A Parametric Study of Stack Performance for a 4.8kW PEM Fuel Cell Stack

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Master of Science

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This thesis titled
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ABSTRACT

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A Parametric Study of Stack Performance for a 4.8kW PEM Fuel Cell Stack (97 pp.)

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Parametric testing was conducted to determine the effects of reactant stream temperature, pressure, humidity and flow rate on the voltage and power output of a 4.8kW PEM fuel cell (FC) stack. The effect of physical orientation and coolant temperature on the voltage and power output of the FC stack is discussed. It was determined that the reactant flow rates could be reduced to approximately 90% of the manufacturer’s recommended values without significantly affecting the performance of the FC stack. Increasing reactant stream temperature, pressure, and relative humidity increased the power output of the FC stack. The power output of the FC stack was shown to be sensitive to reactant stream temperatures. This effect was more pronounced for loads below approximately 100A. The power output of the FC stack was also observed to increase with increasing coolant temperature. This effect was greater for higher loads. Reactant stream pressure was observed to cause a nearly uniform shift in the ohmic region of the FC stack’s polarization curve. The difference in the power output between the high and low pressures tested was approximately 8% from 0-200A load. The power output of the FC stack was not sensitive to changes in the reactant stream relative humidity for values above 70%. Reactant stream relative humidity was shown to have a more pronounced effect for loads less than 100A. The FC stack’s physical orientation did not affect the stack’s power output for inclinations less than 13.5°. The time required for
the FC stack to reach a steady state voltage following abrupt load changes was not significantly different for different step sizes. The voltage observed within 0.1 seconds of all load changes was always within 2% of the steady state value. Based on the results of this study, the FC stack that was tested is well suited for its intended automotive application.

Approved: _____________________________

Greg Kremer

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CHAPTER 1 INTRODUCTION

1.1 CHAPTER SUMMARY

General information concerning the motivation for alternatives to conventional gasoline and diesel propulsion systems is discussed. Polymer Electrolyte Membrane (PEM) fuel cell based propulsion systems are introduced as one potential alternative that is currently receiving significant attention. Challenges that face hydrogen as a primary fuel source are discussed and the use of hydrogen carriers as an alternative is introduced. Ammonia as a potential fuel source and the advantage of ammonia waste recovery is discussed. The Ammonia Car Project of the Russ College of Engineering and Technology at Ohio University is introduced leading to the motivation for this research. The purpose of this research is to determine the effect of fuel and oxidant flow rate, temperature, humidity, back pressure and physical orientation on the performance of a Ballard® Mark9 SSL™ 4.8kW fuel cell stack. Another goal of this research is to determine some basic dynamic response information for the fuel cell stack. The full scope and purpose of this paper are outlined in this section.

1.2 BACKGROUND

Growing public concern over petroleum cost and global climate change has prompted many researchers to develop alternatives to conventional gasoline and diesel powered propulsion systems. One such technology is PEM fuel cells which convert the chemical potential energy of hydrogen gas into electricity that can be utilized by electricity based propulsion systems. However, there are a number of challenges that make PEM fuel cell implementation a difficult option for automotive applications. One of the major problems with hydrogen gas is that it contains very little potential energy per unit volume at standard temperature and pressure compared to petroleum based fuels. As a result, hydrogen gas must be stored at high pressures in order to contain enough energy to propel a vehicle over distances that are competitive with current technology. Such pressures create potential safety hazards and storage issues that are not a problem with gasoline and diesel fueled vehicles. Other significant hurdles that currently limit hydrogen use in the transportation industry are its cost compared to gasoline and diesel
and the net amount of carbon dioxide and other pollutants that are created during hydrogen production and distribution. In order to alleviate some of the pollution and energy density problems, hydrogen carriers can be used instead of hydrogen gas alone. It has been shown that ammonia is a well suited hydrogen carrier for a number of niche transportation applications (6). This is especially true for industries where ammonia waste can be recovered easily and subsequently used as a fuel source. An interdisciplinary research project called the Ammonia Car Project is currently being conducted in the Russ College of Engineering and Technology at Ohio University in order to demonstrate the feasibility of an ammonia electrolysis and PEM fuel cell based propulsion system. The current state of the project requires the performance of a 4.8kW fuel cell stack to be characterized. The purpose of this thesis is to present the results of the performance study and to discuss parametric limitations for the successful implementation of the fuel cell stack.

A considerable motivation for the transition from petroleum powered propulsion systems to other energy alternatives is the expected increase in fuel costs as petroleum reserves are depleted and the demand for petroleum increases. For the general public, especially those living in developed countries, this may be the most important consideration because an increase in fuel costs will affect not only the cost of personal transportation but the cost of commodities requiring long distance distribution as well.

In addition to the expected increase in petroleum costs, the degree to which developed countries rely on petroleum based fuels is equally troubling. For example, the United States used approximately 101.9 quadrillion Btu (1.075x10^{20} J) of energy in 2007 according to the United States Department of Energy (7). Of that, approximately 30% was used for transportation alone. Since the energy used in the transportation industry is almost exclusively generated using petroleum based fuels, it is clear that a significant amount of petroleum dependence exists. Furthermore, a number of statistical and socioeconomic studies have concluded that there will be a major worldwide increase in the total number of vehicles which will drastically affect the demand for petroleum. For example, a model was developed by researchers at the University of Leeds, England and
New York University which predicts an increase in the total world vehicle stock from 800 million in 2002 to over 2 billion in 2030; See Figure 1(2). With a considerable percentage of the world’s overall energy expenditure being used for transportation and the expected increase in the total world vehicle stock, one can immediately recognize the potential impact a shortage of petroleum or increase in petroleum cost will have. As a result, over reliance on petroleum fuels and products should be avoided and alternatives should be investigated.

Figure 1: “Historical and projected regional values for total vehicles. The world stock of vehicles grew from 122 million in 1960 to 812 million in 2002 (4.6% annually), and is projected to increase further to 2.08 billion by 2030 (3.4% annually)” (2)

One alternative to conventional petroleum based propulsion systems are hydrogen based systems such as fuel cells. Of particular interest are polymer electrolyte membrane fuel cell (PEMFC) systems. PEMFC powered vehicles are currently being developed by major automotive manufacturers and are gaining considerable public attention. Unfortunately, implementing PEMFCs has proven to be difficult in automotive applications and there are many issues related to hydrogen production and distribution.
that make hydrogen as a primary fuel source a rather problematic option for the transportation industry.

Although hydrogen is the most abundant element in the universe, it does not readily exist in the pure gaseous state needed for PEMFC applications. Unfortunately, the majority of commercial hydrogen used today must be extracted from hydrocarbon fuels such as natural gas and petroleum. In fact, approximately 65% of the hydrogen produced in the United States is a direct result of petroleum refinery activities (8). These processes result in a significant amount of pollution and do not adequately address the issue of petroleum dependence. Furthermore, the lack of a hydrogen distribution infrastructure and the large initial expense needed to create one may stifle widespread hydrogen powered vehicle implementation. Another major problem is hydrogen’s low specific energy at standard temperature and pressure (STP) when compared to fuels such as gasoline and diesel. Gasoline for example contains approximately 34MJ/l while hydrogen gas contains just 0.01MJ/l at STP. This low energy density eliminates the option of storing hydrogen gas at STP in an automobile’s fuel tank because such a tank could never contain enough energy to propel a vehicle over distances commensurate with gasoline or diesel without refueling. Although hydrogen’s energy density can be adequately increased by increasing its pressure, the pressures required are typically very high. For example, the 2009 Honda FCX Clarity uses a fuel tank that is pressurized to approximately 5000psi (350atm) (9). As a result, a significant safety hazard exists in fuel cell vehicles when hydrogen is the primary fuel source. This safety hazard hinders marketability and increases development costs.

One solution that alleviates some of these problems is the use of hydrogen carriers. Hydrogen carriers are substances that contain hydrogen atoms which can be extracted and reformed into hydrogen gas. One particularly interesting hydrogen carrier, ammonia, is especially well suited for use as a fuel in some niche automotive applications (6). It has been shown that hydrogen can be reformed from ammonia via electrolysis and used as a fuel source for PEMFCs (10). Ammonia is a common waste product in industries such as fertilizer production and livestock. In these industries, ammonia waste
can be recovered and used as a fuel to power vehicles and equipment. Ammonia contains much more energy per unit volume than hydrogen gas at STP which eliminates the need for a pressurized fuel tank in automotive applications. Furthermore, the only products of hydrogen reformation via ammonia electrolysis are hydrogen gas and nitrogen gas. The nitrogen, which goes unused, can be exhausted into the atmosphere with little environmental impact since the earth’s atmosphere is approximately 80% nitrogen.

The Ammonia Car Project is an interdisciplinary project being conducted by faculty and students in the Mechanical, Chemical and Electrical Engineering departments in the Russ College of Engineering and Technology at Ohio University, Athens, Ohio. The goal of this project is to develop a vehicle that uses ammonia as its primary fuel source in order to demonstrate the feasibility of ammonia electrolysis and PEM fuel cell integration for transportation applications. The project is to be developed in three major steps as illustrated in Figure 2.

Figure 2: Major development stages for Ammonia Car Project

The Ammonia Car Project is currently transitioning from a functioning electric vehicle to a functioning PEMFC powered vehicle. The vehicle itself is named the Alternative Energy Testbed and is intended to be a platform on which various energy related technologies can be tested. A Ballard® Mark 9 SSL, 4.8kW PEMFC stack was purchased for the project and will be used to convert the chemical potential energy of hydrogen gas into electricity that can be stored in batteries and discharged through the existing vehicle’s electric drive train. The drive train of the Alternative Energy Testbed consists of a stock 1967 VW 4 speed manual transaxle and a 10kW electric assist motor.
salvaged from a first generation Honda Insight and is built on a 1967 Volkswagen Beetle chassis. The existing vehicle uses a NiMH battery pack which was also salvaged from a first generation Honda Insight (11).

In order to implement the Ballard® fuel cell into the current vehicle, various performance characteristics must be determined. PEMFC performance depends heavily on a number of physical parameters including fuel and oxidant flow rate, temperature, humidity, back pressure and orientation. The manufacturer of the fuel cell stack provided some information about the effects of these parameters. However, a more thorough parametric analysis must be obtained in order to address various control and balance of plant issues.

1.3 PURPOSE

The purpose of this research is to present various performance characteristics of a Ballard Mark9 SSL™ 4.8kW fuel cell stack in order to aid in the development of the Ammonia Car Project currently being conducted at Ohio University, Athens, Ohio. It is a goal of this research to determine the fuel cell stack’s operating constraints and to address special considerations that may affect the fuel cell’s performance. Univariate testing was conducted to determine the effects of the fuel and oxidant temperature, flow rate, humidity and pressure. A brief study of the fuel cell stack’s performance when mounted at various angles was conducted in order to identify locations in the Alternative Energy Testbed where the fuel cell stack can be mounted. A brief study was also conducted to determine the dynamic effect of abrupt load changes on the fuel cell stack’s voltage. The response to several load changes is discussed and can be used in future research to aid in the development of a control system for the Ammonia Car Project. Operating constraints were determined in this study and can be used in future research to determine the component requirements needed for the Ballard® fuel cell stack in order to create the operating conditions necessary for proper implementation. Examples of these components include pumps, dew point humidifiers, flow rate controllers, heaters and cooling systems. The operating constraints that are outlined in this thesis will also serve as target specifications for the development of an ammonia electrochemical reformer that
is currently being developed by researchers in the Chemical Engineering department of the Russ College of Engineering and Technology.

