NISTIR 6848

Proposed Testing Methodology and Laboratory Facilities for Evaluating Residential Fuel Cell Systems

Mark W. Davis
Building Environment Division
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National Institute of Standards and Technology
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January 2002

U.S. Department of Commerce
Donald L. Evans, Secretary

Technology Administration
Phillip J. Bond, Under Secretary for Technology

National Institute of Standards and Technology
Arden L. Bement, Jr., Director

Introduction

Fuel cells are emerging as one of the most promising technologies for meeting the nation's energy needs. Fuel cell efficiencies, approaching 60 %, are nearly twice as efficient as conventional power plants.[1] Fuel cells are environmentally clean and emit almost none of the sulfur and nitrogen released by conventional generating methods. In addition to electricity generation, waste heat from residential fuel cells can be captured to provide space or water heating, further increasing the overall efficiency. Manufacturers of fuel cell technologies predict that residential fuel cell units will be on the market within the next two years. One manufacturer, Plug Power[*], is currently beta testing approximately 40 residential fuel cell units.

Currently, ASME, ANSI, NFPA, and other standards organizations are developing standards for fuel cells. The ANSI and NFPA standards address the safe operation, construction, installation, and acceptable performance of all fuel cell units. The ASME standard seeks to rate the performance of a wide range of fuel cell types and sizes. The ASME standard calls for testing at a single, steady-state point of operation.

The ASME single point comparison does not accurately reflect the performance of a fuel cell unit in a residential setting. The electrical load of a residence is transient in nature. Additionally, if the fuel cell unit is providing a portion of the space or water-heating load, the flow rate and temperature of the water being supplied to the fuel cell will vary. A method of test and accompanying rating methodology to accurately capture the overall performance of residential fuel cell units will provide prospective owners with the information needed to make informed selections.

The National Institute of Standards and Technology (NIST) proposes a test method and rating methodology that will capture the overall performance of a residential fuel cell system in the same manner that NIST derived methods of tests exist for heat pumps, gas furnaces, water heaters, and other household appliances. The test method will take into account any inefficiencies associated with the fuel cell stack and reformer; the conversion efficiency of the inverter; and any useful water or space heating contributions. The test method will identify and specify environmental and electrical load parameters that may affect performance, as well as the effect of transient loads on the system performance. Finally, rating methodologies will be developed that allow the annual performance of a residential fuel cell unit to be determined under representative load and climatic conditions for a specified geographical location. The rating methodologies would be a valuable tool allowing the fuel cell industry, as well as consumers, to evaluate the electrical and thermal energy output of residential fuel cells and maximize their efficiency. These efforts would continue NIST's history of collaborating with the Department of Energy and industry to develop metrology and standards that define the energy efficiency of heat pumps, gas furnaces, water heaters, and other household appliances.

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[1] Source – Department of Energy, Fossil Energy – Fuel Cell Power Systems Overview web site, "http://www.fe.doe.gov/coal-power/fc-sun"

[*] Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

This report describes the test procedures and laboratory facilities required for the development of these rating methodologies. A brief introduction to fuel cells, their operation, and the key parameters that affect the performance of residential fuel cells is included. The tests required to determine the relative performance of the units, along with the necessary instrumentation, are described. Finally, a detailed explanation of the proposed test facility is provided.

Background

Fuel cells convert stored chemical energy directly to electrical energy in a very clean and efficient manner. Proton exchange membrane fuel cells (PEMFC) are the predominant type of fuel cell being considered for residential use, but solid oxide fuel cells (SOFC) are also being developed for this purpose. PEM fuel cells are low temperature (80 °C to 120 °C) units, which allows for fast startup times. SOFCs are high temperature fuel cells (700 °C to 1000 °C), which provides an excellent source of waste heat for combined heat and power (CHP) applications. Both types of fuel cell use hydrogen and air to create direct current electricity.

