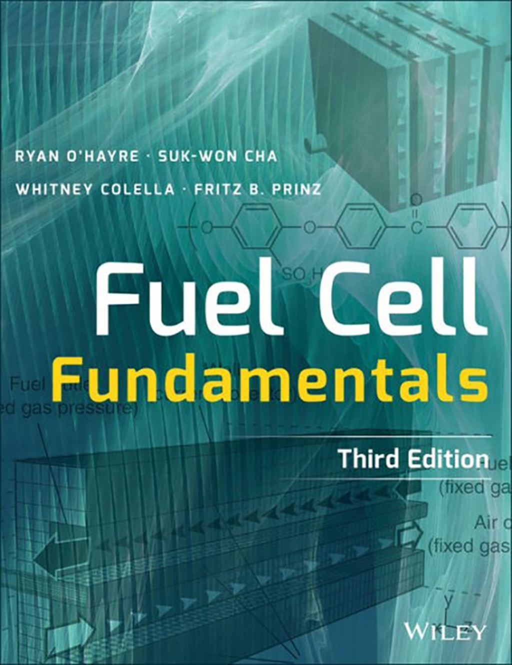

RYAN O'HAYRE · SUK-WON CHA
WHITNEY COLELLA · FRITZ B. PRINZ

# Fuel Cell Fundamentals

## Third Edition

WILEY

# FUEL CELL FUNDAMENTALS

Third Edition

**RYAN O'HAYRE**
Department of Metallurgical and Materials Engineering
Colorado School of Mines
[PhD, Materials Science and Engineering, Stanford University]

**SUK-WON CHA**
School of Mechanical and Aerospace Engineering
Seoul National University
[PhD, Mechanical Engineering, Stanford University]

**WHITNEY G. COLELLA**
The G.W.C. Whiting School of Engineering, and The Energy, Environment, Sustainability and Health Institute
The Johns Hopkins University
Gaia Energy Research Institute
[Doctorate, Engineering Science, The University of Oxford]

**FRITZ B. PRINZ**
R.H. Adams Professor of Engineering
Departments of Mechanical Engineering and Material Science and Engineering
Stanford University

WILEY

This book is printed on acid-free paper. ∞


Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.



**Library of Congress Cataloging-in-Publication Data is available:**

ISBN 9781119113805 (Cloth)
ISBN 9781119114208 (ePDF)
ISBN 9781119114154 (ePub)

Cover Design: Wiley
Cover Illustrations: Ryan O'Hayre
Cover Image: Glacial abstract shapes © ppart/iStockphoto

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

*To the parents who nurtured us.*

*To the teachers who inspired us.*

# CONTENTS

# PREFACE

Imagine driving home in a fuel cell car with nothing but pure water dripping from the tailpipe. Imagine a laptop computer that runs for 30 hours on a single charge. Imagine a world where air pollution emissions are a fraction of that from present-day automobiles and power plants. These dreams motivate today's fuel cell research. While some dreams (like cities chock-full of ultra-low-emission fuel cell cars) may be distant, others (like a 30-hour fuel cell laptop) may be closer than you think.

By taking fuel cells from the dream world to the real world, this book teaches you the *science* behind the technology. This book focuses on the questions "*how*" and "*why*." Inside you will find straightforward descriptions of *how* fuel cells work, *why* they offer the potential for high efficiency, and *how* their unique advantages can best be used. Emphasis is placed on the fundamental scientific principles that govern fuel cell operation. These principles remain constant and universally applicable, regardless of fuel cell type or technology.

Following this philosophy, the first part, "Fuel Cell Principles," is devoted to basic fuel cell physics. Illustrated diagrams, examples, text boxes, and homework questions are all designed to impart a unified, *intuitive* understanding of fuel cells. Of course, no treatment of fuel cells is complete without at least a brief discussion of the practical aspects of fuel cell technology. This is the aim of the second part of the book, "Fuel Cell Technology." Informative diagrams, tables, and examples provide an engaging review of the major fuel cell technologies. In this half of the book, you will learn how to select the right fuel cell for a given application and how to design a complete system. Finally, you will learn how to assess the potential environmental impact of fuel cell technology.

Comments or questions? Suggestions for improving the book? Found a typo, think our explanations could be improved, want to make a suggestion about other important concepts to discuss, or have we got it all wrong? Please send us your feedback by emailing us at fcf3@yahoogroups.com. We will take your suggestions into consideration for the next edition. Our website http://groups.yahoo.com/group/fcf3 posts these discussions, fliers for the book, and additional educational materials. Thank you.

# ACKNOWLEDGMENTS

The authors would like to thank their friends and colleagues at Stanford University and the former Rapid Prototyping Laboratory (RPL), now the Nano-Prototyping Laboratory (NPL), for their support, critiques, comments, and enthusiasm. Without you, this text would not have been written! The beautiful figures and illustrations featured in this textbook were crafted primarily by Marily Mallison, with additional illustrations by Dr. Michael Sanders—their artistic touch is greatly appreciated!

