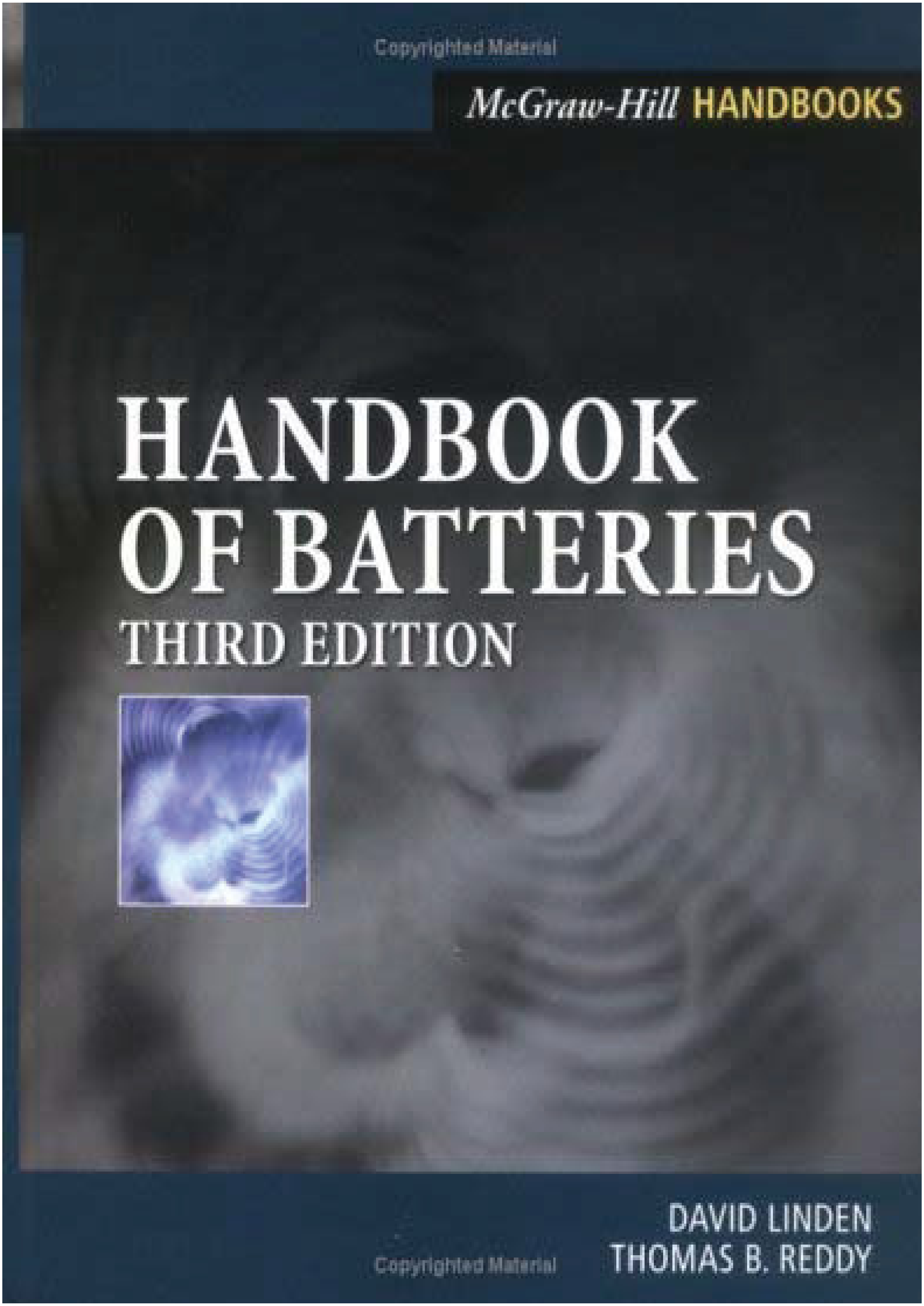

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HANDBOOK OF BATTERIES

THIRD EDITION

DAVID LINDEN
THOMAS B. REDDY

HANDBOOK OF BATTERIES

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Thomas B. Reddy Editor

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PREFACE

Since the publication of the second edition of the *Handbook of Batteries* in 1995, the battery industry has grown remarkedly. This growth has been due to the broad increase in the use of battery-operated portable electronics and the renewed interest in low- or zero-emission vehicles and other emerging applications with requirements that can best be met with batteries. Annual worldwide battery sales currently are about $50 billion, more than double the sales of a decade ago.

This growth and the demand for batteries meeting increasingly stringent performance requirements have been a challenge to the battery industry. The theoretical and practical limits of battery technology can be a barrier to meeting some performance requirements. Batteries are also cited as the limiting factor for achieving the application's desired service life. Nevertheless, substantial advances have been made both with improvement of the performance of the conventional battery systems and the development of new battery systems. These advances have been covered by significant revisions and updating of each of the appropriate chapters in this third edition of the *Handbook.*

Recent emphasis on the performance of the primary alkaline manganese dioxide battery has been directed toward improving its high-rate performance to meet the requirements of the new digital cameras and other portable electronics. The new high-rate (Ultra or Premium) battery was first sold in 2000 and already commands about 25% of the market.

The lithium primary battery continues its steady growth, dominating the camera market and applications requiring high power and performance over long periods of time. It now accounts for over $1 billion in annual sales.

Development has been most active in the area of portable rechargeable batteries to meet the needs of the rapidly growing portable electronics market. The portable nickel-metal hydride battery, which was becoming the dominant rechargeable battery replacing the nickel-cadmium battery, is itself being replaced by the newer lithium-ion battery. Recognizing the significance of this new technology, a new chapter, Chapter 35 ''Lithium-ion Batteries,'' has been added to the third edition of the *Handbook.*

The revived interest in electric vehicles, hybrid electric vehicles, and energy storage systems for utilities has accelerated the development of larger-sized rechargeable batteries. Because of the low specific energy of lead-acid batteries and the still unresolved problems with the high temperature batteries, the nickel-metal hydride battery is currently the battery system of choice for hybrid electric vehicles. This subject is covered in another new chapter, Chapter 30 ''Propulsion and Industrial Nickel-Metal Hydride Batteries.''

The inherent high energy conversion efficiency and the renewed interest in fuel cell technology for electric vehicles has encouraged the development of small subkilowatt fuel cell power units and portable fuel cells as potential replacements for batteries. Because of this new interest, Part 6 ''Portable Fuel Cells'' has been added that includes two new chapters, Chapters 42 and 43, covering portable fuel cells and small subkilowatt fuel cells, respectively. Large fuel cells are beyond the scope of this third edition of the *Handbook.* Much information has been published about this subject; see references listed in Appendix F.

Several editorial changes have been instituted in the preparation of this edition of the *Handbook.* The term ''specific energy'' is now used in place of gravimetric energy density (e.g., Wh/kg). The term ''energy density'' now refers to volumetric energy density (Wh/L). Similarly, ''specific power'' (W/kg) and power density (W/L) refer to power per unit weight and volume, respectively.

Another point that has been defined more clearly in this edition is the distinction between a ''cell'' and a ''battery.'' Manufacturers most commonly identify the product they offer for sale as a ''battery'' regardless of whether it is a single-cell battery or a multicell one. Accordingly, we have defined the cell as ''the basic electrochemical unit providing a source of electrical energy by direct conversion of chemical energy. The cell consists of an assembly of electrodes, separators, electrolyte, container, and terminals.'' The battery is defined as ''the complete product and consists of one or more electrochemical cells, electrically connected in an appropriate series/parallel arrangement to provide the required operating voltage and current levels, including, if any, monitors, controls and other ancillary components (e.g., fuses, diodes, case, terminals, and markings).''

In this edition, the term ''cell'' has been used, almost universally by all of the authors, when describing the cell components of the battery and its chemistry. Constructional features have been described as either cells, batteries, or configurations depending on the particular choice of the author. This has not been uniformly edited, as it does not appear to cause any confusion. The term ''battery'' has been generally used when presenting the performance characteristics of the product. Usually the data is presented on the basis of a single-cell battery, recognizing that the performance of a multicell battery could be different, depending on its design. In some instances, in order not to mislead the reader relative to the performance of the final battery product, some data (particularly in Chapter 35 on lithium-ion batteries and in the chapters in Part 5 on advanced batteries) is presented on a ''cell'' basis as hardware, thermal controls, safety devices, etc., that may ultimately be added to the battery (and have not been included in the cell) would have a significant impact on performance.

This third edition of the *Handbook of Batteries* has now grown to over 1400 pages, recognizing the broad scope of battery technology and the wide range of battery applications. This work would not have been possible without the interest and contributions of more than eighty battery scientists and engineers who participated in its preparation. Their cooperation is gratefully acknowledged, as well as the companies and agencies who supported these contributing authors.

We also acknowledge the efforts of Stephen S. Chapman, Executive Editor, Professional Book Group, McGraw-Hill Companies for initiating this project and the McGraw-Hill staff, and Lois Kisch, Tom Reddy's secretary, for their assistance toward its completion. We further wish to express out thanks to our wives, Rose Linden and Mary Ellen Scarborough, for their encouragement and support and to Mary Ellen for the editorial assistance she provided.

David Linden
Thomas B. Reddy

The major battery technologies that have been considered from time to time for electric-vehicle, utility energy storage, and renewable energy storage applications are listed in Table 37.5, together with the chapter numbers in the Handbook in which each is discussed. The companies that are most active in the development of improved and/or advanced batteries for these applications are listed in Table 37.6. U.S. National Laboratories and similar organizations that are involved in advanced battery R&D are also shown in Table 37.6.

TABLE 37.5 Index of Rechargeable Battery Systems and Refuelable Technologies Chapters in this Handbook

	Chapter or section
Conventional battery systems	
Lead-acid	23 and 24
Nickel-iron*	25
Nickel-hydrogen*	32
Nickel-cadmium	26 and 27
Nickel-zinc	31
Nickel-metal hydride	30
Zinc/silver oxide	33
Aqueous batteries	
Metal/air	38
Iron/air*	25
Zinc/air	38
Flow Batteries	
Zinc/chlorine*	Sec. 37.4.1
Zinc/bromine	39
Iron/chromium redox*	Sec. 37.4.1
Vanadium-redox	Sec. 37.4.1
Polysulfide/bromine redox (Regenesys)	Sec. 37.4.1
High-temperature batteries	
Lithium/sulfur*	41
Lithium-aluminum/iron sulfide	41
Lithium-aluminum/iron disulfide*	41
Sodium/sulfur	40
Sodium/metal chloride*	40
Lithium ambient-temperature batteries	
Liquid electrolyte	34
Lithium-ion	35
Lithium-polymer	34 and 35
Refuelable systems	
Fuel cells**	41 and 42
Zinc/air batteries	37 and 38
Aluminum/air batteries	37 and 38
Lithium/air batteries*	38

* No significant work underway on this system.

** Portable fuel cells are discussed in Chap. 43. Fuel cells for EVs and large-scale power generation are beyond the scope of this Handbook (see Bibliography, Appendix F).

37.4 ADVANCED RECHARGEABLE BATTERIES-GENERAL CHARACTERISTICS

Advanced rechargeable batteries can be classified into three main types: advanced aqueous electrolyte systems, or as they are more-commonly known, flow batteries; high-temperature systems; and ambient-temperature lithium batteries.

37.4.1 Flow Batteries

These advanced aqueous-electrolyte battery systems have the advantage of operating close to ambient temperature. Nevertheless, complex system design and circulation of electrolyte are needed to meet performance objectives. Work on developing flow batteries started with the invention of the zinc/chlorine hydrate battery in 1968.[14] This system was the subject of development for EV and electric utility storage applications[15] during from the early-1970s to the late-1980s in the United States, and from 1980 to 1992 in Japan,[16] but has now been abandoned in favor of other flow battery chemistries that appear more attractive. Three main types of flow batteries continue to be developed: zinc/bromine, vanadium-redox, and Regenesys.

Zinc/Bromine Batteries. The *zinc/bromine* battery technology is currently being developed primarily for stationary energy storage applications (see Chap. 39). The system offers good specific energy and design flexibility, and battery stacks can be made from low-cost and readily available materials using conventional manufacturing processes. Bromine is stored remotely as a second-phase polybromide complex that is circulated during discharge. Remote storage limits self-discharge during standby periods. An added safety benefit of the complexed polybromide is greatly reduced bromine vapor pressure compared to that of pure bromine.

