degradation modeling are crucial for estimating the current state of health (SOH) based on historical usage data, optimizing present operating conditions, and predicting future battery performance. These approaches support more reliable and efficient long-term battery operation. In general, the estimation of battery health based on its historical operating conditions is referred to as state of health (SOH) estimation. As a battery ages, its key performance characteristics such as available capacity, available energy, and available power gradually decrease. Therefore, the battery management system (BMS) must accurately estimate the SOH using appropriate aging mechanism analysis and degradation models. The SOH estimation results serve as critical inputs for other diagnostic and predictive algorithms within the BMS. Based on reliable SOH information, batteries can be operated under appropriate conditions, helping to prevent misuse, extend service life, and reduce the risk of safety-related incidents. Accurate SOH estimation thus plays an essential role in ensuring both the performance reliability and operational safety of battery systems. So, as shown in Picture 1, the battery aging mechanism and the impact of battery degradation should be considered to optimize the battery design and management.
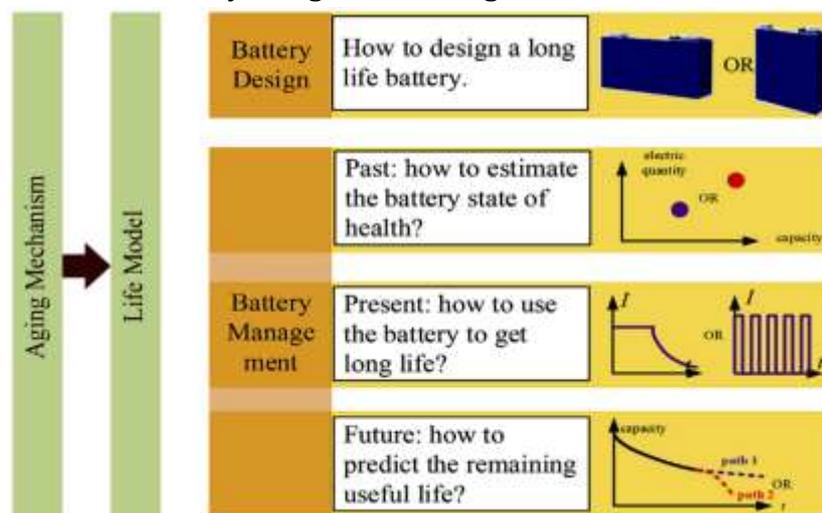
Picture 1: Battery Design and Management Challenges Based on Aging Mechanisms and Lifetime Modeling.

In general, the optimization of current battery operating conditions mainly involves state of power (SOP) estimation and effective thermal management strategies. Different operating conditions have varying impacts on the future lifetime and performance degradation of batteries. Therefore, based on the understanding of aging mechanisms under different working conditions and the corresponding battery degradation models, the battery management system (BMS) can evaluate the extent of damage caused by various operational stresses. Using this information, the BMS can intelligently coordinate charging and discharging

processes as well as temperature regulation through online optimization methods, thereby improving both battery lifetime and operational performance.

Furthermore, prediction of future battery performance generally refers to remaining useful life (RUL) estimation. Accurate RUL prediction plays a critical role in real-time battery management, second-hand vehicle evaluation, and second-life (echelon-use) applications, and it is particularly important for assessing the residual economic value of batteries. Due to the nonlinear degradation characteristics of lithium-ion batteries, conventional extrapolation-based approaches are often insufficient for reliable lifetime prediction. Therefore, accurate RUL estimation should be based on dominant aging mechanisms and appropriate battery lifetime models that account for different operating conditions and various degradation stages. From a system-level perspective, addressing a wide range of battery design and management challenges associated with battery aging requires a comprehensive review and analysis of existing research on battery degradation. This includes examining key influencing factors, aging mechanisms, degradation models, and diagnostic methods. However, most existing review studies tend to focus primarily on individual aspects of battery degradation rather than providing an integrated and systematic analysis of these interconnected issues. Moreover, many previous studies have been conducted under standard laboratory conditions or within moderate climatic environments, which limits their applicability to regions characterized by large seasonal temperature variations, such as Uzbekistan. In such environments, batteries are exposed to both high summer temperatures and low winter temperatures, which can significantly accelerate degradation processes and influence long-term performance, safety, and reliability.

Therefore, there is a clear need for a comprehensive and climate-oriented investigation that integrates aging mechanisms, degradation modeling approaches, and battery management strategies under region-specific operating conditions. Such an approach would contribute to improving battery lifetime prediction accuracy, optimizing battery management system performance, and enhancing the reliability of electric vehicles operating in Uzbekistan's climatic conditions. This research aims to address these gaps by systematically analyzing lithium-ion battery aging behavior from both cell-level and system-level perspectives, with particular emphasis on temperature-related degradation effects and their implications for long-term battery performance and management strategies.

