Test Facility for Determining the Seasonal Performance of Residential Fuel Cell Systems

Mark W. Davis
and
A. Hunter Fanney

Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8632 USA

Proceedings of the Hydrogen and Fuel Cells 2003
Conference and Trade Show

Vancouver, BC, Canada, June 9-11, 2003

Test Facility for Determining the Seasonal Performance of Residential Fuel Cell Systems

Mark W. Davis
A. Hunter Fanney
Heat Transfer and Alternative Energy Systems Group
National Institute of Standards and Technology, Gaithersburg, MD

Abstract

The National Institute of Standards and Technology (NIST) has designed and constructed a test facility for determining the seasonal performance of residential fuel cell systems. A consumer-oriented performance rating to guide consumers in their economic decisions is essential to the widespread commercialization of residential fuel cell systems. NIST's history of developing test procedures and rating methodologies for residential appliances will aid in the development of a similar test procedure and rating methodology for the seasonal performance of residential fuel cells.

The test facility, which was created to support the development of the rating methodology, incorporates an environmental chamber capable of maintaining the ambient temperature and relative humidity over a range of –18 °C to 40 °C and 20 % to 95 %, respectively. Various measurement systems within the facility permit the determination of the fuel source's energy content, the electrical power and energy generated by the fuel cell unit, and for units that offer cogeneration capabilities, the thermal output of the fuel cell unit. Both grid connected and grid independent systems can be accommodated within the test facility.

NIST's fuel cell test facility incorporates thermal conditioning apparatus that permits tests to be conducted while supplying a fixed flow rate and temperature to the unit or while capturing the thermal energy by means of a domestic hot water preheat tank under simulated load conditions.

Tests will be conducted thoroughly to map the performance of residential fuel cell systems over a range of ambient temperatures, relative humidity levels, and load conditions. NIST will then identify the smallest combination of tests that reasonably capture the performance characteristics of the fuel cell. These tests will provide the needed inputs to an algorithm that predicts the seasonal performance and economic savings of the fuel cell system. With this information the consumer can then make a more informed buying decision.

Introduction

NIST has proposed a methodology for determining the seasonal performance of residential and small commercial fuel cell systems [1]. This methodology would provide fuel cell system purchasers with a realistic estimate of the annual electrical energy output, thermal energy output, and fuel usage. The performance of residential fuel cell systems varies with electrical load and thermal load conditions as well as the surrounding environmental conditions. NIST's residential fuel cell test facility was designed to investigate the effect of load and environmental conditions on the overall performance of fuel cell units. Once the effects are quantified, a parametric model will be developed that predicts the fuel cell system's performance as a function of its load and environmental conditions. This model will be incorporated into a proposed rating methodology, including procedures that standardize the determination of the model parameters.

It should be acknowledged that several test procedures and performance standards are either published or under development by consensus standards organizations. Primarily, the American Society of Mechanical Engineers (ASME) has published performance test code 50 (PTC 50) [2], which measures a fuel cell's electrical efficiency and thermal effectiveness. The standard specifies the testing procedure and calculation of results for a single steady-state test. PTC 50 is applicable to any size fuel cell, any type of fuel cell, and a wide variety of fuel sources. Its main purpose is to provide a standard test method by which different fuel cell systems can be compared. Similarly, the International Electrotechnical Commission (IEC) is developing test code 105 (TC 105) [3] for fuel cell systems. Its scope and purpose are equivalent to ASME's PTC 50, but it will include a partial load test, transient response test, emissions testing, and noise testing. Finally, the American National Standards Institute (ANSI) has developed ANSI Z21.83 [4], which will soon be published as CSA FC 1. While this standard does contain performance tests, the purpose of these performance tests is to ensure that the output matches the nameplate value. Each of these standards will provide valuable help to the fuel cell industry by providing standardized testing procedures by which to compare fuel cell systems.

However, neither ASME PTC 50, IEC TC 105, nor ANSI Z21.83 provide any information concerning the performance of these units as a function of the environmental conditions. Each of the standards requires testing at a single, steady ambient temperature. Also, while the IEC test procedure measures the electrical and thermal efficiency at full and partial electrical load, neither the ASME or ANSI standards determine the fuel cell's performance at various load levels. The test procedure and rating methodology proposed by NIST would account for the varying performance at a range of environmental conditions and load levels. Additionally, it would reduce the seasonal performance of the residential fuel cell system to a single metric, which would allow consumers to greater understand the true costs and benefits of purchasing a system.

In order to develop a seasonal performance index, an in depth investigation of the effects of environmental conditions at various electrical and thermal loads is required. For this purpose, NIST has designed, constructed, and instrumented a residential fuel cell test facility. The tests identified in Table 1 will be performed at various ambient temperatures, relative humidities,

Table 1. Electrical and Thermal Load Types for Possible Performance Tests

Test #	Electrical Load Type	Thermal Load Type
1	Steady-State	None
2		Steady-State
3		Transient
4		Real-world
5	Transient	None
6		Steady-State
7	Startup	None

