Dynamic Performance of the Nexa Fuel Cell Power Module

Hal H Ottesen, Ph.D.
Principal Investigator
University of Minnesota Rochester
Rochester, Minnesota

Study sponsored by:
Rochester Public Utilities
Rochester, Minnesota

January 2004

Table of Contents

Background

There is a surge of alternate power sources, like wind power, fuel cell power, etc., that are more economical and environmentally cleaner than the current power sources. Of great interest is the combination of various power sources to provide a more efficient power system for residential and business customers. This is the background for the Hybrid Energy System Study (HESS) project between Rochester Public Utilities (RPU) and University of Minnesota Rochester (UMR). The HESS project is divided into three phases:

- **Phase I (funded)**
  Working knowledge and dynamic evaluation of a commercially available Proton Exchange Membrane (PEM) fuel cell system.

- **Phase II**
  A symbiotic combinational arrangement between a PEM fuel cell and a geothermal heating system. This phase is likely to involve other corroborative partners, like a fuel cell manufacturer and a geothermal manufacturer.

- **Phase III**
  Dynamic fuzzy-logic controller regulation of a hybrid, three-component, energy delivery system, i.e., the electric grid, the geothermal system and the PEM fuel cell. The control system will determine, based on an optimal cost/efficiency algorithm, the best mix of energy being supplied from the hybrid, three-component, energy delivery system.

Acknowledgments

The principle investigator of the HESS project is Dr. Hal Ottesen, UMR. Dr. James Licari from UMR, is the lead technology manager, and Jim Walters from RPU is the overall project manager. Sophronis Mantoles is responsible for laboratory operations and is a graduate student at UMR. These four people constitute the main HESS project team.

Many thanks go to Jim Walters, RPU, who is the main force at RPU for exploring alternate energy sources, for his great experience and enthusiasm, for finding a suitable location at the main RPU site and for providing the necessary additional funding for the implementation of a safe hydrogen supply system. Many other RPU employees and subcontractors contributed substantially to make HESS
(Phase I) project, a success. The implementation of the fuel-cell measurement system and the resistive load-board were very ably handled by Sophronis Mantoles. Many thanks goes to Jim Licari, UMR, for our many great project discussions, and his great managerial and planning skills. Jim Licari is also focusing on HESS, Phase II, and the necessary corroboration between any new partners and RPU and UMR.

Hal H Ottesen, Ph.D.
University of Minnesota Rochester

Dynamic Performance of the Nexa Fuel Cell Power Module

1.0 Introduction

This research report is part of the University of Minnesota Rochester's deliverables for Phase I of the Hybrid Energy System Study (HESS) sponsored by Rochester Public Utilities (RPU). A 1,200 watts Nexa Fuel Cell Power Module, see Figure 1, was purchased by RPU from Ballard Power Systems in Canada. A very useful and informative one-day training and installation course was conducted at RPU on March 31, 2003 by Mr. Gary Schubak, Ballard Power Systems. This course included turning on power on the Nexa Fuel Cell Power Module. Much of the ensuing research, tests and measurements were conducted in a small research laboratory at RPU.

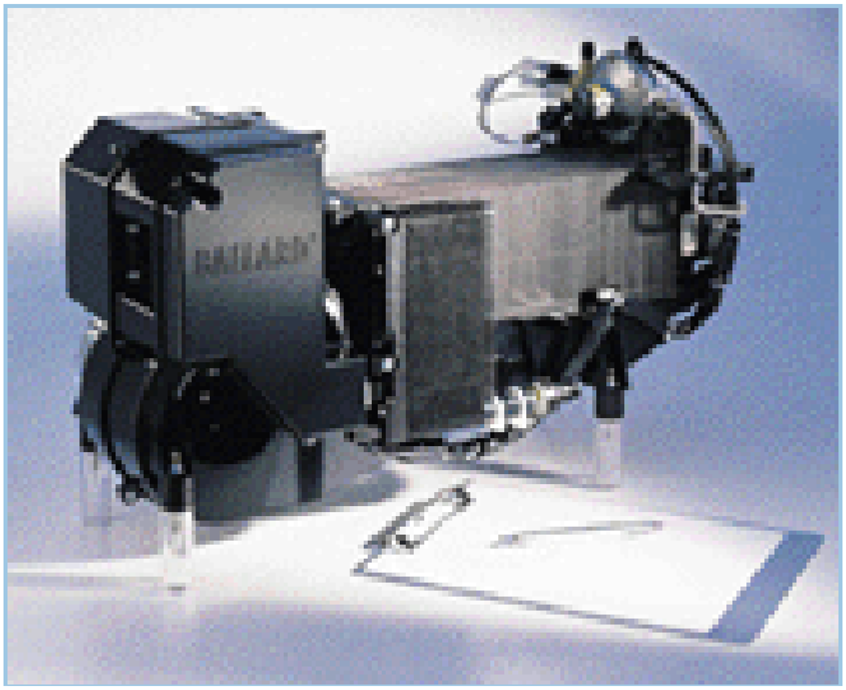


Figure 1. A 1,200-watt Nexa Fuel Cell Power Module from Ballard Power Systems.

Physical size (L x W x H):	22" x 10" x 13"
Weight:	27 lbs.

Hal H Ottesen, Ph.D.
University of Minnesota Rochester

2.0 Nexa Power Module [1]

The 1,200-watt Nexa power module was first introduced in 2001. It is the world's first volume-produced proton exchange membrane (PEM) fuel cell designed for integration into a wide variety of stationary and portable power generation applications. The Nexa power module enables original equipment manufacture products to be used to generate power in an indoor environment not possible with the conventional internal combustion engine (ICE) generators. The Nexa power module generates up to 1,200 watts of unregulated DC electric power by converting hydrogen (H2) fuel and oxygen (O2) from the ambient air in a non-combustive electrochemical reaction. The by-products of this electrochemical power generation, are safe heat and water. The quiet operation and compact size, make it ideal for integration into uninterruptible power supply systems and emergency power backup systems. Unlike battery-powered devices with limited run-times, the Nexa power module is capable of producing full power in back-up operations or intermittent electrical power as long as hydrogen fuel is supplied to the unit.

Table 1. Nexa Power Module Specifications

Performance	* Rated net output power * Heat dissipation * Current * Voltage * Lifetime	1,200 watts 1,600 watts (at rated net output) 46 Amps DC (at rated net output) 26 Volts DC (at rated net output) 1,500 hours
Fuel	* Gaseous hydrogen * Supply pressure	99.99%, dry 10 to 250 PSIG
Operating Environment	* Ambient temperature * Humidity * Indoor outdoor locations	38 to 86 degrees (F) 0% to 95% non-condensing Unit must be protected form inclement weather, sand, dust, marine and freezing conditions
Certification	USA and Canada	UL, CSA
Emissions	* Pure water (vapor and liquid) * CO, CO2, Nox, SO2 particulates * Noise	Maximum 25 fluid ounces per hour (at rated net output) 0 ppm 72 dBA @ 40 inches
Physical	* Dimensions * Weight	22" x 10" x 13" 27 lbs

2.1 Fuel Cell Controller

The Nexa power module is a fully integrated system that includes hydrogen delivery, oxidant air supply and cooling air supply. The Fuel Cell Controller consists of a control board with a microprocessor that fully automates the operation by monitoring the system performance. The Nexa power module also incorporates operational safety systems for indoor operation. The Nexa system schematic is shown in Figure 2. The diagram shows the important interface connections to the Fuel Cell Controller. Hydrogen, oxidant air and cooling air must be supplied to the unit, while exhaust air, water and coolant air from fans are emitted. Battery power (24 volts) must be supplied for startup and shutdown can be accomplished. The Fuel Cell Controller also has a communications interface that will provide for remote start/stop signals and for receiving serial port communications relative to performance status and safety issues.