Redox Batteries. Another type of aqueous flowing electrolyte system is the redox flow technology. There are several systems of this type, only one of which, the *vanadium redox battery* or VRB as it is known, has any significant development continuing as of 2001. Work on this category of flow battery started with a development program at NASA[17] on a system using $FeCl_3$, as the oxidizing agent (positive) and $CrCl_2$, as the reducing agent (negative). The aim of this work was to develop the redox flow batteries for stationary energy storage applications. The term ''redox'' is obtained from a contraction of the words ''reduction'' and ''oxidation.'' Although reduction and oxidation occur in all battery systems, the term ''redox battery'' is used for those electrochemical systems where the oxidation and reduction involves only ionic species in solution and the reactions take place on inert electrodes. This means that the active materials must be mostly stored externally from the cells of the battery. Although redox systems are capable of long life, their energy density is low because of the limited solubility of the active materials typically involved.[18]

In Japan, development of *iron/chromium redox flow battery* technology was included as part of the Moonlight Project[9] in the 1980s. The goal of this work was electric utility energy storage. Improvements made in the course of the Moonlight Project included new electrode materials and a reduction in the requirement for pumping power.[19] A 60 kW battery was tested[20] and 1-MW system was designed,[21] but the redox flow technology was not chosen for development to a 1-MW pilot plant stage.[22]

Other redox systems were also proposed in the past, such as the *zinc/alkaline sodium ferricyanide* [$Na_3Fe(CN)_6 \cdot H_2O$] couple, and initial development work was performed.[23] However, none of these efforts proved successful, mainly because of difficulties resulting from the efficacy and resistance of the ionic exchange membranes, until the development of the vanadium redox battery, by the University of New South Wales, Australia, in the late 1980s. Almost concurrently with this, development work started on VRBs at Sumitomo Electric Industries (SEI) of Osaka, Japan.[24] Starting in the mid-1990s, VRB development has also been conducted at Mitsubishi Chemical's Kashima-Kita facility, although at a lower level of effort than at SEI.

The electrolytes in the positive and negative electrode compartments of VRBs are different valence states of vanadium sulfate. Both solutions are 2 M in concentration and contain sulfuric acid as a supporting electrolyte. The electrode reactions occur in solution, with the reaction at the negative electrode in discharge being:

$$V^{2+} \rightarrow V^{3+} + e$$

and at the positive electrode:

$$V^{5+} + e \rightarrow V^{4+}$$

Both reactions are reversible on the carbon felt electrodes that are used. An ion-selective membrane is used to separate the electrolytes in the positive and negative compartments of the cells. Cross-mixing of the reactants would result in a permanent loss in energy storage capacity for the system because of the resulting dilution of the active materials. Migration of other ions (mainly H^+) to maintain electroneutrality, however, must be permitted. Thus, ion-selective membranes are required.

A schematic of a VRB system is shown in Fig. 37.4.[24] The construction of the cell stacks is bipolar. The electrolyte solutions are stored remotely in tanks and are pumped through the cells.

Several multi-kW systems have been built and tested by SEI and Mitsubishi Chemical. A photograph of an SEI 100 kW-8hr VRB system is shown in Fig. 37.5. Two electrolyte tanks are installed in a sub-basement below the level of the battery stacks and the AC-DC-AC converter.

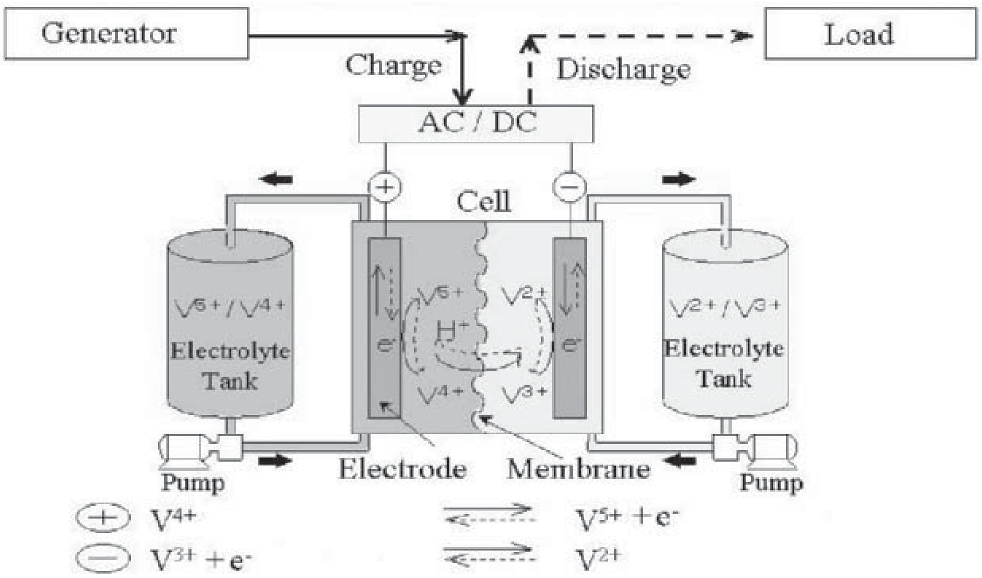
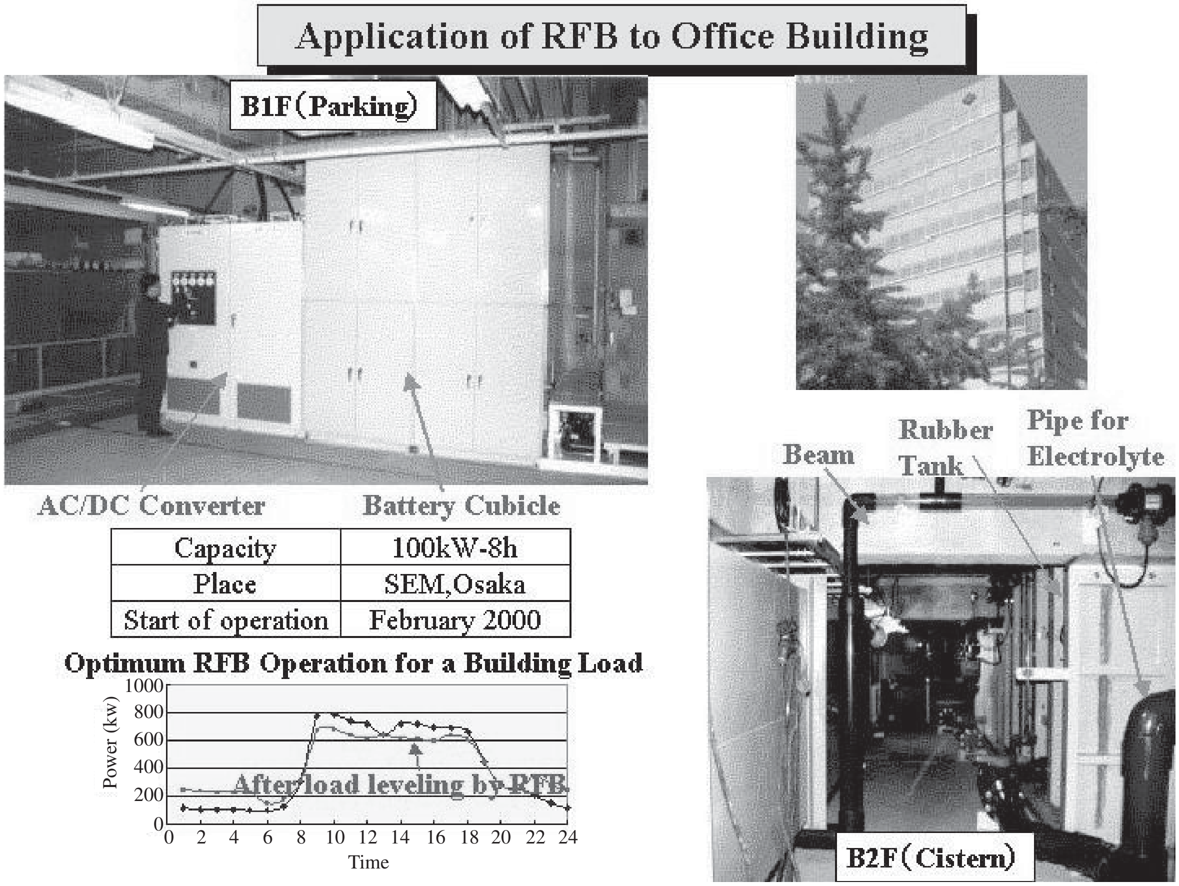


FIGURE 37.4 Block diagram of vanadium-redox system, showing principle of operation.



Capacity	100kW-8h
Place	SEM,Osaka
Start of operation	February 2000

FIGURE 37.5 Application of Vanadium redox battery in an office building.

Regenesys System. The third type of flow battery that it is being actively developed is the *polysulfide-bromine,* or *Regenesys* system of Innogy (formerly National Power) in the United Kingdom. Innogy has been involved in the development of this redox-like system, in which both reactants and products of the electrode reactions remain in solution, since the early 1990s. Regenesys is similar to a redox system but both the positive and negative reactions involve neutral species. The discharge reaction at the positive electrode is:

$$NaBr_3 + 2Na^+ + 2e \rightarrow 3NaBr$$

and that at the negative is:

$$2Na_2S_2 \rightarrow Na_2S_4 + 2Na^+ + 2e$$

Sodium ions pass through the cation exchange membranes in the cells to provide electrolytic current flow and to maintain electroneutrality. The sulfur that would otherwise be produced in discharge dissolves in excess sodium sulfide that is present to form sodium polysulfide. The bromine produced at the positives on charge dissolves in excess sodium bromide to form sodium tribromide. A block diagram of a Regenesys energy storage plant is shown in Fig. 37.6.

Innogy built many multi-kW batteries in their development program in the 1990s, with this part of the effort culminating in construction of 100 kW cell stacks (modules) with electrodes of up to one square meter in area[25] (see Fig. 37.7). Innogy has announced that by the end of 2002 they should have completed construction and acceptance testing of a 15 MW, 120 MWh Regenesys energy storage plant at the Little Barford power station in the United Kingdom.

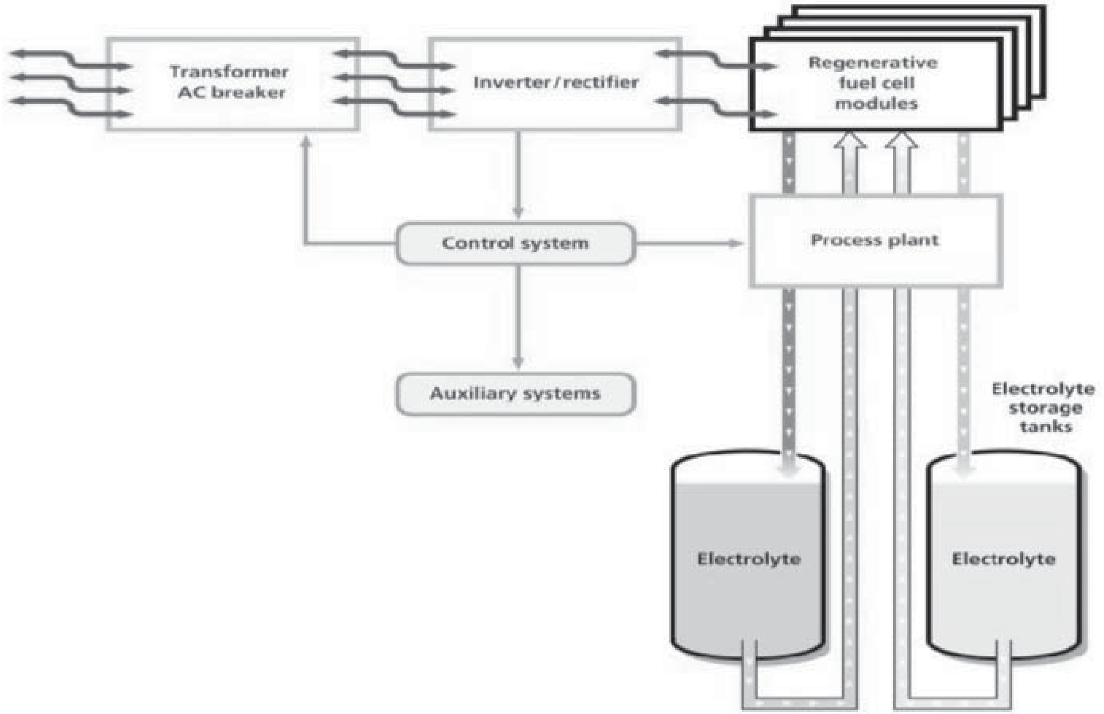


FIGURE 37.6 Block diagram of Regenesys Energy Storage Plant. (*From Ref. 25.*)

