

Introduction: Batteries and Fuel Cells

This special issue of *Chemical Reviews* covers the electrochemical storage and generation of energy in batteries and fuel cells. This area is gaining tremendous importance for powering high technology devices and for enabling a greener and less energy-intensive transportation industry. Whether the demand is from a cell phone, a computer, or an iPod, consumers are demanding a longer life in a smaller package and at a lower cost with minimal if any wired connection. The consumer generally does not care whether the power source is a battery, a fuel cell, or something else, as long as it works. In the area of greener transportation, there has been a surge of interest in vehicles that are electrically powered, either totally, as planned for the green Beijing Olympic Games, or partially, as in hybrid electric vehicles. The present generation of such vehicles uses a combination of an internal combustion engine and a battery, today nickel metal hydride, as in the Toyota Prius, and tomorrow lithium; a future generation is likely to be a hybrid of a fuel cell and a battery.

Both batteries and fuel cells utilize controlled chemical reactions in which the desired process occurs electrochemically and all other reactions including corrosion are hopefully absent or severely kinetically suppressed. This desired selectivity demands careful selection of the chemical components including their morphology and structure. Nanosize is not necessarily good, and in present commercial lithium batteries, particle sizes are intentionally large. All batteries and fuel cells contain an electro-positive electrode (the anode or fuel) and an electro-negative electrode (the cathode or oxidant) between which resides the electrolyte. To ensure that the anode and cathode do not contact each other and short out the cell, a separator is placed between the two electrodes. Most of these critical components are discussed in this thematic issue.

The issue starts with a general introduction by Brodd and Winter to batteries and fuel cells and the associated electrochemistry. It then continues first with several papers discussing batteries and then with papers discussing fuel cells.

Batteries

Outside of the above introduction, the battery papers describe lithium batteries, where most chemi-

cal and materials research has been focused during the past three decades. The second paper, by Whittingham, begins with a general historical background to lithium batteries and then focuses on the next generation of cathodes. The third, by Xu, gives an in-depth review of the presently used and future electrolytes; this is followed by an extensive review by Arora and Zhang of the separators used in lithium and related batteries. The following paper, by Long, Dunn, Rolison, and White, addresses new three-dimensional concepts for increasing the storage capacity. Critical to the development of new materials are advanced characterization and modeling techniques, and some of these are described by Grey and Dupre and by Reed and Ceder in the last two papers of the battery group. Several papers covering anodes, phosphate and nickel oxide cathodes, and nickel metal hydride batteries did not meet the publication deadline, and it is hoped that they will appear in future issues.

Fuel Cells

Although fuel cells were invented in the middle of the 19th century, they didn't find the first application until space exploration in the 1960s. Since then, the development of fuel cell technology has gone through several cycles of intense activity, each followed by a period of reduced interest. However, during the past two decades, a confluence of driving forces has created a sustained and significant world-wide effort to develop fuel cell materials and fuel cell systems. These driving needs include the demand for efficient energy systems for transportation, the desire to reduce CO₂ emissions and other negative environmental impacts, and the demand for high energy density power sources for portable electronic applications. Due to the high level of interest in fuel cells during the last decade or so, there have been numerous summary articles and symposia focused on the technology state of the art. In this thematic issue, we present a series of summary articles that deal with some of the fundamental scientific issues related to fuel cell development.

A fuel cell that has desirable features for transportation and portable power is the polymer electrolyte membrane (PEM) system. The core of this technology is a polymer membrane that conducts

protons but separates the fuel from the oxidant. The material used historically and most frequently in PEM fuel systems is Nafion, a perfluorocarbon-based polymer carrying sulfonic acid residues. Nafion is a commercial material and has received the most extensive study of any PEM fuel cell membranes. Mauritz and Moore prepared a summary of the current understanding of the large volume of research that has gone into optimizing and understanding this membrane system. Other polymer systems that would have even better performance than Nafion and/or have lower costs are being sought by researchers around the world. Hickner, Ghassemi, Kim, Einsla, and McGrath summarize work on such alternative polymer systems for proton exchange membranes. These types of materials have complex transport properties that involve not just proton movement but also the movement of water. Theoretical treatments of the transport mechanisms and processes in these proton conductors are given by Kreuer, Paddison, Spohr, and Schuster and by Weber and Newman.

In PEM fuel cells, catalyst activity and catalyst efficiency are still significant issues. Russell and Rose summarize fundamental work involving X-ray absorption spectroscopy on catalysts in low temperature fuel cell systems. These types of studies are very useful for developing a detailed understanding of the mechanisms of reactions at catalyst surfaces and could lead to the development of new improved efficient catalysts. Important in the development of fuel cell technology are mathematical models of engineering aspects of a fuel cell system. Wang writes about studies related to this topic.

Finally, in order for PEM fuel cell systems to be affordable for portable power applications, a source

of high energy density fuel must be considered. To this end, Holladay, Wang, and Jones present a review of the developments of using microreactor technology to convert liquid fuels into hydrogen for directly feeding into a PEM fuel cell.

Another fuel cell system undergoing intense research is the solid oxide type. Adler presents the factors that govern the rate limiting oxygen reduction reaction within the solid oxide fuel cell cathodes. McIntosh and Gorte, on the other hand, treat the anode in the solid oxide fuel cell by examining catalytic direct hydrocarbon oxidation. Finally, Calabrese Barton, Gallaway, and Atanossov take a look at the future. In their article, they present a summary of some of the enzymatic biological fuel cells that are being developed as implantable devices and also to power microscale devices.

We hope this collection of papers will provide new researchers in the field with a starting point for advancing research. Furthermore, our hope is to stimulate the next generation of breakthroughs that will lead to the success of fuel cell development.

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