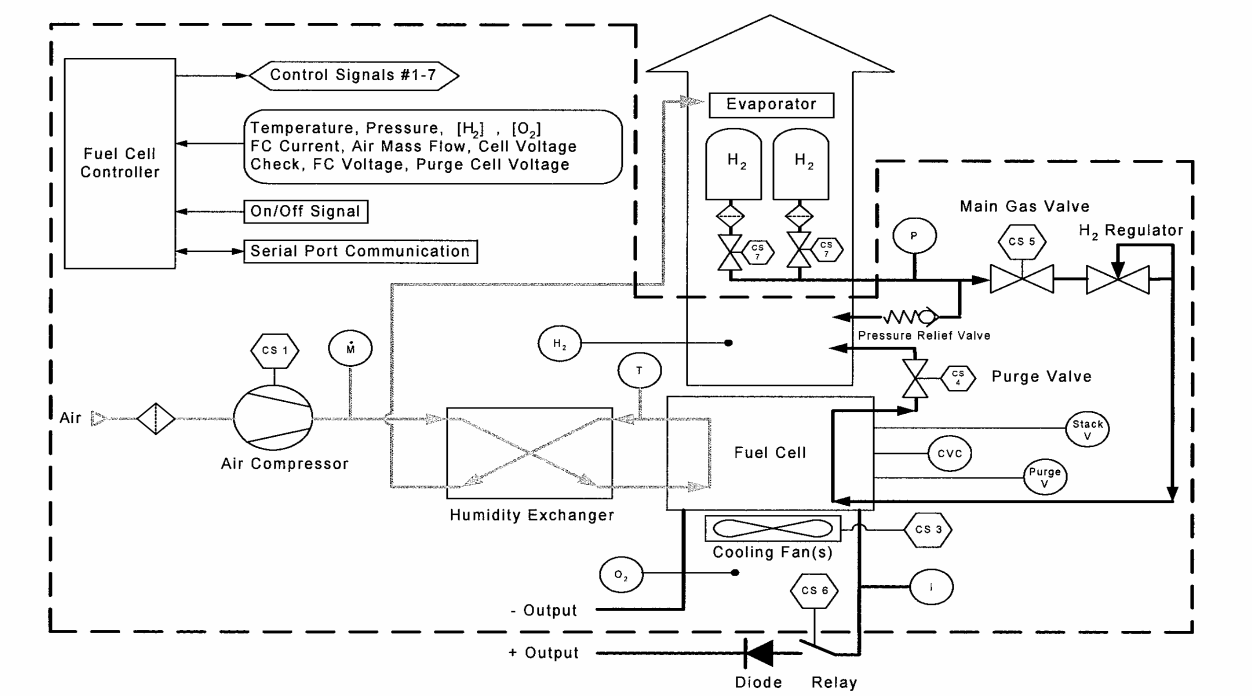


Figure 2. Schematic of the Nexa Power Module System

Without going through the electrochemical fuel PEM cell operation, the Nexa fuel cell consists of a stack of multiple thin, fuel cell elements sandwiched together in series to provide the required electrical power. A single fuel cell element produces about 1 volt at open-circuit and about 0.6 volts at full current output. The cross-sectional area of the fuel cell element is proportional to the amount of current produced. Thus, the geometrical shape for the fuel cell stack can be tailored to provide the desired output voltage, current and power. The Nexa fuel cell stack has 43 fuel cell elements, the fuel-cell diagnostic system also located in the Fuel Cell Controller can monitor the performance of individual fuel cell elements and detect the presence of a poorly performing cell.

Hal H Ottesen, Ph.D.
University of Minnesota Rochester

2.2 Hydrogen Supply System

The Nexa power module operates on pure, dry hydrogen (H2) from any suitable source. The Fuel Cell Controller monitors and regulates the supply of hydrogen to the fuel cell stack, as shown in Figure 2. The following components are involved in the fuel supply subsystem:

- A pressure transducer monitors the fuel delivery conditions to ensure an adequate fuel supply is present for system operation.
- A pressure relief valve protects downstream components from over-pressure conditions.
- A solenoid valve provides isolation from the fuel cell supply during shut down.
- A pressure regulator maintains adequate hydrogen supply pressure to the fuel cell elements.
- A hydrogen-leak-detector monitors the hydrogen level near the fuel delivery subassembly. Warning and shut down alarms are implemented for product safety.

The fuel cell stack is pressurized with hydrogen during operation. The pressure regulator continuously replenishes hydrogen, which is consumed in the fuel cell's electrochemical reaction. Nitrogen and product water in the air stream slowly migrates across the fuel cell membranes and gradually accumulates in the hydrogen stream and causes an accumulation of nitrogen and water at the anode, i.e., the negative terminal. This results in the steady decrease in performance of certain "key" fuel cells, which are called "purge cells." In response to the purge-cell voltage, a hydrogen purge valve at the stack outlet is periodically opened to flush out inert constituents at the anode to restore performance.

Only a small amount of hydrogen is purged from the fuel cell system, less than one percent of the overall fuel consumption rate. Purged hydrogen is discharged into the cooling airstream before it leaves the Nexa power module, as shown in Figure 2. The purged hydrogen quickly diffuses into the cooling airstream and is diluted to levels many times less than the lower hydrogen flammability limit (LFL). The hydrogen leak-detector is situated in the cooling exhaust and insures that the flammability limits for hydrogen are not reached. This feature permits safe, indoor operation of the Nexa power module.

The lower flammability limit (LFL) of hydrogen is the smallest amount of hydrogen that will support a self-propagating flame when mixed with air and ignited. At concentrations less than the LFL, there is insufficient fuel present to support combustion. The LFL of hydrogen is 4% by volume.

2.3 Oxidant Air System

A small air compressor provides excess oxidant air to the fuel stack in order to sustain the fuel cell electrochemical reaction, see Figure 2. An intake filter protects the air compressor and downstream components from particulates in the surrounding air. The compressor speed is controlled to suit the DC current demands of the fuel cell stack. Larger DC currents require more oxidant airflow. A downstream sensor measures the airmass flow rate and fine-tunes the compressor speed for the required DC current output.

The oxidant air is humidified before reaching the fuel cell stack to maintain water saturation of the proton exchange membrane (PEM) and prolong the lifetime of the fuel cell system. Any drying of the PEM, will greatly reduce the life of the fuel cell system. A humidity exchanger transfers both fuel cell product water and heat from the wet cathode outlet to the dry incoming air. (The cathode is the positive terminal.) Excess product water is discharged from the system, as both liquid and vapor in the exhaust.

2.4 Cooling System

About 57% of the hydrogen energy consumed by the Nexa Power Module is converted into heat [2,5]. At high DC current levels, more heat is generated. It is important to keep the fuel cell stack temperature at a constant operating temperature, therefore, the fuel cell stack temperature has to be controlled. Fuel cell systems are either liquid-cooled or air-cooled. Hot liquid or hot air from the cooling system may be used, via a heat exchange system, for thermal integration purposes. This will be done in Phase II of the HESS project.

The Nexa fuel cell stack is air-cooled. A cooling fan located at the base of the Nexa Power Module blows air through vertical cooling channels in the fuel cell stack. The fuel cell stack operating temperature is maintained at 65 degrees C (149 degrees F) by controlling the speed of the cooling fan. The fuel cell stack-temperature is measured at the wet cathode air-exhaust, see Figure 2.