1.4 THESIS OBJECTIVES

The primary objective of this research is to provide data that can be used to predict the static behavior of a Ballard® 4.8kW fuel cell stack when operated at various gas temperatures, gas flow rates, gas humidities, gas pressures and physical orientations. The data collected were used to develop I-V (load current vs. stack voltage), and power curves that show how the fuel cell’s performance is affected by each of these variables. This information was also used to develop recommended operating condition ranges for each of the variables tested. Parametric testing was conducted for this research and the variables, whose effects are not being tested during an experiment, were set to the manufacturer’s recommended values. Current interrupt testing was also used to provide information about the dynamic response of the fuel cell stack. The dynamic portion of this study provides only the most basic response information including the settling time for a variety of abrupt load changes and plots of the stack’s voltage as a function of time. For a detailed explanation of the experiments that were used to determine these effects, refer to Sections 3.3 and 3.4. A brief description of the testing that was conducted is outlined as follows:

- Parametric testing was conducted to determine the effect of the following operating conditions on the power output of a Ballard® Mark9 SSL™ 4.8kW fuel cell stack:

1. Fuel and Oxidant Flow Rate
2. Fuel and Oxidant Humidity
3. Fuel and Oxidant Pressure
4. Fuel and Oxidant Temperature
5. Coolant Temperature
• Current Interrupt testing was conducted in order to determine the settling time for
  a variety of abrupt load changes and produce plots of voltage as a function of
time.

• Mounting limitations for a Ballard® Mark9 SSL™ 4.8kW fuel cell stack were
developed based on the following considerations:

  1. Performance when operated at orientations that may be encountered in the
     Alternative Testbed Vehicle’s suitable fuel cell mounting locations
  2. Manufacturer’s suggested vibration and shock protection limits

• Based on the experimental results, recommendations are made in order to
  effectively implement a Ballard® Mark9 SSL™ 4.8kW fuel cell stack into the
  Alternative Energy Testbed vehicle. These recommendations include:

  1. Ranges for gas temperature, flow rate, humidity, and back pressure
     beyond which the fuel cell should not be operated
  2. Recommended locations where the fuel cell stack could be mounted and
     operated successfully
CHAPTER 2 LITERATURE REVIEW

2.1 CHAPTER SUMMARY

This chapter outlines what is already known about the effects of physical orientation and reactant flow rate, temperature, humidity and pressure on PEMFC power output and fuel utilization efficiency. Section 2.2 provides a review of general PEMFC theory. Section 2.3 provides a discussion about the difference between predicted and experimental fuel cell performance. Section 2.4 provides information regarding the known effects of physical orientation and reactant flow rate, temperature, humidity and pressure on PEMFC performance.

2.2 PEM FUEL CELL THEORY

Fuel cell characterization is well known in the academic community. As a result, many books, papers and journal articles can be found containing the governing thermodynamic, electrochemical and mass transport equations used to predict their performance. Of particular importance to this thesis are the effects of fuel and oxidant flow rate, temperature, humidity and pressure. It has been shown that these can all be estimated analytically to determine the theoretical performance of a PEMFC. However, as is the case in most engineering problems, the performance of real fuel cell systems varies from the theoretical performance that is predicted. Because of this, it is important to thoroughly test a fuel cell stack before using it in a dynamic energy system. Many variables must be considered in order to successfully implement a fuel cell system. These include conditions related to the surrounding environment, the age of the fuel cell stack and space constraints just to name a few. For example, automotive applications demand successful operation in winter and summer, at varying altitudes, and with considerable vibration and inclination changes.

A brief review of PEMFC fundamentals is provided as a background in order to better understand this thesis. PEMFC operation involves two major chemical processes called the reduction and oxidation reactions. The oxidation reaction involves the decomposition of hydrogen gas into protons and electrons and the reduction reaction involves the combination of protons, electrons, and oxygen ions to form water. These two
processes are called the electrochemical half reactions and can be seen below in Equations 1 and 2. The reaction of hydrogen and oxygen is exothermic and as a result heat is a product. It is useful to recall that the site where the oxidation reaction occurs is called the anode and the site where the reduction reaction occurs is called the cathode.

\[
\begin{align*}
\text{H}_2 & \rightarrow 2\text{H}^+ + 2e^- \quad \text{(Oxidation Reaction)} \\
\frac{1}{2} \text{O}_2 + 2\text{H}^+ + 2e^- & \rightarrow 2\text{H}_2\text{O} + \text{Heat} \quad \text{(Reduction Reaction)}
\end{align*}
\]

The anode and cathode of a PEMFC are separated by a thin polymer membrane that allows only protons to pass through. A PEM fuel cell produces electricity by separating and directing the flow of electrons and protons that result from the oxidation reaction. The protons are able to pass directly from the anode side of the cell to the cathode side through the electrolyte membrane. The electrons, unable to pass through the membrane, are directed through an external circuit where they can provide electrical power. After passing through the external circuit the electrons accumulate at the cathode side of the cell where they combine with protons and oxygen ions to produce water and heat. See Figure 3 for a simplified PEM fuel cell diagram.

Figure 3: Simplified diagram of PEM fuel cell
“The maximum exploitable work potential that a chemical reaction can provide is equal to the negative of the Gibb’s free energy” (12). The Gibb’s free energy can also be used to determine the maximum electrical potential that a PEM fuel cell can achieve. This relationship is called the standard-state free energy change for the reaction and assumes that stoichiometric quantities of each reactant are supplied and consumed (12). However, this is never the case in real systems. In order to take into account the effect of varying reactant concentrations, the Nernst equation is used. The Nernst equation is shown in Eq. 3. However, it is important to realize that fuel cells never achieve the voltage predicted by the Nernst equation because there are three major operational losses that occur. These losses are referred to as the activation, ohmic and concentration losses and can be estimated analytically. However, real fuel cell systems must be physically tested because a fuel cell’s performance characteristics often vary considerably from theoretical approximations.

\[
E = E^0 - \frac{RT}{nF} \ln \sum_{i} \frac{a_{products}^{v_i}}{a_{reactants}^{v_i}} \quad \text{(Nernst eqn.)} \quad \text{(Eq. 3)}
\]

where,

\[R = \text{ideal gas constant}\]
\[T = \text{temperature (K)}\]
\[n = \text{number of electrons transferred}\]
\[a_{products} = \text{activity of moles of product species } i\]
\[a_{reactants} = \text{activity of moles of reactant species } i\]
\[v_i = \text{stoichiometric coefficient of species } i\]
\[
E^0 = -\frac{\Delta \theta_{r,xn}^0}{nF} \quad \text{(standard-state reversible voltage)} \quad \text{(Eq. 4)}
\]
\[
\Delta \theta_{r,xn}(T) = \Delta \bar{h}_{r,xn}^0 - T \Delta \bar{s}_{r,xn}^0 \quad \text{(Gibb’s free energy of reaction)} \quad \text{(Eq. 5)}
\]
\[
\Delta \bar{h}_{r,xn}^0 = \text{change in enthalpy of reaction}
\]
23

\[ \Delta s_{rxn}^0 = \textit{change in entropy of reaction} \]

The preceding discussion is intended to be a review for those who are already familiar with fuel cell theory. For a more thorough discussion please refer to Fuel Cell Fundamentals (12) or equivalent fuel cell theory resource.

2.3 PEMFC – PREDICTED VS. MEASURED

Although the performance of a PEMFC may be estimated using analytical methods, the behavior of a real fuel cell can only be predicted accurately if physical testing has been performed. This is because many assumptions used to simplify fuel cell analysis are not applicable for real systems. For example, an analytical approach requires assumptions to be made about the purity and composition of reactants, the rates that chemical reactions occur and many other parameters that drastically affect a real fuel cell’s power output and response. In addition to these problems, a real fuel cell must be connected to pumps, heaters, humidifiers and other devices whose behaviors are ignored using analytical methods. As a result, it is important to physically test a fuel cell before attempting to implement it into a dynamic energy system even if analytical methods have been used to estimate its performance.

For this project, information was provided by the fuel cell stack’s manufacturer that describes how the performance of the fuel cell varies with respect to the input variables. However, the fuel cell is nearly 3 years old and preliminary tests have shown that there is a difference between the performance predicted by the manufacturer and that obtained in the lab. PEM fuel cell performance is commonly observed to degrade over time and age is likely the reason the fuel cell stack is not performing as well as it has previously. PEMFC reliability has not been widely researched. However, a general model has been developed that predicts PEMFC performance degradation over time (13). Reactant crossover, particularly hydrogen, is a primary source of PEMFC performance losses as the electrolyte membrane degrades over time (14). As a result, testing must be
performed to understand the current behavior of the fuel cell that was purchased for the Ammonia Car Project. This is one of the motivations for this research.

A commonly used tool for evaluating fuel cell performance is the “IV curve.” An IV curve is a plot of a fuel cell’s voltage as a function of load current and is useful for visualizing a fuel cell’s performance. IV curves provide information that can be related to the various fuel cell losses. An IV curve has three distinct regions, the activation, ohmic and concentration regions. The fuel cell used in this research will be operated in the ohmic region most often. A typical IV curve can be seen in Figure 4.

![IV Curve Diagram](image)

Figure 4: IV curve showing activation, ohmic and concentration regions

2.4 EFFECT OF GAS TEMPERATURES

The effect of fuel and oxidant temperature on PEMFC power output and fuel utilization efficiency is considerable. In general, increasing a PEMFC stack’s reactant stream temperatures (up to approximately 60-100°C) will increase the power output of the stack. The recommended reactant supply temperature for the fuel cell stack used in this research is 61°C (1). A PEMFC’s power output and efficiency for a given load current will drop if the temperature of the reactant streams drops below the operating temperature of the fuel cell stack (3). Also, lower reactant stream temperatures cannot
support as much water as higher reactant stream temperatures and are therefore less effective at wetting the PEMFCs membrane. The water content in the reactant supply streams plays a considerable role in wetting a PEMFCs electrolyte membrane which is required for optimal hydrogen ion conductivity (3). As a result, performance for low temperature reactant streams suffers. A typical example of the effect that the inlet gas temperatures have on fuel cell performance can be seen in the polarization curves presented in Figure 4. According to Amirinejad, there are two major reasons why PEM fuel cell performance improves at elevated temperature. At elevated temperature, “… [gas] diffusivity increases and mass transport resistance decreases.” (15) Also, the ohmic-conductivity of Nafion membranes increases with increasing temperature (15). It can be seen in Figure 5 that the effect of reactant temperature is more pronounced as the load current is increased. It can also be seen that the reactant temperature has less effect in the activation and concentration regions of the IV curve. However, the fuel cell used in this research will not likely be operated in these regions.