Generally, residential fuel cell units are the combination of three major components. The reformer takes a hydrogen rich fuel and strips off the hydrogen. Most often, the source of hydrogen is a hydrocarbon fuel, such as natural gas, propane, or methanol. Due to the high operating temperature of SOFCs, the hydrocarbon fuel can be reformed internally, which eliminates this costly component. The fuel cell takes the hydrogen along with oxygen from the air and creates electricity through an electrochemical process. Finally, the inverter takes the direct current electricity from the fuel cell and transforms it into alternating current, compatible with the electricity grid. To increase the efficiency of the system, the heat produced by the unit can be used for space or water heating, although heating water will be the most likely application.

Fuel cells have many modes of operation. Ideally, the fuel cell would provide all of the power to the home, which is termed independent operation. The fuel cell could also work with the existing power grid to supply power. This grid-connected operation can be done several ways. For example, the fuel cell could be sized to provide a baseline level of electricity with the grid supplying the extra power needed to supply the electrical load. This mode, which is usually called baseline operation, would allow the unit to run at its maximum efficiency at all times. Alternatively, the fuel cell unit could be used in a peak-shaving mode. The majority of power would be supplied from the grid, but any power required greater than a pre-set limit would be supplied by the fuel cell. Peak-shaving is generally used in commercial or industrial settings to reduce demand charges during peak electricity usage times. However, if the unit is not running constantly and cools down while not in use, the start-up time can be significant, which severely impacts the efficiency. Each of these operating modes forces the residential fuel cell unit to act in a different manner, which complicates the formulation of test methods and rating procedures. In any mode of operation, there are many parameters that affect the performance of residential fuel cell systems. These parameters, shown in Figure 1, must be accounted for to ensure an equitable rating procedure. This compliation of parameters resulted from conversations with several fuel cell manufacturers. Some of the parameters relate to the operation and application of the fuel cell, while other parameters describe the input conditions.