The cooling system is also used to dilute hydrogen that is purposely purged from the Nexa Power Module during normal operation. Hydrogen is released into the cooling airstream via the purge solenoid valve, as illustrated in Figure 2. The hydrogen quickly diffuses into the cooling air and is diluted to levels far below the lower flammability level (LFL) of hydrogen. For safety, a hydrogen sensor is located within the outlet of the cooling airstream and provides feedback to the Fuel Cell Controller. The Fuel Cell Controller generates warning and alarm signals if the hydrogen concentration in the cooling airstream approaches 25% of the LFL.

2.5 Safety Systems

The Nexa Power Module provides automatic provisions to ensure operator safety and prevent equipment damage. A warning or alarm occurs when an unusual or unsafe operating condition occurs, depending on severity. During a warning, the Nexa Power Module continues to operate and the Fuel Cell Controller attempts to remedy the condition if possible. During an alarm, the Fuel Cell Controller initiates a controlled shutdown sequence. The Nexa Power Module employs the following monitoring and shutdown mechanisms to ensure that safe fuel cell operation is maintained at all times:

- Fuel cell operating parameters are continuously monitored to ensure they stay within desired limits. These include fuel cell stack temperature, fuel cell stack current, output voltage and fuel cell supply pressure. Warnings and alarms are implemented on each of these parameters.
- A cell voltage checker (CVC) system continuously monitors operation and performance of individual fuel cell elements. The presence of a failing cell will cause the Nexa module to shut down.
- A hydrogen leak-detector is implemented within the hydrogen fuel delivery system. Imbedded properly into the cooling airstream, this sensor can also detect excessive hydrogen purge amounts or the presence of an external fuel leak in the fuel cell stack. The Nexa Power Module will shut down automatically if an external hydrogen leak is detected.
- The Nexa Power Module comes equipped with an oxygen sensor for measuring ambient oxygen levels. This feature prevents users from operating the Nexa Power Module in non-ventilated areas, where oxygen depletion may become a safety concern. The power module shuts down automatically when low ambient oxygen concentration levels are measured.

In addition to warnings and alarms, other safety features are including the design of the Nexa power module:

- A hydrogen fuel shutoff solenoid valve closes whenever the power module is shut down. This isolates the hydrogen fuel supply and prevents hydrogen from entering the fuel cell stack in the event of an alarm shutdown.
- Under normal operation, hydrogen released vie the purge solenoid valve mixes with the cooling airstream, where it quickly diffuses and dilutes to levels far below the lower flammable limit (LFL) of hydrogen. This eliminates the potential formation of a flammable gas mixture in the cooling airflow and permits indoor operation.
- A pressure relief valve discharges hydrogen into the cooling airstream during over-pressure conditions to protect the fuel cell stack from damage. When the relief valve opens, the hydrogen concentrations measured in the cooling airstream exceed the hydrogen alarm setting, and the Nexa Power Module shuts down.

3.0 Experimental Setup

There were several issues, including the safety of working around hydrogen fuel, that came up before the decision of an appropriate site for the fuel cell experiments. With all of the anecdotal histories about the Hindenburg airship fueled with hydrogen that blew up in 1937, hydrogen gas has had a reputation of being a very dangerous substance to be around. Fortunately, these stories are not true. In 1997, a retired NASA scientist, Addison Bain, was finally able to scientifically prove from a 60-year-old colorized photograph of the Hindenburg airship as it burned, that it was the extreme flammability of the outside fabric cover, and not the hydrogen inside, which caused the disaster. A short article [3] by J. C. Bokow of the Hindenburg disaster and Bain's scientific work has been included in the appendix of this report.

Among the experimental site-issues was a well-vented area with secure access, access to the RPU information technology (IT), access to a hydrogen supply located outdoors, relatively low levels of electromagnetic (EM) noise and safe surroundings. The site that was finally selected, referred to as the Fuel Cell Laboratory, was a heated room at the Rochester Public Utilities next to the stock warehouse. The location was far away from a practical area for an outdoor hydrogen supply, but otherwise satisfied most of the other requirements.

3.1 Hydrogen Supply and Safety

Two T-sized hydrogen tanks, connected in a manifold, were located at an outdoor, fenced-in area about 60 feet away from the fuel cell. A one-inch copper gas-pipe, placed at ceiling level, connected the hydrogen gas supply to the fuel cell. About one half of the gas-pipe passed through an adjoining mechanical room with banks of high-powered electric switches. For safety reasons, the gas-pipe was enclosed in a two-inch Crestline PVC pipe-sleeve as it passed through the mechanical room to the outside. The PVC pipe was slightly slanted (1:30), such that any leakage of, the lighter than air, hydrogen gas would self-vent to the outside.

At the outside, a manifold-pressure regulator controlled the hydrogen pressure at the entry to the gas-pipe. Next to the manifold-pressure regulator was a shut-off valve that was controlled by an MSR Polyguard hydrogen detector located directly above the fuel cell location. This hydrogen detector was also connected to RPU IT for around-the-clock monitoring. The outside shut-off valve could also be controlled manually from the fuel-cell test site, as can be seen from Figure 5. We had also access to a manual hydrogen shut-off valve right next to the experiment station, which usually was used during experiments.

3.2 Experimental Fuel-Cell Setup

The experimental fuel cell setup consists of the Nexa Power Module, the resistor load-board and a measurement system. The resistor load-board provides a variable load to the fuel cell, which will be used to test its dynamic performance. Three resistive loads are available under computer control to be explained later.

Figure 3 shows a side-view of the Ballard Nexa Power Module, Model 310-0027-02, that was used in the experiments. The Fuel Cell Controller is located on the electronic card in the center foreground. The accordion-shaped object, right behind and to the upper left of the Fuel Cell Controller, is the fuel cell stack, consisting of 43 sandwiched fuel cell elements. On the left side and on the top of the fuel cell stack is the hydrogen pressure regulator. The shiny object to the lower right is the location of the fuel cell cooling fan.

