 In the modern age, where every gadget from your smartphone to your electric vehicle relies on stored energy, the humble battery has emerged as the unseen engine driving our technological lives. These unassuming little cylinders and rectangles hold within them a world of fascinating physicsan elegant dance of electrons, ions, and chemistry wrapped in modern materials and human ingenuity. But how exactly do batteries work? What allows a battery to power a flashlight for hours or drive a car for hundreds of miles? The answer lies in the invisible forces of the atomic world, where physics and chemistry intertwine to store and deliver energy on demand.To understand the magic inside a battery, we must journey into the realms of thermodynamics, electrochemistry, and electromotive force. We'll break open the black box of the battery and explore not just what happens, but why it happens, following the trail of energy from chemical bonds to glowing light bulbs and spinning motors.Before diving into the battery itself, we must first grasp what energy is in the physical sense. Energy, in all its various forms, is the ability to do work. In physics, work means any transfer of energy that results in movement against a forcelifting a weight, moving a charge, spinning a wheel.Batteries are unique because they store energy chemically, not mechanically or thermally. This stored chemical energy is potential energywaiting to be unleashed. Inside a battery, this energy is stored in the chemical bonds of the materials in its electrodes. The trick is to design a system where these materials can undergo reactions that release this energy in a controlled wayspecifically, through the movement of electrons from one place to another. And therein lies the genius of the battery.A battery is essentially an electrochemical cell, a device that converts chemical energy into electrical energy. The basic building blocks of any battery include two electrodescalled the anode and the cathodeand an electrolyte, a medium that allows ions to move between the electrodes.At the atomic level, the process begins with redox reactionsshort for reduction and oxidation. Oxidation occurs when a substance loses electrons, while reduction occurs when a substance gains electrons. In a battery, the anode is where oxidation happens: electrons are stripped away from atoms. These free electrons are then forced to travel through an external circuit to the cathode, where reduction takes place: atoms there accept the incoming electrons.This flow of electrons through the external circuit is what we harness as electricity.When we connect a battery to a circuitsay, a flashlightthe battery doesnt just turn on. What happens is a beautifully orchestrated movement of charges. Electrons released at the anode flow through the circuit, doing electrical worklighting up bulbs, powering chipsbefore arriving at the cathode.But electrons dont move in isolation. In the battery itself, there must be a way for the circuit to be completed internally. This is where the electrolyte comes in. While electrons travel through the wire, ionscharged atoms or moleculesmove through the electrolyte from one electrode to the other, maintaining charge balance.This synchronized movement of electrons externally and ions internally is what keeps the electrochemical reactionand the batterygoing.Lets dig deeper into each of these components.The anode, often made from metals like lithium or zinc, is the site where oxidation occurs. These materials are chosen because they are willing to give up electrons easily. The electrons freed from the anode travel through your device before being accepted at the cathode.The cathode is typically made from compounds that are good electron acceptorssuch as manganese dioxide or lithium cobalt oxide. These materials can incorporate the incoming electrons into their structure, completing the redox reaction.The electrolyte, which may be a liquid, gel, or solid, must be capable of allowing ions to flow while preventing electrons from taking a shortcut through the battery, which would cause a short circuit. Its a medium, a bridge, and a gatekeeper all in one.Voltage is the measure of electrical potential difference between the anode and cathode. Think of it as the pressure behind the electrons. The greater the difference in the energy levels of the electrons in the two electrodes, the higher the voltage.Each chemical reaction pair in a battery generates a specific voltage. For instance, a zinc-carbon battery typically produces about 1.5 volts per cell, while a lithium-ion cell might produce around 3.7 volts. This is why batteries are often stacked in series inside devicesto add up to a higher total voltage.The concept of the battery dates back to the late 18th century, when Italian scientist Alessandro Volta constructed the first true battery, the voltaic pile. His invention consisted of alternating layers of zinc and copper separated by pieces of cloth soaked in saltwater. It was primitive, but it workedit produced a steady electric current. This early work laid the foundation for modern electrochemistry and the birth of portable electricity.Voltas pile worked because of the same principles we use today: different metals have different tendencies to give up or accept electrons. By arranging them cleverly and providing a path for both electrons and ions to move, Volta created the first controllable source of electric current.Today, batteries come in many shapes, sizes, and chemistries. Alkaline batteries, commonly used in household devices, rely on zinc and manganese dioxide. Theyre reliable, cheap, and safe, but not rechargeable.Rechargeable batterieslike nickel-metal hydride (NiMH), nickel-cadmium (NiCd), and lithium-ion (Li-ion)operate on the same principles but use different materials that can be returned to their original state via charging.In a rechargeable battery, the chemical reactions that produce electricity can be reversed by applying an external voltage. This forces electrons to move in the opposite direction, restoring the original chemical states of the electrodes. This cycle can be repeated hundreds or even thousands of times, depending on the batterys design.Lithium-ion batteries, in particular, have revolutionized portable