Next-Generation Batteries and Fuel Cells for Commercial, Military, and Space Applications

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Summary: "Next-generation batteries have higher power density and higher energy density and can be put into new forms with lower-cost mass production. This book focuses on technologically advanced secondary (rechargeable) batteries in both large and small format. It covers advanced technologies as replacements for NiCd and NiMH, especially advanced lithium-ion batteries that make use of new electrode materials and electrolytes. The author discusses printable batteries and thin-film battery stacks as enablers of micropower applications as well as hybrid battery/fuel cell systems, which are emerging as complements to consumer electronics batteries"-- Provided by publisher.

Includes bibliographical references and index.
1. Storage batteries. 2. Fuel cells. 3. Electric batteries. I. Title.
This book comes at a time during which high global demand for oil is coupled with the anticipation of a shortage in the near future. To reduce this dependency on foreign oil and eliminate the greenhouse effects associated with oil, several automobile-manufacturing companies have been engaged in the mass development and production of electric vehicles (EVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs). To address these objectives, the author of this book, A. R. Jha, gives serious attention to cutting-edge battery technology. Advanced material technology must be given consideration in the development of next-generation batteries and fuel cells for deployment in EVs and HEVs. In addition, Jha identifies and describes next-generation primary and secondary (rechargeable) batteries for various commercial, military, spacecraft, and satellite applications for covert communications, surveillance, and reconnaissance missions. Jha emphasizes the cost, reliability, longevity, and safety of the next generation of high-capacity batteries that must be able to operate under severe thermal and mechanical environments.

This book addresses nearly every aspect of battery and fuel cell technology involving the use of the rare earth materials that are best suited for specific components and possible applications in EVs, HEVs, and PHEVs. Use of certain rare earth materials offers significant improvement in electrical performance and a reduction in the size of alternating current induction motors and generators that will yield additional space inside these vehicles. Jha proposes ultra-high-purity metallic nano-technology PVD films in the design and development of the low-power batteries best suited for implantable medical devices and diagnostic applications. This particular technology can be used in the near future in the development of noninvasive medical diagnostic equipment such as magnetic resonance imaging and computed tomography scans.

Jha continues, throughout this book, his distinguished track record of distilling complex theoretical physical concepts into an understandable technical framework that can be extended to practical applications across a wide array of modern industries. His big-picture approach, which does not compromise the basic underlying science, is particularly refreshing. This approach should help present-day students,
both undergraduate and graduate, master these difficult scientific concepts with the full confidence they will need for commercial engineering applications to benefit emerging economies around the world.

This book is well organized and provides mathematical expressions to estimate the critical performance parameters of rechargeable batteries. Jha covers all of the important design aspects and potential applications of rechargeable batteries with an emphasis on portability, reliability, longevity, and cost-effective performance. This book also provides a treatment of the underlying thermodynamic aspects of cells housed in a battery pack that contains several cells. Jha identifies their adverse heating effects on the reliability and electrical performance of the battery pack. Notably, thermodynamic evaluation of the battery pack assembly is of critical importance because it can affect the reliability, safety, and longevity of the pack. Jha’s background enables him to provide an authoritative account of many of the emerging application requirements for small, lightweight, high-reliability rechargeable batteries, particularly for portable and implantable medical devices and diagnostic capsules. Jha summarizes the benefits of all-solid-state lithium-ion batteries for low-power medical devices, such as cardiac pacemakers, cardioverters, and implantable cardioverter defibrillators.

Critical performance parameters and the limits of rechargeable batteries, including state of charge, depth of discharge, cycle life, discharge rate, and open-circuit voltage, are identified. The aging effects of various batteries are identified as well. Rechargeable battery requirements for EVs, HEVs, and PHEVs are summarized with an emphasis on reliability, safety, and longevity. Memory effects resulting from voltage depression are discussed in great detail. The advantages of solid polymer electrolyte technologies are briefly mentioned because the polymer electrolytes tend to increase room temperature ionic conductivity. This increase in ionic conductivity offers improved battery performance at medium to high temperatures ranging from 60° to 125°C.