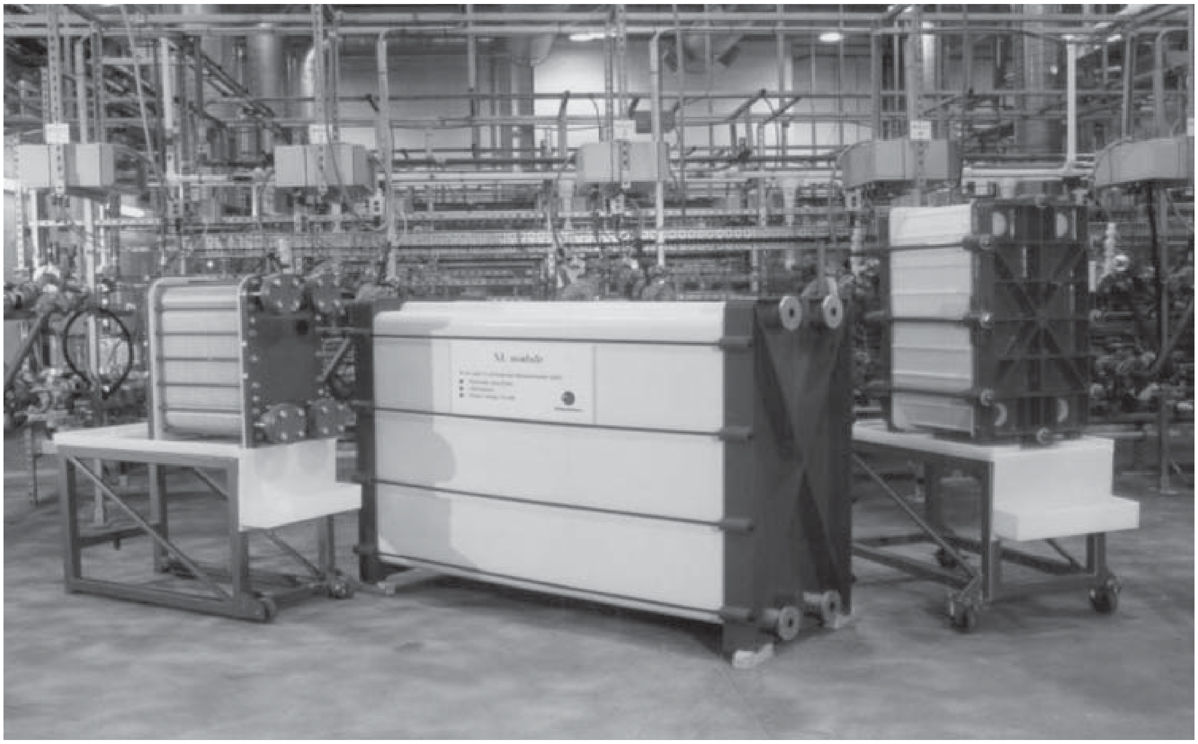


FIGURE 37.7 Regenesys modules of varying sizes. (*From Ref. 25.*)

37.4.2 High-Temperature Systems

High-temperature systems operate in the range of 160 to 500°C and have high-energy density and high specific power compared to most conventional ambient-temperature systems. The negative electrode material is an alkali metal, such as lithium or sodium, which has a high voltage and electrochemical equivalence. Aqueous electrolytes cannot be used because of the chemical reactivity of water with alkali metals. Molten salt or solid electrolytes that require high temperatures are used instead. Benefits are high ionic conductivity, which is needed for high power density, and insensitivity to ambient temperature conditions. However, high operating temperatures also increase the corrosiveness of the active materials and cell components and thereby shorten the life of the battery. Also, thermal insulation is needed to maintain operating temperatures during standby periods.

The main high-temperature battery systems are the sodium/beta and lithium/iron sulfide systems:

The sodium/beta battery system includes designs based on either the sodium/sulfur or the sodium/metal chloride chemistries (see Chapter 40). The sodium/sulfur technology has been in development for over 30 years and multi-kW batteries are now being produced on a pilot plant scale for stationary energy storage applications.[26] At least two 8 MW/40 MWh sodium/sulfur batteries have been put into service for utility load leveling by TEPCO in Japan.

Sodium/nickel chloride is a relatively new variation of the sodium/beta technology and was being developed mainly for electric-vehicle applications. There has not been nearly the effort on this chemistry as on the sodium/sulfur battery.

Sodium/sulfur and sodium/metal chloride technologies are similar in that sodium is the negative electrode material and beta-alumina ceramic is the electrolyte. The solid electrolyte serves as the separator and produces 100% coulombic efficiency. Applications are needed in which the battery is operated regularly. Sodium/nickel chloride cells have a higher open-circuit voltage, can operate at lower temperatures, and contain a less corrosive positive electrode than sodium/sulfur cells. Nevertheless, sodium/nickel chloride cells are projected to be more expensive and have lower power density than sodium/sulfur cells.

The lithium/iron sulfide rechargeable battery system is another high-temperature system and must be operated above 400°C so that the salt mixture (LiCl-KCl) used as an electrolyte remains molten (see Chapter 41). The negative electrode is lithium, which is alloyed with aluminum or silicon, and the positive electrode can be either iron monosulfide or iron disulfide. No development is being performed on these technologies at this time because room temperature battery systems are showing comparable performance.

37.4.3 Ambient-Temperature Lithium Batteries

Rechargeable lithium batteries, which operate at or near ambient temperature, have been and continue to be developed because of their advantageous energy density and charge retention compared to conventional aqueous batteries. The lithium-ion version of this chemistry has been commercialized for consumer electronics and other portable equipment in small button and prismatic cylindrical sizes. The attractive characteristics of rechargeable lithium batteries make them promising candidates for aerospace, electric vehicles, and other applications requiring high-energy batteries. High energy and power densities have been achieved with rechargeable lithium batteries, despite the lower conductivity of the organic and polymer electrolytes that are used to ensure compatibility with the other components of the lithium cell. Scaling up to the sizes and power levels, and achieving the cycle life required for electric vehicles and maintaining the high degree of safety needed for all batteries, remains a challenge.

A number of different approaches are being taken in the design of rechargeable lithium batteries. The rechargeable lithium cell that can deliver the highest energy density uses metallic lithium for the negative electrode, a solid inorganic intercalation material for the positive electrode, and an organic liquid electrolyte. Manganese dioxide appears to be the best material for the positive electrode based on performance, cost, and toxicity. Poor cycle life and safety, however, are concerns with this type of battery because the porous, high-surface-area lithium that is plated during recharge is highly reactive and susceptible to forming dendrites which could cause internal short-circuiting and they are no longer marketed commercially.

Another approach is the use of a solid polymer electrolyte. These electrolytes are considered to have a safety advantage over the liquid electrolyte because of their lower reactivity with lithium and the absence of a volatile and sometimes flammable electrolyte. These electrolytes, however, have a lower conductivity that must be compensated for by using thinner electrodes and separators and by having larger electrode areas.

The approach that has been commercialized successfully for portable-sized batteries is the ‘‘lithium-ion’’ battery. This battery uses a lithiated carbon material in place of metallic lithium. A lithiated transition metal intercalation compound is used for the positive active material, and the electrolyte is either a liquid aprotic organic solution or a gel polymer electrolyte. Lithium ions move back and forth between the positive and negative electrodes during charge and discharge. As metallic lithium is not present in the cell, lithium-ion batteries are less chemically reactive and are safer and have a longer cycle life than other options.[27] These systems require battery management circuitry to prevent overcharge, over-discharge and to provide cell balancing and other safety features. Larger lithium-ion batteries, in sizes up to 100 Ah, are under development.

The ambient temperature lithium battery technologies, especially the lithium-ion, are among the most promising for EVs, HEVs, electric utility energy storage, and other such applications. The scaling, safety, life issues, and cost remain a significant challenge to their use in these emerging applications.

37.5 REFUELABLE BATTERIES AND FUEL CELLS—AN ALTERNATIVE TO ADVANCED RECHARGEABLE BATTERIES

Another category of aqueous battery systems is the metal-air battery. These batteries are noted for their high specific energy as they utilize ambient air as the positive active material, and light metals, most commonly aluminum or zinc, as the negative active material. Except for the iron/air battery, on which earlier development work for EV applications has now been abandoned, metal-air batteries have either limited capability for recharge, as for zinc/air, or they cannot be electrically recharged at all, as in the case of the aluminum/air system.

The zinc/air system is commercially available as a primary battery. For EV and other applications, there are efforts underway to develop a ‘‘mechanically’’ rechargeable battery where the discharged electrode is physically removed and replaced with a fresh one. Recycling or recharging of the reaction product is done remotely from the battery. There also was a significant effort in the 1980s and 1990s to develop an aluminum/air battery with mechanical recharging,[28] but this work is now continuing at a reduced level.

Fuel cells can in a sense be regarded as refuelable batteries, and are being considered for use in portable electronic equipment (see Chaps. 42 and 43).

CHAPTER 42

PORTABLE FUEL CELLS—INTRODUCTION

David Linden and Thomas B. Reddy

42.1 GENERAL CHARACTERISTICS

A fuel cell is a galvanic device that continuously converts the chemical energy of a fuel (and oxidant) to electrical energy. Like batteries, fuel cells convert this energy electrochemically and are not subject to the Carnot cycle limitation of thermal engines, thus offering the potential for highly efficient conversion. The essential difference between a fuel cell and a battery is the manner for supplying the source of energy. In a fuel cell, the fuel and the oxidant are supplied continuously from an external source when power is desired. The fuel cell can produce electrical energy as long as the active materials are fed to the electrodes. In a battery, the fuel and oxidant (except for metal/air batteries) are an integral part of the device. The battery will cease to produce electrical energy when the limiting reactant is consumed. The battery must then be replaced or recharged.

The electrode materials of the fuel cell are inert in that they are not consumed during the cell reaction, but have catalytic properties which enhance the electroreduction or electrooxidation of the reactants (the active materials).

The anode active materials used in fuel cells are generally gaseous or liquids fuels (compared with the metal anodes generally used in most batteries), such as hydrogen, methanol, hydrocarbons, natural gas, which are fed into the anode side of the fuel cell. As these materials are like the conventional fuels used in heat engines, the term ''fuel cell'' has become popular to describe these devices. Oxygen, most often air, is the predominant oxidant and is fed into the cathode

Fuel cell technology can be classified into two categories:

1. Direct systems where fuels, such as hydrogen, methanol and hydrazine, can react directly in the fuel cell (see Sec. 43.4).
2. Indirect systems in which the fuel, such as natural gas or other fossil fuels, is first converted by reforming to a hydrogen-rich gas which is then fed into the fuel cell.

Fuel cell systems can take a number of configurations depending on the combinations of fuel and oxidant, the type of electrolyte, temperature of operation, application, etc. Table 42.1 is a summary of various types of fuel cells distinguished by the electrolyte and operating temperature. The PEM fuel cell is currently the predominant one for portable and small fuel cells as it is the only one operating near ambient conditions.*

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*Large fuel cells are beyond the scope of this Handbook. See Appendix F, Bibliography for references.

TABLE 42.1 Types of Fuel Cells

1. **Solid Oxide (SOFC):** These cells use a solid oxygen-ion-conducting metal oxide electrolyte. They operate at about 1000°C, with an efficiency of up to 60%. They are slow to start up, but once running, provide high grade waste heat which can be used to heat buildings. They may find application in industrial and large-scale applications.
2. **Molten Carbonate** (MCFC): These cells use a mixed alkali-carbonate molten salt electrolyte and operate at about 600°C. They are being developed for continuously operating facilities, and can use coal-based or marine diesel fuels.
3. **Phosphoric** Acid (PAFC): This is the most commonly used type of fuel cell for stationary commercial sites such as hospitals, hotels, and office buildings. The electrolyte is concentrated phosphoric acid. The fuel cell operates at about 200°C. It is highly efficient and can generate energy at up to 85% (40% as electricity and another 45% if the heat given off is also used).
4. **Alkaline (AFC):** These are used by NASA on the manned space missions, and operate well at about 200°C. They use alkaline potassium hydroxide as the electrolyte and can generate electricity up to 70% efficiency. A disadvantage of this system is that it is restricted to fuels and oxidants which do not contain carbon dioxide.
5. **Proton** Exchange Membrane (PEM): These cells use a perfluorinated ionomer polymer membrane electrolyte which passes protons from the anode to the cathode. They operate at a relatively low temperature (70 to 85°C), and are especially notable for their rapid start-up time. These are being developed for use in transportation applications and for portable and small fuel cells.
6. **Direct Methanol** (DMFC): These fuel cells directly convert liquid methanol (methyl alcohol) in an aqueous solution which is oxidized at the anode. Like PEMs, these also use a membrane electrolyte, and operate at similar temperatures. This fuel cell is still in the development stage.
7. **Regenerative (RFC):** These are closed-loop generators. A powered electrolyzer separates water into hydrogen and oxygen, which are then used by the fuel cell to produce electricity and exhaust (water). That water can then be recycled into the powered electrolyzer for another cycle.

Source: Connecticut Academy of Science and Engineering Reports, Vol. 15, No. 1, 2000.

A practical fuel cell power plant consists of three basic subsystems:

1. A power section, which consists of one or more fuel cell stacks—each stack containing a number of individual fuel cells, usually connected in series to produce a stack output ranging from a few to several hundred volts (direct current). This section converts the fuel and the oxidant into DC power.

2. A fuel subsystem that manages the fuel supply to the power section. This subsystem can range from simple flow controls to a complex fuel-processing facility. This subsystem processes fuel to the type required for use in the fuel cell (power section).

3. A power conditioner that converts the output from the power section to the type of power and quality required by the application. This subsystem could range from a simple voltage control to a sophisticated device that converts the DC power to an AC power output.

In addition, a fuel cell power plant, depending on size, type, and sophistication, may require an oxidant subsystem, thermal and fluid management subsystems, and ether ancilliary subsystems.

