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Review: Li-ion Batteries: Basics, Advancement, Challenges & Applications in Military

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Abstract: Li-ion battery technology has become very important in recent years as these batteries show great promise as power source. They power most of today's portable devices and seem to overcome the psychological barriers against the use of such high energy density devices on a larger scale. Lithium-ion batteries are being widely used in military applications for over a decade. These man portable applications include tactical radios, thermal imagers, ECM, ESM, and portable computing. In the next five years, due to the rapid inventions going on in li-ion batteries, the usage of lithium batteries will further expand to heavy-duty platforms, such as military vehicles, boats, shelter applications, aircraft and missiles. The aim of this paper is to review key aspects of Li-ion batteries, the basic science behind their operation, the most relevant components, anodes, cathodes, electrolyte solution as well as important future directions for R&D of advanced Li-ion batteries for demanding use in Indian Armed Forces which are deployed in very harsh conditions across the country.
Keywords: Li-ion Battery, NiCd battery

I. INTRODUCTION

Electrical energy powers lives of armed forces, whenever and wherever they need it, and can now be accessed with evermore ease and efficiency - even in the absence of power outlets in remote locations. Armed forces can be made to move in unbound and wireless ways, and enjoy high mobility in a potentially healthier local environment in remote areas with dramatic development which has been made possible by efficient energy storage devices. In principle, armed forces can enjoy the use of mobile phones, cameras, laptops, power tools, etc. in harsh environment, relying on efficient batteries to power them. In addition, efficient energy storage is an important complement to fluctuating energy sources, such as wind and sunlight in forward areas. With batteries, the supply-demand chain can thus be balanced over time, even in situations when no energy can be produced. To a large extent, these developments have been made possible by the lithium-ion battery. This type of battery has revolutionized the energy storage technology and enabled the mobile revolution. Through its high potential, and high energy density and capacity, this battery type has already contributed to improving lives of armed forces, and arguably will continue to do so in the years to come. However, battery development is very daunting and challenging in general, and perhaps particularly so when it comes to lithium-based cells. Many scientists and engineers, working in academia, industry, and even independently, have contributed to this development, realizing that the identification of solutions for efficient batteries is a highly difficult task. The development has thus been relatively sluggish and only very few efficient battery configurations have been successfully designed over the years. For example, military still relies on the lead–acid battery discovered in the mid-19th century. Nevertheless, due to several ground-breaking multidisciplinary scientific discoveries, encompassing electrochemistry, organic/inorganic chemistry, materials science, etc., these challenges could indeed be met, and the lithium-ion battery becomes a reality that essentially changed Armed Forces.

The working principle of a battery is relatively straightforward in its basic configuration (Figure 1). The cell is composed of two electrodes, each connected to an electric circuit, separated by an electrolyte that can accommodate charged species. Frequently, the electrodes are physically separated by a barrier material that prevents them from coming into physical contact with one another, which would cause the battery to short-circuit. In the discharge mode, when the battery serves to drive the electric current, an oxidation process takes place at the negative electrode (anode), resulting in electrons moving from the electrode through the circuit. A complementary reduction process takes place at the positive electrode (cathode), replenished by electrons from the circuit. The cell voltage largely depends on the potential difference of the electrodes, and the overall process is spontaneous. For rechargeable (secondary) batteries the process can be reversed and external electricity can be used to produce complementary redox reactions at the electrodes. This process is energy-dependent and non-spontaneous.

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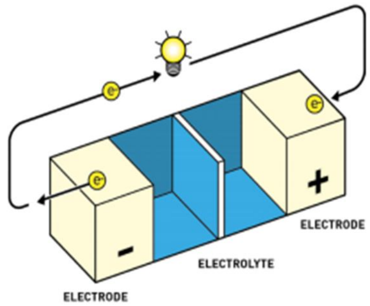

Figure 1. Working principle of basic battery in the discharge mode (Galvanic element) [1].

According to the Nobel Foundation, “this lightweight, rechargeable and powerful battery is now used in everything from mobile phones to laptops and electric vehicles. It can also store significant amounts of energy from solar and wind power, making possible a fossil fuel-free society”, which is of significant application in Armed Forces. In the early 1970s, Whittingham, who at the time was a chemist at Exxon, started exploring the idea of a new battery that could recharge on its own in a short amount of time: a Li-ion battery. While his first attempt worked, it was based on a metallic lithium anode which was found to chemically react with the electrolyte, leading to instability and the growth of lithium ‘whiskers’ (i.e., dendrites) that could cause the battery to explode. Then in the 1980s, Goodenough, who was an engineering professor at the University of Texas at Austin at the time, had a different idea. He experimented using lithium cobalt oxide as the cathode instead of titanium disulfide. This doubled the battery’s energy potential from 2 V to 4 V. Finally, five years later, Yoshino, who was working at Asahi Kasei Corporation, developed the use of graphite for the anode. Initially, petroleum coke was used, but graphite was found to be a far better material. The Li-ion intercalated into the layered graphite, providing a huge boost as no free metallic lithium is used in the battery. This made the battery far safer and enabled the first prototype Li-ion battery to be produced.

The materials involved in Li-ion batteries consist of carbon which is porous in nature, usually graphite, as the anode, and metal oxide for the cathode. Like most battery technologies, the working principle of Li-ion batteries involves Lithium stored in the anode terminal that is transported to the cathode terminal by an electrolyte. Some of the most common cathode components are Lithium Nickel, Manganese Cobalt Oxide, Nickel Oxide, Cobalt Oxide, Manganese spinel, Iron Phosphate, and Titanate. Among them, Lithium Nickel and Manganese Cobalt Oxide have a higher energy density and cell voltage. The electrolytic solution is lithium salt in organic carbonate solvent containing “lithiated” ions. Lithium will be stored inside the cell until the battery is later recharged. At times of high current discharge, there is a possibility that the cell can suddenly lose power depending on the Li concentration, if saturated or depleted at the electrolyte surface. There are different types Li-ion cell geometries according to the current manufacturing practices, namely the prismatic, cylindrical, coin, and the pouch cell geometry which is the most recent method. Both the cylindrical and prismatic cells are commonly made of “laser-welded” aluminum can and consist of liquid electrolyte. The pouch cell with aluminized plastic bag contains Li-ion polymer electrolyte or gel. Bellcore researchers were the first to advance their research on the polymeric electrolyte called “plastic Li-ion (PLiON)”. This thin film battery technology gives the advantage of lightness, flexibility and shape versatility when compared to the cylindrical, prismatic or coin cell geometries [2].

