FUEL CELLS FOR BUILDING APPLICATIONS

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PREFACE

Fuel cell systems are a promising new type of on-site power generation technology that offers modularity, efficient operation across a wide range of load conditions, minimal environmental impact, and opportunities for integration into cogeneration systems. Cogeneration systems simultaneously provide power and heat and offer a number of advantages including economic benefits, better utilization of energy resources, and reduced environmental impact. The advent of fuel cell cogeneration systems promises to make these advantages available in applications that were previously not well suited for cogeneration.

There are four types of fuel cell technology that are applicable for building systems. Proton exchange membrane fuel cells (PEMFC) operate at low temperatures and are applicable in sizes as small as a few kWe. Phosphoric acid fuel cells (PAFC) have been demonstrated in several hundred building applications, typically at sizes of approximately 200 kWe. Molten carbonate fuel cells (MCFC) operate at higher temperatures and offer more flexibility in fuel processor design and integration. Solid oxide fuel cells (SOFC) operate at temperatures as high as 1000ºC (1800ºF) and offer flexible fuel processor design and integration as well as opportunities for additional electricity production using the high-temperature exhaust stream.

Each of the four technologies is currently the subject of extensive research and development efforts. Research is underway to improve the performance, extend the operating life, reduce the initial cost, and improve the tolerance to fuel stream impurities. These goals are being accomplished through improvements in materials, optimization of operating conditions, and advances in manufacturing methods. A variety of demonstration projects are underway for each technology. These projects provide valuable data on the actual field performance of these systems.

Fuel cell systems include not only the fuel cell itself but also the fuel processor, power conditioner, thermal management, and water management subsystems. These different subsystems are integrated to form fuel cell systems that yield electrical conversion efficiencies that can exceed 45 percent. Furthermore, fuel cell systems can maintain high efficiency at loads as low as 50 percent of full load. Thus, fuel cell systems exhibit performance characteristics that are comparable to the most efficient stationary power systems and provide this performance over a broad range of loads and in relatively small sizes.

Emissions from the fuel cell system occur primarily from the fuel processor and are usually far below regulatory limits. With low emissions, minimal noise, and a relatively unobtrusive appearance, fuel cell systems can be sited in a variety of locations near the point of power use. The life expectancy of a fuel cell system is projected to be twenty years, with replacement of the fuel cell stack required at roughly five-year intervals. Other than stack replacement, fuel cell system maintenance consists of the routine maintenance procedures that are required for the fans, pumps, and controls that comprise the support systems. Estimates of annual maintenance costs, including a sinking fund for stack replacement, range from less that $0.01/kWh to as high a $0.03/kWh.

Application of fuel cell cogeneration systems in buildings requires selection of an operating strategy, coordination with the local utility systems, and evaluation of the economic value of the system. A simple calculation of the cost of electricity provided by the fuel cell system can provide a preliminary indication of the economic potential. A more detailed hour by hour model can provide a more accurate estimate of the savings associated with a fuel cell cogeneration system. Simple cost of electricity calculations indicate that fuel cell systems can be competitive in residential and commercial applications provided initial costs can be reduced to approximately $1,500/kWe. Current projections indicate that fuel cell systems can be provided at costs below $2,000/kWe with some projections indicating costs as low as $500/kWe. Once the economic criteria are satisfied, implementation of fuel cell cogeneration systems will require meeting the requirements of building codes and standards. Currently, a variety of codes and standards are under development, including codes governing installation in buildings, standards for fuel cell system construction and performance testing, and standards for interconnection with the local utility.

Considerable progress is being made in the development and commercialization of fuel cell cogeneration systems for buildings. Progress is being made in the development of fuel cell technology, system inte-

gration, manufacturing methods, and in the development of a regulatory infrastructure to facilitate the implementation of fuel cell technology. Building designers are a critical link in the dissemination of this new technology. By understanding fuel cells and cogeneration systems, designers can identify appropriate applications that will yield economic and environmental benefits for their clients and for society.

