Objective of the fuel cell experiments:
To familiarize the working principles and performance characteristics of proton exchange membrane fuel cells.

Experimental Procedures

Instrumentation

A Scriber Associates Model 850C will be used in this experiment. A schematic of the fuel cell test system is shown in Figure 1. The system consists of the following primary components: 1 of fuel load (sink and power supply), 3 of temperature controllers, 2 of heated/insulated gas lines, 2 humidifiers (stainless steel) and 4 mass flow controllers (MCF). Figure 2 illustrates the front panel of the Scriber Associates Model 850C fuel cell test system.

Figure 1. Schematic of Scriber Associates Model 850C fuel cell system.
Figure 2. Picture of the Scriber Associates Model 850C fuel cell test system.

**Materials**

1. Fuel, oxidant and purge gases with appropriate regulators and pressure settings
   1. N₂ (Regulator code CGA No. 580), 40-60 psi
   2. H₂ (Regulator code CGA No. 350), 40-60 psi
   3. O₂ (Regulator code CGA No. 540), 40-60 psi
   4. Air 40-60 psi
2. Deionized water, wrenches and other accessories

**Software Program**

Fuel cell system is controlled with a computer program. The software displays 4 main screens; cell setup, fuel setup, main operating screen, experiment selection and setup menu. The cell setup screen, as shown in Figure 3, is used to set inputs to desired initial values for the cell. The set values can be changed at any time from the main operating screen by clicking on the cell setup menu icon.
Figure 3. Setup cell screen is used to set up the desired initial values for the cell.

The fuel setup screen, as shown in Figure 4, can be used to set operating parameters for the anode and cathode feeds.

Figure 4. The fuel Setup screen is used to set operating parameters for the anode and cathode feeds.
After entering cell and fuel parameters, the main operating screen will be displayed, as illustrated in Figure 5. Then, the settings chosen in the cell setup and fuel setup screens will be applied and the fuel cell test system is ready for operation.

Figure 5. Operating screen displays the chosen operating parameters in the cell setup and fuel setup, which are applied to the fuel cell system.

By clicking the new experiment icon in the main operating screen, a “select experiment type” screen, as shown in Figure 6, will be displayed and the specific experiment can be selected.

Figure 6. Select experiment type screen displays types of experiments available.
**Background Information**

**Voltage-Current Relationship**

There are three regions in the voltage-current relationship, as shown in Figure 7. The activation of the electrode reaction dominates at the low current density regime. The mid-current range is dominated by the Ohmic resistance. At high current density region, it is dominated by transport limitation.

![Diagram of voltage-current relationship](image)

**Figure 7.** Cell voltage as a function of cell current density.

The open circuit voltage (OCV), at zero current, is less than the theoretical voltage, $E_{\text{theor}}$, due to fuel crossover and internal currents. The $E_{\text{theor}}$ at specific temperature can be determined with the Nernst equation

$$E_{\text{theor}} = E^\circ + \left(\frac{RT}{nF}\right) \ln \left[\frac{(P_{H_2})(P_{O_2})^{1/2}}{P_{H_2O}}\right]$$

where $E_{\text{theor}}$ is the theoretical cell voltage at non-standard concentrations and at temperature in V, $E^\circ$ is the theoretical cell voltage at standard concentrations and at temperature $T$ in V, $R$
is the gas constant (8.314 J/mole-K), $T$ is the temperature in K, $F$ is the Faraday’s constant (96485 C), $n$ is the moles of electron produced per more of $H_2$ reacted ($n=2$ for this reaction) and $P_{H_2}$, $P_{O_2}$, $P_{H_2O}$ are the partial pressures of $H_2$, $O_2$ and $H_2O$, respectively. The theoretical cell voltage, $E^\circ$, at standard concentrations and at a specific temperature $T$ can be expressed as