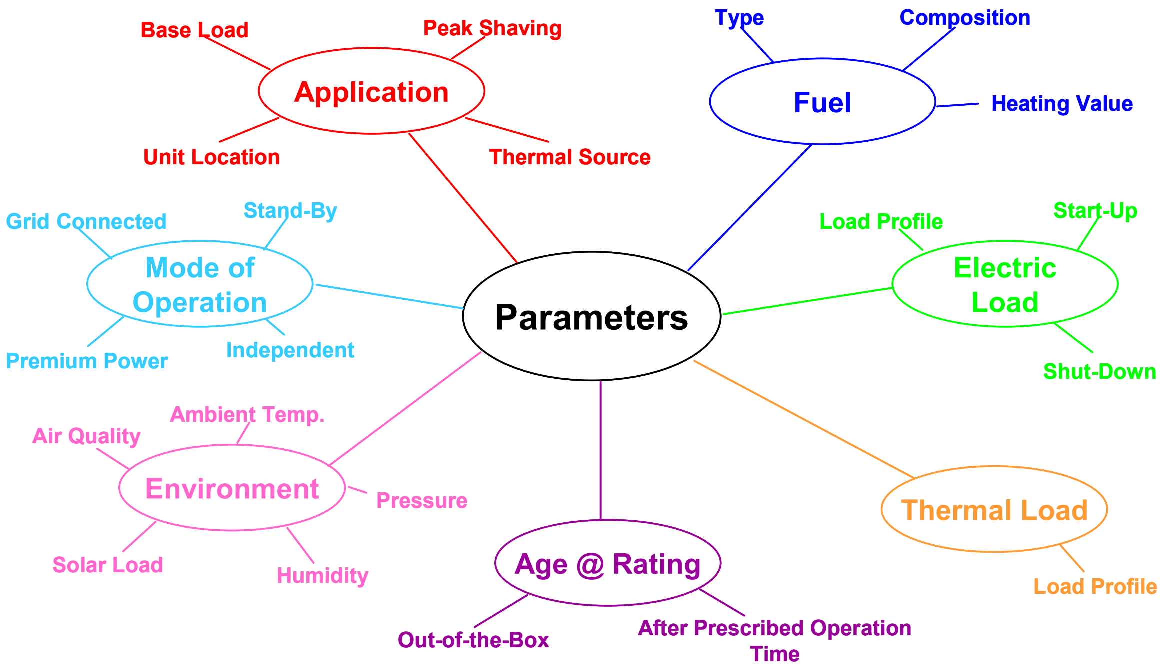


Figure 1. Parameters affecting the performance of residential fuel cells

The fuel, electrical load, thermal load, and environmental conditions all affect the output of the fuel cell unit. With respect to the fuel, different types of fuel have different heating values. In addition to changes of heating value between fuel types, the heating value of a fuel may change over time, depending on the source of the fuel. The electrical and thermal loads have a significant effect on the performance of the unit. The performance of all three major components, the reformer, fuel cell, and inverter, depends on the electrical output of the unit. Also, each component reacts differently to transient changes in the supplied power. In combined heat and power units, the thermal load also impacts the performance of residential fuel cells. In applications where the primary function of the residential fuel cell unit is to provide useful heat, the units actually adjust their electrical output to control the outlet temperature of the heat exchange fluid. Therefore, whether used primarily to supply electricity or heat, the load profile affects the performance of the unit.

Environmental conditions have a significant effect on the performance of the unit. The air temperature and pressure both affect the oxygen concentration, which affects performance. The quality of the air also affects the oxygen concentration. Since the inlet gas streams to the fuel cell must be humidified, the relative humidity of the air also plays a key role in the unit's performance.

Developing an equitable test method and rating methodology requires that each of these parameters be measured. Additionally, some of these parameters must be controlled in such a way that helps determine the effect on the fuel cell unit's performance. The effect of each of the parameters on the fuel cell performance must be determined before a test procedure can be developed. The series of tests presented in the following section will help determine those effects.

Description of Test Procedures

To determine the seasonal efficiency of a residential fuel cell unit, its performance with respect to some of the key parameters must be measured under steady state and transient loads as well as during start-up of the unit. Four separate tests are envisioned to determine the overall performance of residential fuel cell systems: steady state, steady state with thermal load, transient, and the initial start-up.

Steady State Test

A steady state test would measure the electrical performance of the unit at a prescribed set of inlet conditions (ambient temperature, relative humidity, and electrical power factor). The efficiency would be measured as the ratio of useful energy output by the unit to the energy supplied to the unit. Under steady state conditions without a thermal load, the efficiency can be calculated as shown below.

$$\eta = \frac{q_{electrical}}{q_{fuel} + q_{auxiliary}} \tag{1}$$

where:

$q_{electrical}$ = electrical output of the fuel cell unit (kW·h),
q_{fuel} = energy content of the fuel supplied to the unit (kW·h),
$q_{auxiliary}$ = energy supplied to the fuel cell unit in addition to the primary fuel source (kW·h)

During the steady state test, the load and environmental conditions would remain constant. The variables needed to compute the efficiency in Eq. 1 would be measured at prescribed time intervals. The test would conclude when the electrical efficiency did not vary greater than two percent. It is envisioned that this test would be repeated for a number of rating conditions in order to provide a performance map of the unit's electrical efficiency.

Thermal Load Test

For residential fuel cell units that produce useful heat as well as electrical energy, the thermal load test would measure the overall efficiency of the unit at prescribed inlet conditions. The useful heat is transferred to a fluid, usually water, which is maintained at a specified inlet temperature and flow rate. Similar to the steady state test, the efficiency can be calculated as the ratio of useful energy output by the unit to the energy supplied to the unit, but in this case, the useful energy output includes both thermal and electrical energy as shown below.

$$\eta = \frac{q_{electrical} + q_{thermal}}{q_{fuel} + q_{auxiliary}} \tag{2}$$

where:

$q_{electrical}$ = electrical output of the fuel cell unit (kW·h),
$q_{thermal}$ = thermal output of the fuel cell unit (kW·h),
q_{fuel} = energy content of the fuel supplied to the unit (kW·h),
$q_{auxiliary}$ = energy supplied to the fuel cell unit in addition to the primary fuel source (kW·h)

The thermal output of the unit would be computed as the sum of the heat output measured periodically as shown below.

$$q_{thermal} = \sum \left(\frac{\rho \cdot \dot{V} \cdot C_P \cdot (T_{Outlet} - T_{Inlet}) \cdot \Delta t}{3600} \right) \quad (3)$$

where:
ρ = the density of the heat transfer fluid (kg/m^3),
$\dot{V}$ = volumetric flow rate of fluid (m^3/s),
C_P = specific heat of the fluid (kJ/kg K),
T_{Outlet} = temperature of the fluid at the outlet of the CHP unit (°C),
T_{Inlet} = temperature of the fluid at the inlet of the CHP unit (°C), and
Δt = time between measurements (s).