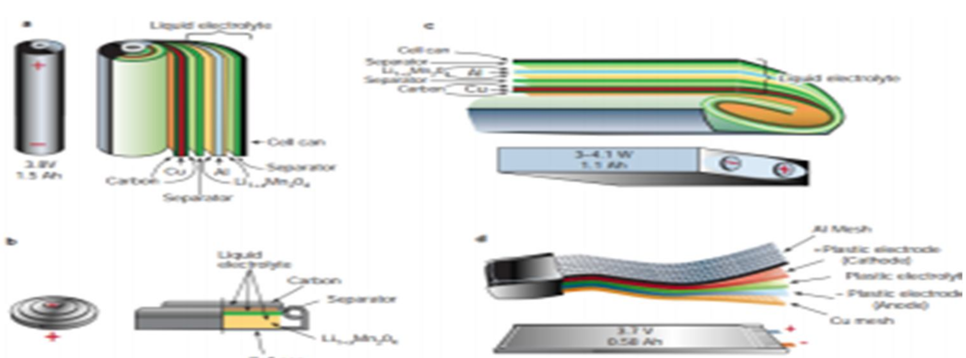

Figure 2. Different types of cell geometry a) cylindrical b) coin c) prismatic d) pouch [2]

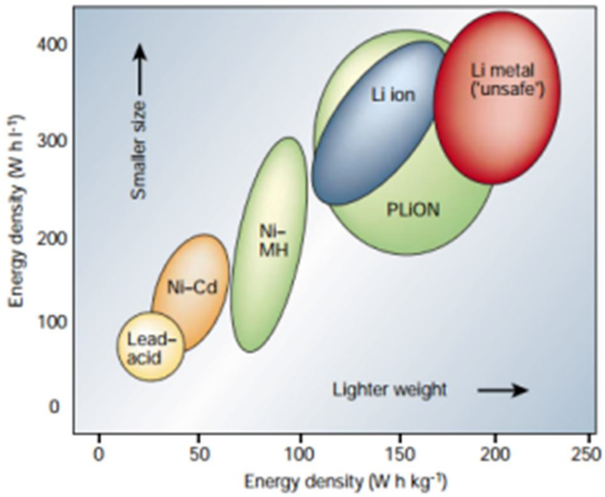

Figure 3. Energy Density of different Batteries [2]

The electrical energy that a battery is able to give is a function of both the cell and its capacity which are dependent on the chemistry of the battery. For the purpose of application, Nickel Metal Hydride (Ni-MH) is the common battery technology currently being used [2]. However, different research efforts have proven that Lithium ion (Li-ion) chemistry has twice the power efficiency and density of NiMH.

Out of the common batteries used in various applications, lead acid, Nickel Cadmium (Ni-Cd), Nickel Metal Hydroxide (Ni-MH), and Li-ion batteries have higher energy density, as shown in Fig.3.

Li-ion batteries are the power house for the digital electronic revolution, which is a result of intensive research and contribution by many great scientist and engineers. There are still lots of challenges being faced by Li-ion batteries related to volumetric energy density, cyclability, charging rate, stability and safety. In [3], the basic concepts, recent progress and challenges regarding Li-ion batteries are provided.

The field of Li-ion batteries is very interesting, important and attractive for the large scientific and technology communities in material science, electrochemistry, chemical engineering, computational chemistry, solid state chemistry, physics, electrical engineering, etc.. because these battery systems are complicated and their development requires multi-disciplinary skills and efforts [4]. Li-ion batteries introduced by Sony Corporation for digital camcorders in 1991 have achieved widespread use in personal electronics and in the past decade in electrified transportation. Although the progress of LIBs has been significant since their introduction, there are several technical challenges for LIBs to meet the future needs of the automotive applications. When compared to consumer electronics, automotive applications have more stringent technical requirements such as calendar life (10 years), cycle life (1000 cycles), temperature range (-30 to 52 ^{o} C) and cost ($ 100/kWh), thus a variety of challenges and opportunities exist for automotive LIB [5].

Apart from the military operations the imp factor for survival during extreme weather conditions holds an important factor for morale and motivation of troops. For this the equipment back up is most important aspect which are utilized in different applications to include Mobility , Surveillance , Communication and other survival factors. It is to be noted that currently army is procuring various types of batteries for day to day requirements. The current inventory includes the batteries of 1.5V, 3V, 5V, 8V and 12V ratings.

The batteries currently in use are lead acid and NiCd battery, apart from this few sophisticated equipments are currently using li ion battery. The lead acid battery and NiCd battery are erstwhile batteries with low energy density , fast discharging, short life span during extreme hot and cold conditions.

The comparison of li ion battery, lead acid battery and NiCd battery is as mentioned in table 1.

Table 1. comparison of li ion bty , lead acid bty and ni cd battery [5]

Applications	Unit of measurement	Lead acid	NiCd	NiMH	Li-ion
Cell Voltage	Volts	2	1.2	1.2	2.4-3.8
Specific Energy	Wh/Kg	30-40	35-80	55-110	100-300
Energy Density	Wh/l	50-90	50-70	160-420	125-600+
Power Density	W/Kg	100-200	100-150	100-500	500-5000
Maximum Discharge	Rate	6-10C	20C	15C	80C
Useful Capacity	Depth of Discharge%	50	50	50-80	>80
Charge Efficiency	%	60-80	60-80	70-90	>95
Self Discharge	% Month	3-4	15-20	15-30	2-3
Temperature Range	^{o}C	40-60	20-70	20-65	-30-70
Cycle life	Number of cycles	200-400	300-1000	500-1000	>2000
Memory effect		No	Yes	Yes(<NiCd)	No
Micro cycle tolerance		Deteriorates	Deteriorates	Yes	Yes
Robustness (Over/under voltage)		Yes	Yes	Yes	Needs BMS

It is clearly visible from the table1 that li ion batteries are way ahead than its other counterparts in various applications namely specific energy, energy density, power density, life cycle and charge efficiency. There is a need to replace current inventory by li ion battery so as to enhance the reliability and effectiveness of the equipments in military.

