Manuscript for 14th World Hydrogen Energy Conference, June 2002

FUEL CELL/PHOTOVOLTAIC INTEGRATED POWER SYSTEM FOR A REMOTE TELECOMMUNICATIONS REPEATER

P. Lehman[1], C. Chamberlin[2], J. Zoellick[3],
R. Engel[4], and D. Rommel[5]

The Schatz Energy Research Center built and operated a PEM fuel cell power system to supply back-up power to a remote photovoltaic-powered radio-telephone repeater. The fuel cell starts automatically when solar insolation is insufficient to maintain the state-of-charge of the system's battery. A cellular modem permits remote monitoring and control. In 229 days of operation, the original fuel cell stack logged 3239 hours of run time. An improved and rebuilt fuel cell stack subsequently ran for 3836 hours during 269 days. The authors discuss system performance, long-term fuel cell voltage decay, and lessons learned and applied in system refurbishment.

1. Introduction

Remote telecommunication systems present a special energy supply challenge, requiring reliable, unattended power system operation in locations where grid power is not available. For the Schoolhouse Peak telecommunications repeater, located in Redwood National Park in northwestern California, there was a further requirement: the National Park Service insisted that the system create no noise or air pollution in this pristine parkland setting. The Schatz Energy Research Center (SERC) and the Yurok Tribe met this challenge by installing a hybrid photovoltaic/fuel cell system that powers the Tribe's communications repeater. The system also supports essential loads for a fire lookout stationed at the site during the summer months.

Schoolhouse Peak is located within Redwood National Park in Humboldt County, California, approximately thirty miles by line-of-sight from the city of Eureka (see Figure 1). The repeater station and two other nearby repeaters, known as the Wiregrass and Miners Creek sites, form a chain that allows the upper Yurok reservation to maintain a telephone communications link via microwave signals with Pacific Bell's central system in Eureka.

The original fuel cell stack used in this system was replaced after seven months in service with a rebuilt stack. The system and the original stack are described in detail in two earlier papers [1,2]. This paper will focus on the performance of the second stack used in the system.

[1-5] Schatz Energy Research Center, Humboldt State University, Arcata, California