The authors would like to thank the Deans of the Stanford School of Engineering, Jim Plummer and Channing Robertson, and John Bravman, Vice Provost Undergraduate Education, for the support that made this book possible. We would also like to acknowledge Honda R&D, its representatives J. Araki, T. Kawanabe, Y. Fujisawa, Y. Kawaguchi, Y. Higuchi, T. Kubota, N. Kuriyama, Y. Saito, J. Sasahara, and H. Tsuru, and Stanford's Global Climate and Energy Project (GCEP) community for creating an atmosphere conducive to studying and researching new forms of power generation. All members of RPL/NPL are recognized for stimulating discussions. Special thanks to Dr. Tim Holme for his innumerable contributions, including his careful review of the text, integration work, nomenclature and equation summaries, and the appendixes. Thanks also to Professor Rojana Pornprasertsuk, who developed the wonderful quantum simulation images for Chapter 3 and Appendix D. The authors are grateful to Professor Yong-il Park for his help in the literature survey of Chapter 9 and Rami Elkhatib for his significant contributions in writing this section. Professor Juliet Risner deserves gratitude for her beautiful editing job, and Professor Hong Huang deserves thanks for content contribution. Dr. Jeremy Cheng, Dr. Kevin Crabb, Professor Turgut Gur, Shannon Miller, Masafumi Nakamura, and A. J. Simon also provided significant editorial advice. Thanks to Dr. Young-Seok Jee, Dr. Daeheung Lee, Dr. Yeageun Lee, Dr. Wonjong Yu, and Dr. Yusung Kim for their contributions to Chapters 6 and 13. Special thanks to Rusty Powell and Derick Reimanis for their careful editing contributions to the second edition. Finally, thanks to colleagues at the Colorado School of Mines (CSM), including Bob Kee and Neal Sullivan for their helpful discussions and for a decade's worth of students at CSM for catching typos and identifying areas in need for clarification for this third edition.

We would like to extend our gratitude to Professor Stephen H. Schneider, Professor Terry Root, Dr. Michael Mastrandrea, Mrs. Patricia Mastrandrea, Dr. Gerard Ketafani, and Dr. Jonathan Koomey. We would also like to thank the technical research staff within the U.S. Department of Energy (DOE) complex, including researchers at DOE national laboratories [Sandia National Laboratories (SNL), Lawrence Berkeley National Laboratory (LBNL), Argonne National Laboratory (ANL), the National Renewable Energy Laboratory (NREL), and Lawrence Livermore National Laboratory (LLNL), among others]. We would also like to thank research participants within the International Energy Agency (IEA) Stationary Fuel Cell Annex, the American Institute of Chemical Engineers (AICHE) Transport and Energy Processes Division (TEP), and the National Academy of Engineering (NAE) Frontiers of Engineering (FOE) program.

For intellectually stimulating discussions on energy system design, we also would like to thank Dr. Salvador Aceves (LLNL), Dr. Katherine Ayers (ProtonOnsite Inc.), Professor Nigel Brandon (Imperial College London), Mr. Tom Brown (California State University Northridge), Dr. Viviana Cigolotti [Energy and Sustainable Economic Development (ENEA)], Professor Peter Dobson [University of Oxford (Oxon)], Dr. Elango Elangovan (Ceramatec Inc.), Professor Ferhal Erhun, Dr. Angelo Esposito (European Institute for Energy Research), Dr. Hossein Ghezel-Ayagh [FuelCell Energy Inc. (FCE)], Dr. Lorenz Gubler [Paul Scherrer Institut (PSI)], Dr. Monjid Hamdan (Giner Inc.), Dr. Joseph J. Hartvigsen (Ceramatec Inc.), Professor Michael Hickner (The Pennsylvania State University), Professor Ben Hobbs (Johns Hopkins University), Professor Daniel M. Kammen [University of California at Berkeley (UCB)], Professor Jon Koomey, Dr. Scott Larsen (New York State Energy Research and Development Authority), Mr. Bruce Lin (EnerVault Inc.), Dr. Ludwig Lipp (FCE), Dr. Bernard Liu (National Cheng Kung University), Professor V. K. Mathur (University of New Hampshire), Dr. Marianne Mintz (ANL), Professor Catherine Mitchell (University of Exeter), Dr. Cortney Mittelsteadt (Giner Inc.), Dr. Yasunobu Mizutani (ToHo Gas Co. Ltd.), John Molburg (Argonne National Laboratory), Dr. Angelo Moreno [Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA)], Professor Vincenzo Mulone (University of Rome Tor Vergata), Dr. Jim O'Brien (Idaho National Laboratory), Professor Joan Ogden (University of California at Davis), Dr. Pinakin Patel (FCE), Dr. Randy Petri (Versa Power Inc.), Professor Bruno Pollet (University of Ulster), Dr. Peter Rieke [Pacific Northwest National Laboratory (PNNL)], Dr. Subhash C. Singhal (PNNL), Professor Colin Snowdon (Oxon), Professor Robert Socolow (Princeton University), Mr. Keith Spitznagel (KAS Energy Services LLC), Professor Robert Steinberger-Wilckens (University of Birmingham), Dr. Jeffry Stevenson (PNNL), Professor Richard Stone (Oxon), Professor Etim Ubong (Kettering University), Professor Eric D. Wachsman (University of Maryland), Professor Xia Wang (Oakland University), and Professor Yingru Zhao (Xiamen University).

Fritz B. Prinz wants to thank his wife, Gertrud, and his children, Marie-Helene and Benedikt, for their love, support, and patience.

Whitney G. Colella would like to thank her friends and family, especially the Bakers, Birchards, Chens, Colellas, Culvers, Efthimiades, Hoffmans, Jaquintas, Judges, Louies, Mavrovitis, Omlands, Pandolfis, Panwalkers, Qualtieris, Scales, Smiths, Spielers, Tepers, Thananarts, Tragers, Wasleys, and Wegmans.

Suk-Won Cha wishes to thank Unjung, William, and Sophia for their constant support, love, and understanding.