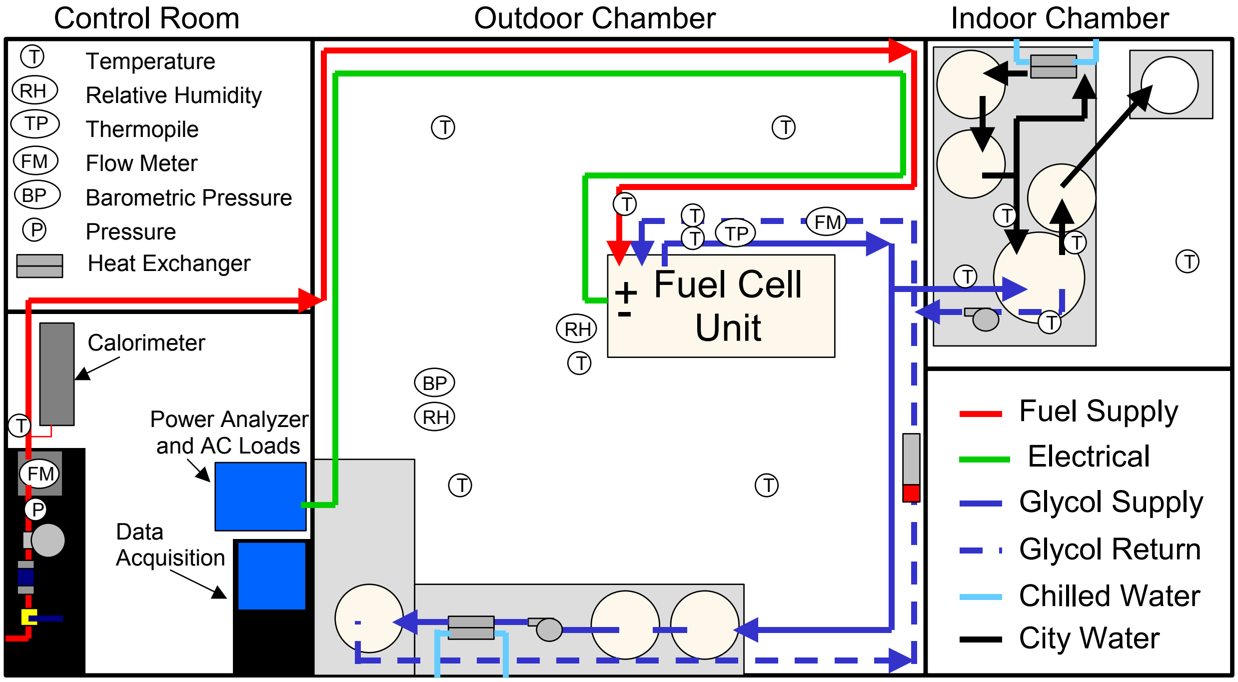


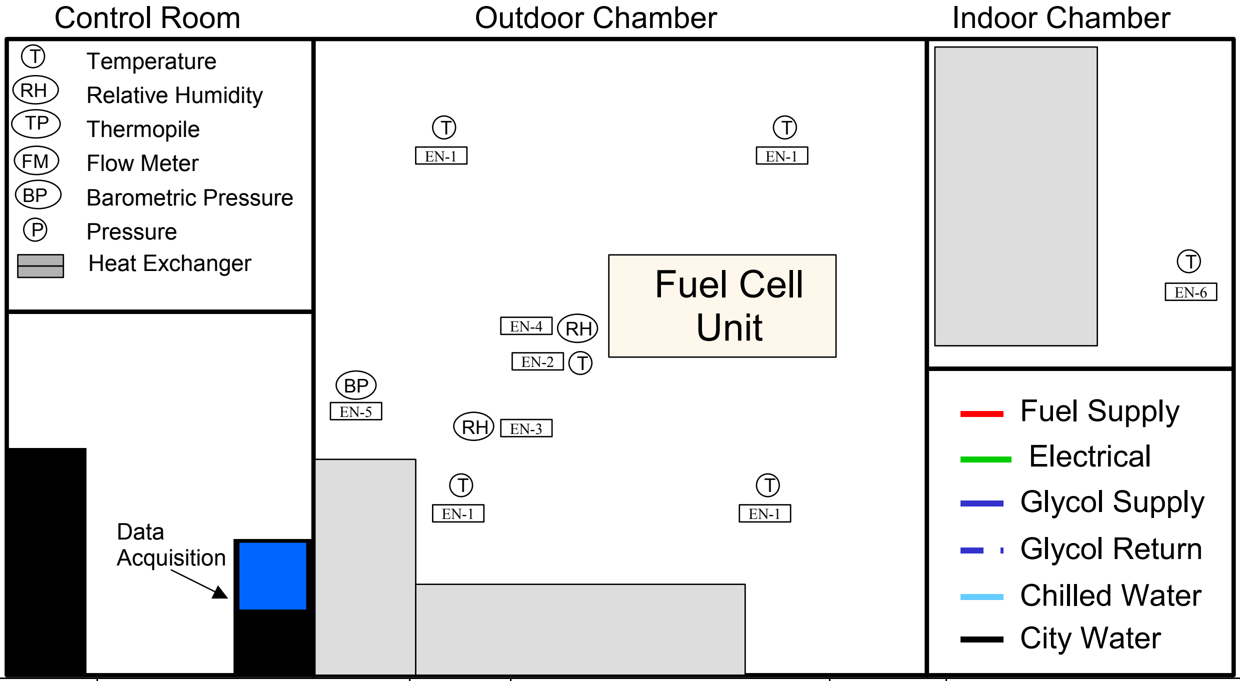
Figure 1. Residential Fuel Cell Test Facility Schematic

electrical load levels, and thermal loads. The resulting fuel cell performance data will be used as inputs to an algorithm for predicting seasonal performance. The goal of this research is to minimize the total number of tests and environmental conditions while adequately characterizing the seasonal performance of residential fuel cell systems.

Test Facility Description

The NIST residential fuel cell test facility consists of three rooms: a large environmental chamber, a smaller environmental chamber, and a control room. The large chamber is controlled to approximate outdoor environmental conditions, and houses fuel cell equipment that would typically be installed outdoors. The small environmental chamber is controlled to maintain indoor environmental conditions. Equipment such as water heaters for domestic hot water heating applications and pumps are installed in the indoor chamber. The control room holds all of the data acquisition equipment, electrical loads used to dissipate the electrical energy when the systems is operated independent of the electrical grid, and equipment to measure the energy content of the fuel. Currently, a commercially available residential fuel cell is installed in the test facility. The fuel cell produces 5 kW of power at 120 VAC, uses natural gas as its fuel, and can produce approximately 9 kW of thermal energy. The unit can be grid interconnected or can supply energy to dedicated electrical loads.

The test facility can be separated into five major systems: environmental measurement and control, fuel energy measurement, electrical energy measurement, thermal energy measurement, and safety. Each of these systems is measured and/or controlled using a single computer program that controls the data acquisition system. Three 60-channel data acquisition units are used to measure the analog signals associated with various sensors; output control voltages;



EN-1	Outdoor Ambient TC	EN-3	Outdoor Ambient RH	EN-5	Barometric Pressure
EN-2	Fuel Cell Intake TC	EN-4	Fuel Cell Intake RH	EN-6	Indoor Ambient TC