II. BASIC AND ADVANCEMENT IN LI-ION BATTERY

An electrochemical battery consists of a cathode, an anode and electrolyte that acts as a catalyst. When charging a buildup of positive ions forms a cathode/ electrolyte interface. This leads electron moving towards the cathode, creating a voltage potential between the cathode and the anode. Release is by passing current from the positive cathode through an external load and back to the negative anode. On charge, the current flows in the other direction. A battery has two separate pathways; one is the electric circuit through which electrons flow, feeding the load, and the other is the path where ions move between the electrodes through the separator that acts as an insulator for electrons. Ions are atoms that have lost or gained electrons and have become electrically charged. The separator electrically isolates the electrodes but allows the movement of ions.

Li -ion uses a cathode (positive electrode), an anode (negative electrode) and electrolyte as conductor. (The anode of a discharging battery is negative and the cathode positive). The cathode is metal oxide and the anode consists of porous carbon. During discharge, the ions flow from the anode to the cathode through the electrolyte and separator; charge reverses the direction and the ions flow from the cathode to the anode. Fig. 4 illustrates the process.

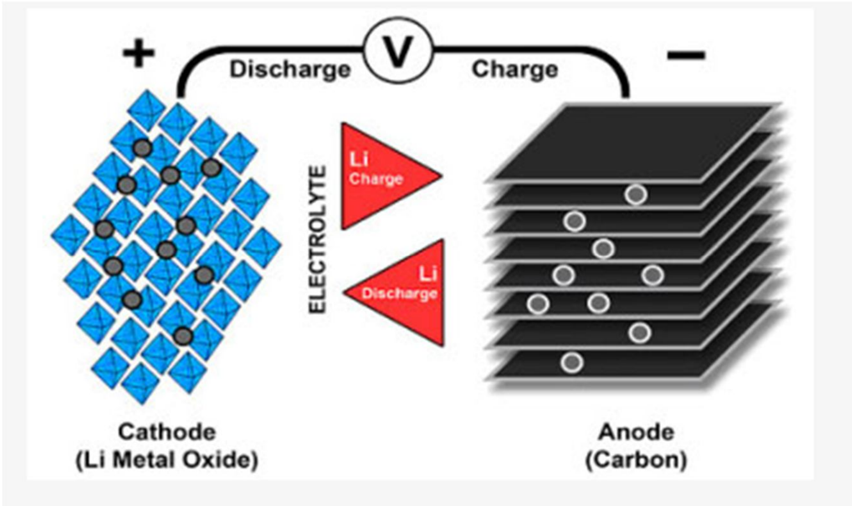

Fig. 4 Ion Flow in Li -ion Battery [6]

When the cell charges and discharges, ions shuttle between cathode and anode. On discharge. the anode undergoes oxidation, or loss of electrons and the cathode sees a reduction, or gain of electrons. Charge reverses the movement. Sony's original li-ion battery used coke as the anode, however in 1997 it shifted to graphite to attain a flatter discharge curve. Graphite is a form of carbon that has long term cycle stability. A future material that promises to enhance the performance of li-ion is graphene. Fig.5 illustrates the voltage discharge curve of a modern Li-ion with graphite anode and the early coke version.

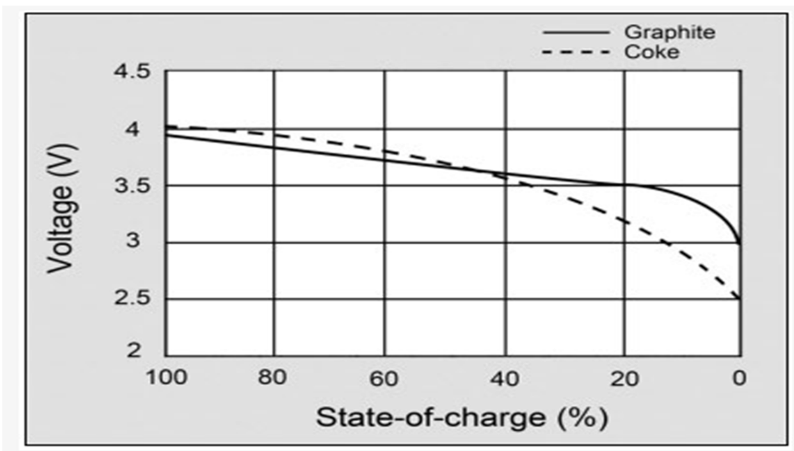

Fig. 5 Voltage Discharge curve of Li-ion [6]

A battery should have a flat voltage curve in the usable discharge range. The modern graphite anode does this better than the early coke version. Several additives have been tried, including silicon based alloys, to enhance the performance of the graphite anode. It takes six carbon (graphite) atoms to bind to a single li-ion ; a single silicon atom can bind to four lithium ions. This means that the silicon anode could theoretically store over 10 times the energy of graphite, but expansion of the anode during charge is a problem. Pure silicon anodes are therefore not practical and only 3-5 percent of silicon is typically added to the anode of a silicon based to achieve good cycle life. Using nano structures lithium titanate as an anode additive shows promising cycle life, good load capabilities, excellent low temperature performance and superior safety, but the specific energy is low and cost is high. Manufacturers can attain a high specific energy and low cost relatively easily by adding nickel in lieu of the more expensive cobalt, but this makes the cell less stable. Most Li-ion batteries share a similar design consisting of a metal oxide positive electrode (cathode) that is coated onto an aluminum current collector, a negative electrode (anode) made from carbon/ graphite coated on a copper current collector, a separator and electrolyte made of lithium salt in an organic solvent.

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A. Different Types of Lithium-Ion Batteries

Table 2 below shows the comparison of various types of lithium-ion cell with respect to various parameters as mentioned below.