Ryan O'Hayre sends his thanks and gratitude to Lisa for her friendship, encouragement, confidence, support, and love. Thanks also to Kendra, Arthur, Morgan, little Anna, and little Robert. Ryan has always wanted to write a book … probably something about dragons and adventure. Well, things have a funny way of working out, and although he ended up writing about fuel cells, he had to put the dragons in somewhere. …

# NOMENCLATURE

| Symbol | Meaning | Common Units |
|---|---|---|
| $A$ | Area | $cm^2$ |
| $A_c$ | Catalyst area coefficient | Dimensionless |
| $a$ | Activity | Dimensionless |
| ASR | Area specific resistance | $\Omega \cdot cm^2$ |
| $C$ | Capacitance | F |
| $C_{dl}$ | Double-layer capacitance | F |
| $c^*$ | Concentration at reaction surface | $mol/cm^2$ |
| $c$ | Concentration | $mol/m^3$ |
| $c$ | Constant describing how mass transport affects concentration losses | V |
| $c_p$ | Heat capacity | $J/mol \cdot K$ |
| $D$ | Diffusivity | $cm^2/s$ |
| $E$ | Electric field | V/cm |
| $E$ | Thermodynamic ideal voltage | V |
| $E_{thermo}$ | Thermodynamic ideal voltage | V |
| $E_T$ | Temperature-dependent thermodynamic voltage at reference concentration | V |
| $F$ | Helmholtz free energy | J, J/mol |
| $F$ | Faraday constant | 96,485 C/mol |
| $F_k$ | Generalized force | N |
| $f$ | Reaction rate constant | Hz, $s^{-1}$ |
| $f$ | Friction factor | Dimensionless |

| Symbol | Meaning | Common Units |
|---|---|---|
| $G$, $g$ | Gibbs free energy | J, J/mol |
| $g$ | Acceleration due to gravity | $m/s^2$ |
| $\Delta G^{\ddagger}$ | Activation energy barrier | J/mol, J |
| $\Delta G_{act}$ | Activation energy barrier | J/mol, J |
| $H$ | Heat | J |
| $H$, $h$ | Enthalpy | J, J/mol |
| $H_C$ | Gas channel thickness | cm |
| $H_E$ | Diffusion layer thickness | cm |
| $h$ | Planck's constant | $6.63 \times 10^{-34}$ J · s |
| $\hbar$ | Reduced Planck constant, $h/2\pi$ | $1.05 \times 10^{-34}$ J · s |
| $h_m$ | Mass transfer convection coefficient | m/s |
| $i$ | Current | A |
| $J$ | Molar flux, molar reaction rate | $mol/cm^2 \cdot s$ |
| $\hat{J}$ | Mass flux | $g/cm^2 \cdot s$, $kg/m^2 \cdot s$ |
| $J_C$ | Convective mass flux | $kg/m^2 \cdot s$ |
| $j$ | Current density | $A/cm^2$ |
| $j_0$ | Exchange current density | $A/cm^2$ |
| $j_0^0$ | Exchange current density at reference concentration | $A/cm^2$ |
| $j_L$ | Limiting current density | $A/cm^2$ |
| $j_{leak}$ | Fuel leakage current | $A/cm^2$ |
| $k$ | Boltzmann's constant | $1.38 \times 10^{-23}$ J/K |
| $L$ | Length | m |
| $M$ | Molar mass | g/mol, kg/mol |
| $M$ | Mass flow rate | kg/s |
| $M_{ik}$ | Generalized coupling coefficient between force and flux | Varies |
| $m$ | Mass | kg |
| $mc_p$ | Heat capacity flow rate | kW/kg · °C |
| $N$ | Number of moles | Dimensionless |
| $N_A$ | Avogadro's number | $6.02 \times 10^{23}$ $mol^{-1}$ |
| $n$ | Number of electrons transferred in the reaction | Dimensionless |
| $n_g$ | Number of moles of gas | Dimensionless |
| $P$ | Power or power density | W or $W/cm^2$ |
| $P$ | Pressure | bar, atm, Pa |
| $Q$ | Heat | J, J/mol |
| $Q$ | Charge | C |
| $Q_h$ | Adsorption charge | $C/cm^2$ |
| $Q_m$ | Adsorption charge for smooth catalyst surface | $C/cm^2$ |
| $q$ | Fundamental charge | $1.60 \times 10^{-19}$ C |
| $R$ | Ideal gas constant | 8.314 J/mol · K |
| $R$ | Resistance | Ω |
| $R_f$ | Faradaic resistance | Ω |

| Symbol | Meaning | Common Units |
|---|---|---|
| Re | Reynolds number | Dimensionless |
| $S, s$ | Entropy | $J/K,\ J/mol \cdot K$ |
| $S/C$ | Steam-to-carbon ratio | Dimensionless |
| Sh | Sherwood number | Dimensionless |
| $T$ | Temperature | K, °C |
| $t$ | Thickness | cm |
| $U$ | Internal energy | $J,\ J/mol$ |
| $u$ | Mobility | $cm^2/V \cdot s$ |
| $\bar{u}$ | Mean flow velocity | $cm/s,\ m/s$ |
| $V$ | Voltage | V |
| $V$ | Volume | $L,\ cm^3$ |
| $V$ | Reaction rate per unit area | $mol/cm^2 \cdot s$ |
| $v$ | Velocity | $cm/s$ |
| $v$ | Hopping rate | $s^{-1}$, Hz |
| $v$ | Molar flow rate | $mol/s,\ mol/min$ |
| $W$ | Work | $J,\ J/mol$ |
| $X$ | Parasitic power load | W |
| $x$ | Mole fraction | Dimensionless |
| $x_v$ | Vacancy fraction | mol vacancies/mol sites |
| $y_x$ | Yield of element $X$ | Dimensionless |
| $Z$ | Impedance | Ω |
| $z$ | Height | cm |