Similar to the steady state test, the load, heat transfer fluid, and environmental conditions would remain constant throughout the testing period. Measurements would be made at a prescribed time intervals, and the test would conclude when the overall efficiency did not vary greater than two percent. Again, the test would most likely be repeated for a number of rating conditions in order to provide a performance map of the unit's overall efficiency.

Transient Test

The transient electrical performance of residential fuel cells may have a significant effect on the efficiency of the unit, especially in grid-independent applications where the electrical load changes rapidly. The magnitude of this effect would be measured by repeatedly changing the load level according to a prescribed load profile with the rating conditions held at fixed values.

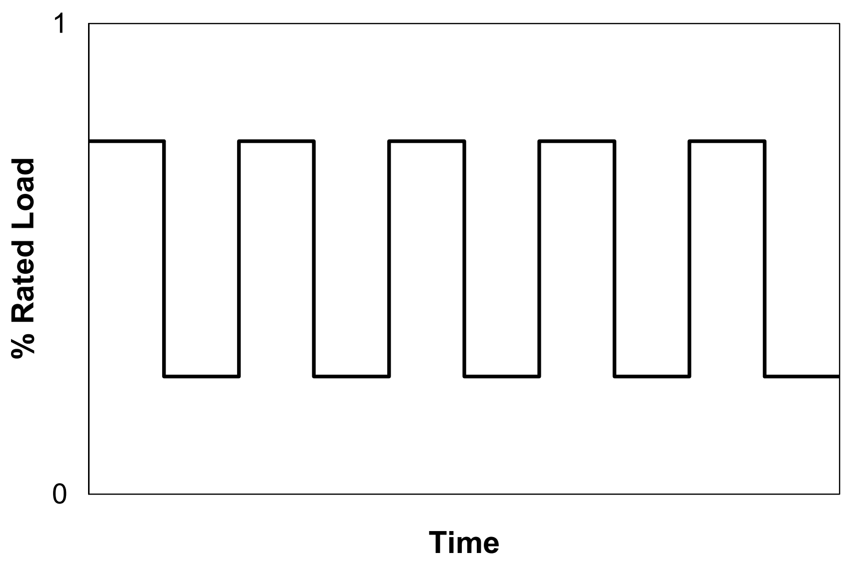


Figure 2. Sample load profile for transient electrical performance test.

If transient electrical loads have no effect on the efficiency of the unit, the efficiency would be equal to the time-weighted sum of each load level. For the sample load profile shown in Figure 2, the time-weighted efficiency would be the average of the efficiencies at the two load levels.

The electrical efficiency would be measured in the same manner as the steady state test over the period of the test. The transient test would be performed at several rating conditions to establish the overall effect of transient electrical loads on the performance of residential fuel cell systems.

Start-Up Test

When residential fuel cells are allowed to cool below operating temperature, the unit must reheat to the appropriate temperature before producing power. The start-up test will determine the amount of time required to reach an operational temperature from ambient conditions and the relative electrical performance of the unit as it reaches steady state. To prepare for the test, no power would be drawn from the unit allowing it to cool to the ambient temperature of the environmental chamber. Then, power would be drawn from the unit initializing its start-up procedure, which would bring the unit to an operational temperature over some period of time. Data would be recorded as the unit heats up. The environmental conditions would remain constant throughout the test. The test would continue until the electrical efficiency of the unit, which would be measured as in the transient load test, becomes steady within 2 %.