Fuel cells have been of interest for over 150 years as a potentially more efficient and less polluting means for converting hydrogen and carbonaceous or fossil fuels to electricity compared to conventional heat engines. A significant application of the fuel cell has been the use of the hydrogen/oxygen fuel cell by NASA, using cryogenic fuels, in space vehicles for over 40 years including the current fleet of space shuttles. Use of the air-breathing fuel cell in terrestrial applications, such as for utility power and electric vehicles, has been ongoing for some time but has been developing slowly. Recent advances have now revitalized interest for these and other new applications.

During this past decade, interest in small air-breathing fuel cells has arisen for dispersed or on-site electric generators, remote devices and other such applications in the subkilowatt power range, replacing engine-generators, power sources and larger-sized batteries. At lower power levels, from below 1 to 50 watts, historically the domain of batteries, fuel cell technology is seen as an approach to achieve higher specific energy than those delivered by batteries. Progress has been made with fuel cell systems in the sizes above 50 watts, especially for extended long-term service (see Chap. 43). However, the development of yet smaller portable fuel cells (which can be ‘‘recharged,’’ for example, by replacing a small container of fuel), competitive in size and performance with batteries remains a challenge (see Sec. 42.3).

42.2 OPERATION OF THE FUEL CELL

42.2.1 Reaction of Mechanisms

A simple fuel cell is illustrated in Fig. 42.1*a*. Two catalyzed electrodes are immersed in an electrolyte (acid in this illustration) and separated by a gas barrier. The fuel, in this case hydrogen, is bubbled across the surface of one electrode while the oxidant, in this case oxygen from ambient air, is bubbled across the other electrode. When the electrodes are electrically connected through an external load, the following events occur:

1. The hydrogen dissociates on the catalytic surface of the fuel electrode, forming hydrogen ions and electrons.
2. The hydrogen ions migrate through the electrolyte (and a gas barrier) to the catalytic surface of the oxygen electrode.
3. Simultaneously, the electrons move through the external circuit, doing useful work, to the same catalytic surface.
4. The oxygen, hydrogen ions, and electrons combine on the oxygen electrode’s catalytic surface to form water.

The reaction mechanisms of this fuel cell, in acid and alkaline electrolytes, are shown in Table 42.2. The major differences, electrochemically, are that the ionic conductor in the acid electrolyte is the hydrogen ion (or, more correctly, the hydronium ion, H_3O^+) and the OH^- or hydroxyl ion in the alkaline electrolyte. The only by-product of a hydrogen/oxygen fuel cell is water; in the acid electrolyte water is produced at the cathode and, in the alkaline electrolyte fuel cell, it is produced at the anode.

The net reaction is that of hydrogen and oxygen producing water and electrical energy. As in the case of batteries, the reaction of one electrochemical equivalent of fuel will theoretically produce 26.8 Ah of DC electricity at a voltage that is a function of the free energy of fuel-oxidant reactions. At ambient conditions, this potential is ideally 1.23 V DC for a hydrogen/oxygen fuel cell.

Figure 42.1(*b*) is a schematic of the Proton Exchange Membrane Fuel Cell (PEMFC), presently the best candidate for use in small portable fuel cells. Passing through a gas diffuser, hydrogen reacts on a catalyst (small circles) at the anode, sending protons, and electrons to the cathode. The protons migrate through the membrane and the electrons through the external circuit. The protons react with the oxygen, supplied at the cathode, to form water. Products and unused reactants exit through the gas vents.

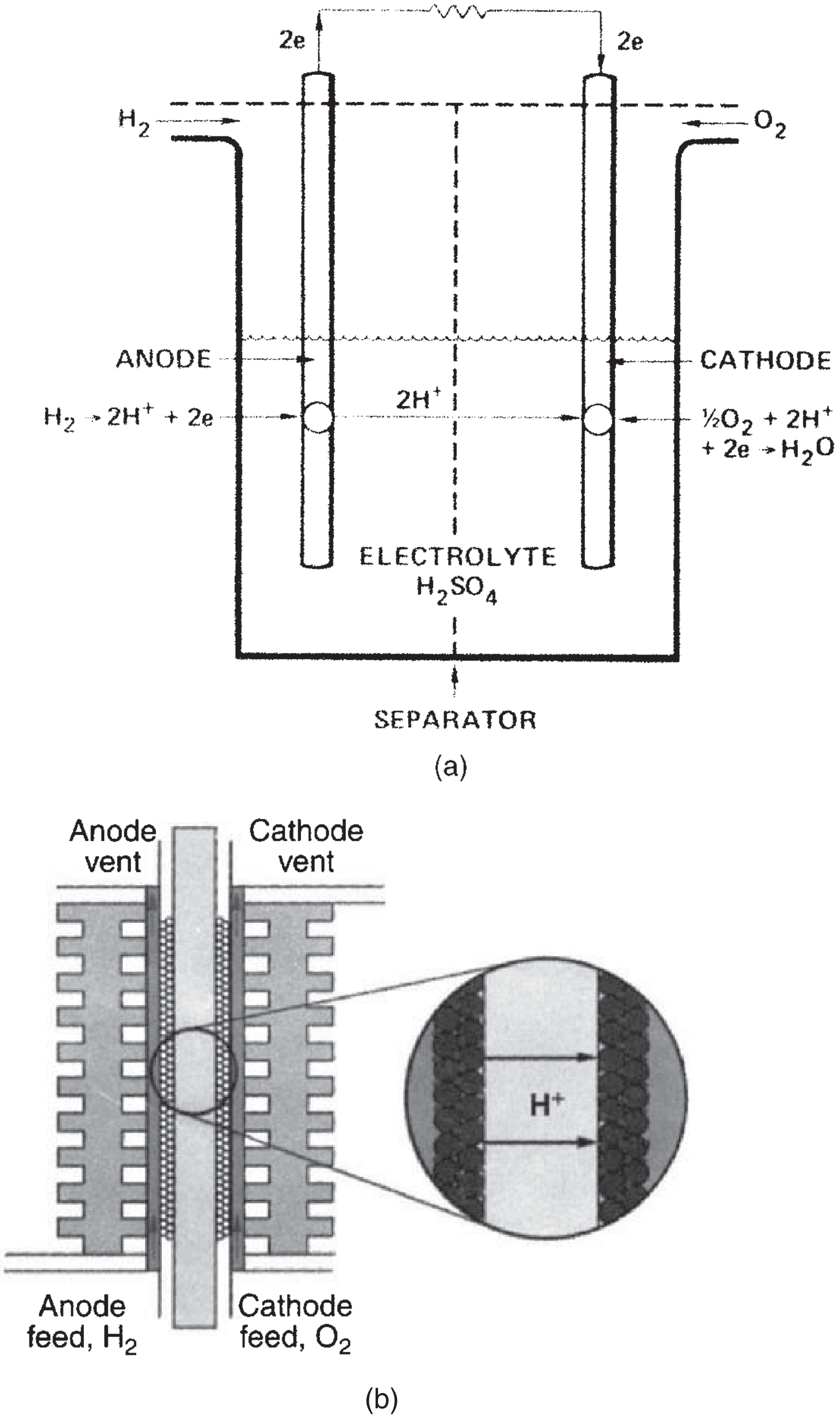

FIGURE 42.1 Operation of the fuel cell. (*a*) Reactions in an acid electrolyte. (*b*) Based on a proton exchange membrane. (*Source: Chemical and Engineering Areas,* American Chemical Society, Washington D.C., June 14, 1999.)

TABLE 42.2 Reaction Mechanisms of the H_2/O_2 Fuel Cell

	Acid electrolyte	Alkaline electrolyte
Anode	$H_2 \rightarrow 2H^+ + 2e$	$H_2 + 2OH^- \rightarrow 2H_2O + 2e$
Cathode	$1/2O_2 + 2H^+ + 2e \rightarrow H_2O$	$1/2O_2 + 2e + H_2O \rightarrow 2OH^-$
Overall	$H_2 + 1/2O_2 \rightarrow H_2O$	$H_2 + 1/2O_2 \rightarrow H_2O$

42.2.2 Major Components of the Fuel Cell

The important components of the individual fuel cell are:

1. The *anode* (fuel electrode) must provide a common interface for the fuel and electrolyte, catalyze the fuel oxidation reaction, and conduct electrons from the reaction site to the external circuit (or to a current collector that, in turn, conducts the electrons to the external circuit).

2. The *cathode* (oxygen electrode) must provide a common interface for the oxygen and the electrolyte, catalyze the oxygen reduction reaction, and conduct electrons from the external circuit to the oxygen electrode reaction site.

3. The *electrolyte* must transport one of the ionic species involved in the fuel and oxygen electrode reactions while preventing the conduction of electrons (electron conduction in the electrolyte causes a short circuit). In addition, in practical cells, the role of gas separation is usually provided by the electrolyte system. This is often accomplished by retaining the electrolyte in the pores of a matrix. The capillary forces of the electrolyte within the pores allow the matrix to separate the gases, even under some pressure differential. Currently, the technology in use for portable ambient temperature fuel cells is the electrolyte membrane Nafion®.

42.2.3 General Characteristics

The performance of a fuel cell is represented by the current density vs. voltage (or ‘‘polarization’’) curve (Fig. 42.2). Whereas ideally a single H_2/O_2 fuel cell could produce 1.23 V DC at ambient conditions, in practice, fuel cells produce useful voltage outputs that are somewhat less than the ideal and which decrease with increasing discharge rate (current density). The losses or reductions in voltage from the ideal are referred to as ‘‘polarization,’’ as illustrated in Fig. 42.2 (also see Chap. 2).

These losses include:

1. Activation polarization represents energy losses that are associated with the electrode reactions. Most chemical reactions involve an energy barrier that must be overcome for the reactions to proceed. For electrochemical reactions, the activation energy lost in overcoming this barrier takes the form

$$\eta_{act} = a + b \ln i$$

where η_{act} = activation polarization, mV
$a, b,$ = constants
i = current density, mA/cm^2

Activation polarization is associated with each electrode independently and

$$\eta_{act(cell)} = \eta_{act(anode)} + \eta_{act(cathode)}$$

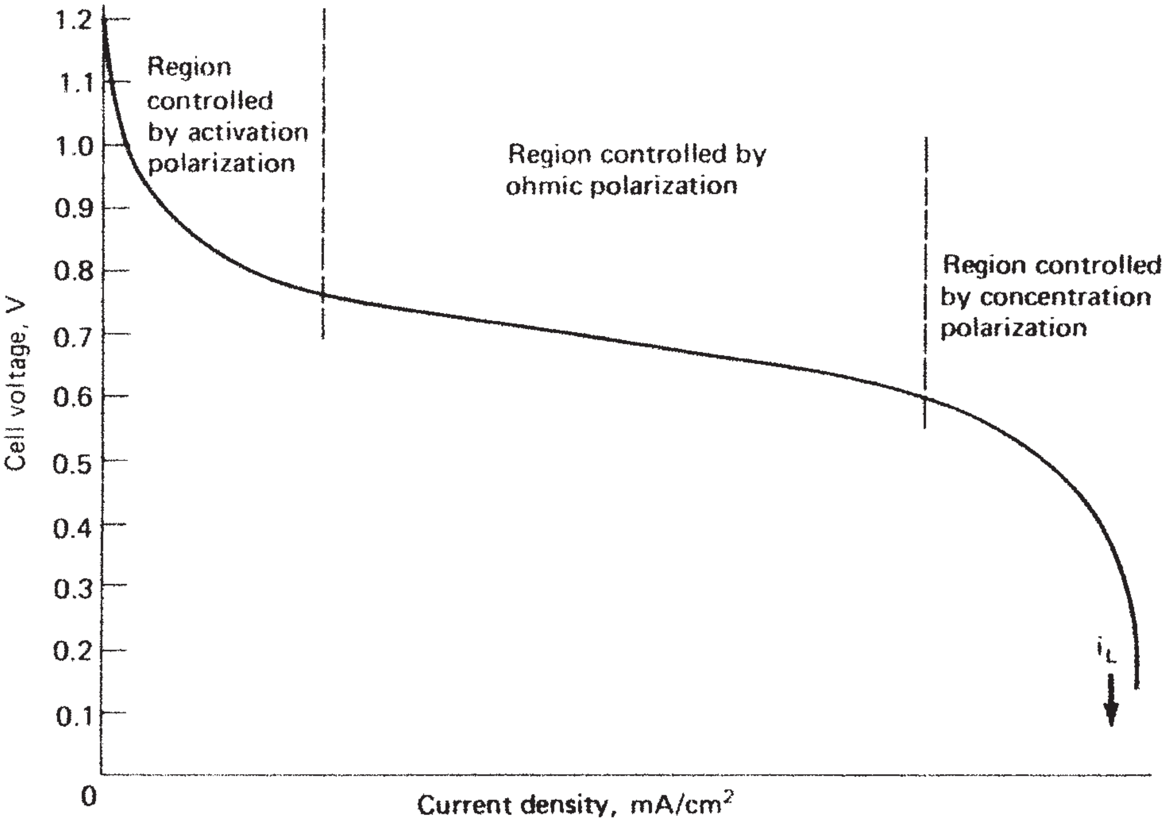

FIGURE 42.2 Fuel cell polarization curve.