Some studies have focused specifically on the aging mechanisms of lithium-ion batteries, providing comprehensive reviews of degradation processes in cells that utilize carbon-based anodes and lithium metal oxide cathodes, particularly lithium manganese oxide ($LiMn_2O_4$) and lithium nickel–cobalt mixed oxides ($Li(Ni,Co)O_2$). These works contribute significantly to understanding the electrochemical mechanisms responsible for capacity fade and performance deterioration in commonly used electrode material systems [3]. The other related experiments give a comprehensive review on one typical aging mechanism such as lithium deposition [4]. Some other researches focused on the modelling. It gave a review of models for predicting the cycling performance of lithium-ion batteries [5]. They provided a detailed review on the modeling of solid electrolyte interface (SEI) film [6]. And some other focus on the management method, they gave some critical reviews on the state of health estimation methods of the batteries [7, 8].
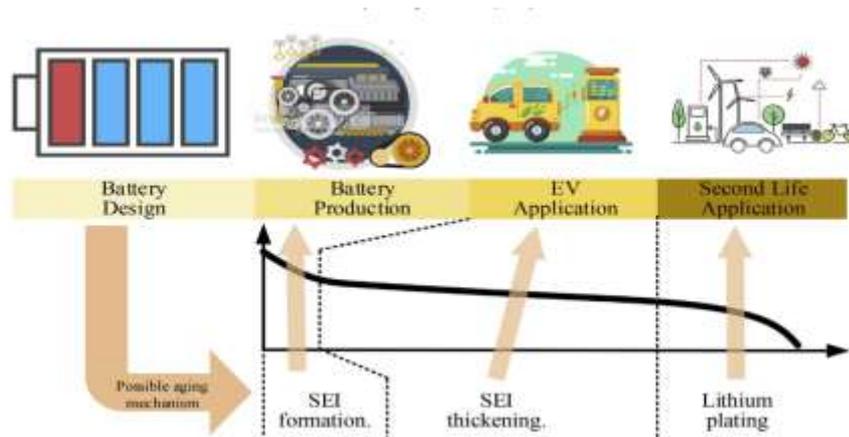
Picture 2: Comprehensive Life Cycle of Lithium-Ion Batteries: Design, Manufacturing, Electric Vehicle Application, and Second-Life Utilization.

The complete life cycle of a battery encompasses design, production, electric vehicle (EV) application, and second-life utilization, as illustrated in Picture 2. Battery performance degradation should be taken into account from the earliest stages of battery design. Moreover, at different stages of the life cycle, the degradation phenomena and underlying internal aging mechanisms may vary significantly. From a systematic perspective, this paper aims to provide a comprehensive review of the key issues related to battery degradation and experimental investigation, including the following aspects: the internal aging mechanisms and observable characteristics of batteries and the aging mechanisms. In general, battery aging analysis should be conducted on multiple levels, encompassing influencing factors, internal side reactions, degradation mechanisms, and observable external effects, as illustrated in Picture 3. The most apparent external manifestations of battery degradation are capacity fade and power fade [9,10]. Currently, the majority of studies still focus primarily on these two aspects when investigating and modeling battery aging. It is worth noting, however, that power fade is generally more challenging to assess directly, so internal resistance is often used as a proxy for its evaluation [11]. Regarding degradation modes, for purposes of battery management and online diagnostics, the battery aging mechanisms can be primarily categorized as loss of lithium-ion inventory (LLI) and loss of active materials in the anode or cathode (LAM) [12,13].
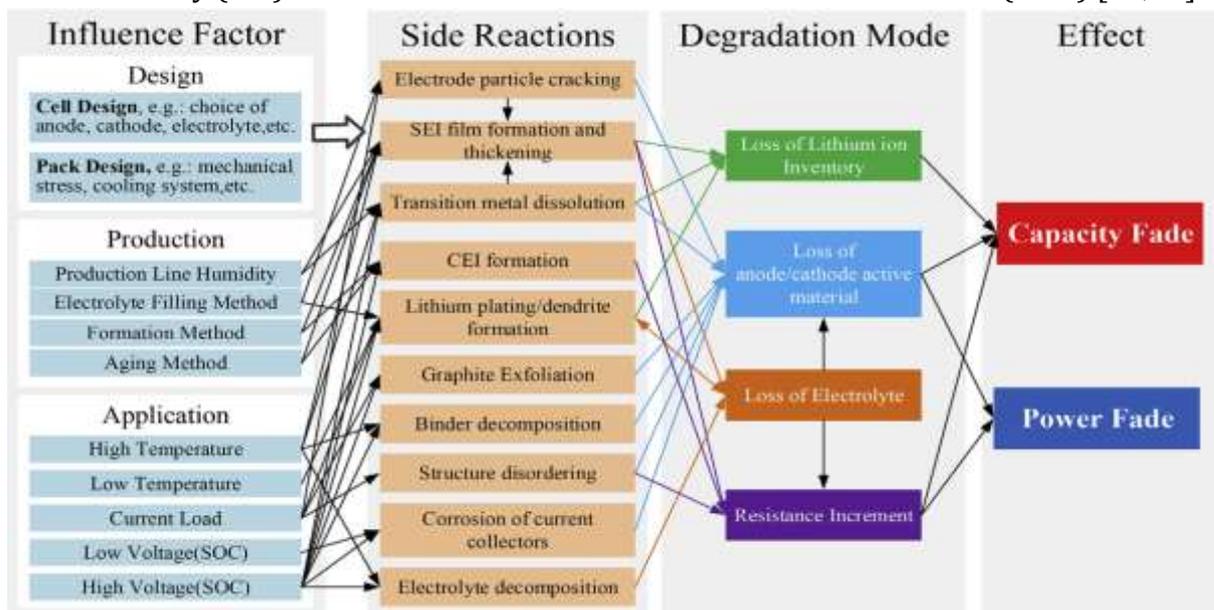
Picture 3: Causes and effects of degradation mechanisms and their associated modes.