Performance capabilities of long-life, low-cost, rechargeable batteries, including silver zinc and other batteries, are summarized. Such batteries are best suited for aerospace and defense applications. Batteries for unmanned underwater vehicles, unmanned air vehicles, anti-improved explosive devices, and satellites or spacecraft capable of providing surveillance, reconnaissance, and tracking of space-borne targets are identified with an emphasis on reliability, longevity, safety, weight, and size. Cathode, anode, and electrolyte materials are summarized for several rechargeable batteries.

Jha dedicates a chapter specifically to fuel cells and describes the three distinct types of practical fuel cells, including those that use (1) aqueous electrolytes, (2) molten electrolytes, and (3) solid electrolytes. The fuel cell is an electricity generation system that combines an oxidation reaction and a reduction reaction. In a fuel cell, both the fuel and oxidant are added from an external source to react at two separate electrodes, whereas in a battery, the two separate electrodes are fuel and oxidant. Therefore, in the fuel cell in an energy conversion device, chemical energy
is isothermally converted to direct current electricity. These devices are bulky and heavy and operate mostly at high temperatures (500° to 850°C). Hydrogen-oxygen fuel cells generate high power with maximum economy and are best suited for transport buses. Electrode kinetics play a key role in achieving the most efficient operation of a fuel cell. Jha identifies the basic laws of electrochemical kinetics and notes that a superior nutrient-electrolyte media is essential for generating higher electrical power in biochemical fuel cells.

A wide variety of readers will benefit from this book, in particular the advanced undergraduate and graduate students of mechanical and materials engineering who wish to pursue a career in designing next-generation batteries and fuel cells. In view of the critical interdependencies with other technical disciplines, however, this book also is of interest to a wider variety of engineering students or practicing engineers in such industries as medical equipment, defense electronics, security, and space as well as in other yet-to-be-established disciplines. This book is particularly useful for research scientists and engineers who are deeply involved in the design of the portable devices best suited for medical, military, and aerospace systems. Technical managers will also find this book useful for future applications. I strongly recommend this book to a broad audience, including students, project managers, aerospace engineers, life-science scientists, clinical scientists, and project engineers immersed in the design and development of compact, lightweight batteries best suited for industrial, commercial, military, and space applications.

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The publication of this book comes at a time when free nations are at odds with oil-producing nations and can be threatened with an interruption of the continuous flow of oil because of political differences and prevailing conditions in these respective regions. Western and other free nations are looking for alternative energy sources to avoid the high cost of oil and to reduce greenhouse gas emissions. This book briefly summarizes the performance capabilities and limitations of existing primary and secondary (rechargeable) batteries for the benefits of readers. I address critical and vital issues affecting the performance capabilities of next-generation batteries and fuel cells for commercial, military, and aerospace applications and propose cutting-edge battery technology best suited for all-electric and hybrid electric vehicles (HEVs) in an effort to help eliminate dependency on unpredictable foreign oil sources and supplies.

I also identify the unique materials for electrolytes, cathodes, and anodes that are most cost-effective for next-generation rechargeable batteries with significant improvements in weight, size, efficiency, reliability, safety, and longevity. Likewise, I identify rechargeable batteries with minimum weight, size, and form factor that are most ideal for implantable medical devices, unmanned aerial vehicles (UAVs), and space system applications. I identify battery designs using microelectromechanical systems (MEMS) and nanotechnologies, which are best suited for applications where weight, size, reliability, and longevity are of critical importance. Integration of these technologies would lead to significant improvements in weight, size, and form factor without compromising the electrical performance and reliability of the battery.

