Development of a Modular Fuel Cell Generator: Description of 4kW Modular Unit

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Diesel generators are already a major source of air pollution in the United States and they are growing in numbers and in total installed capacity every year. Now is an ideal time for regulators and industry to pursue strategies to advance the fuel cell which is a clean and economic alternative to the diesel generator. More specifically, PEM fuel cells are commonly considered the most promising fuel cell technology in that they combine high power density and specific power with fast start up, fast response, and environmental friendliness. Fuel cells need hydrogen gas as their fuel but that can be generated by reformation or electrolysis and stored in compressed gas cylinders at reasonable densities. At MER, we have designed, built and tested a compact 4kW fuel cell modular unit as a part of a 72 kW fuel cell generator. The viability, flexibility, redundancy, reliability and cost-effectiveness of the modular concept are demonstrated in this paper.

Over View of the Modular Generator

At MER, research concerning commercially viable generator configurations was undertaken to guide MER's business plan for the marketing and commercial fabrication of fuel cell generators. MER has determined that the market segment of 4 kW, 48 VDC generators is a viable market niche for both civilian and non-civilian use. Besides the relatively low production cost of the stack at the 4kW power level, the 48 V DC operation voltage is compatible with telecom and other IT applications as a direct current output (1-4). MER had identified an efficient Power Circuit Unit (PCU) for the 4 kW modular generator that converts 48 V DC to 110V nominal AC so that alternating current can be another output.

A packaging and assembly concept for a modular fuel cell generator modeled on this existing generator was examined. Different possible outputs voltages for the stacks were analyzed in conjunction with the size and cost of the modular fuel cell system. MER had designed and developed a 87-cell PEM fuel cell stack. This fuel cell stack uses humidified air obtained from a passive membrane humidifier and humidified hydrogen obtained from a closed-loop hydrogen recirculation system. Our closed-loop hydrogen recirculation system facilitates the removal of water diffusing out from the anode thus enhancing the fuel utilization efficiency. MER uses commercial off-the-shelf (COTS) hardware since it is easier and cheaper to order replacement parts directly from the original vendor rather than from the fuel cell manufacturer. The modular fuel cell system provides an inverter as a part of each module rather than one large inverter handling all of the modules.

Typically, the DC voltage of the stack is increased by connecting the cells in series mode and converting the total DC output to AC voltage. Converting the high DC voltage from stacks connected directly in series would require the output voltage to be held fixed within narrow limits. This would significantly restrict the flexibility of the modular design and increase the cost unnecessarily. It could also require a heavy make up transient voltage for step load applications that would have to be supplied by batteries. In the modular system, each module is connected in parallel after the inverter. Organizing the power architecture in this way allows more flexibility in the number of generator modules that can be connected together. Also, in this way, the commercially available standard size inverters with a nominal voltage of 48V can be used. This is more cost-effective compared to a single inverter which would have to be custom designed and built. The inverters are operated in parallel for a combined output of 120VAC.

Fuel Cell Stack Development

MER has designed and fabricated a 87-cell stack, which is shown in Figure 1. A commercially available 7-layer MEA was used. The stack was operated with a closed-loop hydrogen recirculation system (pressurized to 3 psi) and an open blower driven air supply (at < 0.5 psi) using a passive membrane humidifier that collects water from or supplies water to the stack. The polarization curve of this 87-cell stack showing a 4 kW power output at 48V DC is given in Figure 2.