As illustrated in Picture 4, the dual-tank model can be employed to represent the corresponding aging mechanisms [14]. Fundamentally, the charging and discharging of a battery are governed by the intercalation and deintercalation of lithium ions within the anode and cathode active materials. Consequently, the battery's capacity is directly determined by the quantity of active material and the availability of lithium ions. In this analogy, the active material functions like a tank, while the lithium ions are analogous to the water contained within it Picture 4. Accordingly, the primary aging mechanisms of lithium-ion batteries are loss of active materials, representing changes in the tank itself, and loss of lithium-ion inventory, corresponding to the loss of water from the tank.
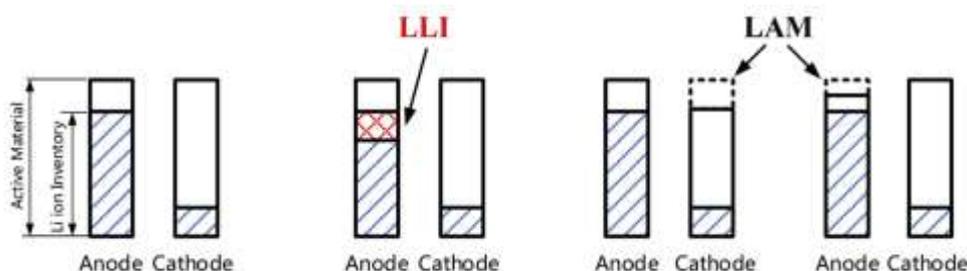

Picture 4: Model of dual-tank.

In addition, battery degradation also encompasses the increase of internal resistance (RI) and the loss of electrolyte (LE). An increase in internal resistance can directly contribute to power fade, while the available capacity may decrease if the charge and discharge cut-off voltages remain constant. Electrolyte loss, including the depletion of additives, is another critical degradation mode. While a small amount of electrolyte loss may have negligible impact on performance, excessive loss can result in a sharp decline in capacity toward the end of the battery's life. Internally, these degradation modes arise from complex physical and chemical side reactions, which may be interrelated or coupled. loss of active materials can result from graphite exfoliation, metal dissolution coupled with electrolyte decomposition, loss of active material contacts due to current collector corrosion, binder decomposition, and loss of electrolyte. loss of lithium-ion inventory may originate from SEI (solid electrolyte interface) formation and continuous thickening, CEI (cathode electrolyte interface) formation, and lithium deposition. loss of electrolyte can be caused by electrolyte consumption during side reactions such as solid electrolyte interface thickening or electrolyte decomposition at high potentials. Internal resistance is similarly affected by solid electrolyte interface formation and growth, as well as electrolyte loss. Furthermore, the rates of these side reactions are influenced by numerous factors associated with battery design, manufacturing, and operational conditions. These factors collectively determine the internal reaction kinetics, ultimately affecting battery life characteristics. Therefore, a detailed discussion of these influences is essential for a comprehensive understanding of battery degradation.

