A WATER PURIFICATION SYSTEM FOR REMOTE VILLAGES UTILIZING ULTRAVIOLET STERILIZATION AND PHOTOVOLTAICS

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ABSTRACT

This design project involved the research, design and manufacture of a water purification system using renewable energy for a Peruvian village. We carefully reviewed methods of drinking water purification and selected a ultraviolet (UV) lamp sterilizer system with power supplied by photovoltaic (PV) modules, based on cost, easy of use, robustness, and effectiveness. The system included power supply components, piping, filters, a fail-safe shutoff valve, storage tank and a shelter. It was installed and tested successfully in Peru. With an estimated one billion people in the world lacking clean water, this design may be useful for water purification in a variety of remote settings.

1. INTRODUCTION

Since 1997, UMass Lowell has been involved in projects aiding remote villages in the Andes Mountains in Peru as part of a service-learning project for students and volunteers. Presently there is a lack of developed infrastructure due to the poor economic situation and the remote location of these villages; electrical power, communications and sanitation are important issues. As part of the project, the indigenous lifestyles and values are considered in the context of the social and economical aspects of this project. Engineering students have made ten trips since 1998. Over 55 volunteers have traveled to Peru and have helped install over forty renewable energy systems.

In the small town of Quian, about 250 km north of Lima, water was drawn from the nearby irrigation canal for drinking, cooking and cleaning. In order to be safe for consumption, the water had to be boiled; this is both time consuming and uses scarce resources. The people requested a water supply and purification system. The town has no grid electricity. Most people live in houses with bamboo mats or adobe for walls. The indigenous Quechua people engage mainly in subsistence farming.

The water purification design goals include providing a safe water supply at low cost with high reliability. To accomplish this goal, impurities, such as sediment must be removed and bacteria along with other organisms killed. Additionally, the water must be stored so that any recontamination from bacterial growth is limited. Alternative design methods were explored for feasibility, ease of maintenance, low cost, and adaptability to an austere environment. The methods explored for water purification include pasteurization in a solar collector, UV-C radiation, slow sand filtration and chemical treatment. Additionally, safe methods of water storage were investigated so that there will be a water supply available if the treatment plant is not operating.

Through investigation, it was determined that an average person must consume one gallon (3.8 liters) of water a day to survive (1). The projected water supply goal for each person was 2 gallons (7.6 liters) per day to ensure an adequate supply and safeguard against loss of production due to days with insufficient sun. The minimum water supply goal was to produce 500 gal/day (1900 liters). This was based on the village population estimate of about 250 residents.

The PV and battery systems were sized to meet a loss of

{From the *Proceedings of the 2003 National Solar Energy Conference* of the American Solar Energy Society}

load probability (LOLP) of 0.1 %. A failsafe valve was designed and built to shutoff water in case the UV lamp burned out or if there was no energy available from the batteries or PV modules. Along with local residents and two other volunteers, we installed the system in Quian in July 2002. The system functioned properly, although the supply head was much lower than expected, resulting in a lower flow rate than planned. An outflow booster pump was installed in January 2003.

2. INITIAL DESIGN APPROACHES

Water purification methods researched as part of this project were slow sand filtration, chemical disinfectants and reverse osmosis; these were not pursued in detail for a variety of reasons. Considerations included cost, complexity of construction, energy requirements, maintenance, needed operator expertise, and effectiveness of the method. Explored in more detail were solar pasteurization and ultraviolet sterilization. These two approaches are discussed below.

2.1 Solar Pasteurization

Louis Pasteur first discovered the method of killing microorganisms by heating water to a required temperature, which is now called pasteurization. It was found that pasteurizing liquids at a high temperature for a shorter duration of time is preferred over a longer span of time at a lower temperature. Andreatta states that water has to be raised to “65˚C for six minutes” to kill any harmful organisms (2). To be more conservative, we assumed that heating the water to 80˚C for 6 minutes would pasteurize the water. Filtration requirements for pasteurization are minimal and require at least the removal of sediment particles such as sand and organic material.