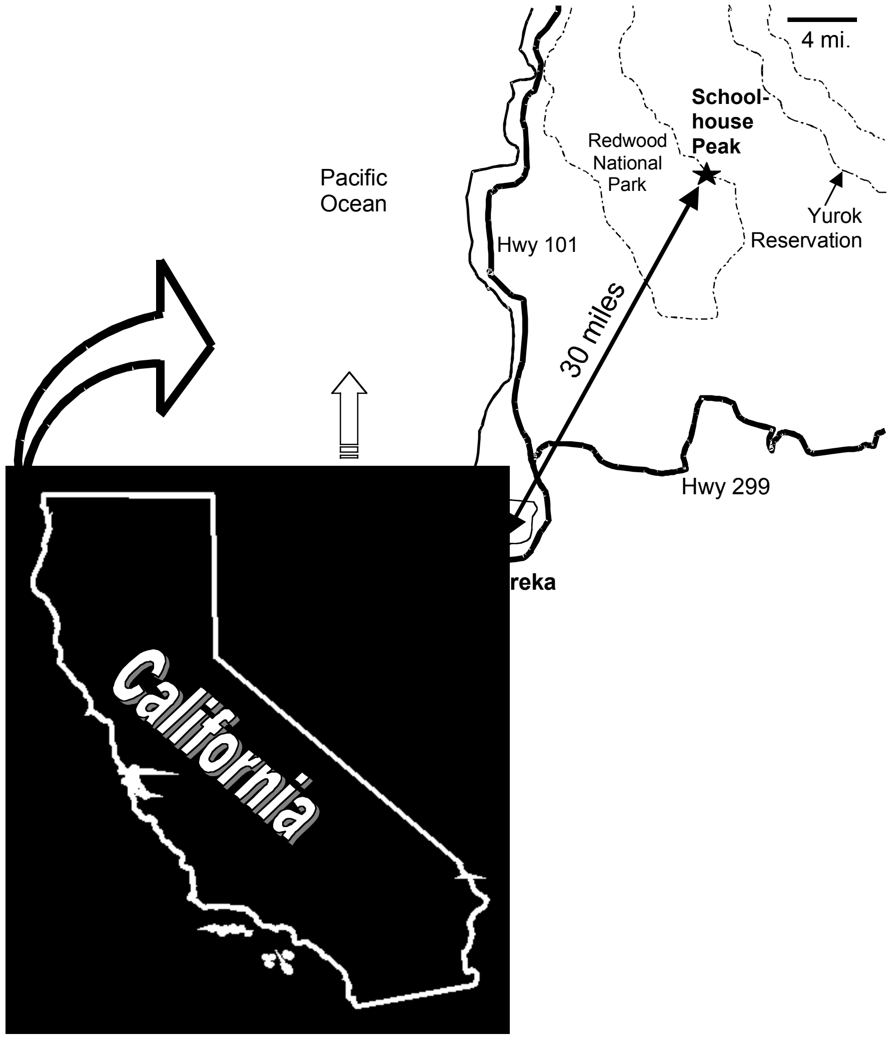

Figure 1. Schoolhouse Peak location

2. System Description

Figure 2 shows a schematic of the hybrid power system. Primary power is supplied by the photovoltaic (PV) array, consisting of twelve Siemens SP65 12-Volt, 65-Watt modules. In this 24-Volt system, the modules are configured as six series pairs wired in parallel. Due to National Park Service design requirements, the modules are mounted flush on the wall of the lookout tower, which is inclined 7º from vertical (see Figure 3). The location has an excellent solar window, unobstructed from horizon to horizon in all seasons. The array powers the telecommunications load directly, with surplus energy charging a set of ten Solar Electric Specialties 12SC225 12-Volt, 225 Amp-hour deep cycle batteries, arranged as five series pairs wired in parallel. When the solar array is unable to maintain battery state of charge above a voltage setpoint, the fuel cell system is activated automatically and carries the load until the battery voltage is able to recover.