2. Battery aging mechanisms

To clearly illustrate battery degradation characteristics and the underlying internal aging mechanisms, this section first provides a brief overview of the cathode and anode materials commonly employed in lithium-ion power batteries. Subsequently, the primary physical and chemical side reactions occurring within the battery are analyzed in detail. Since the side reactions are strongly dependent on the electrode materials, those occurring at the anode and cathode are discussed separately. Side reactions involving other components, such as the electrolyte and separator, primarily occur at the electrode surfaces and are therefore

addressed within the corresponding electrode sections. Currently, there are many kinds of commercial intercalation materials which can be used in lithium-ion power batteries for electric vehicles. Some typical cathode materials include Lithium manganese oxide (LMO, $LiMn_2O_4$), Lithium iron phosphate (LFP, $LiFePO_4$), layered metal oxide like $Li[Ni_xCo_yMn_{1-x-y}]O_2$ (NCM) and Li rich materials. And the anode materials include graphite (C), $Li_4Ti_5O_{12}$ (LTO), and some alloy anode materials such as Si.
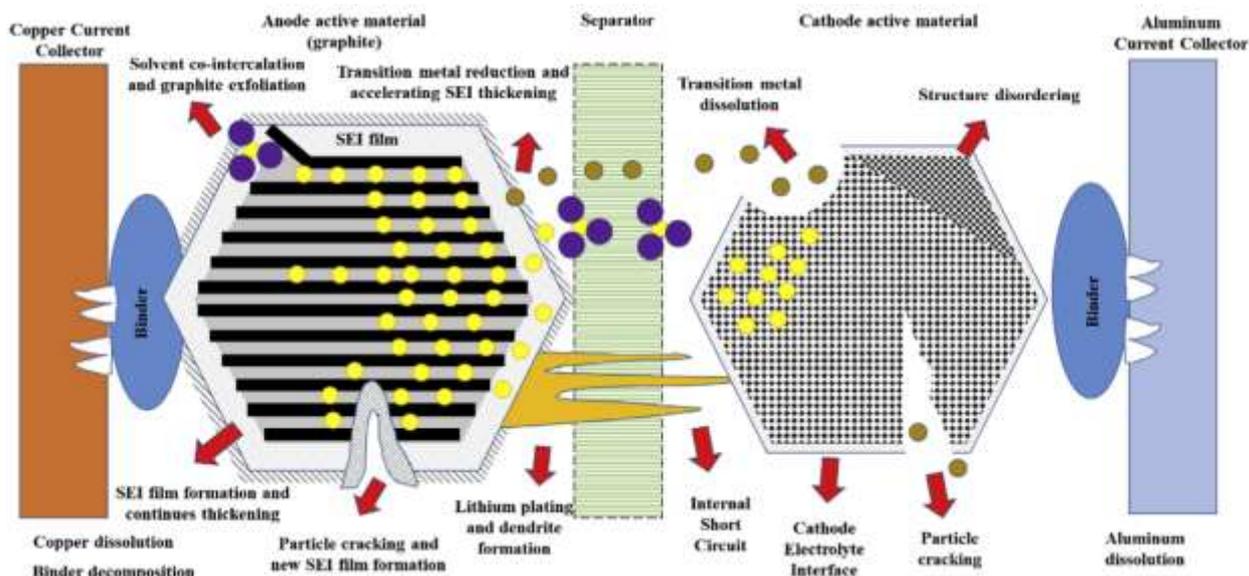
Picture 5: Overview of the primary degradation mechanisms in lithium-ion cells.

The primary aging mechanisms of NCM cathodes include: (1) volume changes during charge–discharge cycling, (2) dissolution of transition metal ions, and (3) formation of a cathode electrolyte interface (CEI) film due to side reactions between the cathode material and electrolyte. For Ni-rich layered oxide cathodes, although specific capacity and energy density may improve, safety and durability concerns are more likely to arise, as illustrated in Picture 6. Since the atomic radius of Ni^{2+} is close to that of Li^+, increasing the Ni content makes cation mixing more likely, which adversely affects battery performance and lifespan. Additionally, phase transformations are more prone to occur in Ni-rich cathode materials, leading to structural degradation at the particle surfaces. Furthermore, the thermal stability of Ni-rich materials is lower, meaning that at elevated temperatures the cathode is more susceptible to decomposition, oxygen release, and subsequent impacts on battery safety and longevity.
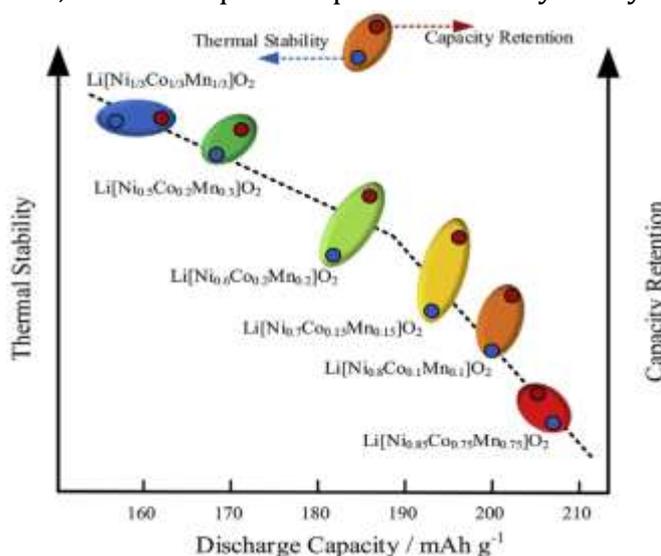
Picture 6: Relationship between discharge capacity, thermal stability, and capacity retention of $LiNi_xCo_yMn_{1-x-y}O_2$.