Figure 5: Polarization curves for PEMFC operating at various reactant inlet temperatures (3)
2.5 EFFECT OF GAS FLOW RATES

The flow rates of the fuel and oxidant that are required for optimal stack performance are dependent on the load current that is applied to the fuel cell stack. In order to determine the required flow rates for the fuel and oxidant, Equations 6 and 7 were derived by the fuel cell stack’s manufacturer. Equations 6 and 7 are presented as follows (1):

\[ F_{H_2} = 0.00696 \times I \times N \times \lambda_{H_2} \]  \hspace{1cm} (Eq. 6)

Where,
\[ F_{H_2} = \text{Required } H_2 \text{ Flow Rate in slpm (standard liters per minute)} \]
\[ I = \text{Load Current in } A \]
\[ N = \text{Number of Cells in the Stack} \]
\[ \lambda_{H_2} = \text{Hydrogen Stoichiometry} \]

And,
\[ F_{Air} = 0.0166 \times I \times N \times \lambda_{Air} \]  \hspace{1cm} (Eq. 7)

Where,
\[ F_{Air} = \text{Required Air Flow Rate in slpm} \]
\[ I = \text{Load Current in } A \]
\[ N = \text{Number of Cells in the Stack} \]
\[ \lambda_{Air} = \text{Air Stoichiometry} \]

According to the implementation guide of the Ballard fuel cell stack, “Stoichiometry is defined as the ratio of actual flow rate to the flow rate required to support the reaction. The minimum theoretical stoichiometry required to support the reaction is 1.0 for both fuel and oxidant.” (1). In real systems, a stoichiometry equal to 1.0 is never used because it does not adequately mitigate issues related to water accumulation and reaction kinetics (1). For low load currents, a minimum pressure drop is necessary to remove water from the fuel cell stack. This pressure drop is the determining factor for the choice of stoichiometries (1). According to Ballard, “At high
current, reactant concentration at the catalyst is the critical factor.” (1). The fuel and oxidant consumption as a function of load current for the fuel cell stack is presented in Figure 6 and Figure 7 respectively (1).

![Graph showing hydrogen flow rate as a function of load current for the Ballard Mark 9 SSL fuel cell stack.](image)

Figure 6: Hydrogen flow rate as a function of load current for the Ballard Mark 9 SSL fuel cell stack. Adapted from (1)
Figure 7: Air flow rate as a function of load current for the Ballard Mark 9 SSL fuel cell stack. Adapted from (1)

For this research, the “recommended” fuel and oxidant flow rates were determined using the equations supplied by the fuel cell’s manufacturer. However, to determine the effect of reactant starving, only a fraction of these values were supplied to the fuel cell. For instance, one experiment was supplied just 90% of the recommended fuel and oxidant flow rates. It is obvious that supplying less than the required amounts of fuel and oxidant will negatively affect the performance of the fuel cell stack. It has been shown that starving a PEMFC of fuel will decrease the voltage for a given load value (4). Figure 8 demonstrates the effect of fuel starvation on a PEM fuel cell’s polarization curve. It should be noted that the fuel flow rate in Kim’s study was not changed (4). Instead, nitrogen was added in place of hydrogen. For example, 100% hydrogen with 0% nitrogen, 80% hydrogen with 20% nitrogen and so on. For this research, the flow rate of the reactants was adjusted to change the amount of reactants supplied to the fuel cell stack. The composition of the reactants will always be ≈100% hydrogen for the fuel and
100% air for the oxidant. However, the effect that is shown in Figure 8 is similar to the effect that was observed for this study.

![Polarization curves for a PEMFC supplied with 100%, 80% and 40% hydrogen](image)

Figure 8: Polarization curves for a PEMFC supplied with 100%, 80% and 40% hydrogen (4)

It can be seen in Figure 8 that there is a noticeable drop in cell voltage when less fuel is provided. The effect of fuel starvation is not significant in the activation region of the I-V curves. However, fuel cell stacks are not often operated in this range. For 80% Hydrogen at 1.0 A/cm² (a typical operating current density) there is approximately a 3.5% decrease in voltage when compared to 100% hydrogen. This decrease in cell voltage would result in a considerable amount of power loss for a large fuel cell stack. For instance, if a 3.5% power loss occurred for the peak power (4.8kW) of the fuel cell used in this research, 168W would be lost. However, such a loss might be acceptable for certain applications if the benefits from decreased fuel use outweigh the performance losses.
2.6 EFFECT OF GAS HUMIDITY

The relative humidity of the reactant in let streams is extremely important for optimal PEMFC performance. This is because a PEMFC’s electrolyte membrane must be kept moist in order to adequately conduct hydrogen ions (3). It has been shown that a decrease in reactant stream relative humidity negatively affects a PEMFC’s performance (5). Figure 9 demonstrates the effect that the reactant stream relative humidities have on PEMFC performance for two different membrane materials (3). Nafion is the membrane material for the fuel cell that was tested in this research. According to Wang, perfluorosulfonic acid (PFSA) ionomers, such as Nafion require humidification to effectively conduct protons (5).

![Figure 9: “Fuel cell performance of MEAs with…Nafion membranes with various RH at 95 °C.” Adapted from (5) ](image)

It can be seen in Figure 9 that reactant stream humidification has a significant effect on the performance of a fuel cell. At a current density of 1.0 A/cm² (a typical
operating current density), there is approximately a 20% decrease in cell voltage when the relative humidity is 50% compared to 95%. The relative humidity of the reactant streams for the fuel cell stack used in this research will be between 90-100% except for the parametric humidification study.

2.7 EFFECT OF GAS PRESSURE

Reactant stream pressurization has been shown to have an effect on the performance of PEMFCs. There are a number of reasons why this occurs. According to Amirinejad(15), pressurizing the reactant streams of a PEMFC increases the reactant gas diffusivity which reduces the mass transport resistance thereby improving performance (15). Also, since vapor water is easier to transport than liquid water, the ability to mitigate flooding related performance losses is improved. Figure 10 shows the effect of reactant stream pressurization on the performance of the fuel cell used in this experiment (1). This information was provided by the fuel cells manufacturer, Ballard Power Systems. The recommended reactant stream pressure increases with increasing load current, however, the “high pressure” used below is approximately two times the “low pressure” for every load.
Figure 10: High and low pressure polarization curves according to the manufacturer’s suggested reactant pressurizations (1)

It can be seen in Figure 10 that reactant stream pressurization has a significant effect on the polarization of the fuel cell stack used in this research. The voltage difference between the high and low pressure polarization curves is approximately 300 mA over the entire load range. Therefore, it can be concluded that the reactant stream pressures play a major role in the successful operation of the fuel cell stack used in this research.

2.8 EFFECT OF PHYSICAL ORIENTATION

The power output and efficiency of a PEM fuel cell can be affected by physical orientation due to water production and accumulation in the gas diffusion layer (GDL) and gas flow channel (GFC) of the fuel cell’s cathode (16). Some water is necessary to maintain proper electrolyte wetness; however, too much water can impede a PEM fuel cell’s reaction kinetics. The result of too much water accumulation can dramatically
decrease the power output and efficiency of a fuel cell and is referred to as “flooding.” According to Montello (16), “Li et al. claim that the problem of flooding in PEMFC is not well understood, and that there is also not a single widely applicable solution to the water management issue (17)”. However, a fuel cell’s physical orientation can be used to help mitigate flooding by taking advantage of gravity or other external accelerations that cause water to dislodge from and exit the GDL and GFC.

In order to reduce the risk of flooding, the fuel cell stack used in this research may be mounted in the Alternative Energy Testbed Vehicle so that gravity will assist excess water removal. The amount of water that is produced as a function of load current for the fuel cell stack used in this research is shown in Figure 11. The fuel and oxidant volumes (flow channels inside the fuel cell stack) for the fuel cell stack used in this research are 110 mL and 190 mL respectively (1). Therefore, the amount of water produced according to Figure 11 could create performance losses in a short period of time if not properly managed.

Figure 11: Water production as a function of load current for the Ballard Mark 9 SSL fuel cell stack. Adapted from (1)
CHAPTER 3 EXPERIMENTAL METHODOLOGY

3.1 EXPERIMENTAL SETUP

The experimental setup was composed of an Arbin Instruments Fuel Cell Test Stand (FCTS), a Ballard Mark9 SSL™ 4.8kW fuel cell stack, a coolant chiller and circulation pump, computer station, water reservoir and gas supplies. The data acquisition and FCTS control software was MITS Pro and was supplied with the FCTS. The fuel (hydrogen gas) was supplied to the FCTS via a hydrogen gas cylinder. The oxidant (air) was supplied to the system via Stocker Engineering Center’s main air supply. Nitrogen gas was supplied to the system via a nitrogen gas cylinder and was used to purge the fuel and oxidant plumbing. Fuel, oxidant, coolant, air, nitrogen and water were supplied to the FCTS which distributes them in controlled amounts to the fuel cell stack being tested. The computer station was used to specify and monitor the amounts and conditions of the substances being supplied to the fuel cell stack and was also used to acquire data. The experimental setup can be seen in Figures 12 and 13.
Figure 12: FCTS experimental setup showing hydrogen and nitrogen supplies, FCTS, fuel cell stack, fume hood and computer station

Figure 13: Coolant chiller/pump (left); Water reservoir (right)
The water reservoir was necessary in order to humidify the fuel and oxidant gas supplies before sending them to the fuel cell stack. Humidification was achieved via a dew point humidifier inside the FCTS. The coolant chiller and pump unit was necessary in order to remove heat from the fuel cell stack so that the stack’s temperature can be controlled.

The FCTS was capable of controlling the fuel and oxidant flow rates, temperatures, humidities and back pressures, as well as the coolant flow rate and temperature. All of these conditions were monitored and adjusted using the MITS Pro software. The FCTS had current and maximum power limits of 200A and 4kW respectively. When current was being drawn from the fuel cell, the resulting voltage and power were monitored and recorded using the MITS Pro software. For safety information and procedures related to the experimental setup, refer to Appendix A.

3.2 EXPERIMENTAL SETUP LIMITATIONS

The fuel cell stack produced more heat than the coolant chiller could remove when the fuel cell’s power output exceeded approximately 1kW. Therefore, above this power, the coolant and stack operating temperatures began to climb. This is important because the power output of a PEM fuel cell is affected by the operating temperature. As a result, true univariate testing was not possible for this research when the fuel cell stack was operated above 1kW. However, testing revealed that the coolant temperature can be kept in the range of 45-58°C by shortening test times. There was little change (≤ 10% difference) in the fuel cell stack’s performance when operated at coolant temperatures in this range. A typical plot of coolant temperature as a function of time for the fuel cell used in this research can be seen in Figure 14. Notice the sinusoidal response of the coolant temperature while the coolant chiller is able to remove all of the heat produced by the fuel cell stack. This is a result of the coolant chiller’s control strategy. It can also be seen in Figure 14 that the coolant temperature will continue to climb when more heat is produced by the fuel cell stack than can be removed.
The fuel cell stack that was tested has a maximum power of 4.8kW @ 300A load current. This is higher than the maximum load current that the FCTS can draw. The FCTS is only capable of drawing 200A from the fuel cell stack. Therefore, the fuel cell stack could not be tested to its maximum power.

3.3 PROCEDURE – PARAMETRIC STUDY

The gas temperature and humidity values for the fuel were always equal to those of the oxidant (recommended by manufacturer). However, the flow rate and pressure values were different for the fuel and the oxidant. The flow rates that were applied to the fuel and oxidant were determined as a percentage of the manufacturer’s recommended values. The pressures that were applied to the fuel and oxidant were determined using linear interpolation and extrapolation based on the recommended high and low pressure values provided by the manufacturer. For each parametric test, the variables whose effects were not being tested were set to the manufacturers recommended values. However, due to limitations in the experimental setup, the reactant stream flow rates were not changed for different loads. Instead, the flow rates supplied were those recommended by the manufacturer for a 200A load.
The basic procedure for conducting experiments was the same for each variable that was tested. A schedule was developed using the MITS Pro software that prescribed the magnitude and duration of loads that were applied to the fuel cell stack. A load was applied which increased linearly from open circuit to full load (200A) with \( \frac{dt}{dV} = 1 \frac{A}{s} \). After the fuel cell’s voltage was measured at each current interval, I-V, power and fuel utilization efficiency curves were developed.