Table 2. Comparison of Various Types of Li-ion Batteries [6]

S. No.	Name	Voltages	Specific Energy (capacity)	Charge (C-rate)	Discharge (C-rate)	Cycle life	Thermal runaway	Applications	Comments
01	Lithium Cobalt Oxide ($LiCoO_2$), LCO	3.6V, operating range (3.0-4.2V)/cell	150-200Wh/kg	0.7-1C Charge current above 1C shortens battery life	1C; 2.5V cut off, Discharge current above 1C shortens battery life	500-1000, related to depth of discharge, load, temp	150°C	Mobile phones, laptops, tablets	Cobalt is expensive, very high specific energy, limited specific power
02	Lithium Manganese Oxide	3.7V, operating range (3.0V-4.2V/cell)	100-150W/kg	0.7-1C	1C, 10Cpossible with some cells	300-700 related to depth of discharge, load, temp	250°C	Power tools, medical devices, electric power train	High power but less capacity, safer than LCO, commonly mixed with NMC to improve performance
03	Lithium Nickel Managanese Cobalt Oxide ($LiNiMnCoO_2$)	3.6V, typical operating range 3.0-4.2V/cell	150-220Wh/kg	0.7-1C charges to 4.2V, Charge above 1C shortens battery lige	1C; 2C possible on some cell, 2,5V cu off	1000-2000 (related to depth of discharge, temp)	210°C, high charge promotes thermal runaway	E bikes, medical devices, EVs, Industrial	Provides high capacity and high power. Serves as hybrid cell
04	Lithium Iron Phospahte ($LiFePO_4$)	3.2V, nominal operating range 2.5-3.65V/cell	90-120W/kg	1C typical, charges to 3.65V	1C, 25C on some cells, 40A pulse	2000 and higher(related to depth of discharge, temperature)	270°C	Portable and stationary needing high load currents and endurance	Very flat voltage discharge curve but low capacity, one of safest Li-ion, elevated self discharge
05	Lithium Nickel Cobalt Aluminium Oxide ($LiNiCoAlO_2$)	3.6V, nominal typical operating range 3.0-4.2V/cell	200-260Wh/kg	0.7C, charges to 4.2V	1C, typically 3.0 V cut off, high discharge rate shortens battery life	500 (related to depth of discharge, temp)	150°C	Medical devices, industrial, electric power train (Tesla)	Shares similarities with LCO. Serves as energy cell
06	Lithium Titanate (LTO)	2.4V, typical operating range 1.8-2.85V/cell	50-80Wh/kg	1C typical, 5C maximum, charges to 2.85V	10C possible 30C 5s pulse, 1.8V cut off	3000-7000	One of safest Li-ion batteries	UPS, electric power train (Mitsubhishi, Honda Fit EV), solar power street lighting	Long life, fast charge, wide temp range but low specific energy and expensive. Among safest Li-ion battery

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B. Advancement in Materials for Li-ion Batteries

The lack of thermodynamic stability and the critical importance of passivation phenomena in the operation of Li-ion battery systems mean that the development of each single component: new electrode materials, solution species, new separators and even cases requires rigorous studies of the correlation among composition, morphology structure, surface chemistry, intrinsic electrochemical behavior and thermal stability. There new horizons for Li-ion batteries and intensive efforts are underway regarding new materials that can bring these batteries to a high energy density. $LiFePO_4$can be considered as a superb cathode material in terms of rate capability, reasonable capacity, relative low price and excellent stability. The electrolyte usually functions as an electronic separator and ionic conductor between cathode and anode. In a commercial LIB, a porous plastic film as separator is soaked in $LiPF_6$ which is dissolved in a mixture of organic solvents such as ethylene carbonate (EC), ethyl methyl carbonate (EMC) or diethyl carbonate (DEC). If the membrane itself is a Li-ion conductor, the liquid electrolyte is not a necessity. Another case is to incorporate the liquid electrolyte into the polymer matrix to form a polymer gel electrolyte. These are the most common types of membrane used in LIB. The main function of these membranes is to prevent the positive and negative electrodes electrically contacting each other and allow rapid ionic transport to complete the circuit for the passage of current in Li-ion batteries, thus affecting the electrochemical energy efficiency. In [7] an attempt is made to summarize the knowledge about some selected membranes in li-ion batteries, based on the type of electrolyte used, literature concerning ceramic-glass and polymer solid ion conductors, microporous filter type separators and polymer gel-based membranes are reviewed.

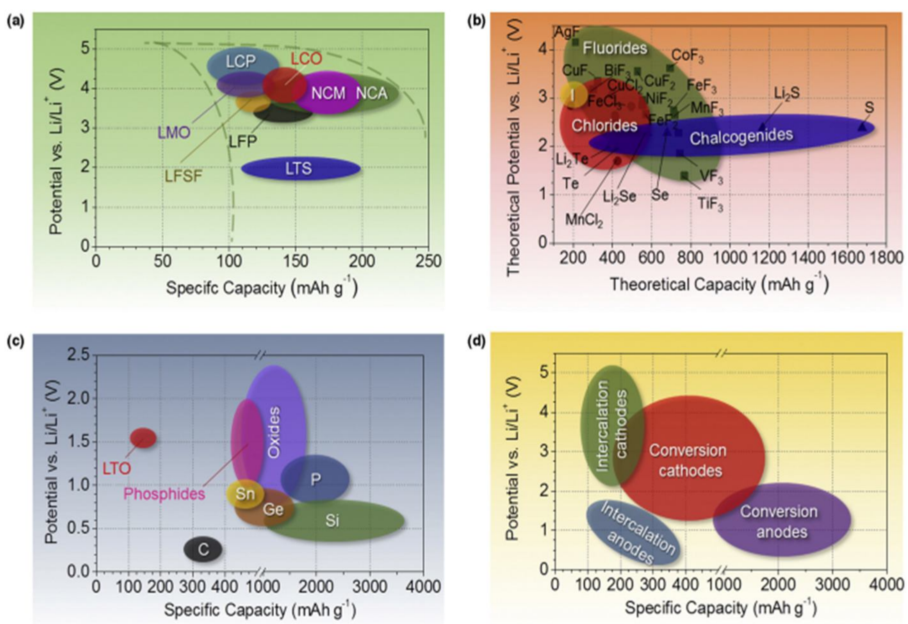

Figure. 6 Approximate range of average discharge potentials and specific capacity of some of the most common (a) intercalation-type cathodes (experimental), (b) conversion-type cathodes (theoretical), (c) conversion type anodes (experimental), and (d) an overview of the average discharge potentials and specific capacities for all types of electrodes [8].