2. Ohmic polarization represents the summation of all the ohmic losses within the cell, including electronic impedances through electrodes, contacts, and current collectors and ionic impedance through the electrolyte. These losses follow Ohm's law

$$\eta_{\text{ohm}} = iR$$

where η_{ohm} = ohmic polarization, mV
i = current density, mA/cm^2
R = total cell impedance, $\Omega \cdot \text{cm}^2$

3. Concentration polarization represents the energy losses associated with mass transport effects. For instance, the performance of an electrode reaction may be inhibited by the inability for reactants to diffuse to or products to diffuse away from the reaction site. In fact, at some current, the limiting current density i_L, a situation will be reached wherein the current will be completely limited by the diffusion processes (see Fig. 42.2). Concentration polarization can be represented by

$$\eta_{\text{conc}} = \frac{RT}{nF} \ln \left(1 - \frac{i}{i_L}\right)$$

where η_{conc} = concentration polarization, mV
R = gas constant
T = temperature, °K
n = number of electrons
F = Faraday's constant
i = current density, mA/cm^2
i_L = limiting current density, mA/cm^2

Concentration polarization occurs independently at either electrode. Thus, for the total cell

$$\eta_{\text{conc(cell)}} = \eta_{\text{conc(anode)}} + \eta_{\text{conc(cathode)}}$$

The net result of these polarizations is that fuel cells generally operate between 0.5 and 0.9 V DC. Fuel cell performance can be increased by increasing cell temperature and reactant partial pressure. However, for small or portable fuel cells, operation at ambient conditions is usually a requirement, particularly when the fuel cell is to be used as a replacement for batteries.

42.3 SUB-KILOWATT FUEL CELLS

The fuel cell has many attractive features that have increased interest in its use in small and/or portable power sources below a kilowatt in power output. At the same time, because of the unique requirements of portable devices, there are limitations in fuel cell technology that will present challenges for its deployment, particularly in the sizes below 20 watts as replacements for batteries.

These include:

1. *Hydrogen and Energy-rich Fuels.* The use of hydrogen and other energy-rich fuels that have a higher energy density than the active materials normally used in batteries:

Table 42.3 lists the theoretical specific energy and energy density of several of these materials which are significantly higher than those of batteries and which are practical for use in portable fuel cells. Of these, hydrogen stands out not only because of its high specific energy, but because it can be directly converted to electrical energy in a fuel cell operating at ambient temperatures. Natural gas, propane, gasoline and other fossil fuels cannot be considered as they cannot be converted directly, except at very high temperatures. Incorporating a fuel processing unit would not be feasible for a small portable device for battery replacement. Methanol is the only liquid fuel that, at this time, shows promise for direct conversion at reasonable temperatures (see Sec. 43.4.4).

The necessity for containing and supplying hydrogen to the fuel cell, in a practical and safe method, substantially reduces its practical specific energy. A number of methods are being used, including compressed gas cylinders, storage in hydrides, and chemical methods for generating hydrogen, each of which requires a specific method for generating and controlling the generation of hydrogen (see Sec. 43.4.1). Table 42.3 also lists the theoretical values of the various methods for supplying hydrogen and, as applicable, the status of current technology. While these values, albeit much lower than that of hydrogen gas, are still higher than those of most battery systems, a comparison to the specific energy of battery systems, which is often done, is not a correct one. It compares only the fuel supply of the fuel cell (omitting the fuel cell stack and other fuel cell components) to a complete battery system. A more reasonable method of comparison is discussed below and illustrated in Fig. 42.3.

TABLE 42.3 Characteristics of Fuels for Use In Portable Fuel Cells

	Theoretical[1]		Current State-of-Art[2]	
	Wh/kg	Wh/L	Wh/kg	Wh/L
Hydrogen				
Hydrogen (gas)	32705	—		
Hydrogen (liquid) cryogenic	32705	2310		
Pressurized H_2 containers				
34.5×10^6 Pa	1023		400	250
Metal Hydride			160	420
MH(2%H_2)	655			
MH(7%H_2)	2290	3400		
Chemical Hydrides			400[3]	500[3]
$LiH + H_2O$	2540	—		
$NaBH_4 + 2H_2O$	3590	—		
30% $NaBH_4$ solution	2375	2080		
Carbon-based H_2 Storage				
Carbon nanofibres (6.5% H_2)	2130			
Methanol (MeOH)				
100% MeOH	6088	4810		
MeOH, H_2O solution (equal molar)	~3900	~3350		

[1] Based on 1.23 V for H_2/O_2 fuel cell
[2] Based on actual watt-hour output of a fuel cell running on the specified H_2 source
[3] Includes container/packaging and required water

2. *Electrochemical Conversion.* The fuel cell converts chemical energy to electrical energy electrochemically at high conversion efficiencies (in the order of 30 to 60% depending on the output voltage) in small as well as large units and even when it is operating at partial power. However, while conversion efficiency may not be affected, scaling down to the lower power levels may not result in a proportional decrease in the weight and size of the power unit or the auxiliary devices.

3. *Operating Temperature*. Portable fuel cells, from a practical point of view, should operate at ambient temperatures. Based on the current technology, as summarized in Table 42.1, this limits the choice to the Proton Exchange Membrane Fuel Cell (PEMFC). This also limits the choice of fuels to those that can be directly converted to electrical energy at that temperature. It precludes the use of those fuels that have to be reformed to a hydrogen-rich fuel because of the high operating temperatures of the reformer. But operation at the relatively low temperatures results in a lower conversion efficiency and the use of the polymer limits operation at sub-freezing temperatures. Water embedded in the polymer will tend to freeze and, while the polymer can withstand this condition, start-up and operation are impeded and an external energy source, such as external heat or a battery, may be required.

4. *Modular Features.* The modular features of the fuel cell, with separate units for power conversion and fuel storage, facilitate designing the fuel cell system to meet application requirements and equipment footprints. The power conversion unit (the fuel cell stack) can be sized to meet the power requirement and the fuel container can be sized to contain sufficient fuel to meet the service time requirement.

Figure 42.3 compares the performance of several primary and secondary batteries with that of a fuel cell, showing the total weight of each system designed, in this example, to deliver 50 watts, for different times of operational service. The secondary battery systems deliver their rated capacity even at the highest discharge rates shown in the figure; hence, their performance is characterized by a straight sloping line. The slope is equivalent, as shown, to their specific energy and the weight of the battery is reduced almost proportional to the reduction in service time. The primary battery systems, which generally do not perform as well at high discharge rates, show the straight sloping line over the longer periods of service. At the high discharge rates or at the short hours of operational life, the curve levels off indicating little reduction in weight with decreasing service life. The curves for the fuel cell look similar. At the low operational time, the weight reflects the "dead" weight of the system, i.e. the fuel cell stack and other auxiliaries required to produce the required power, the weight of the fuel being inconsequential. At the longer service times, the weight of the power unit becomes insignificant and the system weight increases by the specific energy of the fuel.

This figure graphically illustrates the respective advantages of batteries and fuel cells. The battery shows its advantage on the relatively short term life applications as the fuel cell is penalized by the weight of the power unit. On longer term applications, the fuel cell benefits as the replacement fuel has a higher specific energy than most of the battery systems.

A similar relationship exists if the comparison is made on a volumetric basis.

This figure points out the direction that fuel cell development must take to compete successfully with battery systems in the low power range. The weight and size of the power unit must be reduced substantially as the emphasis in the design of portable equipment is towards lower size and weight even at the sacrifice of service time. Unless, this is done, the advantage of the fuel cell, the lighter weight fuel replacement, will not be significant.

An interesting consideration is a possible tradeoff in the design of the fuel cell component and the fuel source. In the case of the direct methanol fuel cell (DMFC), for example, water is required for the reaction of methanol. The discharge product of the fuel cell, water, can be used if the water management or recovery is incorporated in the fuel cell; a one-time cost of increased size, weight and complexity of the fuel cell. Or water can be added to the fuel source at the expense of a recurring lower specific energy of the diluted fuel source.

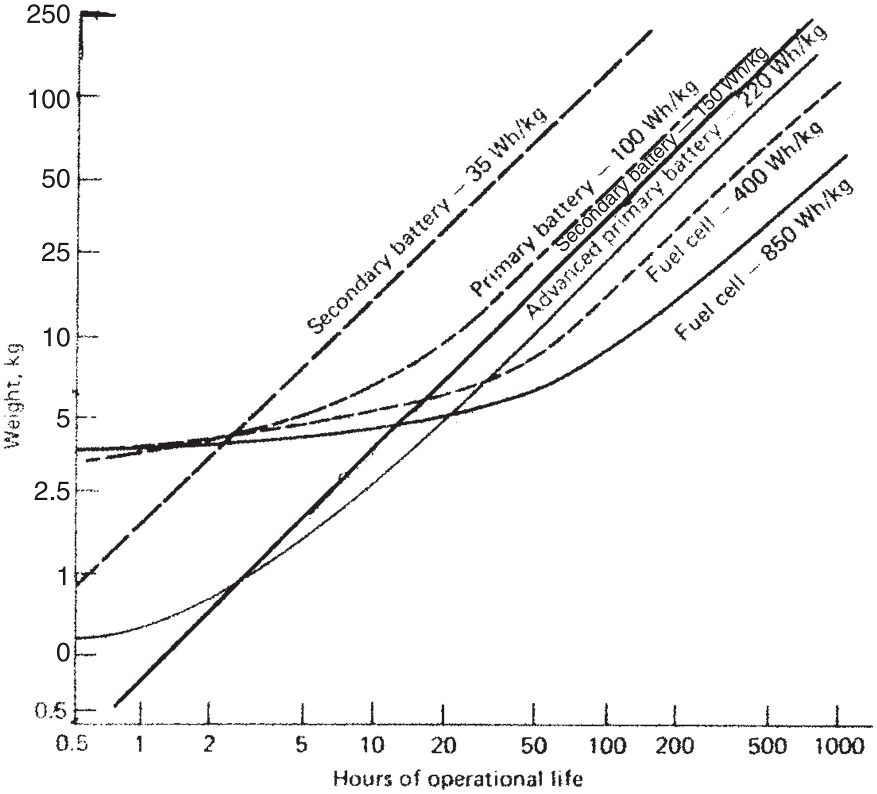

FIGURE 42.3 Comparison of electrochemical systems—weight vs. service life (based on 50 watt W output and stated specific energy.)

5. *Air-Breathing Systems.* Most terrestrial fuel cells are air-breathing and an oxidant does not have to be stored and carried with the fuel cell, thus keeping the size and weight of the system to a minimum. Depending on the power level, the air-flow may be insufficient, necessitating the addition of fans or other means of forced convection for the electrochemical reaction, cooling and water balance.

6. *Environmentally Friendly.* Fuel cells are *environmentally friendly* and, while the large sizes can be complex, much like a chemical plant, in the small and portable sizes they can be quiet and relatively simple in design. While these characteristics are superior to the engine-generators and other heat engines they may replace, for these characteristics they offer no advantage over batteries. Further, the need to provide a method for attaching the fuel supply and a mechanism to supply the fuel makes it more complex as these components are not required for the battery which is self-contained.

7. *Cost.* Cost will be a major factor for the acceptance of fuel cell as a replacement for batteries. The cost of the fuel cell is determined by its two components: the fuel cell and auxiliaries, and the fuel source. At this time, the cost of the fuel cell is high compared to batteries, not only because it has not attained commercial production status, but also because the polymers, catalysts and its other components are expensive. A potential advantage of the fuel cell again focuses on the fuel supply. If the cost of fuel replacement can be reduced so that it is lower than that of battery replacement, fuel cell deployment may be a cost effective approach for extended long term periods of operation.

42.4 INNOVATIVE DESIGNS FOR LOW WATTAGE FUEL CELLS

The development of fuel cells that may be competitive with batteries in the low power range for use in cellular phones, laptop computers and other similar equipments will require innovative designs incorporating thinner components and smaller light-weight auxiliaries. Scale-down of current fuel cell technology will not be adequate to meet the size and weight requirements of these portable devices.

One new concept[1,2] as shown in Fig. 42.4, is a micro fuel cell using diluted methanol, which will be supplied in replaceable ampoules, as a fuel. It is planned to use manufacturing techniques employed in the electronics industry to mass-produce the fuel cell. In this design, a thin film of plastic is bombarded with nuclear particles and then chemically etched to form fine pores (the cells) into which a polymeric electrolyte is added. Chipmaking techniques, including vacuum deposition, are used to layer and etch on the plastic structure, a preferentially permeable barrier (to limit methanol leakage to the cathode), two electrode plates, a catalyst material and a conductive grid to connect the individual cells. Start-up is still sluggish and power levels are low, but a portable charger has been developed to charge a cell phone battery, the advantage being that fuel cell has a higher specific energy than rechargeable batteries.