In order to determine the exact tests that were conducted, the following methods were used. For the parametric temperature study, the fuel cell stack was tested in the range of 30-70°C in 10°C increments. The upper limit of this range was selected because it is close to the maximum limit suggested by the manufacturer. The lower limit of this range was selected because it is close to the minimum temperature that can be provided by the FCTS. For the parametric flow rate study, the applied flow rates were a percentage of the manufacturer’s recommended values. The ratio of fuel to oxidant flow rates remained the same for each of the flow rate study tests. A specific range of flow rates could not be predefined because its effects were unknown. Instead, the maximum power achieved for a test was the criterion used to determine when enough tests had been conducted. For the flow rate study, tests were conducted until the maximum power achieved during a test was less than or equal to 50% of the maximum power achieved using the manufacturer’s recommended conditions. Figure 15 shows how power curves were used to determine the range of flow rates and pressures that were tested.
For the pressure study, the applied pressures were determined using linear interpolation and extrapolation based on the high and low pressure values recommended by the manufacturer. For the fuel cell stack used in this study, very low pressures (e.g. < 3psi (20.7kPa)) were difficult to achieve using the FCTS. As a result, the minimum pressure values that were tested are based on the limitations of the experimental setup. The minimum pressure values that were achievable while still maintaining a linear relationship with the manufacturers recommended values are approximately, $P_{H_2} = 7psi (48.3kPa), P_{Air} = 2.5psi (17.2kPa)$. Similarly, the upper limit of the pressure study was based on the limitations of the experimental setup. The maximum pressure values that were achievable while still maintaining a linear relationship with the manufacturers recommended values are approximately, $P_{H_2} = 24psi (165.5kPa), P_{Air} = 21psi (144.8kPa)$. The relative humidity range that was tested was 50-100%. The lower limit of this range was selected because lower relative humidity can lead to cell drying which may cause fuel crossover and internal leaks (1). If hydrogen is allowed to crossover to the cathode, a combustion reaction may occur which can permanently damage the fuel cell stack.
The effect of the fuel cell stack’s mounting orientation with respect to power output and fuel utilization efficiency was also determined based on several orientations that are likely to be encountered while the Alternative Testbed Vehicle is operating. The orientation of the fuel cell stack is a combination of the mounting orientation and the road surface orientation. For this study, it was assumed that the road surface is level in the direction perpendicular to the path of the vehicle (side to side of vehicle). In order to determine where the fuel cell stack could be mounted in the Alternative Energy Testbed, a mock fuel cell stack was constructed out of foam board and used to visually identify locations that could support the stack’s space requirements. The mock fuel cell stack and actual fuel cell stack can be seen in Figure 16. It was observed that the fuel cell stack would most likely be mounted in one of two orientations shown in Figure 17.

Figure 16: Mock fuel cell stack shown with actual fuel cell stack
The maximum grade that the Alternative Testbed Vehicle could encounter in Athens, Ohio is 24% (≈13.5°) (18). The inclinations that were tested simulate an uphill or downhill driving condition and were directed in such a way as to produce a worst and best case scenario. The worst case scenario occurs when the fuel cell stack is tilted so that water has difficulty exiting the stack’s gas outlet. The best case scenario occurs when the fuel cell stack is tilted so that water can more easily exit the stack’s gas outlet. This approach will permit testing for the best and worst case scenarios related to orientation that the fuel cell stack is likely to encounter during operation. For Orientations A and B, the best and worst case scenarios occur when the stack is tilted about the x-axis. See Figure 17 for the axis definition.

A detailed description of the testing that was conducted is presented as follows:

Note: Each of the variables whose effects were not being actively tested during an experiment were set to the manufacturer’s recommended values. e.g. when testing the effect of fuel and oxidant temperature, the flow rates, humidities and pressures were those recommended in the Ballard manual.
Effect of Gas Temperature

1. 0-200A load @ 70°C
2. 0-200A load @ 60°C
3. 0-200A load @ 50°C
4. 0-200A load @ 40°C
5. 0-200A load @ 30°C

Effect of Gas Flow Rate

6. 0-200A load @ ideal flow rate \( F_{H_2} = 56 \text{slpm}, F_{Air} = 150 \text{slpm} \)
7. 0-200A load @ 90% of ideal
8. 0-200A load @ 80% of ideal
9. 0-200A load @ 70% of ideal
10. 0-200A load @ 60% of ideal
11. 0-200A load @ 50% of ideal
12. 0-200A load @ 40% of ideal
13. 0-200A load @ 30% of ideal
14. 0-200A load @ 20% of ideal

Effect of Gas Pressure

15. 0-200A load @ \( P_{H_2} = 24 \text{psi}, P_{Air} = 21 \text{psi} \) \( (P_{H_2} = 165.5kPa, \ P_{Air} = 144.8kPa) \) (maximum pressure values achievable with FCTS) note: gauge pressure
16. 0-200A load @ \( P_{H_2} = 15 \text{psi}, P_{Air} = 8 \text{psi} \) \( (P_{H_2} = 103.4kPa, P_{Air} = 55.6kPa) \) (≈50% manufacturers recommended “high pressure” values) note: gauge pressure
17. 0-200A load @ \( P_{H_2} = 7 \text{psi}, P_{Air} = 2.5 \text{psi} \) \( (P_{H_2} = 48.3kPa, P_{Air} = 17.2kPa) \) (≈25% manufacturers recommended “high pressure” values; minimum pressure values achievable with FCTS) note: gauge pressure

Effect of Gas Humidity

18. 0-200A load @ 100% relative humidity
19. 0-200A load @ 90% relative humidity
20. 0-200A load @ 80% relative humidity
21. 0-200A load @ 70% relative humidity
22. 0-200A load @ 60% relative humidity
23. 0-200A load @ 50% relative humidity
Effect of Physical Orientation

24. 0-200A load @ Orientation A on level surface  
25. 0-200A load @ Orientation A +13.5° about x-axis (Maximum Uphill)  
26. 0-200A load @ Orientation A -13.5° about x-axis (Maximum Downhill)  
27. 0-200A load @ Orientation B on level surface  
28. 0-200A load @ Orientation B +13.5° about x-axis (Maximum Uphill)  
29. 0-200A load @ Orientation B -13.5° about x-axis (Maximum Downhill)

3.4 PROCEDURE – DYNAMIC TESTING

The step response of the fuel cell stack’s voltage was investigated for a variety of abrupt load changes. The manufacturer’s recommended operating conditions were used during all of the dynamic response tests. The settling time was determined for each load change and a plot of the stack’s voltage as a function of time was produced for each test. A typical plot of voltage as a function of time for a variety of load changes can be seen in Figure 18. The irregular, wavy shape of the voltage plot is a result of changing coolant temperature which varies sinusoidally. Figure 18 was developed using data collected for the fuel cell stack that was used in this research.

![Figure 18: Typical plot of voltage vs. time resulting from 25A load steps for the tested FC stack](image-url)
For each of the following tests, voltage vs. time plots were produced and the response time for each load change was determined. The response time was defined as the amount of time required for $\frac{dv}{dt}$ (first time derivative of voltage) to reach 0.02 V/s. An example of a typical $\frac{dv}{dt}$ plot for 50A load steps is shown in Figure 19. This threshold was selected because preliminary tests showed that the voltage of the FC stack does not significantly change beyond this point.

![Figure 19: Typical plot of $\frac{dv}{dt}$ for 50A load steps with response time interval shown](image)

Dynamic Testing
1. 0-200A in 25A steps (8 load changes)
2. 0-200A in 50A steps (4 load changes)
3. 0-200A in 100A steps (2 load changes)

3.5 TEST VALIDATION

In order to validate the results that are obtained through testing, the first and last test for each parametric study was repeated one additional time. If the average difference for the data points of the first and second trials of a test was less than or equal to 10%, the results were considered validated. The tests for the dynamic portion of the study were
conducted twice. The average of the two tests is presented. Normally, more testing would be conducted in order to validate the results. However, the proposed test plan provides the best balance of meaningful results and cost effectiveness based on funding constraints and resources available for this research.
CHAPTER 4 EXPERIMENTAL RESULTS

4.1 EFFECT OF GAS FLOW RATES

Tests were conducted by varying the flow rate of the fuel and oxidant from 100% to 20% of the manufacturer’s recommended values (for a 200A load) in 10% increments. The results for the gas flow rate study are summarized in Figure 20. It can be seen that there is no significant difference in the voltage output of the fuel cell when the stack is supplied with at least 80% of the manufacturer’s recommended reactant flow rates for the load range of 0-200A. The root mean square (RMS) value of the percent difference in voltage output between various curves was calculated for data points taken at the same current. The RMS difference between the voltage outputs at these points for 80% and 100% recommended values was 0.5%.

Figure 20: Effect of reactant flow rates on FC stack voltage output
The validity of the flow rate study results was shown by conducting two trials for the 100% and 20% flow rate conditions. The average difference between the two trials for the 100% flow rate condition was 0.2%. The average percent difference between the two trials for the 20% flow rate condition was 4.6%. The results of the flow rate validation study can be seen in Figure 21. Power curves for the flow rate study can be found in Appendix B.

Figure 21: Validation of flow rate study results

4.2 EFFECT OF GAS TEMPERATURE

The effect of reactant gas stream temperature on the FC stack’s voltage output was determined for a temperature range of 30-70°C in 10°C increments. It can be seen in Figure 22 that the FC stack generally has a lower power output when supplied with lower temperature reactants. It was also observed that this effect was non linear and temperature differences had a more pronounced effect on the FC stacks voltage output for lower
reactant stream temperatures. For loads beyond 100A, the difference in power output between the 60°C and 70°C reactant stream curves was not significant. The difference in the voltage between the 30°C and 70°C temperature curves at 200A was 43%.

The validity of the gas temperature study results was shown by conducting two trials for both the 70°C and 30°C conditions. The RMS difference between the two trials for the 70°C condition was 2.8%. The RMS difference between the two trials for the 30°C condition was 1.1%. The results for the validation study and can be found in Appendix B. Power curves for the gas temperature study can also be found in Appendix B.

Figure 22: Effect of reactant stream temperature on FC voltage
4.3 EFFECT OF GAS HUMIDITY

The effect of reactant stream relative humidity on the FC stack’s voltage output was determined for the range of 30-100% relative humidity in 10% increments. The FC voltage output was lower for lower reactant stream relative humidities. The results of the gas humidity study can be seen in Figure 23.

![Figure 23: Effect of reactant stream relative humidity on FC voltage output](image)

The validity of the humidity study results was shown by performing two trials for the 100% and 30% relative humidity conditions. The RMS difference between the two trials for the 100% relative humidity condition was 1.3%. The RMS difference between the two trials for the 30% relative humidity condition was 2.5%. The results of the
validation study for the gas humidity data can be seen in Appendix B. Power curves for the gas humidity study can also be found in Appendix B.

4.4 EFFECT OF GAS PRESSURE

The effect of reactant gas stream pressure on the FC stack’s voltage output was determined for several pressures ranging from \( H_2 = 7 \text{psi} \) (48.3kPa) to \( H_2 = 24 \text{psi} \) (165.5kPa). The exact pressures tested and results of the gas pressure study can be seen in Figure 24. The voltage output of the FC stack was lower for lower reactant stream pressures. Changing the pressure caused a shift in the V-I curve data which was relatively constant throughout the entire ohmic region of the curve. The voltage shift in the ohmic region resulting from the change in pressure from \( H_2 = 15 \text{psi} \) (103.4kPa) to \( H_2 = 24 \text{psi} \) (165.5kPa) was approximately 0.33V. The voltage shift in the ohmic region resulting from the change in pressure from \( H_2 = 7 \text{psi} \) (48.3kPa) to \( H_2 = 24 \text{psi} \) (165.5kPa) was approximately 1.2V.