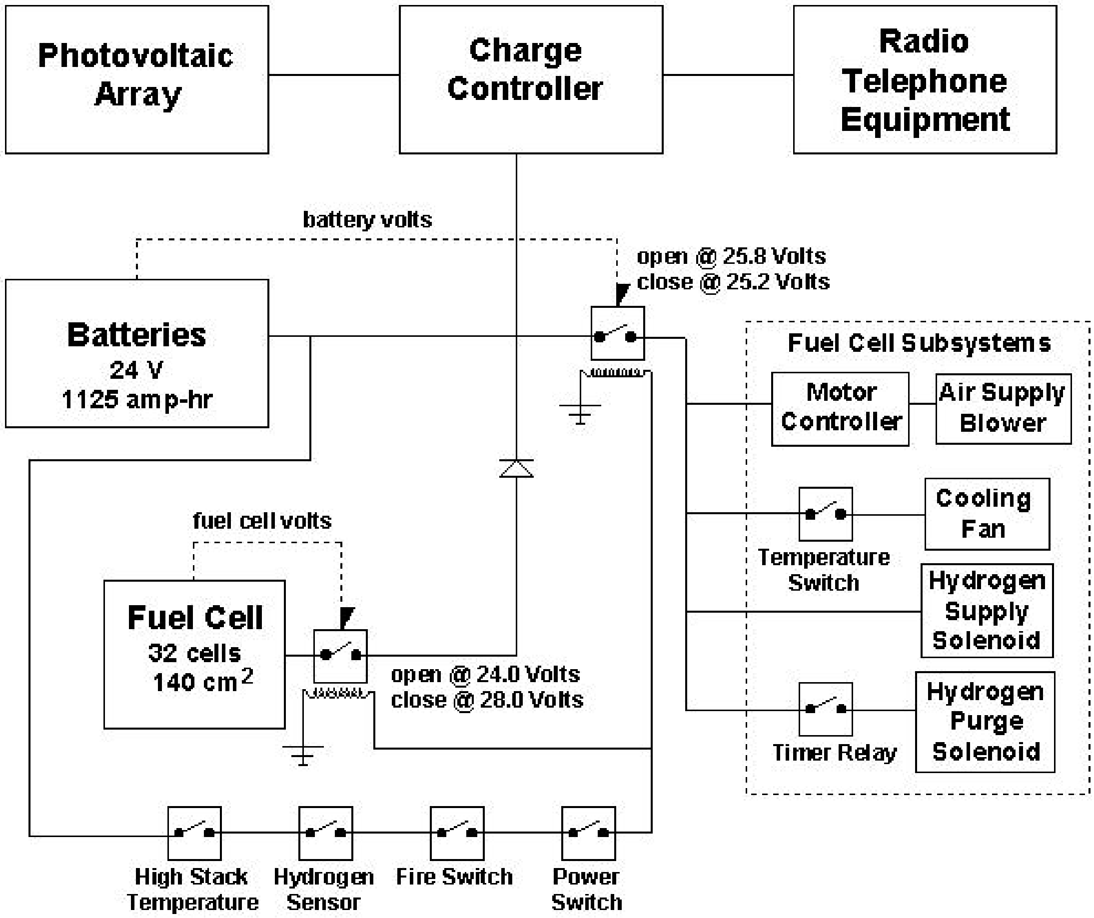

Figure 2. System schematic

The fuel cell (see Figure 4) is a 32-cell PEM stack with 140 cm^2, PRIMEA® 5510 membrane-electrode assemblies from W.L. Gore and Associates, Inc. and E-Tek ELAT gas diffusion media. SERC engineers designed and fabricated the stack in-house. It operates on hydrogen delivered at approximately 3 psig (absolute pressure = 120 kPa). A solid-state controller switches the stack subsystems on when battery voltage falls below 25.2 V and switches them off when voltage rises above 25.8 V. A second controller allows the fuel cell to deliver power at start-up when stack voltage rises above 28.0 V (open circuit) and disconnects the stack at shut-down when voltages fall below 24.0 V (after the subsystems are turned off). Safety interlocks are included to sense high stack temperature, the presence of hydrogen in the fuel cell enclosure, or a fire. Both controllers open, thus shutting down the fuel cell system, if any of these safety interlocks are activated.

Atmospheric air is supplied to the stack with a small centrifugal blower. Cooling is achieved using ambient air blown onto the stack surface from beneath by a pair of muffin fans.

The hydrogen supply for the system consists of twelve industrial gas cylinders manifolded together (see Figure 5). Cylinder pressure is initially 2000 psig, resulting in

Figure 3. Fire lookout tower with PV array

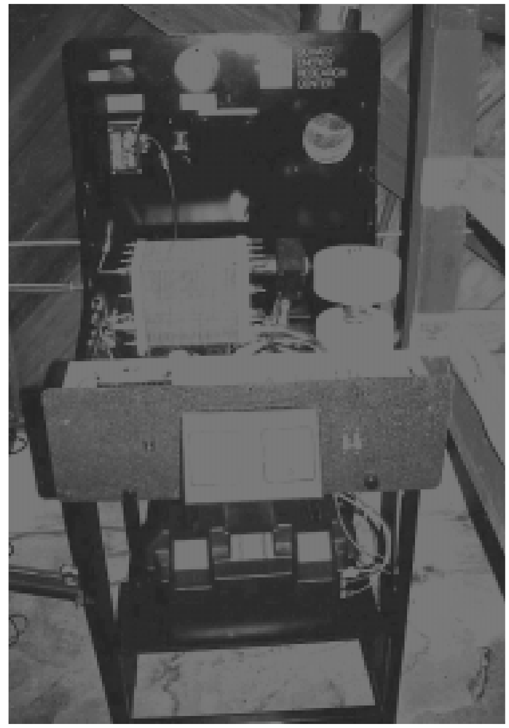

Figure 4. The fuel cell system

Figure 5. Hydrogen storage at Schoolhouse Peak

60,000 standard liters total storage. Regulators reduce the line pressure to about 100 psig, then to about 3 psig for delivery to the fuel cell. Replacement cylinders are delivered to the site as needed by a commercial supplier. During the winter rainy season, deliveries are required approximately once every two months. In the summer the PV array is able to carry the load, thus making hydrogen deliveries unnecessary.

The load is a telecommunications repeater transceiver with a continuous power demand of approximately 100 watts DC. Parasitic loads include the fuel cell blower, the cooling fans (when needed), and hydrogen purge and supply solenoids, totaling approximately 24 watts. As data acquisition is not integral to system operation, it is not considered a parasitic load in calculating system efficiency.

During the dry season (July-October), the fire lookout stationed at Schoolhouse Peak uses a small number of electric devices including a two-way radio and electric lights. The devices are used intermittently and together draw approximately 50 Watts. These loads use 12 Volts DC and were originally powered by a small separate PV array (visible on the ground at the base of the wall in Figure 3). This system no longer uses its own PV array and is now connected to the 24-Volt system via a DC-to-DC converter. During the fire lookout season each year, this 12-Volt system acts as an additional load on the 24-Volt system.