The proposed pasteurization system consists of a batch operation flat plate solar collector. The collector encloses a serpentine pipe configuration. The main reason is that this configuration can produce a higher temperature change per unit area. The calculated area for an individual serpentine collector is approximately $2m^2$ and is estimated to produce about 11.3 liters/hour at an insolation of $600W/m^2$ (3). Based on an average operating day of 6 hour at this insolation level, about 31 collectors would be required. Advantages of solar pasteurization include minimal electrical components, limited filtration needs and easily available spare parts. Although there are advantages to this approach, the disadvantages are considerable, including a higher capital cost, operation only during the day, multiple locations and higher exit water temperature that may foster bacteria growth in the storage tank.

2.2 Ultraviolet Sterilization

An ultraviolet sterilization system requires that the water pass by an ultraviolet lamp that produces UV-C light at a wavelength of 254 nm and a minimum dosage of 40,000 μW/cm2 per NSF/EPA Standards (4). Ultraviolet light treats water by disrupting the DNA of target organisms rendering them inactive; the inactivated bacteria perish or become benign. The advantage to this system is that if backup batteries are used, water availability is not limited to daylight hours, whereas the pasteurization method water will only be produced during the day when sufficient irradiation is present. However, UV requires better filtration and regular maintenance. Since there is little available power in Quian, an external power source must be installed. The power production element of the UV system consisted of PV modules, batteries, a charge controller and additional safety controls. A key advantage of the UV system is that excess power can be stored in the batteries for days in which cloud cover limits the PV power generation. Ultraviolet treatment requires a level of prefiltration to 5 microns to ensure that all particle surfaces are exposed to the UV light. The main disadvantages to this system are that it requires regular filter maintenance and subsequently higher annual incurred costs.

3. FINAL DESIGN APPROACH

An ultraviolet sterilizer was chosen to treat the water. This system was the least expensive and most reliable system investigated. It has the added benefit in that it can easily be expanded to meet future requirements of the village due to its modular design.

A four-day reserve power capacity was incorporated; determined using the LOLP approach (described below) to ensure continued operation of the UV system. The system has an advantage over pasteurization, in that it can operate 24 hours a day and has a higher hourly production rate than pasteurization.

3.1 UV Sterilizer

The chosen ultraviolet purification system is from R-Can Environmental Inc, Model #S2Q-P/12VDC. This UV system can treat up to 2 GPM ($7.6\ l\text{-}min^{-1}$) and uses 19 watts, it was chosen because it is the least expensive and most adaptable of all the UV systems investigated.

To prevent untreated water from contaminating the treated system a control valve was designed and is described in more detail later. Fault conditions addressed by the control valve system are bulb burnout and system power loss. When either of these conditions occurs the control valve closes, isolating the treated water supply and keeping it safe.

3.2 Photovoltaic System

Due to the constraints of cost and a lack of specific local meteorological data, the PV system had to be sized as small as possible without sacrificing dependability. Three different sizing methods were used and compared to one another to determine the minimum number of PV modules and batteries needed for an adequate amount of storage days to ensure reliable and sustained service. The three methods used were developed by the Florida Solar Energy Center (FSEC), BP Solar, and Bloom and Duffy.

Quian was assumed to receive a worst month irradiation of approximately 4.5 kWh/m^{2}day based on information from San Ramon, which has similar latitude, longitude and altitude as Quian (5). Using design insolation maps from the BP Solar website, Quian was estimated to receive a solar irradiation of 4 to 5 kWh/m^{2}day for the worst month at an optimal tilt angle of ten degrees (6).

The UV sterilizer and control systems consume about 20 watts; for continuous operation the system would require a minimum capacity of 480 Wh per day. In addition, 105 Ah lead acid deep discharge batteries were specified in this design and were modeled with an 80% depth of discharge. The system utilized Model ASE-50-AL, 50 Wp PV modules donated by ASE Americas, Inc. The designed maximum allowable voltage drop for the system was chosen to be 2%. Additional components included a charge controller to protect the batteries and the load, a lightning arrestor to protect the system, and circuit breakers. Figure 1 shows the system wiring diagram as installed.

Using the stand-alone system sizing procedures provided by FSEC and taking into account a dust reduction factor of 7% and assumed losses from the charge controller and the entire system; the daily load requirement was calculated to be 572 Wh (7). Using an assumption of a four day battery reserve and that the PV modules would be operating at standard test conditions (STC), the system required a battery capacity of 238 Ah. Therefore the system required three 12 volt 105 Ah batteries connected in parallel as well as four 50 Wp PV modules for uninterrupted operation.