![Figure 24: Effect of reactant stream pressure on FC voltage output](image)

The validity of the gas pressure data was shown by conducting two trials for both the maximum and minimum pressure conditions. The RMS difference between the two trials for the maximum pressure condition was 1.6%. The RMS difference between the two trials for the minimum pressure condition was 1.6%. The results of the validation
study for the gas pressure data can be seen in Appendix B. Power curves for the gas pressure study can be found in Section

4.5  EFFECT OF PHYSICAL ORIENTATION

The effect of physical orientation on the FC stack’s voltage output was determined for two different orientations as described in section 3.3. For both orientations, the FC stack was tested while sitting level and also inclined ±13.5° to simulate uphill and downhill driving. No significant difference in the FC stacks voltage output was observed between any of the orientations tested. The results of the physical orientation study for Orientation A (see sec. 3.3) can be seen in Figure 25. The results of the physical orientation study for Orientation B can be seen in Figure 26. In order to demonstrate the validity of the physical orientation data, two trials were performed for all of the different orientations. The validation results for Orientation A can be seen in Appendix B. The validation results for Orientation B can be seen in Appendix B. Power curves for the orientation study can also be found in Appendix B.

Figure 25: Effect of inclination on Orientation A
4.6 EFFECT OF COOLANT TEMPERATURE

Coolant temperature was shown to have a significant effect on the voltage and power output of the FC stack. For constant 50A, 100A, and 200A loads, the difference between the initial voltage following load application and the voltage value obtained at elevated temperature was measured. For a constant 50A load, the voltage was observed to change by approximately 0.99V when the coolant temperature was changed from 30-60°C. For a constant 100A load, the voltage was observed to change by approximately 1.1V when the coolant temperature was changed from 32-57°C. For a constant 200A load, the voltage was observed to change by approximately 1.9V when the coolant temperature was changed from 30-59°C. For a 50A load, the increase in coolant temperature resulted in a 5.4% increase in the power output of the FC stack. For a 100A load, the increase in coolant temperature resulted in a 6.8% increase in the power output of the FC stack. For a 200A load, the increase in coolant temperature resulted in a 14.4% increase in the power output of the FC stack. Based on these results, it can be seen that coolant temperature affects the output of the FC stack more for higher loads. A plot of the
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FC voltage output and corresponding coolant temperature as a function of time can be seen in Figure 27 for a constant 50A load. Similar plots for constant 100A and 200A loads can be seen in Appendix B.

![Figure 27: Effect of coolant temperature on stack output voltage for a constant 50A Load](image)

4.7 RESPONSE TIME DUE TO LOAD CHANGES

The settling time of the FC stack’s voltage following sudden load changes was determined for 25A, 50A and 100A load steps. Response time was defined as the time required for $\frac{dv}{dt}$ (first time derivative of voltage) to reach 0.02 V/s. Plots of voltage as a function of time were produced for each set of load changes. Also, plots were produced of $\frac{dv}{dt}$ as a function of time. These plots were used to determine the settling time following load changes. The voltage after each load change was considered to be steady state when $\frac{dv}{dt}$ fell below $0.02 \frac{V}{s}$ while approaching $0 \frac{V}{s}$. These plots are presented in Figure 28 and
Figure 29 for 25A load steps. Similar plots for 50A and 100A load steps can be seen in Appendix B.

The results of the response time study are summarized in Tables 1 to 3. The output of the FC stack within 0.1 seconds of any of the tested load changes was always within 2% (relative to the step) of the steady state output. It can be seen that the steady state value of the FC stack was always achieved in less than 5 seconds for any of the tested load changes. There was no significant difference between the response times observed for the 25A, 50A and 100A load steps.

Table 1: Response time data for 25A load steps from 0-200A. Percent difference between low and high values following each load change.

<table>
<thead>
<tr>
<th>Load Step</th>
<th>Response Time</th>
<th>Percent Difference between initial (low) value and S.S. value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-25A</td>
<td>2.12s</td>
<td>0.58%</td>
</tr>
<tr>
<td>25-50A</td>
<td>2.43s</td>
<td>0.71%</td>
</tr>
<tr>
<td>50-75A</td>
<td>2.37s</td>
<td>0.53%</td>
</tr>
<tr>
<td>75-100A</td>
<td>1.91s</td>
<td>0.50%</td>
</tr>
<tr>
<td>100-125A</td>
<td>2.22s</td>
<td>0.52%</td>
</tr>
<tr>
<td>125-150A</td>
<td>2.65s</td>
<td>0.60%</td>
</tr>
<tr>
<td>150-175A</td>
<td>2.99s</td>
<td>0.57%</td>
</tr>
<tr>
<td>175-200A</td>
<td>1.80s</td>
<td>0.20%</td>
</tr>
</tbody>
</table>

Table 2: Response time data for 50A load steps from 0-200A. Percent difference between low and high values following each load change.

<table>
<thead>
<tr>
<th>Load Step</th>
<th>Response Time</th>
<th>Percent Difference between initial (low) value and S.S. value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50A</td>
<td>2.53s</td>
<td>0.72%</td>
</tr>
<tr>
<td>50-100A</td>
<td>3.18s</td>
<td>1.29%</td>
</tr>
<tr>
<td>100-150A</td>
<td>4.23s</td>
<td>1.45%</td>
</tr>
<tr>
<td>150-200A</td>
<td>4.44s</td>
<td>0.67%</td>
</tr>
</tbody>
</table>
Table 3: Response time data for 100A load steps from 0-200A. Percent difference between low and high values following each load change.

<table>
<thead>
<tr>
<th>Load Step</th>
<th>Response Time</th>
<th>Percent Difference between initial (low) value and S.S. value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100A</td>
<td>2.22s</td>
<td>0.37%</td>
</tr>
<tr>
<td>100-200A</td>
<td>3.59s</td>
<td>0.47%</td>
</tr>
</tbody>
</table>

Figure 28: Voltage as a function of time with 25A load steps up to 200A
Figure 29: $\frac{dv}{dt}$ as a function of time for 25A load steps from 0-200A
CHAPTER 5 DISCUSSION

5.1 EFFECT OF GAS FLOW RATES

As expected, supplying the FC stack with lower reactant stream flow rates reduced the stack’s maximum achievable output power. This effect can be seen in Figure 30. The “Recommended” flow rates used in this study were those values prescribed by the manufacturer for a 200A load. The result of this study indicates that more fuel is recommended by the manufacturer to achieve a particular power output than is actually needed. According to the testing that was performed, the FC stack only requires approximately 90% of the reactant stream flow rates recommended by the manufacturer to support a desired power output. It should be noted however, that the maximum current tested for this study was 200A and the FC stack is capable of sourcing up to 300A. Therefore, it is unclear whether the FC stack can be supplied with less than the recommended reactant flow rates for current levels exceeding 200A.

Figure 30: Power curves for various reactant flow rates
Figure 30 is useful for determining the minimum reactant flow rates needed to achieve a desired power output. For instance, it can be seen that 1113W is achievable using fuel and oxidant flow rates of 11.2slpm and 30slpm (20% curve) respectively. Similarly, 2208W is achievable using fuel and oxidant flow rates of 28slpm and 75slpm (50% curve) respectively. Using this information plots of fuel and oxidant flow rate as a function of load current that give peak power were developed and can be seen in Figure 31.

![Figure 31: Reactant flow rates as a function of load current](image)

The last three data points in Figure 31 represent flow rates that had not yet produced their maximum achievable output power. As a result, excess reactant is being supplied to produce a given power at these points. The difference in power between the 80% and 100% curves shown in Figure 30 is approximately 1% at 200A which is
statistically insignificant since the error in this study was shown to be up to 4.6% between trials under the same conditions.

5.2 EFFECT OF GAS TEMPERATURE

PEM fuel cell power output depends on the temperature of the reactant and product species where the reactions occur (12). This behavior was expected because “… kinetic losses tend to decrease with increasing temperature.” (12) This effect was observed in the tests conducted for this research and can be seen in Figure 32. Reactant stream temperature also affects the amount of water that is transported to the FC stack’s electrolyte membranes. This is important because the conductivity of the FC stack’s membranes is affected by their wetness (5). All of the tests for the temperature study were conducted with fully saturated air (100% relative humidity). However, the humidity ratio (kg moisture per kg dry air) is a function of temperature (19). In order to determine the actual amount of water being transported to the FC stack, a psychrometric chart must be used. Using a psychrometric properties calculator (available for Engineering Equation Solver software), the humidity ratio for the oxidant at 30°C was approximately 0.023. The humidity ratio for the oxidant at 70°C was approximately 0.22.

\[ x = \frac{m_w}{m_a} \]  

(Eq. 8)

\[ x = \text{humidity ratio} \]
\[ m_w = \text{mass of water in air (kg)} \]
\[ m_a = \text{mass of dry air (kg)} \]

Therefore, nearly 10 times more moisture was supplied to the FC stack via the oxidant stream when the gas temperature was 70°C compared to 30°C. Furthermore, the flow rate of the oxidant was roughly three times greater than the flow rate of the fuel. As a result, the amount of water supplied to the FC stack by the reactant streams was largely contributed by the oxidant.
It can be seen in Figure 32 that around roughly 80A load, the voltage of the 30°C, 40°C and 50°C curves begins to increase. This is likely due to the wetness of the electrolyte membrane being increased by water production at the FC stack’s anodes. According to Wang et al (20), the performance of PEM fuel cells improves for higher loads due to improved membrane humidification resulting from increased water production. The amount of water produced by the FC stack as a result of the reaction between the fuel and oxidant can be seen in Figure 33. The plots shown in Figure 33 suggest that reactant streams with temperatures below roughly 70°C are unable to supply enough moisture to adequately wet the FC stack’s electrolyte for load currents under 80A.
Figure 33: Water production as a function of load current for the Ballard Mark 9 SSL fuel cell stack plotted with results of temperature study. Adapted from (1)

5.3 EFFECT OF GAS PRESSURE

The gas pressure data collected for this study behaved similar to the data provided by the manufacturer. Increasing the reactant stream pressures caused a nearly uniform voltage shift throughout the entire 0-200A load range. The difference in FC stack power as a function of load current can be seen in Figure 34. The difference between the high (H₂=165.5kPa, Air=144.8kPa) and low (H₂=48.3kPa, Air=17.2kPa) pressure power curves was approximately 8% for the entire load range tested. At 200A load, the percent difference in the FC stack’s power output between the high and low pressures tested was 8.24%. Although the test apparatus was unable to test the FC stack up to the maximum 300A load, the data that were collected can be extended using linear regression since the manufacturer’s data behaves nearly linearly up to 300A. Forecasted V-I and power curve are shown in Figure 35 and Figure 36 for the whole 300A load range. This data suggests
that the maximum achievable power for the FC stack at $H_2=165.5\text{kPa}$ and $\text{Air}=144.8\text{kPa}$ (all other inputs set to manufacturer’s recommended) will be approximately 4 kW. Based on the forecasted data, at 300A load the percent difference in the FC stack’s power output between the high and low pressures tested was approximately 11.6% for the forecasted data. The maximum power output predicted by the manufacturer at 300A load for conditions similar to those tested is approximately 4.75kW. Although the maximum power predicted using the forecasted data in this study is somewhat lower, the data collected up to 200A correlated well with that provided by the manufacturer. It can be seen in Table 4 that the data collected during this research is similar to that provided by the FC stack’s manufacturer at 200A. It should be noted however that the pressure was lower for this research than the manufacturers. This suggests that the performance of the FC stack tested in this research may behave similarly to the specifications outlined by the manufacturer.