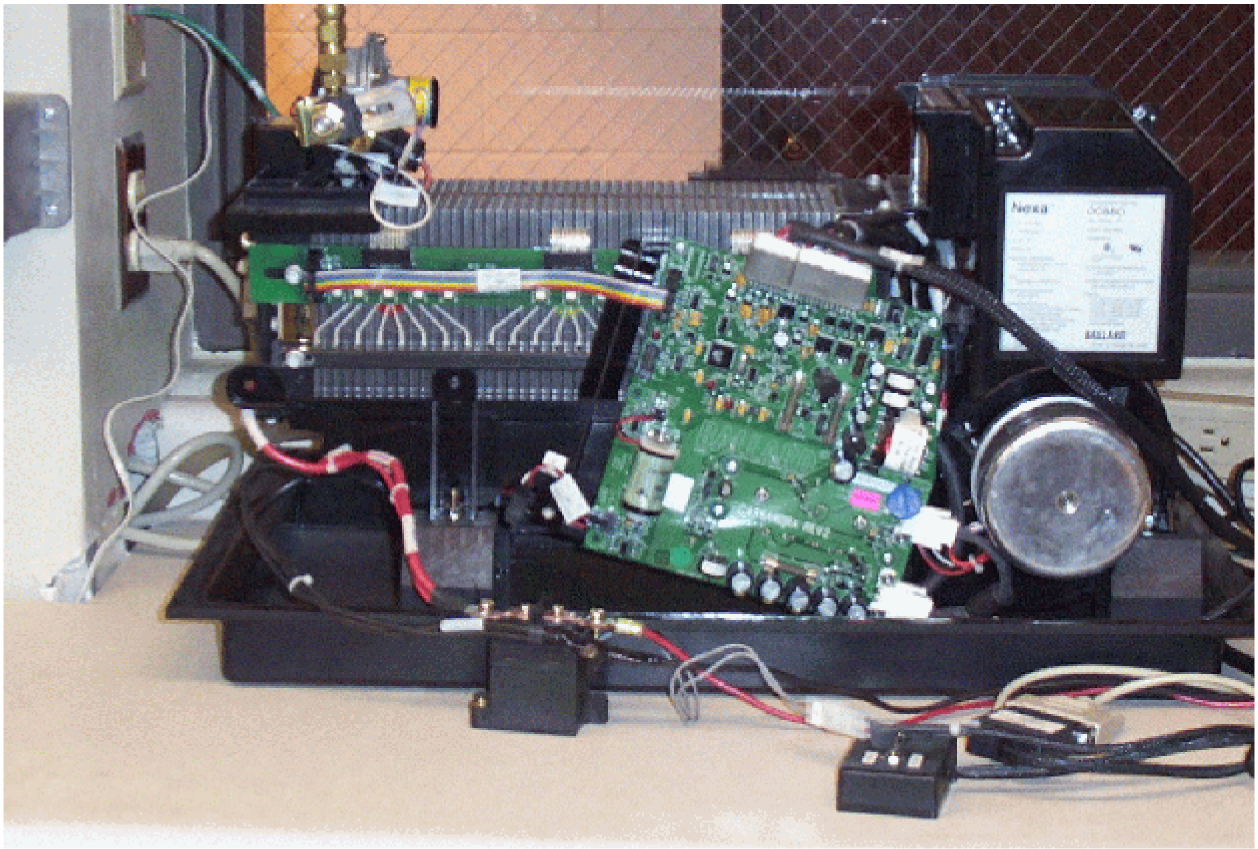


Figure 3. Nexa Power Module on the table in the Rochester Public Utilities laboratory.

The resistor load-board is depicted in Figure 4. It consists of a four-foot, 1"x12"pine-board with several components mounted on it. The four main power-resistors are the foot-long tubular cylinders as indicated on the figure, and there are two smaller resistors located on the right side behind the relay. The resistor load-board was designed to provide a maximum load-current of about 40 amperes. The four 2.6-ohm (+/- 10%) power-resistors are non-inductive bulk ceramic and wire-wound, Kanthel Globar, P/N 889SP2R6K, each resistor is capable of dissipating 275 watts at a maximum temperature of 350 degrees C (662 degrees F). The resistors are divided into two pairs, where each pair of resistors is connected in parallel to provide 1.3-ohm resistive units. The reason for the parallel connections, is to provide for a 550-watt power dissipation from each resistive unit for a total of 1,100 watts. Behind each resistive unit are banks of three fans, Pabst 24 volts, 6 watts, to provide the necessary cooling. The two smaller resistors, behind the relay on the right side, are connected in series. Each of the 2.5"-long resistors is 26.0 ohms (+/- 10%), non-inductive bulk ceramic and wire-wound, Kanthel Globar, P/N 885SP260K, capable of dissipating 45 watts each.

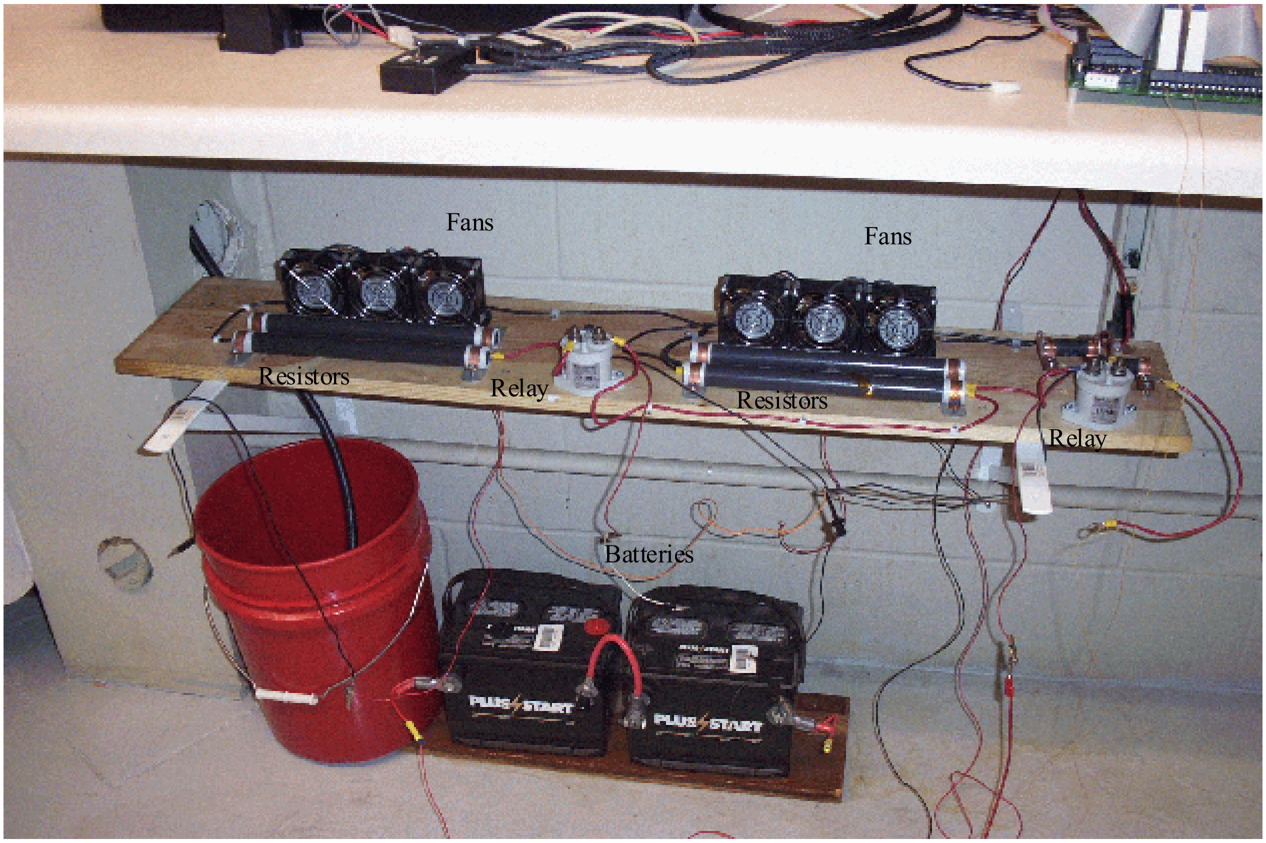


Figure 4. Fuel cell resistor-load board and external components.

Two high-current, normally-open, relays, P/N EV200AANA, CII Technologies, are used to independently switch the 1.3-ohm resistive units across the fuel-cell output. Roughly 23 amps of load-current with one relay ON and the other OFF, we call this the half-load mode. If both relays are ON, then about 40 amps of DC load-current is dissipated on the resistor load-board. This mode is called the full-load mode. The relays can be operated by the measurement system. The wiring shown in Figure 4 is 12-gauge wire, which heated up at the higher current levels. This wire was later changed to the larger 6-gauge wire to better handle DC currents in excess of 40 amps.