3. Battery Degradation Characteristics and Influencing Factors.

3.1. Influence of temperature.

From the perspective of electric vehicle applications, the most critical aspects of a battery system are its capacity and power performance, which must be accurately estimated by the Battery Management System (BMS) as the State of Health (SOH). As illustrated in Picture 1, the battery degradation is typically reflected in changes in electrical performance, particularly in capacity and power, which are the focus of this section. In general, both usable capacity and available power decline as the battery ages. For energy-focused applications such as Battery Electric Vehicles (BEVs), high-energy batteries are commonly used, and the primary function of the battery is energy storage. Therefore, capacity fade serves as the main indicator of degradation. In contrast, for power-focused applications such as Hybrid Electric Vehicles (HEVs), high-power batteries are employed, and the battery must meet high pulse power demands; thus, power fade is of greater concern. For Plug-in Hybrid Electric Vehicles (PHEVs), both capacity fade and power fade must be considered. Capacity fade is primarily caused by the loss of active materials (LAM) and loss of lithium-ion inventory (LLI), while increases in internal resistance also reduce usable capacity under fixed charge/discharge cut-off voltages and C-rates. The Power fade, on the other hand, is mainly attributable to increased internal resistance. Currently, for high-energy batteries, the end of life (EOL) is typically defined as the point at which capacity decreases to 80% of its initial value, as the battery can no longer meet vehicle requirements. For high-power batteries, the end of life is usually defined when available power drops to 50% of the initial value, corresponding to a 100% increase in internal resistance. Battery life can generally be divided into two components: calendar life and cycle life. Calendar life refers to degradation occurring during storage without cycling, while cycle life accounts for degradation resulting from charge–discharge cycling, which corresponds to real-world battery use in vehicles. In practice, electric vehicle batteries may undergo charge and discharge cycles while driving or at charging stations, while also experiencing periods of rest when parked. Therefore, both calendar life and cycle life must be considered in evaluating overall battery longevity.

In general, most batteries currently used in electric vehicles exhibit nonlinear aging behavior [15,16], which can be roughly divided into three stages, as illustrated in Picture 7. In the first stage, the formation of the solid electrolyte interphase (SEI) on the anode leads to a loss of lithium-ion inventory (LLI), causing a rapid decrease in capacity during the initial cycles, particularly the first charge. This results in a low first-cycle coulombic efficiency, a critical parameter in battery design and manufacturing research. During the second stage, battery performance declines steadily due to ongoing side reactions within the cell. In the third stage, a rapid capacity drop [16] and internal resistance increase [15] occur near the end of life. This accelerated degradation is attributed to factors such as rapid lithium-ion inventory loss caused by lithium deposition [15, 16], active material loss due to electrolyte depletion [17], binder failure, and structural changes from volume expansion/contraction [18]. This pronounced capacity decline significantly affects the feasibility of second-life battery applications and warrants further detailed investigation. In addition, the battery capacity may occasionally exhibit abnormal increases. This phenomenon is often observed during the early stages of cycling or after an interruption in the cycling test followed by prolonged storage [19]. The

underlying causes of this behavior remain under investigation. One possible explanation is the passive electrode effect, which suggests that geometric excess in the anode can provide additional lithium ions during storage, resulting in a temporary capacity increase. Another potential factor is charging redistribution, where areas of the electrode that are not actively participating in charge–discharge may become more electrochemically active due to improved electrolyte wetting. Additionally, lithium plating and stripping processes may contribute to this anomalous improvement in battery performance [20].
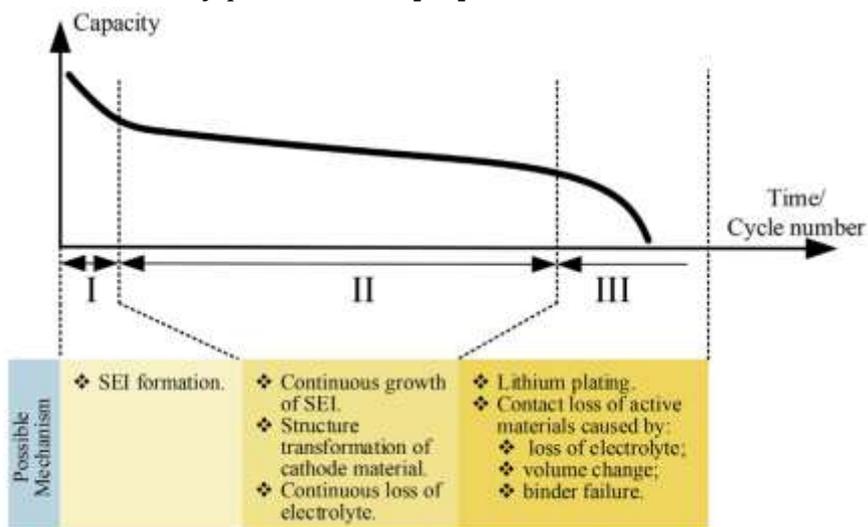
Picture 7: Battery capacity fade and possible internal mechanism in different stages.