The BP solar method was used to verify the calculations obtained from the FSEC approach (6). This method used a factor of 1.2 to account for all system losses and environmental factors. Again assuming four day reserves and modules operating at STC the recommended nominal battery capacity is 240 Ah; thus this system would require four 50 Wp PV modules and three 105 Ah batteries.

The Bloom and Duffy approach takes into account LOLP to estimate the required array and storage size needs for continuous operation (8). LOLP is defined as the percent of the total load that will not be satisfied by the system because of insufficient insolation levels. Based on the criterion for a "life-threatening situation" or 0.1% LOLP as opposed to that for a, "critical situation" or 0.5% LOLP the system would require four 50 Wp modules and three 105 Ah batteries for sustained operation.

3.3 Control Valve Assembly

Contaminated water must not be allowed to pass the UV treatment plant and enter the clean portion of the piping system. Therefore, a valve was needed as a means of controlling the water supply through the UV plant in the

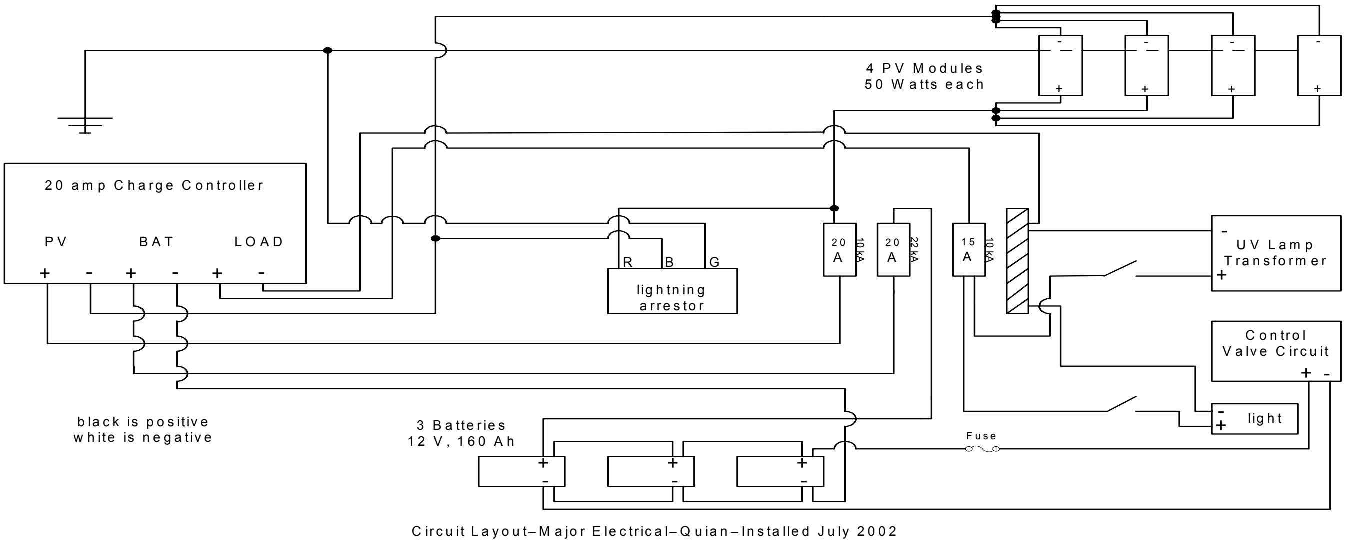

Fig. 1 PV system electrical design

event of a system failure. Two modes of possible failure to be controlled are total system loss of power and UV sterilizer lamp burnout. Options that were considered for these situations were a solenoid valve that is energized in the open position while the sterilizer is in operation or a self-actuating valve that requires an impulse to close the valve when a fault is detected. The ten or more watts of power required for a solenoid valve would have increased the number of PV modules and batteries needed. Existing valves that could perform the necessary operation are expensive and are generally made for different operations. Because of the limited budget available, a design was made that would modify inexpensive components to be used in the control valve assembly.

The selected control valve design employs a self-closing valve that will shut when triggered by the above situations. The valve will require a manual reset so that the cause of the fault may be investigated. The control valve assembly may be broken down into two components, the mechanical portion and the electrical portion. The control valve was a design/build module, due to the necessity of hand fitting some components before dimensions could be specified for other parts.