Also seen in Figure 4, are two 12-volt car batteries supplying power to the Nexa Power Module during startup, to the two fan-banks, and to manually control the two relays located on the resistor load-board. The bucket, to the lower left, collects excess product water that is discharged from the system. About one pint of clean water per hour is discharged from the fuel cell at a full load.

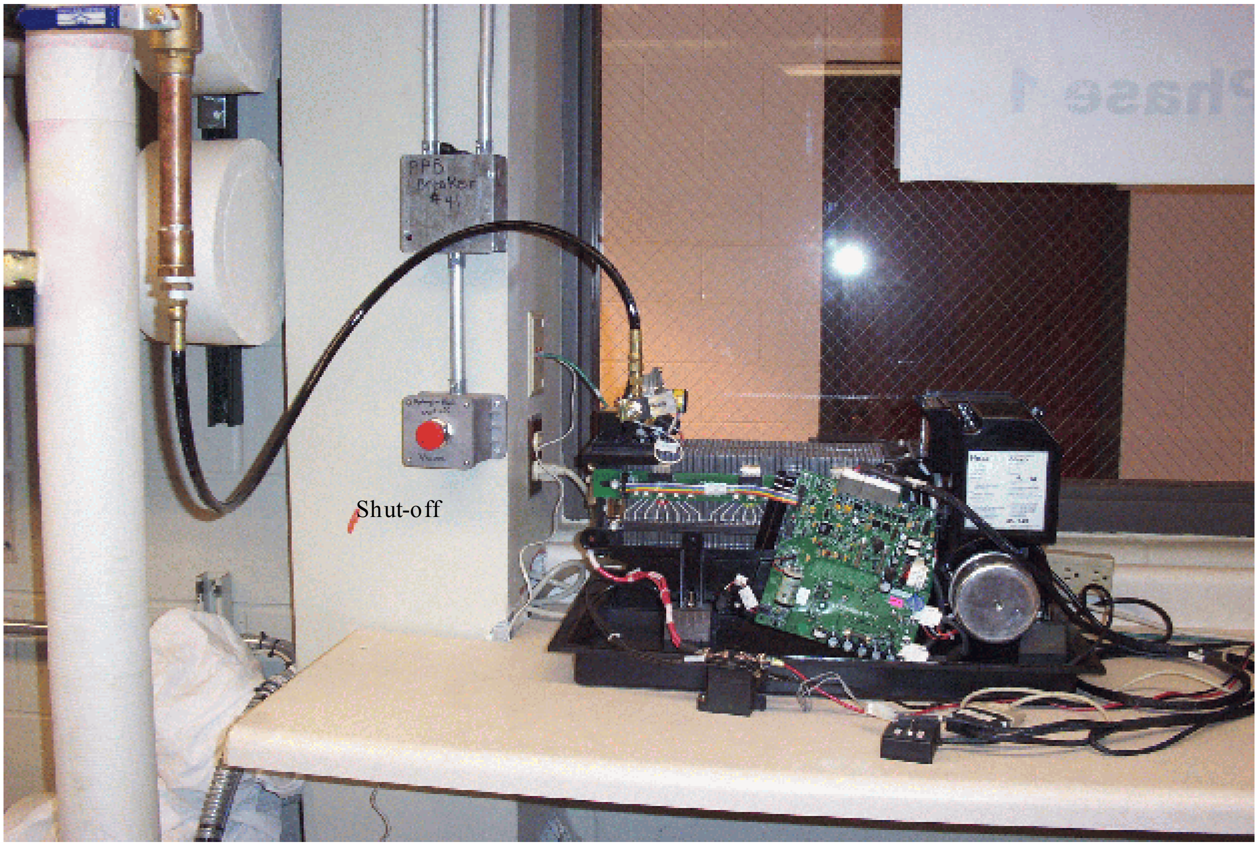


Figure 5. Hydrogen supply connection to the Nexa Power Module and the Manual Shutoff Switch.

The gas-hose connection between the 1-inch hydrogen gas supply pipe and a pressure regulator attached to the Nexa Power Module as shown in Figure 5. Mounted to the wall, to the left of the fuel cell, is a manual shutoff switch that controls the shutoff valve located outdoor at the hydrogen-tank manifold. Immediately above the manual shutoff switch (not shown) is an MSR Polyguard hydrogen gas detector. This hydrogen detector is also connected to RPU IT for around-the-clock monitoring.

3.3 Measurement System

As mentioned before, the Nexa Power Module's system operation is automated by the Fuel Cell Controller. The Fuel Cell Controller (FCC) also receives various system parameters from sensors located at strategic positions around the Nexa Power Module. Analog sensor signals include: fuel cell stack temperature, hydrogen pressure, fuel cell stack current, fuel cell stack voltage, airflow, purge cell voltage, hydrogen concentration, cumulative hydrogen consumption, oxygen concentration and ambient temperature. The FCC communicates to an external personal computer (PC) using a serial protocol, RS-485 and special Ballard software. When the fuel cell power is ON, the FCC continuously transmits data once every 200 milliseconds. Transmitted data includes system status codes, warning codes and alarm codes. Also, included are the floating-point versions of the selected sensor signals for monitoring and display purposes.

In addition to the Ballard monitoring and display system, we added an independent computer-based measurement system for observing the dynamic performance of the Nexa Power Module. The PC-based data acquisition (DAQ) selected for this was miniLAB 1008, Measurement Computing. Combined with powerful software, it turns your personal computer into a measurement system that may be used to automate experiments. This device is a rugged Universal Serial Bus (USB)-based DAQ device with 8 single-ended analog inputs or four differential 12-bit analog inputs and two 10-bit analog outputs. The device comes with free application software and is a USB 1.1 compatible device supported under Microsoft Windows 98SE/ME/2000/XP.

The dynamic measurements of the Nexa Power Module involved current and voltage measurements at the input to the resistor load-board. The sampling period for the measurements was set to 0.1 second/sample or a sampling rate of 10 Hz. For the current measurements, a Sanwa CL-22AD Clamp-on AC/DC Current Probe was used. This battery-powered current probe had a sensor-output signal of 1.0 millivolts/ampere, which is somewhat low considering the ambient EM noise levels in the test area. The differentially measured signal from the current probe was disturbed by current ripples and some additive EM noise as can be seen Figure 7(a), however, nonlinear filtering methods applied to the noisy signal was very effective (Figure 7(b)). The differential voltage measurements, taken from a simple voltage divider at the input to the resistor load-board, were much simpler and less noisy as can be seen from Figure 8(a).

4.0 Experimental Results

Much time was spent on integrating the measurement system with the computer and the fuel cell. Several problems related to current ground-loops from various power sources were minimized or solved. An equivalent block-diagram of the fuel cell connected to the resistor load-board has been illustrated in Figure 6.