The lifespan of the same battery can vary significantly under different operating conditions. Key factors affecting battery life includes high temperature which accelerates internal side reactions low temperature [4], which promotes metal ion reduction, lithium plating, and structural damage to active materials; high state of charge (SOC) or overcharge, it leads to electrolyte decomposition, side reactions at the cathode, and lithium deposition; low SOC or over-discharge, which can cause corrosion of the anode copper current collector and collapse of the active material crystal structure; and high charge/discharge rates, which can induce structural fatigue in active materials and increase temperature, further accelerating internal side reactions.

In general, the battery operates within a defined safe window, as illustrated in Picture 8. The primary roles of the Battery Management System (BMS) and Thermal Management System (TMS) are to ensure that the battery functions within this high-performance, long-life operating range and to prevent operation in hazardous conditions, issuing timely alerts and taking protective measures when necessary.
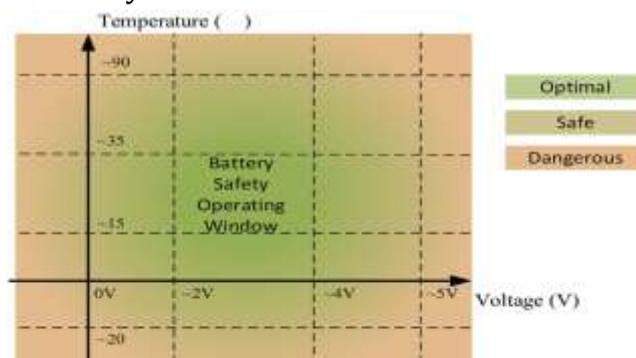
Picture 8. Battery working window scheme.

Temperature is one of the most critical factors influencing battery life, as both high and low temperatures can accelerate degradation. For most commercial lithium-ion batteries, the recommended operating temperature range is typically 15–35 °C. The rates of both primary and side reactions within the battery are temperature-dependent; higher temperatures increase the rate of side reactions and, if exceeding a critical threshold, can trigger self-heating and potentially lead to thermal runaway. At low temperatures, internal resistance increases, causing higher polarization and promoting additional side reactions. Charging under low-temperature conditions may result in lithium plating, which can rapidly degrade the battery and compromise safety. Furthermore, material embrittlement at low temperatures can adversely affect battery longevity. Therefore, maintaining battery operation within an appropriate temperature window is essential for maximizing life and ensuring safe performance. Battery temperature is influenced by multiple factors, including the ambient environment, battery heat capacity, thermal conductivity, internal heat generation, and the heating and cooling systems of the Thermal Management System (TMS), as illustrated in Picture 9. Each of these factors can significantly impact the battery's temperature and, consequently, its performance and lifespan.
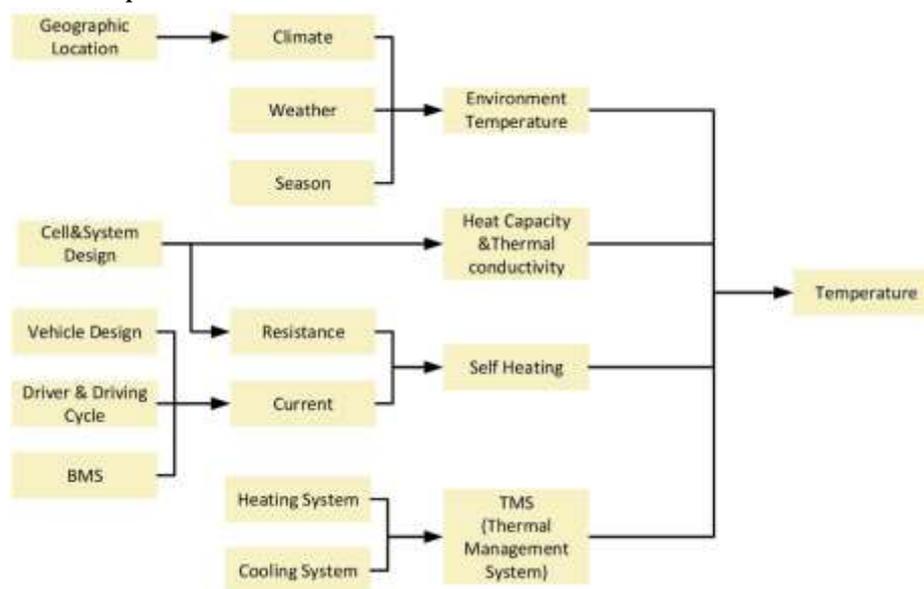
Picture 9. The Factors influencing the battery temperature.