electronics. With their high energy density, lightweight design, and long life, they power everything from phones to cars to spacecraft. The physics behind them is intricate, involving layers of nanostructured materials and precise control of ionic diffusion paths.One of the most important metrics for batteries is energy densityhow much energy a battery can store per unit mass or volume. This determines how long your phone lasts between charges or how far an electric car can go.Physics sets limits on energy density based on the materials used and the fundamental thermodynamics of their reactions. Lithium, for example, is extremely light and has a high electrochemical potential, making it ideal for high-energy-density batteries.Efficiency is another key concern. Not all the energy stored in a battery is recoverable. Some is lost as heat due to internal resistance. Engineers strive to design batteries with low resistance and minimal self-discharge (where the battery loses charge even when not in use).Charging a battery is essentially running the redox reactions in reverse. An external power source pushes electrons back into the anode and pulls them from the cathode. At the same time, ions in the electrolyte move in the opposite direction, restoring the original chemical composition.This requires precise voltage control. Too little voltage and the reaction wont occur; too much, and you risk damaging the battery or causing unwanted side reactions. Overcharging can lead to gas buildup, overheating, and in the worst cases, fire or explosion.Lithium-ion batteries are particularly sensitive and include built-in circuits to prevent overcharging and excessive discharging. Their charging curves follow specific profiles, with constant current followed by constant voltage, ensuring safety and longevity.Despite their apparent robustness, batteries degrade over time. Each charge-discharge cycle causes slight structural changes in the electrode materials. Tiny cracks form, ions get trapped, and chemical impurities accumulate. The result is a gradual loss of capacity.Thermal effects also play a role. High temperatures accelerate chemical reactions that degrade the electrolyte and corrode the electrodes. Cold temperatures slow down ion movement, reducing performance temporarily.Scientists are exploring new materials like solid electrolytes, silicon anodes, and lithium-sulfur chemistries to combat these issues and extend battery life.As our energy demands grow, so does the need for better batteries. Physicists and engineers are exploring new frontiers in materials science and nanotechnology to build the next generation of energy storage.Solid-state batteries, which replace the liquid electrolyte with a solid one, promise higher energy density and improved safety. Quantum batteries concept still largely theoreticalenvision energy storage at the level of quantum states, potentially allowing ultra-fast charging.Flow batteries, meanwhile, separate the energy-storing chemicals from the electrodes, allowing for easier scaling in grid-level storage. These might become vital for balancing renewable energy inputs from solar and wind power.At its core, a battery is a self-contained universe of tiny enginesatoms undergoing transformations, pushing electrons through wires, and powering the vast ecosystem of modern life. It is a marvel of physics and chemistry, a triumph of human understanding of the fundamental forces that govern matter and energy.When you tap your phone screen, flip on a flashlight, or drive a silent electric vehicle, youre witnessing the silent ballet of ions and electrons, choreographed by the principles of thermodynamics and electrostatics. Youre using the physics of stored energya legacy stretching back to Volta, shaped by Faraday and Maxwell, and still evolving today.In a world that increasingly runs on portable power, the battery is no longer a luxuryits a necessity. And as we chase dreams of electric flight, energy-autonomous homes, and interplanetary travel, the battery remains the beating heart of those aspirations.The physics of stored energy is far from simple. But its nothing short of miraculous. The next time you see a battery, remember that inside it, invisible forces are at play, patient, and incredibly powerful. That is the physics of stored energy. That is how batteries work.Think this is important? Spread the knowledge! Share now. Without batteries, there would be no cell phones, watches, tablets, hearing aids, flashlights, electric cars or communication satellites and the list goes on. The first battery was invented over 200 years ago, and ever since then, these ingenious devices have become indispensable in our daily lives. Simply speaking, a battery is any device that can provide a portable temporary source of electrical energy.In an electric circuit, batteries serve as a power source by creating a potential difference that drives the flow of electric current. As current passes through the circuit, it transfers energy to any devices connected to it. In such a circuit, the type of current that flows is direct current. In other words, the current that flows goes in one, continuous direction.Conversely, power supplied by a power plant is accessed via the outlets in your home and is in the form of alternating current. This type of current alternates direction with a certain frequency in order to power devices. A typical battery is composed of one or more cells that have a cathode (positive terminal) on one end and an anode (negative terminal) on the other end. Chemical reactions contained within cause a buildup of electrical charge at the terminals, producing an electric potential across the nodes via the release of chemical energy. The chemical reactions in a battery also create an electric potential between the cathode and anode. The electrons want to make it to the cathode in order to neutralize the charge, but they cannot do so by traveling through the electrolytic material inside the battery itself. Instead, electrons flow easily through a conducting wire connecting the anode to the cathode.Eventually, the chemical processes creating the surplus of electrons in the anode come to a stop, and the battery dies. With rechargeable batteries (also called secondary batteries), however, this