I propose high-power battery technologies best suited for automotive-, aircraft-, and satellite-based system applications with an emphasis on reliability, safety, and consistent electrical performance over long durations. In such applications, I recommend unique battery technologies that offer exceptionally high-energy densities that exceed 500 Wh/kg. I also describe the performance capabilities of next-generation rechargeable sealed nickel-cadmium and sealed lead-acid batteries that are most ideal for satellite communications, space-based surveillance and reconnaissance systems, unmanned ground combat vehicles (UGCVs), UAVs, and other battlefield applications where high energy density, minimum weight and size, and reliability under harsh conditions are the principal performance requirements.
This book summarizes the critical performance parameters of rechargeable batteries developed for various commercial, military, and space applications backed by measured values of parameters obtained by reliable sources through actual laboratory measurements. The book is well organized and contains reliable rechargeable battery performance characteristics for a wide range of applications, including commercial, military, and aerospace disciplines. Cutting-edge battery design techniques are discussed in the book backed by mathematical expressions and derivations wherever possible. The book provides mathematical analysis capable of projecting the critical performance parameters under various temperatures. It is especially prepared for design engineers who wish to expand their knowledge of next-generation batteries.

I have made every attempt to provide well-organized materials using conventional nomenclatures, a constant set of symbols, and easy-to-understand units for rapid comprehension. The book provides state-of-the-art performance parameters of some batteries from various reference sources with due credit given to the authors or organizations involved. It comprises eight distinct chapters, each of which is dedicated to a specific application.

Chapter 1 presents the current status of various primary and secondary (rechargeable) batteries and fuel cells for various applications. The performance capabilities and limitations of batteries and fuel cells are summarized for the benefits of readers and design engineers. The current energy sources suffer from weight, size, efficiency, discharge rates, disposal issues, and recharge capacity, thus making them unsuitable for medical, battlefield, and aerospace applications. General Motors and Siemens have invested a significant amount of money in research and development of rechargeable lithium-based rechargeable batteries for possible applications in electric vehicles (EVs) and HEVs. Current fuel cells generate electrical energy by using electrochemical conversion techniques that have serious drawbacks. I discuss direct methanol fuel cells (DMFCs) for future applications that will be found most ideal for high-, portable-power sources. DMFC technology offers improved reliability, compact form factor, and significant reduction in weight and size. I identify appropriate anode, cathode, and membrane electrode assembly configurations that will yield significantly improved electrical performance over long durations with minimum cost and complexity.

Chapter 2 briefly describes the performance capabilities and limitations of current rechargeable batteries for various applications. Performance requirements and projections for next-generation primary and secondary batteries are identified with an emphasis on cost, reliability, charge rate, safety, reliability, and longevity. I discuss the performance requirements for next-generation high-power rechargeable lithium-based batteries and sealed nickel-cadmium and lead-acid batteries best suited for applications requiring high-energy and -power densities. Battery design configurations for some specific applications are identified with a particular emphasis on safety, reliability, longevity, and portability.

In Chapter 3 I discuss fuel cells that are best suited for applications where electrical power requirements vary between several kilowatts (kW) to a few megawatts (MW).
Fuel cells generate electrical power by an electrochemical conversion technique. The early fuel cells deploy this technique, and the devices using this technique suffer from excessive weight, size, and reliability problems. In past studies I have indicated that DMFC technology offers the most promising fuel cell design configuration for applications where compact form factor, enhanced reliability, and significant reduction in weight and size are the principal fuel cell design requirements. DMFC is a system that combines an oxidation reaction and reduction reaction in a most convenient way to produce electricity with minimum cost and complexity. Such fuel cells are expected to be used extensively in the future. Studies performed by C. H. J. Broers and J. A. A. Ketelaar (Proceedings of the IEEE, May 1963) indicate that the fuel cells developed before 1990 used high temperatures and semisolid electrolytes. Even earlier fuel cells, such as the Bacon HYDROXZ fuel cells, were designed to operate at medium temperatures and high pressures. It was reported by C. G. Peattie (IEEE Proceedings, May 1963) that such fuel cell operations are difficult to maintain and require constant monitoring to ensure that the fuel cell is reliable. I discuss next-generation fuel cell design configurations capable of operating with high efficiency and high power output levels over long durations.

Chapter 4 describes the high-power batteries currently used by EVs and HEVs. Performance reviews of these batteries indicate that the rechargeable batteries suffer from poor efficiency as well as excessive weight, size, and operating costs. I describe various next-generation rechargeable batteries best suited for all-electric cars, EVs, and HEVs. Some next-generation batteries might deploy rare earth materials to enhance the battery’s electrical performance and reliability under harsh operating environments. I propose rechargeable battery design configurations capable of providing significant improvements in depth of discharge, state of charge, and service life or longevity.