SERC provided a Campbell Scientific remote data acquisition and transmission subsystem to monitor fuel cell voltage and current, ambient and stack temperatures, hydrogen storage pressure, hydrogen concentration in the fuel cell enclosure, battery voltage, and the voltage and temperature of the data acquisition subsystem.

3. System History

The project began with the Yurok Tribe's desire to establish telephone service to its remote upper reservation. The Yurok Reservation consists of a two-mile-wide corridor of land straddling the lowermost fifty miles of the Klamath River in northwestern California. The communities on the downriver portion of the reservation have access to utility power and telephone service, but the upriver communities enjoy no such amenities. Even cellular phone signals cannot reach this deep, forested canyon. The Tribe decided to establish a radio-telephone network, initially to provide communications for the upper reservation's health clinic and tribal office, with plans to subsequently expand service to nearby residences and schools.

Linking to Pacific Bell's regional telephone network required the installation of three microwave repeater stations. Two of these stations are located outside of Redwood National Park and use conventional remote power systems consisting of PV arrays with small engine generators for backup. The Schoolhouse Peak station is located within the park, where environmental and aesthetic concerns must be addressed when installing new infrastructure. The park administration gave permission for installation of this facility in an existing fire lookout tower on the condition that the system not produce any air pollution or significant noise. In addition, the Park Service required that the Tribe limit the number of PV modules and mount them flush on the walls and roof of the lookout tower to minimize their visual impact on the landscape.

Given the site's tendency for long periods of rainy, foggy weather in the winter months, a PV-only system with no backup power would have required a prohibitively large PV array as well as a large number of batteries to ensure reliable operation in winter. As neither a conventional engine generator nor a PV-only system was feasible for this site, the Tribe was at a loss as to how to power their telecommunications repeater.

The Schatz Energy Research Center (SERC), based at nearby Humboldt State University, had already built and operated fuel cell systems for field service at other locations. SERC offered to work with the Tribe and the Park Service to develop a system using a PEM fuel cell as backup for the planned PV array.

The fuel cell system was designed and constructed by SERC over a period of several months and was first activated in November 1999. The system operated reliably until June 2000, logging 3239 operating hours over 229 days and 177 automated start-stop cycles. Batteries were maintained at an average state-of-charge of 74%.

In June 2000, the fuel cell stack developed a cross-leak, requiring the system to be taken out of service. The stack failure was apparently related to a sharp increase in ambient temperature. The system includes a small muffin fan mounted beneath the stack. This fan runs whenever the stack is operating and serves to cool the stack. During the cold winter months, it was observed that the fan cooled the stack to below its optimal operating temperature. The fan was disconnected, with the intention of reconnecting it at the beginning of the warm season. In mid-June, the stack failed during a sudden warm spell. The apparent cause of failure was volatilization of the resin in the graphite separator plates, causing the plates to become porous and hydrogen and air to bypass the cell membranes.

Following failure of the stack, the system was out of commission for several months awaiting delivery of materials needed to rebuild the stack. The system was rebuilt after re-sealing the separator plates using a high-temperature surface treatment. In the original system design, SERC engineers had chosen not to include a temperature-activated switch on the cooling fan in order to avoid unneeded complexity. Based on the failure of the first stack, SERC staff decided to incorporate the switch to avoid future overheating problems. The fuel cell went back into service on January 19, 2001.

The second stack ran for 3836 hours over 269 days, completing 283 start-stop cycles. While this second stack was in service, the Yurok Tribe completed installation of telecommunications equipment at their new Tribal offices on the upper reservation, and they were able to use the full telecommunications capability of the system for several months. Tribal staff and health care providers working on the reservation were able to use voice, fax, and internet communications over the system for several months. Unfortunately, continuing problems at the Wiregrass and Miners Creek sites, where power was provided by PV arrays with batteries and engine generator backups, limited the overall performance of the system

After the installation of the rebuilt stack, the battery bank was observed to have deteriorated in charge capacity during the hiatus between fuel cells. Battery capacity dropped to the extent that even during periods of sunny weather, the fuel cell needed to come on before midnight each night due to low battery voltage.

The fuel cell stack experienced a failure in October 2001 indicated by a sharp drop in cell voltage at one cell. Although the other cells continued to show normal voltages, the power output of the entire stack was greatly reduced due to the series arrangement of cells in the stack. The stack was removed from service and is currently being renovated.