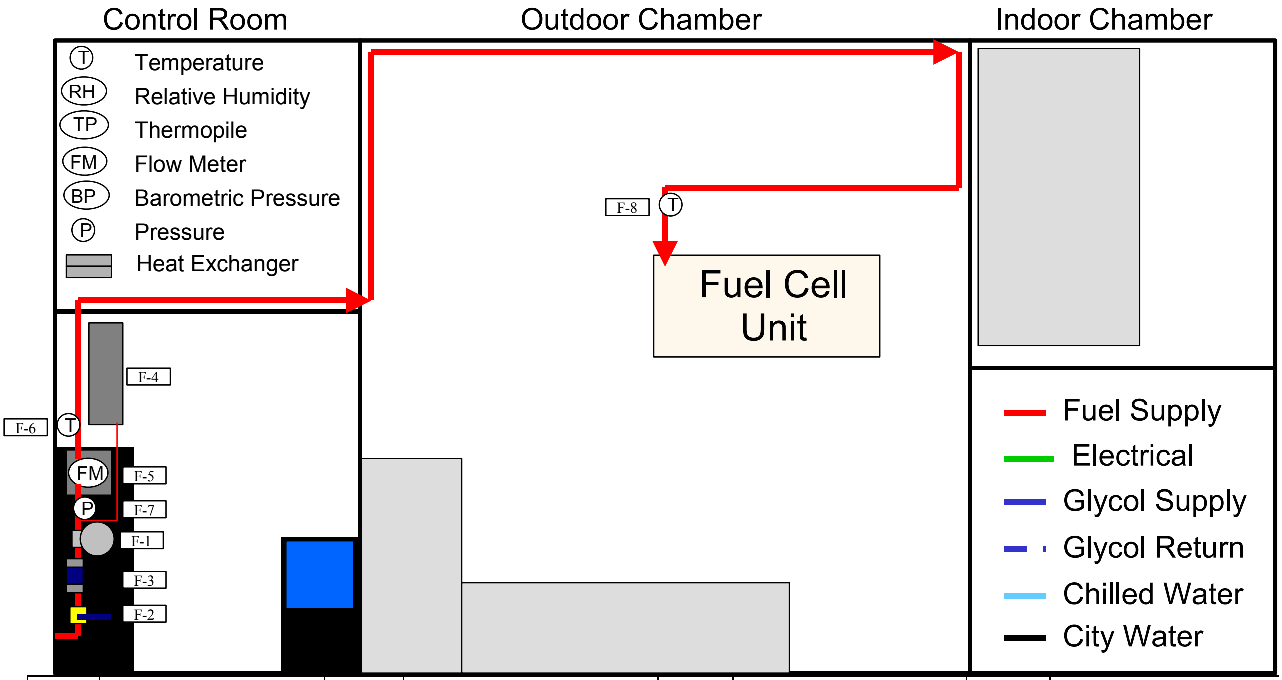
Figure 2. Environmental Measurement and Control System Schematic

count pulse signals; and control various relays. Most of the temperature measurements are made with type-T thermocouples, and the cold-junction of the thermocouples are measured by a platinum resistance thermometer (PRT) in an isothermal junction.

Environmental Measurement and Control System

The large environmental chamber (7 m x 7.6 m) is controlled to the desired outdoor ambient temperature and relative humidity. The ambient temperature can vary from –18 °C to 40 °C, and the relative humidity can be set between 20 % and 95 %. The fuel cell system and any other outdoor-installed periphery equipment are installed within this chamber. Type T thermocouples measure the ambient temperature at the center of the four quadrants of the outdoor chamber and at the air intake of the fuel cell system. Two transducers measure the relative humidity within the chamber. One transducer records the bulk relative humidity in the room whereas the second one measures the relative humidity at the air intake of the fuel cell. Additionally, a barometric pressure transducer measures the atmospheric pressure in the room. A table containing the uncertainty and range of the instrumentation in the test facility can be found in Appendix 1.

The indoor chamber (3 m x 3.6 m) is controlled to approximate typical indoor conditions. The domestic hot water heating equipment and all other periphery equipment are installed in this chamber. The ambient temperature is measured using a type T thermocouple in the center of the room.



F-1	Regulator	F-3	Solenoid Control Valve	F-5	Natural Gas Flow Meter	F-7	Flow Meter Pressure
F-2	Manual Control Valve	F-4	Calorimeter	F-6	Flow Meter TC	F-8	Fuel Cell Inlet TC

Figure 3. Fuel Supply System Schematic

Fuel Energy Measurement System

The NIST residential fuel cell test facility is designed to accommodate several different fuels, such as natural gas, hydrogen, and propane. For the current fuel cell installation, the fuel supply system is configured for natural gas. The natural gas is supplied from the building utility system at 1.75 kPa gauge (7 in w.c.), and the pressure is further reduced to 1.25 kPa gauge using a natural gas pressure regulator, as shown in Figure 3. A manual shut-off valve and a solenoid valve are located upstream of the pressure regulator. Gas detection sensors in the outdoor chamber, as shown in Figure 6, the data acquisition system, and an emergency stop button control the solenoid valve. After the regulator, a sample of gas is supplied to a calorimeter, which provides a constant measurement of the energy content of the fuel. The natural gas then passes through a dry-type positive displacement natural gas flow meter. For recording the volume of gas consumed by the fuel cell, the flow meter has a large dial with a needle that makes a full revolution for one liter of gas flow, and proximity sensors installed on the faceplate of the dial count four times for every liter of gas that passes through the meter and into the fuel cell.

The flow meter measures the actual volume of gas that is used whereas the calorimeter determines the energy content of the fuel as a function of the volume at standard temperature and pressure (25 °C, 101.3 kPa). Therefore, the actual temperature and pressure are needed to convert the volume of gas at actual conditions to the volume at standard conditions. For this purpose, the temperature and pressure of the gas is recorded using a type T thermocouple and pressure transducer, respectively. The temperature of the gas is also measured just prior to the inlet of the fuel cell. With the specific energy content of the fuel and its volumetric flow rate, the energy of the fuel used by the fuel cell system can be determined.

$$E = V_{actual} \cdot \frac{T_{STP}}{T_{actual}} \cdot \frac{P_{actual}}{P_{STP}} \cdot e_{gas} \tag{1}$$

where E = energy of fuel consumed (kJ)
V_{actual} = volume of fuel consumed (L)
T_{STP} = temperature at standard conditions (298 K)
T_{actual} = measured gas temperature (K)
P_{STP} = pressure at standard conditions (101.3 kPa)
P_{actual} = measured gas pressure (kPa)
e_{gas} = specific energy content of gas at standard conditions (kJ/L)

Assuming a natural gas consumption of 2500 L with a specific energy content of 36 kJ/L at a temperature and pressure of 20 °C and 1.5 kPa (guage), respectively, the fuel energy consumed would amount to 85 MJ, and at a 95 % confidence level, the expanded uncertainty of the measurement based on the specifications in Appendix 1 would be approximately 1 %, as shown below:

$$u_E = \frac{\sqrt{\left(\frac{\partial E}{\partial V} \cdot u_V \cdot k\right)^2 + \left(\frac{\partial E}{\partial T} \cdot u_T \cdot k\right)^2 + \left(\frac{\partial E}{\partial P} \cdot u_P \cdot k\right)^2 + \left(\frac{\partial E}{\partial e} \cdot u_e \cdot k\right)^2}}{E} \cdot 100 \tag{2}$$