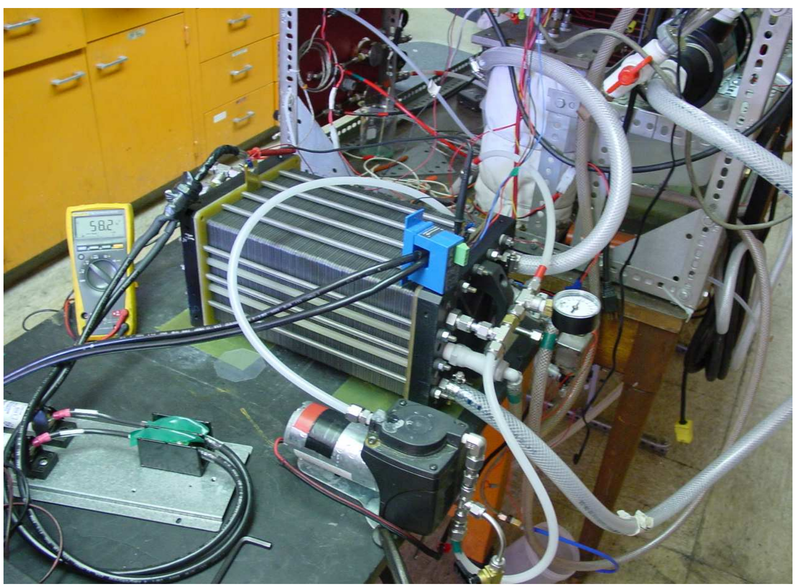

Figure 1. 87-Cell stack operated horizontally with U-flow feed of hydrogen and air.

The 87-cell stack needs 37.7 lpm of hydrogen @ 3 psi and 148 lpm (stoichiometry 1.3) of air @ RT, 1 atm to operate at the design point power level. Before the stack could be integrated into the generator system, parameters such as, the minimum hydrogen flow rate requirement inside the recirculation loop, the minimum air requirement, the appropriate pattern (Z or U) of the fuel and oxidant flows and the ideal operational temperature and pressure for the stack need to be determined. Accordingly, the stack was first tested with different hydrogen flow rates within the recirculation-loop while maintaining the temperature and pressure of the stack constant.

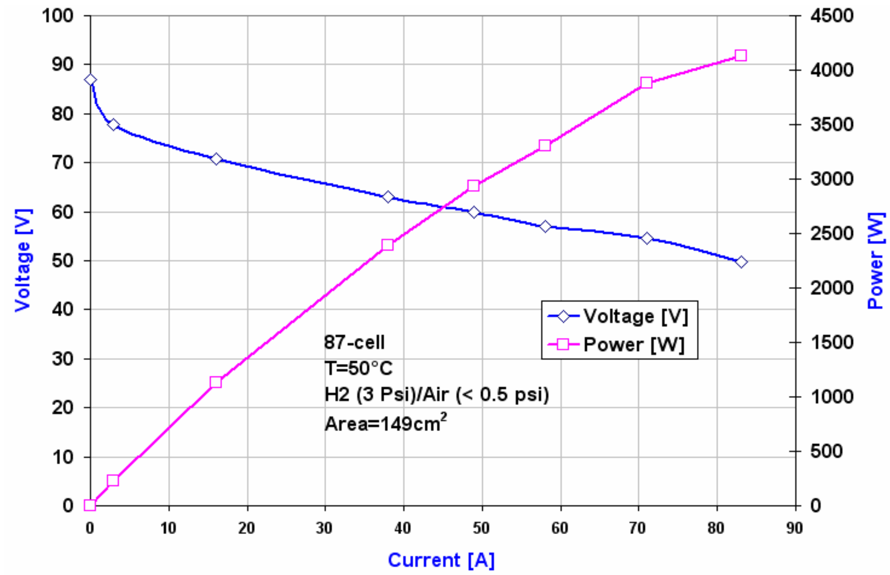

Figure 2. Performance of the stack operated horizontally with U-flow of hydrogen/air.

Three pumps with different flow rates, namely 3, 17.5 and 28 lpm were chosen and experiments were conducted. The results are shown in Figure 3. It can be seen from Figure 3 that the recirculation flow of 3 lpm is insufficient. The performance obviously suffers. However, at first sight there does not appear to be a noticeable difference between using a hydrogen recirculation rate of 17.5 lpm or 28 lpm. The difference only becomes apparent when the individual subset voltages are monitored. The performance of the individual subsets is much more consistent at a recirculation rate of 28 lpm than at 17.5 lpm. Therefore, the higher flow rate is preferable. The standard deviation of the subset values was lower for the 28 lpm flow rate versus the 17.5 lpm flow rate, as indicated in Figure 4. Stability and consistency of performance is extremely important for long term operation and for the life of the stack.