Ambient temperature has a significant impact on battery life. In most real-world electric vehicles, power batteries spend the majority of time in a storage state, corresponding to the vehicle being parked with all electrical systems turned off. In this condition, battery temperature is largely determined by the surrounding environment. The key factors affecting calendar life under these conditions are temperature and state of charge (SOC). In regions with high ambient temperatures, batteries experience greater capacity loss during storage. Cycle life is also influenced by temperature, as elevated or fluctuating temperatures accelerate degradation during charge–discharge cycles. Environmental temperature is primarily governed by climate, weather, and seasonal variations, which are in turn related to the vehicle's geographical location; for instance, lower latitudes generally experience higher temperatures.

In high-latitude regions, where winter temperatures may drop below 0 °C, it is essential to use a heating system to prevent lithium deposition during low-temperature charging, which can compromise both battery safety and longevity. During charging and discharging, the battery generates significant ohmic heat. The resulting temperature change depends on the

battery's thermal properties (such as heat capacity and thermal conductivity), its electrical resistance (including internal resistance, as well as the resistance of wires, busbars, and welds), and the current passing through the cells. Optimizing cell and system design can improve both thermal properties and resistance. However, the current is also influenced by vehicle design. In battery electric vehicles (BEVs), the discharge rate is generally low, causing the battery temperature to rise gradually. In contrast, hybrid electric vehicles (HEVs) typically experience higher charge and discharge rates, leading to more rapid temperature increases. Road conditions and driver behavior further affect the battery's operating state, and under severe conditions, extreme currents can cause substantial temperature rises. A reliable battery management system (BMS) can estimate the battery's state of power (SOP), considering safety and lifespan, and can limit current flow to mitigate thermal stress. Additionally, the charging system plays a crucial role in temperature regulation. For instance, future ultra-fast chargers with power levels up to 350 kW can impose charging rates much higher than typical driving discharge rates, potentially causing significant battery heating and impacting long-term durability.

Season	Average High (°C)	Average Low (°C)	Notes / Regions Affected
Summer	30–40	18–25	The Hottest in southern/desert regions; peaks can reach 40–50 °C
Winter	0–6	–6 to 2	Coldest in northern regions; desert nights can be very cold
Spring	15–28	4–15	Mild temperatures, gradually warming
Autumn	15–30	5–18	Cooling period; temperatures drop steadily

**Table 1:** The average temperatures in Uzbekistan by season.

3.2. Influence of State of Charge.

The battery state of charge (SOC) also has a significant impact on battery life. It is important to note that SOC and battery voltage are interdependent. For a given SOC and current, the battery voltage can be calculated, and this relationship is typically represented by a battery model. SOC reflects the usable energy stored in the battery, which is more relevant for vehicle operation. Therefore, in this section, voltage is not discussed independently. As shown in Picture 10, the battery SOC is primarily influenced by vehicle usage.

Generally speaking, higher state of charge (SOC) indicates higher terminal voltage, which suggests lower anode potential and higher cathode. For the graphite anode with lower potential, the side reactions rate such as the SEI thickening will be higher, resulting in battery higher aging rate [6]. And in case of abnormal charging like overcharging or low temperature charging, the anode potential may be too low and may reach the lithium deposition potential, then the side reaction of lithium deposition may occur to accelerate the battery aging [4]. A lower SOC corresponds to a higher anode potential and a lower cathode potential, which generally benefits battery life. However, if the state of charge (SOC) becomes too low, it can lead to accelerated corrosion of the anode copper current collector and structural degradation of the cathode active material, both of which can severely reduce battery lifespan. The battery calendar life at different higher state of charge (SOC) levels is illustrated in Picture 11. In storage

conditions, maintaining the battery at a relatively low SOC, around 20%, is generally beneficial for both battery longevity and safety performance.

In battery electric vehicle (BEV) operation, the battery is typically fully charged and then discharged to a specific depth of discharge (DOD), as defined in Picture 12. For example, a DOD of 80% generally corresponds to cycling the battery between 20% and 100% SOC. In this scenario, battery life is strongly affected by depth of discharge (DOD), and the relationship is complex. Experimental results shown in Picture 12 indicate that as depth of discharge (DOD) increases, battery life initially improves due to a lower average state of charge and anode potential, which reduce the rate of side reactions. However, beyond a certain point, higher depth of discharge (DOD) accelerates degradation because the cathode and anode materials experience multiple phase transitions, causing severe structural and volumetric changes. Consequently, battery life is significantly reduced at high depth of discharge (DOD) levels.