3.3.1 Control Valve Mechanical Subassembly

The control valve mechanical subassembly is comprised of four segments: a ball valve, support frame, latch mechanism with solenoid, and a spring. The ball valve body is held in the support frame, with the latch and solenoid affixed so the valve handle is held in the open position by the latch. The spring is attached to the valve handle so that it closes the valve when the solenoid activates. Figure 2 is a CAD view of the designed valve assembly.

The spring is pretensioned when the valve handle is in the closed position to ensure that the valve is completely seated. An intermittent duty pull type solenoid was used to release a latch holding the spring-loaded handle in the open position. The latch was designed to give a mechanical advantage of about 2:1, and is self-locking when engaging the valve handle, by aid of a small return spring that rotate the latch in the closed position.

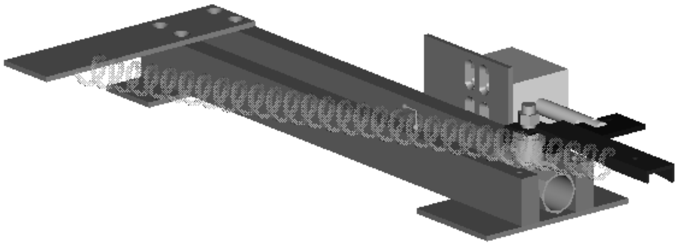

Fig. 2 CAD sketch of failsafe water shut off valve

3.3.2 Control Valve Electrical Subassembly

The electrical portion of the control valve consists of five major segments: a photo resistor, comparator circuit, relay, capacitor, and solenoid. The capacitor holds the energy to trigger a solenoid when normal power is lost and is wired in series with the relay contacts and solenoid. When the relay closes, the capacitor is allowed to drain through the solenoid actuating the latch mechanism, causing the valve to spring shut. Additionally, when the relay closes the capacitor is isolated from its charging voltage so the solenoid will not overheat due to continuous duty. During normal operation, the relay is held open in an energized state by the output from the comparator. If power to the comparator is lost, the relay will close, actuating the valve; this satisfies the condition for power loss to the UV sterilizer, as the power supply is the same. The lamp-out portion of the circuit consists of a photo resistor input compared to a trigger

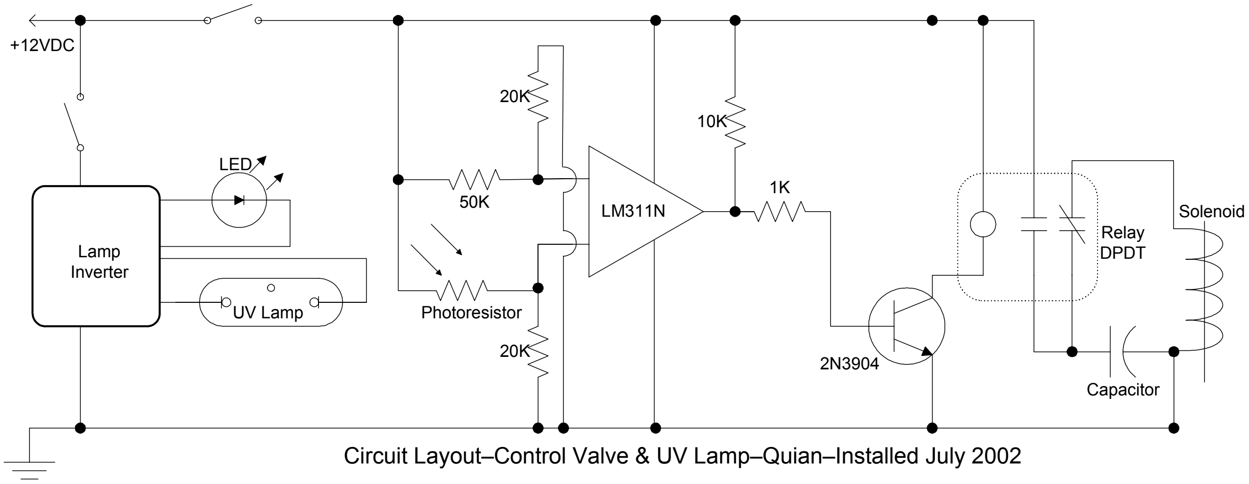

Fig. 3 Fail Safe Valve Circuit

resistance in the comparator. The photo resistor is installed in the end cap of the UV sterilizer so the UV bulb illuminates it. When the UV lamp burns out, the resistance of the photo resistor will be greater than the compared resistance value causing the output from the comparator to switch off, allowing the relay to close, actuating the valve. The capacitor must store enough energy to be able to operate the solenoid; by experiment, it was found that two 8200 μF electrolytic capacitors would supply the necessary energy. The control circuit operates using 12 volt DC, the same as the UV sterilizer. The circuit diagram is shown in Figure 3. Power consumption of the control valve circuit is less than 1 watt.