Greek Symbols

| Symbol | Meaning | Common Units |
|---|---|---|
| $\alpha$ | Charge transfer coefficient | Dimensionless |
| $\alpha$ | Coefficient for $CO_2$ equivalent | Dimensionless |
| $\alpha^*$ | Channel aspect ratio | Dimensionless |
| $\beta$ | Coefficient for $CO_2$ equivalent | Dimensionless |
| $\gamma$ | Activity coefficient | Dimensionless |
| $\Delta$ | Denotes change in quantity | Dimensionless |
| $\delta$ | Diffusion layer thickness | m, cm |
| $\varepsilon$ | Efficiency | Dimensionless |
| $\varepsilon_{FP}$ | Efficiency of fuel processor | Dimensionless |
| $\varepsilon_{FR}$ | Efficiency of fuel reformer | Dimensionless |
| $\varepsilon_{H}$ | Efficiency of heat recovery | Dimensionless |
| $\varepsilon_{O}$ | Efficiency overall | Dimensionless |
| $\varepsilon_{R}$ | Efficiency, electrical | Dimensionless |
| $\varepsilon$ | Porosity | Dimensionless |
| $\dot{\varepsilon}$ | Strain rate | $s^{-1}$ |

| Symbol | Meaning | Common Units |
|---|---|---|
| $\eta$ | Overvoltage | V |
| $\eta_{act}$ | Activation overvoltage | V |
| $\eta_{conc}$ | Concentration overvoltage | V |
| $\eta_{ohmic}$ | Ohmic overvoltage | V |
| $\lambda$ | Stoichiometric coefficient | Dimensionless |
| $\lambda$ | Water content | Dimensionless |
| $\mu$ | Viscosity | kg · m/s |
| $\mu$ | Chemical potential | J, J/mol |
| $\tilde{\mu}$ | Electrochemical potential | J, J/mol |
| $\rho$ | Resistivity | Ω cm |
| $\rho$ | Density | $kg/cm^3$, $kg/m^3$ |
| $\sigma$ | Conductivity | $S/cm$, $(\Omega \cdot cm)^{-1}$ |
| $\sigma$ | Warburg coefficient | $\Omega/s^{0.5}$ |
| $\tau$ | Mean free time | s |
| $\tau$ | Shear stress | Pa |
| $\varphi$ | Electrical potential | V |
| $\varphi$ | Phase factor | Dimensionless |
| $\omega$ | Angular frequency ($\omega = 2\pi f$) | rad/s |

Superscripts

| Symbol | Meaning |
|---|---|
| 0 | Denotes standard or reference state |
| eff | Effective property |

Subscripts

| Symbol | Meaning |
|---|---|
| diff | Diffusion |
| $E$, $e$, elec | Electrical (e.g., $P_e$, $W_{elec}$) |
| $f$ | Quantity of formation (e.g., $\Delta H_f$) |
| (HHV) | Higher heating value |
| (LHV) | Lower heating value |
| $i$ | Species i |
| $P$ | Product |
| $P$ | Parasitic |
| $R$ | Reactant |
| rxn | Change in a reaction (e.g., $\Delta H_{rxn}$) |
| SK | Stack |
| SYS | System |

# PART I

# FUEL CELL PRINCIPLES

*Fuel Cell Fundamentals: Third Edition.* Ryan O'Hayre, Suk-Won Cha, Whitney G. Colella and Fritz B. Prinz

# CHAPTER 1

# INTRODUCTION

You are about to embark on a journey into the world of fuel cells and electrochemistry. This chapter will act as a roadmap for your travels, setting the stage for the rest of the book. In broad terms, this chapter will acquaint you with fuel cells: what they are, how they work, and what significant advantages and disadvantages they present. From this starting point, the subsequent chapters will lead you onward in your journey as you acquire a fundamental understanding of fuel cell principles.

## 1.1 WHAT IS A FUEL CELL?

You can think of a fuel cell as a "factory" that takes fuel as input and produces electricity as output. (See Figure 1.1.) Like a factory, a fuel cell will continue to churn out product (electricity) as long as raw material (fuel) is supplied. This is the key difference between a fuel cell and a battery. While both rely on electrochemistry to work their magic, a fuel cell is not consumed when it produces electricity. It is really a factory, a *shell*, which transforms the chemical energy stored in a fuel into electrical energy.

Viewed this way, combustion engines are also "chemical factories." Combustion engines also take the chemical energy stored in a fuel and transform it into useful mechanical or electrical energy. So what is the difference between a combustion engine and a fuel cell?