Chapter 1

INTRODUCTION

This technology assessment guide is intended to introduce the reader to the basic principles of fuel cell technology, to assess the current status of fuel cell technology for building applications, and to provide an understanding of fuel cell systems and their application in building cogeneration systems. Cogeneration systems simultaneously provide both electrical and thermal energy. Cogeneration systems based on conventional generating technologies, such as reciprocating engines, gas turbines, and steam turbines, have been employed in industrial facilities, district heating systems, and, to a limited extent, in large commercial buildings. From an energy use and environmental impact point of view, cogeneration systems are very attractive. In a traditional electric power plant, only about 30% to 40% of the fuel energy is converted to electric power, and the remainder is discharged to the atmosphere or a nearby river. With cogeneration, this thermal energy can be recovered and used for space heating, water heating, manufacturing processes, etc. Typically, an additional 30% to 40% of the fuel energy can be utilized. This means that 30% to 40% less primary energy is used, and emissions of CO_2 and other pollutants can be reduced.

The widespread application of cogeneration systems in buildings has been limited by several factors:

- Conventional generating technology tends to be more economical in large sizes.
- Conventional generating technology is most efficient in large sizes and when operating near full load.
- Conventional generating technology tends to require a larger, more skilled maintenance staff than is available in many building applications.
- Noise and environmental emissions restrict the potential sites for conventional generating technology.

Fuel cell-based cogeneration systems overcome many of these limitations and greatly expand the possible applications for cogeneration.

Chapter 1 of this guide provides a discussion of fuel cell fundamentals and introduces the four major types of fuel cells that are most applicable in buildings. Chapter 2 provides a detailed discussion of the current status of each of the fuel cell technologies with respect to design, manufacturing, and commercialization. Chapter 3 discusses the integration of the fuel cell into a fuel cell system that typically includes a fuel processor, power conditioner, and thermal, water, and air management subsystems. Chapter 3 also reviews the system characteristics that are most significant to building applications. Chapter 4 discusses the application of fuel cell cogeneration systems in buildings and highlights the economic, regulatory, and application issues that must be considered when evaluating these systems. Chapter 5 summarizes the material presented in the guide and discusses the future of fuel cell cogeneration systems in buildings.

FUEL CELL FUNDAMENTALS

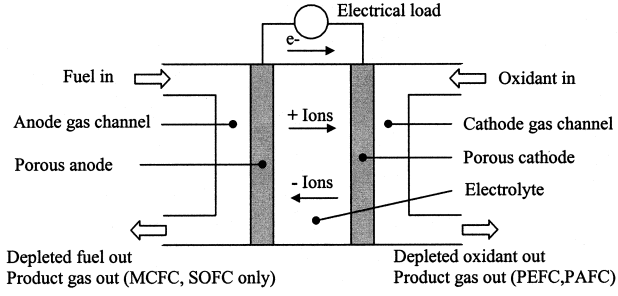
Fuel Cell Description

Fuel cells are electrochemical devices that convert chemical energy to electrical energy and heat. In a fuel cell the conversion process from chemical energy to electricity is direct. In contrast, conventional energy conversion processes first transform chemical energy to heat through combustion and then convert heat to electricity through some type of power cycle (e.g., steam power plant, gas turbine, or internal combustion engine) coupled with a generator. The direct nature of the fuel cell process yields relatively high efficiencies and, in many cases, simplified power systems when compared to conventional energy conversion systems.