3.4 Additional System Components

3.4.1 Piping Design and Considerations

For the design project the piping system design was broken down into three main segments: the supply to the treatment plant, the treatment plant, and the Quian distribution network. This was done so that each section could be analyzed separately. Major considerations that were addressed were water hammer, head loss and maximum working pressure. Due to the constraints of cost and a lack of specific local topographical information the piping system was specified with a significant amount of flexibility, due to the necessity of designing the piping network onsite. The total daily output of the UV treatment plant was 5,450 liters with an additional storage capacity of approximately 10,000 liters. Because of the limitations inherent with the available photovoltaic power to drive pumps, a gravity flow system was originally envisioned. Additionally, the working pressure of the piping and fittings control the maximum elevation change allowed. Peruvian class 15 PVC pipe with a maximum working pressure of 210 psi (1.5 Mpa), was used where appropriate.

Based upon a planned maximum and minimum working pressure of 125 and 80 psi (862 and 552 kPa), respectively, the location of the treatment plant was to be located between 80 and 50 meters below the water source. The source will eventually be a spring 1.5 km away connected by pipe, which we are providing the town. The water pressure supplied to the treatment plant must be no higher than 125 psi (862 kPa), the maximum working pressure of the lowest rated component in the system, the filter housing. A pressure relief valve was used to protect this portion of the system. To reduce the possibility of water hammer the fluid velocity can not be allowed to exceed 5 ft/sec (1.5 m/sec), this minimizes hydraulic shock effects in the PVC pipe. To accomplish this, an inline-regulating valve was chosen due to its low cost and pressure range flexibility. The control mechanism is a flexible orifice that varies its effective area inversely to the applied pressure. The valve will provide a 1 GPM ±15% flow rate. The purpose for limiting the flow is

Fig. 4 Part of installed system inside adobe shelter: flexible tank to left on floor, UV light in stainless tube to right of tank horizontal on plywood (near center of photo), filters below and to the right, failsafe shutoff valve mounted to bottom of plywood on the right just above filters.

to ensure that the water receives a dosage of at least 40,000 μW-sec/cm^2 in the event that the bulb degrades faster than expected.