In a conventional combustion engine, fuel is burned, releasing heat. Consider the simplest example, the combustion of hydrogen:

$$H_2 + \tfrac{1}{2}O_2 \rightleftharpoons H_2O \tag{1.1}$$

*Fuel Cell Fundamentals: Third Edition.* Ryan O'Hayre, Suk-Won Cha, Whitney G. Colella and Fritz B. Prinz

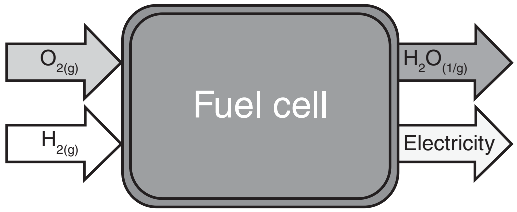


**Figure 1.1.** General concept of a ($H_2$–$O_2$) fuel cell.

On the molecular scale, collisions between hydrogen molecules and oxygen molecules result in a reaction. The hydrogen molecules are oxidized, producing water and releasing heat. Specifically, at the atomic scale, in a matter of picoseconds, hydrogen–hydrogen bonds and oxygen–oxygen bonds are broken, while hydrogen–oxygen bonds are formed. These bonds are broken and formed by the transfer of electrons between the molecules. The energy of the product water bonding configuration is lower than the bonding configurations of the initial hydrogen and oxygen gases. This energy difference is released as heat. Although the energy difference between the initial and final states occurs by a reconfiguration of electrons as they move from one bonding state to another, this energy is recoverable only as heat because the bonding reconfiguration occurs in picoseconds at an intimate, subatomic scale. (See Figure 1.2.) To produce electricity, this heat energy must be converted into mechanical energy, and then the mechanical energy must be converted into electrical energy. Going through all these steps is potentially complex and inefficient.

Consider an alternative solution: to produce electricity directly from the chemical reaction by somehow harnessing the electrons as they move from high-energy reactant bonds

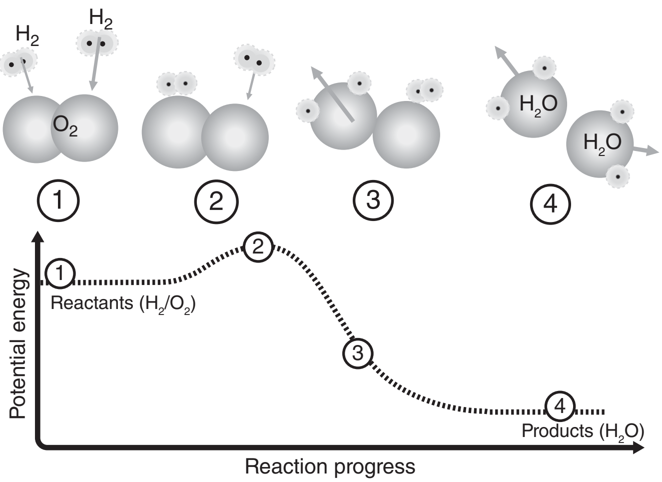


**Figure 1.2.** Schematic of $H_2$–$O_2$ combustion reaction. (Arrows indicate the relative motion of the molecules participating in the reaction.) Starting with the reactant $H_2$–$O_2$ gases (1), hydrogen–hydrogen and oxygen–oxygen bonds must first be broken, requiring energy input (2) before hydrogen–oxygen bonds are formed, leading to energy output (3, 4).

to low-energy product bonds. In fact, this is exactly what a fuel cell does. But the question is, how do we harness electrons that reconfigure in picoseconds at subatomic length scales? The answer is to spatially separate the hydrogen and oxygen reactants so that the electron transfer necessary to complete the bonding reconfiguration occurs over a greatly extended length scale. Then, as the electrons move from the fuel species to the oxidant species, they can be harnessed as an electrical current.

### BONDS AND ENERGY

Atoms are social creatures. They almost always prefer to be together instead of alone. When atoms come together, they form bonds, lowering their total energy. Figure 1.3 shows a typical energy–distance curve for a hydrogen–hydrogen bond. When the hydrogen atoms are far apart from one another (1), no bond exists and the system has high energy. As the hydrogen atoms approach one another, the system energy is lowered until the most stable bonding configuration (2) is reached. Further overlap between the atoms is energetically unfavorable because the repulsive forces between the nuclei begin to dominate (3). Remember:

- Energy is released when a bond is formed.
- Energy is absorbed when a bond is broken.

For a reaction to result in a net release of energy, the energy released by the formation of the product bonds must be more than the energy absorbed to break the reactant bonds.

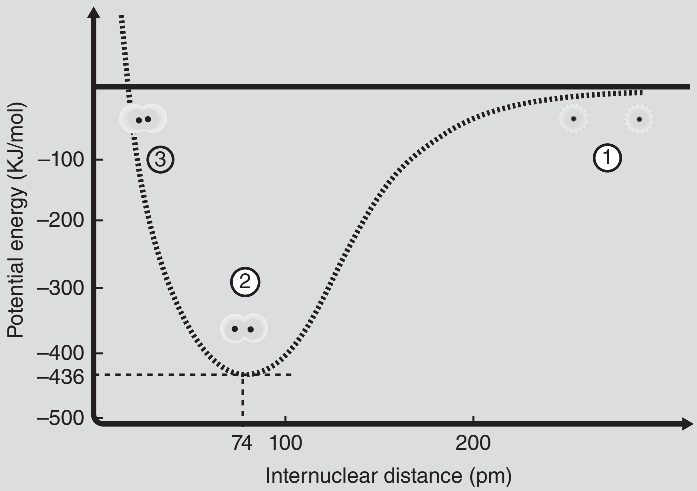


**Figure 1.3.** Bonding energy versus internuclear separation for hydrogen–hydrogen bond: (1) no bond exists; (2) most stable bonding configuration; (3) further overlap unfavorable due to internuclear repulsion.