A schematic of a fuel cell is illustrated in Figure 1-1. The fuel cell consists of the following five major elements:

1. Fuel flow channel
2. Anode
3. Electrolyte
4. Cathode
5. Oxidant flow channel

Fuel enters the cell through the fuel flow channel and then travels into the anode where it is oxidized, yielding electrons that travel through the external electrical load. Oxidant enters the cell through the oxidant flow



Fuel cell type	+ Ion	- Ion
PEFC	H^+	none
PAFC	H^+	none
MCFC	none	CO_3^{2-}
SOFC	none	O^{2-}

Figure 1-1 Fuel cell schematic.

channel and then travels into the cathode where it is reduced as it reacts with electrons from the external circuit. Ions are exchanged between the anode and the cathode to balance the reaction. The details of the half reactions and the composition of the ions travelling within the electrolyte depend on the type of fuel cell, but the net fuel cell reaction is:

$$H_2 + 1/2\ O_2 \rightarrow H_2O \qquad (1\text{-}1)$$

Fuel cells are most commonly classified by the type of electrolyte and include

- proton exchange membrane fuel cells (PEMFC),[1]
- alkaline fuel cells (AFC),
- phosphoric acid fuel cell (PAFC),
- molten carbonate fuel cells (MCFC),
- solid oxide fuel cells (SOFC), and
- direct methanol fuel cells (DMFC).

1. Proton exchange membrane fuel cells (PEMFC) are also referred to as polymer electrolyte fuel cells (PEFC).

The AFC is of historical interest as it was one of the first types to see practical use, serving as the primary power source on the Apollo space missions and on the space shuttle. However, this type of fuel cell is being phased out in favor of the PEMFC for space applications and is of limited value in terrestrial applications (where the oxidant is air) because of the sensitivity of the AFC electrolyte to CO_2. In transportation and portable power applications, the portability of liquid methanol makes the direct methanol fuel cell attractive. In stationary applications, methanol is not as attractive as more readily available fuels, such as natural gas and LP gas, which are used in the other four fuel cell types. This book will focus on the remaining four cell types—PEMFC, PAFC, MCFC, and SOFC—that are being actively developed for stationary applications.

Thermodynamics of Fuel Cell Operation

The reversible work associated with a chemical reaction involving N moles of fuel is given by the change in the Gibbs function,

$$W = -N\Delta\overline{G}, \tag{1-2}$$

where $\Delta\overline{G}$ is the change in Gibbs function per mole of fuel.

For a reaction among ideal gases given by

$$\alpha A + \beta B \rightarrow \chi C + \delta D, \tag{1-3}$$

the Gibbs function change per mole of fuel (i.e., reactant A) is given by

$$\Delta\overline{G} = \Delta\overline{G}^{\circ}(T) + RT\ln\frac{p_C^{\chi}p_D^{\delta}}{p_A^{\alpha}p_B^{\beta}} \tag{1-4}$$

where $\Delta\overline{G}^{\circ}(T)$ is the Gibbs function change per mole of fuel at standard pressure and the indicated temperature, and p is the partial pressure of each constituent in atmospheres.

The work associated with an electrochemical reaction can also be determined by the amount of charge that is moved through the electrical potential, E, associated with the reaction

$$W = nNFE \tag{1-5}$$

where n is the number of electrons involved per mole of fuel and F is Farraday's constant. Combining Equations 1-2 and 1-5 yields

$$E = \frac{-\Delta \bar{G}}{nF}. \tag{1-6}$$

Incorporating Equation 1-4 for a reaction among ideal gases gives the open circuit potential,

$$E = E°(T) - \frac{RT}{nF} \ln \frac{p_C^{\chi} p_D^{\delta}}{p_A^{\alpha} p_B^{\beta}} \tag{1-7}$$

where $E°(T)$ is the open circuit potential at standard pressure and the indicated temperature, defined by

$$E°(T) = \frac{-\Delta G°(T)}{nF}. \tag{1-8}$$

The open circuit potential given by Equation 1-7 represents the maximum voltage between the anode and cathode for the given cell reaction at the indicated temperature and reactant pressure. For substances other than ideal gases, Equation 1-7 can be generalized as

$$E = E°(T) - \frac{RT}{nF} \ln \frac{a_C^{\chi} a_D^{\delta}}{a_A^{\alpha} a_B^{\beta}} \tag{1-9}$$

where the a_i represent the activities of the products and reactants. Equation 1-9 is the general form of the Nernst equation [1].