In another approach,[3] a proton exchange membrane fuel cell (PEMFC) has been fabricated on a silicon chip, again using methods of the microelectronics industry. Porous gas diffusion electrodes, electrical interconnects and gas manifolds were created using lithography and etching processes and solid polymer electrolytes were deposited using thin film deposition techniques. Several novel fuel cell architectures were investigated, including a planar design in which the anodes and cathodes are side-by-side in the same plane. Combined with a hydride as a source for hydrogen, a prototype power source demonstrated an energy density higher than batteries. These small silicon PEMFCs offer advantages including flexible form factors and manufacturability.

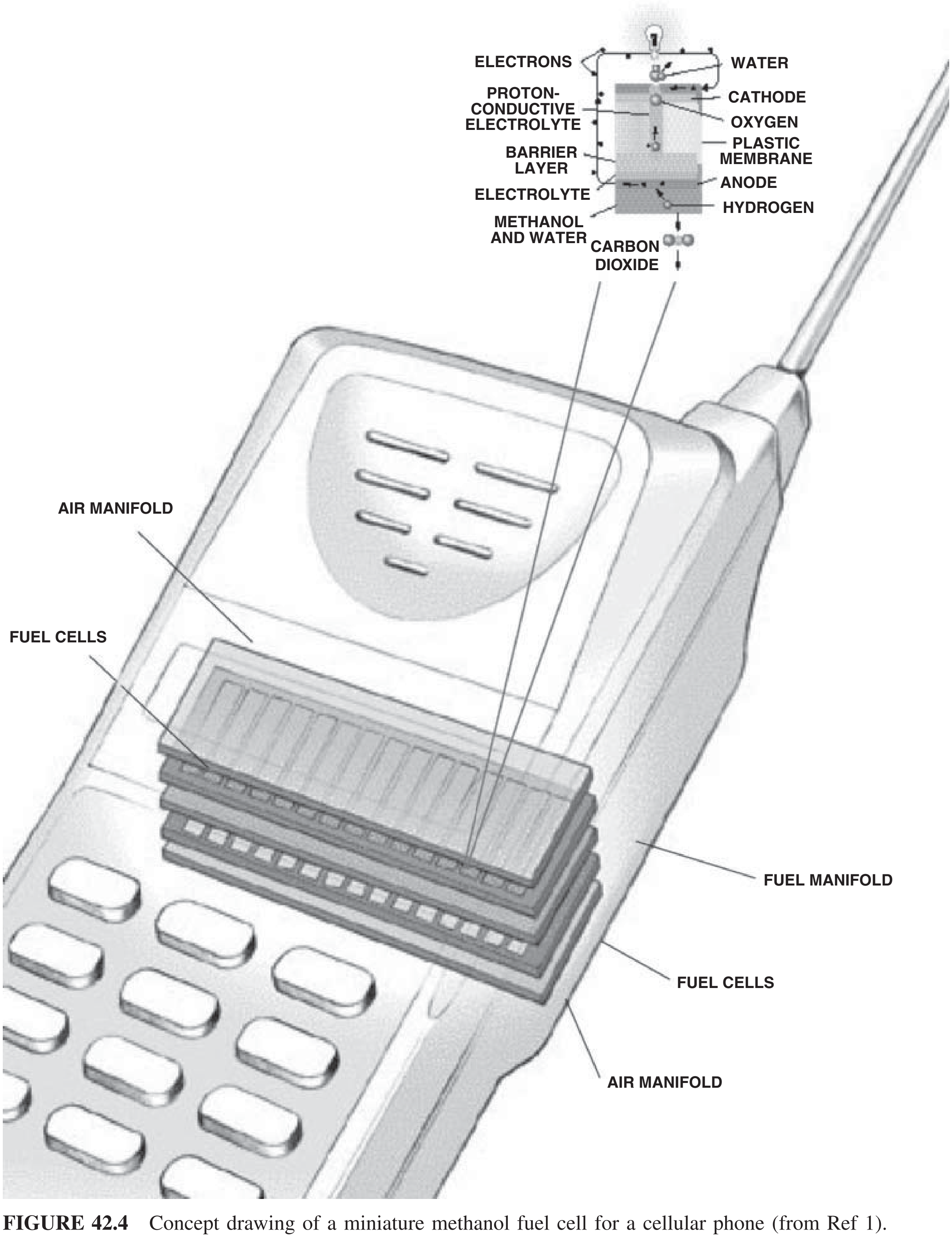

FIGURE 42.4 Concept drawing of a miniature methanol fuel cell for a cellular phone (from Ref 1).

an exothermic process, usually carried out at higher temperatures (perhaps 1000°C), while the ATR process is almost thermally neutral and typically operates at or somewhat above SR temperatures. Representative reactions for these processes using methane as the fuel can be expressed as follows:

$$\text{SR: } CH_4 + H_2O \rightleftharpoons CO + 3H_2$$

$$\text{POX: } CH_4 + 0.5O_2 \rightleftharpoons CO + 2H_2$$

$$\text{ATR: } CH_4 + 0.25\ O_2 + 0.5H_2O \rightleftharpoons CO + 2.5H_2$$

In simplistic terms, the SR process generally provides the highest hydrogen yield and consequently the highest efficiency. Because of the endothermic reaction, its thermal management tends to be the most complex and bulky. Conversely, POX is typically the least efficient but has the simplest configurations. The ATR process tends to be intermediate to the other two in both respects.

The selection of a preferred fuel processor type depends heavily on the application requirements. For example, a conventional stationary fuel cell system operating continuously on natural gas might be best suited to the SR processor to minimize fuel cost, while a small, mobile system requiring rapid start-up might be best served via a POX, or ATR, system.

Process Gas Upgrading. The high-temperature processes described above yield a reformate gas that is high in carbon monoxide (CO) content (usually greater than 10 percent). In order to maximize the hydrogen yield (and, in the case of low-temperature fuel cells like PEM, minimize the fuel cell anode-catalyst inhibiting effects of CO), the reformate gas is then passed through a catalytic water-gas shift-converter at lower temperature (perhaps in two stages) where the following reaction takes place

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

Here again, as in the case of methanol steam reforming, the formation of methane under these conditions is prevented via the specificity of the shift-converter catalyst. For PEM fuel cells, further reduction in CO concentration is necessary (from about 0.5 percent down to less than 100 ppm). This is often carried out by way of catalytic preferential oxidation of CO in the presence of hydrogen with the addition of air at a flow rate that is a small multiple of the stoichiometric rate required for complete oxidation of the CO.

It is evident that steam or water vapor is an essential player in the fuel processor, whether it be in the reforming reaction itself or in the subsequent shift-conversion stage. The source of this water must come from storage, make-up, or condensation and recovery from the fuel cell system. In any event, the design and logistics for water management must be provided for the system, and the selected mode must best reflect the requirements for the specific application.

The complexity of the overall fuel processing system for carbonaceous fuels indicates the challenge associated with adapting conventional fuels for use in small fuel cell systems. Considerable effort is required in designing and optimizing the system to achieve the requisite miniaturization and low cost in these applications.

43.4.4 Direct-Methanol Fuel Cell (DMFC) Technology

It is clear that a system that can utilize a liquid fuel directly at the fuel cell anodes would be particularly appealing in small fuel cell applications. As mentioned earlier, at this time methanol is the only carbonaceous species that can both serve as a practical fuel and provide reasonable electrochemical performance at the fuel cell anode. Substantial research and development efforts have been directed at direct-methanol fuel cells using PEM electrolyte for more than a decade, in the context of small, field-deployable systems.

While the direct-methanol approach is inherently appealing for small fuel cells, this technology is challenging and complex. Specifically, (a) the electrochemical activity at the anode is poor, producing low cell voltages and requiring relatively high precious metal loadings to attain desirable current densities; (b) methanol is soluble in conventional PEM electrolytes, and its ''cross-over'' to the cathode results in wasted fuel consumption along with inhibition of normal oxygen transport and electrochemical reduction at this electrode; and (c) maintenance of water balance within the cells requires that water vapor discharged at the cathode flowfield exit be condensed and returned to the circulating methanol-water anode feed solution which, in order to retard methanol migration across the electrolyte membrane to the cathode, is maintained in a very dilute state, typically about 3 percent by weight.

Despite the issues cited above, the DMFC is considered to have much potential for implementation in small fuel cell systems. Research and development work that specifically focuses on these challenges is proceeding[4] and meaningful advances are anticipated in the period ahead. Also, for applications requiring extremely low power, approaches involving the feed of methanol, or methanol and water, without recirculation can be considered since heat removal (generally via a heat-exchanger in the recirculation loop) could be accomplished via natural convection.[4,5,6,7] In any event, when DMFCs are ready for commercial service, they will offer attractive incentives, especially for extended-duration missions, because of their simplicity of storage and relatively high energy densities and specific energies (approximately 2000 Wh/kg at a practical cell voltage of 0.4 V).

43.5 FUEL CELL STACK TECHNOLOGY

The technology of the PEM fuel cell stack must be in keeping with the small fuel cell system design approach described in Sec. 43.3.

43.5.1 Design

The requirements of the small fuel cell system translate into a fuel cell stack that is compact, externally air-cooled and utilizes unconditioned ambient air as a reactant. For hydrogen-fueled systems (which are the majority to date) the anode compartments of the stack are virtually dead-ended. The need for compactness calls for internal reactant manifolding and bolting as well as thin end-plates. A representative stack for a small fuel cell system is shown in Fig. 43.3. The cell components, of course, should also be as thin as possible.

43.5.2 Electrolyte

The most suitable electrolyte for small fuel cell systems is the proton-exchange membrane (PEM). For the most part, these are based on trifluoromethanesulfonic acid in a tetrafluoroethylene-based polymer backbone. The material's equivalent weight is typically 1100, although versions with an equivalent weight near 1000 are also in use. Membranes with lower equivalent weight tend to have superior proton-exchange and water-transport properties but they also have greater vulnerability to dry-out conditions. The thickness of membranes in use in fuel cells of all types today is roughly in the 20 to 200 μm range. Thinner membranes, of course, exhibit higher proton-conductance as well as rate of water transport, while posing a somewhat higher risk of failure, either in processing or in operation. Membranes used in small fuel cells are generally on the thinner side, under 100 μm and sometimes far thinner.

43.5.3 Electrodes

Electrodes used in PEM fuel cells typically employ an electrocatalyst layer with a porous, carbonaceous, electronically-conductive substrate that has been rendered hydrophobic. The catalyst layer usually comprises platinum, or a platinum-containing alloy, on a carbonaceous support (typically carbon black), dispersed ionomeric material similar in constituency to the electrolyte-membrane, and dispersed hydrophobic polymer such as polytetrafluoroethylene. The substrate, which serves as a reactant-gas diffusion layer, may be a carbon paper or a woven or non-woven cloth. The catalyst layer may be deposited directly onto the electrolyte-membrane or onto the substrate and later placed in contact with the membrane.

Anodes are usually very similar to, if not identical to those that serve as cathodes. Anodes that operate on reformed-hydrocarbon fuels, which contain some carbon monoxide, generally utilize a platinum-alloy catalyst to enhance co-tolerance. The catalyst-layer structure is sometimes altered between anodes and cathodes to adjust their respective hydrophobicity and reactant-diffusion properties. The thickness of the catalyst layer typically ranges from 10 to 20 μm, that of the substrate from 0.1 To 0.5 mm (uncompressed).

43.5.4 Bipolar Plates

The typical stack construction for PEM (and other) fuel cells is a series-connection of cells with bipolar plates interposed between adjacent cells (or membrane-electrode assemblies). The bipolar plate must provide for electronic conduction from one cell to the next; isolation of fuel on one side from oxidant (air) on the other side; and distribution of fuel and air reactants to the respective adjacent anode and cathode. In an edge-cooled stack of the type described above, the bipolar plate also contributes to heat rejection by conducting heat laterally to its finned edges, where forced-air convection is employed.

Graphite-based bipolar plates are often preferred for small fuel cell stacks because of their relatively high thermal conductivity as well as their electrochemical stability. These plates are generally comprised of graphite and a polymeric resin that have been compression-molded from powders into a nominally pore-free structure. High resin content promotes impermeability, but graphite content in the neighborhood of 80 percent by weight is usually necessary in order to achieve acceptable electronic conductivity. Their thickness requirements must take into account the depth of fuel and air reactant channels as well as structural soundness and avoidance of reactant permeability. Nevertheless, thicknesses down to about 1 mm can be implemented in small stacks.

43.5.5 Seals

Sealing means must be provided at the edges of the cells to prevent reactants from escaping to the atmosphere from porous elements of the electrodes. Also, since reactant manifolding is usually internal to the stack in small fuel cells (for the sake of compactness), sealing around manifold holes is required to prevent the mixing of reactants between manifolds and electrodes; the considerations are the same for internal tie-bolt holes.

The sealing methodology generally employed involves a polymeric frame element (gasket) on each side of the electrolyte-membrane, separating the respective, truncated electrodes from the outside. These elements contain appropriate holes to allow for reactant manifolding and tie-rods in these regions.