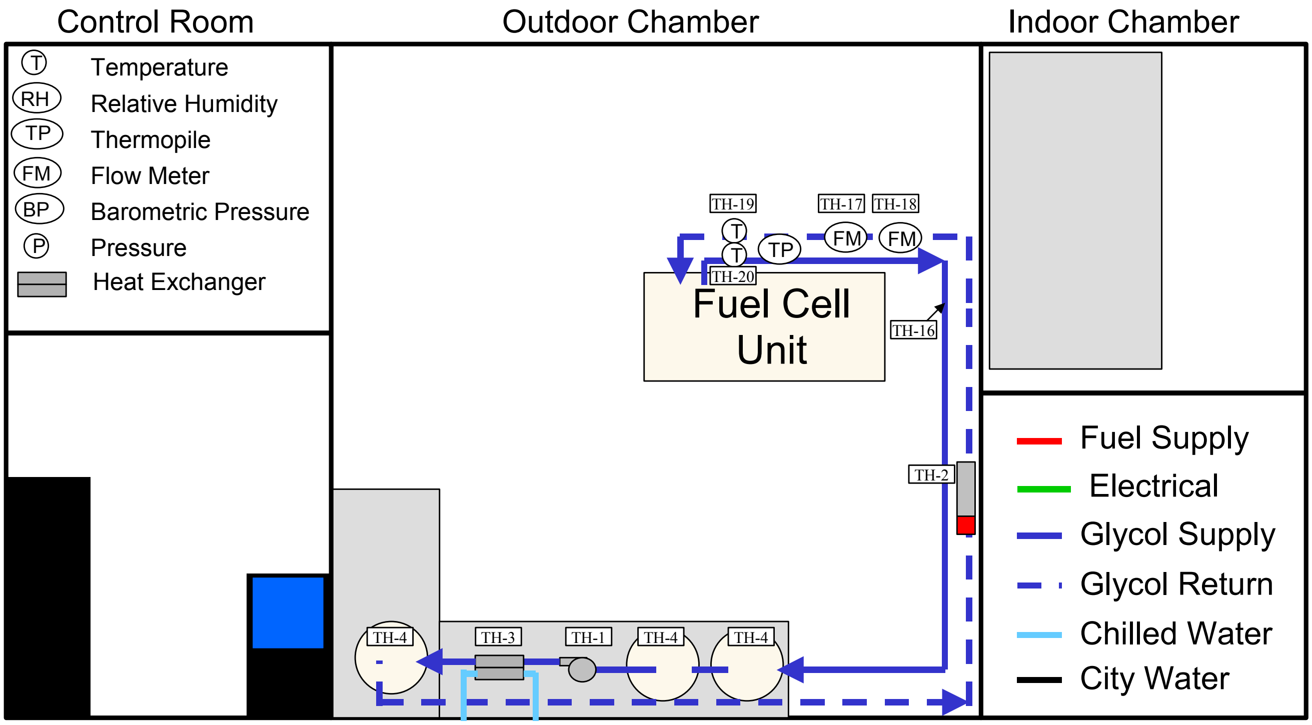
where u_E = expanded uncertainty of fuel energy consumed (%)
$\frac{\partial E}{\partial V}$ = partial derivative of fuel energy with respect to gas volume
u_V = uncertainty of gas volume measurement
$\frac{\partial E}{\partial T}$ = partial derivative of fuel energy with respect to gas temperature
u_T = uncertainty of gas temperature measurement
$\frac{\partial E}{\partial P}$ = partial derivative of fuel energy with respect to gas pressure
u_P = uncertainty of gas pressure measurement
$\frac{\partial E}{\partial e}$ = partial derivative of fuel energy with respect to energy content
u_e = uncertainty of energy content measurement
k = coverage factor, which is 2 for 95 % confidence level
E = energy of fuel consumed (kJ)

Electrical Energy System

The electrical energy produced by the fuel cell unit can be supplied to the electrical grid or to electrical loads independent of the grid. When connected to the grid, a digital power analyzer measures the true RMS voltage, RMS current, and power. Additionally, the power analyzer measures the energy delivered to the grid. If the fuel cell is operated in the grid independent mode, the electrical energy is dissipated by means of programmable alternating current load banks. The power level, power factor, and crest factor can be independently selected. A second digital power analyzer is used to measure the RMS voltage, RMS current, power, and energy delivered to the electrical load banks. Using the conditions cited in the Fuel Energy System section above and assuming an electrical efficiency of 25 %, the fuel cell would produce approximately 6 kW·h of electricity with an expanded uncertainty of 0.5 % at a 95 % confidence level.