Equation 1-6 can be used to derive an expression indicating the variation of open circuit potential with temperature and pressure. The Gibbs function is defined as

$$G = H - TS. \tag{1-10}$$

Taking the derivative of this expression using the chain rule yields

$$dG = dH - TdS - SdT. \tag{1-11}$$

Substituting the second Gibbs equation,

$$TdS = dH - Vdp, \tag{1-12}$$

into Equation 1-11 yields

$$dG = -SdT + Vdp \tag{1-13}$$

Equation 1-13 applies to both reactants and products:

$$dG_P = -S_P dT_P + V_P dp_P \tag{1-14a}$$

$$dG_R = -S_R dT_R + V_R dp_R \tag{1-14b}$$

If the products and reactants are at the same temperature and pressure, Equations 1-14a and 1-14b can be combined with Equation 1-6 to yield

$$\left.\frac{\partial E}{\partial T}\right)_{\substack{constant\\pressure}} = \frac{\Delta S}{nF} \tag{1-15a}$$

and

$$\left.\frac{\partial E}{\partial p}\right)_{\substack{constant\\temperature}} = -\frac{\Delta V}{nF} \tag{1-15b}$$

where ΔS and ΔV are the changes in entropy and volume, respectively, that are associated with the chemical reaction.

For example, for the reaction of hydrogen and oxygen to produce water, Equation 1-1, the change in Gibbs function, entropy, and volume at standard conditions of 25ºC (77ºF) and 1 atm are given by:

$$\Delta G = -229{,}000 \text{ J/gmol} \tag{1-16a}$$

$$\Delta S = -44 \text{ J/gmol-K} \tag{1-16b}$$

$$\Delta V = -0.0123 \text{ m}^3/\text{ g mol-K} \tag{1-16c}$$

when the product water is in the gas phase.

Thus, for a fuel cell operating on hydrogen and oxygen with the product water in the gas phase, Equation 1-7 yields an open circuit voltage of

$$E = \frac{229{,}000 \dfrac{\text{J}}{\text{gmol} - \text{H}_2}}{2\dfrac{\text{gmol} - \text{e}^-}{\text{gmol} - \text{H}_2} \times 96{,}487 \dfrac{\text{Coul}}{\text{gmol} - \text{e}^-}}$$

$$- \frac{8.314 \dfrac{\text{J}}{\text{gmol} - \text{H}_2 \times \text{K}} \times 298\text{K}}{2\dfrac{\text{gmol} - \text{e}^-}{\text{gmol} - \text{H}_2} \times 96,487 \dfrac{\text{Coul}}{\text{gmol} - \text{e}^-}} \times \ln \frac{(\text{latm})^1}{(\text{latm})^1 \times (\text{latm})^{0.5}} \tag{1-17}$$

$$E = 1.18 \frac{\text{J}}{\text{Coul}} - 0.0128 \times \ln(1) \frac{\text{J}}{\text{Coul}} = 1.18 \text{ V}.$$

This is the voltage that would be measured across the fuel cell when there is no current flow.

Since ΔS is negative, Equation 1-15a indicates that the open circuit voltage decreases with increasing temperature. Since the change in volume due to the reaction is negative, Equation 1-15b indicates that the open circuit voltage increases with increasing pressure. Figure 1-2 illustrates the variation of open circuit voltage with temperature. Neglecting other factors, this would predict a higher efficiency for hydrogen-fueled cells operating at a lower temperature. However, when current flows through the cell, other effects, called polarization losses, reduce the cell voltage below the open circuit value. These polarization losses tend to be reduced at elevated temperatures, thus counteracting the trend illustrated in Figure 1-2.