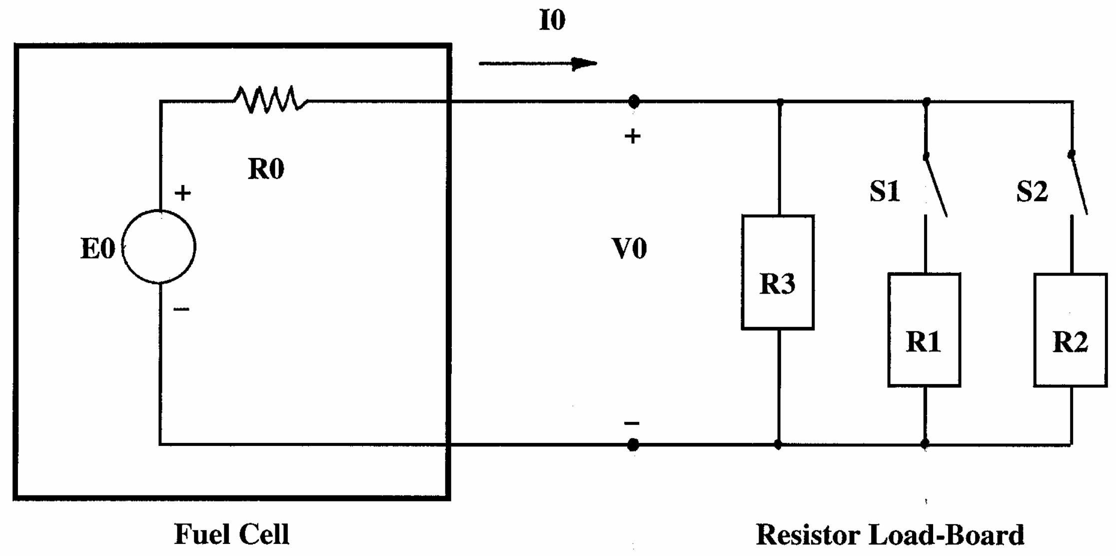


Figure 6. An equivalent circuit diagram of the fuel cell connected to the resistor load-board.

Referring to the above diagram, the electrical portion of the fuel cell can be represented by a voltage source E0 in series with the internal resistance R0 of the fuel cell stack. The unregulated output fuel cell voltage and load-current are designated as V0 and I0, respectively. Both the fuel cell voltage source E0 and internal resistance R0 are highly nonlinear parameters, and they are functions of several conditions of the proton exchange membrane (PEM), the hydrogen pressure, the oxygen supply, and the operating temperature, to name a few. As the current-load I0 increases, there will be a drop in the unregulated fuel cell output V0-voltage, due to the resistive voltage drop across the internal resistance R0. The fuel cell output V0-voltage can be expressed as

$$V0 = E0 - R0 \times I0. \quad (1)$$

The resistor load-board is represented by three resistors, R1, R2 and R3, and two normally-open relays S1 and S2. The approximate resistor values are R1 = 1.3 ohms, R2 = 1.3 ohms, and R3 = 52 ohms. Physically, both R1 and R2 are parallel combinations of two 2.6-ohm non-inductive ceramic bulk tubular resistors, while R3 is the series combination of two 26-ohm non-inductive ceramic bulk tubular resistors.

The two relays, S1 and S2, are used to control the load-demand of the fuel cell. When both relays are OFF or OPEN, then the output load-I0-current is roughly 0.7 amperes. With one of the relays ON (or CLOSED) and the other relay OFF, the output load I0-current is about 23 amps, and if both relays are ON, the output I0-current is about 40 amps.

An estimated value internal resistance R0 was computed by measuring the output fuel cell V0-voltage and I0-current at two different load-current demands. Using Equation (1), the internal fuel cell resistance R0 can be computed from

$$R0 = [V0(2) - V0(1)] / [I0(1) - I0(2)]. \qquad (2)$$

For two the load-current demands: (1) full current with both S1 and S2 ON, and (2) S1 ON and S2 OFF, the measurements, after the fuel cell temperature and the load-resistor temperatures had settled out, were as shown in Table II, below.

Table II. Internal Fuel Cell Resistance Measurements

	(1) S1 = ON, S2 = ON	**(2) S1 = ON, S2 = OFF**
Fuel cell voltage V0	**V0(1) = 28.4 volts**	**V0(2) = 31.45 volts**
Fuel cell current I0	**I0(1) = 39.6 amps**	**I0(2) = 22.3 amps**

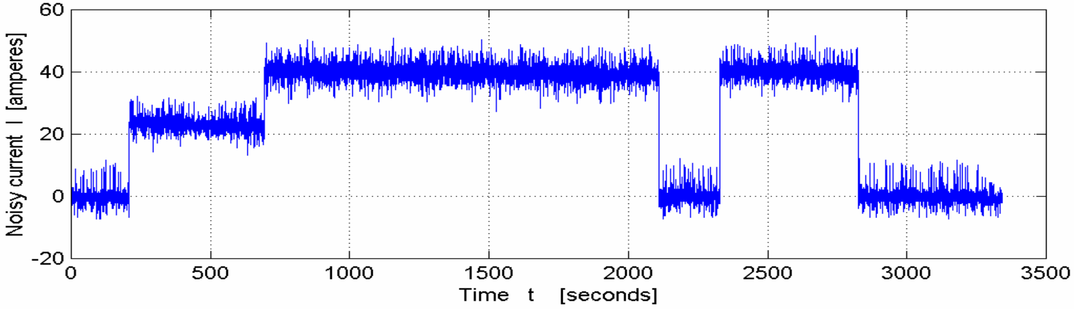
Estimated Internal Resistance R0 = 0.176 ohms

Using the measurement values in Table II and Equation (2), we see that the estimated value for the internal resistance R0 is 0.176 ohms. This is about two to three orders-of-magnitude larger than that found in a common, fully charged car battery.

The results from a set of simultaneous dynamic current and voltage measurements have been graphed in Figure 7 and Figure 8. Referring to these two figures, the load-events relative to the time period (in seconds) were:

0 – 200	Maintenance current	(S1 and S2 are OFF)
200 - 700	Half load current	(S1 is ON, S2 is ON)
700 - 2100	Full load current	(Both S1 and S2 are ON)
2100 - 2300	Maintenance current	(S1 and S2 are OFF)
2300 - 2800	Full load current	(Both S1 and S2 are ON)
2800 - 3300	Maintenance current	(S1 and S2 are OFF)

(a) Noisy unfiltered current measurement



(b) 25-point median-filtered current

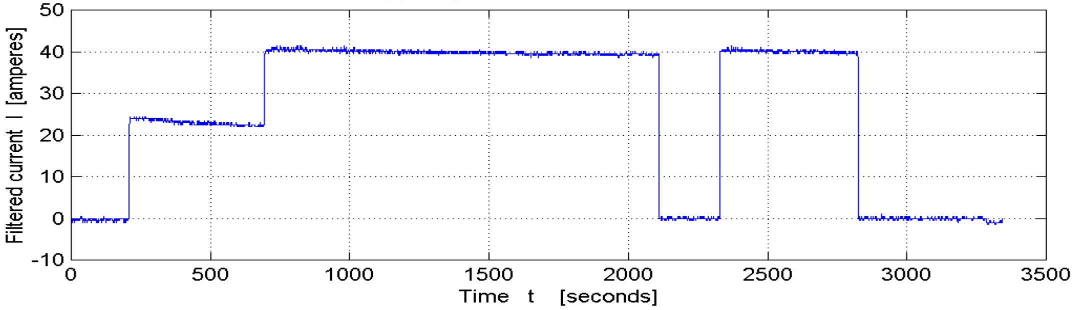
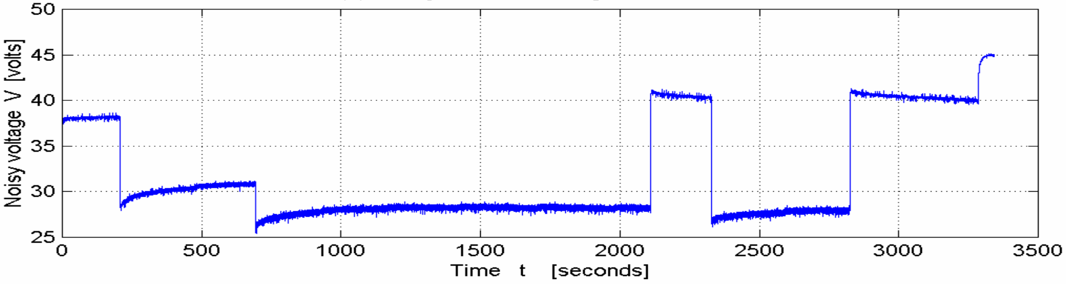


Figure 7. Unfiltered and filtered fuel-cell I0-current for various resistive load-demands.