Figure 6 [8] is a fairly comprehensive form of a popular chart, depicting average electrode potential against experimentally accessible (for anodes and intercalation cathodes) or theoretical (for conversion cathodes) capacity. This allows the reader to evaluate various anode and cathode combinations and their theoretical cell voltage, capacity, and energy density. The chart can also be used to identify suitable electrolytes, additives, and current collectors for the electrode materials of choice. The acronyms for the intercalation materials are: LCO for ''lithium cobalt oxide'', LMO for ''lithium manganese oxide'', NCM for ''nickel cobalt manganese oxide'', NCA for ''nickel cobalt aluminum oxide'', LCP for ''lithium cobalt phosphate'', LFP for ''lithium iron phosphate'', LFSF for ''lithium iron fluorosulfate'', and LTS for ''lithium titanium sulfide''.

Lithium ion batteries that are capable of extreme fast charging (XFC) are highly desirable to accelerate adoption of electric vehicles (EVs) in military. To identify the rate limiting factors for XFC, both half cells and symmetric cells to investigate the fast charging behavior of the cathode and anode separately are used in [9].

The symmetric cells enabled accurate measurements of charge transfer at each electrode without complications from counter electrodes. The battery materials and electrode design were comparable to the state-of-the-art for EV cells. Under these conditions, the graphite anode is the rate limiting electrode for fast charging in NMC811/Graphite pouch cells. The effective N/P ratio falls below 1.0 at high charging rates, which also causes Li plating. The use of symmetric cells in this study provides new insights to identify the limiting electrode in Li-ion batteries, especially those designated for extreme fast charging applications. As promising alternatives to the currently used graphite anode in next-generation LIBs, CTAMs (Conversion Type Anode Materials) are of great significance because of their high theoretical capacity, tunable operation voltages, and the diversity of chemical composition and phases. Nevertheless, many obstacles, including poor intrinsic conductivity and severe pulverization during conversion reactions, need to be addressed before the widespread implementation of CTAMs [10]. Since there is significant interest in utilizing lithium-ion batteries for electric vehicles, the development of methods to generate a stable anode SEI (Solid electrolyte Interphase), which is a key factor for the performance of lithium-ion batteries are essential. In addition, widespread implementation of electric vehicles will require lowering production costs and improving fast charging. The long time associated with formation cycling (1 week) is costly for manufacturers while the resistance associated with lithium ion transport through the SEI limits the charging rate for lithium-ion batteries. Finally, the development of the next generation anode materials such as silicon or lithium metal is dependent upon the development of superior passivation layers to stabilize these high-capacity anode materials. Thus, developing a better understanding of the formation mechanisms, decomposition mechanisms, and ion transport mechanisms of the anode SEI is imperative [11].

III. CHALLENGES IN LI-ION BATTERIES

The various challenges faced by Li-ion batteries are

1) *Overheating:* They overheat and explode if charged too fast
2) *Short life Time:* They die after less than 1000 charge/discharge cycles
3) *Flammable:* They use chemicals that are flammable. This causes electric cars to explode when hit in certain ways
4) *Toxic:* These chemicals are toxic, requiring special care when disposed.
5) *Underperform in Extreme Temperatures:* The chemicals underperform when temperatures are lower than 0 degree Celcius and greater than 50 degree Celcius.
6) *Expensive Casing:* The chemicals are liquid, requiring rigid and expensive casing to prevent leakage.
7) *Expensive to Transport:* Extra precautions are needed to avoid explosions and additional approval are required to ship batteries.

As rechargeable batteries, li-ion batteries serve as power sources in various application systems. Temperature as a critical factor, significantly impacts on the performance of li-ion batteries and also limits the application of li-ion batteries. Moreover, different temperature conditions result in different adverse effects. Accurate measurement of temperature inside li-ion batteries and understanding the temperature effects are important for the power battery management. In [12], the effects of temperature to li-ion batteries at both low and high temperature ranges are discussed. The current approaches in monitoring the internal temperature of li-ion batteries via both contact and contactless processes are also discussed in [12]. Lithium is the lightest of all metals, has the greatest electrochemical potential and provides the largest specific energy per weight. Rechargeable batteries with lithium metal on the anode could provide extraordinarily high energy densities, however it was discovered in the mid 1980s that cycling produced unwanted dendrites on the anode. These growth particles penetrate the separator and cause an electrical short. The cell temperature would rise quickly and approach the melting point of lithium, causing thermal runaway, also known as “venting with flame”.

Unfortunately, for a country like India it is very difficult to run an electric vehicle at the average temperature is quite high in most cities in the country. Running an electric vehicle at a higher temperature will obviously increase the chance of battery explosion, risking life. Li-ion battery explodes due to dendrite formation, which grows like spike onto the anode material, thus short circuiting the battery internally and can explode. The newly material, developed by IITB [13], does not allow dendrite formation in battery as well as tolerate high temperature operation, thus calling it ultra safe battery. Li-ion batteries due to their wide range of safe operating temperatures (i.e -10^{o}C to 50^{o}C), are preferred over other types of matured battery technologies such as lead acid and nickel cadmium. However, operating the Li-ion batteries at cold climate conditions can potentially harm the batteries and lead to issues such as degradation and reduction in their capacity and power density. In [14], experimental investigation of the behavior of a Li-ion cell operating at low temperatures (ie -15^{o}C to 25^{o}C) with respect to its charging and discharging behavior is carried out. It was observed that at sub zero temperatures (i.e -5^{o}C, -10^{o}C and -15^{o}C) the Li-ion cells capacity is reduced due to the impedance effect which then increases the cells internal resistance.