process can be reversed by connecting the batteries to battery chargers after they die. Recharging a battery reverses the flow of electrons by using another power source. The chemical processes in the battery are able to reverse due to this added energy, and the battery will once again be able to power a circuit on its own. An excellent way to better understand how a battery works is to create your own battery at home with a lemon, a zinc nail and a copper coin, and to use it to power a small light bulb.Insert a copper coin into one side of the lemon, and insert the galvanized (zinc-coated) nail into the other side (making sure the two items do not touch inside the lemon). The nail will serve as the positive electrode (cathode), and the coin will be the negative electrode (anode). The lemon's juice serves as the electrolyte. You can then connect a voltmeter across your lemon battery to see how much voltage it creates. If necessary, you can connect several lemon batteries in series to create enough voltage to power a small light bulb. TOWELL, GAYLE. "How Do Batteries Work? Parts, Types & Terminology (W/ Diagram)" sciencing.com, . 2 March 2020. APA TOWELL, GAYLE. (2020, March 2). How Do Batteries Work? Parts, Types & Terminology (W/ Diagram). sciencing.com. Retrieved from Chicago TOWELL, GAYLE. How Do Batteries Work? Parts, Types & Terminology (W/ Diagram) last modified August 30, 2022. Read time: 30 minutes Any device that can transform its chemical energy into electrical energy through reduction-oxidation (redox) reactions involving its active materials, commonly known as electrodes, is pedagogically now referred to as a battery.1 Essentially, a battery contains one or many identical cells that each stores electrical power as chemical energy in two electrodes that are separated by an electrolyte.2 By immersing two different metals or metal compounds (electrodes) into an ion-conducting system (electrolyte), electrons tend to move from one electrode to the other, utilizing the basic electrochemical property of the electrodes. When a load is connected, electrons start flowing from one electrode to the other, generating electricity. This is called discharging. During the charging or recharging process, an opposite potential is applied to the electrodes, causing electrons to return to their original positions. Usually, an ion-porous separator is placed in the electrolyte between the two electrodes to prevent short circuiting. Figure 1 shows a schematic of the first lithium ion (Liion) rechargeable battery.3 Figure 1: Schematic illustration of the first Li-ion battery. Credit: The Author, adapted from Goodenough et al.3 In this article, we will consider the main types of batteries, battery components and materials and the reasons for and ways in which battery materials are tested. Batteries are perhaps the most prevalent and oldest forms of energy storage technology in human history.4 Nonetheless, it was not until 1749 that the term "battery" was coined by Benjamin Franklin to describe several capacitors (known as Leyden jars, after the town in which it was discovered), connected in series. The term "battery" was presumably chosen based on the analogy to existing terminology used to describe a grouping of similar equipment operating collectively, like a battery of artillery guns. Interestingly, in present times, unless explicitly specified otherwise, the term "battery" universally refers to electrochemical cells used for generating electrical energy, and even a single cell is now referred to as a battery. Along the timeline of technological development, several notable advancements have played a significant role in shaping and evolving modern batteries. It was speculated that the inhabitants of the Parthian civilization in the 1700s electroplated gold onto silver using jars comprised of an iron rod within a copper cylinder, an assemblage which is known as the Bagdad Battery. However, Alexander Volta is considered the real discoverer of batteries.1 He made and introduced the first successful demonstration of a modern battery in 1800, commonly referred to as the Voltaic pile. Other developments include the Daniel cell in 1836 and the first rechargeable battery, the leadacid battery, in 1854. Lithium-based batteries were the last to emerge in the progression of battery technology, only introduced in the 1970s. Figure 2 illustrates the timeline of introduction of the common types of batteries. Figure 2: The historical timeline of the introduction of some common batteries. Credit: The Author. Continue reading below... There are two main types of batteries. These are primary batteries and secondary batteries. Table 1 provides an overview of the principal commercial battery chemistries, together with their class (primary/secondary) and examples of typical application areas. Lets consider the more common types in more detail. Primary batteries These are also known as non-rechargeable batteries. They are designed for single use and discarded without the possibility to be recharged. Once their energy is depleted, they need to be replaced. Primary batteries are assembled in the charged state and their capacity is limited to the amount of energy obtainable from the volume of reactants placed in them during manufacture. Figure 3 shows the process flow diagram of materials and resources through the life cycle of primary batteries.5 Notable examples of primary batteries include alkaline batteries and lithium metal batteries. Figure 3: The process flow diagram for primary batteries. Credit: Technology Networks. - Alkaline battery An alkaline battery is a common type of primary battery that is widely used in various electronic devices such as flashlights, remote controls, toys and portable electronics. This type of battery typically uses zinc (Zn) as the negative electrode and manganese dioxide (MnO2) as the positive electrode, with an alkaline electrolyte, usually potassium hydroxide (KOH) in between the electrodes. Alkaline batteries offer high energy density and good performance under moderate loads with a long shelf life - Lithium metal battery Lithium metal batteries (not to be confused with Liion batteries) are a type of primary battery that uses metallic lithium (Li) as the negative