## 1.2 A SIMPLE FUEL CELL

In a fuel cell, the hydrogen *combustion* reaction is split into two *electrochemical* half reactions:

$$H_2 \rightleftharpoons 2H^+ + 2e^- \tag{1.2}$$

$$\tfrac{1}{2}O_2 + 2H^+ + 2e^- \rightleftharpoons H_2O \tag{1.3}$$

By spatially separating these reactions, the electrons transferred from the fuel are forced to flow through an external circuit (thus constituting an electric current) and do useful work before they can complete the reaction.

Spatial separation is accomplished by employing an electrolyte. An electrolyte is a material that allows ions (charged atoms) to flow but not electrons. At a minimum, a fuel cell must possess two electrodes, where the two electrochemical half reactions occur, separated by an electrolyte.

Figure 1.4 shows an example of an extremely simple $H_2$–$O_2$ fuel cell. This fuel cell consists of two platinum electrodes dipped into sulfuric acid (an aqueous acid electrolyte). Hydrogen gas, bubbled across the left electrode, is split into protons ($H^+$) and electrons following Equation 1.2. The protons can flow through the electrolyte (the sulfuric acid is like a "sea" of $H^+$), but the electrons cannot. Instead, the electrons flow from left to right through a piece of wire that connects the two platinum electrodes. Note that the resulting current, as it is traditionally defined, is in the opposite direction. When the electrons reach the right electrode, they recombine with protons and bubbling oxygen gas to produce water following Equation 1.3. If a load (e.g., a light bulb) is introduced along the path of the electrons, the flowing electrons will provide power to the load, causing the light bulb to glow. Our fuel cell

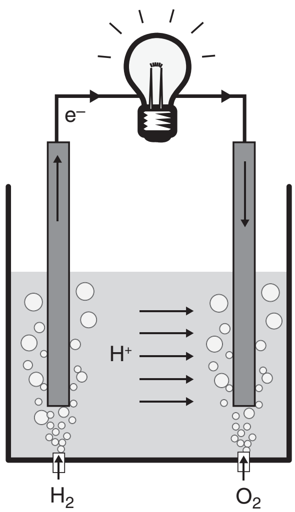


**Figure 1.4.** A simple fuel cell.

is producing electricity! The first fuel cell, invented by William Grove in 1839, probably looked a lot like the one discussed here.

### ENERGY, POWER, ENERGY DENSITY, AND POWER DENSITY

To understand how a fuel cell compares to a combustion engine or a battery, several quantitative metrics, or *figures of merit*, are required. The most common figures of merit used to compare energy conversion systems are *power density* and *energy density*.

To understand energy density and power density, you first need to understand the difference between energy and power:

*Energy* is defined as the ability to do work. Energy is usually measured in joules (J) or calories (cal).

*Power* is defined as the rate at which energy is expended or produced. In other words, power represents the *intensity* of energy use or production. Power is a rate. The typical unit of power, the watt (W), represents the amount of energy used or produced per second (1 W = 1 J/s).

From the above discussion, it is obvious that energy is the product of power and time:

$$\text{Energy} = \text{power} \times \text{time} \tag{1.4}$$

Although the International System of Units (SI) uses the joule as the unit of energy, you will often see energy expressed in terms of watt-hours (Wh) or kilowatt-hours (kWh). These units arise when the units of power (e.g., watts) are multiplied by a length of time (e.g., hours) as in Equation 1.4. Obviously, watt-hours can be converted to joules or vice versa using simple arithmetic:

$$1\,\text{Wh} \times 3600\,\text{s/h} \times 1\,(\text{J/s})/\text{W} = 3600\,\text{J} \tag{1.5}$$

Refer to Appendix A for a list of some of the more common unit conversions for energy and power. For portable fuel cells and other mobile energy conversion devices, power density and energy density are more important than power and energy because they provide information about *how big* a system needs to be to deliver a certain amount of energy or power. Power density refers to the amount of power that can be produced by a device per unit mass or volume. Energy density refers to the total energy capacity available to the system per unit mass or volume.

*Volumetric power density* is the amount of power that can be supplied by a device per unit volume. Typical units are $\text{W/cm}^3$ or $\text{kW/m}^3$.

*Gravimetric power density (or specific power)* is the amount of power that can be supplied by a device per unit mass. Typical units are W/g or kW/kg.

*Volumetric energy density* is the amount of energy that is available to a device per unit volume. Typical units are $Wh/cm^3$ or $kWh/m^3$.

*Gravimetric energy density (or specific energy)* is the amount of energy that is available to a device per unit mass. Typical units are Wh/g or kWh/kg.

## 1.3 FUEL CELL ADVANTAGES

Because fuel cells are "factories" that produce electricity as long as they are supplied with fuel, they share some characteristics in common with combustion engines. Because fuel