For each of the four tests, a large environmental chamber will control the ambient temperature and relative humidity. The ambient temperature, relative humidity, and barometric pressure of the chamber will be measured with a type T thermocouple, relative humidity transducer, and a barometric pressure transducer, respectively. Determination of the electrical and overall efficiency in each of the tests will utilize a programmable AC load to adjust the power level and the electrical power factor. A Watt-hour meter will measure the power produced by the unit. An additional meter will be used to measure any auxiliary electrical power used by the unit. To determine the energy content of the fuel, the flow rate and heating value must be measured. A dry-type gas meter will measure the flow rate, and the heating value will be measured in situ with a calorimeter or by using fuels with certified heating values. Finally, the thermal load test requires the measurement of the useful heat transferred to a fluid as shown in Eq. 3. The inlet and outlet temperature will be measured with type T thermocouples. The flow rate of the heat transfer fluid will be determined with a flow meter, and the density and specific heat of the fluid (usually water) are well established tabulated values. These measurements will provide the necessary information for the development of a test procedure and rating methodology for residential fuel cell units.

Description of Test Facility

A test method or rating methodology that permits the comparison of various residential fuel cells requires the accurate and precise measurement and control of the parameters identified in the test procedures. These measurement and control parameters are summarized in Table 1, and described in detail in the following subsections. A schematic of the test facility is shown in Figure 2. Table 2 provides an estimate of the time required to complete the construction, calibration, and evaluation of the test facility relative to the receipt of funding. Finally, a complete list of parts and instrumentation described is found in Appendix 1.

Ambient Environment

A large environmental chamber will control the ambient environment of the residential fuel cell test facility. The chamber can maintain the ambient temperature from –12 °C to 40 °C with an uncertainty of ±0.1 °C. It can also hold the wet bulb temperature within ±0.1 °C over a range of relative humidity of 10 % from 95 %.

The air temperature, pressure, and relative humidity measurements will be made by thermocouples, a barometric pressure sensor, and a relative humidity transducer, respectively. A grid of type T thermocouples will be positioned at the air intake of the residential fuel cell unit. This will provide an average air inlet temperature for the unit.

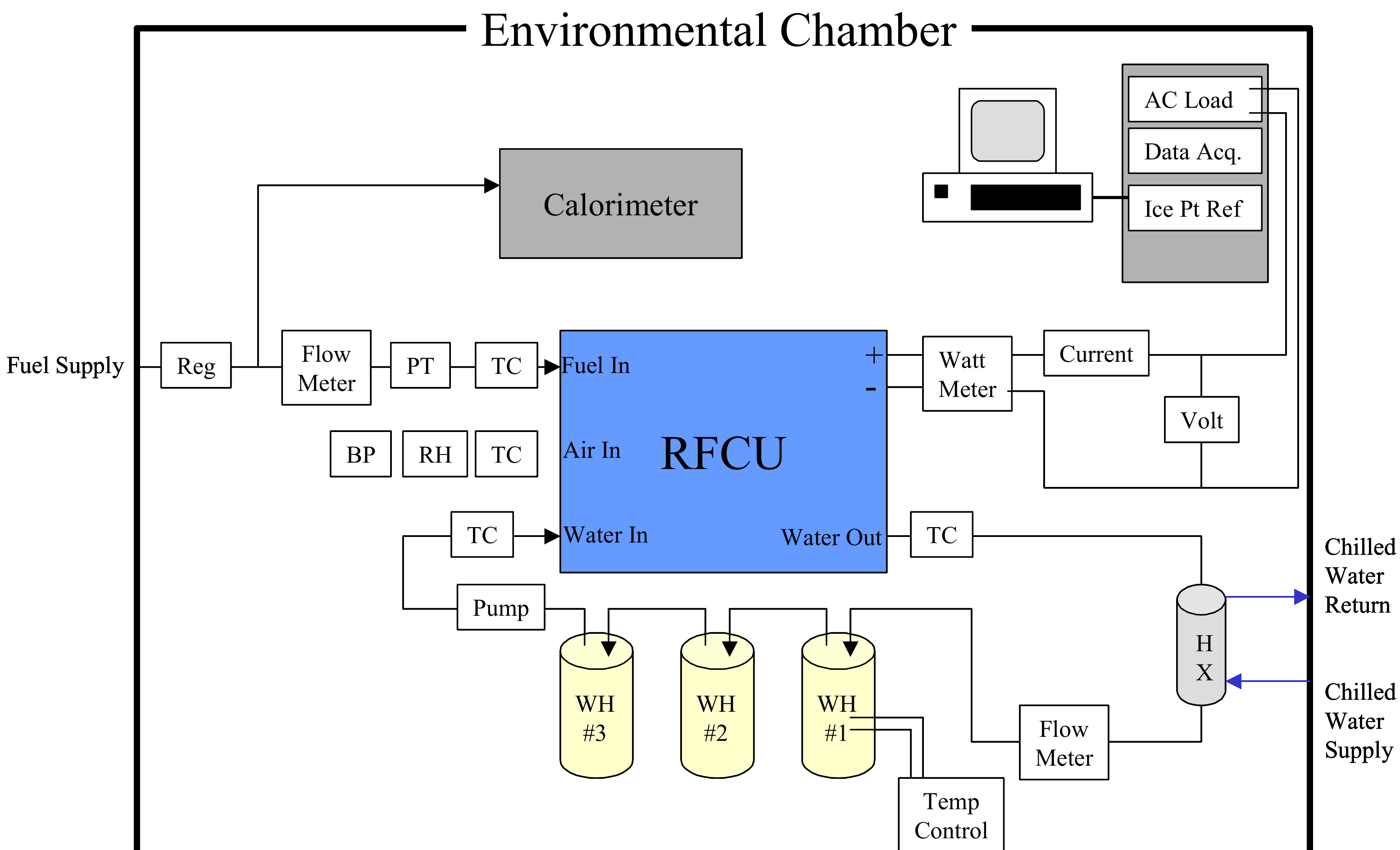
A Setra model 270 barometric pressure transducer will measure the absolute pressure of the environmental chamber. The pressure transducer has a range of 600 mbar to 1100 mbar and an accuracy of ±0.5 mbar. The inlet air relative humidity will be measured with a Vaisala* model HMP 240. This instrument measures the dewpoint temperature, which can be translated to relative humidity. The sensor is able to measure the dewpoint temperature at any relative humidity (0 % to 100 %). It has an accuracy of 0.6 °C over the applicable temperature and humidity range of the environmental chamber. All three of these instruments will output a signal voltage to be recorded by the data acquisition system.