electrode and a combination of different materials such as iron disulfide (FeS2) or MnO2 as the positive electrode. These batteries offer high energy density, lightweight design and excellent performance at both low and high temperatures. Lithium metal batteries offer long shelf life and reliable power. As such, they are commonly used in medical devices, watches, calculators and backup power systems. Secondary batteries Secondary batteries can be recharged after being discharged by reversing the flow of current through the battery. Other terms for this type of battery are rechargeable battery or accumulator. Secondary batteries are usually assembled in the discharged state and have to be charged first before they can undergo discharge in a secondary process.6 The process flow for rechargeable batteries is shown in Figure 4.5 After being manufactured, rechargeable batteries can be used by the consumer over and over again until the end of their useful life. If battery materials are recycled following disposal, the recovered metals may be used in the production of new batteries, or they may be used for another application. Secondary batteries are therefore more environmentally friendly and cost-effective in the long run compared to primary batteries. Examples of secondary batteries include nickelmetal hydride (NiMH) batteries, leadacid batteries, Liion batteries and solid-state batteries. Figure 4: The process flow diagram for secondary batteries. Credit: Technology Networks. - Nickel metal hydride battery The NiMH battery is a type of rechargeable battery that utilizes a hydrogen-absorbing alloy as the negative electrode and nickel oxide (NiO) as the positive electrode. They are commonly used in portable electronics, such as digital cameras, cordless phones and handheld gaming devices due to their relatively low cost, good energy storage capacity and the absence of toxic materials like cadmium (Cd). They, however, suffer from self-discharge and are less tolerant to overcharge. - Lead acid batteries Leadacid batteries are the oldest and most commonly used rechargeable battery. They consist of a lead (Pb) negative electrode and lead oxide (PbO) positive electrode submerged in a sulfuric acid (H2SO4) electrolyte. Leadacid batteries are known for their reliability and robustness, making them suitable for applications such as automotive starting batteries, backup power systems and renewable energy storage. Although leadacid batteries have a relatively lower energy density compared to newer battery technologies, they remain popular due to their relatively low cost and ability to deliver high currents. - Lithium ion batteries Liion batteries are rechargeable batteries that use Li compounds as the active material in both positive and negative electrodes. Liion batteries offer high energy density and a low self-discharge rate with a lightweight design. They have a longer lifespan and higher power density compared to other rechargeable batteries. Liion batteries have become the standard choice for a wide range of applications including electric vehicles (EVs), mobile devices and renewable energy storage systems. - Solid state batteries Solid-state batteries have attracted considerable attention due to their potential safety, higher energy density, faster charging capabilities, wider operating temperature ranges and longer cycle-life benefits. They employ a solid electrolyte instead of the liquid or gel used in other traditional batteries. Solid-state batteries are considered a promising next-generation battery technology with the potential to revolutionize various industries, including EVs and consumer electronics, by providing improved energy storage solutions with reduced environmental impact. Table 1: Overview of common commercial battery systems together with examples of typical applications, adapted from Winter et al.7 and Smith et al.6 Type Designation Anode/Negative Electrolyte Cathode/Positive Typical Applications PRIMARY Zinccarbon (Leclanch) Zn Aqueous NH4Cl or ZnCl2 MnO2, C Used in a wide range of small portable electronic devices; low-cost modest discharge performance; 1.5 V cell potential Zinccarbon (Zincchloride) Zn Aqueous ZnCl2 MnO2 Used in small portable electronic devices with 1.5 V cell potential Alkalinemanganese Zn Aqueous KOH MnO2, C More energy and power but also more expensive; 1.5 V cell potential Mercury Zn Aqueous NaOH or KOH HgO, C Previously used in hearing aids, cameras and calculators, discontinued because of Hg toxicity; 1.35 V cell potential Lithium metal Li Li salt in organic solvent MnOp, C Available in a range of systems with various cathodes with voltages between 1.5 and ~ 3.6 V Lithiummanganesedioxide Li LiCF3SO3orLiClO4 in organic solvent MnO2 Operating voltage of 3 V with high specific energy and a stable discharge curve Lithiumcarbonmonofluoride Li LiCF3SO3orLiClO4 in organic solvent CFx Used extensively in cameras and smaller devices providing ~ 3.2 volts per cell Lithiumironsulfide Li LiCF3SO3and/orLiClO4 in organic solvent FeS2 Deliver around 1.5 V cell voltage and operate even in extreme temperatures from as low as - 40 C up to + 60 C Lithiumiodine Li LiI in organic solvent I2 Commonly used in medical devices, such as pacemakers and implantable medical devices. Around 2.7 V cell potential Lithiumsilvervanadiumoxide Li LiAsF in organic solvent Ag2V4O11 Typically used in medical devices, electronics and military equipment with around 3 V cell potential Lithiumsulfurdioxide Li SO2LiBr in organic solvent SO2(C) Used in applications that require high energy density, such as military and aerospace applications Lithiumthionylchloride Li SOCl2LiAlCl4 SOCl2(C) Used in applications that require long-term energy storage, such as utility metering, remote monitoring and security systems Lithiumironsulfide(thermal) Li Molten salt mixture LiClLiBrLiF FeS2 Used in high-temperature applications, such as thermal batteries for military and aerospace systems; 1.8 to 2.2 V cell potential Magnesiumsilverchloride Mg Seawater AgCl Used in military and aerospace systems, due to their high energy density and long shelf life; around 1.6 V cell potential Zincair Zn Aqueous KOH Air, C Principal niche market of hearing aids; good cell performance with nominal 1.4 V, but high