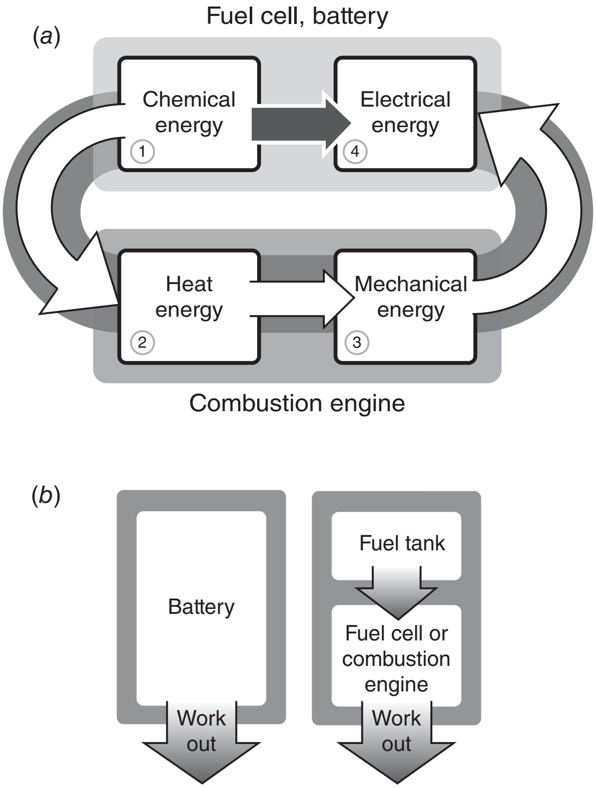


**Figure 1.5.** Schematic comparison of fuel cells, batteries, and combustion engines. (*a*) Fuel cells and batteries produce electricity directly from chemical energy. In contrast, combustion engines first convert chemical energy into heat, then mechanical energy, and finally electricity (alternatively, the mechanical energy can sometimes be used directly). (*b*) In batteries, power and capacity are typically intertwined—the battery is both the energy storage and the energy conversion device. In contrast, fuel cells and combustion engines allow independent scaling between power (determined by the fuel cell or engine size) and capacity (determined by the fuel tank size).

cells are electrochemical energy conversion devices that rely on electrochemistry to work their magic, they share some characteristics in common with primary batteries. In fact, fuel cells combine many of the advantages of both engines and batteries.

Since fuel cells produce electricity directly from chemical energy, they are often far more efficient than combustion engines. Fuel cells can be all solid state and mechanically ideal, meaning no moving parts. This yields the potential for highly reliable and long-lasting systems. A lack of moving parts also means that fuel cells are silent. Also, undesirable products such as $NO_x$, $SO_x$, and particulate emissions are virtually zero.

Unlike batteries, fuel cells allow easy independent scaling between power (determined by the fuel cell size) and capacity (determined by the fuel reservoir size). In batteries, power and capacity are often convoluted. Batteries scale poorly at large sizes, whereas fuel cells scale well from the 1-W range (cell phone) to the megawatt range (power plant). Fuel cells offer potentially higher energy densities than batteries and can be quickly recharged by refueling, whereas batteries must be thrown away or plugged in for a time-consuming recharge. Figure 1.5 schematically illustrates the similarities and differences between fuel cells, batteries, and combustion engines.

### FUEL CELLS VERSUS SOLAR CELLS VERSUS BATTERIES

Fuel cells, solar cells, and batteries all produce electrical power by converting either chemical energy (fuel cells, batteries) or solar energy (solar cells) to a direct-current (DC) flow of electricity. The key features of these three devices are compared in Figure 1.6 using the analogy of buckets filled with water. In all three devices, the electrical output power is determined by the operating voltage (the height of water in the bucket) and current density (the amount of water flowing out the spigot at the bottom of the bucket).

Fuel cells and solar cells can be viewed as "open" thermodynamic systems that operate at a thermodynamic steady state. In other words, the operating voltage of a fuel cell (or a solar cell) remains constant in time so long as it is continually supplied with fuel (or photons) from an external source. In Figure 1.6, this is shown by the fact that the water in the fuel cell and solar cell buckets is continually replenished from the top at the same rate that it flows out the spigot in the bottom, resulting in a constant water level (constant operating voltage).

In contrast, most batteries are closed thermodynamic systems that contain a finite and exhaustible internal supply of chemical energy (reactants). As these reactants deplete, the voltage of the battery generally decreases over time. In Figure 1.6, this is shown by the fact that the water in the battery bucket is not replenished, resulting in a decreasing water level (decreasing operating voltage) with time as the battery is discharged. It is important to point out that battery voltage does not decrease linearly during discharge. During discharge, batteries pass through voltage plateaus where the voltage remains more or less constant for a significant part of the discharge cycle. This phenomenon is captured by the strange shape of the battery "bucket."

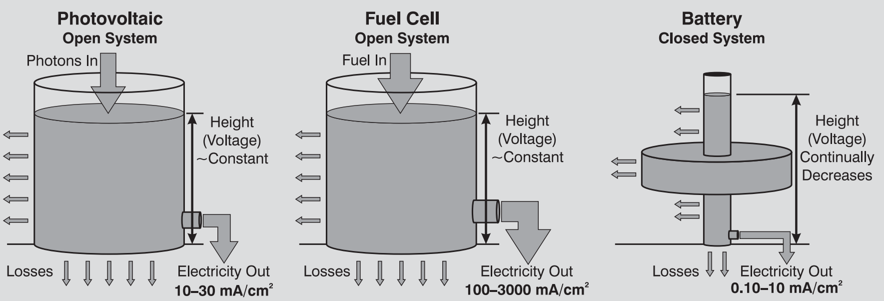


**Figure 1.6.** Fuel cells versus solar cells versus batteries. This schematic diagram provides another way to look at the similarities and differences between three common energy conversion technologies that provide electricity as an output.

In addition to the thermodynamic operating differences between fuel cells, solar cells, and batteries, Figure 1.6 also shows that fuel cells typically operate at much higher current densities than solar cells or batteries. This characteristic places great importance on using low-resistance materials in fuel cells to minimize ohmic ("*IR*") losses. We will learn more about minimizing ohmic losses in Chapter 4 of this textbook!