Moreover, at such low temperatures the best state of charge (SOC) of the cell (ie during the charging mode) has reduced to about 7-23% of its maximum initial SOC (ie 100%). Safety [15] is a key aspect of any energy storage device, including batteries. Batteries contain both the oxidizer (cathode) and fuel (anode) in a sealed container; under normal operation the fuel and oxidizer convert the chemical energy to electrical energy with minimal heat and negligible gas. If allowed to react chemically in an electrochemical cell, the fuel and oxidizer convert the chemical energy directly into heat and gas. Once started, chemical reaction will likely proceed to completion because of the intimate contact of fuel and oxidizer. Safety needs to be addressed at the cell, module, pack and ultimately vehicle levels. Failure at one level can quickly escalate to much more severe failures at higher level. LiFePO4 or LFP is a comparatively modern cathode material for li-ion batteries and was originally proposed as a cathode material. It is a material hoped to replace the commonly used oxide materials containing manganese (unstable) and cobalt (expensive and toxicological issues). LFP has a very static voltage profile over its charging range and therefore provides reliable electromotive force during usage. Furthermore it has a high thermal stability, which is an important safety feature in lithium batteries should the battery endure failures like short circuiting. The fact that LiFePO4 does not release oxygen, even at higher temperature means that there is less risk for combustion of the electrolyte [16]. Overheating of Li-ion batteries typically takes place during normal high-rate discharges and abnormal discharges such as short circuits. For high-rate discharges, the parasitic heat generation of Li-ion batteries can accelerate the capacity fading. In abnormal discharges, the overheating issue becomes more severe, and the battery temperature could even reach the threshold for exothermic reactions and trigger thermal runaway. In [17], phase change material (PCM)-based and heat pipe-based battery thermal management (BTM) systems were designed to dissipate the heat generated by cylindrical and prismatic batteries respectively during normal discharges. The major concerns with Li-ion batteries failures are temperature rise and temperature non uniformity during adverse operating conditions like fast charging/discharging and extreme ambient conditions (extreme hot/cold weather). These problems lead to safety issues like thermal runaway of the battery pack. To negate these issues and to ensure better performance of the battery pack, battery thermal management system (BTMS) is adopted in EVs. The prominent BTMSs are air based BTMS, liquid based BTMS and phase change based BTMS. . In [18] various thermal management issues and numerous cooling methods developed to mitigate these problems are discussed in detail. In general, the thermal hazards of the LIB can be caused or aggravated by several factors including physical, electrical and thermal factors, manufacturing defect and even battery aging. Due to the activity and combustibility of traditional battery components, they usually possess a relatively high thermal hazard and a series of side reactions between electrodes and electrolytes may occur under abusive conditions, which would further lead to the thermal failure of LIBs. Besides, the thermal hazards generally manifest as the thermal runaway behaviors such as high-temperature, ejection, combustion, explosion and toxic gases for a single battery, and it can even evolve to thermal failure propagation within a battery pack.

To decrease these hazards, some countermeasures are reviewed in [19] including the application of safety devices, fire-retardant additives, battery management systems, hazard warnings and firefighting should a hazard occur. In an electric vehicle, energy recovery during regenerative braking causes recharge periods of high current rate, which might damage the Li-ion traction battery A valuable new insights on the impact of regenerative braking on battery aging: A higher level of regenerative braking has generally led to reduced battery aging is provided in [20].

This can be attributed to a reduction of lithium plating, as the depth of discharge is reduced with an increased amount of charge recovered by regenerative braking. The study in [21] has shown that it is not the short-time recharging with high current rates, but the long-lasting charging periods, even with only low current rates, that promotes lithium plating. Moreover, the comparison of usage-dependent and usage-independent battery aging has revealed that cyclic aging decreases with temperature, whereas calendar aging increases with temperature.

Thus, battery life can be extended by optimized operating conditions. Unmanned aerial vehicles (UAVs) have more and more potential in the emergency rescue tasks under disastrous conditions. Thus, the environmental adaptability of UAVs under extreme high and low temperature levels is very important. The electrical performance of lithium-ion battery used in UAVs was investigated under extreme temperature (-30^{o}C—60^{o}C) in [20]. Main conclusions were: (a) The high temperature condition even 60 °C had little effect on the flying performance of UAVs, while significantly degraded the lifetime and discharging capacity, and even damaged the lithium-ion battery. (b) The low temperature condition significantly decreased the flying performance and the battery performance. UAV could not work normally when the environmental temperature was below −25 °C. (c) The low-temperature condition played greater effect on the battery performance than that of high-temperature condition and the testing results of battery discharge experiments well explained this phenomenon. (d) The irreversible and the reversible heat took the dominant role for lower and high temperatures, respectively.

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A. Manufacturing of Li-ion Cell/Battery

As per the projection by NITI Aayog, 300 billion U.S dollar market exists only for electric vehicles within the time period of 2017 to 2030. The report (India's Energy Storage Mission' 2017) also says 80% of market coverage is possible if India goes for battery manufacturing rather than importing them. Undoubtedly it is a great time for India to move into li-ion battery manufacturing rather than importing them. Battery manufacturing involves various steps and these different steps impact the cost, energy consumption and throughput which prevent innovation in battery manufacturing. In [22] the state of the art manufacturing technology and analyze the cost, throughput, and energy consumption based on the production processes is introduced. The research progress focusing on the high cost, energy, and time demand steps of LIB manufacturing is also reviewed. Currently the manufacturing of LIBs still needs to get through slurry mixing, coating, drying, calendaring, slitting, vaccum drying, jelly roll fabrication (stacking for pouch cells and winding for cylindrical and prismatic cells), welding, packaging, electrolyte filling, formation and aging a multi-staged process being adopted by industry. The demand for LIBs is low in the country, but it is anticipated to increase in the future owing to the governments initiatives like National Electric Mobility Mission Plan (NEMMP), Faster Adoption and Manufacturing of (Hybrid) & Electric Vehicles (FAME) and RE initiatives like the National Solar Mission by the Ministry of New and Renewable Energy (MNRE). Given the huge market potential and evolving policies, indigenous manufacturing of battery technology could be a potential solution to bring down its costs, however choosing the right capacity of a manufacturing plant is a big challenge [23]. A special emphasis is placed on constituent-material production and the subsequent manufacturing of batteries. The estimation of impact of battery material recycling on battery manufacturing is discussed in detail. Because some of the materials come from comparatively less plentiful resources, a discussion is presented in [24] on the recycling of these batteries and its potential impact on battery production life cycle burdens. Li-ion batteries with high energy density (upto 705 Wh/L) and power density (upto 10,000W/L) exhibit high capacity and great working performance. The knowledge gained from the information about battery pack assembly process in [25] will guide the reader in evaluating and understanding the battery pack assembly facilities needed to meet the growing battery market and demand. As the industry eagerly awaits the forthcoming storage policy, the information in [25] will guide the reader in evaluating opportunities to set up battery pack assembly facility and capture the share of the growing battery market and demand in India. Most of the rechargeable batteries procured by the department of defense are assembled from critical components manufactured outside the United states, principally in Asia, where many consumer devices containing such batteries are manufactured [26]. Research found [26] that government and battery industry representatives expressed concerns about the security and surge capability of the soldiers-portable battery supply chain, the potentially unmanageable cost of establishing a U.S. production base, and the potential incompatibility of commercial batteries with military requirements. Unless the U.S. manufacturing base were to become competitive in the much larger market for consumer devices, fully domestically produces batteries for military applications will remain expensive compared to those produced in Asia. Policymakers must make their decision based on the predicted future power needs of soldiers and the risk associated with a foreign- dependent battery supply chain balanced against other supply chain risks and the costs of risk mitigation.