self-discharge rate Zincsilver oxide Zn Aqueous KOH Ag2O, C Typical application in watches or calculators with good discharge performance. Expensive because of Ag content. Nominal 1.55 V cell potential SECONDARY Nickel cadmium Cd Aqueous KOH NiO(OH) Substantial market presence in portable devices, has a high cycle life but suffers from memory effect. Nominal 1.2 V cell potential; Cd is toxic Nickel metal hydride AB5 or AB2 intermetallic compound Aqueous KOH NiO(OH) Substitute for traditional NiCd cell with improvement in both electrochemical and environmental performance. Nominal 1.2 V cell potential Leadacid Pb Aqueous H2SO4 PbO2 Generally used in automotive applications, as a traction battery or as a reserve power source. It has high toxicity but is easy to recycle. Nominal 2 V cell voltage Lithium ion C, Lix Li salt in organic solvent Li(1x)MnOp High-performance cell widely used in portable electronic equipment with low environmental impact. Nominal 3.6 V cell potential Lithium sulfur Li Li salt in organic solvent S Has a voltage window of 1.5 V to 3 V. Utilizes cost-effective and abundant materials, promise high energy densities (> 600 W h/kg) surpassing those of Liion batteries Lipoly C, Lix Li salt in polymer gel Li(1x)MnOp Proposed as substitute for Li-ion. Cheaper and safer with comparable performance and nominal 3.7 V cell voltage Sodium ion C, Nax Na salt in organic or aqueous solvents Na(1x)MnOp Lower material costs as compared to lithium-based batteries due to the abundance of sodium Nickelhydrogen H2(Pt) KOH NiOOH Nickelhydrogen batteries are commonly used in aerospace applications, such as satellites and space probes. Around 1.2 volts cell potential Solid-state Li Ion conducting polymer, metal oxides, perovskite, NASICON, LISICON Li(1x)MnOp Provide increased safety, decreased battery net weight and volume, higher output of energy and easier ion transfer. Suitable for applications in both mobile and small-scale sectors including transportation, aerospace, military and medical instrumentation. Flow battery C Separate electrolyte containing redox-active species for positive and negative electrode C They can retain an exceptional lifetime of up to 100,000 cycles, thus corroborating their applicability in bulk energy storage systems. Cell potential is typically in the range of 1 to 2 V What are batteries made of and what are the main battery components? The major components of a battery include the anode (or negative electrode) and the cathode (or positive electrode), the electrolyte, the separator and the current collectors. In addition to these primary components, batteries may also incorporate other components like current-limiting devices, safety features and thermal management systems, depending on the specific battery chemistry and intended application. The housing of the battery is another component that should not be overlooked. It provides physical protection and prevents external contamination. Importantly, the specific components and their configurations may vary depending on the type of battery chemistry, such as Liion, leadacid, NiMH or others. Each chemistry has its own unique set of materials and design considerations. The main components are discussed below. A battery separator is usually a porous membrane placed between the negative and positive electrodes to keep the electrodes apart to prevent electrical short circuits.8 They should be very good electronic insulators and at the same time allow the rapid transport of ions that are needed to complete the circuit during the discharge and/or charge of the battery. The ion transport can be achieved through inherent ionic conductivity or by impregnating the separator with electrolyte. As batteries have advanced, the function of separators has become more complex and demanding. The characteristics of each available separator must be evaluated against the requirements of the battery system when selecting a separator. Key considerations that influence separator selection include the following as they must have/be: 8 Electronic insulator propertiesMinimal electrolyte (ionic) resistanceMechanical and dimensional stabilityEnough physical strength to allow easy handlingChemical resistance to degradation by electrolyte, impurities and electrode reactants and productsEffective in preventing migration of particles or colloidal or soluble species between the two electrodesReadily wetted by electrolyteUniform in thickness and other properties In many applications, a compromise in requirements for the separator must generally be made to optimize performance, safety, cost, etc. For example, if batteries are desired that have small internal resistance, they may require separators that are highly porous and thin, but the need for adequate physical strength may require that they be thick. Separators in sealed nickelcadmium (NiCd) and NiMH batteries require high gas permeability to protect against overcharging. Liion cell separators should have a shutdown mechanism for enhanced safety. Alkaline battery separators need to be flexible enough to wrap around the electrodes. 8 Battery electrolyte Alexander Volta first defined the electrolyte in 1800.9 It is an electron-insulating and ion-conductive layer, either liquid or solid, interposed between the negative and positive electrodes. Electrolytes are often thought of as liquids, such as water or other solvents, with dissolved salts, acids or alkalis. However, many batteries, including the conventional (AA/AAA/D) batteries, contain solid electrolytes that act as ionic conductors at room temperature. Although the specific characteristics of electrolytes can vary across different types of batteries, their fundamental role remains the same. Electrolyte chemistry plays a major part in determining cell safety, cycle life and power capability. In aqueous batteries, such as leadacid and NiMH batteries, the electrolyte is typically a water-based solution containing various salts or acids. Aqueous electrolytes offer good ionic conductivity and are generally cost-effective and are even being developed for Liion cells, mainly due to safety and environmental concerns.10 They, however, suffer from a narrow electrochemical stability window limited by water electrolysis.11 In 2015, the concept of