4. System Performance

The Schoolhouse Peak system was originally designed so that the PV array and batteries would carry the load through most of the year, with the fuel cell expected to run only 400-800 hours per year. However, the degradation of the battery bank's storage capacity, coupled with the undersizing of the PV array due to the theft of several modules from the Tribe, have resulted in the fuel cell running a much greater portion of the time than was anticipated. Both the first and the second stacks averaged about 14 hours run time per day during their operating life. Figure 6 shows fuel cell current, fuel cell voltage, and battery voltage over several days of typical duty cycling of the second stack. High I_{FC} and V_{FC} values show that the fuel cell was running during nighttime and early morning hours, during which time battery voltage was constant or slowly declining. During daytime hours, the PV array brought the batteries up to a higher state of charge, making it unnecessary for the fuel cell to run.

Figure 7 shows the distribution of kilowatt-hours produced per day by the second fuel cell stack. The histogram shows that the system produced more than 1 kWh/day more than 85% of its days of operation. On an average day it produced 1.4 kWh, and on some days (5% of operating days), it produced over 2.5 kWh.

All PEM fuel cells exhibit voltage decay over time, and the two stacks used in this system were no exception. Figure 8 shows fuel cell stack voltage at three selected fuel cell currents (within a band of 50 mA of 3.5A, 4.0A, and 4.5A) plotted vs. hours of fuel cell operation. The trend lines for the voltage decay have been determined by linear regression and are also shown in the figure, along with the corresponding voltage decay rates (i.e. slopes in μV/cell/hr). These rates of long-term decay are very low (all are less than 10 μV/cell/hr) and indicate robust and durable performance of the stack.

SERC's previous experience with fuel cells has suggested that voltage degradation includes both reversible and non-reversible components, i.e. that some of the voltage degradation seen during periods of prolonged fuel cell operation can be recovered when the fuel cell is turned off and later switched on again. The data shown in Figure 8 support this observation. During an extended period of non-stop operation around 2200-2300 hours, a steep drop in stack voltage in the 4.50-4.55A current band is seen. In subsequent operation, this voltage loss is seen to have recovered. Cleghorn [3] discusses reversible and non-reversible voltage decay in PEM fuel cell membranes.

Figure 9 shows fuel cell operating voltages and currents during three distinct seven-day time periods near the beginning, middle and end of the second stack's time in service. These field "polarization curves" show a progressive increase in slope over the life of the fuel cell, which is the result of increased cell resistance from a slope of –0.30Ω to –0.49Ω. Figures 8 and 9 both demonstrate that the fuel cell stack's operating voltage at a given current declined as the fuel cell accumulated operating hours.