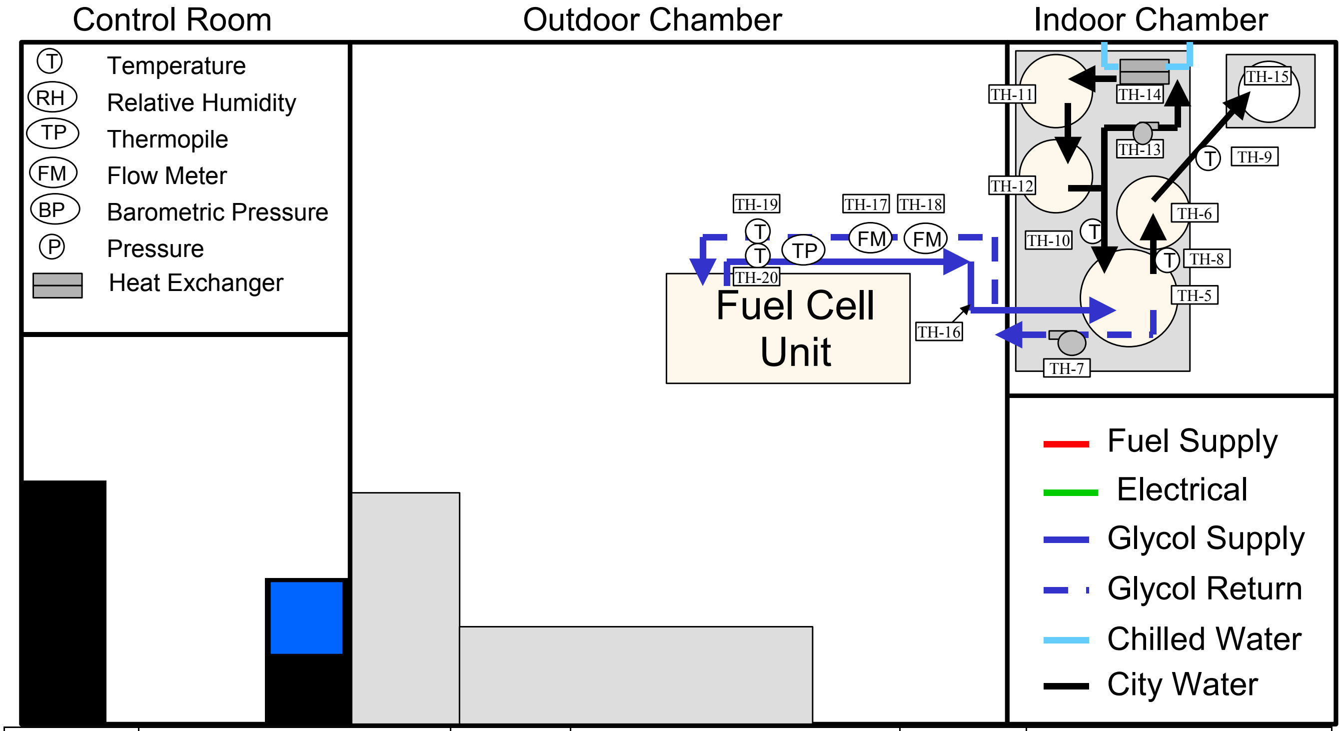
Thermal Energy System

In most cases, the thermal energy produced by fuel cell systems is an added benefit, and for residential fuel cell systems, the thermal energy is usually in the form of domestic hot water. It is assumed that the fuel cell system will supply an inlet and outlet port for the heat transfer fluid and nothing else. The test facility is equipped with the necessary tanks, pumps, and other



TH-1	FCL Pump	TH-4	Thermal Storage Tank	TH-17	Mag. Flow Meter
TH-2	In-Line Heater	TH-5	Preheat Tank	TH-18	Turb. Flow Meter
TH-3	Heat Exchangers	TH-16	Three-Way Valves	TH-19	Inlet Manifold
TH-20	Outlet Manifold				

Figure 4. Thermal Energy System Schematic – Fluid Conditioning Loop



TH-5	Preheat Tank	TH-11	Supply Water Heater	TH-16	Three-Way Valves
TH-6	Main Elec. Water Htr	TH-12	Supply Thermal Storage	TH-17	Mag. Flow Meter
TH-7	TRL Pump	TH-13	Circulation Pump	TH-18	Turb. Flow Meter
TH-8	Preheat Outlet TC	TH-14	Heat Exchanger	TH-19	Inlet Manifold
TH-9	Main WH Outlet TC	TH-15	Weigh Tank and Scale	TH-20	Outlet Manifold
TH-10	Preheat Supply TC				

Figure 5. Thermal Energy System Schematic – Residential Water Heating Loop

equipment to remove thermal energy from the fuel cell system, Figure 4. The test facility can capture the thermal output of a fuel cell system in two different ways. First, a fluid-conditioning loop sends the heat transfer fluid, which is a volume fraction mixture of 35 % propylene glycol and 65 % water, through the fuel cell at a user-selected constant flow rate and inlet temperature. A variable speed centrifugal pump, as shown in Figure 4, adjusts the flow rate of the glycol mixture between 7.5 L/min and 38 L/min (2 gal/min to 10 gal/min). An in-line electric heater and heat exchangers cooled with the building's chilled water supply can raise or lower, respectively, the fluid temperature from 8 °C to 60 °C. Three 0.3 m^3 (80 gal) insulated tanks provide sufficient thermal mass to maintain the inlet temperature at a constant value. Over this wide range of flow rates and fluid temperatures the overall efficiency of the unit can be determined for various electrical loads and environmental conditions.

Secondly, the fuel cell can be used to heat water in a preheat tank for a typical domestic hot water heating system, as seen in Figure 5. This consists of an indirect (or preheat) water heater, the main electric water heater, and a circulation pump. The pump, a variable speed centrifugal pump, circulates the glycol mixture through the fuel cell and into the indirect water heater, which uses a heat exchanger to heat the water within the tank. As the fuel cell heats the glycol mixture, the heat is transferred to the preheat tank, and the main water heater draws from this preheated tank, which reduces the amount of electricity needed to bring the water to the desired temperature setting. Type T thermocouples monitor the water temperature leaving the preheat tank, leaving the main water heater during a draw, and the supply temperature for the preheat tank. The supply water temperature for the preheat tank is also controlled. A circulation loop, which includes an electric water heater, another inactive water heater that provides thermal storage, a small circulation pump, and a heat exchanger (cooled by building chilled water) to cool the water, is used to maintain the supply water temperature at a constant value. This typical residential loop will be used while making periodic draws from the main electric water heater to approximate the typical load on a residential water heater. The draws will empty into a 200 L weigh tank on a scale that will measure the mass of water withdrawn. A Watt-hour transducer with a pulse output measures the electrical energy required by the main water heater to maintain the desired temperature setting.

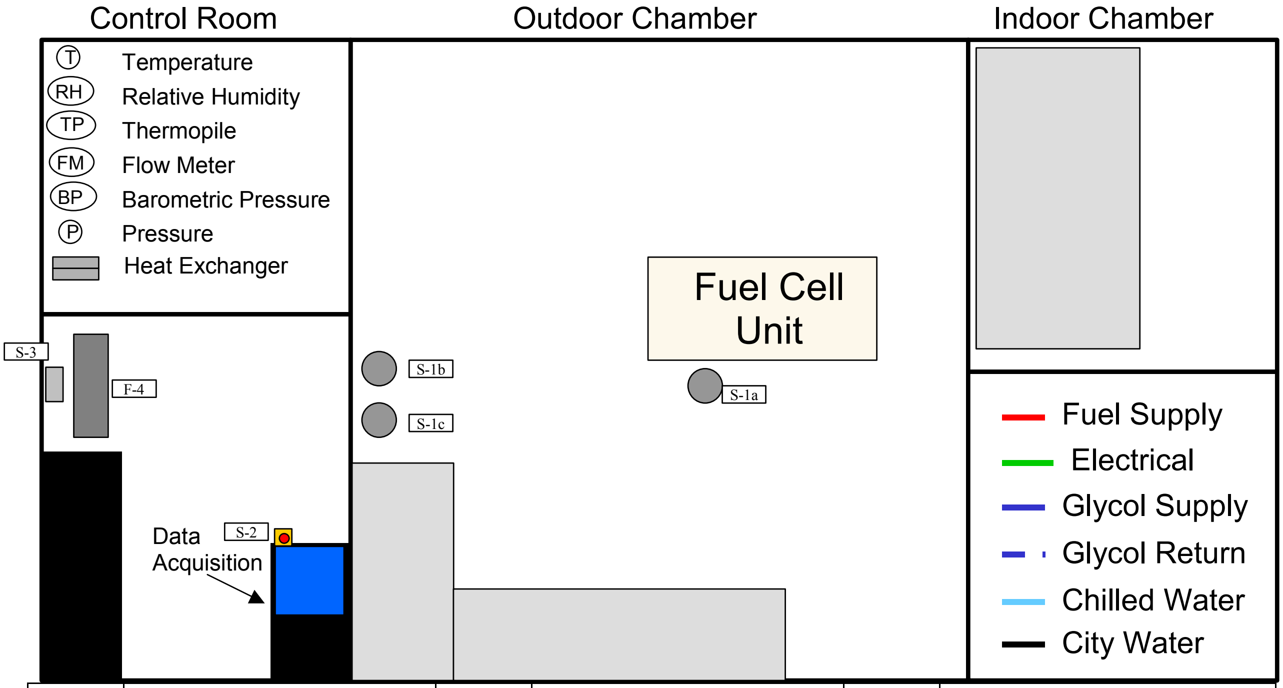
A series of manual three-way valves divert the flow between the fluid conditioning loop and the residential water-heating loop. In each of these fluid loops, the thermal energy transferred by the fuel cell to the glycol mixture is measured the same way. The volumetric flow rate of the glycol traveling towards the fuel cell system is measured by both a magnetic flow meter and a turbine flow meter for redundancy. Just before the fluid enters the fuel cell, the inlet temperature is measured using a PRT and a type T thermocouple. These measurements are performed in a manifold to ensure that the PRT and thermocouple at the inlet of the fuel cell measure the same bulk fluid. The fluid enters the fuel cell, where the system's control strategy decides whether or not to transfer heat, and as the fluid exits the fuel cell, another manifold holds a second PRT and type T thermocouple that measure the outlet temperature. Also, one end of a thermopile is inserted into each manifold to more accurately measure the temperature change across the fuel cell, which is a key component in the calculation of the thermal energy transfer. Aside from the volumetric flow rate and temperature of the fluid entering and leaving the fuel cell, the density and specific heat of the fluid must be known to determine the thermal energy imparted by the fuel cell. The density and specific heat of the glycol mixture are temperature dependant, and NIST engineers and scientists have measured these quantities.