water-in-salt electrolytes (WiSE), in contrast to typical salt-in-water electrolytes, was proposed showing an extended electrochemical stability window of 3.0 V.10 Currently, the state-of-the-art electrolyte for Liion battery applications is Li salts, e.g., lithium hexafluorophosphate (LiPF6), dissolved in nonaqueous organic-based carbonate solvents, e.g., ethylene carbonate (EC) and dimethyl carbonate (DMC).12 Despite its ubiquitous use in EV applications, these organic electrolytes limit the cell safety due to their combustibility and limited cell operating temperature range of - 10 C to 60 C in the most optimistic scenarios.12 A recent new class of electrolytes has been developed by hybridizing aqueous with non-aqueous solvents, that inherits the non-flammability and non-toxicity characteristics from aqueous and better electrochemical stability from non-aqueous systems.13 There is, however, a strong push from the automotive industry to consider organic or inorganic solid-state electrolytes to be used by solid state batteries. These electrolytes can be ceramic- or polymer-based materials with high ionic conductivity. They enable the use of metallic lithium anodes, which can increase the energy density of the battery. The main benefit of solid-state batteries has been their increased safety, which stems from the absence of the flammable liquid electrolytes typically employed in Liion cells.14 Inorganic solid electrolytes could also support battery operation at low and high temperatures (for example, - 50 to 200 C or higher) in which conventional liquid electrolytes would freeze, boil or decompose.14 Anode The anode is the negative electrode of the battery associated with oxidative chemical reactions that release electrons into the external circuit.6 Liion batteries commonly use graphite, a form of carbon (C) as the anode material. Graphite has a layered structure, allowing lithium ions to be inserted into the layers during charging and extracted during discharge. However, the nature of the chemical interaction with lithium leads to low energy density. Silicon is an alternative to graphite due to its higher theoretical capacity for lithium ions. However, silicon experiences significant volume expansion and contraction during charging and discharging respectively, which causes mechanical stress and results in electrode degradation and battery failure. It is possible to use lithium metal directly as an anode material.Lithium metal anodes have the highest theoretical capacity and energy density since they are the most lithium dense material. However, the use of metallic lithium anodes presents challenges, such as dendrite formation, which can cause short circuits, safety concerns and reduced cycle life. Leadacid batteries feature a Pb-based anode, typically composed of PbO2 on a Pb substrate. NiMH batteries use a hydrogen-absorbing alloy, such as a mixture of nickel (Ni) and metal hydride, as the anode material. The anode absorbs hydrogen ions during charging and releases them during discharge. Cathode The cathode is the positive electrode of a cell, associated with reductive chemical reactions.6 Liion batteries employ various cathode materials, including lithium cobalt oxide (LCO), lithium iron phosphate (LFP) and lithium nickel manganese cobalt oxide (NMC). These cathode materials can reversibly accept and eject lithium ions into and from out of their crystal structure during charge and discharge cycles. NiMH batteries typically feature a nickel oxyhydroxide (NiOOH) cathode material. The cathode absorbs hydroxide ions during charging and releases them during discharge. Lithiumair batteries employ a porous carbon-based cathode that interacts with oxygen from the surrounding air, enabling the reversible electrochemical reaction between lithium ions and oxygen during charge and discharge. The reaction on the cathode is electrocatalytic in nature and requires an electrocatalyst. Current collectors Current collectors are typically metallic foils or conductive materials that collect and distribute the electrical current generated during battery operation. They are in direct contact with their respective electrodes and are usually made from copper and aluminum due to their high electrical conductivity. Current collectors sometimes act as terminals for the external connection of the individual cells of the battery, allowing electrical current to flow to and from the battery. Before we consider how batteries are made, it is important to note that battery development typically takes a long time and involves progression from the laboratory scale through prototype testing and ultimately to the assembly line and production. The process can be briefly outlined as follows: Laboratory research to explore new materials, chemistries and configurations for batteries. Proof of concept to demonstrate the viability of promising battery chemistry and materials identified in the lab.Prototype development after a successful proof of concept by further refining the battery chemistry and scaling it up.Performance evaluation and iterative improvement using extensive testing to assess various performance parameters, such as energy density, power density, cycle life and safety characteristics. Pilot production of the optimized prototype design.Scale-up and commercial production after successful pilot production.Market deployment of commercialized batteries for various applications, such as EVs, portable electronics or grid-scale energy storage. Significant effort is therefore required before commercialization of a battery chemistry. Building a manufacturing plant can also take several years to commission due to challenges such as the complex value chains, with dozens of suppliers required to source all the materials and components. Most importantly, the final commercial production and manufacturing of the battery also involves several steps from the raw materials to the assembly of battery cells. A typical battery manufacturing process is shown in Figure 5 below. Continue reading below... Modern manufacturing plants use precision manufacturing and high automation to be cost-competitive.15 Rigorous testing is important at all stages to ensure compliance of the final battery with all the necessary specifications. These