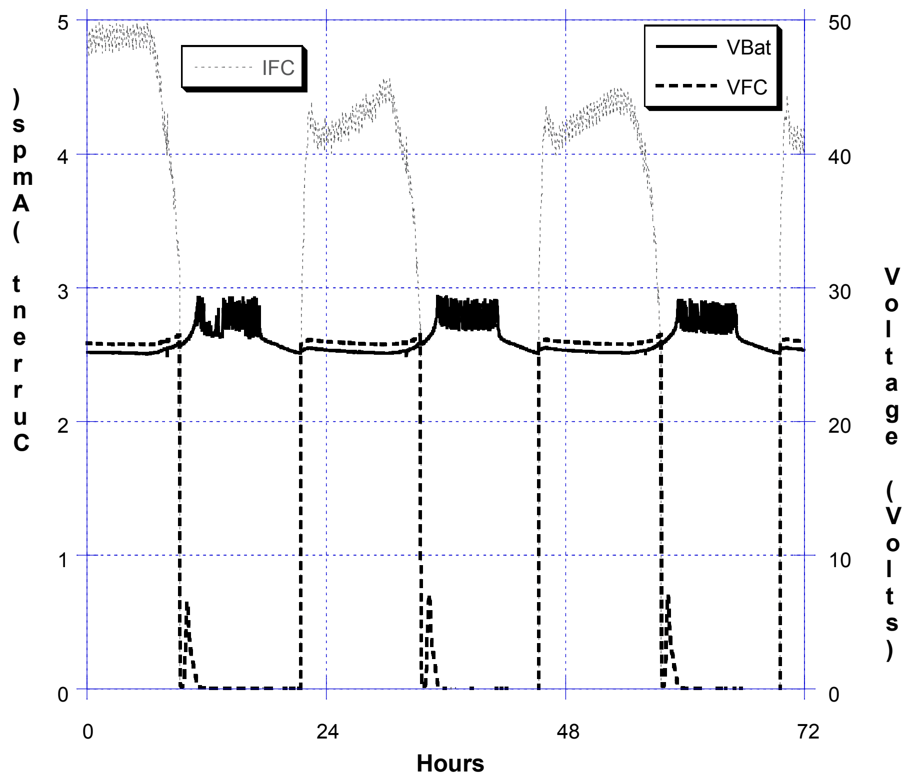

Figure 6. Typical operation of Schoolhouse Peak fuel cell (current and voltages)