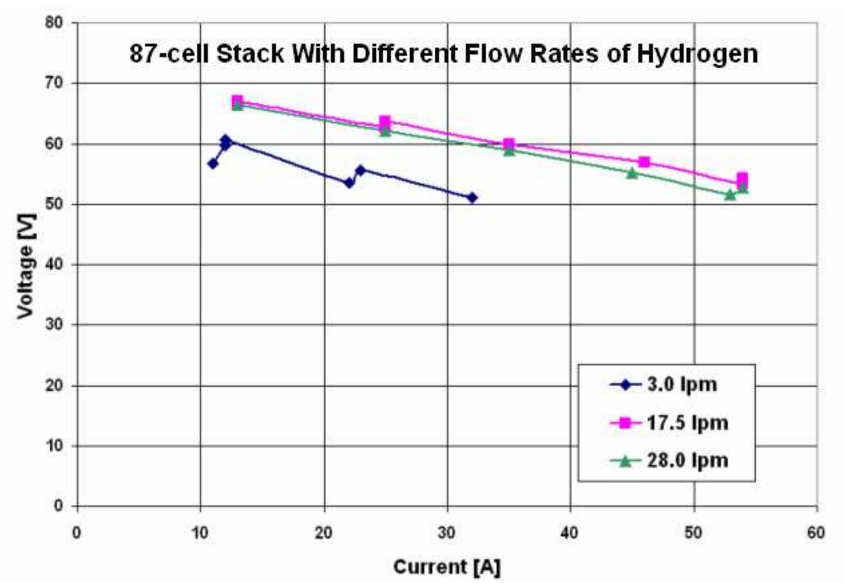

Figure 3. Performance of the stack with different H_2 recirculation rates.

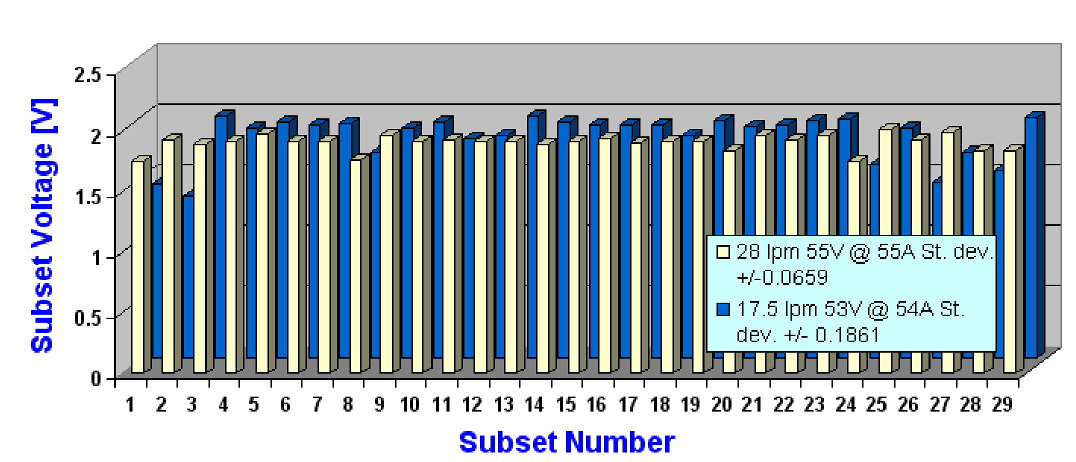

Figure 4. Subset Values with different H_2 recirculation rates.

An efficient regenerative air blower was used. The blower is powered by the 36 V DC controlled by a 0-10 V signal resulted in 0 to 100 % blower output. This blower helps the fuel cell stack to generate 4 kW of DC power comfortably with a stoichiometry of 1.3. The improved stoichiometry is due to the combined effect of a superior quality gas diffusion layer, thinner membranes, and well-designed air flow-field channels. The individual subsets voltage values were monitored during operation of the stack and were consistent within a standard deviation of ± 0.032 V. Moreover, the pressure drop across the stack was observed to be as low as 0.5 psig over the entire operating range. This experiment demonstrated stability and consistency for operation of the stack in the horizontal orientation and with the U-flow configuration for optimized hydrogen and air feeds. The stack was operated intermittently for more than 300 hours total.

Experiments were conducted to verify the performance of the "Recirculated-Closed-Loop Hydrogen" against the performance of the "Open Flow Humidified Hydrogen" design. In both modes of operation, the observed performance was nearly the same, as shown in Figure 5. This indicated that external humidification to the anode provides no performance advantage over recirculation.

Similarly, at the cathode, performance was measured using compressed air from a bottle and from an air blower. The observed stack outputs were almost the same. The first concern was that operating the stack with too little air flow could possible lead to starvation which would decrease the cycle life of the stack, therefore the observed stoichiometry was carefully verified by supplying excess air. The stack was operated with 174 lpm from bottled air, which was nearly 25% in excess of the quantity needed. Nonetheless, the obtained performance difference was very small. This is illustrated in Figure 6.