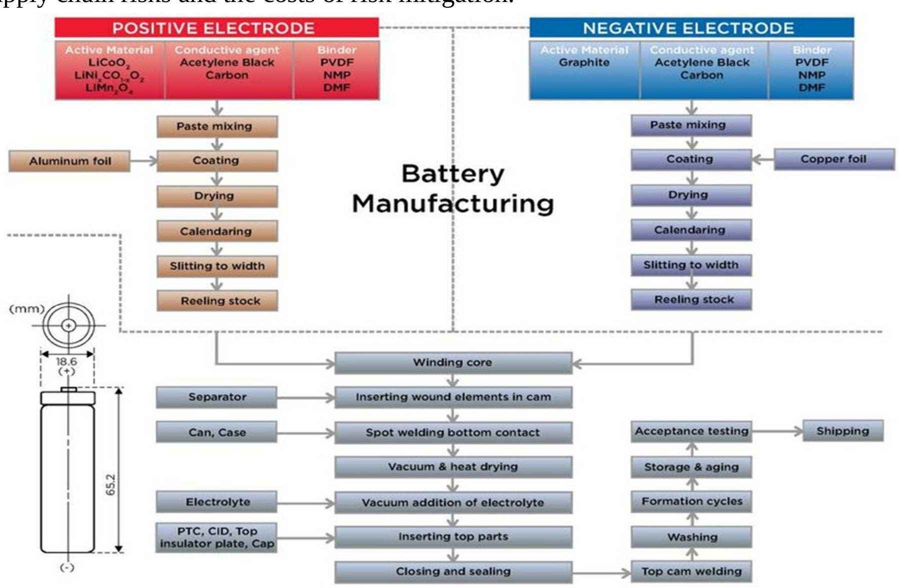

Fig 7. Manufacturing process of Li-ion Battery[22]

IV. MILITARY APPLICATIONS OF LI-ION BATTERY:

A wide variety of equipments are currently in use for military applications. Depending upon the type and usage of these equipments, the battery back up is provided. Li ion battery can provide once and all solution for these equipments due to its wide range of applications. Replacing the current inventory of batteries by Li ion batteries in military applications will enhance the reliability and dependability of the equipments. Li ion battery can be used in following military applications.

1) *Mobility:* The most important aspect of a military operation to be successful is the rapid mobility of its vehicles and equipments to the desired location. The military vehicles such as ALS, 2.5 ton ,Gypsies, Buses, Tatras etc currently use lead acid battery for cranking purpose. As discussed earlier the lead acid batteries are inferior to li ion batteries (ref table). Li ion batteries replacing the lead acid batteries will definitely boost the functionality of the vehicles in terms of high capacity back up and long life.
2) *Communication:* The various communication equipments currently in use in military applications are Motorola set, STARS V MK II, satellite phone etc. The present battery in use for Motorola set is nickel cadmium battery which over a period of time degrades so much that the battery backup is hardly 30 mins to one hour. Therefore with the evident use of li ion battery in communication equipments, the battery backup of these equipments will increase multifold. Thus it will reduce the fatigue of troops due to its light weight and less charging equipment /replacement batteries to be carried.
3) *Surveillance:* Surveillance holds an imp factor in various operations both during peace and war. The current inventory includes Surveillance Radars, HHTIs, Drones and PNVDs etc. These equipments use the erstwhile NiCd batteries which degrade and thus the reliability of the batteries is questionable. With the new technology invention in Li ion batteries, they prove to be highly effective as compared to NiCd batteries. Replacement of these batteries will ensure precise and effective surveillance in military operations.
4) *Misc Applications*

a) Li ion batteries can be used in fighter aircrafts, ships and submarines for power back up.
b) Other applications such as use in GPS, soldier back pack battery backup, energy storage for lighting purpose etc.

Batteries provide electrical energy to many devices from power tools to military portable equipment. The battery technology has evolved over the years which led to the creation of lithium based batteries that are equipped to face the power-demanding military devices. Battery quality is a critical issue in military applications since the portable devices use power consuming algorithms for security. There is a need to efficiently use the available battery power. The existing battery technologies by taking into consideration lithium based batteries over other batteries like nickel-cadmium, nickel metal-hydride and reusable alkaline which are considered the most common are reviewed in [27].

The relevance of lithium batteries in military is outlined looking at the demands posed by the military environment. Rechargeable Li-ion batteries provide significant advantages over lead acid and nickel cadmium batteries for manned and unmanned aerial vehicles. Li-ion has excellent cycle life and calendar life and exceptionally low self discharge. The high energy density li-ion provides weight and volume savings, which allows for additional aircraft payload. Cell configurations containing high surface area electrodes and low temperature electrolyte can provide required power over military temperature extremes of -40^{o}C to +71^{o}C. such batteries provide engine starting, load level levelling, switching and emergency aircraft power. Hermetically sealed cell construction and electronic cell balancing and charge control provide maintenance free operation. In [28] cylindrical cells in high energy and high power configurations are suggested. The modular, 24-volt energy storage system utilizes International Battery's Hyper Class large-format Lithium Iron Phosphate (considered the safest form of Lithium-ion chemistry) cells combined with an advanced thermal management technology to deliver reliable energy in a compact, small footprint package to deliver strict military specifications. Batteries provide electrical energy to many devices from power tools to military portable equipment. The battery technology has evolved over the years which led to the creation of lithium based batteries that are equipped to face the power-demanding military devices. Battery quality is a critical issue in military applications since the portable devices use power consuming algorithms for security. There is a need to efficiently use the available battery power. The existing battery technologies by taking into consideration lithium based batteries over other batteries like nickel-cadmium, nickel metal-hydride and reusable alkaline which are considered the most common are reviewed in [29]. The relevance of lithium batteries in military is outlined looking at the demands posed by the military environment.