(a) Noisy unfiltered voltage measurement



(b) 25-point median-filtered voltage

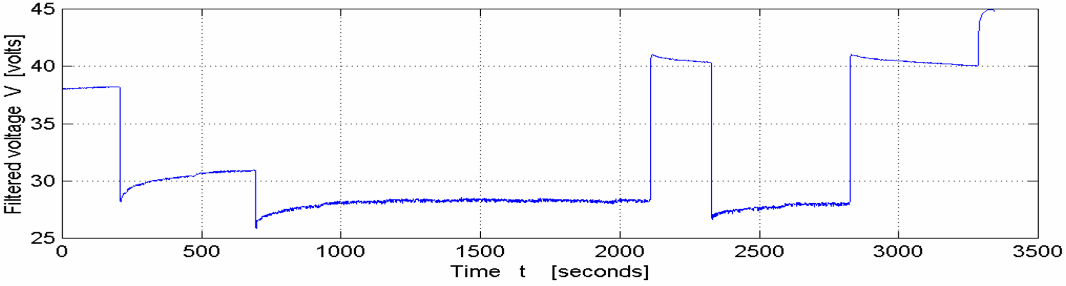


Figure 8. Simultaneous V0-voltage measurements to the I0-current measurements in Figure 7.

Hal H Ottesen, Ph.D.
University of Minnesota Rochester

As can be seen from Figure 7(a), the current measurements made by the clamp-on current probe are noisy mostly due to current ripples from the fuel cell and additive extemporaneous electromagnetic field noise from the fuel cell components (fans, etc.) and in test area. The EM noise can be reduced by adding extensive and expensive shielding to the experimental fuel cell setup. Figure 7(a) shows that the I0-current switching transients are very rapid. Zoomed versions of these waveforms show that the switching transients are less than one sampling period or 0.1 second, when switching between maintenance current (0.7 amps) and full current (40 amps) or vice versa. This observation is very important, since it shows that the Nexa Power Module can be used in application that has rapidly changing load demands.

The additive EM noise, for plotting purposes, can effectively be removed by means of a nonlinear median filter. A linear filter would have a serious effect on the rise and fall time of the switching transients. The median filter has the advantage that it does not distort or alter the switching action in the waveforms of the current and voltage. This can be from Figures 7(b) and 8(b), where a 25-point median filter has been used to filter the waveform in Figures 7(a) and 8(a).

It is interesting to observe in Figure 7(b), that the current drops slightly for half load-current, between 200 seconds and 700 seconds, this is due to initial resistive heating of the resistive element R1 in Figure 6. The temperature coefficient of the non-inductive, bulk ceramic Kanthel Globar resistors, is around +0.1% per degree C. The resistors heat up to 125 - 175 degree C above the ambient temperature with the cooling fans running. This would imply roughly a 12.5 - 17.5% increase in the resistance value when R1 and R2 are carrying a load current. Correspondingly in Figure 8(b), the unregulated fuel cell output V0-voltage, within the same time-period, increases due to the increasing R1 resistance and the lower voltage drop across the internal fuel cell resistance R0.

Consistent with Equation (1), we observe when the load I0-current is high, the fuel cell output V0-voltage is low, and the vice versa. For the experimental setup in Figure 6, the maximum output V0-voltage is about 40 volts, when the I0-current is 0.7 amps, and at a full I0-current of 40 amps, the output V0-voltage is about 27 volts.

5.0 Discussions

The objective of the first part of the Hybrid Energy System Study (HESS) was to gain a working experience with a commercially available fuel cell product and to characterize its dynamic performance relative to changes in load-current demand and ambient temperature. The selection of the Nexa Power Module made by Ballard Power Systems, Canada was based on the scope of HESS, Part I, and the reputation of Ballard as a premier fuel cell manufacturer.

The experiments verified that during normal operating conditions, the Nexa Power Module can respond to load-increases and load-decreases of more than 40 amperes in less than 0.1 seconds or about 6 cycles at 60 Hz. This response may be adequate for many applications, or it can be augmented by capacitors or batteries to provide an even faster response to large changes in energy load demands.

Hal H Ottesen, Ph.D.
University of Minnesota Rochester

The Nexa Power Module seemed to be emitting current ripples. This was observed mostly in the current measurements, as can be observed in Figure 7(a). The EM noise was expected, since it is well known that large currents emit large magnetic fields. In an application, the Nexa Power Module should be well shielded so that it does not interfere with other electrical systems in the same application.

The effects of ambient temperature measurements on the fuel cell operation could not be completed. This is due to the Fuel Cell Controller, which regulates the fuel cell stack temperature to 65 degrees C during normal operating conditions. Deactivating this temperature control feature in the Nexa Power Module, will cause a system shutdown. The Nexa Power Module Installation Manual [1] calls for an ambient temperature range from 3 degrees to 40 degrees C (38 - 104 degrees F). If the internal, non-operating fuel cell temperature falls below freezing, any water within the fuel cell stack will freeze and ruin the delicate proton exchange membranes (PEMs). The minimum time to achieve rated power from a cold start condition is two minutes [4,5]. The previous information suggests that the fuel cell should be operating in a maintenance mode running a small I0-current of around 0.1 amps. In this mode, the fuel cell will be able to respond quickly to any load-demand, while maintaining the internal stack temperature at a constant 65 degrees C (149 degrees F). If the unit is located outdoors, it should be enclosed in a thermally insulated compartment, where the compartment temperature could be kept within the specified ambient temperature range. Continuous operation of the PEM fuel cell, substantially increases its lifetime, while start/stop operations reduce the number of potential operating hours [4]. Therefore, fuel cells used in automobiles have a shorter lifetime than those used in a continuous mode.

As can be seen from Table I, when the Nexa Power Module is operating at maximum, net rated power of 1,200 watts, the unit is dissipating 1,600 watts of heat. This implies that 57% of the 2,800-watt-equivalent hydrogen energy supplied to the fuel cell is dissipated as heat, while 43% is in the form of electric energy. In comparison, the internal combustion engine in a modern car is less than 20% efficient [4]. It is reported that some fuel cells can be up to 60% efficient in providing electric power depending on the fuel used and the size of the unit. Large fuel-cell systems are more efficient than the smaller fuel-cell systems [5], like the Nexa Power Module. HESS, Phase II is predicated on harnessing some of the dissipating fuel cell heat to improve the efficiency of a geothermal system. In some stationary residential applications, the heat dissipated by the fuel cell is being used for a hot water heater or for heating up the basement floor. As a power source, the PEM fuel cells are much more efficient and cleaner than the common “hydro-carbonized” powered sources. The PEM fuel cells have broad industrial applications in the distributed power area. Examples are:

- Homes and small commercial businesses
- Remote locations (farm operations, telecommunication towers, off-grid buildings, vending machines, etc.)
- Backup power (hospitals, governmental and computer centers, etc.)
- Premium power (data warehouse centers)

Some of the advantages of having a portion of the electricity producing capability using PEM fuel cell generators, are:

- High quality energy supply with a reliable and consistent level of power.
- Dedicated power on-site, which eliminates the power glitches and outages that in the electric grid.
- Efficient alternative to maintaining and upgrading overused and congested transmission/distribution lines.
- Eliminating higher priced peak loads, and provide more level-based loads.
- Energy savings, depending on the local price of natural gas versus the electric grid.
- Convenient and reliable backup power.
- Low operating temperatures of 65 C makes it suitable for indoor environments.