$$E^\circ = -\Delta G^\circ/(n \times F)$$

and the changes in Gibbs free energy, $\Delta G^\circ$(J/mole) is

$$\Delta G^\circ = 45.99 \times T-242,297$$

There is a net current produced when the cell connected to an external load. The current density, defined as the current of cell divide by the active area of the cell (4 cm$^2$), is proportional to the net rate of the electrochemical reaction of the cell. The cell voltage and reaction rate of the cell are governed by some non-equilibrium irreversible losses. The $E^\circ$ for $H_2/O_2$ cell reaction is 1.23 eV per mole of $H_2$ at 25°C as determined by the $\Delta G^\circ$. The $E^\circ$ for the $H_2/O_2$ cell is indicated on the current density-voltage plot in Figure 7 as the horizontal line drawn at the voltage of 1.23 V.

When an external load is connected to the cell, a net current is produced at the electrodes. Due to some irreversible losses, this net electrochemical reaction is a non-equilibrium reaction. Thus the current density-voltage relationship is highly dependent on irreversible losses; kinetic activation resistance, Ohmic resistance and transport resistance.

Even there is no current is drawn from a fuel cell, there is an irreversible voltage loss due to crossover of fuel through the electrolyte, electronic conduction through the electrolyte and oxidation of catalyst and electrode materials. Supposedly, the electrolyte should only allow the transporting ions, but some fuel also across the membrane and some direct transfer of electrons across the membranes occurring as an electronic short. The combinations of losses make the difference between $E^\circ$ and open circuit cell voltage. In addition, activation polarization is another irreversible voltage loss associated with overpowering the energy barrier to the reactions at the electrodes and these loss are a function of temperature, pressure, fuel concentration and electrode properties. The exchange current density, $i_0$, represents the reaction rate proceeding at equilibrium, when the net reaction rate is zero. $i_0$ can be obtained by extrapolating the experimentally linear portion of the log $i$ v.s. voltage curve back to $V= 0$. Kinetic resistance dominates the voltage loss in the low current density regime of the current density-voltage curve. Tafel equation is usually used to represent the current density-voltage characteristics in the region.

$$\Delta V_{act} = b \times \log (i) - a$$

where $\Delta V_{act}$ is the voltage loss due to activation polarization (the difference between open circuit voltage and cell voltage) in V, $a$ is the kinetic parameter proportional to the log ($i_0$) in V and $b$ is the Tafel slope in V/dec. The Tafel slope is the reciprocal of the slope for plotting the log (current density) v.s. voltage loss at the small current density region.
Ohmic Losses

The voltage loss due to the resistance of ionic current in the electrolyte and electronic current in the electrodes is called Ohmic loss, $\Delta V_{\text{Ohm}}$.

$$\Delta V_{\text{Ohm}} = i \times R_{\text{Ohm}}$$

where $R_{\text{Ohm}}$ is the Ohmic resistance of the cell in $\Omega$-cm$^2$. Electronic resistances are related to contact resistances at junctions around cell electrodes associated with gas diffusion layers and current collectors, but the electronic resistance is not the dominated component of Ohmic losses as compared to the resistance from the ion transport through the electrolyte; transporting protons in the polymer membrane and catalyst layers.

Transport Limitations

Concentration voltage drop is due to quick reactant consumption at the electrode surfaces, and produce a fuel concentration gradient around the electrode. The concentration voltage drop can be expressed as

$$\Delta V_{\text{conc}} = 2.303 \frac{(RT)}{(nF)} \times \ln(i_{\text{lim}}/(i_{\text{lim}} - i))$$

where $i_{\text{lim}}$ is the limiting current density defined as the current density corresponding to zero surface concentration. When the current density increasing to the limiting current density, the
concentrations at the surface of the electrodes fall to zero, and current density of the cell will not be further increased.