The thermal energy supplied by the fuel cell, q, is calculated by:

$$q = V \cdot \rho \cdot c_p \cdot \left(T_{outlet} - T_{inlet}\right) \tag{3}$$

where V = volume of fluid passed through fuel cell (L)
ρ = density of the fluid (kg/L)
c_p = specific heat of the fluid (kJ/kg·K)
$\left(T_{outlet} - T_{inlet}\right)$ = temperature added to fluid by the fuel cell (K)

Assuming a 1 h test duration, a 35 L/min volumetric flow rate, a density of 1 kg/L, a specific heat of 3.8 kJ/kg K, and a temperature difference of 3 K, the resulting thermal energy produced by the fuel cell is 24 MJ. The expanded uncertainty of this measurement is 5 % at the 95 % confidence level.



S-1a	Combust. Gas Detector	S-1c	Oxygen Gas Detector	S-3	Calorimeter Gas Detector
S-1b	CO Gas Detector	S-2	Emergency Stop Switch	F-4	Calorimeter

Figure 6. Safety System Schematic

Safety System

The protection of equipment, instrumentation, and personnel is critical. The most imminent danger in the facility is the presence of natural gas or other fuels. As mentioned when describing the fuel supply system, a solenoid valve rated for use with natural gas and other gaseous fuels, Figure 3, is installed at the connection of the fuel system to the building supply of natural gas. This solenoid will not allow passage of gas if (1) the emergency stop switch, as shown in Figure 6, is activated, (2) the main measurement and control program is not operational, (3) the gas detection system records a high concentration of combustible gas or carbon monoxide, or (4) any of the gas detection sensors has failed due to power loss or other malfunction.

The gas detection system consists of three separate sensors. A combustible gas sensor is configured to close one of its three relays if the concentration of combustible gases, such as hydrogen, natural gas, propane, etc., reaches 20 %, 40 %, or 60 % of the lower explosive limit of hydrogen, which is 4 % by volume. Secondly, a carbon monoxide (CO) sensor closes relays if the concentration of CO exceeds 0.17 g/m^3 (150 ppm), 0.23 g/m^3 (200 ppm), or 0.29 g/m^3 (250 ppm). The natural gas solenoid will shut if the first level of alarm on either of these two sensors is reached, and the lack of natural gas should alleviate any high concentrations of combustible gas or CO. However, if the concentration of either gas continues to rise, a damper will open and an exhaust fan will turn on at the second level of alarm to remove any harmful gases and replenish the chamber with clean air. If the third level of alarm is reached, which is unlikely considering that any source of combustible gas or CO has been shut off, a visual and audible alarm is triggered outside the test facility. The third gas detection sensor measures the concentration of oxygen in the room to determine if the consumption of oxygen by the fuel cell as adversely affected the oxygen concentration in the chamber, but since fuel cells use air as a source of oxygen and do not produce it, this sensor does not activate the natural gas solenoid. All three levels of gases are recorded by the data acquisition system and monitored by the main control program, and all three sensors are mounted in the outdoor environmental chamber. Finally, a separate combustible gas alarm is mounted above the calorimeter in the control room to warn of any malfunction resulting from a fuel leak.

Methods of Testing

There are seven major tests envisioned for the laboratory. Each test will provide different information about the electrical and/or thermal performance of residential fuel cell systems. Performing each of these tests at varying environmental conditions and varying load levels will help determine the seasonal performance variations.

Steady-State Electrical Load

This test consists of a steady electrical load without output of thermal energy. With the fuel cell producing electricity at its setpoint and the environmental conditions steady at their desired levels, the fuel flow rate, fuel energy content, and the accumulated electrical energy produced by the unit will be monitored. This test will be performed at various electrical load levels and environmental conditions. The steady state electrical efficiency, $\eta_{electrical}$, will be calculated in the following manner:

$$\eta_{electrical} = \frac{E_{electrical}}{\sum_{i=1}^{I}\left(V_{fuel_i} \cdot e_{fuel_i}\right)} \tag{4}$$

where $E_{electrical}$ = accumulated electrical energy during test period (kJ)
V_{fuel_i} = volume of fuel used between scans (L)
e_{fuel_i} = average specific energy content of fuel between scans (kJ/L)
I = number of scans (typically at 30 s intervals) during test period
i = index of individual scans

Using the previously calculated fuel energy usage and electrical energy output, the expanded uncertainty of the electrical efficiency is 2.1 % at a 95 % confidence level. This most basic test will provide critical information about the electrical performance of the fuel cell system at various environmental conditions.