specifications include but are not limited to safety, cycle life, cost, reusability and sustainability of the manufacturing process. Some areas where battery testing is essential are outlined below. Figure 5: Schematic of the battery manufacturing process based on Li-ion batteries, detailing the main steps (gray cogs), their corresponding necessary elements (pale blue) and the control measurements and tests (dark blue). Credit: Technology Networks, adapted from Zanotto et al.19 Battery material impurity Impurities in raw materials can adversely affect battery performance, safety and lifespan. Analytical testing of raw materials helps identify and control impurities to ensure consistent and high-quality battery production. Impurities in electrode materials can hinder electrochemical reactions, reduce capacity and accelerate degradation. Testing of electrode materials helps ensure purity and consistency, leading to optimal battery performance. Almost all the components of the battery are isolated and tested individually. Battery safety Heat, flammable and/or toxic gas production are the basic factors that lead to battery failure. Consequently, the safety of a battery system can be improved by firstly avoiding the conditions that lead to heat and gas generation, and secondly, if it does occur, by managing the heat and gas generated to alleviate battery failure. Safety vents and current interruption devices that open in response to pressure increase inside the cell to allow the gases escape are installed in modern batteries to avoid cell rupture. Shut down separators and intelligent battery management systems are also used. All these features are tested for reliability before being introduced into the production line. Significant modifications can also be made to the battery components, such as the cathode, anode or electrolyte, to make them inherently safe. The failure rate of Li-ion batteries is estimated to be 1 in 40 million if stored and operated within manufacturer-recommended limits.16 However, unpredictable circumstances, such as overcharging, external heating and mechanical abuse, may significantly increase this failure probability. There have been numerous high-profile battery failure accidents, many of which caused significant adverse impacts for the cell manufacturers as well as companies utilizing the specific battery technology within their products. As such, rigorous testing of battery materials, components and related auxiliary systems is performed under harsh conditions to test the worst case scenario even if the battery may never experience such conditions under normal use. Thermal runaway Thermal runaway is a significant problem associated with batteries, especially Li-ion batteries. It refers to a situation where a battery experiences a self-sustaining and uncontrollable rise in temperature as a result of electrochemical reactions during charge and/or discharge. The heat, when not effectively dissipated, further accelerates other reactions that increase the battery temperature, creating a positive feedback loop. Thermal runaway can potentially result in battery failure, fire or even explosion. Modern batteries pack a lot of energy. For example, a 55 Ah battery is equivalent to the energy of a hand grenade (150 g of TNT).17 Battery cells or packs are therefore packaged, often with safety features such as protection circuits and thermal management systems. Each of these systems must be tested for precise functionality. Quality control measures, including visual inspection, electrical testing and environmental testing, are implemented to ensure that batteries can control an unexpected temperature rise as well as meet specifications and safety standards set by the various regulatory bodies. Battery degradation After battery manufacturing, ongoing monitoring and testing are essential to assess long-term performance, safety and reliability. Material testing is important to identify potential degradation mechanisms, such as electrode material decomposition or electrolyte breakdown. By monitoring these materials, manufacturers can identify improvements in composition or design to enhance battery lifespan and stability. Modern battery management systems have a wide range of functions, including estimation of the state of charge, depth of discharge, state of health and state of function. These together protect the battery from overheating and are useful for data reporting. In effect, each battery produced continues to report critical data to the manufacturer to ensure optimization of processes and identify key components causing battery degradation. Cost reduction To stay competitive, battery manufactures need to drive down cost. By testing and understanding material characteristics, manufacturers can optimize battery designs, reduce reliance on expensive or scarce materials and develop more cost-effective production processes. Manufacturers can also identify ways to enhance electrochemical reactions, improve energy storage capacity and extend cycle life. Testing during manufacturing is crucial for meeting regulatory standards and certifications related to safety, environmental impact and performance requirements to avoid the risk of fines or accidents. Analytical testing is integral to the battery industry to ensure the quality, performance and safety of battery components and products. By employing a range of techniques and analyzing various components, manufacturers can optimize battery performance, identify potential issues and meet the increasing demands for reliable and efficient energy storage systems. These tests are carried out at various stages, including development, production and post-production monitoring using a range of analytical techniques. Manufacturers typically assess the composition, properties and behavior of raw materials, battery slurries, electrodes, electrolytes and other components. An overview of the key aspects of analytical testing is outlined below. This overview is based around Li-ion batteries as one of todays most common battery types but is not exclusive to Li-ion batteries. Raw materials analysis: Raw materials are the starting point of the battery manufacturing process and hence the starting point of analytical testing. The