Operating with a closed-loop system does, however, dramatically increase fuel efficiency and eliminate potentially dangerous hydrogen exhaust. While using optimized flow rates of hydrogen and air, the individual subsets values were monitored during the operation, as shown in Figure 7, and were consistent with each other to within a standard deviation of ±0.032 V. The low standard deviation values show the stability and consistency of operation for a stack in the horizontal orientation with the U-flow configuration for hydrogen and air feeds.

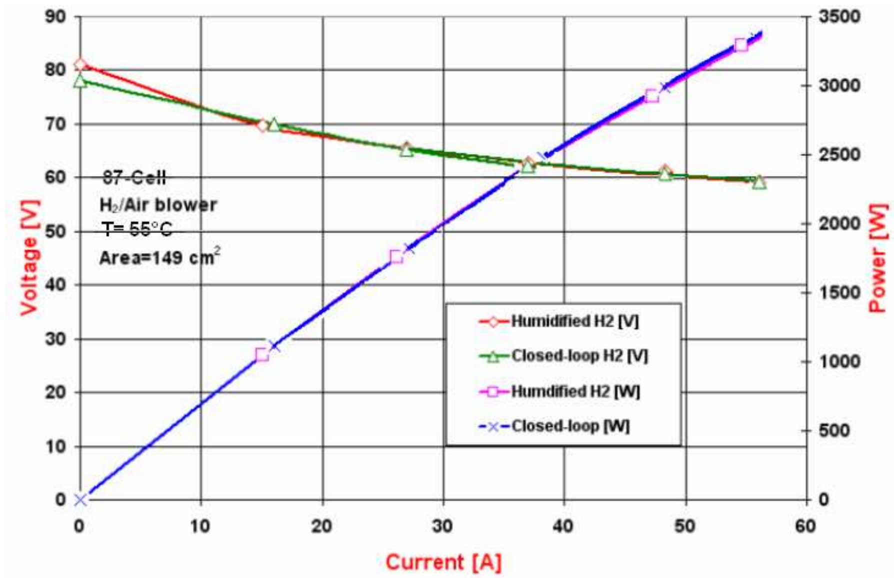

Figure 5. The performance of a 87-cell stack with humidified H_2 and recirculated H_2.

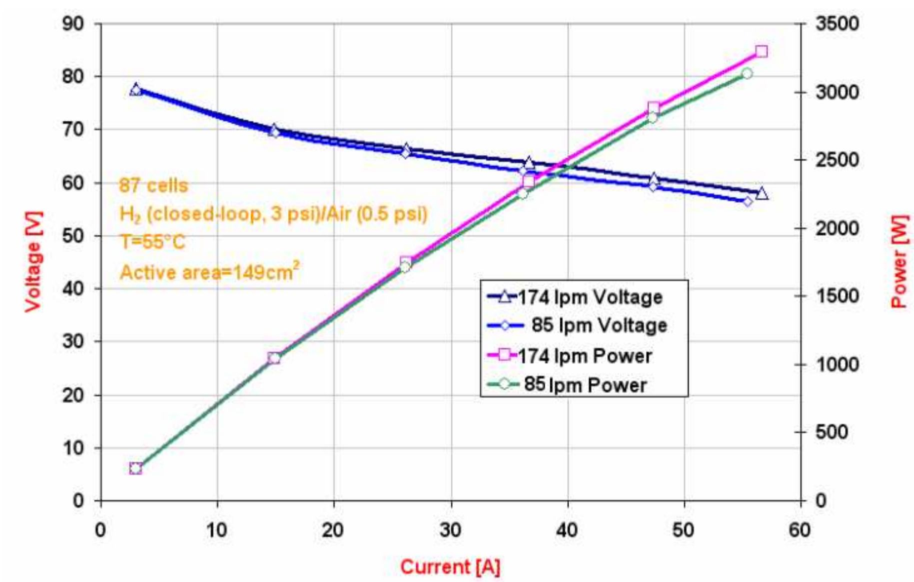

Figure 6. Performance of the stack using 83 lpm and 174 lpm of air.