Table 4: Comparison of data collected in this research and data supplied by the FC stack’s manufacturer (1).

<table>
<thead>
<tr>
<th></th>
<th>Manufacturer's Data</th>
<th>Data Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power @ 200A =</td>
<td>3350W</td>
<td>3196W</td>
</tr>
<tr>
<td>H2 Pressure =</td>
<td>26psi (179.3kPa)</td>
<td>24psi (165.5kPa)</td>
</tr>
<tr>
<td>Air Pressure =</td>
<td>23psi (158.6kPa)</td>
<td>21psi (144.8kPa)</td>
</tr>
</tbody>
</table>

The experimental setup was also unable to achieve the maximum allowable pressure limits according to the FC stack’s manufacturer. The FC stack can be operated at nearly 75% higher pressures than those that were tested. Based on the experimental results, it is reasonable to expect the performance increase resulting from such high pressure to be significant. However, for a closed energy system such as an automotive application it is important to consider the additional amount of energy required to pressurize the reactant streams. It is unclear whether the extra power output is sufficient enough to offset the additional energy required by a compressor to pressurize the gases.
Figure 34: Stack power for two pressure scenarios

Figure 35: V-I curve showing data that were forecasted to 300A using linear regression
5.4 EFFECT OF GAS HUMIDITY

The voltage output of the FC stack was observed to decrease when the stack was supplied with gasses having less than approximately 70% relative humidity. The voltage difference between the 100%, 90% and 80% relative humidity curves was statistically insignificant. The difference between these curves was equal to or less than the difference between the two 100% relative humidity curves produced in the validation plot shown in Appendix B. The V-I curves produced for various reactant stream humidities can be seen in Figure 37. The reason for the voltage drop due to lower reactant stream humidities is the decreased amount of water being supplied to the electrolyte membranes of the FC stack. These membranes must maintain a minimum level of moistness in order to properly conduct ions. It can be seen in Figure 37 that at approximately 100A load, the humidity curves begin to converge. This is likely because of the increasing amount of water being produced as a result of the chemical reaction between the fuel and oxidant. This effect was also observed in the temperature study. A psychrometric chart can be
used to determine the exact amount of water being supplied to the fuel cell via the reactant streams.

Figure 37: V-I curves for various reactant stream humidities

5.5 EFFECT OF PHYSICAL ORIENTATION

The FC stack’s physical orientation was shown to have no significant effect on the voltage or power output of the FC. This is because the reactant stream flow rates were always sufficiently high to remove any liquid water that could otherwise accumulate in the FC stack and cause stack flooding. Water accumulation at the FC stack’s reaction sites is the primary reason for testing at various physical orientations. Performance losses due to stack flooding were never observed for any of the tests that were conducted in this research. However, the flow rates that were applied to the FC stack were those
recommended for a 200A load, even when the loads were lower. This is because the reactant stream flow rates could not be automatically changed by the experimental apparatus as the load current increased. Furthermore, supplying more than the recommended amount of reactants to the FC stack does not increase the stack’s voltage or power output. However, the flow rates of the reactant streams does affect the FC stack’s ability to mitigate water accumulation issues that could lead to cell flooding. Also, the FC stack was only tested for relatively small inclinations. It is unclear from this research whether or not increased inclination (with the reactant stream inlets lower than the outlets) would lead to water accumulation problems.

The FC stack’s manufacturer recommends that the stack should not be mounted with the reactant stream inlets directly below the outlets. This suggests that the manufacturer has observed water management problems when the FC stack is inclined in this way. Based on the amount of water observed in the reactant stream plumbing (transparent tubing), it is likely that the FC stack could operate without flooding issues for flow rates much less than those applied in this research. According to Montello (16), water droplet growth and removal in PEM FCs depends on the velocity of the supplied gasses. It has also been shown that the supply gas velocity needed to remove water droplets depends on the size of the droplets (21). The geometry of the FC stack’s flow channels for this research is not well known. Therefore, it is difficult to compare the results of studies that determine critical reactant stream velocities for liquid water removal. Further research needs to be conducted in order to determine whether the orientation of the FC stack can cause flooding. Suggested research is outlined in section 6.1.

5.6 EFFECT OF COOLANT TEMPERATURE

Coolant temperature was shown to have a significant effect on the voltage and power output of the FC stack. Higher coolant temperatures resulted in higher voltage and power outputs for constant loads. This effect was amplified for higher loads. For a 50A load, the voltage increased by approximately 0.99V when the coolant temperature was
increased from 30-60°C. However, for a 200A load, the voltage increased by approximately 1.9V when the coolant temperature was increased from 30-59°C. This resulted in a 5.4% increase in power for the 50A load compared to a 14.4% increase for a 200A load. The reason coolant temperature has such a pronounced effect on the power and voltage output of the FC stack is because the coolant temperature changes the operating temperature of the FC stack. The operating temperature is the average temperature at the reaction sites of the FC stack. This is the temperature that would be used to model the FC stack using fundamental FC theory. Higher coolant temperatures also promote decreased liquid water condensation inside of the FC stack. This may be beneficial for preventing cell flooding at high loads.

5.7 RESPONSE DUE TO LOAD CHANGES

The output of the FC stack within 0.1 seconds following any of the tested load changes was always within 2% of the steady state output. Also, the steady state value of the FC stack was always achieved in less than 5 seconds for any of the tested load changes. There was no significant difference between the response times observed for the 25A, 50A and 100A load steps. This indicates that the FC stack used in this research is especially well suited for applications requiring sudden load changes. Based on the results of the response time study, it was determined that the FC stack tested in this research will be appropriate for the intended automotive application. It is important to note that this FC stack cannot supply enough power to be the primary energy source for the Alternative Energy Testbed. As a result, it may be more practical to use this FC stack as a generator for recharging the Alternative Energy Testbed’s batteries. While used as a generator it is unlikely that the FC stack will be required to respond more quickly or accurately than the results obtained in this study.

5.8 CRITICAL IMPLEMENTATION CONSIDERATIONS

One of the most important constraints that must be addressed in order to successfully implement the FC stack tested in this research is water management. The power output of this FC stack can be severely degraded by supplying it with either too
little or too much water. During preliminary testing, the reservoir of water used to humidify the FC stack emptied. This caused the FC stack’s electrolyte membranes to dry and stop conducting ions. At that time, no load was being applied to the FC stack. However, the open circuit voltage was observed to decrease by more than 50% in approximately 10min. Based on this observation, it is clear that the FC stack can quickly become inoperable if less than adequate water is supplied. If the stack is supplied with too much water, the power output will also decrease due to cell flooding. When a FC stack “floods”, water accumulates on the reaction site surfaces. This causes a reduction in the area available for reactions to occur leading to power losses. Although flooding was never observed during this research, it may be possible at lower reactant flow rates than those tested. Low reactant stream flow rates are supplied when the current density (load) of the FC stack is low. Flooding may also be possible for inclinations that exceed those tested in this research (13.5°). In order to reduce the likelihood of flooding, the FC stack can be mounted with the reactant inlets higher than the outlets. This will improve the removal of excess liquid water by taking advantage of gravitational forces.

Based on the data from the temperature and humidity studies, it is clear that the moisture supplied by the reactant streams is especially important for loads between 0-100A. As the load on the FC stack increases, the water produced by the reaction of the fuel and oxidant increases as well. As a result, the moisture supplied by the reactant streams has less of an effect on the power output of the FC stack for high loads. However, the data from these studies suggests that the moisture content of the reactant streams still has a significant effect on the power output of the FC stack up to 200A. Therefore, when selecting operating conditions, it is important to consider the amount of water supplied to the FC stack by the reactant streams and reaction.

Another very important consideration is the temperature of the FC stack. The temperature at the reaction sites of the FC stack have a significant effect on the power that can be achieved. The temperature at these sites depends on three major processes; the temperature of the reactant streams, the temperature of the coolant and the amount of heat
produced by the fuel and oxidant reaction. Testing revealed that the power output of the FC stack was highly dependent on the coolant temperature. In order to achieve a steady power output from the FC stack the coolant temperature must also be steadily controlled. Accurately controlling the temperature of the coolant should be a primary concern when implementing this FC stack if accurate power output is desired.

5.9 RECOMMENDED OPERATING CONDITIONS

Based on the results of this study, the FC stack will achieve its optimum performance when using the recommended operating conditions outlined by the manufacturer should be used. The manufacturer’s recommended operating conditions are listed in Figure 38. Therefore, it has been shown that the FC stack operates nearly as predicted by the manufacturer despite being used and aged for over three years. However, there are some conditions outside of those recommended by the manufacturer that can be used. The following operating conditions may be used if necessary.

1.) Fuel and Oxidant Temperature: if load ≤ 100A, use 60-70°C
   if load ≥ 100A, use 50-70°C

2.) Fuel and Oxidant Flow Rates: no less than 90% of the values recommended by the manufacturer
<table>
<thead>
<tr>
<th>Reactant Parameter</th>
<th>Current (A)</th>
<th>15</th>
<th>30</th>
<th>60</th>
<th>120</th>
<th>240</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel (Pure Hydrogen)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet Stoichiometry Min.</td>
<td>~5.6 *</td>
<td>~3.0*</td>
<td>~1.8*</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Nominal Inlet Pressure kPa (abs)</td>
<td></td>
<td>115</td>
<td>116</td>
<td>131</td>
<td>157</td>
<td>200</td>
<td>220</td>
</tr>
<tr>
<td>Pressure Drop kPa</td>
<td></td>
<td>6.0 *</td>
<td>6.0 *</td>
<td>6.0 *</td>
<td>9.0</td>
<td>14.2</td>
<td>17.5</td>
</tr>
<tr>
<td>Nominal Inlet Temperature °C</td>
<td></td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>60</td>
</tr>
<tr>
<td>Relative Humidity** %</td>
<td></td>
<td>95 ± 5</td>
<td>95 ± 5</td>
<td>95 ± 5</td>
<td>95 ± 5</td>
<td>95 ± 5</td>
<td>95 ± 5</td>
</tr>
<tr>
<td>Oxidant (Ambient Air)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet Stoichiometry Min.</td>
<td>~2.2 *</td>
<td>2.0</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Nominal Inlet Pressure kPa (abs)</td>
<td></td>
<td>108</td>
<td>110</td>
<td>117</td>
<td>135</td>
<td>180</td>
<td>200</td>
</tr>
<tr>
<td>Pressure Drop kPa</td>
<td></td>
<td>5.0 *</td>
<td>5.0 *</td>
<td>15.5</td>
<td>27.0</td>
<td>39.0</td>
<td>45.0</td>
</tr>
<tr>
<td>Nominal Inlet Temperature °C</td>
<td></td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>60</td>
</tr>
<tr>
<td>Relative Humidity** %</td>
<td></td>
<td>95 ± 5</td>
<td>95 ± 5</td>
<td>95 ± 5</td>
<td>95 ± 5</td>
<td>95 ± 5</td>
<td>95 ± 5</td>
</tr>
<tr>
<td>Coolant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal Inlet Pressure kPa (abs)</td>
<td>≤ Oxidant Inlet Pressure</td>
<td>62</td>
<td>64</td>
<td>67</td>
<td>68</td>
<td>69</td>
<td>70</td>
</tr>
<tr>
<td>Inlet Temperature Max. °C</td>
<td></td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>60</td>
</tr>
<tr>
<td>Outlet Temperature Max. °C</td>
<td></td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>60</td>
</tr>
<tr>
<td>Cross Pressure between Fluid Streams</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Fuel over Oxidant kPa</td>
<td>7</td>
<td>8</td>
<td>10</td>
<td>13</td>
<td>20</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Maximum Fuel over Oxidant kPa</td>
<td></td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Coflow kPa</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Counterflow kPa</td>
<td></td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Minimum Reactant over Coolant kPa</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Maximum Coolant over Reactant Transient kPa</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
* Operation at currents of 60A or less are dominated by minimum pressure drop requirements. Reactant flows are determined by minimum pressure drop on Fuel (>6.0 kpa) and Oxidant (> 5.0kpa) circuits.
** Anode inlet relative humidity is relative to:
  Coflow - coolant inlet temperature
  Counterflow - coolant outlet temperature.