main properties of interest include chemical composition, purity and physical properties of the materials such as lithium, cobalt, nickel, manganese, lead, graphite and various additives. Spectroscopy techniques, such as X-ray fluorescence and atomic absorption, chromatography and elemental analysis help identify impurities, ensure material quality and assess their suitability for battery applications.18 Most of the metals are extracted from their respective ore and also require rigorous analysis during the purification. This is, however, not considered part of the battery manufacturing process. Battery slurry analysis: Most battery electrodes consist of electroactive materials coated on the current collector. To coat this active material, the powders are transformed into slurries by mixing with suitable solvents. Battery slurries typically consist of the active materials, binders, conductive additives and solvents. The slurries are evaluated for their viscosity, solid content, particle size distribution and chemical composition. Techniques like rheology measurement help analysts understand the properties of slurries to ensure proper electrode coating and facilitate energy efficient drying of the electrodes to optimize battery performance and reduce cost.19 Electrode analysis: The electrodes are the heart of the battery where all the electrochemical reactions occur. Testing of the electrodes prior to battery assembly provides insights into their composition, morphology and electrochemical performance. Techniques such as scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR) are commonly used. These methods help assess the integrity of electrode structures, identify any defects or impurities and evaluate the effectiveness of active materials. Modern electrochemical testing techniques, such as scanning electrochemical microscopy20,21 and scanning electrochemical cell microscopy,22,23 also enable analysis of single electrodes and electrode materials at the nanoscale for a better understanding of the general electrochemical properties of the electrode. Electrolyte analysis: The electrolyte is a critical component of batteries, and its analysis involves examining its stability and ionic conductivity. These properties generally depend on the chemical composition, which is also analyzed. Techniques such as chromatography, mass spectrometry (MS), and nuclear magnetic resonance (NMR) spectroscopy help analyze the electrolyte's constituents, detect impurities and ensure proper ionic mobility. Electrochemical impedance spectroscopy (EIS) is another technique used to assess the performance of electrolytes in terms of resistance and ion diffusion. Battery performance testing: Analytical testing also involves evaluating battery performance parameters such as capacity, energy density, cycle life and safety characteristics. Techniques like cyclic voltammetry, galvanostatic charge-discharge testing, differential scanning calorimetry (DSC) and thermal stability analysis are widely employed. These tests assess the battery's ability to store and deliver energy efficiently, monitor its degradation over time and ensure compliance with safety standards.24 Post-production monitoring: After battery production, ongoing analytical testing is essential for post-production monitoring and quality control. This includes periodic sampling and testing of battery batches to verify consistency and compliance with specifications. Techniques used during this phase may involve the same methods mentioned earlier, with a focus on performance verification, safety assessment and batch-to-batch consistency. The increasing demand for energy storage in various sectors, including EVs and renewable energy systems, makes battery development a promising technological field.25 Automakers are striving to increase EV driving ranges, reduce charging times and enhance overall vehicle performance. Battery technology will continue to evolve, aiming for higher energy densities, longer cycle life, faster charging capabilities, improved thermal management and safety. Researchers will keep exploring novel electrode materials, such as silicon-based anodes and advanced cathode chemistries (e.g., nickel-rich formulations) to enhance overall performance. With growing emphasis on developing environmentally friendly and sustainable materials, a reduction in the reliance on critical raw materials like cobalt and nickel, which are often associated with social and environmental concerns, is expected. Alternative chemistries using more abundant and environmentally friendly materials like sodiumion, zincion, and lithiumsulfur batteries may become popular. Safety concerns currently associated with Li-ion batteries continue to drive the development of solid-state batteries offering benefits like higher energy density, improved safety and wider operating temperature ranges.26 While still in the research and development phase, solid-state batteries have the potential to revolutionize energy storage applications, especially in EVs. The battery industry will play a crucial role in meeting these demands through continuous innovation and scaling up production capacities. Grid-scale energy storage systems, utilizing large-scale batteries, will be necessary for stabilizing electricity grids, managing peak demand and storing excess renewable energy from sources like solar and wind power. The battery industry will need to develop cost-effective and efficient solutions to meet the growing demands of grid-scale energy storage. In particular, as the volume of batteries in use increases, the importance of battery recycling and second-life applications is being emphasized. Establishing robust recycling infrastructure and processes will be essential to recover valuable materials and minimize environmental impact. For example, retired EV batteries can be either recycled or repurposed for stationary energy storage, which could be tested and validated using, if it does scale of digitalization15 and benefit from computer assistance such as machine learning27 and artificial intelligence.28 References (Click to expand)

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The components of a battery. Explain the components of a battery. What components make up a battery.