System Cooling

A 4.0 kW fuel cell produces 4.0 kW of heat at the design point. The main heat rejection mechanism for the fuel cell stack is through the closed cooling water loop. A heat exchanger with a Q/T of 116 W/°C at a water flow of 2 gal/min was selected for the cooling water loop. The air stream used to operate the fuel cell also contributes to the cooling. This additional cooling occurs through convective heat loss from the outside of the stack and from the water lines. At an air flow of 148 l/min, ~ 4 W/°C of heat is removed by the air. Together, a total of 120 W/°C of cooling capacity is available from these two cooling sources combined.

Due to this cooling, a fuel cell operating temperature no more than of 55°C can be sustained indefinitely at an ambient air temperature of >25°C for continuous operation at the 100 % power level. As an electrochemical device, the fuel cell is self-regulating as long as some cooling is present. There will be no permanent damage to this fuel cell provided the fuel cell temperature stays below 75°C.

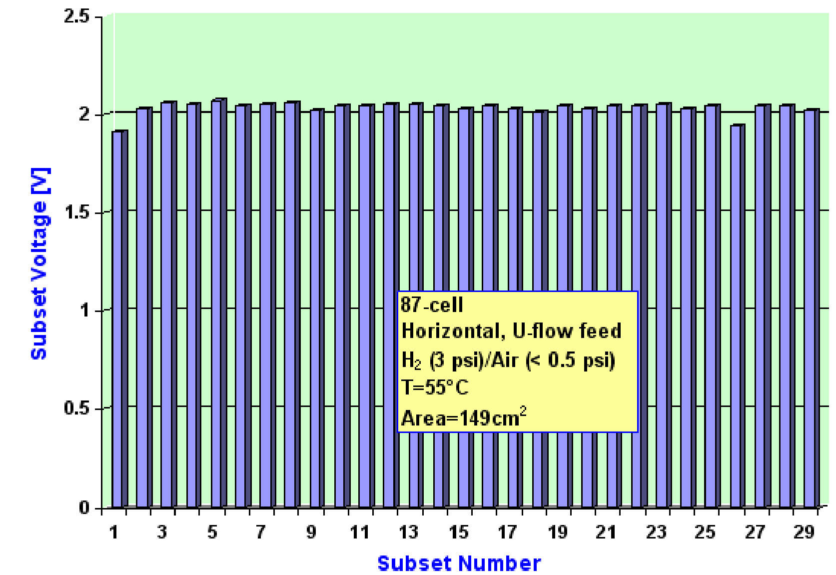

Figure 7. Subset values with U-flow configuration for fuel and oxidant.

Controller

A commercially available inverter was used. Air flow to the fuel cell, hydrogen purge valve operation and the cooling system has to be regulated for optimum efficiency and the most reliable operation. The dependence of blower speed as a function of load level was determined in the laboratory and included in the control program.

To develop this state-of-the-art generator, the latest generation embedded programmable microprocessor controller was selected. The controller uses about 5 W of power. The actual dependencies between temperature, fuel cell voltage, and blower output voltage have been experimentally determined. First, the digital reading - cooling water temperature dependency has been determined. The 87-cell fuel cell stack was combined with all auxiliary components into a stand-alone generator prototype. The operating procedures and parameters including orientation for the developed stack and its fuel, oxidant and water feed configuration have been optimized for the best possible performance.

At MER, we conducted optimization of the power system through experiments which followed the performance of various types of materials through numerous trials and errors. We uses 3D solid modeling to provide design guidelines and thus to accelerate the process of optimization. Figure 8 shows the 3D model system where all components have been mounted closely surrounding the fuel cell to obtain a rugged and small system. The outer and inner images of the 4kW system are shown in Figures 10 to 12.