Polarization Losses

To produce work, current must flow between the anode and cathode. The flow of current leads to a reduction in cell voltage that is referred to as the *polarization loss* or *overvoltage*. The polarization loss is generally divided into three components—activation polarization, ohmic polarization, and concentration polarization.

Activiation polarization refers to the voltage drop required to move the electrochemical reaction forward at a finite rate. At both the anode and cathode, reactants diffuse to reaction sites where the reduction and oxidation reactions take place. At the reaction sites, an activation potential (or voltage difference) must be overcome before the reaction can proceed. Catalysts are used in the low-temperature fuel cells to lower the activation potential and allow the reaction to proceed. At higher

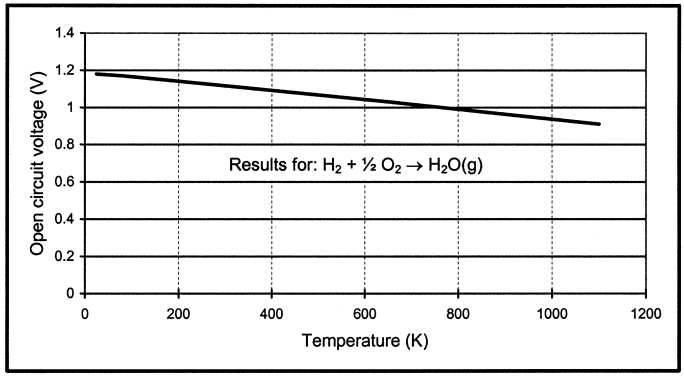


Figure 1-2 Variation of open circuit potential with temperature.

temperatures, the activation potential is reduced and there is less need for catalysts.

When the current density is very low, the required reactant transport rates are also low and, thus, the concentration gradients across the fuel cell are small. In this case, the reaction rate is controlled by the activation overpotential and the concentrations of reactants at the reaction sites approach the inlet concentrations. For this case, the activation polarization is commonly expressed as a function of the current density using an empirical equation called the Tafel equation,

$$V_{act} = a\log(i/i_0)\,, \tag{1-18}$$

where the Tafel slope, a, and the exchange current density, i_0, are experimentally determined constants [1].

As this equation indicates, the activation polarization increases logarithmically with current density. Thus the activation polarization changes rapidly at low current density and then changes more slowly at higher current densities. The Tafel slope and the exchange current density determine the activation polarization for a particular current density. Catalysts reduce the value of the Tafel slope and increase the exchange current density, thus decreasing the activation polarization for a given current density.

Ohmic polarization refers to the voltage drop that is attributable to the resistance to the flow of electrons and ions through the cell. Ohmic losses are roughly a linear function of the cell current:

$$V_{ohm} = iR \tag{1-19}$$

Concentration polarization refers to the voltage drop that is attributable to reactant flow restrictions at the electrodes. As the current density increases, the reactant flow rates required to sustain the reaction also increase. Eventually, the rate of transport through the cell cannot keep up with the rate at which the reactants are consumed. The reactant concentration at each reaction site begins to drop and thus the voltage drops.

The net cell voltage is the open circuit voltage less the various polarization losses:

$$V_{cell} = V_{oc} - V_{act} - V_{ohm} - V_{conc} \tag{1-20}$$

The power supplied by the fuel cell, $\dot{W}$, is given by the product of the current and the cell voltage:

$$\dot{W} = V_{cell}I_{cell} \tag{1-21}$$

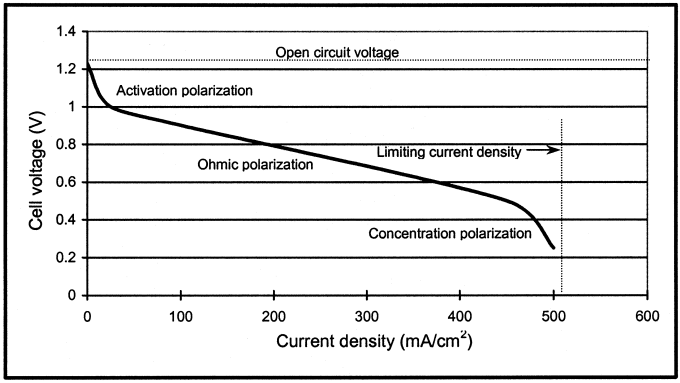


Figure 1-3 Typical fuel cell polarization curve.