Table 1. Measurement variables for test facility

Subsystem	Measurement	Control
Ambient Environment	Temperature	Temperature
	Pressure	
	Relative humidity	Relative humidity
Fuel Supply	Flow rate	
	Temperature	
	Pressure	
	Heating value	
Heat Transfer Fluid	Inlet temperature	Inlet temperature
	Outlet temperature	
	Flow rate	
Electrical	Voltage	Voltage
	Current	Current
	Output power	Output power
	Power Factor	Power Factor
	Input power	

Table 2. Schedule of residential fuel cell test facility relative to receipt of funding

Task	Month of Completion
Acquire Instrumentation	2nd
Construction and Integration of Test Facility	3rd
Development of LabVIEW frontend	4th
Calibration and Evaluation	5th



Legend

TC	Thermocouple	RFCU	Residential Fuel Cell Unit
PT	Pressure Transducer	WH	Water Heater Tank
RH	Relative Humidity Transducer	HX	Heat Exchanger
BP	Barometric Pressure Transducer	Reg	Fuel Filter – Regulator

Figure 2. Schematic of residential fuel cell test facility

Fuel Supply

Currently natural gas appears to be the predominant fuel for residential systems, but some manufacturers are considering propane, methanol, or hydrogen as fuel choices. The environmental chamber is capable of supplying natural gas. Additional equipment would be needed in order to provide these other fuel options. The fuel temperature, pressure, and flow rate will not be controlled during testing. The test facility will have the capability to measure the fuel flow rate, temperature, and pressure. The fuel will first be regulated to an appropriate operating pressure using an American Meter Company* CR4000 residential natural gas regulator. The fuel flow rate will be measured with a diaphragm gas flow meter, which can measure the volumetric flow rate of any dry gas. The American Meter Company* AL-425 is capable of measuring flows of 0.2 m^3/min (425 scfh) at 0.18 m (7 in) of water column, which exceeds the design flow rate for natural gas, 0.15 m^3/min (320 scfh), as shown below. The design flow rate of propane is half that of natural gas ($N_{Fuel} = 8$).