(a) Storage Mode   (b) BEV Mode

(c) HEV Mode   (d) PHEV Mode
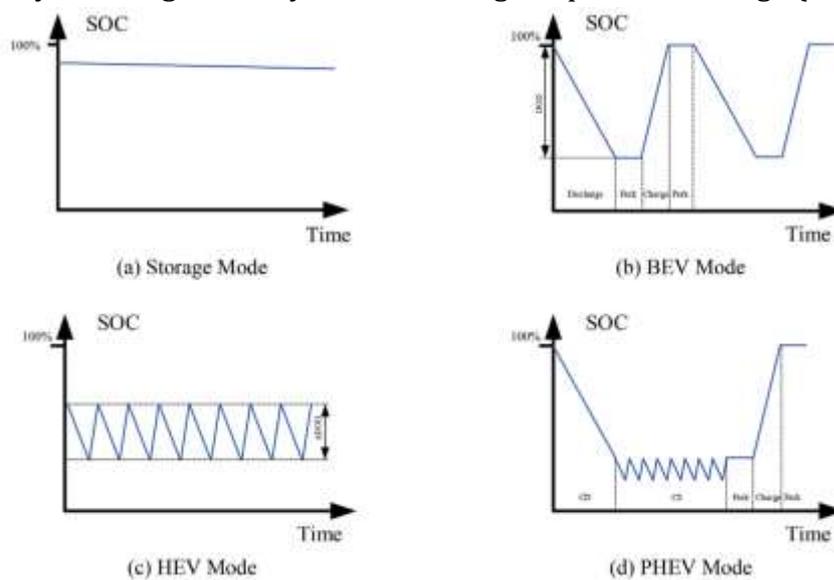
Picture 10. The Battery working SOC in different vehicles.

Overall, there appears to be an optimal depth of discharge (DOD) that maximizes battery life, but this value is often too low to meet practical driving range requirements. Therefore, in real electric vehicle applications, battery capacity must be carefully designed to avoid excessive depth of discharge (DOD) while still satisfying the user's range expectations.
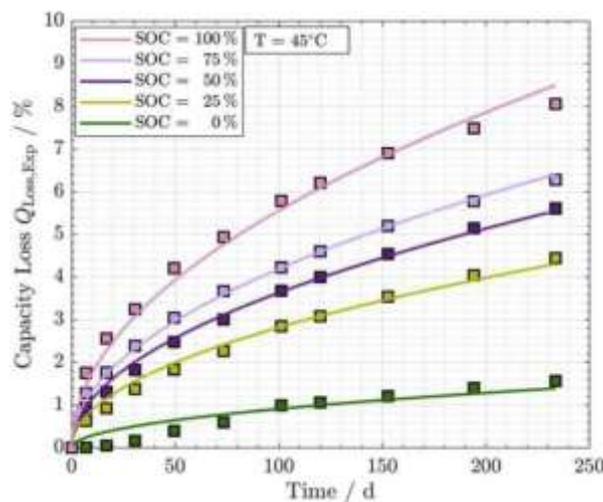
Picture 11. Capacity loss versus state of charge.

4. Summary.

Lithium-ion batteries are complex systems subject to numerous degradation mechanisms, making research on battery aging critically important. Understanding the aging mechanisms and developing accurate models are central scientific challenges in the field of battery research. Capacity and power fade can result from multiple, interrelated side reactions, which are in turn influenced by factors such as battery design, manufacturing processes, and usage conditions. This article presents a comprehensive review of battery degradation across the entire life cycle. Despite significant progress, battery degradation remains an area requiring further research, particularly for high-energy-density chemistries such as Ni-rich cathodes, Li-rich cathodes, lithium–sulfur batteries, and all-solid-state batteries. Battery aging manifests primarily as capacity fade and power fade, while internal aging mechanisms can be categorized as LAM (loss of active material), LLI (loss of lithium inventory), LE (lithium electrochemical side reactions), and RI (resistance increase). These internal side reactions vary depending on the anode and cathode materials and are influenced by factors such as battery design, manufacturing processes, and operational conditions.

To maximize battery lifespan, careful design is essential. Model-based optimization methods can help reduce internal side reactions, and maintaining high production quality—especially process homogeneity—is critical. During operation, temperature and voltage must be kept within optimal ranges through thoughtful vehicle design, battery pack configuration, thermal management systems (TMS), and battery management system (BMS) algorithms. Charging current should also be carefully controlled according to the anode potential to prevent lithium plating and other detrimental reactions.

Battery system degradation is complex, as it depends not only on the aging of individual cells but also on the evolution of system consistency. Tools such as electric quantity–capacity scatter diagrams can be used to visually assess the state of the battery system. Additionally, optimizing cell compression and implementing effective battery balancing algorithms can help extend overall system life.

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