6.0 Conclusions

The Hybrid Energy System Study (HESS), Phase I, has been a very rewarding project. The physical setup of the test area with a safe hydrogen supply system was quite a learning process. Many hydrogen experts might see several of the implemented safety features, as being an “overkill.” However, the setup provided a good sense of safety working around hydrogen, and might be used by RPU as a templet for future fuel cell installations. While some experts claim that it is no more hazardous working around hydrogen than it is with gasoline, the common public perception about hydrogen is well entrenched. The scientific explanation for the Hindenburg disaster has been covered in 8.0 Appendix.

The experiments verified that during normal operating conditions, the Nexa Power Module can respond to load-increases and load-decreases of more than 40 amperes in less than 0.1 seconds or about 6 cycles at 60 Hz. This response may be adequate for many applications, or it can be augmented by capacitors or batteries to provide an even faster response to large changes in energy load demands.

It seems logical to run a fuel cell in a continuous “maintenance-mode” setting, i.e., the fuel cell is producing a small current, say about 1% of maximum current. This would substantially increase the lifetime of the fuel cell unit and make the fuel cell power “instantly” available to the associated application. In this mode, the fuel cell will be able to respond quickly to any load-demand, while maintaining the internal stack temperature at a constant 65 degrees C (149 degrees F). If the unit is located outdoors, it should be enclosed in a thermally insulated compartment, where the compartment temperature could be kept within the specified ambient temperature range.

Of special interest is the heat dissipated by the fuel cell. Utilizing this heat could be very advantageous in many applications. In some stationary residential applications, the heat dissipated by the fuel cell is being used for a hot water heater or for heating up the basement floor. In the future, HESS, Phase II is predicated on harnessing some of the dissipating fuel cell heat to improve the efficiency of a geothermal system.

Hal H Ottesen, Ph.D.
University of Minnesota Rochester

7.0 References

[1] *Nexa Power Module Installation Manual*, Ballard Power Systems

[2] Ottesen, H. H., *HESS: The PEM Fuel Cell. Background Information and Energy Calculations*, September 2003

[3] Bokow, J. C., *Hydrogen Exonerated in Hindenburg Disaster*, National Hydrogen Association News (1997) http://www.hydrogenus.com/advocate/ad22zepp.htm

[4] Milliken, J., et. al., *Department of Energy, Transportation Fuel Cell Program,* Sensor Workshop, January 25-26, 2000, Berkeley, CA http://www.ott.doe.gov/pdfs/jtb_fuel_cell.pdf

[5] Larminie, J. and Dicks, A., *Fuel Cell Systems Explained,* Wiley (2000)

8.0 Appendix

The memory of the spectacular destruction of the Hindenburg airship affects people's perception of hydrogen and their acceptance of the gas as an energy source. The lighter-than-air craft burst into flame - in full view of a crowd of reporters and newsreel cameras - while landing in Lakehurst, New Jersey, U.S.A., on 6 May 1937. Hydrogen has long taken the blame for the disaster, which effectively ended travel by zeppelin.

But retired NASA [National Aeronautics and Space Administration] engineer and long-time hydrogen advocate Addison Bain, who has been conducting extensive research on the incident, concludes that hydrogen played no part in starting the Hindenburg fire. To learn what really happened 60 years ago, Bain used NASA's latest investigative techniques to analyze original wreckage from the Hindenburg; conducted interviews with the few remaining survivors and those who have detailed knowledge of the Hindenburg's construction; examined original film footage and other documentary evidence; and visited the airship's former mooring sites in Lakehurst and Akron, Ohio, U.S.A. The dramatic findings of his research were reported at the National Hydrogen Association''s *8th Annual U.S. Hydrogen Meeting* and are the subject of the cover story of the May 1997 issue of the Smithsonian Institution's *Air and Space* magazine, published in observance of the incident''s 60th anniversary. (Bain also plans to publish a complete manuscript with all data as well as two books for the general public and young adults.)

Observations of the incident show evidence inconsistent with a hydrogen fire: (1) the Hindenburg did not explode, but burned very rapidly in omnidirectional patterns, (2) the 240-ton airship remained aloft and upright many seconds after the fire began, (3) falling pieces of fabric were aflame and not self-extinguishing, and (4) the very bright color of the flames was characteristic of a forest fire, not a hydrogen fire (hydrogen makes no visible flame). Also, no one smelled garlic, the scent of which had been added to the hydrogen to help detect a leak. A colorized photograph of the Hindenburg airship as it burned gives several proofs to the theory that it was the extreme flammability of the fabric cover, not the hydrogen inside, which caused the disaster.

Bain’s study uncovered two contributing factors: the prevailing atmospheric conditions and the unorthodox method of landing at Lakehurst. First, thunderstorms had come through the Lakehurst area that day; lightning could still be seen at the time of the Hindenburg’s landing. Secondly, the airship made a “high” landing: the zeppelin was moored at a high altitude and winched down to the ground via landing lines dropped from the airship. This, in effect, created a ready-made ground-to-cloud electrical path in the highly charged atmosphere. This combination of factors could prompt severe corona activity on any airship. In fact, an eyewitness reported seeing a blue glow of electrical activity atop the ill-fated Hindenburg before the fire started, which is indicative of the extremely high temperatures typical of a corona discharge.

Bain’s suspicions of the zeppelin’s fabric covering were raised when he learned that a cellulose nitrate dope with powdered aluminum might have been used on the Hindenburg. Bain was able to obtain two 60-year-old fabric samples representative of those used on the airship. At the NASA Materials Science Laboratories at Kennedy Space Center, testing included chemical and physical analysis using the scanning electron microscope, X-ray energy dispersive spectroscopy, optical microscopy, infrared spectroscopy, and tests of flammability, electrostatics, conductivity, surface and volume resistivity, thermogravimetric analysis, and corona discharge exposure.

At the NASA lab, one of the fabric samples subjected to a flame propagation test burnt up in seconds, still volatile after six decades. The remaining sample was subjected to high-voltage electrical fields, replicating the atmospheric conditions surrounding the Hindenburg that fateful night. The electric arc burned a hole in the fabric; however, when the sample was mounted so it remained parallel to the arc (as the airship was), the fabric ignited and disappeared in seconds.

The Hindenburg fabric was found to be made of a cotton substrate with an aluminized cellulose acetate butyrate dopant. The observations of the fire listed above, in fact, are consistent with a huge *aluminum* fire. (The brightness of the space shuttle’’s rocket boosters are an example of aluminum-based combustion.) So, it was the extreme flammability of the Hindenburg’s fabric envelope which caused the disaster and not the lifting gas inside.

Files examined at the Zeppelin Archive in Friedrichshafen, Germany, yielded final confirmation of Bain’s theory. Several handwritten letters, when finally translated from German, corroborate what Bain uncovered. Wrote electrical engineer Otto Beyersdorff on 28 June 1937, “The actual cause of the fire was the extreme easy flammability of the covering material brought about by discharges of an electrostatic nature.”

Hal H Ottesen, Ph.D.
University of Minnesota Rochester