$$\dot{V}_{CH_4} = \frac{N_{H_2}}{N_{Fuel}} \frac{Power \cdot SR}{n \cdot F \cdot V_{cell}} \cdot \left(\frac{\overline{R} \cdot T}{P} \right) \tag{4}$$

where,

N_{H_2} = number of hydrogen atoms in a molecule of hydrogen gas (2),

N_{Fuel} = number of hydrogen atoms in a molecule of fuel (natural gas = 4)

Power = power produced by the fuel cell (10000 W),

SR = stoichiometric ratio of hydrogen (2),

n = number of electrons involved in the electrochemical reaction (2),

F = Faraday's constant (96484 C/mol),

V_{cell} = design voltage of a single cell in the fuel cell stack (0.5 V),

$\overline{R}$ = gas constant (8.314 J/mol K),

T = temperature of natural gas (298 K), and

P = pressure of natural gas (101.3 kPa).

The gas meter is fitted with a remote pulse totalizer that can be used to measure the gas consumption over a period of time. The output of the meter can be scaled to accommodate fuel gases other than natural gas. The temperature of the fuel will be measured directly before entering the residential fuel cell unit by inserting a type T thermocouple in the fuel piping. The pressure of the fuel will also be measured directly before entering the unit. An Omega* PX303 series pressure transducer will send a 0-5V signal to the data acquisition system to record the fuel pressure. It has an accuracy of ±0.25 % of full scale.

The heating value of the fuel will be measured using a Cutler Hammer* gas calorimeter. The calorimeter provides a continuous measurement of the higher heating value (HHV) of any gaseous combustible fuel. To measure the HHV, a stream of fuel is drawn into the calorimeter (prior to measurement of the flow rate entering the fuel cell unit) along with a fixed ratio of air. The mixture is combusted, and the resulting energy is used to heat a stream of air. The combustion products are returned to the conditions of the reactants, which provides the higher heating value. The calorimeter, which graphically outputs the heating value to a stripchart, is fitted with a retransmitting slidewire millivolt generator that produces a signal voltage corresponding to the heating value of the fuel. This millivolt signal will be read by the data acquisition system. For non-gaseous fuels, such as methanol, the heating value will be sampled throughout the test period and measured afterward by separate laboratory.

Thermal Load

Those residential fuel cell units that are supplied with a combined heat and power system require a fluid to be heated with the waste heat from the fuel cell. Most likely, the CHP system will supply heat to domestic hot water, but it may also be used for space heating as well. In the case of a domestic hot water heating system, water will be supplied at a specified inlet temperature and flow rate. The range of water inlet temperatures could vary from the temperature of the NIST chilled water supply, 6 °C (42 °F), to the typical maximum domestic hot water temperature, 70 °C (160 °F). The inlet water temperature would be controlled with a series of three 0.2 m^2 (50 gal) domestic water heating tanks heating recirculated water to the specified temperature. The first tank, which is located at the exit of the heat exchanger, will be controlled to the specified inlet temperature by an Omega* CNi8 temperature controller. The last two tanks will only hold the water to provide sufficient thermal mass. The heated water exiting the CHP system on the residential fuel cell unit will be cooled below the inlet temperature using a stainless steel brazed plate heat exchanger and the 6 °C (42 °F) chilled water supply. The heat exchanger has an active area of 0.6 m^2 (6.5 ft^2). This system and the required instrumentation can be seen in Figure 2.

The domestic hot water subsystem will have the capability to measure the flow rate of the water running through the CHP as well as the temperature difference between the inlet and outlet of the water. The temperature at the inlet and outlet will be measured with type T thermocouples. The flow rate will be measured with an Omega* FTB-102 turbine flow meter. The meter has a range of $4.7 \cdot 10^{-5}$ m^3/s (0.75 GPM) to $4.7 \cdot 10^{-4}$ m^3/s (7.5 GPM), and the accuracy of the unit is 0.5 % of the 0 V to 5 V reading. The water will be circulated with a centrifugal pump at approximately $1.9 \cdot 10^{-4}$ m^3/s (3 GPM).