Chapter 5 focuses on low-power battery configurations that are best suited for compact commercial, industrial, and medical applications. I identify the design aspects and performance characteristics of micro- and nanobatteries best suited for detection, sensing, and monitoring devices. These batteries offer minimum weight, size, and longevity that are highly desirable for certain applications such as perimeter security devices, temperature and humidity sensors, and health monitoring and diagnostic medical system applications. I identify compact, low-power batteries using unique packaging technology for emergency radios and security monitoring devices operating under temperatures as low as −40°C. Most batteries cannot operate under such ultra-low temperatures.

Chapter 6 describes rechargeable batteries for military and battlefield applications where sustainable performance, reliability, safety, and portability are principal operating requirements. Sustaining electrical performance, reliability, safety, and longevity are given serious considerations for rechargeable batteries operating in battlefield environments that involve severe thermal and structural parameters. I emphasize the reliable electrical performance, safety, longevity, compact packaging, advanced materials, and portability for the batteries capable of operating in
military and battlefield systems such as tanks, UAVs, UGCVs, and robot-based battlefield fighting systems.

Chapter 7 is dedicated to rechargeable batteries for possible applications in aerospace equipment and space-based surveillance, reconnaissance, and tracking systems of space-based targets. Stringent performance requirements for the rechargeable batteries deployed in commercial aircraft and military aircraft—including fighter aircraft, helicopters, UAVs for offensive and defensive missions, electronic attack drones, and airborne jamming equipment—are defined to ensure sustainable electrical energy and significantly improved reliability, safety, and longevity, which are essential for carrying out successful missions. I suggest that stringent safety and reliability requirements are needed in severe vibration, shock, and thermal environments. Improved design concepts for aluminum-air batteries using alkaline electrolyte are identified for communication satellite applications, where high-energy density (>500 Wh/kg), ultra-high reliability, and high portability are the principal performance specifications. Reliable modeling and stringent test requirements are defined for the sealed nickel-cadmium and lead-acid batteries because these batteries are ideal for next-generation communications satellites, supersonic fighters, and space-based systems for precision surveillance, reconnaissance, and tracking missions.

Chapter 8 deals with low-power batteries that are widely used for various commercial, industrial, and medical devices that can operate with electrical power ranging from nanowatts to microwatts. Low-power batteries are widely used consumer electronic products such as in infrared cameras, smoke detectors, cell phones, medical devices, minicomputers, tablets, iPhones, iPads, and a host of electronic components. These low-power batteries must meet minimum weight, size, and cost requirements in addition to being exceptionally safe and long-lasting. In past studies, I have indicated that advances in materials and packaging technology can play a significant role in the performance improvements in existing batteries such as nickel-cadmium, alkaline manganese, and lithium-based batteries. I briefly summarize the performance characteristics of low-power batteries in this chapter.

I want to express my sincere gratitude to Ed Curtis (Project Editor) and Marc Johnston (Senior Project Manager) for their meaningful suggestions and assistance in incorporating last-minute changes to the text, completing the book on time, and seeing everything through to fruition—all of which they did with remarkable coherency and efficiency.

Last, but not least, I also want to thank my wife Urmila D. Jha, my daughters Sarita Jha and Vineeta Mangalani, and my son U.S. Army Captain Sanjay Jha for their support, which inspired me to complete the book on time despite the tightly prescribed production schedule.
A. R. Jha received his BS in engineering (electrical) from Aligarh Muslim University in 1954, his MS (electrical and mechanical) from Johns Hopkins University, and his PhD from Lehigh University.

Dr. Jha has authored 10 high-technology books and has published more than 75 technical papers. He has worked for companies such as General Electric, Raytheon, and Northrop Grumman and has extensive and comprehensive research, development, and design experience in the fields of radars, high-power lasers, electronic warfare systems, microwaves, and MM-wave antennas for various applications, nanotechnology-based sensors and devices, photonic devices, and other electronic components for commercial, military, and space applications. Dr. Jha holds a patent for MM-wave antennas in satellite communications.
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