Steady-State Electrical Load with Steady-State Thermal Output

Similar to the steady-state electrical load test without any thermal output, the fuel cell will be set to provide the specified electrical load, but the fluid-conditioning loop will also be controlled to a constant flow rate and inlet temperature. With the electrical output, thermal output, and environmental conditions at steady-state conditions for several hours, the accumulated electrical energy, thermal energy output, and fuel usage will be measured. With the steady electrical efficiency calculated in Equation (4), the thermal, $\eta_{thermal}$, and combined efficiency, $\eta_{combined}$, will be calculated as follows:

$$\eta_{thermal} = \sum_{i=1}^{I} \left(\frac{q_{fluid,i}}{V_{fuel,i} \cdot e_{fuel,i}} \right) \tag{5}$$

$$\eta_{combined} = \sum_{i=1}^{I} \left(\frac{q_{fluid,i} + E_{electrical,i}}{V_{fuel,i} \cdot e_{fuel,i}} \right) \tag{6}$$

where $q_{fluid,i}$ = thermal energy transferred to fluid between scans (kJ)
$E_{electrical,i}$ = electrical energy produced between scans (kJ)
$V_{fuel,i}$ = volume of fuel used between scans (L)
$e_{fuel,i}$ = average specific energy content of fuel between scans (kJ/L)
I = number of scans (typically at 30 s intervals) during test period
i = index of individual scans

The estimated uncertainty with a 95 % confidence level for the thermal effectiveness is 4.4 %.

Steady-State Electrical Load with Transient Thermal Load

A transient thermal load is accomplished by starting the fluid-conditioning loop while the fuel cell is meeting a steady electrical load. The transient response of both the fuel cell's electrical and thermal output will be determined by cycling the thermal load on and off, as shown in Figure 7, while monitoring the thermal output, electrical output, and fuel usage. Prior to this test, the heat transfer fluid flow rate and inlet temperature will be set at the desired levels, as well as the fuel cell's electrical output. Two steady-state tests at the desired electrical load level, one with and one without a thermal load on the fuel cell unit, will be performed prior to the transient thermal load test. These tests will be used to establish a baseline for the steady-state output of the fuel cell. The transient thermal load test is essentially an alternating series of steady electrical load tests with and without a steady thermal load. For a system with a perfect transient response, the performance would be equal to the summation of the baselines for these tests. However, the thermal transient response for the electrical, $\theta_{electrical}$, and thermal output, $\theta_{thermal}$, can be calculated relative to a perfect response by the following calculations:

$$\theta_{electrical} = \frac{E_{test}}{E_{steady,off} \dfrac{t_{off}}{t_{steady,off}} + E_{steady,on} \dfrac{t_{on}}{t_{steady,on}}} \tag{7}$$

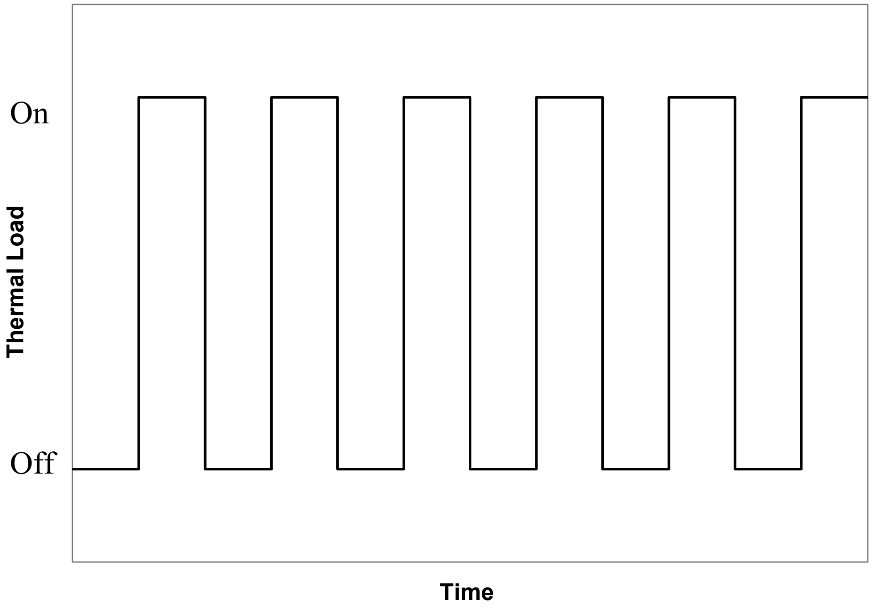


Figure 7. Thermal load schedule for steady electrical load with transient thermal load test

$$\theta_{thermal} = \frac{q_{test}}{q_{steady,on}\,\frac{t_{on}}{t_{steady,on}}} \tag{8}$$

where E_{test} = total electrical energy output during transient test period (kW·h)

q_{test} = total thermal energy output during transient test period (kJ)

$E_{steady,off}$ = electrical output during steady-state test without thermal load

$E_{steady,on}$ = electrical output during steady-state test with thermal load

$q_{steady,on}$ = thermal energy output during steady-state test with thermal load

t_{off} = cumulative duration of transient test without thermal load

t_{on} = cumulative duration of transient test with thermal load

$t_{steady,on}$ = duration of steady-state test with thermal load

While the actual performance of a fuel cell unit to a thermal transient test is not known yet, assume that during the steady-state portions of the test, each one hour in duration, the electrical output of the fuel cell unit with and without a thermal load are 5 kW·h and 6 kW·h, respectively. Also, assume that during the thermal transient portion of the test, which is also one hour in duration, the fuel cell unit is thermally loaded for only 15 minutes of the hour test and the total electrical output during the test is 5.25 kW·h.

Therefore, the $\theta_{electrical}$ is:

$$\theta_{electrical} = \frac{5.25kW \cdot h}{6kW \cdot h\frac{45\min}{60\min} + 5kW \cdot h\frac{15\min}{60\min}} = 0.913 \tag{9}$$

The expanded uncertainties of the electrical and thermal response to a thermal transient are 0.7 % and 6.5 %, respectively, with a 95 % confidence interval. Thermal transients will be common in units that preheat domestic hot water systems, and the effectiveness of residential fuel cell systems to maintain the proper electrical output would be an important variable in determining the seasonal performance of these units. The response of the thermal output to thermal transients will have less of an impact on the overall performance, but it could provide useful information on the quickness of the unit's thermal performance.

Steady-State Electrical Load with Real-World Thermal Load

While electrical energy is used as it is produced, thermal energy is often stored for later use, which makes predicting the thermal effectiveness of a system difficult. A typical real-world thermal energy storage system is described in the "Thermal Energy System" section above. In this configuration, the inlet temperature of the heat-transfer fluid will vary with the preheat tank temperature varies, which varies as the water is consumed. A consumption schedule has been developed in the testing of residential water heaters according to the US Department of Energy's performance test standard [5]. The 24 h schedule consists of six 40 L draws at each of the first 6 h and no draws thereafter. The electrical energy use of the main water heater has already been characterized according to this consumption schedule, and the fourth test will repeat this schedule while drawing from the preheat tank heated by the fuel cell. An energy savings will be calculated by subtracting the preheated electrical usage from the normal energy usage.