Electrical Load

The electrical output of the fuel cell unit will be managed by four NH Research* 4600 series AC loads in parallel. Each is capable of drawing 3000 Watts of AC power at various power factors or crest factors. The load can operate in any one of four modes: constant current, constant voltage, constant resistance, or constant power. It is also capable of drawing power at frequencies from 45 Hz to 440 Hz, and the power factor can be adjusted from 0 to 1 either leading or lagging.

While the AC load has the capability to measure the votlage, current, and power, more accurate measurements will also be made using two Hewlett Packard* 3458A digital multimeter and a Yokogawa* WT 1000 digital Watt meters. One Hewlett Packard* 3458A will measure the output voltage and the other will measure the output current. With the measurement of the output power with the Yokogawa* Watt meter, the phase between the voltage and current waveforms can be determined as well, as shown below. A current transformer is required to scale the current to a measureable level for the Watt meter.

$$\phi = \cos^{-1}\left(\frac{V \cdot A}{W}\right) \tag{5}$$

where V = RMS voltage,
A = RMS current, and
W = active power.

Data Acquisition System

All of the measured data will be collected and saved electronically. A Hewlett Packard 34970A will measure all of the thermocouple, voltage, and current signals. The thermocouple signals will pass through a Kaye* K170 ice point reference to provide a high level of accuracy for the temperature measurements. The ice point reference keeps the junctions of 24 thermocouple channels at the ice point within 0.05 °C. The data acquisition system will be controlled using a LabVIEW program that will read all of the measurement signals, control any necessary parameters, collect and save data, and provide a graphical interface to the test operator.

Conclusion

The residential fuel cell test facility specified above has the capability to measure and control the key variables affecting the performance of proton exchange membrane and solid oxide residential fuel cell units. The facility can control the ambient temperature and relative humidity; the inlet temperature of the heat transfer fluid for CHP applications; and the voltage, current, and power factor of the electrical output. The control of these variables allows the measurement of changes in performance with respect to one parameter. Quantifying the changes in performance according to isolated variables will lead to a greater understanding of residential fuel cell units, and this understanding will aid the creation of test procedures and rating methodologies that will help customers compare different units to make informed buying decisions. These test procedures will be developed in concert with fuel cell manufacturers through professional organizations such as ASHRAE, ASME, etc. This collaboration will specify the number of tests, rating conditions, and other details important to the test procedures and rating methodologies.

Acknowledgements

We would like to thank Jerry Caesar and the Advanced Technology Program at NIST for funding this research. We appreciated the help of George Earle III, Richard Maddaloni, and Richard Romer at Plug Power, and James Cross III and John Batal at Nuvera Fuel Cells in developing a list of key parameters influencing fuel cell performance.

Appendix 1

Part Description	Model	Manufacturer
Fuel Supply Regulator	CR4000	American Meter Company
Fuel Flow Meter	AL-425 with Remote Pulse Totalizer	American Meter Company
Fuel Line Pressure Transducer	PX303	Omega
Fuel Line Thermocouple (type T)	GTMQSS-062G-6	Omega
Fuel Line Calorimeter		Cutler-Hammer
Air Inlet Thermocouple	GTMQSS-062E-6	Omega
Air Inlet Barometric Pressure Transducer	270	Setra
Air Inlet Dewpoint Temperature Sensor	HMP240	Vaisala
Heat Transfer Fluid Thermocouple	GTMQSS-062G-6	Omega
Heat Transfer Fluid Flow Meter	FTB-102	Omega
Heat Transfer Fluid Heat Exchanger	35115K27	McMaster-Carr
Heat Transfer Fluid Temperature Controller	CNi8	Omega
Heat Transfer Fluid Water Heater	3570K32	McMaster-Carr
Electrical Output Watt meter	1000	Yokogawa
Electrical Output Voltmeter	HP3458A Multimeter	Hewlett-Packard
Electrical Output Ammeter	HP3458A Multimeter	Hewlett-Packard
Electrical Output AC Load	4600-3	NH Research
Data Acquisition Multiplexer	HP34970A	Hewlett-Packard
Data Acquisition Ice Point Reference	K170	Kaye