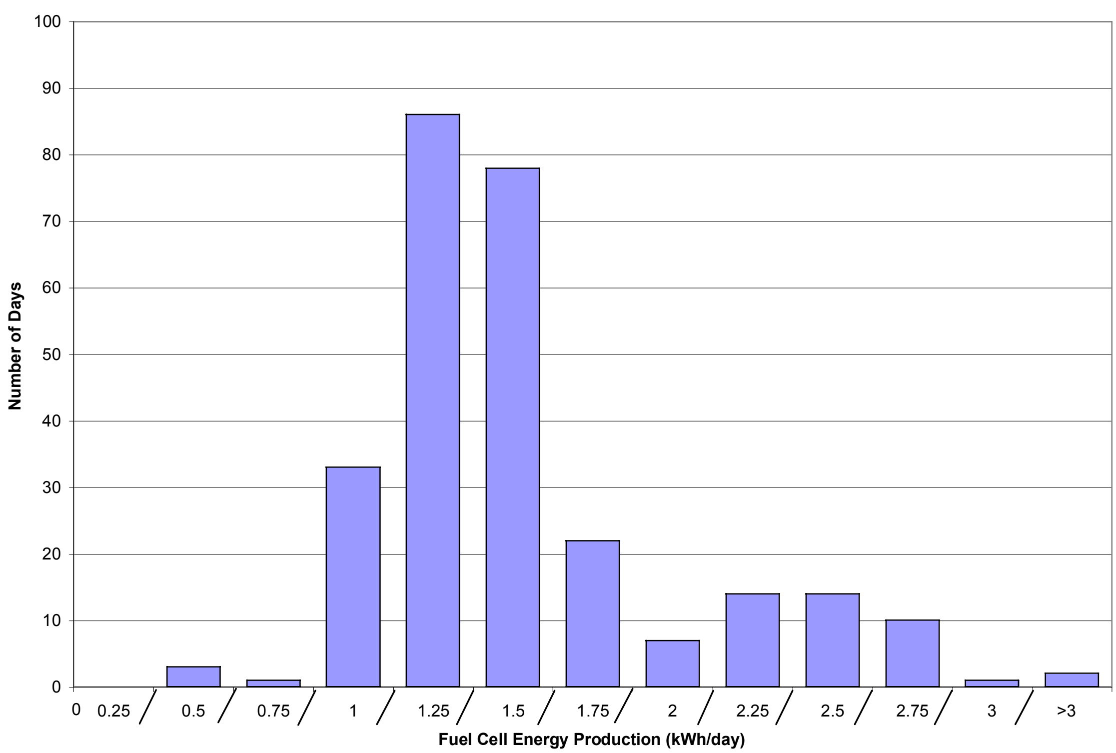

Figure 7. Fuel cell daily energy production distribution

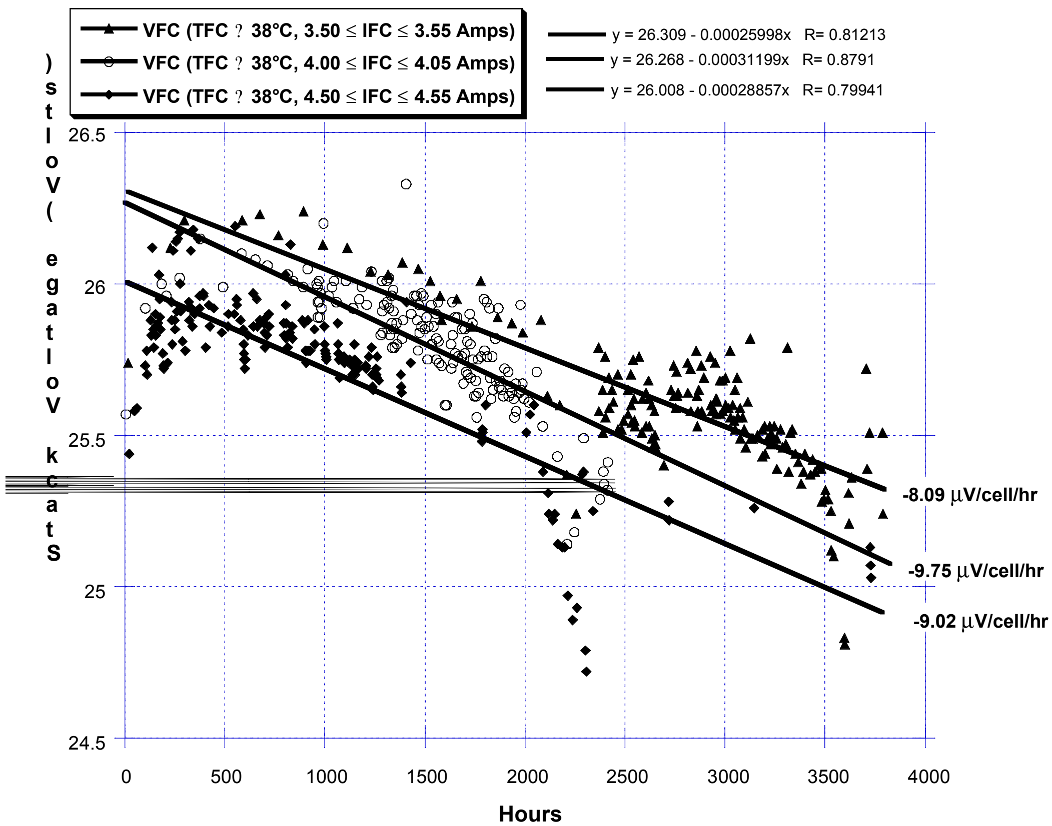

Figure 8. Stack voltage vs. time

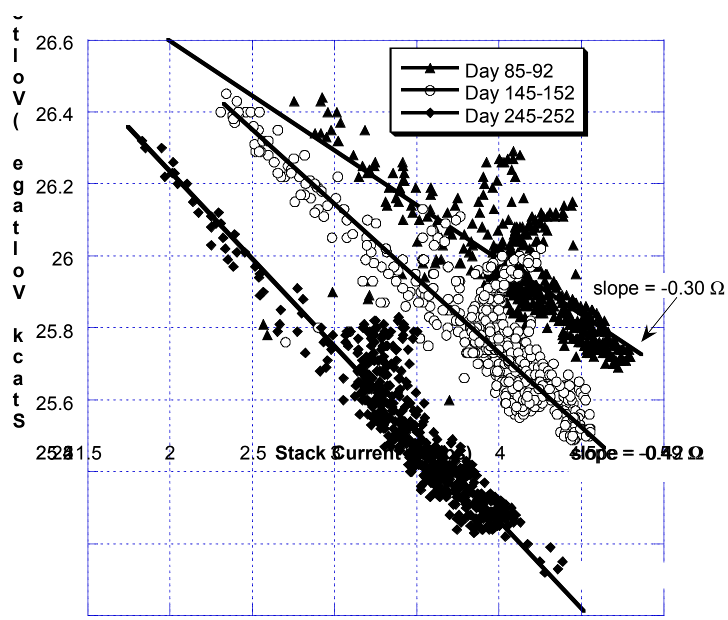

Figure 9. Voltage and current “polarization curves” over stack lifespan

The addition of a temperature switch, which automatically turns the cooling fan on when needed and turns it off to reduce parasitic load when cooling is unnecessary, appears to have benefited the system by improving the control of fuel cell temperature. Figure 10 shows how, as ambient temperature rises, the fuel cell is cooled by the fan coming on. The fuel cell temperature then oscillates up and down within the temperature switch's hysteresis band. Eventually the ambient temperature rises to a level at which fuel cell temperature can no longer be maintained in the hysteresis band, but the fuel cell operating temperature is always limited to less than 60°C.

Figure 10. Fuel cell and ambient temperatures

5. Planned Improvements to System

SERC and the Tribe have implemented a new agreement that will govern renovation and improvement of the power system. The agreement will provide for the replacement of the fuel cell stack and the batteries, as well as expansion of the PV array.