Transient Electrical Load

The concept of a transient electrical load test is similar to that of the transient thermal load test. The fuel cell will alternate between two electrical output setpoints, and the total electrical energy output will be compared to the expected output as determined by the time-weighted average of two steady-state electrical load tests at the high and low electrical load level used in the transient test. These steady-state tests would be performed before and after the transient electrical load test. The electrical transient response is defined as:

$$\alpha_{electrical} = \frac{E_{test}}{E_{steady,low}\frac{t_{low}}{t_{steady,low}} + E_{steady,high}\frac{t_{high}}{t_{steady,high}}} \tag{10}$$

where E_{test} = total electrical energy output during testing period (kW·h)

$E_{steady,low}$ = total electrical output at low electrical load level steady-state test

$E_{steady,high}$ = total electrical output at high electrical load level steady-state test
t_{low} = cumulative duration of transient test at low output level
t_{high} = cumulative duration of transient test at high output level
$t_{steady,low}$ = duration of steady-state test at low output level
$t_{steady,high}$ = duration of steady-state test at high output level

At a 95 % confidence level, the expanded uncertainty of this response parameter is 0.7 %. The electrical transient response will demonstrate the effectiveness of the residential fuel cell system to vary its electrical output, and this will be especially important if predicting the seasonal performance of load-following units, as opposed to units operated to provide the baseload power.

Transient Electrical Load with Steady-State Thermal Load

The electrical transient performance of residential fuel cells under a steady thermal load is also an important metric for units that will vary their electrical output to match the load level at any given time, i.e. load-following. The test procedure will be the same as the transient electrical load test, but it will include the steady thermal load as previously specified. Additionally, the calculations of the electrical transient response and the thermal output will follow the respective test calculations as described above.

Start-up Electrical Load

Occasionally, residential fuel cell systems will need to be shut-down, and restarting the system could take up to several hours. The electrical efficiency during that period will vary and be determined by recording the total fuel usage and electrical output from the initial start-up command until the electrical efficiency reaches a steady value.

Rating Methodology

After each of the seven tests have been completed at various load levels and environmental conditions, the relative effect of different variables, such as ambient temperature, relative humidity, electrical load levels, thermal load levels, transient electrical loads, transient thermal loads, and start-up performance, on the overall performance of the fuel cell will be determined. Sound engineering judgment will be used to eliminate from consideration any variables whose relative effect is negligible. Additionally, the number of environmental condition measuring points will be minimized. Then, a standard electrical load profile, thermal load profile, and environmental condition schedule will be developed incorporating all of the significant performance variables. The measured performance of the fuel cell will be mapped to the load profiles, and the resulting electrical energy output, thermal energy output, and fuel energy consumption will be used to determine the overall performance of the fuel cell system.

Conclusions

NIST seeks to accelerate the widespread commercialization of residential fuel cells by developing a proposed seasonal rating index. The index would be designed to aid the purchaser of a residential fuel cell in determining the economic impact of such a system, and would provide a combined metric of the seasonal performance of the electrical and thermal outputs of a specific fuel cell system. NIST recognizes the important work of many consensus standards organizations and their respective performance standards that are already published and in development, and desires to supplement those efforts with a test procedure and rating methodology that accounts for any change in performance as a function of the environmental conditions. To quantify those effects, NIST has designed, constructed, and instrumented a test facility for the seasonal performance of residential fuel cell systems. The facility measures the fuel energy provided to the system and the electrical and thermal energy output by the system. A battery of tests will be performed to determine these quantities at various ambient temperatures, relative humidity levels, thermal loads, and electrical loads. The results will help form a draft test procedure and rating methodology that will be submitted to a consensus standards organization for review, refinement, and acceptance by a committee of industry, academic, and government representatives.

References

[1] Davis, Mark, "Proposed Testing Methodology and Laboratory Facilities for Evaluating Residential Fuel Cell Systems", NISTIR 6848, National Institute of Standards and Technology, Gaithersburg, MD (2002).

[2] ASME PTC 50-2002, "Fuel Cell Power Systems Performance", American Society of Mechanical Engineers, New York, 2002.

[3] IEC TC 105 "Fuel Cell Technologies – Test Methods for Performance of Fuel Cell Power Systems" International Electrotechnical Commission, Draft.

[4] ANSI Z21.83 - 1998 "Fuel Cell Power Plants" CSA America, Charlotte, NC (1998).

[5] U.S. Department of Energy-Office of Energy Efficiency and Renewable Energy, "Energy Conservation Program for Consumer Products: Uniform Test Method for Measuring the Energy Consumption of Water Heaters" 10 CFR Part 430. Appendix E to Subpart B of Part 430, 1998.

Appendix 1: Instrumentation List

Instrument	**Measurement**	**Range**	**Uncertainty**
Data Acquisition System	DC Voltage	10 V	0.0015 % Rdg + 40 µV
	DC Current	100 mA	0.01 % Rdg + 4 µA
	Resistance	1000 Ω	0.003 % Rdg + 6 m Ω
Thermocouple	Temperature	-20 °C to 75 °C	0.2 °C
PRT	Temperature	-20 °C to 75 °C	0.05 °C
Thermopile	Temp. Difference	25 °C	0.05 °C
Rel. Humidity Transducer	RH	0 % to 95 %	1.5 %
Bar. Pressure Transducer	Barometric Pressure	600 mbar to 1100 mbar	3 mbar
Pressure Transducer	Gauge Pressure	0 kPa to 3.7 kPa	3.7 Pa
Calorimeter	Specific Energy	33.5 MJ/m^3 to 44 MJ/m^3	44 MJ/m^3
Nat. Gas Flow Meter	Volumetric Flow Rate	4 counts/L	1.0 % of Reading
Scale	Mass	0 kg to 500 kg	0.05 kg
Magnetic Flow Meter	Volumetric Flow Rate	0 L/min to 57 L/min	0.15 L/min
	Volumetric Total Flow	26.4 counts/L	0.25 % Rdg + 0.08 L
Turbine Flow Meter	Volumetric Flow Rate	0 L/min to 57 L/min	0.15 L/min
	Volumetric Total Flow	26.4 counts/L	0.25 % Rdg + 0.08 L
AC Load	True RMS Voltage	350 V	0.1 % Full Scale
	True RMS Current	60 A	0.2 % Full Scale
	True Power	0 kW to 6 kW	0.5 % Full Scale
Power Analyzer	True RMS Voltage	150 V	
	True RMS Current	0 A to 50 A	
	True Power	7500 W	0.15 % Rdg + 7.5 W
	Accumulated Energy		Uncertainty of power + 0.2 %
Watt Hour Transducer	Electrical Energy	5000 W	0.1 %