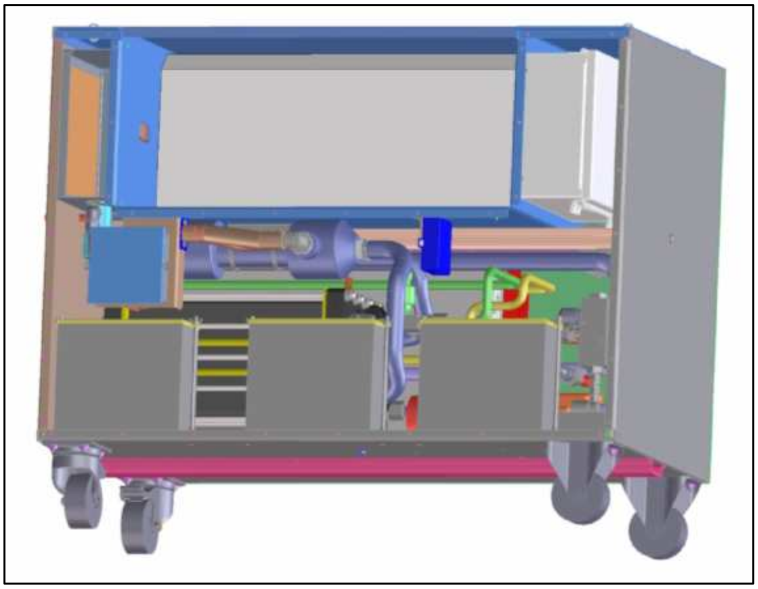

Figure 9. 3D Computer Model of 4 kW Fuel Cell Prototype.

Figure 10. The 4kW Modular Prototype.

The hydrogen exiting the water separation vessel is circulated and fed back into the hydrogen inlet using a pump. An additional solenoid valve next to the hydrogen inlet allows for start-up and hydrogen purge, if necessary. A cooling water circulation pump under the fuel cell stack circulates the cooling water as necessary through the fuel cell and the heat exchanger. An expansion vessel allows cooling water expansion and contraction with temperature. The heat exchanger has cooling fans that drive the forced airflow and two fans are used. A 4 kW inverter on the top of the generator takes in DC power from the fuel cell and outputs AC power.

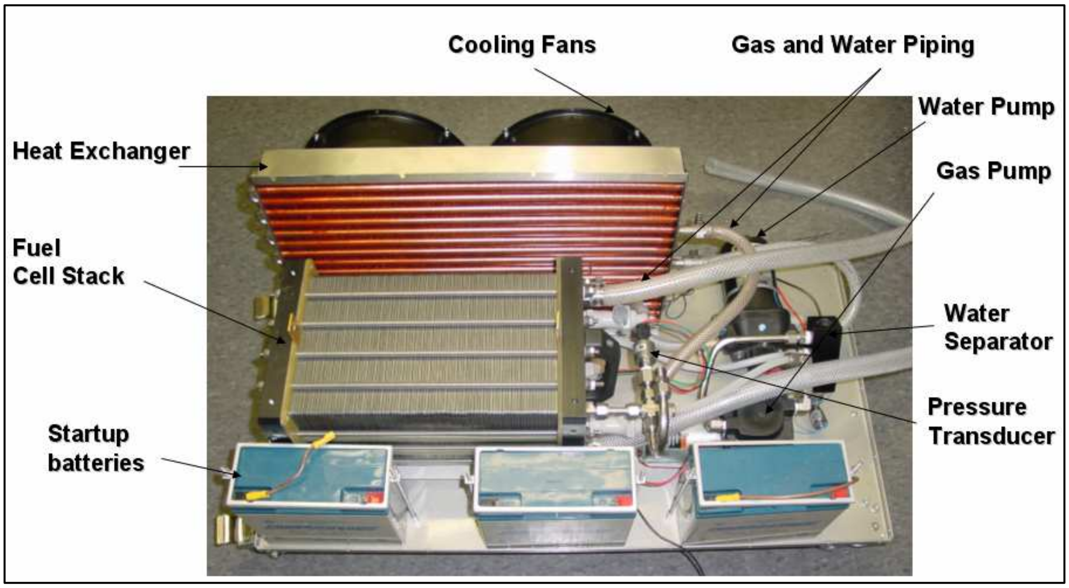

Figure 11. Inside the Prototype.