Figure 38: Manufacturer’s recommended operating conditions for the FC stack tested in this research (1)
CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Polarization and power curves were produced for all of the variables that were tested. The range of operating conditions that are acceptable for normal use were outlined. Recommendations for mounting the FC stack in the Alternative Energy Testbed were made. It was also shown that the FC stack’s response to abrupt load changes will be adequate for the Alternative Energy Testbed. It was determined that fuel utilization curves were not a meaningful addition to this research based on the experimental method used. The tests conducted in this research were performed using constant reactant stream flow rates for the entire 0-200A load range. For the Alternative Energy Testbed, the reactant stream flow rates will change depending on the desired power output. Therefore, the fuel utilization efficiency was not considered in this thesis.

The flow rate study revealed that the power output of the FC stack will not be significantly affected as long as at least 90% of the recommended reactant flow rates are used. Reducing the reactant flow rates by 10% from the recommended values will result in considerable fuel savings for the intended automotive application. It was shown in the gas temperature study that reactant stream temperatures can have a drastic effect on the power output of the FC stack. It was shown that gas temperature was important for proper stack hydration for loads below 100A. Based on the temperature study, the reactants should be heated to at least 60°C for loads up to 100A and at least 50°C thereafter.

The reactant stream pressures were also shown to have a significant effect on the voltage and power output of the FC stack. When implementing the FC stack used in this research, it is recommended that the minimum reactant stream pressure needed to achieve a desired power level is used in order to conserve energy when implemented. Humidity was also shown to have a significant effect on the voltage and power output of the FC stack. Similar to the temperature study, the effect of reactant stream humidity was shown to diminish over time. Due to the potentially damaging effects of cell drying, it is recommended that the reactant stream relative humidities never fall below 90%.
The physical orientation of the fuel cell was shown to have no significant effect on the voltage and power output of the FC stack. However, the worst case scenario tested in this research was only an inclination of 13.5° towards the FC stack’s reactant inlets. It is unclear whether or not increasing the degree of inclination beyond 13.5° will affect the voltage or power output of the FC stack. Based on the physical orientation study, there will be some flexibility in the mounting location for the FC stack in the Alternative Energy Testbed. The Alternative Energy Testbed has multiple locations that could support the space and orientation requirements of the FC stack.

The dynamic study revealed that the FC stack is capable of reaching steady state voltages within 5s following load changes of 25A, 50A and 100A. Furthermore, within 0.1s of any load change up to 100A, the FC stack’s voltage will be within 2% of steady state. There was no significant difference between the 25A, 50A and 100A load changes in the amount of time that it took the FC stack to reach steady state voltages. Also no significant difference was observed between the response times measured at low currents versus high currents. Based on the response to load changes that were observed, the FC stack tested in this research will be capable of achieving the load changes required for its intended automotive application.

Further research needs to be conducted in order to determine whether or not the physical orientation of the FC stack can cause FC flooding to occur. Stack inclination and reactant stream velocity are the two major variables that contribute to liquid water removal. The worst case scenario for water accumulation in the FC stack is when the reactant stream velocities are low, the load on the FC stack is low and the stack’s gas outlets are above the inlets. It is recommended that tests be conducted so that the critical flow rates, stack inclination and current density which lead to cell flooding can be determined.

6.2 RECOMMENDATIONS

Due to limitations related to coolant temperature control for the experimental apparatus used in this research, it was necessary to shorten individual test times to less
than approximately 4 minutes. As a result, some conclusions made in this research may not apply to operation over long periods of time. This is not likely the case for the gas pressure, flow rate or response time studies. However, the gas temperature, humidity and physical orientation studies may behave differently for long versus short test times. The reason for this difference is related to water management in the FC stack. If water accumulation or depletion occurs slowly, it may take a long time to observe any performance losses related to cell drying or flooding. In order to determine what happens over long periods of time, the coolant control limitations mentioned in Section 3.2 must be resolved. In order to limit the amount of coolant temperature fluctuation, the gain values for the PID controller used in the experimental apparatus will need to be adjusted. The gain values can be adjusted using the MITS software that is used to control the FCTS. In order to improve the cooling capacity of the test stand, additional cooling units must be used or a more capable chill unit purchased. The coolant system should be capable of removing approximately 5kW of heat from the FC stack. This will allow tests to be conducted at 200A for as long as needed without cooling capacity limitations.

The dynamic portion of this research was limited due to the capabilities of the experimental apparatus used. In order to fully understand the behavior of this FC stack, an Equivalent Circuit Model (ECM) should be developed. The output characteristics of a PEMFC can be modeled using basic circuit elements (12). The values of the circuit elements are determined using an experimental technique called Electrochemical Impedance Spectroscopy (EIS) (12). A simple ECM is shown in Figure 39. EIS and the resulting ECMs are considered the gold standard in PEMFC characterization techniques. A parametric dynamic study would be much more costly in terms of resources and time. Once an ECM is developed, it can be incorporated into any circuit modeling software. As a result, dynamic tests can be performed without actually using the real FC stack. This will save considerable resources and accelerate the development process for the Alternative Energy Testbed.
It is still unclear what the overall efficiency of the FC stack and accompanying hardware will be when implemented into the Alternative Energy Testbed. It was shown that increasing the FC stack’s reactant stream pressure and temperature results in increased power output. However, in order to increase these parameters additional energy must be supplied to heaters and compressors. It is recommended that research be done to resolve these balance of plant issues. Compressing the hydrogen will not be necessary since it is stored at higher pressures than the FC stack can be operated at.

For this research, the performance of the entire FC stack was of primary concern. As a result, the performance of each of the stack’s 25 individual cells is unknown. However, monitoring individual cells may provide some useful information. For example, if cell flooding or drying is observed initially for some cells and not others, the operating conditions of the FC stack could be changed in order to improve water management. The FCTS used in this research is capable of monitoring the output of up to 16 different cells. Therefore, up to 16 of the FC stack’s 25 cells could be monitored at a time. One test that could help determine the difference in output between cells in different locations in the stack would be to monitor every other cell. A test like this could help identify if cell drying or flooding begins in a predictable location.
Safety must be a primary concern when planning the implementation of the FC stack used in this research. The FCTS had many safety features that must be duplicated in the Alternative Energy Testbed. These features include automatic shutdown if voltage or current limits are exceeded. There must also be a system in place to purge the entire gas supply plumbing with inert gas (nitrogen for instance) in case of emergency. Operation of the FC stack in the Alternative Energy Testbed should also follow many of the same procedural guidelines that are outlined in Appendix A. Most importantly, there should be some procedure and system in place for detecting hydrogen leakage.
WORKS CITED


APPENDIX A: RESULTS OF DATA VALIDITY TESTS

Figure 40: Validation of reactant temperature data

Figure 41: Validation of gas humidity data
Figure 42: Validation of gas pressure study results

Figure 43: Validation of inclination data for Orientation A
Figure 44: Validation of inclination data for Orientation B
EFFECT OF COOLANT TEMPERATURE

Figure 45: Effect of coolant temperature on stack output voltage for a constant 100A Load

Figure 46: Effect of coolant temperature on stack output voltage for a constant 200A Load

RESPONSE TIME
Figure 47: Voltage as a function of time with 50A load steps up to 200A

Figure 48: $\frac{dv}{dt}$ as a function of time for 50A load steps from 0-200A
Figure 49: Voltage as a function of time with 100A load steps up to 200A

Figure 50: $\frac{dv}{dt}$ as a function of time for 100A load steps from 0-200A
POWER CURVES

Figure 51: Effect of gas humidity on stack power output

Figure 52: Effect of Orientation A on stack power output
Figure 53: Effect of Orientation A on stack power output

Figure 54: Effect of reactant stream temperature on stack power output
Institute for Sustainable Energy and the Environment (ISEE)

Experimental Safety Evaluation Report
(Template)

For

"Fuel Cell Testing – Ballard 4.8kW Fuel Cell using Arbin Test Stand"

Document Number:
ESER_NH3Car_1_FCTest_090225

Last Updated:
04/21/2009

Contributor(s):
Tyler Edwards
PURPOSE / SCOPE OF WORK

The purpose of this project is to characterize the performance of a Ballard® 4.8kW fuel cell using an Arbin Instrument’s fuel cell test stand (FCTS). The scope of this project is to determine the performance characteristics of the fuel cell including their dependence on temperature, gas flow rates, humidity, and pressure. The end result of the testing will be to determine the parameters needed to successfully implement the fuel cell in an automobile according to the requirements of the Ammonia Car Project.

HIA

ERGONOMIC HAZARDS

No Ergonomic Hazards

CHEMICAL HAZARDS

1.) Compressed hydrogen cylinder is uncapped while being used. Maximum cylinder pressure is \( \leq 3000 \text{psi} \). MSDS Emergency Overview: Hydrogen is a flammable, colorless, odorless, compressed gas packaged in cylinders at high pressure. It poses an immediate fire and explosive hazard when concentrations exceed 4%. It is much lighter than air and burns with an invisible flame. Enclosed spaces with high concentrations that will cause suffocation are within the flammable range and must not be entered.
   a. Cylinder must be secured to the wall using supplied hardware and straps.
   b. Plumbing between the cylinder and test stand must be properly leak tested after initial installation.

2.) Compressed nitrogen cylinder is uncapped while being used. Maximum cylinder pressure is \( \leq 3000 \text{psi} \). MSDS Emergency Overview: Nitrogen gas is colorless, odorless and non-flammable. It is non-toxic. The primary health hazard is asphyxiation by displacement of oxygen. Maintain oxygen levels above 19.5%. Contact with the liquid or cold gas can cause freezing of exposed tissue.
   a. Cylinder must be secured to the wall using supplied hardware and straps.
   b. Plumbing between the cylinder and test stand must be properly leak tested after initial installation.

3.) Pressurized air is supplied by the building’s main air supply at a maximum pressure \( \leq 60 \text{ psi} \).

PHYSICAL HAZARDS

1.) Electric shock hazard: The Arbin Instrument’s FCTS may require as much as 6kW of power during operation.

2.) Electric shock hazard: The Ballard® Mark 9 SSL Fuel Cell stack (25 cells) may produce as much as 4.8kW @ 300A of power during operation. The electrode terminals on the fuel cell are separated by only 4 inches creating a serious short circuit hazard. See Ballard® Mark 9 SSL Fuel Cell manual for necessary safety precautions.
   a. Operator must wear rubber or other insulating gloves when touching the fuel cell electrodes or the current drawing connections of the test stand

PSYCHOLOGICAL AND ORGANIZATIONAL HAZARDS
No Psychological/Organizational Hazards

BIOLOGICAL HAZARDS
No Biological Hazards

PROJECT TIMELINE
A brief description or overview of the total time required to complete the project and elaborate on possible delays.