While only one membrane appears to be in need of replacement at this time, SERC has decided to replace all membranes in the stack, as the rebuilt stack has logged nearly 4,000 hours of run time. Replacing only the failed cell's membrane may cause the stack to require service again in the near future, creating an inconvenience for those who rely on the telecommunications system.

The existing sealed lead-acid batteries will be replaced with flooded batteries. The sealed batteries were originally specified because they are maintenance-free, an attractive feature for this remote, unattended site. Although flooded batteries require some periodic maintenance, their lower purchase cost and longer cycle life (500-1,250 cycles vs. 150-400 cycles for sealed batteries [4]) ultimately makes them more suitable for this project.

The PV array was originally designed to be larger than the twelve modules that were installed; however, due to the theft of several modules from another telecommunications repeater site, the Tribe elected at the time of system installation to reduce the number of modules installed at Schoolhouse Peak, diverting modules for use at the other site. The Tribe now plans to add four modules to the wall-mounted array and add an eight-module sub-array to the tower's roof, bringing the total number of modules to twenty-four.

6. Conclusions

The project at Schoolhouse Peak constitutes, to the best of the authors' knowledge, the longest-running field test of a PEM fuel cell to date. SERC engineers have learned from both the successes and the shortcomings of this system. All of the peripheral fuel cell equipment, including the hydrogen storage and delivery subsystem, the battery voltage-sensing relay, the safety shutdowns, and the remote data acquisition and control equipment, has performed flawlessly. Experience with the two fuel cell stacks has shown that the additional complexity of a temperature-controlled fan switch is justified to protect the stack from sudden temperature increases while minimizing unneeded parasitic loads. The success of the stack rebuild also suggests that pyrosealing the graphite components may help to avoid the crossleaks that occurred at high operating temperatures with the original resin-impregnated graphite.

SERC's experiences with the Schoolhouse Peak system demonstrate that PEM fuel cells are a viable alternative to engine generators as a backup for PV power at remote, unattended locations. PEM fuel cell technology, while still facing economic and technical hurdles on the way to becoming a popular energy supply alternative, can now claim to be a durable and reliable choice for specialized applications such as the Schoolhouse Peak telecommunications system.

7. References

1. Lehman, P.A. et al. [a], *Performance of a Photovoltaic/Fuel Cell Power System for a Remote Telecommunications Station*, 2000 Fuel Cell Seminar Proceedings, pp. 364-367.

2. Lehman, P.A. et al. [b], *A Photovoltaic/ Fuel Cell Power System for a Remote Telecommunications Station*, 2000 IEEE Photovoltaic Specialists Conference Proceedings, pp. 1552-1555.

3. Cleghorn, Simon, *Production of a Qualified Polymer Electrolyte Fuel Cell Membrane Electrode Assembly for Emerging Commercial Applications*, 2000 Fuel Cell Seminar Proceedings, pp. 35-39.

4. Spiers, David and Royer, Jimmy, *Guidelines for the Use of Batteries in Photovoltaic Systems*, Canadian Energy Diversification Research Laboratory of CANMET, Varennes, Quebec, Canada, 1998.

Curriculum Vitae

PETER A. LEHMAN
Director, Schatz Energy Research Center (SERC)
Professor, Department of Environmental Resources Engineering
Humboldt State University, Arcata, CA 95521
Phone: (707) 826-4345 FAX: (707) 826-4347 email: pal1@humboldt.edu

Massachusetts Institute of Technology: B.S. in Chemistry, 1966
University of Chicago: Ph.D. in Physical Chemistry, 1971

Lehman, P.A., Chamberlin, C.E., Engel, R.A., Reid, R.M., Rommel, D.S., and Zoellick, J.I., "Performance of a Photovoltaic/Fuel Cell Power System for a Remote Telecommunications Station," 2000 Fuel Cell Seminar, Portland, OR, November 2000

Chamberlin, C.E., Lehman, P.A., Reid, R., and Rommel, D.S., "Design and Performance of the PEMFC Power System for the Remote Area Power Project," 2000 Fuel Cell Seminar, Portland, OR, November 2000

Acknowledgements
The authors wish to gratefully acknowledge the assistance of the Yurok Tribe in developing the PV/fuel cell power system described in this paper. We are also thankful to the staff of Redwood National Park for their assistance.