Then the cell voltage, $V_{\text{cell}}$, can be expressed as

$$V_{\text{cell}} = E_{\text{theor}} - b \times \log(i) - a - I \times Rohm - B \times \ln(1 - i/i_{\text{lim}})$$

**Power Density**

The power density delivered by a fuel cell is the product of the current density and the cell voltage at a specific current density,

Power Density (W/cm$^2$) = $i \times V$

Power density of a non-linear function of the current density and reaching a maximum around 2/3 of the limiting current density, as illustrated in Figure 8. The size of fuel cell is also employed specify the power of the fuel, such as power generated by the mass of cell or number of stack of the cell.
Figure 8. Power density as a function of the current density with different oxygen percentage in the cathode stream.

**Faraday’s Law and Reactant Consumption**

Faradays’ law governs the relationship between the total current passed the cell in a given amount time and the amount of reactants consumed or product produced, which can be expressed as

\[ i = \frac{(w \times n \times F)}{(t \times M \times s)} \]

or

\[ \frac{i}{2F} = \frac{d(\text{moles H}_2\text{O})}{dt} = -\frac{d(\text{moles H}_2)}{dt} = -2\frac{d(\text{moles O}_2)}{dt} \]

where \( w \) is the weight of the reactant consumed or product produced, \( t \) is the time, \( M \) is the molecular mass of the reactant or product, \( s \) is the stoichiometric coefficient of the product or the reactant.

**Cell Efficiency**

Voltage efficiency, \( \varepsilon_v \), is defined as

\[ \varepsilon_v = \frac{V_{\text{cell}}}{E_{\text{theor}}} \]

Current efficiency, \( \varepsilon_c \), is defined as

\[ \varepsilon_c = \frac{\text{actual current produced}}{\text{theoretical current should be produced for a given reactant feed rate}} \]

**Reactant Utilization**

Fuel consumption, \( U \), is an important factor of fuel cell efficiency, and fuel consumption is defined as

\[ U = \frac{\text{amount of reactant consumed}}{\text{amount of reactant fed to the fuel cell}} \]

**Experiment 1: Study the effect of oxygen concentrations on fuel cell performance**

*Set up scan current experiments*
1. Vary the oxygen concentrations ranging from 100, 21 and 2% oxygen and keep the cell, anode as well cathode humidifier temperature at 90°C.
2. Plot cell voltage vs current density/power density at different oxygen concentrations.
3. Determine the OCV experimentally and theoretically for the cell running with 100, 21 and 2% oxygen.
4. Determine theoretical cell voltage, Tafel slope, Ohmic resistance and limiting current for the cell running with 100, 21 and 2% oxygen.
5. Determine the maximum power density, cell efficiencies and reactant utilization for the cell running with 100, 21 and 2% oxygen.

Experiment 2: Study the effect of humidity on fuel cell performance

1. Vary the humidity of the anode and cathode humidifiers by setting the anode and cathode temperature at 40, 60 or 80°C while keeping the cell temperature at 80°C.
2. Plot cell voltage vs current density/power density at different humidity.
3. Determine the OCV experimentally and theoretically for the cell running at different humidity.
4. Determine theoretical cell voltage, Tafel slope, Ohmic resistance and limiting current for the cell running at different humidity.
5. Determine the maximum power density, cell efficiencies and reactant utilization for the cell running with different humidity.

Experiment 3: Study the effect of cell temperatures on fuel cell performance

1. Vary the temperature of anode and cathode humidifiers as well as the cell temperature at 40, 60 or 80°C.
2. Plot cell voltage vs current density/power density by setting the temperatures of both humidifiers and cell at 40, 60 or 80°C.

3. Determine the OCV experimentally and theoretically by setting the temperatures of both humidifiers and cell at 40, 60 or 80°C.

4. Determine theoretical cell voltage, Tafel slope, Ohmic resistance and limiting current by setting the temperatures of both humidifiers and cell at 40, 60 or 80°C.

5. Determine the maximum power density, cell efficiencies and reactant utilization by setting the temperatures of both humidifiers and cell at 40, 60 or 80°C.