## 1.4 FUEL CELL DISADVANTAGES

While fuel cells present intriguing advantages, they also possess some serious disadvantages. Cost represents a major barrier to fuel cell implementation. Because of prohibitive costs, fuel cell technology is currently only economically competitive in a few highly specialized applications (e.g., onboard the Space Shuttle orbiter). Power density is another significant limitation. Power density expresses how much power a fuel cell can produce per unit volume (volumetric power density) or per unit mass (gravimetric power density). Although fuel cell power densities have improved dramatically over the past decades, further improvements are required if fuel cells are to compete in portable and automotive applications. Combustion engines and batteries generally outperform fuel cells on a volumetric power density basis; on a gravimetric power density basis, the race is much closer. (See Figure 1.7.)

Fuel availability and storage pose further problems. Fuel cells work best on hydrogen gas, a fuel that is not widely available, has a low volumetric energy density, and is difficult

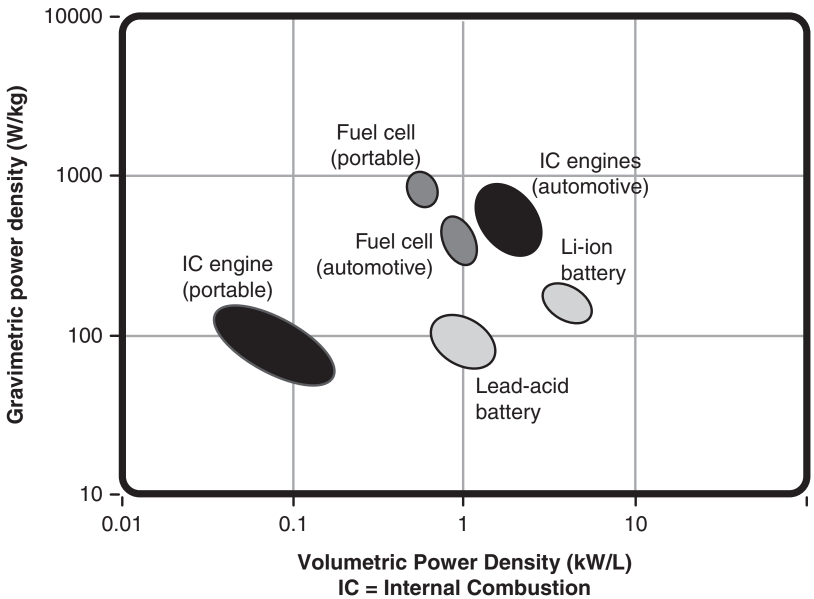


**Figure 1.7.** Power density comparison of selected technologies (approximate ranges).

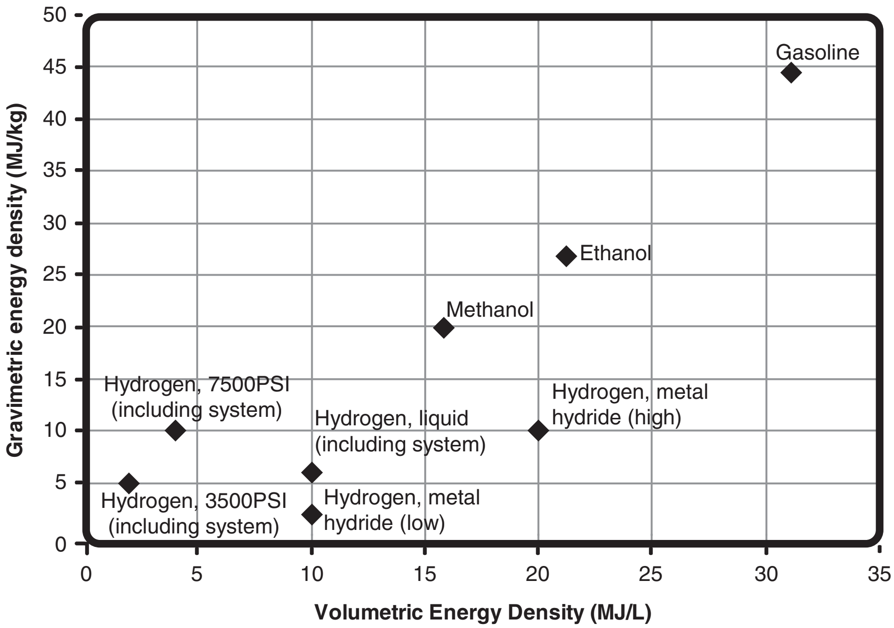


**Figure 1.8.** Energy density comparison of selected fuels (lower heating value).

to store. (See Figure 1.8.) Alternative fuels (e.g., gasoline, methanol, formic acid) are difficult to use directly and usually require reforming. These problems can reduce fuel cell performance and increase the requirements for ancillary equipment. Thus, although gasoline looks like an attractive fuel from an energy density standpoint, it is not well suited to fuel cell use.

Additional fuel cell limitations include operational temperature compatibility concerns, susceptibility to environmental poisons, and durability under start–stop cycling. These significant disadvantages will not be easy to overcome. Fuel cell adoption will be severely limited unless technological solutions can be developed to hurdle these barriers.

## 1.5 FUEL CELL TYPES

There are five major types of fuel cells, differentiated from one another by their electrolyte:

1. Phosphoric acid fuel cell (PAFC)
2. Polymer electrolyte membrane fuel cell (PEMFC)
3. Alkaline fuel cell (AFC)
4. Molten carbonate fuel cell (MCFC)
5. Solid-oxide fuel cell (SOFC)