APPENDIX A
DEFINITIONS

Adsorption The taking up or retention of one material or medium by another by chemical or molecular action.

Accumulator See SECONDARY BATTERY.

Activated Stand Life The period of time, at a specified temperature, that a battery can be stored in the charged condition before its capacity falls below a specified level.

Activation The process of making a reserve battery functional, either by introducing an electrolyte, by immersing the battery into an electrolyte, or by other means (see Part 3).

Activation Polarization Polarization resulting from the charge-transfer step of the electrode reaction (see POLARIZATION).

Active Cell or Battery A cell or battery containing all components and in a charged state ready for discharge (as distinct from a RESERVE CELL or BATTERY).

Active Material The material in the electrodes of a cell or battery that takes part in the electrochemical reactions of charge or discharge.

Aging Permanent loss of capacity due either to repeated use or to passage of time.

Ambient Temperature The average temperature of the surroundings.

Ampere-Hour Capacity The quantity of electricity measured in Ampere-hours (Ah) which may be delivered by a cell or battery under specified conditions.

Ampere-Hour Efficiency The ratio of the output of a secondary cell or battery, measured in Ampere-hours, to the input required to restore the initial state of charge, under specified conditions (also coulumbic efficiency).

Anion Ion in the electrolyte carrying a negative charge.

Anode The electrode in an electrochemical cell where oxidation takes place. During discharge, the negative electrode of the cell is the anode. During charge, the situation reverses and the positive electrode of the cell is the anode.

Anolyte The portion of the electrolyte in a galvanic cell adjacent to the anode; if a diaphragm is present, the electrolyte on the anode side of the diaphragm.

Aprotic Solvent A nonaqueous solvent that does not contain any reactive protons although it may contain hydrogen atoms in the molecule.

Available Capacity The total capacity (Amp-hours) that will be obtained from a cell or battery at defined discharge rates and other specified discharge or operating conditions.

Battery One or more electrochemical cells electrically connected in an appropriate series/parallel arrangement to provide the required operating voltage and current levels including, if any, monitors, controls and other ancillary components (fuses, diodes), case, terminals and markings (see p. 1.3).

Bipolar Plate An electrode construction where positive and negative active materials are on opposite sides of an electronically conductive plate.

Bobbin A cylindrical electrode (usually the positive) pressed from a mixture of the active material, a conductive material, such as carbon black, the electrolyte and/or binder with a centrally located conductive rod or other means for a current collector.

Boost Charge Charging of batteries in storage to maintain their capacity and counter the effects of self-discharge.

Boundary Layer The volume of electrolyte solution immediately adjacent to the electrode surface in which concentration changes occur due to the effects of the electrode process.

C Rate The discharge or charge current, in Amperes, expressed as a multiple of the rated capacity in ampere-hours.

$$I = M \times C_n$$

where I = current, A
C = numerical value of rated capacity of a battery in ampere-hours (Ah)
n = Time in hours for which rated capacity is specified
M = multiple or fraction (of C)

For example, the $0.05C$ or $C/20$ discharge current for a battery rated at 5 Ah at the $0.2C$ or $C/5$ rate is 250 mA.

$$I = M \times C_{0.2} = (0.05)(5) = 0.250 \text{ Amperes}$$

Conversely, a battery rated at 300 mAh at the $0.5C$ or $C/2$ rate, discharged at 30 mA, is discharged at the $0.1C$ or $C/10$ rate, which is calculated as follows:

$$M = \frac{I}{C_{0.5}} = \frac{0.030}{0.300} = 0.1 \text{ or } C/10$$

Capacitance Current The fraction of the cell current consumed in charging the electrical double layer.

Capacity The total number of Ampere-hours (Ah) that can be withdrawn from a fully charged cell or battery under specified conditions of discharge. (See also AVAILABLE CAPACITY, RATED CAPACITY.)

Capacity Fade Gradual loss of capacity of a secondary battery with cycling.

Capacity Retention The fraction of the full capacity available from a battery under specified conditions of discharge after it has been stored for a period of time.

Cathode The electrode in an electrochemical cell where reduction takes place. During discharge, the positive electrode of the cell is the cathode. During charge, the situation reverses, and the negative electrode of the cell is the cathode.

Catholyte The portion of an electrolyte in a galvanic cell adjacent to a cathode; if a diaphragm is present, the electrolyte on the cathode side of the diaphragm.

Cation Ion in the electrolyte carrying a positive charge.

Cell The basic electrochemical unit providing a source of electrical energy by direct conversion of chemical energy. The cell consists of an assembly of electrodes, separators, electrolyte, container and terminals (see p 1.3.)

Charge The conversion of electrical energy, provided in the form of a current from an external source, into chemical energy within a cell or battery.

Charge Acceptance Ability of a battery to accept charge. May be affected by temperature, charge rate, and state of charge.

Charge Control Techniques for effectively terminating the charging of a rechargeable battery.

Charge Efficiency See EFFICIENCY.

Charge Rate The current applied to a secondary cell or battery to restore its capacity. This rate is commonly expressed as a multiple of the rated capacity of the cell or battery. For example, the $C/10$ charge rate of a 500-Ah cell or battery (rated at the 0.2 rate) is expressed as

$$\frac{C_{0.2}}{10} = \frac{500\text{ Ah}}{10} = 50\text{ A}$$

Charge Retention See CAPACITY RETENTION.

Closed-Circuit Voltage (CCV) The potential or voltage of a cell or battery when it is discharging, normally under a specified load.

Concentration Polarization Polarization caused by the depletion of ions in the electrolyte at the surface of the electrode. (See also POLARIZATION.)

Conditioning Cycle charging and discharging of a battery to ensure that it is fully formed and fully charged. Sometimes indicated when a battery is first placed in service or returned to service after prolonged storage.

Constant Current Charge A method of charging the battery using a current having little variation.

Constant Voltage Charge A method of charging the battery by applying a fixed voltage, and allowing variations in the current. Also called constant potential charge.

Continuous Test A test in which a battery is discharged to a prescribed end-point voltage without interruption.

Coulometer Electrochemical or electronic device, capable of integrating current-time, used for charge control and for measurement of charge inputs and discharge outputs. Results usually reported in Ampere-hours.

Counter Electromotive Force A voltage of an electrochemical cell opposite to the applied external voltage. Also referred to as back EMF.

Couple Combination of anode and cathode materials that engage in electrochemical reactions that will produce current at a voltage defined by the reactions.

Creepage The movement of electrolyte onto surfaces of electrodes or other components of a cell with which it is not normally in contact.

Current Collector An inert member of high electrical conductivity used to conduct current from or to an electrode during discharge or charge.

Current Density The current per unit active area of the surface of an electrode.

Cutoff Voltage The battery voltage at which the discharge is terminated. Also called end voltage.

Cycle The discharge and subsequent or preceding charge of a secondary battery such that it is restored to its original conditions.

Cycle Life The number of cycles under specified conditions which are available from a secondary battery before it fails to meet specified criteria as to performance.

Cycle Service A duty cycle characterized by frequent and usually deep discharge-charge sequences, such as motive power applications.

Deep Discharge Withdrawal of at least 80% of the rated capacity of a battery.

Density The ratio of a mass of material to its own volume at a specified temperature.

Depolarization A reduction in the polarization of an electrode.

Depolarizer A substance or means used to prevent an increase polarization. The term ‘‘depolarizer’’ is often used to describe the positive electrode or cathode of a primary cell.

Depth of Discharge (DOD) The ratio of the quantity of electricity (usually in Ampere-hours) removed from a cell or battery on discharge to its rated capacity.

Desorption The opposite of absorption, whereby the material retained by a medium is released.

Diaphragm A porous or permeable material for separating the positive and negative electrode compartments of an electrochemical cell and preventing admixture of catholyte and anolyte.

Diffusion The movement of species under the influence of a concentration gradient.

Discharge The conversion of the chemical energy of a cell or battery into electrical energy and withdrawal of the electrical energy into a load.

Discharge Rate The rate, usually expressed in Amperes, at which electrical current is taken from the cell or battery.

Double Layer The region in the vicinity of an electrode-electrolyte interface where the concentration of mobile ionic species has been changed to values differing from the bulk equilibrium value by the potential difference across the interface.

Double-Layer Capacitance The capacitance of the electrical double layer at an electrode-electrolyte interface.

Dry Cell A cell with immobilized electrolyte. The term ‘‘dry cell’’ is often used to describe the Leclanché cell.

Dry Charged Battery A battery in which the electrodes are in a charged state, ready to be activated by the addition of the electrolyte.

Duplex Electrode or Plate See BIPOLAR PLATE.

Duty Cycle The operating regime of a cell or battery including factors such as charge and discharge rates, depth of discharge, cycle length, and length of time in the standby mode.

E Rate The discharge or charge power, in Watts, expressed as a multiple of the rated capacity in Watthours.

$$P = M = E_n$$

where P = power, W
E = numerical value of the rated energy of a battery in Watt-hours (Wh)
n = time in hours, at which the battery was rated
M = multiple or fraction (of E)

For example, the $0.05E$ or $E/20$ discharge power for a battery rated at 5 h at the $0.2E$ or $E/5$ rate is 250 mW.

$$P = M \times E_{0.2} = (0.05)(5) = 0.250 \text{ Watts}$$

Conversely, a battery rated at 300 mWh at the $0.5E$ or $E/2$ rate, discharged at 30 mW, is discharged at the $0.1E$ or $E/10$ rate, which is calculated as follows:

$$M = \frac{I}{E_{0.5}} = \frac{0.030}{0.300} = 0.1$$

Efficiency The ratio of the output of a secondary cell or battery on discharge to the input required to restore it to the initial state of charge under specified conditions. (see also AMPERE-HOUR EFFICIENCY, ENERGY EFFICIENCY, VOLTAGE EFFICIENCY, and WATTHOUR EFFICIENCY.)

Energy Efficiency See WATT HOUR EFFICIENCY.

Electrical Double Layer See DOUBLE LAYER.

Electrocapillarity The surface tension between liquid mercury and an electrolyte solution is modified by the potential difference across the interface. The effect is termed ''electrocapillarity.''

Electrochemical Cell A cell in which the electrochemical reactions are caused by supplying electrical energy or which supplies electrical energy as a result of electrochemical reactions: if the first case only is applicable, the cell is an electrolysis cell; if the second case only, the cell is a galvanic cell.

Electrochemical Couple See COUPLE.

Electrochemical Equivalent Weight of one equivalent of a substance being electrolyzed which is its gram atomic weight or its gram molecular weight divided by the number of electrons in the electrode reaction (see Faraday).

Electrochemical Series A classification of the elements according to the values of the standard potentials of specified electrochemical reactions.

Electrode The site, area, or location at which electrochemical processes take place.

Electrode Potential The voltage developed by a single plate either positive or negative against a standard reference electrode typically the standard hydrogen electron. The algebraic difference in voltage of any two electrodes equals the cell voltage.

Electroformation A term applied to the conversion of the material in both the positive and negative plates to their respective active materials. Also referred to as formation.

Electrolyte The medium which provides the ion transport mechanism between the positive and negative electrodes of a cell.

Electromotive Force (EMF) The standard potential of a specified electrochemical action.

Electromotive Series See ELECTROCHEMICAL SERIES.

Electron The elemental particle of an atom having a negative charge.

Element The negative and positive electrodes together with the separators of a single cell. It is used almost exclusively in describing lead-acid cells and batteries.

End Voltage The prescribed voltage at which the discharge (or charge, if end-of-charge voltage) of a battery may be considered complete (also cutoff voltage).

Energy Density The ratio of the energy available from a battery to its volume (Wh/L). See SPECIFIC ENERGY.

Equalization The process of restoring all cells in a battery to an equal state of charge.

Equilibrium Electrode Potential The difference in potential between an electrode and an electrolyte when they are in equilibrium for the electrode reaction which determines the electrode potential.

Equivalent Circuit An electrical circuit that models the fundamental properties of a device (e.g., a cell) or a circuit.

Exchange Current Under open circuit conditions, the forward and backward current of an electrochemical process are equal and opposite. This equilibrium current is defined as the exchange current.

Faraday One gram equivalent weight of matter is chemically altered at each electrode of a cell for each 96,494 international coulombs, or one Faraday, of electricity passed through the electrolyte.

Fast Charge A rate of charging which returns full capacity to a rechargeable battery, usually within an hour.

Fauré Plate See PASTED PLATE.

Flash Current See SHORT-CIRCUIT CURRENT.

Flat-Plate Cell A cell fabricated with rectangular flat-plate electrodes (also called a Prismatic Cell).

Float Charge A method of maintaining a battery in a charged condition by continuous, long-term constant-voltage charging, at a level sufficient to balance self-discharge.

Flooded Cell A cell design which incorporates an excess amount of electrolyte.

Forced Discharge Discharging a cell or battery below zero Volts into voltage reversal.

Formation Electrochemical processing of a battery plate or electrode which transforms the active materials into their usable form.