<table>
<thead>
<tr>
<th>Task</th>
<th>Timeframe</th>
<th>Deliverable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental Setup</td>
<td>2 days</td>
<td>Attach fuel cell stack to test stand</td>
</tr>
<tr>
<td>Perform fuel cell “Break-in” testing</td>
<td>5 days</td>
<td>Conduct open circuit and low power tests to break-in fuel cell.</td>
</tr>
<tr>
<td>Perform fuel cell input response testing</td>
<td>15 days</td>
<td>Conduct tests to determine the effect of temperature, humidity, pressure,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and gas flow rates on the fuel cell’s performance.</td>
</tr>
<tr>
<td>Perform simulated automobile application</td>
<td>5 days</td>
<td>Perform simulated drive cycle testing based on intended automobile</td>
</tr>
<tr>
<td>testing</td>
<td></td>
<td>application.</td>
</tr>
<tr>
<td>Possible Delays</td>
<td>10 days</td>
<td>Longer than anticipated break-in period. Leaks requiring purchase of new</td>
</tr>
<tr>
<td></td>
<td></td>
<td>hardware. Running out of hydrogen or nitrogen. Poor test results</td>
</tr>
<tr>
<td></td>
<td></td>
<td>requiring repeated tests.</td>
</tr>
</tbody>
</table>

Here you can add additional notes (if needed).

PERSONNEL AND PROJECT SITE PREPARATIONS
Required Personnel Training (include everything)

<table>
<thead>
<tr>
<th>No.</th>
<th>Operator Training</th>
<th>Offered by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OSHA Laboratory Chemical Hygiene Training</td>
<td>EHS - Ohio University</td>
</tr>
<tr>
<td>2</td>
<td>Plan for Excellence, Safety, and Operation (PESO)</td>
<td>CHO - ISEE</td>
</tr>
<tr>
<td>3</td>
<td>Shop and/or Laboratory Tool Usage Guidelines</td>
<td>CHO - ISEE</td>
</tr>
<tr>
<td>4</td>
<td>Analytical Instruments Usage Guidelines</td>
<td>CHO - ISEE</td>
</tr>
<tr>
<td>5</td>
<td>Arbin Instrument’s FCTS Usage Training</td>
<td>EERL</td>
</tr>
</tbody>
</table>

Required Safety Equipment (include everything)

<table>
<thead>
<tr>
<th>No.</th>
<th>Safety Equipment</th>
<th>Purpose</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Protective Eyewear</td>
<td>To protect eyes from pressurized system containing Hydrogen, Nitrogen, and water.</td>
<td>Available upon request.</td>
</tr>
<tr>
<td>2</td>
<td>Insulating Gloves</td>
<td>To protect user from short circuiting fuel cell electrodes</td>
<td>Available upon request.</td>
</tr>
</tbody>
</table>
### Required Tools /Analytical Equipment (include everything)

<table>
<thead>
<tr>
<th>No.</th>
<th>Tools/Analytical Equipment</th>
<th>Purpose</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Arbin Instrument’s 4kW fuel cell test stand (including associated coolant pump)</td>
<td>Facilitates fuel cell operation by controlling reactant flow rates, temperature, pressure, coolant, and loading conditions.</td>
<td>Stocker 042 Electrochemical Engineering Research Lab</td>
</tr>
<tr>
<td>2</td>
<td>Ballard® Mark 9 SSL Fuel Cell (25 cell)</td>
<td>The device being tested</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Associated fittings and plumbing</td>
<td>Allows fuel cell to be integrated with testing equipment</td>
<td></td>
</tr>
</tbody>
</table>

### Required Supplies (things not permanently attached to project)

<table>
<thead>
<tr>
<th>No.</th>
<th>Equipment/Supplies</th>
<th>Purpose</th>
<th>Qty.</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Snoop® Liquid Leak Detector</td>
<td>To detect leaks in pressurized fuel cell system.</td>
<td>1</td>
<td>Stocker 042 Electrochemical Engineering Research Lab</td>
</tr>
<tr>
<td>2</td>
<td>Adjustable wrench and wrench set.</td>
<td>To connect plumbing to fuel cell and test stand</td>
<td>1</td>
<td>Stocker 042</td>
</tr>
<tr>
<td>3</td>
<td>Teflon Tape</td>
<td>To prevent leaks at threaded connections in plumbing</td>
<td>1</td>
<td>Stocker 042</td>
</tr>
<tr>
<td>4</td>
<td>Hydrogen Cylinder</td>
<td>To provide fuel to FC</td>
<td>1</td>
<td>Stocker 042</td>
</tr>
<tr>
<td>5</td>
<td>Nitrogen Cylinder</td>
<td>To purge test system of hydrogen</td>
<td>1</td>
<td>Stocker 042</td>
</tr>
<tr>
<td>6</td>
<td>Distilled Water</td>
<td>Coolant/ Humidity</td>
<td>5 gal</td>
<td>Stocker 042</td>
</tr>
</tbody>
</table>

### Required Services (include electrical, gas, water, etc.)

<table>
<thead>
<tr>
<th>No.</th>
<th>Services</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Electrical</td>
<td>To provide power (up to 6kW) to fuel cell test stand, walk-in fume hood and coolant pump.</td>
</tr>
<tr>
<td>2</td>
<td>Air</td>
<td>Provides oxygen to fuel cell test stand</td>
</tr>
</tbody>
</table>

### Required Procedures (as referenced within this document)

<table>
<thead>
<tr>
<th>No.</th>
<th>Procedures / Manuals</th>
<th>Server / Physical Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Assemble Fuel Cell to Test Stand/ See Ballard® Mark 9 SSL Owner’s Manual for setup</td>
<td>Stocker 042 Chemical Engineering Lab</td>
</tr>
</tbody>
</table>
2 | Fuel Cell Testing/ See both fuel cell and FCTS owner’s manuals | Stocker 042 Chemical Engineering Lab

Required Operators and/or Technical Assistance

<table>
<thead>
<tr>
<th>No.</th>
<th>Operator(s)</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 operator needed</td>
<td>To monitor testing and to insure proper shut down in case of emergency</td>
</tr>
</tbody>
</table>

OPERATION (provide step by step instructions for all aspects of operation, including calibration and set up, start up, monitoring, data collection, and shut down. Use pictures to show the operations whenever possible. Highlight all safety critical items.)

The system consists of an Arbin Instrument’s FCTS, Ballard® Mark 9 SSL Fuel Cell (25 cells) and associated plumbing. Additionally, there is 1 tank (max pressure ≤ 3000psi) each of hydrogen, and nitrogen. Pressurized air is supplied to the system by Stocker Center’s main air supply. Coolant is circulated through the FCTS and the fuel cell by a medium sized stand alone pump/heating unit. The FCTS is located directly beneath a large fume hood. The FCTS also includes a large stand alone water container. These components can be seen below in figure 1.
Figure 55: FCTS, fuel cell, gas tanks and computer station (top); Coolant pump (bottom left); Water reservoir (bottom right)

Ballard® Mark 9 SSL Fuel Cell testing using Arbin Instrument’s Fuel Cell Test Stand (FCTS)
Test Preparation and Start Up

Put on safety glasses and locate electrically insulated gloves. Turn on fume hood fan and lights. Insure pressure drop gauge on fume hood reads approximately 0.25.

Insure the water container is between 1/2 - 2/3 full

Turn on coolant pump and select 20°C temperature. Open cap on top of coolant pump and insure water is circulating.

Perform leak test
Attach fuel cell to fuel cell test stand. See Ballard Mark 9 SSL Fuel Cell manual for details.
Open main valve on nitrogen tank and insure that the outlet pressure is 60psi. Check the nitrogen pressure gauge on the back of the FCTS and insure the pressure reading is also 60psi.
Apply Snoop® Liquid Leak Detector to all plumbing connections leading to and from the fuel cell. If there is a leak, tighten the connection. If there is still a leak after tightening, improve seal by wrapping threads with Teflon tape.

When no leaks can be detected, close main valve on nitrogen tank
Turn on computer
Turn on FCTS main power

Fuel Cell Testing

Open MITS Pro. This is the FCTS monitoring software. See MITS Pro user’s manual for details.
Insure that the green light on the FCTS’s light tree is lit. This indicates that the FCTS and computer are communicating properly.
Open main valves on hydrogen and nitrogen tanks. Turn the regulator’s pressure adjustment handles so that their regulated pressures are 60psi. Also check gauges on back of FCTS and insure their pressures read 60psi.

In MITS Pro software, run the background settings. Background settings are the desired testing conditions and include gas temperatures, pressures, flow rates, etc. See MITS Pro user’s manual for details.

CAUTION: At this time, hydrogen and air will be supplied to fuel cell.

When the parameters specified in the background settings are satisfied, PUT ON INSULATED GLOVES and connect the test stands load cables to the fuel cells electrodes. The user should be at least 3 feet away from fuel cell before removing the gloves.

Load and run a schedule file. A schedule file contains a schedule of current loads to be applied to the fuel cell. For instance, a schedule file can be written to simulate the power requirements of an automobile. See MITS Pro user’s manual for details.

At this time the orange light on the FCTS’s light tree should be lit. This indicates that testing is being conducted.

Open appropriate window in MITS Pro software to view the data being collected. See MITS Pro user’s manual for details.

Monitor the data and the background settings to insure there are no unsafe conditions being created by the test system. If an unsafe condition is detected by the FCTS, the schedule will automatically stop and the red light on the light tree will light up. For instance, the FCTS utilizes a hydrogen sensor that will alert the system to unsafe levels of hydrogen in the air surrounding the test stand and cause
the experiment to stop. At this time, follow instructions from part (b) of “EMERGENCY SHUTDOWN” in this report. The parameters that define an “unsafe condition” can be explicitly defined by the user in the MITS Pro software. See Arbin Instrument’s FCTS user’s manual for details.

When schedule is complete, stop background settings. 

**PUT ON INSULATING GLOVES** and remove the current drawing cables from the fuel cell. The user should be at least 3 feet away from the fuel cell before removing the gloves.

**System Shutdown**

**Purge system with nitrogen until fuel cell voltage drops to nearly 0V.** If this takes more than 15 minutes, unhook the fuel outlet tube from the fuel cell and purge the remaining gas in the system directly into the fume hood using nitrogen. Do not increase the flow rate of the nitrogen to speed up this process unless permission is granted by the lab coordinator. This can be done by using the purge command in the monitoring software (while FCTS is powered) or by opening the main valve on the nitrogen tank after the FCTS has been turned off.

Close main valves on hydrogen and nitrogen tanks

**Turn off power to FCTS**
Exit MITS Pro monitoring software and stop DAQ data acquisition software (DAQ is stopped from the task bar).

Turn off coolant pump

Turn off lights and fume hood

EMERGENCY SHUTDOWN

Press emergency stop button on the front of the FCTS. This will stop all schedules and background settings.

Immediately close hydrogen cylinder. Leave the nitrogen cylinder open so that the system can be purged of hydrogen. The nitrogen cylinder can only be closed once the system is considered safe again or if a failure in the system has caused a detectable leak.

Disconnect the test stands current drawing terminals from the fuel cell’s electrodes as shown in the following picture.
Notify laboratory personnel in charge. See emergency contact list posted on the front wall of laboratory if necessary.

PROJECT / SITE CLEANUP (provide step by step instructions for all aspects of test system shut down)
System Shutdown
   Disconnect fuel cell from test stand, place it in the manufacturer supplied box and return it to an appropriate storage location.

   Return any tools that were used to their original storage locations in the lab

ESER PROJECT RESULTS
Here you should write the results of your test. You can add as many pictures, graphs, tables, etc. as necessary to help clarify the findings and to provide meaningful results as if you were presenting to the group.