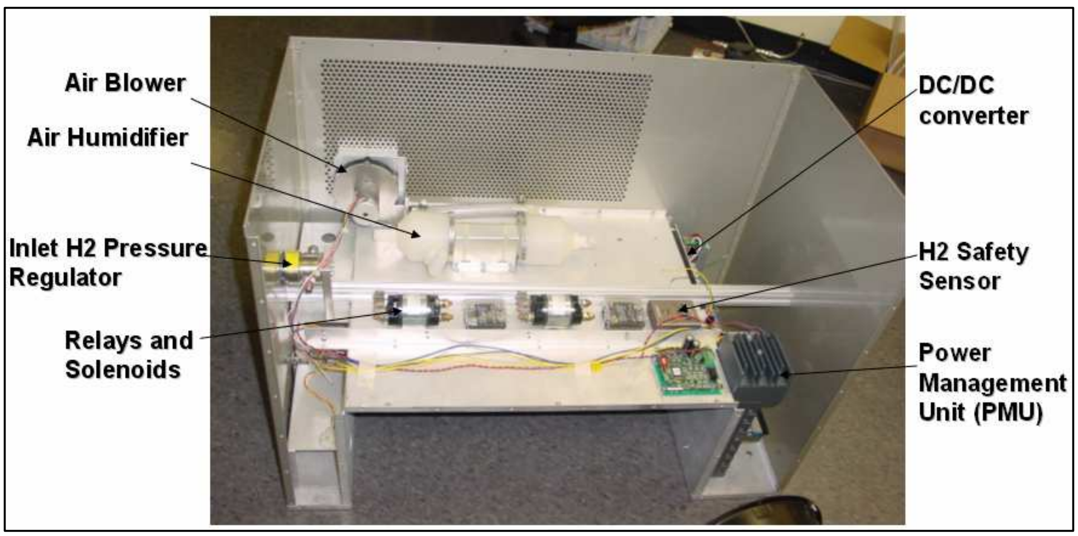

Figure 12. Inside the Prototype.

At present, we are testing the long-term performance of the generator and hardware used in the system. Up to now, the generator has been tested for 300 hours. Figure 13 shows the performance for our first 100 hours operation. It can be seen from Figure 13 that there was very little decay in performance in the operated period. Figure 14 shows the redundancy of the stack that was tested after an idle time of 24 days. During the idle time, the fuel cell was stored in an environmental as low temperature that went as 30°F and as high as 75°F. The performance of the stack after this 24 days idle testing was very encouraging. Further long-term testing is ongoing out at MER.

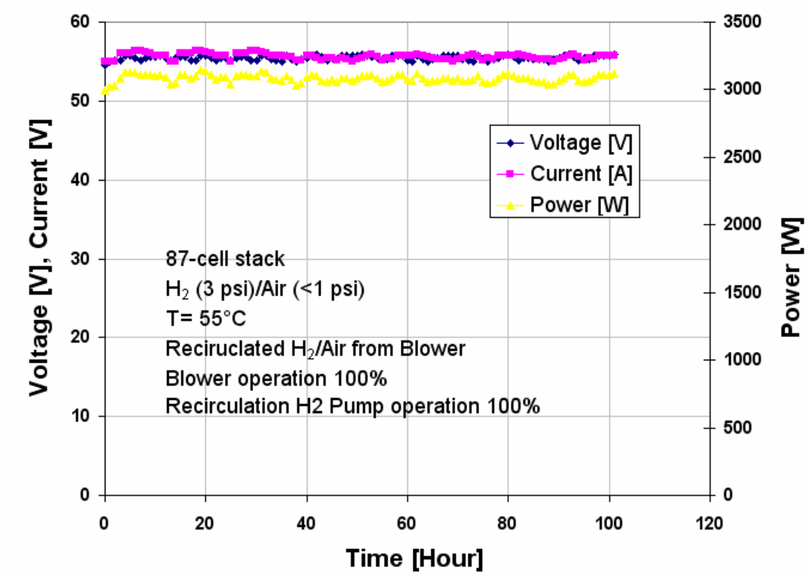

Figure13. The long-term performance of the generator.