Thus, the polarization losses, by reducing the cell voltage, directly reduce the electrical power available from the cell. Due to these losses, energy that would be available as electricity must instead be transferred from the cell as heat.

A polarization curve relates the cell voltage to the cell current. A typical polarization curve is presented in Figure 1-3. As the figure indicates, the open circuit voltage is the cell voltage when the current flow is zero. As current begins to flow, the voltage drops due to the activation polarization. Due to the logarithmic behavior, the activation polarization increases rapidly at first and then more slowly as the current density increases. At some point, increases in the ohmic polarization become more significant than those associated with the activation polarization. The polarization curve then takes on the linear shape associated with the ohmic losses. Finally, at high current densities, restrictions to the flow of reactants to the reaction sites lead to a limiting current density. While the values associated with the curve may change, all fuel cell technologies exhibit this general behavior. In addition to varying with the type of fuel cell, the polarization curve is affected by the fuel cell operating conditions. For example, changes in temperature and pressure can cause the curve to shift up or down and can change the value of the limiting current.

Fuel Cell Performance Measures

Fuel cell performance can be measured in terms of voltage (V), current density (mA/cm^2), power density (W/cm^2), and efficiency. The cell voltage and current density are related by a polarization curve such as

the one in Figure 1-3. The power density is the product of the cell voltage and current density. At low current densities, the power density increases with increasing current. However, as the limiting current density is approached, the decreasing cell voltage becomes more significant than the increasing cell current, and the power begins to decrease. Thus, the cell can be characterized by a maximum power density.

There are a number of ways to describe the fuel cell efficiency. The fuel cell transforms chemical energy into electrical power and heat. The reversible, or *ideal efficiency*, is the maximum electrical power that could be obtained from the chemical reaction occurring in the cell divided by the rate at which chemical energy is transformed by the complete reaction of the fuel entering the cell. The ideal efficiency is given by

$$\eta_{ideal} \equiv \frac{\dot{W}_{ideal}}{N \cdot \overline{HV}_a} = \frac{V_{oc} nNF}{N \cdot \overline{HV}_a} = \frac{V_{oc} nF}{\overline{HV}_a} \tag{1-22}$$

where $\dot{W}_{ideal}$ is the ideal power, N is the molar rate of reaction of the fuel (mol/s), n is the number of electrons involved in the electrochemical reaction ($n = 2$ for H_2), F is Faraday's constant, and $\overline{HV}_a$ is either the higher or lower heating value of the fuel supplied to the anode on a molar basis. If the heating value is expressed on a mass basis, Equation 1-22 becomes

$$\eta_{ideal} = \frac{V_{oc} nF}{M_a HV_a} \tag{1-23}$$

where M_a is the molar mass of the fuel supplied to the anode.

The heating value, HV, is the amount of energy released by the complete reaction of the fuel and depends on whether the product water leaving the fuel cell is in the liquid or vapor phase. If water is produced in the liquid phase, as it is in PEMFCs, more energy is available from the reaction and the heating value is called the higher heating value (HHV). If water is produced in the vapor phase, as it is for most other fuel cells, less energy is available from the reaction and the heating value is called the lower heating value (LHV).

The ideal efficiency does not reflect the losses associated with the activation, ohmic, and concentration polarizations. These effects reduce the cell voltage below the open circuit value. A second measure of efficiency that captures these effects is the *voltage efficiency*, given by