V. CONCLUSIONS AND FUTURE SCOPE:

This paper has provided an overview of Li-ion batteries as a method for energy storage for various applications for Armed forces. Different materials for positive and negative electrodes, various types of electrolytes and the physical implementation of Li-ion batteries are presented and compared, and components of battery management systems are described. The performance of existing lithium batteries is heavily dependent on material and thermal characteristics. The various challenges that need to be worked upon are covered which will surely lead to advancement in the near future. Nanotechnology holds an important role in the near future to enhance the charging capacity and further increasing the life span of the batteries.

A. Future Scope

In terms of longevity, advancements are being made in the li-ion battery by using single crystal cathode material. In terms of specific energy, the silicon nanowire anode achieves high watt-hour per kg that can be twice that of commercial li-ion cells, but Si nanowire-based structure have limited cycle life. Microscale Si islands form under the nanowire arrays with cycling that produces stress and cracking. The resulting capacity loss is caused by reduced contact with current collectors. Researchers have also developed an anode structure for Li-ion batteries that is based on silicon-carbon nano composite materials. A silicon anode could theoretically store 10 times the energy of a graphite anode, but expansions and shrinkage during charge and discharge make the system unstable. Adding graphite to the anode is said to achieve a theoretical capacity that is five times that of regular Li-ion with stable performance, however, the cycle life would be limited due to structural problems when inserting and extracting lithium ion at high volume.

1) *Solid-state Li-ion:* High specific energy but poor loading and safety.
2) *Lithium-Sulphur:* High specific energy but poor cycle life and poor loading
3) *Lithium Air:* High specific energy but poor loading needs clean air to breathe and has short life.

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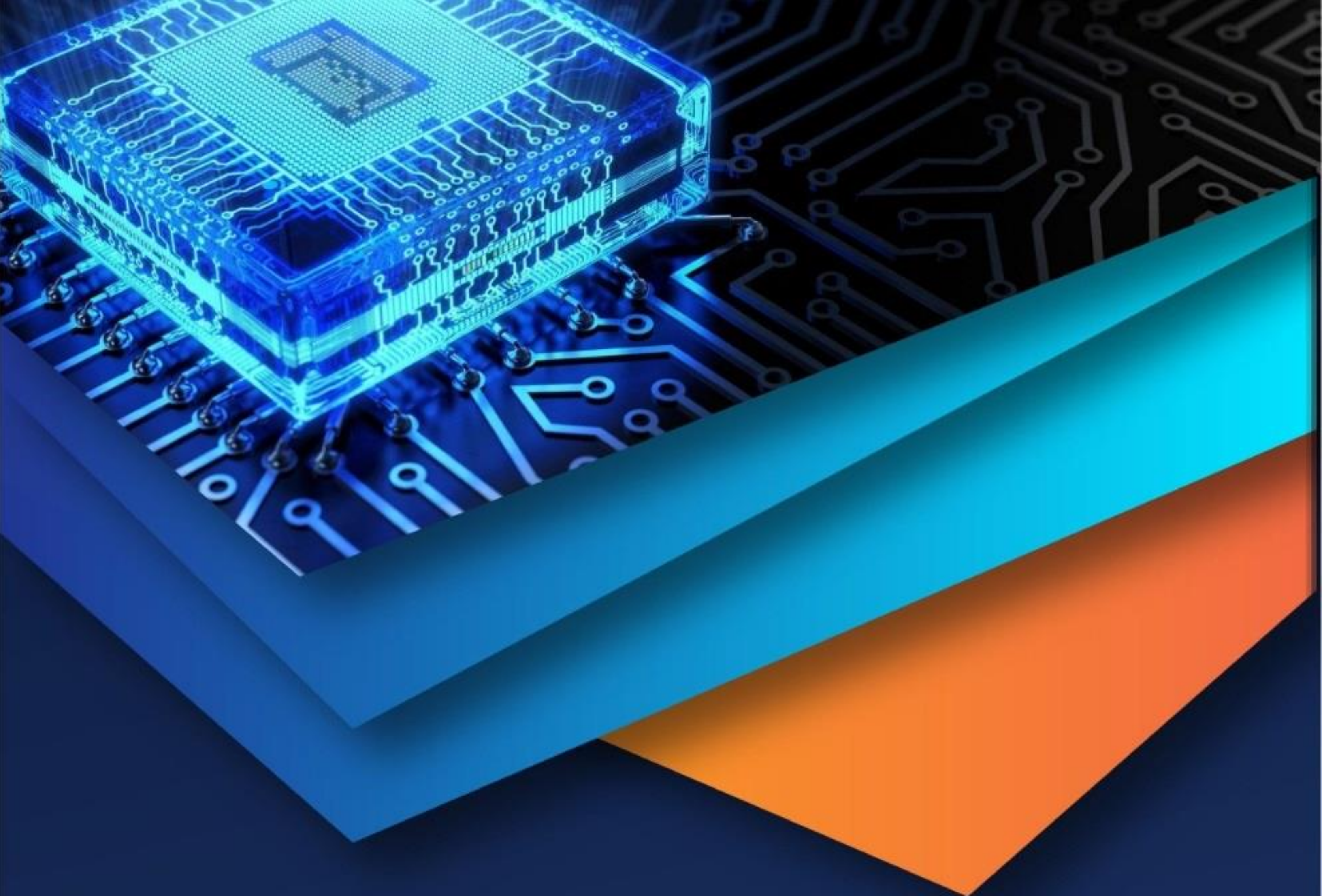

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