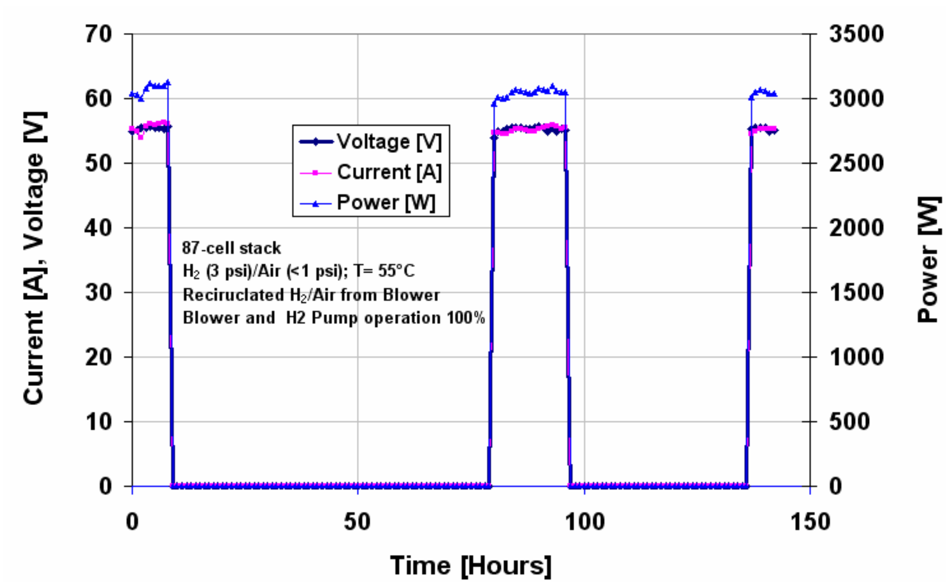

Figure14. Redundancy test of the stack.

The net DC power production and the parasitic losses for the 87-cell stack were calculated. Parasitic loads from the blowers, water pumps, heat exchanger with two cooling fans, and hydrogen recirculation pump were measured and shown to total 6.3% of the 4 kW fuel cell power output. Figure 15 shows the net DC power and the parasitic loss, which comes to about 180 Watts.

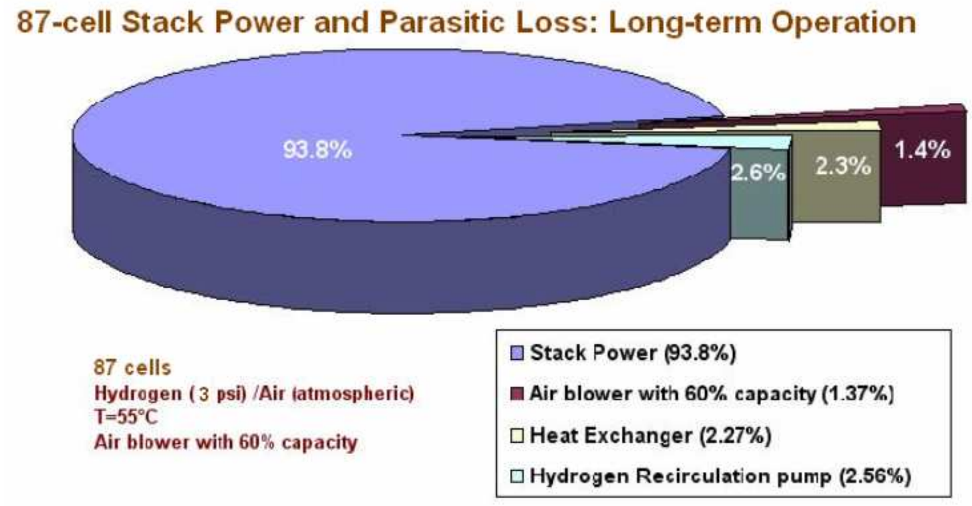

Figure 15. The 4kW Modular Prototype: Net DC power & parasitic losses of the stack.

The cost of operation at MER for the fuel cell generator was determined to be $0.6 per kWh. This is based on the current real purchase price of a cylinder refill for compressed hydrogen, which is $21.80. This cost only considers the fuel consumption and does not take into account the initial cost of the generator or maintenance costs. By comparison, the gasoline gallon equivalent (gge) cost of hydrogen at the present market rate is $8.5 (bulk rate) versus $2.00 for gasoline. However, this price is projected to drop significantly to $1.00 to $1.50 by the year 2015.

Conclusions

It is possible to build a low cost modular fuel cell generator. The modular concept offers an array of advantages that include improved redundancy, simple reconfiguration to meet deferent load levels, interchangeability, and hence the potential for wide applicability.

References

1. W. H. J. Hogarth and J. B. Benziger, *J. Power Sources*, **159,** 968 (2006).
2. W. Choi, Jo.W. Howze and P. Enjeti, *J. Power Sources*, **157,** 311 (2006).
3. J. Garnier, A. D. Bernardinis, M. Péra, D. Hissel, D. Candusso, J. Kauffmann and G. Coquery, *J. Power Sources*, **156,** 108 (2006).
4. M. C. Williams, J. P. Strakey and Subhash C. Singhal, *J. Power Sources,* **131,** 79 (2004).