Fuel Cell A galvanic cell in which the active materials are continuously supplied from a source external to the cell and the reaction products continuously removed converting chemical energy to electrical energy.

Galvanic Cell An electrochemical cell that converts chemical energy into electrical energy by electrochemical action.

Gas Recombination Method of suppressing hydrogen generation during charging by recombining oxygen gas on the negative electrode as the cell approaches full charge.

Gassing The evolution of gas from one or more of the electrodes in a cell. Gassing commonly results from local action (self-discharge) or from the electrolysis of the electrolyte during charging.

Grid A framework for a plate or electrode which supports or retains the active materials and acts as a current collector.

Group An assembly of positive or negative plates which fit into a cell.

Half-Cell An electrode (either the anode or cathode) immersed in a suitable electrolyte.

Hourly Rate A discharge rate, in Amperes, of a battery which will deliver the specified hours of service to a given end voltage.

Hydrogen Electrode An electrode of platinized platinum saturated by a stream of pure hydrogen, immersed in an electrolyte of known acidity (pH).

Hydrogen Overvoltage The activation overvoltage for hydrogen discharge on an electrode.

Initial (Closed-Circuit) Voltage The on-load voltage at the beginning of a discharge.

Inner Helmholtz Plane The plane of closest approach of ions in solution. It corresponds to the plane which contains the adsorbed ions and the innermost layer of water molecules.

Intermittent Test A test during which a battery is subjected to alternate periods of discharge and rest according to a specified discharge regime.

Internal Impedance The opposition or resistance of a cell or battery to an alternating current of a particular frequency.

Internal Resistance The opposition or resistance to the flow of an electric current within a cell or battery; the sum of the ionic and electronic resistances of the cell components.

Ion A particle in solution which carries a negative or positive charge.

"IR" A voltage which is the product of the electrical resistance (R) of a cell or battery and the current (I). The value is the product of the resistance in Ohms and the current in Amperes.

Life For rechargeable batteries, the duration of satisfactory performance, measured in years (float life) or in the number of charge/discharge cycles (cycle life).

Load A term used to indicate the current drain on a battery.

Local Action Chemical reactions within a cell that convert the active materials to a discharged state without supplying energy through the battery terminals (self-discharge).

Luggin Capillary The bridge from an external reference electrode to a cell solution often has a capillary tip. The capillary which is often situated close to the working electrode to minimize the IR drop, is called a Luggin capillary.

Maintenance-Free Battery A secondary battery which does not require periodic ‘‘topping up’’ to maintain electrolyte volume.

Maximum-power Discharge Current, I_{mp} Discharge rate at which maximum power is transferred to the external load. This is the discharge rate when the discharge voltage is approximately equal to one-half of the open circuit voltage if the discharge is purely ohmic.

Mean Diffusion Current In polarography, the periodic detachment of mercury drops from the dropping mercury electrode impart an oscillation to the measured current. The average value of this current is termed the mean diffusion current.

Mechanical Recharging Restoring the capacity of a cell by replacing a spent or discharged electrode with a fresh one.

Memory Effect A phenomenon in which a cell, operated in successive cycles to the same, but less than a full, depth of discharge experiences a depression of its discharge voltage and temporarily loses the rest of its capacity at normal voltage levels. See Secs. 28.4.11 and 29.4.9.

Midpoint Voltage The voltage of a battery midway in the discharge between the fully charged state and the end voltage.

Migration The movement of a charged species under the influence of a potential gradient.

Motive Power Battery See TRACTION BATTERY.

Negative Electrode The electrode acting as an anode when a cell or battery is discharging.

Negative-Limited The operating characteristics (performance) of the cell is limited by the negative-electrode.

Nominal Voltage The characteristic operating voltage or rated voltage of or battery (as distinct from MIDPOINT VOLTAGE, WORKING VOLTAGE, etc.)

Off-Load Voltage See OPEN-CIRCUIT VOLTAGE.

Ohmic Overvoltage Overvoltage caused by the ohmic drop in an electrolyte.

On-Load Voltage The difference in voltage between the terminals of a cell or battery when it is discharging.

Open-Circuit Voltage (OCV) The difference in voltage between the terminals of a cell or voltage when the circuit is open (no-load condition).

Outer Helmholtz Plane The plane of closest approach of those ions which do not contact-absorb but approach the electrode with a sheath of solvated water molecules surrounding them.

Overcharge The forcing of current through a battery after all the active material has been converted to the charged state. In other words, charging continued after 100% state of charge is achieved.

Overdischarge Discharge past the point where the full capacity of the battery has been obtained.

Overvoltage The potential difference between the equilibrium potential of an electrode and that of the electrode under an imposed polarization current.

Oxygen Recombination The process by which oxygen generated at the positive plate during charge is reacted at the negative plate.

Paper-Lined Cell Construction of a cell where a layer of paper, wetted with electrolyte, acts as the separator.

Parallel Term used to describe the interconnection of cells or batteries in which all of the like terminals are connected together. Parallel connections increase the capacity of the resultant battery as follows:

$$C_p = n \times C_n$$

where C_p = the resultant capacity
n = the number of cells or batteries connected in parallel
C_u = capacity of the unconnected cell or battery.

Passivation The phenomenon by which an electrode, although in conditions of thermodynamic instability, remains unattacked because of its surface condition.

Paste Mixtures of various compounds that are applied to positive and negative grids of lead batteries. These pastes are then converted to positive and negative active materials. (See also FORMATION.)

Paste-Lined Cell Leclanché cell constructed so that a layer of gelled paste acts as the separator.

Pasted Plate A plate, manufactured by coating a grid or support strip with active materials in paste form.

Planté Plate A plate for a lead-acid battery in which the active materials are formed directly from a lead substrate by electrochemical processing.

Plate A structure containing active materials held firmly to a grid or conductor.

Pocket Plate A plate for a secondary battery in which active materials are held in perforated metal pockets on a support strip.

Polarity Denoting either positive or negative potential.

Polarization The change of the potential of a cell or electrode from its equilibrium value caused by the passage of an electric current.

Activation Polarization That part of electrode or battery polarization arising from the charge-transfer step of the electrode reaction.

Concentration Polarization That part of electrode or battery polarization arising from concentration gradients of battery reactants and products caused by the passage of current.

Ohmic Polarization That part of electrode or battery polarization arising from current flow through ohmic resistances within an electrode or battery.

Positive Electrode The electrode acting as a cathode when a cell or battery is discharging.

Positive-Limited The operating characteristics (performance) of the cell is limited by the positive electrode.

Power Density the ratio of the power available from a battery to its volume (W/L). See SPECIFIC POWER.

Primary Cell or Battery A cell or battery which is not intended to be recharged and is discarded when the cell or battery has delivered all its electrical energy.

Prismatic Cell See FLAT-PLATE CELL.

Rate Constant At equilibrium, the forward and backward Faradic currents of an electrode process are equal and referred to as the exchange current. This exchange current can be defined in terms of a rate constant called the standard heterogeneous rate constant for the electrode process.

Rated Capacity The number of Ampere-hours a battery can deliver under specific conditions (rate of discharge, end voltage, temperature); usually the manufacturer's rating.

Recharge See CHARGE.

Rechargeable Battery See SECONDARY BATTERY.

Recombination A term used in a sealed cell construction for the process whereby internal pressure is relieved by reaction of oxygen with the negative active material.

Recovery See RECUPERATION.

Recuperation The lowering of the polarization of a cell during rest periods.

Redox Cell A secondary cell in which two soluble ionic reactants, separated by a membrane, form the active materials.

Reference Electrode A specially chosen electrode which has a reproducible potential against which other electrode potentials may be measured. (See HYDROGEN ELECTRODE).

Reserve Cell or Battery A cell or battery which may be stored in an inactive state and made ready for use by adding electrolyte, another cell component, or, in the case of a thermal battery, melting a solidified electrolyte.

Reversal The changing of the normal polarity of a cell or battery.

Secondary Battery A galvanic battery which, after discharge, may be restored to the charged state by the passage of an electric current through the cell in the opposite direction to that of discharge.

Self-Discharge The loss of useful capacity of a cell or battery due to internal chemical action (local action).

Semi-Permeable Membrane A film that will pass selected ions.

Separator An ion permeable, electronically nonconductive, spacer or material which prevents electronic contact between electrodes of opposite polarity in the same cell.

Series The interconnection of cells or batteries in such a manner that the positive terminal of the first is connected to the negative terminal of the second, and so on. Series connections increase the voltage of the resultant battery as follows:

$$V_s = n \times V_u$$

where V_s = the resultant voltage
n = the number of cells or batteries connected in series
V_u = voltage of the unconnected cell or battery

Service Life The period of useful life of a primary battery before a predetermined end-point voltage is reached.

Shallow Discharge A discharge on a secondary battery equalling only a small part of its total capacity.

Shape Change Change in shape of an electrode due to migration of active material during charge/discharge cycling.

Shedding The loss of active material from a plate during cycling.

Shelf Life The duration of storage under specified conditions at the end of which a cell or battery still retains the ability to give a specified performance.

Short-Circuit Current The initial value of the current obtained from a battery in a circuit of negligible resistance.

Sintered Electrode An electrode construction in which active materials are deposited in the interstices of a porous metal matrix made by sintering metal powder.

SLI Battery A battery designed to start internal combustion engines and to power the electrical systems in automobiles when the engine is not running (starting, lighting, ignition).

Specific Energy The ratio of the energy output of a cell or battery to its weight (Wh/kg). (See also ENERGY DENSITY.)

Specific Gravity The specific gravity of a solution is the ratio of the weight of the solution to the weight of an equal volume of water at a specified temperature.

Specific Power The ratio of the power delivered by a cell or battery to its weight (W/kg). (See also POWER DENSITY.)

Spirally Wound Cell A cylindrical cell which uses an electrode structure made by winding the electrodes and separators into a cylindrical ‘‘jelly-roll’’ construction. (See Fig. 28.2 and Fig. 14.8).

Standard Electrode Potential The equilibrium value of an electrode potential when all the constituents taking part in the electrode reaction are in the standard state.

Standby Battery A battery designed for emergency use in the event of a main power failure.

Starved Electrolyte Cell A cell containing little or no free fluid electrolyte. This enables gases to reach electrode surfaces during charging and facilitates gas recombination.

State-of-Charge (SOC) The available capacity in a battery expressed as a percentage of rated capacity.

Stationary Battery A secondary battery designed for use in a fixed location.

Storage Battery See SECONDARY BATTERY.

Storage Life See SHELF LIFE.

Sulfation Process occurring in lead batteries that have been stored and allowed to self-discharge for extended periods of time. Large crystals of lead sulfate grow that interfere with the function of the active materials.

Taper Charge A charge regime delivering moderately high rate charging current when the battery is at a low state of charge and tapering the charging current to lower rates as the battery is charged.

Thermal Runaway A condition whereby a battery on charge or discharge will overheat and destroy itself through internal heat generation caused by high overcharge or overdischarging current or other abusive condition.

Traction Battery A secondary battery designed for the propulsion of electric vehicles or electrically operated mobile equipment operating in a deep-cycle regime.

Transfer Coefficient The transfer coefficient determines what fraction of the electrical energy of a system resulting from the displacement of the potential from the equilibrium value that affects the rate of electrochemical transformation. (See Chap. 2.)

Transition Time The time of an electrode process from the initiation of the process at constant current to the moment an abrupt change in potential occurs signifying that a new electrode process is controlling the electrode potential.

Transport Number The fraction of the total cell current carried by the cation of an electrolyte solution is called the ‘‘cation transport number.’’ Similarly, the fraction of the total current carried by the anion is referred to as the ‘‘anion transport number.’’ Also called Transference Number.

Trickle Charge A charge at a low rate, balancing losses through a local action and/or periodic discharge, to maintain a battery in a fully charged condition.

Tubular Plate A battery plate in which an assembly of perforated metal or polymer tubes holds the active materials.

Unactivated Shelf Life The period of time, under specified conditions of temperature and environment, that an unactivated or reserve battery can stand before deteriorating below a specified capacity.

Vent A normally sealed mechanism which allows for the controlled escape of gases from within a cell.

Vented Cell A cell design incorporating a vent mechanism to relieve excessive pressure and expel gases that are generated during the operation or abuse of the cell.

Voltage Delay Time delay for a battery to deliver the required operating voltage after it is placed under load.

Voltage Depression An abnormal low voltage, below the expected value, during the discharge of a battery.

Voltage Efficiency The ratio of average voltage during discharge to average voltage during recharge under specified conditions of charge and discharge.

Watthour Capacity The quantity of electrical energy measured in Watthours which may be delivered by a cell or battery under specified conditions.

Watthour Efficiency The ratio of the Watthours delivered on discharge of a battery to the Watthours needed to restore it to its original state under specified conditions of charge and discharge. Also called Energy Efficiency.

Wet Shelf Life The period of time that a battery can stand in the charged or activated condition before deteriorating below a specified capacity.

Working Voltage The typical voltage or range of voltages of a battery during discharge.