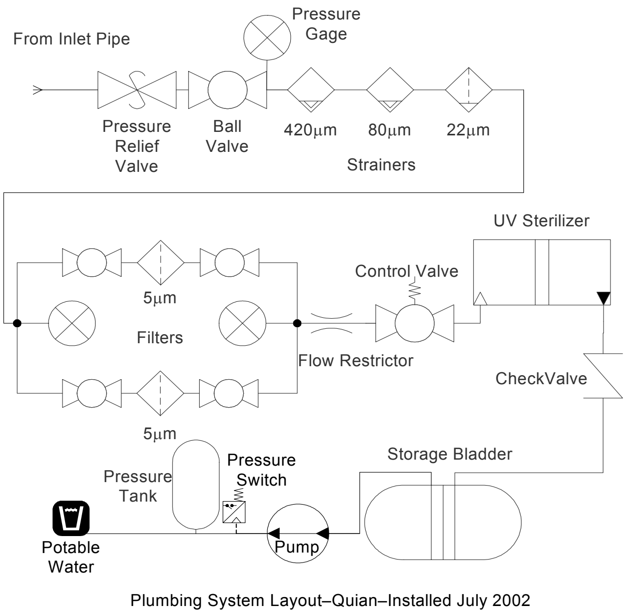

Fig. 5 Water System Components

3.4.2 Filters & Strainers

To ensure that all particle surfaces are exposed to the UV light, the water particles must be filtered down to 5μm in diameter. Due to a significant loss in pressure as filters become clogged, it is recommended that a combination of filters and strainers be used to ensure that adequate pressure is available for the flow controller and UV unit. For the treatment plant, three mesh strainers connected in series and two 5μm polypropylene filters piped in parallel were used. Each filter run is separated from the piping network by a series of valves so filters may be changed without interrupting the operation of the system. The three phase straining process incorporate an inline strainer with a 420μm stainless steel mesh and two “Y-strainers” with mesh sizes of 80 and 22μm respectively. The strainers remove heavy to moderate particles and contribute minimal pressure drop; they can be cleaned out, ensuring a long operational lifespan. The pressure loss due to the 5μm filter and filter housing is a maximum of about 35 psi (241 kPa) per filter unit before change out is needed. Three pressure gauges located at either end of the filter runs and in front of the inline strainer were used to indicate the pressure differential between the filters and strainers to indicate when maintenance is required. Figure 5 represents the layout of the strainers and filters with other components in the treatment system.

3.4.3 Post Treatment Water Storage & Supply

Due to the slow rate of water treatment, a tank was required to provide for peak water usage demands. Based upon the initial estimate of water needed for the village an appropriate tank size would be about 1900 liters for one day’s supply. A 10000 liter flexible water bladder tank located at the treatment point was used based on the ease of installation and as a design compromise since it had been purchased for another project and was not used. Locating the tank at the treatment point allows for easier maintenance and troubleshooting by locating more system elements in one area. A flexible tank has the advantage of being easy to transport to the site due to low weight and bulk; it also limits exposure of treated water to airborne contaminants. Problems with flexible tanks occur due to the difficulty of cleaning inside and their temporary nature. The main concern with using a tank with UV sterilization is the possibility of post treatment contamination due to water sitting for too long in a tank. The bladder was manufactured by SEI Industries and measure 3.7 x 3.6 x 0.9 meters when full. The tank is protected from sunlight to prevent degradation from UV exposure. A permanent tank should replace the bladder tank once the village is able to build one.

Occasional flushing with a chlorine solution is needed to ensure that bacteriological growth due to standing water is limited. Regular water quality testing will be used to determine when this action must be performed.

As part of a follow-on project, an outflow pump was added in January 2003 to provide pressurized post treatment water to more of the village. A 12 volt DC diaphragm pump was used in conjunction with a small pressure tank and pressure switch to boost the line pressure to 20 to 40 psi (138 to 276 kPa).

Local residents constructed an adobe block building to protect the 10000 liter tank and the system components from weather exposure, livestock, vandalism and theft over the course of a day and a half. The dimensions of the building are 5 meters square with a sloped corrugated tin roof 2 meters high on the southern side, and about 1 meter high on the north side. The roof supports four PV panels that weigh 5 to 7 kg each. A view of the adobe building and some of the authors and villagers is shown in Figure 6.

4. CONCLUSION AND RECOMMENDATIONS

The design of a water purification system was accomplished that will exceed the original production estimate needed for drinking water in Quian. This design project shows the necessity of teamwork, research techniques, the realities of the design process, the inability to find the perfect solution

Fig. 6 Adobe shelter with PV modules mounted showing some of the authors and villagers.

for a real world problem, and the necessity of making decisions with less than optimum information. The water purification system was installed successfully in Quian in July 2002. An outlet water pressure booster pump and five-gallon pressure tank with a pressure-stat were installed as part of the PV-powered system in January, 2003. It contains some unique features, such as the failsafe shutoff valve.

Future design considerations that may be pursued are improvements to the control circuit to automatically open and close the control valve, perhaps with a motorized valve, so that a manual reset is not required. A level control system could also be implemented so that only the needed amount of water is produced, lessening the chance of post treatment recontamination.

This system could well serve as at least a starting point for systems to serve other similar parts of the world in need of drinking water.

5. ACKNOWLEDGEMENTS

Funding from Rotary International, U Mass Lowell, St. Mary’s Parish, Winchester, MA, and several individual donors for the project are gratefully acknowledged. Assistance in the design and installation of the system by Steve Kurkowski, Juan Pablo Trelles, Janice Dauphinais, and Elena Franzen as well as many of the local people is appreciated. Donation of many PV modules by ASE Americas for this system and many others in the Peru project is gratefully acknowledged.

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{From the *Proceedings of the 2003 National Solar Energy Conference* of the American Solar Energy Society}